INTRODUCTION TO BEYOND THE STANDARD MODEL PHYSICS

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QSFP School, Jan 7 2020

OUTLINE

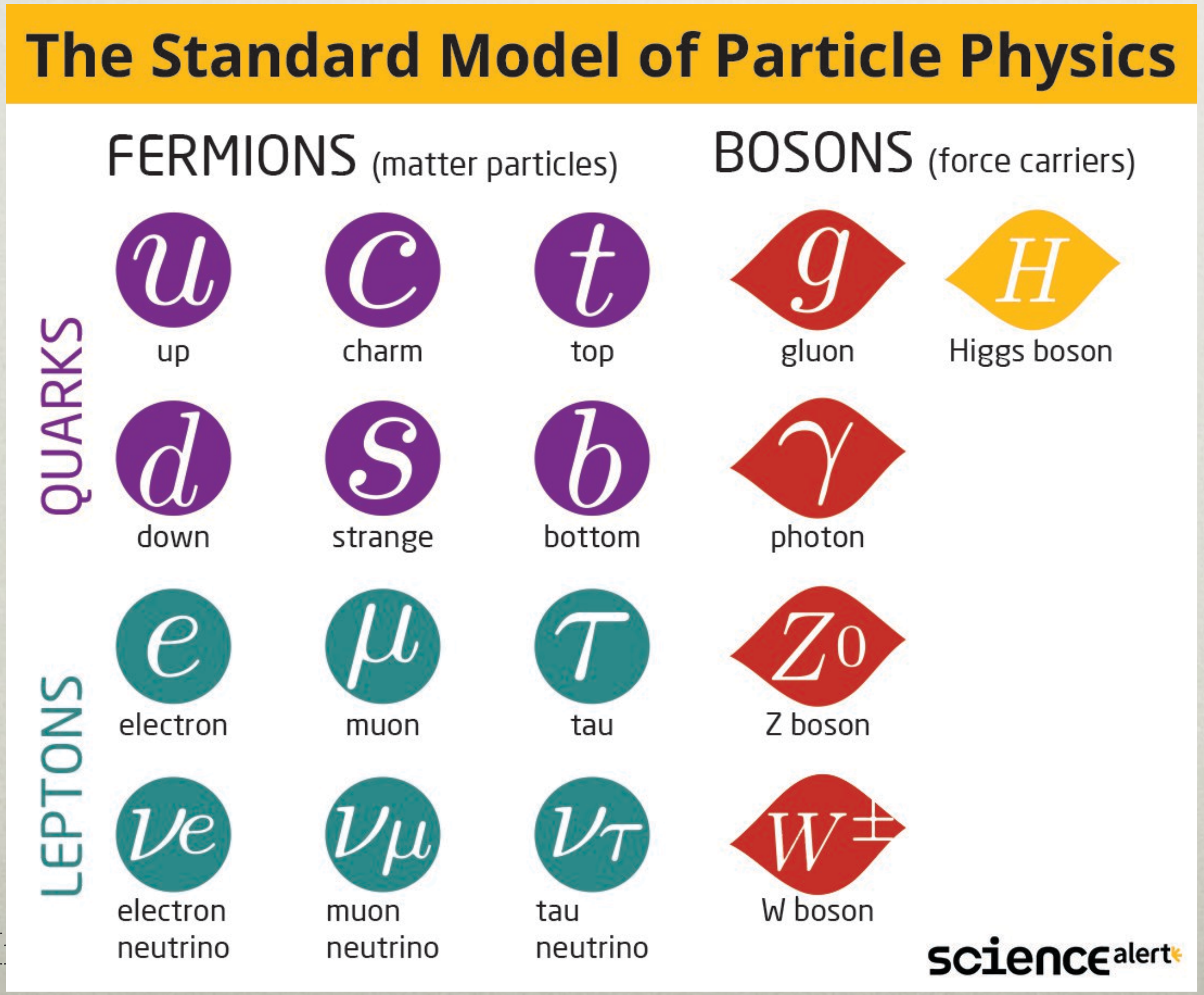
- Lecture 1
  - why Beyond Standard Model (BSM)?
  - evidence for Dark Matter (DM)
- Lecture 2
  - DM production
  - DM models
  - DM detection
- Lecture 3
  - axion
  - relaxion
  - baryogenesis ⇒gravity wave

NATURAL UNITS

- in this talk use natural units
  $c = \hbar = k_B = 1$
- conversions
  $r = \hbar c/E: \quad 200\,\mathrm{MeV} \Longleftrightarrow 1/\mathrm{fm}$
  $t = \hbar/E: \quad 6.6\,\mathrm{MeV} \Longleftrightarrow 1/(10^{-22}\,\mathrm{s})$
  $k_B T = E: \quad 1\,\mathrm{eV} \Longleftrightarrow 1.2 \cdot 10^4\,\mathrm{K}$
  $p = E/c: \quad 1\,\mathrm{MeV}/c \Longleftrightarrow 1\,\mathrm{MeV}$

STANDARD MODEL

- Standard Model (SM) of particle physics
  - is a Quantum Field Theory
  - field content: quarks+leptons
  - gauge forces+the Higgs force



FIVE STANDARD MODEL FORCES

- the five SM forces are $F \propto 1/r^2$ at short distances
  - E&M and gravity $V \propto 1/r$
  - weak nuclear and Higgs force $V \propto e^{-mr}/r$
  - strong nuclear force $V \propto 1/r + kr$
- relative strengths very different
  - for instance, for top quarks

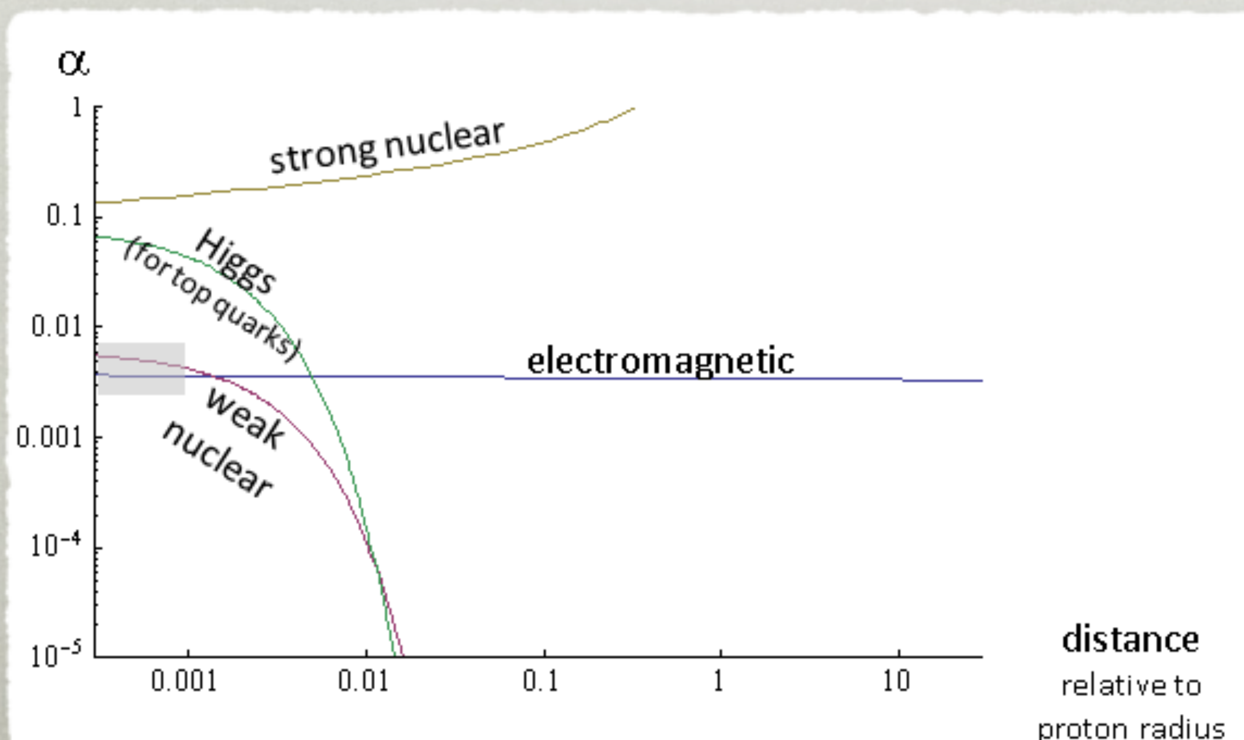


figure by M. Strassler

STATUS OF PARTICLE PHYSICS

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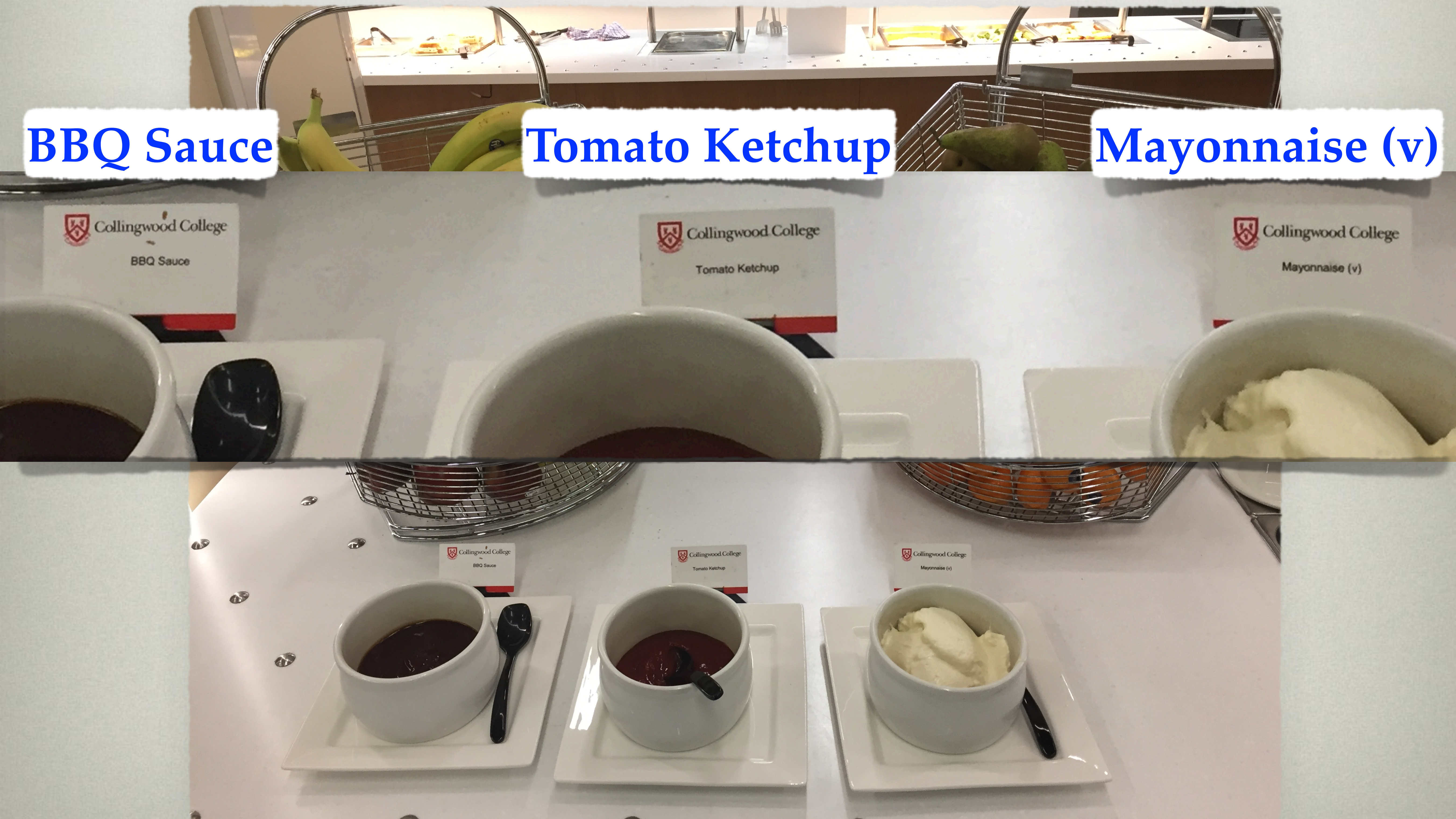
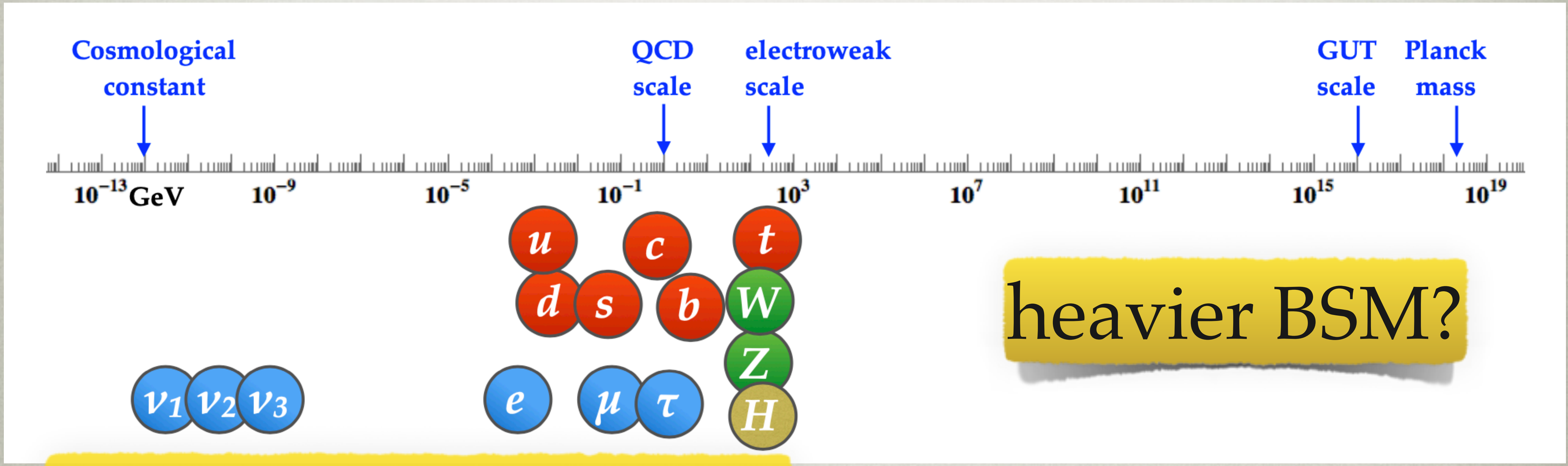


REASONS FOR BEYOND THE STANDARD MODEL

- existence of dark matter
  - the nature of dark matter/dark sectors
- strong CP problem
  - why is strong interaction Charge Parity symmetric?
- the electroweak hierarchy problem
  - why is Higgs so "light"?
- dominance of matter over antimatter
  - baryogenesis/leptogenesis?

PHYSICS BEYOND THE STANDARD MODEL

- have we discovered all the forces?
- all the particles?



heavier BSM?

light but
weakly coupled BSM?

DARK MATTER

UPSHOT

- many different probes point to the existence of dark matter
- evidence from different length scales
  - mini: galaxies
    - rotation curves
  - midi: clusters of galaxies
    - weak gravitational lensing: the bullet cluster
  - maxi: the Universe
    - CMB acoustic peaks
    - large scale structure formation
- they give a consistent value for DM energy density

$$\Omega_{\rm DM} = 0.265 \pm 0.007$$

$$\Omega_i = \rho_i / \rho_{\rm cr}$$

MINI: GALAXIES

MEASURING MASS

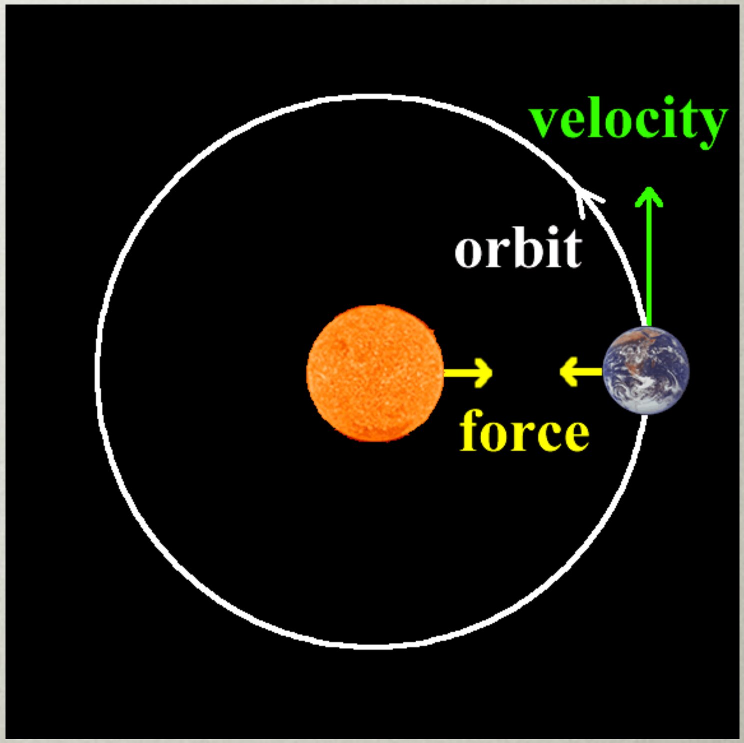
- how does one measure how much mass is in the galaxy?
- first a simpler question
  - how does one measure the mass of the Sun?

MEASURING MASS

- how does one measure how much mass is in the galaxy?
- first a simpler question
  - how does one measure the mass of the Sun?
  - through its gravitational pull

$$F_g = G_N \frac{m_{\rm sun} m_{\rm earth}}{r^2}$$

$$G_N = 6.6738(8) \times 10^{-11} m^3 kg^{-1} s^{-2}$$

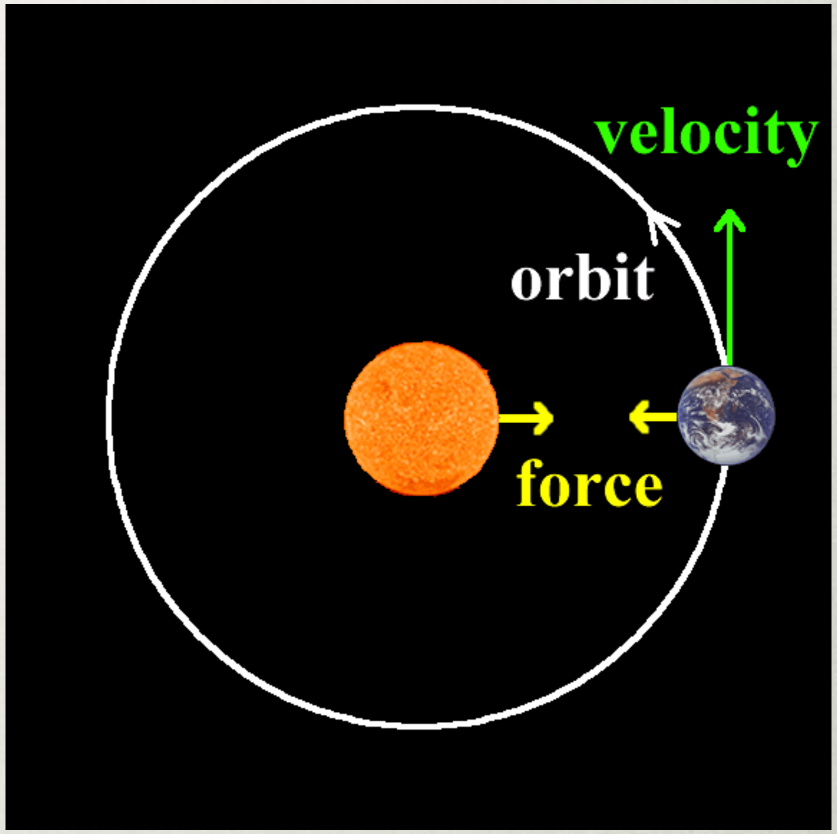


MASS OF THE SUN

- what do we know?
  - the distance to the Sun: *1au=149 597 870 700m*
  - the orbital velocity of Earth around the Sun: $v \simeq 2\pi r/T_0 \simeq 30 km/s$
- from $F_g = F_c$

$$G_N \frac{m_{\rm sun} m_{\rm earth}}{r^2} = \frac{m_{\rm earth} v^2}{r}$$

$$m_{\rm sun} = \frac{1}{G_N} v^2 r = 2.01 \cdot 10^{30} kg$$



- with higher order corrections:

$$m_{\rm sun} = 1.9885(2) \times 10^{30} \mathrm{kg}$$

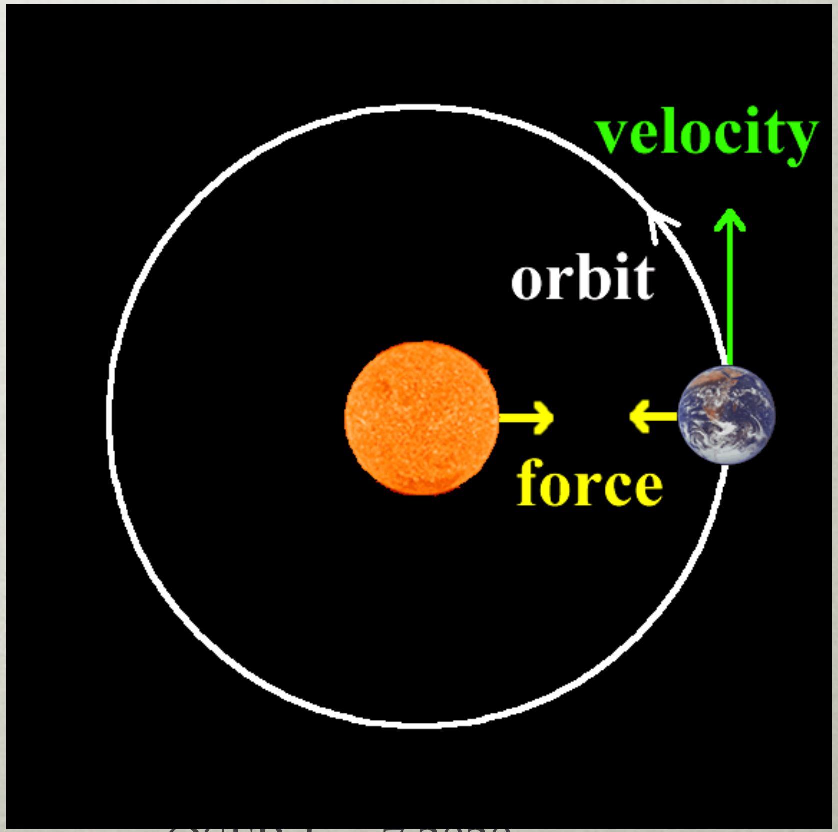
VELOCITY CURVES

- from velocity of the orbiting body (=Earth)
  - we know the encompassed gravitational mass

$$\boxed{m_{\text{sun}} = \frac{1}{G_N} v^2 r = 2.01 \cdot 10^{30} kg}$$

- depending on the mass distribution $\Rightarrow v(r)$

$$\boxed{v(r) = \sqrt{\frac{G_N M(r)}{r}}}$$



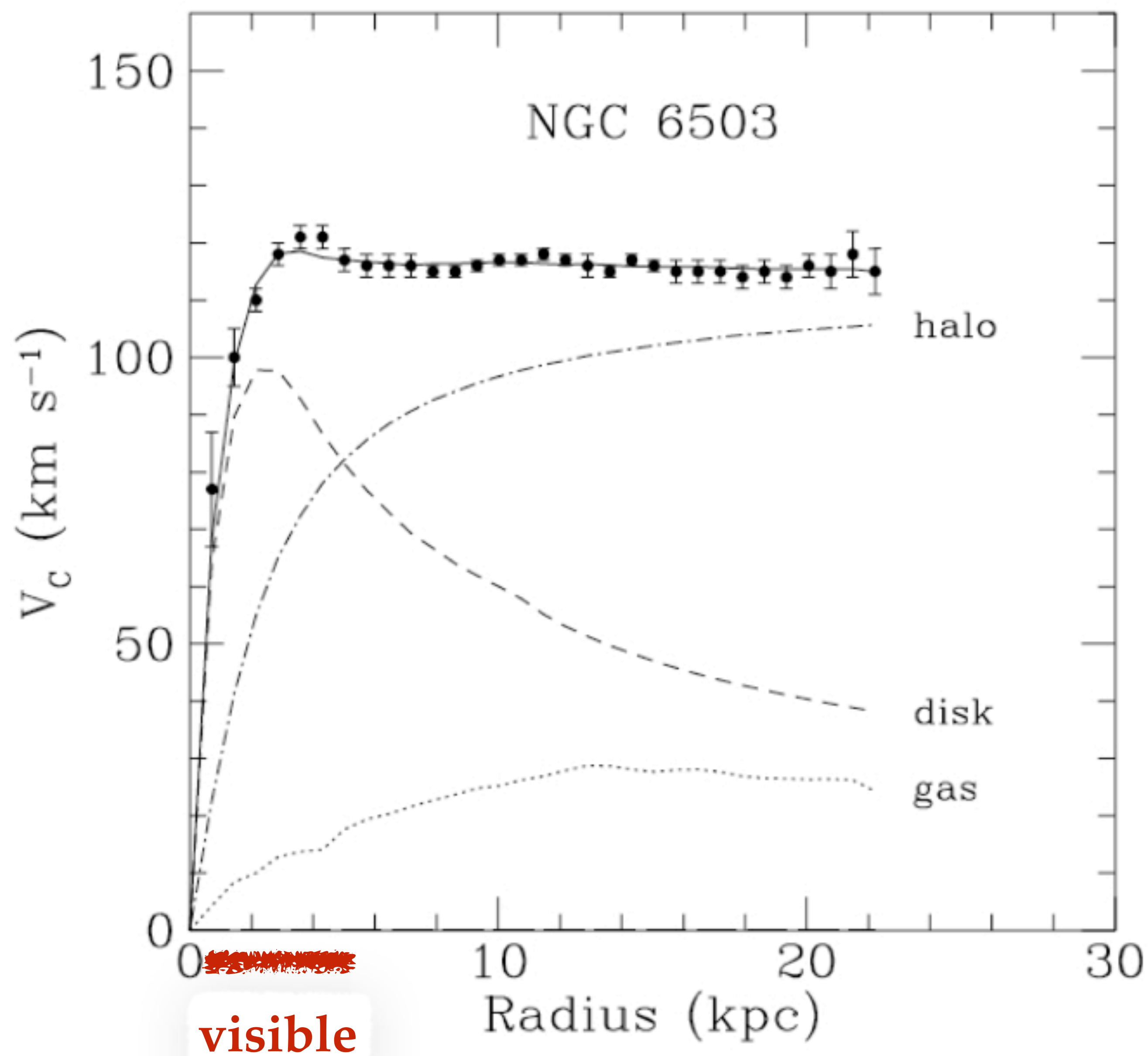
ROTATIONAL CURVES

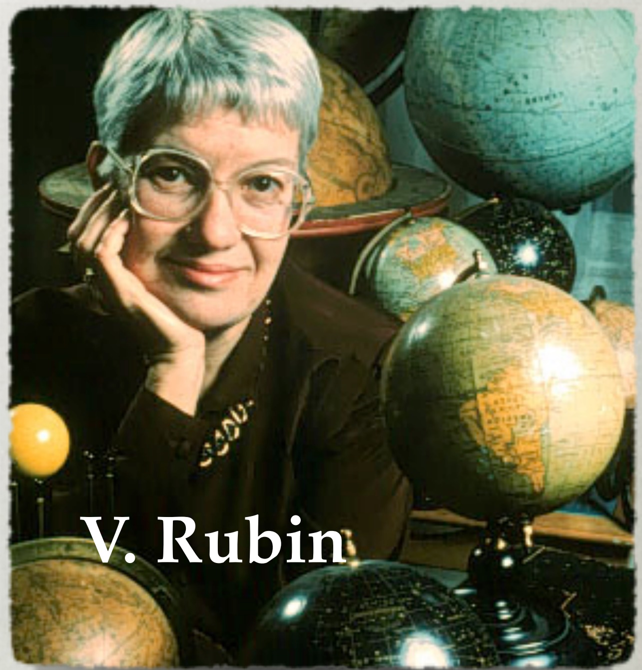
Rubin, Ford (1970)

- rotational curves on galactic scales

Rotation curves

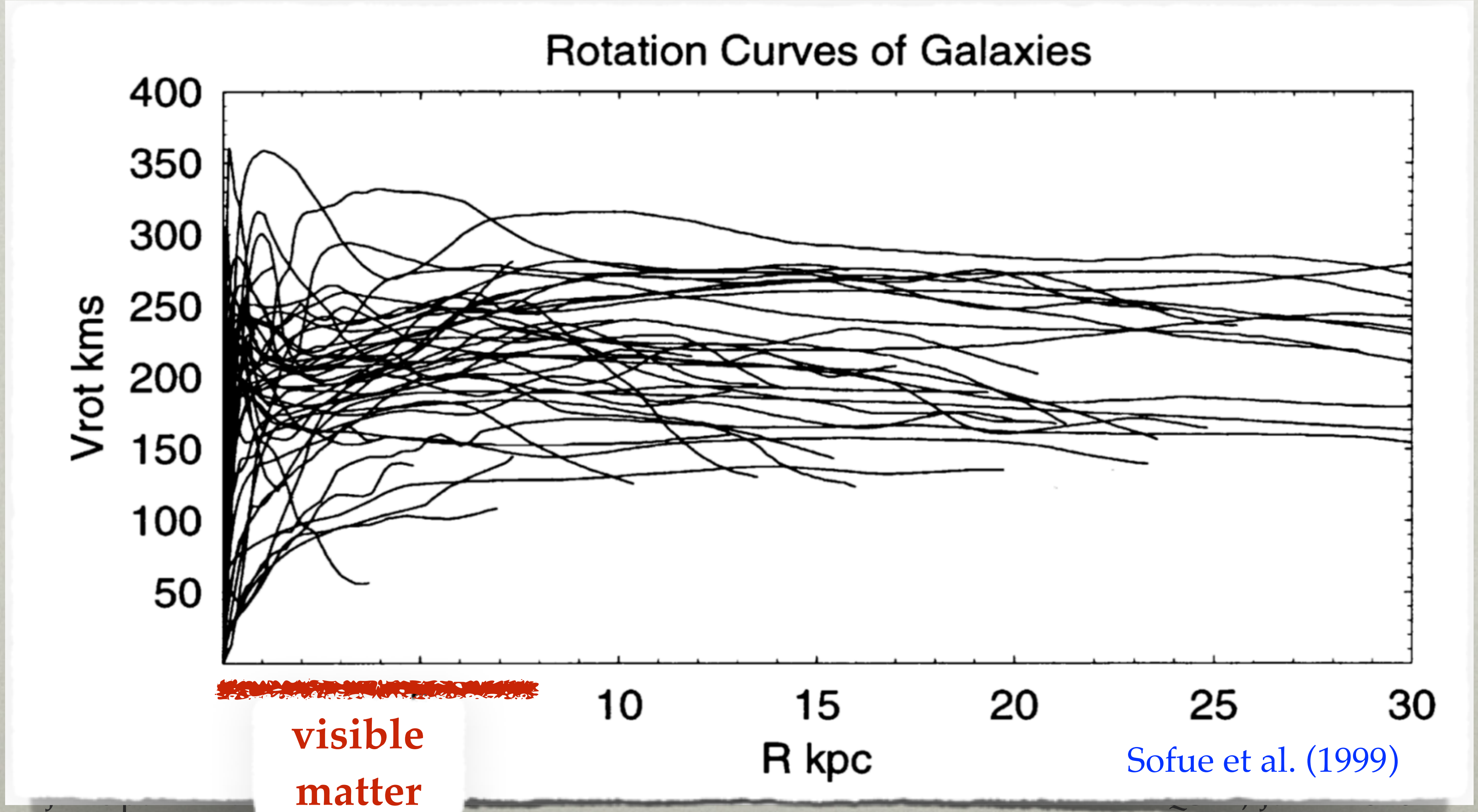
Begeman et al. 1991





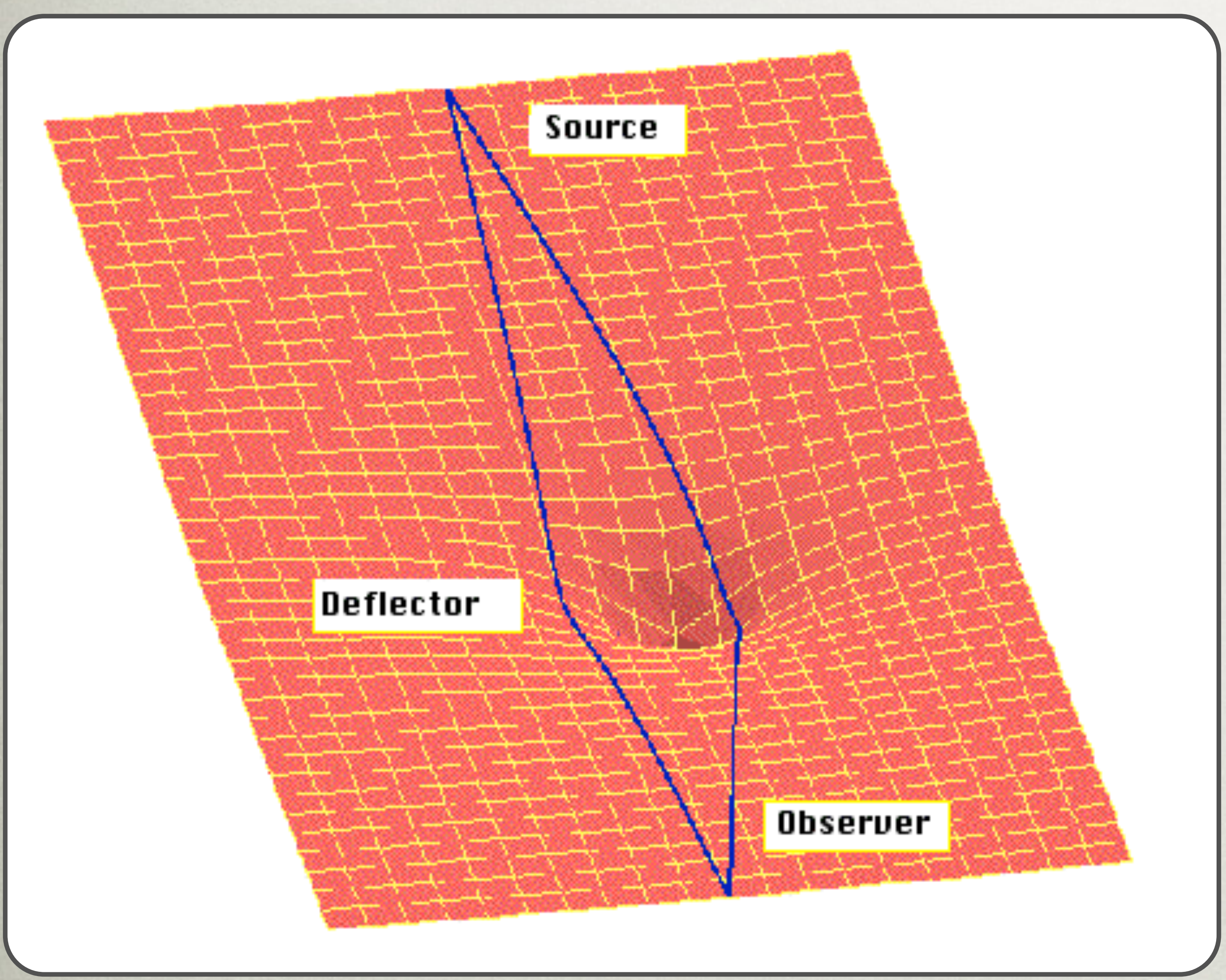
ROTATIONAL CURVES

- many more rotational curves measured
- they all flatten out at large *r*, as expected if DM halo is present



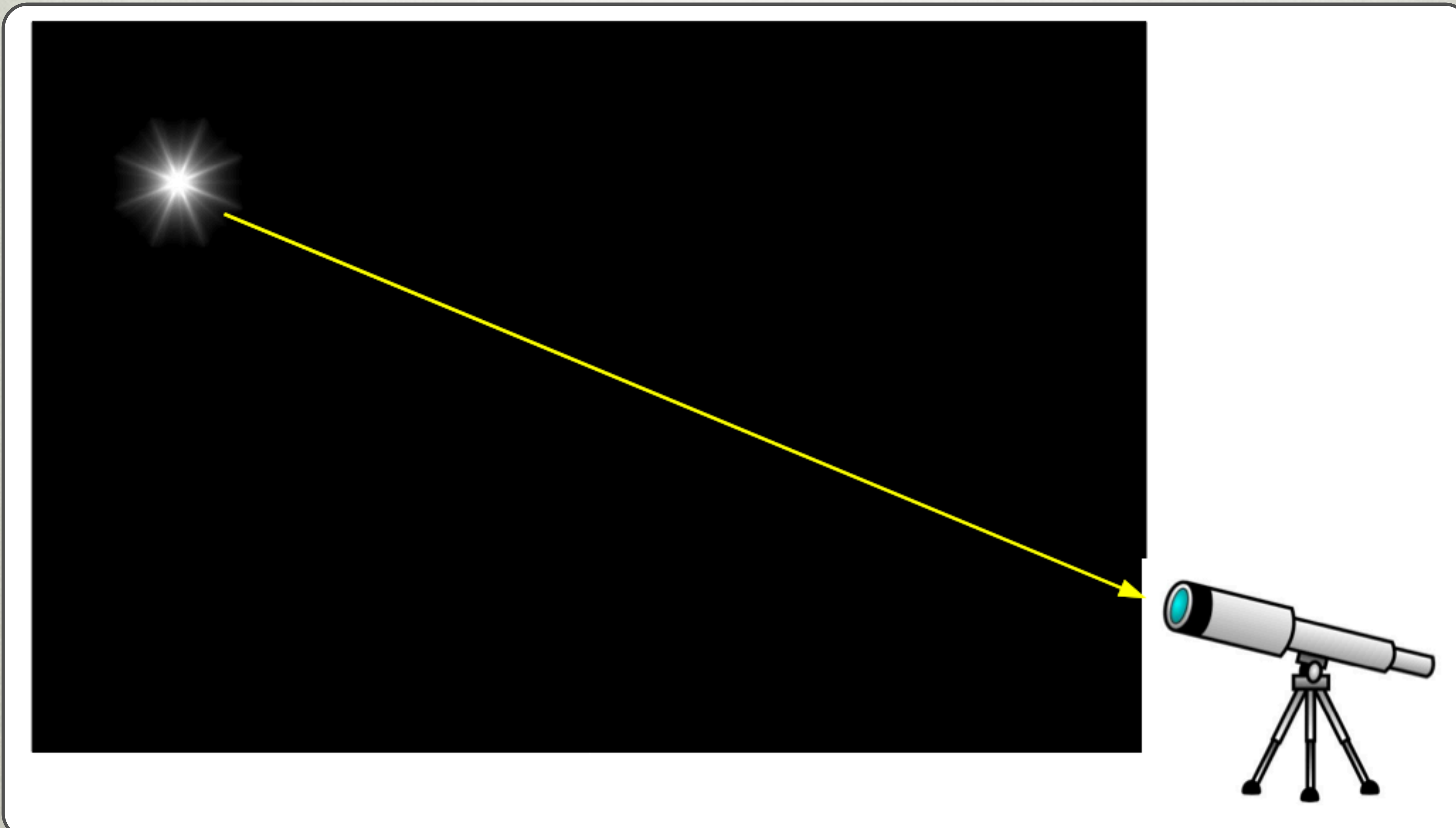
MIDI: CLUSTERS OF GALAXIES

WEAK GRAVITATIONAL LENSING



- light bends in a gravitational field
- more massive objects bend light more
- massive objects act like gravitational lenses

GRAVITATIONAL LENSING



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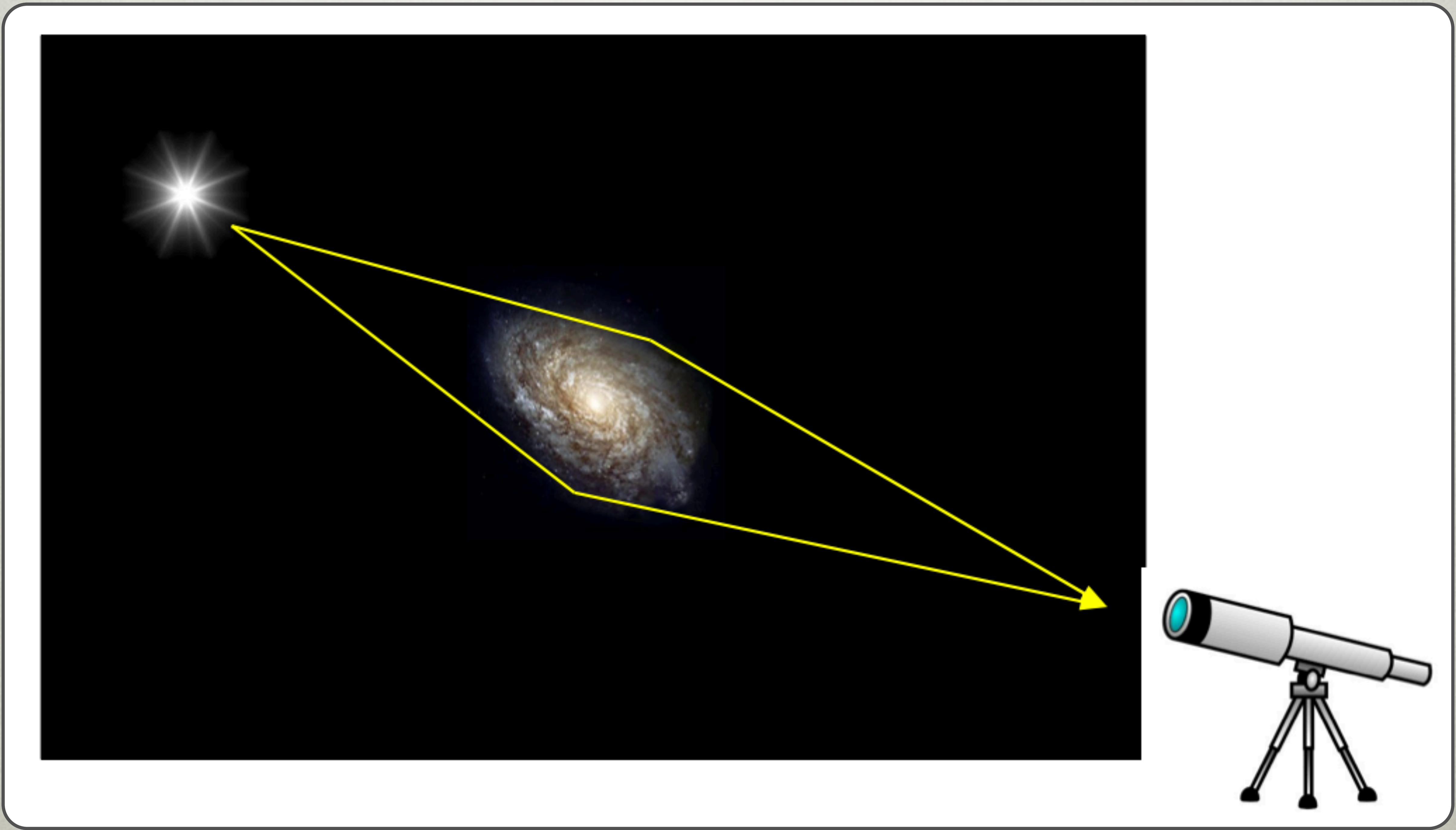
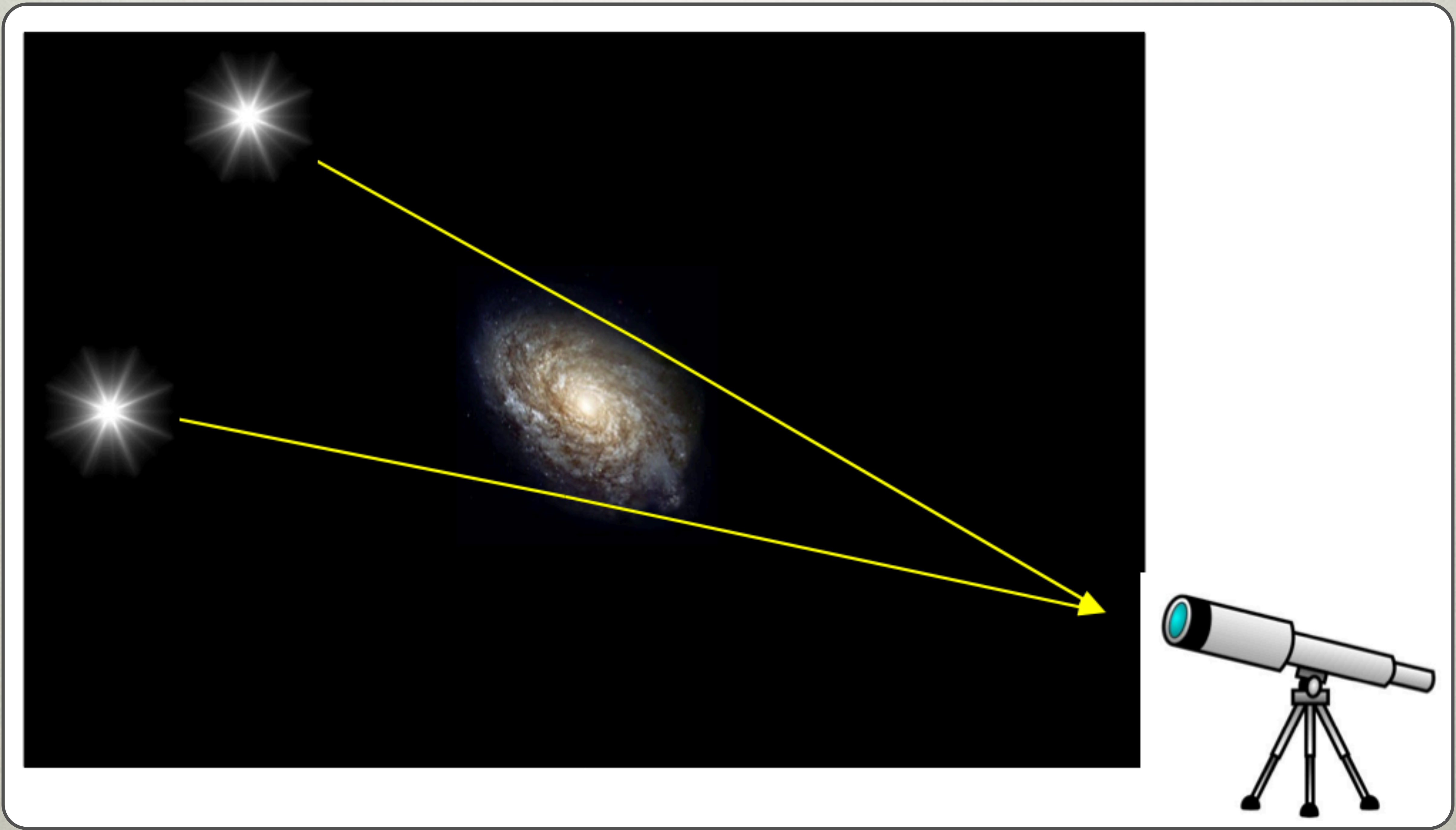
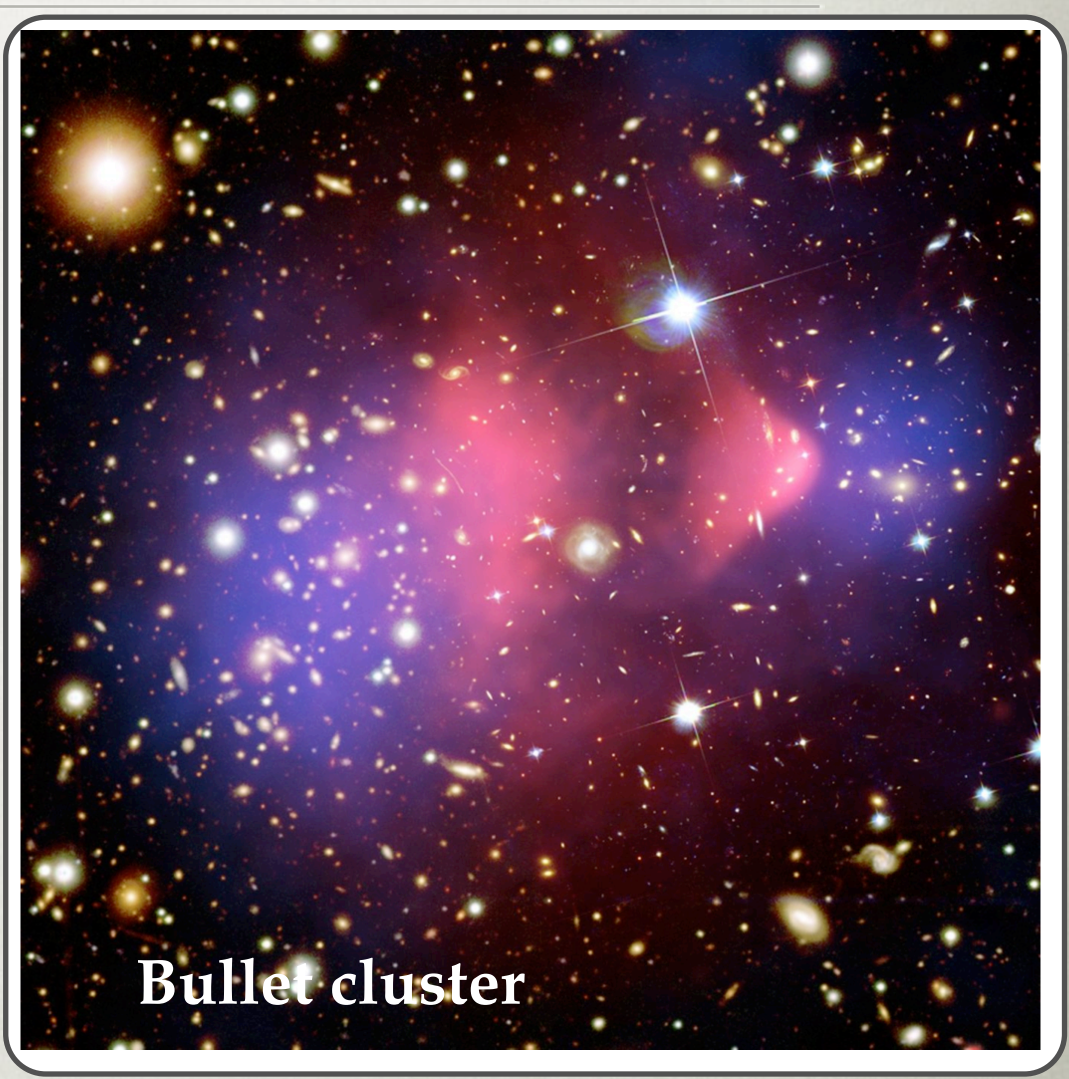


GRAVITATIONAL LENSING



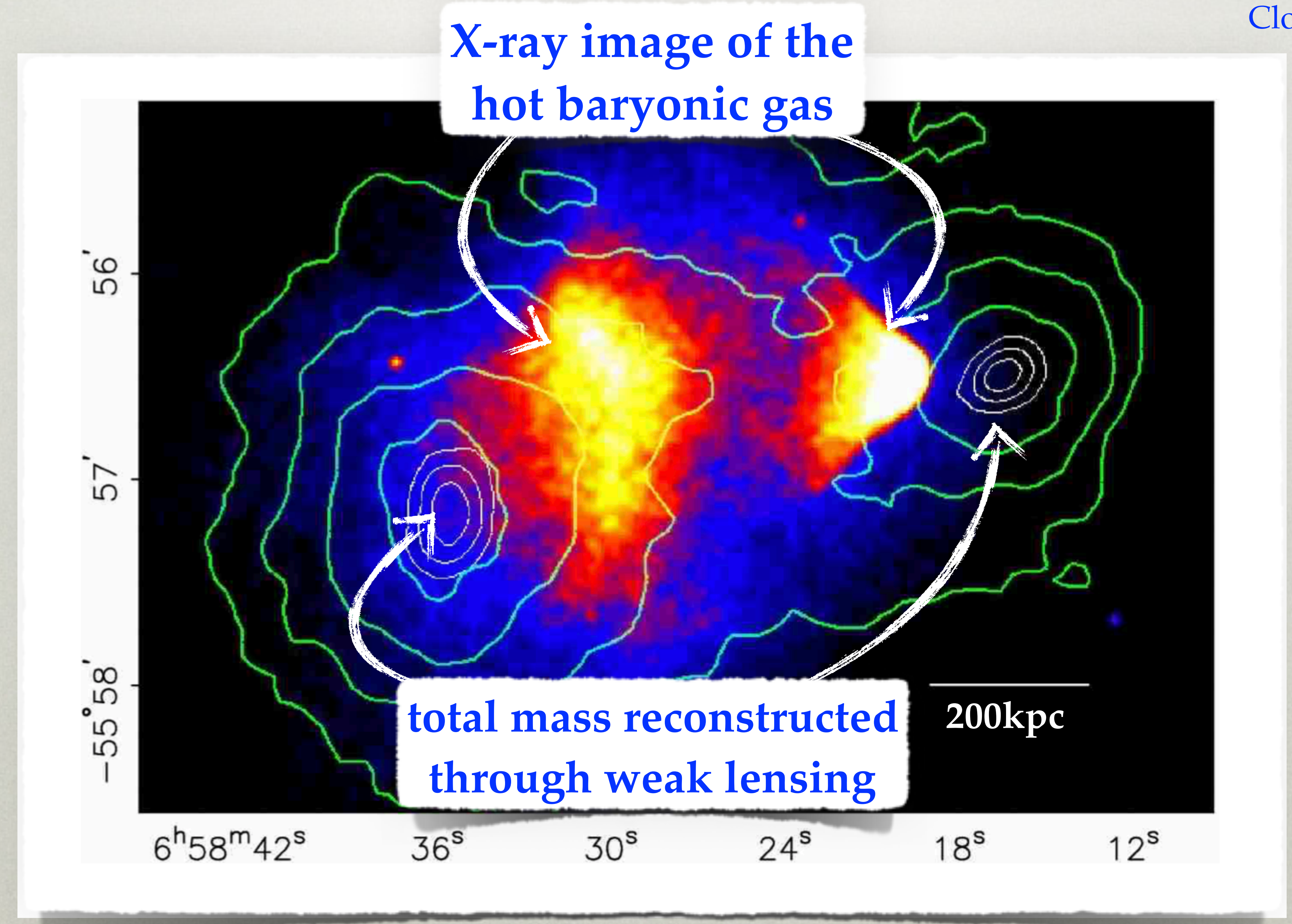
BULLET CLUSTER

- two colliding clusters of galaxies
- two figures superimposed
  - red:the emission from gas in X-ray
    - most of the visible mass
  - blue: gravitational lensing
    - this is the distribution of DM
- best evidence for collisionless dark matter



DARK MATTER INTERACTS LESS

Clowe et al. (2006)



OTHER EXAMPLES

- train wreck

DARK MATTER SELF INTERACTIONS

- shows that DM and ordinary matter behave differently
- puts a bound on DM interactions

$$\frac{\sigma}{M} \lesssim 1\,\frac{\mathrm{cm}^2}{\mathrm{g}} = 1.8\,\frac{\mathrm{mb}}{\mathrm{GeV}}$$

- compare with QCD *pp* cross section of $\sigma_{pp} \sim 50\,\mathrm{mb}$

MAXI: THE UNIVERSE

DARK MATTER AND THE EVOLUTION OF THE UNIVERSE

- the most convincing and most precise evidence for the existence of DM
  - from the largest scales possible = the entire observable Universe
- before we go there a seemingly unrelated question
  - why is the night sky dark?

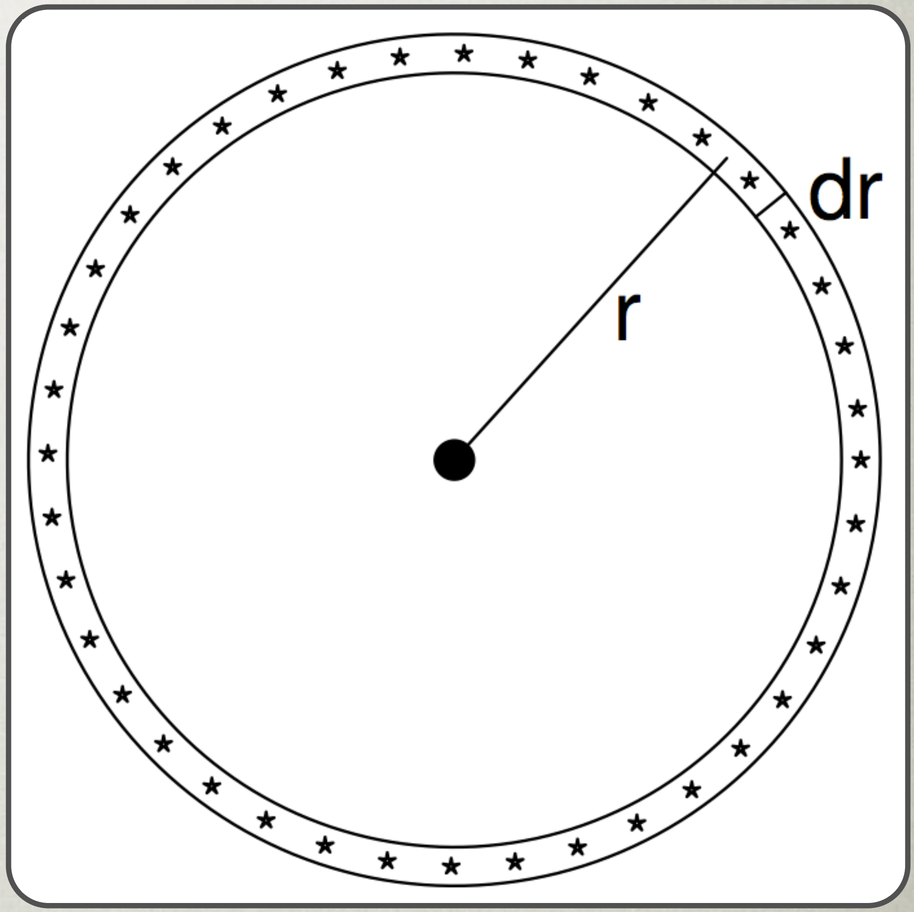
SHOULD THE NIGHT SKY BE DARK?

- imagine that we live in infinite universe filled with stars
- the flux of light on Earth from a single star

$$f(r) = \frac{L}{4\pi r^2}$$

- now from the whole thin shell of a sphere filled with stars
  - the intensity of the radiation on Earth (power per unit area per steradian of the sky)

$$dJ(r) = \frac{L}{4\pi r^2} \cdot n \cdot r^2 dr = \frac{nL}{4\pi} dr$$



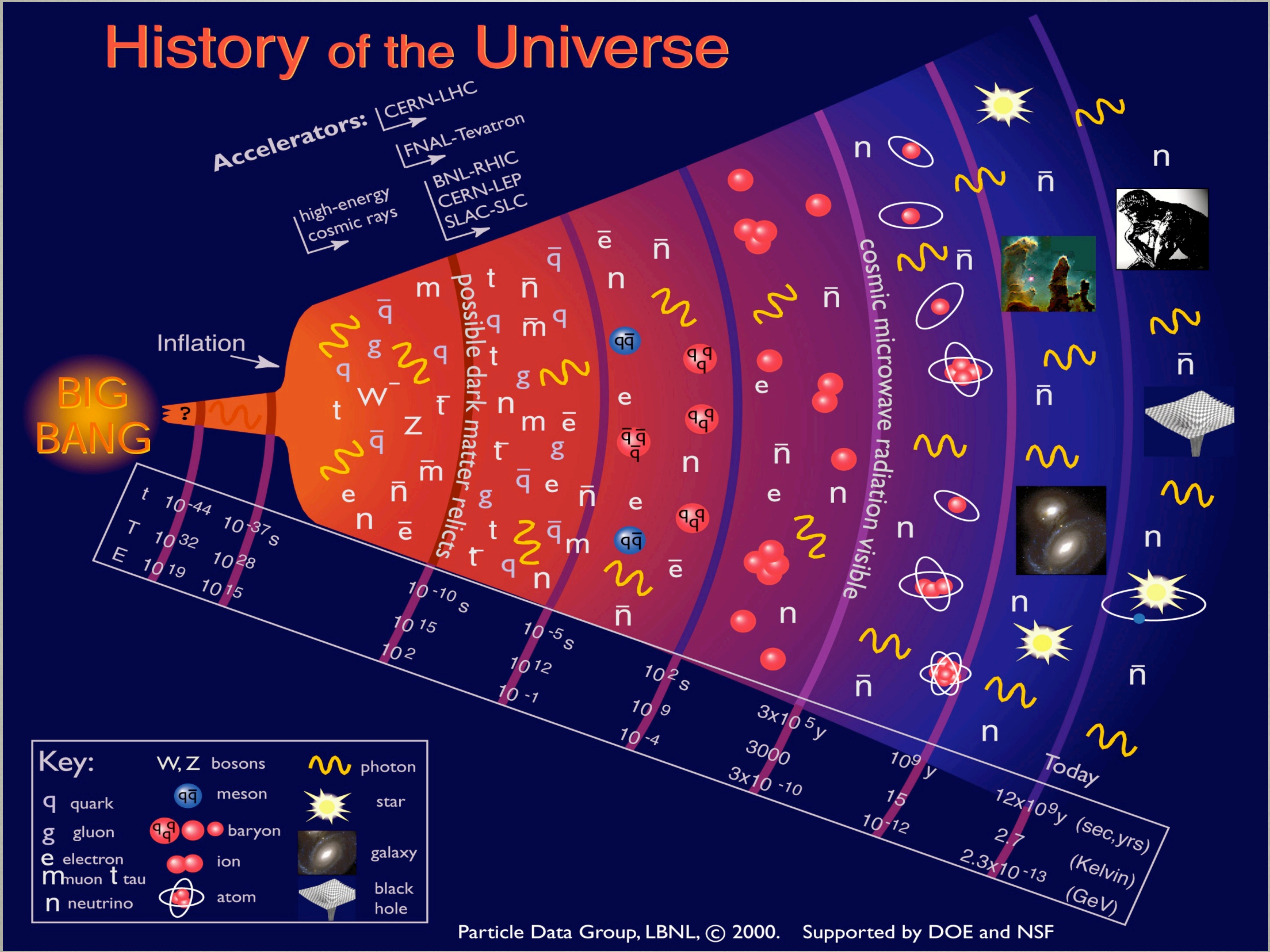
- so from each thin shell equal intensity
  - sum over all shells ⇒ infinite intensity

Olber's paradox

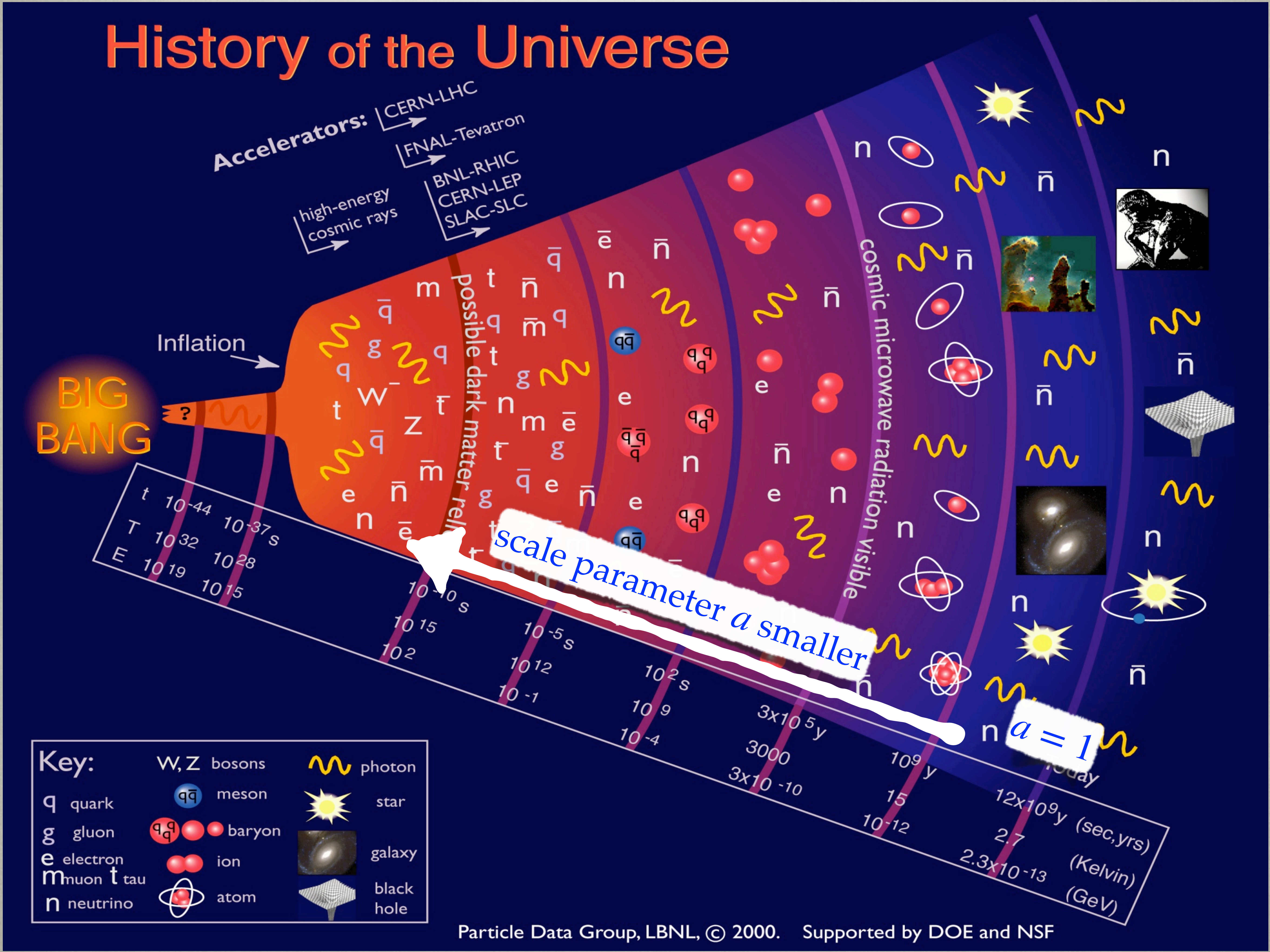
- the night sky should be glowing!
    - if Universe static, infinite and homogeneous, uniformly filled with stars
    - Olber's paradox, 1826
- so what is going on?

BIG BANG

- the resolution
  - universe is not static
  - Big Bang 13.8 billion years ago
    - at large distances (early times) no stars



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF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?
possible dark matter relic
cosmic microwave radiation visible
scale parameter a smaller
$a = 1$
t 10-44 10-37 s 10-10 s 10-5 s 102 s 3x105 y 109 y 12x109 y (sec,yrs)
T 1032 1028 1015 1012 109 3000 15 2.7 (Kelvin)
E 1019 1015 102 10-1 10-4 3x10-10 10-12 2.3x10-13 (GeV)
today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
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star
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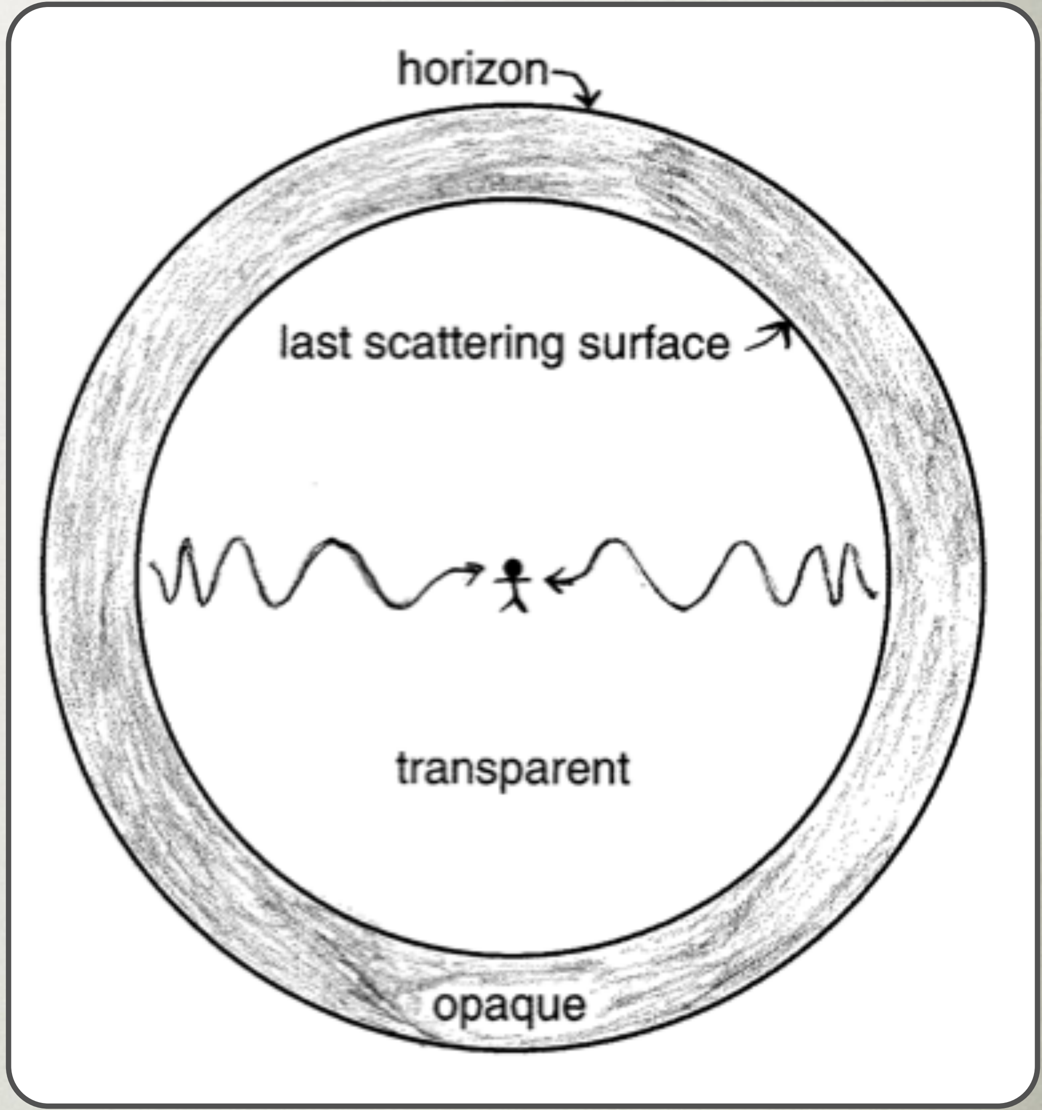
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

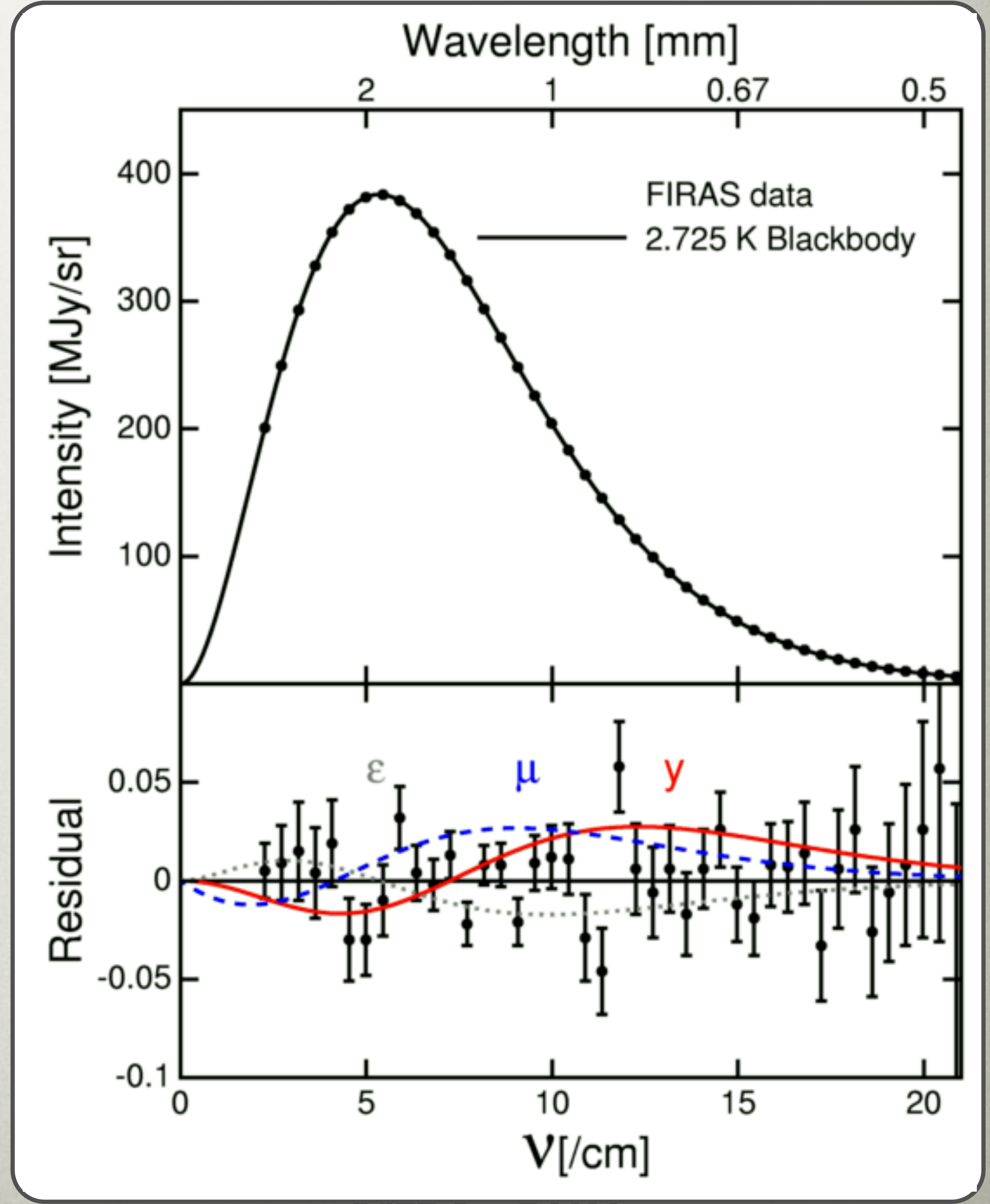
COSMIC MICROWAVE BACKGROUND

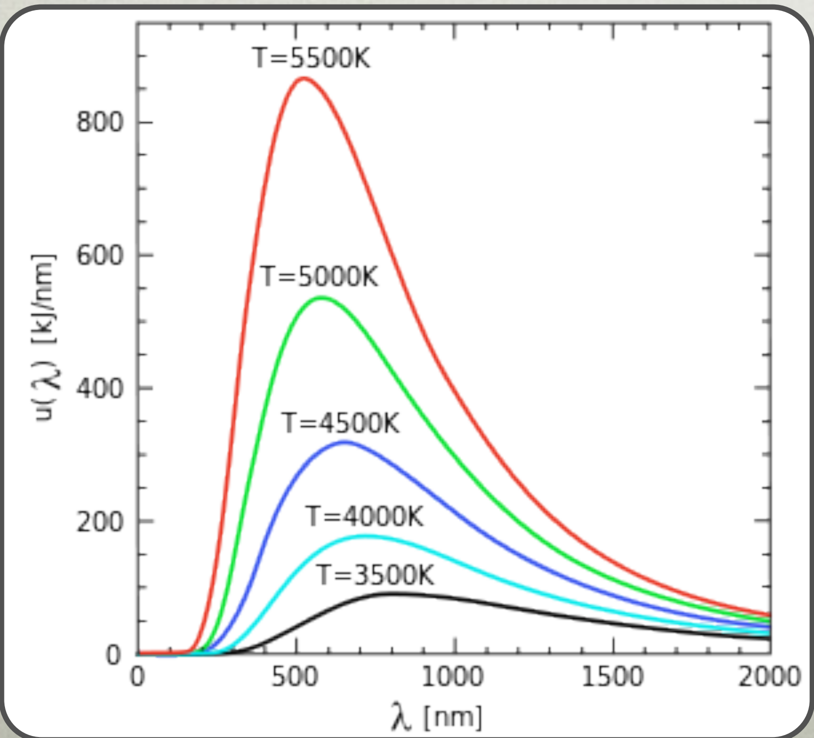


- in fact dark night is not dark
  - in microwave spectrum it glows
  - the radiation from the time when the universe was ~400 kyrs old
  - the snapshot of universe when the hydrogen plasma recombined
  - the wavelength has been stretched, it used to be at *few μm* now at *few mm*
  - redshifted due to expanding universe

CMB TEMPERATURE

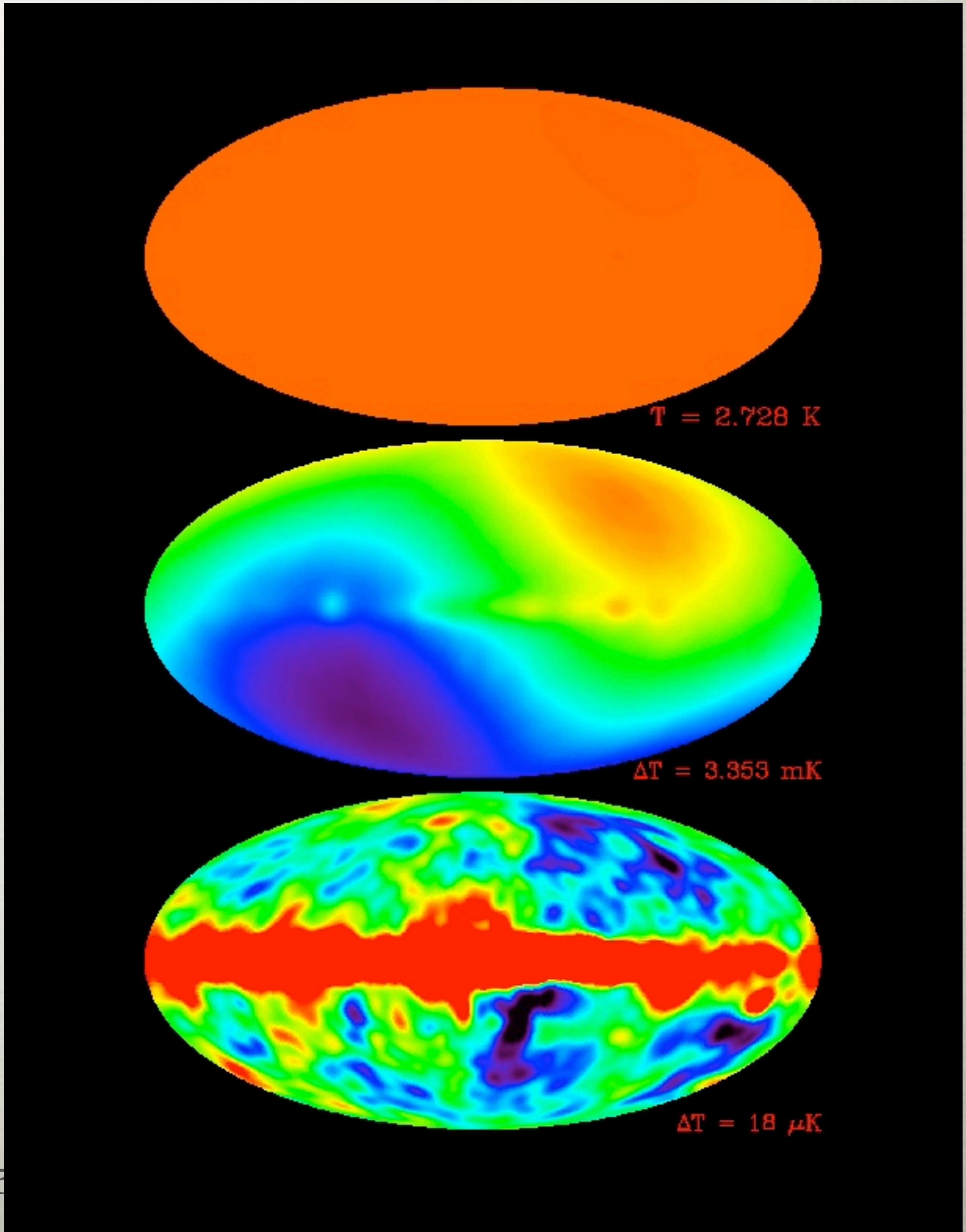
- CMB has a black body spectrum
  - *T=2.725 K*





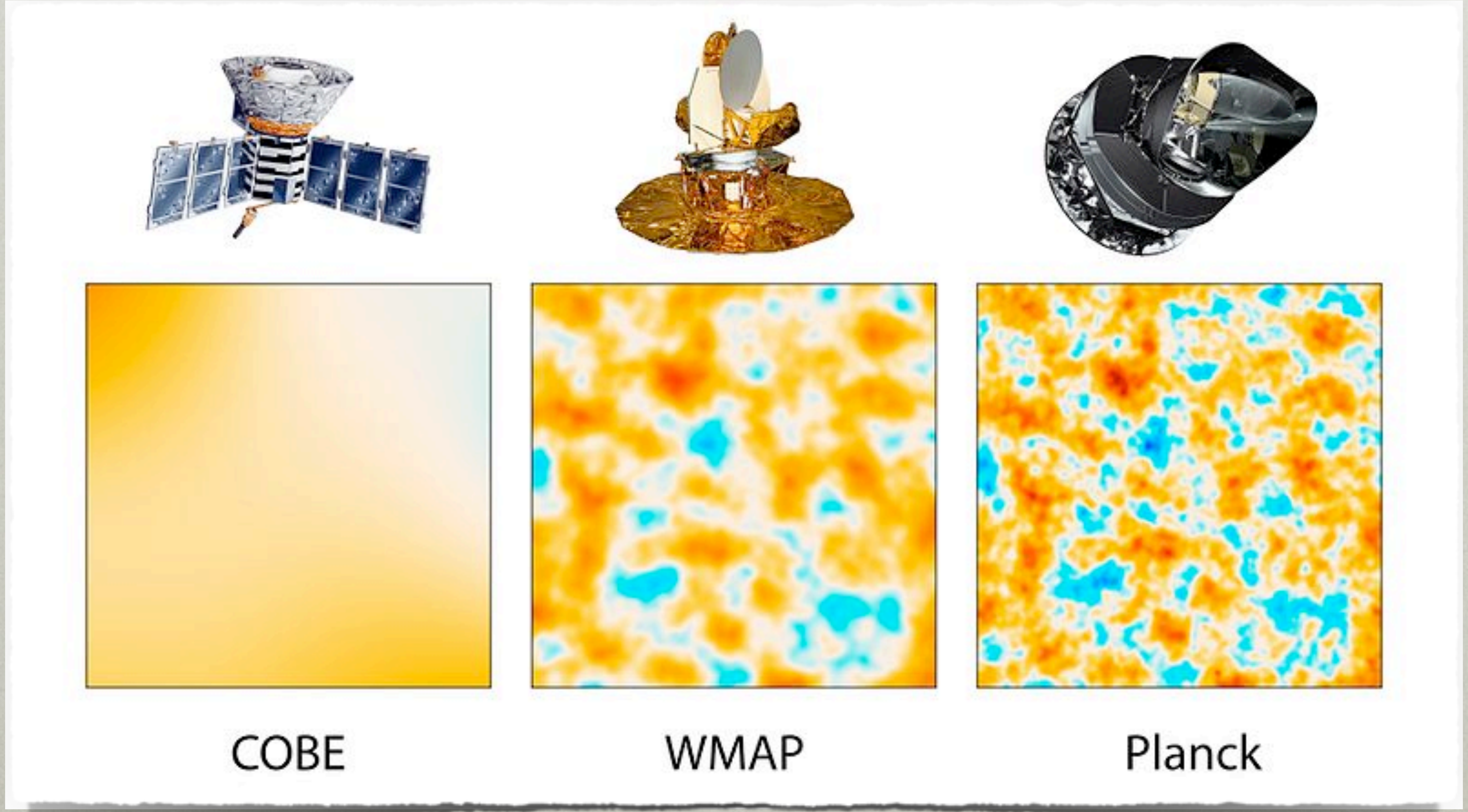
BLACK BODY RADIATION

- COBE data
  - very uniform
  - dipole structure due to Doppler
  - inhomogeneities $\delta T/T=10^{-5}$
    - seeds for matter collapse into galaxies, etc

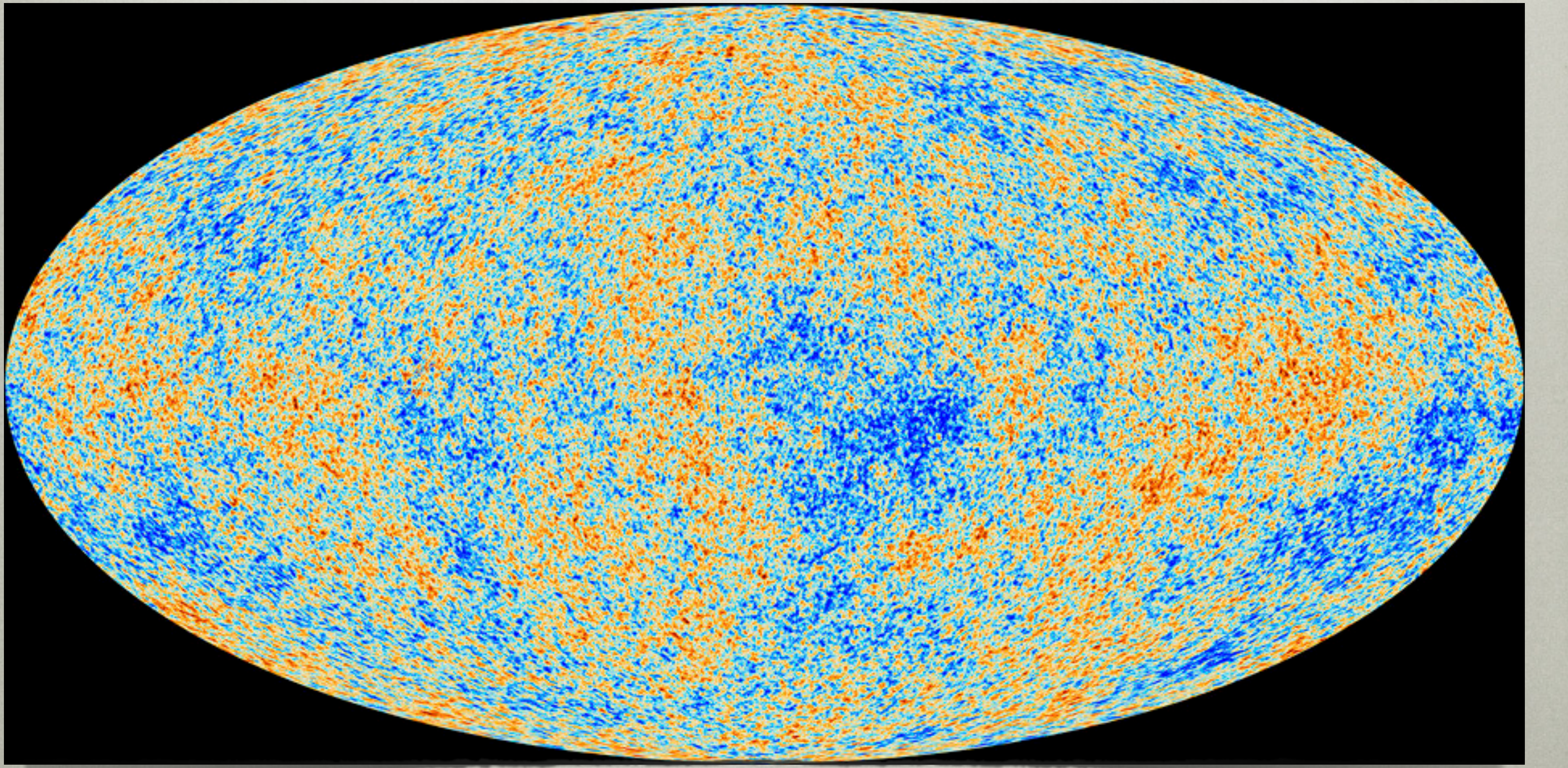


INHOMOGENEITIES

1989-1993 **2001-2010** **2009-2013**



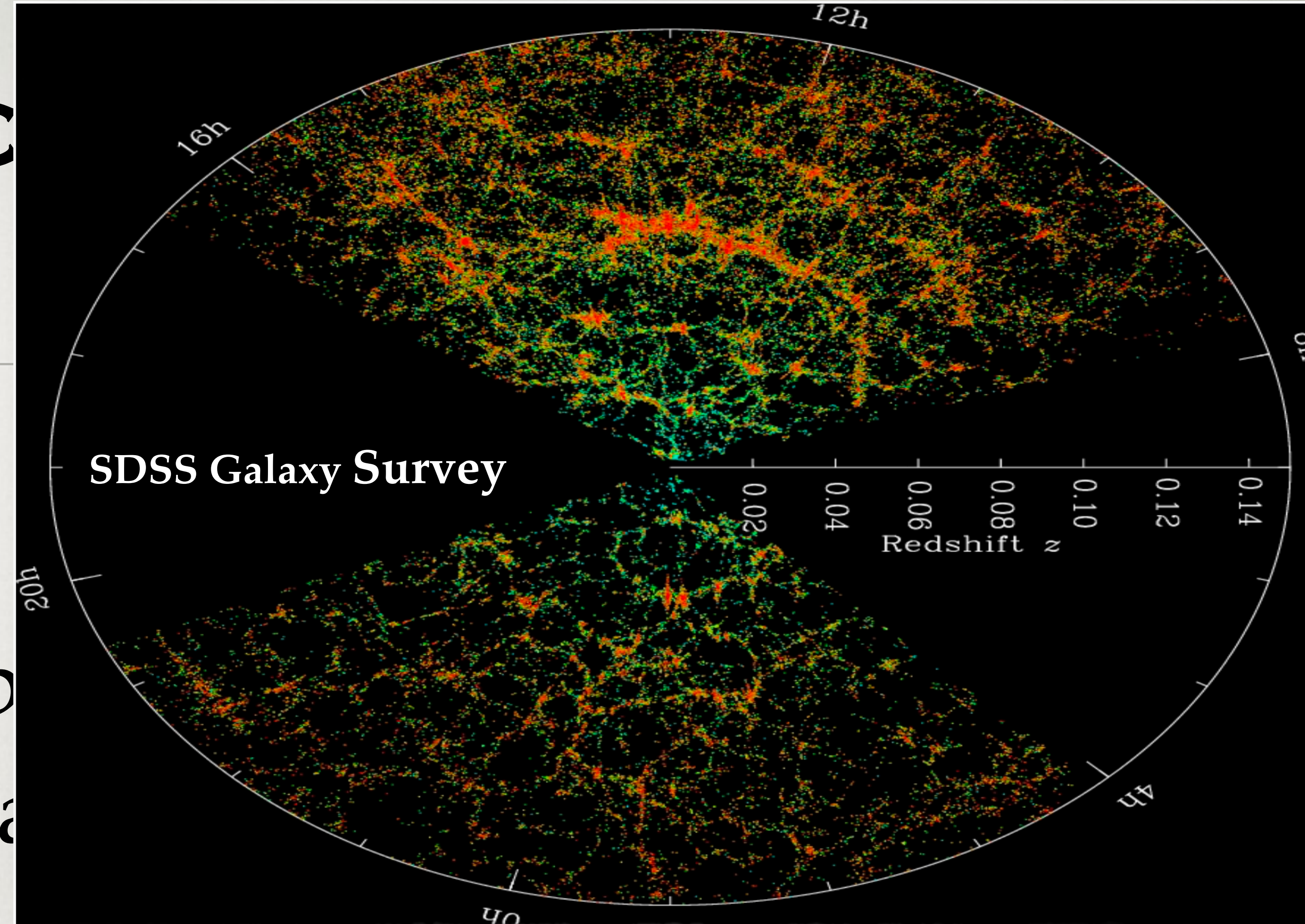
PLANCK RESULT



IMPLICATIONS FOR DARK MATTER

- gives two important proofs for existence of dark matter
  - dark matter needed for structure formation
  - DM imprinted in the correlations of CMB temperature fluctuations

IMPLIC
DAR



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  existence of da
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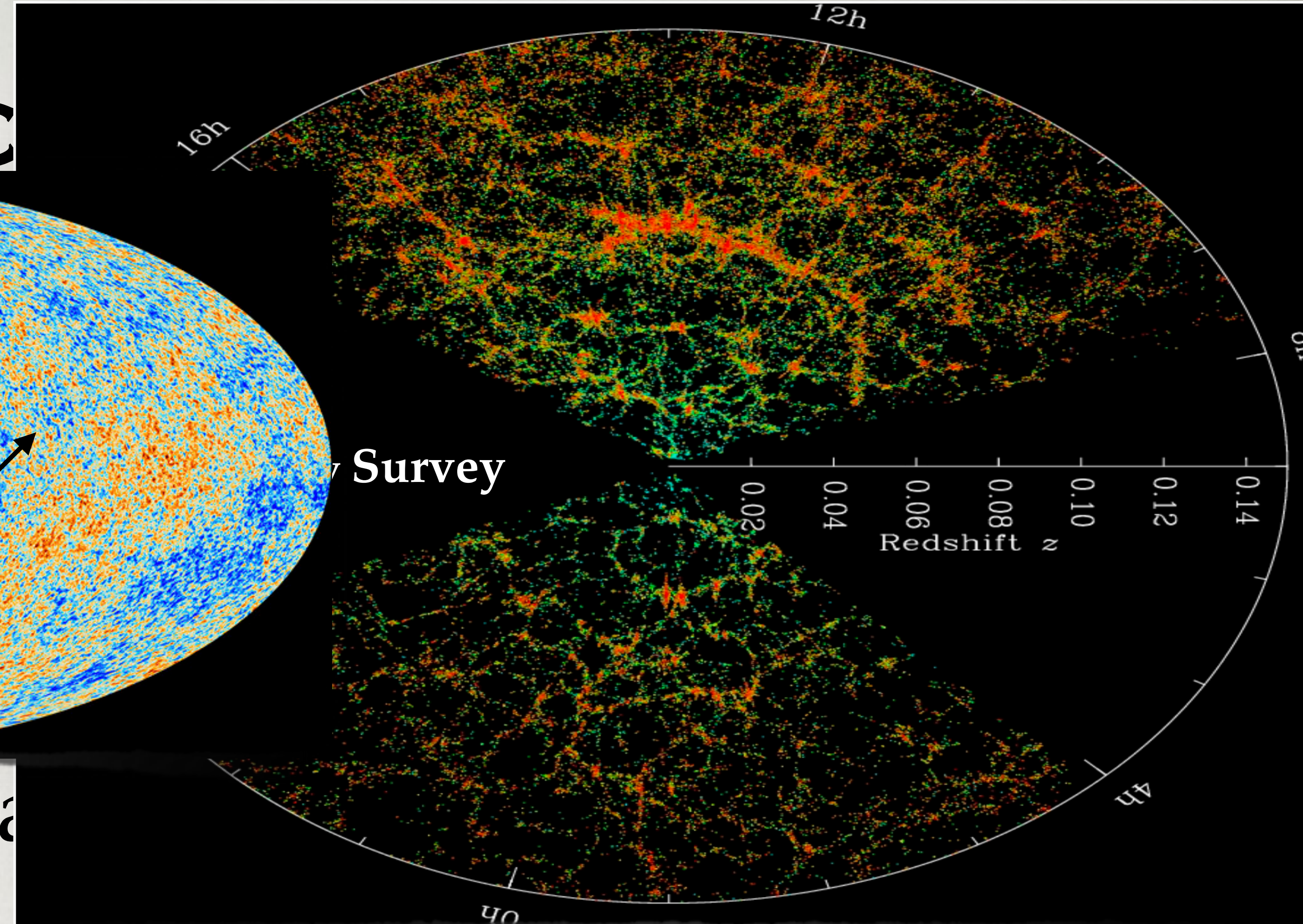
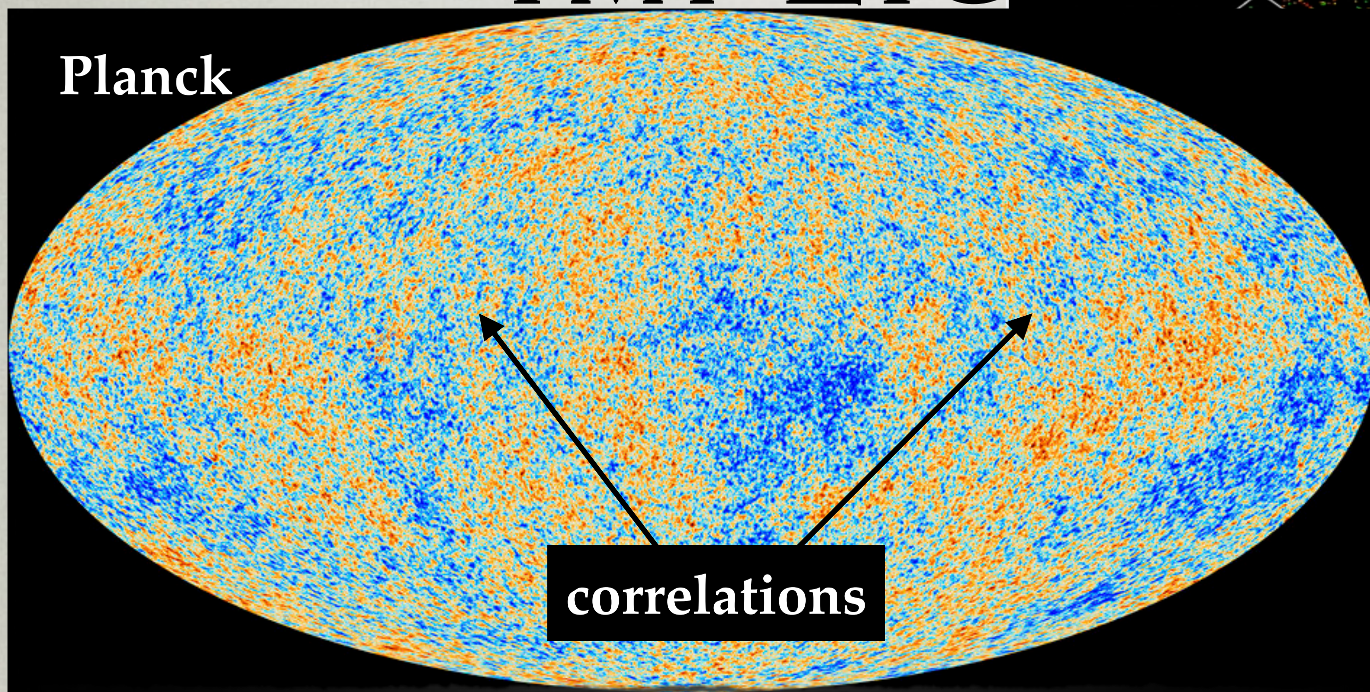
IMPLIC





existence of da

- dark matter needed for structure formation
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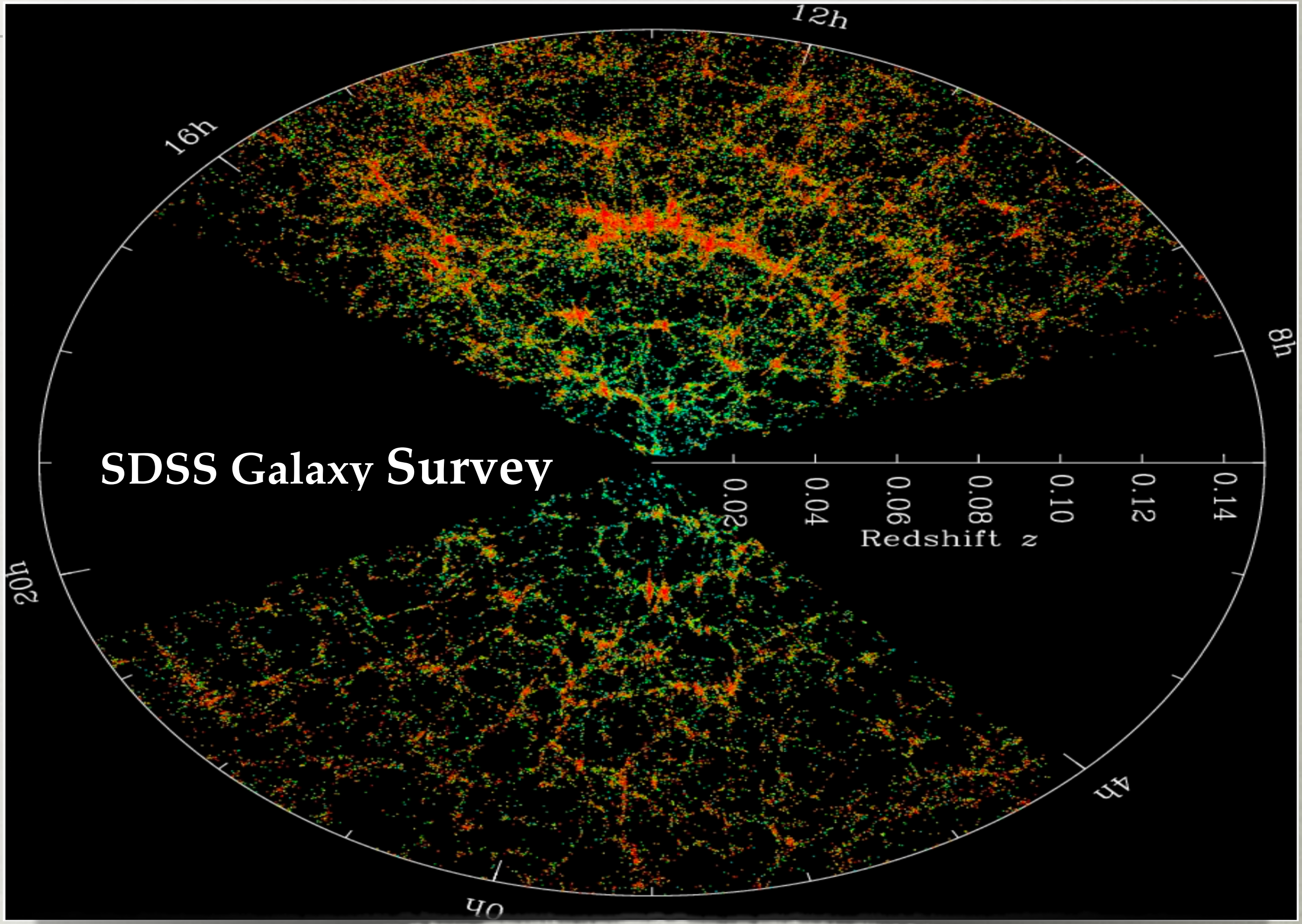
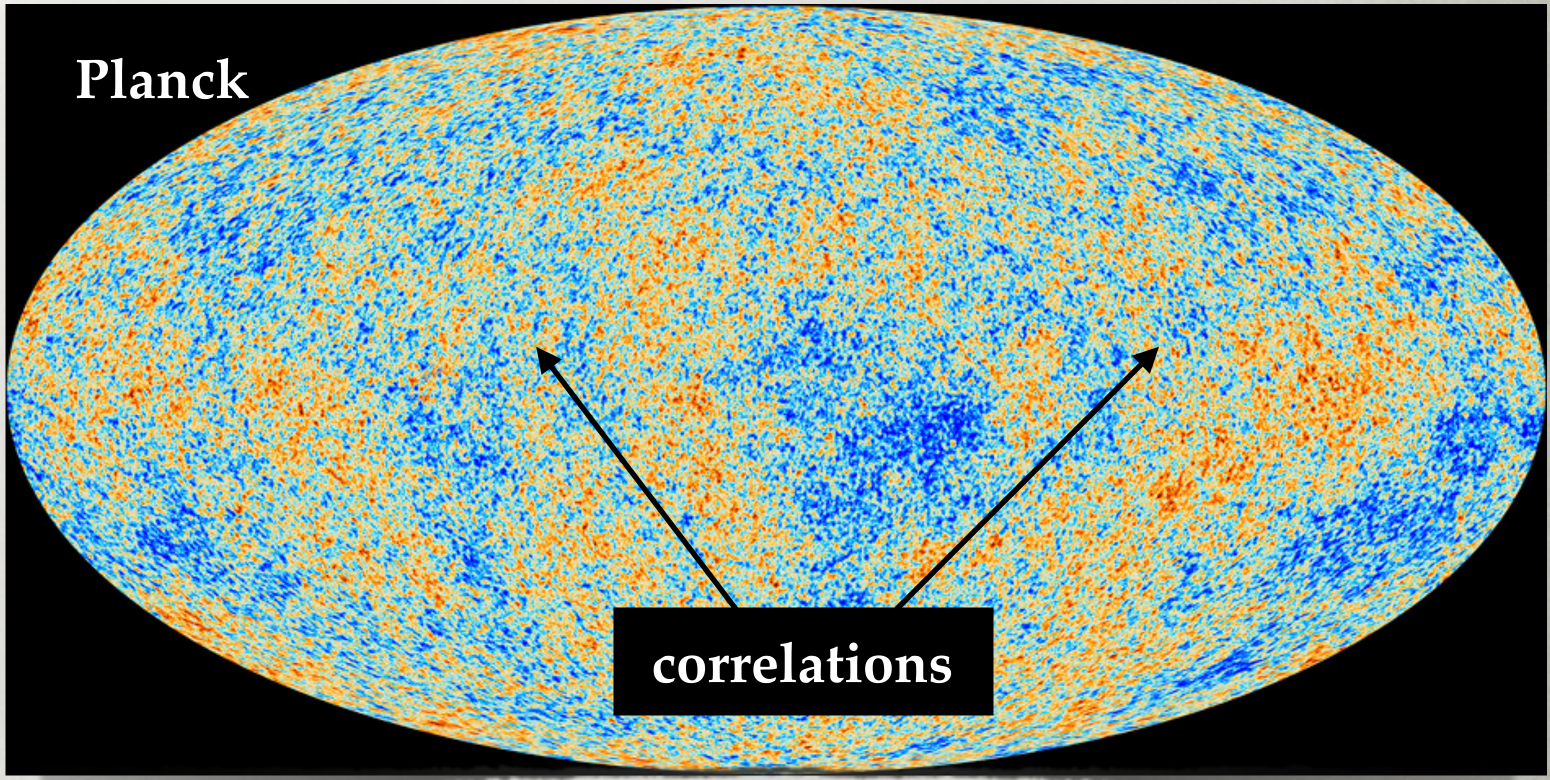
STRUCTURE FORMATION AND DARK MATTER



- fluctuations at recombination (z_{rec}≃1100, t_{rec}≃370kyears)
$$\left.\frac{\delta\rho_b}{\rho_b}\right|_{\rm rec} \simeq \left.\frac{\delta T}{T}\right|_{\rm CMB} \simeq 10^{-5}$$
- need to grow to $\delta\rho_b/\rho_b \sim 1$ for Galaxies, etc, to form
- grow linearly with redshift, thus if plasma of only visible matter
$$\left.\frac{\delta\rho_b}{\rho_b}\right|_{\rm now} \simeq \left.\frac{\delta\rho_b}{\rho_b}\right|_{\rm rec} \cdot z_{\rm rec} \sim 10^{-2} \ll 1$$
- need non-iteracting dark matter fluid to be present
  - density fluctuations in DM fluid start collapsing before t_{rec}
  - makes the growth of structure possible

CMB and dark matter

- in the CMB
  - correlations of hot and cold spots
  - baryons and DM collapse in the gravitational wells
  - CMB photons need to traverse these gravitational wells
  - affects their spectrum
- is sensitive to the amount of dark matter



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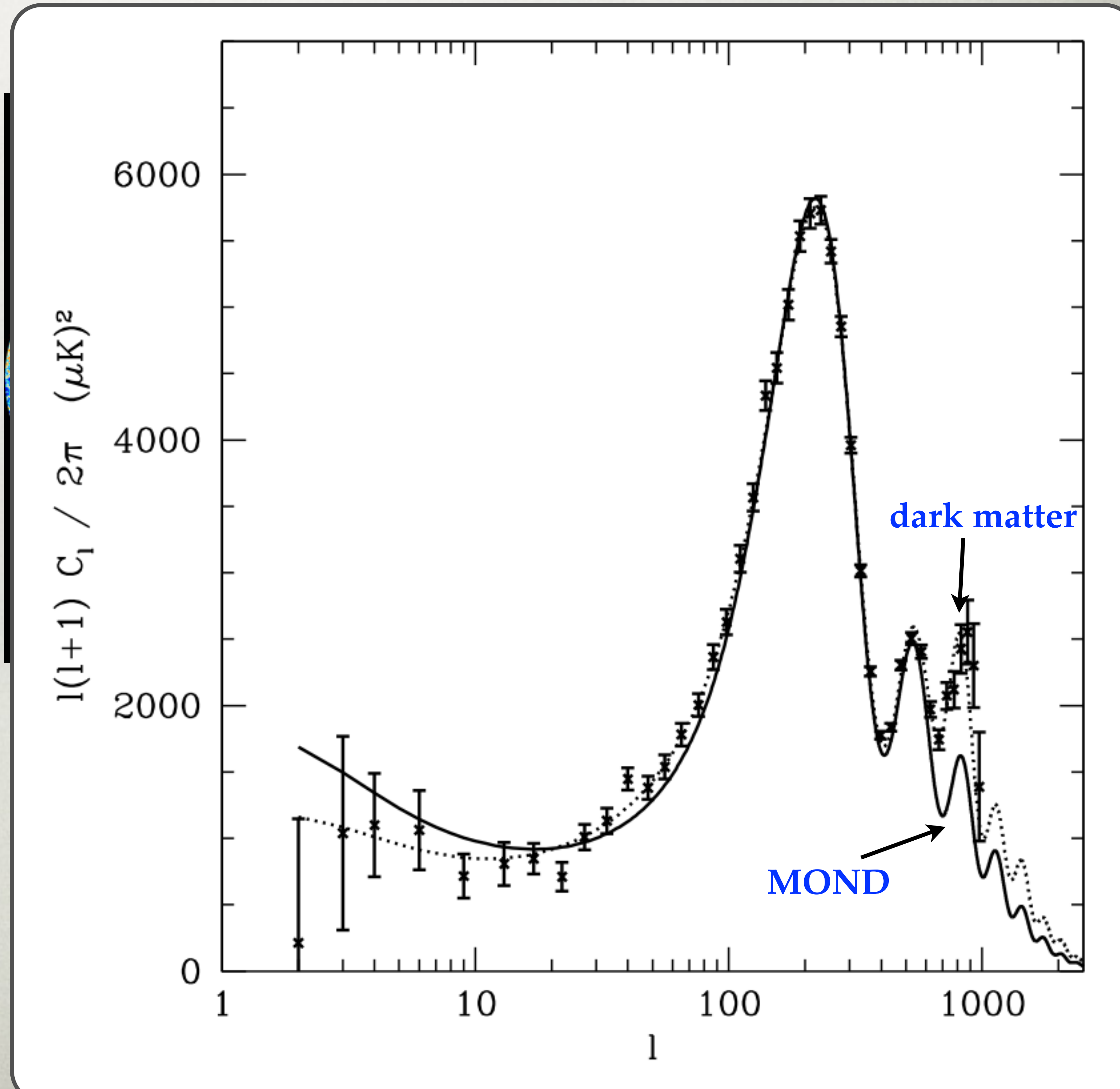

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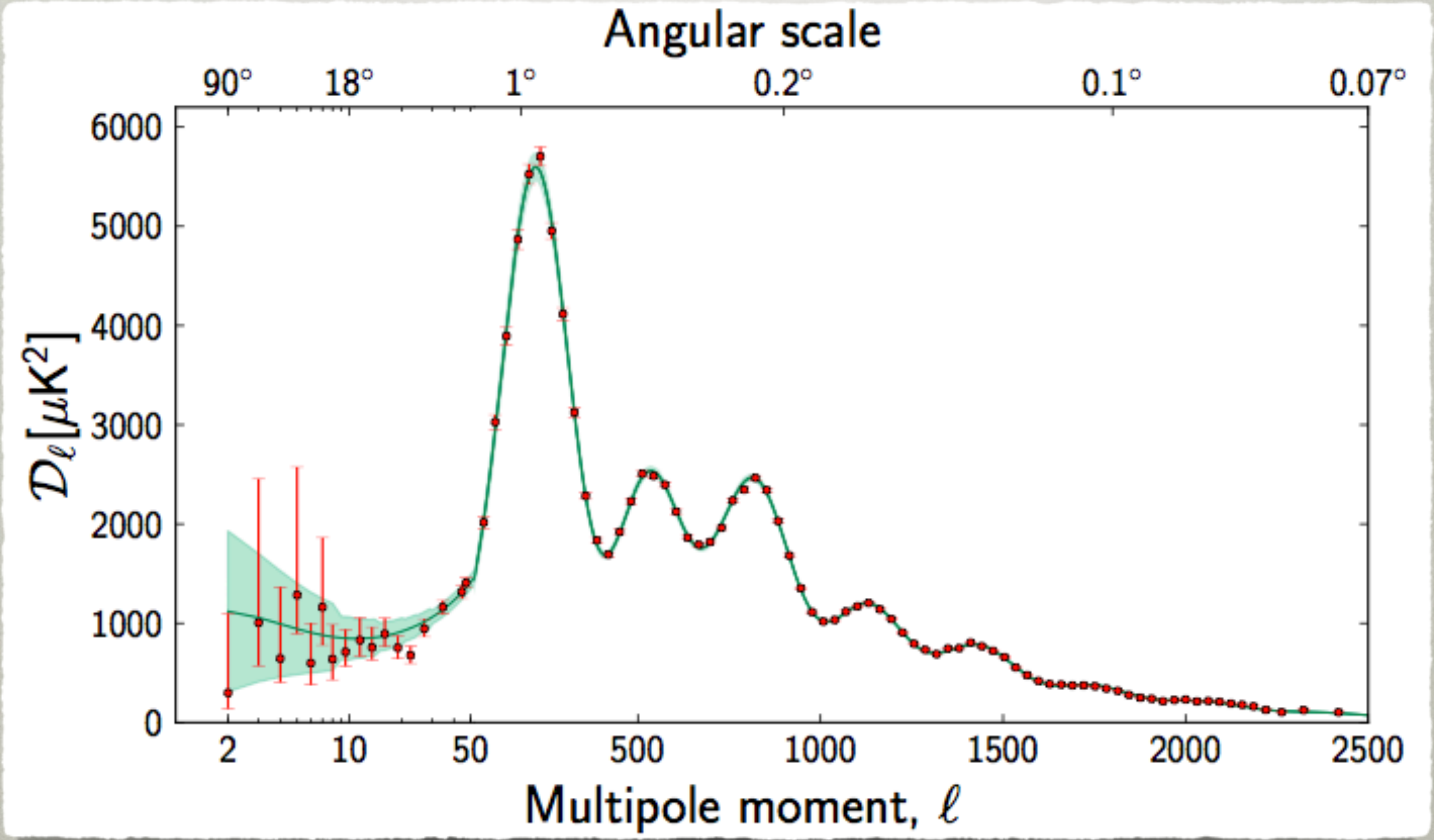
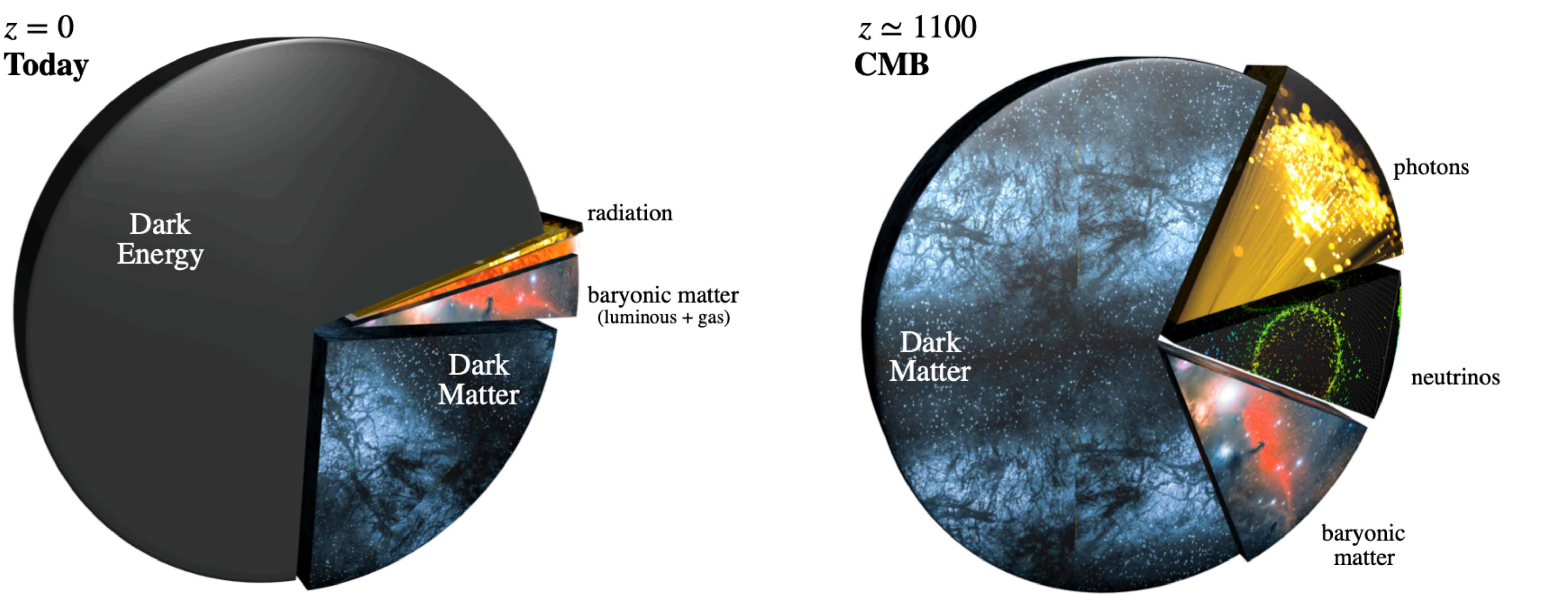


THE ENERGY BUDGET OF THE UNIVERSE

- DM *O(1)* fraction of the universe's energy budget
- the fraction evolves with time



Cirelli, Strumia, JZ, review to appear

WHAT DO WE KNOW ABOUT DARK MATTER

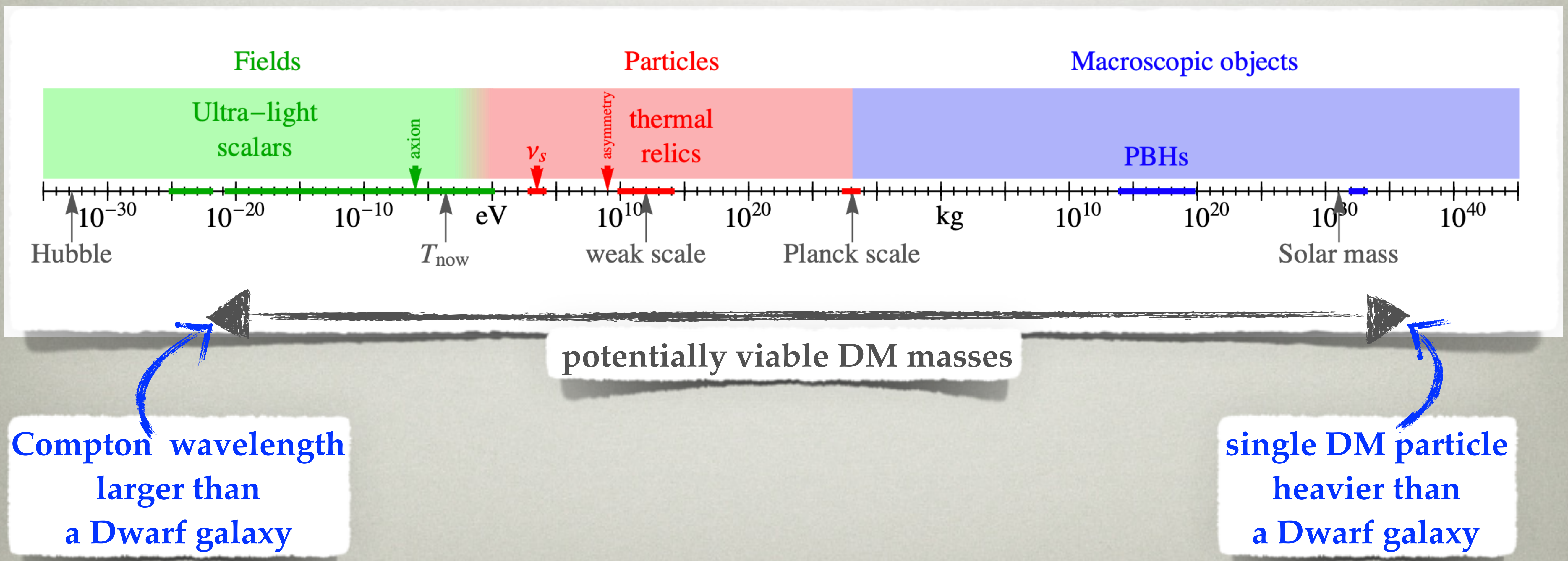
- DM is **cold**: DM behaves like a nonrelativistic fluid ($v_{DM} \ll c$)
  - If DM made of thermalized particles ⇒ more massive than a few keV
- **non-interacting (collisionless):**
  - interactions among DM particles, or between DM and other particles, are small enough to be neglected
  - unlike ordinary matter which couples to E&M field (light)
  - as a result DM is **dissipationless:** cannot easily cool down since it doesn't emit light
- **stable:** did not decay until now (present bound: $\tau_{DM} \gtrsim 10^9\, t_{Universe}$)
- **adiabatic:** DM is denser where ordinary matter and photons are denser (natural consequence of inflation)

WHAT WE DO NOT KNOW ABOUT DARK MATTER

- we do not know the properties of the DM particle
  - mass, spin, is there anti-DM?
  - is it absolutely stable?
  - nongravitational interactions?

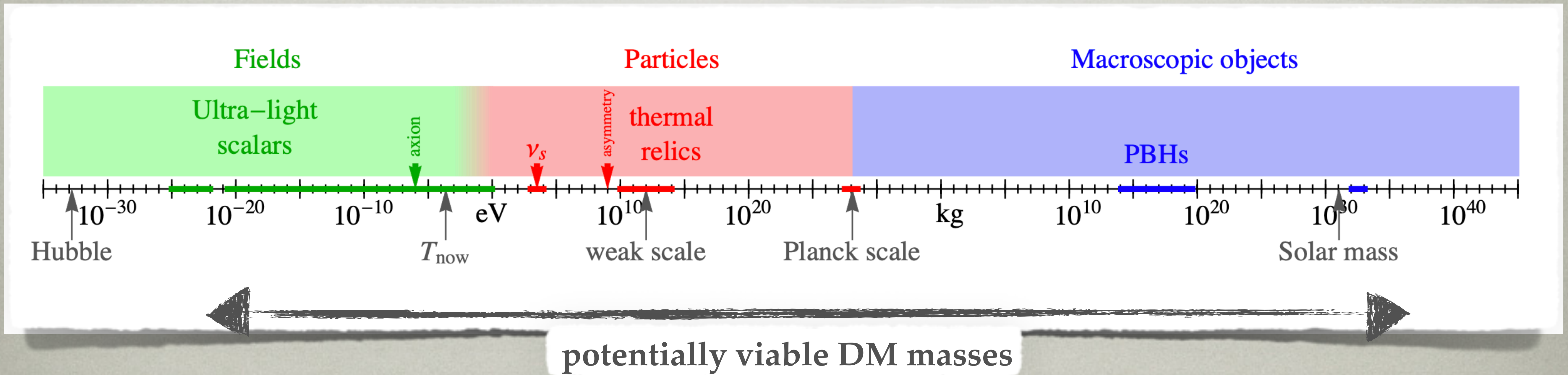
RANGE OF DARK MATTER MASSES

- very large range of possible dark matter masses
  - more than 90 orders of magnitude



RANGE OF DARK MATTER MASSES

- three different regimes
  - for $M \gtrsim M_{Pl} = 1.2 \cdot 10^{19}\,\text{GeV}$: DM is in the form of macroscopic objects
    - quite severely bounded by astrophysical observations
  - for $M \lesssim 1\,\text{eV}$: DM behaves as a classical field
  - for $1\,\text{eV} \lesssim M \lesssim M_{\text{Pl}}$: DM is a particle



FIELDS VS. PARTICLES

- if DM in the form of light scalar particles
  - high occupancy number per quantum state

$$N_{\text{occupation}} \sim \frac{(2\pi)^3}{4\pi/3}\frac{n_\phi}{m_\phi^3 \delta v^3} \simeq 10^5 \left(\frac{\rho_{\text{DM}}}{0.3\ \frac{\text{GeV}}{\text{cm}^3}}\right)\left(\frac{eV}{m_\phi}\right)^4 \left(\frac{10^{-3}}{\delta v}\right)^3$$

$n_\phi = \rho_{DM}/m_\phi$

~ **DM mass density at solar system**

typical escape velocity in galaxy: 500km/s

- can use classical field ϕ to describe DM
- the same as classical EM field describes many quanta: photons

LOWER BOUNDS ON DARK MATTER MASS

- lower bounds on DM mass from astrophysics
- for fermions: Pauli exclusion principle allows only one fermion per quantum state
  - occupancy number reduces for heavier DM, gives

Tremaine, Gunn, PRL42 (1979) 407

Paolo, Nesti, Villante , 1704.06644

$$m_\psi > 0.1\text{keV}$$

$$N_{\text{occ}} \sim \simeq 10^5 \left(\frac{\rho_{\text{DM}}}{0.3\,\frac{\text{GeV}}{\text{cm}^3}}\right)\left(\frac{eV}{m_\phi}\right)^4\left(\frac{10^{-3}}{\delta v}\right)^3$$

- for bosons: its Compton wavelength needs to fit into a galaxy

$$\lambda = \frac{2\pi}{m_\phi v} = 401\,\text{kpc}\frac{10^{-25}eV}{m_\phi}\frac{10^{-3}}{v}$$

  - more detailed analysis of large scale structure formation+Lyman α forest data

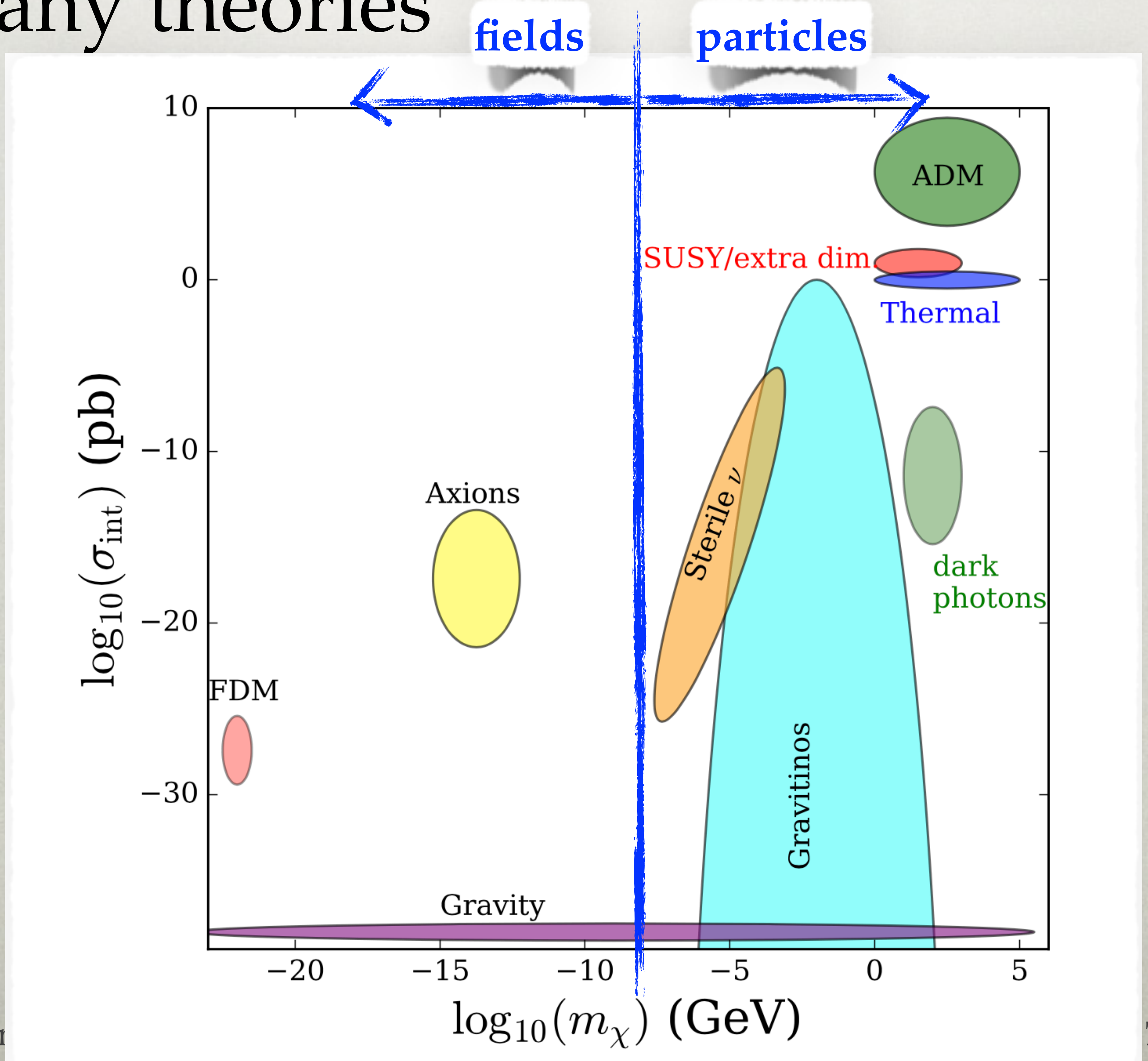
$$m_\phi > 2.9 \cdot 10^{-21}\text{eV}$$

Armengaud et al., 1703.09126

HEAVY OR LIGHT?

- many theories

Buckley, Peter, 1712.06615



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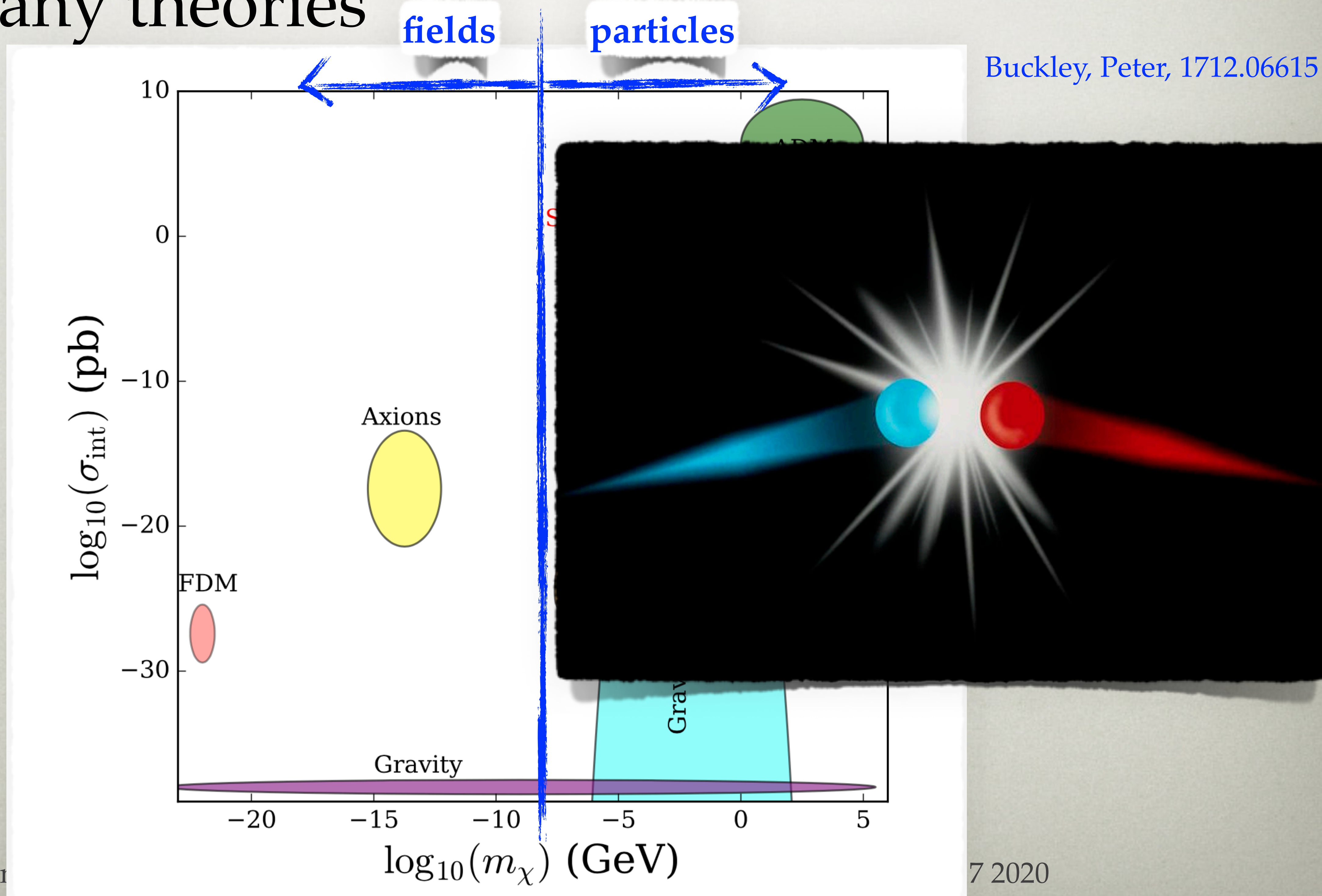

Buckley, Peter, 1712.06615

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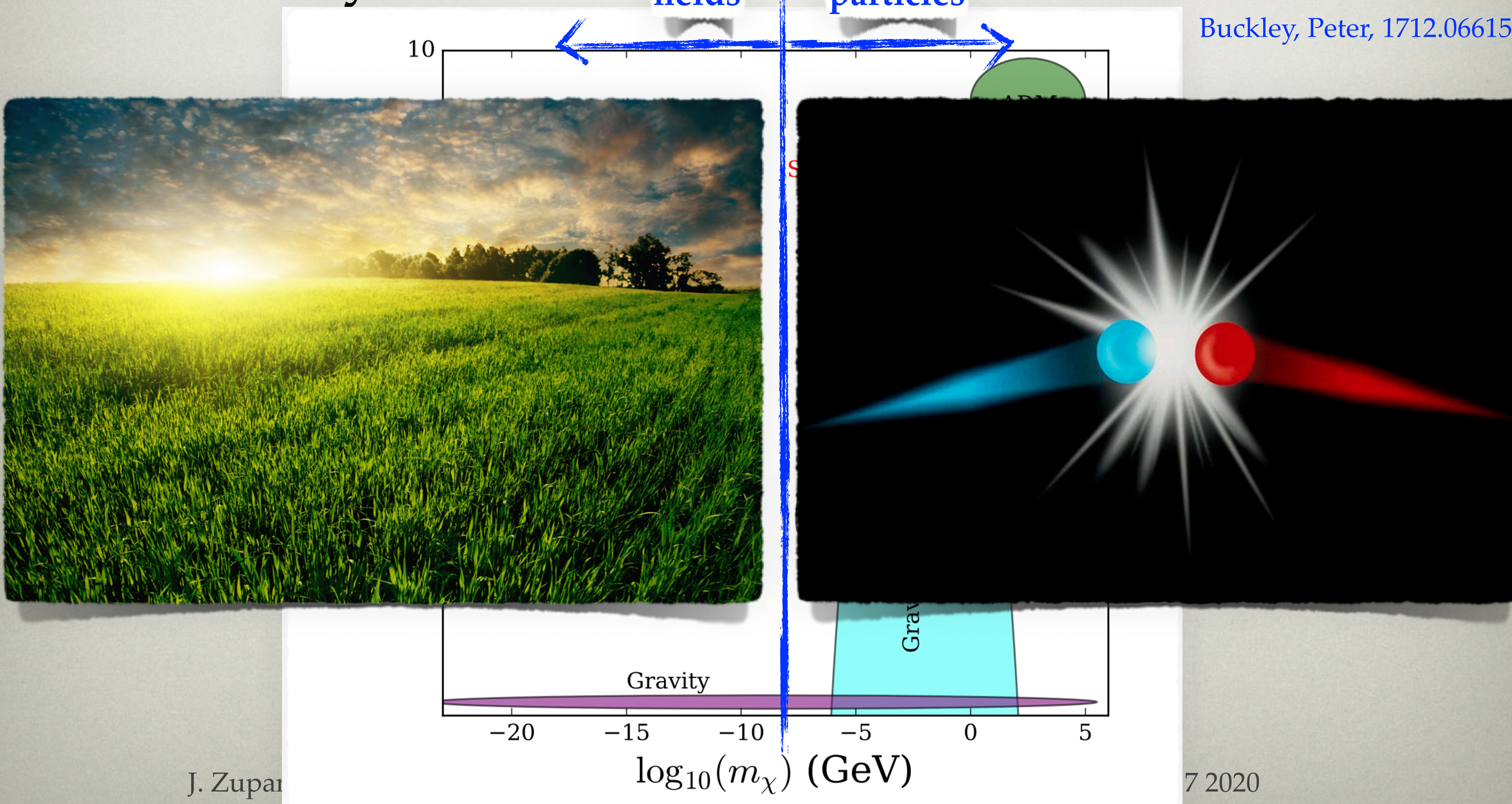
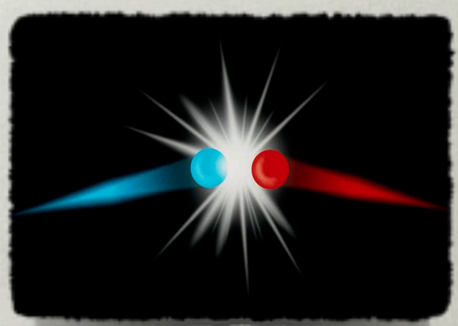


SEVERAL QUESTIONS

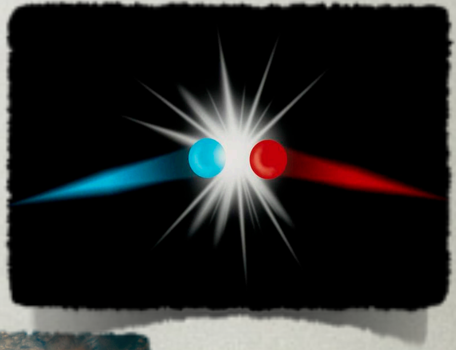
- how is dark matter produced in the early universe?
- how do we search for dark matter?
  - in both cases the value of DM mass very important
- next: give examples for light (fields) and heavy (particle) DM
  - heavy: WIMP (Weakly Interacting Massive Particle)
  - light: WISP (Weakly Interacting Slim Particle)



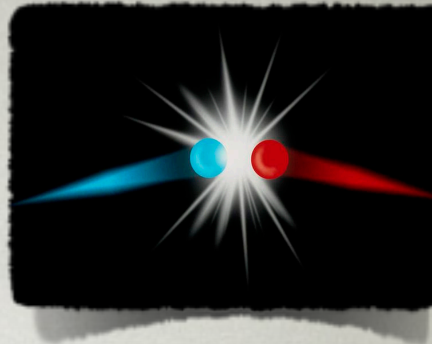
DARK MATTER PRODUCTION

COLD DARK MATTER

- review two production mechanisms
  - heavy (WIMP): thermal freeze-out
  - light (WISP): misalignment mechanism
- in both cases end up with cold DM



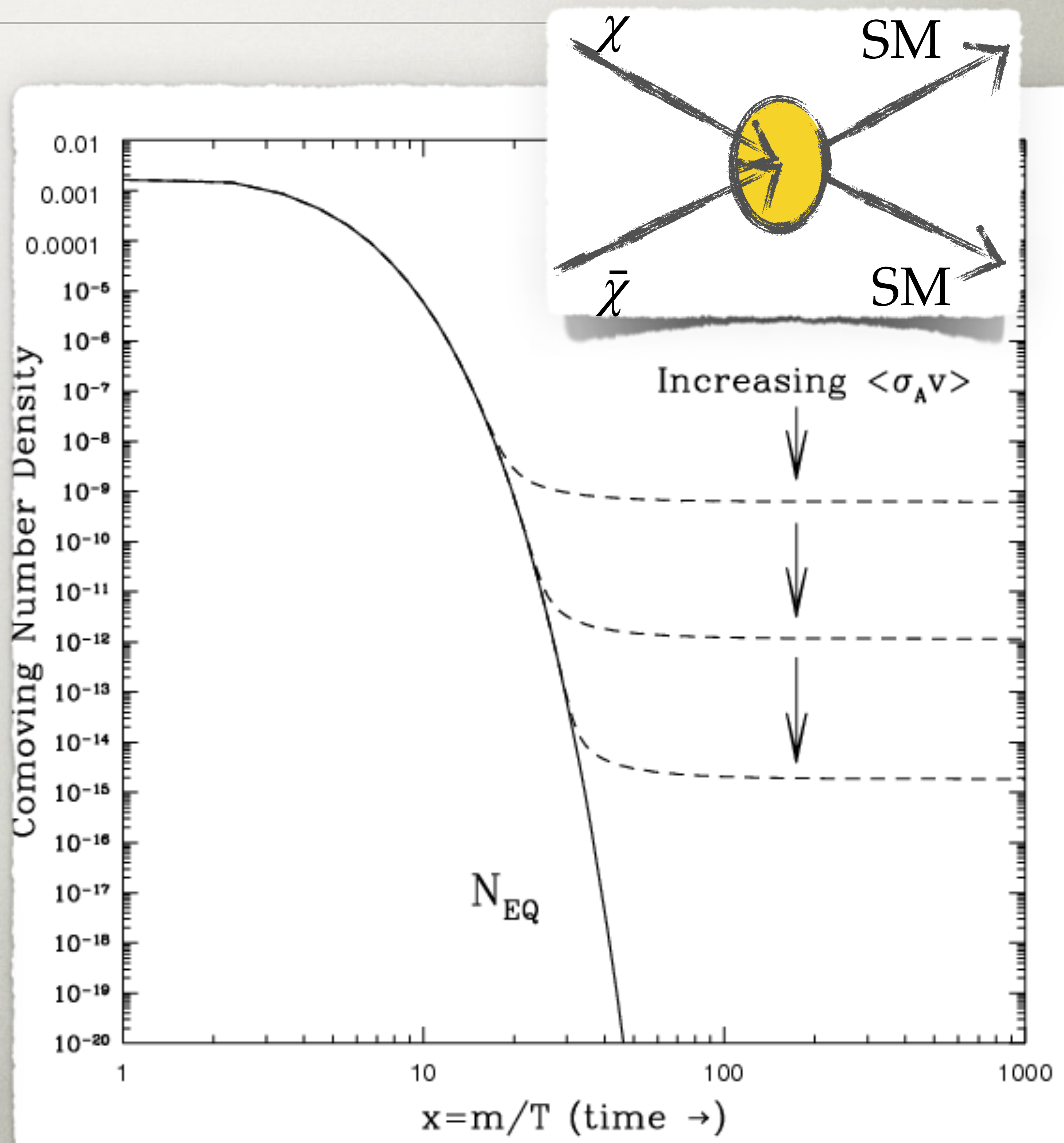
WIMP: THERMAL FREEZE-OUT

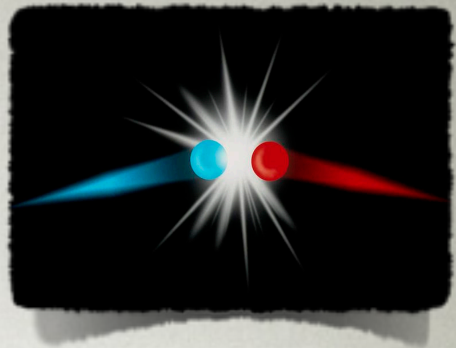


- assume WIMP interacts with visible matter
- thermalized with the SM plasma in the early universe
- as the universe cools DM drops out of chemical equilibrium
  - thermal freeze-out

$$\Omega_\chi h^2 \approx \frac{3\times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}$$

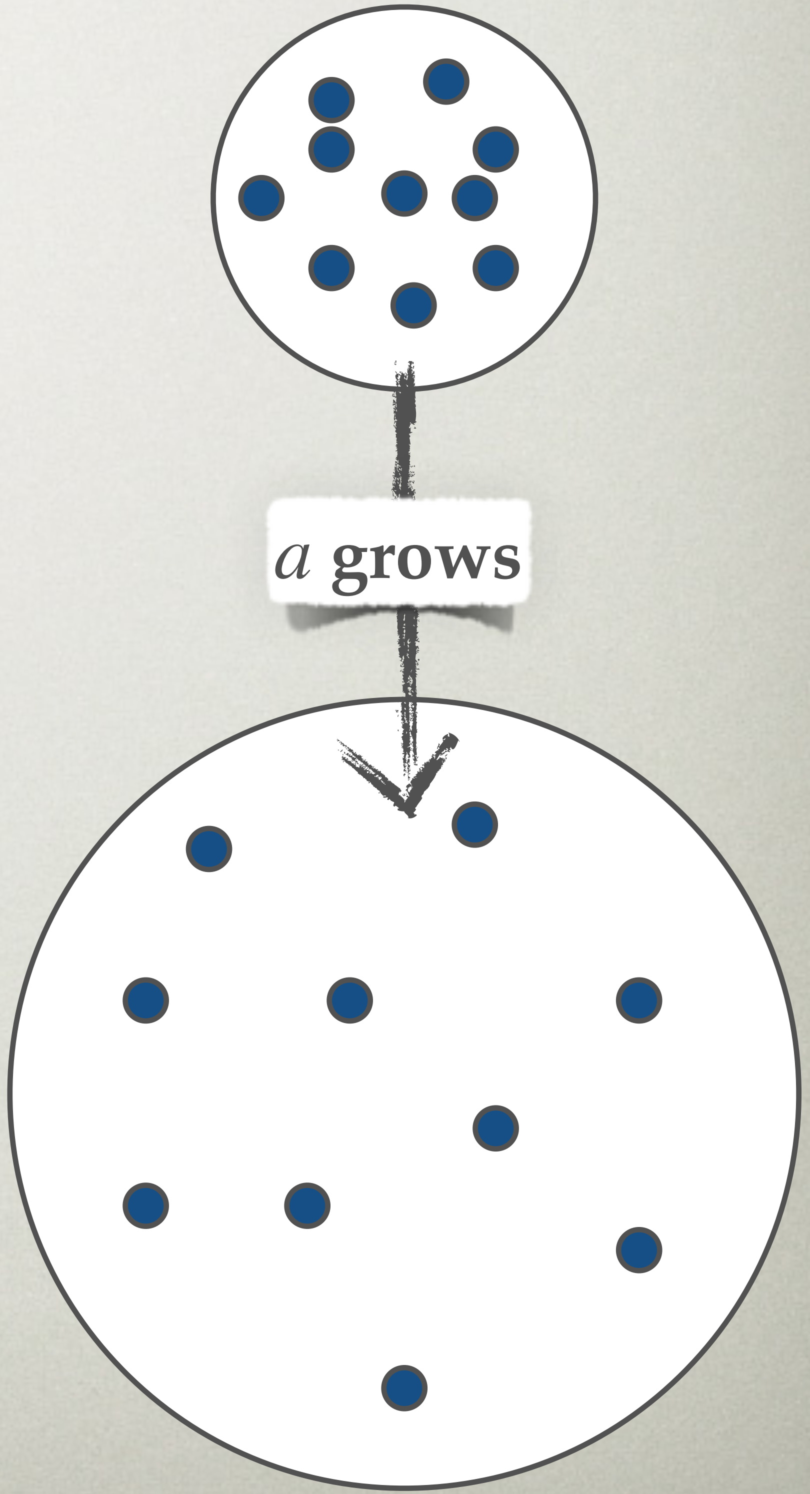
h~0.7, **scaling factor for Hubble expansion rate**





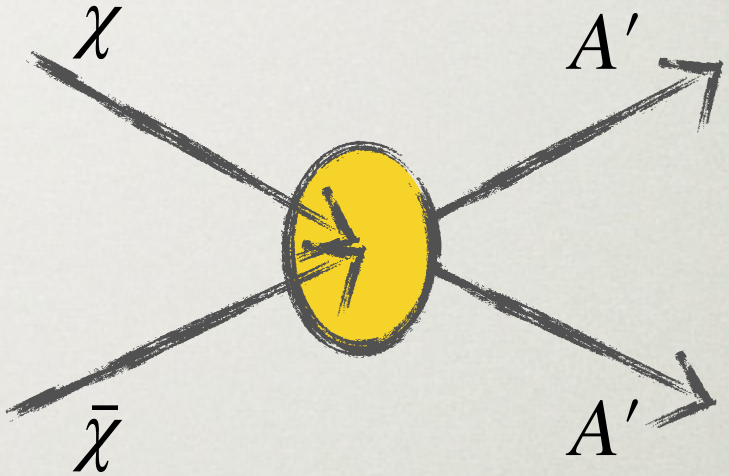
COLD DARK MATTER

- at freeze-out DM gas has thermal distribution
- keeps cooling as universe expands: $\rho \propto 1/a^3$
- result: non-relativistic presure-less ($p \simeq 0$) gas
  - **<u>cold dark matter</u>**



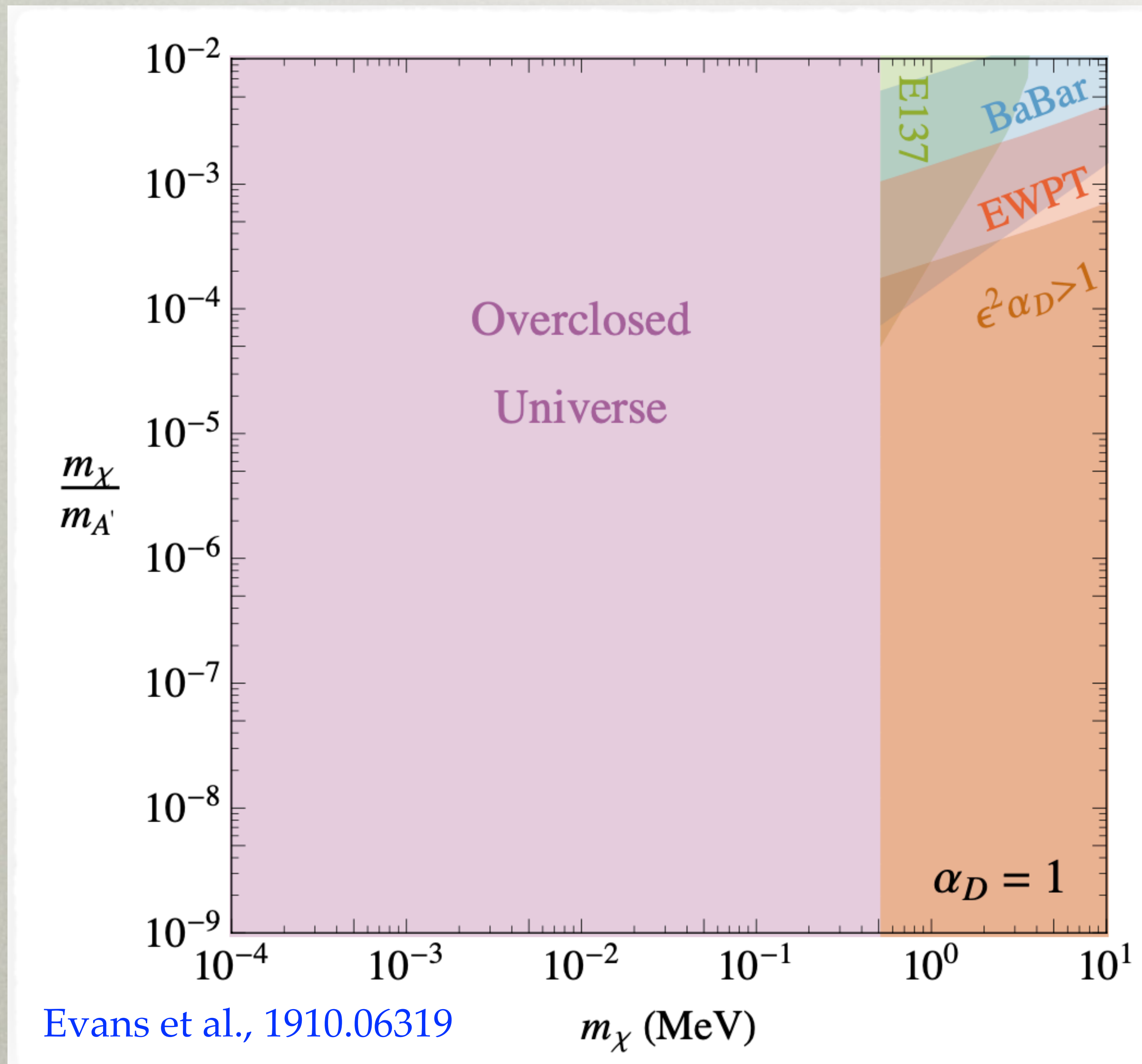
LIGHT-ISH THERMAL DARK MATTER

- thermal DM in the MeV-GeV is overproduced if only the SM interactions
  - requires additional light d.o.f.s (mediators) to deplete the overabundance



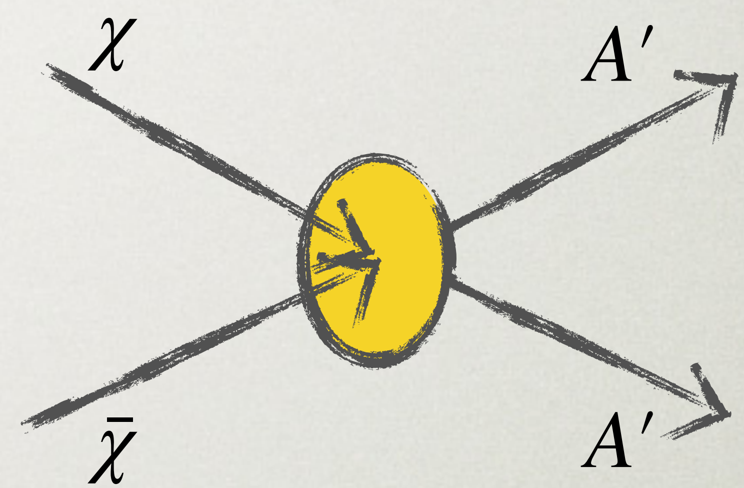
- the other option: heavy mediators but more complicated cosmological history
  - example: heavy state that decays and heats up (mostly) just the SM plasma

LIGHT-ISH THERMAL DARK MATTER



Evans et al., 1910.06319

eV is overproduced



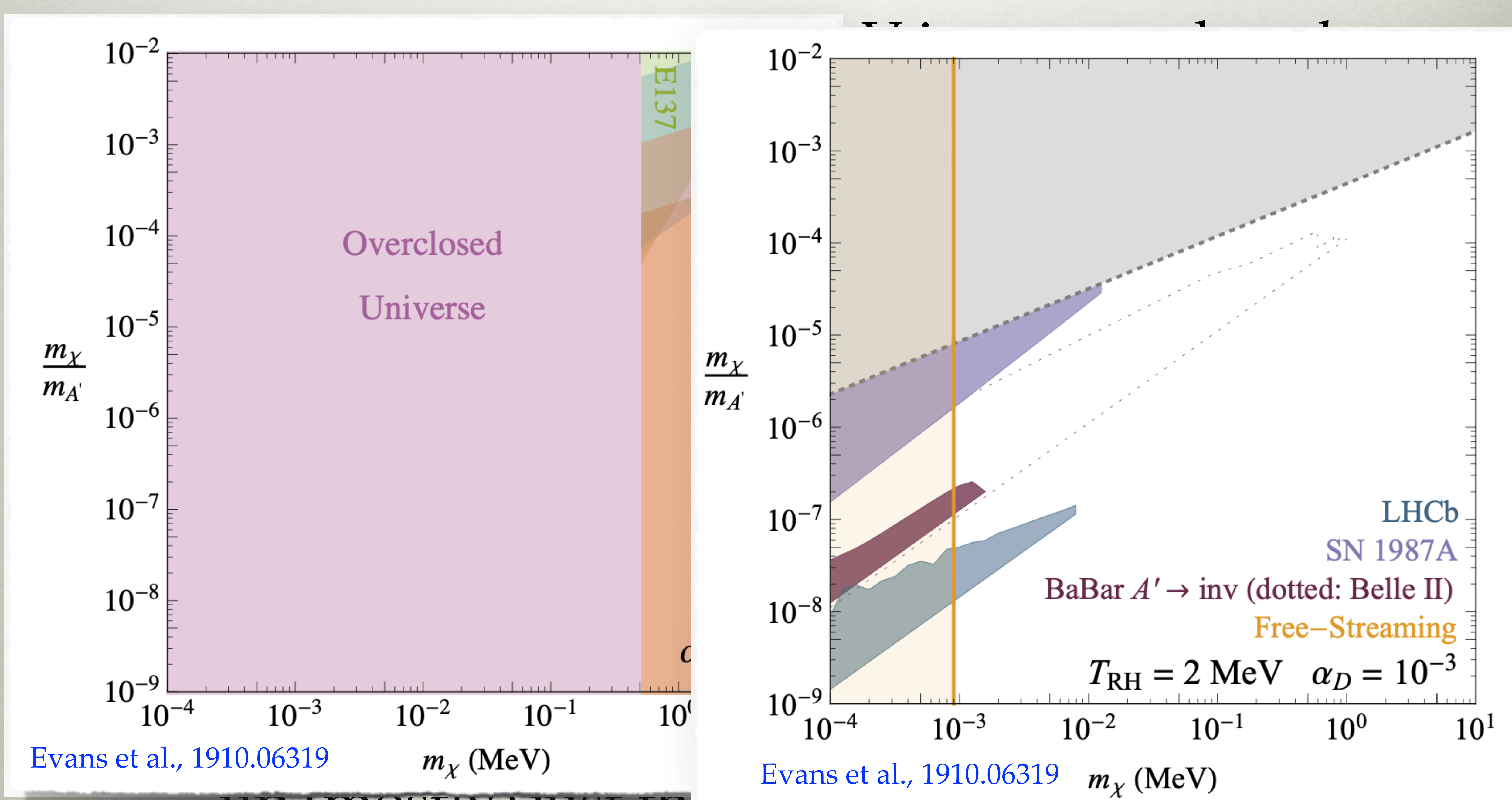
ediators but more

history

t decays and heats

up (mostly) just the SM plasma

LIGHT-ISH THERMAL DARK MATTER

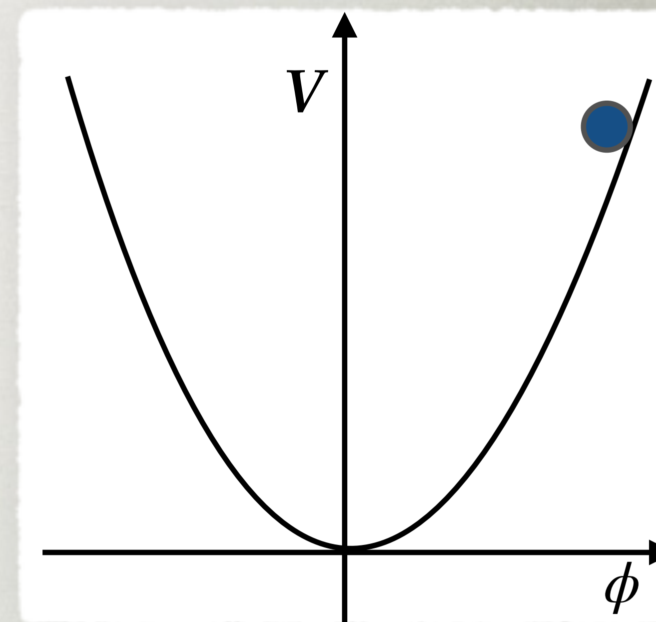


up (mostly) just the SM plasma

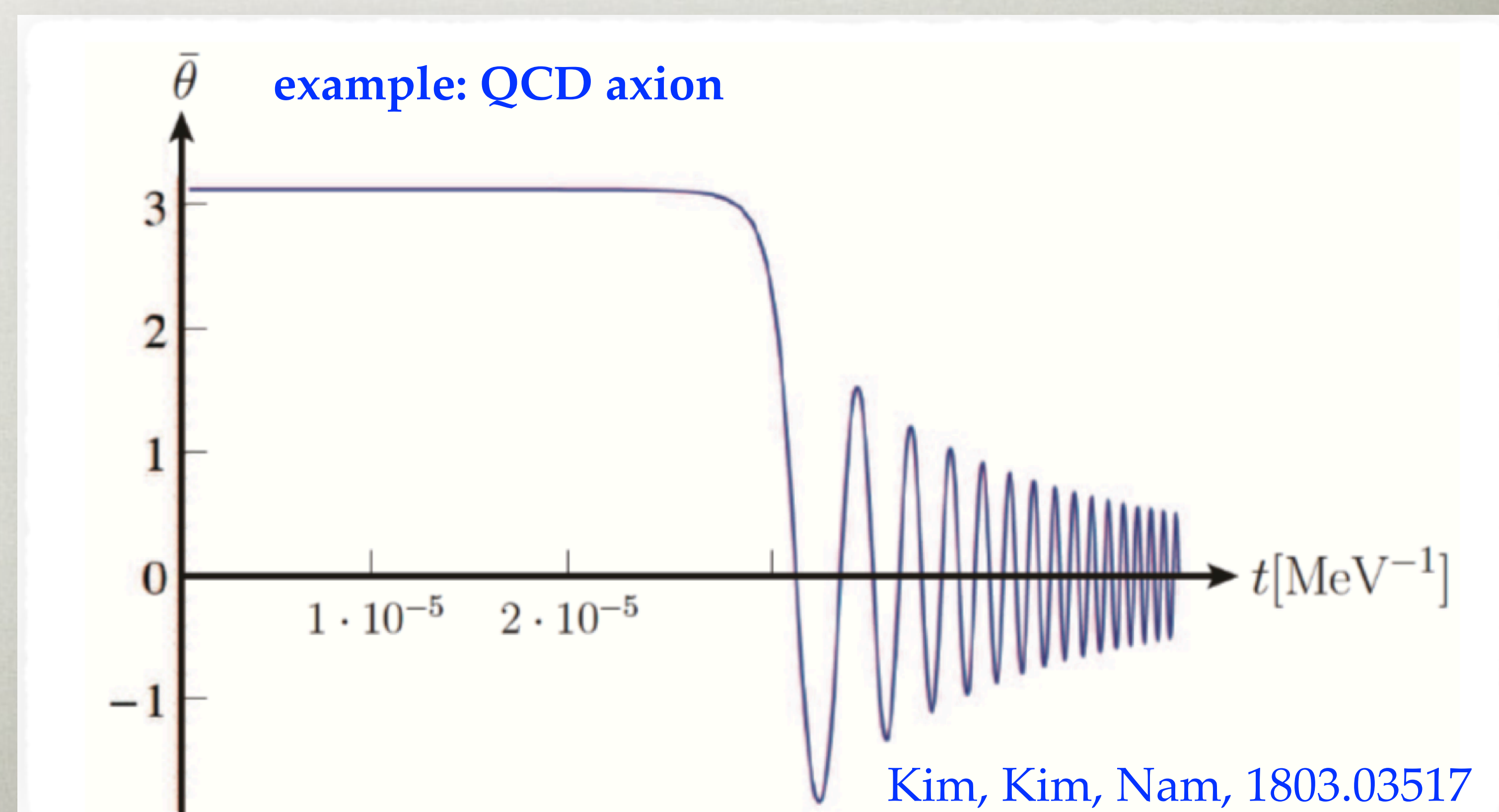
WISP: misalignment mechanism

Linde, PLB201, 437 (1988)
see also, e.g., Arias et al., 1201.5902

- assume field ϕ has a random initial value in the early universe
  - e.g., as from quantum fluctuations during inflation
  - nonzero value of ϕ= "misalignment"
    - i.e., not in the minimum of the potential, $V = \frac{1}{2} m_\phi^2 \phi^2$



- field evolves on timescales $t \sim 1/m_\phi$
  - after $t \sim 1/m_\phi$ field wants to minimize the potential
  - oscillates around the minimum
- the oscillations behave as cold DM fluid
  - since eng. density diluted by expansion of the universe as $\rho \propto a^{-3}$



MORE QUANTITATIVELY...

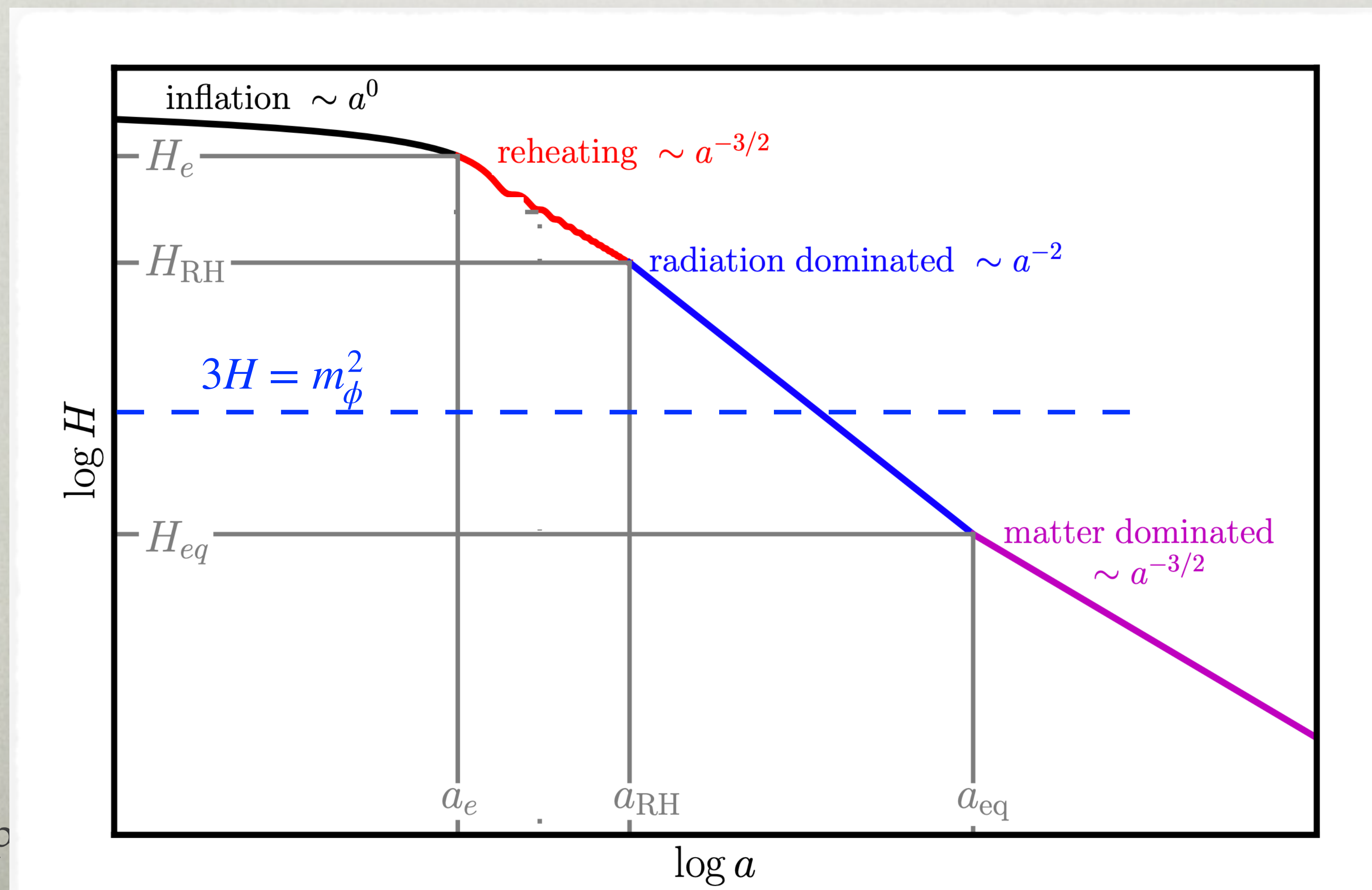
- equation of motion for ϕ in the expanding universe

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

Hubble parameter

$$H = \frac{\dot{a}}{a}$$

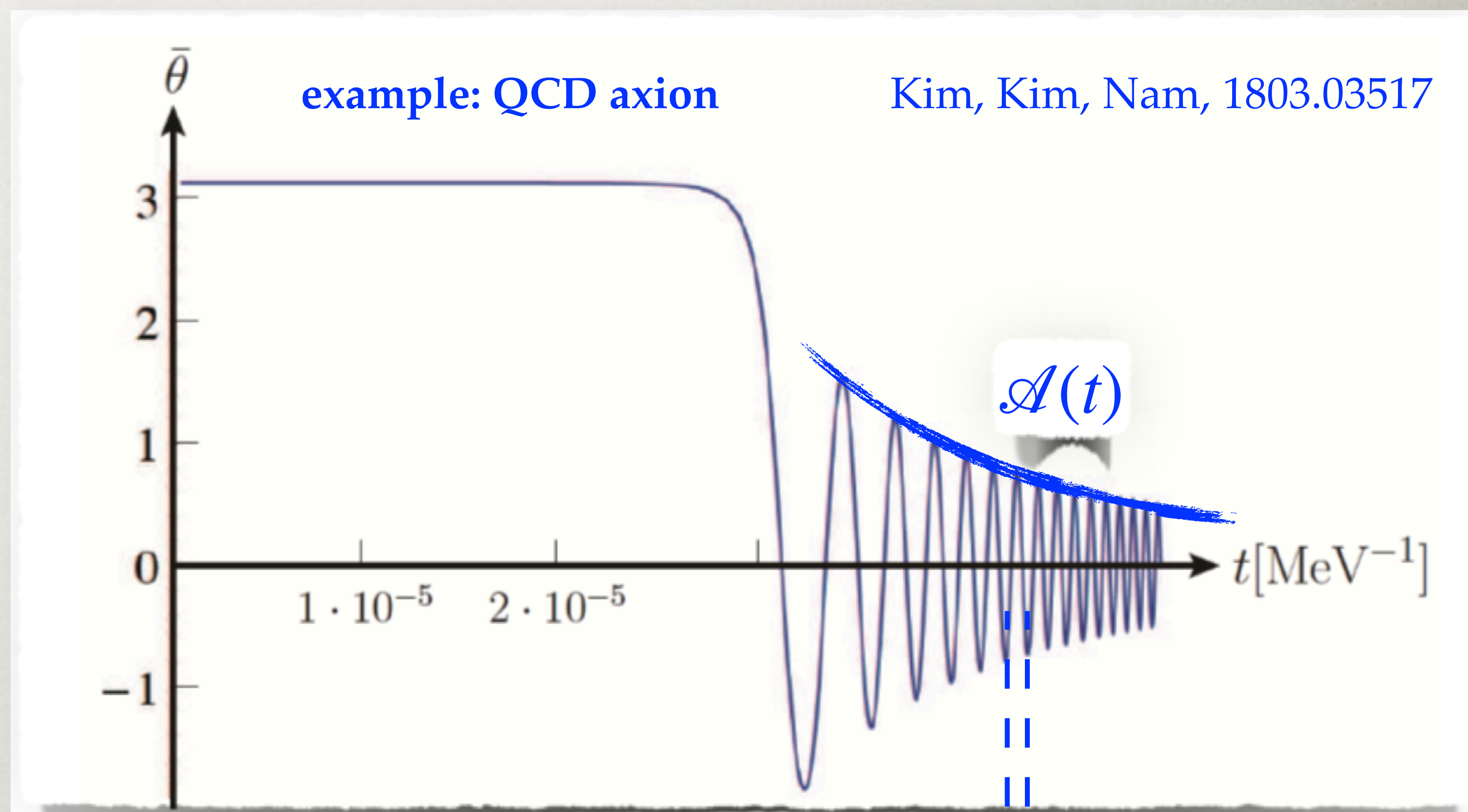
- early times: $3H \gg m_\phi^2 \Rightarrow \dot{\phi} = 0$
- late times: $3H \ll m_\phi^2 \Rightarrow \phi$ oscillates



adapted from
Kolb, Long, 1708.04293

MORE QUANTITATIVELY...

- at early times
  value of ϕ frozen
- at late times
  evolves as
  $\phi(t) = \mathscr{A}(t) cos(m_\phi t)$
- the amplitude changes
  slowly with time
  $\mathscr{A}(t) \propto a(t)^{-3/2}$
  - slow compared to oscillations m_ϕ
    $\dot{\mathscr{A}}/\mathscr{A} \ll m_\phi$



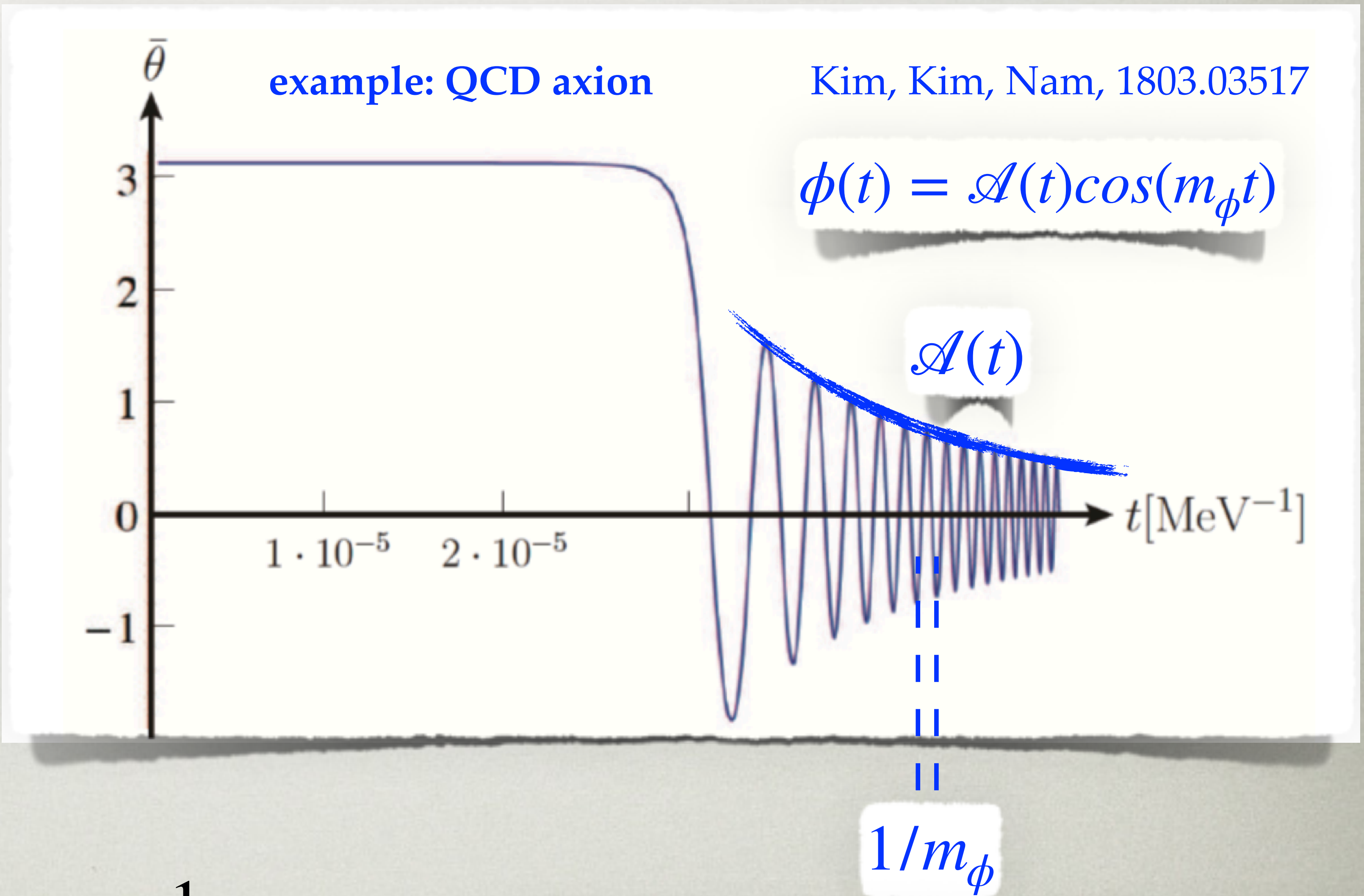
- note: m_ϕ in general T dependent, eqs. change slightly

MORE QUANTITATIVELY...

- energy density
$$\rho = \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}m_\phi^2\phi^2 =$$
$$= \frac{1}{2}m_\phi^2\mathscr{A}^2 + \cdots$$
- since $\mathscr{A}(t) \propto a(t)^{-3/2}$ this behaves as matter
$$\rho \propto 1/a^3$$
- pressure is small
$$\langle p \rangle = \langle \frac{1}{2}\dot{\phi}^2 - \frac{1}{2}m_\phi^2\phi^2 \rangle = \frac{1}{2}\dot{\mathscr{A}}^2 \ll \rho$$

time average

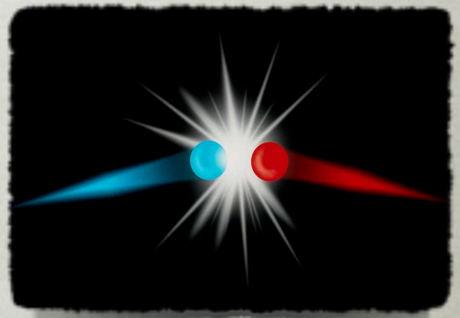
- **<u>cold dark matter</u>**: $\rho \propto 1/a^3, p \simeq 0$



Note: if WISP is DM then amplitude of oscillations fixed by local DM density
$$\mathscr{A} = \sqrt{2\rho_{\rm DM}}/m_\phi$$

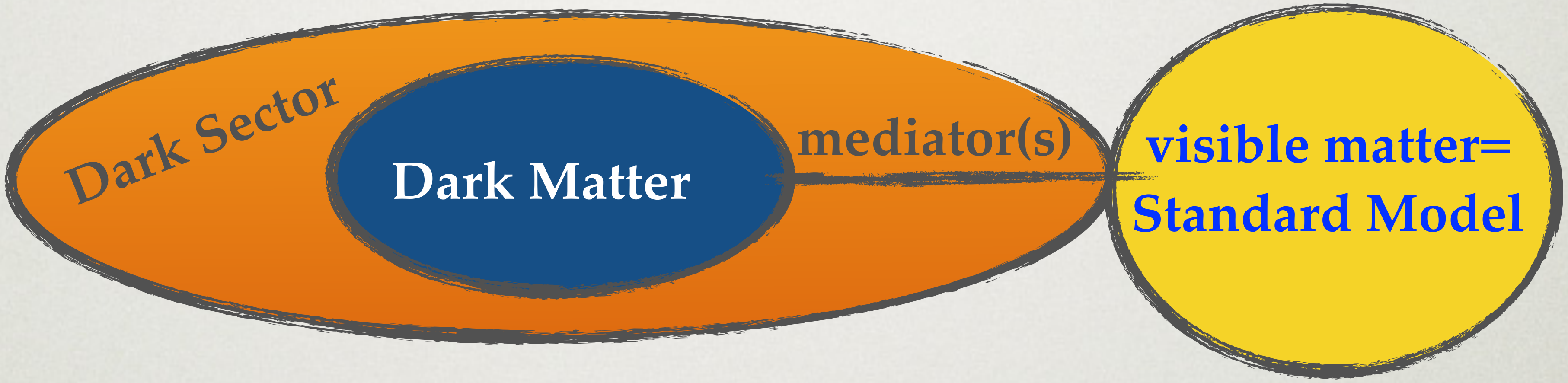
DARK MATTER DETECTION

- how to seach for dark matter?
- strategies again depend on the DM mass
  - searches for heavy DM/WIMPS
  - searches for light DM/WISPS
- first though a brief review of DM models



DARK SECTORS

- typical structure

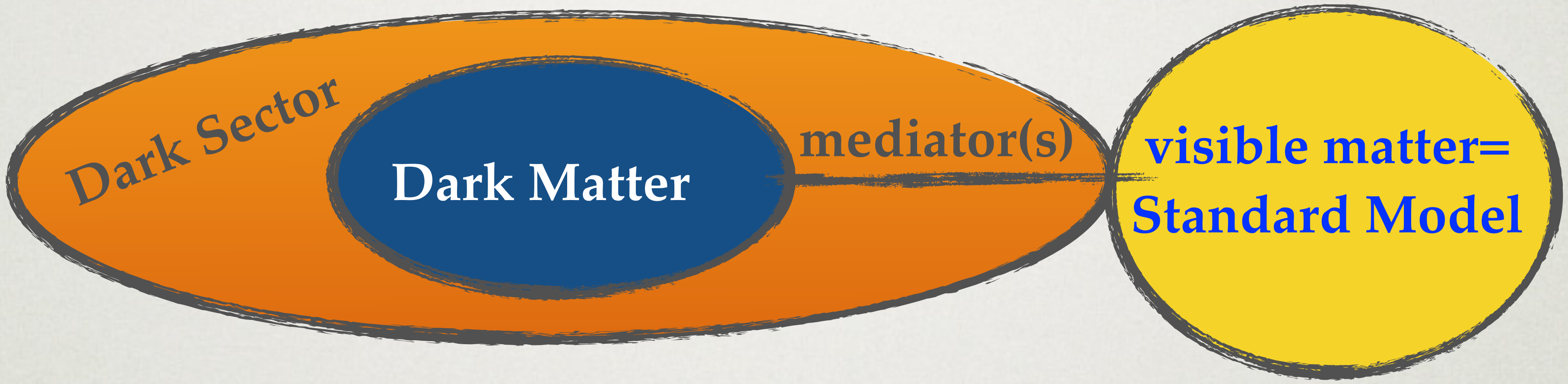


- can search for both - dark matter or for the dark sector mediator(s)
- examples of light mediators
  - dark photon (can also be the DM)
  - light scalar that mixes with the Higgs

MODELS OF DARK MATTER

DARK MATTER MODELS

- typical structure

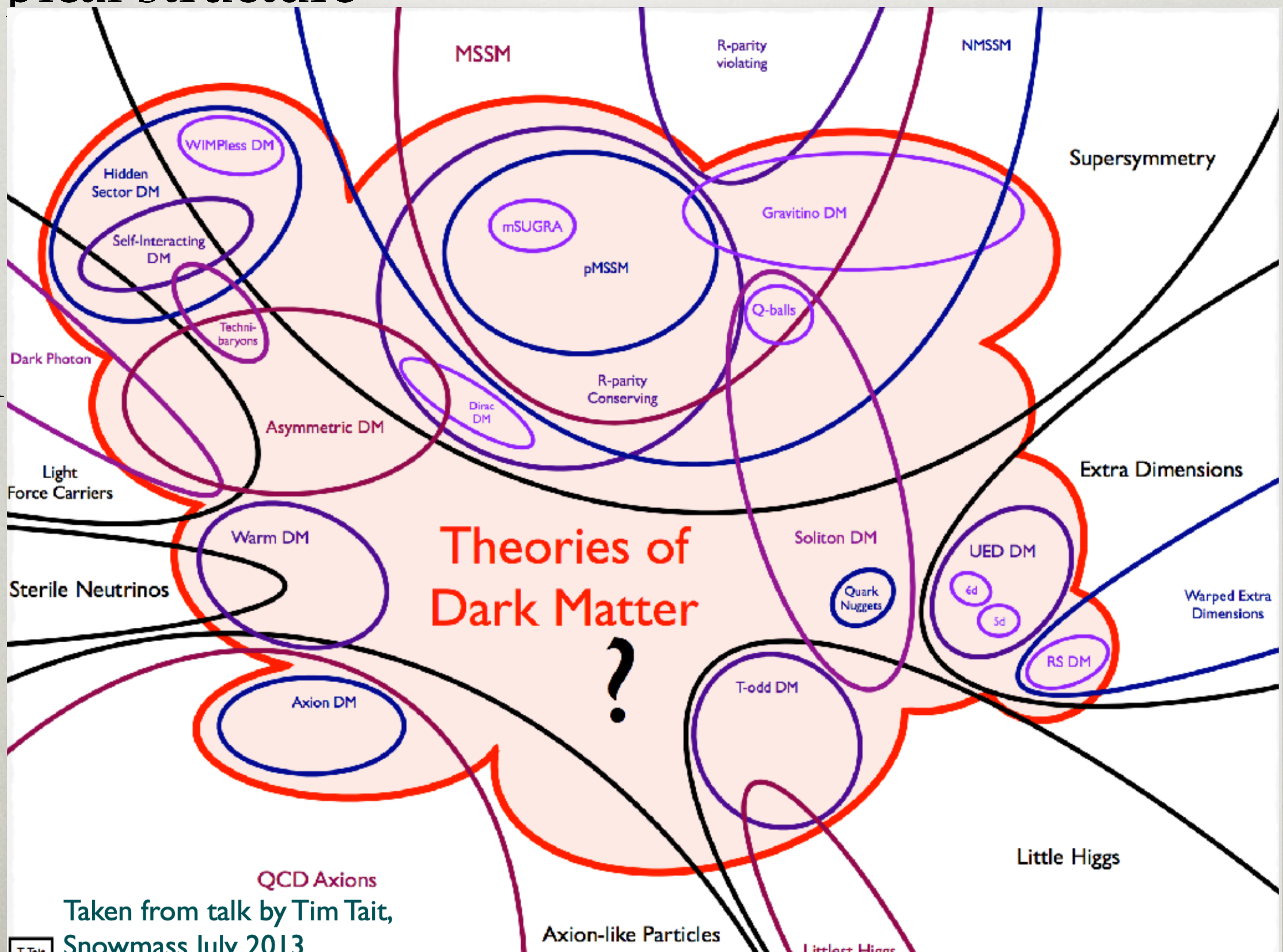


- many dark matter models

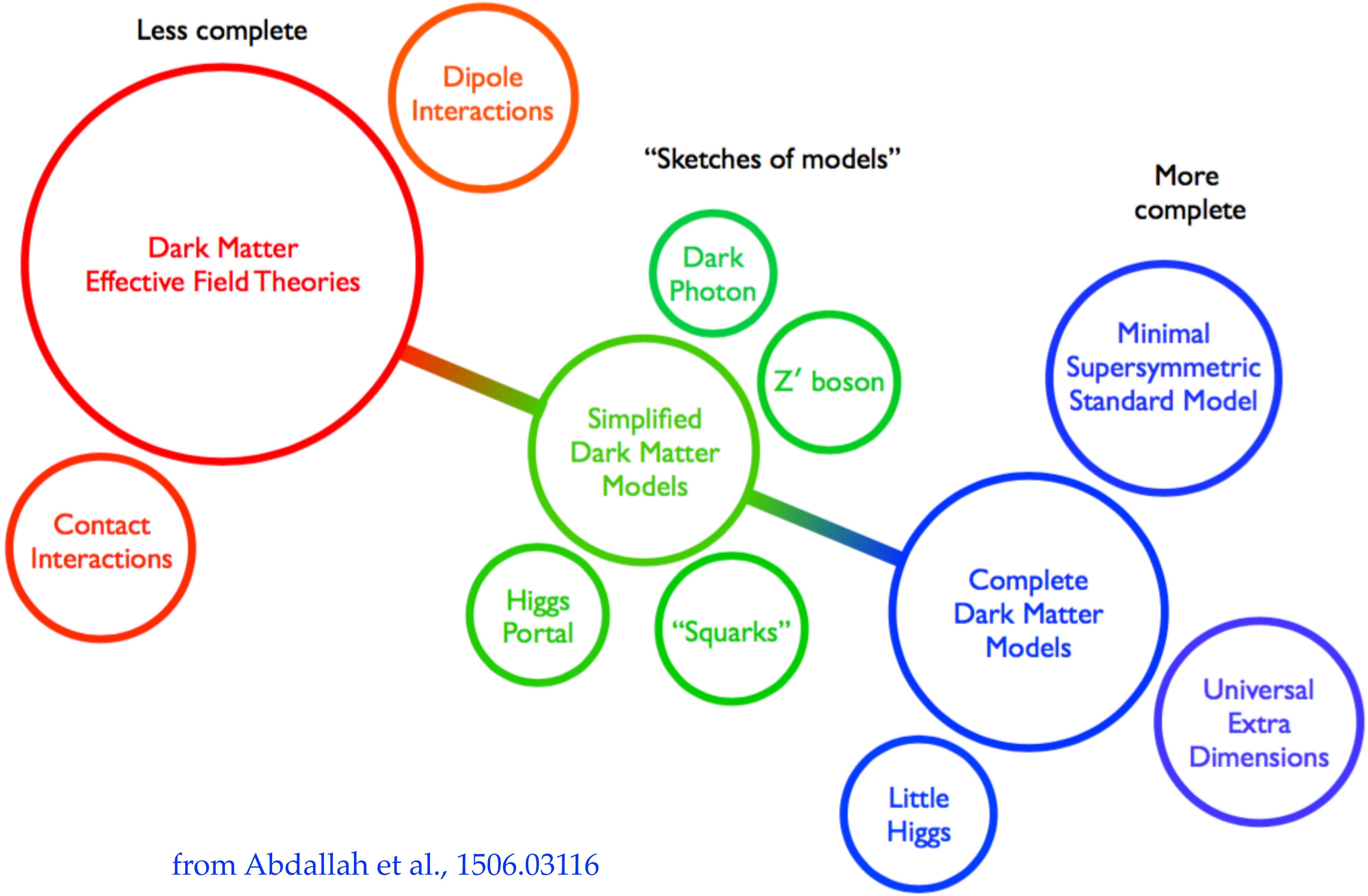
DARK MATTER MODELS

- typical structure

- m



DARK MATTER MODELS



from Abdallah et al., 1506.03116

DARK SECTOR PORTALS

- bottom up approach
- assume that DM couples to the visible sector
- adopt minimality: DM+mediator (=dark sector portal)

$$\mathcal{L}_{\rm portal} = \sum O_{\rm SM} \times O_{\rm DS}.$$

Portal	Coupling
Dark Photon, A_μ	$-\frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Axion, a	$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a} G_{i,\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\overline{\psi}\gamma^\mu\gamma^5\psi$
Sterile Neutrino, N	$y_N L H N$

DARK PHOTON PORTAL

- light new vector (dark photon) A'_μ
- dark matter χ (can be scalar or fermion)
- the minimal vector portal interaction

all dark sector-visible sector interactions through this term, always down by ϵ

$$\mathcal{L}_{\text{vector}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - \frac{\epsilon}{2\cos\theta_W} F'_{\mu\nu} B_{\mu\nu}$$

$$\mathcal{L}_{\text{DS}} = -\frac{1}{4}(F'_{\mu\nu})^2 + \frac{1}{2} m^2_{A'} (A'_\mu)^2 + |(\partial_\mu + i g_D A'_\mu)\chi|^2 + \ldots$$

- both mass of DM and dark photon are free parameters
  - the model can be both in the WIMP and WISP regime

SCALAR PORTAL

- light new scalar S
- dark matter χ (can be scalar or fermion)

$$\mathcal{L}_{\text{scalar}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{DS}} - (\mu S + \lambda S^2) H^\dagger H.$$

$$\mathcal{L}_{\text{DS}} = S\bar{\chi}\chi + \ldots.$$

two parameters control dark sector-visible sector interactions

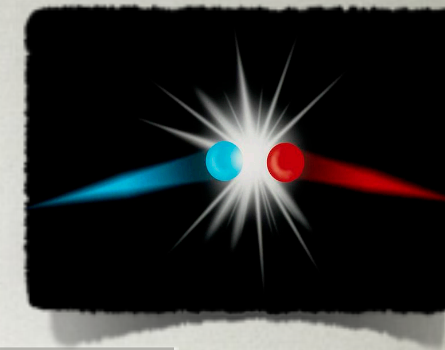
- most viable DM models in the sub-EW scale range imply $2m_\chi > m_S$

SEARCHING FOR DARK MATTER

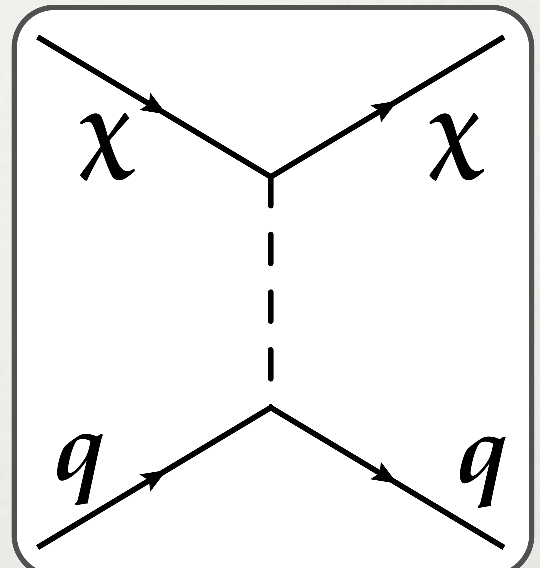
- how to search for DM?
  - can search directly for DM
  - or search for the mediator

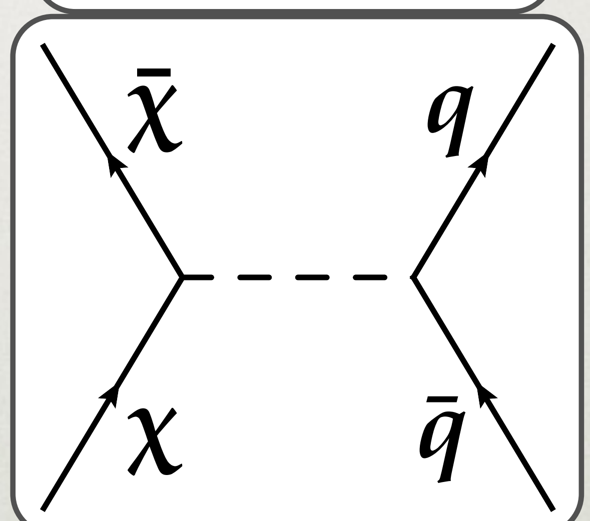
SEARCHING FOR WIMPS

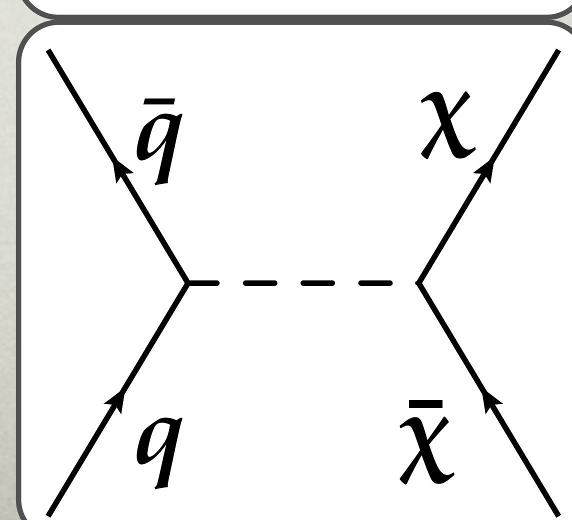
SEARCHING FOR HEAVY DARK MATTER / WIMPS

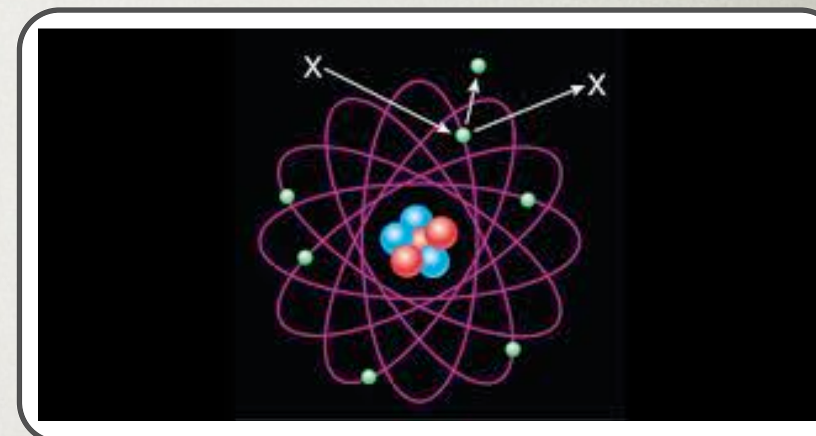


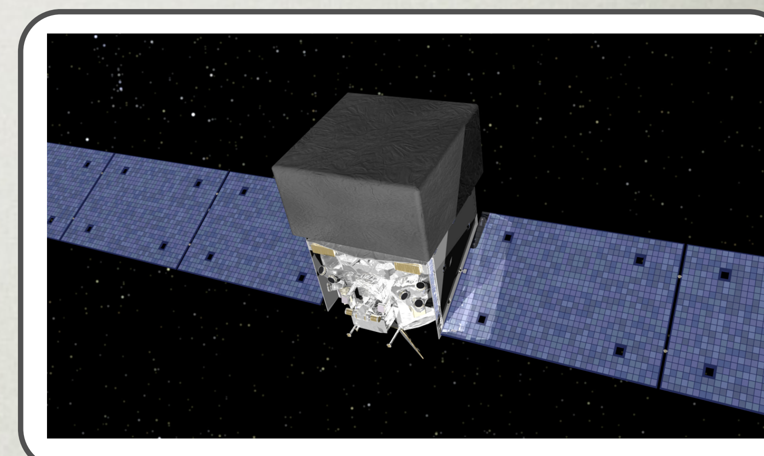
- several probes of heavy DM
  - direct detection
  - indirect detection
  - production at colliders

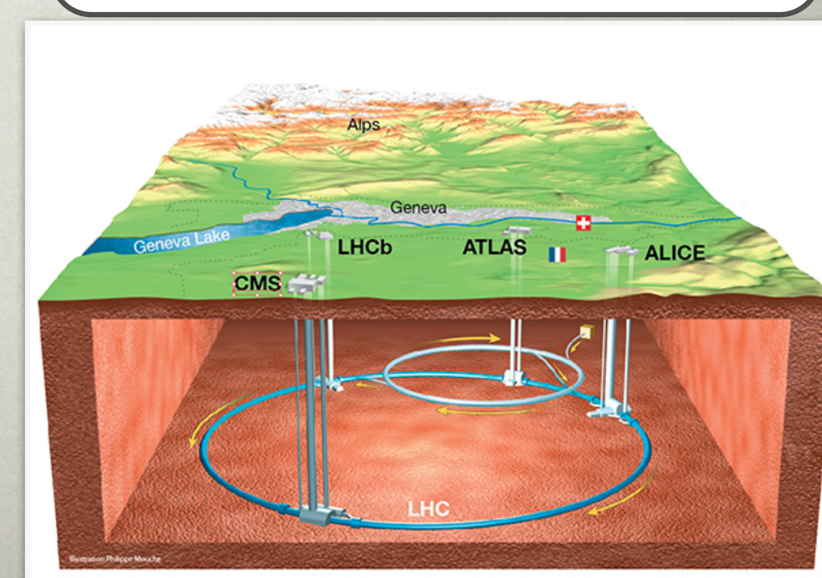




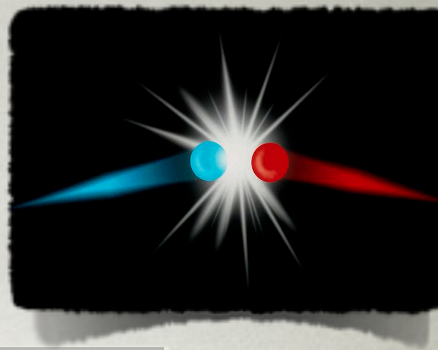








DIRECT DM DETECTION

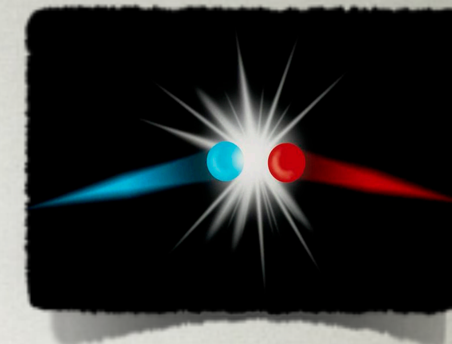


- WIMPs form DM halo
  - typical velocity $v \sim 10^{-3}$
- scatters on target nuclei $\chi N \to \chi N$
  - leaves energy in the detector

$$E_d = 2\frac{\mu_\chi^2}{M_A}v^2 \sim 2\text{keV}\Big(\frac{120GeV}{M_A}\Big)\Big(\frac{\mu_\chi}{10\text{GeV}}\Big)^2\Big(\frac{v}{10^{-3}}\Big)^2$$

  - energy deposit measured through: ionization, scintillation light, phonons

ct DM detection



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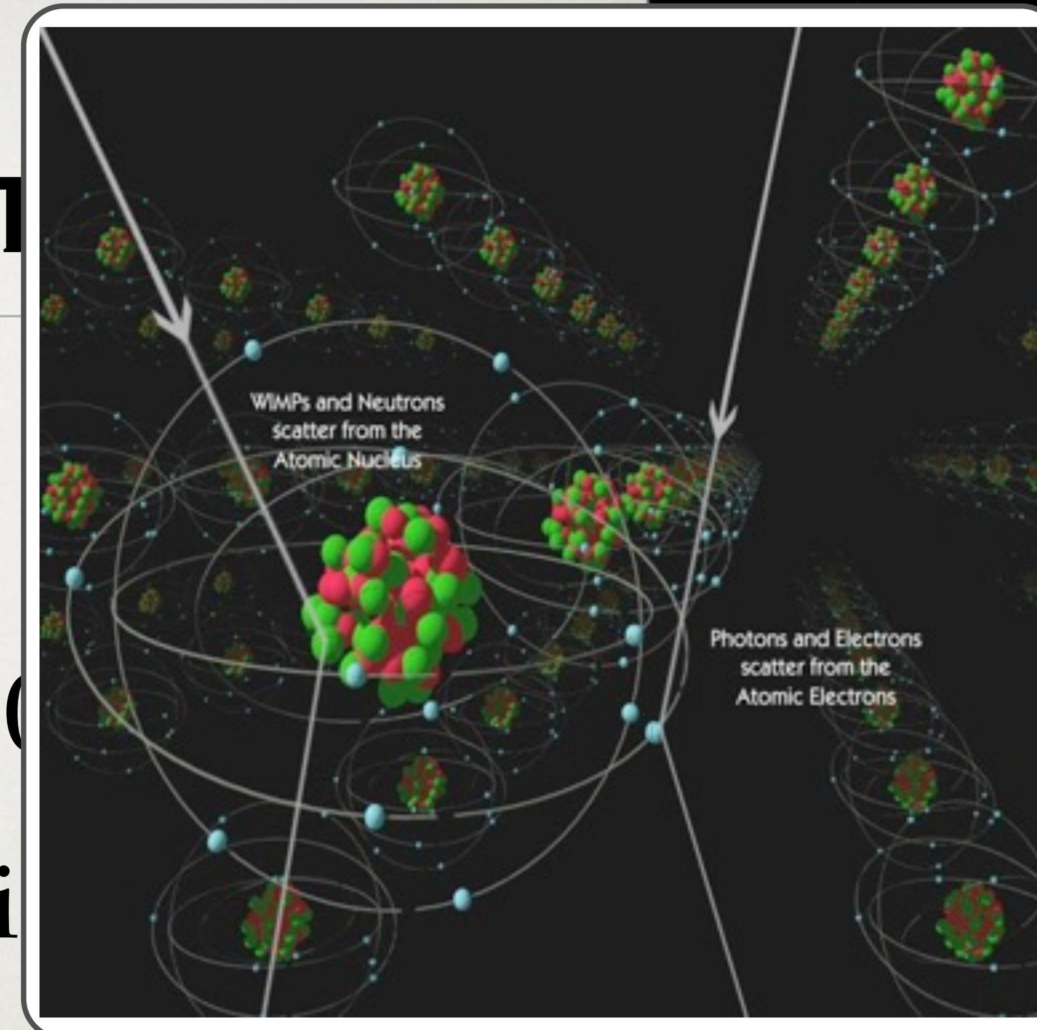
...ct DM det...



- ...s form DM halo
  - ...ypical velocity $v \sim 1$...
- scatters on target nuclei
  - leaves energy in the detector

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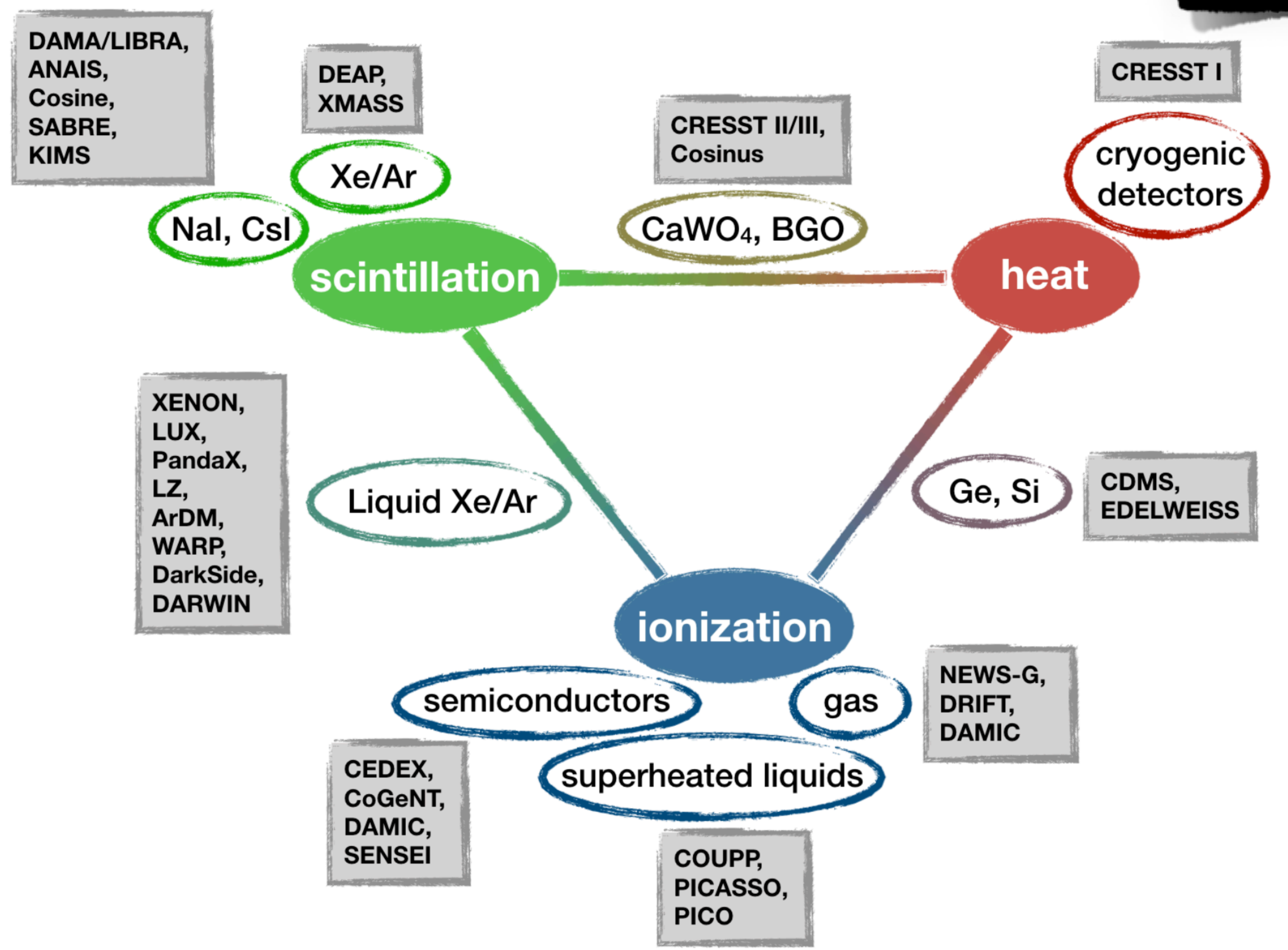
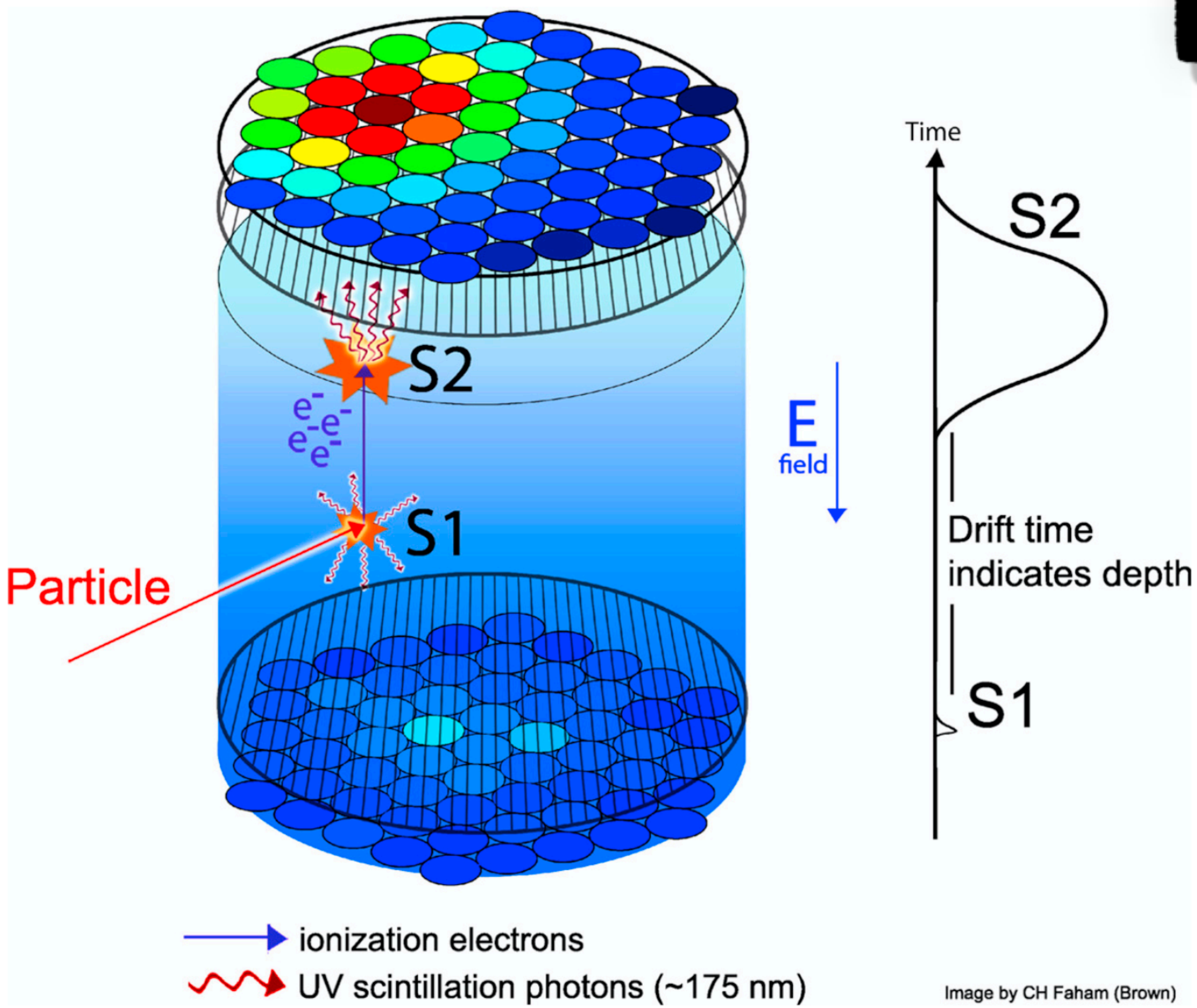
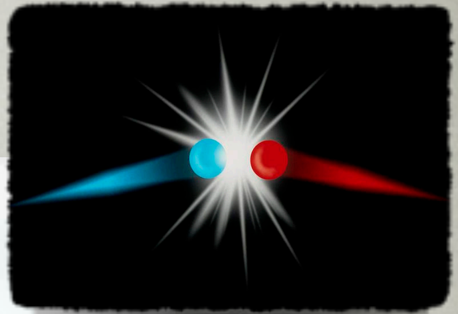
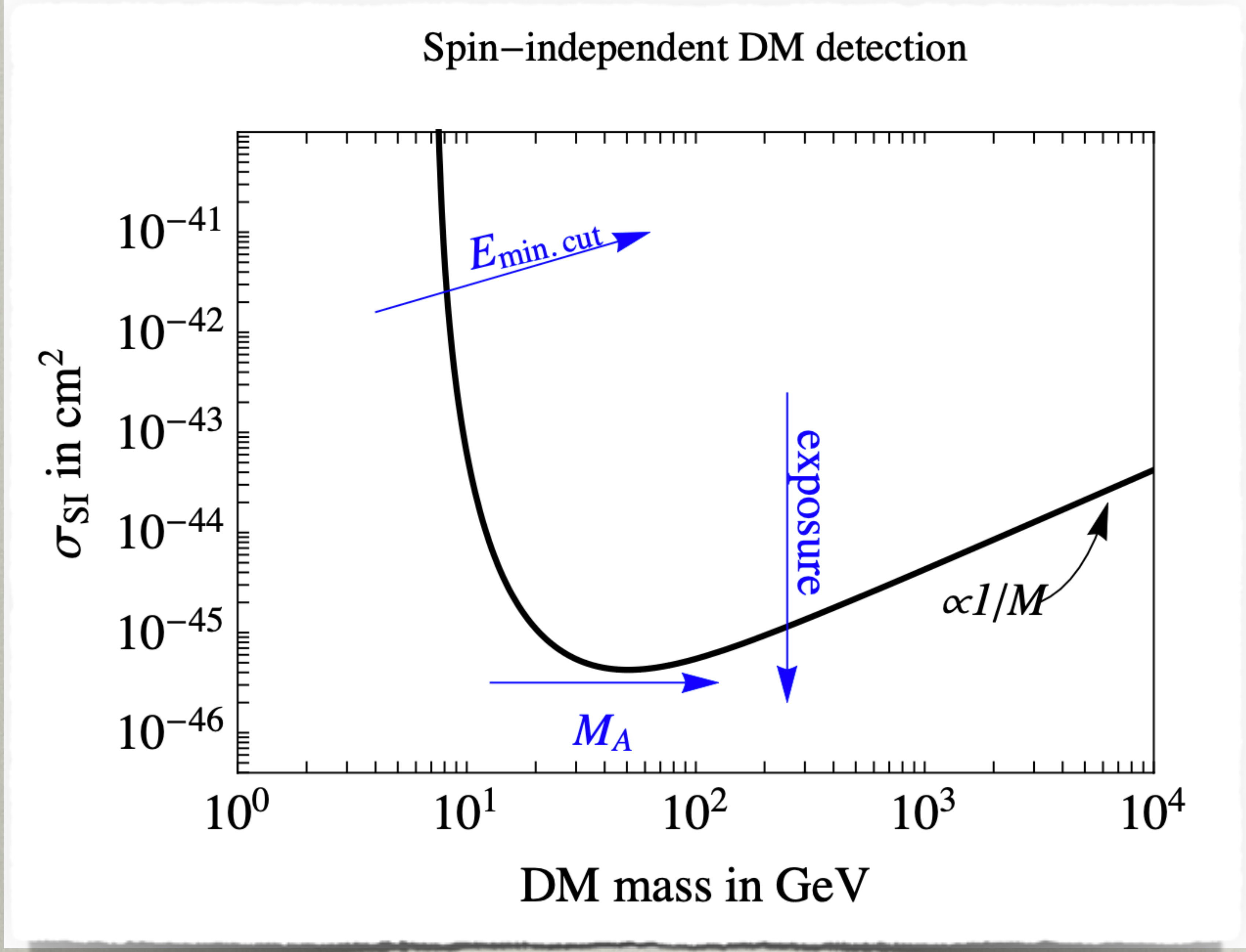


DAMA/LIBRA, ANAIS, Cosine, SABRE, KIMS
DEAP, XMASS
Xe/Ar
NaI, CsI
scintillation
CRESST II/III, Cosinus
CaWO4, BGO
CRESST I
cryogenic detectors
heat
XENON, LUX, PandaX, LZ, ArDM, WARP, DarkSide, DARWIN
Liquid Xe/Ar
Ge, Si
CDMS, EDELWEISS
ionization
semiconductors
gas
NEWS-G, DRIFT, DAMIC
superheated liquids
CEDEX, CoGeNT, DAMIC, SENSEI
COUPP, PICASSO, PICO


Time
S2
S2
E
field
S1
Drift time
indicates depth
S1
Particle
ionization electrons
UV scintillation photons (~175 nm)
Image by CH Faham (Brown)

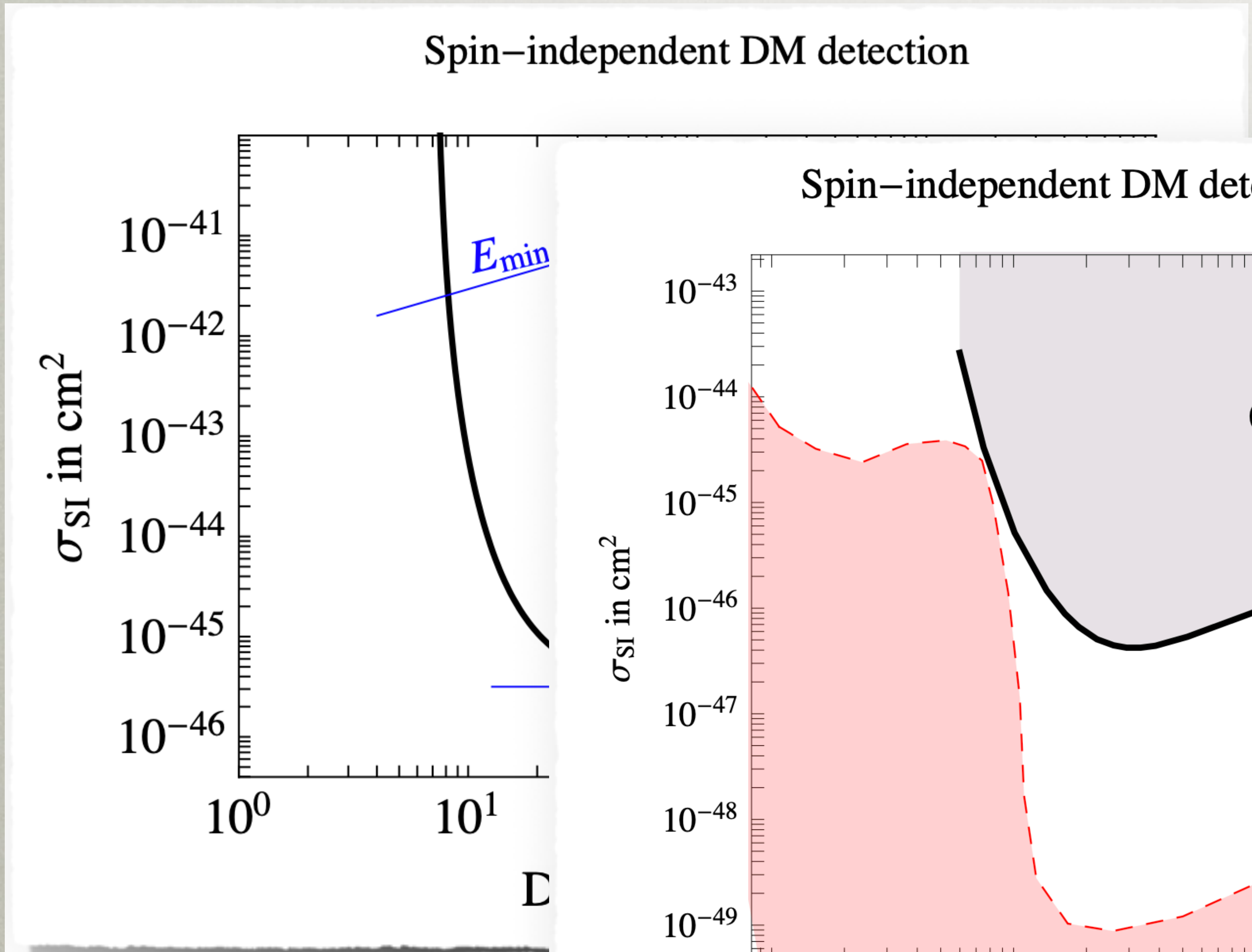


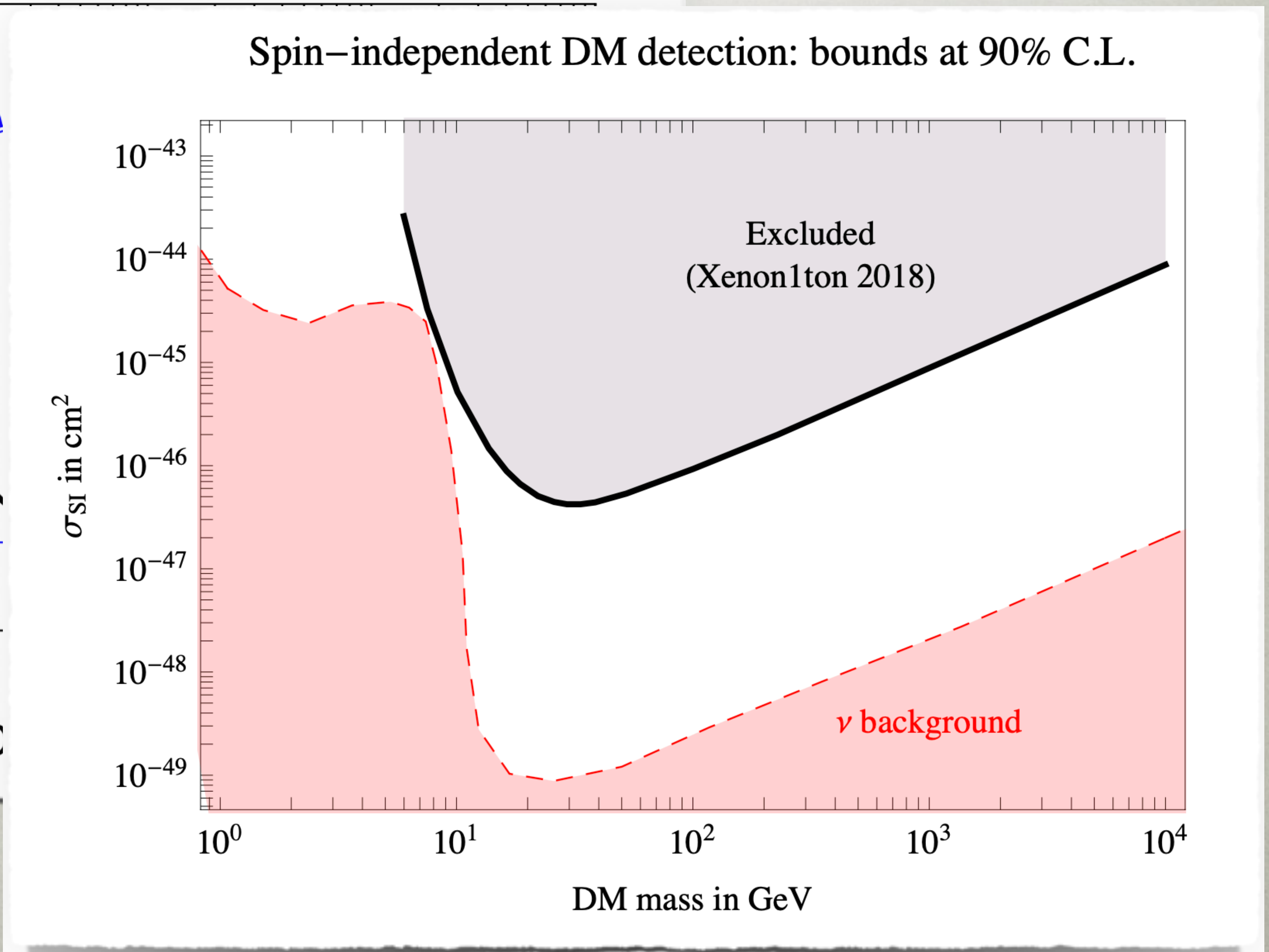
EXCLUSION PLANES



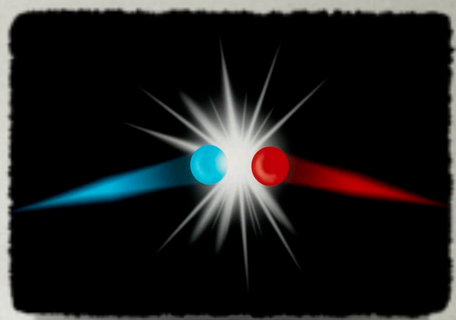
Cirelli, Strumia, JZ, to appear

EXCLUSION PLANES

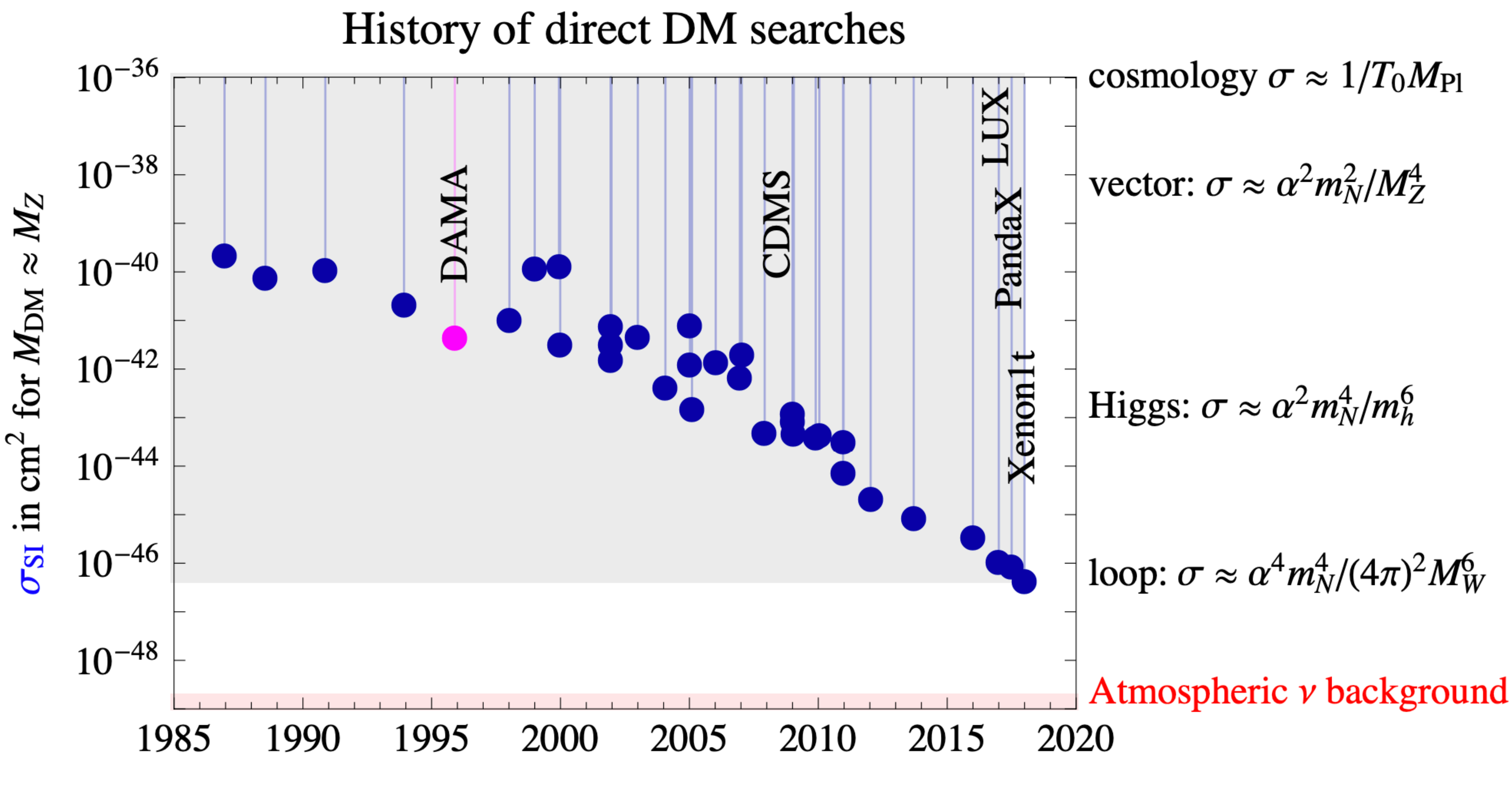




Cirelli, Strumia, JZ, to appear

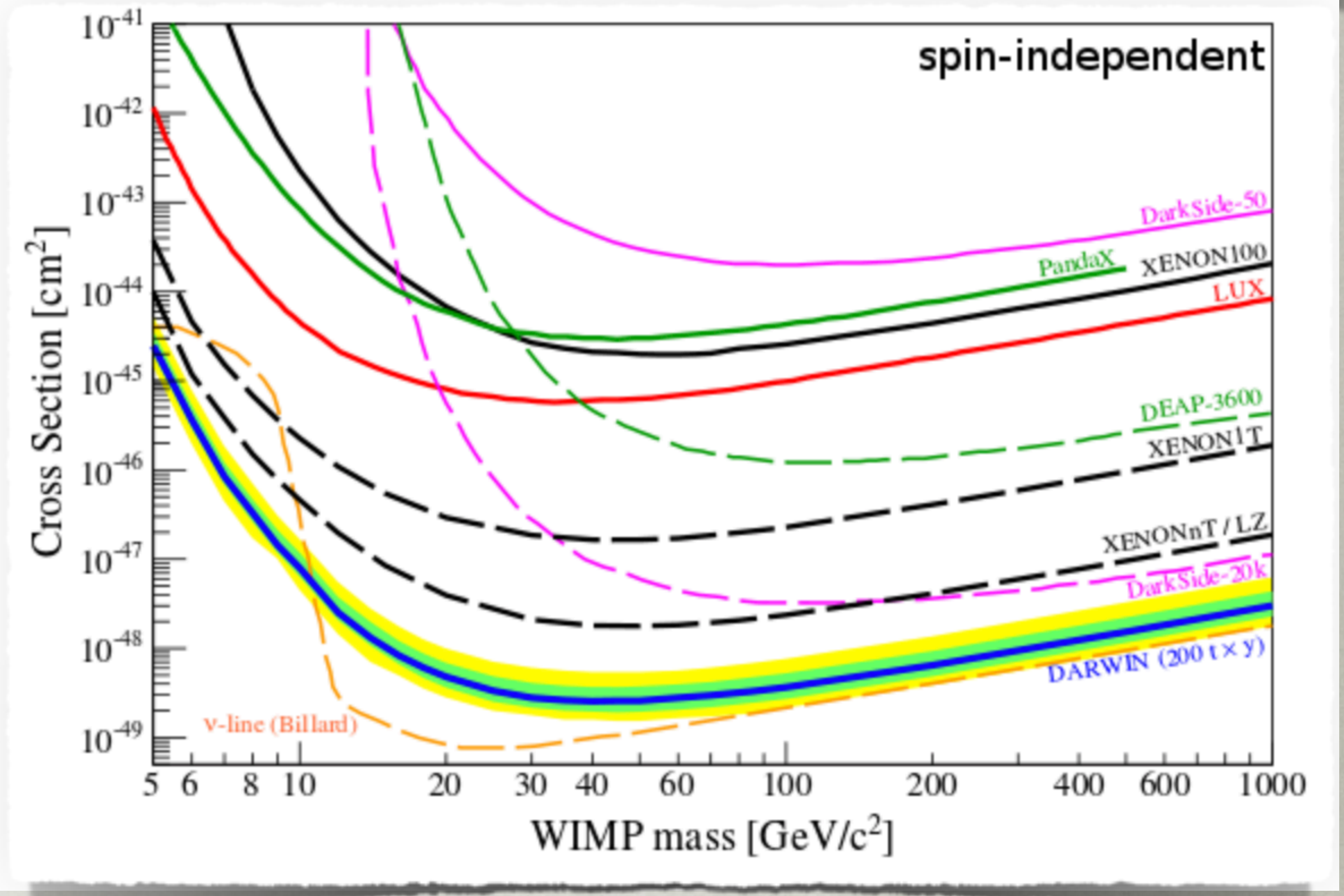


THE PAST



Cirelli, Strumia, JZ, to appear

THE FUTURE

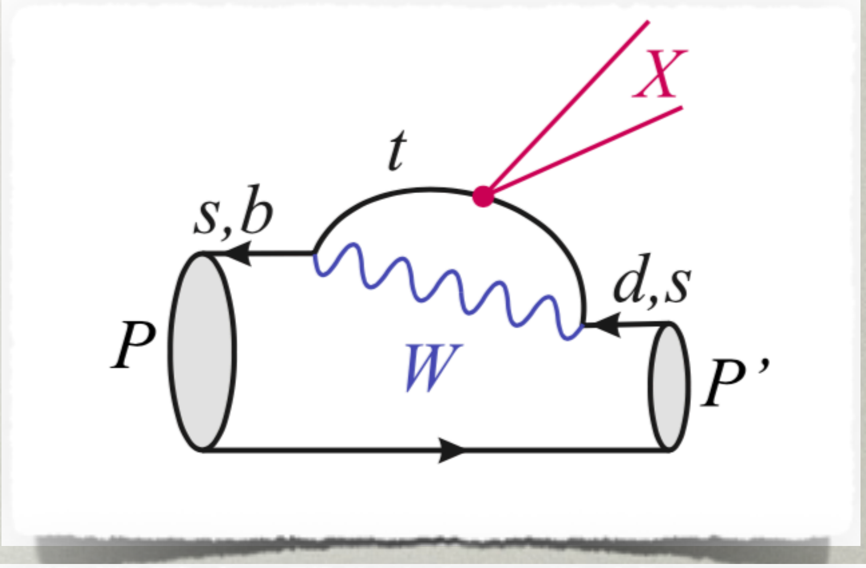


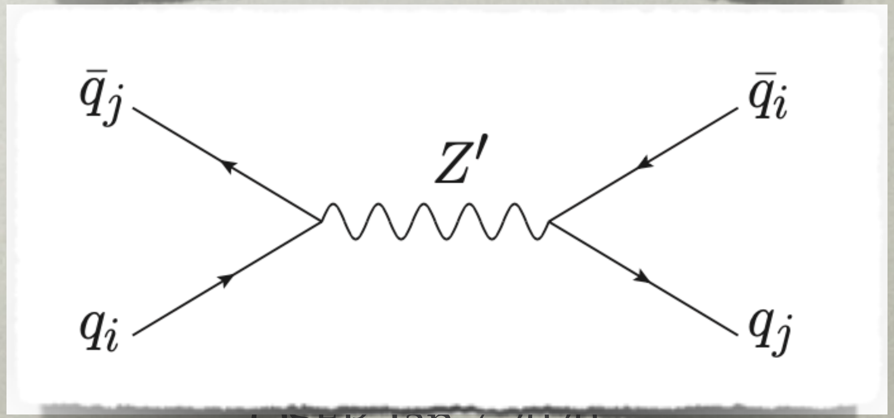
- more exposure
- lower thresholds
    - scatterings on electrons, phonons,...

see e.g., "US Cosmic Visions: New Ideas in Dark Matter 2017: Community Report ", 1707.04591

SEARCHING FOR WIMPY MEDIATORS

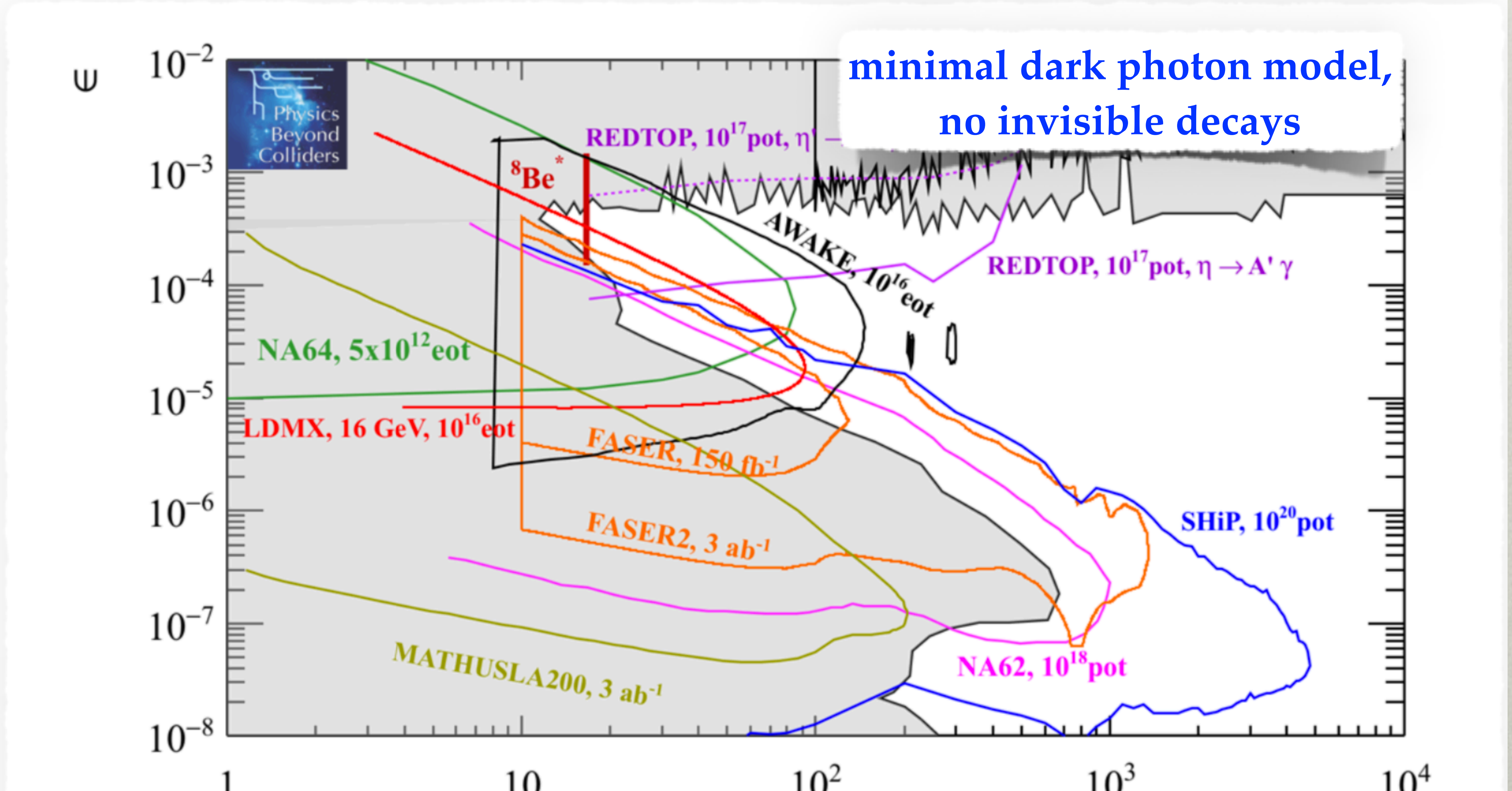
- searching for (heavy) mediators
- using colliders:
  - beam dumps, e.g., $pp \to A' + X$, look for decays of A'
  - flavor transitions, e.g., $b \to sA'$, look for decays of A'
  - quantum corrections due to A' (present in the loops or even tree level off-shell exchanges)





DARK PHOTON

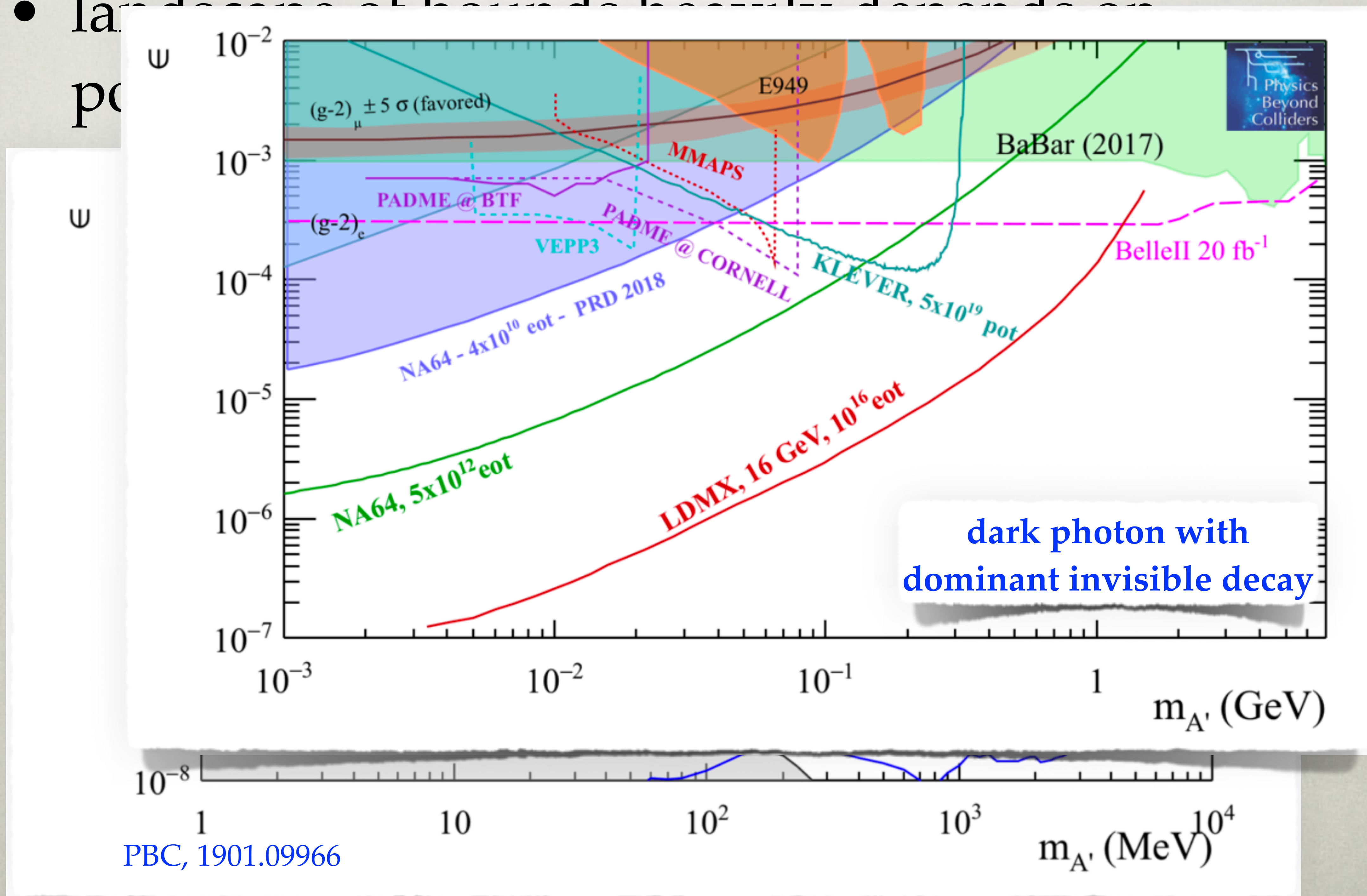
- landscape of bounds heavily depends on possible decays



PBC, 1901.09966

DARK PHOTON

- la[...]
  po[...]



PBC, 1901.09966

SEARCHING FOR WISPS

SEARCHING FOR WISPS

$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

- the general Lagrangian for scalar ϕ

$$\mathscr{L}_{\text{int}} = \frac{\sqrt{4\pi}}{M_{\text{Pl}}}\phi\left[\frac{1}{4}c_F F_{\mu\nu}F^{\mu\nu} + \frac{\alpha_s}{12\pi}c_G G^A_{\mu\nu}G^{A\mu\nu} - c_e m_e \bar{e}e - c_u m_u \bar{u}u - c_d m_d \bar{d}d\right]$$

  - c_i are dimensonless coeffs., depend on the WISP model

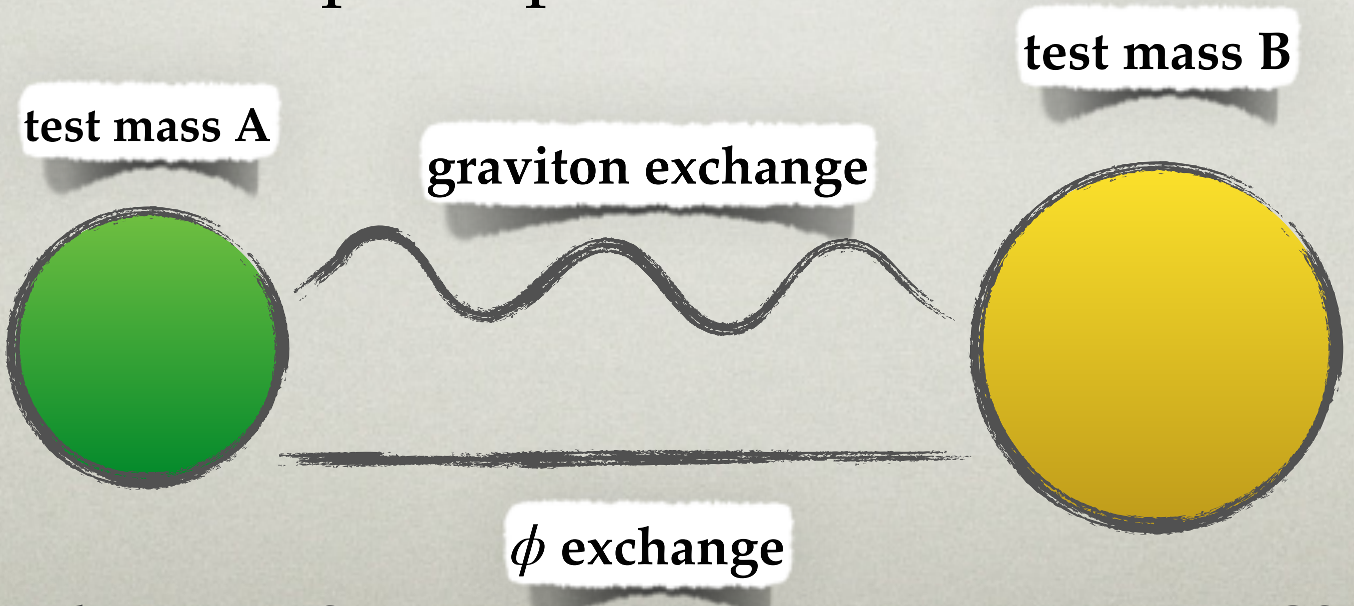
- two general ways to search for WISPs
  - search for new force mediated by ϕ
    - need not be dark matter
  - search for the effects of the background field ϕ
    - essential that it is dark matter

NEW FORCE DUE TO WISPS

- light bosons mediate a new force
- modifies for instance gravitational interaction between objects

$$V = -G_N \frac{m_A m_B}{r}\left(1 + c_A c_B e^{-m_\phi r}\right)$$

- searched for using
  - fifth force experiments
  - equivalence principle tests



NEW FORCE DUE TO WISPS

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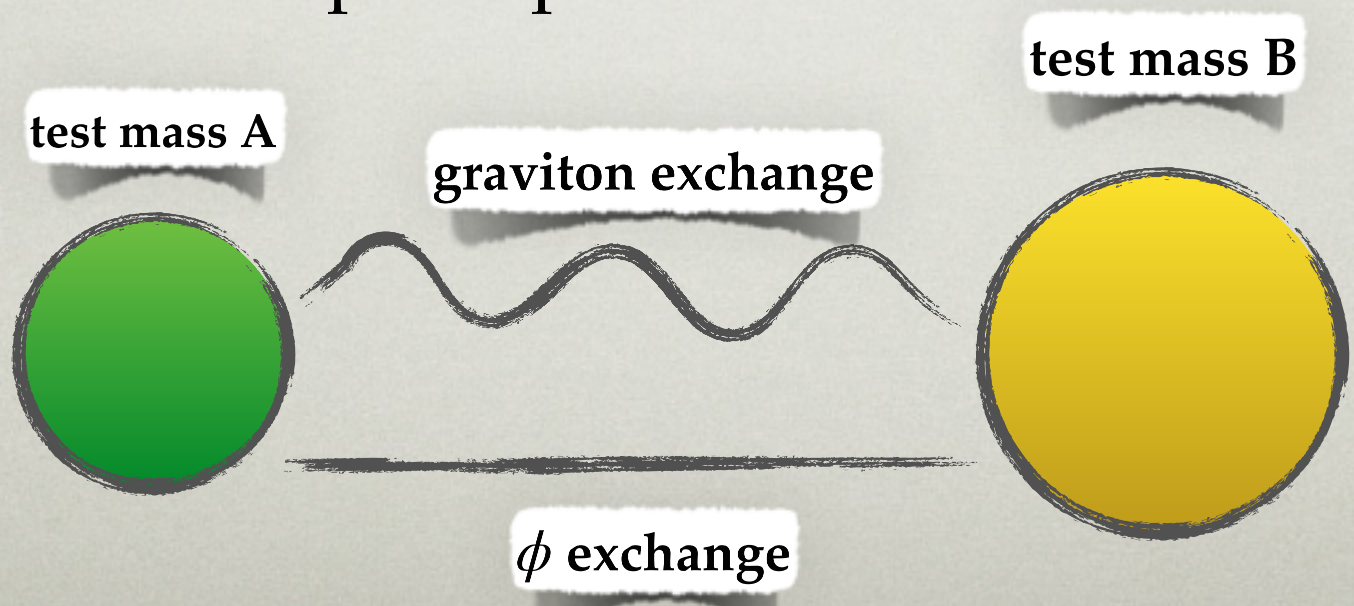
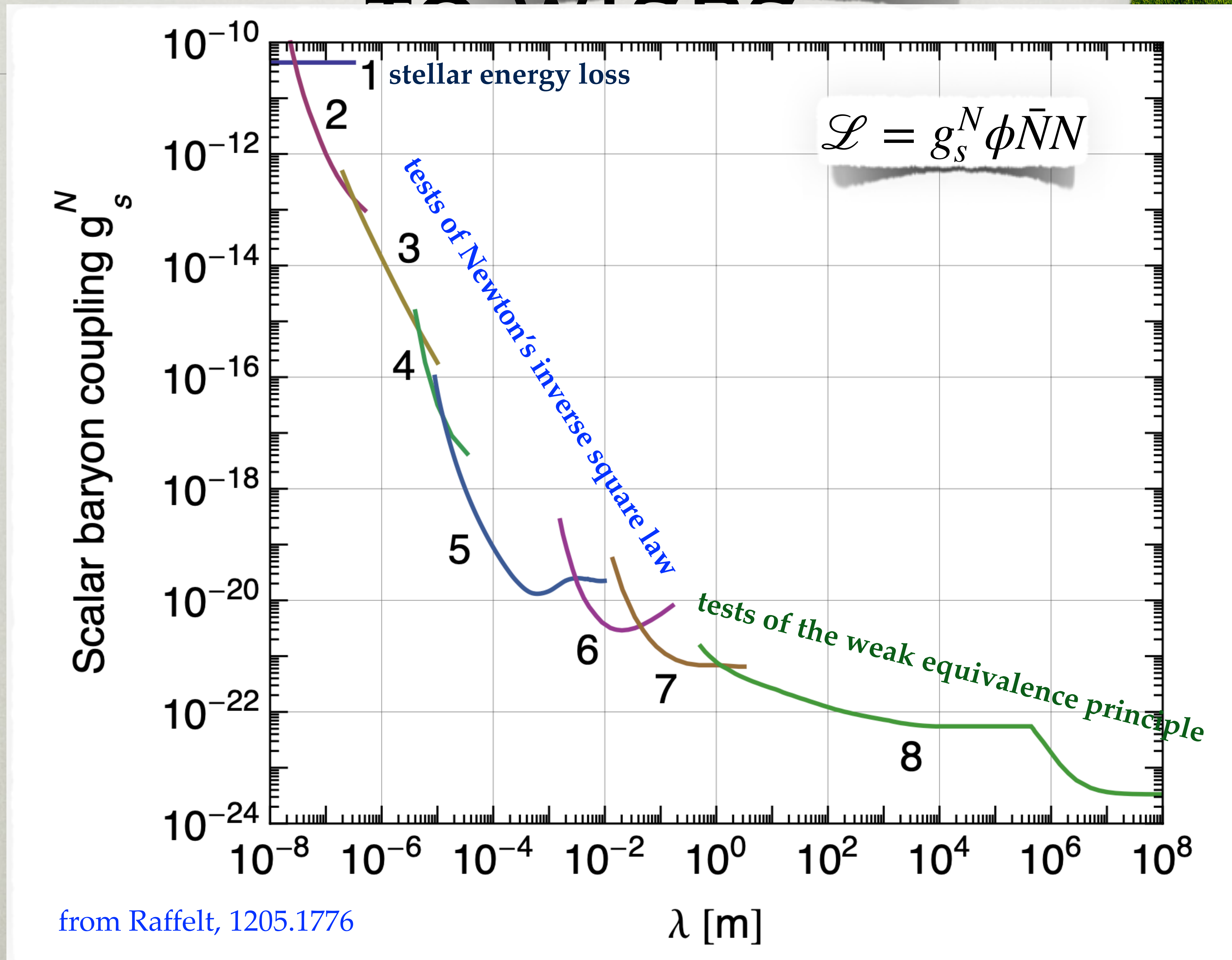
$$V = -G_N \frac{m_A m_B}{r}\left(1 + c_A c_B e^{-m_\phi r}\right)$$

- sea[illegible] using
  - **sixth force**
  - ~~fifth force~~ experiments
  - equivalence principle tests



NEW

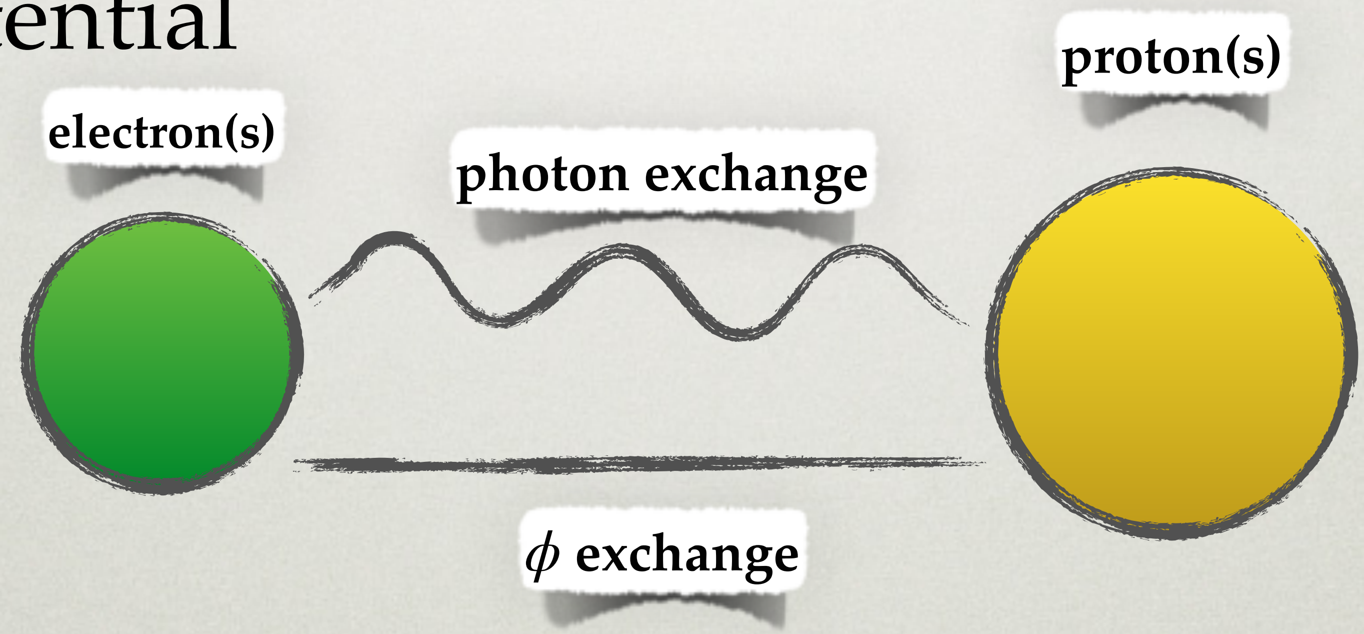
$$\lambda = m_\phi^{-1} = 19.73 \text{ cm } \frac{\mu\text{eV}}{m_\phi}$$



ϕ exchange

NEW FORCE DUE TO WISPS

- can also be searched for from atomic transitions
  - potential modification of *1/r* Coulomb potential



- the trick to enhance sensitivity: searching for isotope shifts and King non-linearity

for details see lectures by Michal Zawada

NEW FORCE DUE TO WISPS

- can a ... ansitions
  - po ... o
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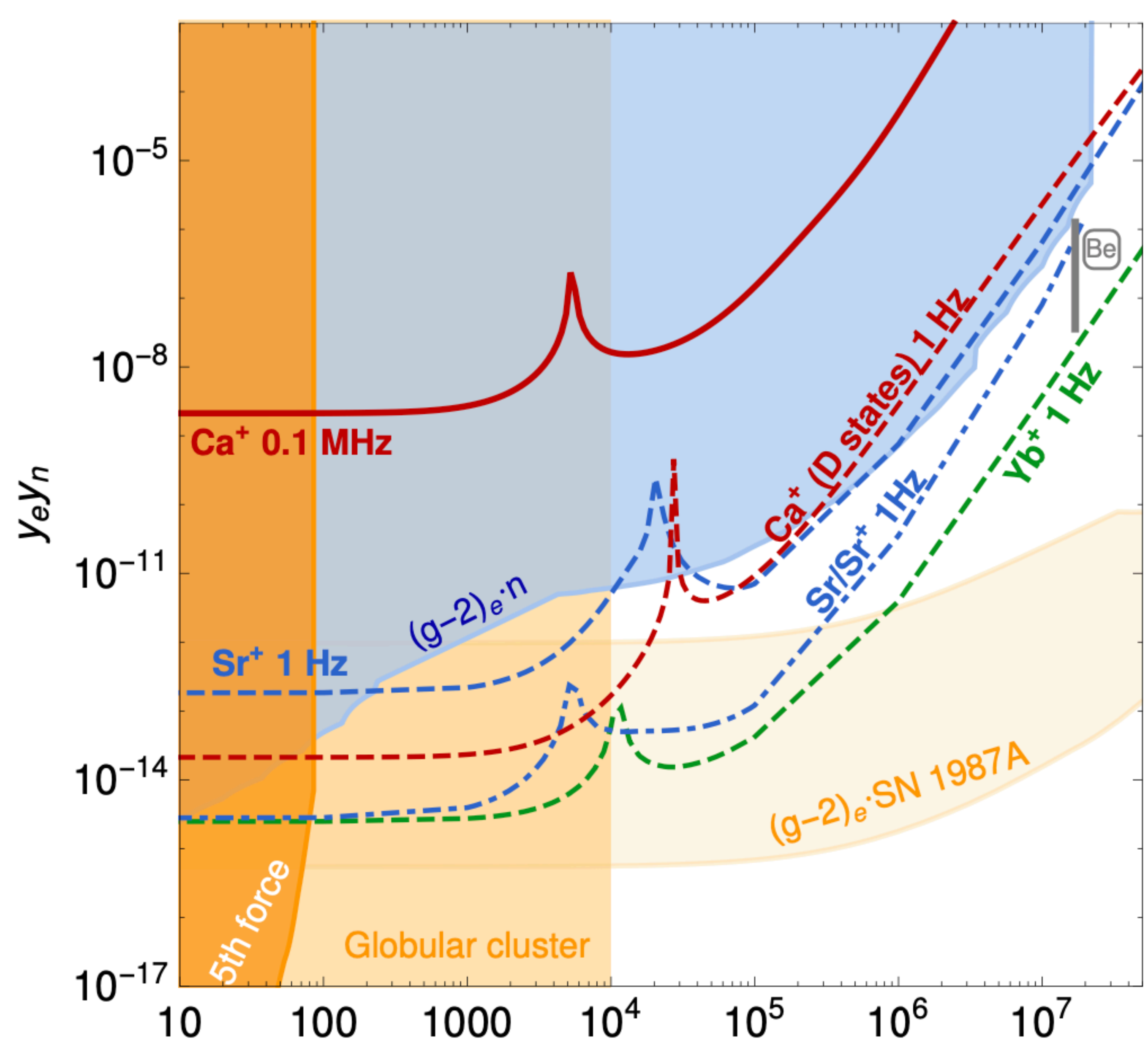

Berengut et al, 1704.05068

- the t ... ng for
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for details see lectures by Michal Zawada

SEARCHING FOR BACKGROUND WISPS

- the Lagrangian
  $$\mathscr{L}_{\text{int}} = \hat{\phi}\Big[\tfrac{1}{4}c_F F_{\mu\nu}F^{\mu\nu} + \tfrac{\alpha_s}{12\pi}c_G G^A_{\mu\nu}G^{A\mu\nu} - c_e m_e \bar{e}e - c_u m_u \bar{u}u - c_d m_d \bar{d}d\Big]$$
- gives the following effective Lagrangian for ϕ coupling to nonrelativistic electrons, neutrons, protons

$$\hat{\phi} \equiv \frac{\sqrt{4\pi}}{M_{\text{Pl}}}$$

$$\mathscr{L}_{\text{eff}} = \frac{c_F}{4}\hat{\phi}F_{\mu\nu}F^{\mu\nu} - m_e(\hat{\phi})\mathbf{1}_e - \sum_{N=n,p} m_N(\hat{\phi})\mathbf{1}_N + \cdots$$

- field dependent masses
  $$m_e(\hat{\phi}) = m_e\big(1 + c_e\hat{\phi}\big),\ \ m_N(\hat{\phi}) \simeq m_N\big(1 + 0.07c_G\hat{\phi} + (0.02 - 0.04)c_q\hat{\phi}\big)$$
- after canonically normalizing $A'_\mu = \sqrt{1 - c_F\hat{\phi}}\,A_\mu$ thus
  $$D_\mu\psi = (\partial_\mu + e'A'_\mu)\psi$$
  - therefore field dependent structure constant $\alpha' = \alpha/(1 - c_F\hat{\phi})$

QED Lagrangian

$$\mathscr{L} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

- note: they are time dependent: $\hat{\phi} = \hat{\phi}_0\cos(m_\phi t)$

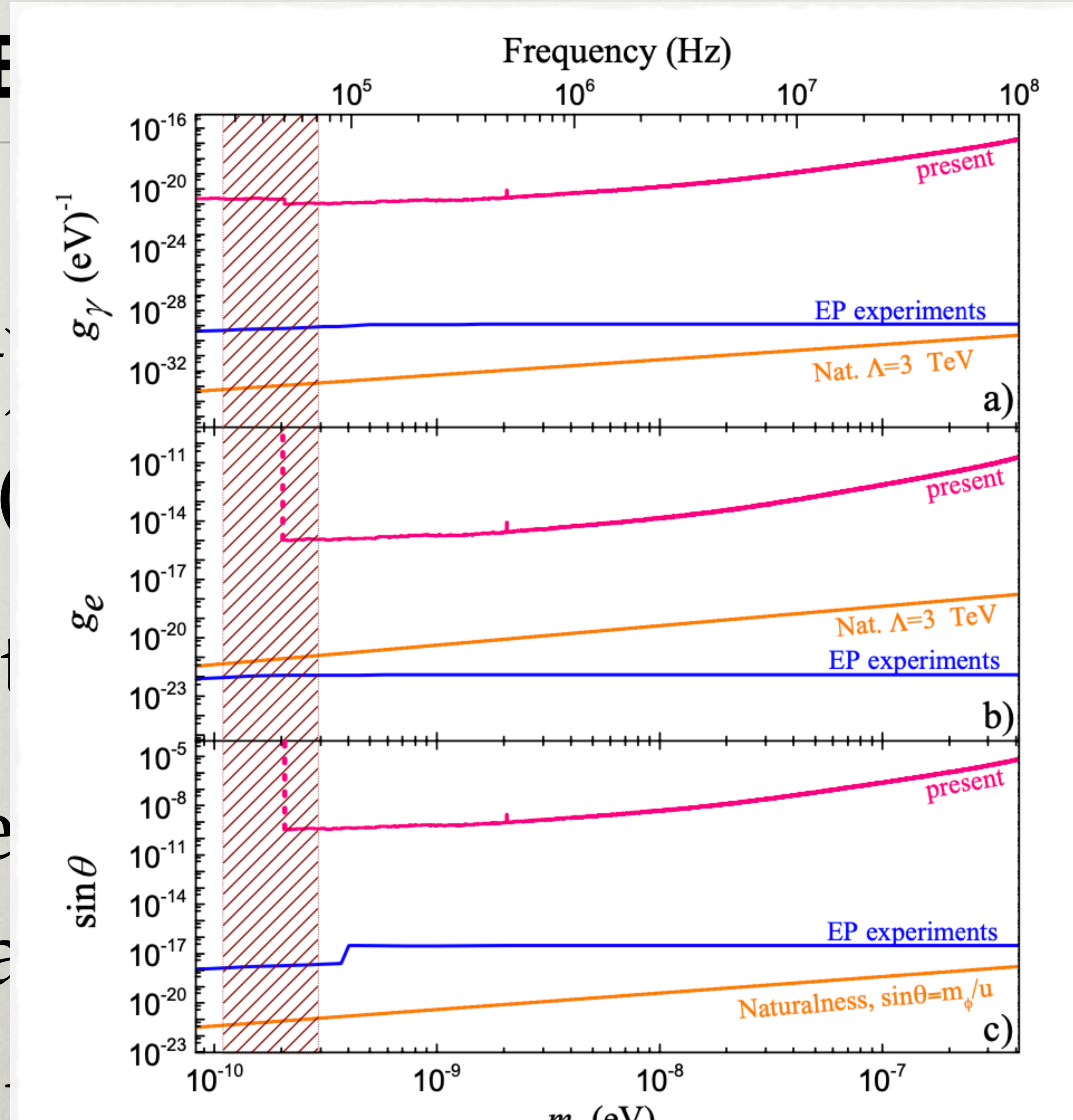
SEARCHING FOR BACKGROUND WISPS

- $\phi(t)$ makes time dependent: $\alpha_{\mathrm{EM}}(t)$, $m_N(t)$, $m_e(t)$, magnetic moments,...
  - atomic levels become time dependent
- use the time dependence for search strategies
- look at the stability of atomic transitions

for details see lectures by Marianna Safronova

SEARCHING FOR
E ... SPS

- $\phi(t)$ ... $\alpha_{\mathrm{EM}}(t)$, $m_N($ ... nts,...
  - at ... dependent
- use ... search stra...
- loo... transitions



Antypas et al., 1905.02968

for details see lectures by Marianna Safronova

RECAP

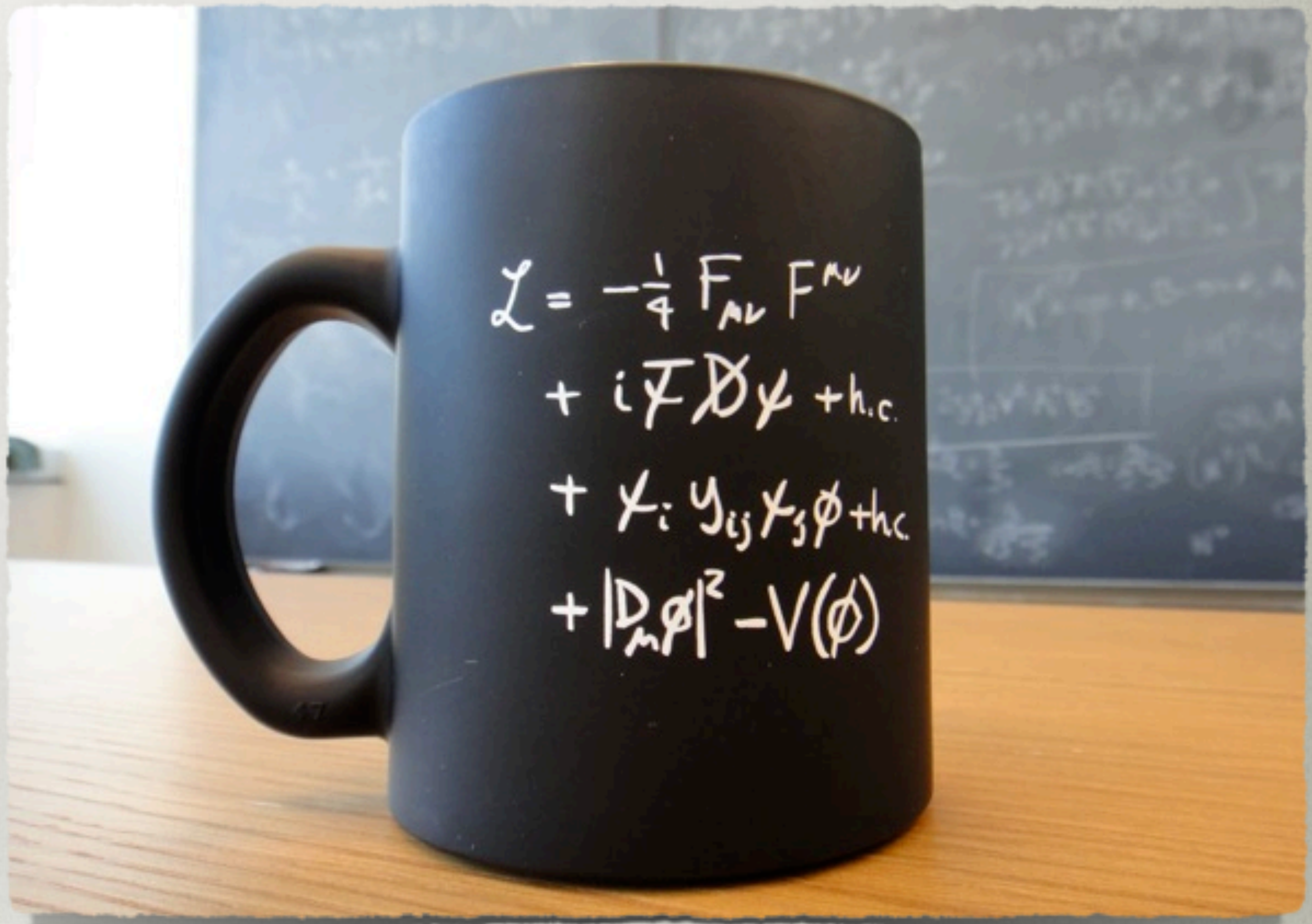
- to be able to search for wisps in this way
  - they had to couple to matter
- next we look at two important examples where this is required for other reasons
  - axion
  - relaxion

strong CP problem and axions

BEFORE WE BEGIN…

- a general rule: *"what is not explicitly forbidden is allowed"*
- examples from particle physics
    - $e^+p^+ \to e^-p^+$ forbidden by charge conservation, thus it never occurs
    - beta decay $n \to p^+e^-\bar{\nu}_e$ is allowed by charge conservation
        - though occurs only through weak interactions
        - a long decay time $\tau \sim 900s$

- corolary of this is the structure of the SM Lagrangian
- given field content + gauge symmetries write all possible (renormalizable) terms



- all these coefficients are known to be nonzero <u>**except one**</u>

STRONG CP PROBLEM

- Lorentz and gauge invariance allow

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

    - naively one would expect $\theta \sim \mathcal{O}(1)$
- experimentally though

$$d_n \approx 4 \times 10^{-16} \bar{\theta}\, e\,\mathrm{cm} \longleftrightarrow |d_n|_{\mathrm{exp}} < 3 \times 10^{-26}\, e\,\mathrm{cm}$$

$$\bar{\theta} < 10^{-10}$$

- why $\bar{\theta}$ so small?
    - **strong CP problem**

STRONG CP PROBLEM

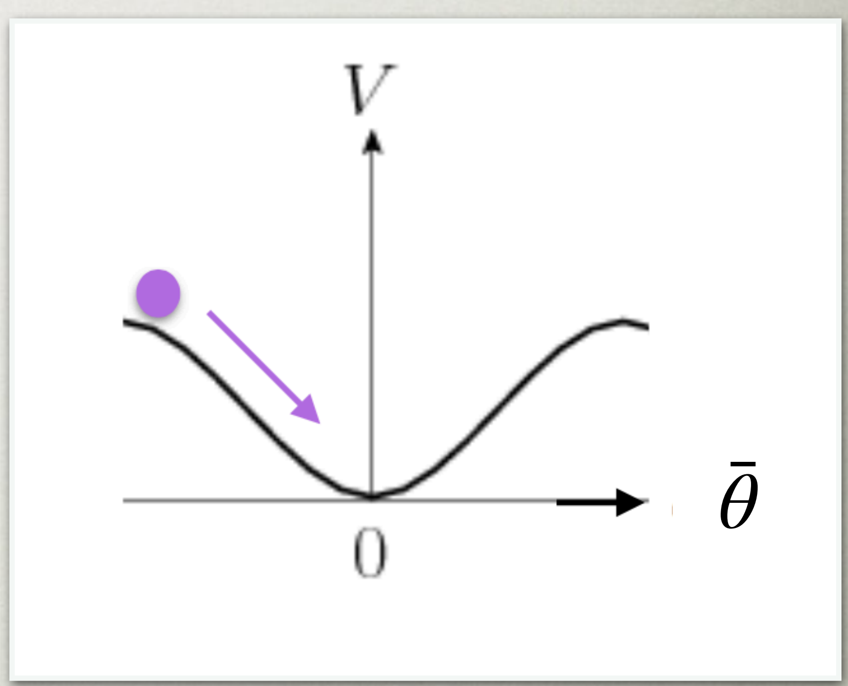
- several peculiar things about this term

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

- it is Charge-Parity (CP) violating
  - setting it simply to zero by postulating CP invariance not satisfactory
  - the other CP violating param., the phase in the CKM matrix is $\mathcal{O}(1)$
- there is no such term for QED
  - non-Abelian naure of QCD crucial
- can be shifted away by field redefinitions if any of the quark masses is zero (i.e., $\bar{\theta}$ is physical only, if all quark masses nonzero)
  - since above electroweak phase transition quarks are massless there is no such term for the weak $SU(2)_L$ gauge group

AXION

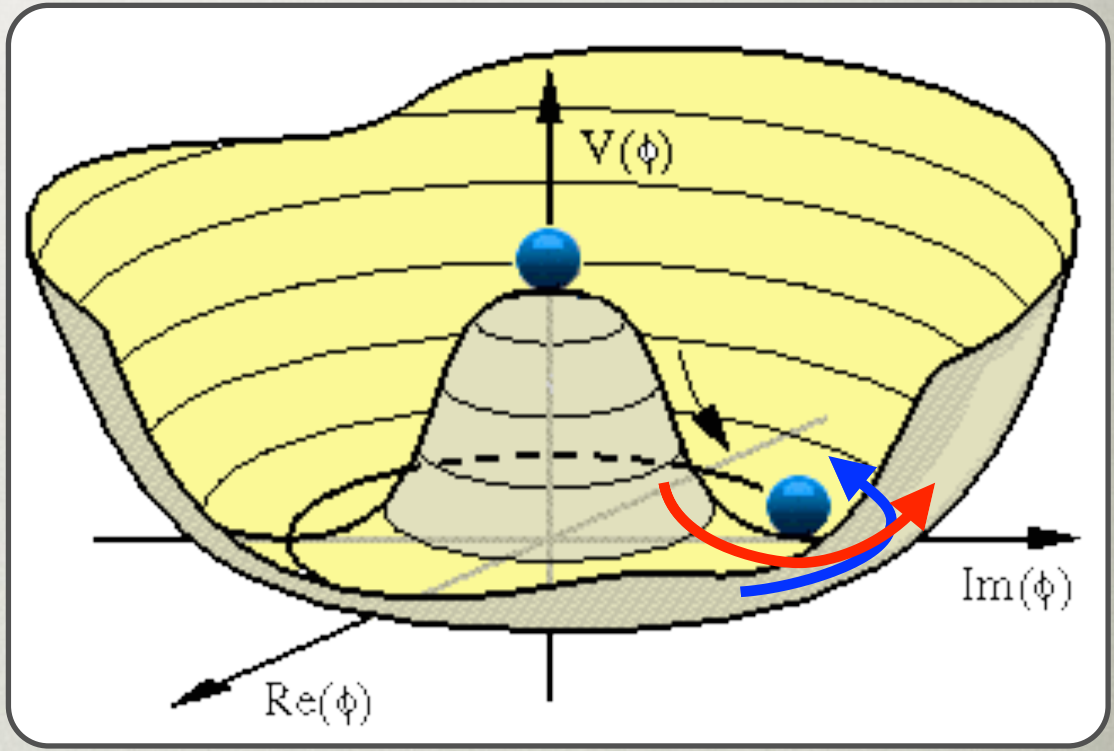
- axion solution to the strong CP problem:
- if $\bar{\theta}(x)$ is a dynamical field with no other potential but $\bar{\theta} G \tilde{G}$
- the rest of QCD is CP conserving
  - $\Rightarrow$ non-perturbative QCD dynamics generates the potential with a minimum at $\bar{\theta}(x) = 0$
- new ultra-light particle - **axion**



Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

THE AXION MECHANISM

- field without a potential: Goldstone boson $\bar{\theta} = a/f$ PQ symmetry
    - need a new global U(1) symmetry that is spontaneously broken
    - experimentally the scale of spontaneous breaking $\sim f$ required to be large
- a simple example: single scalar field, with Mexican hat potential $V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4$
    - parametrize $\phi = [f + s(x)]\ \exp[i\bar{\theta}(x)]$
    - shift symmetry $\bar{\theta} \to \bar{\theta} + \alpha$
- two directions
    - massless Goldstone boson: $\bar{\theta}$
    - massive scalar boson: s



- nontrivial requirement: coupling of $\bar{\theta} = a/f$ to $G\tilde{G}$
    - achieved if U(1) anomalous with respect to QCD

THE AXION

- in general the axion will couple to all the SM fields

$$\mathscr{L} = \frac{\alpha_s}{8\pi}\frac{a}{f}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f}F\tilde{F} + \sum_{\psi=e,u,d,\dots} m_\psi \frac{a}{f}(\lambda_\psi \bar{\psi}\psi + i\lambda'_\psi \bar{\psi}\gamma_5\psi)$$

  - to solve strong CP problem only coupling to $G\tilde{G}$ needed
- all the couplings are controlled by the scale of spontaneous symmetry breaking $\sim f$
  - experimentally f required to be large, well above 10^{10}GeV
- $E, N, \lambda_\psi, \lambda'_\psi,$ are UV model dependent parameters
  - in general expected to be *O(1)*
  - axion only feebly couples to the SM particles

THE AXION MASS

- the couplings to gluons generates mass for the axion

$$V_{\rm eff} = \frac{a}{f}\ \frac{\alpha_s}{8\pi} G_a^{\mu\nu}\tilde{G}_{a,\mu\nu} \xrightarrow[\text{effects}]{\text{non-PT}} V(a) \sim -m_\pi^2 f_\pi^2 |\cos\frac{a}{f}$$

$$m_a \sim m_\pi f_\pi / f$$

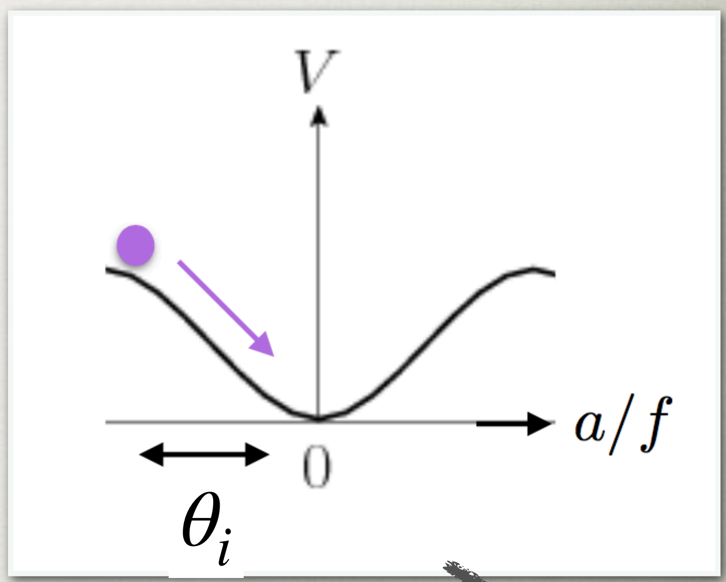
- larger *f* means lighter axion

$$m_a = 5.7\,\mu\text{eV}\left(\frac{10^{12}\text{GeV}}{f_a}\right)$$

- axion is an example of a WISP

AXION AS DARK MATTER

- axion can be a viable cold DM candidate
  - essentially stable for $m_a \lesssim 20$ eV
  - the production of axions in the early univers from misalignment mechanism
  - energy stored in oscillations contributes as CDM relic density



$$\Omega_A^{\mathrm{VR}} h^2 \approx 0.12 \left(\frac{f_A}{9 \times 10^{11}\ \mathrm{GeV}}\right)^{1.165} F\,\Theta_{\mathrm{i}}^2$$
$$\approx 0.12 \left(\frac{6\ \mu\mathrm{eV}}{m_A}\right)^{1.165} F\,\Theta_{\mathrm{i}}^2\,,$$

assuming pre-inflation breaking of PQ U(1)

  - correct relic abundance for

$$\boxed{10^{-8}\,\mathrm{eV} \lesssim m_a \lesssim 10^{-3}\,\mathrm{eV}}$$

SEARCHING FOR AXIONS

- often when comparing low energy experiments only two params kept:

$$\mathcal{L} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F}\,,$$

  - the axion mass $m_a \Leftrightarrow f_a$ and E/N
- searching for axion through its coupling to photons

$$g_{a\gamma\gamma} a\,\vec{E}\cdot\vec{B} \qquad\qquad g_{a\gamma\gamma} \sim \frac{E}{N}\frac{1}{10^{16}\mathrm{GeV}}\frac{m_a}{\mu\mathrm{eV}}$$

  - Primakoff conversion of photons (affects e.g. star cooling)

$$\gamma + Ze \to a + Ze$$

  - in static B conversion $a \to \gamma$, photon of frequency m_a, resonantly enhanced in microwave cavities of size $1/m_a$
- also through couplings to nucleons (CASPER wind), also from SN, star cooling also sensitive to couplings to electrons

for more details see lectures by Edward Daw

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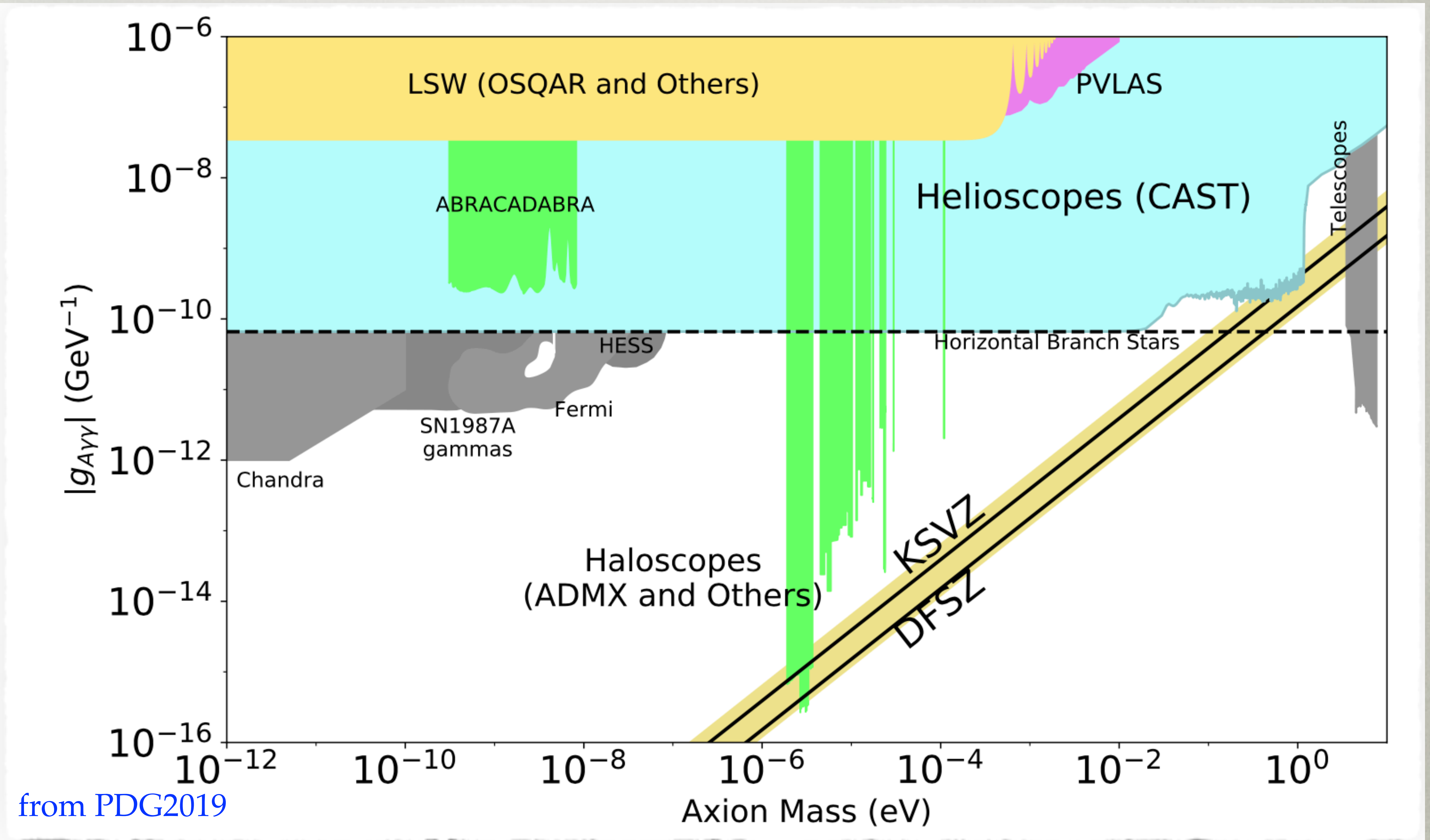


from PDG2019

resonantly enhanced in microwave cavities of size $1/m_a$

- also through couplings to nucleons (CASPER wind), also from SN, star cooling also sensitive to couplings to electrons

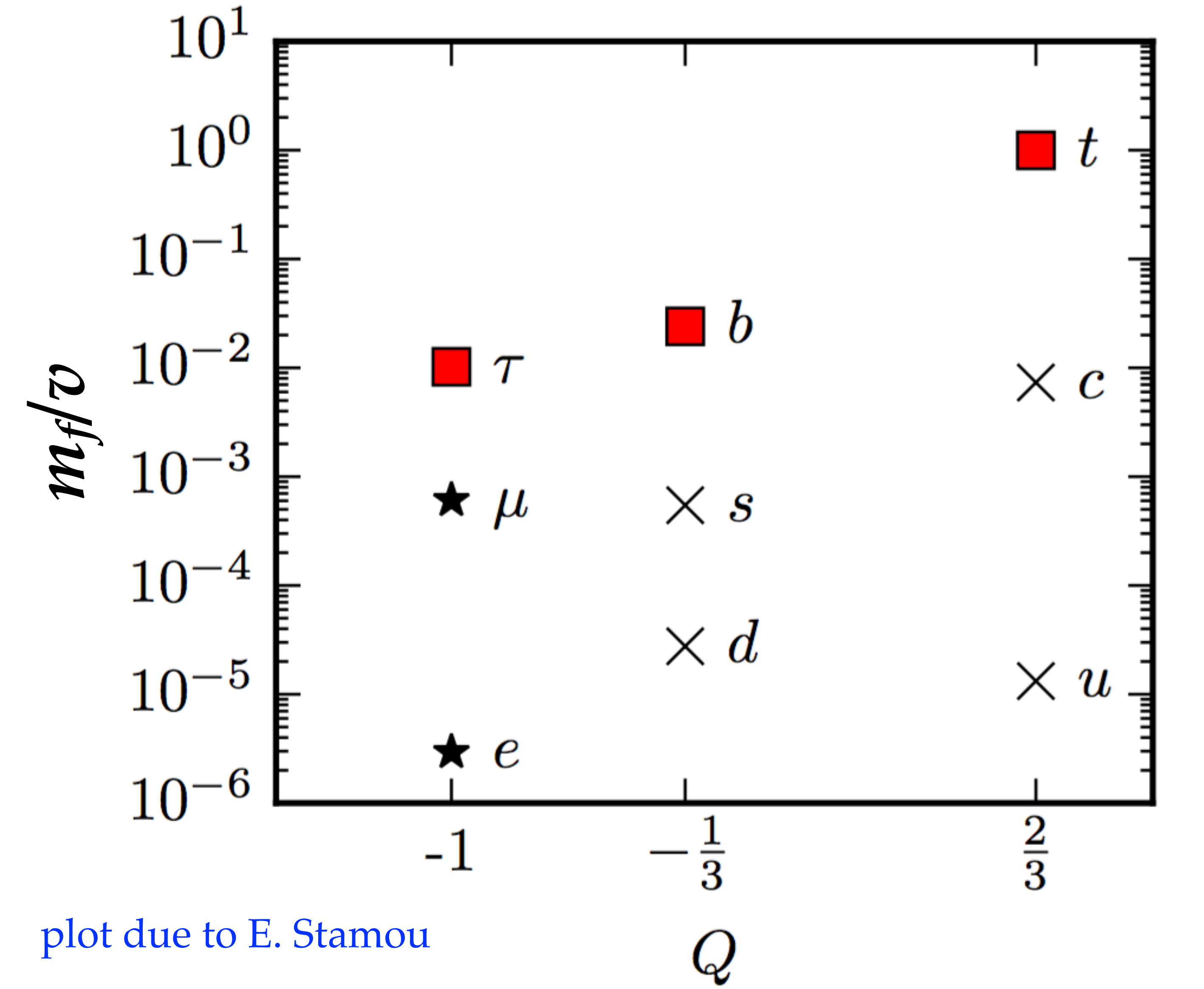
for more details see lectures by Edward Daw

AXIFLAVON

- so far axion solved
  - the strong CP problem
  - dark matter
- can be even more ambitious
  - the SM flavor problem
- a common solution: axiflavon

STANDARD MODEL FLAVOR PUZZLE

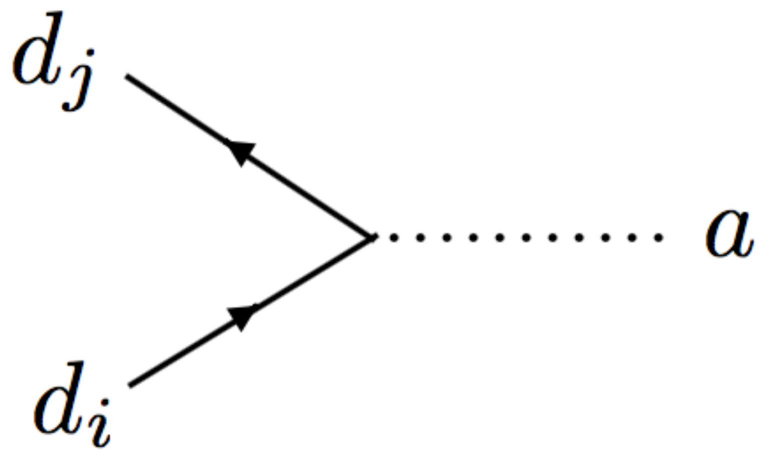
- where does the hierarchical structure of charged lepton masses come from?
- the mixing patterns in quark and lepton sectors?
- possible that due to spontaneously broken U(1) symmetry
  - **<u>axiflavon</u>** the related Goldstone boson



plot due to E. Stamou

AXIFLAVON: COUPLINGS TO FERMIONS

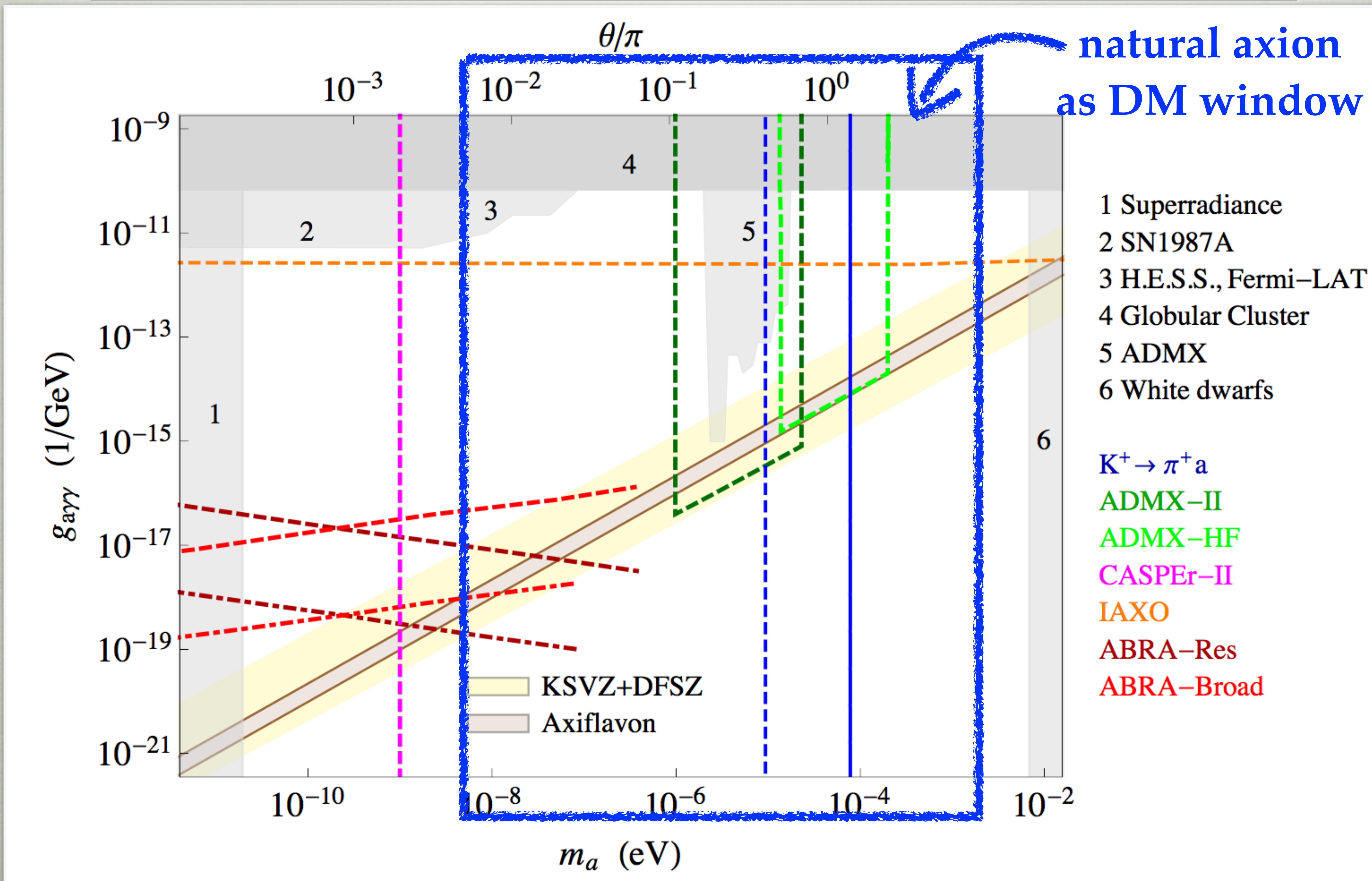
- crucial new ingredient flavor violating couplings to fermions
  - in the minimal model up to *O(1)* uncertainties



$$\sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\mathrm{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\mathrm{GeV}}$$

- observation of such couplings (in addition to usual axion searches) a smoking gun for axiflavon

SEARCHING FOR AXIONS



HIERARCHY PROBLEM AND RELAXION

THE HIERARCHY PROBLEM

- the hierarchy problem- an analogy
  - imagine that you have 2 companies
  - the only thing you know is that their total annual profit is *$10*
  - how big do you think the companies are?

THE HIERARCHY PROBLEM

- a good guess would be two lemonade stands by kids

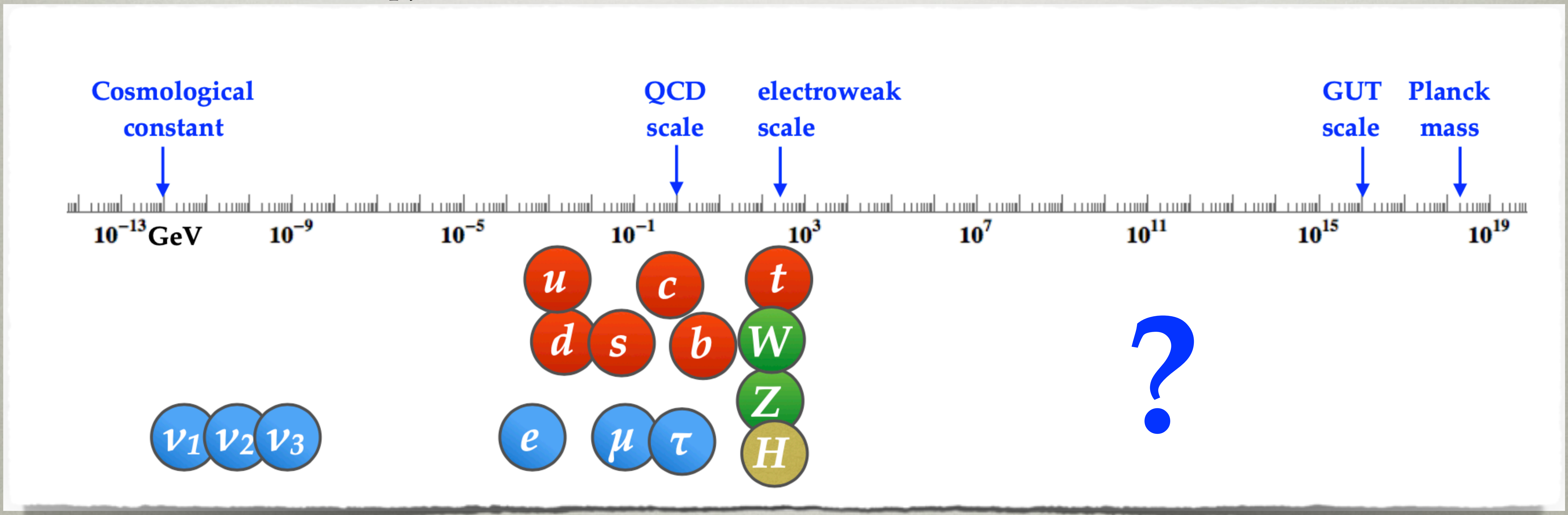
?

THE HIERARCHY PROBLEM

- then you find out that the two companies are
    - amazon and Apple
    - each with annual revenue ~$250 billion…
    - how can this be without them conspiring?
- this is the **hierarchy problem**
    - actually, the hierarchy problem in particle physics is even much worse

THE HIERARCHY PROBLEM IN PARTICLE PHYSICS

- why weak scale ~ 100 GeV $\ll$ quantum gravity scale $M_{\rm Pl} \sim 10^{19}$ GeV?
  - quantum mechanics predicts $m_H \sim M_{Pl}$ if any particles with M_{Pl} masses



SOLUTIONS TO THE HIERARCHY PROBLEM

- two radically different solutions to the hierarchy problem
- symmetry based
    - Higgs mass is protected against quantum corrections
    - electroweak scale superymmetry, strong interactions, extra dimension,...
    - since symmetry clearly broken, requires heavy new physics, at or above EW scale
    - large program at Large Hadron Collider devoted to this
- the other solution: environmental selection of some sorts
    - relaxion

RELAXION MECHANISM

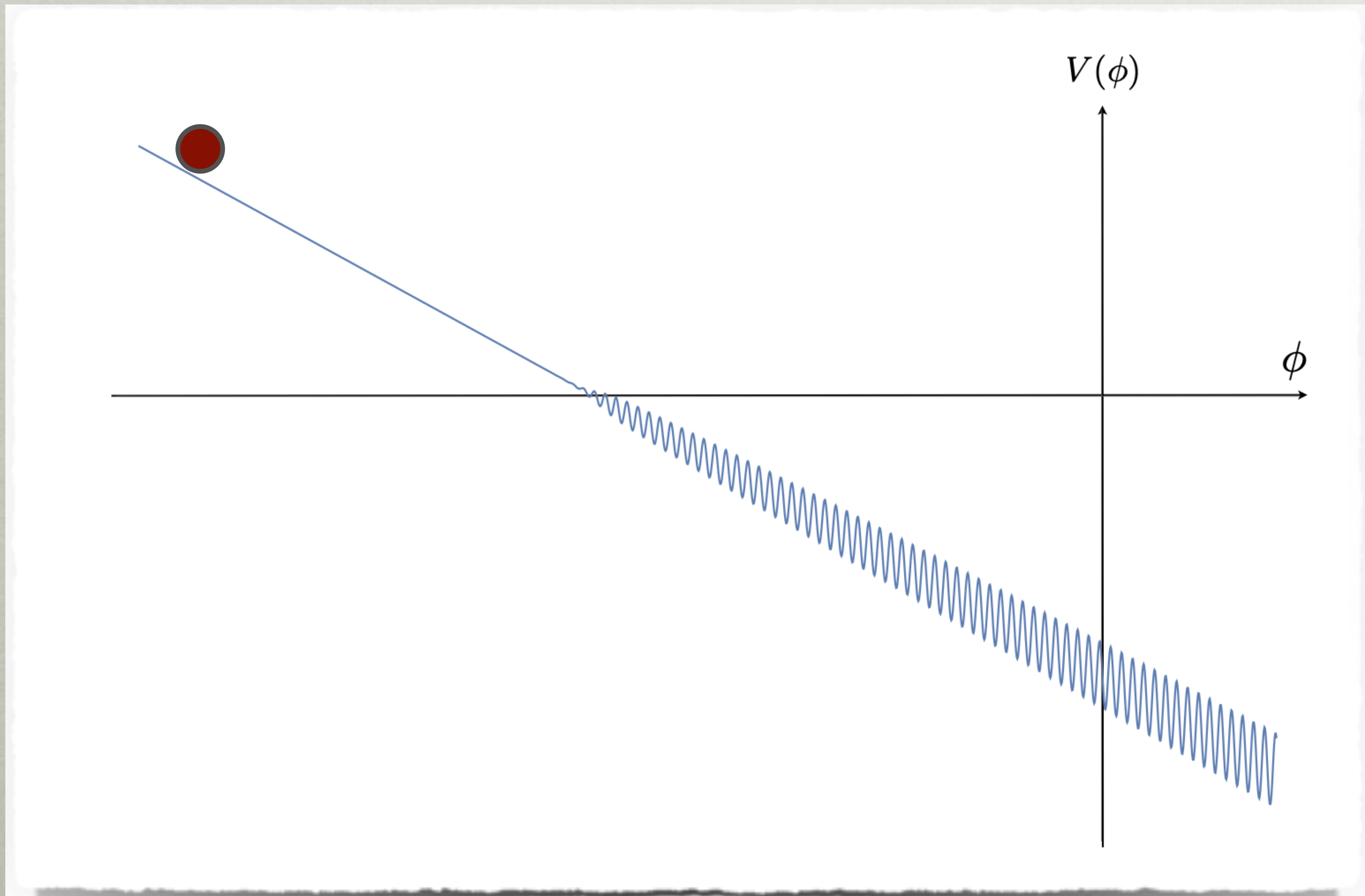
- relaxion ϕ: a (pseudo)-scalar that couples both to Higgs and $G\tilde{G}$

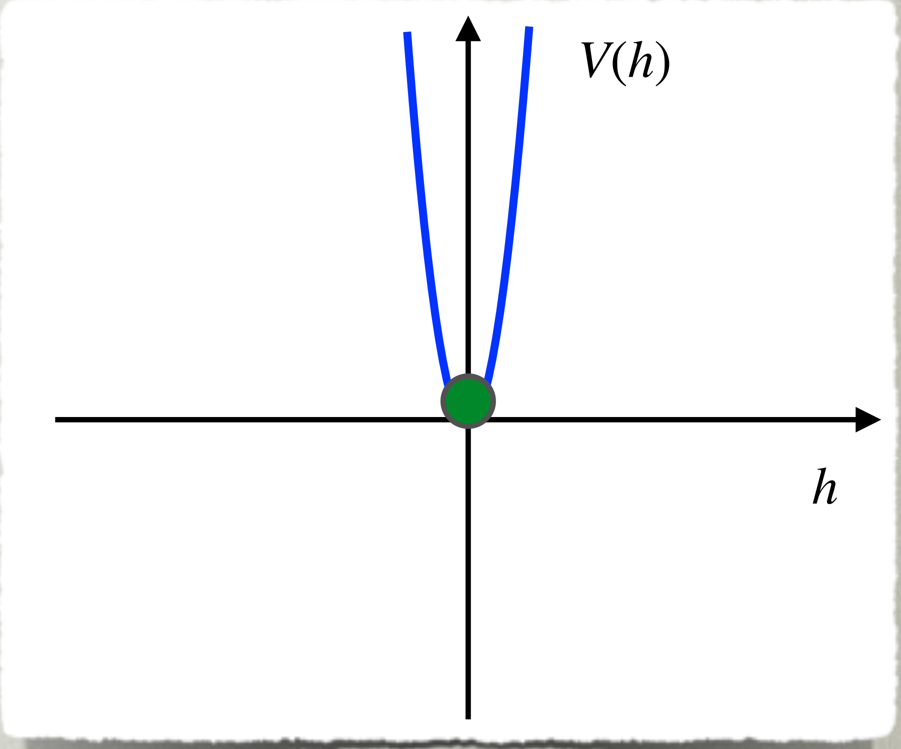
$$\mathscr{L} = \mathscr{L}_{\rm SM} + (-M^2 + g\phi)|h|^2 - V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$-\lambda|h|^4$

large mass, possibly $M_{\rm Pl}$

- in the early Universe slowly rolls, so that the Higgs mass is being scanned





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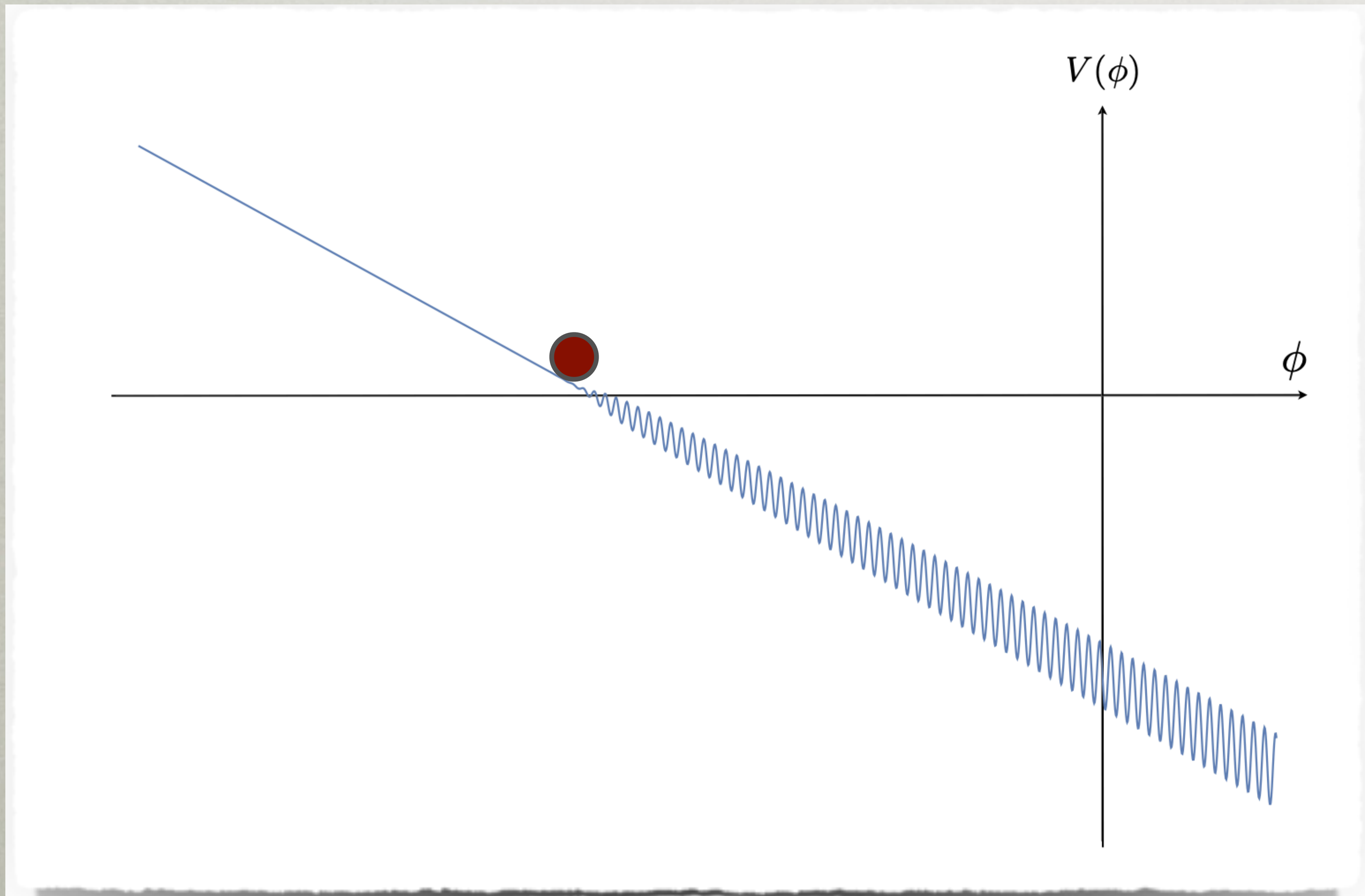
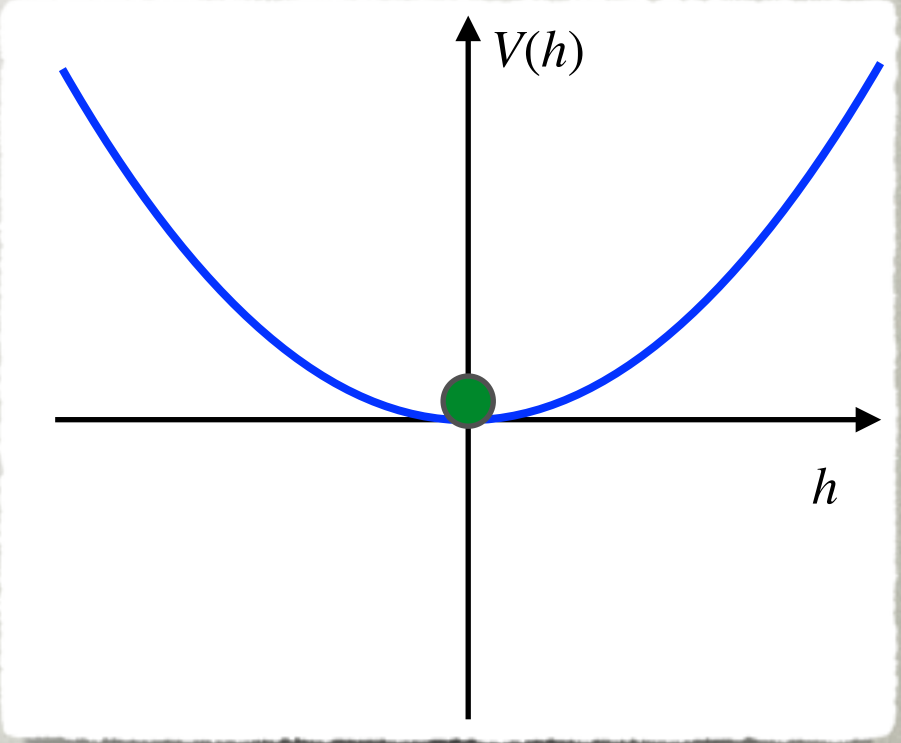




Graham, Kaplan, Rajendran, 1504.07551

RELAXION MECHANISM

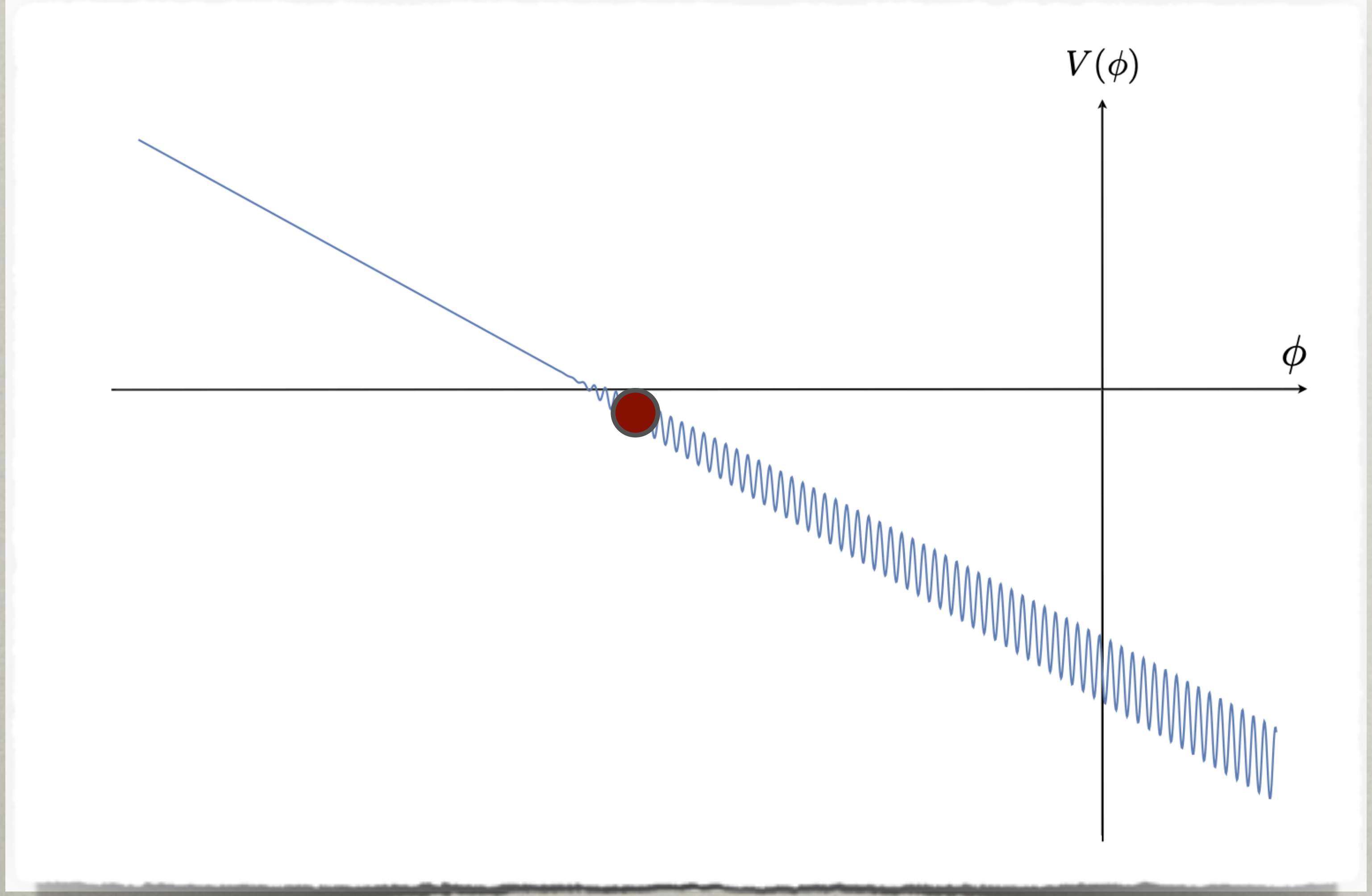
- when Higgs mass term becomes negative Higgs develops a vev

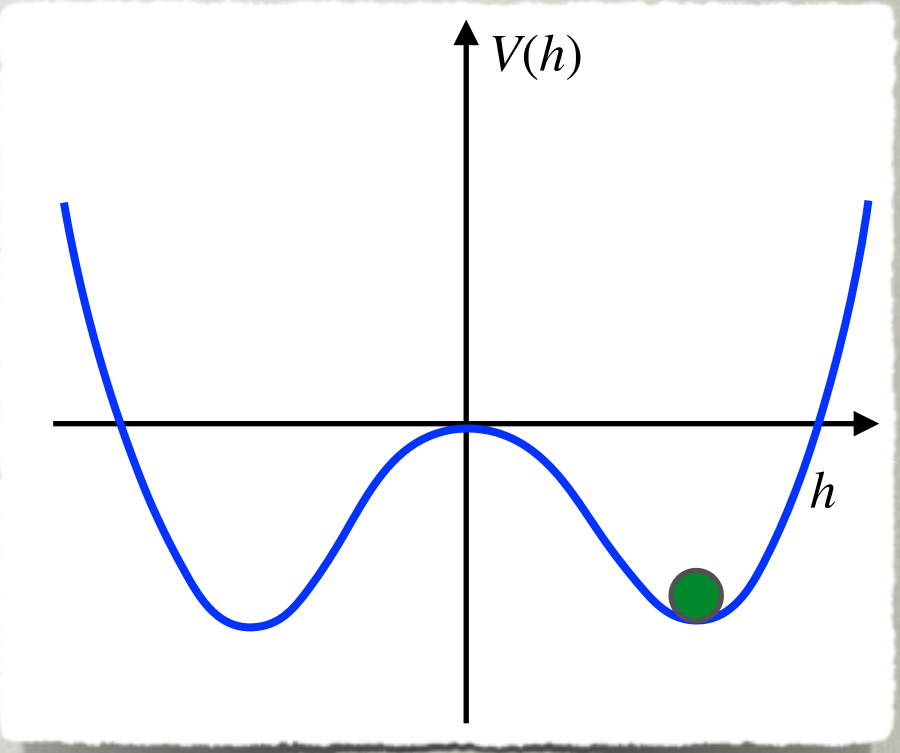
$$\mathscr{L} = \mathscr{L}_{SM} + (-M^2 + g\phi)|h|^2 - V(g\phi) + \frac{1}{32\pi^2}\frac{\phi}{f}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\mathscr{L} = \mathscr{L}_{SM} + \quad \mu^2|h|^2 \quad - V(g\phi) + \sim m_\pi^2 f_\pi^2 \cos\left(\frac{\phi}{f}\right)$$

$-\lambda|h|^4$ **small mass, EW size** $\propto m_q = y_q v_{EW}/\sqrt{2}$

- relaxion gets "stuck" in a region where Higgs mass is small



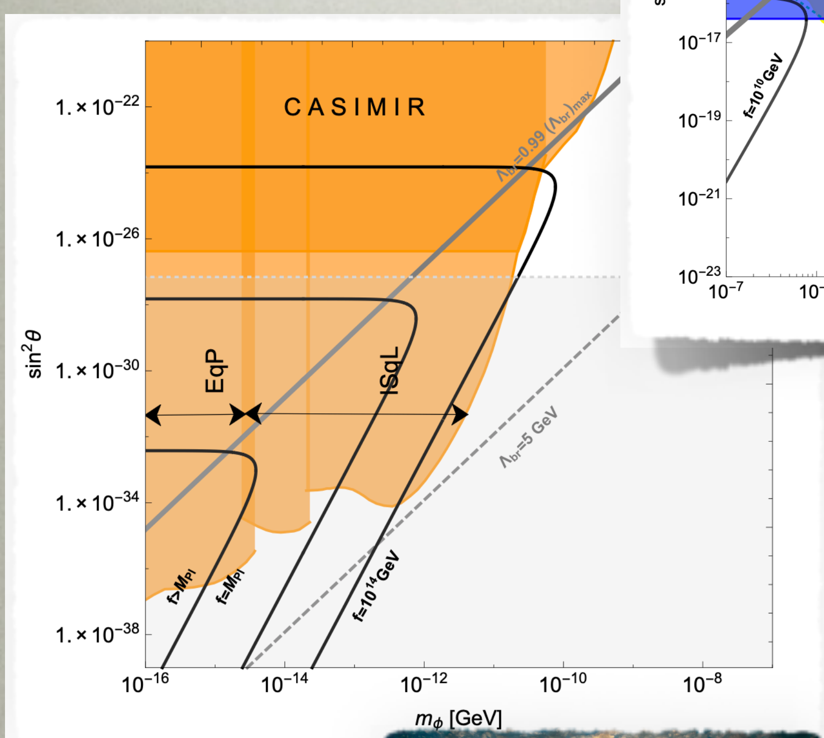


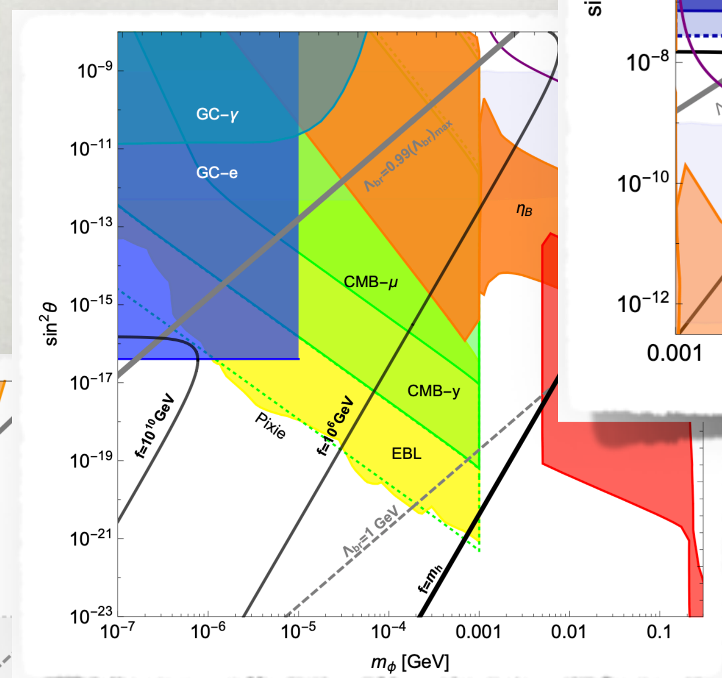
SEARCHING FOR THE RELAXION

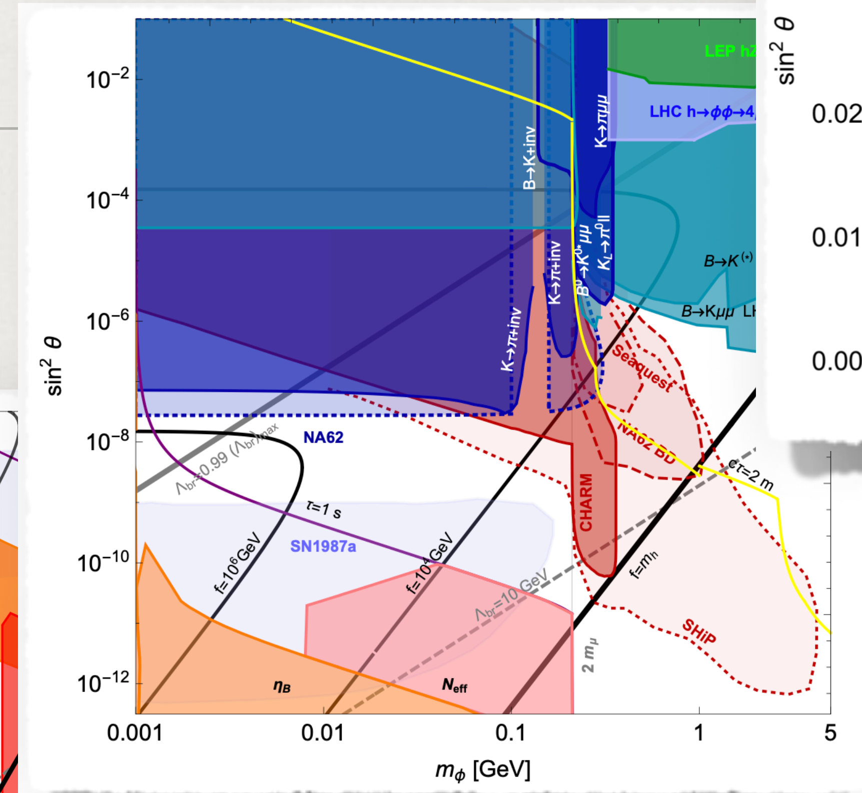
- relaxion mechanism: Higgs light (EW scale small) due to backreaction
  - the simplest model above leads to $\bar{\theta} \sim \mathcal{O}(1)$, in contradiction to exp.
  - many solutions: new strong sector, relaxion potential changed by inflaton, ...
- backreaction in all models leads to relaxion-Higgs mixing

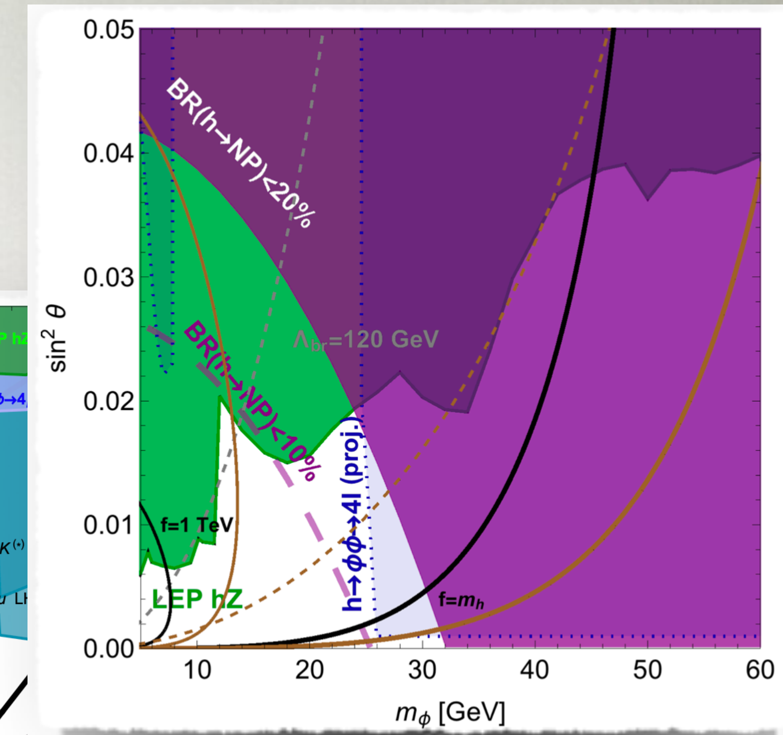
$$\phi' \simeq \phi + \sin\theta_{\text{mix}} h$$

  - induces coupl. of the relaxion to matter through the Higgs
  - mass of the relaxion in general a free parameter

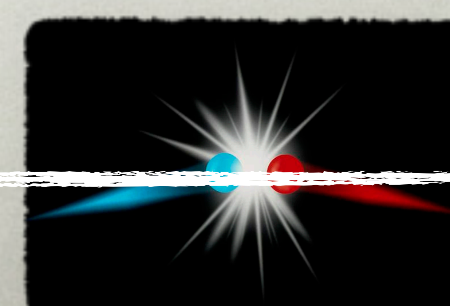


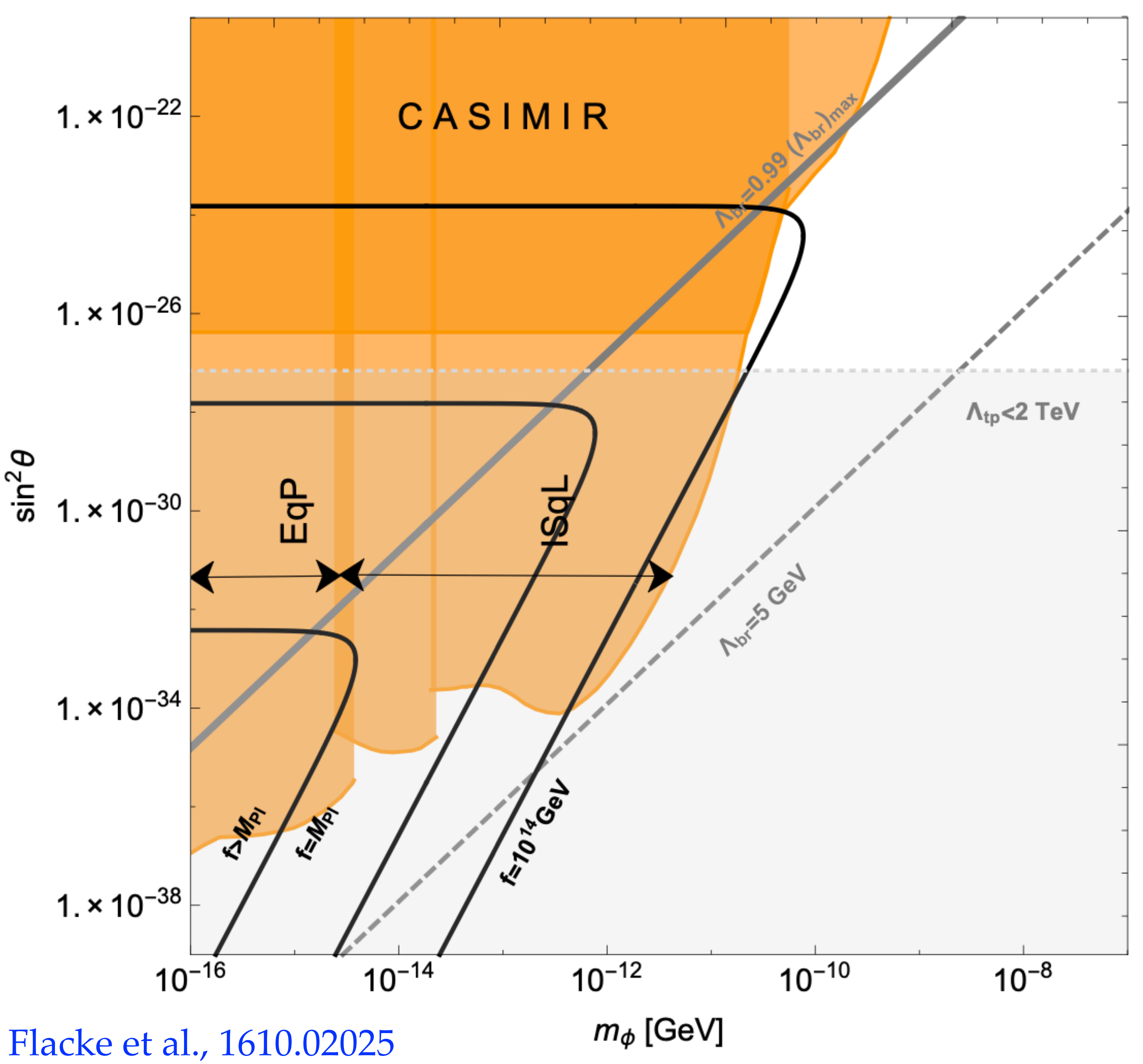




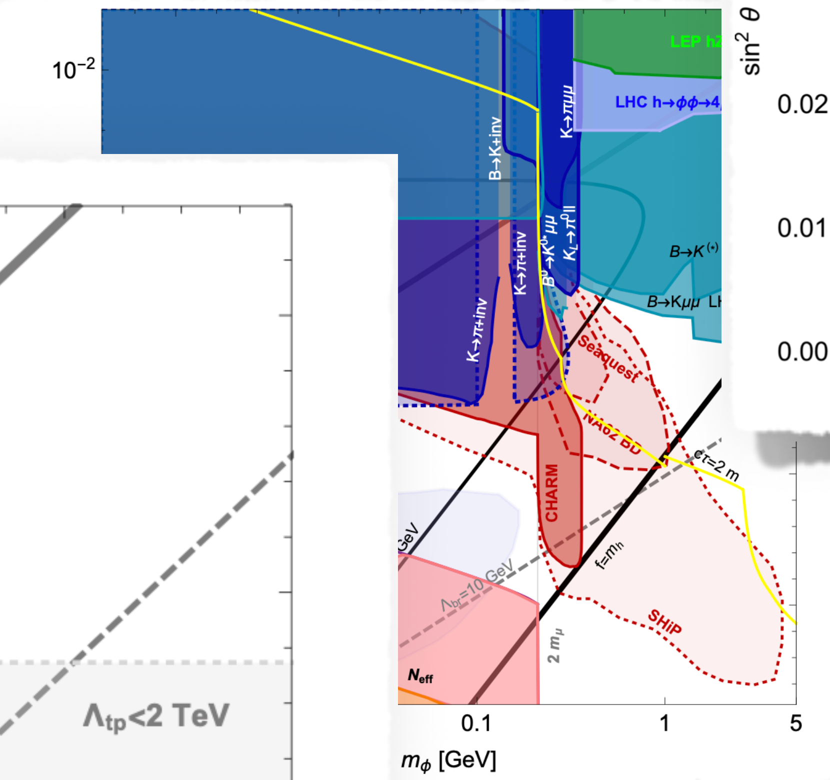


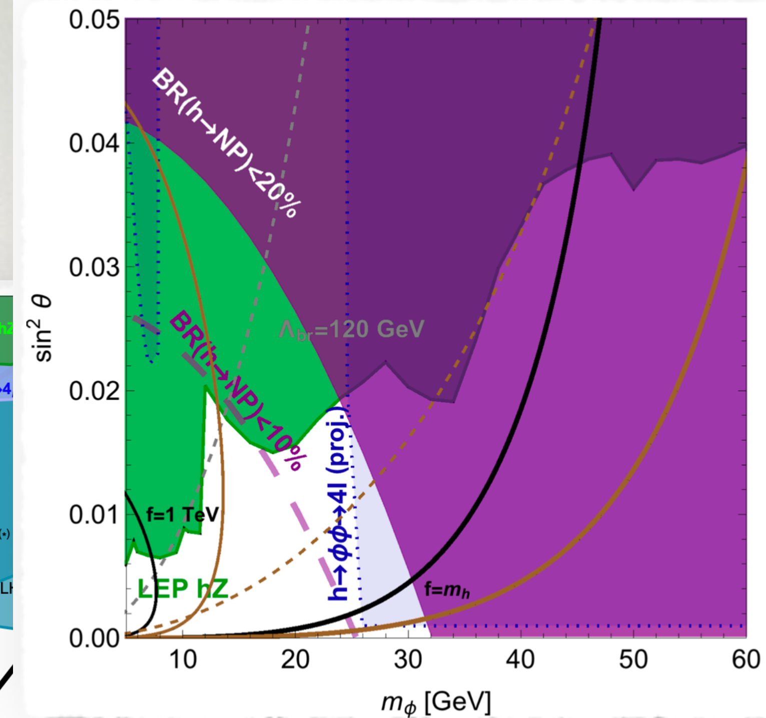
Flacke et al., 1610.02025



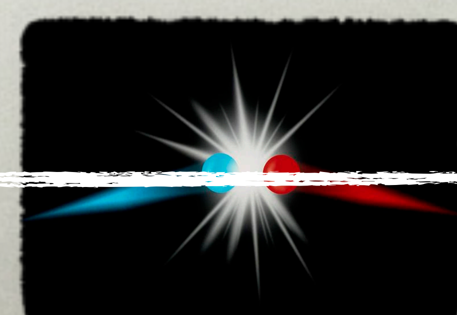


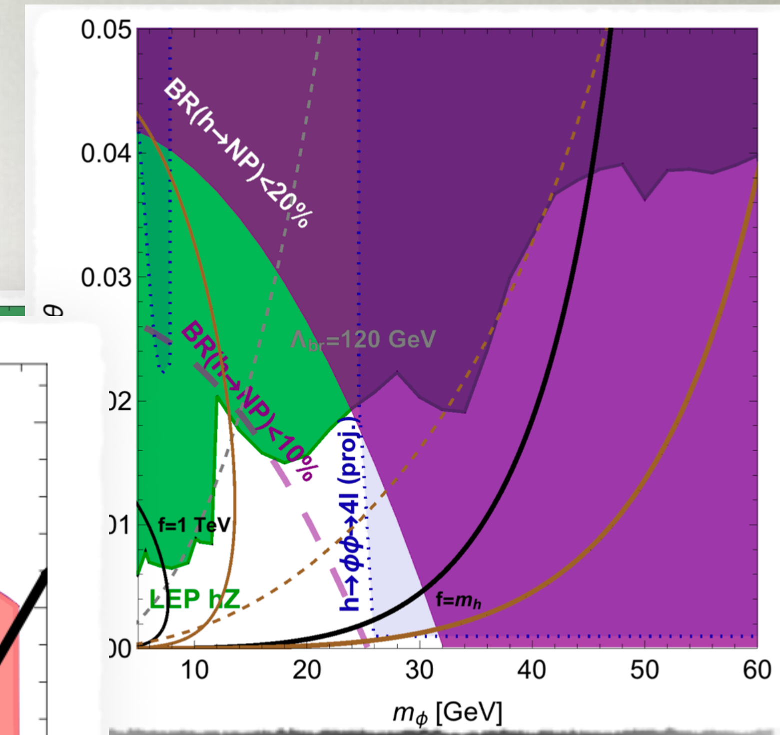
Flacke et al., 1610.02025



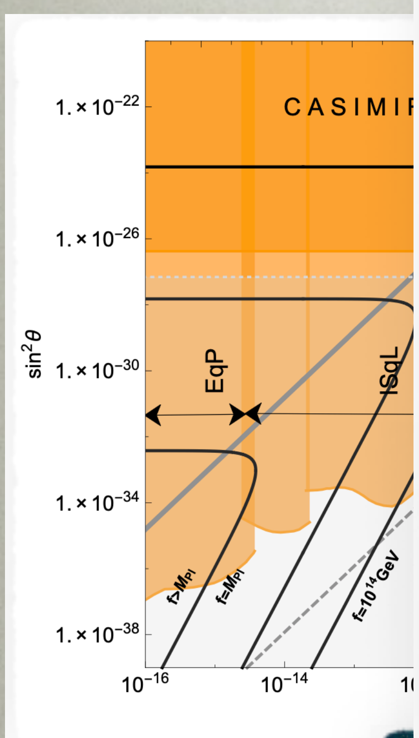


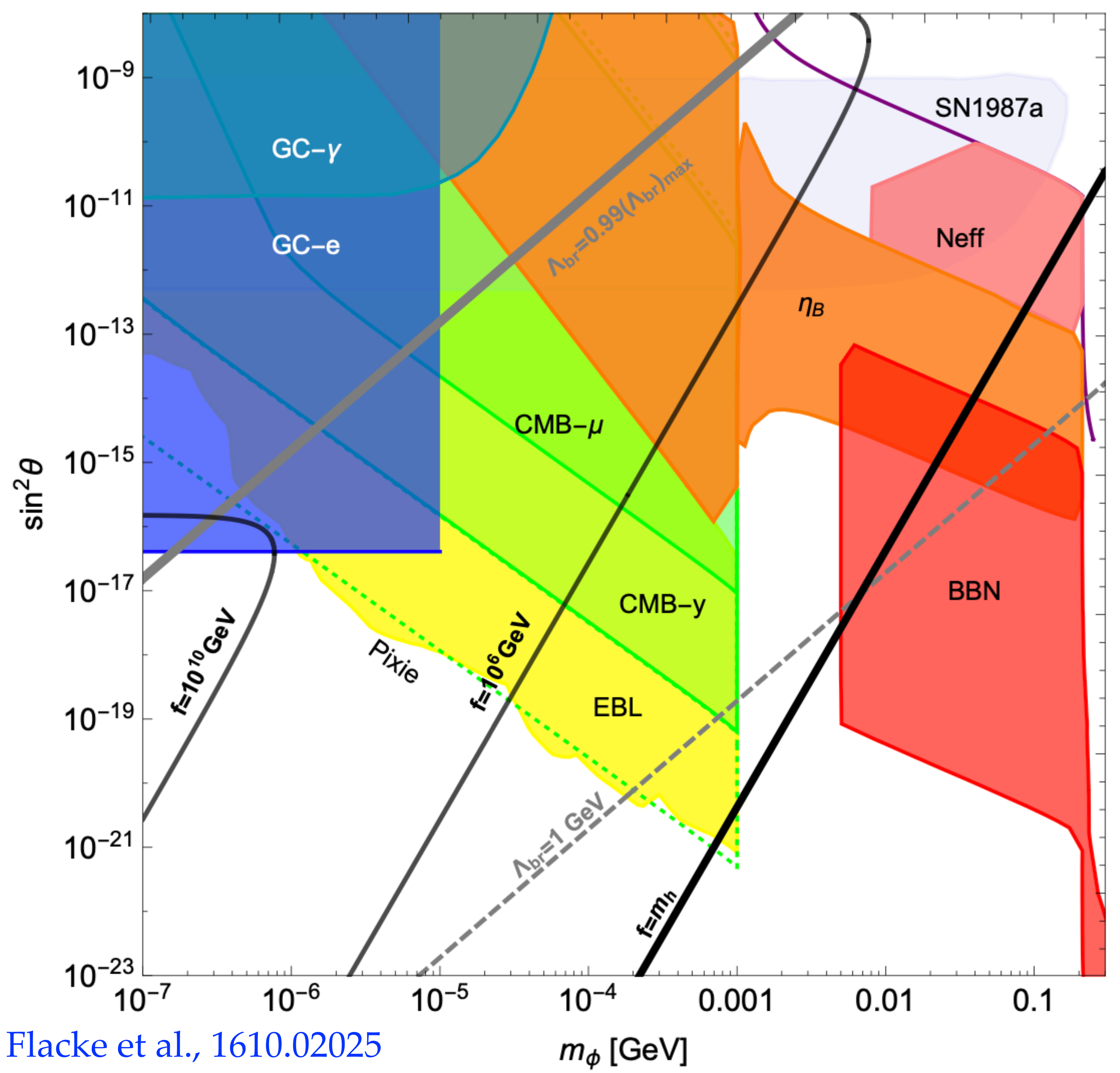
Flacke et al., 1610.02025



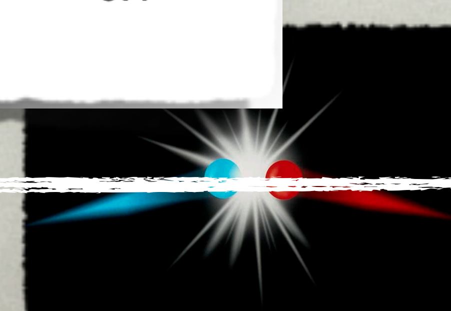


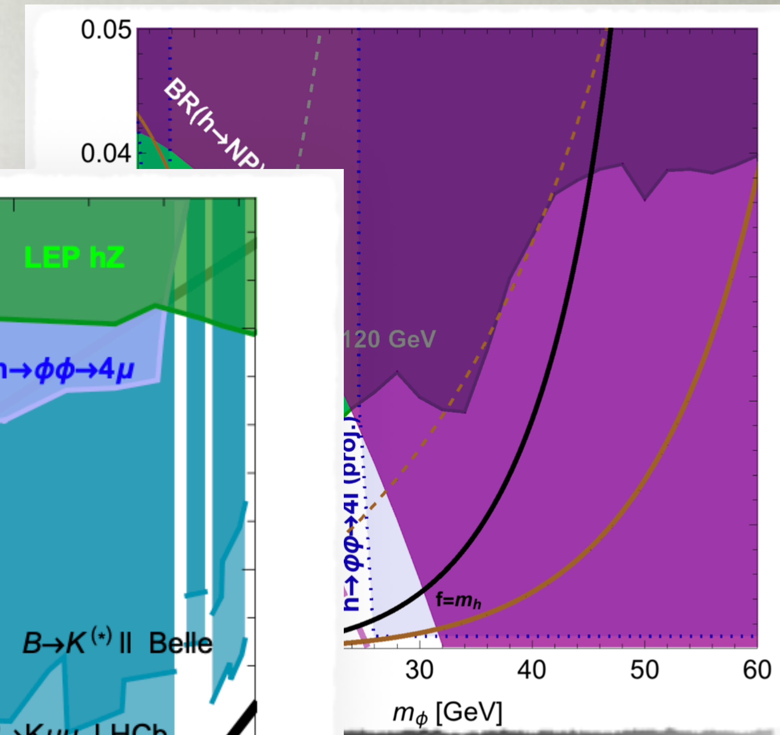
Flacke et al., 1610.02025



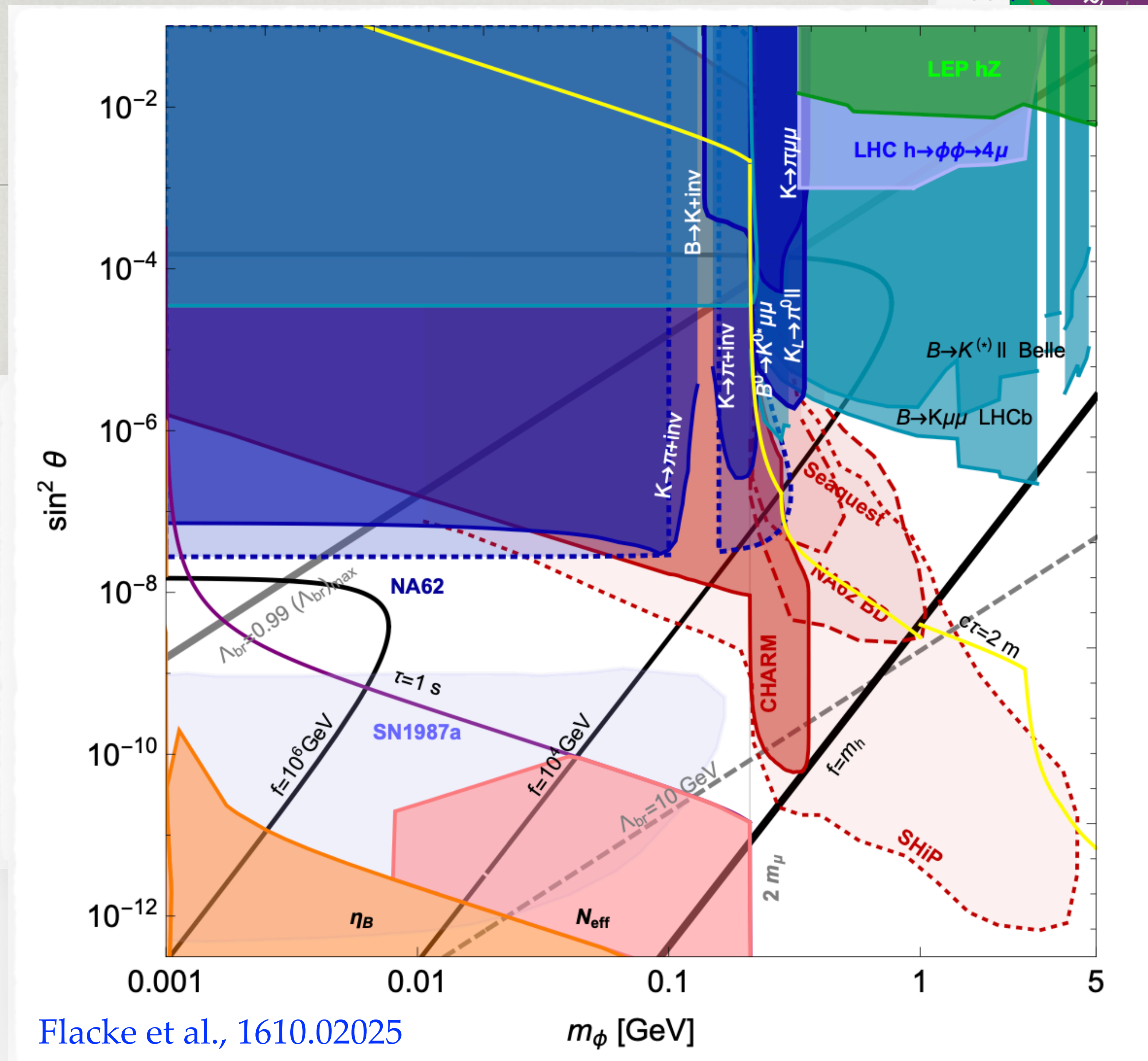


Flacke et al., 1610.02025

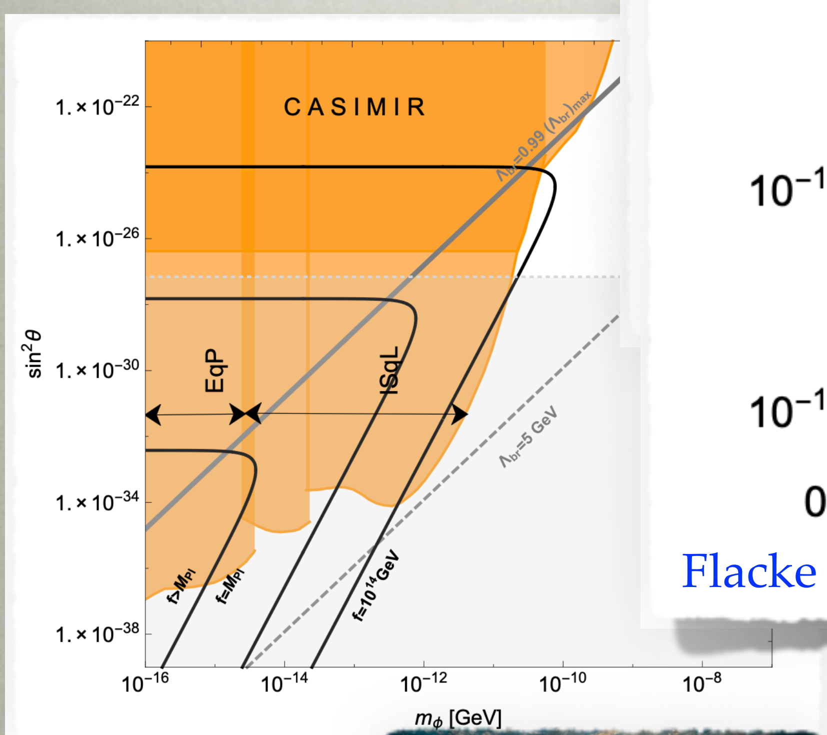


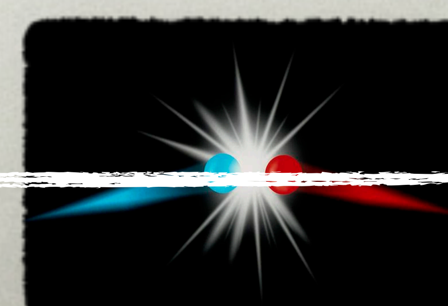


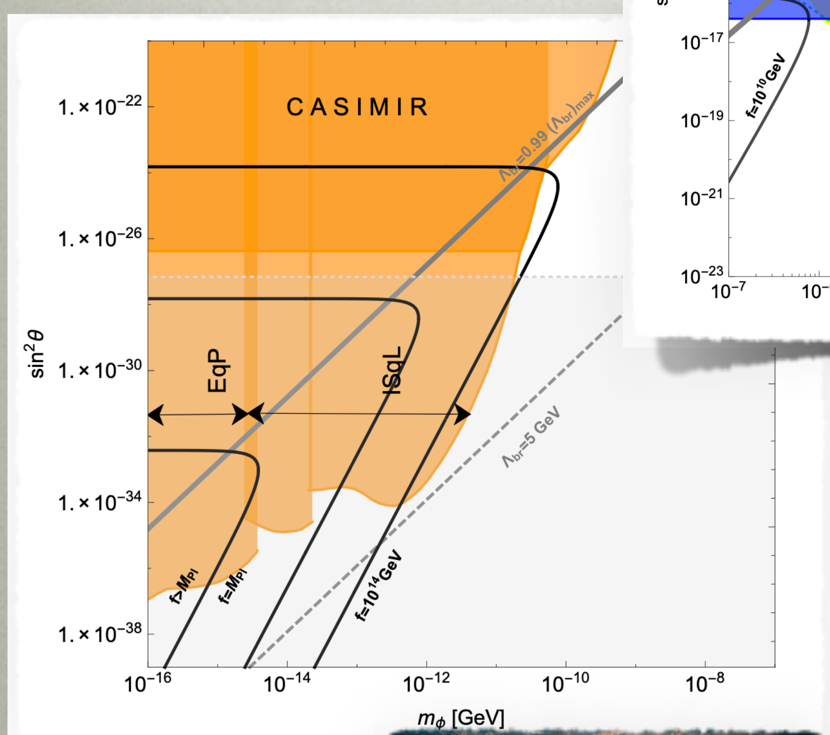
al., 1610.02025

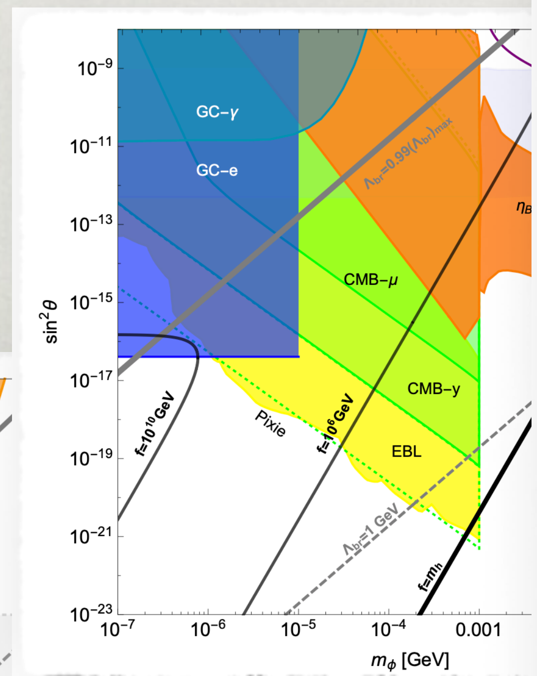


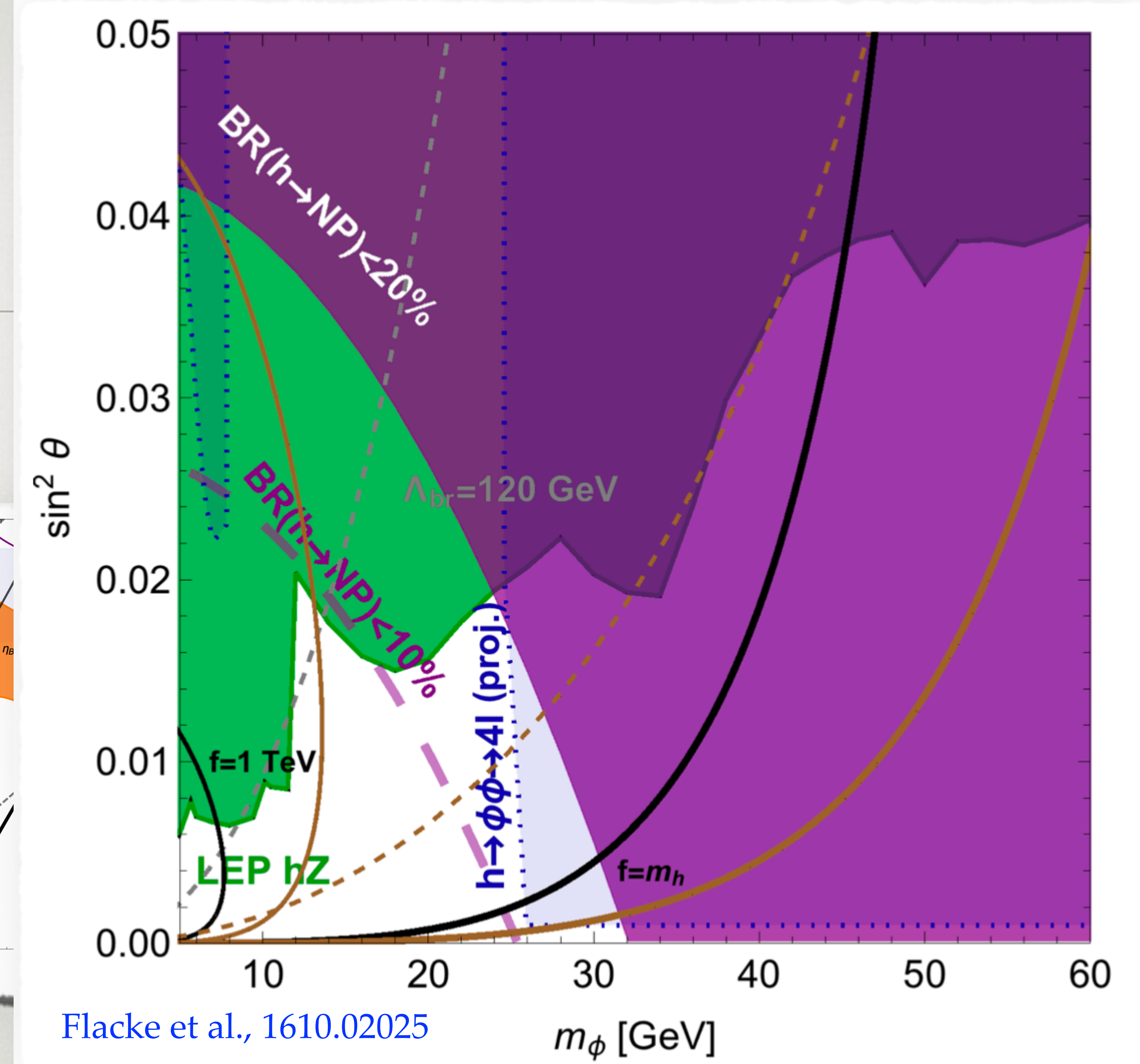
Flacke et al., 1610.02025



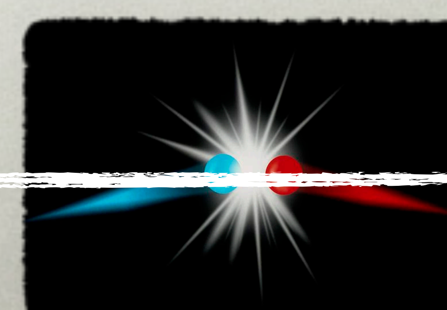








Flacke et al., 1610.02025



BARYOGENESIS/ LEPTOGENESIS

WHY MATTER?

- why matter and anti-matter did not completely annihilate away?
  - now: $\frac{n_B}{n_\gamma} = 6.1(4) \cdot 10^{-10}, n_{\bar{B}} \ll n_B$
- in the early universe: $n_B + n_{\bar{B}} \gtrsim n_\gamma$
- baryogenesis:
  - assume that the initial conditions in the early universe symmetric: $n_B = n_{\bar{B}}$
  - asymmetry between matter and antimatter generated through cosmological evolution

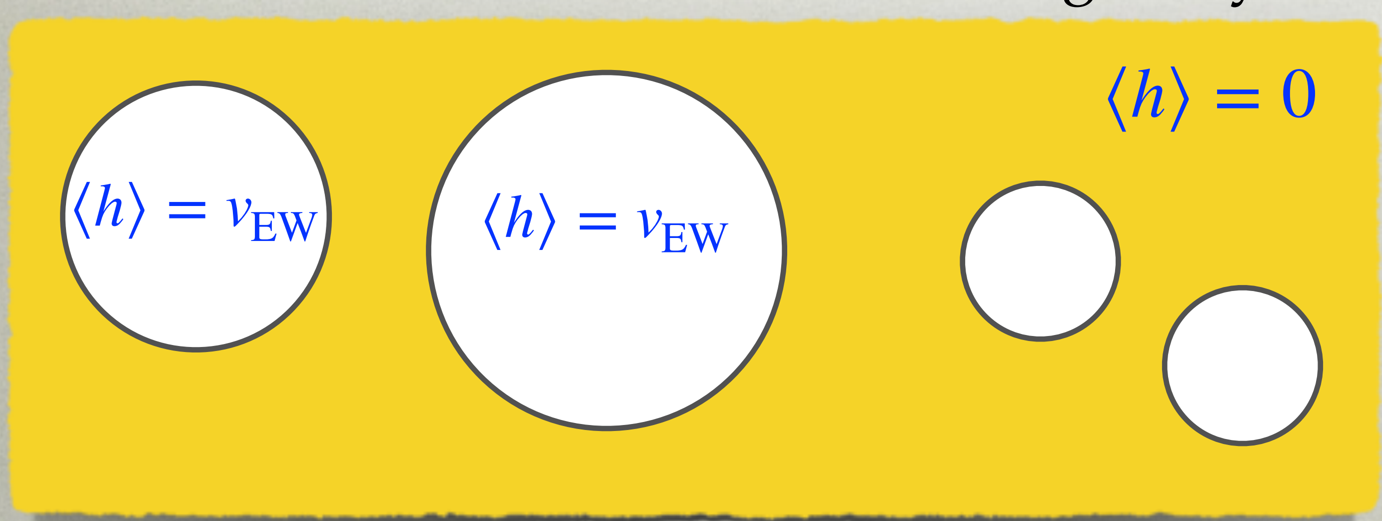
SAKHAROV CONDITIONS

Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967) 32–35

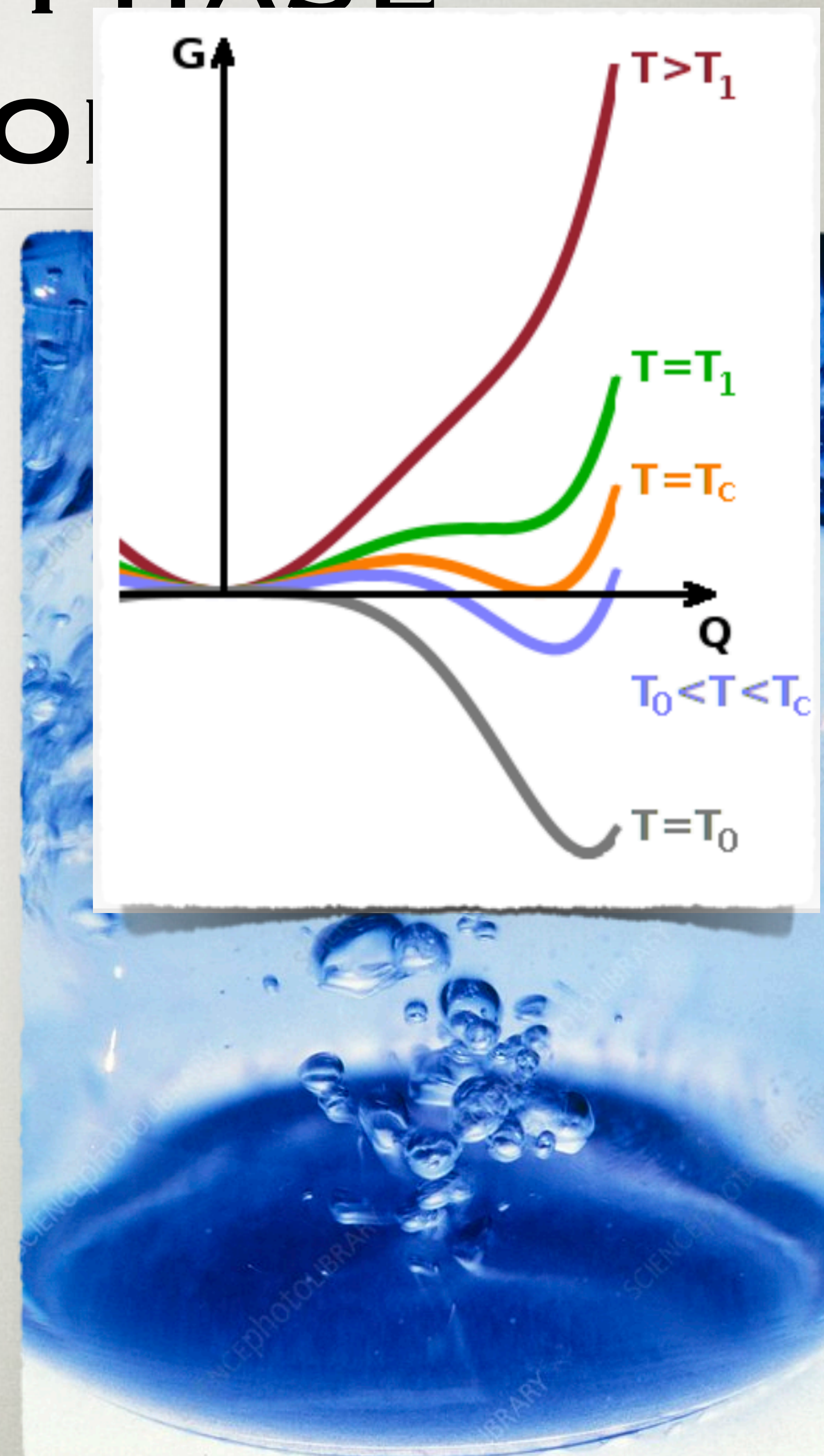
- three conditions required for successful baryogenesis
  - baryon number violated
  - Charge-Parity symmetry violated
  - out of equilibrium processes
- note: all three ingredients present in the SM in principle (electroweak baryogenesis)
  - does not work quantitatively with the measured SM parameters
  - requires new physics

FIRST ORDER PHASE TRANSITION

- one option for the out-of equilibrium: first order phase transition
- non-equilibrium: formation and expansion of bubbles of new phase
  - similar to boiling water
  - for instance electroweak phase transition: outside (inside) bubble $\langle h \rangle = 0(v_{\rm EW})$
  - EW baryogenesis in the walls of the bubbles
- collisions of bubbles $\Rightarrow$ stochastic gravity waves



FIRST ORDER PHASE TRANSITIO



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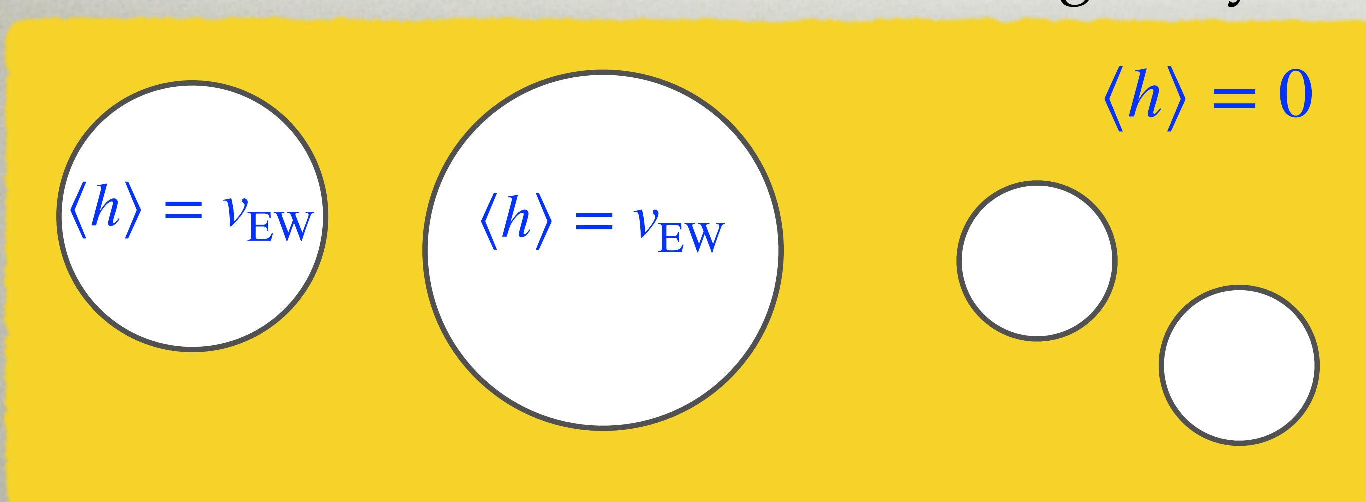
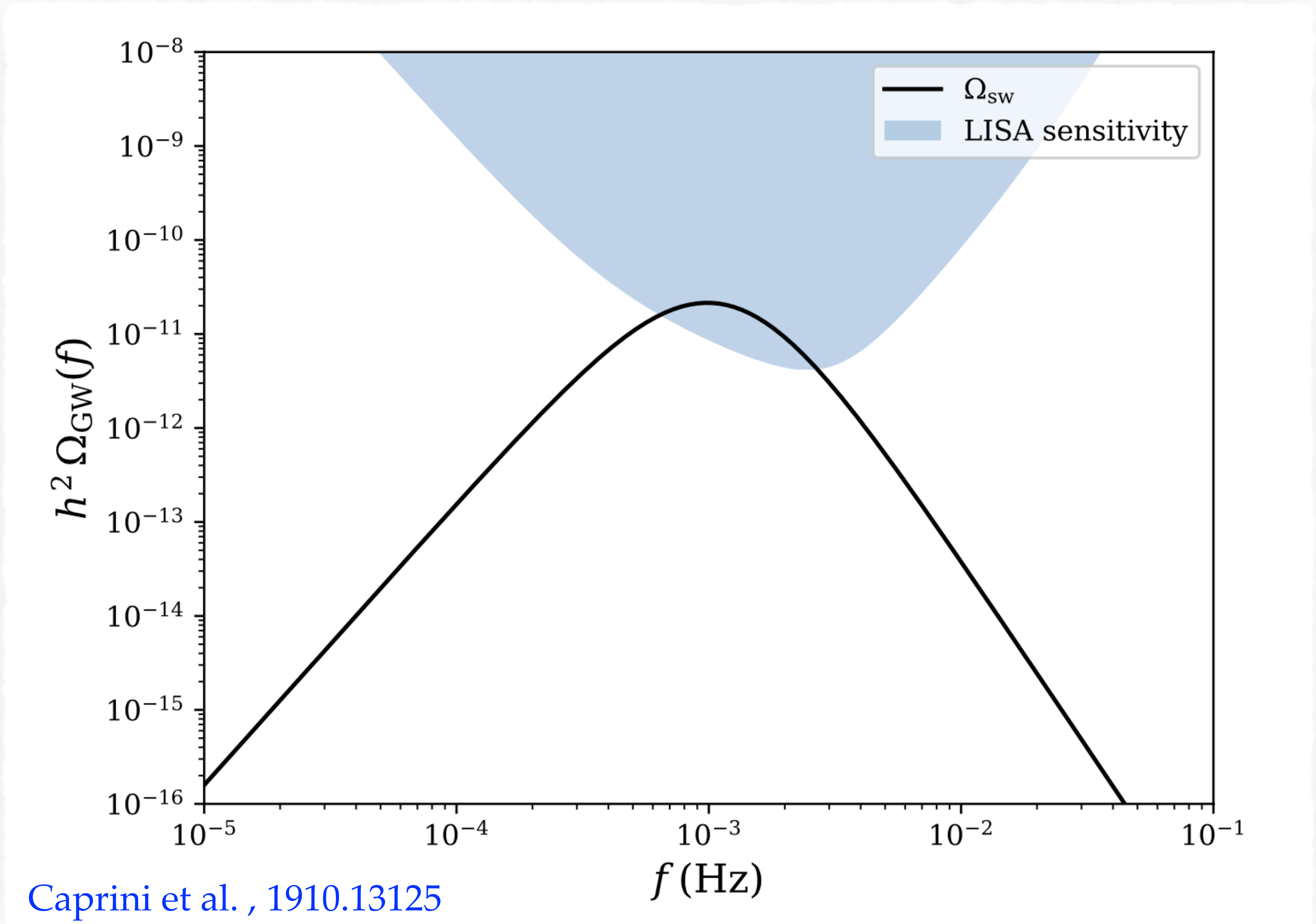


STOCHASTIC GW SPECTRUM

- EW phase transition can well be probed by e-LISA
- sample spectrum



Caprini et al. , 1910.13125

bubble wall speed

strenght of phase transit.

$v_w = 0.9$,
α=0.1,
β/H_* =50,
T_* =200GeV,
g_* =100

percolation temperature

# of relativistic d.o.f. at T_*

β - rate of increase of the nucleation probability

H_*- Hubble rate at T_*

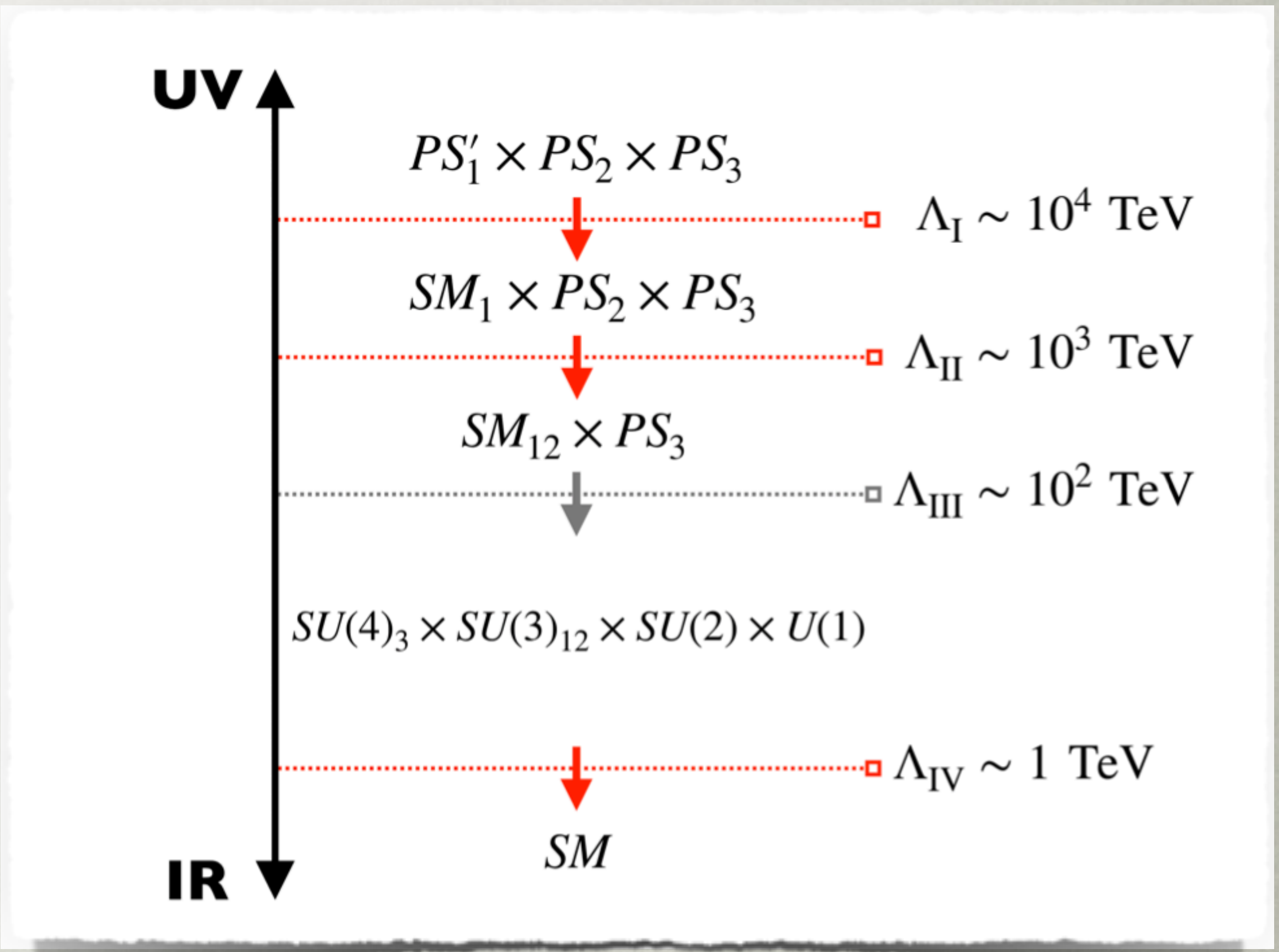
see lectures by Yuta Michimura

TRIGLAV* SIGNATURE

Greljo, Opferkuch, Stefanek, 1910.02014

* Triglav=Three Heads

- the space of phase transitions could be more complicated
- example: series of breakings of flavor gauge groups
- explain the *B* physics anomalies



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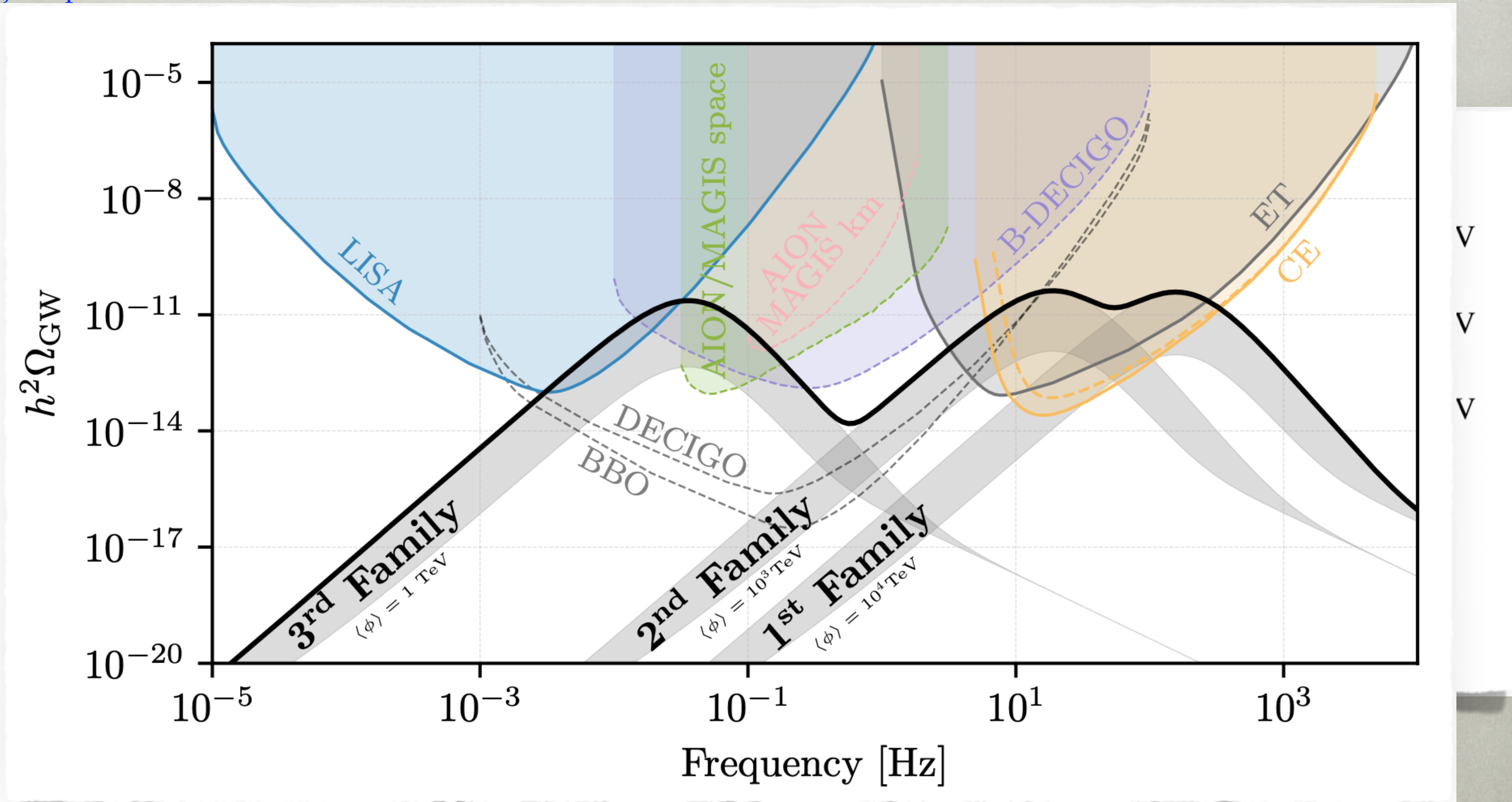

TRIGLAV* SIGNATURE

Greljo, Opferkuch, Stefanek, 1910.

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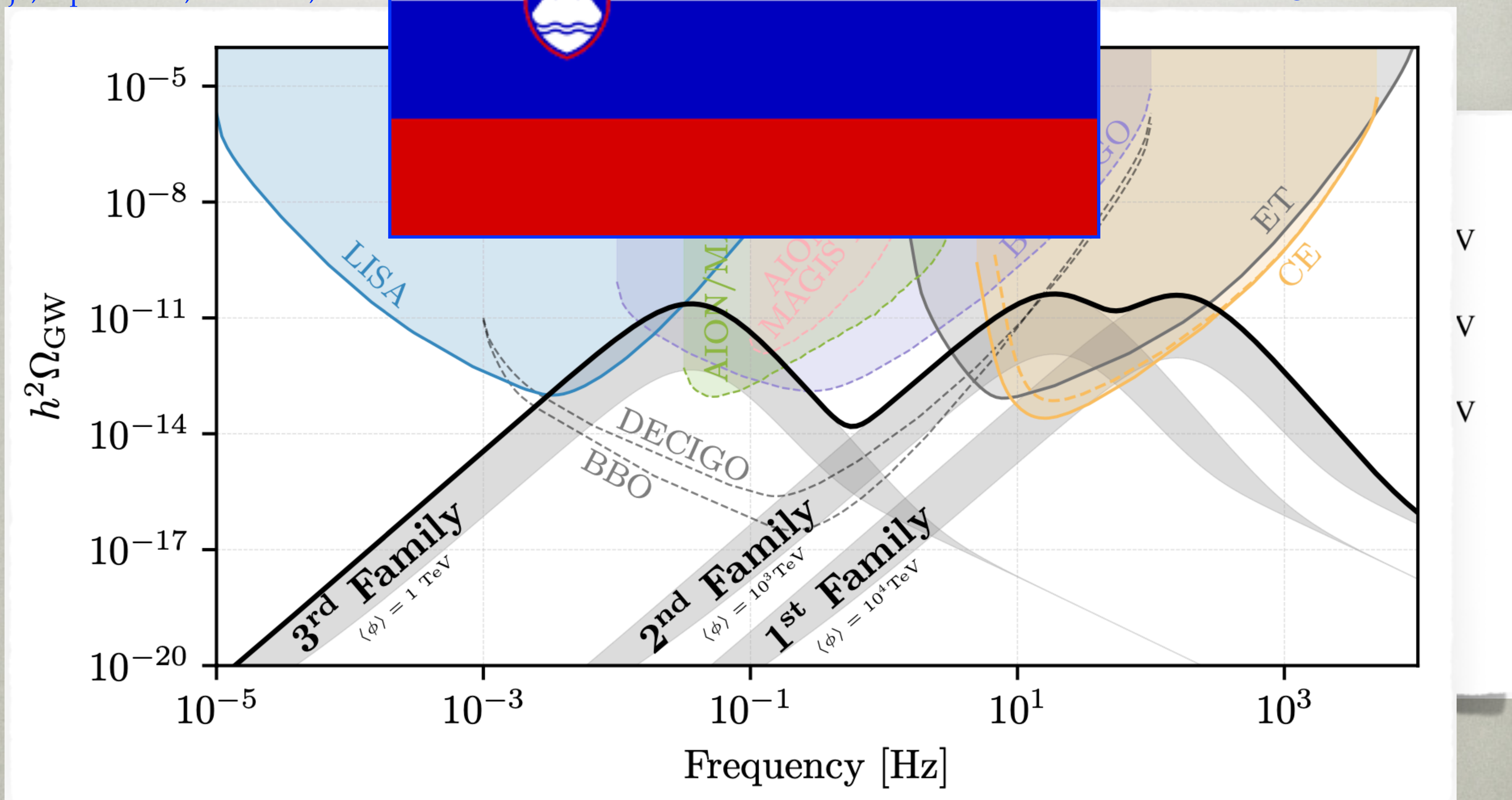

TR… …IATURE

Greljo, Opferkuch, Stefanek, 19…

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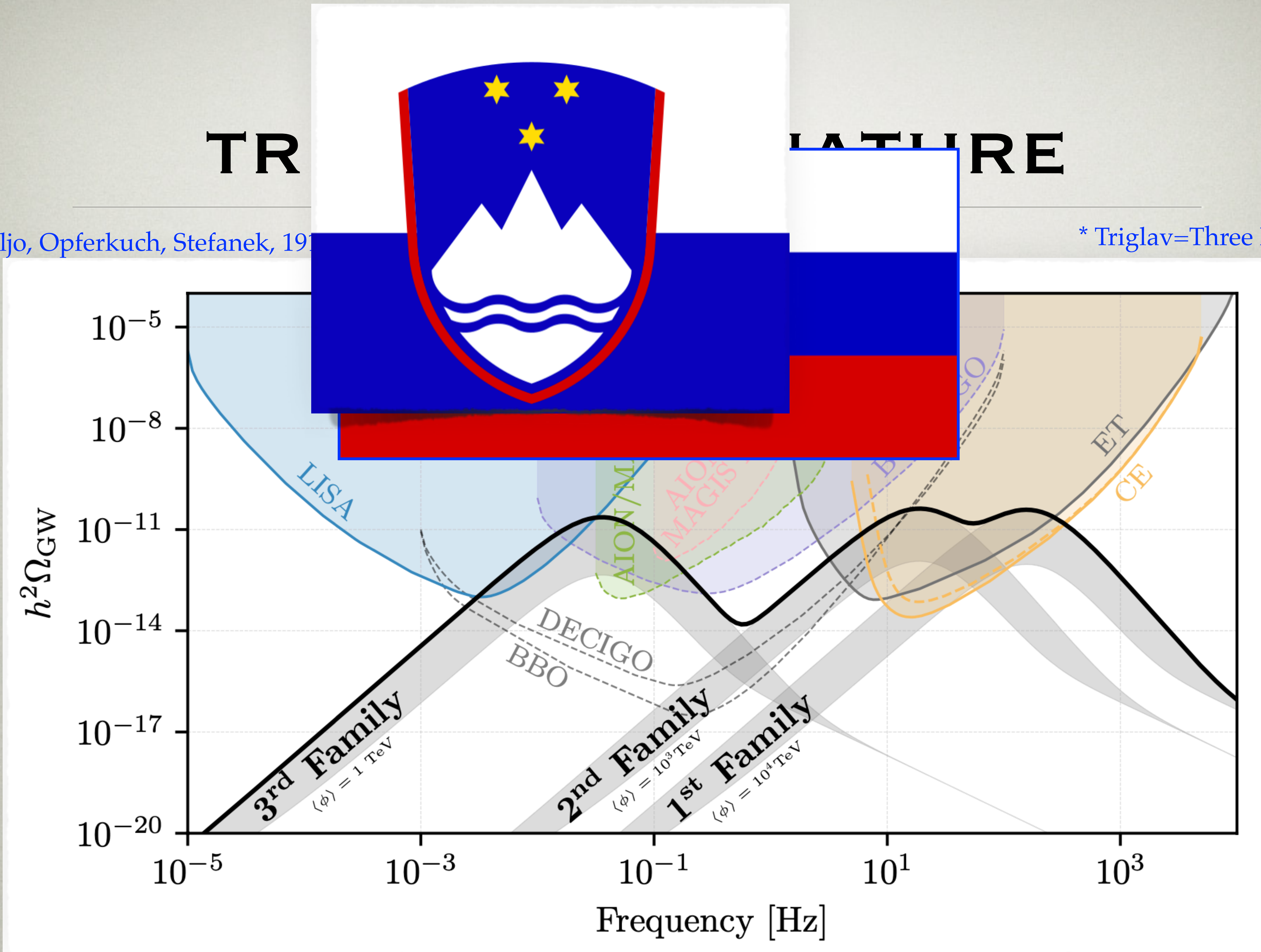

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CONCLUSIONS

- a brief overview of motivations for beyond the standard model physics
  - dark matter, hierarchy problem, strong CP problem, baryogenesis
- searching for light d.o.f.s can well advance our understanding of some of these questions

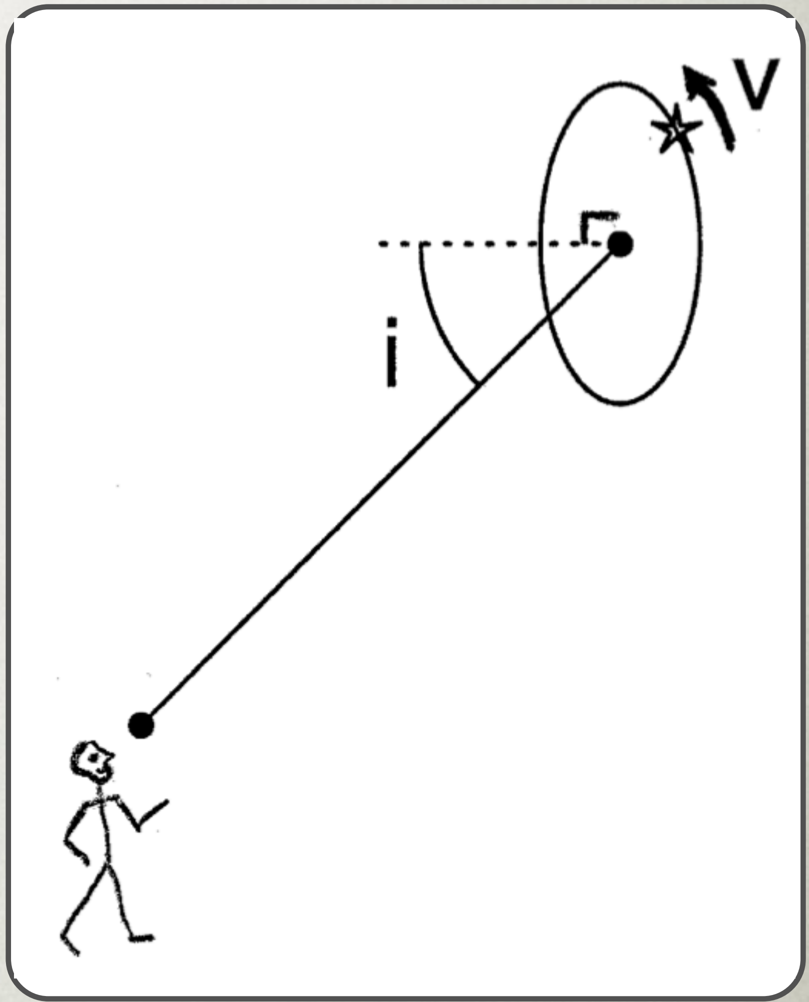
BACKUP SLIDES

NGC 6503

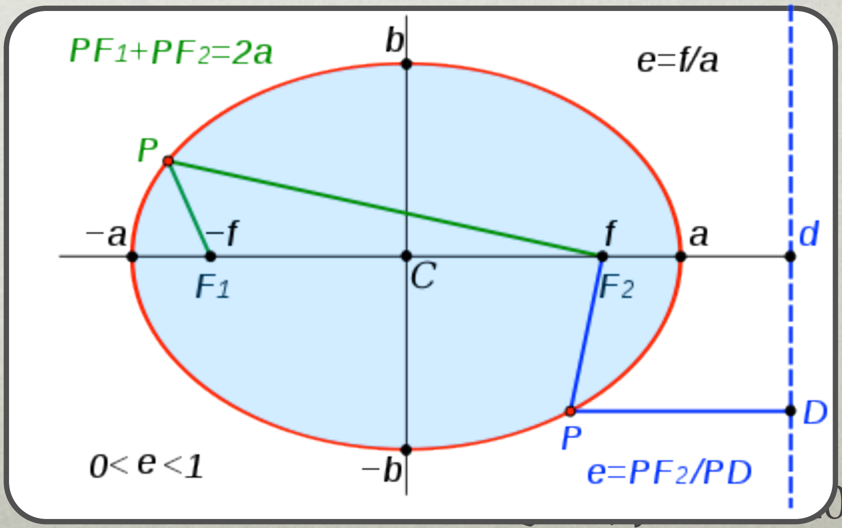
- from Wikipedia about NGC 6503
  - a dwarf spiral galaxy
  - located in a region of space called the Local Void.
  - spans 30,000 light-years
  - lies approximately 17 million light-years away in the constellation of Draco (the Dragon)

VELOCITIES OF STARS IN GALAXY

- orbital v of stars within spiral galaxy from observations
- consider a galaxy that is a thin circular disk
- in general do not see it edge-on
  - at inclination i
- we see it as elliptical not circular



$$b/a = \cos i$$

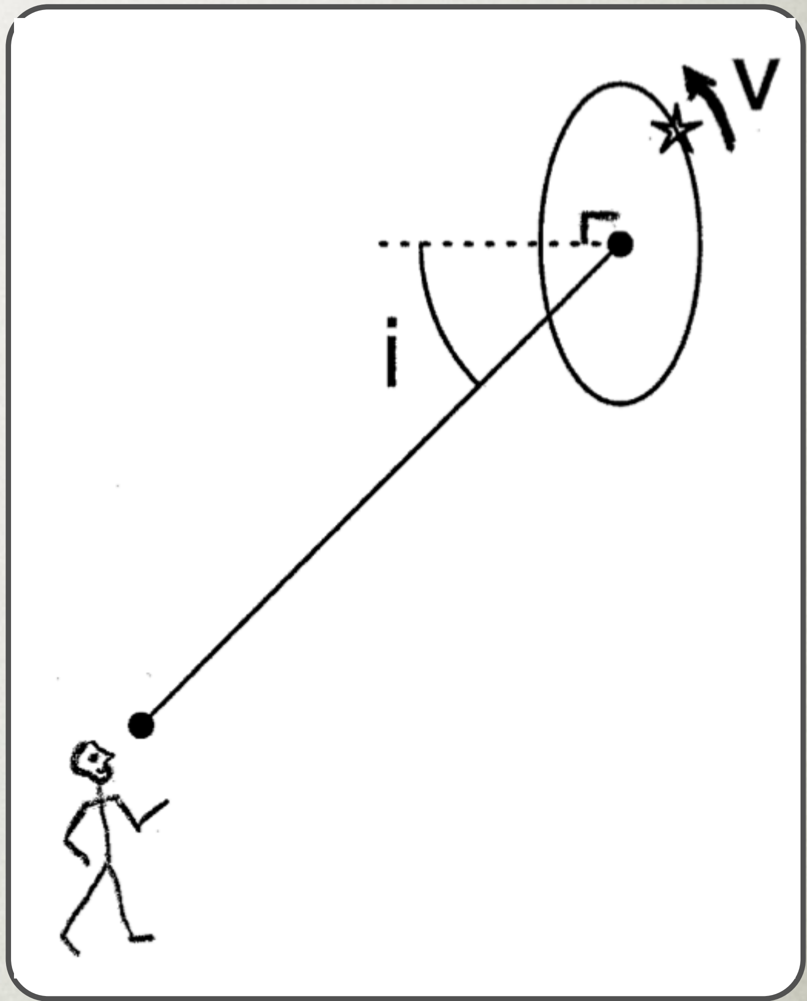


EXAMPLE: M31

- example: Andromeda galaxy (M31)
    - appears extremely elongated seen from Earth
    - $b/a=0.22$
    - so we are seeing it fairly on-edge $i=\cos^{-1}(0.22)=77deg$

FROM DOPPLER TO VELOCITY

- velocity by looking at Doppler shift of emission (or absorption) lines
- can only measure radial velocity $v_r(R)$
  - perp. to line of sight



$$v_r(R) = v_{\text{gal}} + v(R)\sin i$$

$$v(R) = \frac{v_r(R) - v_{\text{gal}}}{\sin i} = \frac{v_r(R) - v_{\text{gal}}}{\sqrt{1 - b^2/a^2}}$$

PARSEC

- the definition of *1pc*
  - A parsec is the distance from the Sun to an astronomical_object which has a parallax angle of one arcsecond (*1⁄3600* of a degree)
  - $1pc = 30.9\ 10^{12} km = 3.26$ *light years*
- distance of Earth to Galactic center: 8.33 ± 0.35 *kpc*
- nearest star Proxima Centauri *4.2421(16)* light years (~*1.3pc*)

M31

- the first astronomer to detect rotation of M31 was Vesto Slipher in 1914
- for outer regions: difficulty of measuring the spectra at low surface brightness
  - another 50years to measure $v(R)$ for $R > 3R_s = 18kpc$
- in 1970 Vera Rubin, Kent Ford
  - emission lines from hot ionized gas in M31
  - up to $R = 24\ kpc = 4R_s$ then too faint
- to go further M. Roberts and R. Whitehurst used atomic hydrogen emission line $\lambda = 21cm$

MEASUREMENTS FROM 1970s

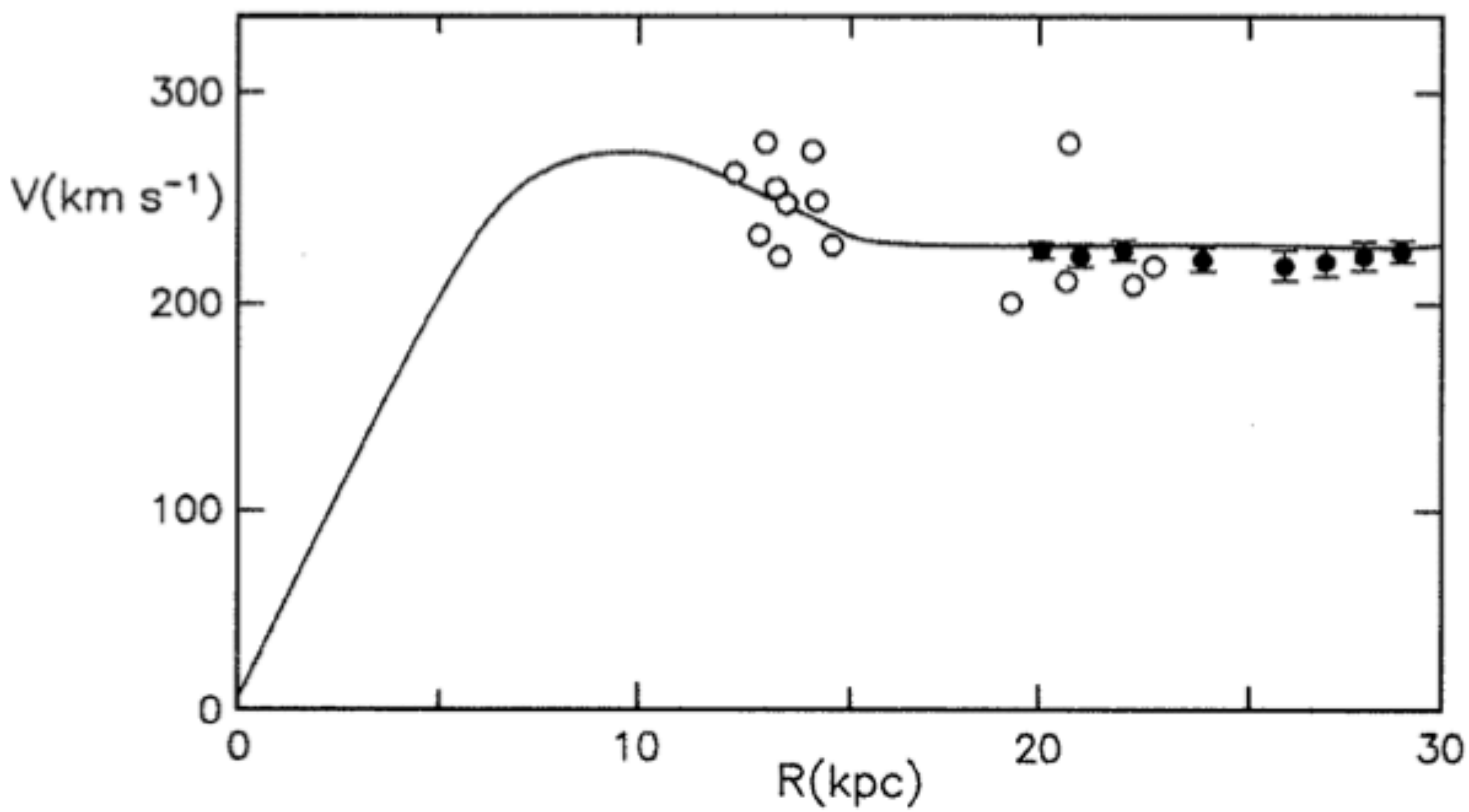
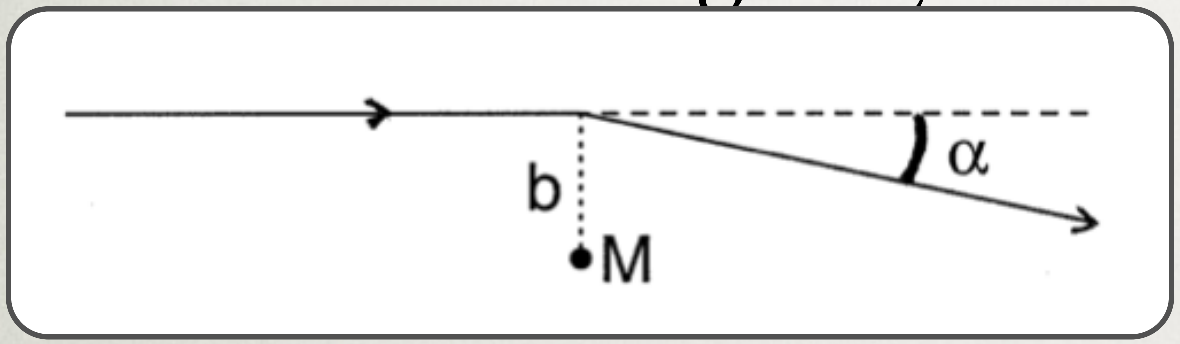


Figure 8.4: The orbital speed v as a function of radius in M31. The open circles show the results of Rubin and Ford (1970, ApJ, 159, 379) at visible wavelengths; the solid dots with error bars show the results of Roberts and Whitehurst (1975, ApJ, 201, 327) at radio wavelengths (figure from van den Bergh, 2000).

WEAK LENSING EQUATIONS

- deflection of light by a massive object



$$\alpha = \frac{4GM}{c^2 b}$$

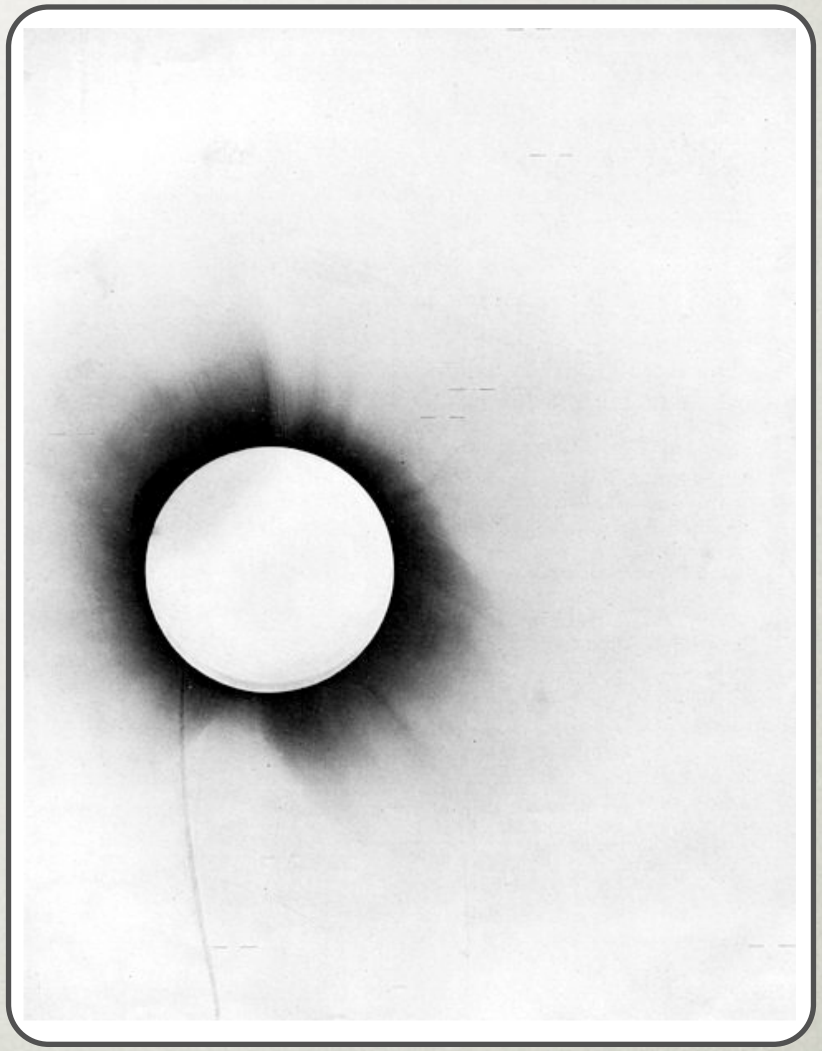
- if the light from distant star just grazes the sun's surface
  - the deflection is

$$\alpha = \frac{4G\,\mathrm{M}_\odot}{c^2\,\mathrm{R}_\odot} = 1.7\,\mathrm{arcsec}$$

  - it was one of the important predictions of Einstein's general theory of relativity

DEFLECTION OF LIGHT

- the first observation of light deflection
  - May 1919 during total solar eclipse
  - movement of apparent position of the star
  - Lord Eddington and collaborators



  - observations simultaneously in Brazil and west Africa
- made Einstein instantaneously famous

SOLUTIONS TO THE STRONG CP PROBLEM

- *massless up-quark:*
  - ruled out by Lattice QCD, $m_u \neq 0$
- *Nelson-Barr solution:* impose CP, break it spontaneously so that $\bar{\theta}$ small, while δ_{CKM} large
  - difficult to test

Nelson, PLB 136, 387 (1984)
Barr, PRL 53, 329 (1984)

- *axion solution:* if $\bar{\theta}(x)$ a dynamical field with no other potential but $\bar{\theta}G\tilde{G} \Rightarrow$ non-perturbative dynamics generates potential with minimum at $\bar{\theta}(x) = 0$
  - new ultra-light particle

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

SOLUTION TO THE FLAVOR PUZZLE

Froggatt, Nielsen, NPB 147, 277 (1979),...

- Large hierarchies in quark + lepton masses and in CKM matrix
  - can be addressed via horizontal *U(1)*$_H$ symmetry

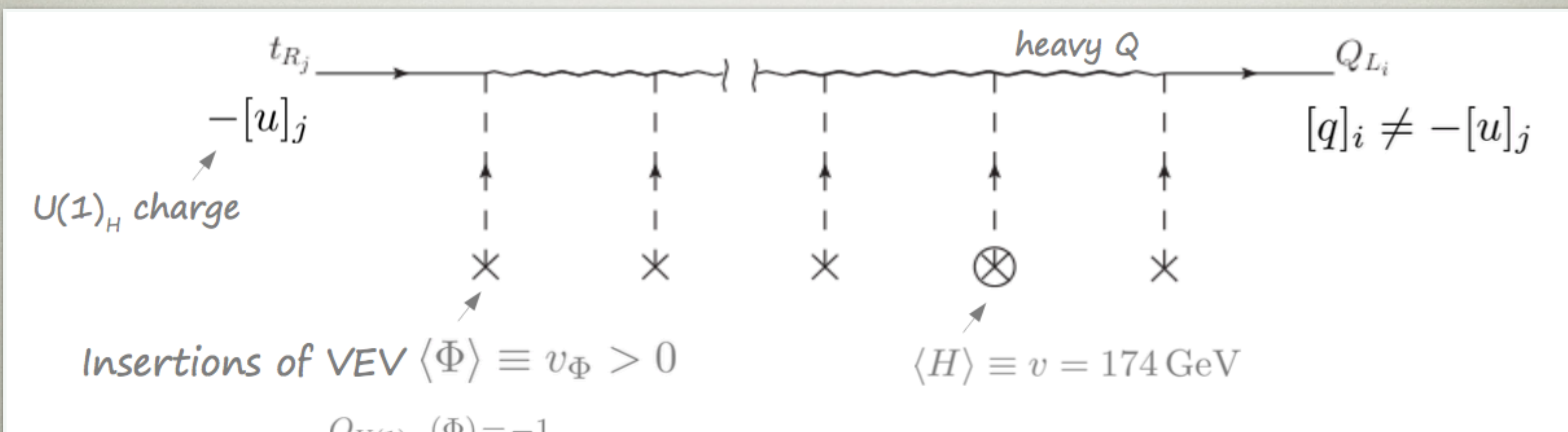


figure due to F. Goertz

AXION MECHANISM IN MORE DETAILS...

- assume there is *U(1)$_{PQ}$* ("Peccei-Quinn") symmetry with fermion charges such that they give QCD anomaly
  - Noether current not conserved $$\partial_\mu j^\mu_{\rm PQ} \sim \frac{\alpha_s}{4\pi} G\tilde{G}$$
- break spontaneously the global *U(1)$_{PQ}$* at scale *f* by vev of complex scalar field *Φ* with charge +1

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$

- *U(1)$_{PQ}$* symmetry non-linearly realized as shift symmetry

$$\Phi \to e^{i\alpha}\Phi \quad \Longrightarrow \quad a \to a + \alpha f$$

AXION MECHANISM IN MORE DETAILS...

- at scales $\mu \ll f$ the effective Lagrangian is

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{\rm SM} + \bar\theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu}\tilde G_{a,\mu\nu} + \underbrace{\frac{1}{2}\partial_\mu a \partial^\mu a}_{\text{kinetic term}} + \underbrace{\mathcal{L}_{\rm a,int}\Big[\frac{\partial_\mu a}{f}, \psi_{\rm SM}\Big]}_{\text{interactions with SM fermions}} + \underbrace{\frac{a}{f}\xi \frac{\alpha_s}{8\pi} G_a^{\mu\nu}\tilde G_{a,\mu\nu}}_{\text{ABJ term for QCD anomaly}} + \underbrace{\mathcal{L}_{\rm anom}\Big[\frac{a}{f}F\tilde F\Big]}_{\text{ABJ term for other anomalies}}$$

[repspects shift symmetry]

[breaks shift symmetry]

[cf. $\frac{\pi^0}{f_\pi}F\tilde F$]

- note that $\bar\theta(x) = \bar\theta + \xi a/f$ is a dynamical field
  - has minimum at $\bar\theta(x)=0$
  - ξ is UV model dependent constant

Strong CP problem solved!

AXION MODELS

- Choose PQ charges of SM and BSM (fermions + scalars) fields such that have QCD anomaly of PQ symmetry
- *PQWW axion:* 2HDM <u>without</u> new fermions

  Peccei, Quinn, Wilczek, Weinberg '78
    - EW scale, $f \sim v$, $m_a \sim 30$ keV **ruled out**
- *DFSZ axion:* 2HDM <u>without</u> new fermions but <u>with</u> extra singlet scalar

  Dine, Fischler, Srednicki, Zhitnitsky '80
    - singlet breaks PQ at scale $f \gg v$, gives $|E/N| \in [0.3, 2.7]$
- *KSVZ axion*: SM model <u>with</u> new (heavy) fermions and extra singlet scalar

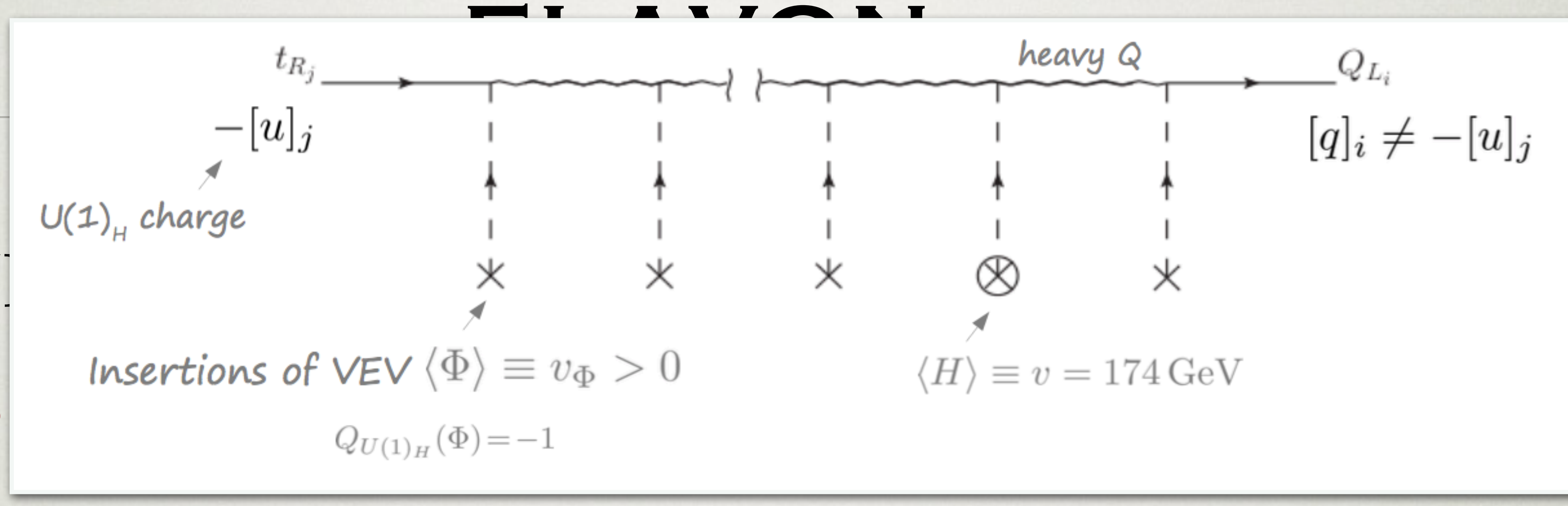
  Kim, Shifman, Vainshtein, Zakharov '80
    - singlet breaks PQ at scale $f \gg v$, gives $|E/N| \in [0, 6]$

FLAVON

- FN mechanism involves
  - vector-like fermions (no QCD anomaly)
  - scalar flavon fields
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F}\right)^{x_{ij}} h\,\overline{q}_i u_j \qquad \epsilon \equiv \frac{\phi}{\Lambda_F}$$

  - hierarchy from powers of small parameter ε



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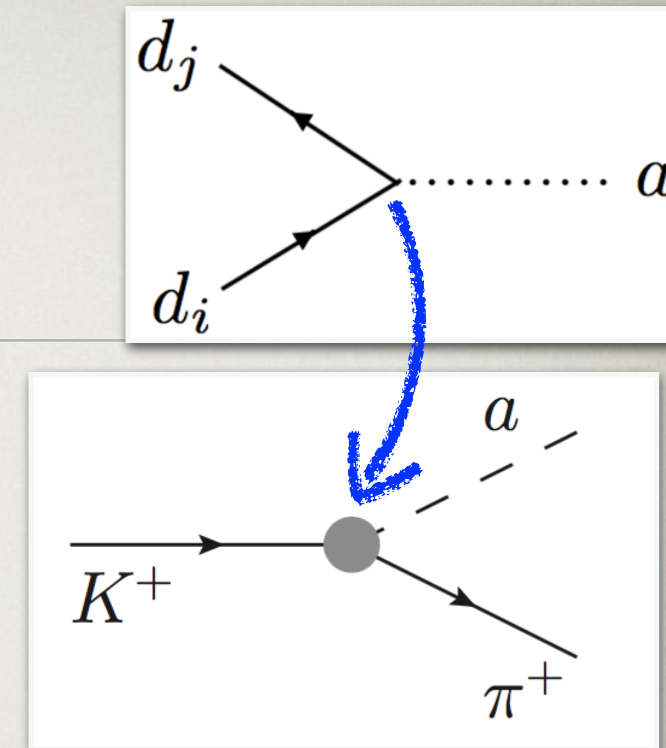
PROBING AXIFLAVON



- most stringent bounds from kaon sector

$$\mathrm{BR}(K^+ \to \pi^+ a) \simeq 1.2 \cdot 10^{-10} \left(\frac{m_a}{0.1\,\mathrm{meV}}\right)^2 \left(\frac{\kappa_{sd}}{N}\right)^2$$

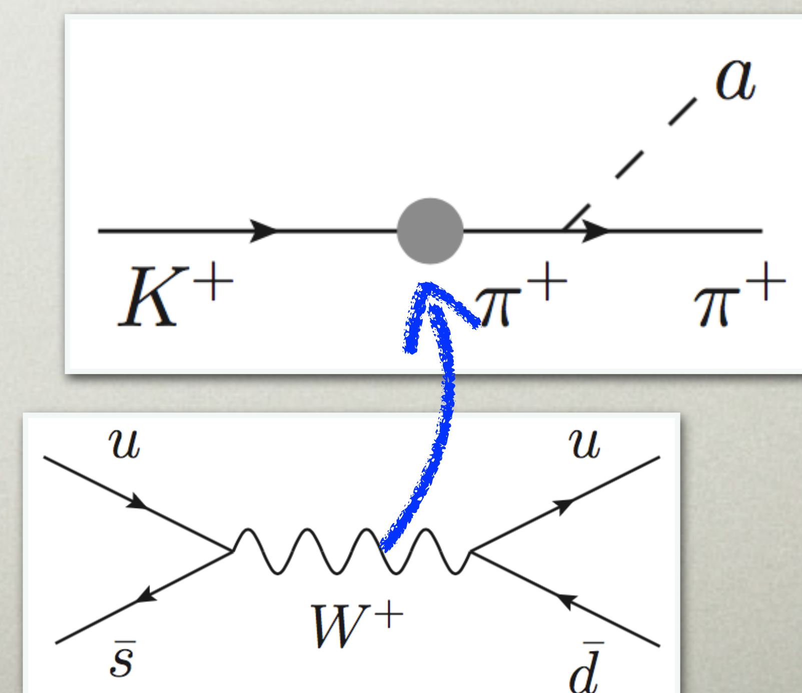
O(1) factor

- 90% CL combined bound from E787 and E949

$$\mathrm{BR}(K^+ \to \pi^+ a) < 7.3 \cdot 10^{-11}$$

$$f_a \gtrsim \frac{\kappa_{sd}}{N} \times 7.5 \cdot 10^{10}\,\mathrm{GeV}$$

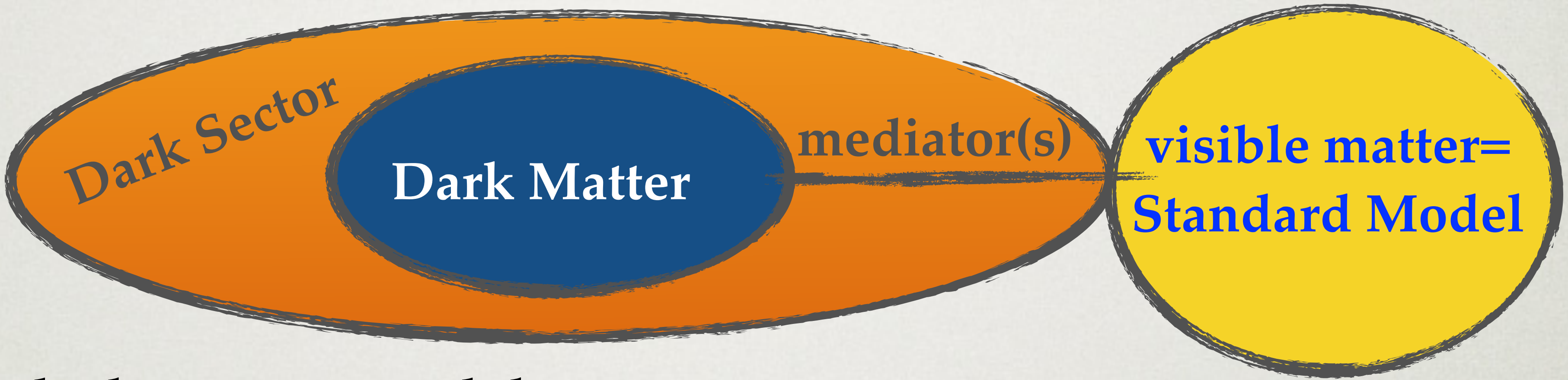
- note: the weak annihilation where FV from *W* exchange is always negligible



$$\frac{\Gamma(K^+ \to \pi + a)_{\mathrm{w.a.}}}{\Gamma(K^+ \to \pi + a)} \sim \left(\frac{f_K f_\pi}{m_W^2}\right)^2 \left(\frac{\lambda^d_{11,22}}{\lambda^d_{12,21}}\right)^2 \sim 10^{-12}$$

DARK MATTER MODELS

- typical structure



- many dark matter models
- roughly three goups
  - UV complete models
    - DM part of a structure that solves other particle physics puzzle (hieararchy problem, flavor puzzle,...)
  - simplified models (can be UV complete)
    - keep only the essentials: DM + mediators
  - just DM + effective interactions

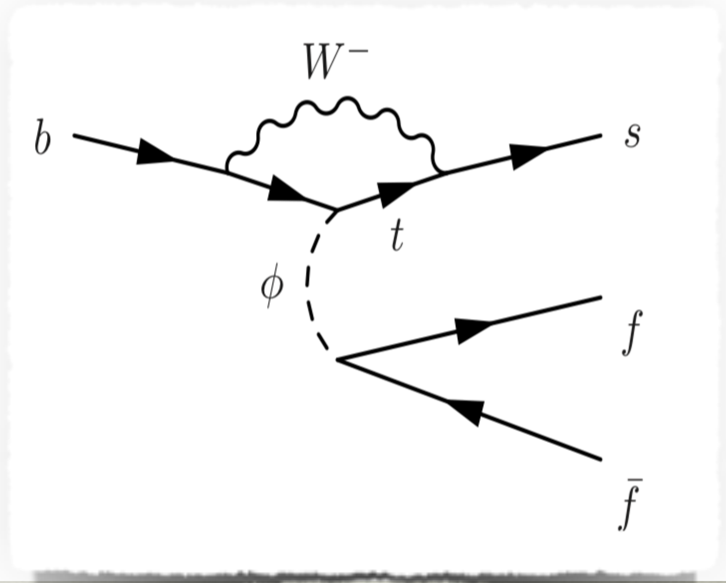
MIXING WITH THE HIGGS

see, e.g., O'Connell et al, hep-ph/0611014; Battell et al, 0911.4938; Winkler, 1809.01876

- another example: a mediator is a light scalar mixing with the Higgs

$$\mathcal{L}_{int} = -\mu S H^\dagger H \qquad \theta \simeq \mu v / m_h^2$$

- at 1 loop FCNC transitions: $B \to K^{(*)} S$, $D \to \pi S$, $K \to \pi S$, etc



- can be searched for
    - as a missing mass peak in $B \to K^{(*)} \nu\bar{\nu}$
    - from decays to the SM, e.g., $S \to \mu^+ \mu^-$

RATE

- differential counting rate

$$\frac{dR}{dE_d} = \frac{\rho_0}{m_\chi}\frac{\eta}{\rho_{\rm det}}\int_{v>v_{\rm min}} d^3v\,\frac{d\sigma}{dE_d}\,v f_\odot(\vec{v})$$

$$\rho_0 = 0.3 \text{ GeV/cm}^3$$

- minimal velocity $\chi N \to \chi' N$

$$v_{\rm min} = \frac{1}{\sqrt{2m_N E_d}}\left(\frac{m_N E_d}{\mu_{\chi N}} + \delta\right) \qquad v_{\rm min} > v_{\rm esc}$$

- for mass splitting large enough

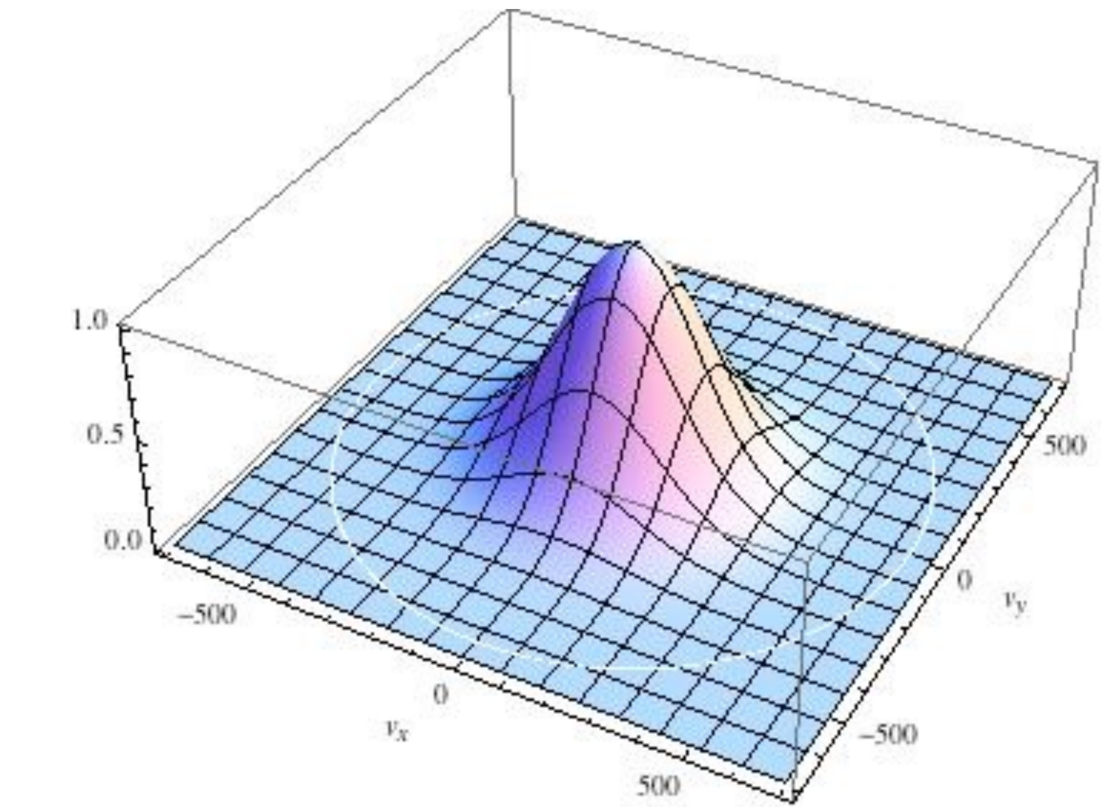
• dif

$\frac{dR}{dE_d}$

ρ

• mi

$$f_{\rm gal}(\vec{v}) \propto \exp(-\vec{v}^2/\bar{v}^2) - \exp(v_{\rm esc}^2/\bar{v}^2)$$



$\bar{v} = 220\,{\rm km\,s^{-1}}$ $\qquad$ $v_{\rm esc} = 650\,{\rm km\,s^{-1}}$

$$v_{\rm min} = \frac{1}{\sqrt{2 m_N E_d}} \left(\frac{m_N E_d}{\mu_{\chi N}} + \delta \right) \qquad v_{\rm min} > v_{\rm esc}$$

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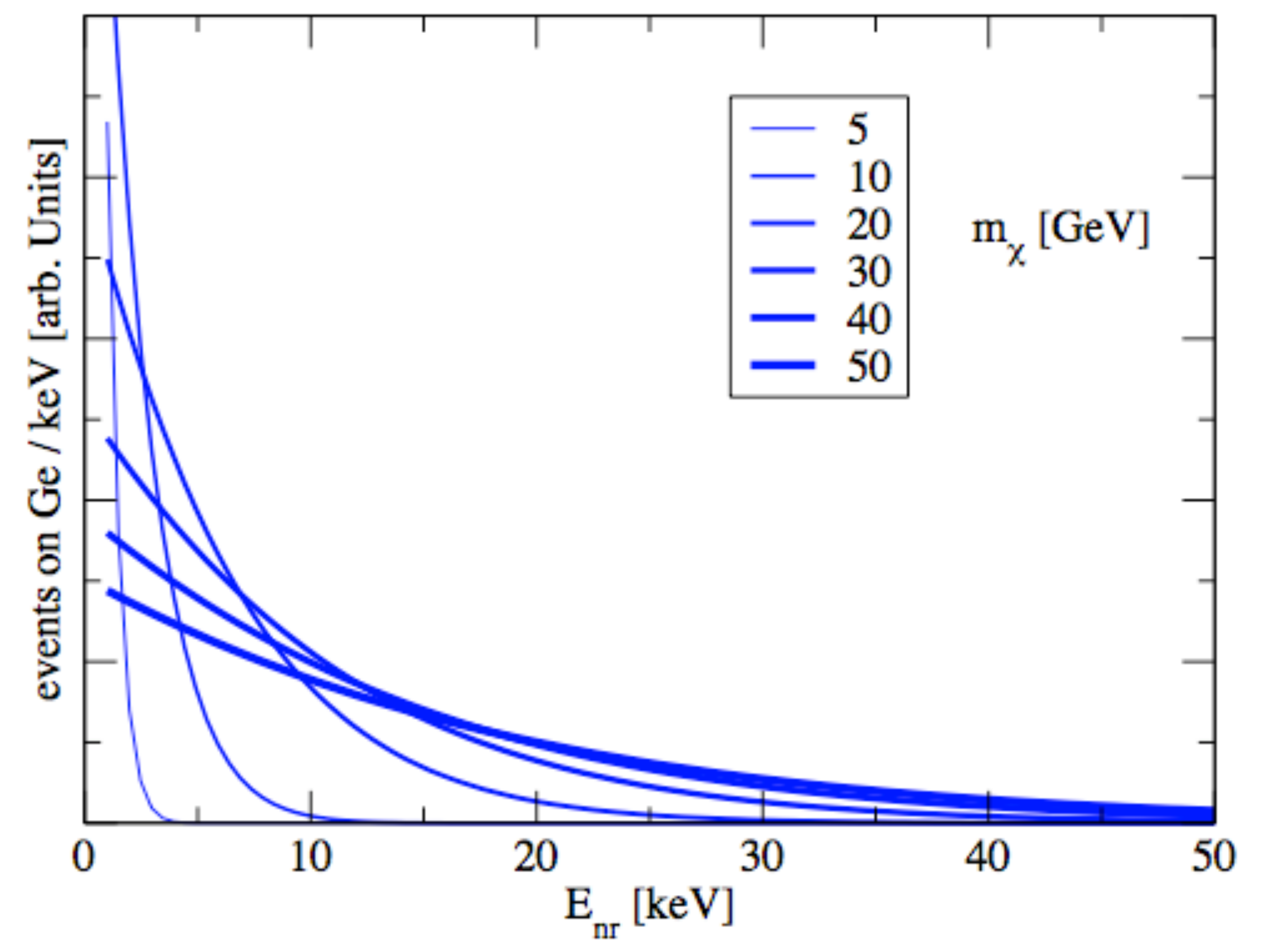
- for mass splitting large enough

ELASTIC SCATTERING

- elastic scattering: featureless spectrum
- lower DM mass $\Rightarrow$ smaller E_{nr}
- for low mass DM crucial low thresholds



Schwetz, GGI Conf., May 2010

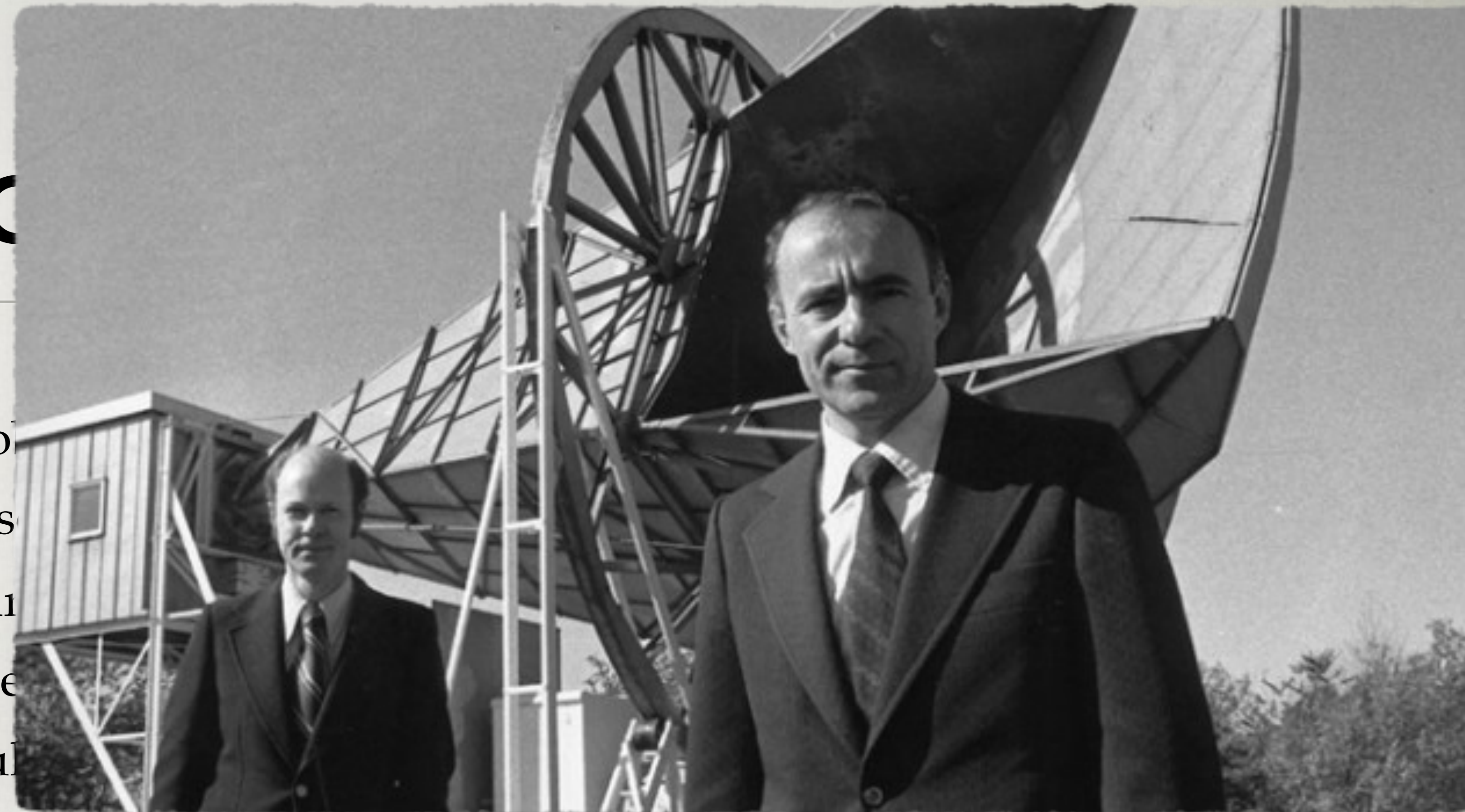
ALPs

- final comment: QCD axion obtains mass from coupling to gluons and then from QCD dynamics
- ALPs= axion like particles are generalizations
  - mass a free parameter (breaks PQ)
  - may have nothing to do with strong CP problem

THE DISCOVERY OF CMB

- in 1964 Arno Penzias and Robert Wilson were radio astronomers at Bell Labs
- 7.35cm radio antenna was used first for telecommunications
  - then they turned it toward the sky
  - found stronger signal then expected
  - did everything they could think of to reduce "noise"
  - even shooed away a pair of pigeons that had roosted in the antenna
    - cleaned up what they later called "the usual white dielectric" generated by pigeons
- excess signal remained
  - was isotropic and constant with time
  - couldn't be associated with an isolated celestial source
- were puzzled until they were put in touch with Robert Dicke at Princeton
  - he deduced prior to that that if Universe started in a hot dense state, should now be filled with microwave radiation
  - in fact Dicke was building a radio antenna to test this when found out of Penzias and Wilson's result

THE DISC



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