Dark Matter: Theory Overview from 10^{-22} eV to 10^{67} eV

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work w/ Asimina Arvanitaki, Savas Dimopoulos, Sergei Dubovsky, Isabel Garcia Garcia, Lawrence Hall, Ed Hardy, Karsten Jedamzik, Nemanja Kaloper, Robert Lasenby, Chris McCabe Matthew McCullough, James Unwin, and Stephen West
(and unpublished with Peter Graham, Jeremy Mardon, Doddy Marsh, Surjeet Rajendran)

The Dark Matter Landscape

~10^{-43} GeV

~10^{67}eV
(non-baryonic
solar mass)

The Dark Matter Landscape

One Possibility: Dark Matter at same scale as SM?

Weakly Interacting Massive Particles (WIMPs)

WIMPs are heavy so low phase space density and looking for *particles*

Favorite cold thermal relic: the neutralino

"a simple, elegant, compelling explanation for a complex physical phenomenon"

The Dark Matter Landscape

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WIMPs are heavy so low phase space density and looking for *particles*

"For every complex natural phenomenon there is a simple, elegant, compelling, wrong explanation."
- *Tommy Gold*

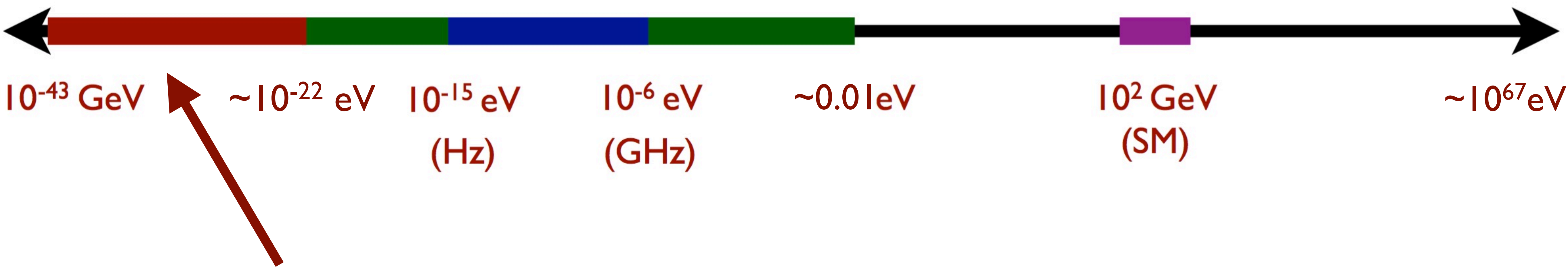
The Dark Matter Landscape

(fermionic)

Forbidden to be all of DM by Fermi degeneracy pressure in dwarf galaxies

The Dark Matter Landscape

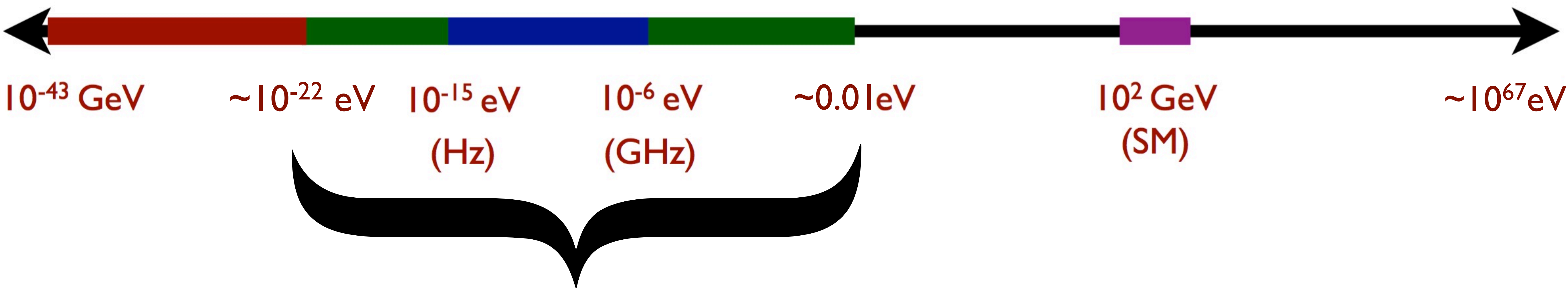
(bosonic)



Forbidden to be all of DM as de Broglie wavelength too large to fit inside dwarf galaxies

The Dark Matter Landscape

(bosonic)



DM is well-described as a *classical field* as high phase space density for $m \lesssim 0.01\,\mathrm{eV}$ since

$$\rho_{\mathrm{DM}} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$$

The Dark Matter Landscape

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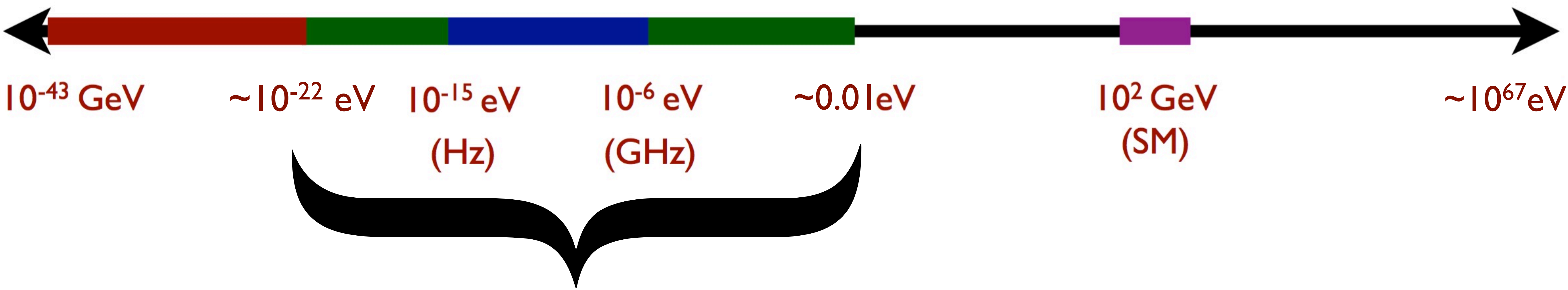

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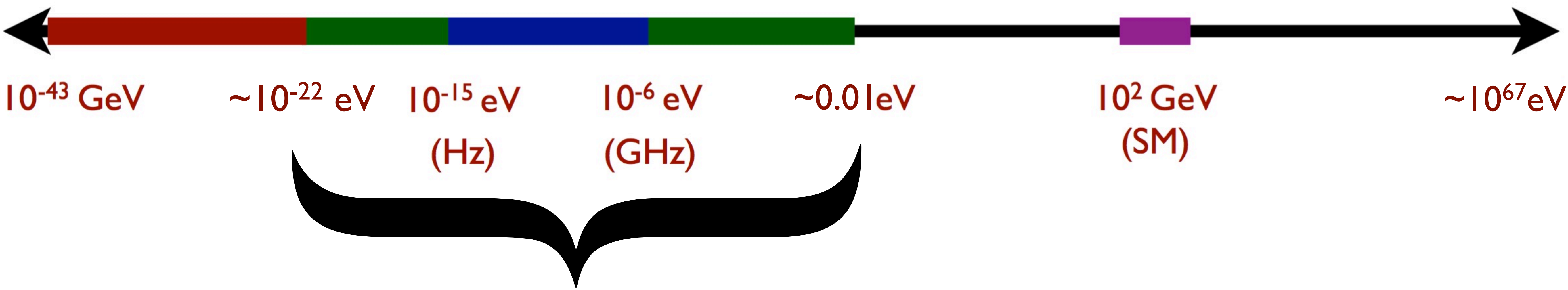
$$\rho_{\rm DM} \approx 0.3\,\frac{\mathrm{GeV}}{\mathrm{cm}^3} \approx (0.04\,\mathrm{eV})^4$$

Generic Candidates: Light Pseudo-Nambu-Goldstones (Axions and Axion Like Particles — ALPs); Massive Hidden Vector Bosons

The Dark Matter Landscape

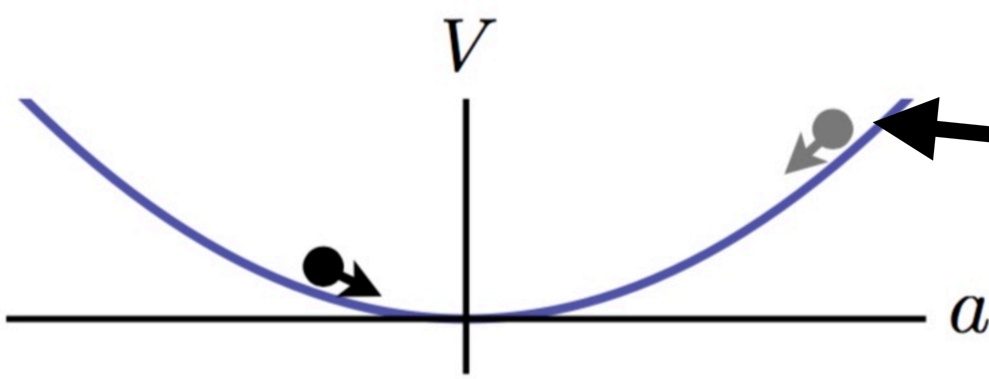
(bosonic)



→ search for *coherent effects of the entire field*, not single hard particle scatterings

Bosonic Field Dark Matter

Early universe production?
eg misalignment mechanism
(other mechanisms possible)



initial value in inflationary patch displaced from minimum (during inflation spatial gradients become small)

$$\ddot{a} + 3H(t)\dot{a} + V'(a) = 0$$

Bosonic Field Dark Matter

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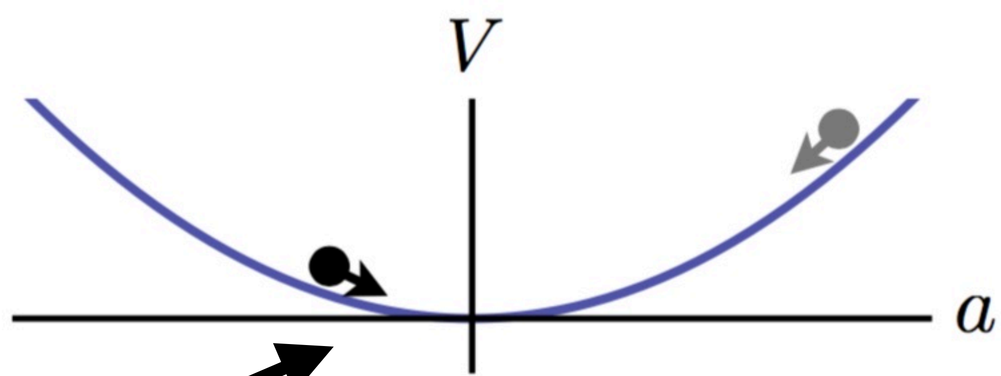

$$\ddot{a} + 3H(t)\dot{a} + V'(a) = 0$$

value of field frozen until $H(t) \lesssim m_a$ when it starts
oscillating at frequency set by mass $a(t) \simeq a_0 \sin(m_a t)$

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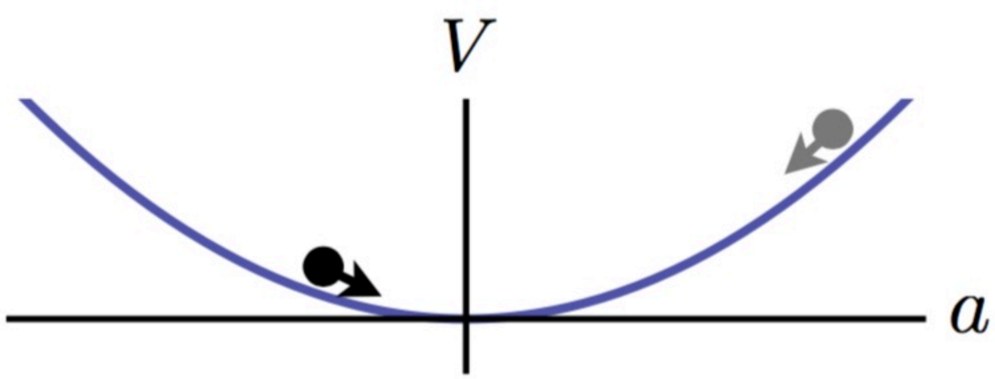

Oscillating field redshifts as non-relativistic matter (due to slow evolution of a_0)

$$m_a^2 a_0^2 \simeq \rho_{DM}$$

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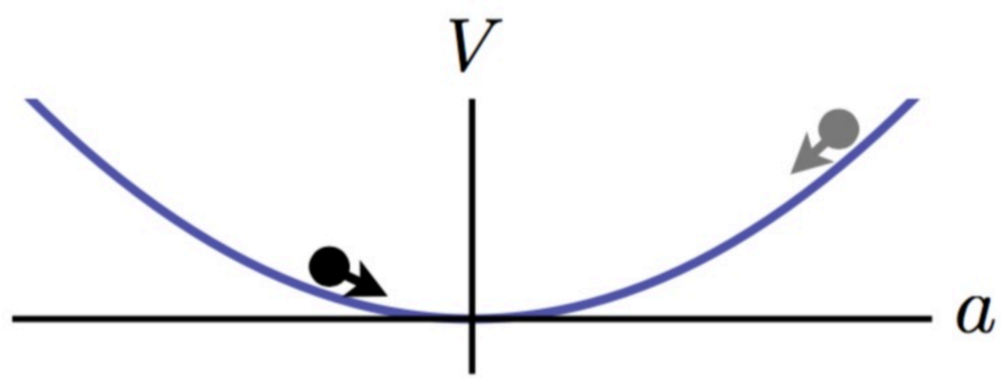


Oscillating field redshifts as non-relativistic matter (due to slow evolution of a_0)

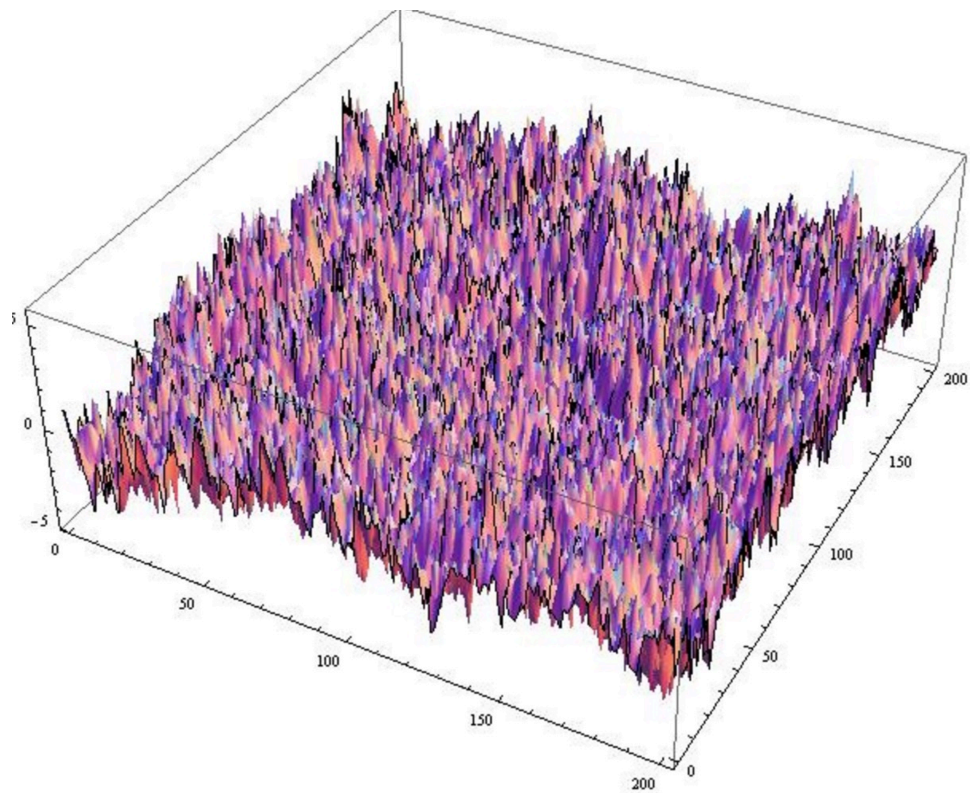
$$m_a^2 a_0^2 \simeq \rho_{DM}$$

For scales longer than deBroglie wavelength *acts just like cold DM*

→ structure formation → today…

Bosonic Field Dark Matter

Today: a random field



Correlation length

$$\ell_c \sim 1/(m_a v)$$

$v =$ Galactic virial velocity $\sim 10^{-3}$

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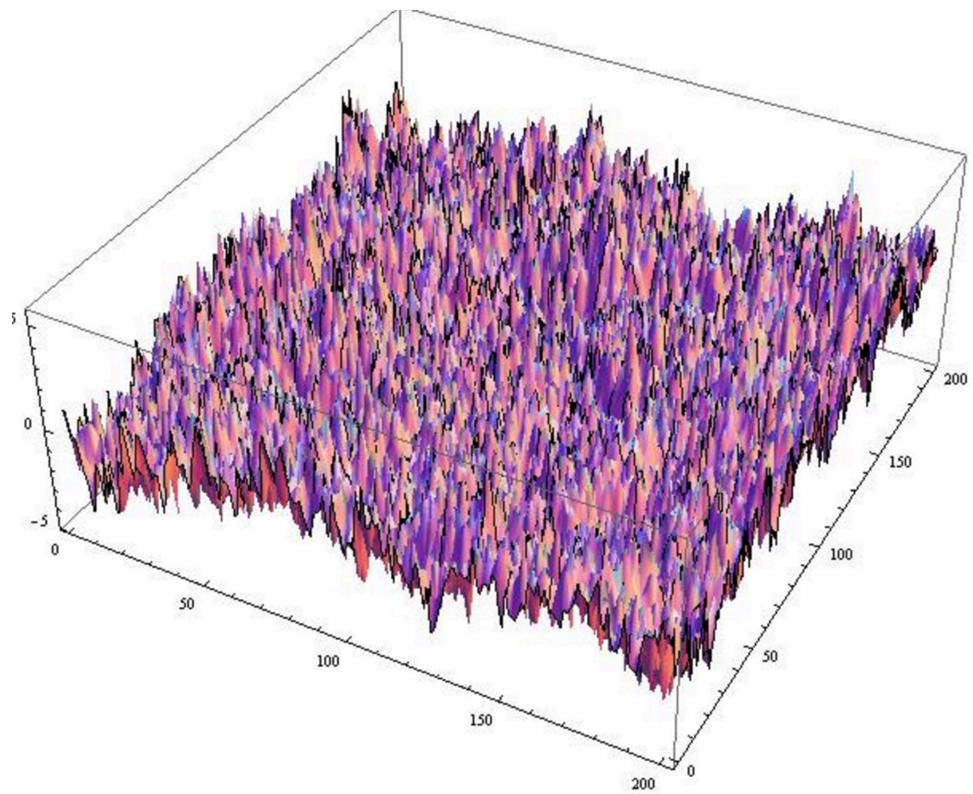

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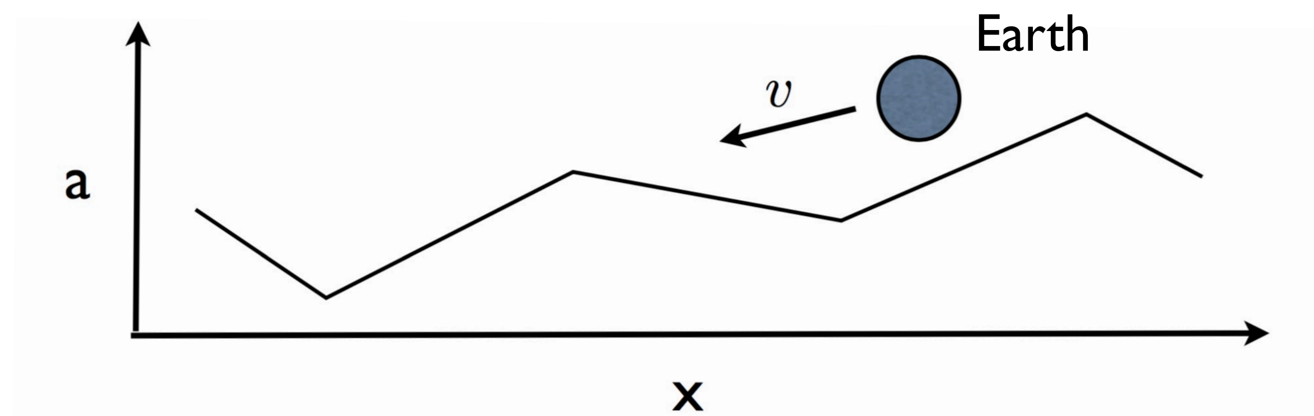
Coherence time for Earth experiments?

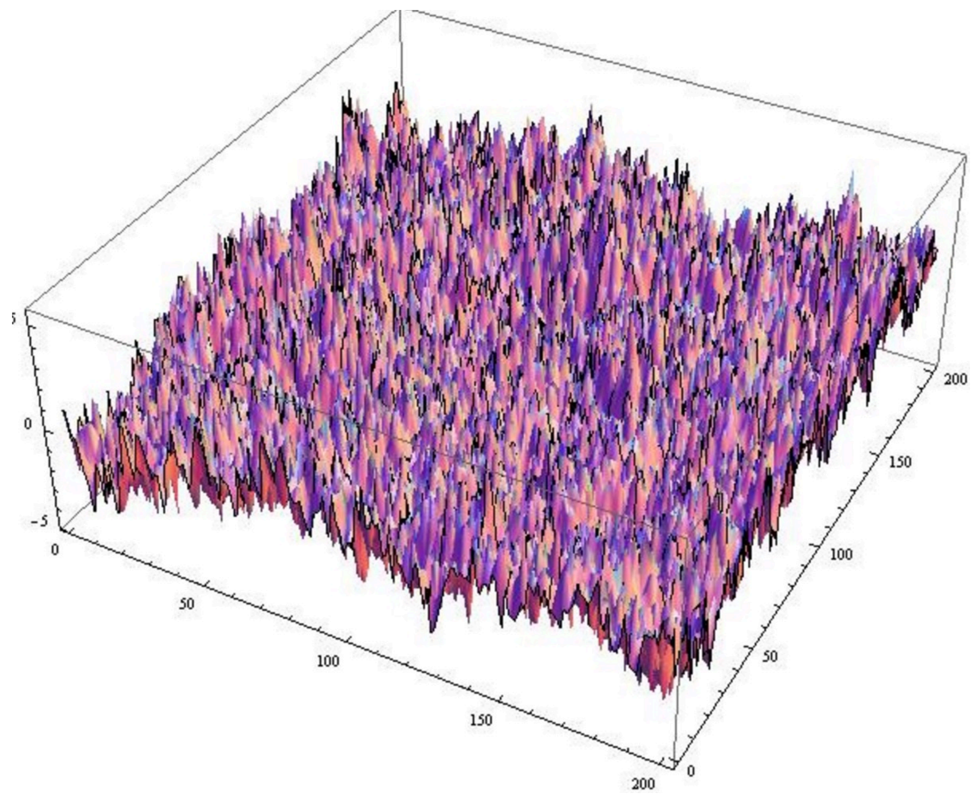


$$t_c \sim 1/(m_a v^2)$$

$$\sim 1\mathrm{s}\left(\frac{\mathrm{MHz}}{m_a}\right)$$

Bosonic Field Dark Matter

Today: a random field



Most important: the frequency spread of oscillation is *small*

$$\frac{\delta\omega}{\omega} \sim \frac{m_a v^2/2}{m_a} \sim 10^{-6}$$

→ *resonant enhancement* in detection is possible with $Q \sim 10^6$

Bosonic Field Dark Matter

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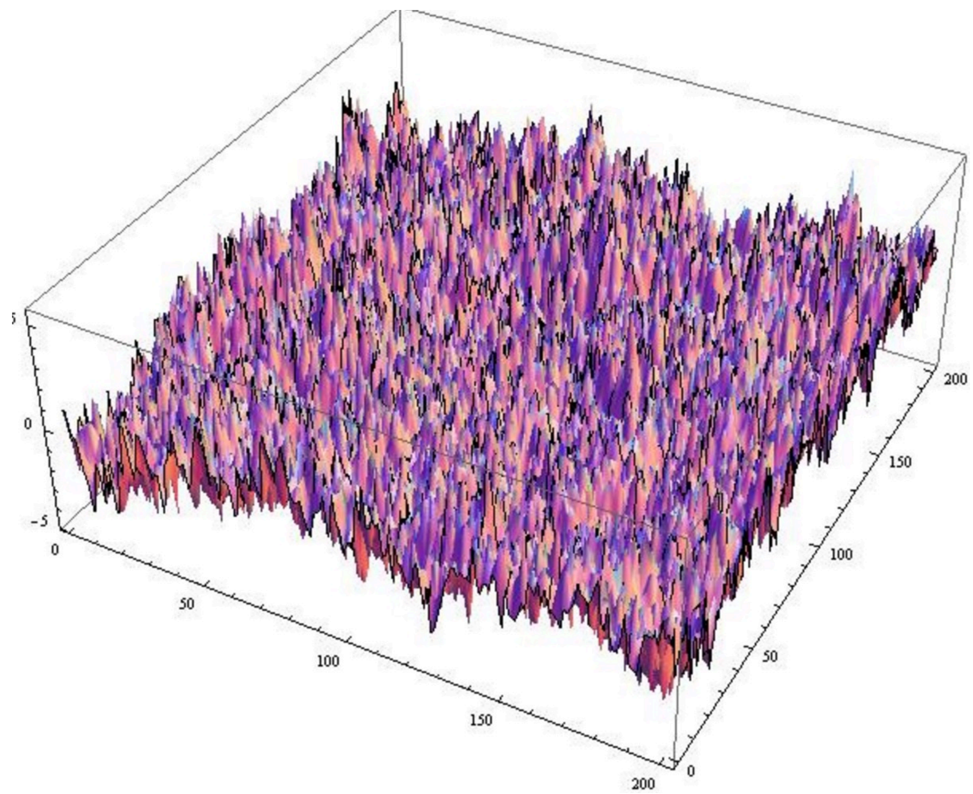

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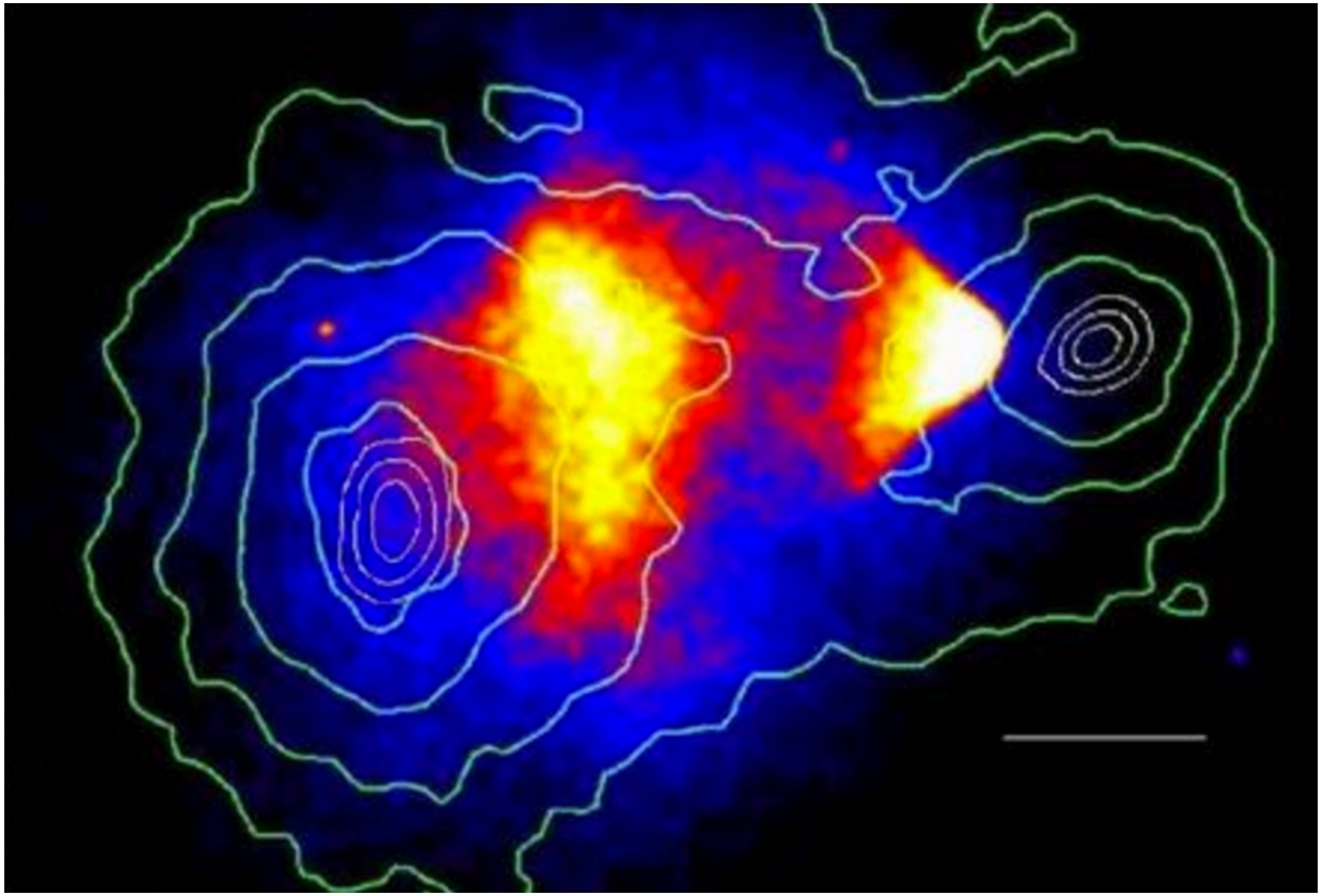
exactly *how* one detects depends on *type* of bosonic DM

Dark Matter



A New Particle (or *Sector*): Non gravitational interactions with SM?

What kind of bosons?

What kind of bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

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Strong CP Problem

$$S_\theta = \frac{\theta}{32\pi^2}\int d^4x\,\epsilon^{\mu\nu\lambda\rho}\mathrm{Tr}\,G_{\mu\nu}G_{\lambda\rho}$$

Neutron edm bound implies

$$\bar{\theta} = \theta + \arg\det m_q \lesssim 10^{-10}$$

- Like Cosmo Const and Electroweak hierarchy problems requires precise cancelation of apparently unrelated quantities
- Unlike CC and EW problems NO anthropic reason

A clear call for *new dynamics*

QCD (Invisible) Axion

Peccei-Quinn-Weinberg-Wilczek
Kim-Shifman-Vainshtein-Zakharov
Dine-Fischler-Srednicki-Zhitnitsky

$$S_a = \int d^4x \left(\frac{1}{2}(\partial_\mu a)^2 + \frac{a}{32\pi^2 f_a} \epsilon^{\mu\nu\lambda\rho} \mathrm{Tr}\, G_{\mu\nu} G_{\lambda\rho} \right)$$

Non-pert: QCD gives potential $V(a)$

$$\Longrightarrow \quad m_a \sim \frac{\Lambda_{QCD}^2}{f_a} \sim 6 \times 10^{-10} \mathrm{eV} \left(\frac{10^{16} \mathrm{GeV}}{f_a} \right)$$

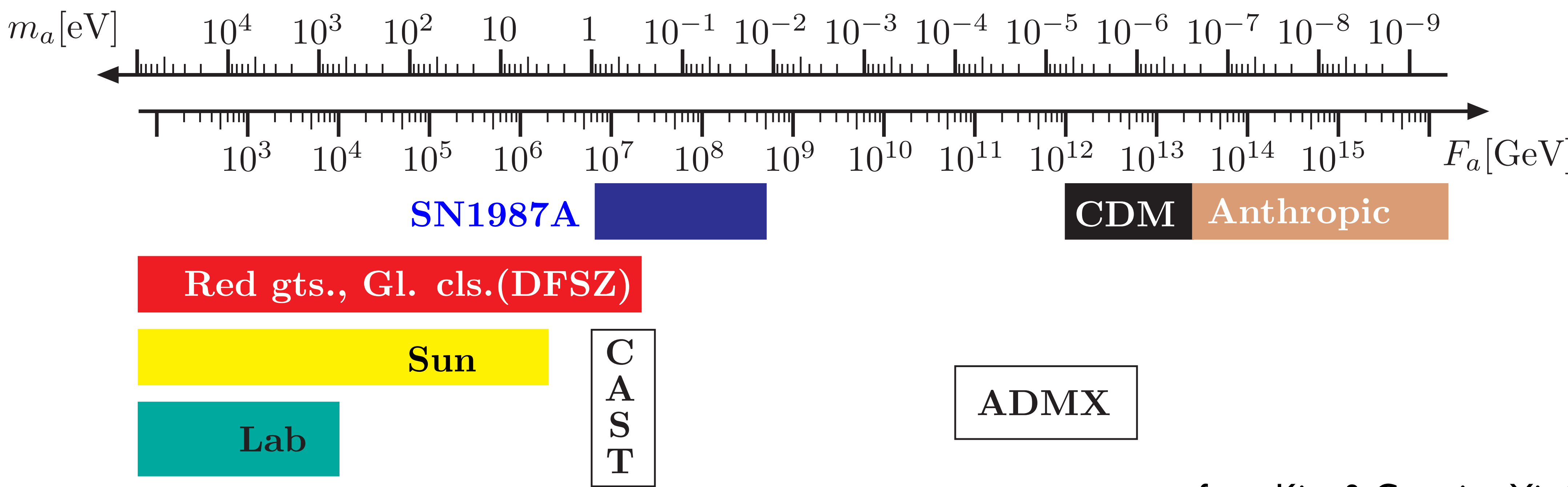
Minimum of potential leads to axion vev such that

$$\theta_{eff} \equiv \frac{\langle a(x) \rangle}{f_a} + \bar{\theta} = 0$$

solves strong CP!

- Axion vev only cancels $\bar{\theta}$ to required 10^{-10} accuracy if all *other* non-pert sources of axion mass smaller than QCD by 10^{-10}

$f_a \lesssim 10^9 \mathrm{GeV}$ is excluded by stellar and supernova 1987A physics



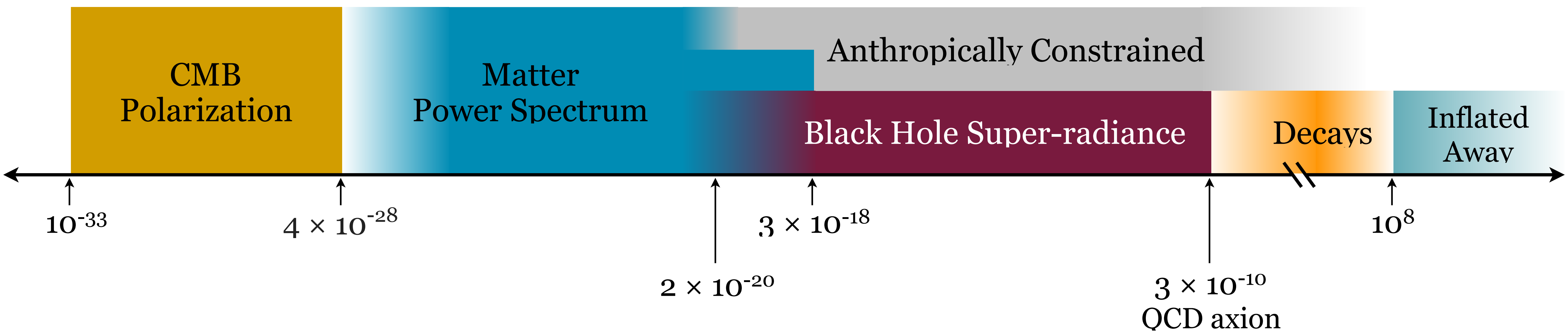
from Kim & Carosi, arXiv:0807.3125

$f_a \gg 10^{12}\mathrm{GeV}$ is an especially interesting region:
would be the evidence that Ω_{DM}
is fixed anthropically

The Axiverse Axion Landscape

Arvanitaki, Dimopoulos, Dubovsky, Kaloper, JMR; arXiv:0905.4720

In the next decade cosmo and astro observations will be exploring 23 orders of magnitude in energy



Taking properties of axions in string theory seriously, there can exist a plenitude of axions with log-flat distribution of masses

Here they are...!

String Axiverse

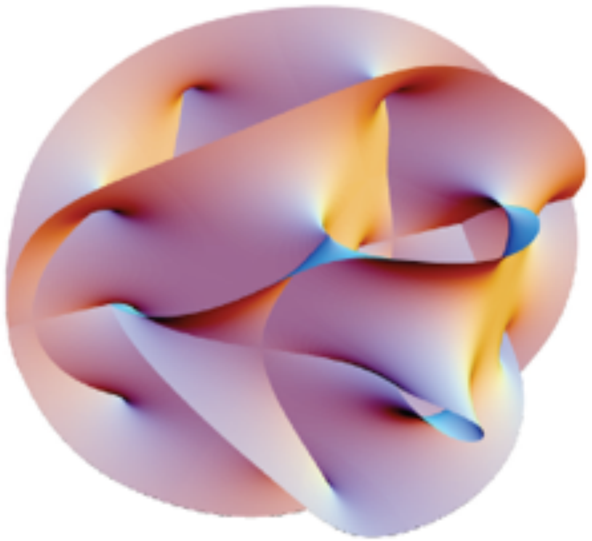
antisymmetric forms

$$B_2$$

$$C_{0,2,4}$$

$$C_{1,3}$$

compactification



many (100-10000) massless axions from topology, eg:

$$a_i = \int_{\Sigma_3^i} C_3$$

axions can be removed from the spectrum by fluxes, branes, orientifold planes, but many survive....

Chern-Simons coupling
(Green-Schwarz anomaly cancelation)

axionic couplings

ALP masses in String Thy

Must suppress all possible non-pert string effects that contribute to the QCD axion mass $> 10^{-10} \times$ QCD $\implies$ action (eg, of Euclidian wrapped D-brane) $S \gtrsim 200$

This QCD axion constraint on string model building impacts phys of all string axions

$$m_a \sim \frac{\mu_{UV}^2}{f_a} e^{-S/2}$$

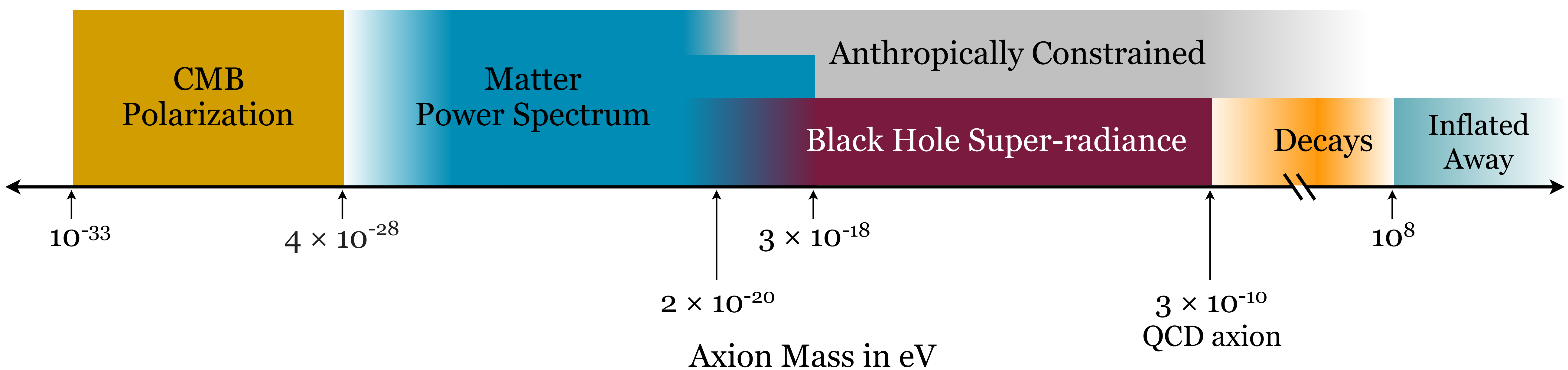
Axion masses exponentially sensitive to precise S

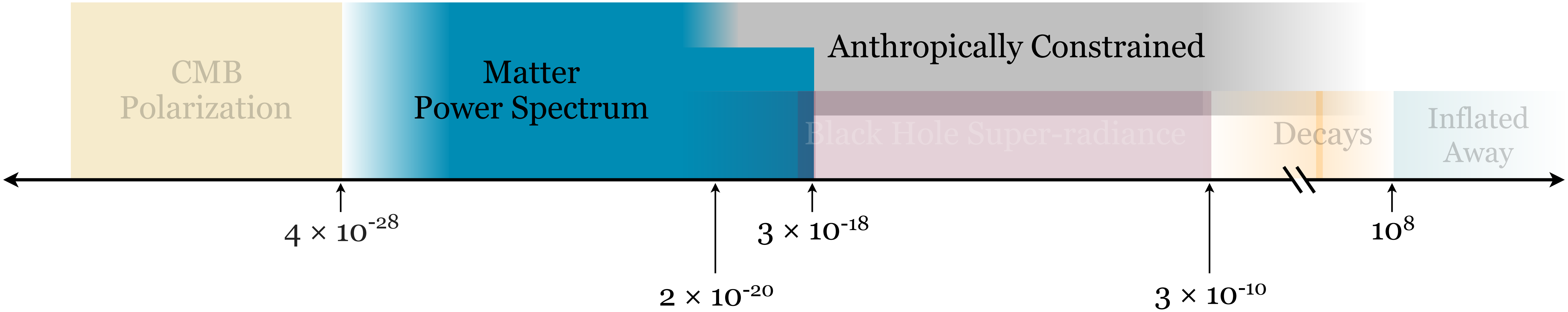
$$f_a \sim \frac{M_{pl}}{S} \sim 10^{16}\mathrm{GeV}$$

Axion couplings only linearly sensitive to S

ALP properties in String Thy

$f_a \sim M_{GUT}$ $\quad m$: homogeneously distributed over log(energy)

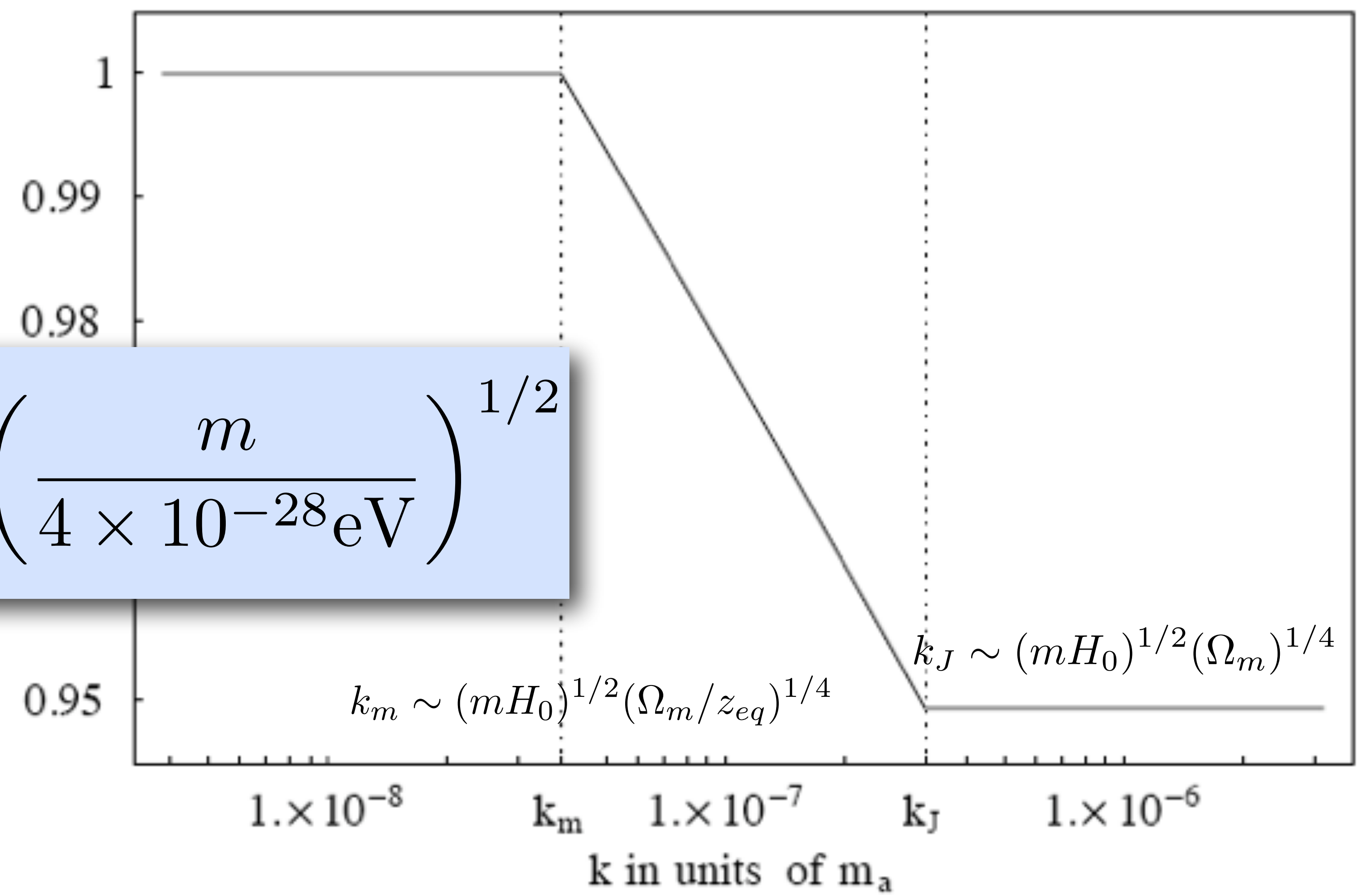




Axion/ALP DM behaves just like ColdDM (despite being a BEC) except at "small" scales

Uncertainty Principle prevents density perturbation growth at

$$\frac{k_J}{a} > \sqrt{Hm}$$



$$k_m = 0.01\mathrm{Mpc}^{-1}\left(\frac{m}{4\times 10^{-28}\mathrm{eV}}\right)^{1/2}$$

step size:

$$S = \frac{\Omega_a}{\Omega_m}\log z_{eq}/z_{obs} \approx 8\frac{\Omega_a}{\Omega_m}$$ for typical observation z

)

What kind of bosons?

Naturalness. Structure set by symmetries.

Spin 0

Axions and other goldstone bosons

Easy to get in many UV theories

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Electromagnetism	Nuclear Force	Nuclear Spin
$\left(\frac{a}{f_a} F\tilde{F}\right)$ $\left(\sim \frac{a}{f_a}\vec{E}.\vec{B}\right)$	$\left(\frac{a}{f_a} G\tilde{G}\right)$ QCD Axion	$\left(\frac{\partial_\mu a}{f_a}\bar{N}\gamma^\mu\gamma_5 N\right)$ General Axions

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all interactions suppressed by (large) scale f_a

What kind of bosons?

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Spin 1

Anomaly free Standard Model couplings

Nuclear Spin	Electro-magnetism	Nucleon Current
$\left(\frac{F'_{\mu\nu}}{f_a}\bar{N}\sigma^{\mu\nu}N\right)$	$\left(\epsilon F' F\right)$	$\left(g A'_{\mu} J^{\mu}_{B-L}\right)$
Dipole moment	Kinetic Mixing	B-L

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QCD Axion

Nuclear Spin

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General Axions

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Dipole moment

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$\left(\epsilon F' F\right)$

Kinetic Mixing

Nucleon Current

$\left(g A'_\mu J^\mu_{B-L}\right)$

B-L

if bosons (part of) DM then oscillating $\omega \simeq m_a + \delta\omega$

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- Electromagnetism $\left(\frac{a}{f_a} F\tilde{F}\right)$ current searches $(m_a \sim \mathrm{GHz})$
- Nuclear Force $\left(\frac{a}{f_a} G\tilde{G}\right)$ QCD Axion
- Nuclear Spin $\left(\frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu \gamma_5 N\right)$ General Axions

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$$\mathrm{Hz} \lesssim \omega \lesssim \mathrm{GHz}$$

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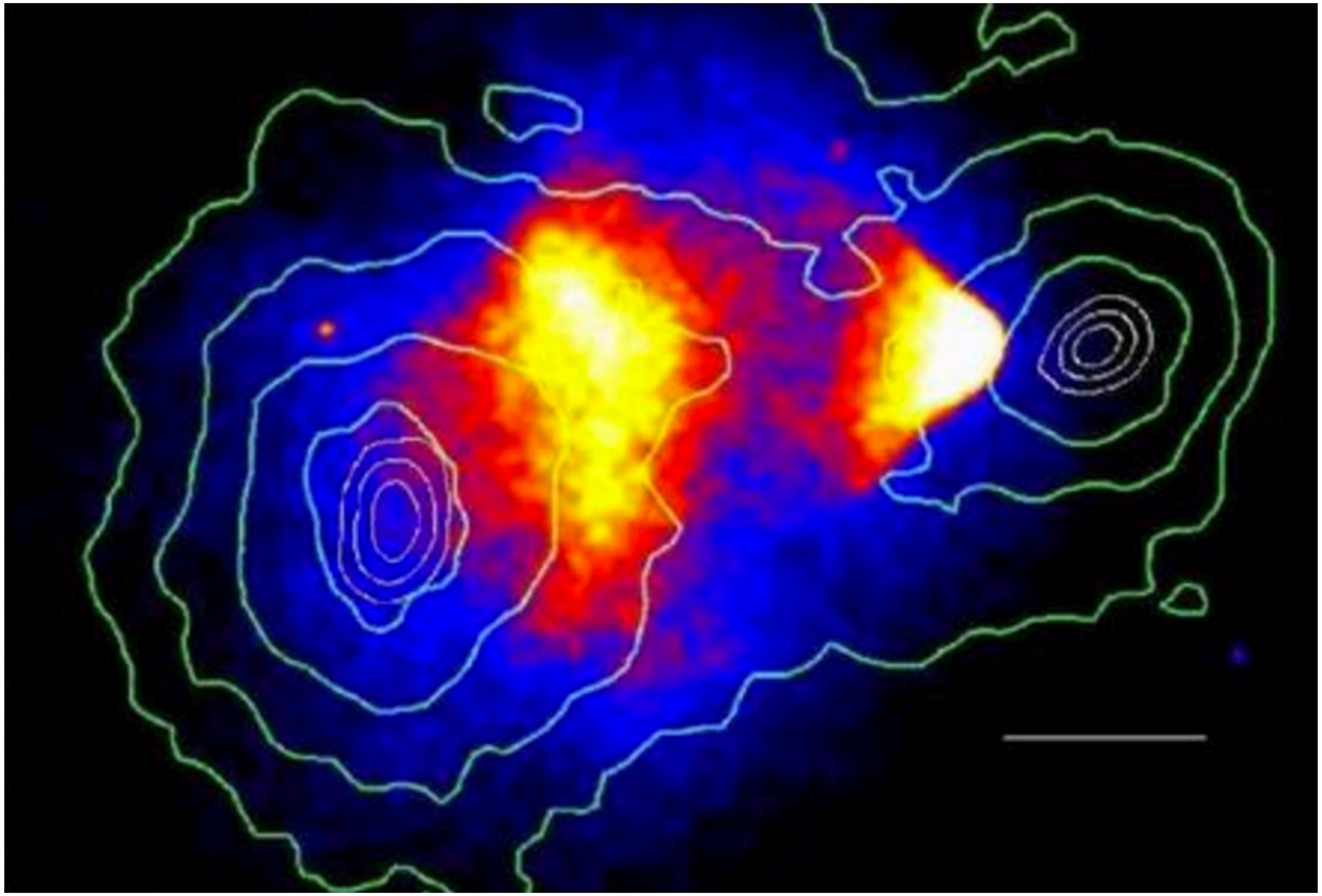
B-L

$$\mathrm{Hz} \lesssim \omega \lesssim \mathrm{GHz}$$

possible new searches

Dark Matter



A New Particle (or *Sector*): Non gravitational interactions with SM?

Need exquisite sensitivity to detect such tiny interactions

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$$\mathrm{Hz} \lesssim \omega \lesssim \mathrm{GHz}$$

for example this…

Massive Hidden Photons as DM

First consider the relatively unexplored possibility of massive Hidden Photon (ie, Z') DM

Pospelov, Ritz, Voloshin arXiv:0807.3279

Nelson, Scholtz arXiv:1105.2812

Arias et al arXiv:1201.5902

DM is classical A'_μ field oscillating at $\omega = m'_A$ (in random dir'n)

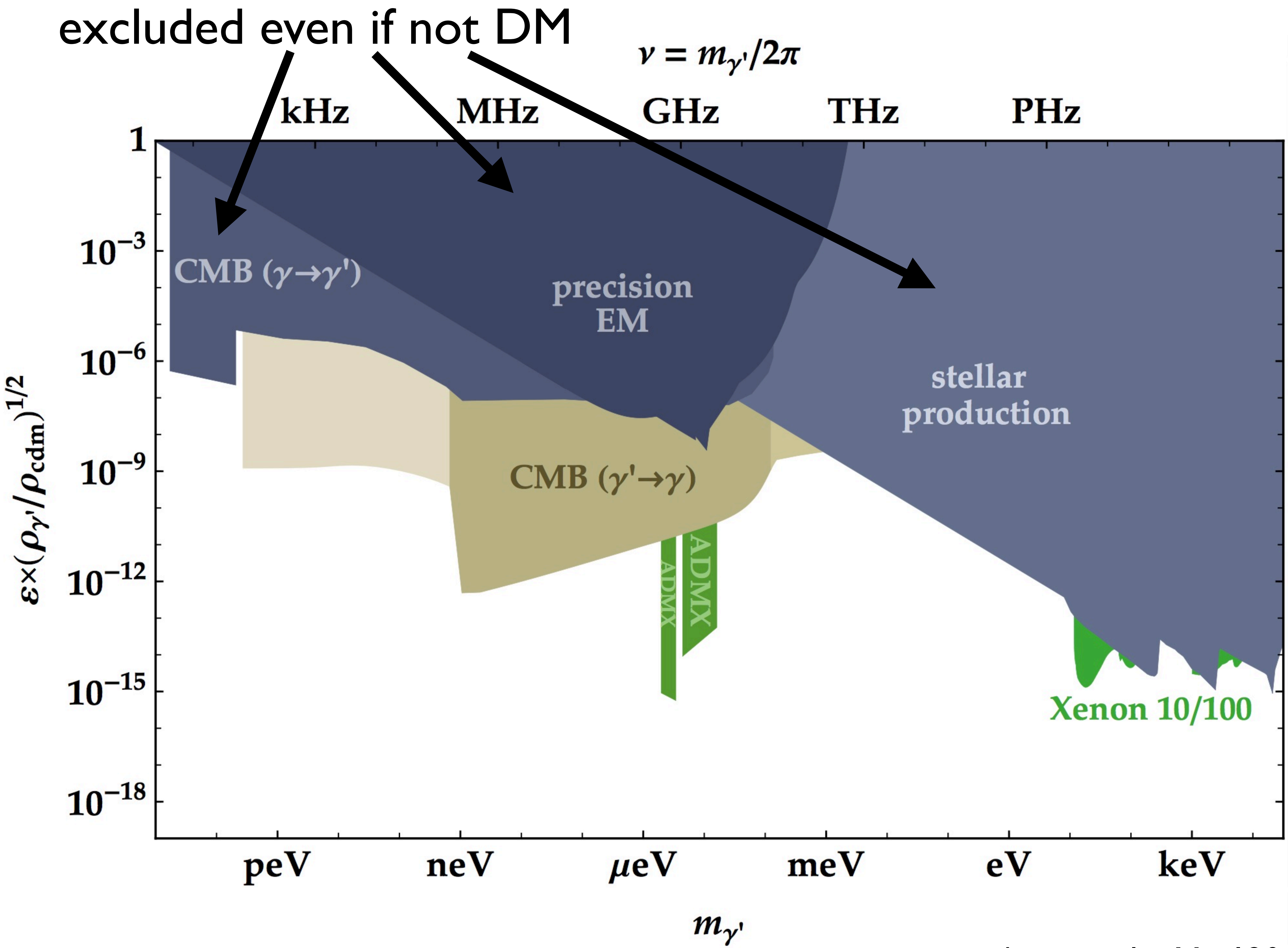
Acts as an electric field that is *not shielded*

$$\boxed{E' \sim \sqrt{\rho_{DM}} \simeq 2000\mathrm{V/m}}$$

→ can excite an EM resonator that is shielded from normal fields

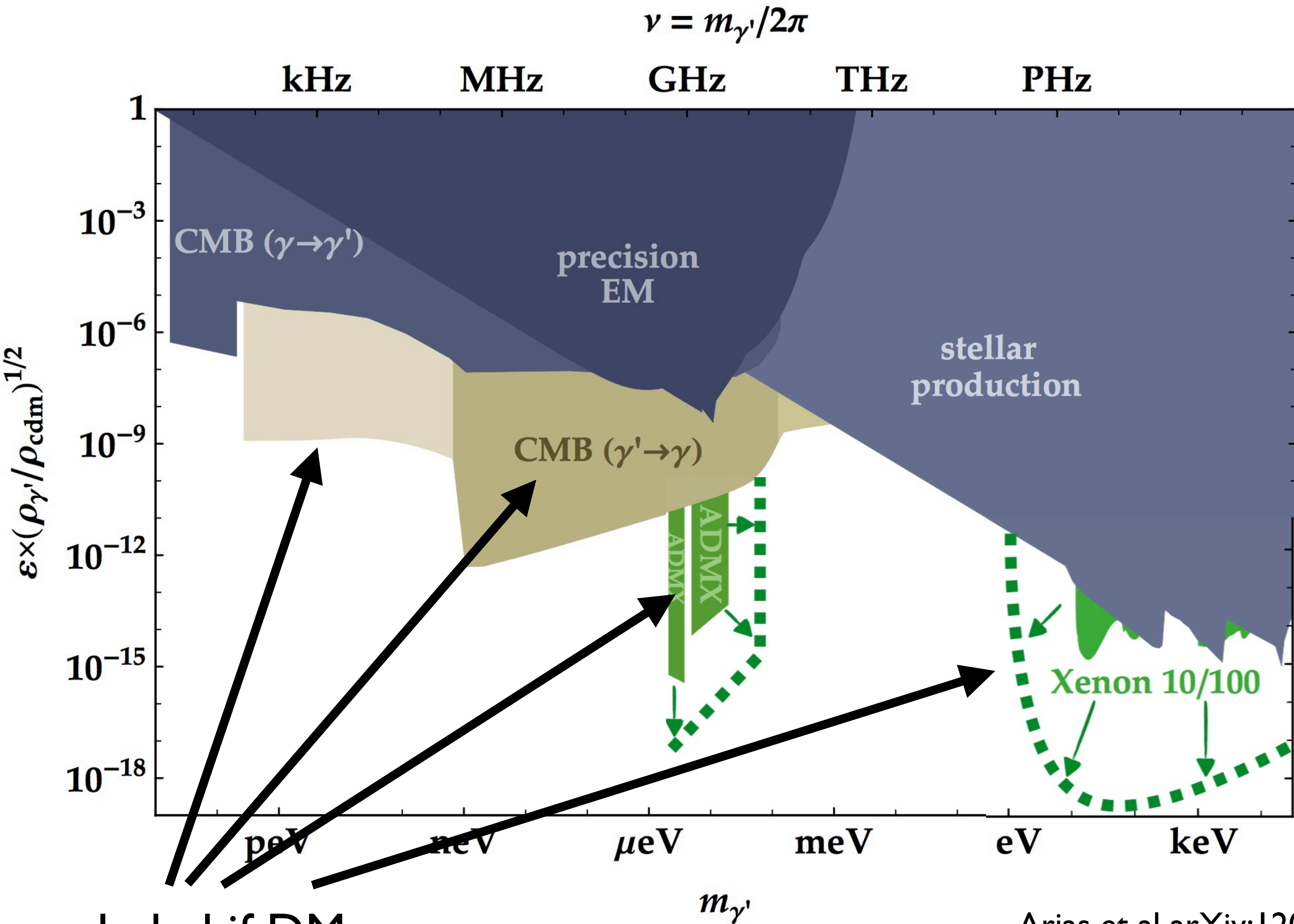
(The axion search experiment ADMX is sensitive in range $10^{-6}\mathrm{eV} \lesssim m_{A'} \lesssim 10^{-4}\mathrm{eV}$ due to cavity size)

Hidden Photon Landscape



Arias et al arXiv:1201.5902

Hidden Photon DM



excluded if DM

Arias et al arXiv:1201.5902
An et al arXiv:1412.8378

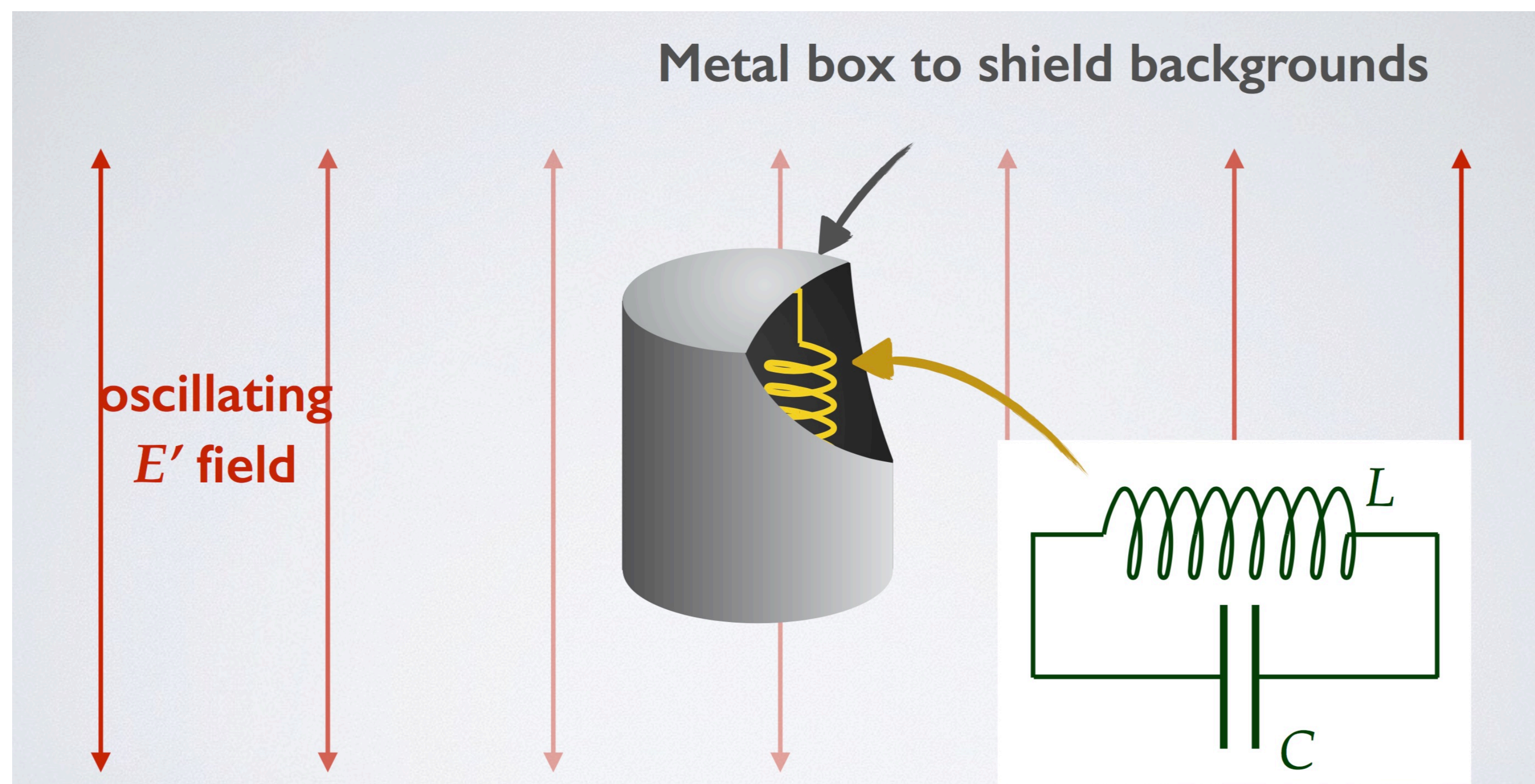
Searching for Hidden Photon DM

A powerful and flexible way is with a high-Q radio

S. Chaudhuri etal arXiv:1411.7382

- a resonant tunable LC circuit inside a Faraday cage with SQUID readout

- lower and wider frequency range possible than with cavities



Searching for Hidden Photon DM

STAGE I

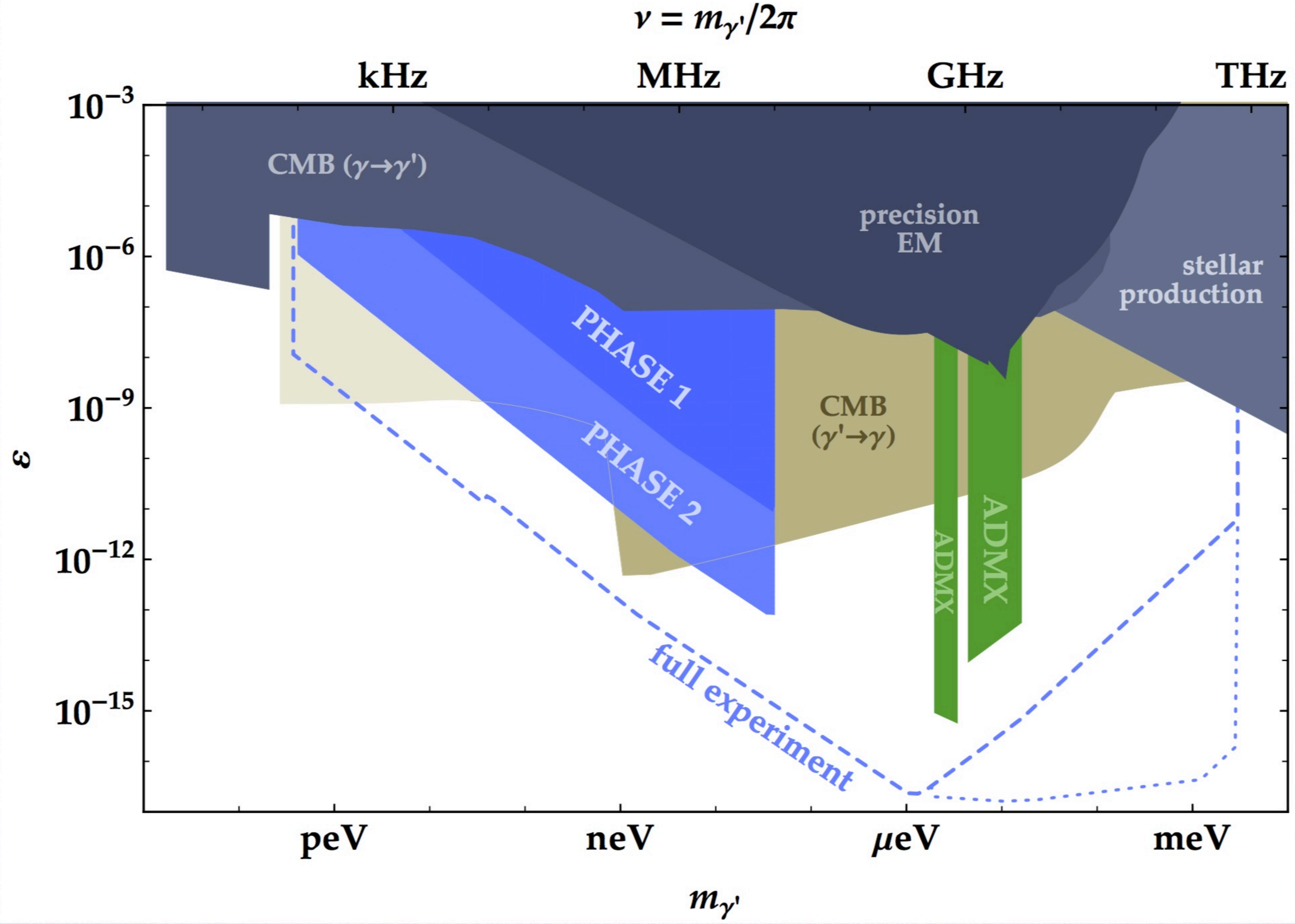
size ~ 350ml — 1m   Q~10^6

T~4K, thermal noise limited

FULL DESIGN

size ~ 1m   Q~10^6

T~0.1K, thermal noise limited



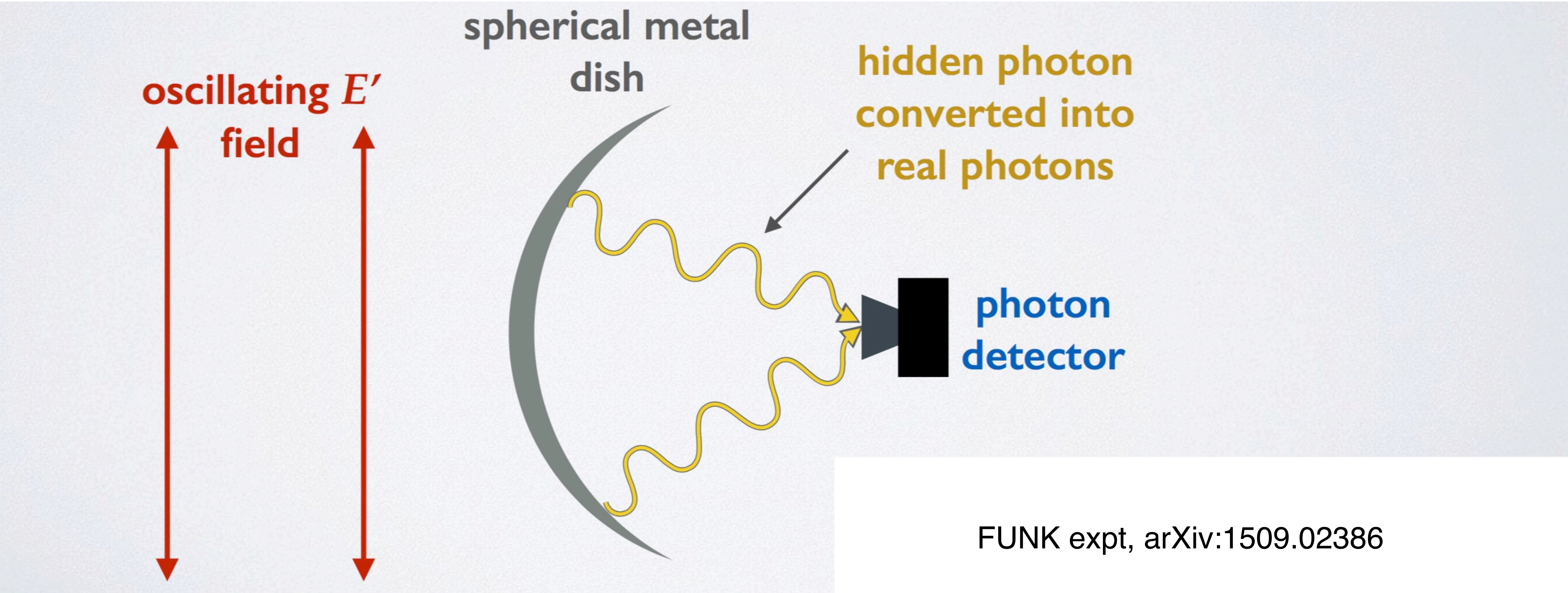
Searching for Hidden Photon DM

Powerful ways to confirm signal is DM

- signal is narrow band at constant frequency
- directional & phase coherence over $\sim 10^3$ wavelengths
- dependence on orientation characteristic of vector

Searching for Hidden Photon DM

another experiment in early stages…



FUNK expt, arXiv:1509.02386

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Electromagnetism

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Nuclea

ion

clear Spin

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General Axions

pin 1

ly free Standard Model couplings

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$\left(\epsilon F' F\right)$

Kinetic Mixing

Nucleon Current

$\left(g A'_\mu J^\mu_{B-L}\right)$

B-L

Vast number of exciting searches possible!

New topic…

Dark Matter Genesis Mechanism?

see, eg, Baer, Choi, Kim, Roszkowski arXiv:1407.0017

- Non-Asymmetric Dark Matter

  Axions & Other Light Bosons: Mis-alignment or thermal or non-thermal production

Dark Matter Genesis Mechanism?

- Non-Asymmetric Dark Matter

  Axions & Other Light Bosons: Mis-alignment or thermal or non-thermal production

  WIMPs: Calculable thermal freeze-out at EW scale v

Dark Matter Genesis Mechanism?

- Non-Asymmetric Dark Matter

  Axions & Other Light Bosons: Mis-alignment or thermal or non-thermal production

  WIMPs: Calculable thermal freeze-out at EW scale v

  FIMPs: Calculable thermal freeze-in (possibly at EW scale v)

Dark Matter Genesis Mechanism?

- Non-Asymmetric Dark Matter

  Axions & Other Light Bosons: Mis-alignment or thermal or non-thermal production

  WIMPs: Calculable thermal freeze-out at EW scale v

  FIMPs: Calculable thermal freeze-in (possibly at EW scale v)

- Asymmetric DM & Baryons

  Sharing

  Co-genesis

  In both cases *final* DM state can often be composite ("atomic", "nuclear"…)

Dark Matter Genesis Mechanism?

- Non-Asymmetric Dark Matter

  Axions & Other Light Bosons: Mis-alignment or thermal or non-thermal production

  WIMPs: Calculable thermal freeze-out at EW scale v

  FIMPs: Calculable thermal freeze-in (possibly at EW scale v)

- Asymmetric DM & Baryons

  Sharing

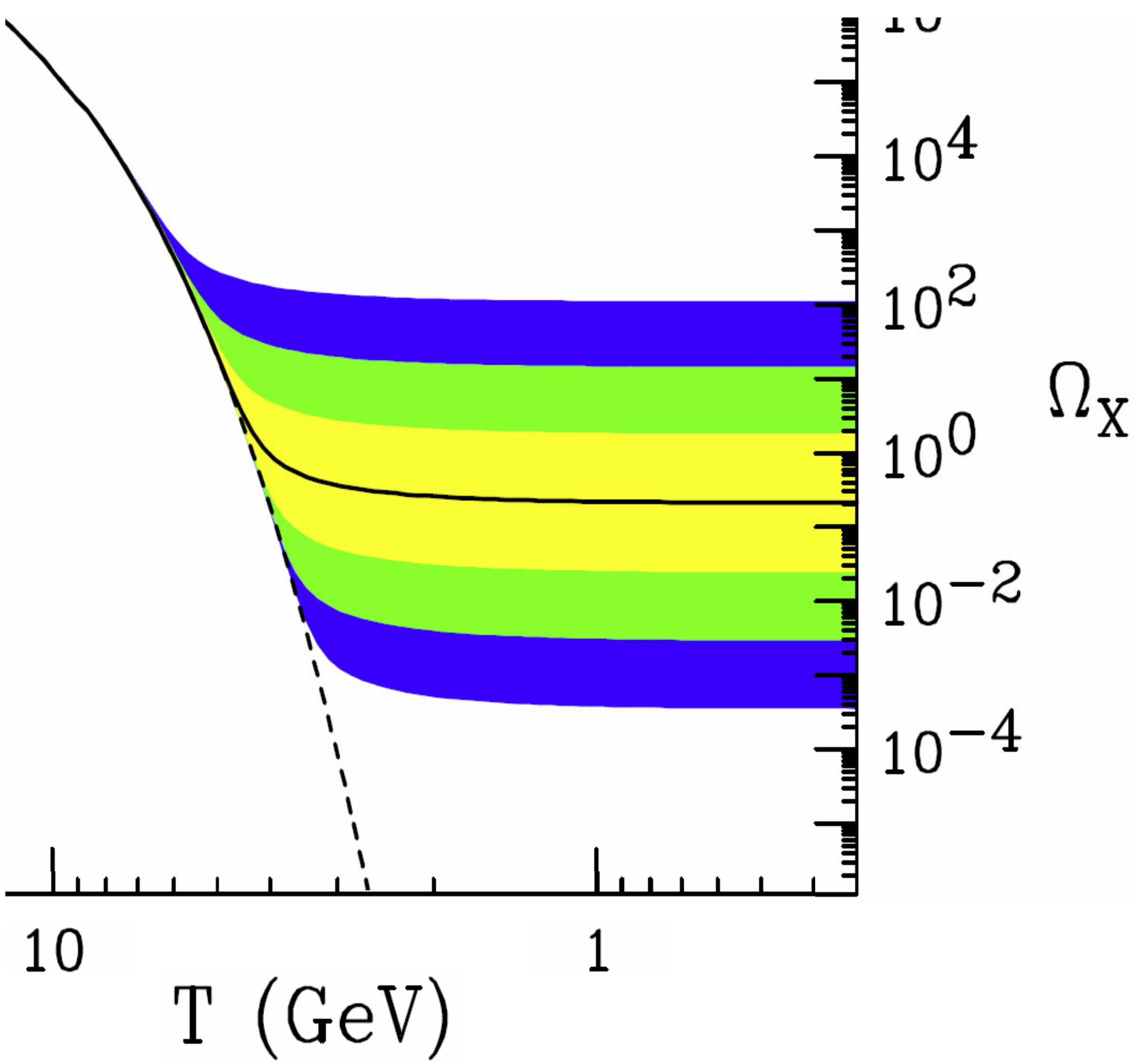
  Co-genesis

- Very Heavy Extended Objects (PBHs, Q-balls,…)

  Many possibilities…

Motivation for Alternatives to Freeze-Out

WIMP Freeze-out: DM starts with full T^3 density but interactions cannot track falling equilibrium density



$$Y_X \sim \frac{1}{m_X M_{Pl} \langle \sigma v \rangle} \sim \frac{v}{M_{Pl}}$$

$$\boxed{m_X Y_X \sim \frac{v^2}{M_{Pl}}}$$

Motivation for Alternatives to Freeze-Out

But Baryon density set by particle-antiparticle asymmetry…

$$\eta_B = Y_B - Y_{\bar{B}}$$

Motivation for Alternatives to Freeze-Out

But Baryon density set by particle-antiparticle asymmetry…

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eg, for EW-anomaly reprocessed leptogenesis

$$m_B \eta_B \sim \sin\phi \frac{m_\nu^2 M_R M_{Pl} \Lambda_{QCD}}{v^4}$$

CP-violating phase

Unrelated origin, involving very different physics, of baryons & DM, makes it hard to understand $\Omega_{DM}/\Omega_B \simeq 4.86$

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CP-violating phase

- Unrelated origin, involving very different physics, of baryons & DM, makes it hard to understand $\Omega_{DM}/\Omega_B \simeq 4.86$

- Freeze-out has dominated our thinking about DM candidates, detection, and LHC phenomenology

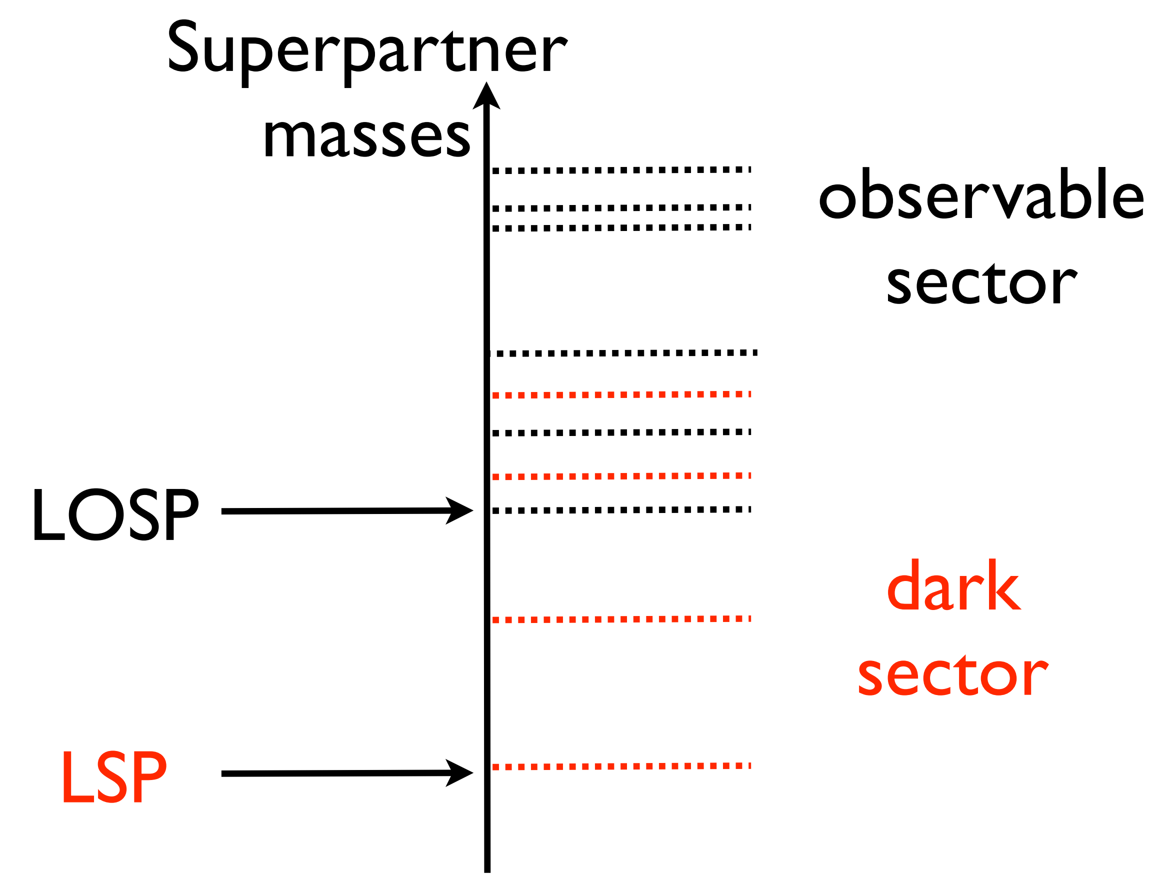
(

A Comment wrt SUSY LSP

Arvanitaki, Craig, Dimopoulos, Dubovsky, JMR: arXiv:0909.5440

In the context of String Theory highly unusual for SM to contain the LSP

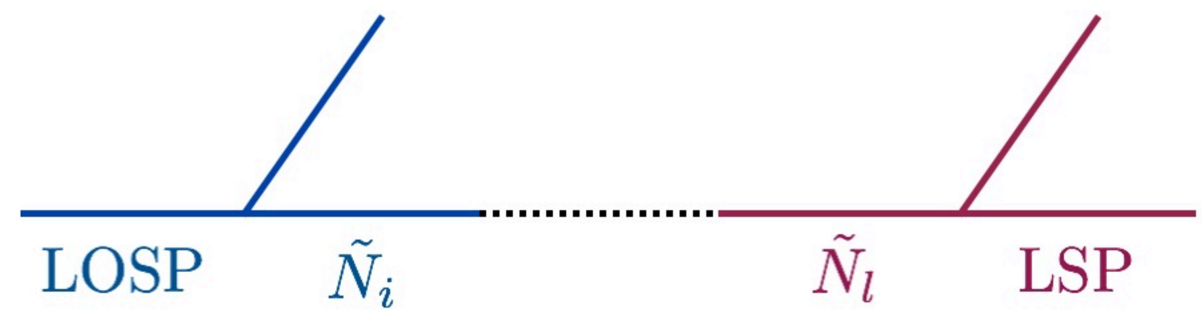
- A plenitude of hidden sectors, each with their gauginos, sfermions, goldstini, moduli,…
- For *Standard Model* sector to have the LSP the SM must be *most weakly coupled of all sectors* to SUSY-breaking



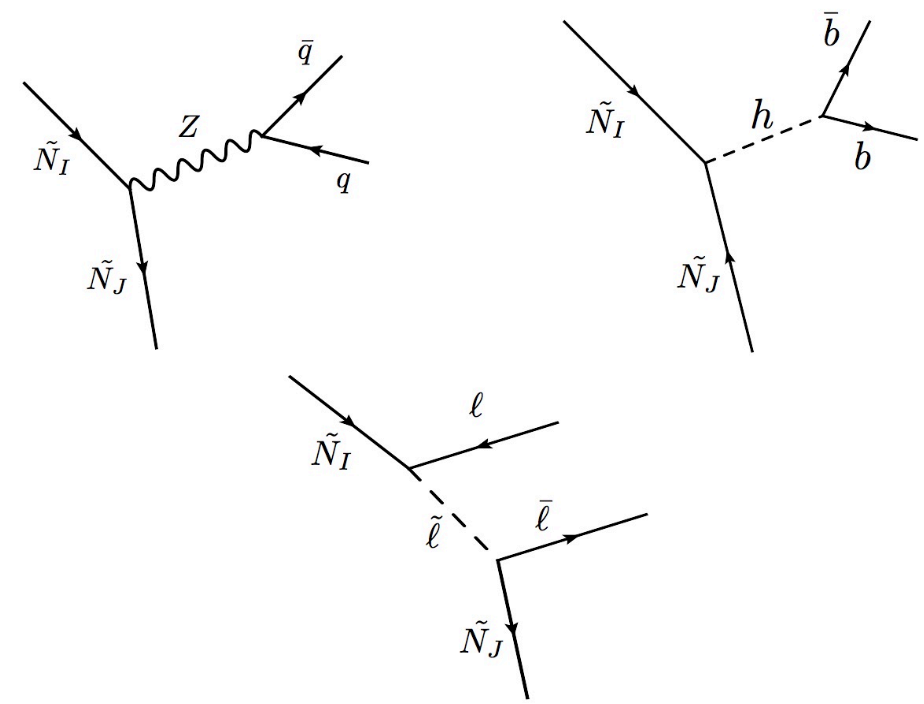
A Comment wrt SUSY LSP

In the context of String Theory highly unusual for SM to contain the LSP

Can get long decay chains of the *many* neutralinos to true LSP via emission of visible or hidden states



eg, for the kinetically mixed "photini" we considered have basic vertices



)

Is FO misleading us?

Freeze-In Production

Hall, Jedamzik, JMR, West, arXiv:0911.1120

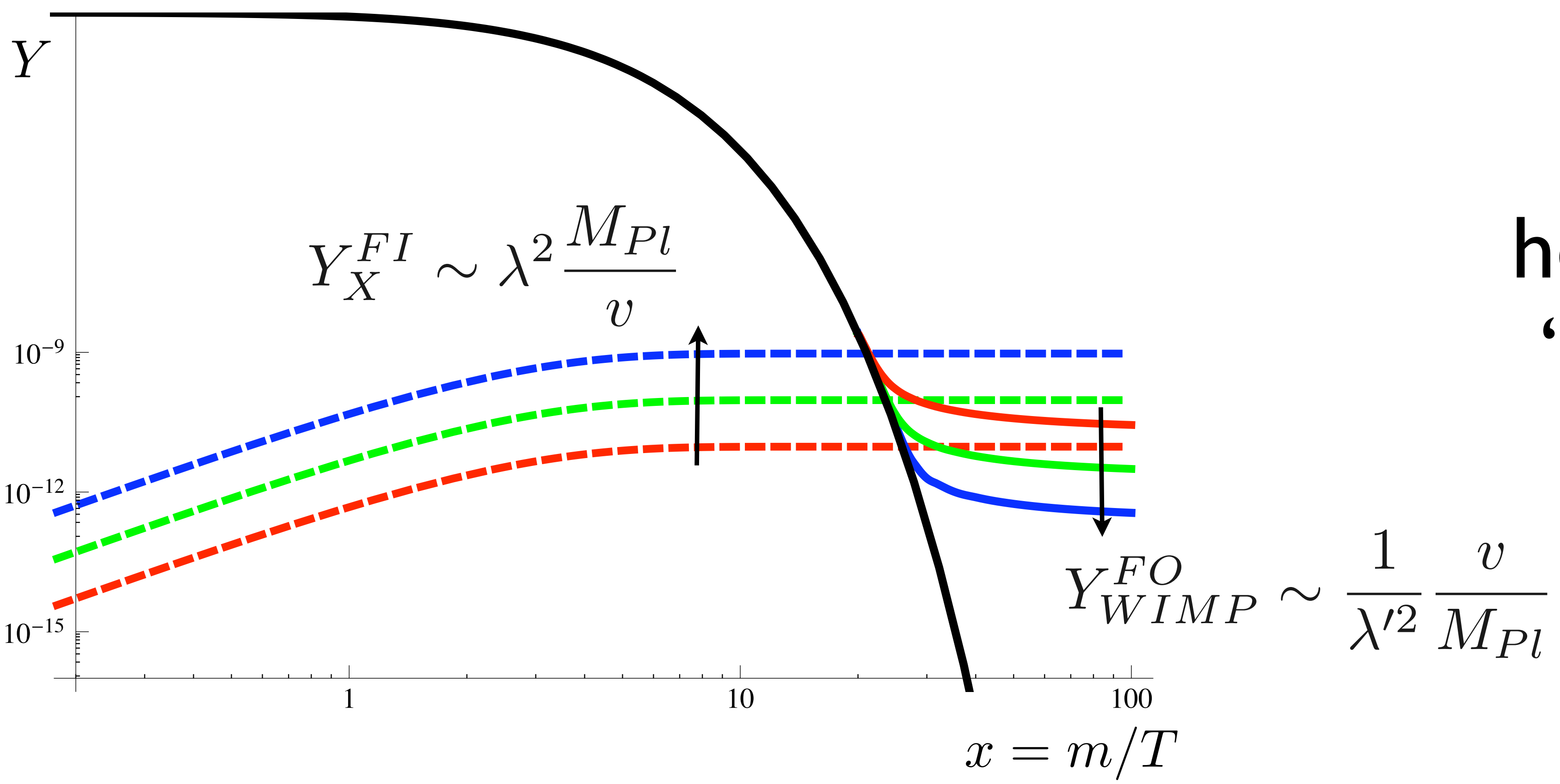
Suppose

- X only feebly coupled to visible-sector thermal bath particles V_i
- X never in thermal equilibrium with SM

as universe evolves, a tiny
X abundance is produced

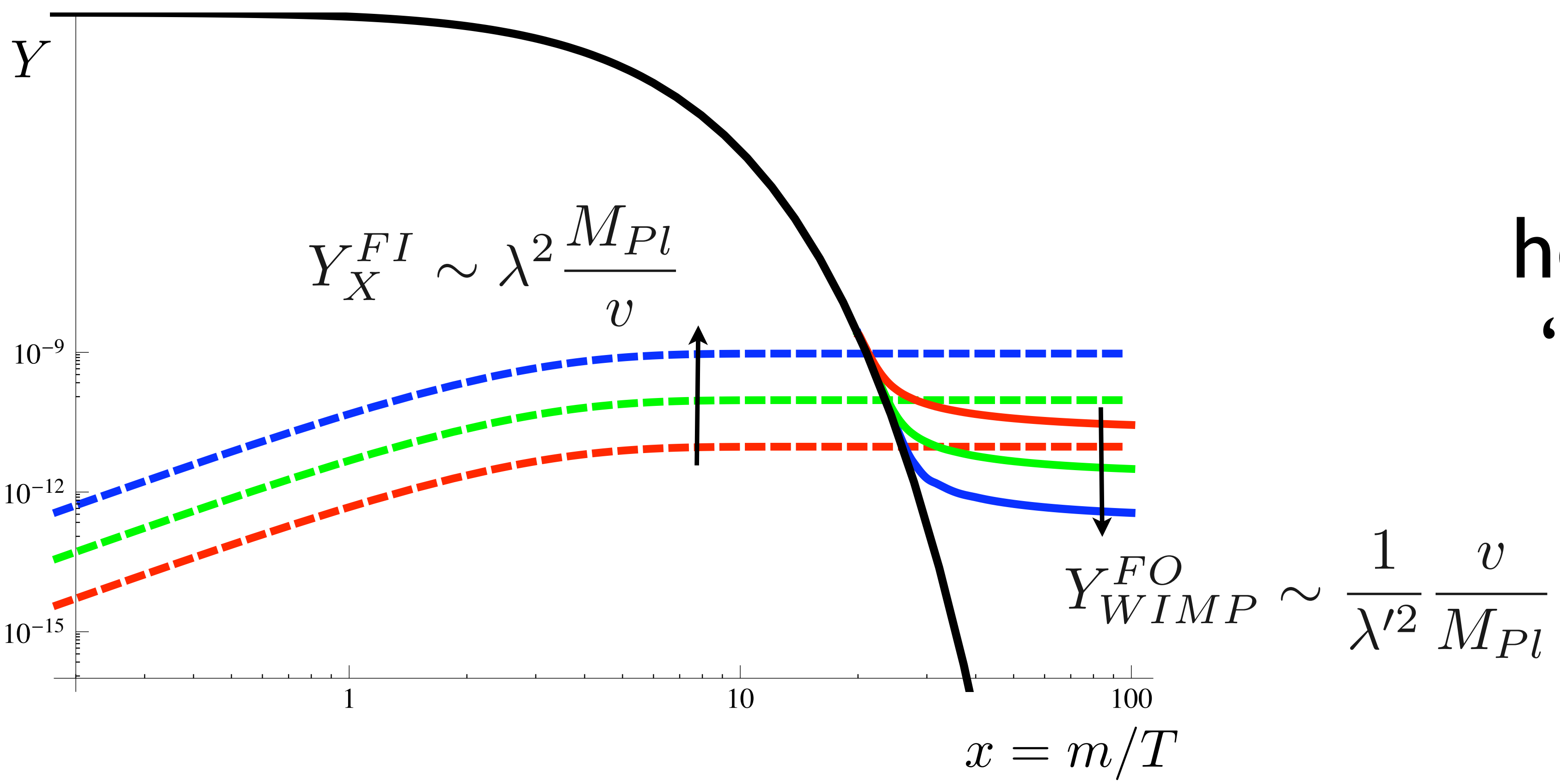
$$Y_X(t) \sim \Gamma_V t$$

Freeze-In Production



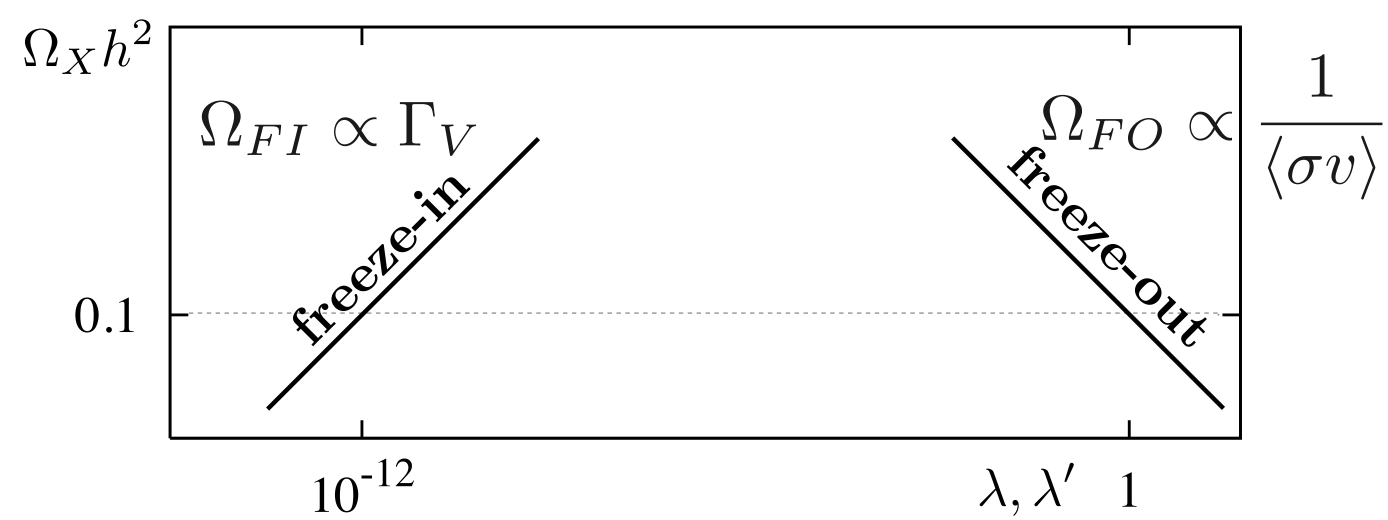
heading either 'in' or 'out' of equilibrium

Freeze-In Production



heading either 'in' or 'out' of equilibrium

two calculable thermal mechanisms



Freeze-In Production

Comments

- FI yield is IR-dominated for renormalizable interactions

$$Y_X^{FI}(T) \sim \lambda^2 \frac{m^2 M_{Pl}}{T^3}$$

dominant production occurs at $T \sim m$ (heaviest particle in vertex)

$\Delta L = \lambda X V_1 V_2$

- The lightest ordinary-sector particle (LOSP) transforming under the X-stabilising symmetry is automatically long-lived

Freeze-In Production

$$\Omega_X h^2 \approx \frac{1.09 \times 10^{27} g_{B_1}}{g_*^S \sqrt{g_*^\rho}} \frac{m_X \Gamma_{B_1}}{m_{B_1}^2}$$

$$\Downarrow$$

Highly displaced decays of LOSP (& out-of-time decay of stopped LOSP's if charged):

$$\tau_{B_1} = 7.7 \times 10^{-3} \mathrm{sec} \;\; g_{B_1} \left(\frac{m_X}{100\,\mathrm{GeV}} \right) \left(\frac{300\,\mathrm{GeV}}{m_{B_1}} \right)^2 \left(\frac{10^2}{g_*} \right)^{3/2}$$

Even if LOSP is neutral so leading decay to X invisible, sub-dominant 3- or 4-body decays can involve charged SM states and allow measurement of lifetime and X mass

Freeze-In Production

- Origin of Small Coupling?

The 'WIMP miracle' is that for $m' \sim v$ and $\lambda' \sim 1$

$$Y_{FO} \sim \frac{1}{\lambda'^2}\left(\frac{m'}{M_{Pl}}\right) \sim \frac{v}{M_{Pl}}$$

gives the observed value of $\Omega_{DM} h^2$

The 'FIMP miracle' is that for $m \sim v$ and $\lambda \sim v/M_{Pl}$

$$Y_{FI} \sim \lambda^2 \left(\frac{M_{Pl}}{m}\right) \sim \frac{v}{M_{Pl}}$$

Suggests that FIMPs occur where small couplings arise at linear order in the weak scale

Freeze-In Production

For example…

- moduli of the SUSY-breaking sector giving MSSM soft terms

$$m^2\left(1+\frac{T}{M}\right)(\phi^\dagger\phi+h^\dagger h) \quad \mu B\left(1+\frac{T}{M}\right)h^2 \quad Ay\left(1+\frac{T}{M}\right)\phi^2 h$$

$$m_{\tilde g}\left(1+\frac{T}{M}\right)\tilde g\tilde g \quad \mu y\left(1+\frac{T}{M}\right)\phi^2 h^* \quad \mu\left(1+\frac{T}{M}\right)\tilde h\tilde h,$$

- similarly for the modulini

$$\mu\,\frac{\tilde T}{M}\,\tilde h h \qquad \frac{m_{susy}}{M}\,\tilde T(q\tilde q^\dagger, l\tilde l^\dagger, \tilde h h^\dagger)$$

For $M \sim M_{GUT}$ (natural value of compactification scale in realistic string theories) give renormalizable couplings $\lambda \sim 10^{-13}$

Freeze-In Production

So far assumed FIMP mass close to weak-scale. For WIMPs this must be so as unitarity limits size of annihilation cross-section

FIMPs completely different:

DM with relic abundance Y and mass m leads to temperature for matter-rad'n equality of parametric form $T_e \sim Y m$

Remarkably for FI this is independent of mass $T_{e,FI} \sim \lambda^2 M_{Pl}$

Calculable thermal production of superheavy FIMP DM possible

w/ apologies to Rocky: FIMPzilla's!

Another possibility…

Asymmetric DM

Alternative: similar physics underlies both Ω_B and Ω_{DM}

(Nussinov '85; Gelmini, Hall, Lin '87; Barr '91; Kaplan '92; Thomas '95; Hooper, JMR, West '04; explosion in last few yrs esp work of Zurek etal; Sarkar etal; Sannino etal; now many others...)

Baryons:	$U(1)_B$	$u, d, s...$	p stable	$\Omega_B \propto m_B \eta_B$
DM:	$U(1)_X$	$X_0, X_1, X_2...$	X_0 stable	$\Omega_X \propto m_X \eta_X$

At some era

Interactions violate B and X to yield related values for η_B and η_X

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B} \frac{m_X}{m_B}$$

ADM Basics

$$\frac{\Omega_X}{\Omega_B} = \frac{\eta_X}{\eta_B}\frac{m_X}{m_B}$$

only true if X density is determined by the asymmetric part otherwise

$$\frac{\Omega_X}{\Omega_B} = \frac{Y_X + Y_{\bar{X}}}{Y_B + Y_{\bar{B}}}\frac{m_X}{m_B}$$

need $Y_X + Y_{\bar{X}} = Y_X - Y_{\bar{X}} + \text{small corrections}$

non-trivial constraint as initially

$$Y_X + Y_{\bar{X}} = \frac{Y_X - Y_{\bar{X}}}{\epsilon}$$

where $\epsilon \ll 1$ measures CP-violation

ADM Basics

$\Longrightarrow$ Must efficiently annihilate away symmetric part to light states

there has to be an efficient X-preserving freeze-out process

Options:

- direct FO to light SM dof

  $\Longrightarrow$ operators connecting X & SM sectors with strength bounded below

- direct FO to light dark sector dof

  $\Longrightarrow$ (potentially) new "long-range" DM interactions

- FO to dark sector dof which then late decay to SM

  $\Longrightarrow$ late-time energy injection in early universe

ADM Basics

- direct FO to light SM dof

limits from direct detection experiments and monojet etc searches at Tevatron and LHC are very constraining

ADM Basics

- direct FO to light SM dof

limits from direct detection experiments and monojet etc searches at Tevatron and LHC are very constraining

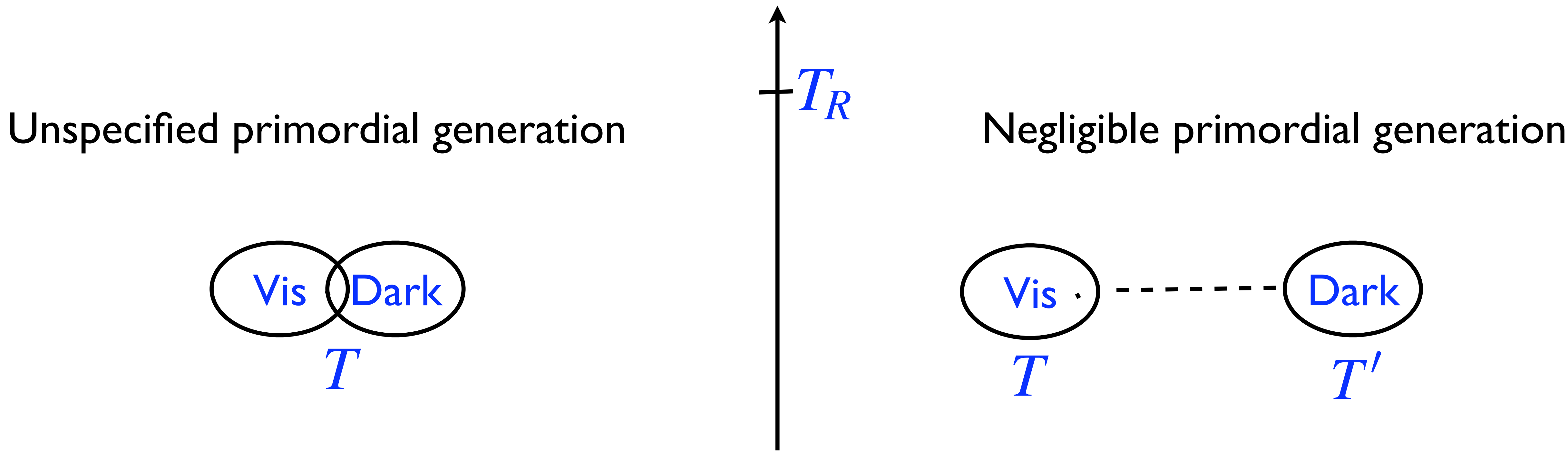
with slight exceptions if we want asymmetric DM in natural region $m_X < 10\ \mathrm{GeV}$ then direct FO to SM is disfavoured

$$\Downarrow$$

eliminating symm component likely implies new dark-sector dynamics

ADM Basics

- Two general categories of theories: "sharing" & "co-generation"



$\eta_X \sim \eta_B$ by sharing

$\eta_X \sim \eta_B$ by co-generation

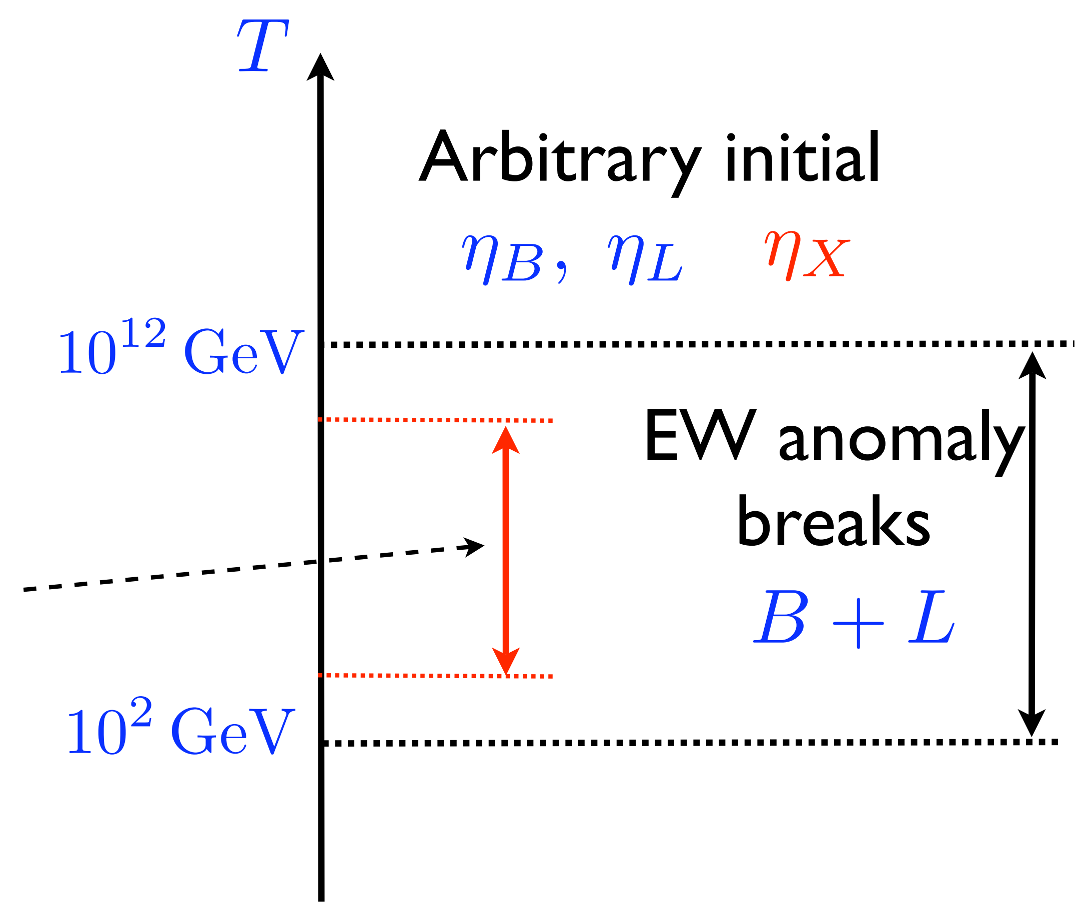
Co-generation is more ambitious: attempts to explain simultaneous origin of B & X asymmetries (if at scale ~ TeV allows test at LHC...)

ADM Basics

Sharing:

Assumes presence of some initial asymmetry in (at least) one of B, L & X

A "connector interaction" breaks a combination of B/L & X, such that



there is an era when only conserved U(1) is

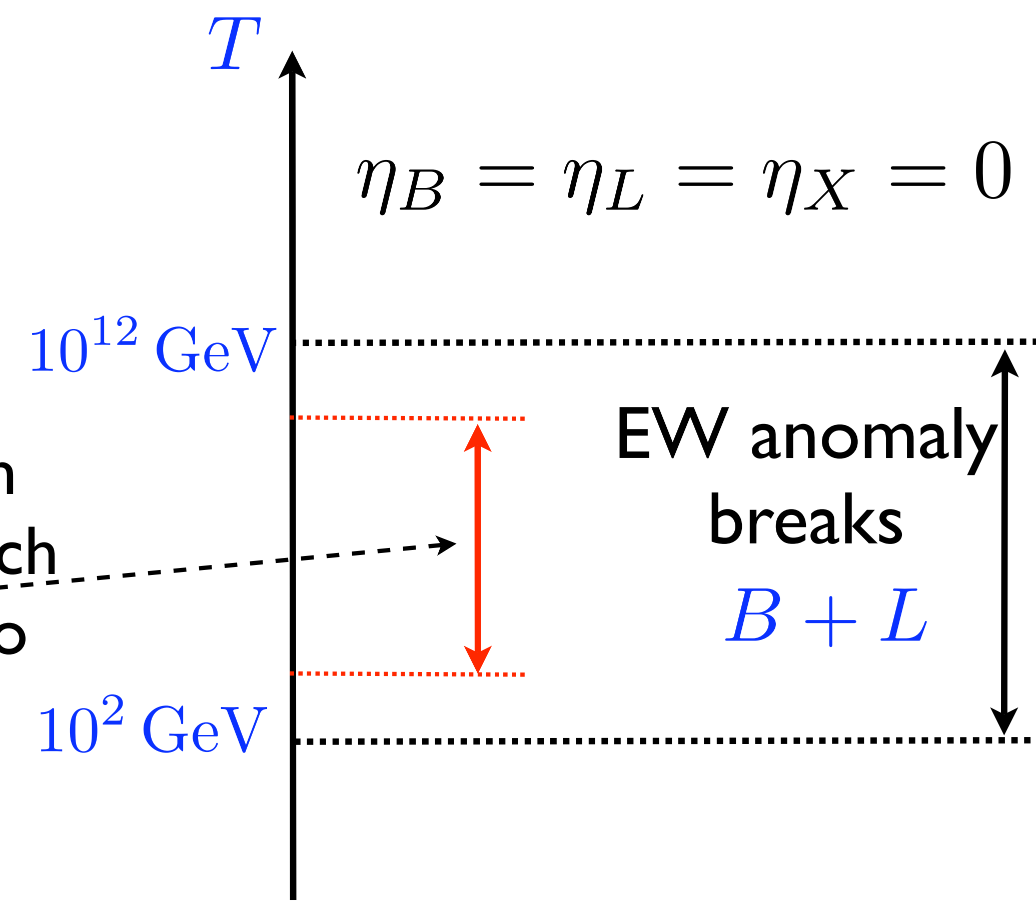
$$B - L + X \quad \Longrightarrow \quad \eta_B : \eta_L : \eta_X = N_1 : N_2 : N_3$$

ADM Basics

Co-generation:

zero initial asymmetry in B, L & X

“Connector interactions” both break a combination of B/L & X, and lead to generation of asymmetry which is simultaneously shared (further later sharing due to EW anomaly can occur too)



ADM Basics

Alternative view (either sharing or co-generation):

- incompatible with standard SUSY neutralino DM
- alters expected LHC signals of new physics
- can change one or both direct/indirect DM detection

major issue is *why* is DM mass near that of baryon?

(but see, eg, Garcia Garcia, Lasenby, JMR; arXiv:1505.07410 for automatic explanation directly connected with naturalness- the "Twin Higgs" mechanism: also see work on "mirror world" models, by Foot, Volkas, etal)

Consequences of ADM

For non-collider DM searches:

- Light DM ~ few GeV is favoured

  (but see, eg, JMR+McCullough, arXiv:1106.4319, and Sarkar etal for other possibilities)

- indirect detection strongly modified - DM can't annihilate to only photons but can give rise to anti-B/L final states (Hall, JMR, Unwin, West, unpublished)

- sharing allows normal direct detection, but co-generation can sometimes kill direct detection (but again see, eg, JMR+McCullough, arXiv:1106.4319 for co-generation theory with direct detection signals)

- exotic possibilites, eg, DM-stimulated nucleon decay

  (Hall, JMR, Unwin, West, unpublished; Huang & Zhao)

Consequences of ADM

Other generic astro signals

both sharing and co-generation generate an initially dominant symmetric $(X + \bar{X})$ component

$$\text{eg} \qquad Y_X + Y_{\bar{X}} \sim \frac{Y_X - Y_{\bar{X}}}{\epsilon}$$

must be efficiently removed

$\Longrightarrow$ typically involves new light Dark-Sector states

$\Longrightarrow$ large-scale structure, CMBR (& maybe BBN) signals

(work in progress w/ West…)

Finally…

Macroscopic DM

There are rich possibilities for getting "macroscopic" DM

eg,

- Scalar solitons like Q-balls…

  Kusenko, Shaposhnikov, etal

- "Nuclear" DM made in process of big-bang-DM-synthesis…

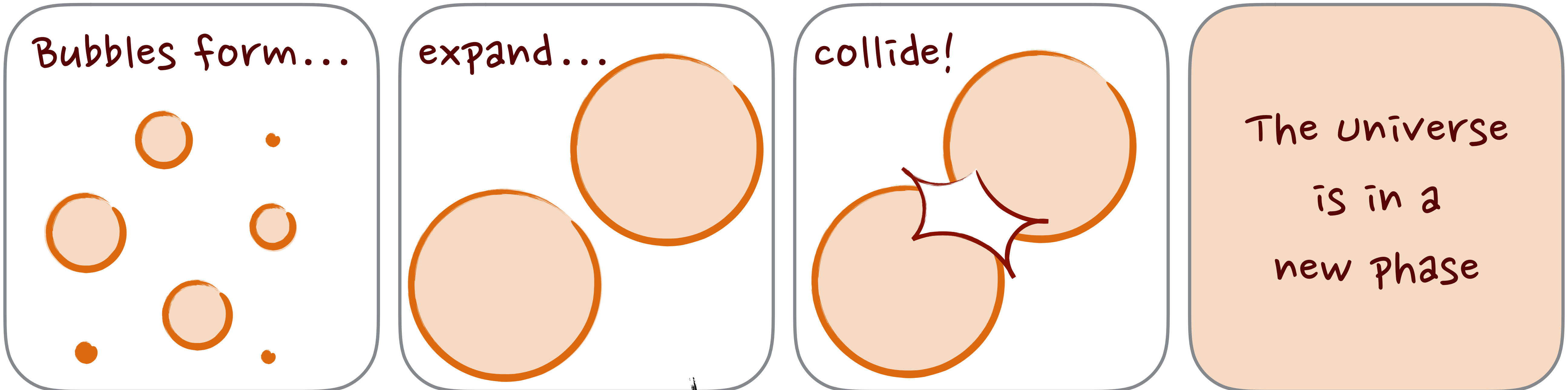
  Hardy, Lasenby, JMR, & West: arXiv:1411.3739 & arXiv:1504.05419

- Primordial BHs…

  Carr; Bird etal; Garcia Bellido, etal

PBHs from T=0 (quantum) vacuum decay?

Garcia Garcia, Kripendorf, JMR; arXiv:1607.06813



They expand ultra-relativistically

Bubbles collide, emitting gravity waves and likely forming some PBHs too

Nobody has reliably computed resulting PBH mass spectrum…!

Conclusions

Huge amount of exciting thy/expt awaits!