Dark matter in particle physics & cosmology

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I. What do astronomical/cosmological observations tell us about the nature of dark matter?

II. (some) dark matter candidates: theory and detection

Direct detection of dark matter-APPEC Committee report, Billard et al.

n.b. throughout (apart from images) will cite white papers/reviews/postgrad lecture notes

I. What do astronomical/cosmological observations tell us about the nature of dark matter (DM)?

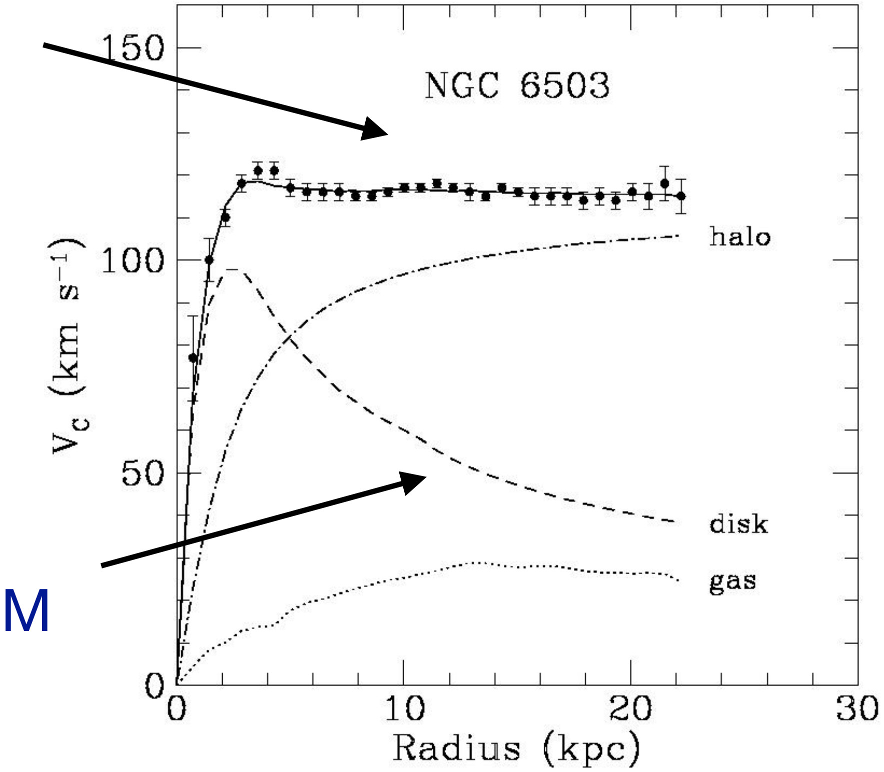
- Observational evidence for DM
- Properties of DM
- But what about:
    - cosmological tensions
    - modified gravity

Observational evidence for DM

'History of dark matter', Bertone & Hooper

Long-standing evidence from observations of luminous matter (stars, gas, galaxies) that galaxies have massive, extended dark matter halos.

spiral galaxy
'rotation curves' v(r)



observed

expected
without DM

Begeman, Broeils & Sanders

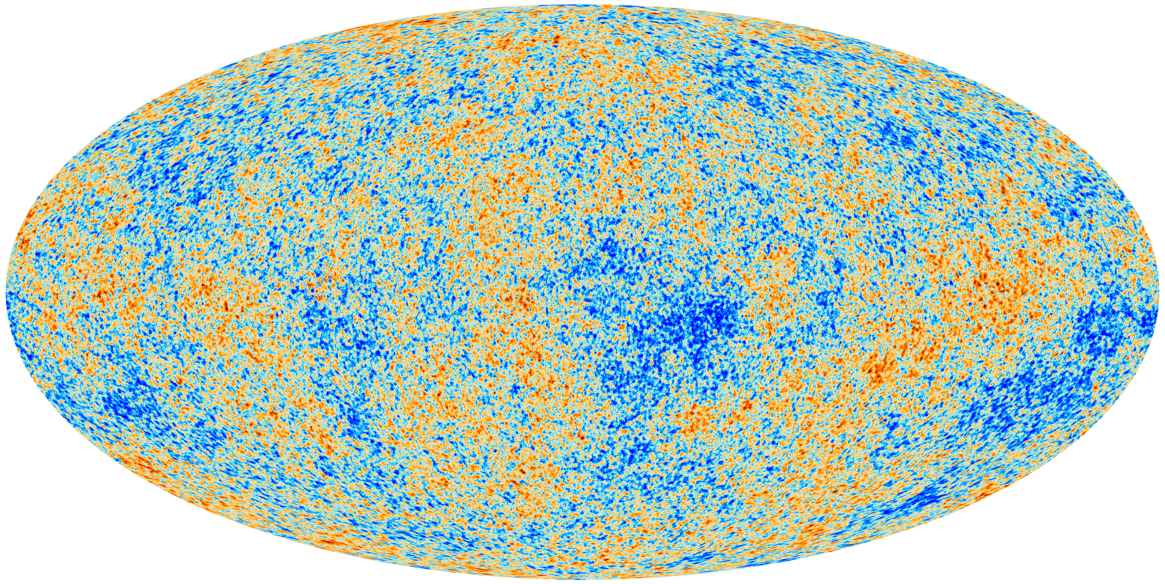
galaxy clusters
(galaxy speeds, X-ray emission,
weak lensing)

bullet cluster

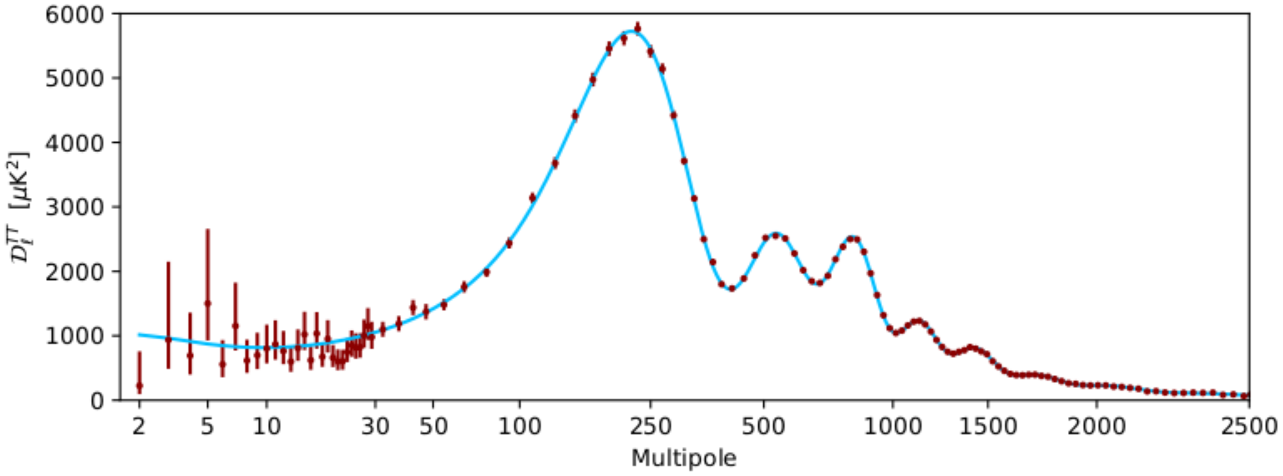
This assumes that Newtonian gravity/general relativity is correct (evidence is all from DM's gravitational effects on luminous matter).

Properties of DM

Cosmological observations (Cosmic Microwave Background anisotropies, galaxy clustering and lensing, type 1a Supernovae, Big Bang Nucleosynthesis) are broadly consistent with $\Lambda\mathrm{CDM}$ model (flat Universe containing a cosmological constant and cold (non-relativistic) dark matter) and parameters are measured with high precision.



angular power spectrum



$$l \propto \frac{1}{\theta}$$

Planck

Properties of DM

Cosmological observations (Cosmic Microwave Background anisotropies, galaxy clustering and lensing, type 1a Supernovae, Big Bang Nucleosynthesis) are broadly consistent with $\Lambda\mathrm{CDM}$ model (flat Universe containing a cosmological constant and cold (non-relativistic) dark matter) and parameters are measured with high precision.

Planck 2018

cold dark matter: $\Omega_{\mathrm{cdm}} h^2 = 0.11933 \pm 0.00091$ $\Omega_{\mathrm{cdm}} = 0.26$

baryons: $\Omega_{\mathrm{b}} h^2 = 0.02242 \pm 0.00014$ $\Omega_{\mathrm{b}} = 0.05$

$$h = 0.6766 \pm 0.0042$$

$\Omega_X = \dfrac{\rho_X}{\rho_{\mathrm{c}}}$ density parameter

ρ_{c} critical density (for which geometry of Universe is flat)

h dimensionless Hubble constant ($H_0 = 100\, h\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$)

Warm dark matter (WDM) e.g. sterile neutrinos

If DM is warm ($m \sim \mathrm{keV}$ for a thermal relic), free streaming erases perturbations on small scales and less light halos form.

Probes of density perturbations (Lyman-alpha forest) and abundance of light halos (observations of MW satellite galaxies, gaps in stellar streams, lensing) constrain warm DM mass: $m_{\mathrm{wdm}} \gtrsim$ a few keV.

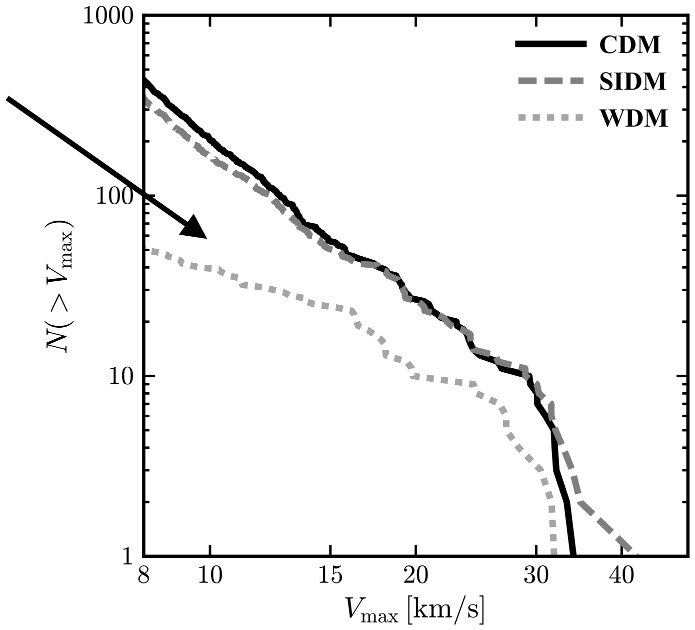
Self-interacting dark matter (SIDM)

Self-interactions lead to DM halos that are more spherical and have a constant density 'core' at small r.

From mergers and lensing probes of halo shape: $\sigma/v \lesssim$ a few cm^2/g.

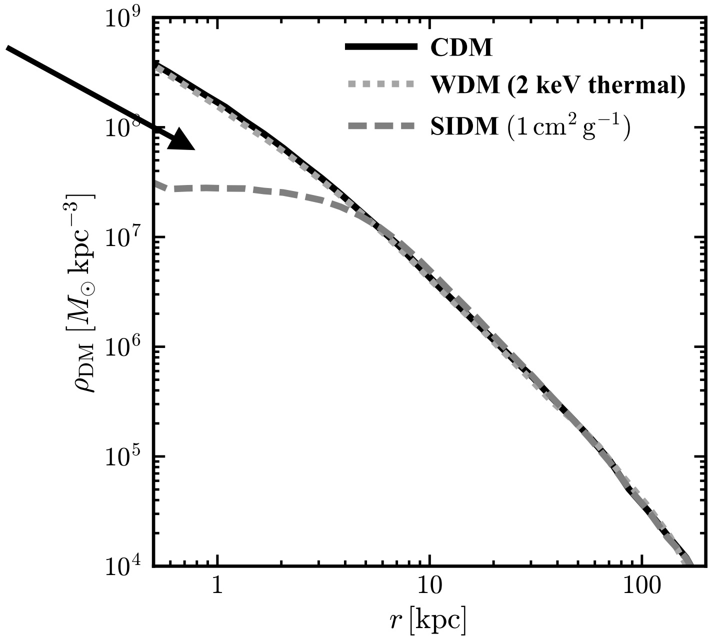
sub-halo 'mass'-function

WDM: less light halos



density profile, $\rho(r)$

SIDM constant density core



Bullock & Boylan-Kolchin

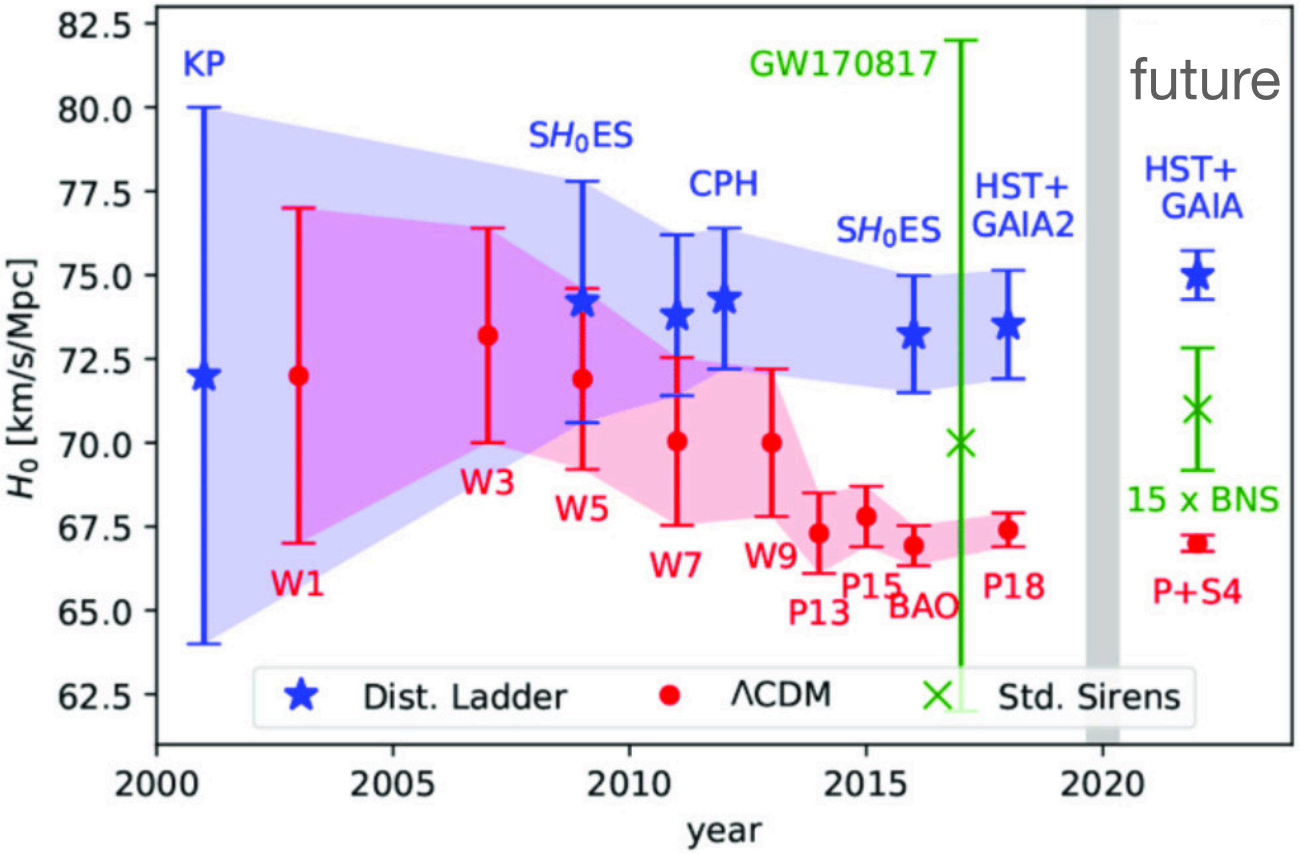
Cosmological tensions

H_0 tension e.g. Verde et al.

The value of H_0, the present day expansion rate, measured at late times (using standard candles + distance ladder) is significantly different from the best fit value in the $\Lambda\mathrm{CDM}$ model.

evolution of H_0 measurements with time

distance ladder, ‘cosmology’, gravitational wave ‘standard sirens’- (binary neutron stars)



Ezquiaga & Zumalacarregui

Due to systematics?

Or new ‘beyond $\Lambda\mathrm{CDM}$’ Physics?? (hard to resolve tension without violating other observational constraints).

S_8 tension

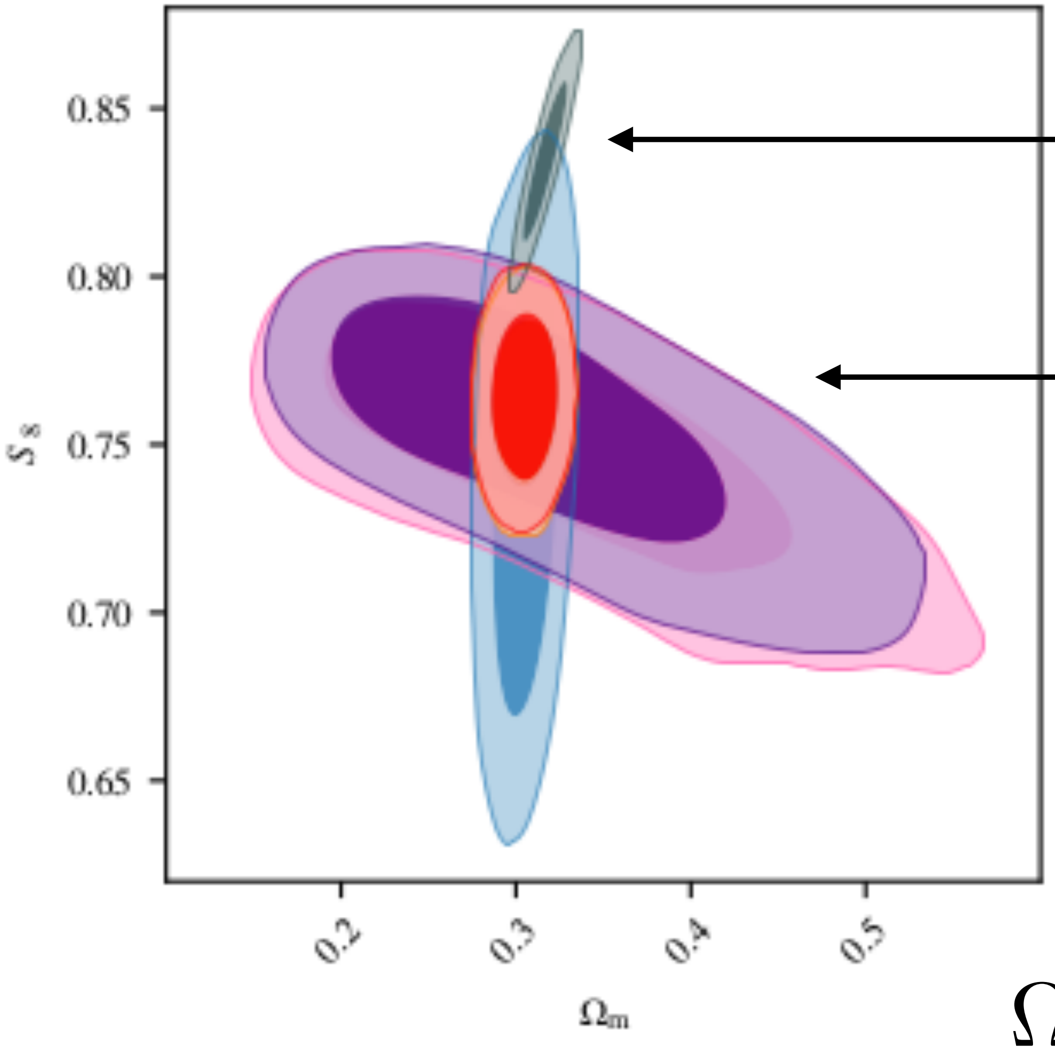
‘Cosmology intertwined’ Snowmass 2021

The clumpiness of the matter distribution measured using weak lensing and galaxy clustering is different from that expected for the $\Lambda\mathrm{CDM}$ model (Planck).

$$S_8 \equiv \sigma_8 \left(\frac{\Omega_\mathrm{m}}{0.3}\right)^{1/2}$$

σ_8 amplitude of perturbations on cluster scales

$8\,\mathrm{Mpc}/h$



Planck

various galaxy clustering & weak lensing surveys

Ω_m

KiDS-1000, Heymans et al.

Due to systematics?

Or new Physics?? (early dark energy, ultra light axions,…).

Modified gravity

Famaey & McGaugh; Clifton, Ferreira, Padilla & Skordis

All the evidence for dark matter to date comes from its gravitational effects.

Could the observations be explained by instead modifying the laws of gravity?

Modified Newtonian Dynamics (MOND) Milgrom

Phenomenological modification of Newton's laws of gravity for small accelerations (proposed to explain galaxy rotation curves without dark matter):

$$F = m\mu(a/a_0)a$$

$$\mu(x) \to 1 \quad \text{for} \quad x \gg 1$$
$$\mu(x) \to x \quad \text{for} \quad x \ll 1$$

$$a_0 \approx 10^{-10}\,\mathrm{m\,s^{-2}}$$

Also explains some properties of galaxies (e.g. Tully-Fisher relationship between baryonic mass and rotation speed).

Ongoing debate re. consistency of MOND with wide binary orbits from Gaia observations.

To explain cosmological observations (CMB, lensing, galaxy clustering…) need a relativistic theory.

Tensor-Vector-Scalar gravity (TeVeS) Bekenstein

TeVeS and other ‘Dark matter emulators’ (where photons/neutrinos & gravitational waves (GWs) couple to different metrics) ruled out by simultaneous observation of GWs and electromagnetic radiation from GW170817 (coalescence of binary neutron stars).

Aether scalar tensor theory Skordis & Zlosnik

Contains field that has has same equation of state and sound speed as dark matter on cosmological scales.

$$S = \int d^4x \frac{\sqrt{-g}}{16\pi\tilde{G}} \left\{ R - 2\Lambda - \frac{K_{\mathrm{B}}}{2} F^{\mu\nu} F_{\mu\nu} + 2(2 - K_{\mathrm{B}}) J^{\mu} \nabla_{\mu}\phi - (2 - K_{\mathrm{B}})\mathcal{Y} - \mathcal{F}(\mathcal{Y}, \mathcal{Q}) - \lambda(A^{\mu} A_{\mu} + 1) \right\} + S_m[g]$$

Reproduces GR for large accelerations, and MOND for small accelerations.

Consistent with $\Lambda\mathrm{CDM}$ CMB temperature & polarisation angular power spectra and matter power spectrum.

GWs travel at speed of light.

I. Summary

A wide range of astrophysical and cosmological observations (galaxies, galaxy clusters, large scale structure and the cosmic microwave background) indicate that 85% of the matter (and 26% of the energy) in the Universe today is cold, non-baryonic dark matter.

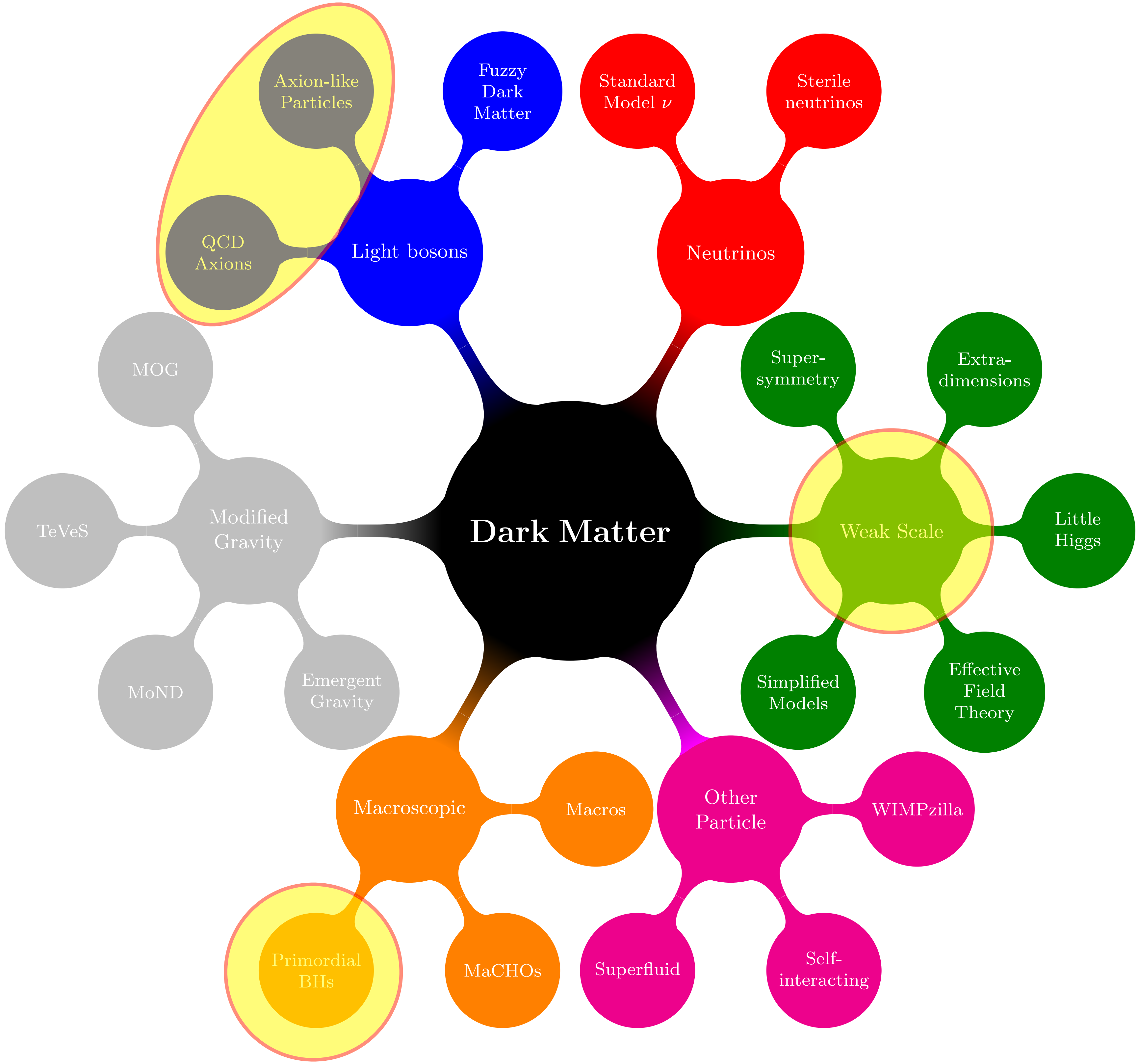
All of the evidence for DM comes from its gravitational effects on luminous matter, however explaining all of the observations by modifying gravity instead is challenging.

Cosmological tensions (Hubble constant and 'S_8' (clumpiness)) might indicate physics beyond ΛCDM (or could be due to systematics).

II. DM candidates: theory and detection

- Weakly Interacting Massive Particles
- Primordial Black Holes
- Axions & Axions Like Particles

Bertone & Tait



Bertone & Tait

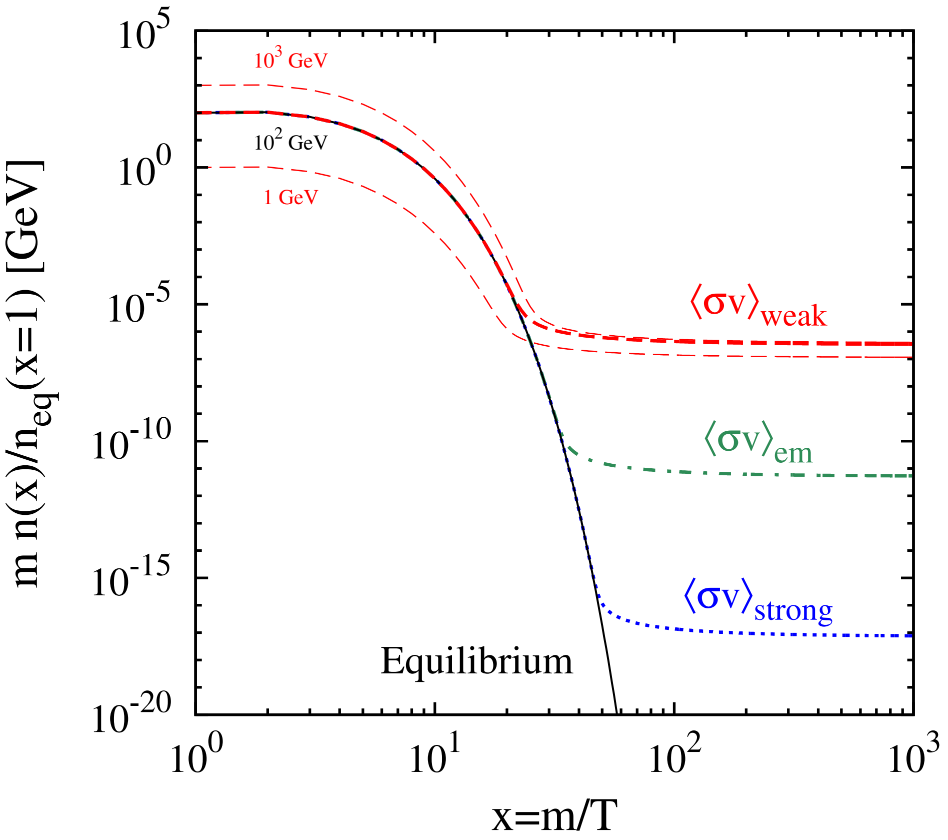
Weakly Interacting Massive Particles

Direct detection of dark matter-APPEC Committee report, Billard et al.

Theoretical motivation

A stable weakly interacting massive particle (WIMP) which is in thermal equilibrium at early times, will “freeze out” with roughly the right abundance to be the dark matter (‘WIMP miracle’).

$$\chi + \chi \longleftrightarrow X + \bar{X}$$



comoving number density

time

Steigman, Dasgupta & Beacom

$$\sigma v \sim 3 \times 10^{-26}\,{\rm cm}^3{\rm s}^{-1} \longrightarrow \Omega_{\rm WIMP} \sim 0.3$$

The gauge hierarchy problem ($M_{\rm w} \sim 100\,{\rm GeV} \ll M_{\rm Pl} \sim 10^{19}\,{\rm GeV}$, “Why is the Higgs mass so much smaller than the Planck mass, despite quadratic radiative correction to its mass?”) suggests that there is new Physics at the weak scale, and concrete models often include a WIMP candidate.

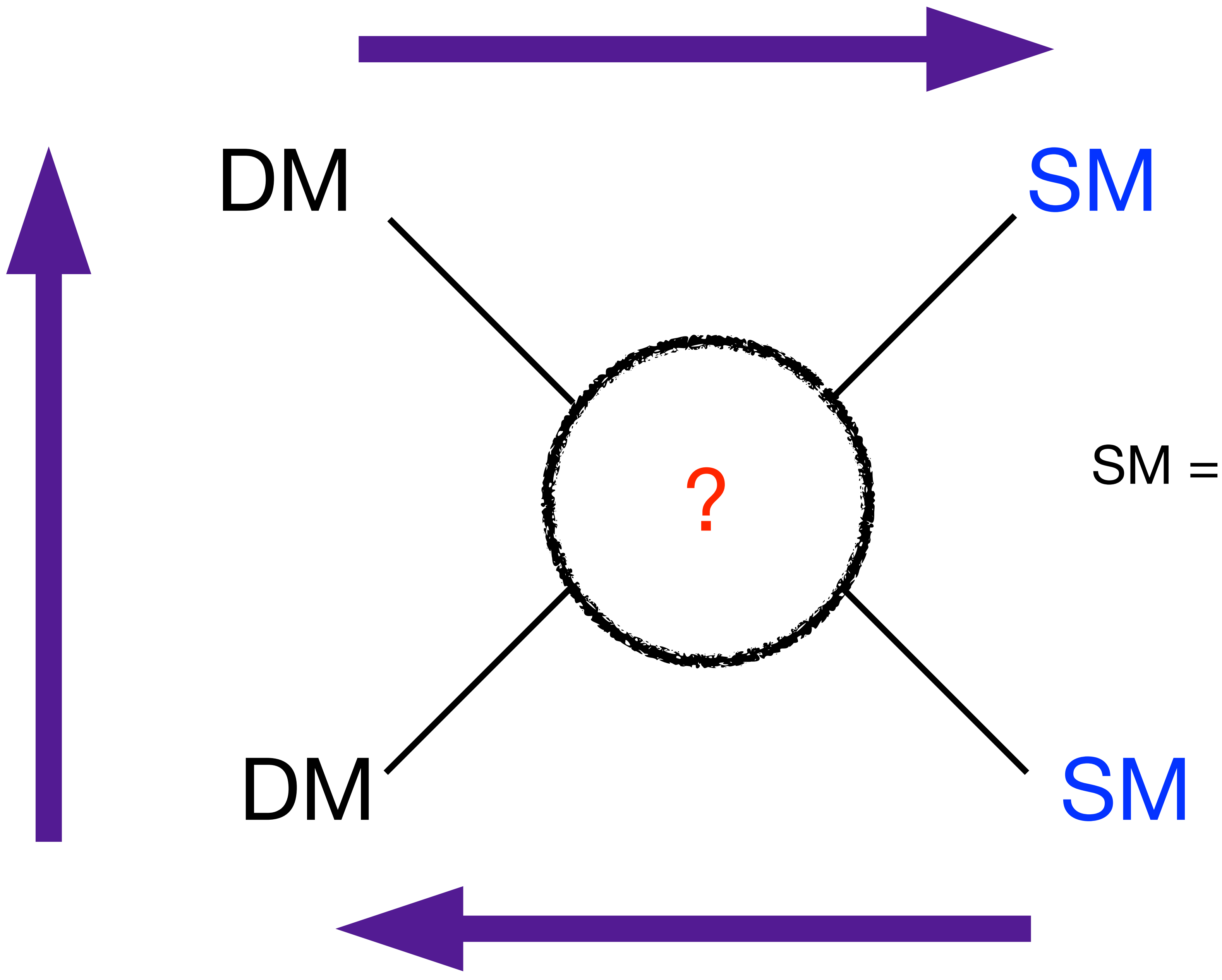
e.g. Supersymmetry:

Supersymmetric partners cancel radiative corrections:

Akrami

The Lightest Supersymmetric Particle (LSP) (which in large regions of parameter spaces is the lightest neutralino, a mixture of the susy partners of the photon, the Z and the Higgs) is stable (R parity is conserved) and is a good CDM candidate.

Detection



indirect detection

direct detection

production at colliders

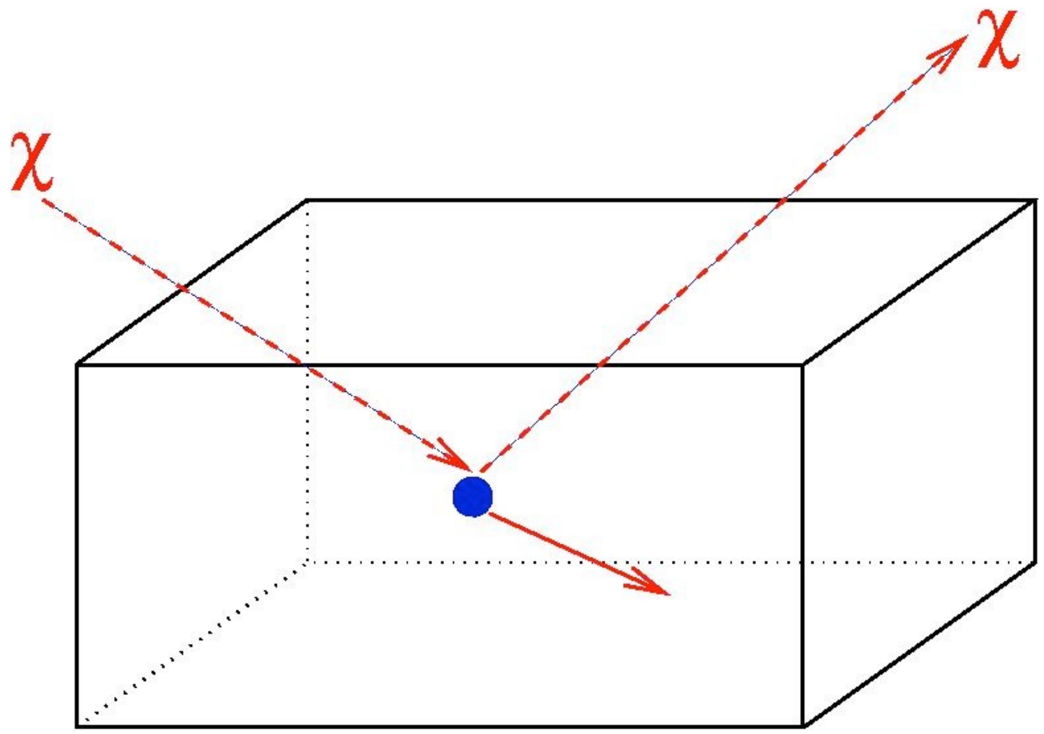
SM = standard model

would be great, but on its own wouldn't tell
us that the particle is
i) cosmologically stable
ii) the DM in galaxies/the Universe

direct detection

By detecting energy deposited when a WIMP (elastic) scatters on detector nuclei in the lab:

$$\chi + N \to \chi + N$$



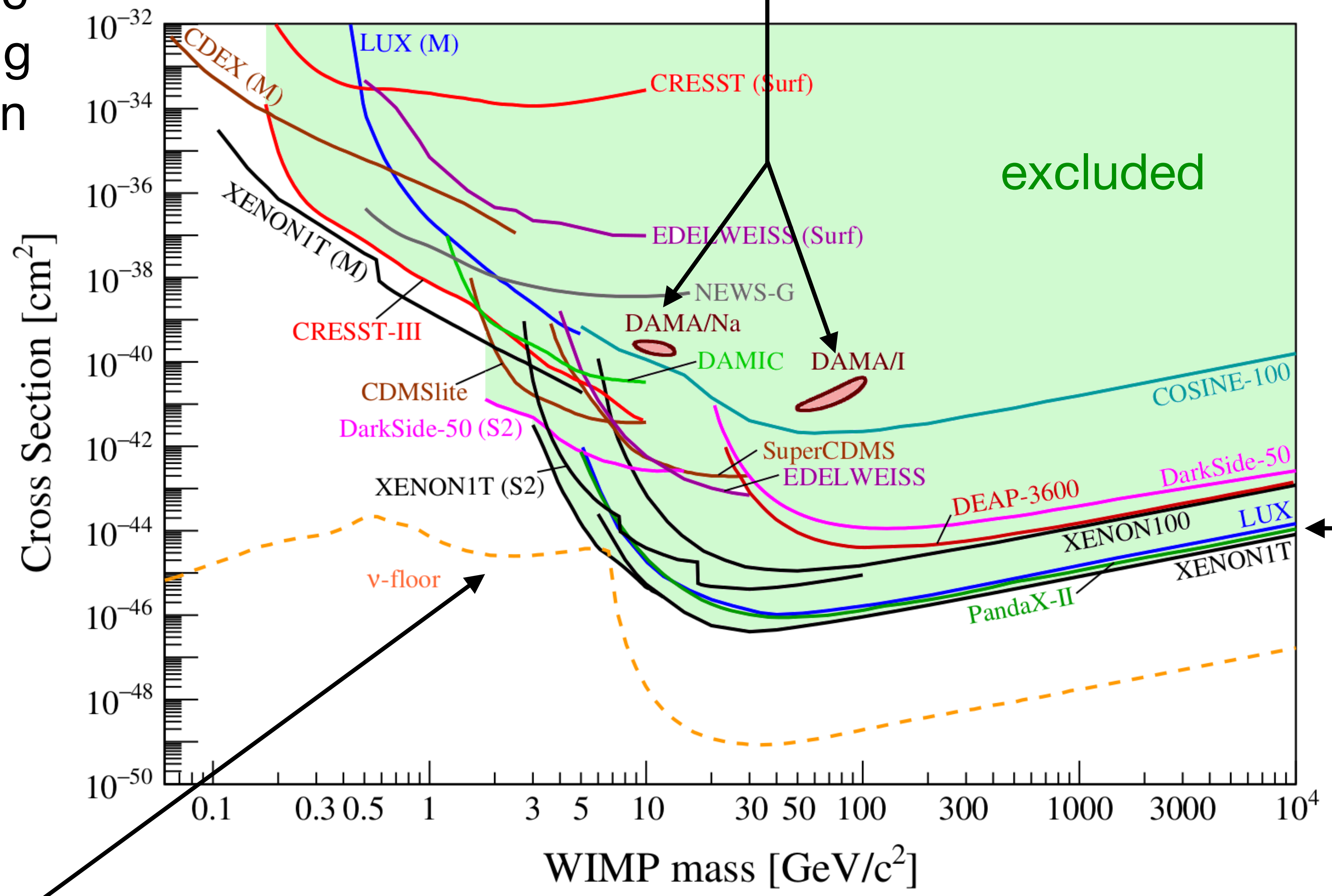
Energy detected via ionisation, scintillations, phonons

Most detectors use 2 of these channels, to aid discrimination of WIMPs from backgrounds (electron recoils due to βs and γs).

status 2021

DAMA ‘annual modulation’ signal

cross section
for elastic
scattering
on proton



Xenon expts
LUX (UK-US)
PandaX
Xenon1T

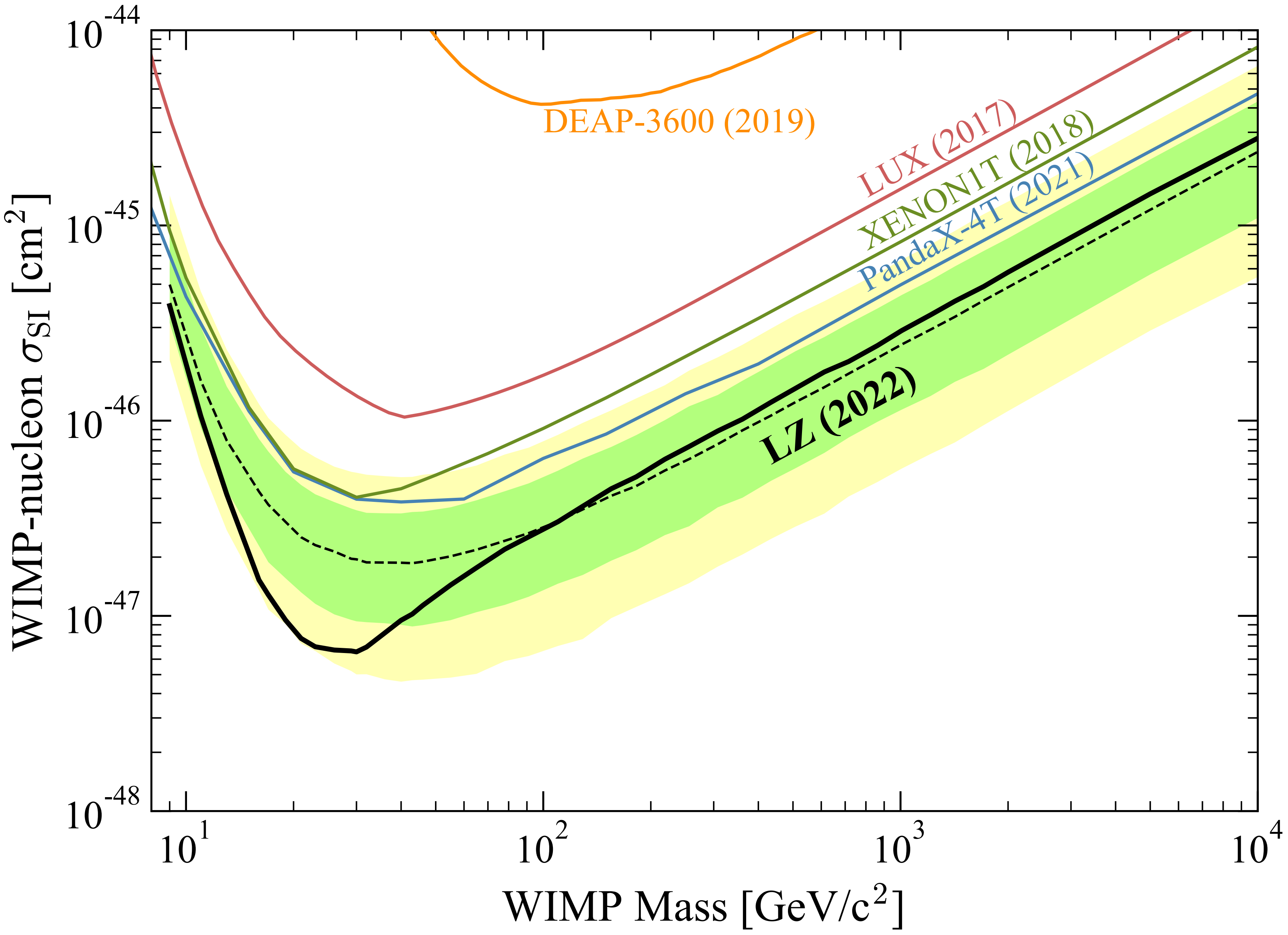
Billard et al.

ν-floor (or fog)

coherent elastic neutrino-nucleus scattering (CE*ν*NS) of Solar, atmospheric & diffuse supernova background neutrinos

current

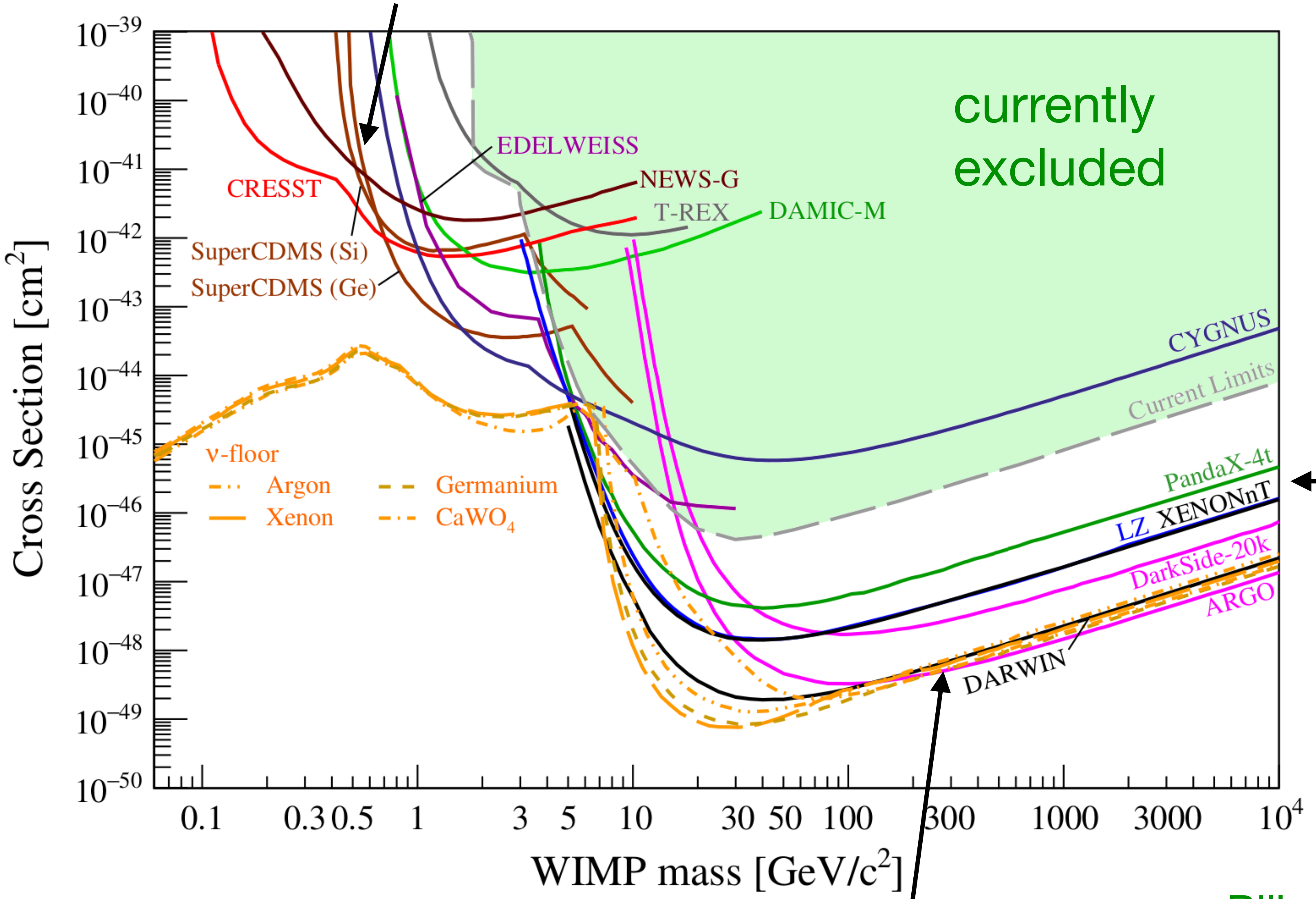
First results from LUX-ZEPLIN (using 6% of planned total data):



Aalbers et al.

future

light target nuclei + low energy thresholds



currently excluded

projected reach of current Xe expts

Billard et al.

‘next generation’ Xe and Ar

Update: XLZD = Xenon + LZ + DARWIN

40-100 tonnes of Xenon, operation early 2030s

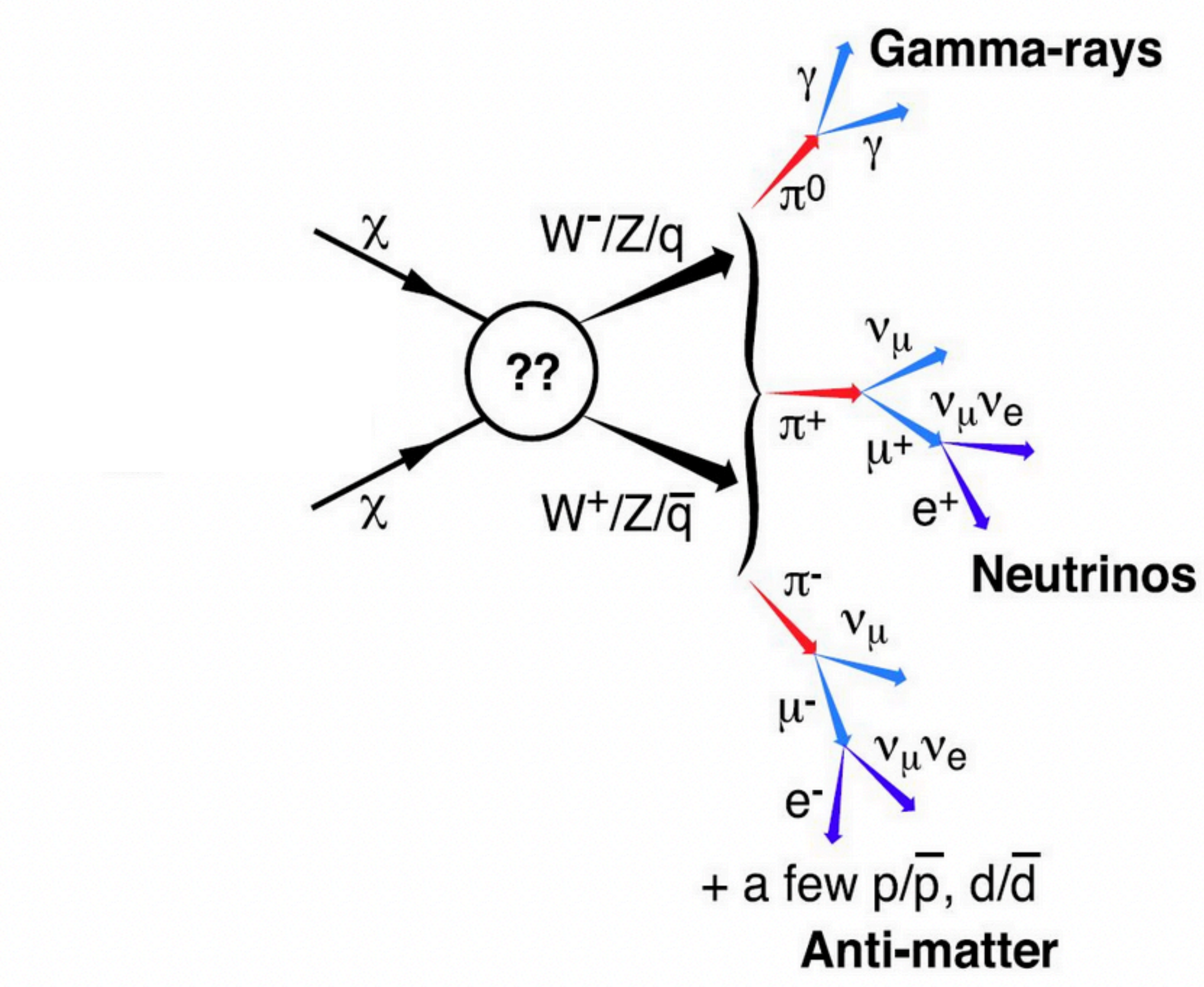
will also probe neutrino physics, Solar physics, SNe, cosmic rays

Boulby mine potential site

indirect detection

Slatyer Les Houches lectures

In high density regions (in particular Galactic centre, dwarf galaxies,…) WIMPs annihilate producing e.g. high energy gamma-rays, anti-matter.



Baltz et al.

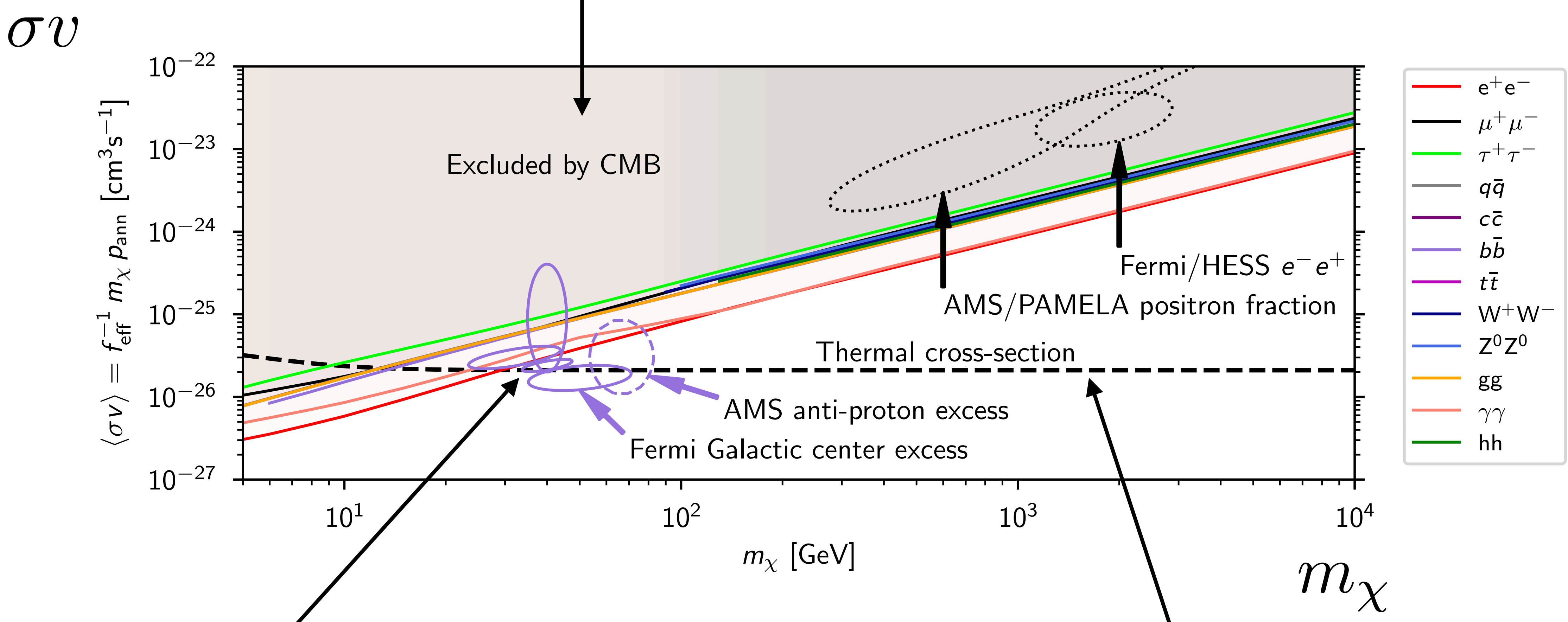
Need to distinguish WIMP annihilation from astrophysical backgrounds.

current

n.b. WIMP parameters corresponding to excesses (or excluded by null-results) depend on annihilation channel

CMB limits

energy input from WIMP annihilation modifies ionisation history of Universe and hence CMB anisotropies

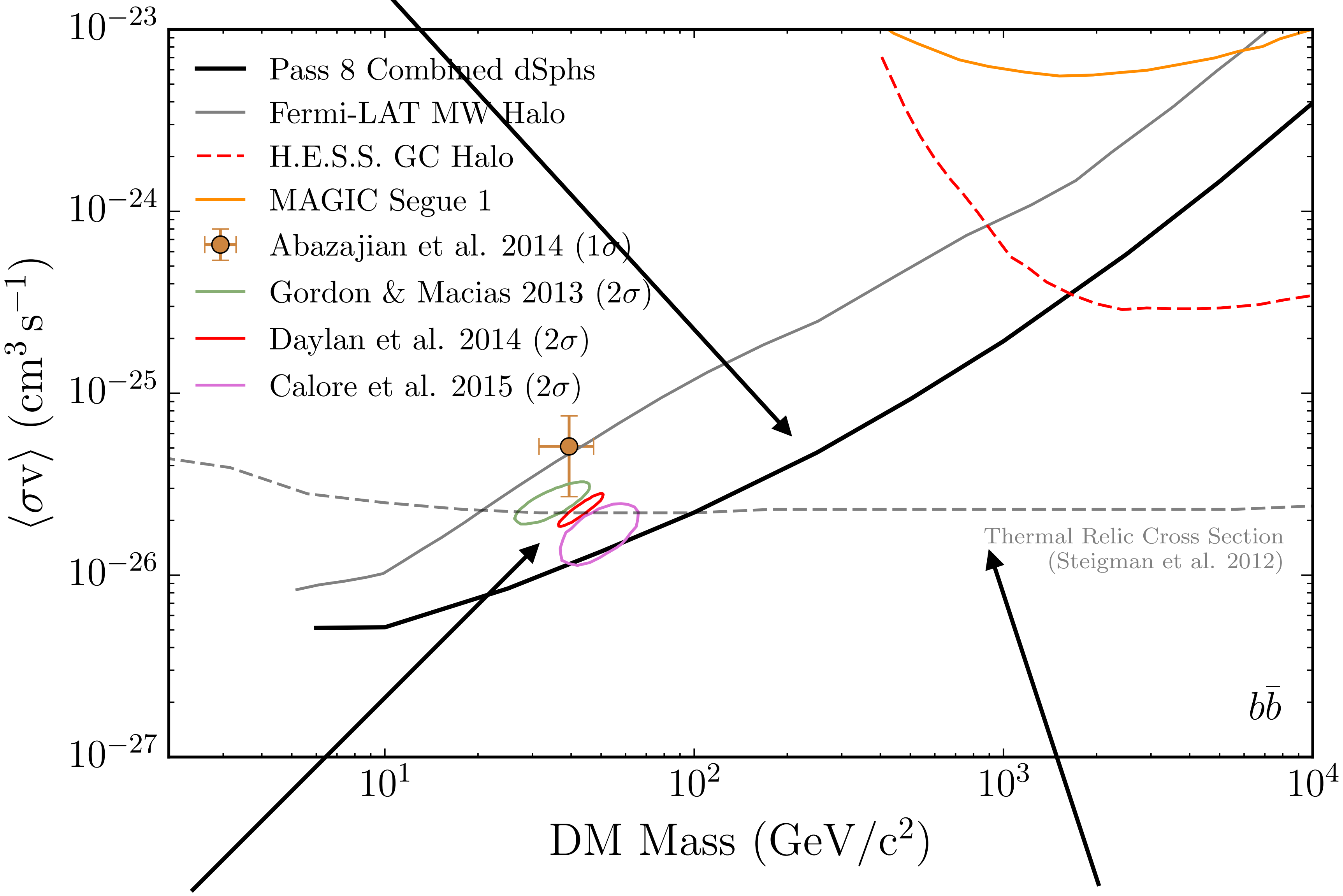


Planck

Fermi Galactic center excess

cross section which matches observed CMB density

Fermi dwarf galaxy exclusion limits (for annihilation via $b\bar{b}$):



Fermi Galactic center excess

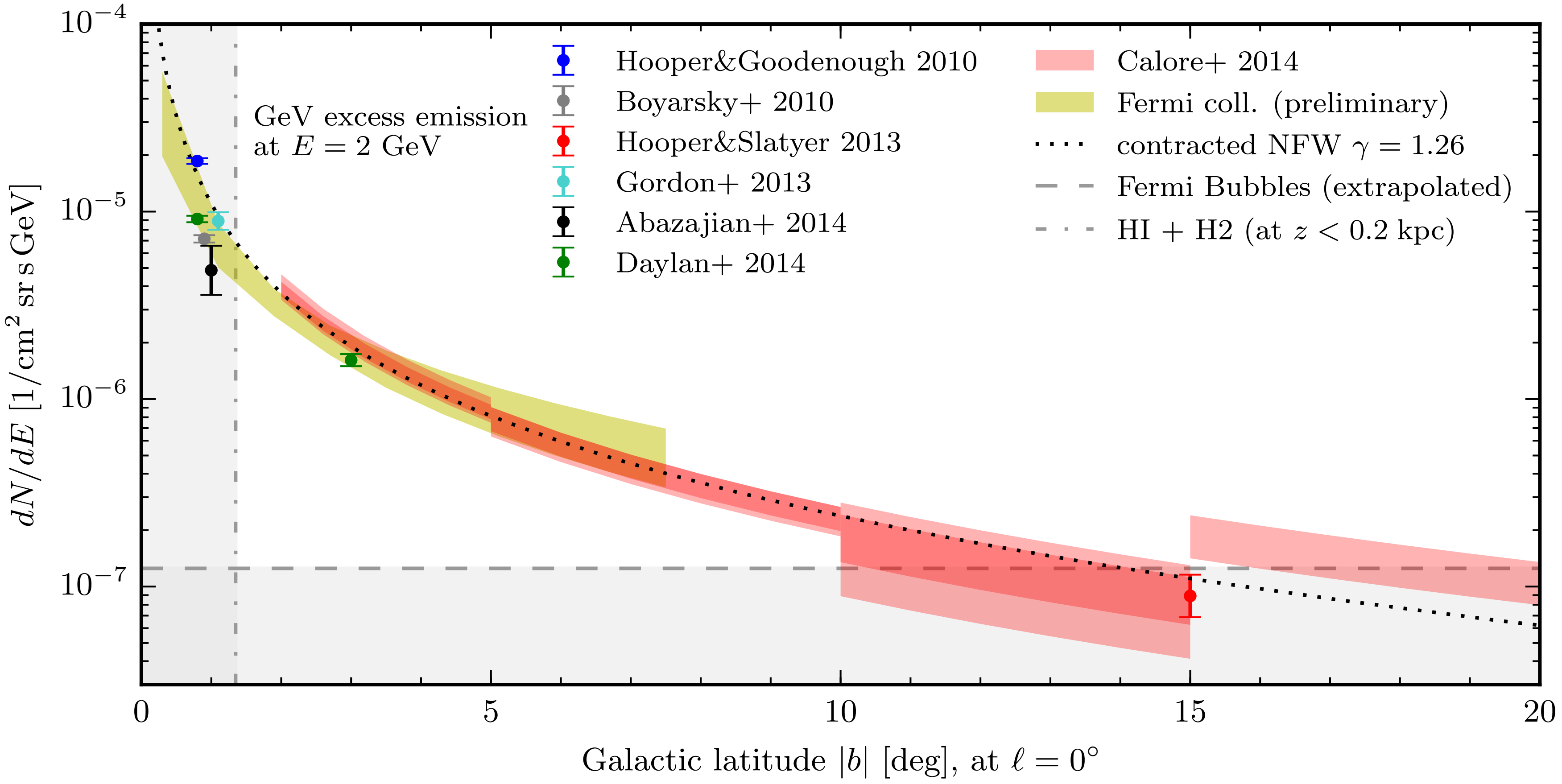
Fermi

cross section which matches observed CMB density

For annihilation via $t\bar{t}$ limits/allowed regions are at smaller σv values.

Galactic centre excess

Energy spectrum and spatial morphology match expectations for WIMP annihilation ($\rho(r) \propto r^{-1.2}$).



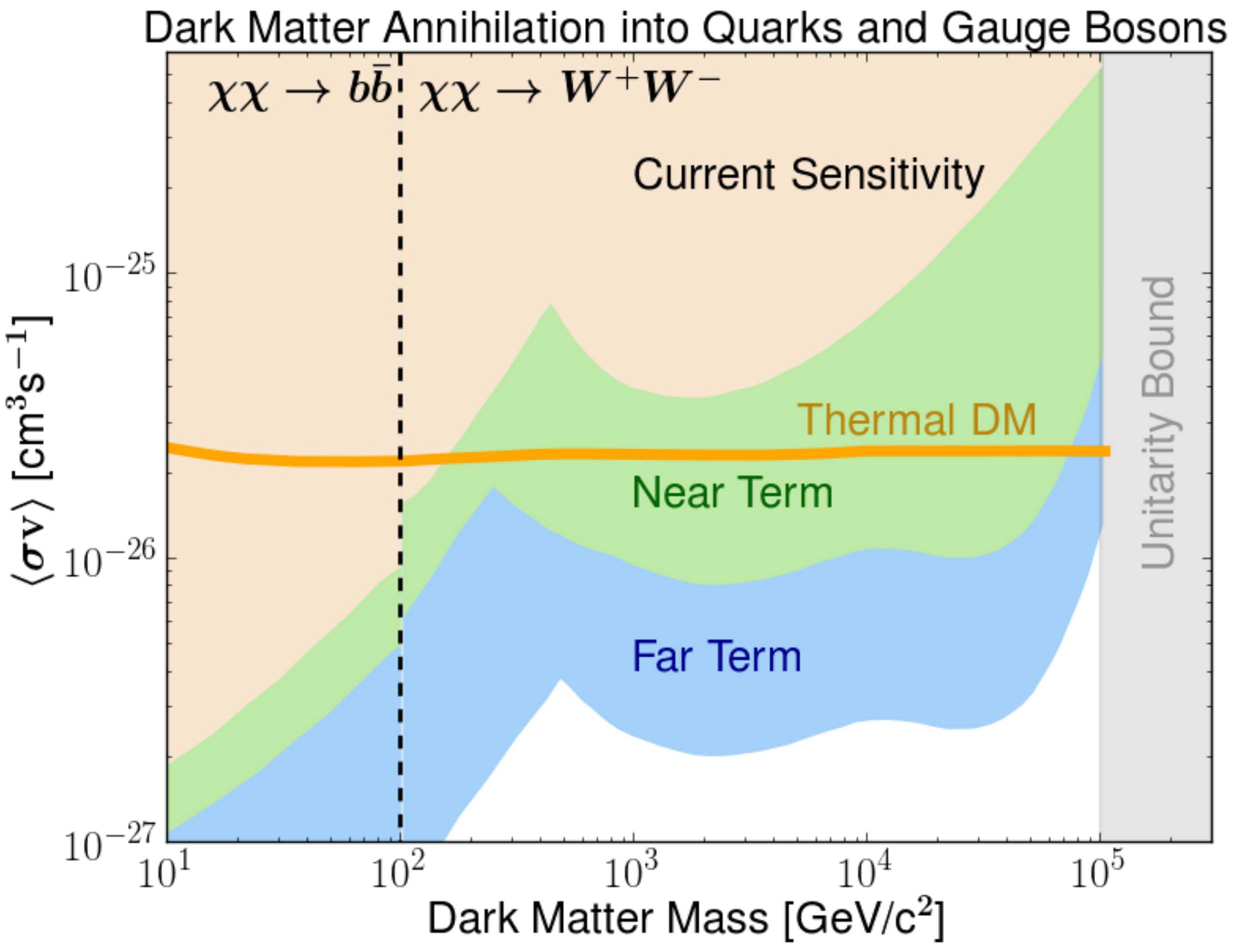
Calore et al.

But could be due to Millisecond Pulsars???

future

Snowmass particle dark matter topical group

gamma-rays



Near Term (~5 years)

increased Fermi sensitivity using dwarf galaxies found by Vera Rubin Observatory (formerly LSST)
+ **C**herenkov **T**elescope **A**rray
+ **S**outhern **W**ide-field **G**amma-Ray **O**bservatory

Far Term

Advanced **P**article-astrophysics **T**elescope (successor to Fermi)
+ successor to SWGO

antimatter

Near term: **G**eneral **A**nti**P**article **S**pectrometer and **A**lpha **M**agnetic **S**pectrometer
Far term: **G**amma-**R**ay and **A**nti**M**atter **S**urvey

Primordial Black Holes (PBHs)

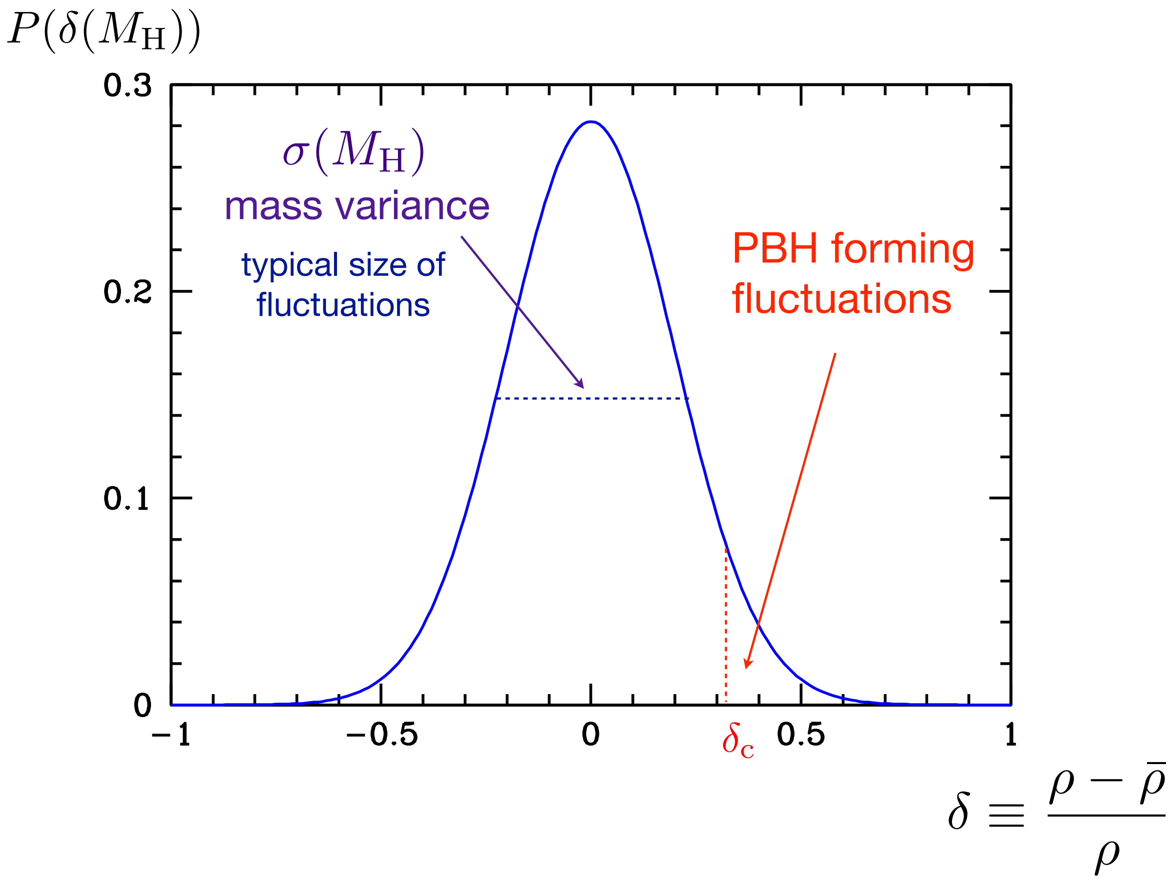
Carr & Kuhnel; Green & Kavanagh

Theory

Primordial Black Holes (PBHs) may form from over densities in the early Universe.

Most 'popular/minimal' mechanism: collapse of large density perturbations during radiation domination.

If a region exceed a critical over-density, δ_c, then it collapses to form a BH with mass roughly equal to the horizon mass.



Mass:

$$M_{\rm PBH} \sim 10^{15}\,{\rm g}\left(\frac{t}{10^{-23}\,{\rm s}}\right) \sim M_\odot\left(\frac{t}{10^{-6}\,{\rm s}}\right)$$

Initial mass fraction $\beta = \frac{\rho_{\rm PBH}}{\rho_{\rm tot}}$:

$$\beta \sim \sigma(M_H)\exp\left(-\frac{\delta_c^2}{2\sigma^2(M_H)}\right)$$

Since PBHs are matter, during radiation domination the fraction of energy in PBHs grows with scale factor, a:

$$\frac{\rho_{\mathrm{PBH}}}{\rho_{\mathrm{rad}}} \propto \frac{a^{-3}}{a^{-4}} \propto a$$

Relationship between PBH initial mass fraction, β, and fraction of DM in form of PBHs, f_{PBH}:

$$\beta \sim 10^{-9} f_{\mathrm{PBH}} \left(\frac{M_{\mathrm{PBH}}}{M_{\odot}} \right)^{1/2}$$

On CMB scales the primordial perturbations have amplitude $\sigma(M_{\mathrm{H}}) \sim 10^{-5}$

If the primordial perturbations are very close to scale-invariant the number of PBHs formed will be completely negligible: $\beta \sim \exp\left(-10^{10}\right)$

To form an interesting abundance of PBHs, $f_{\mathrm{PBH}} \sim \mathcal{O}(1)$, the primordial perturbations must be significantly larger ($\sigma(M_{\mathrm{H}}) \sim 0.1$) on small scales than on cosmological scales.

Primordial perturbations are thought to be generated by inflation, a period of accelerated expansion in the early Universe driven by a scalar field, ϕ, 'slow-rolling' along its potential.

In slow-roll approx: $\sigma \propto \dfrac{V^{3/2}}{V'}$ ← slope of potential

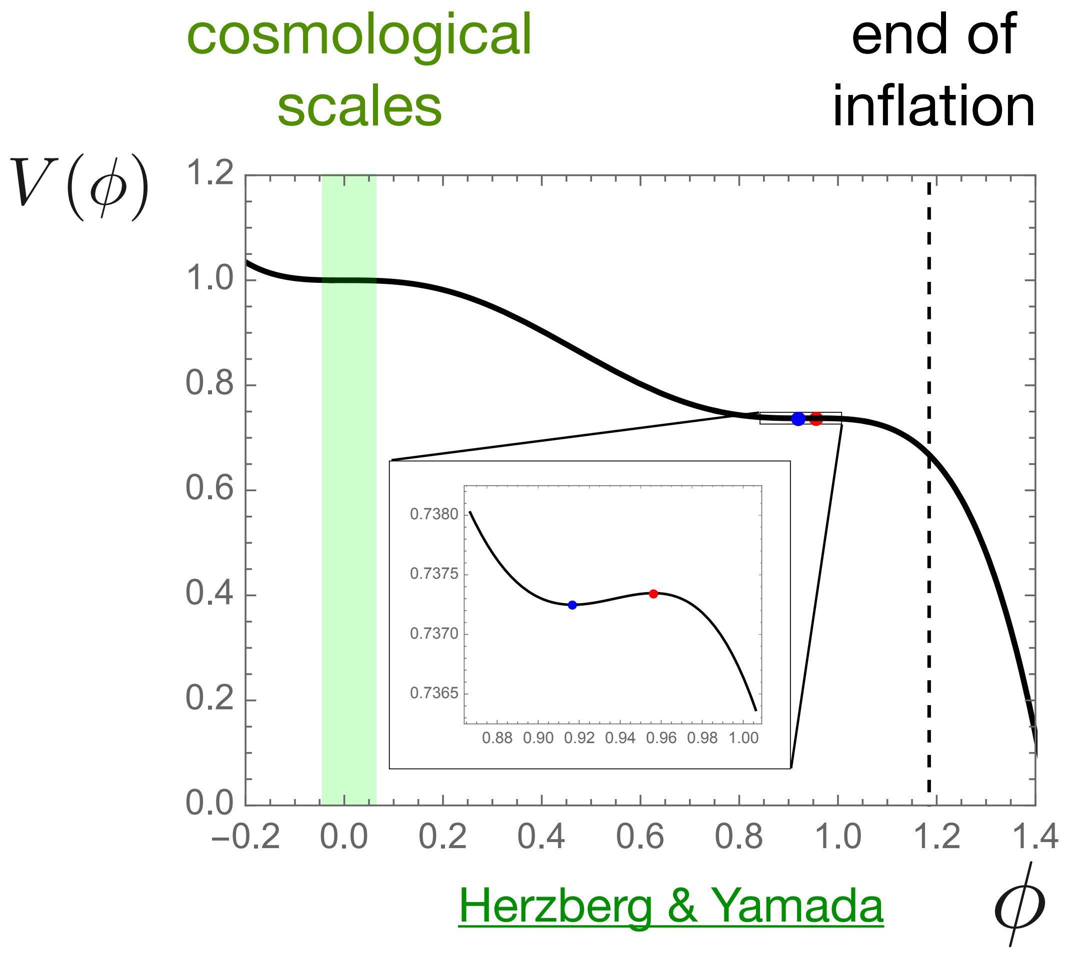
Requirements for a PBH producing inflation model:

i) produce measured power spectrum (amplitude and scale dependence) on cosmological scales,

ii) amplitude of perturbations ~3.5 orders of magnitude larger on some smaller scale,

iii) inflation ends.

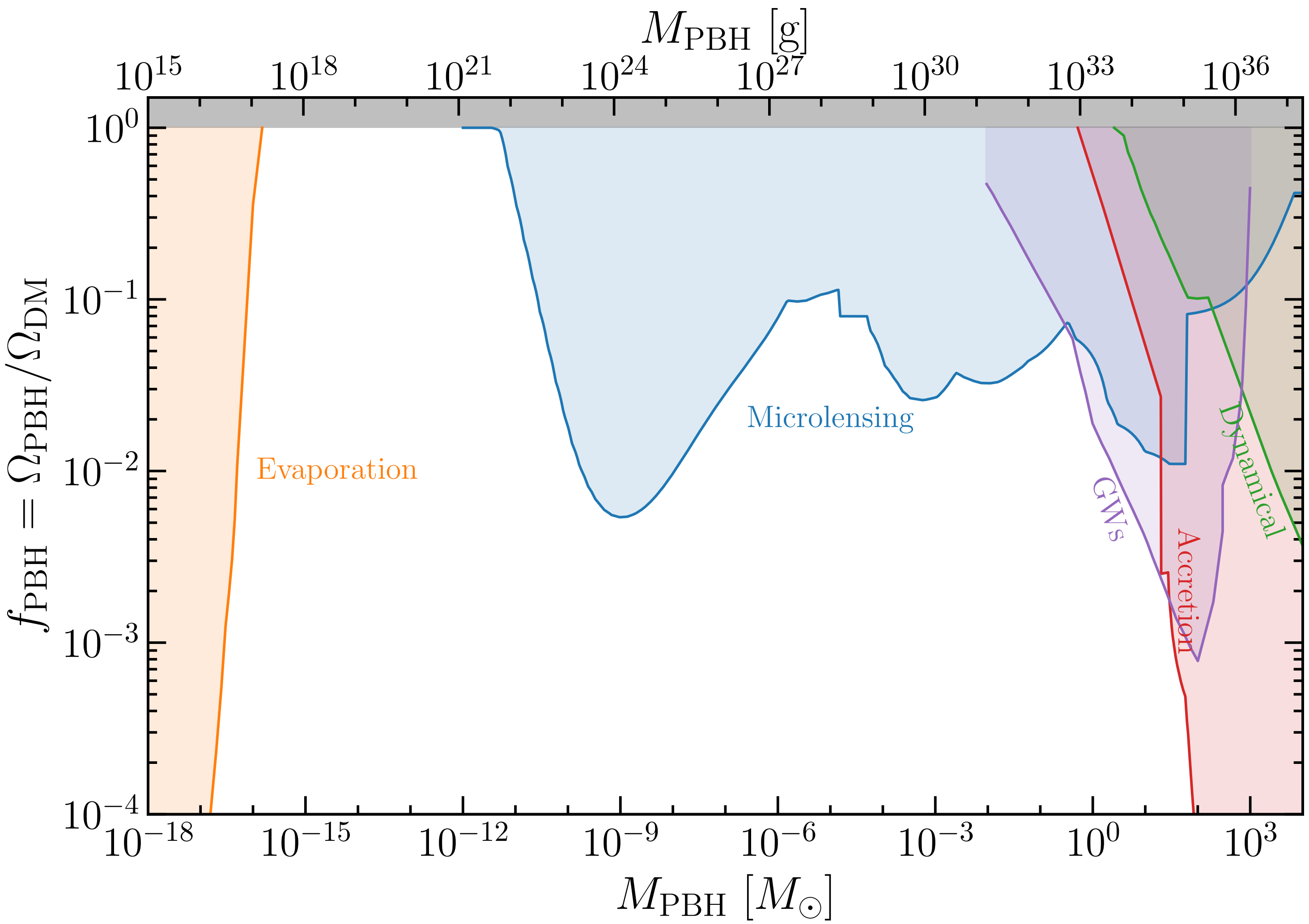
Can be achieved in single-field models (with e.g. a plateau or bump/dip feature) but requires fine-tuning.
see Öszoy & Tasinato; Escriva, Kuhnel & Tada



Herzberg & Yamada

Detection: current

fraction of
dark matter



evaporation

lensing

gravitational waves

accretion

dynamical

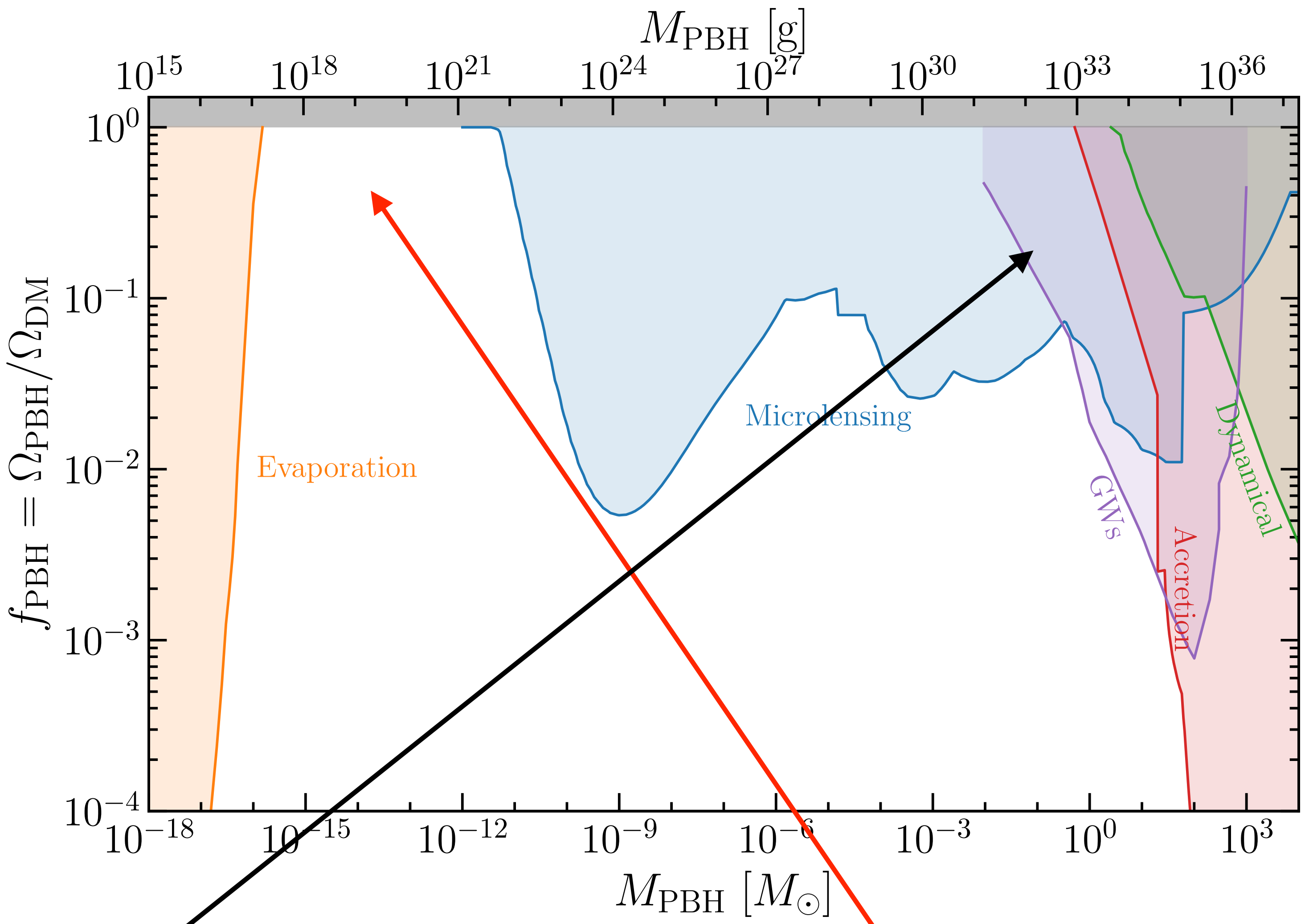
PBH mass

https://github.com/bradkav/PBHbounds

n.b. this plot assumes all PBHs have the same mass, for realistic extended mass functions constraints are ‘smeared out’.

Detection: current

fraction of
dark matter



evaporation

lensing

gravitational waves

accretion

dynamical

PBH mass

https://github.com/bradkav/PBHbounds

multi-Solar mass Primordial Black Holes making up all of the DM appears to be excluded.

However there is a hard to probe, open window for very light (asteroid mass) PBHs.

future prospects ‘asteroid mass window’

Snowmass2021 PBHs

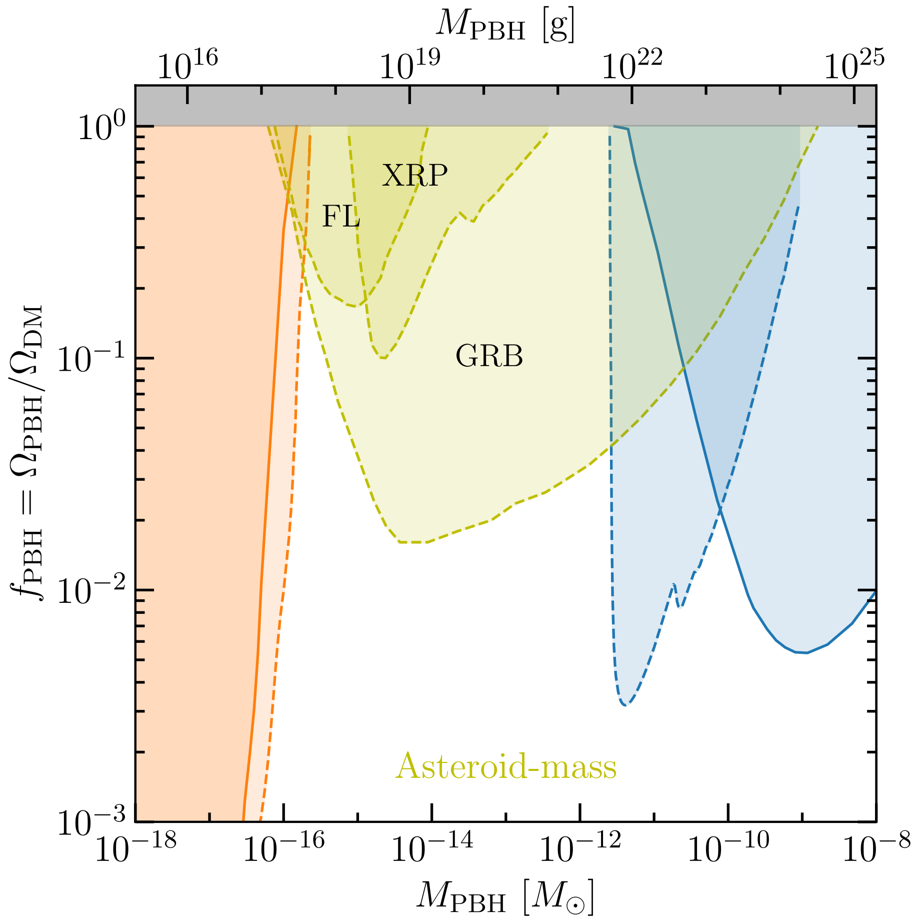
Hard to probe:

evaporation rate small $\mathrm{d}M_{\rm PBH}/\mathrm{d}t \propto M_{\rm PBH}^{-2}$

no optical microlensing due to ‘wave effects’ (Schwarzschild radius comparable to wavelength of light)

Need other methods, e.g. femtolensing (FL) or lensing parallax of gamma ray bursts (GRB), microlensing of X-ray pulsars (XRP)

Could also potentially be probed via their effects on stars, e.g. white dwarfs.



evaporation

stellar microlensing

Axions & Axion Like Particles (ALPs)

Snowmass2021 axions, Marsh: long, popular, various O'Hare talks

Theoretical motivation

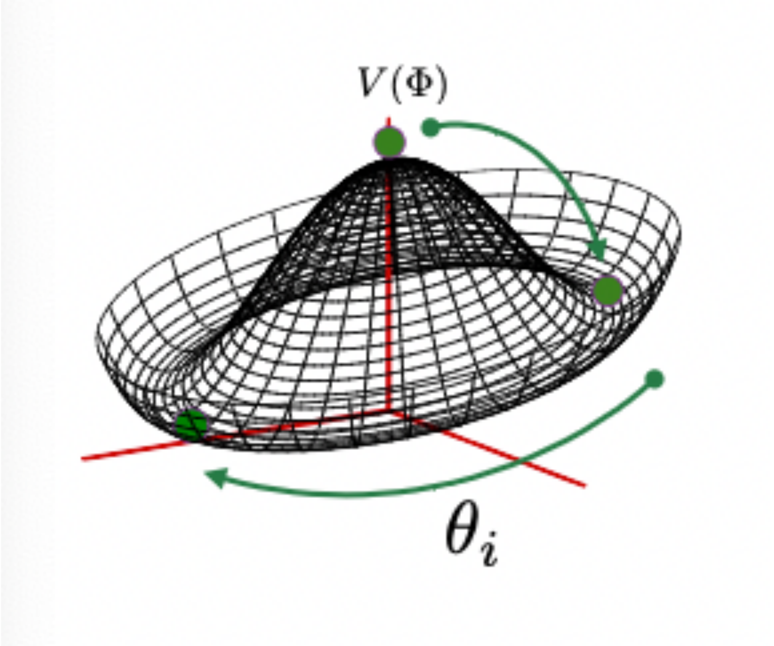
QCD axion is a consequence of Peccei-Quinn (PQ) symmetry proposed to solve strong CP problem ("why is the electric dipole moment of the neutron so small?").

PQ symmetry broken at $T_{\mathrm{PQ}} \sim f_{\mathrm{a}}$, mass of QCD axion, m_{a}, grows and becomes constant at $T_{\mathrm{QCD}} \sim 100\,\mathrm{GeV}$.

Mass m_{a} related to scale of symmetry breaking, f_{a}: $m_a = 0.62\,eV \left(\frac{10^7\,GeV}{f_a}\right)$

More broadly: Axion Like Particles (ALPs) and Ultra Light Axions (ULAs) (light pseudo scalar fields predicted e.g. in low-energy effective theories from string theory).

Can be produced via ‘misalignment angle’ mechanism:



O’Hare

$$V(\theta) = m_{\mathrm{a}}^2(T) f_a^2 (1 - \cos\theta) \qquad \theta \equiv a/f_{\mathrm{a}}$$

$$V(\theta) \approx \frac{1}{2} m_a^2(T) f_a^2 \theta^2$$

Coherent oscillations of field ≡ cold dark matter

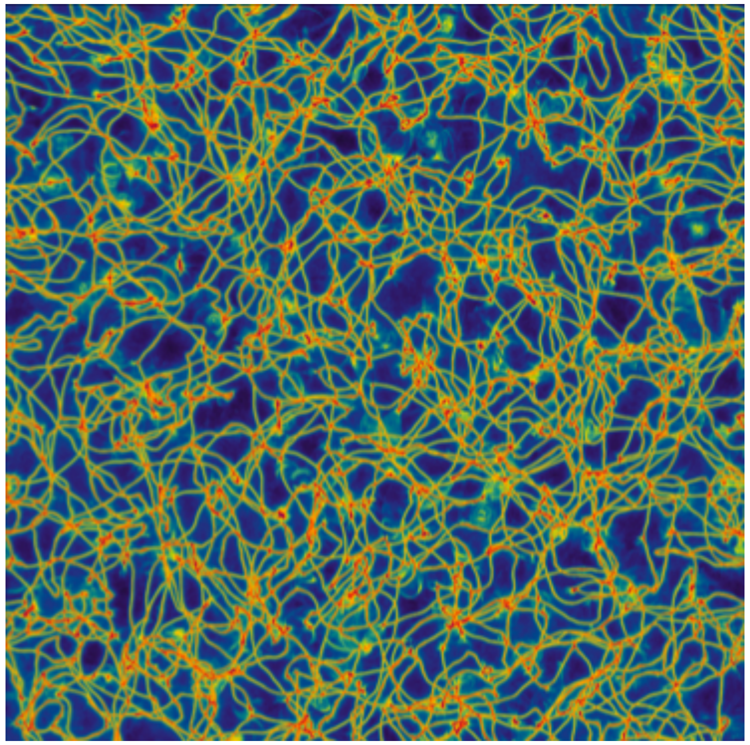
$$\Omega_{\mathrm{a}} \propto \theta_{\mathrm{i}}^2 \, m_{\mathrm{a}}^{-7/6}$$

PQ symmetry broken before inflation ('pre-inflationary')

$\theta_{\rm i}$ has constant, unknown, value everywhere in observable Universe.

PQ symmetry broken after inflation ('post-inflationary')

$\theta_{\rm i}$ varies, $\langle \theta_{\rm i}^2 \rangle = \pi^2/3$, and axions are also produced via topological defects



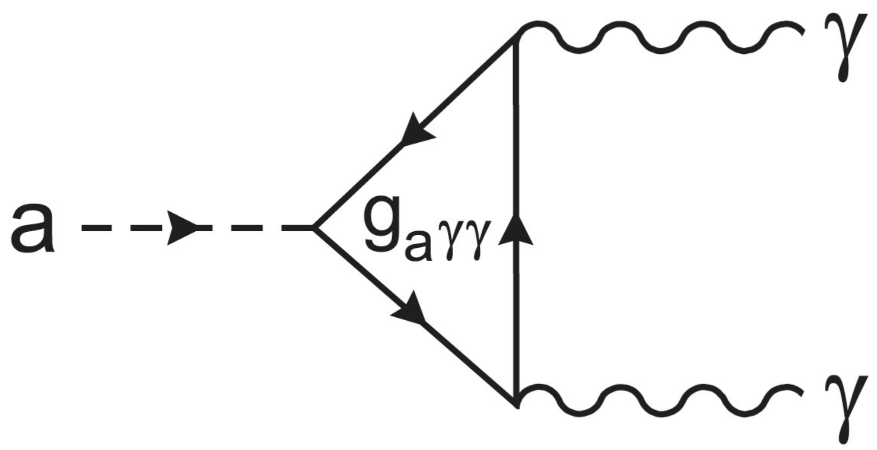
O'Hare

Value of $m_{\rm a}$ for which $\Omega_{\rm a} = 0.26$ isn't accurately known.

In pre-inflationary scenario don't know value of $\theta_{\rm i}$.
In post-inflationary scenario axion-string network is hard to simulation.

Detection:

Axions can be detected by resonant conversion to photons in a strong magnetic field (Primakoff process).



Overduin

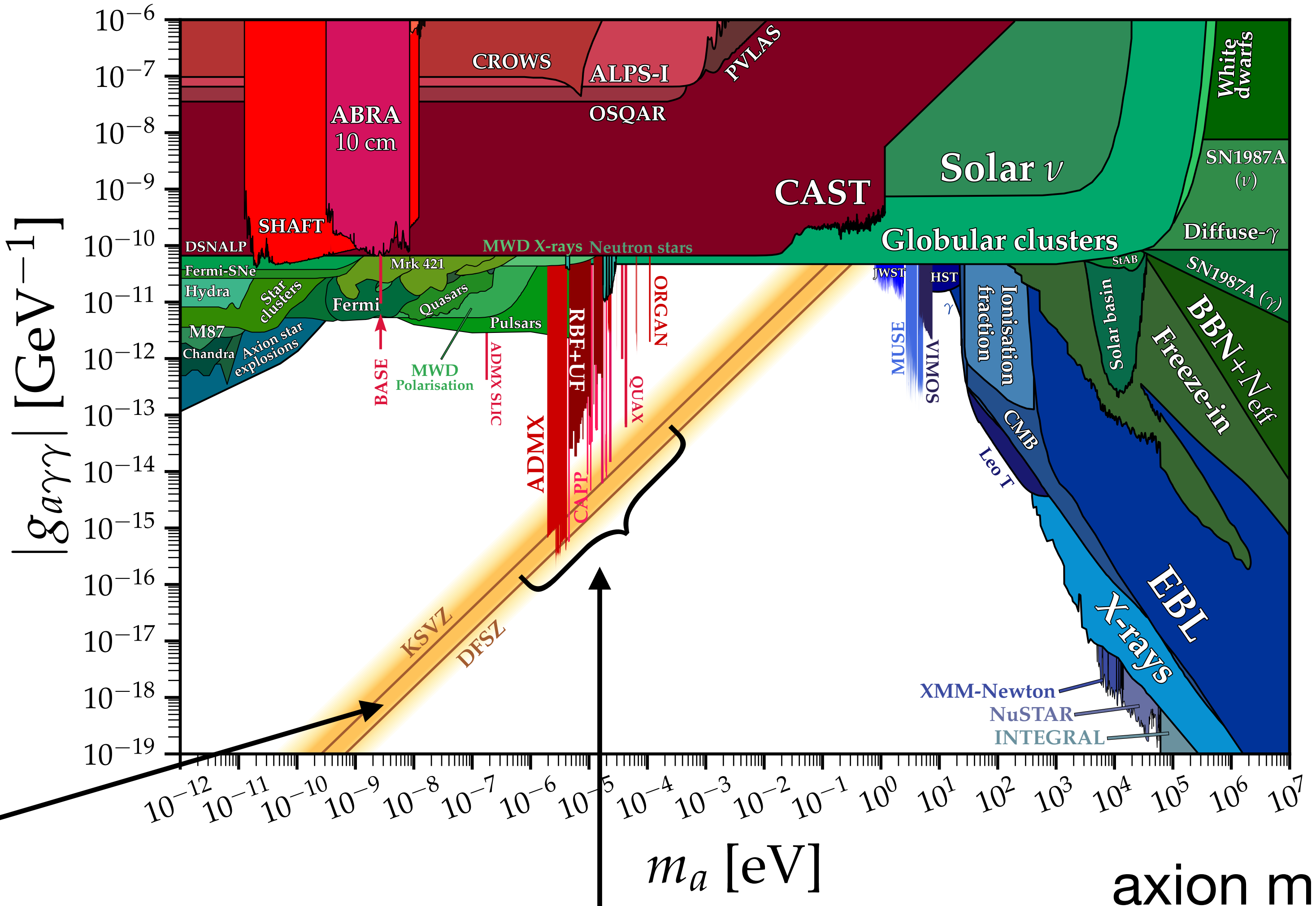
current

experimental searches haloscopes, helioscopes, light shining through a wall

cosmology effect of decay on CMB, extragalactic background light, X-rays,…

astrophysics effects on stellar evolution: solar neutrinos, globular clusters, effects of photon-ALP mixing on gamma-ray spectra

coupling to photons



axion mass

QCD axion

haloscopes
detecting DM in MW halo
in region where $\Omega_a \sim 1$

https://cajohare.github.io/AxionLimits/

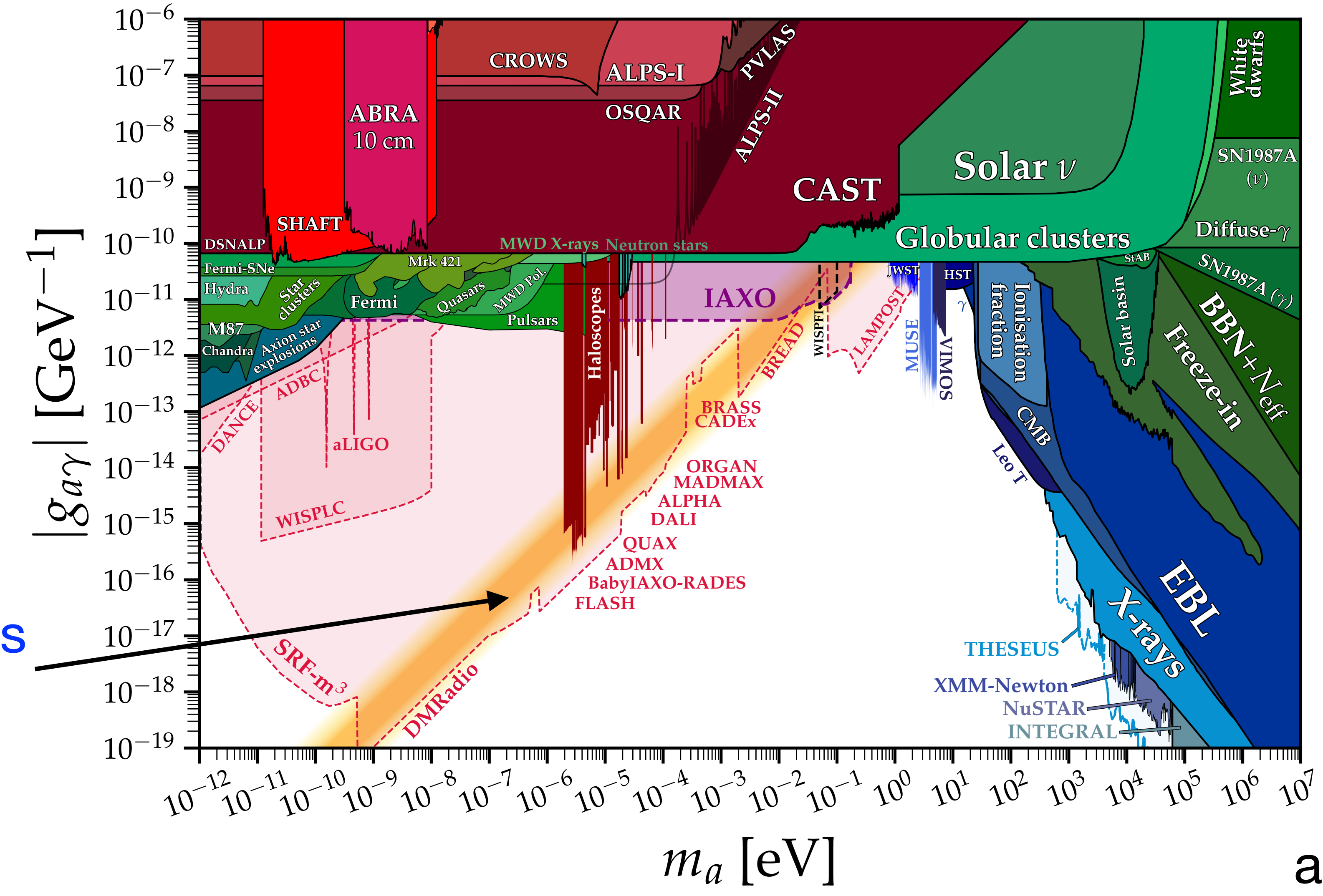
future

experimental searches haloscopes, helioscopes, light shining through a wall

cosmology effect of decay on CMB, extragalactic background light, X-rays,…

astrophysics effects on stellar evolution: solar neutrinos, globular clusters, effects of photon-ALP mixing on gamma-ray spectra

coupling to photons



quantum sensors (e.g. QSHS)

axion mass

https://cajohare.github.io/AxionLimits/

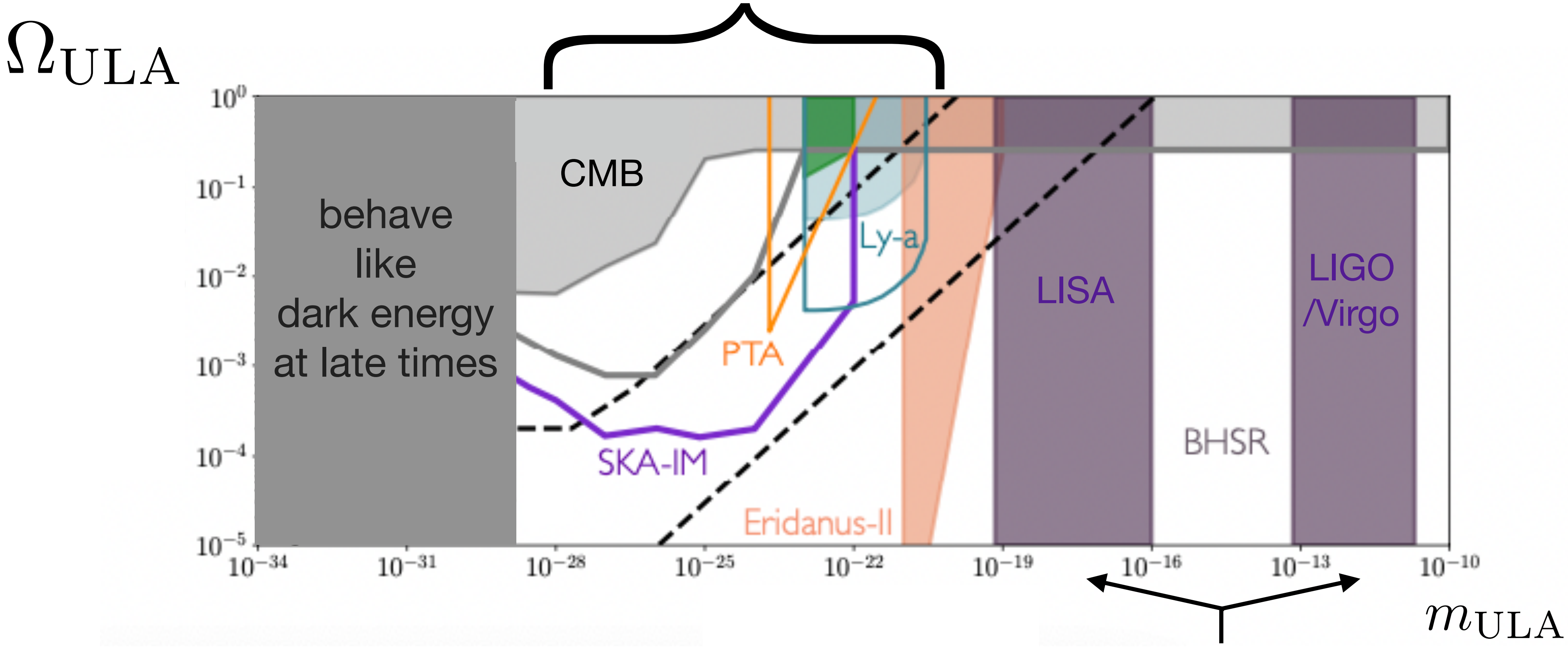
ultra light axions SnowMass, ULA DM LoI

'fuzzy' DM, de Broglie wavelength ~ astronomical scales (> kpc)

suppression of structure formation on small scales

power spectrum of density perturbations (CMB, Lyman-α forest)

individual galaxies



black hole super radiance

axion cloud around BH reduces spin → gravitational radiation

+ atomic experiments (e.g. AEDGE, AION)

II. Summary

Various Dark Matter candidates with different motivations, masses and interactions.

And lots of experimental and observational searches ongoing.

WIMPs:

- arise from new weak scale physics e.g. supersymmetry
- detect directly (in lab) or indirect (via annihilation products).

PBHs:

- can form from over densities in early Universe
- detect via evaporation, lensing, gravitational waves + other effects

Axions *(ALPs)*:

- consequence of Peccei-Quinn symmetry proposed to solve strong CP problem *(motivated by string theory)*
- detect via haloscopes *(various observational/experimental probes)*