DARK MATTER

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1. Observational evidence for dark matter

2. WIMPs (theory and detection)

3. Other dark matter candidates

OTHER DARK MATTER CANDIDATES

- axions
  - theoretical motivation
  - cosmology
  - detection
- other C(or W)DM candidates
  - primordial black holes
  - SuperWIMPs
  - sterile neutrinos
  - MeV dark matter
  - superheavy dark matter

AXIONS:
THEORERETICAL MOTIVATION

✧ consequence of Pecci-Quinn symmetry proposed to solve strong CP problem (non-perturbative effects should induce large CP violation, but constrained to be small by tight experimental limts on the electric dipole moment of the neutron)

✧ very light and very weakly interacting

mass is related to scale of symmetry breaking, f_a :

$$m_a = 0.62\, eV \left(\frac{10^7\, GeV}{f_a} \right)$$

✧ constraints on mass from cosmology, lab searches and from cooling of stars and supernovae (more later)

AXION COSMOLOGY

Thermal production:

Axions are produced in the early Universe by photo-production and pion-axion conversion:

$\gamma + q \to q + a$ dominant process before QCD PT

$N + \pi \to N + a$ only occurs once nucleons form after QCD PT

Principles of abundance calculation essentially same as for WIMPs (Boltzmann equation).

If $m_a > 10^{-3}\, eV$ thermal population of WIMPs produced with:

$$\Omega_a h^2 = \frac{m_a}{130\, eV}\left(\frac{10}{g_\star}\right)$$

$\Omega_a h^2 = O(0.1)$ requires $m_a \sim 10\, eV$ which is excluded by astrophysical constraints.

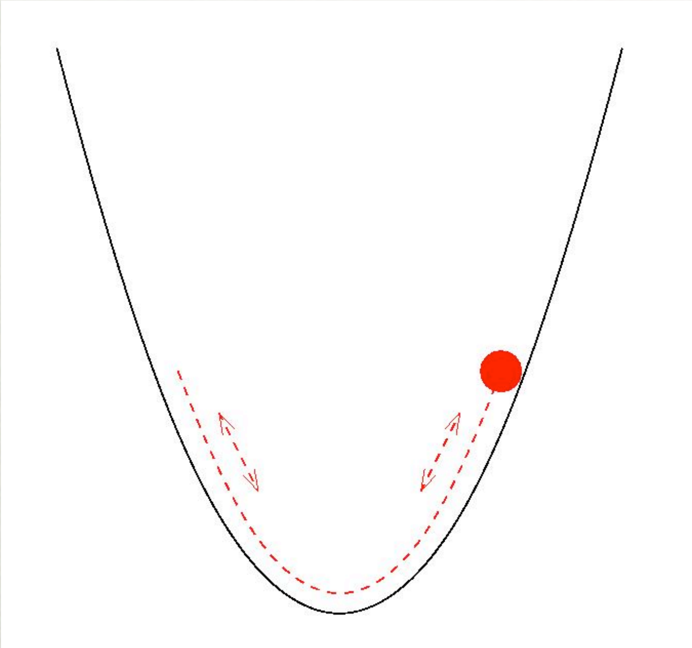
Thermally produced axions can not be the dominant component of the CDM.

(but axions with $m_a \sim O(1\, eV)$ would have thermal density roughly equal to the baryon density and could have observable consequences.....)

mis-alignment angle production:

Axion field appears at Peccei-Quinn phase transition at T~f_a

Axion mass `switches on' much later, around QCD phase transition



$$V(\theta) = m_a^2(T) f_a^2 (1 - \cos\theta) \qquad \theta \equiv a/f_a$$

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

Coherent oscillations of field ≡ cold dark matter

Axion density depends on value of field when oscillations commence at $m_a(T_1) \approx 3H(T_1), \quad T_1 \sim 1\,GeV$:

$$n_a(T_1) = \frac{1}{2} m_a(T_1) \theta_1^2 f_a^2$$

θ_1 depends on cosmological history

i) inflation does not occur OR inflation occurs but re-heat temperature is high enough that Peccei-Quinn symmetry is restored ($T_{RH} > f_a$)

Coherence length of axion field ~ Horizon scale at PQ PT << Horizon scale at QCD PT

Large spatial variations in axion field at T_1:

Large spatial variations in density.

Mean density depends only on axion mass/f_a:

$$\Omega_a h^2 \approx \left(\frac{\Lambda_{QCD}}{200\,\mathrm{MeV}}\right)^{-0.7} \left(\frac{m_a}{10^{-5}\,\mathrm{eV}}\right)^{-1.18}$$

ii) inflation occurs and re-heat temperature is lower than Peccei-Quinn scale ($T_{RH} < f_a$)

Entire observable Universe originates from region smaller than horizon scale at PQ PT.

Axion field uniform (modulo fluctuations generated during inflation....):

Density uniform, and depends on axion mass and (unknown) value of field at PQ-PT

$$\Omega_a h^2 \approx 0.1 \left(\frac{\Lambda_{QCD}}{200\,\mathrm{MeV}}\right)^{-0.7} \left(\frac{m_a}{10^{-5}\,\mathrm{eV}}\right)^{-1.18} f_{an}(\theta_1)\theta_1^2$$

Production by axionic strings:

Network of (global) axion strings produced after PQ phase transition.

Strings radiate axions. Controversy over spectrum (and density) of axions produced (impossible to do simulations of physically relevant regime, therefore calculations rely on extrapolations.....). [e.g. Sikivie, Battye & Shellard, Yamaguchi et al.]

Density roughly comparable to density of mis-alignment axions.

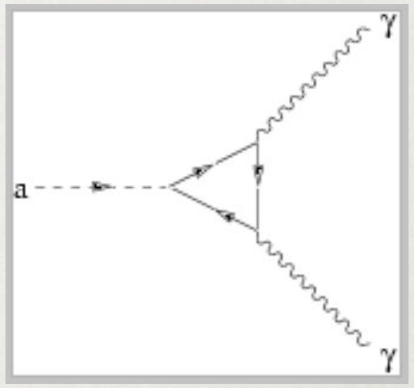
After QCD PT unstable network of domain walls forms, decays producing further axions.

If inflation occurs and re-heat temperature is lower than Peccei-Quinn scale ($T_{RH} < f_a$) axionic strings are inflated away.

AXION DETECTION/BOUNDS

Lab searches:

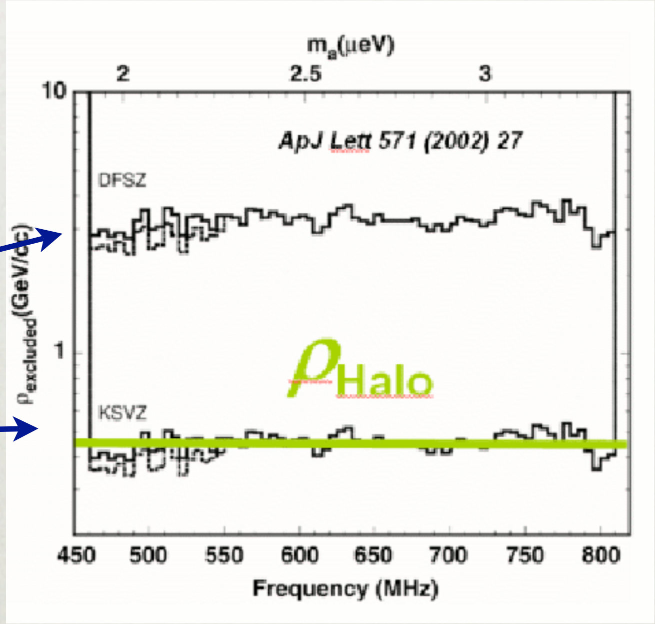
Coupling to two photons leads to resonant conversion of axions to photons in a strong magnetic field (Primakoff process).



ADMX (Axion Dark Matter eXperiment) has sensitivity to detect galactic halo axions

DFSZ: interact with electrons

KSVZ: no tree level coupling to electrons



AMDX

[CAST (CERN Axion Solar Telescope) is trying to detect axions from the Sun using the same process, but is sensitive to axions which are too heavy to be the CDM]

Astrophysical constraints:

see e.g. Raffelt

Coupling to photons (and electrons for DFSZ axions) means that axions could act as (invisible) energy loss channel in various (fairly well-understood) astrophysical situations:

Globular cluster stars

decrease lifetime of helium burning (horizontal branch) stars

White dwarfs

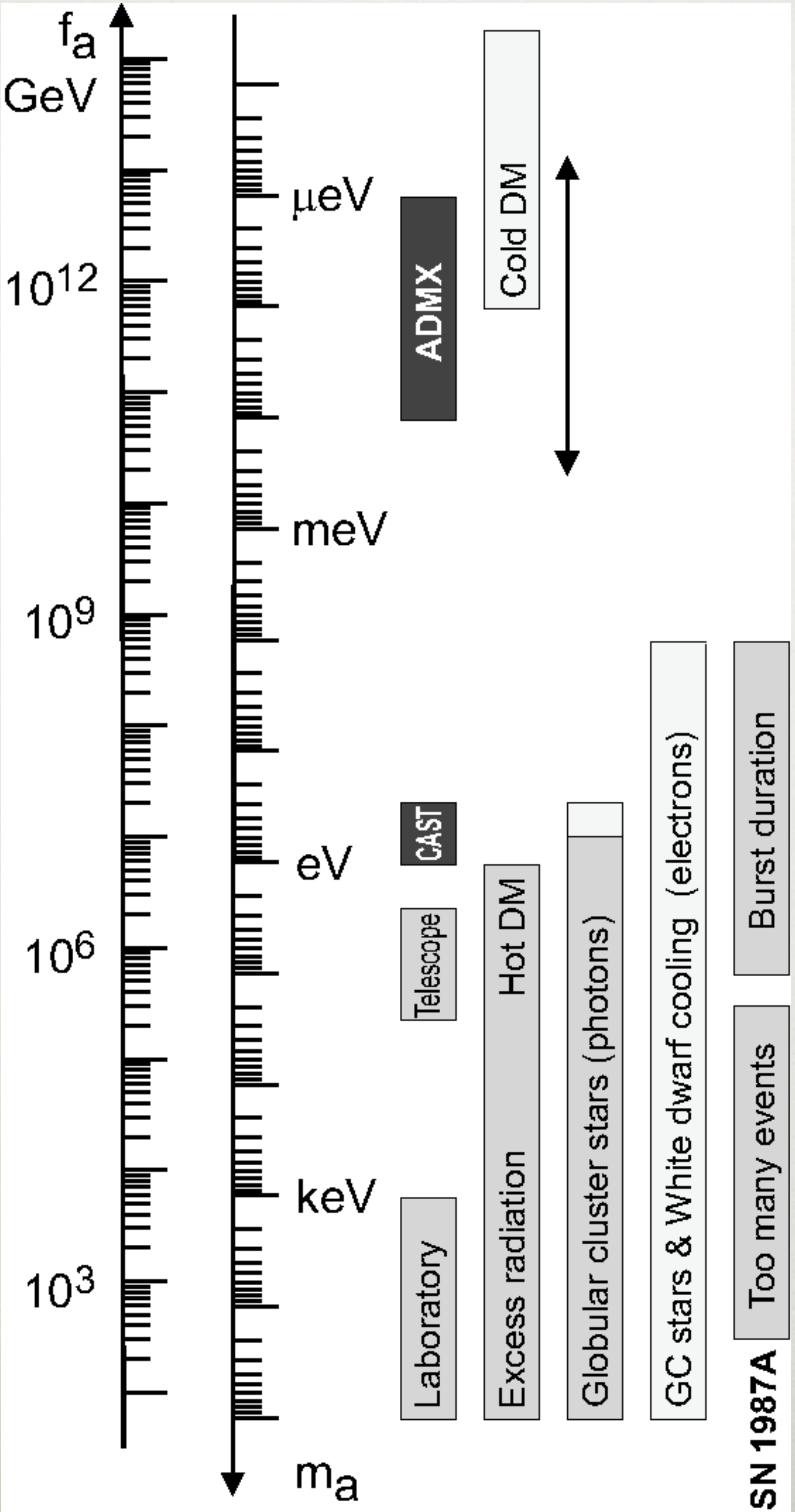
change white dwarf luminosity function

Supernova 1987A

reduce duration of neutrino burst

Hot dark matter axions constrained by same structure formation considerations as neutrinos (perturbations can't be erased on dwarf galaxy and larger scales).

Axions with $m_a >\sim 20\, eV$ have lifetime shorter than Hubble timescale (therefore not cosmological dark matter and also ruled out by consequence of decay photons).



f_a GeV
10^12
10^9
10^6
10^3
μeV
meV
eV
keV
m_a
ADMX
Cold DM
CAST
Telescope
Hot DM
Laboratory
Excess radiation
Globular cluster stars (photons)
GC stars & White dwarf cooling (electrons)
Burst duration
Too many events
SN 1987A

Raffelt

MINI-SUMMARY

AXIONS

Consequence of Pecci-Quinn symmetry proposed to solve strong CP problem.

Various astrophysical constraints on mass (cooling of globular cluster stars and white dwarfs, SN1987A).

If dominant component of dark matter must be produced non-thermally (e.g. mis-alignment mechanism, axionic strings). Abundance depends on cosmology.

Lab searches ongoing, using resonant conversion to photons in strong magnetic field.

PRIMORDIAL BLACK HOLES

Primordial Black Holes (PBHs) can form via various mechanisms (collapse of large density perturbations, cosmic string loops, bubble wall collisions) in the early (radiation dominated) Universe.

Form before nucleosynthesis, therefore are non-baryonic (and no extension of the standard model/new particles required).

Emit Hawking radiation. PBHs with $M_{PBH} >\sim 5 \times 10^{14} g$ have lifetime less than the age of the Universe.

Observational constraints on more massive PBHs:

$10^{17} g < M_{PBH} < 10^{20} g$ Constrained by femtolensing of GRBs to make up less than ~0.2 of critical density.

$10^{26} g < M_{PBH} < 10^{34} g$ Constrained by microlensing observations to make up less than 20% of the Milky Way halo.

$M_{PBH} >\sim 10^{34} g$ Would disrupt globular cluster and heat the Galactic disc (probably...).

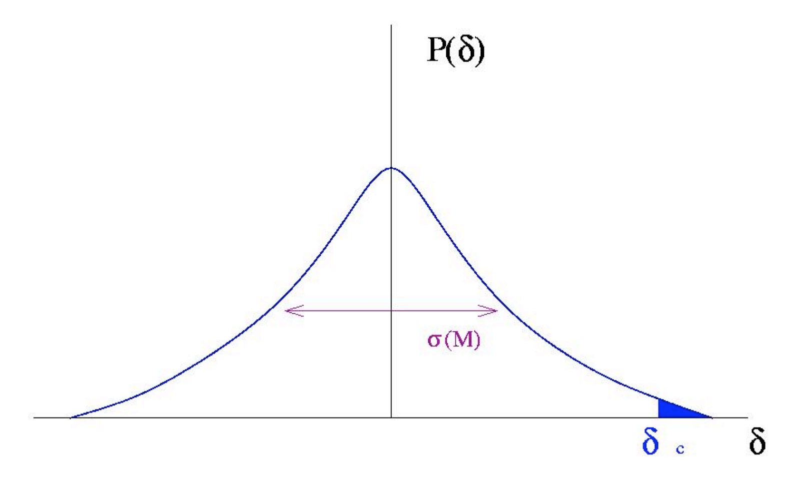
Collapse of density perturbations:

If density fluctuation in a given region is sufficiently large gravity overcomes pressure and fluctuation collapses to form a black hole with mass roughly equal to the horizon mass.

Criteria for PBH formation:

$$\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}} > \delta_c \sim 0.3 - 0.5$$

Carr; Musco et al.



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

Present day density:

$$\Omega^0_{\rm PBH} \sim \mathcal{O}(1) \qquad \rightarrow \qquad \sigma(M) \sim 0.05$$

This requires the density perturbations on small scales to be significantly larger on small scales than they are on cosmological scales ($\sigma(M) \approx 10^{-5}$).

This could happen if the primordial power spectrum has a feature or positive running, $dn/d\ln k > 0$.

But need fine tuning in order not to produce far too many, or too few, PBHs.

SuperWIMPs

Feng and collaborators

Extremely weakly interacting particles produced in late decay of WIMPs (e.g. axino or graviton from decay of neutralino or slepton).

Interesting density inherited from WIMP parent.

Only interact gravitationally, therefore can't be detected directly.

Constraints from

i) effects of photons generated in production (light element abundances, distortion of CMB spectrum).

ii) Large scale structure (e.g. CMB, galaxy clustering and Lyman-alpha forest) limits on suppression of density perturbations (can be produced with large velocity).

Potential collider signal: production of meta-stable (lifetime ~months) sleptons.

STERILE NEUTRINOS

c.f. Mikko Laine's talk

Fermions with no standard model couplings (other than to standard neutrino through mass generation mechanism).

Arise in many extensions of standard model (grand unified models, string-inspired large extra dimensions).

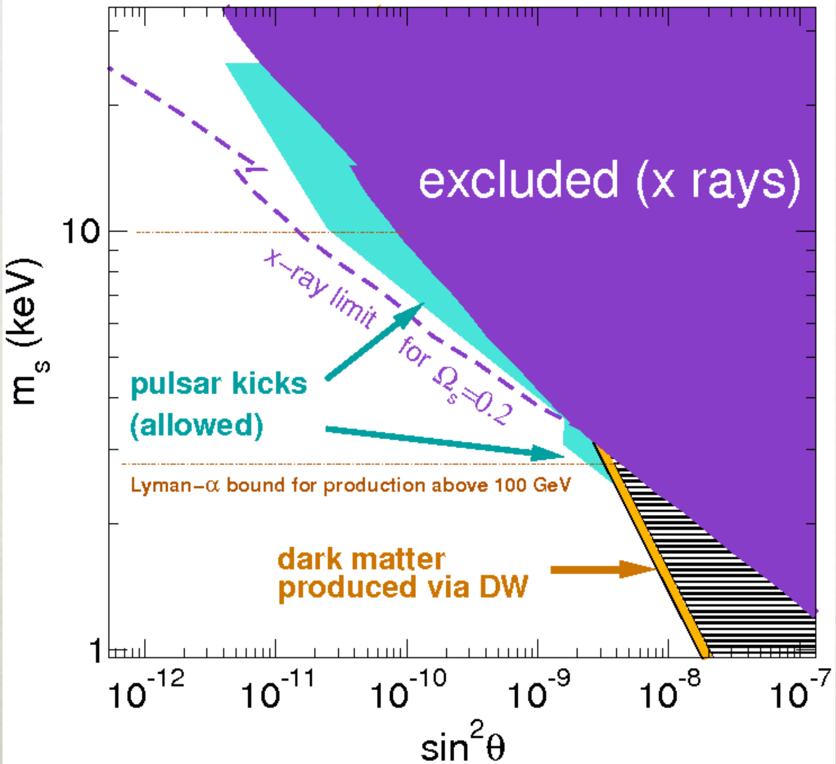
Can be produced with interesting density via oscillations with standard neutrinos (Dodelson-Widrow mechanism).

Other production methods possible.

Constraints from:

i) Large scale structure (e.g. CMB, galaxy clustering and Lyman-alpha forest) limits on suppression of density perturbations (warm dark matter, large free-streaming length).

ii) X-ray photons produced in decays



Kusenko

MEV DARK MATTER

e.g. Boehm, Fayet, Hooper...

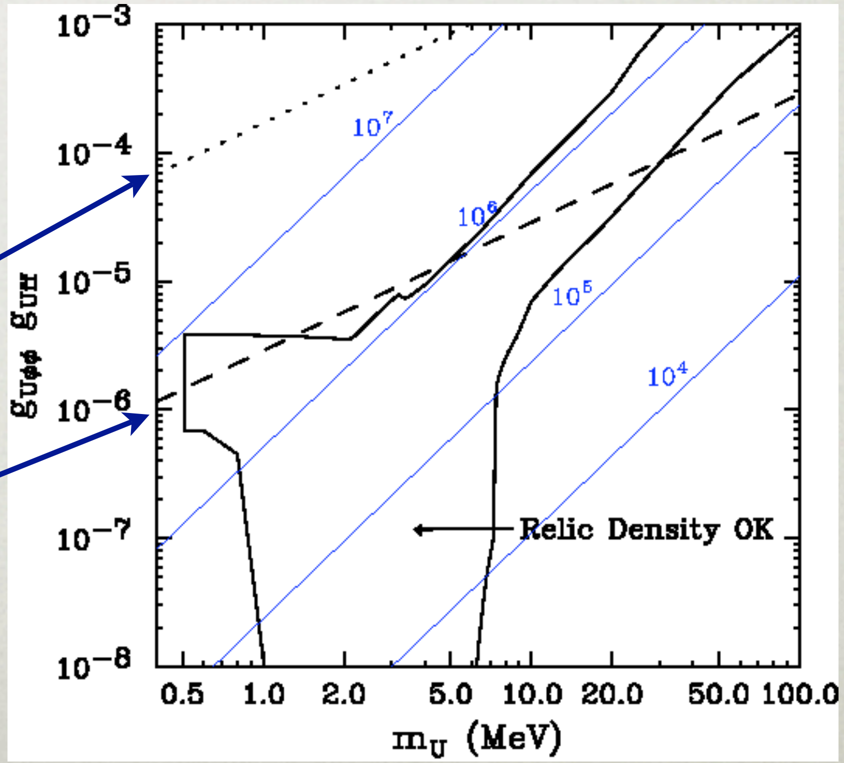
Motivated by observation of 511 keV emission (in particular by INTEGRAL) from Galactic bulge.

MeV mass scalar which annihilates through the exchange of a light gauge boson can

i) be produced in the early Universe with abundance required to be dark matter

ii) produce positrons required to explain 511 keV emission

Various constraints including erasure of small scale structure due to free-streaming.



from e magnetic moment

from νe scattering

free-streaming mass scale

Hooper et al.

SUPER-HEAVY DARK MATTER

(A.K.A WIMPZILLAS)

Kolb, Chung & Riotto, Linde

Super-heavy particles produced non-thermally e.g. during reheating process at end of inflation (mass ~ inflaton mass).

Potential source of Ultra-High Energy Cosmic Rays (probably not so interesting post Auger...).

SUMMARY

Axions: consequence of Peccei-Quinn symmetry, proposed to solve strong CP problem
very light & very weakly interacting (microphysics very different to WIMPs)
detectable in lab via resonant conversion to photons in a strong B field

Primordial Black Holes: could be dark matter if $10^{20}\,g < M_{PBH} < 10^{26}\,g$
no new physics required
can form from collapse of large density fluctuations (but interesting abundance requires fine tuning of size of fluctuations)

SuperWIMPs: e.g. gravitinos produced in decay of NLSP neutralino or slepton
extremely weakly interacting (not directly detectable)
constraints from radiation produced in NLSP decay & free-streaming
collider signature: decay of slepton

Sterile neutrinos: fermions with no standard model coupling
arise in various extensions of standard model
tightly constrained by X-rays & free-streaming

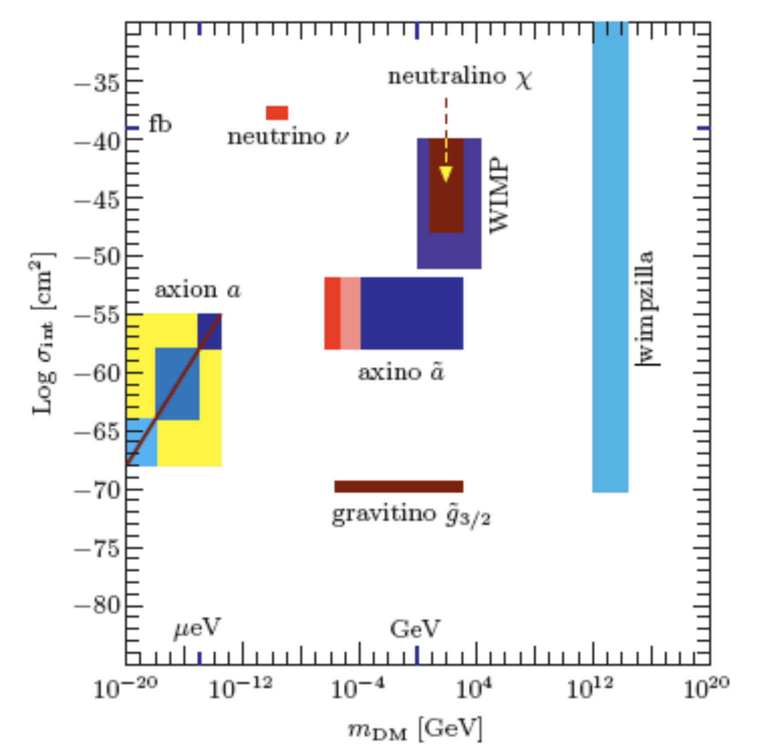
MeV dark matter: invoked to explain INTEGRAL 511 keV emission
constraints from damping of density perturbations

WIMPzillas: superheavy particle produced during reheating era after inflation

And many more which I haven’t had time to cover...

Bottom line:

Lots of DM candidates as well as `vanilla’ WIMPs
(with very different masses and microphysics)



Kim

Most can be constrained/probed with combination of astrophysical and lab based experiments.

OVERALL SUMMARY

★ Lots of cosmological and astronomical evidence for non-baryonic cold dark matter
(imho modified gravity hasn't been completely ruled out yet, but has some tough observational tests to pass).

★ Models of particle physics beyond the standard model provide us with well motivated CDM candidates e.g. WIMPs and axions
(but there are many other dark matter candidates).

★ (convincingly) Detecting CDM (and measuring its properties) will probably require a mixture of lab, collider and astrophysical experiments/observations.