Astroparticle Physics – the Dark Side of the Universe

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Outline

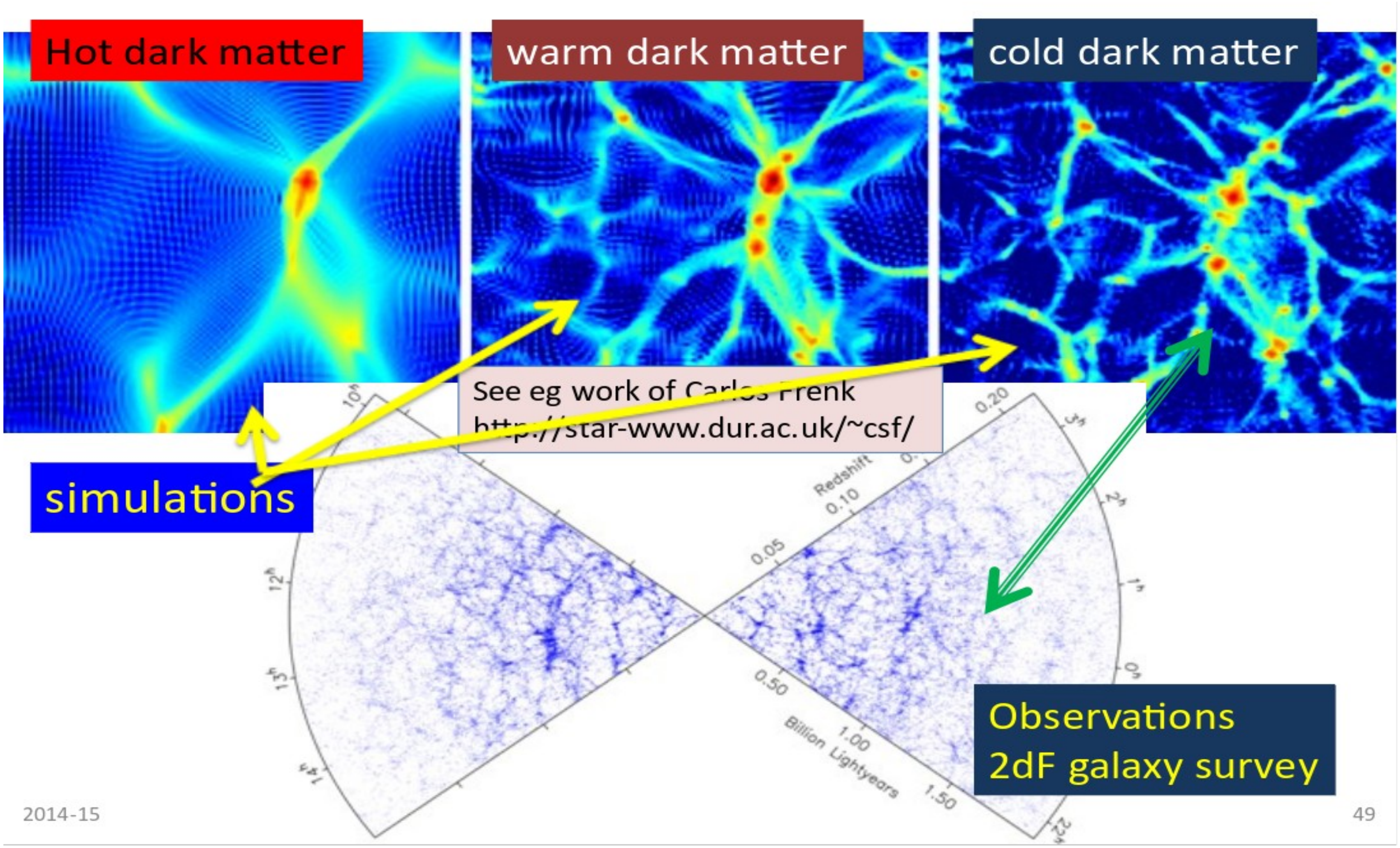
Dark Matter

- Evidence for dark matter
- Theory of dark matter
- Searches for dark matter
- Searches at colliders
- Direct searches
- Indirect searches

Dark Energy and the History and Fate of the Universe

(2) Theory of Dark Matter

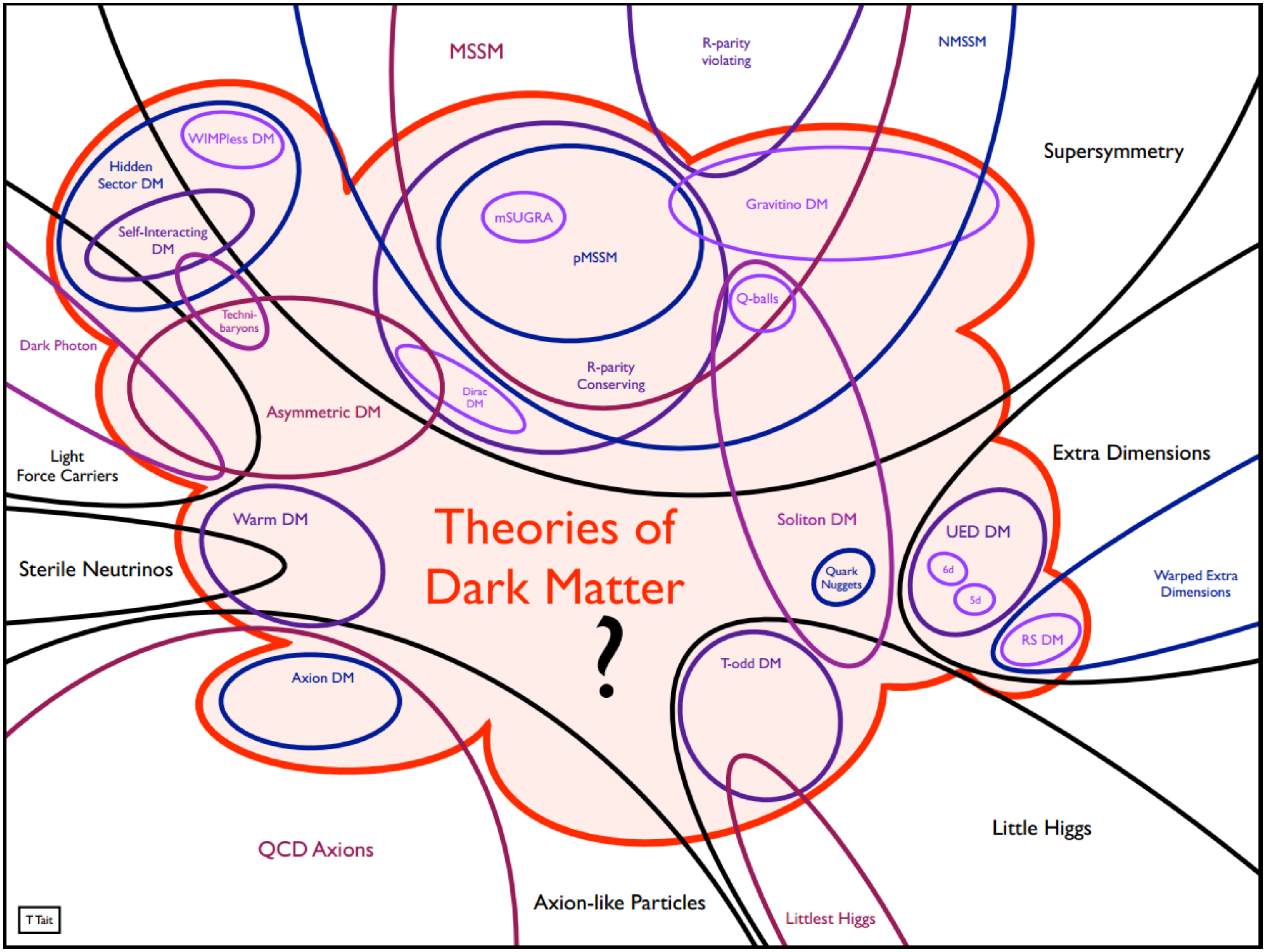
Dark matter needs to be (mostly) cold



Dark matter candidates

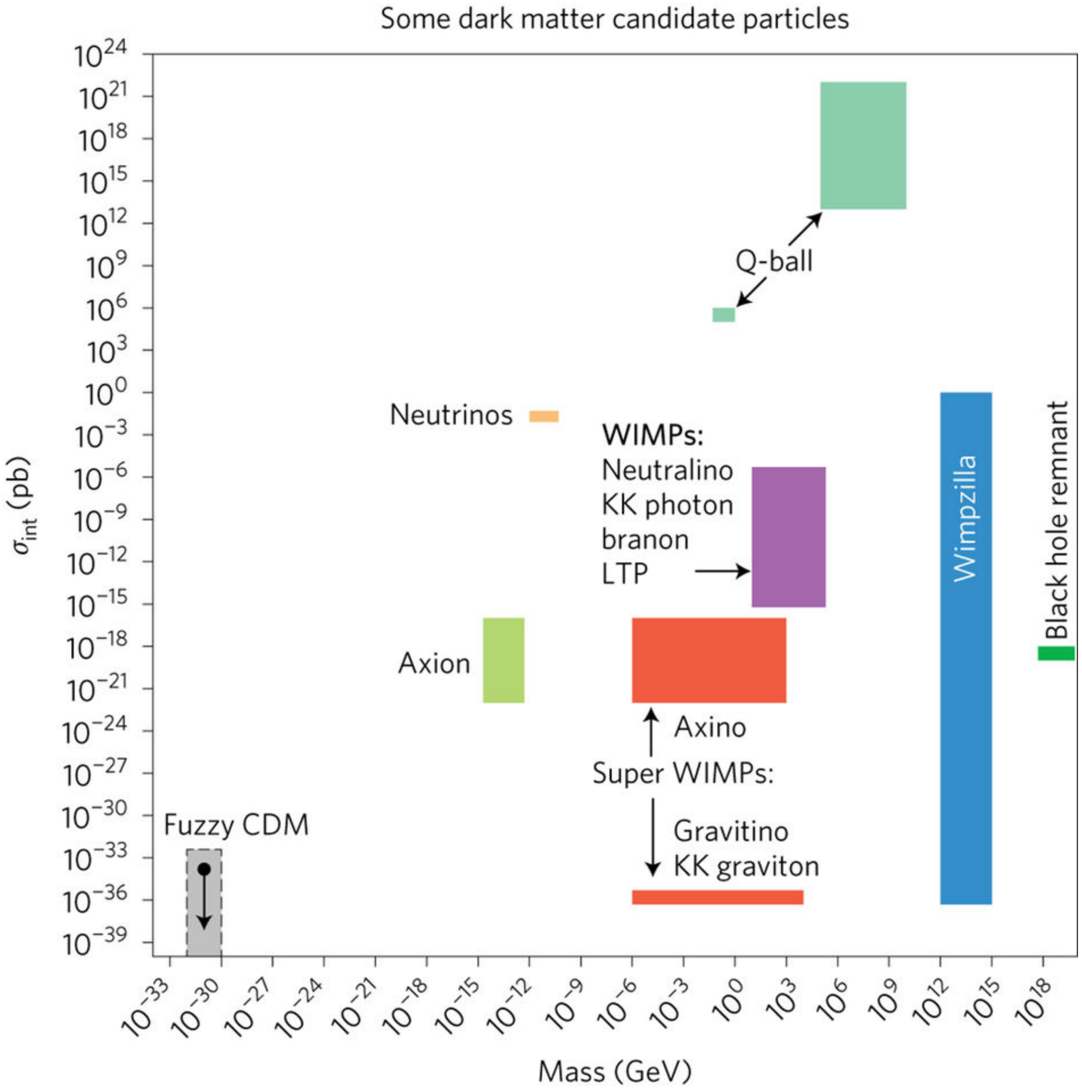
- **Neutrinos**
- **Primordial Black Holes**
- **MACHOS** – massive astrophysical compact halo objects
- **MOND (and TeVeS)** – MOdified Newtonian Dynamics
- **WIMPS** – Weakly interacting massive particles, the darling of particle physicists
- **Axions** – introduced in QCD to solve the strong CP problem
- **Dark photons** – an entire dark sector that talks via a dark force with ordinary matter
- **Emergent Gravity** – there is no fundamental gravity, there is only information

An enormous number of theories ….



arXiv:1401.6085

… on all mass scales!



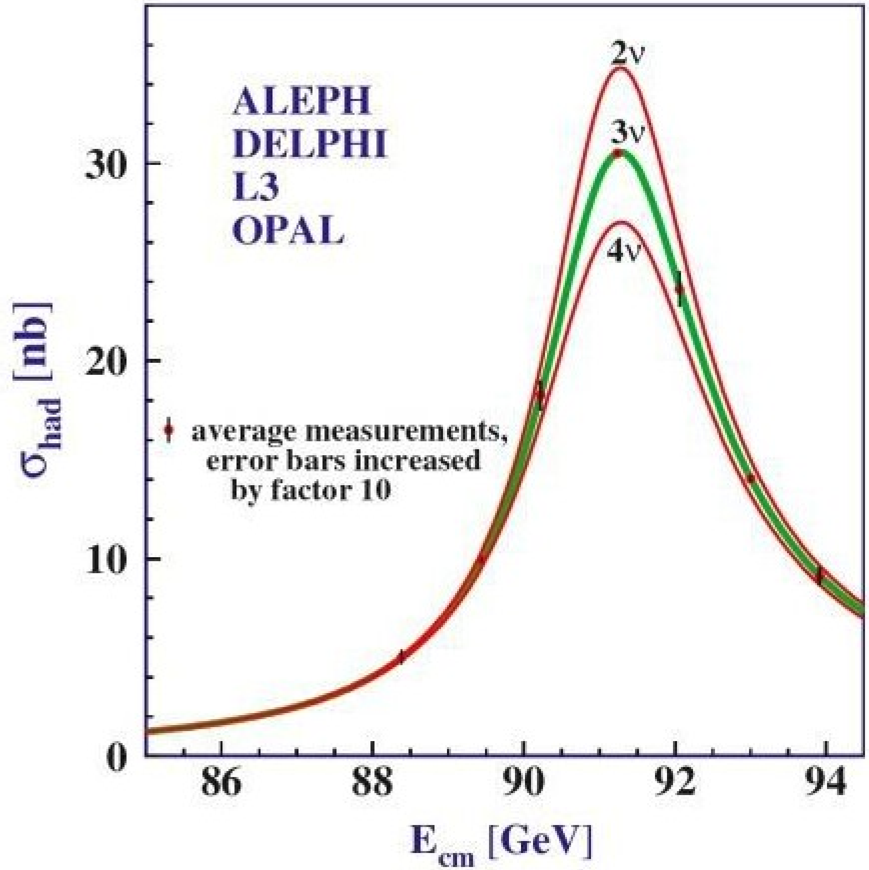
Indirect dark matter searches in gamma and cosmic rays”, J. Conrad and O. Reimer, Nature Physics

Neutrinos

Majority of neutrinos = relic density neutrinos, density comparable to CMB photons (~ 400 cm^{-3})

Neutrinos in eV range → 400 eV / cm^3 could be a significant contribution to dark matter.

But: hot dark matter!!



only three “light” generations of neutrinos

Primordial Black Holes

PBH: A hypothetical type of black hole that is formed not by the gravitational collapse of a large star but by the extreme density of matter present during the universe's early expansion.

No good theory limits of typical size of such black holes, but 10^{17}g – 10^{26}g (size of asteroids) are preferred

arXiv:1607.06077v3

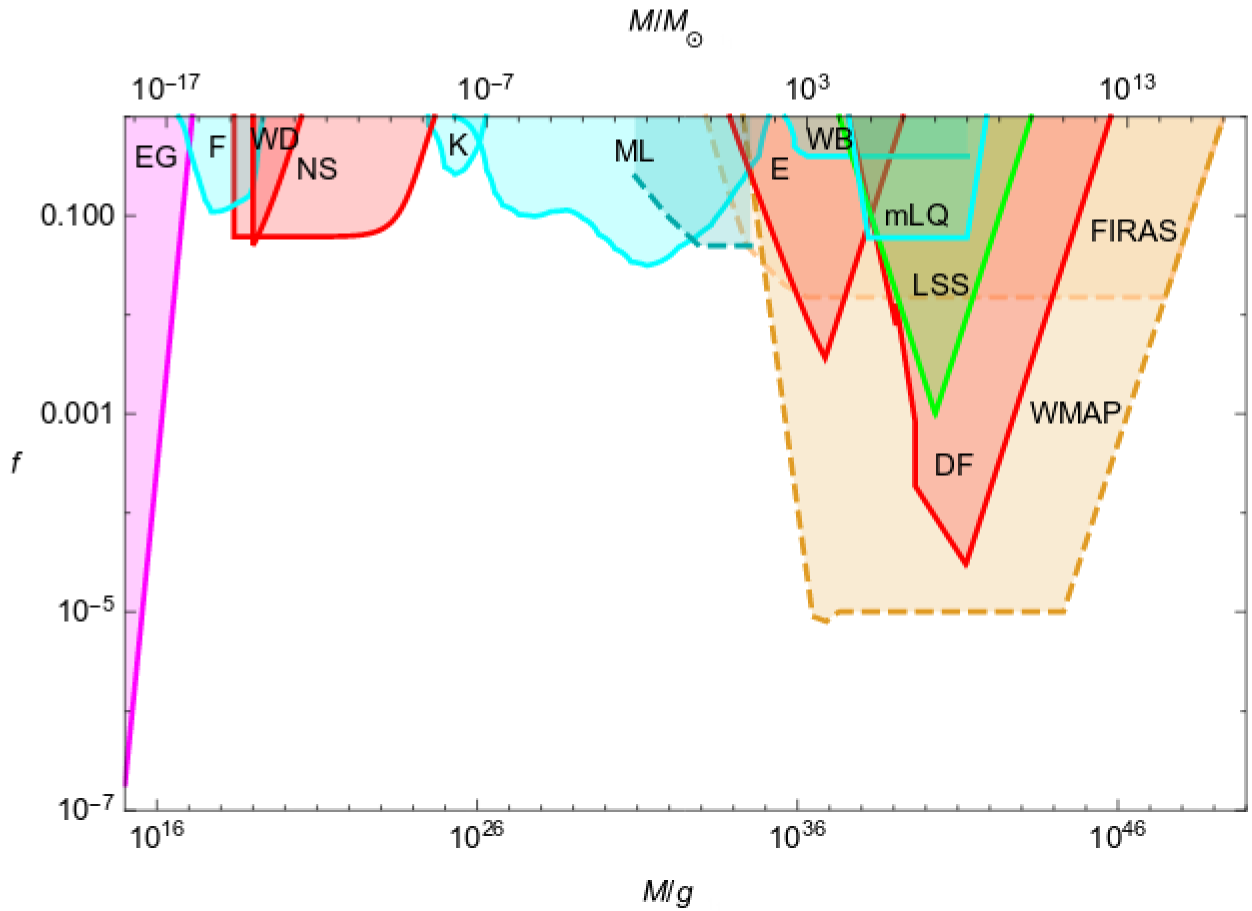
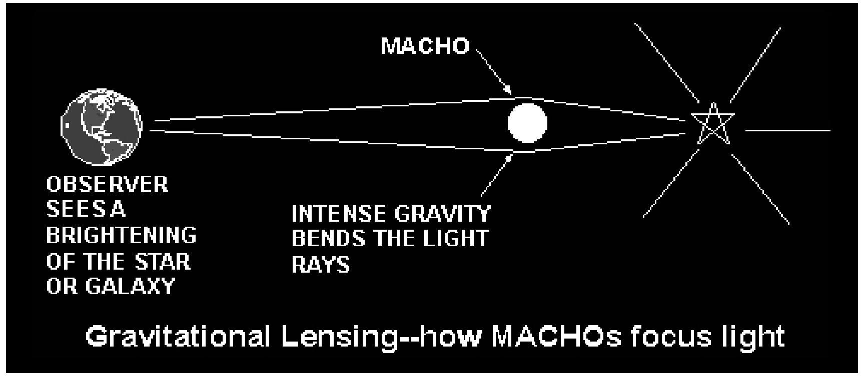


FIG. 3: Constraints on $f(M)$ for a variety of evaporation (magenta), dynamical (red), lensing (cyan), large-scale structure (green) and accretion (orange) effects associated with PBHs. The effects are extragalactic γ-rays from evaporation (EG) [11], femtolensing of γ-ray bursts (F) [187], white-dwarf explosions (WD) [188], neutron-star capture (NS) [36], Kepler microlensing of stars (K) [189], MACHO/EROS/OGLE microlensing of stars (ML) [27] and quasar microlensing (broken line) (ML) [191], survival of a star cluster in Eridanus II (E) [190], wide-binary disruption (WB) [37], dynamical friction on halo objects (DF) [33], millilensing of quasars (mLQ) [32], generation of large-scale structure through Poisson fluctuations (LSS) [14], and accretion effects (WMAP, FIRAS) [15]. Only the strongest constraint is usually included in each mass range, but the accretion limits are shown with broken lines since they are are highly model-dependent. Where a constraint depends on some extra parameter which is not well-known, we use a typical value. Most constraints cut off at high M due to the incredulity limit. See the original references for more accurate forms of these constraints.

MACHOs



MAssive Compact Halo Objects

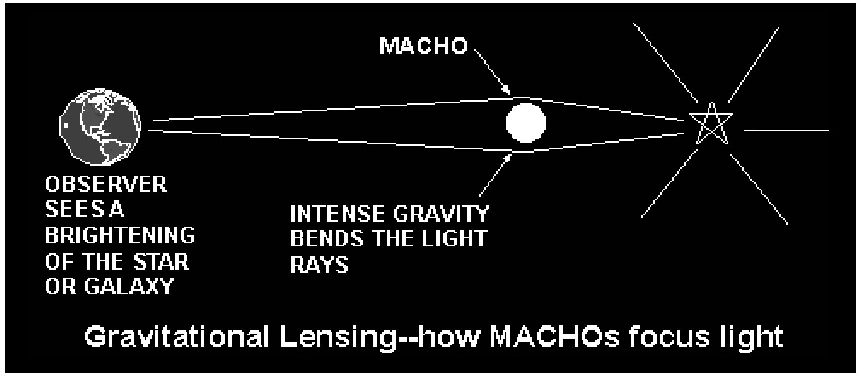
- made up of ordinary baryonic matter

- emits little to no light

- e.g. brown dwarfs, white dwarfs

- can be detected via the gravitational microlensing effect

MACHOs

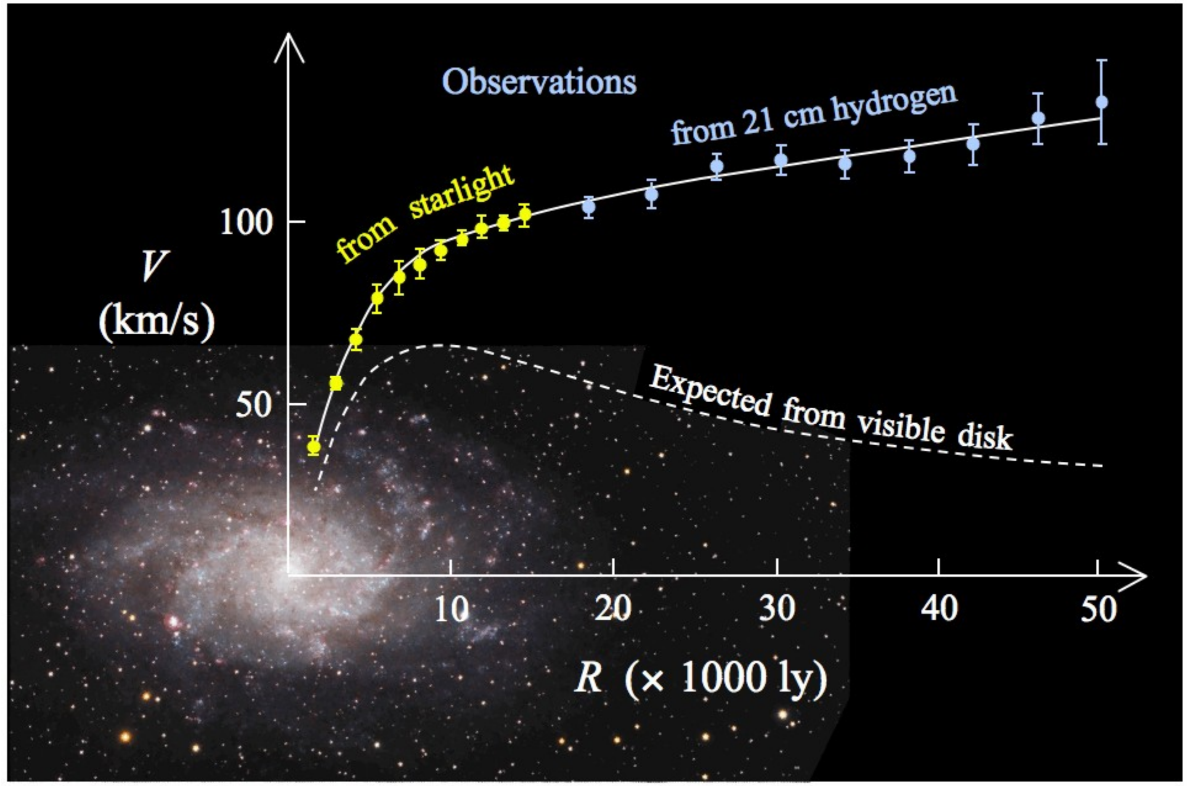


MACHO collaboration [*] claims to see machos with about 0.5 solar masses, but nowhere near enough to account for the entire missing dark matter.

[*] The MACHO Project: Microlensing Results from 5.7 Years of LMC Observations. Astrophys.J. 542 (2000) 281-307

MOND – MOdified Newtonian Dynamics

Idea: explain rotational curves by assuming that Newtonian dynamics works differently at large scales.



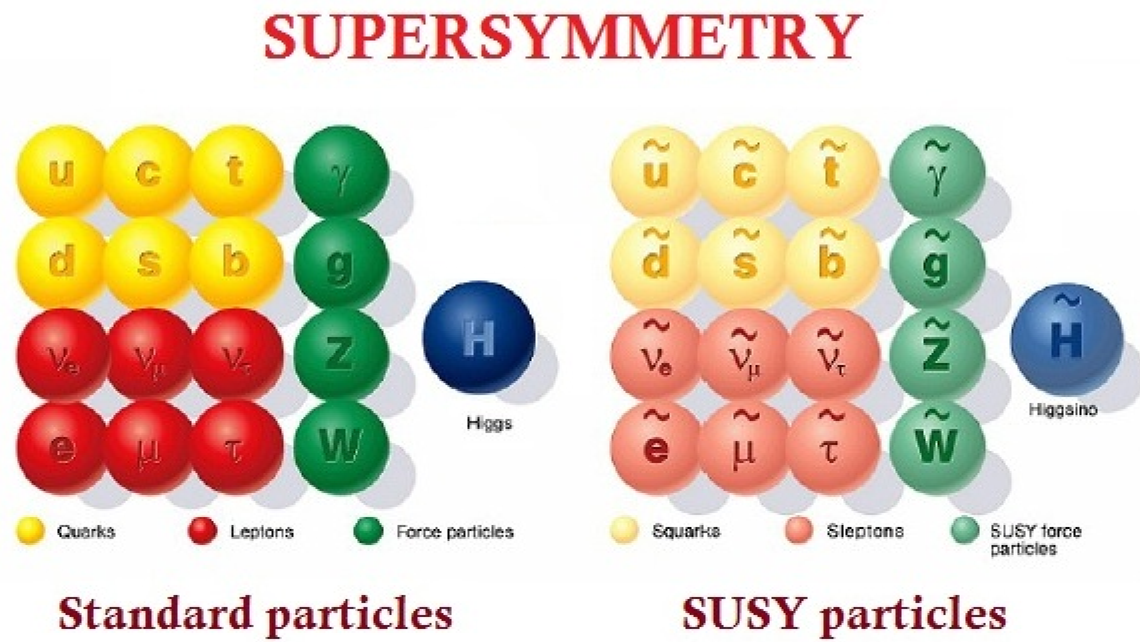
$$F = ma \rightarrow F = m\mu(\frac{a}{a_0})a$$

Does not account for (almost) any phenoma other than rotational curves.
MOND can be made compatible with relativity, e.g. TeVeS (Tensor-Vector-Scalar) Theories

WIMPs

Weakly interacting massive particles.

- Predicted by e.g. supersymmetry, if we impose a so-called “R-parity”.



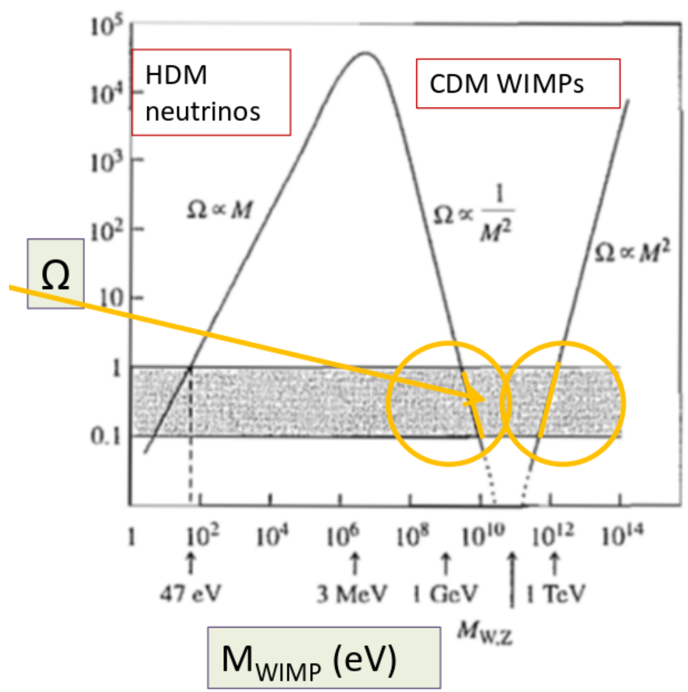
$$Q\left|fermion\right\rangle = \left|boson\right\rangle \qquad Q\left|boson\right\rangle = \left|fermion\right\rangle$$

WIMP miracle

In order to obtain the correct abundance of dark matter today via thermal production, the self annihilation cross section of $\langle \sigma v \rangle \simeq 3 \times 10^{-26} \mathrm{cm}^3\,\mathrm{s}^{-1}$ would be needed.

This is what is expected for a WIMP at a mass of O(100 GeV).

This fact is known as the WIMP miracle.



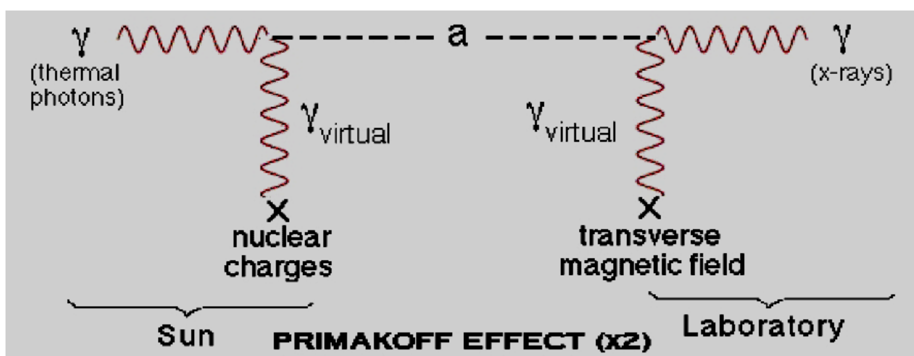
Axions

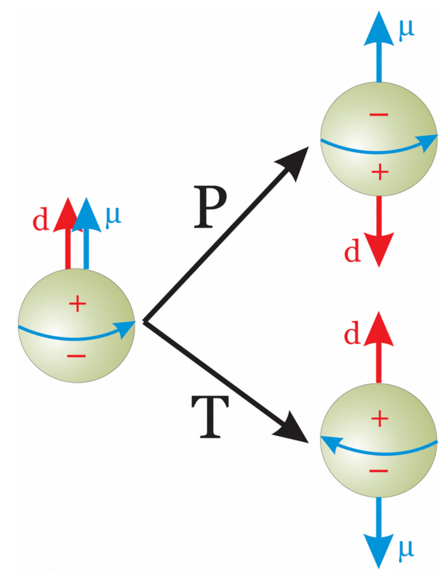
– Introduced in quantum chromodynamics (QCD) as a counterterm to a CP-violating term (the neutron would have an electric dipole moment, but we don't see one)

$$\mathcal{L} = \left(\theta - \frac{\varphi_A}{f_A}\right)\frac{g_S^2 T_F}{16\pi^2} F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

– The counterterm results in a pseudo-scalar light stable particle – the axion

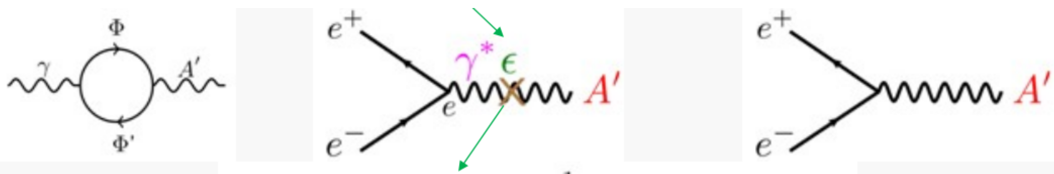
– Primakoff effect: an axion should be created via interaction of a photon with a strong magnetic field, and tunnel through a wall. On the other side, a photon should be created through the inverse process.





Dark Photons

There could be an entire "dark sector", with a "dark photon" being a portal between the Standard Model and the "dark sector" via mixing with the light photon:



$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \frac{\varepsilon}{2} F^{Y,\mu\nu} F'_{\mu\nu} + \frac{1}{4} F'^{\mu\nu} F'_{\mu\nu} + m^2_{A'} A'^{\mu} A'_{\mu}$$