Dark Matter Candidates

Pearl Sandick

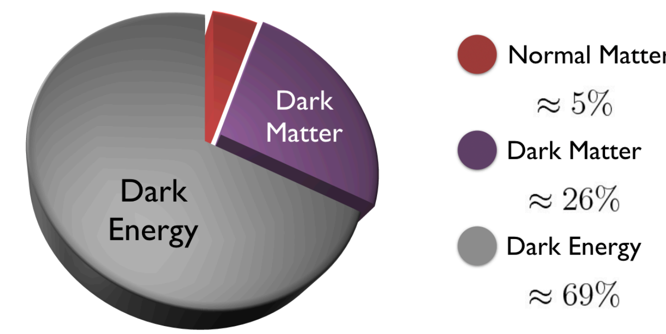
THE UNIVERSITY OF UTAH®

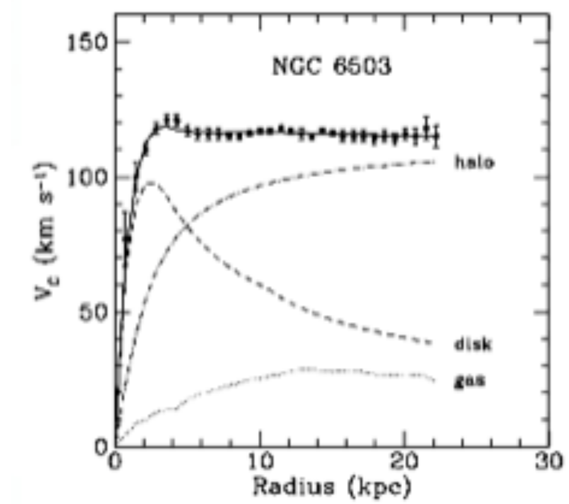
LUPM
LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

Old News

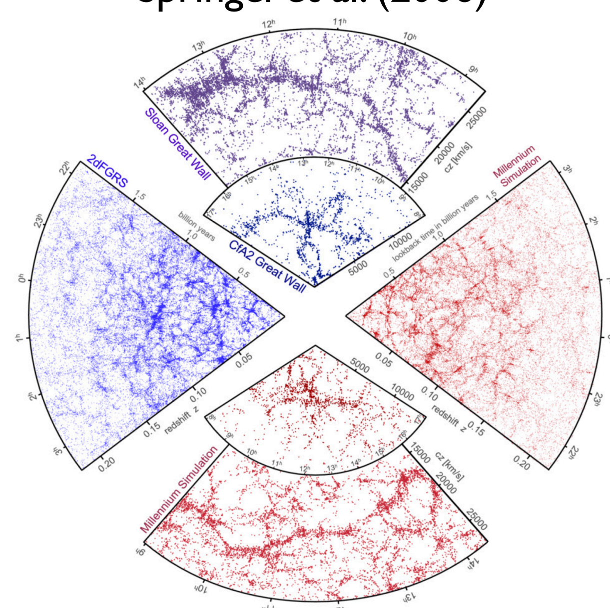
Observations

- Galactic Rotation Curves
- Cluster Dynamics, incl. collisions
- Velocity dispersions of galaxies (dark matter extends beyond the visible matter)
- Weak Gravitational Lensing (distribution of dark matter)
- Structure Formation
- “Concordance Model”

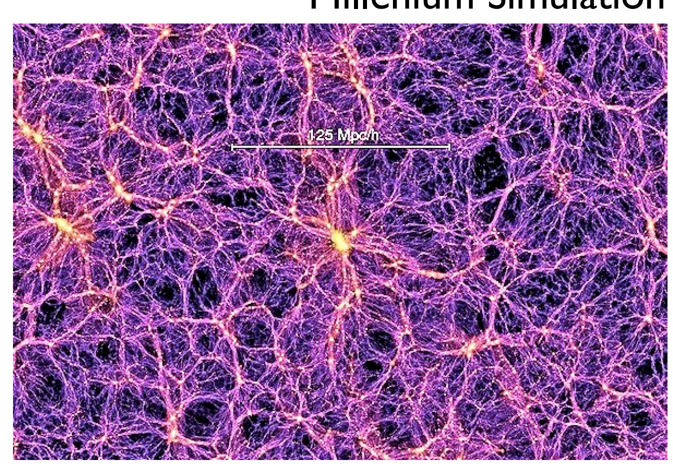




Springel et al. (2006)



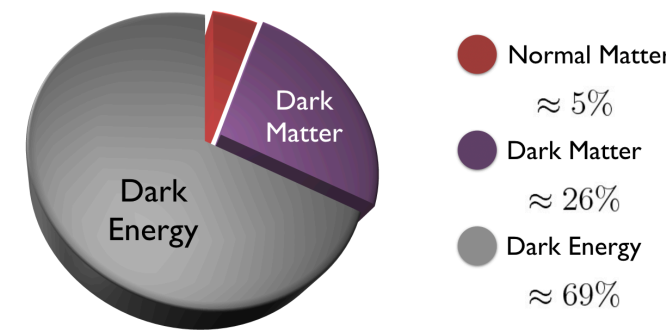
Millenium Simulation



Summary

- Some explanation is necessary for observed gravitational phenomena.
- There’s a lot of it ($\Omega_{DM}h^2$=0.1200±0.0012).
- It’s largely non-relativistic/ cold.
- It’s stable or very long-lived.
- It’s dark ([largely] neutral).
- It’s not regular matter (element abundances, structure formation).

Old News



Dark matter is both a ***challenge*** and an ***opportunity*** for fundamental physics.

[How] Does it relate to the Standard Model?

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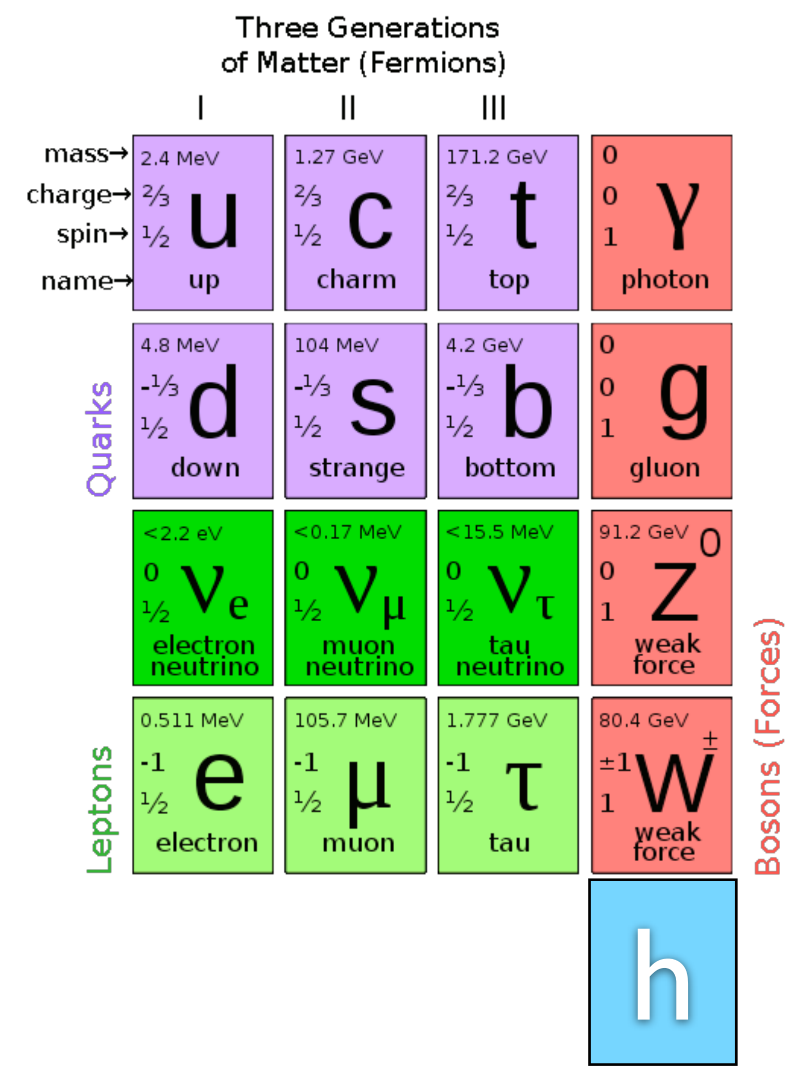
- It's dark ([largely] neutral).
- **It's not regular matter** (element abundances, structure formation).

Standard Model

- The Standard Model **works**.
  - verified by collider experiments
- The Standard Model is **not complete**.
  - does not include dark matter
  - does not include dark energy
  - does not include neutrino masses
  - does not include gravity
  - cannot explain the matter-antimatter asymmetry
  - *does* include a Hierarchy Problem
  - and more…



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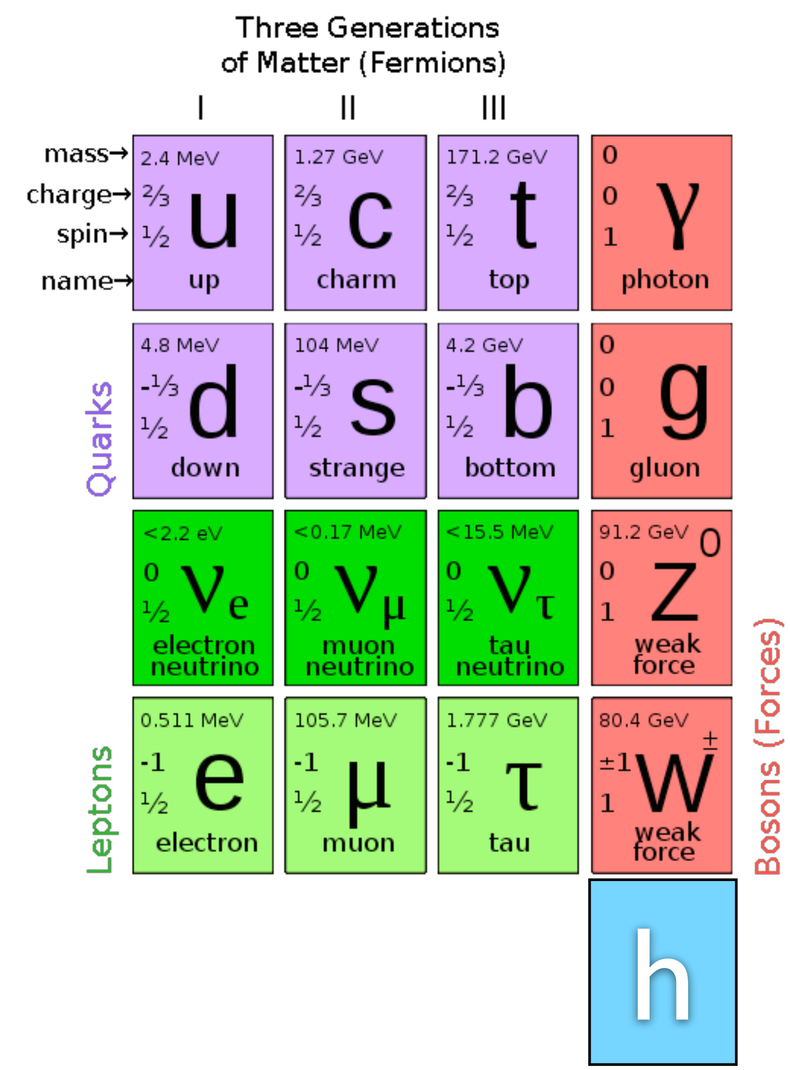
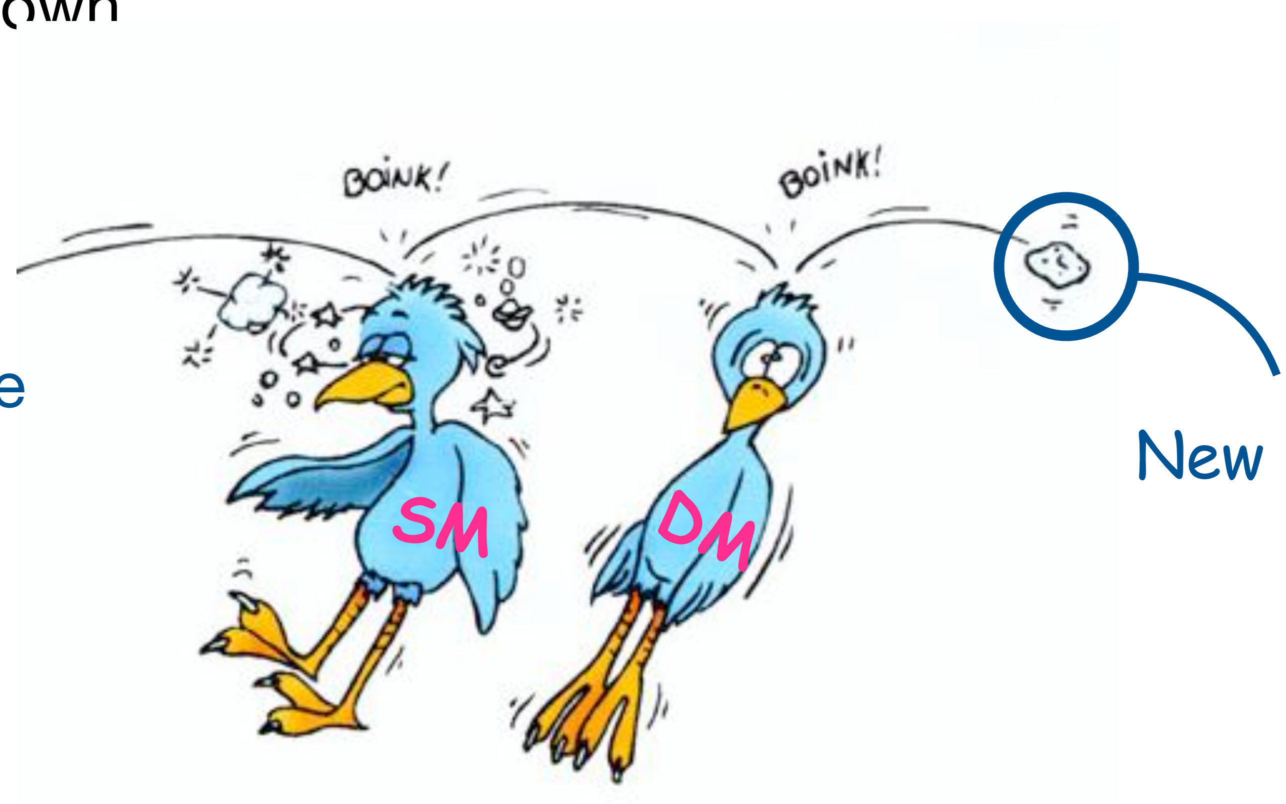


Many of these could or should be addressed within the context of a theory that includes new heavy particles.

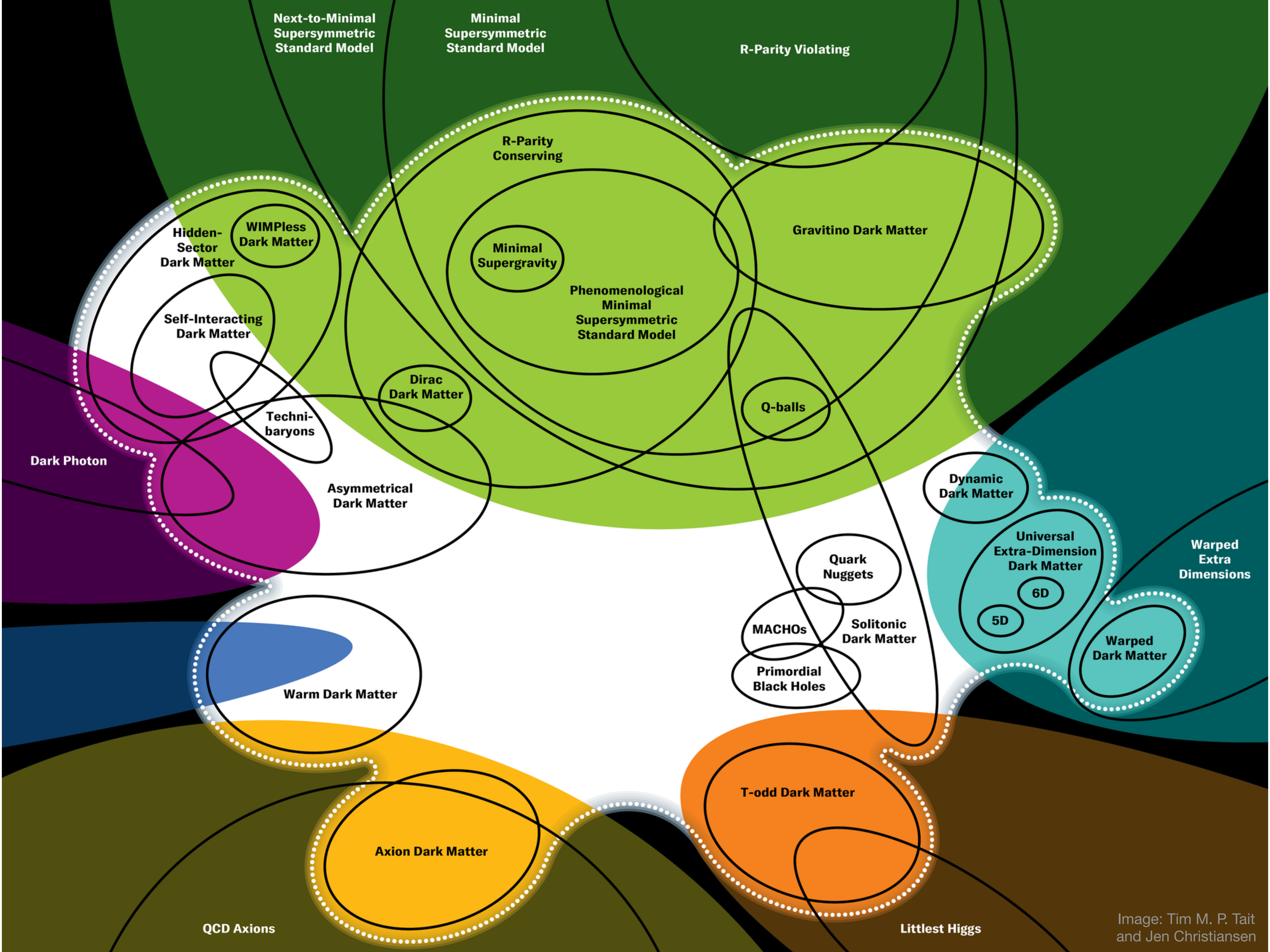
SM-DM Connection?

- Dark Matter could be embedded in a framework that addresses other open questions in particle physics
  - E.g. Hierarchy Problem, Strong-CP Problem, Neutrino Masses and Mixings
  - Principles: naturalness*, elegance/idealism
  - Typically "top-down"

Faire d'une pierre deux coups?



New Physics


Next-to-Minimal Supersymmetric Standard Model
Minimal Supersymmetric Standard Model
R-Parity Violating
R-Parity Conserving
Gravitino Dark Matter
Hidden-Sector Dark Matter
WIMPless Dark Matter
Minimal Supergravity
Phenomenological Minimal Supersymmetric Standard Model
Self-Interacting Dark Matter
Dirac Dark Matter
Techni-baryons
Q-balls
Dark Photon
Asymmetrical Dark Matter
Dynamic Dark Matter
Universal Extra-Dimension Dark Matter
6D
5D
Warped Extra Dimensions
Warped Dark Matter
Quark Nuggets
MACHOs
Solitonic Dark Matter
Primordial Black Holes
Warm Dark Matter
T-odd Dark Matter
Axion Dark Matter
QCD Axions
Littlest Higgs
Image: Tim M. P. Tait and Jen Christiansen

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  - Principles: naturalness*, elegance/idealism
  - Typically “top-down” - embed the SM in a larger framework

DM Properties

- **Type**: Fundamental particle, composite particle, wave, condensate, PBH, multi-component…?
- **Mass**: ~90 orders of magnitude!
- **Temperature**: Cold, warm, (hot)
- **Interactions**: gravitational, w/ self, w/ "portal", w/ extended new physics sector
- **Production**: thermal or non-thermal, freeze-out, freeze-in, cannibalization, number-changing processes, asymmetry, decays, gravitational production, PBH evaporation …

Consequences for cosmological, astrophysical, and galactic dynamics

Katarina Kraljic
Florent Renaud
Patrick Hennebelle
Arturo Nuñez-Castiñeyra
} simulations

Eric Jullo
Natalie Hogg
Giulia Despali
Pier-Stefano Corasaniti
} lensing & structure formation

Philippe Amram
Benoit Famaey
Yassin Rany Khalil
} MW dynamics

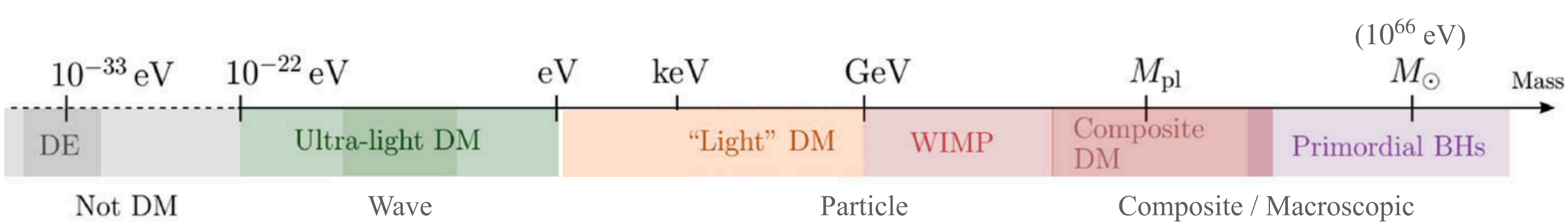

Fig. Adapted from Ferreira (2021)

Candidates

- **Weakly Interacting Massive Particles (WIMPs): neutralinos, sneutrinos, LKP, LTP, +++**
- **Light bosons/Wave DM: Axions, Axion-Like Particles (ALPs), Ultra-Light Dark Matter Matter (ULDM), Fuzzy Dark Matter (FDM)**
- **FIMPs/E-WIMPs/super-WIMPs: gravitino, axino, KK graviton, +++**
- **Sterile neutrinos**
- Q-Balls: non-topological soliton of supersymmetry (usually made up of squarks and sleptons)
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- Strongly Interacting Massive Particles (SIMPs) and Cannibals: DM is feebly coupled to SM (large abundance from thermal freeze out) but strongly coupled to itself; abundance decreases via 3-2 or 4-2 scattering
- WIMPzilla: super-heavy ($\gtrsim 10^8$ GeV), non-thermally produced DM; e.g. heavy gravitino from inflaton decay
- MACHOs: massive compact halo objects (anything dark enough - black holes, neutron stars, brown dwarfs…)***
- **Primordial Black Hole (PBH)**

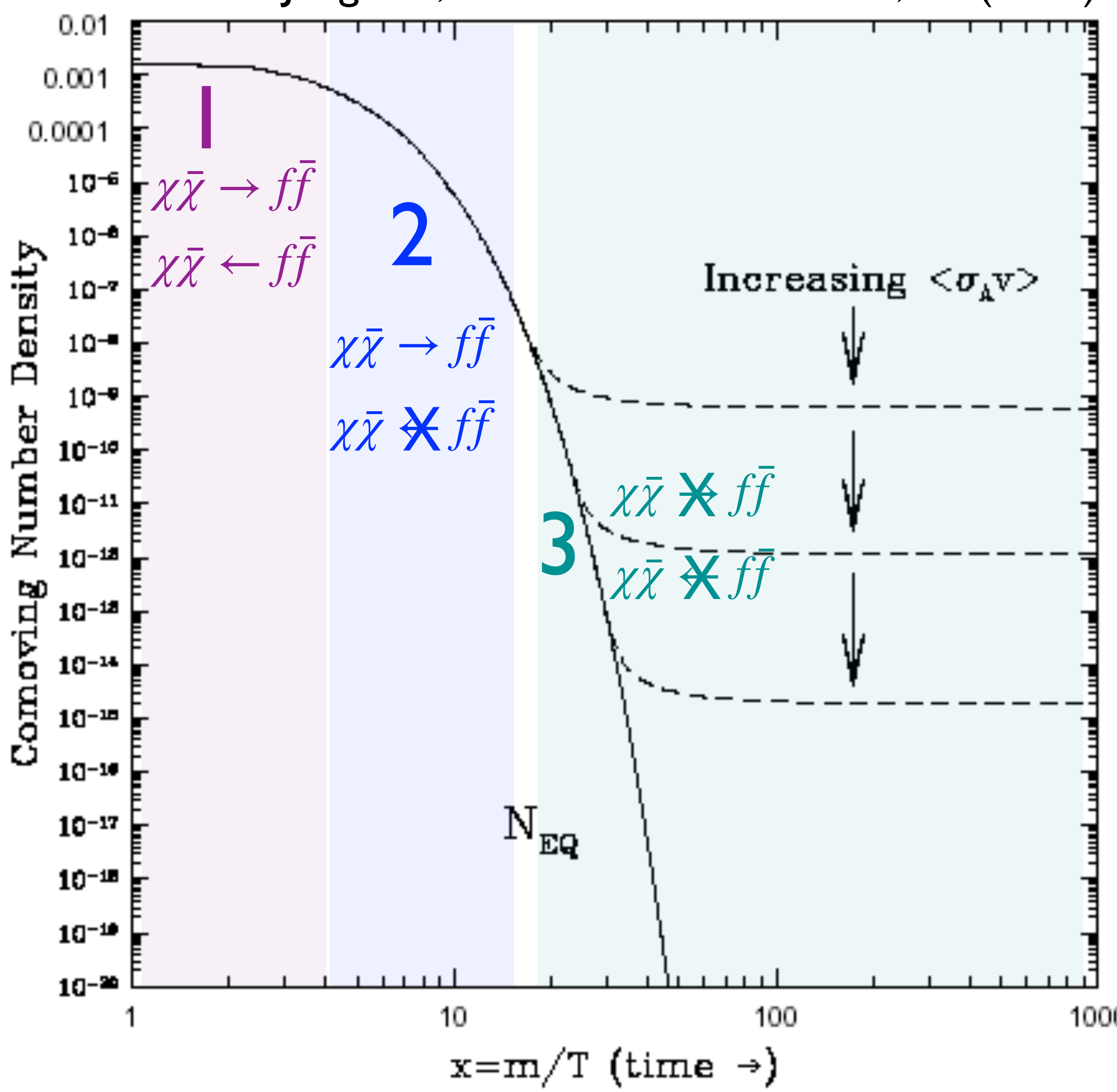
WIMP Relic Abundance

The **Boltzmann Equation** describes the evolution of the dark matter number density.

Expansion and annihilation compete to determine the number density:

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v_{rel} \rangle \left[n_\chi^2 - (n_\chi^{eq})^2 \right]$$

Jungman, Kamionkowski & Griest, PR (1996)



Equilibrium Number Density:

$(T \ll m_\chi)$

$$n_\chi^{eq} = g_\chi \left(\frac{m_\chi T}{2\pi} \right)^{3/2} e^{-(m_\chi - \mu_\chi)/T}$$

When $\Gamma = n_\chi^{eq} \langle \sigma v_{rel} \rangle < H$ the annihilations that maintain equilibrium can't keep up with expansion. WIMPs can't find each other to annihilate.

WIMP Relic Abundance
WIMP “Coincidence”

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Back of envelope:

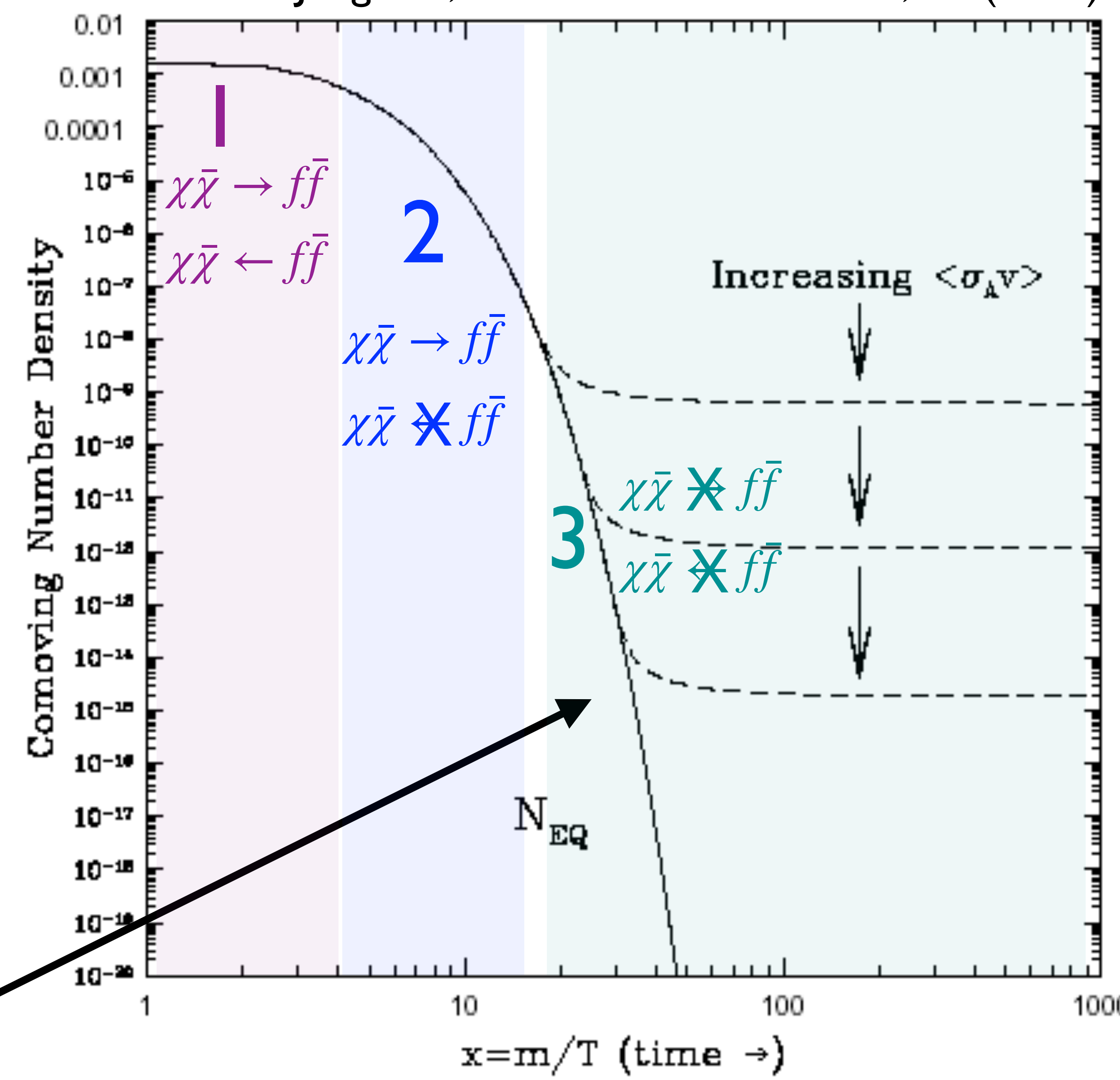
$$n_\chi^{eq} \langle \sigma v_{rel} \rangle \sim H$$

$$\left((m_\chi T)^{3/2} e^{-m_\chi/T} \right) \left(\frac{g^4}{m_\chi^2} \right) \sim \left(\frac{T^2}{M_{Pl}} \right)$$

$$\frac{m_\chi}{T} \sim \log \left(\frac{M_{Pl}}{m_\chi} \right) + \ldots$$

So a weakly-interacting 100 GeV WIMP means $\frac{m_\chi}{T} \sim 40$

Jungman, Kamionkowski & Griest, PR (1996)



WIMPless, too!

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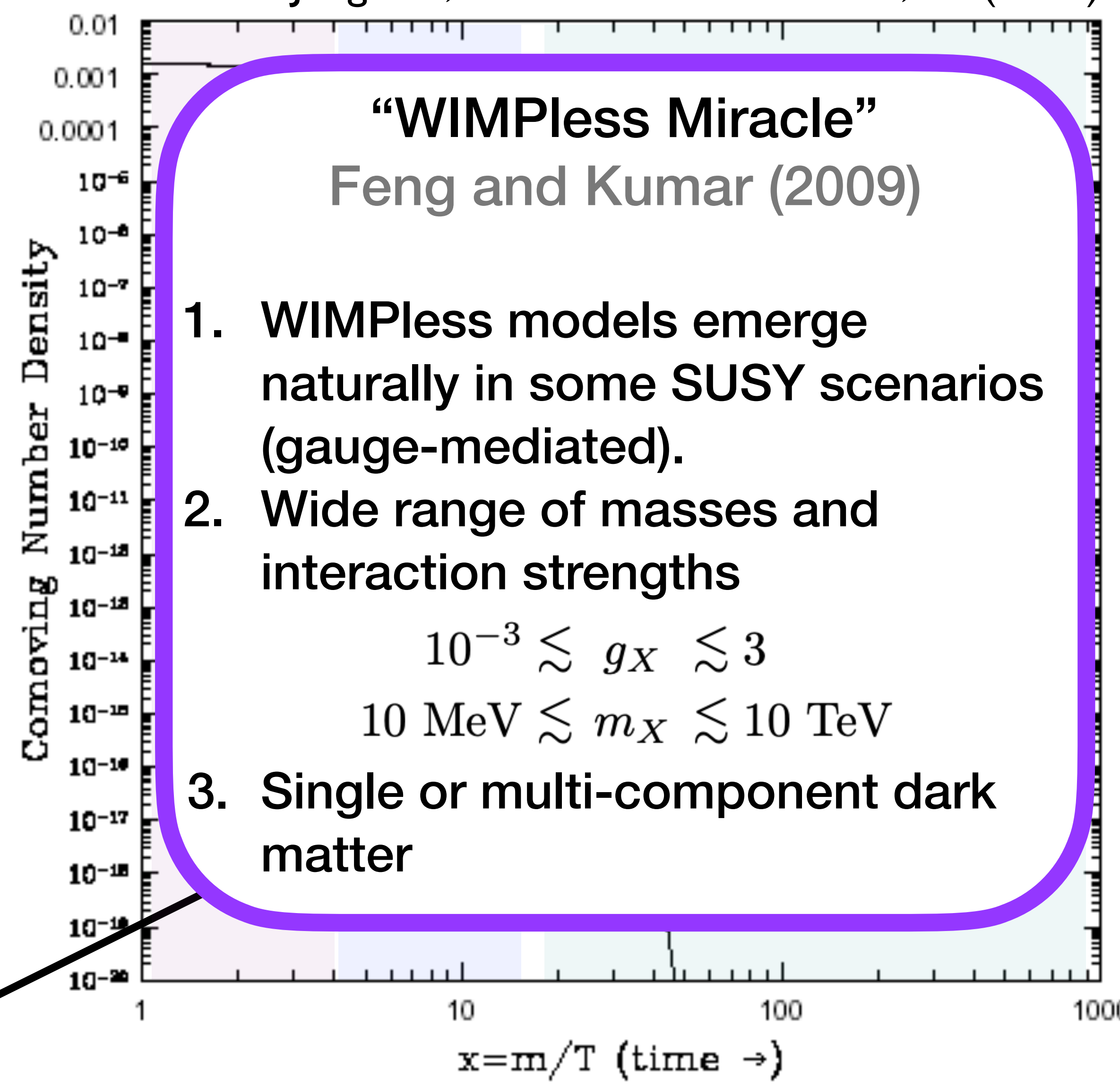


"WIMPless Miracle"
Feng and Kumar (2009)

1. WIMPless models emerge naturally in some SUSY scenarios (gauge-mediated).
2. Wide range of masses and interaction strengths

$$10^{-3} \lesssim g_X \lesssim 3$$
$$10 \text{ MeV} \lesssim m_X \lesssim 10 \text{ TeV}$$

3. Single or multi-component dark matter

WIMPs and Non-WIMPs

~GeV+ WIMP

- Supersymmetric (LSP) Neutralino, Sneutrino
- Lightest KK Particle (LKP) from Universal Extra Dimensions
- Lightest T-odd Particle (LTP) from Little Higgs Models
- "WIMPless"
- Ad hoc or simplified models
- …

GeV+ Non-WIMP

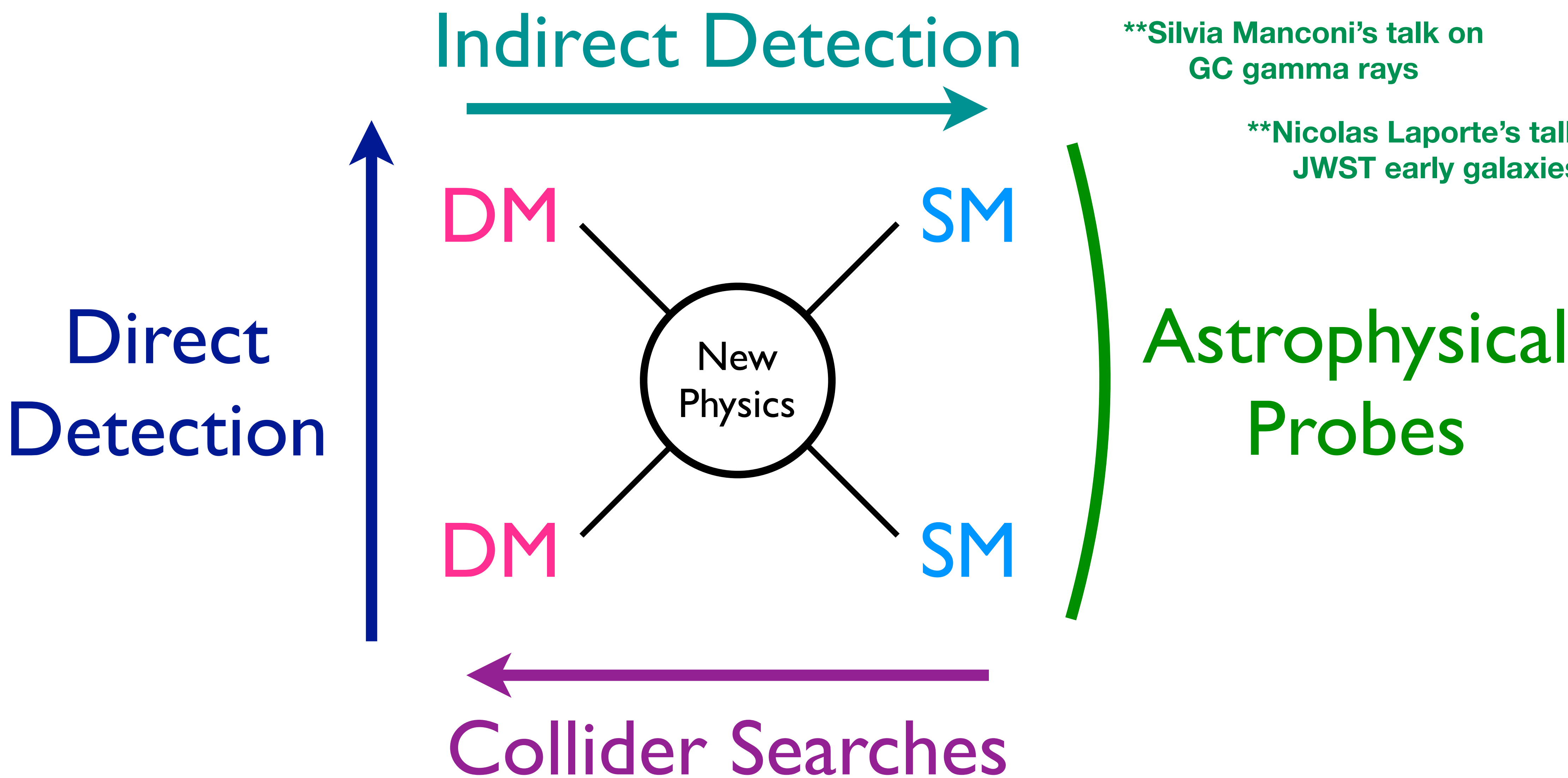
- Sneutrino
- WIMPless DM
- Sterile Neutrinos
- SIMP
- Asymmetric DM
- WIMPzilla
- Ad hoc or simplified models
- …

Sub-GeV

- WIMPless DM
- Sterile Neutrinos
- SIMP
- SIDM
- Dark Photon DM
- Axions/ALPs
- Ad hoc or simplified models
- …

Commonalities in mass, interaction characteristics ↔ Commonalities in detection techniques

WIMP(+) Hunting



**Silvia Manconi's talk on GC gamma rays

**Nicolas Laporte's talk on JWST early galaxies

Goal: determine WIMP mass, spin, and couplings to SM particles.

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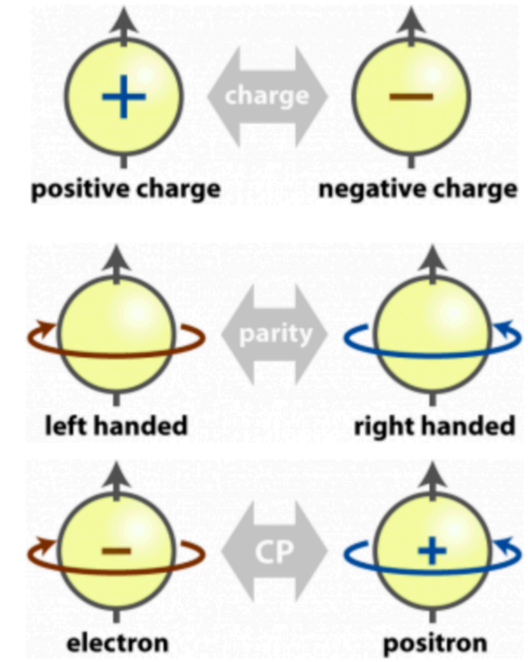
Axions



- Strong CP Problem: CP violating operators are allowed in the QCD Lagrangian, but no CP violation has been observed.
- $L_{\rm QCD} \supset L_\theta = -\theta \frac{g_s^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\mu\nu}$ violates CP. Limit from neutron EDMs: $\theta \lesssim 10^{-10}$.
- Peccei Quinn Mechanism (1977): Allows theta to be ~zero by promoting it to a field ($\theta \to a(\mathbf{x})/f_a$) with a new global (PQ) symmetry spontaneously broken at the scale f_a.
- Weinberg (1978) & Wilczek (1978): spontaneously broken symmetry means there must be a Goldstone boson! Axion.
- QCD vacuum effects: $m_a \approx f_\pi m_\pi / f_a \quad \to \quad m_a \approx 5.7 \left(\frac{10^9\,\mathrm{GeV}}{f_a} \right) \mathrm{meV}$
- Small mass??? Thermal production would result in hot axions, but several non-thermal production mechanisms (e.g. misalignment) yield cold axions that form a condensate.
  - Coherent/wave-like behavior → impact on astrophysical structure and dynamics

Jens Niemeyer
Raquel Galazo-Garcia
Marco Gorghetto
Tanja Rindler-Daller
Rodrigo Vicente

Axions, ALPS, and FDM.. Oh my!

- **QCD Axion** (or just “axion”) solves the strong CP problem.
    - DFSZ and KSVZ are two examples, but there are many more possibilities, covering a lot of parameter space.
- **Axion Like Particles (ALPs)** are scalars that behave similarly to the QCD axion, but might not solve the strong CP or DM problems.
- **Ultra-Light Dark Matter (ULDM)** can be as light as 10^{-22} eV.
- **Fuzzy Dark Matter (FDM)** is a sort of generic term for ULAs/ALPs that contribute to DM. Preferred mass is near 10^{-22} eV, which has galaxy-scale deBroglie wavelength and therefore explains the cored profiles of galaxies.

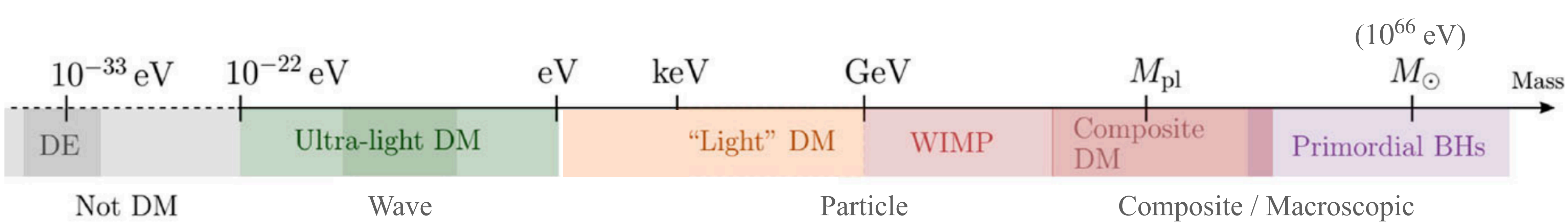
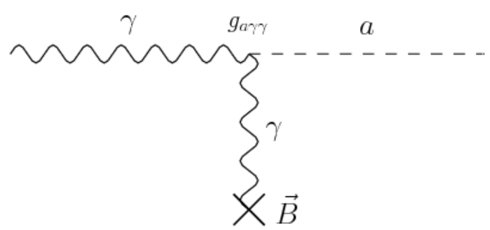


Fig. Adapted from Ferreira (2021)

Some ways to detect ALPs

Fabrice Hubaut's talk

- Primakoff Effect



$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a(x)}{f_a} \vec{E} \cdot \vec{B}$$

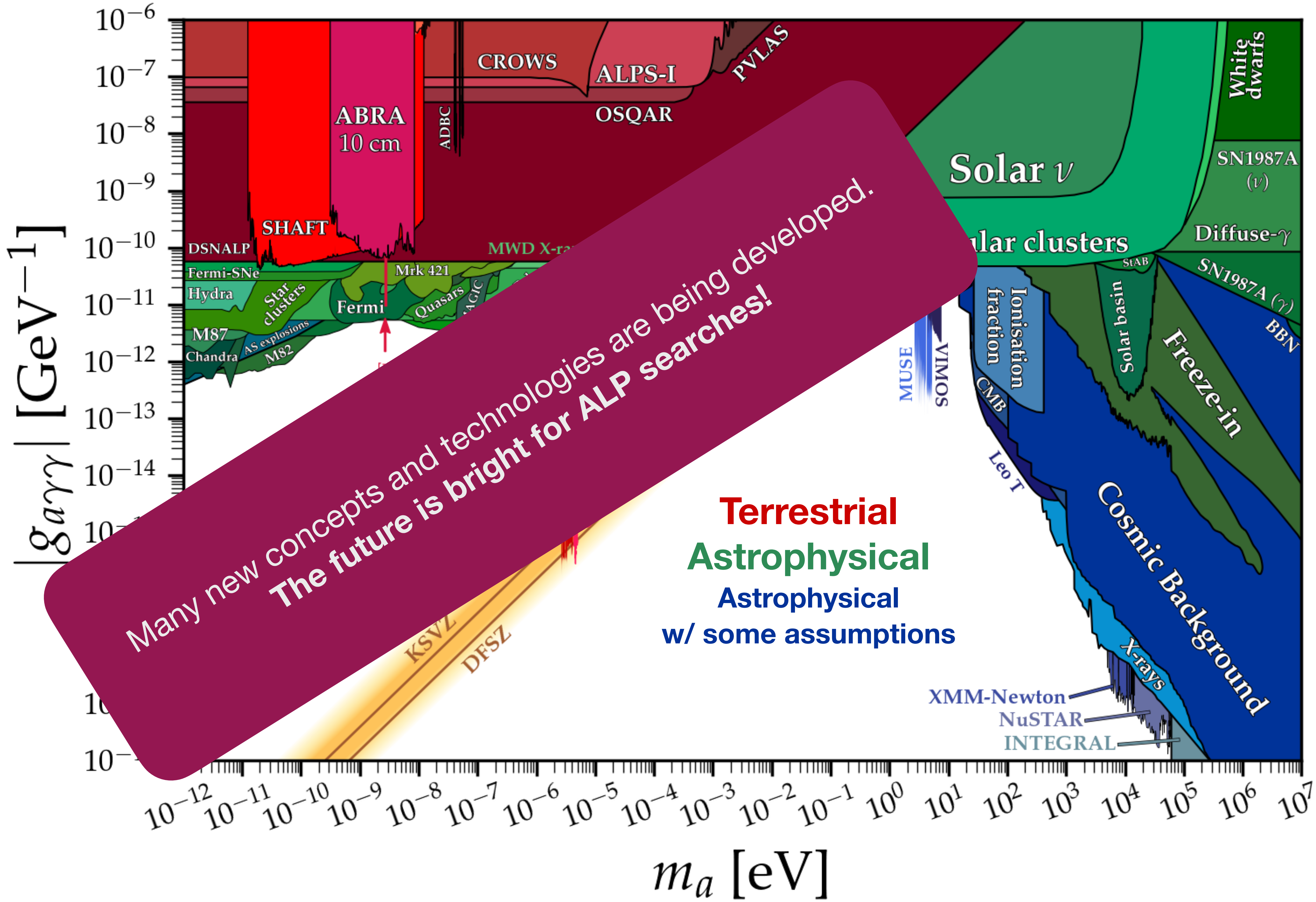
$g_{a\gamma\gamma}$

Note: for QCD axions, mass and coupling are not independent! But for generic ALP, they can be.

- Light through walls (e.g. ALPS)
  - Laser light is shined at a wall. Magnetic field: some photons converted to axions. Axions travel through wall. Magnetic field: some convert back to photons.
- Microwave cavity searches (e.g. ADMX)
  - Axions passing through cavity + magnetic field. Some convert to photons.
- Solar axion searches (e.g. CAST)
  - Photon converts to axion in sun, travels to Earth. Magnetic field: axion converts back to photon.
- ALP decays: CMB, BBN, JWST and other integral field spectrographs
- ALP conversion in astrophysical magnetic fields (constrains high-mass)
- Stellar evolution (cooling from ALP production inside stars)

So much astrophysics!

Axion Search Prospects



Many new concepts and technologies are being developed.
The future is bright for ALP searches!

Image: Ciaran O'Hare, AxionLimits

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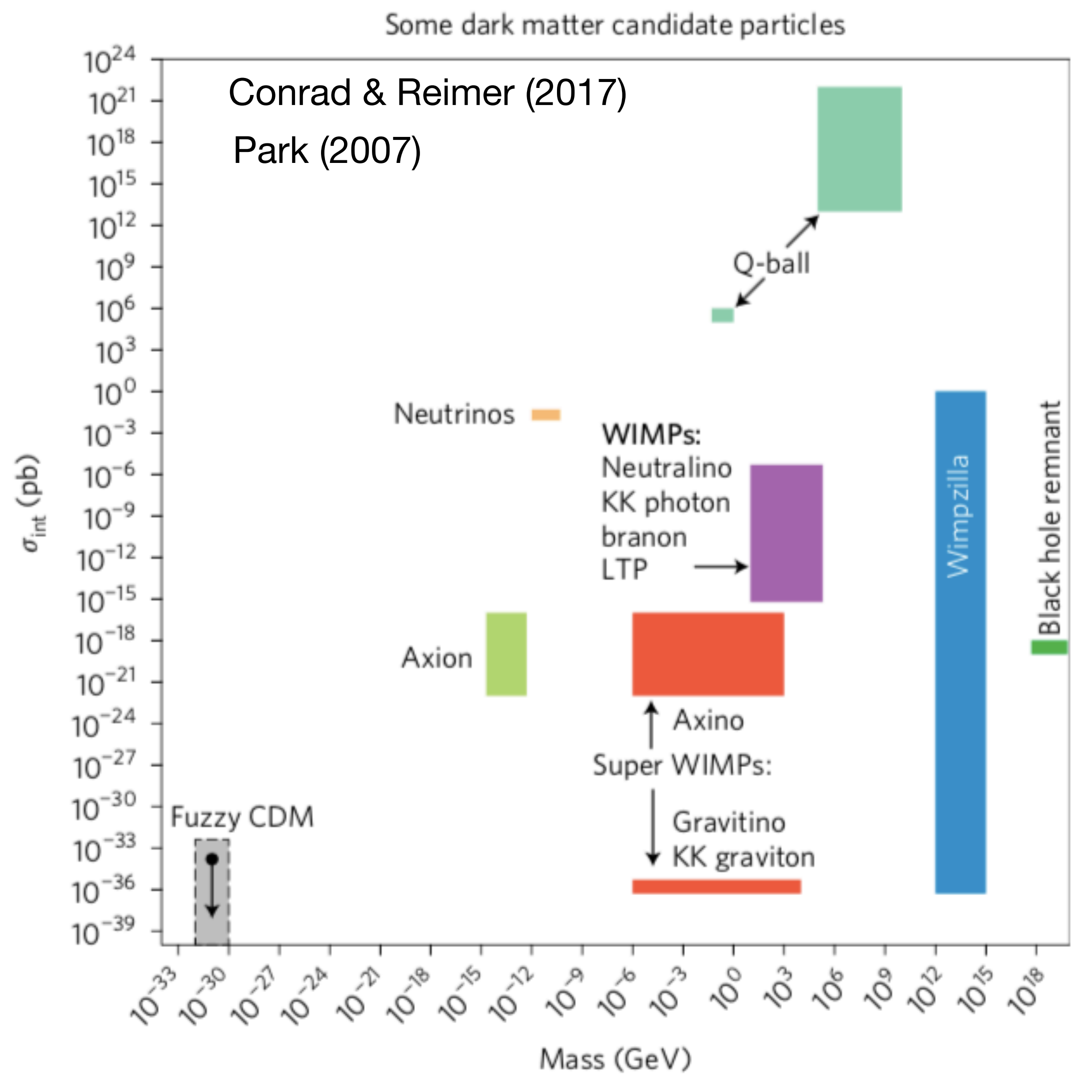
E-WIMPs/Super-WIMPs/FIMPs

- Tiny interactions with SM particles
- Interaction scale with ordinary matter suppressed by a large mass scale.
  - gravitino: $M_{Pl} \sim 10^{19}$ GeV
  - axino: $f_a \sim 10^{11}$ GeV
  - Other candidates: KK graviton, sterile neutrinos…
  - Production: typically freeze-in (or similar)



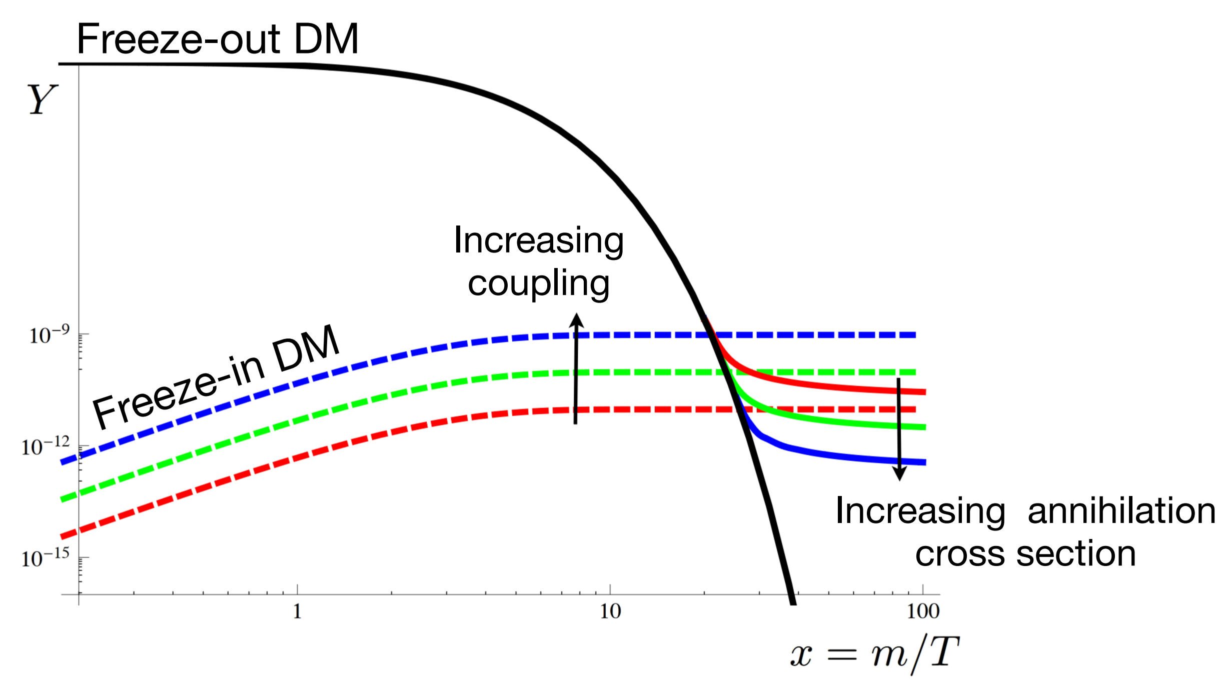
Freeze-In

- Collisional processes and/or decays lead to production of out-of-equilibrium FIMPs. FIMPs could be DM themselves, or decay to DM. Extremely weak interactions, so once DM is produced, it sticks around.

1. Bath of SM particles at high T
2. SM particle interactions produce FIMPs
3. Universe cools such that SM particles no longer have enough energy to produce heavier FIMPs. (If FIMPs are unstable, they decay to DM.)

    - **DM abundance is "frozen-in"**

- Some differences from Freeze-out:
    - Small initial thermal population
    - Larger coupling → more DM produced
    - Works down to ~keV (depending on model)
    - Most models include a *metastable particle*



Hall, Jedamzic, March-Russell, & West (2009)

Detecting the FIMP Scenario

- Detection is challenging due to very weak interactions with SM, but there are still many (model-dependent) possibilities!
- Decays could impact BBN and CMB… →constraints on metastable particles.
- Collider search for long-lived particles (eg. NLSP), anomalous scattering at fixed-target experiments, anomalous decays.
- Indirect signals from decay, or annihilation to an unstable light mediator ($\chi\chi \rightarrow \phi\phi$) that decays to SM particles
- Could be probed by low-threshold direct dark matter searches in the keV-MeV mass range (very large abundance, so some hope?)
- Stellar ($\lesssim 100$ keV) and supernovae (~ MeV) constraints from cooling

Bernal et al. (2017)

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Sterile Neutrinos?

- SM (L-handed) neutrinos have masses. No R-handed neutrinos in the SM → no consistent way to write a term that gives them mass.

- [Minimal Type 1 Seesaw] Solution: add R-handed neutrinos as gauge singlet fermions with Majorana mass M_{RH}. Interactions with LH neutrinos through a Yukawa term with coupling y_ν. L-R mixing → for M_{RH} large enough, the light states get a mass eigenvalue of $m_\nu = y_\nu^2 v_0^2 / M_{RH}$

    - Typical M_{RH} values are 10^{15} - 10^{16} GeV, but there are ways to get it much smaller.

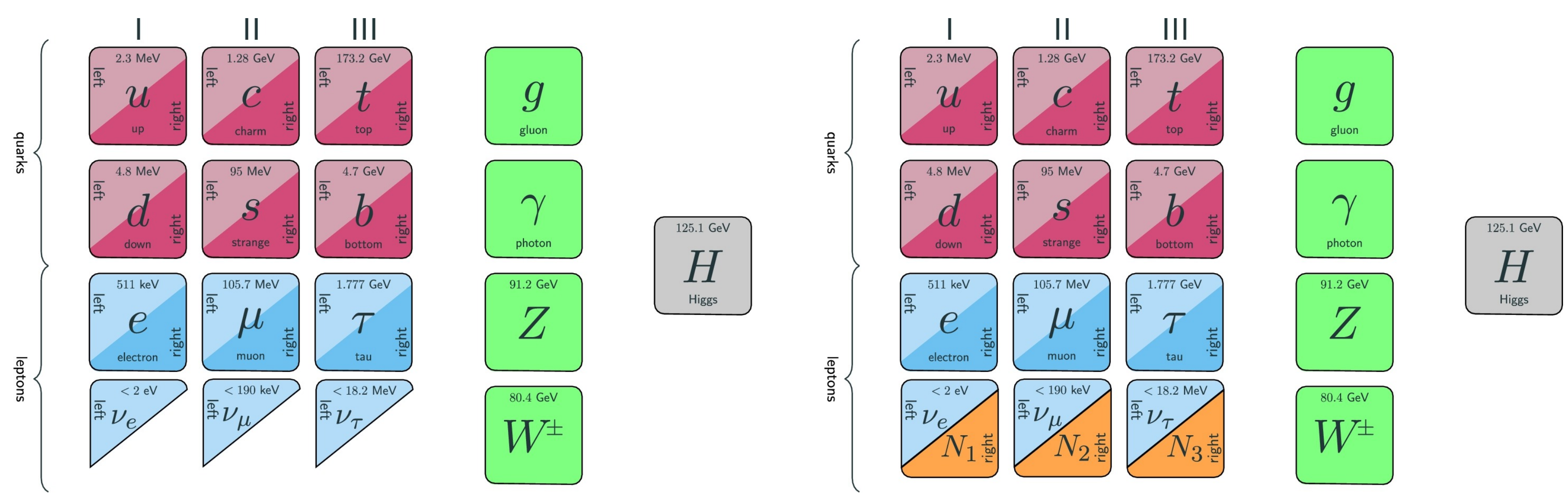


Image: Shaposhnikov (2024)

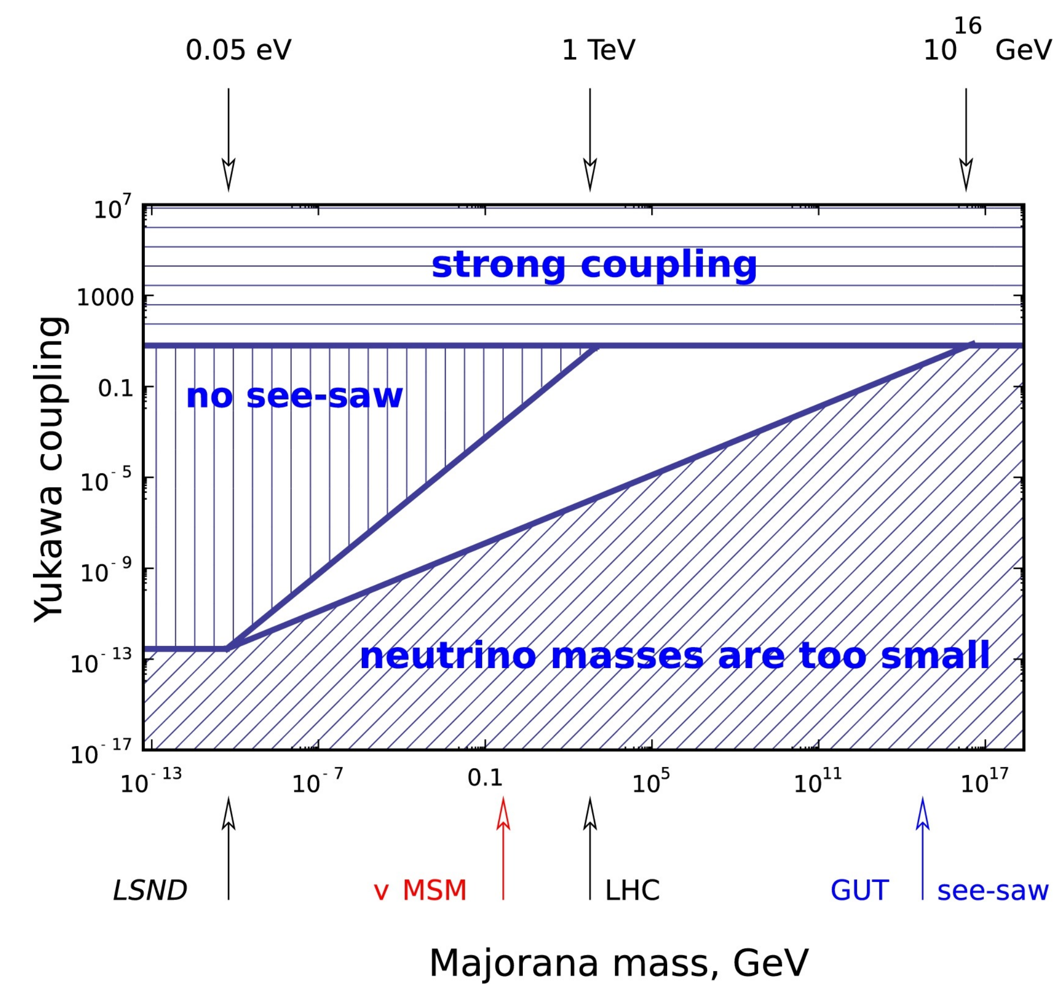
- There are other solutions besides this one. Point is that adding RH neutrinos is reasonable.

- If RH (sterile) neutrinos are light (keV mass range) and not too strongly mixed with LH (active) neutrinos, they can be the DM.

Sterile Neutrino DM

- Sterile does not mean *completely* sterile - interactions with SM particles happen via mixing with active neutrinos, or may arise through new gauge interactions at high energies.
  - Sterile neutrinos have extremely weak interactions, so were never in thermal equilibrium in the early Universe.
  - Possible production mechanisms: Freeze-in, oscillate-in (Dodelson-Widrow or Fuller-Shi), decays of heavy bosons… (all model-dependent)
- Not stable, but very long-lived (related to active-sterile mixing) - can have lifetimes longer than the age of the Universe.
- **O(keV) masses** are viable, though if sterile neutrinos are more decoupled from the SM then they can be much heavier. Neutrino experiments allow a large range of masses and couplings.

Image: Shaposhnikov (2024)



Boyarsky et al. (2018), Shaposhinkov (2024)

Light Sterile Neutrinos

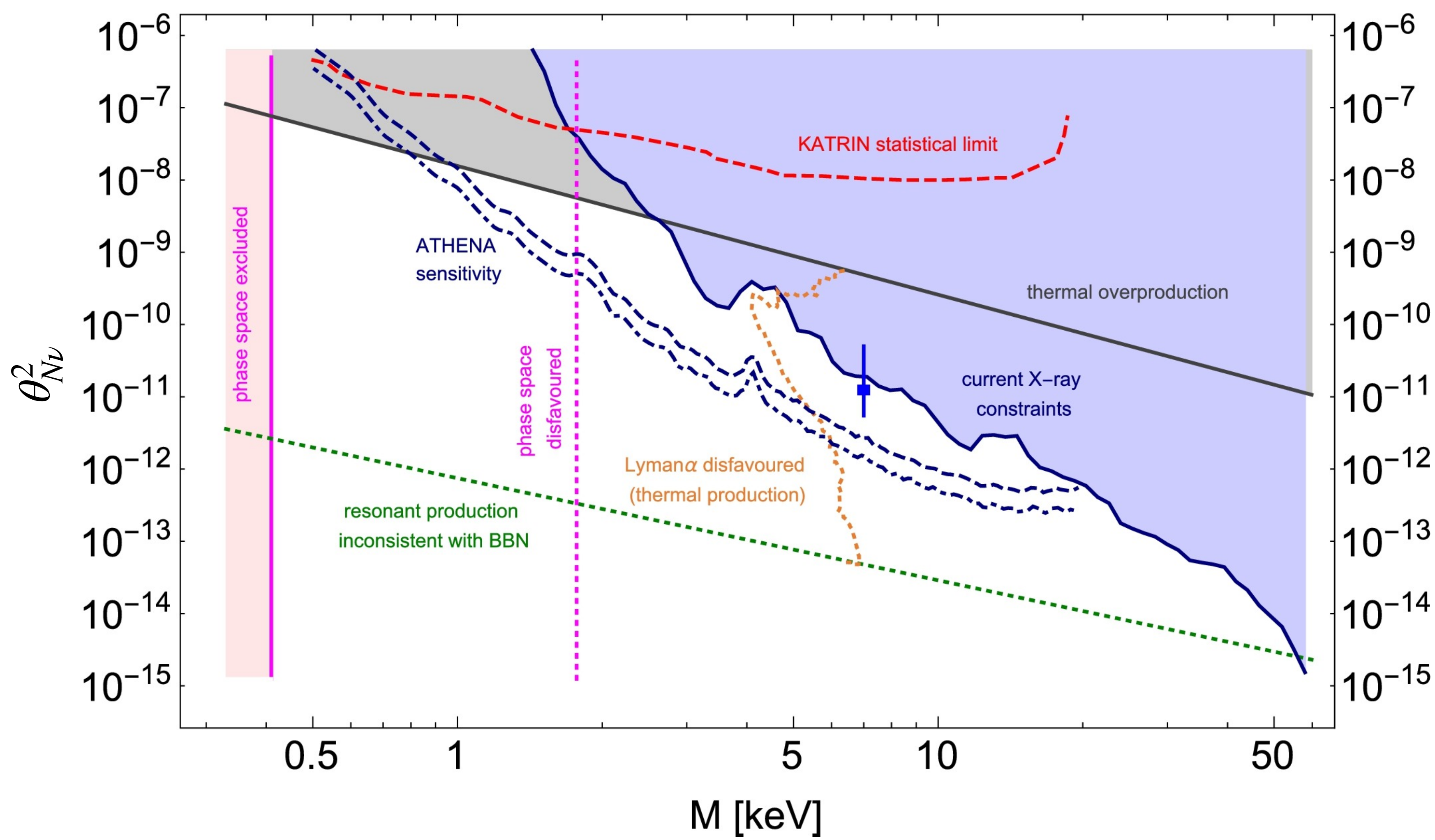
Model independent:

- Main decay mode is $N \to 3\nu$
- More important (for observations) decay mode is $N \to \nu\gamma$
  - Monochromatic photon line signal at $E_\gamma \approx m_N/2$ (x-ray constraints)
- Cosmological production: $\ell^+\ell^- \to N\nu$ (thermal overproduction bound)
- Large number density in dSphs would violate Pauli Exclusion (phase space bound)

Model dependent:

- Dashed contours are constraints/sensitivity that depend on the production mechanism (and other model characteristics)

Image: Boyarsky et al. (2019)



Candidates

- **Weakly Interacting Massive Particles (WIMPs): neutralinos, sneutrinos, LKP, LTP, +++**
- **Light bosons/Wave DM: Axions, Axion-Like Particles (ALPs), Ultra-Light Dark Matter Matter (ULDM), Fuzzy Dark Matter (FDM)**
- **FIMPs/E-WIMPs/super-WIMPs: gravitino, axino, KK graviton, +++**
- **Sterile neutrinos**
- Q-Balls: non-topological soliton of supersymmetry (usually made up of squarks and sleptons)
- Dynamical Dark Matter (DDM): string-inspired, time-evolving ensemble of dark matter particles
- Asymmetric Dark Matter (ADM): DM-antiDM asymmetry which may be related to the baryon-antibaryon asymmetry
- Dark Photon Dark Matter: gauge boson of a dark U(1), mixes with SM gauge bosons
- Self-Interacting Dark Matter (SIDM): DM interacts with SM and has non-negligible self interactions
- Strongly Interacting Massive Particles (SIMPs) and Cannibals: DM is feebly coupled to SM but strongly coupled to itself; abundance via 3-2 or 4-2 scattering
- WIMPzilla: super-heavy ($\gtrsim 10^8$ GeV), non-thermally produced DM; e.g. heavy gravitino from inflaton decay
- MACHOs: massive compact halo objects (anything dark enough - black holes, neutron stars, brown dwarfs…)***
- **Primordial Black Hole (PBH)**

Primordial Black Holes (PBHs)

- Proposed in the 60's, studied extensively by Hawking and others in the 70s
- Primordial Black Holes (PBHs) formed in the very early universe - before BBN
- Various mechanisms:
  - collapse of large density perturbations
  - collapse of cosmic string loops
  - bubble collisions
  - …

Pasquale Serpico's talk

- Can happen during a radiation- or (early) matter-dominated era
- Possible that PBHs themselves come to dominate the energy density of the universe

- Formation requires increased energy density at early times → connection between PBH mass and horizon mass at formation

$$M \sim \frac{c^3 t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\mathrm{s}} \right) \text{g}$$

  - Planck time → 10^{-5} g (Planck mass)
  - 1 second → $10^5 M_\odot$

- Range of masses at formation? Formation over some time period, or power spectrum of inhomogeneities spans some spatial scales.

- **Hawking Radiation and Evaporation**

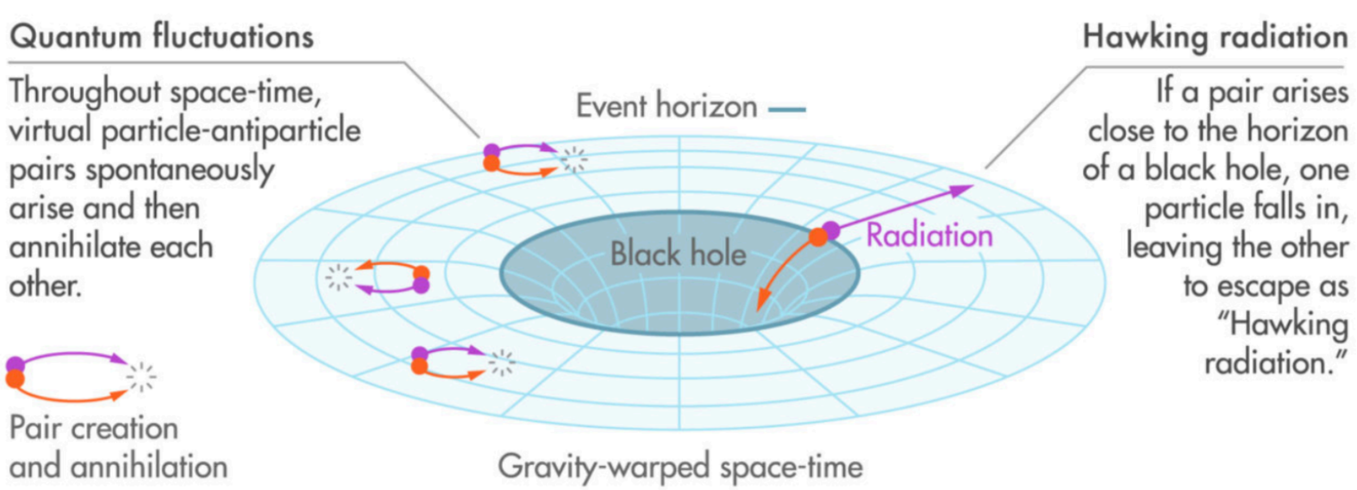
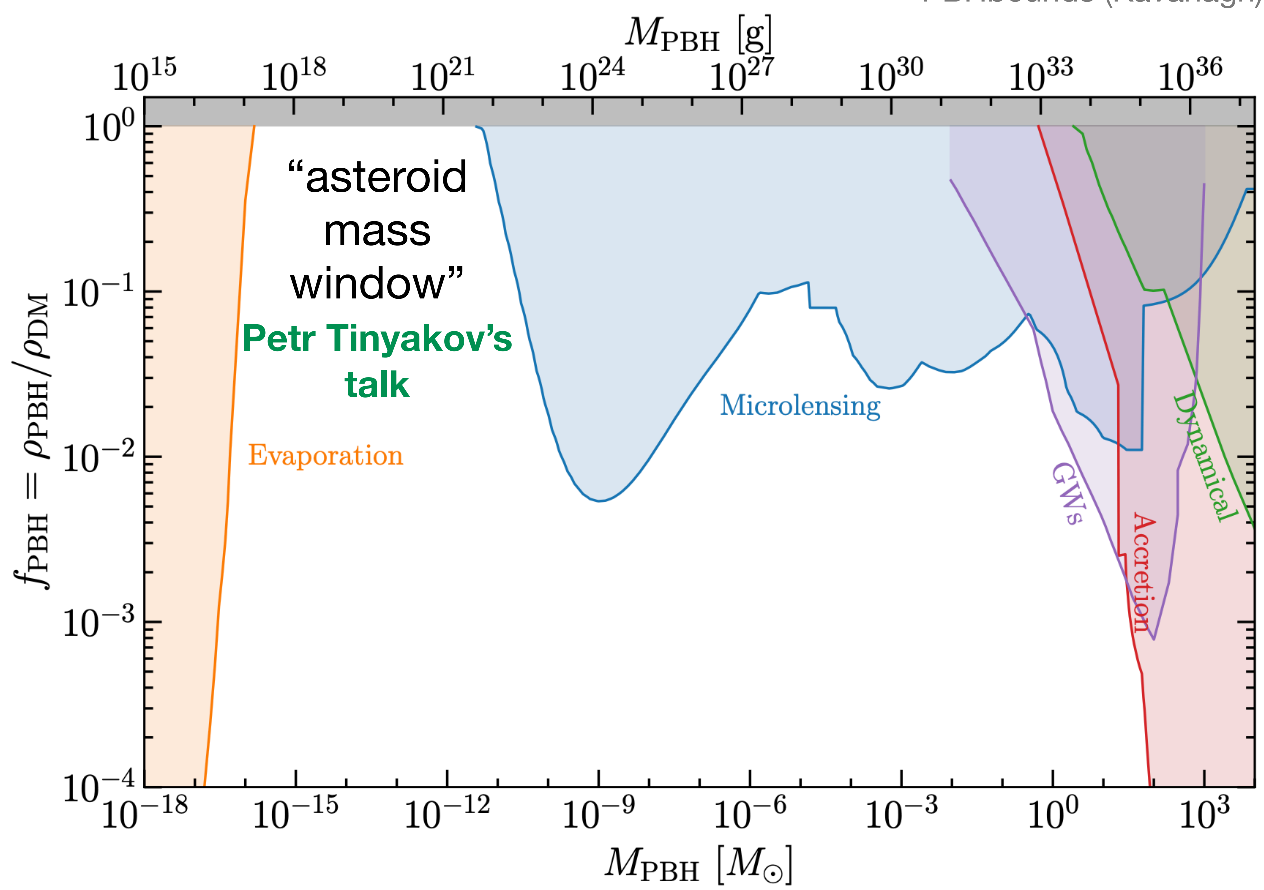


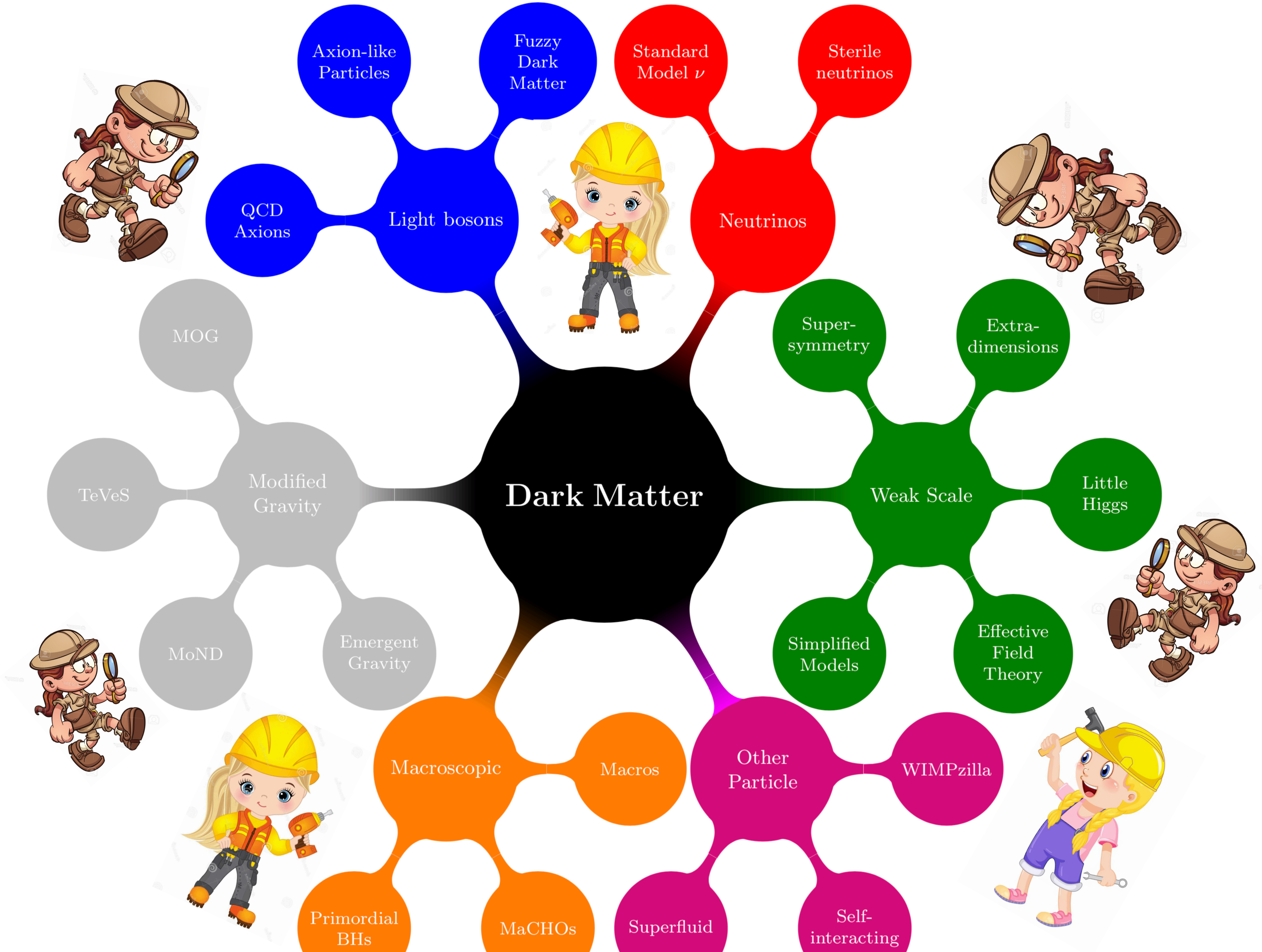
Image: Lucy Reading-Ikkanda for Quanta Magazine

PBH Evaporation and Constraints

- Black Holes evaporate through continuous emission of degrees of freedom, losing mass and angular momentum.
    - Lifetime = time required to evaporate
- **Low Mass range**: 10^{-5} g - 10^{-1} g - 10^{9} g
    - Mass range defined by CMB and BBN. These are *probably* not dark matter, but they may be important to the dark matter story.
    - Note: "memory burden effect" (Dvali et al.) could halt evaporation, leaving remnant PBHs
- **High Mass range**: ~10^{16} g (asteroid mass) - ~10^{23} g (sublunar)
    - DM candidates?
- Picture changes (somewhat) for non-monochromatic mass function
- **Interesting interplay of PBHs and particle particle dark matter (PDM)**
    - PDM production from PBH evaporation
      e.g. Gondolo, Sandick, Shams es Haghi (2020)
    - PDM (spikes) around PBHs
      Pierre Salati's talk
- Search strategies from astrophysics and cosmology.

Fig: Green (2024), w/ PBHbounds (Kavanagh)





Bertone and Tait (2018)

Summary

- There are currently a huge number of viable dark matter candidates spanning ~90 orders of magnitude in mass.
- The WIMP paradigm has been a primary guide for many years. Still possible, but many other candidates are now being taken more seriously.
- Astrophysical and cosmological observations:
    - Indirect detection remains a critical technique.
    - Studying cosmic structures, stellar physics and evolution presents exciting new opportunities to probe the nature of dark matter.