dark matter

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⟶ GRAPPA, University of Amsterdam [Fall 2026]

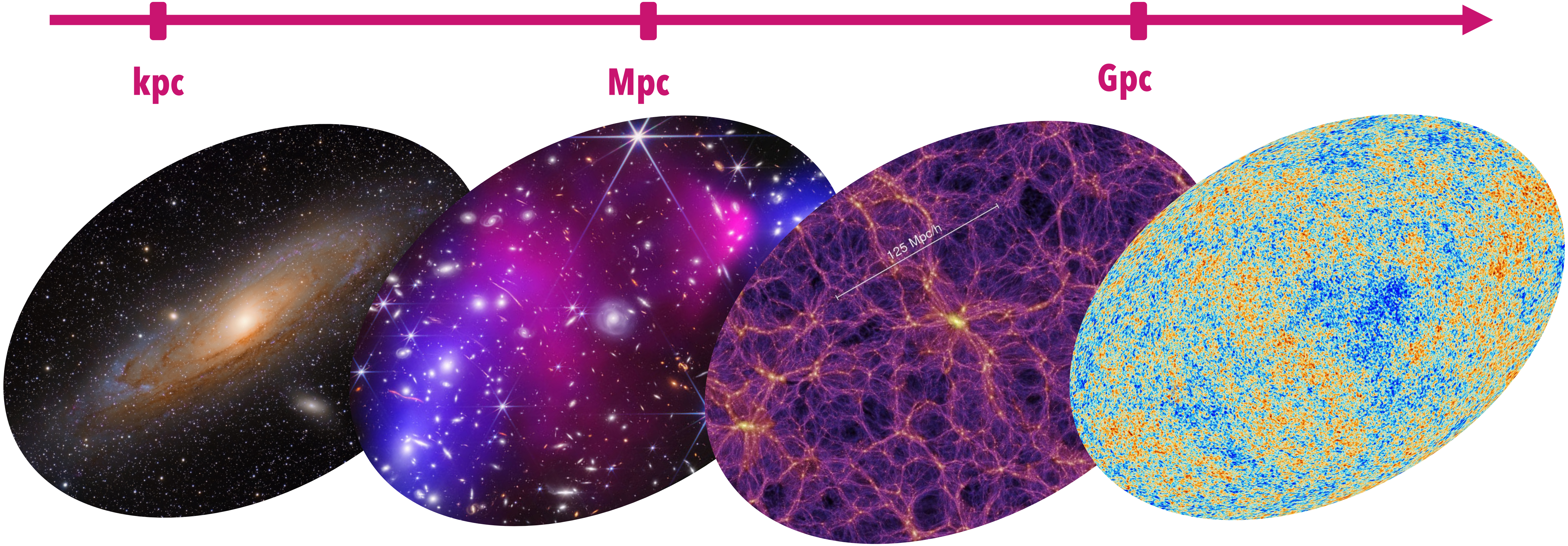
International School of Cosmic Ray Astrophysics
August 4 2026, Erice

Lecture 2/3

dark matter

1. **Dark Matter Introduction**
2. Dark Matter Candidates and Detection Strategies
3. Indirect Detection

Lecture 1: take-home message



A single non-baryonic dark-matter component consistently explains observations across these scales

Cirelli, Strumia & Zupan, "Dark Matter," arXiv:2406.01705

dark matter

1. Dark Matter Introduction
2. **Dark Matter Candidates and Detection Techniques**
3. Indirect Detection

What properties must the dark matter have?
What candidates satisfy these requirements?
How can we detect them?

Active poll

0

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slido.com
#3398 781

Gravitational Anomalies (The Dark Matter Problem)

- Low-mass dark matter particles (e.g., axions)
- High-mass dark matter particles (e.g., WIMPs)
- A modification to classical gravity on galaxy scales (e.g., MOND)
- Primordial black holes
- A hybrid of the above
- Effects of quantum gravity
- Other
- No opinion

Gravitational Anomalies (The Dark Matter Problem)

The observed rotation rates of galaxies are faster than expected, given the gravitational pull of the light-emitting matter contained in the galaxies. These rotation rates and related observations (e.g., clusters of galaxies, baryonic acoustic oscillation, and cosmic microwave background anisotropies) have led to proposals for "new physics" either in the form of dark matter or of modifications to the laws of gravity. In your opinion what is the most likely candidate for explaining these gravitational anomalies?

Low-mass dark matter particles (e.g., axions)	17%
High-mass dark matter particles (e.g., WIMPs)	10%
A modification to classical gravity on galaxy scales (e.g., MOND)	12%
Primordial black holes	5%
A hybrid of the above	21%
Effects of quantum gravity	10%
Other	10%
No opinion	15%

[Big Mysteries Survey: Physicists' Views on Cosmology, Black Holes, Quantum Mechanics, and Quantum Gravity, 2605.11058]

Properties of dark matter (observations)

Requirement	From which observation	Quantitatively
gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$

Planck 2018 VI, 1807.06209

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gravitates & clusters	rotation curves, virial masses, lensing, CMB+BAO fix the cosmological abundance	$\Omega_{DM} \sim 0.26$
non-baryonic	BBN (D/H) + CMB baryon loading	$\Omega_{DM}/\Omega_{\rm b} = 5.36 \longrightarrow$ not ordinary baryonic gas/stars/compact remnants

Pitrou+ 1801.08023; Cooke+ 1710.11129

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dark*/weakly SM-coupled	CMB + matter power + lack of EM signatures	Interaction dependent

*misnomer: dark things absorb. It's *transparent*

LZ 2410.17036; Boddy & Gluscevic 1801.08609

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long-lived	DM still exists; CMB/indirect decay searches	$\tau \gtrsim t_U \sim 4\times10^{17}$ s visible decays $\gtrsim 10^{26}$ s

Slatyer & Wu 1610.06933; Essig+ 1309.4091

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weakly self-interacting	merging clusters, halo dynamics	$\sigma/m \lesssim \mathcal{O}(1)$ cm^2 g^{-1} @ cluster velocities

Clowe+ astro-ph/0608407; Randall+ 0704.0261; Sagunski+ 2006.12515; Tulin & Yu 1705.02358

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weakly self-interacting*	merging clusters, halo dynamics	$\sigma/m \lesssim \mathcal{O}(1)$ $cm^2\ g^{-1}$ @ cluster velocities
dissipationless**	extended halos rather than a cooled dark disk	no universal single number (halo axis ratio ~0.7--1)

*bounds elastic scattering. **bounds inelastic/dissipative processes.

Fan+ 1303.1521; Read 1404.1938; Bruch+ 0804.2896; Ibata+ astro-ph/0004011

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cold/small primordial velocity dispersion	Lyman-α forest & small-scale structure; CMB	pertubation size < $\lambda_{fs} \sim v(t_{eq})/H(t_{eq})$ doesn't survive (est. ~0.17(keV/m_{DM}) Mpc

Viel+ 1306.2314; Iršič+ 1702.01764; Tremaine & Gunn (1979); Alvey+ 2010.03572; Zimmermann+ 2405.20374

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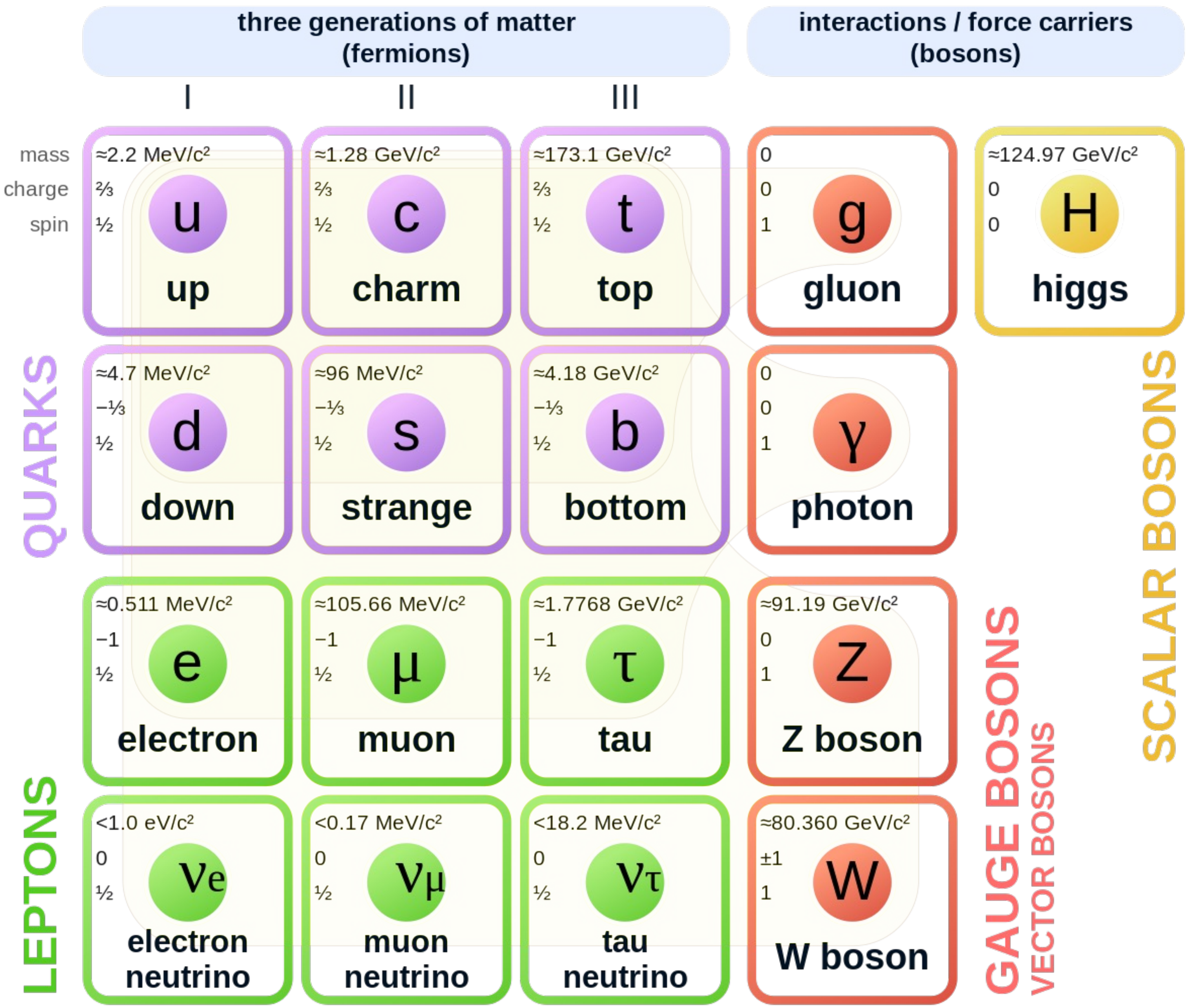
Standard Model of Elementary Particles



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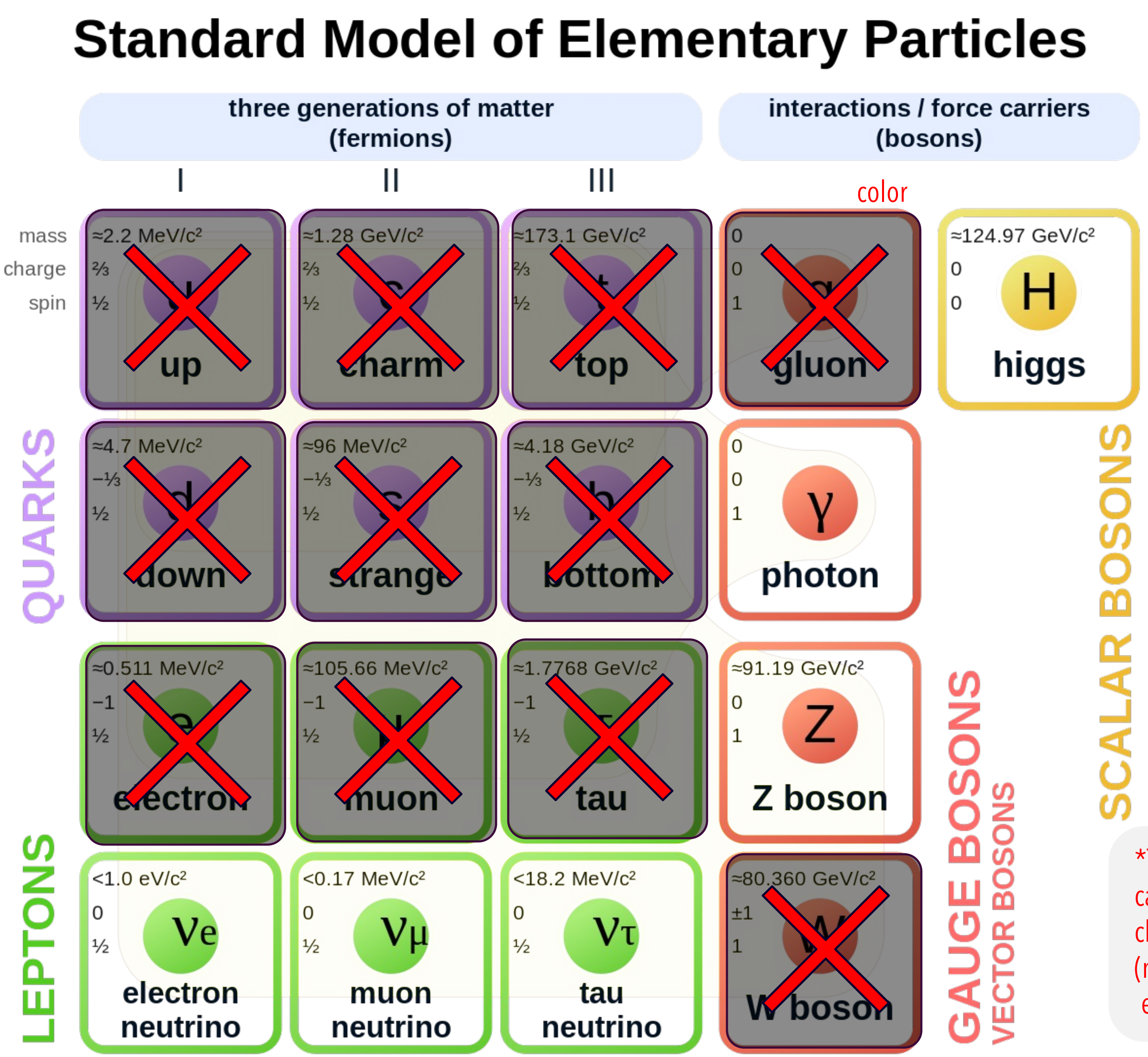

*That is, dark matter cannot have a large charge-to-mass ratio (millicharge ≪ electron charge)

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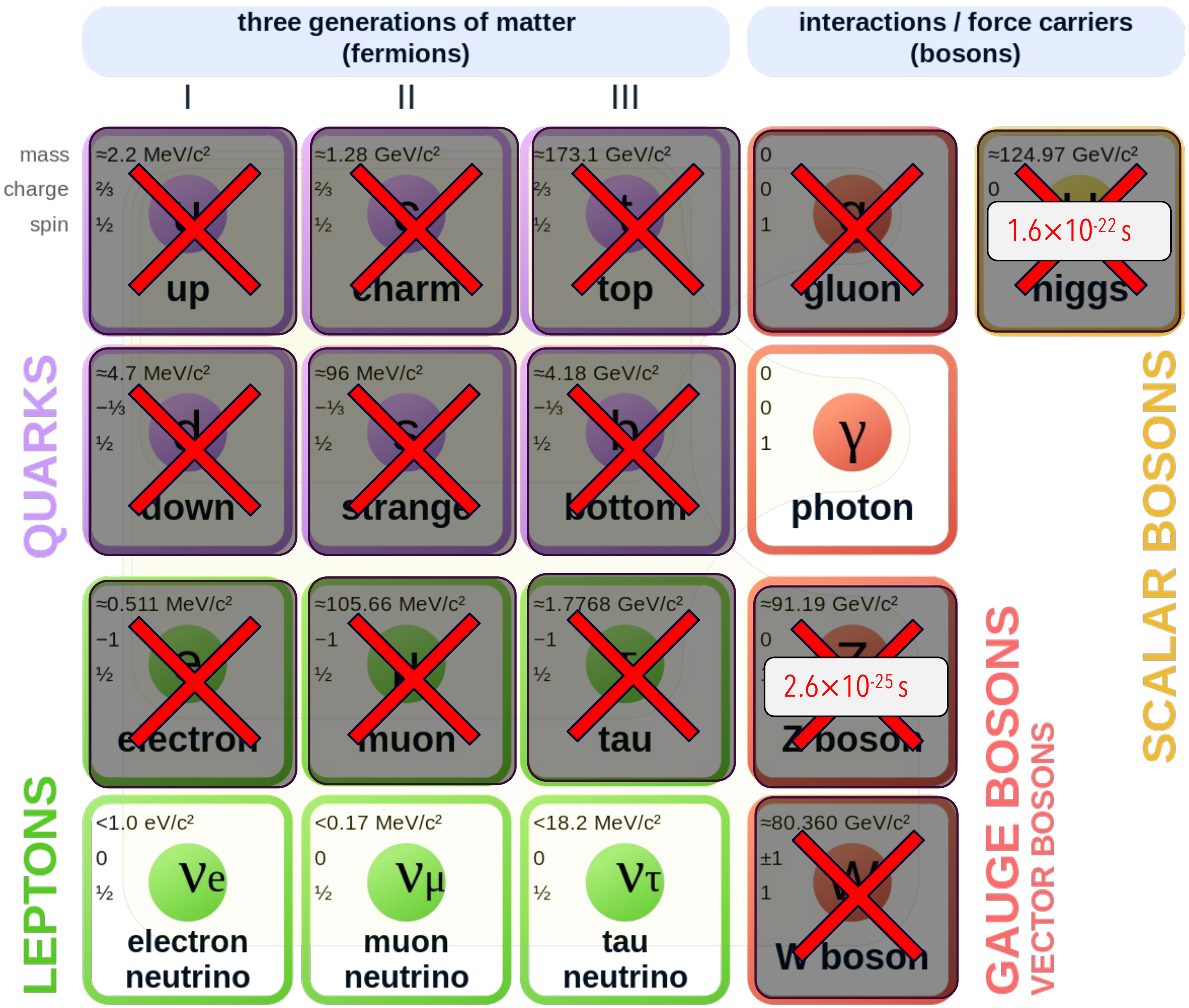

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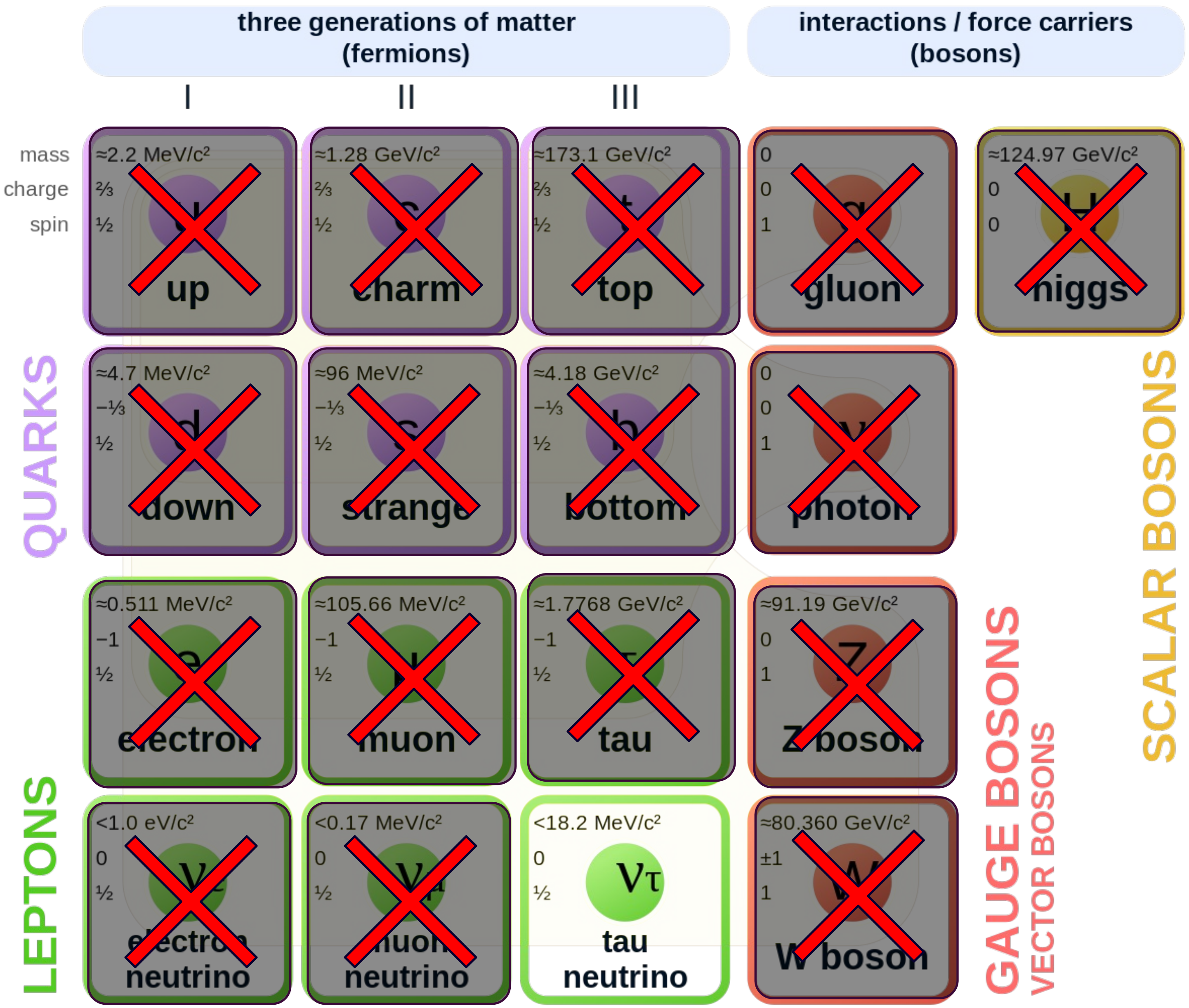

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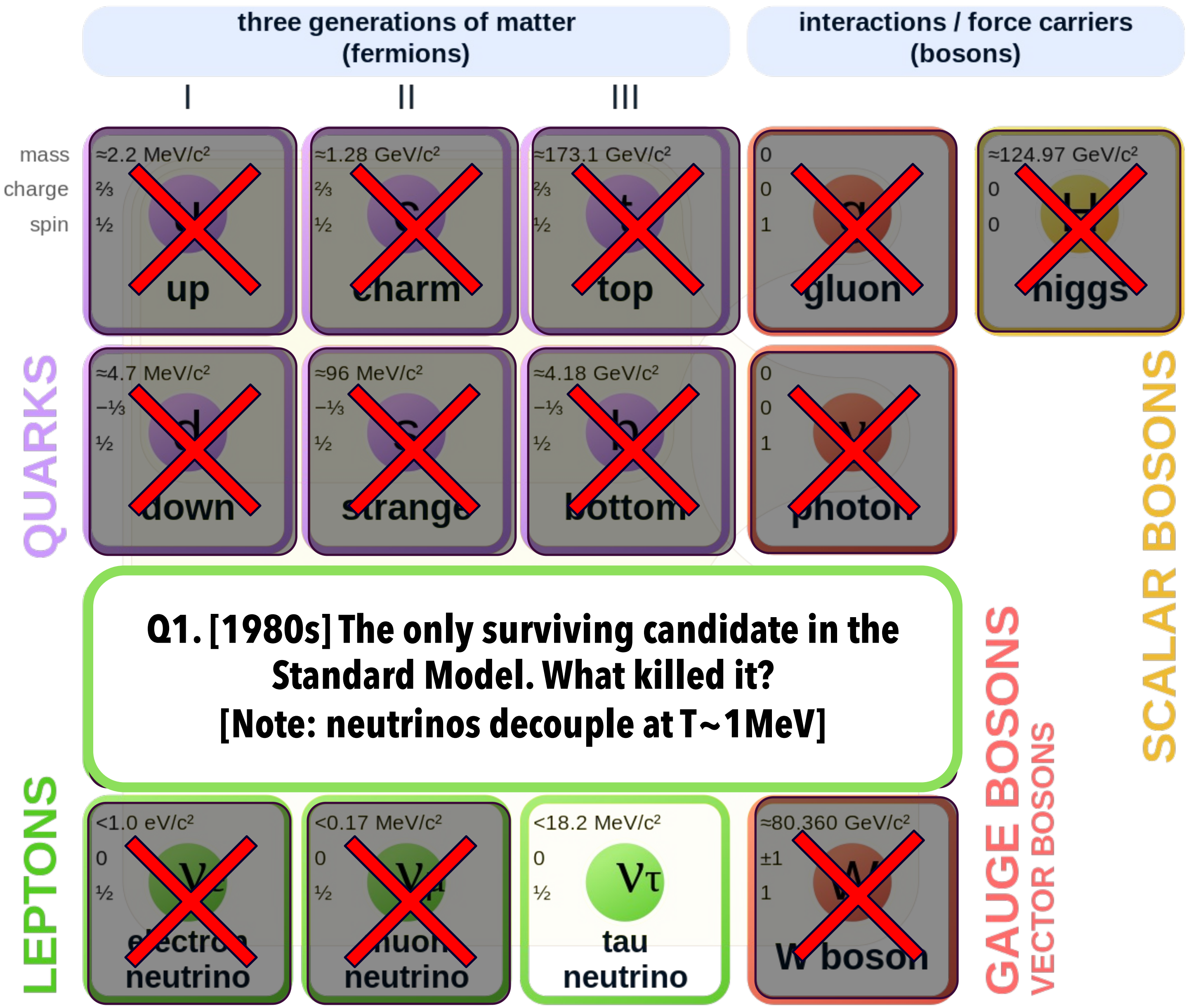

Q1. [1980s] The only surviving candidate in the Standard Model. What killed it?
[Note: neutrinos decouple at T~1MeV]

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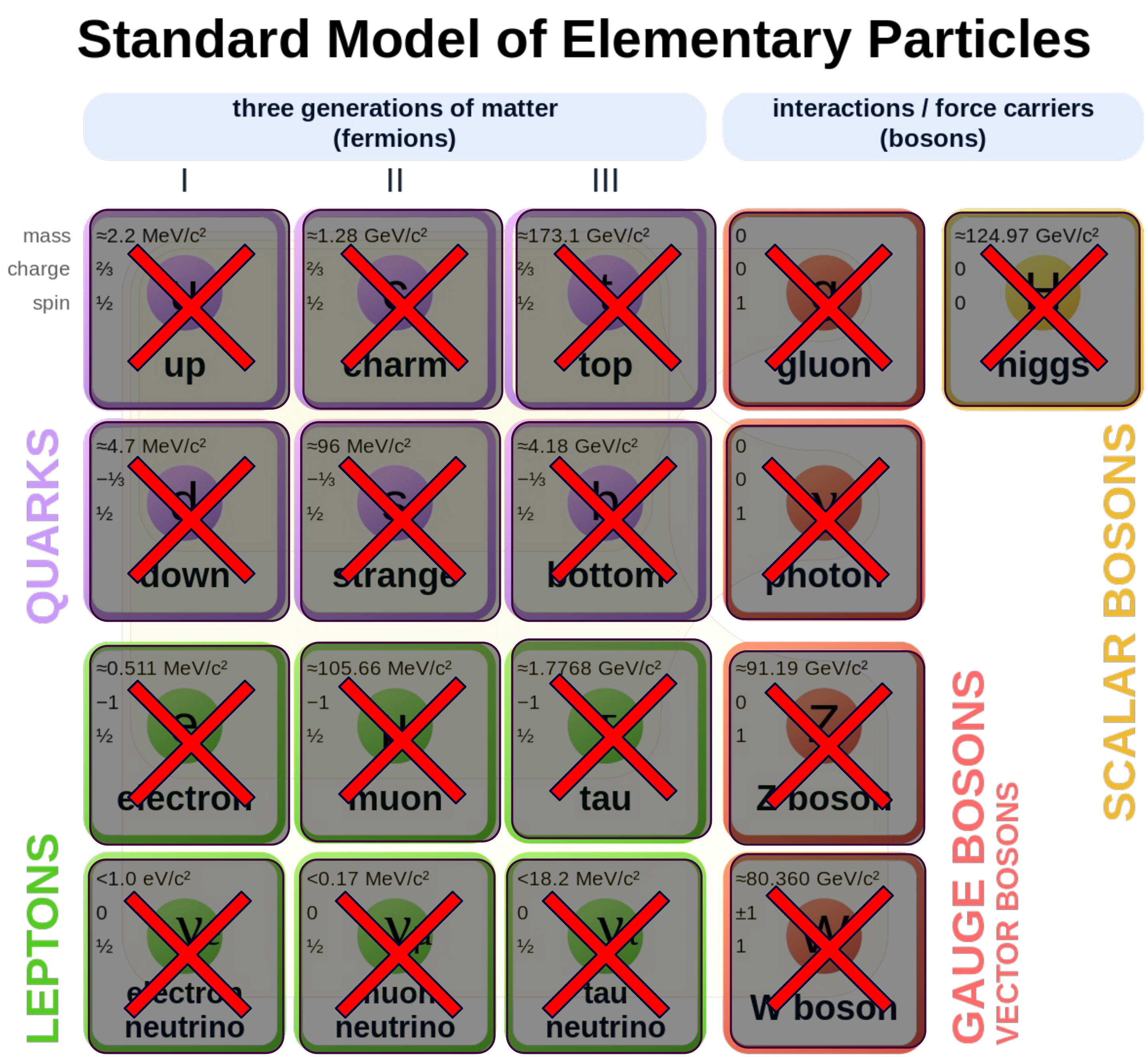

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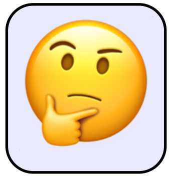
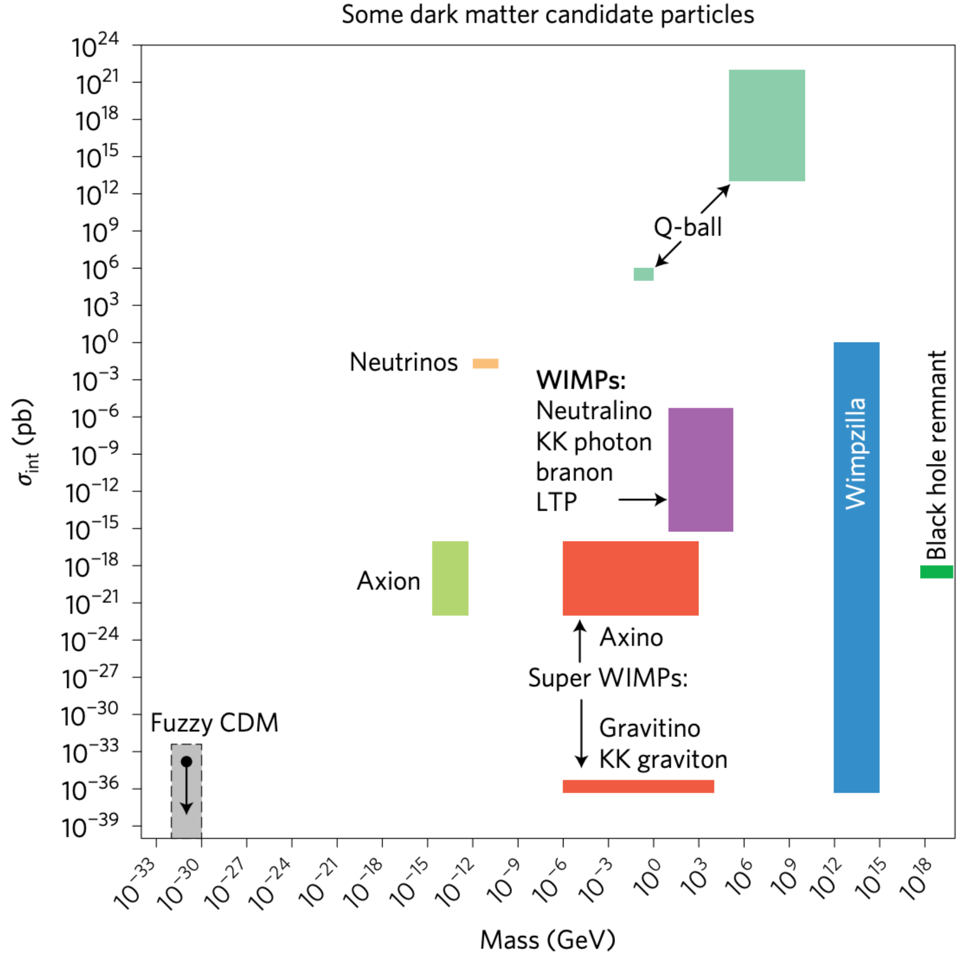
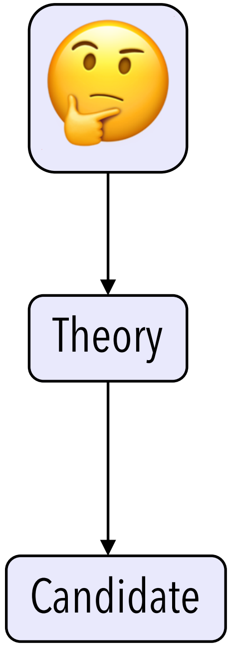


→ Many very different candidates can satisfy the basic DM requirements and span enormous ranges in mass and interaction strength.



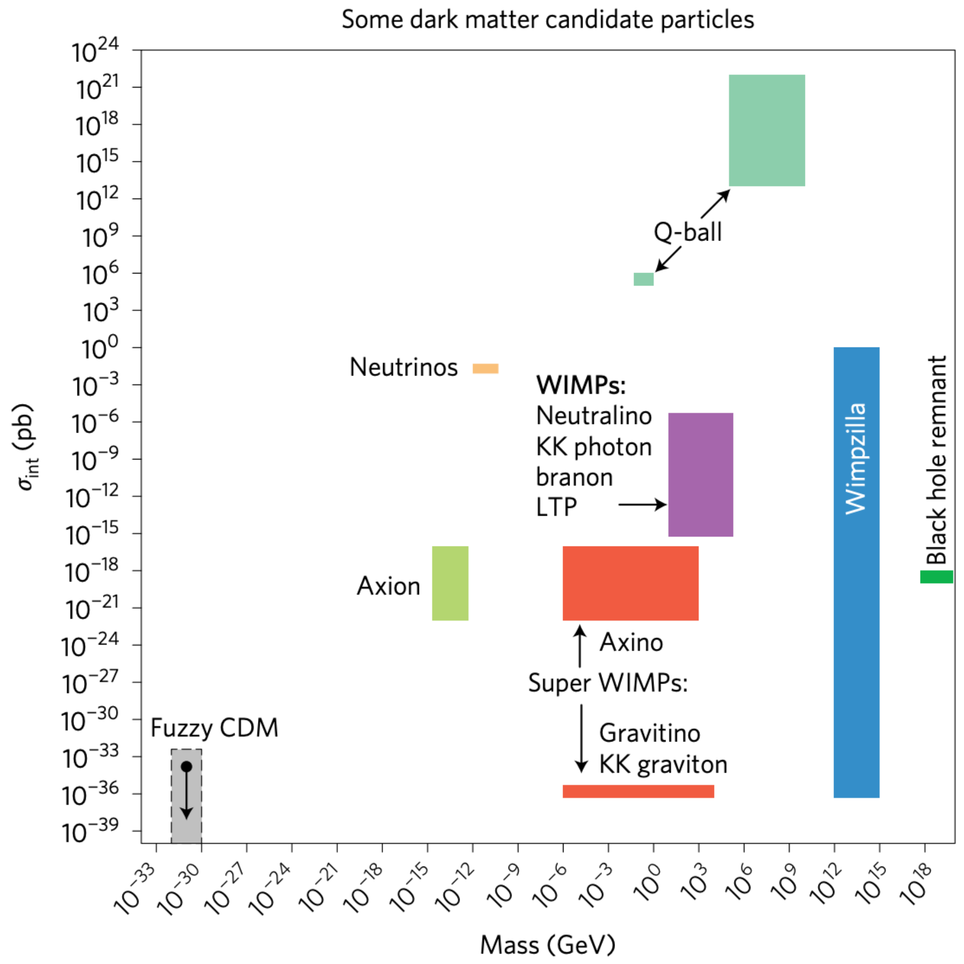
Conrad & Reimer, Nature Physics 13 (2017) 224–231

Observations give us requirements, not a unique particle.



→ Many very different candidates can satisfy the basic DM requirements and span enormous ranges in mass and interaction strength.

→ We need additional input from theory:
What is its mass?
What does it couple to?
How was it produced?
→ **the dark matter zoo**



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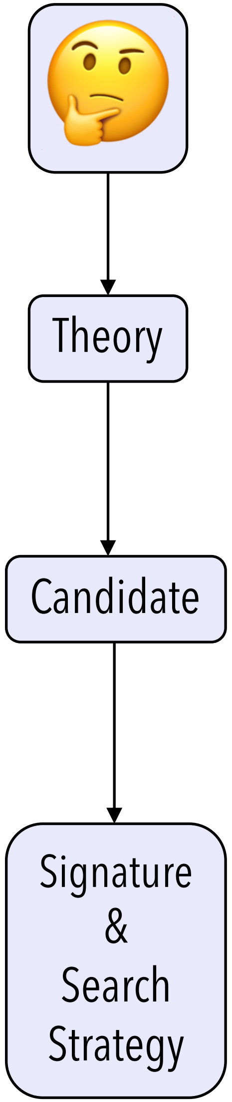

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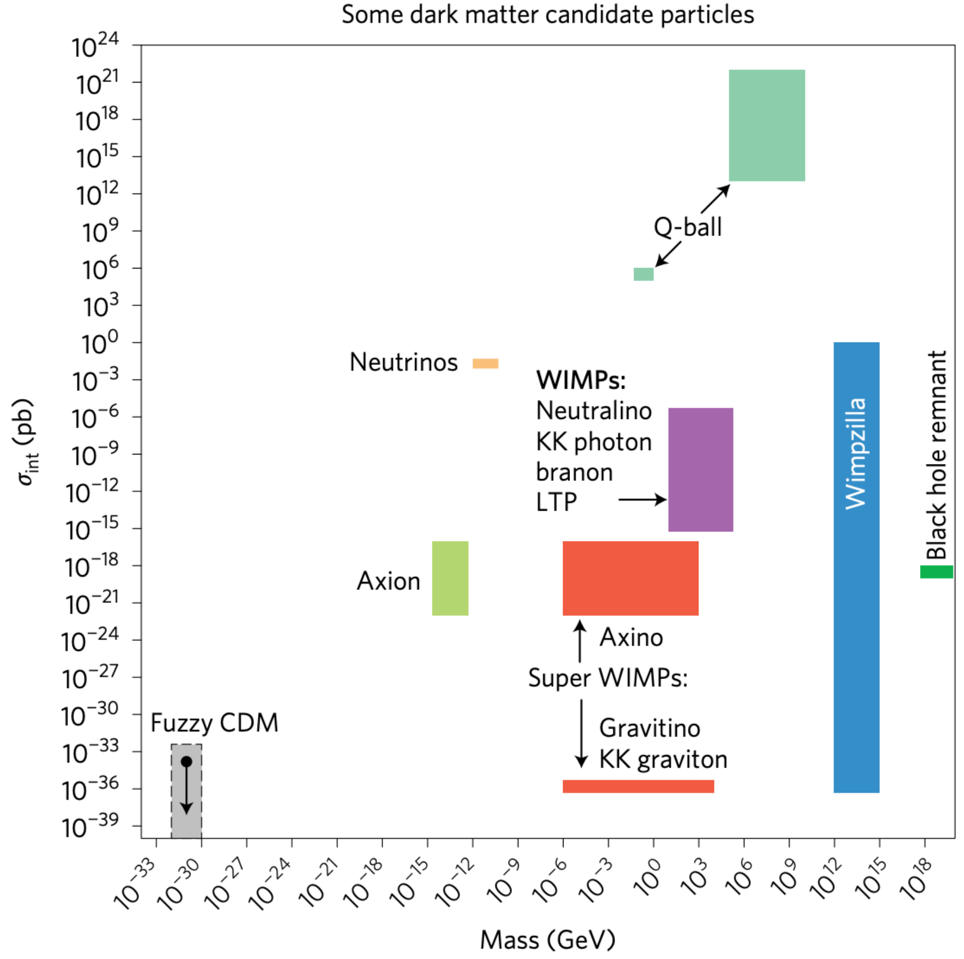
→ Once a theoretical framework is specified, we can ask how that candidate could reveal itself and design the corresponding search.
→ Identification strategies are therefore **necessarily model-dependent** – to varying degrees



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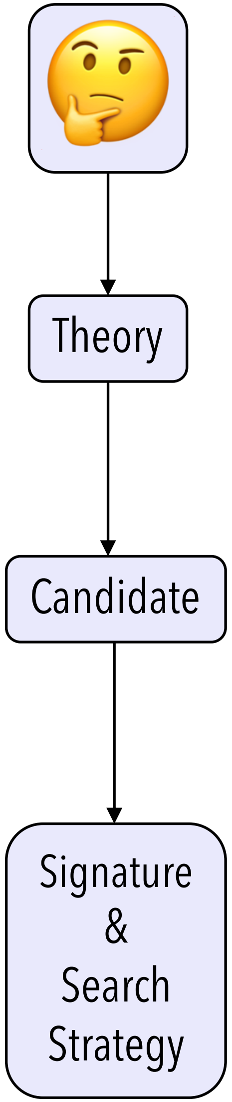
Observations give us requirements, not a



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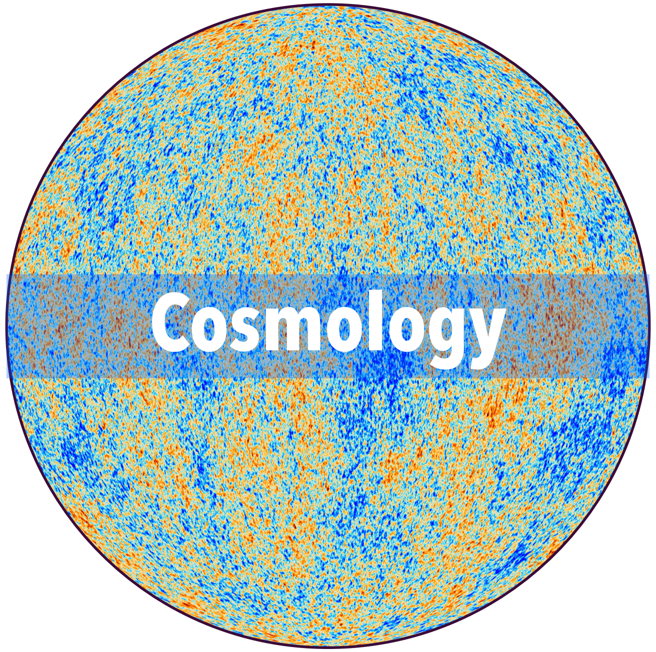
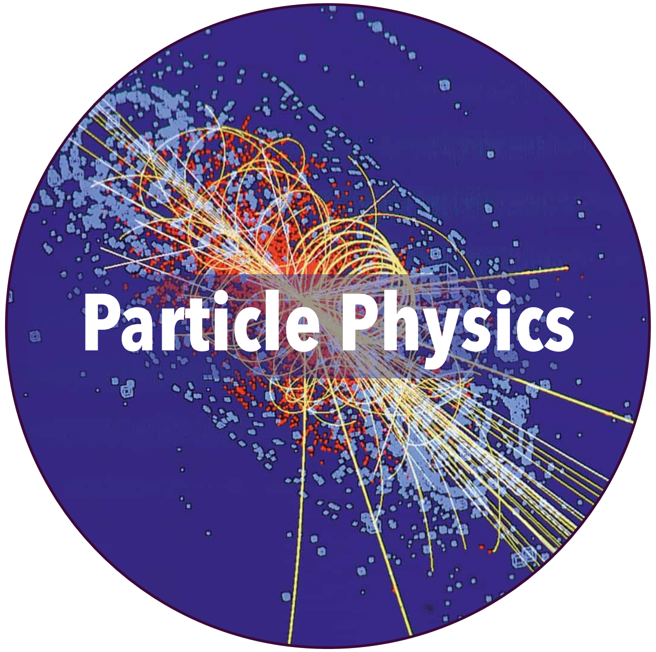
Dark Matter Candidates: A Ten-Point Test

Marco Taoso[1,2], Gianfranco Bertone[2], and Antonio Masiero[1]
[1] *INFN, Sezione di Padova, via Marzolo 8,Padova,35131,Italy and*
[2] *Institut d'Astrophysique de Paris, UMR 7095-CNRS,*
Université Pierre et Marie Curie, 98 bis Boulevard Arago 75014, Paris, France

1. *Does it match the appropriate relic density?*
2. *Is it cold?*
3. *Is it neutral?*
4. *Is it consistent with BBN?*
5. *Does it leave stellar evolution unchanged?*
6. *Is it compatible with constraints on self-interactions?*
7. *Is it consistent with direct DM searches?*
8. *Is it compatible with gamma-ray constraints?*
9. *Is it compatible with other astrophysical bounds?*
10. *Can it be probed experimentally?*

dark matter





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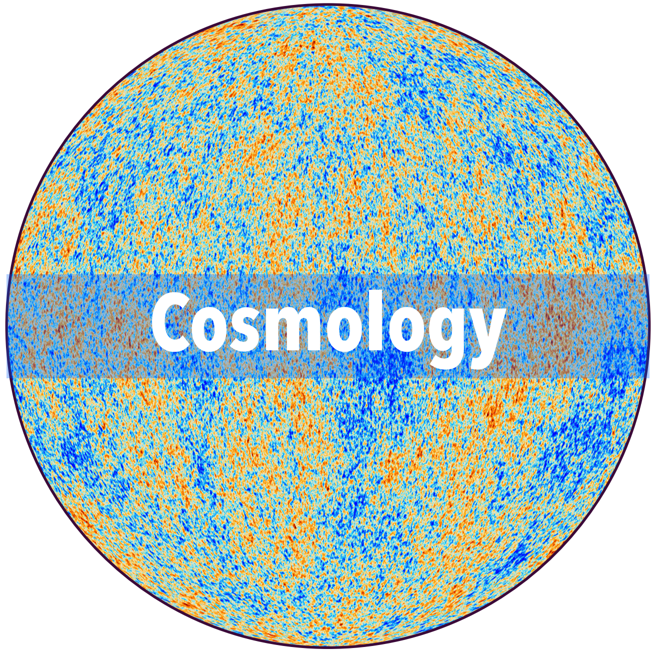
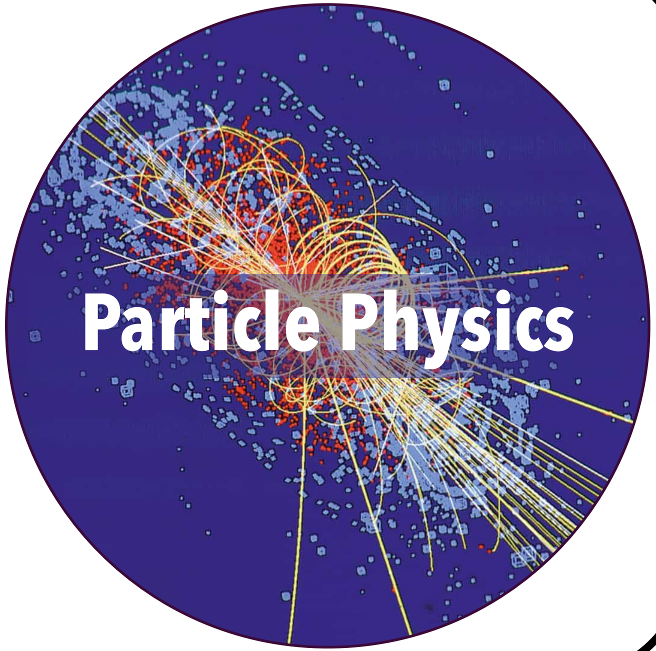


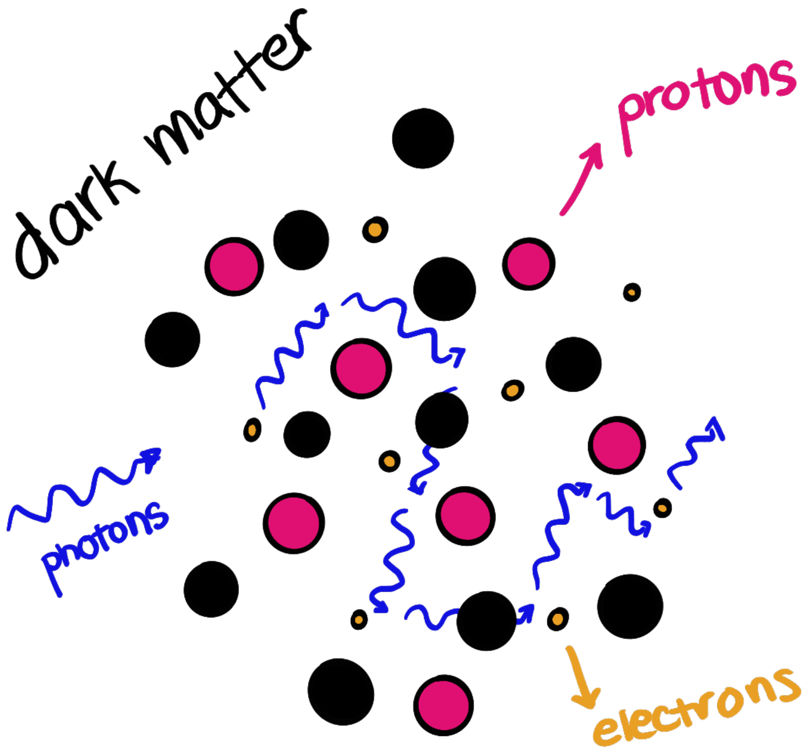


Particle cosmology: thermal freeze-out

- Possibility (not a requirement): dark matter was just another species in the primordial thermal bath
- Suppose dark matter has some weak non-gravitational coupling to the Standard Model

$$\chi + \chi \rightleftarrows \mathrm{SM} + \mathrm{SM}$$

primordial thermal bath



Particle cosmology: thermal freeze-out

- For a species χ in thermal equilibrium, their number density is governed by the Boltzmann Equation.

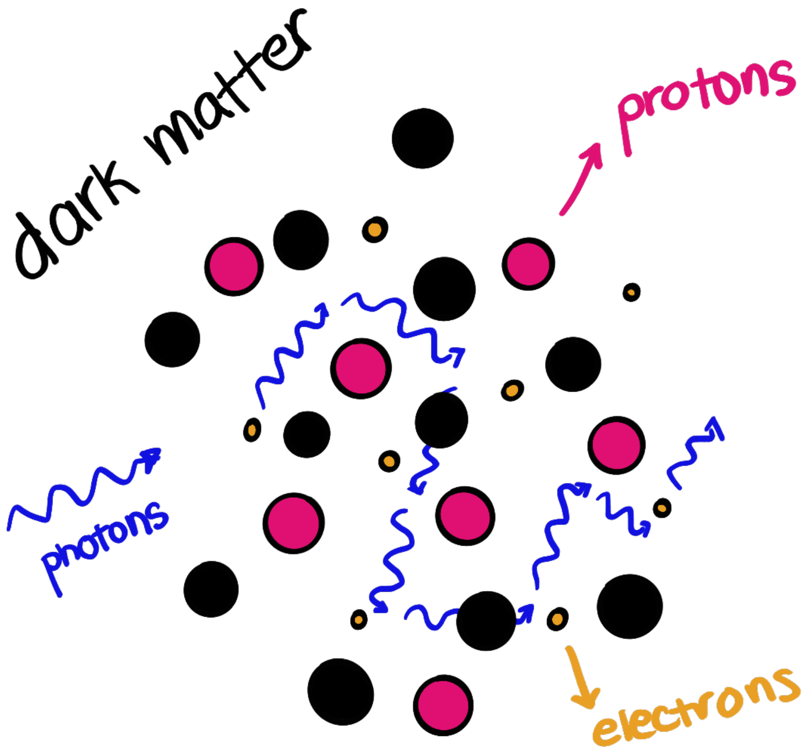
DM annihilation

$$\dot{n}_\chi + \boxed{3Hn_\chi} = -\langle\sigma_{\chi\bar{\chi}}v\rangle_{\rm eq}\left[\boxed{n_\chi^2} - \boxed{n_{\chi,eq}^2}\right]$$

dilution due to expansion

DM production

primordial thermal bath



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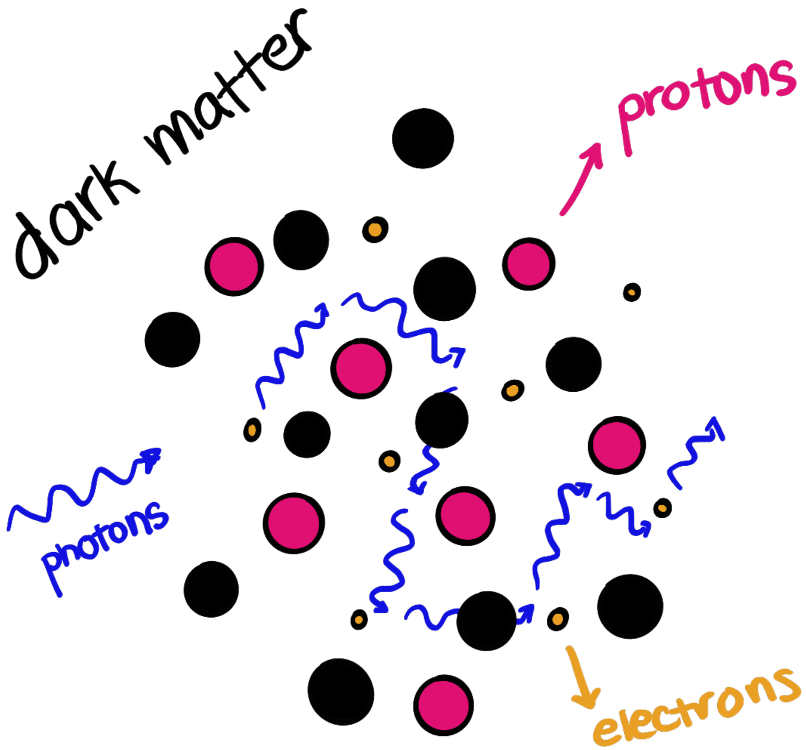
dilution due to expansion — DM production

- Equilibrium number densities:

$$n_{\text{eq}}(T) = \begin{cases} \frac{3}{4}\frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \quad \text{relativistic} \\ g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \quad \text{non-relativistic} \end{cases}$$

primordial thermal bath



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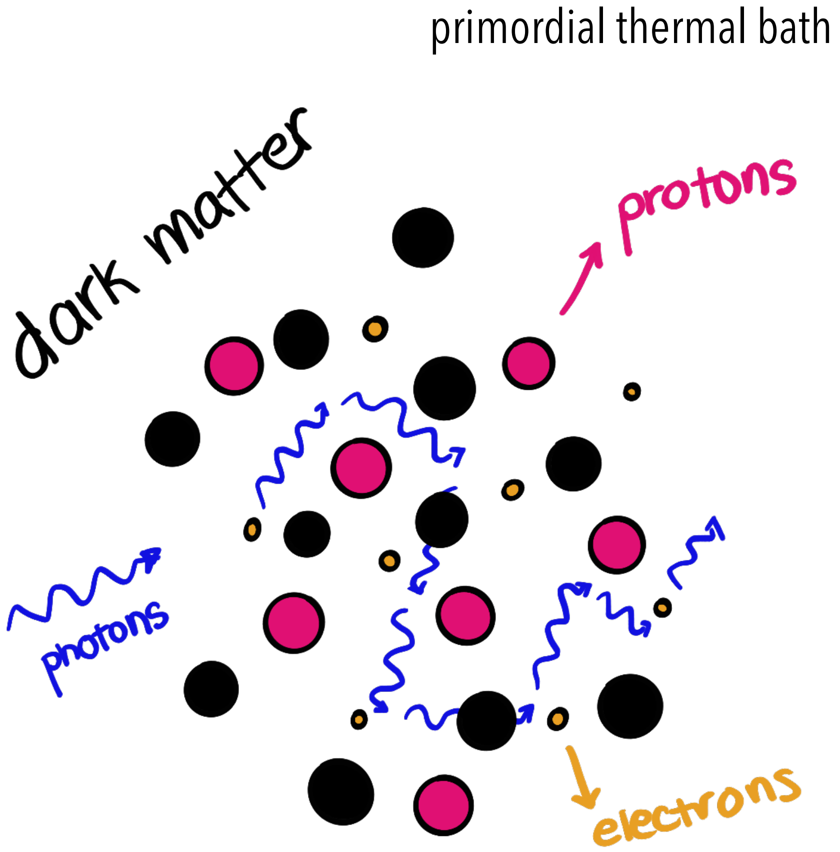

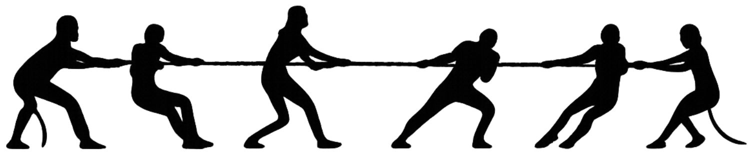

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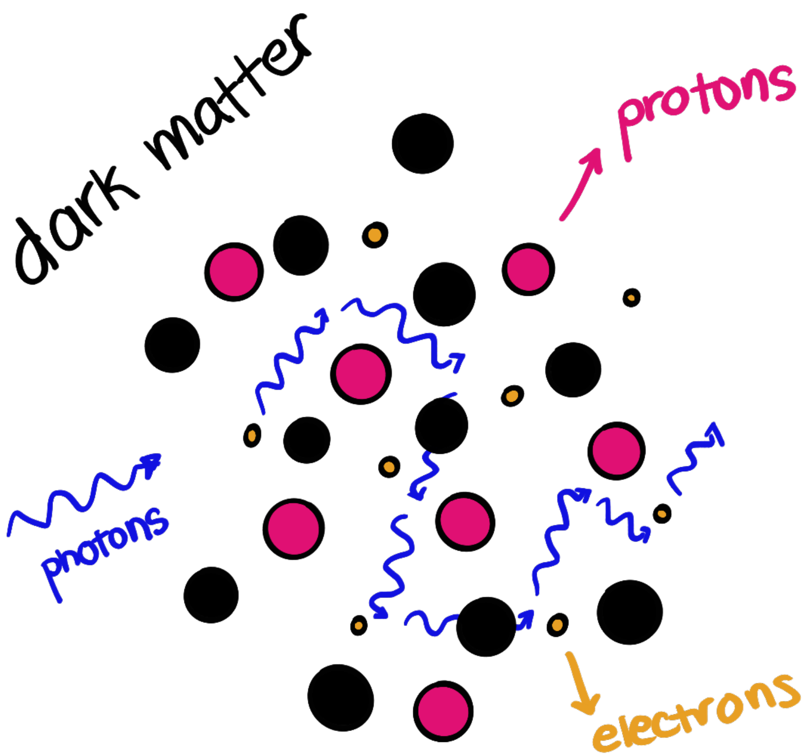
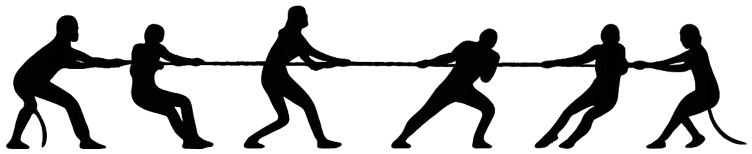


Hubble expansion

H = characteristic expansion time



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dilution due to expansion — DM annihilation — DM production

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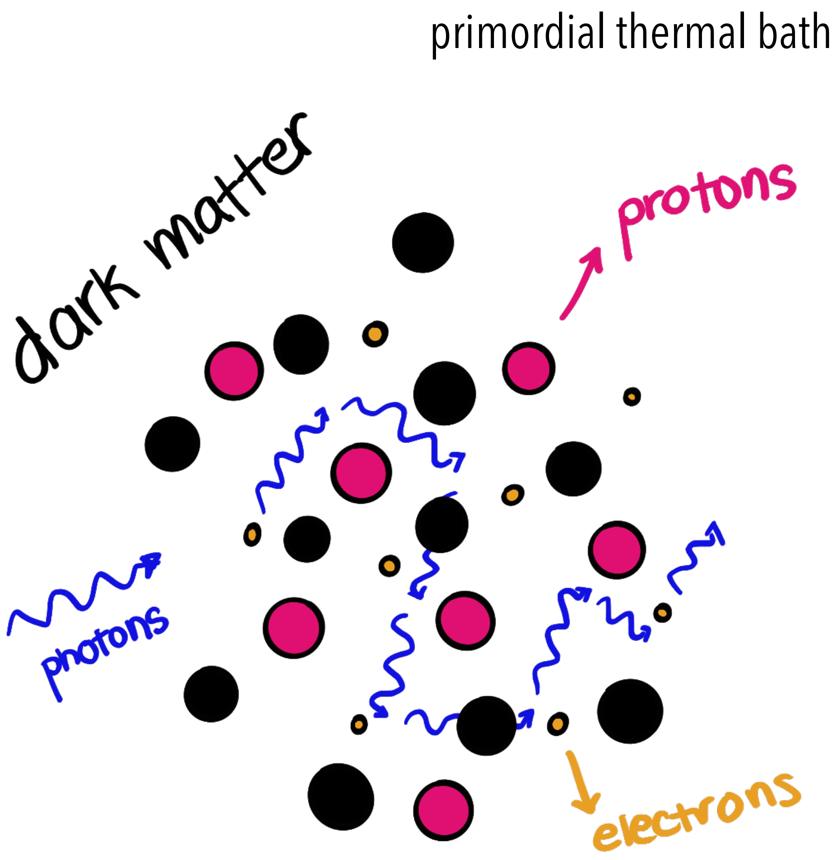

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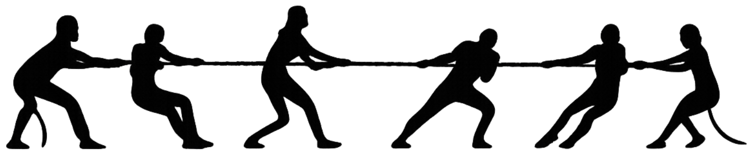
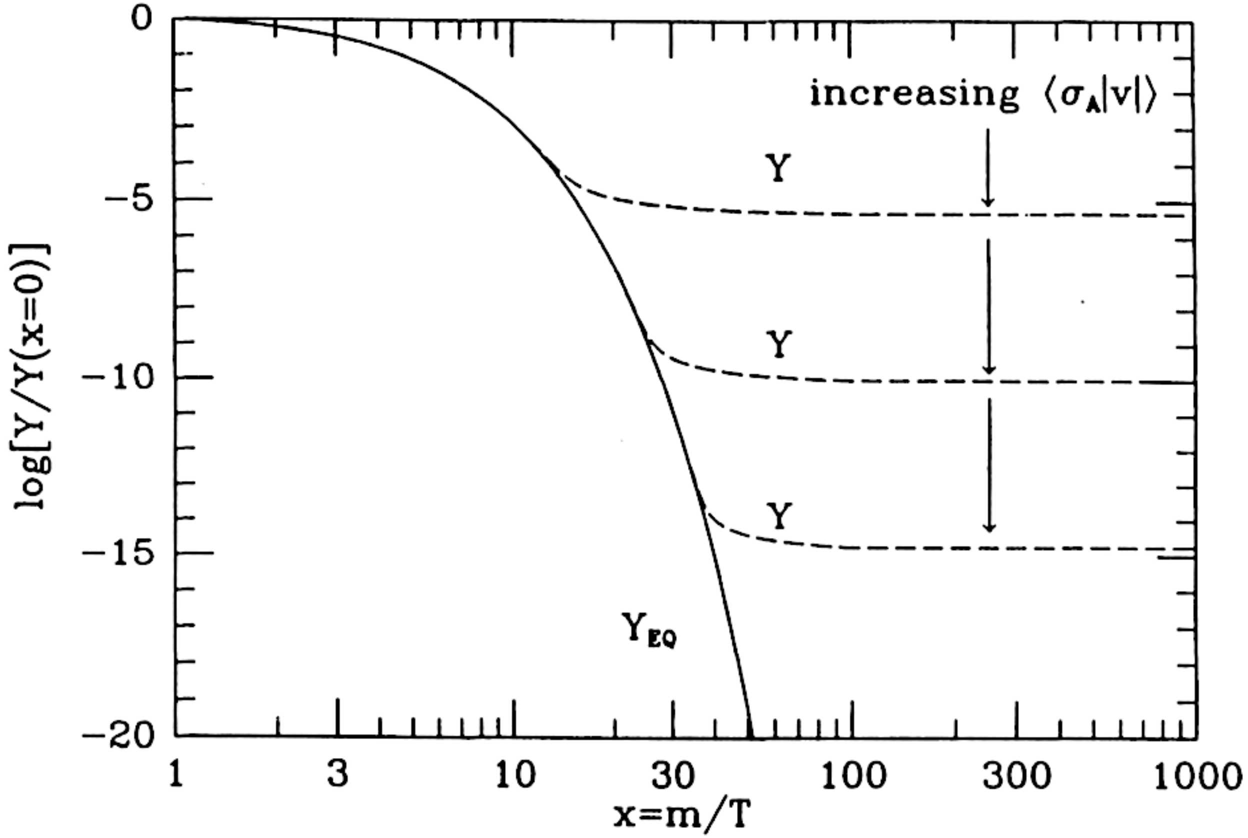


Annihilation rate

$\Gamma = n_\chi \langle\sigma v\rangle =$ time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3$$

Hubble expansion

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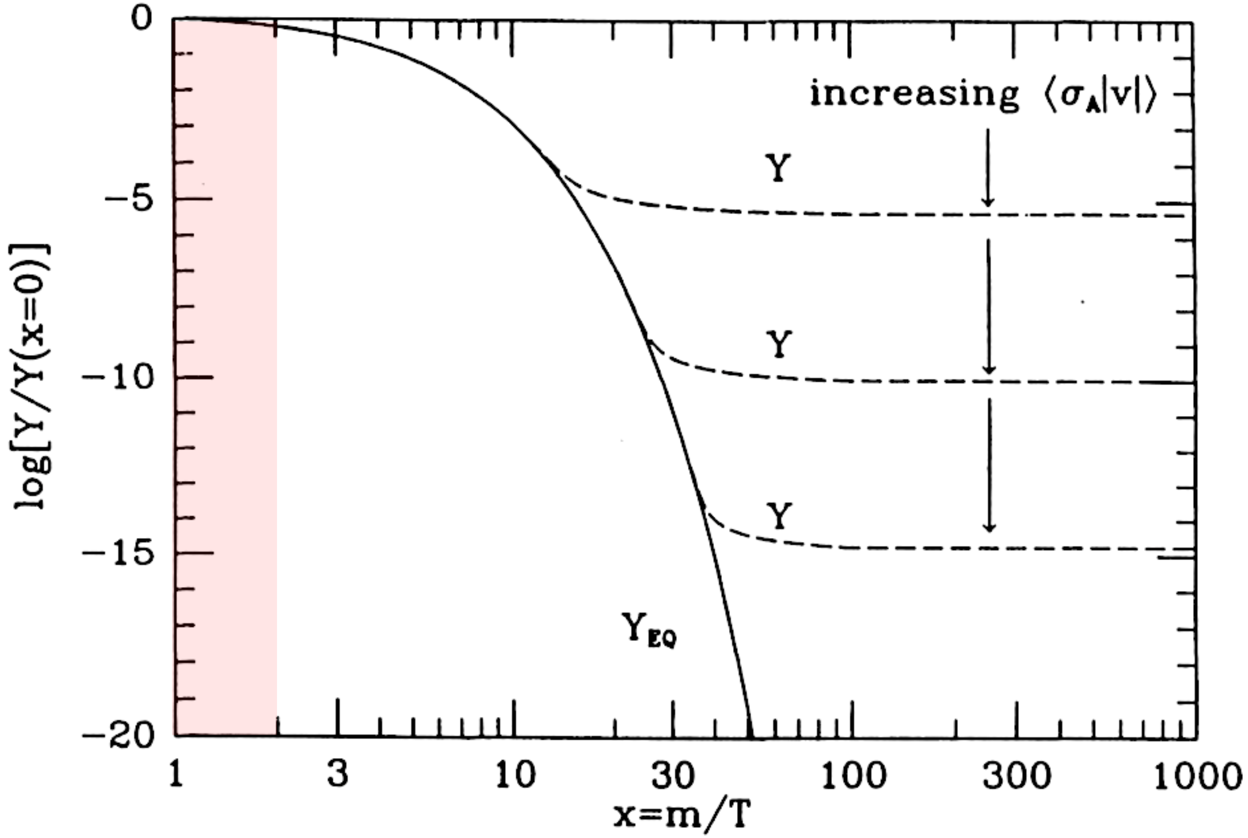
Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 \sim \text{const}$$

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Hubble expansion

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$\ll$

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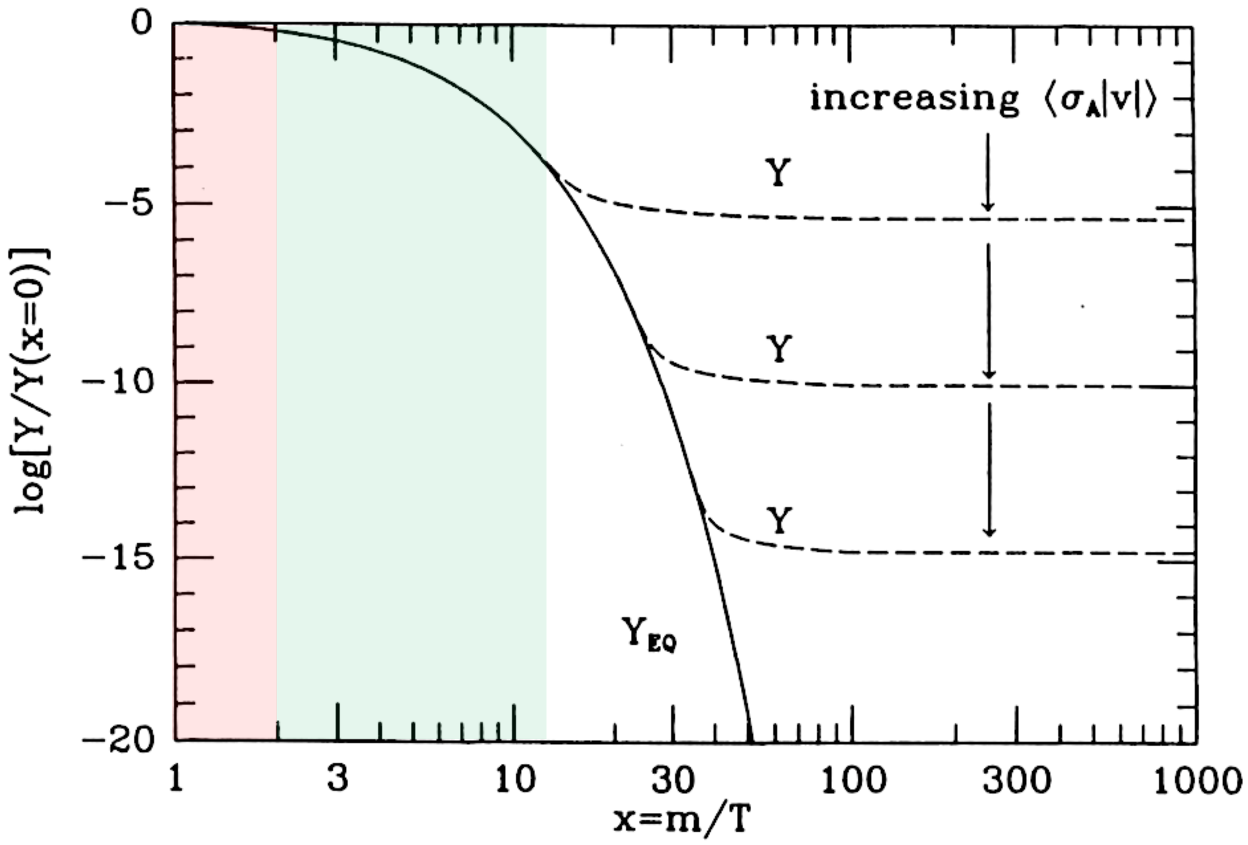
Particle cosmology: thermal freeze-out



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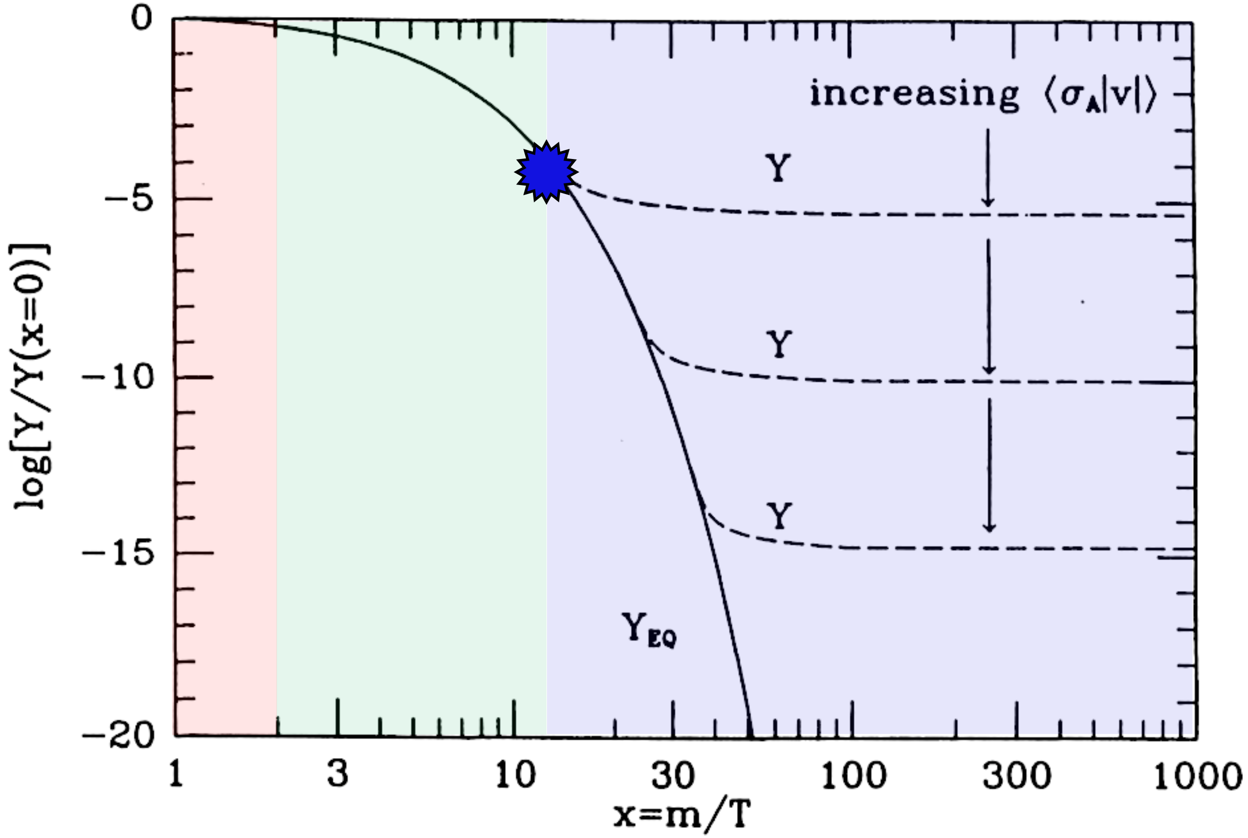

comoving number density

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freeze-out

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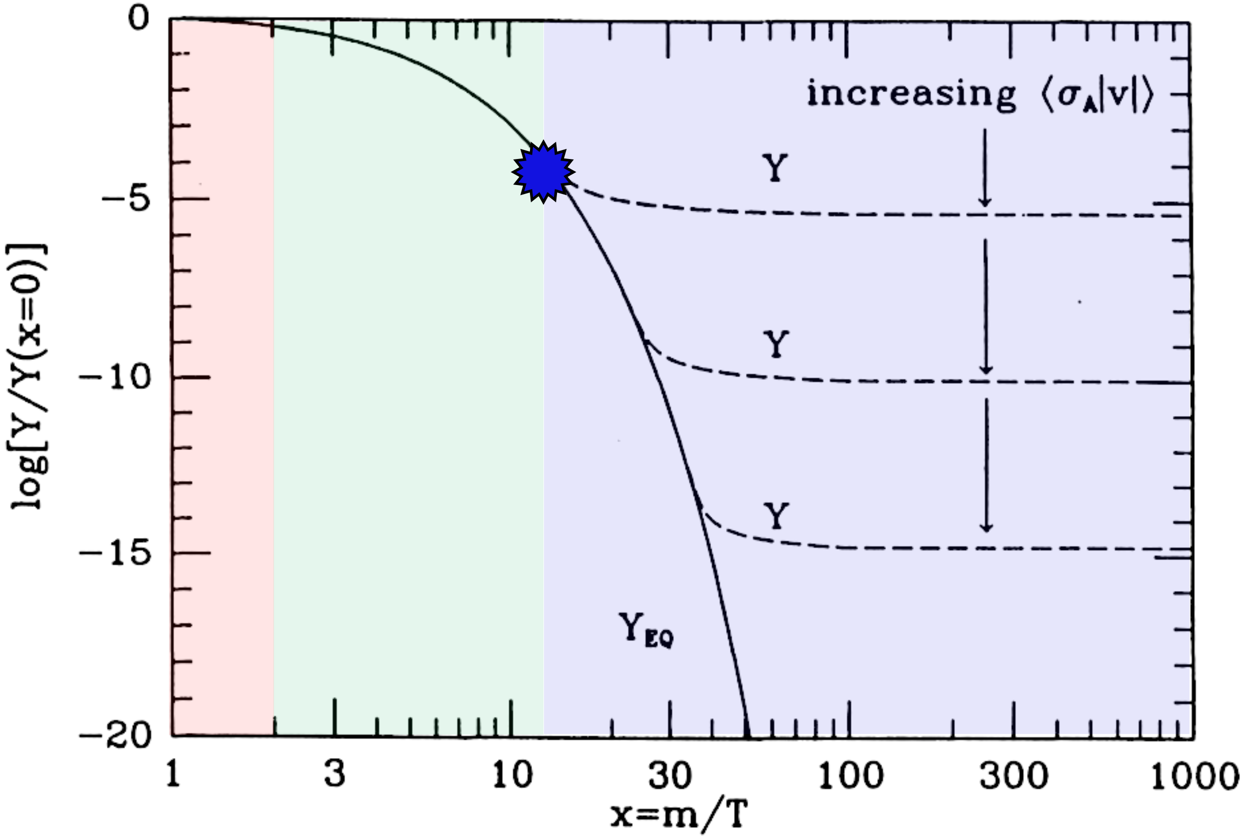
$\Gamma = n_\chi \langle \sigma v \rangle =$ time for a particle to annihilate

Particle cosmology: thermal freeze-out



comoving number density

$$Y_i \equiv \frac{n_i}{s} \sim n_i a^3 = Y_0$$

$$n_{\rm eq}(T) = \begin{cases} \frac{3}{4}\frac{\zeta(3)}{\pi^2} g T^3 & \text{for } T \gg m_\chi \\ g\left(\frac{m_\chi T}{2\pi}\right)^{3/2} e^{-m_\chi/T} & \text{for } T \ll m_\chi \end{cases}$$

freeze-out

- freeze-out leaves a relic abundance controlled primarily by $\langle \sigma v \rangle$

$$\Omega_\chi h^2 \approx 0.12 \times 3\times10^{-26}\ \mathrm{cm^3\ s^{-1}} / \langle \sigma v \rangle$$

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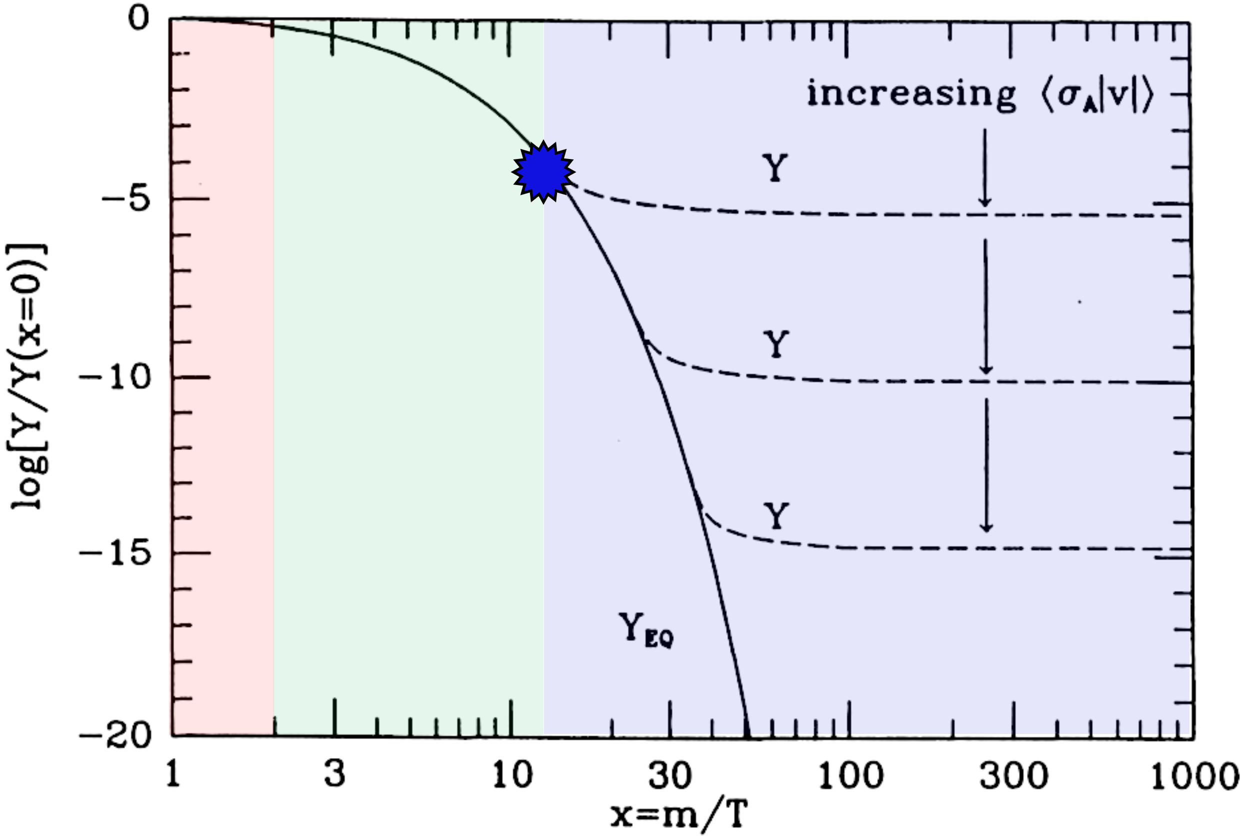

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freeze-out

WIMP “miracle”

- freeze-out leaves a relic abundance controlled primarily by $\langle \sigma v \rangle$

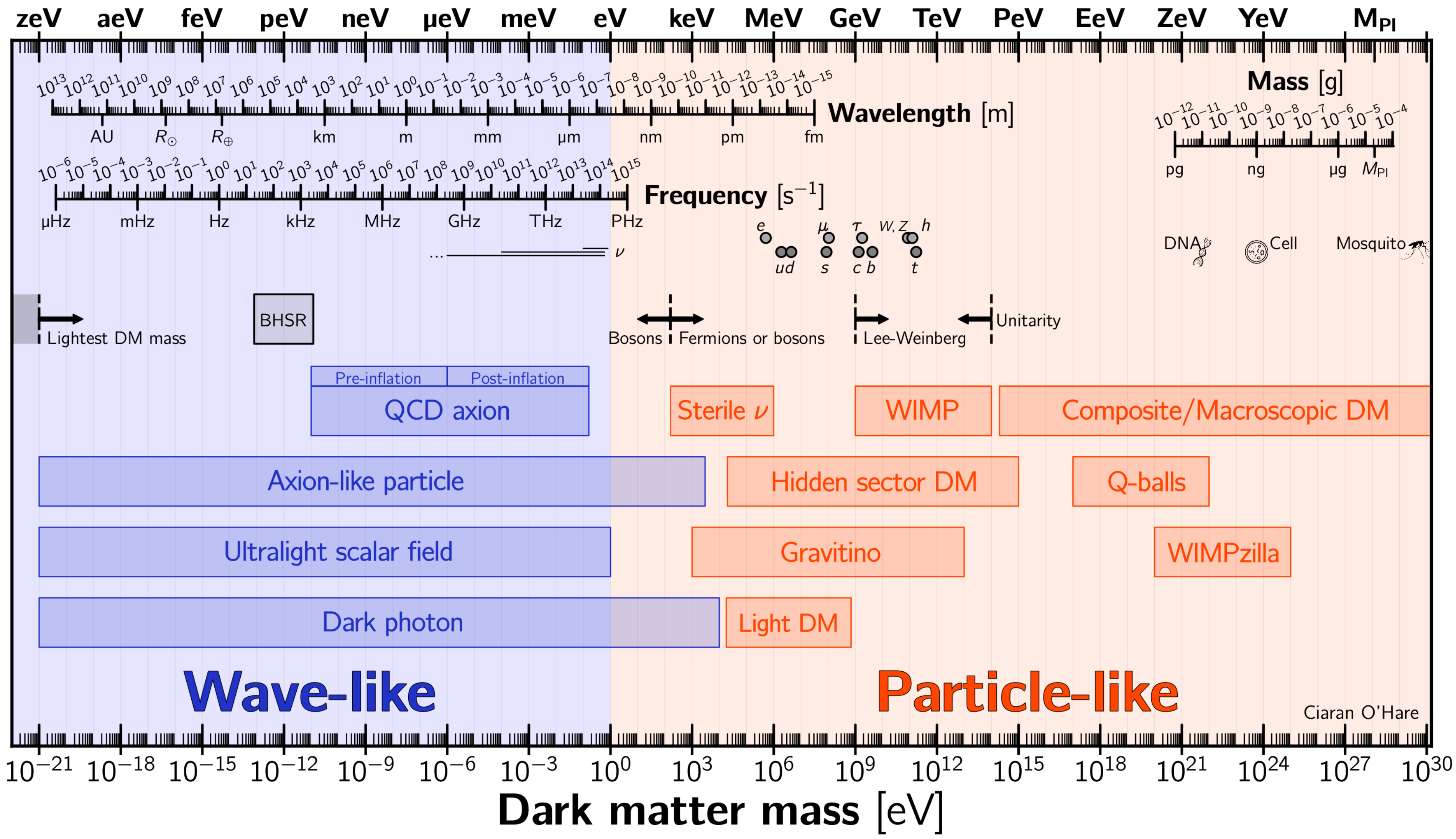
$$\Omega_\chi h^2 \approx 0.12 \times 3\times10^{-26}\ \text{cm}^3\ \text{s}^{-1} / \langle \sigma v \rangle$$

$\langle \sigma v \rangle \sim 1$ pb c $(200\ \text{GeV}/m_{DM})^2$ (weak scale estimate) ~ $3\times10^{-26}\ \text{cm}^3\ \text{s}^{-1}$

Dark Matter Landscape: A Theorist's View

Too light: has wave-like properties on galactic scales

[Ciaran A. J. O'Hare]

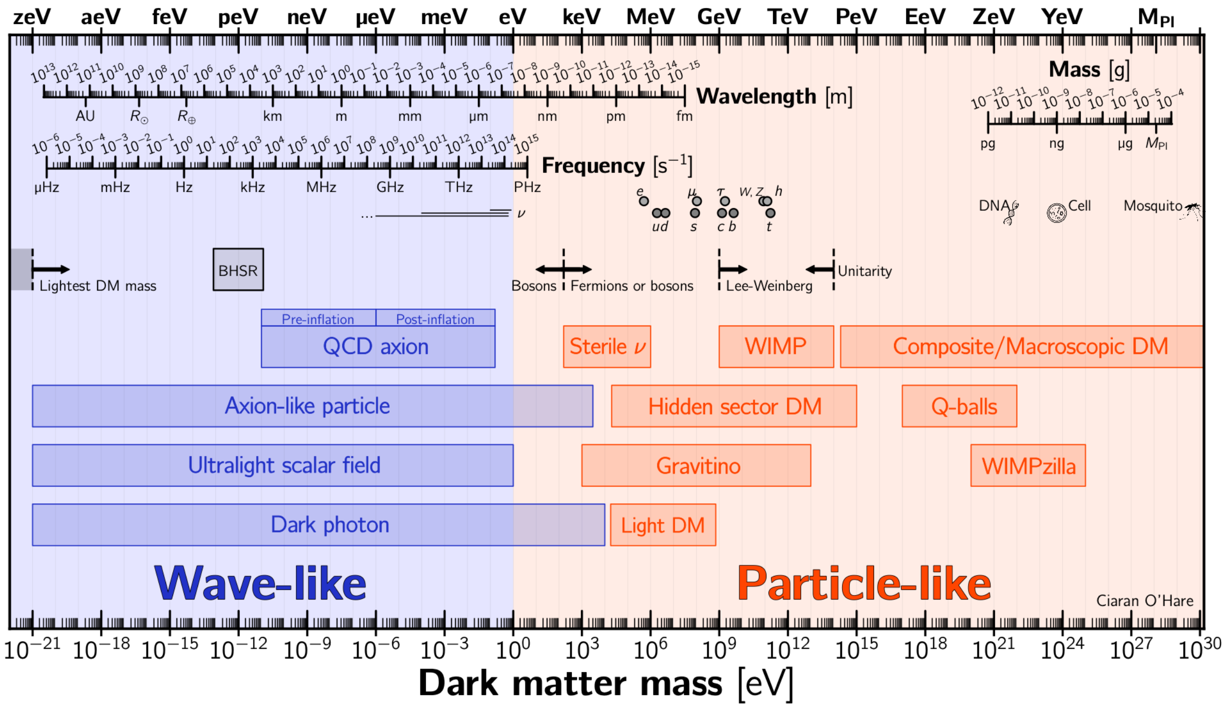


PBHs

~10^{70}

Too heavy: DM mass comparable to galaxy masses

Dark Matter Landscape: A Theorist's View



[Ciaran A. J. O'Hare]

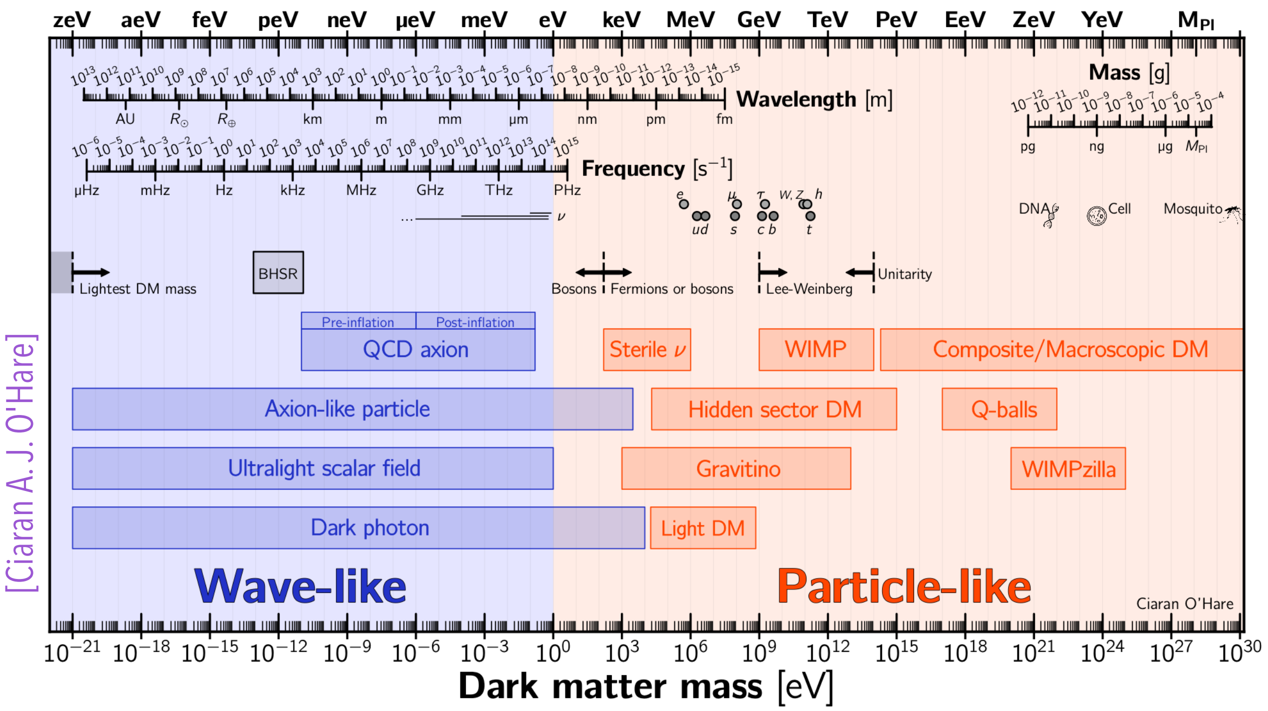
Dark matter spans over

80 orders of magnitude in mass (+ interaction strength)

proton
m~10^{-27} kg

(c) Pablo Carlos Budassi

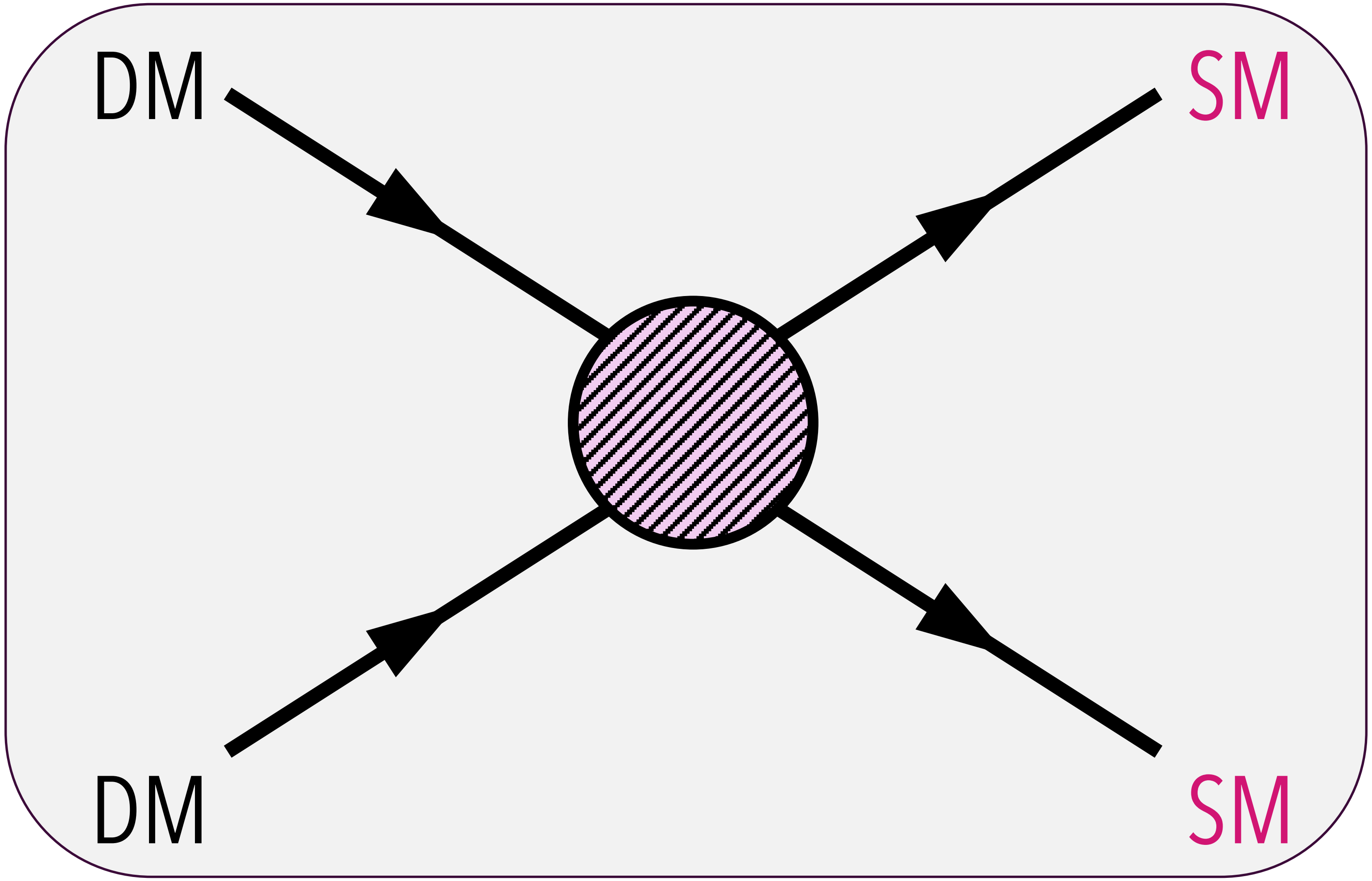
Dark Matter Landscape: A Theorist's View



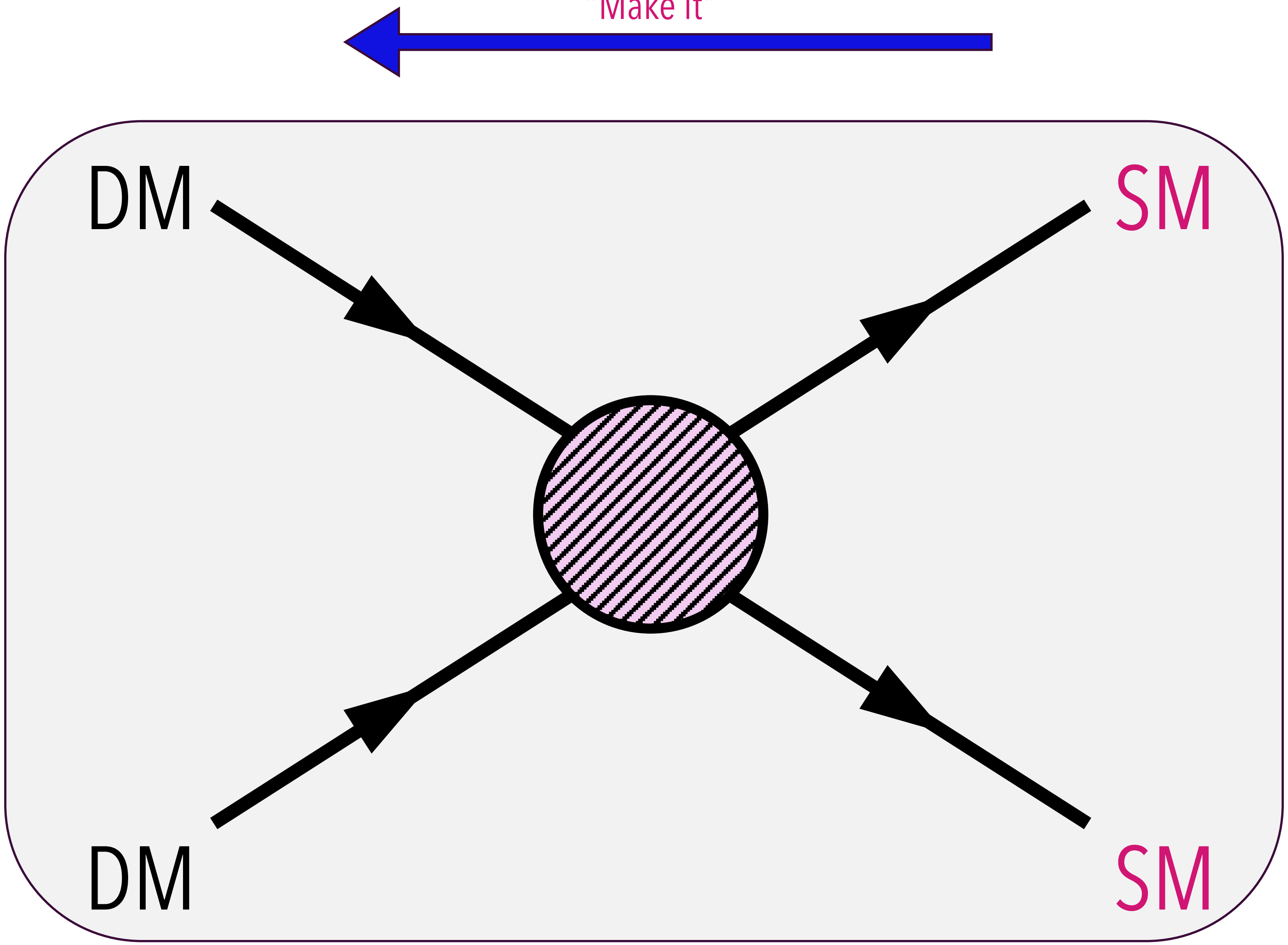
Our search strategies are inherently *biased*

1. **model dependency bias:** theory guides our search strategies
2. **observational bias:** disparity between the data we have and the data we need
3. **identifiable signature bias:** required for observation

Detection strategies

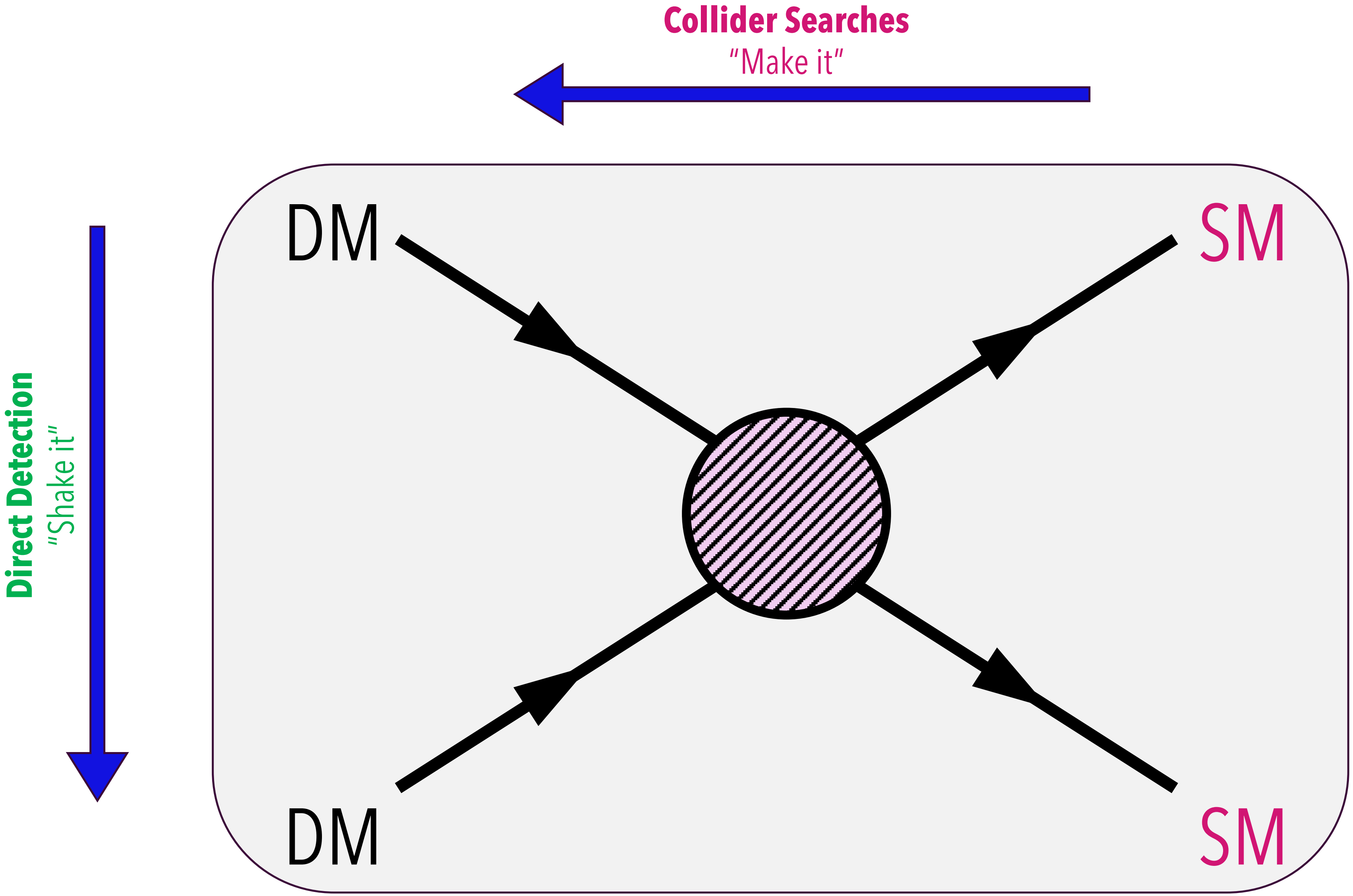

DM
DM
SM
SM

Collider Searches
"Make it"



Collider searches:
Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

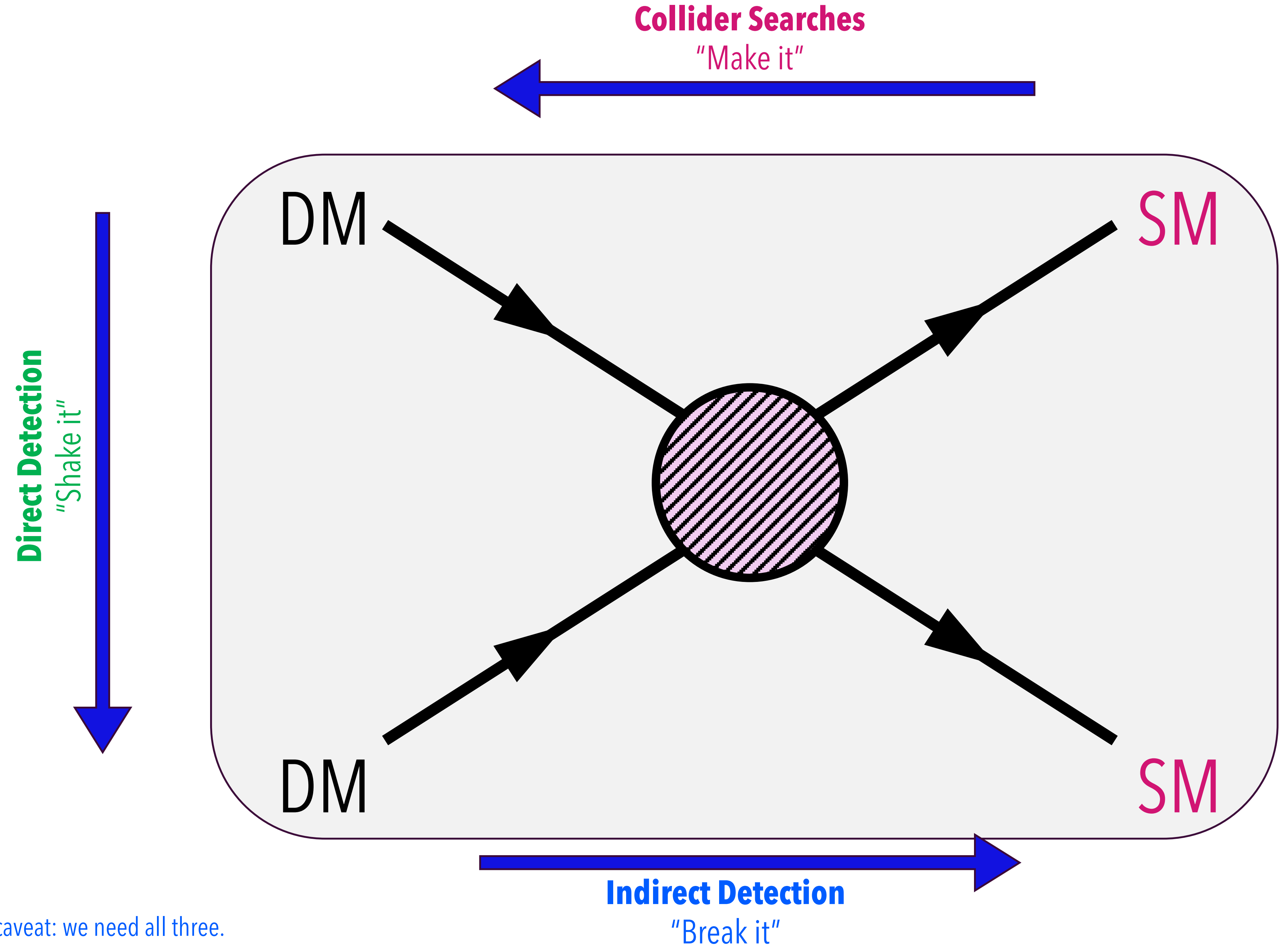
An important caveat: making an "invisible" particle at the LHC does not by itself prove that particle is the cosmological dark matter.



Collider searches: Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

Direct detection: Look for DM scattering off nuclei or electrons in low-background detectors as Milky Way halo dark matter passes through Earth.

An important caveat: can only constrain the combination of the mass and cross section.



Collider searches: Produce DM in high-energy collisions and look for missing momentum/energy or other signatures associated with particles escaping the detector.

Direct detection: Look for DM scattering off nuclei or electrons in low-background detectors as Milky Way halo dark matter passes through Earth.

Indirect detection: Look for SM particles produced by DM, for example through annihilation or decay, in the Milky Way and other astrophysical systems.

An important caveat: we need all three.

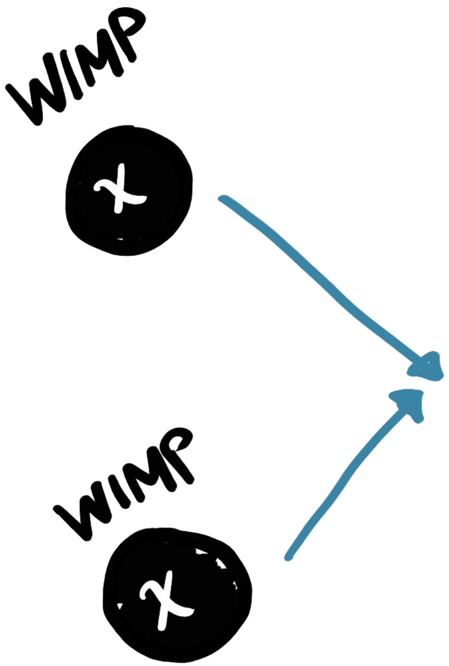
“Break it”

Indirect detection formalism

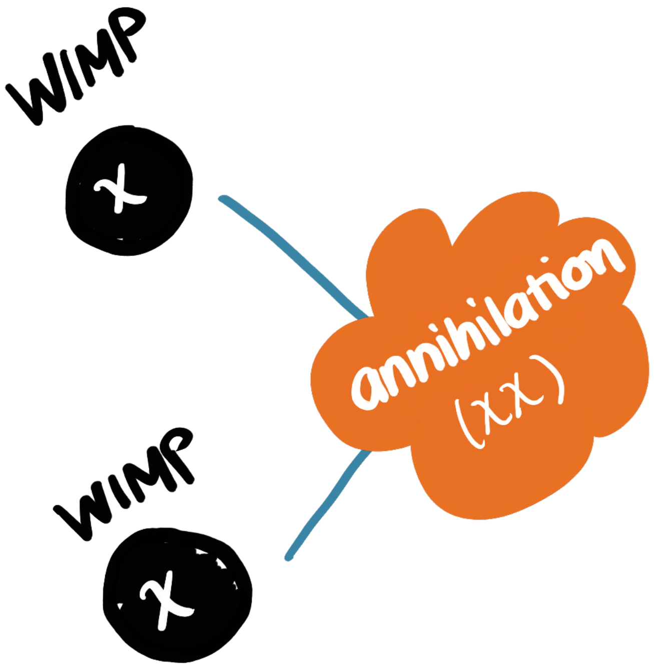
→ Searching for the contribution of DM annihilation to the astrophysical flux of photons, neutrinos and charged particles

Indirect observables

Indirect observables



Indirect observables



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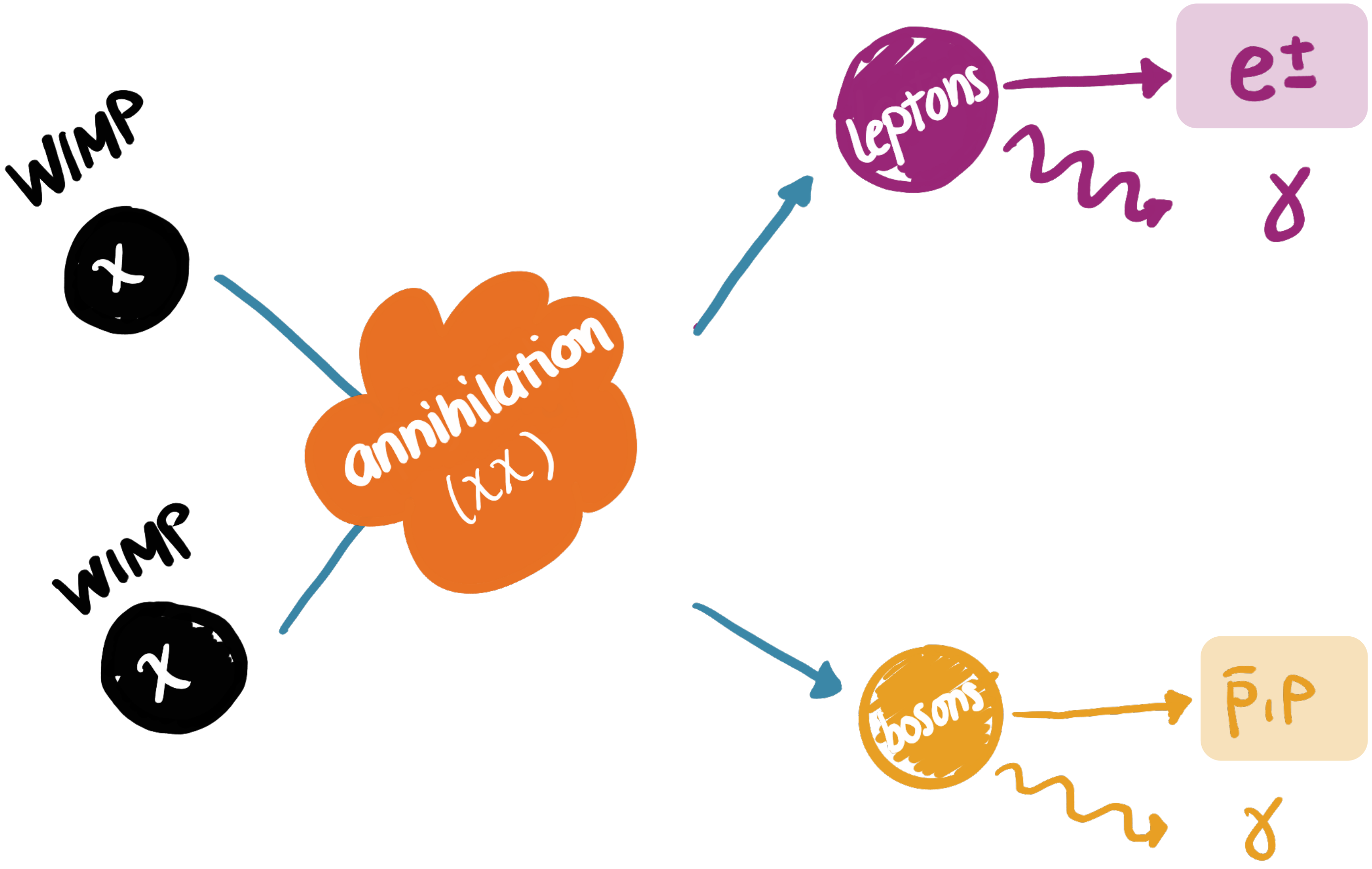
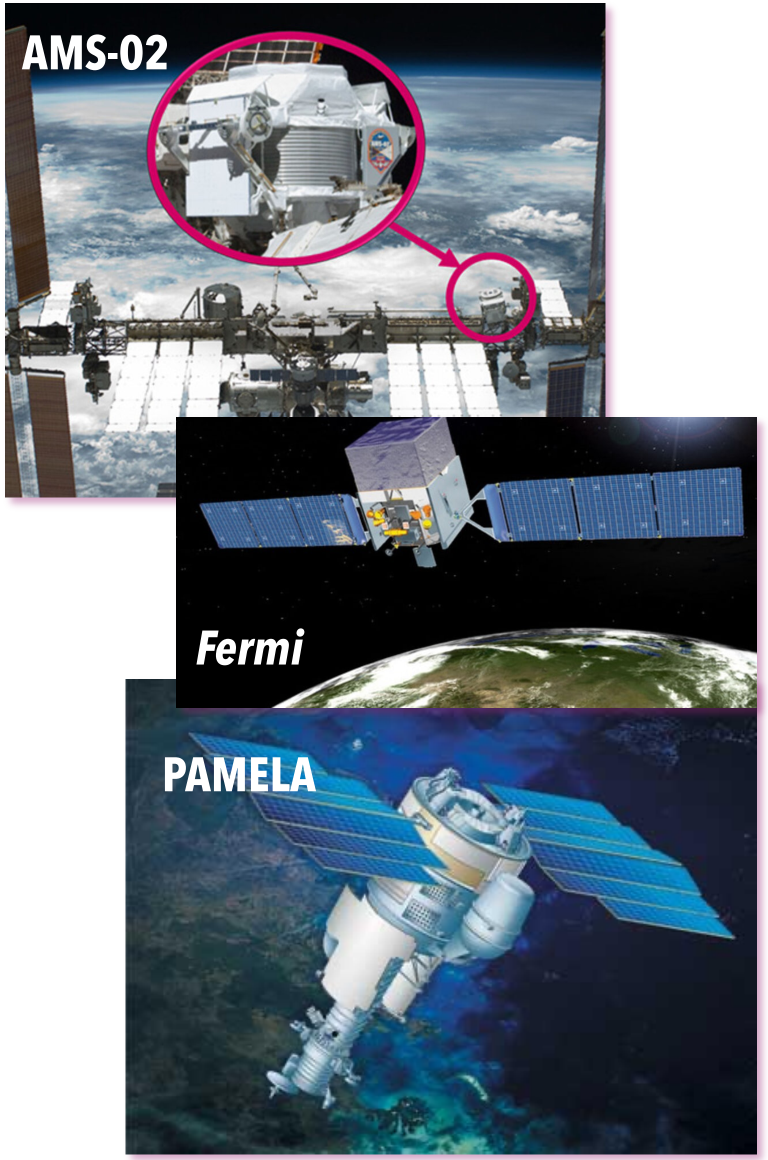
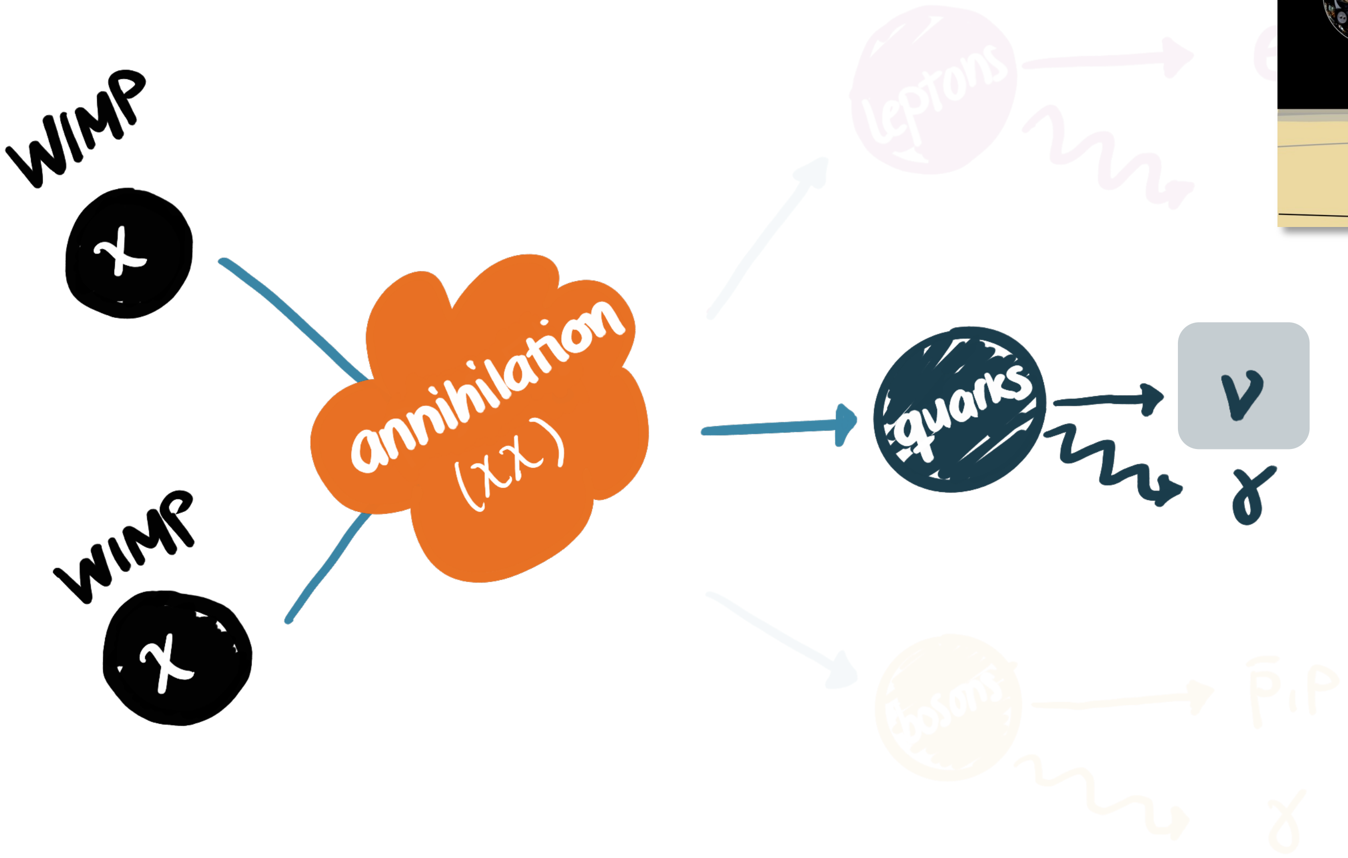
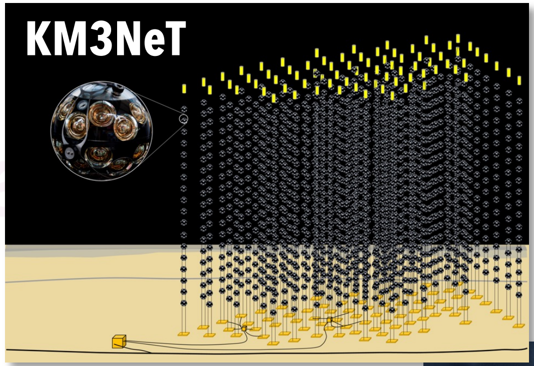
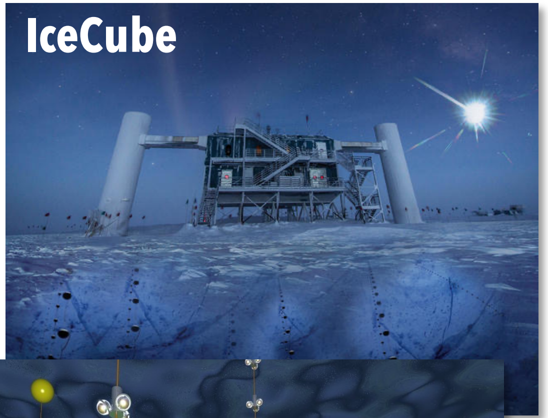


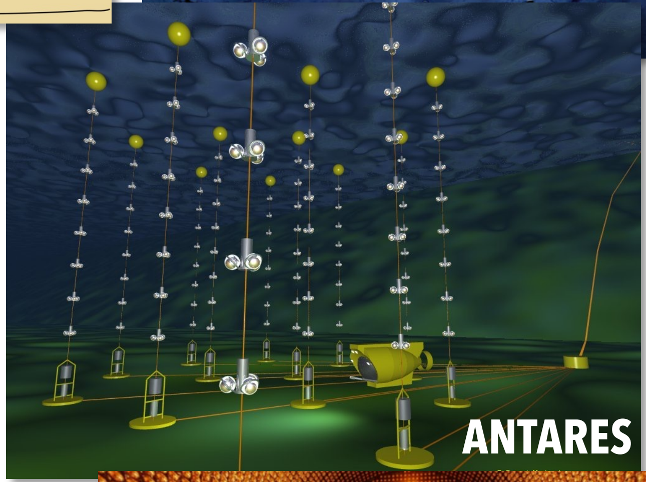


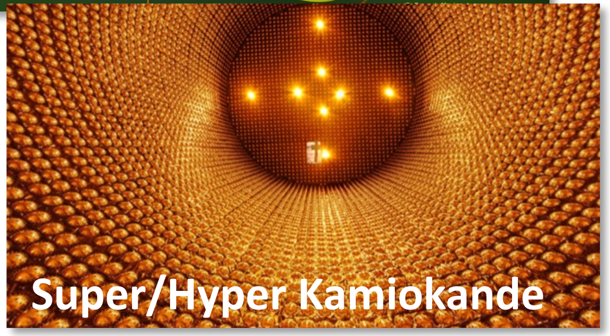
Indirect observables





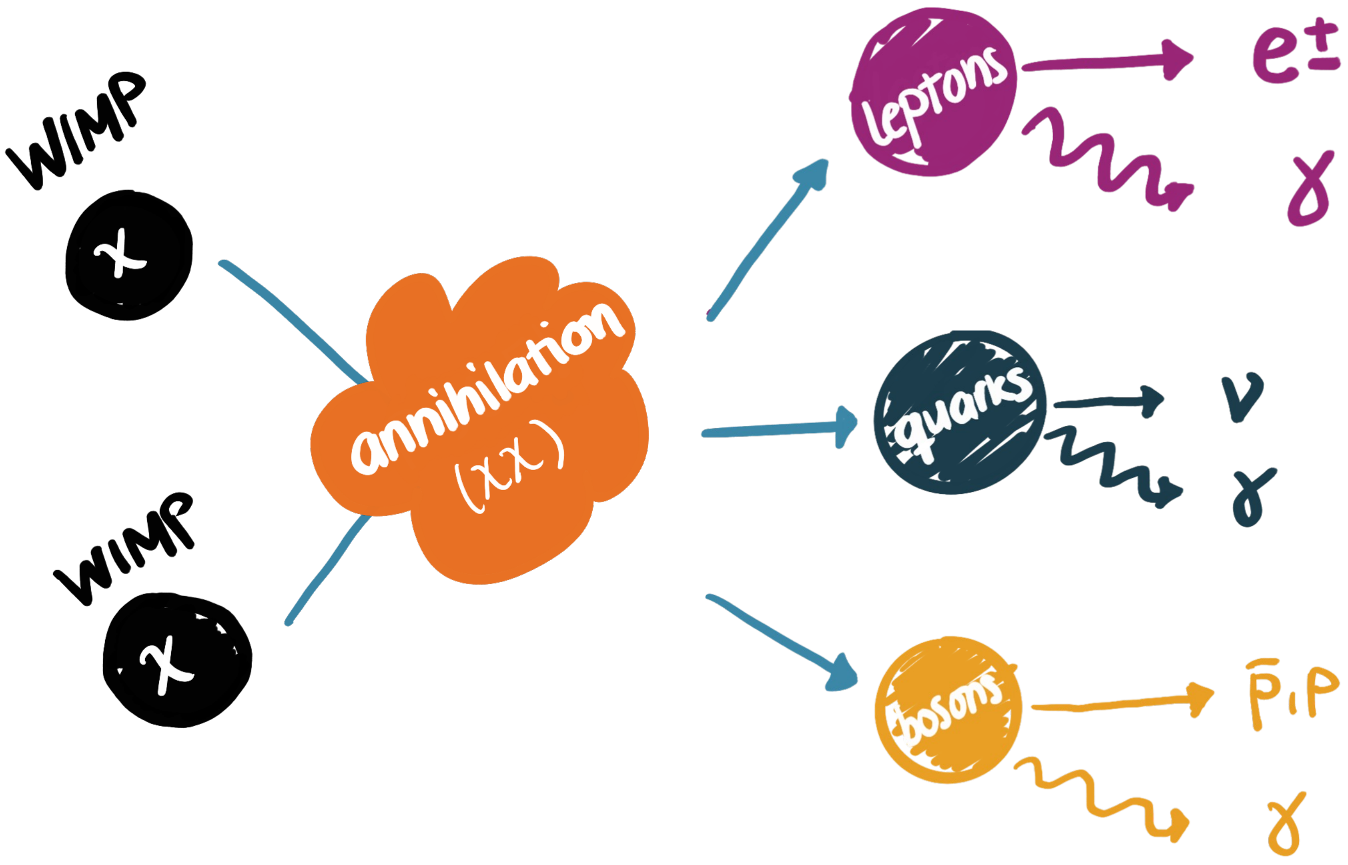






Also directly to neutrinos (suppressed)…

Indirect observables



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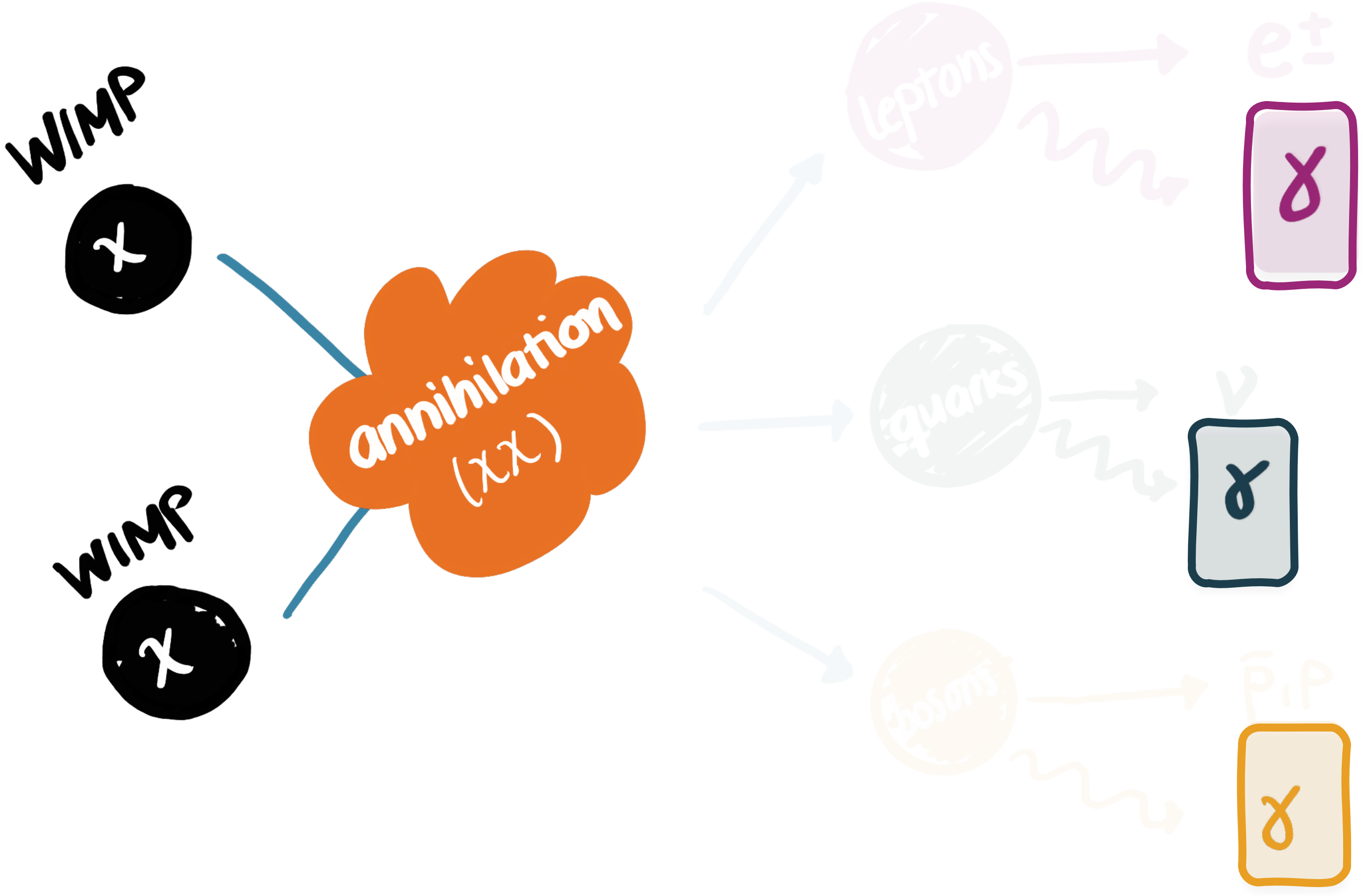

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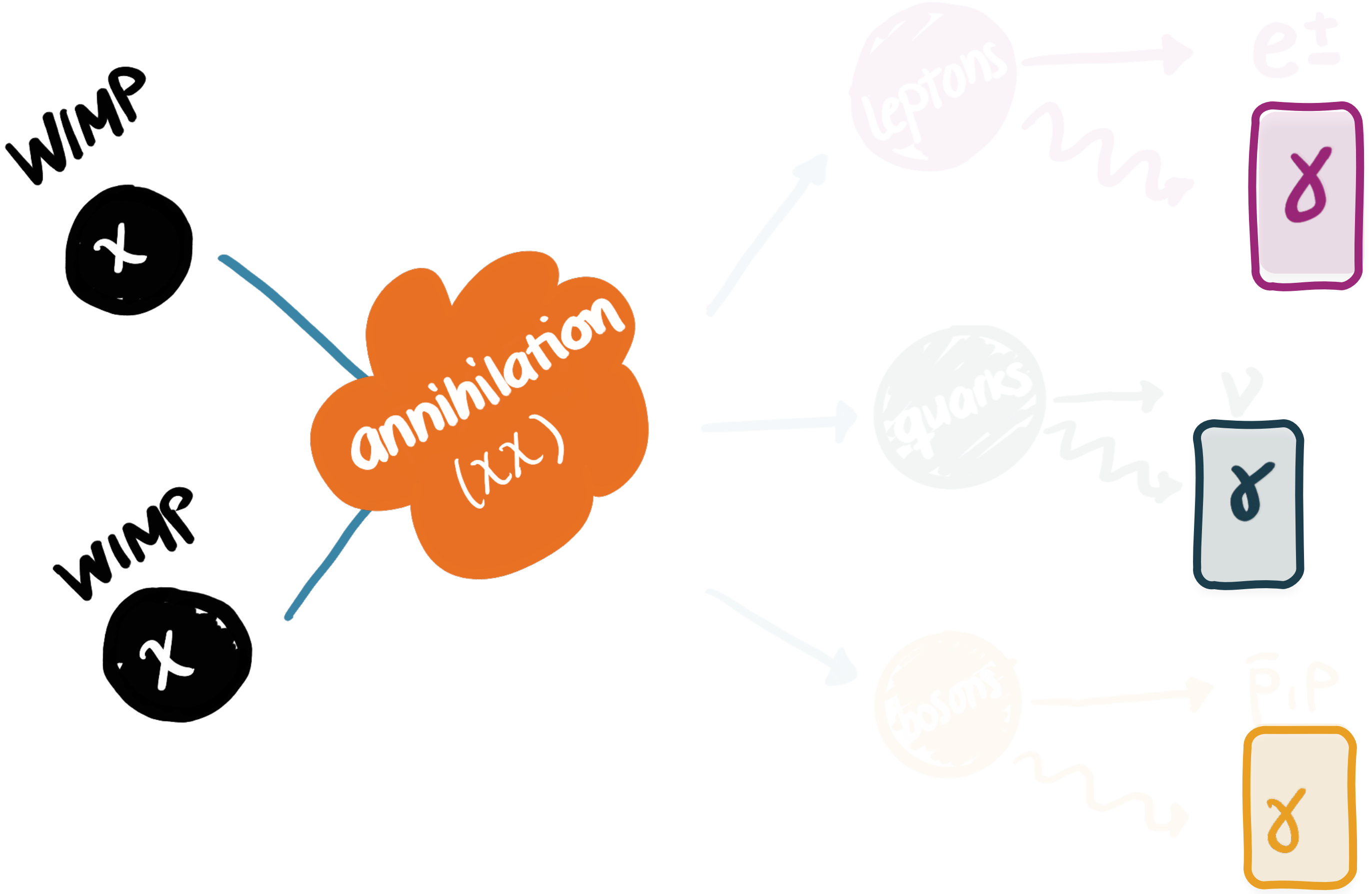
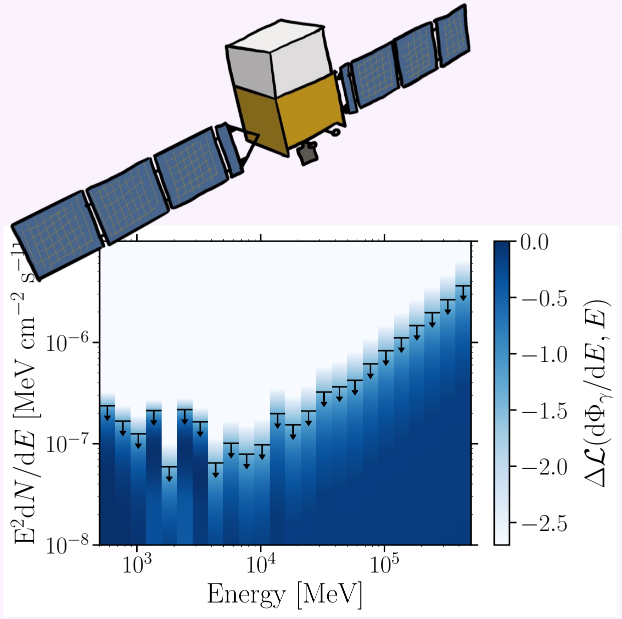


Also directly to gammas (suppressed)…

Dark Matter signal: what do we observe?

DM flux

$$\frac{d\Phi}{dE}$$



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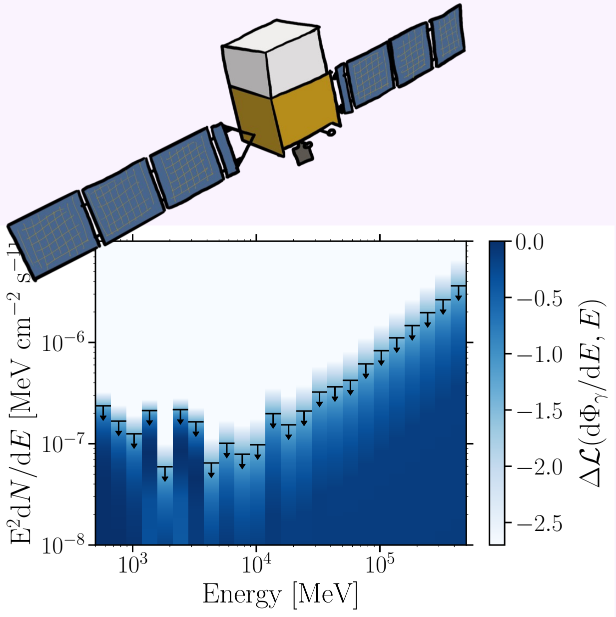
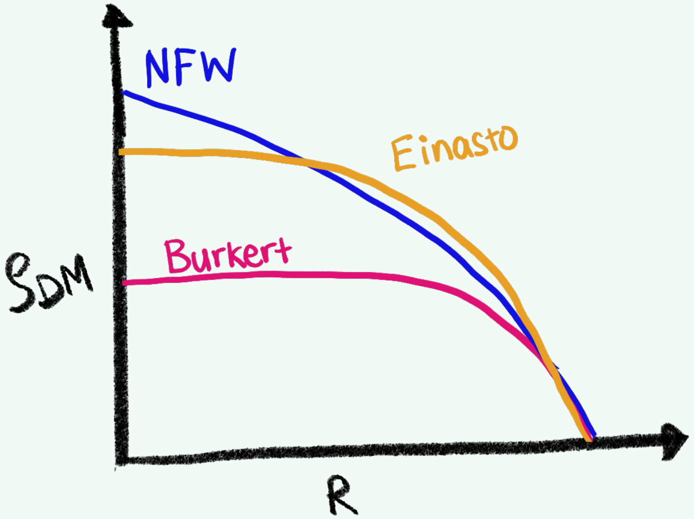


=

astrophysics J-factor

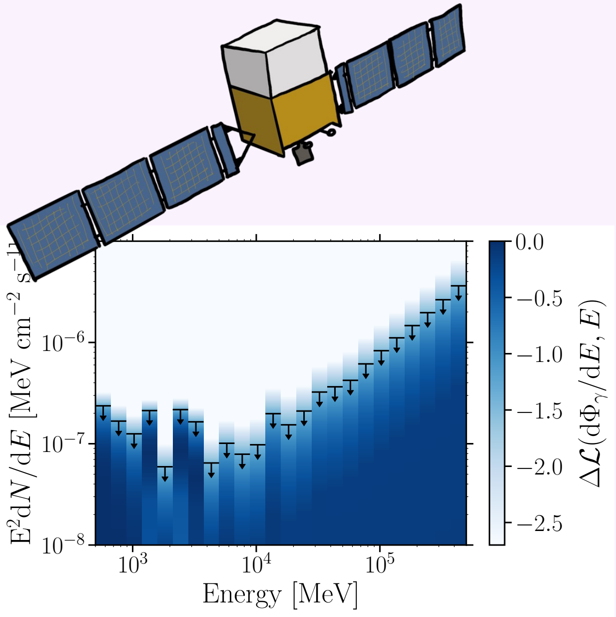
$$\int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2$$

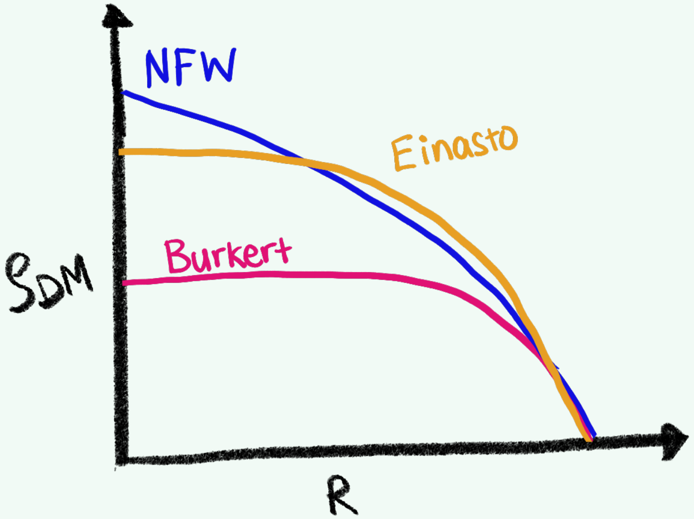


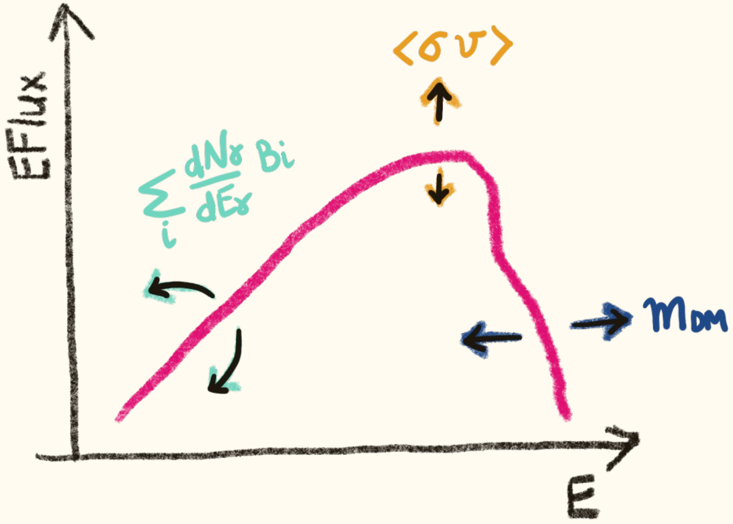
Dark Matter signal: what do we observe?

DM flux = **astrophysics J-factor** × **particle physics**

$$\frac{d\Phi}{dE} = \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \; \frac{\langle\sigma v\rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$







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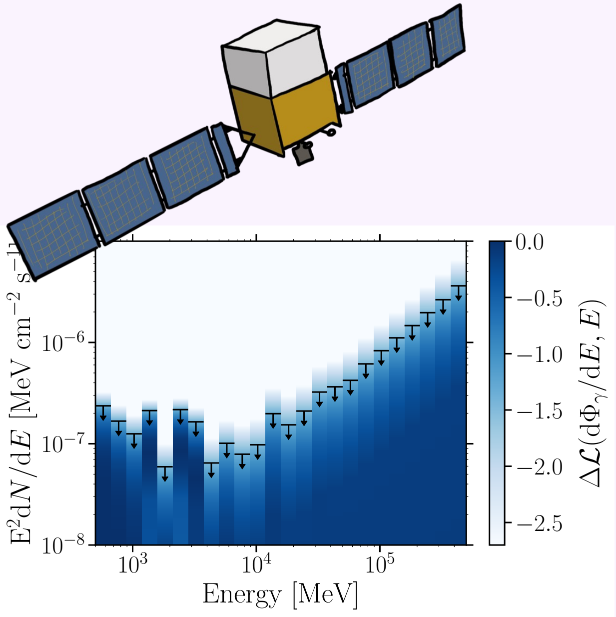

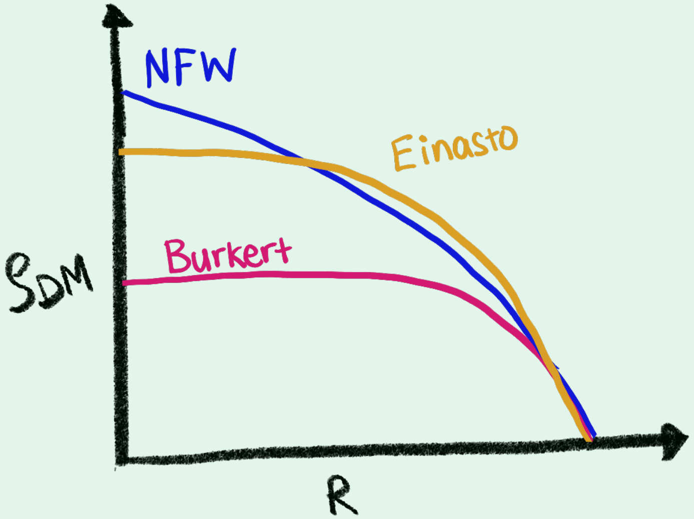

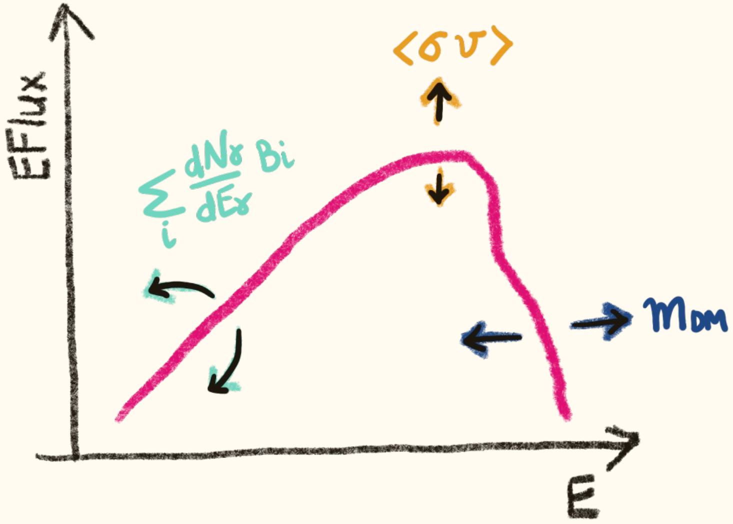

J-factors, D-factors, and density profiles

The astrophysical contribution to the flux depends entirely on the dark-matter distribution.

$$J(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho_{DM}^2(r(\ell,\theta))\mathrm{d}\ell$$

$$D(\Delta\Omega) \equiv \int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{los}} \rho_{DM}(r(\ell,\theta))\mathrm{d}\ell$$

Q2. Annihilation J-factor scales with ρ_{DM}^2, but decay D-factor scales only with ρ_{DM}. Why?

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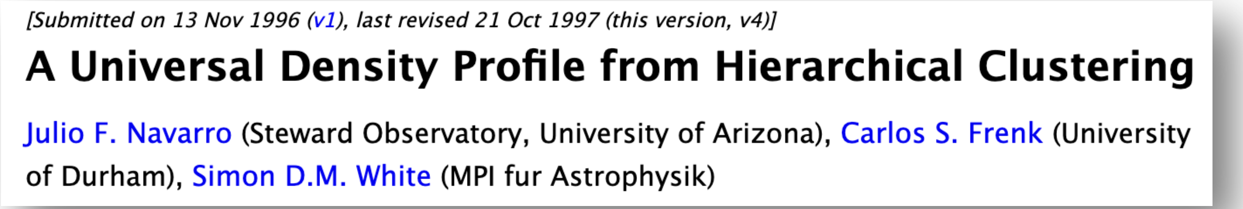
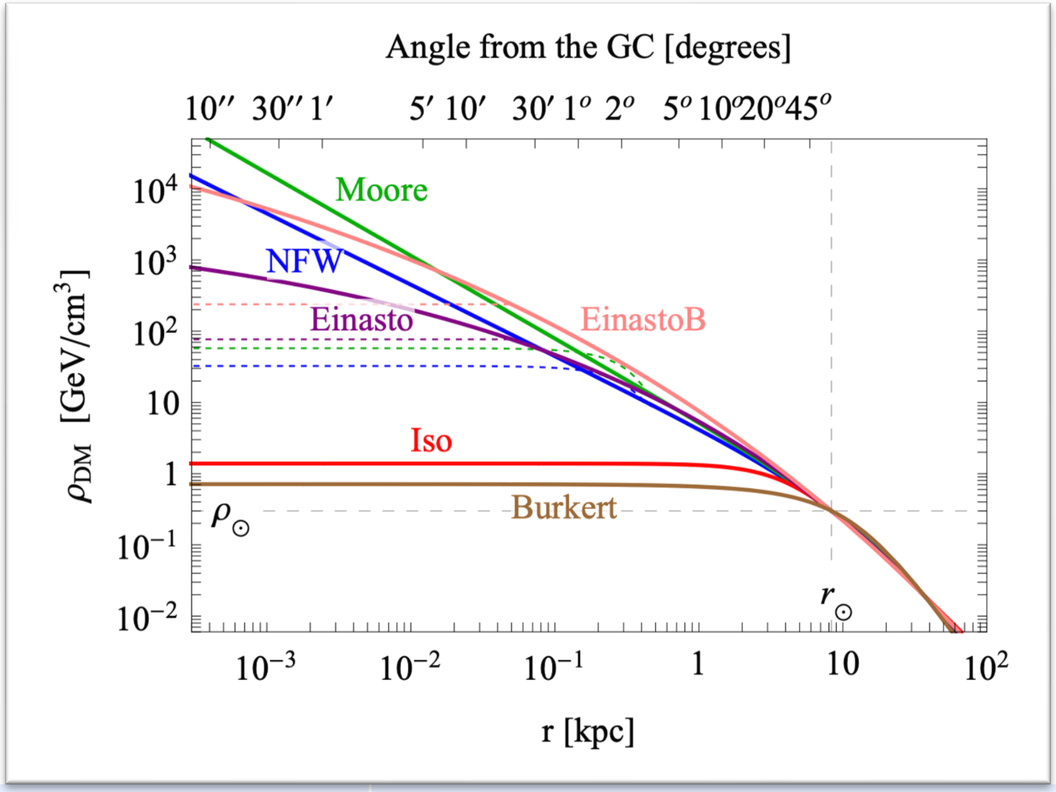

[Submitted on 13 Nov 1996 (v1), last revised 21 Oct 1997 (this version, v4)]

A Universal Density Profile from Hierarchical Clustering

Julio F. Navarro (Steward Observatory, University of Arizona), Carlos S. Frenk (University of Durham), Simon D.M. White (MPI fur Astrophysik)

But what is $\rho_{DM}(r)$?

- **Cuspy:** NFW, Einasto, Moore
- **Cored:** Burkert, isothermal
- Profiles can agree near the Solar position but differ dramatically toward the Galactic Center



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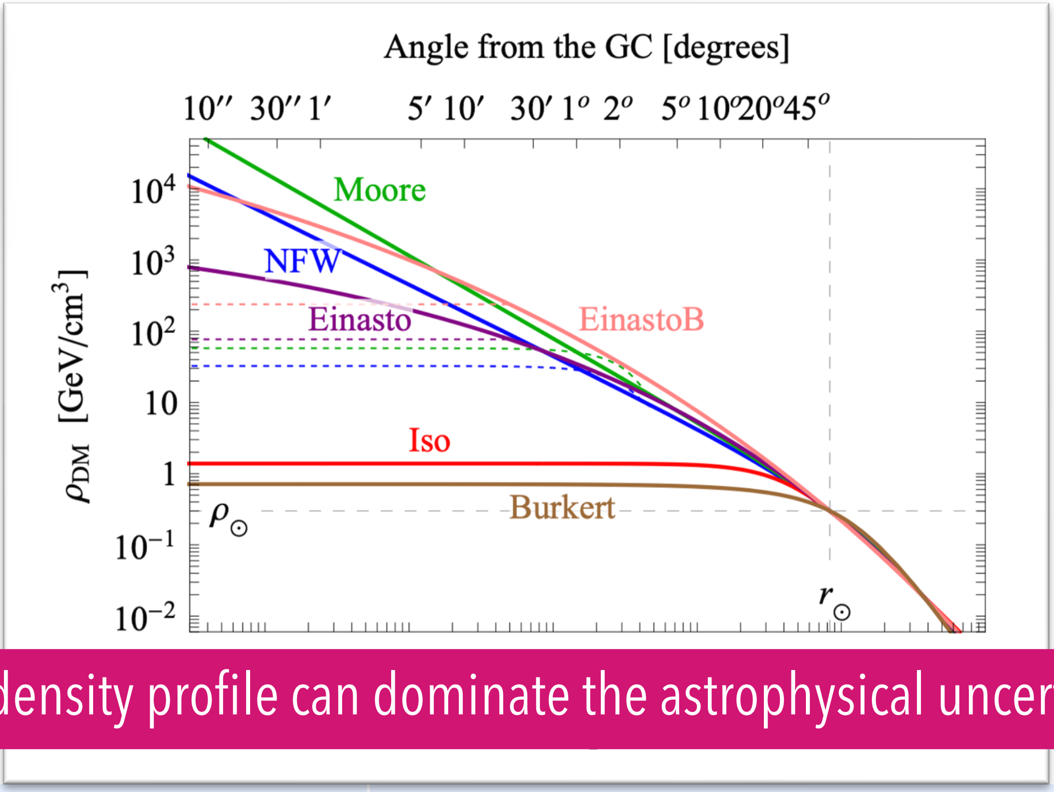

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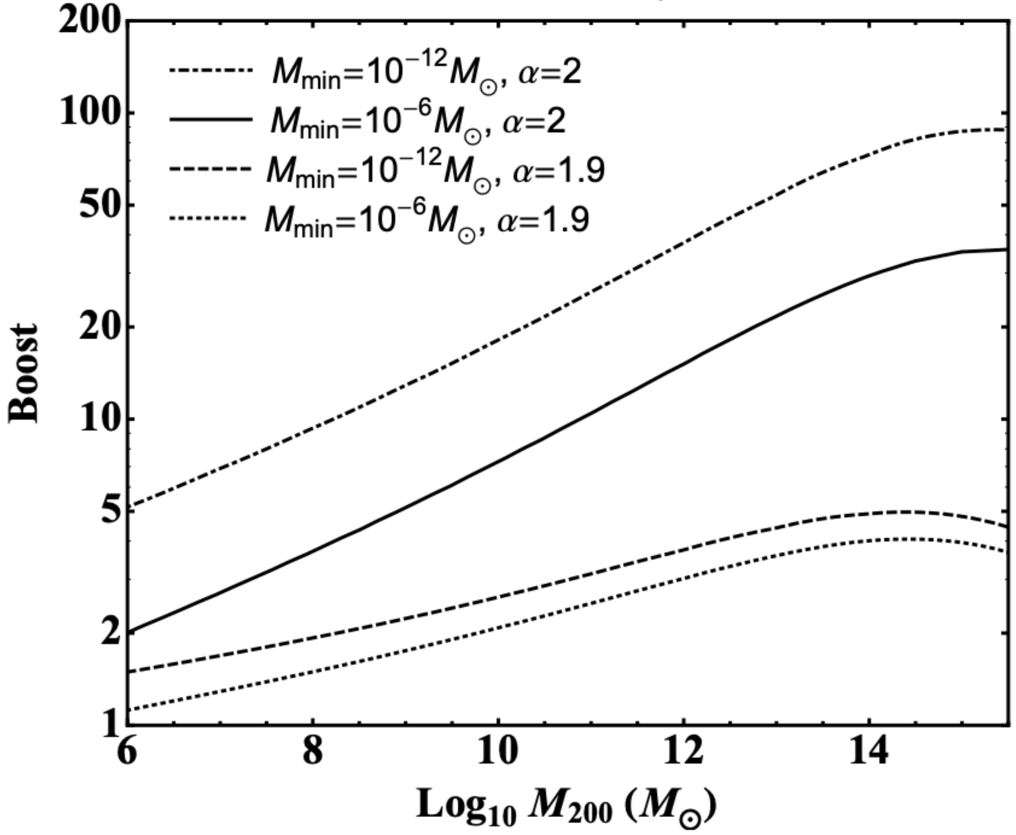
Q3. To the best of my knowledge, the first mention of the term J-factor appears in [Bergstrom & Ullio 1997, hep-ph/9706232]. I never was able to trace back the origin of the name---are you?

For annihilation searches toward the galactic centers, the inner density profile can dominate the astrophysical uncertainty.

Small-scale clumpiness: substructure boosts

- The annihilation signal depends on ρ_{DM}^2, so it is sensitive to **clumpiness**
- Dense subhalos within a larger halo can increase the annihilation luminosity relative to a smooth distribution **(boost factor)**
- For annihilation, the boost factor can be non-negligible (for decay much less significant)
- Very difficult to characterize: the boost factor depends on poorly known properties of the small-scale halo population

Sanchez-Conde & Prada, 2014 [1312.1729]



Dark Matter (DM) spikes

(cold, particle)

Dark Matter (DM) spikes

(cold, particle)

Astrophysical Processes

adiabatic growth of a black hole embedded within a dark matter halo

(see, e.g., Gondolo & Silk 1999)

High Density Fluctuations

such as (primordial) black holes formed in the early Universe

(see, e.g., Bertschinger 1985)

Dark Matter signal: what do we observe?

DM flux = **astrophysics J-factor** × **particle physics**

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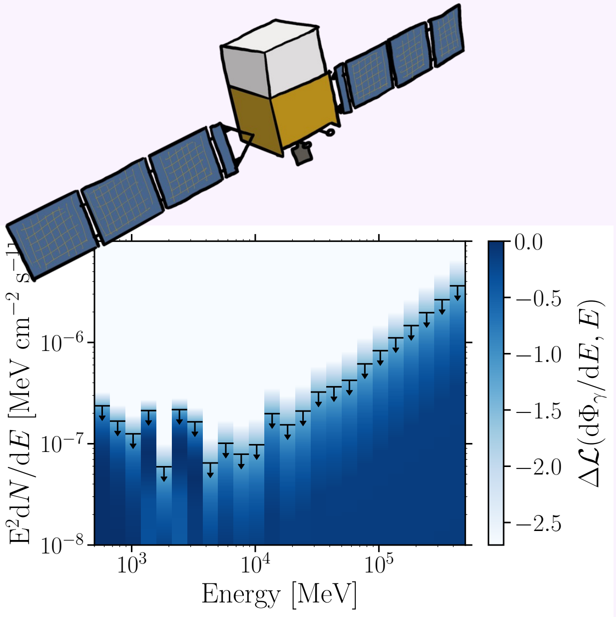

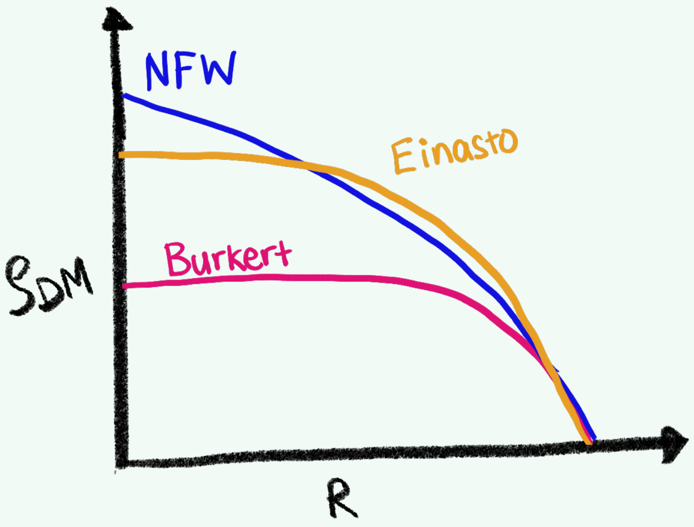

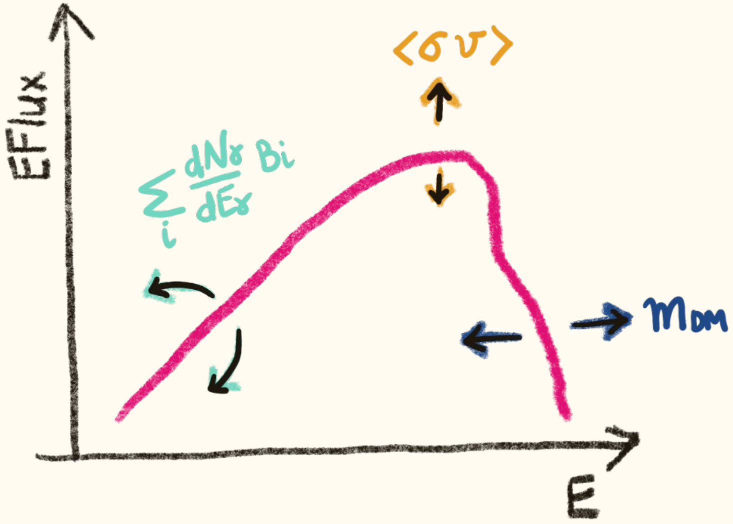

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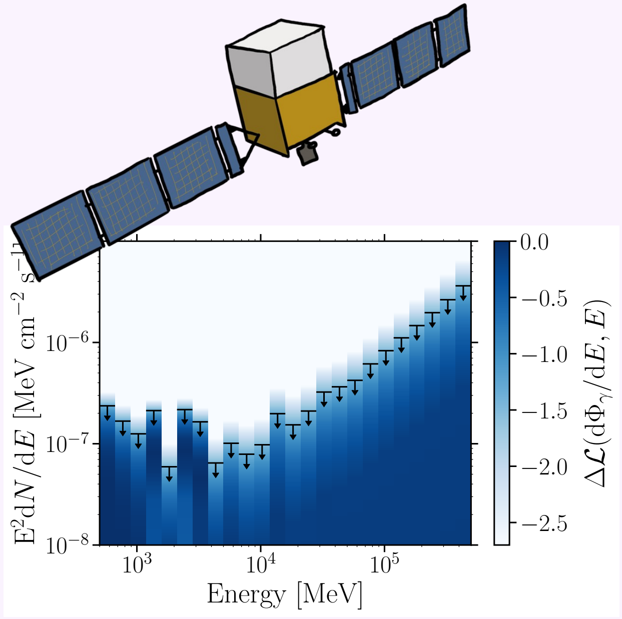
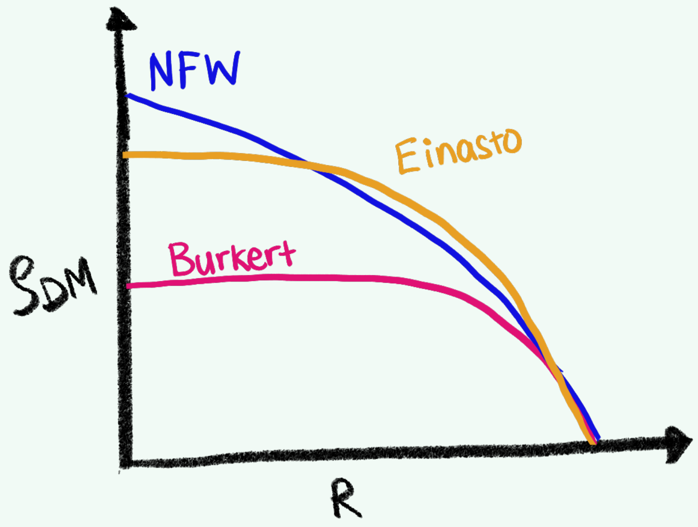
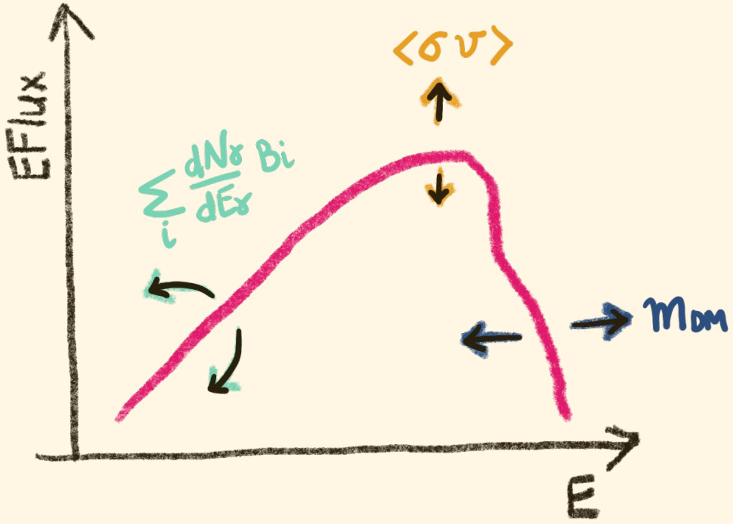




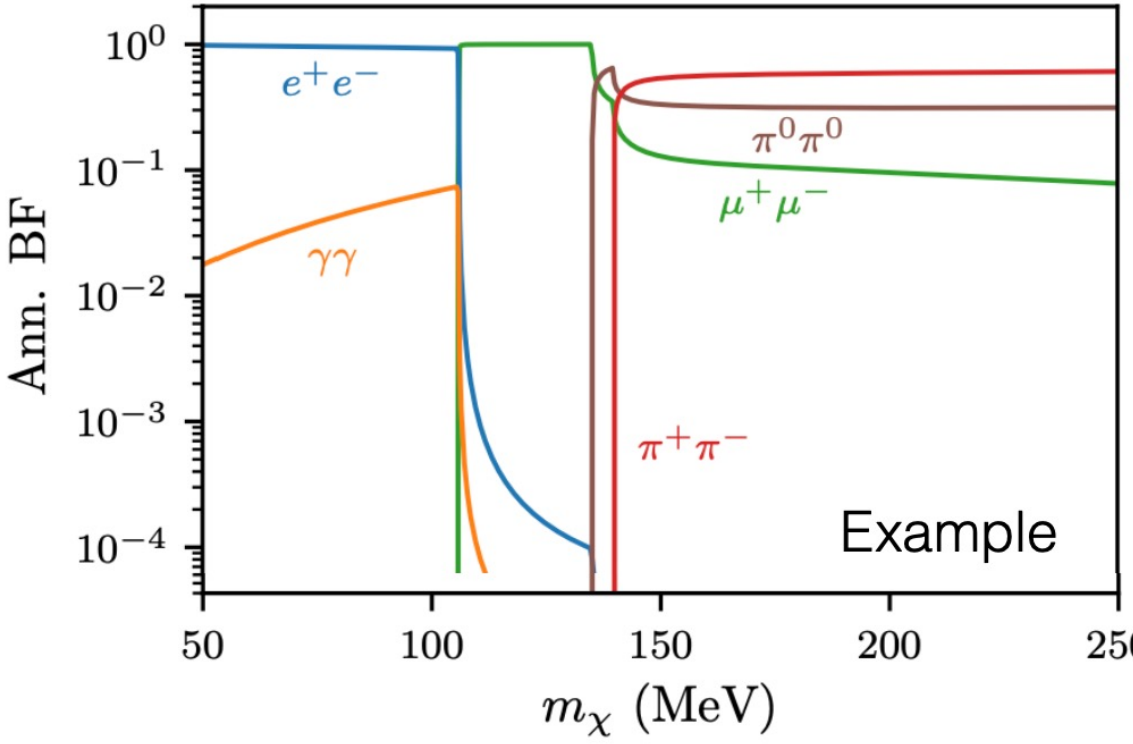


Primary annihilation spectra

- For a specific WIMP model, we can calculate the total number of *x* particles produced per annihilation as:

$$\frac{\mathrm{d}N_x}{\mathrm{d}E} = \sum_f B_f \frac{\mathrm{d}N_{x,f}}{\mathrm{d}E}$$

where *Bf* are the branching fractions into the various final states.

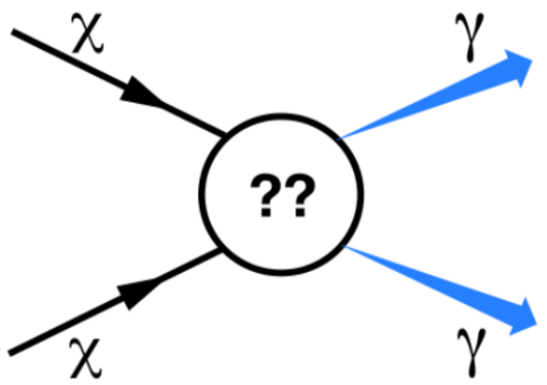


- These branching fractions depend on the couplings and interactions of the DM model, so to be as model-independent as possible, we often constrain a single **annihilation channel** at a time.

c. Bradley J Kavanagh

Gamma-ray lines

- Perhaps the simplest annihilation spectrum is for annihilation into two gamma rays (or neutrinos). This gives rise to a mono-chromatic photon flux. Each photon carries the rest mass energy of the DM:



$$\frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} = 2\delta(E_\gamma - m_\chi)$$

- Considering DM in the mass range GeV-TeV, leads to a spectrum of gamma-rays.
- Gamma-ray lines are hard to produce in nature. This would be a 'smoking gun' signal of Dark Matter!
- Other annihilation channels still produce gamma rays, but with a less distinctive 'continuum' spectrum…
- **Note:** The prompt flux from neutrinos follows in a similar way as for photons

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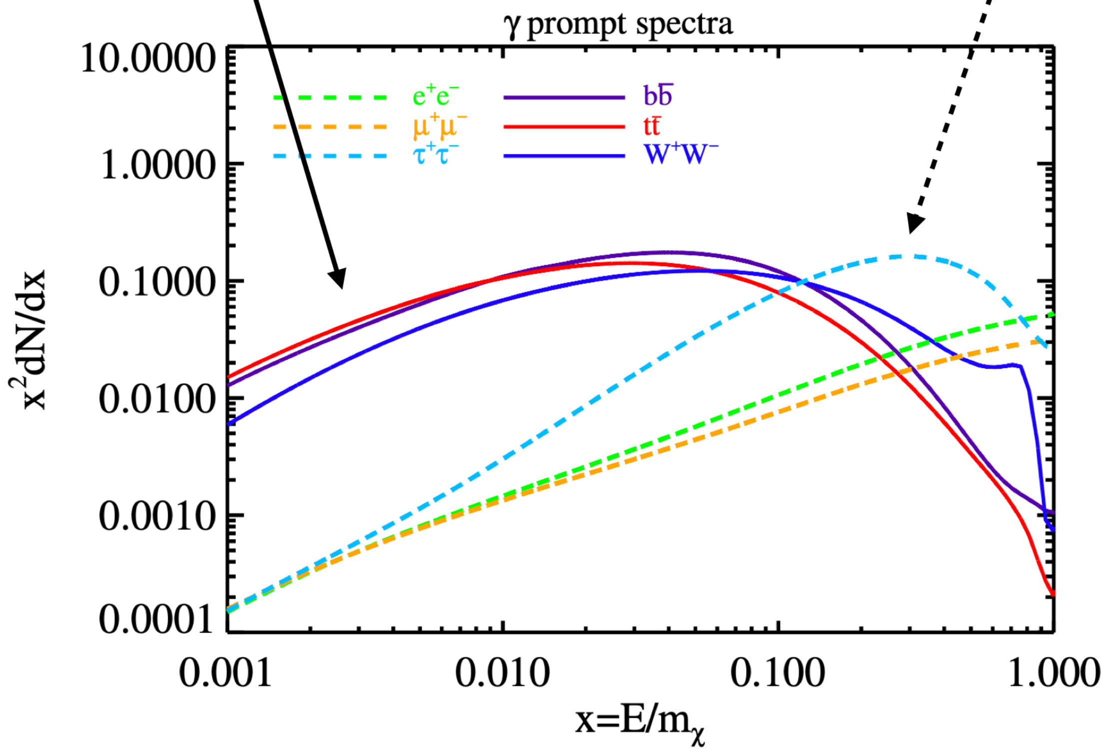
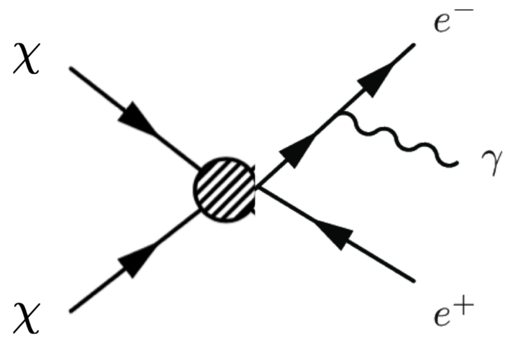
Gamma-ray spectra

Soft channels - hadronisation produces neutral pions which decay into photons

$\pi^0 \rightarrow \gamma + \gamma$

Hard channels - gamma rays from final state radiation



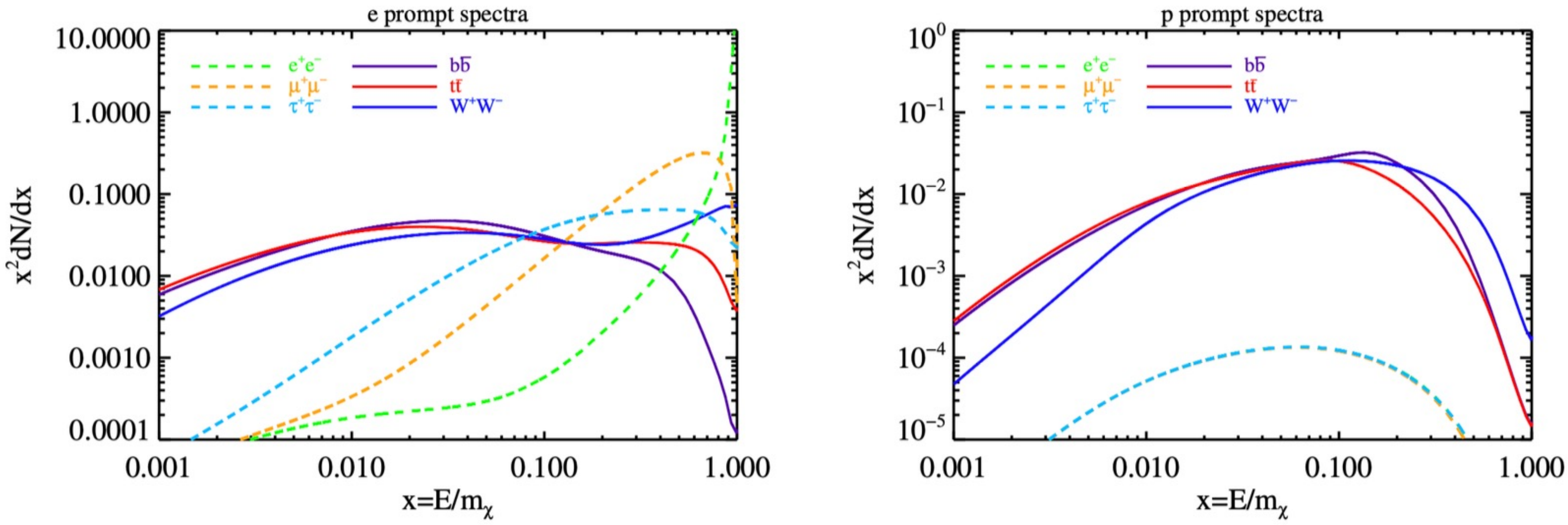


[Tools like PPPC4DMID, 1012.4515; Hazma, 1907.11846, 2207.07634]

NB: Annihilation to light quarks can be more complicated, due to hadronic resonances.

c. Bradley J Kavanagh

Charged particles



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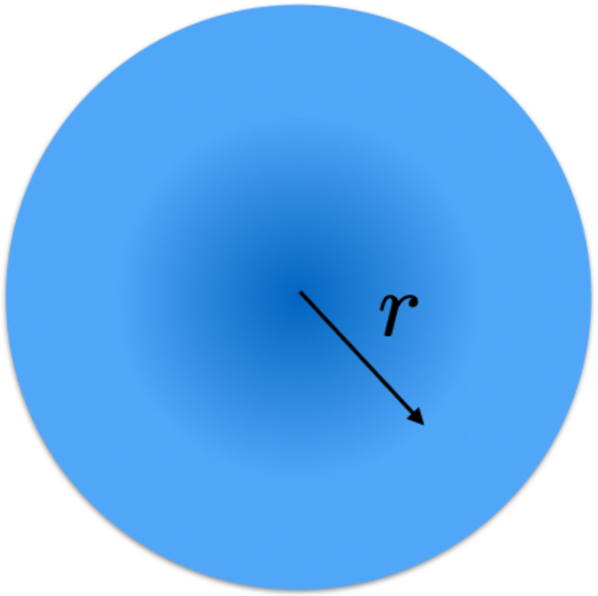
DM annihilation rates

Rate of DM annihilation per unit time:*

$$\Gamma_{\rm ann}(r,v) = \Phi_\chi \times N_T \times \sigma$$
$$= \frac{1}{2} n_\chi v \times n_\chi \times \sigma_{\rm ann}(v)$$
$$= \frac{1}{2}\frac{\rho_\chi(r)}{m_\chi} v \times \frac{\rho_\chi(r)}{m_\chi} \times \sigma_{\rm ann}(v)$$



Average over velocity distribution of DM particles:

$$\langle \Gamma_{\rm ann}(r)\rangle = \frac{1}{2}\left(\frac{\rho_\chi(r)}{m_\chi}\right)^2 \times \int \sigma_{\rm ann}(v) v\, f(\mathbf{v})\, \mathrm{d}^3\mathbf{v}$$
$$= \frac{1}{2}\left(\frac{\rho_\chi(r)}{m_\chi}\right)^2 \times \langle \sigma_{\rm ann} v\rangle$$

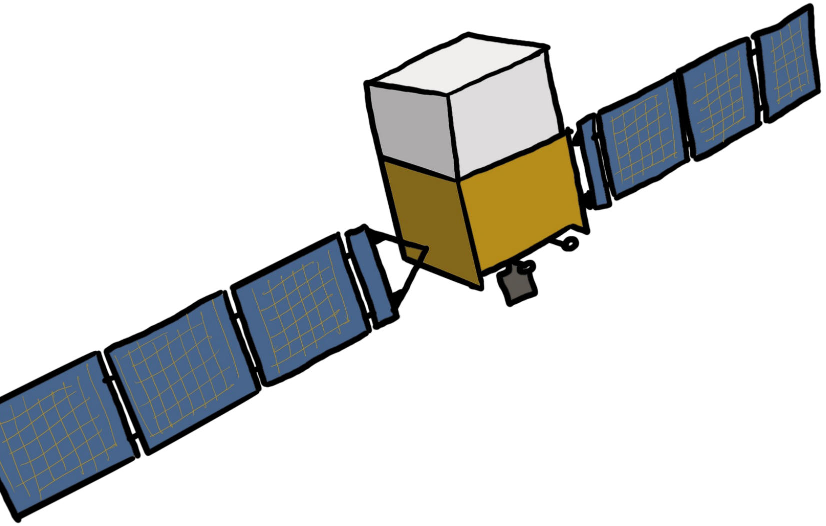
Typical velocity dispersion in Galactic halos and sub-halos:

$$\sigma_v \sim 20 - 200\,\mathrm{km/s}^2$$
$$\sim 10^{-4} - 10^{-3}\, c$$

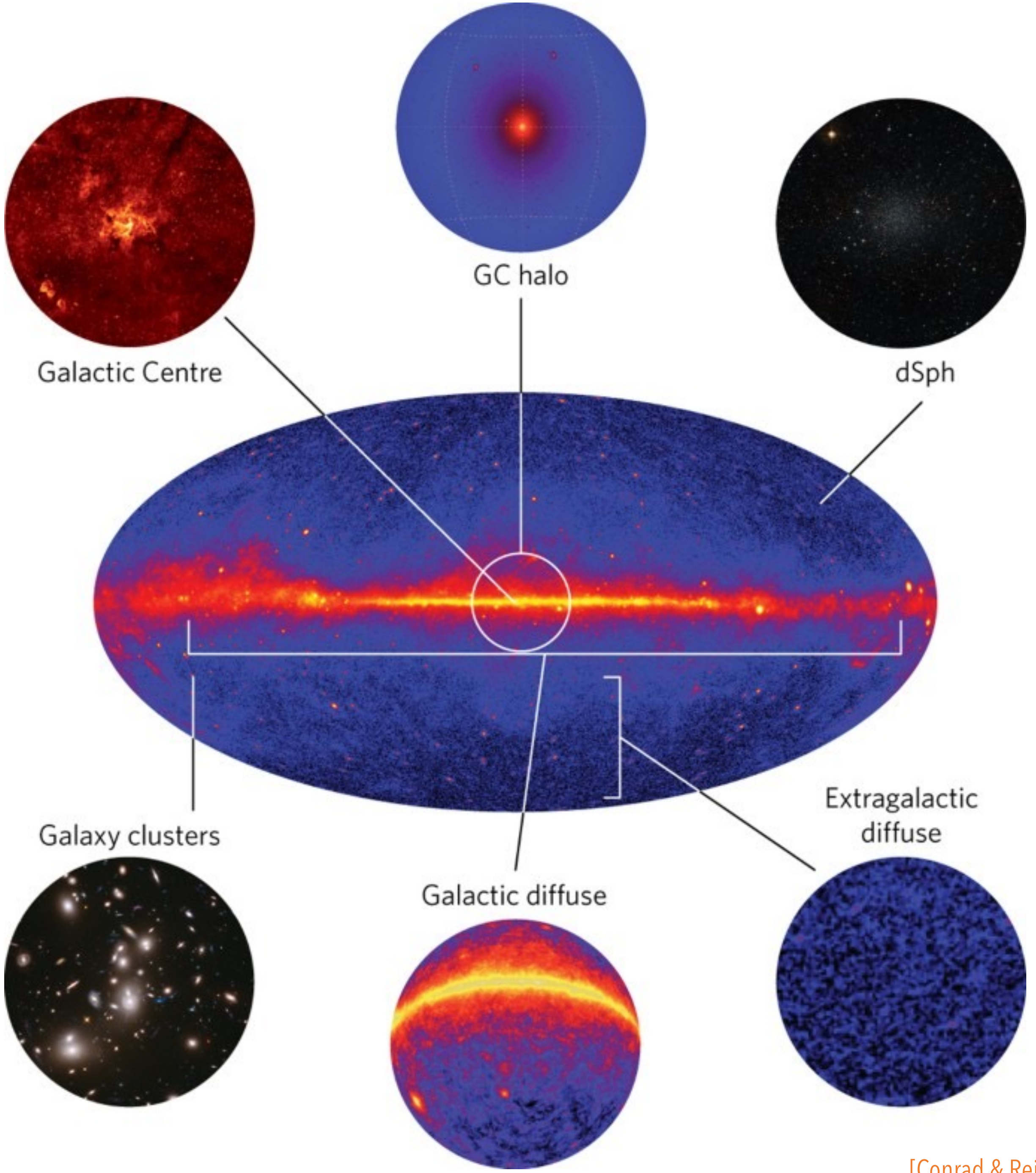
Typically, DM velocity dispersion is small, so only consider leading contribution σ_0 ("s-wave") to annihilation cross section. "P-wave" $\propto (v/c)^2$ is typically suppressed.

$$\sigma(v)v \approx \sigma_0 + \sigma_1 (v/c)^2 + \ldots$$

c. Bradley J Kavanagh



DM targets



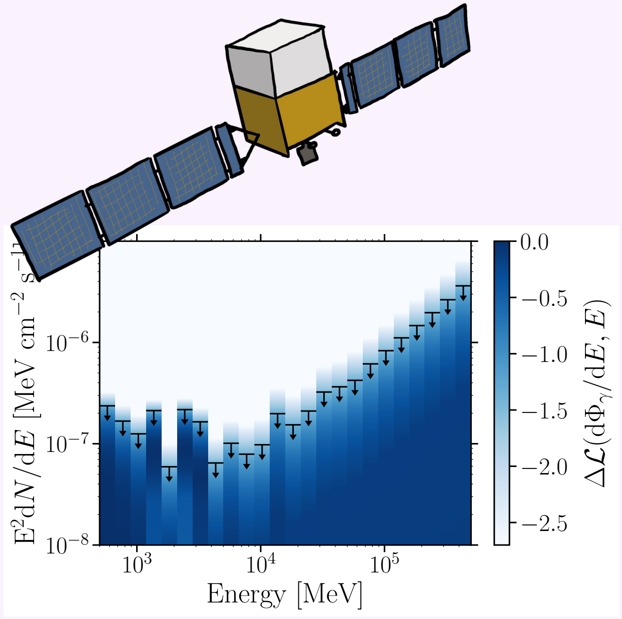
Also: Solar System (Sun, Jupiter), brown dwarfs, exoplanets, etc.
Nguyen+ 25, 26, Leane+ 23, Blanco+ 24, 25, etc.

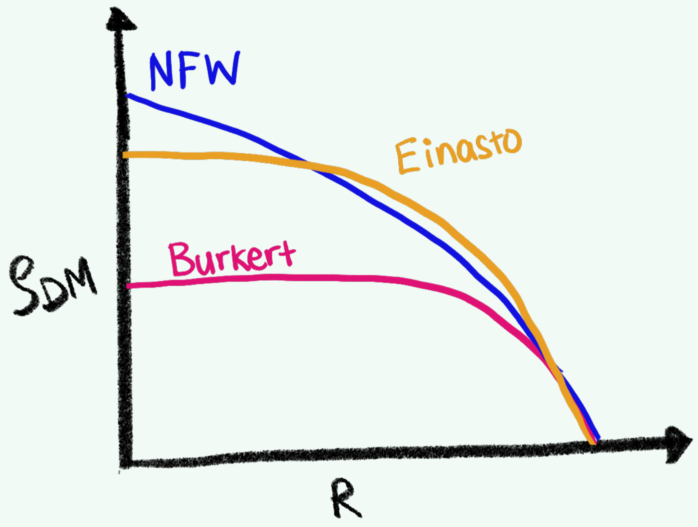
[Conrad & Reimer 2017]

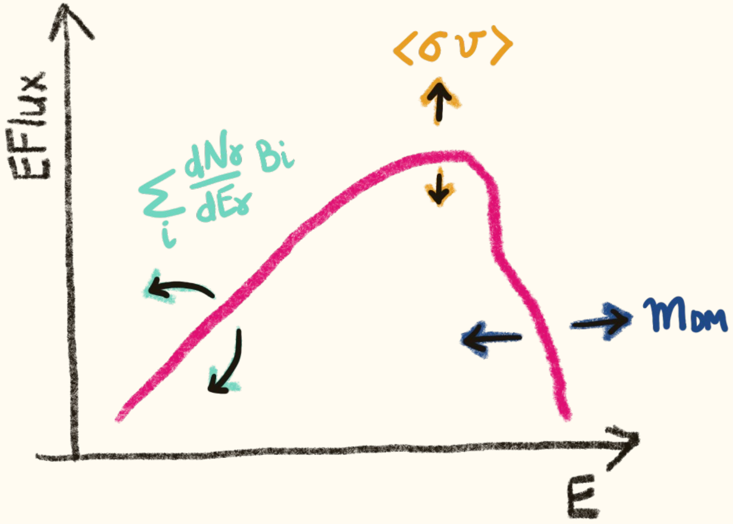
Lecture 2: take-home message

DM flux = **astrophysics J-factor** × **particle physics**

$$\frac{d\Phi}{dE} = \int_{\Delta\Omega,\mathrm{los}} \rho_{DM}^2 \times \frac{\langle \sigma v \rangle}{2M_{DM}^2} \sum B_i \frac{dN_\gamma}{dE}$$







Lecture 2: take-home message

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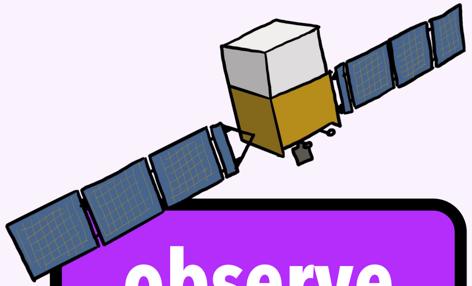

observe | **infer from astrophysical data/assume** | **measure/ constrain**