15th IDPASC Summer School
20 - 29 July 2026 Natal, Brazil

Dark Matter

I. Theory and Candidates
II. Direct and Indirect Searches

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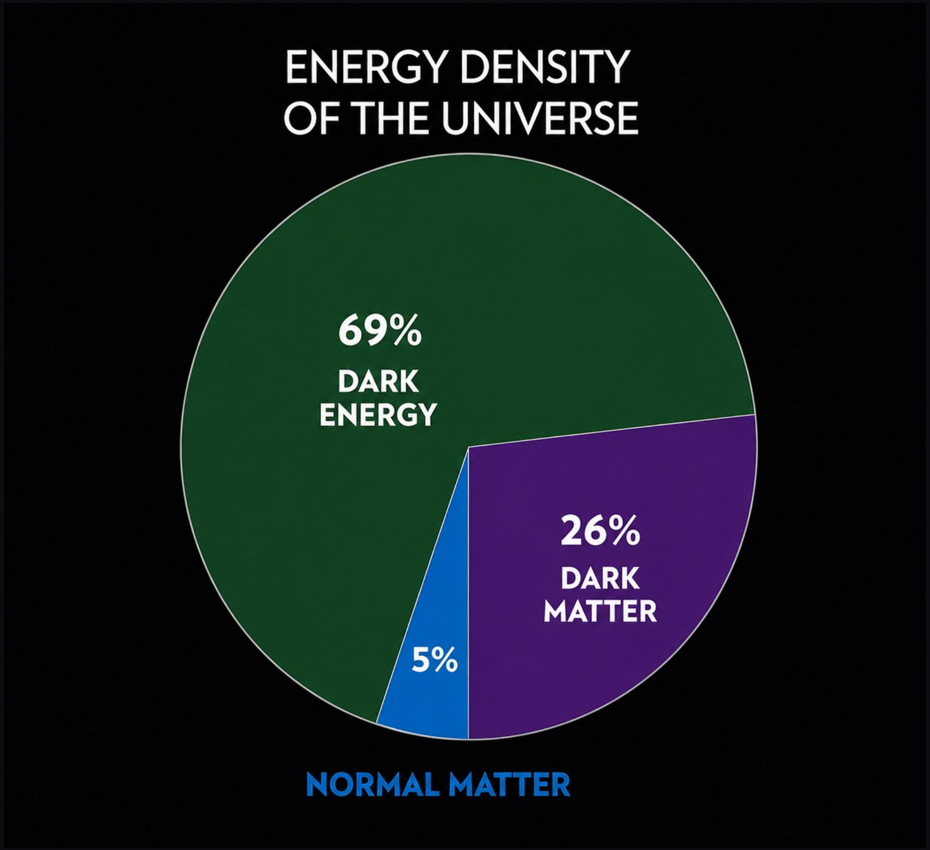
What is our Universe made of?

Ordinary matter is just 5%

The rest (95%) is dark

5 times more dark matter than normal matter



And yet the microscopic nature of dark matter is still unknown

Ordinary matter

Atoms, mostly H and He

↓

Quarks, gluons, electrons, etc

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Ordinary matter

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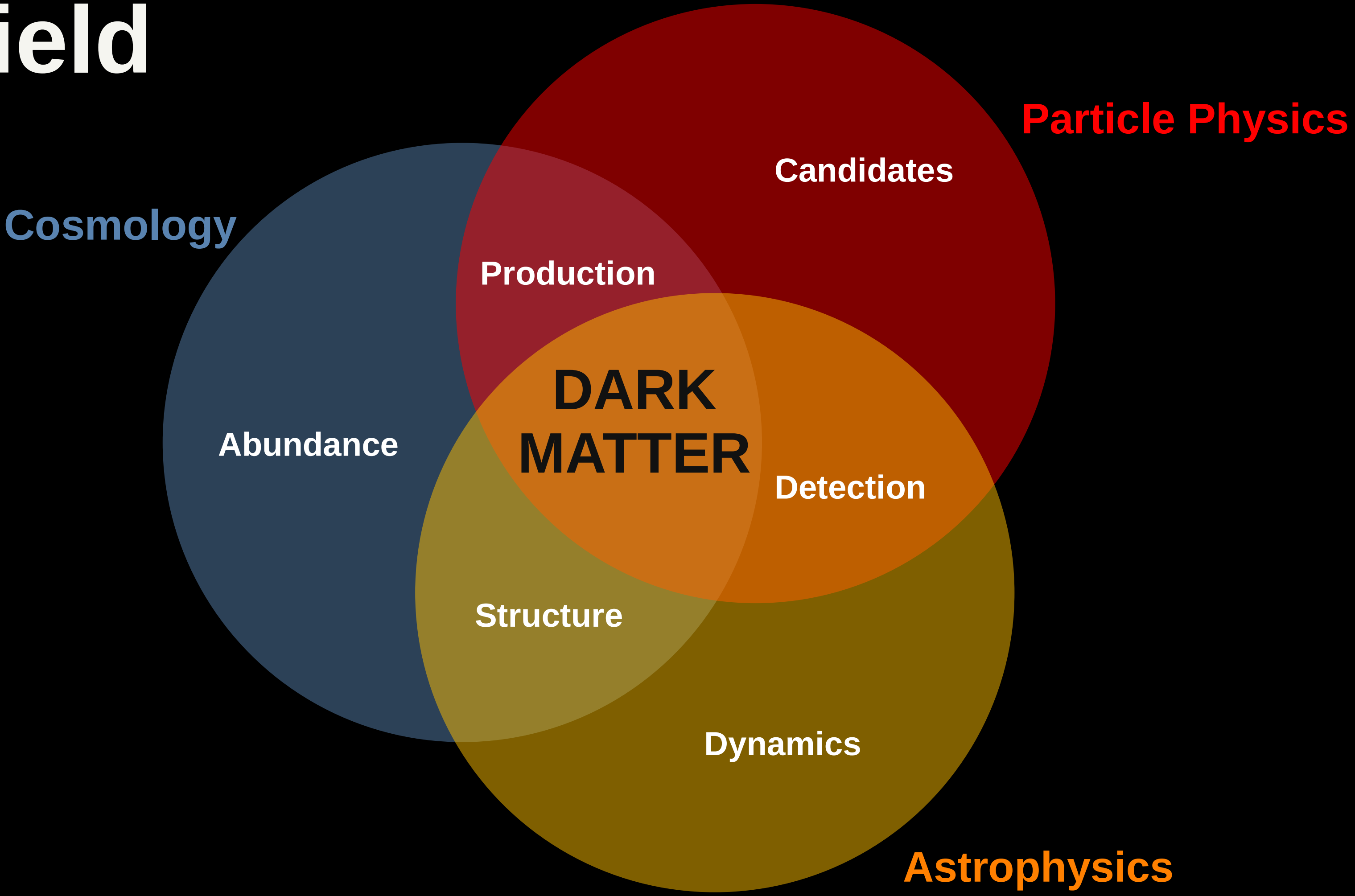
Quarks, gluons, electrons, etc

Dark matter

?

DM research is a multidisciplinary and active field



Dark matter is a discovery opportunity for the next generation

A fundamental mystery

A bridge between fields

A broad research frontier

PhD students can enter this field from many directions

By the end of this lecture, YOU will be able to answer these questions

1. What is dark matter?

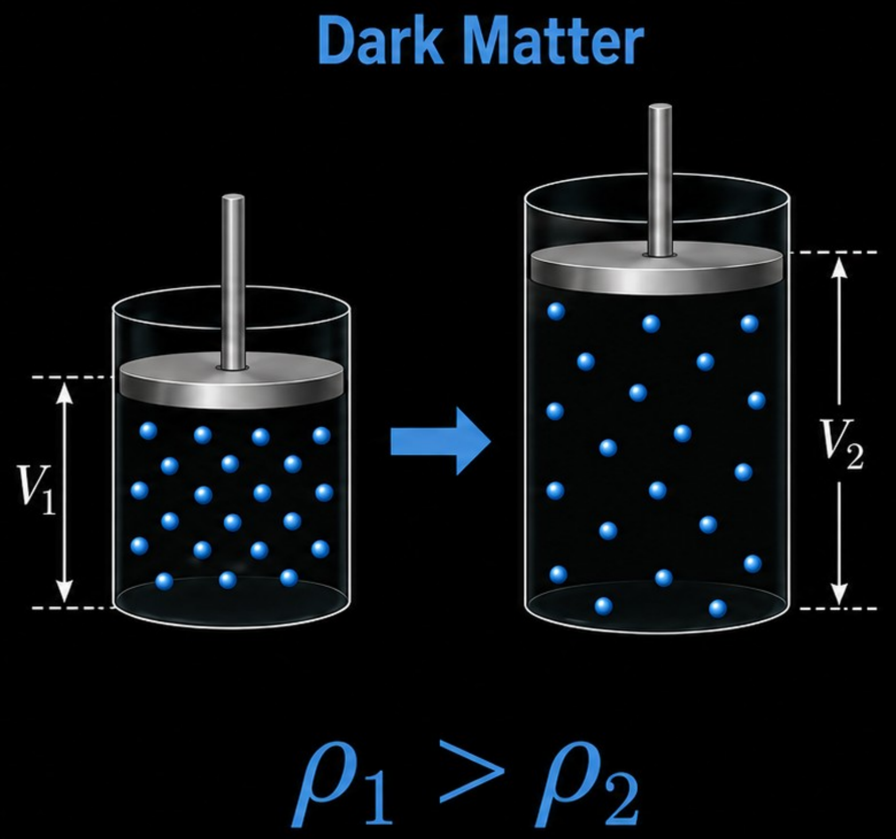
2. Why do we need it?

3. What makes a particle viable as dark matter?

4. Why are WIMPs a classic benchmark?

5. How can minimal WIMP models be built?

Dark matter and dark energy are completely different



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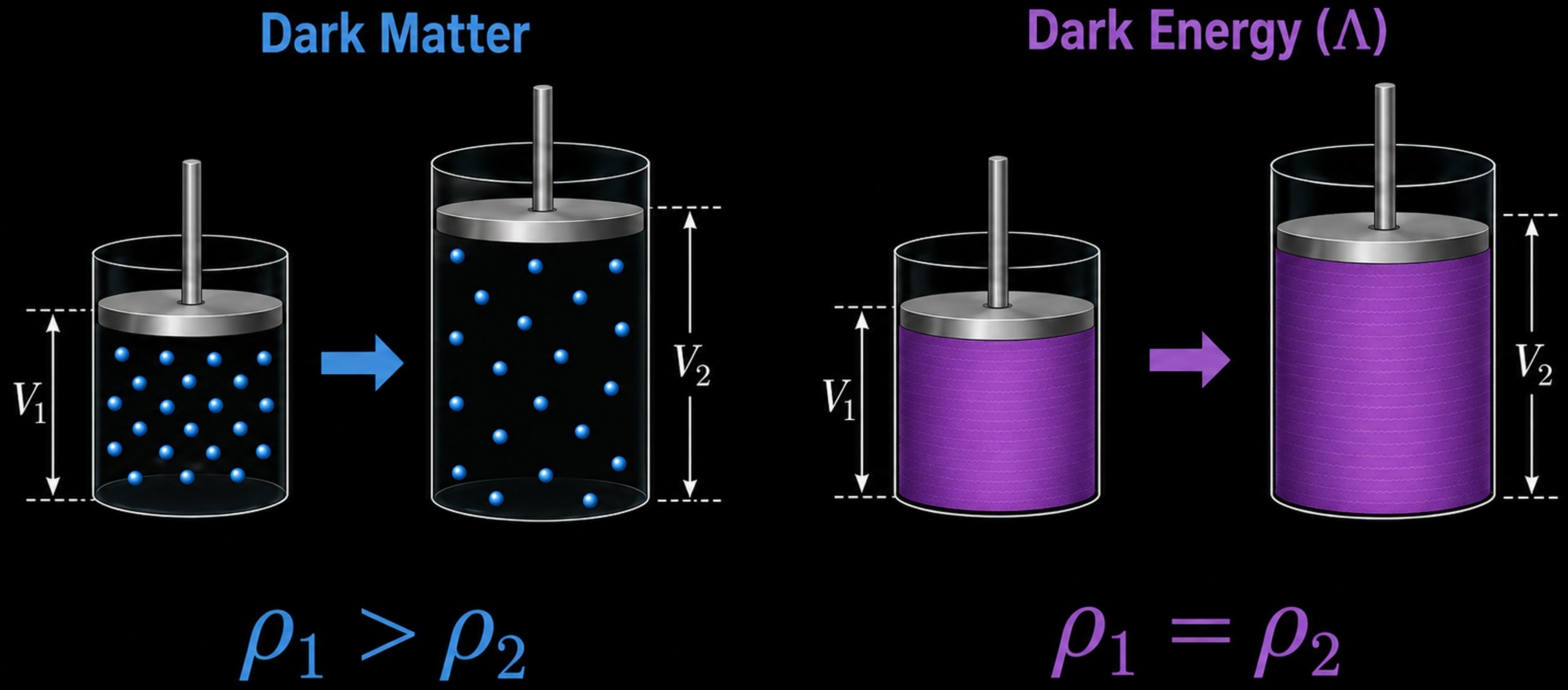
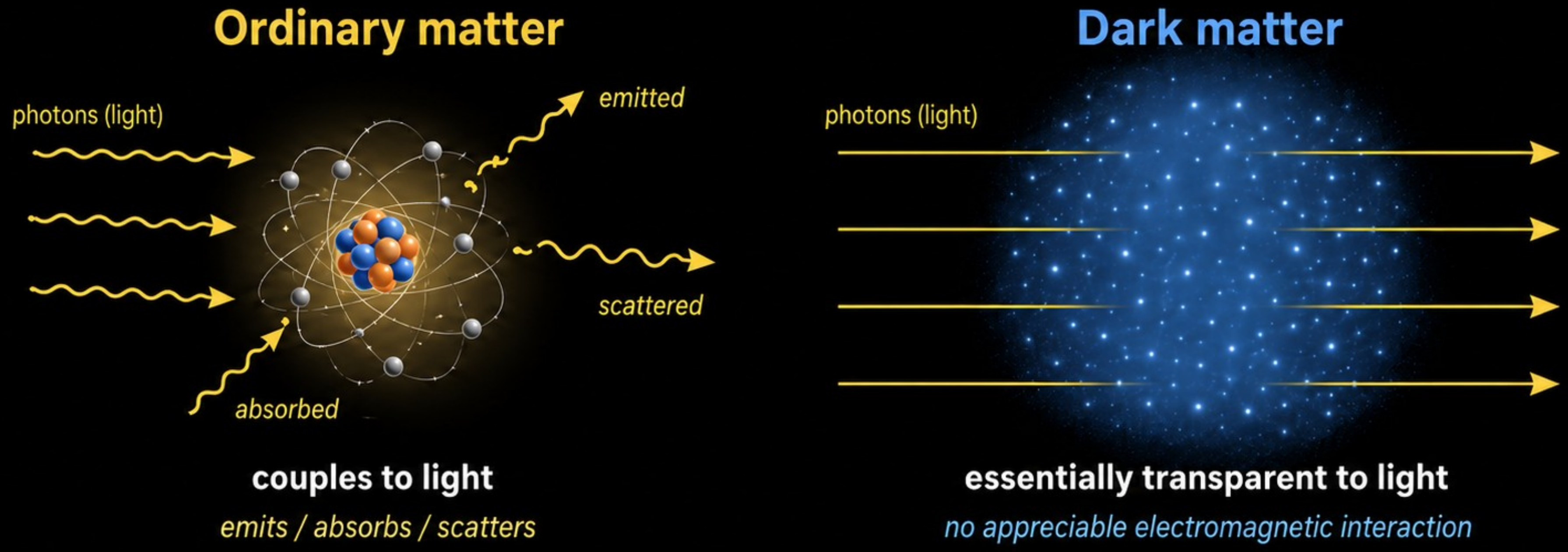


Dark matter does not emit, absorb, or scatter light appreciably



We will use multiple-choice questions to check our understanding

Think first

Choose the best answer

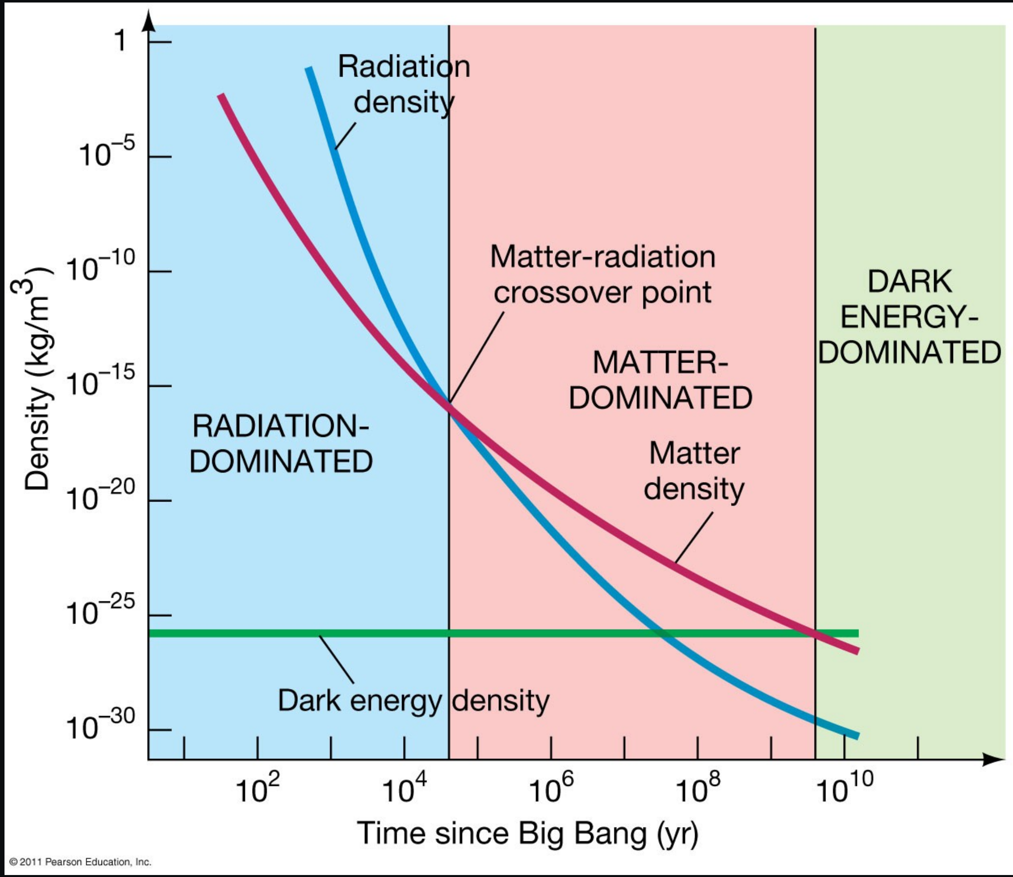
Apply the ideas

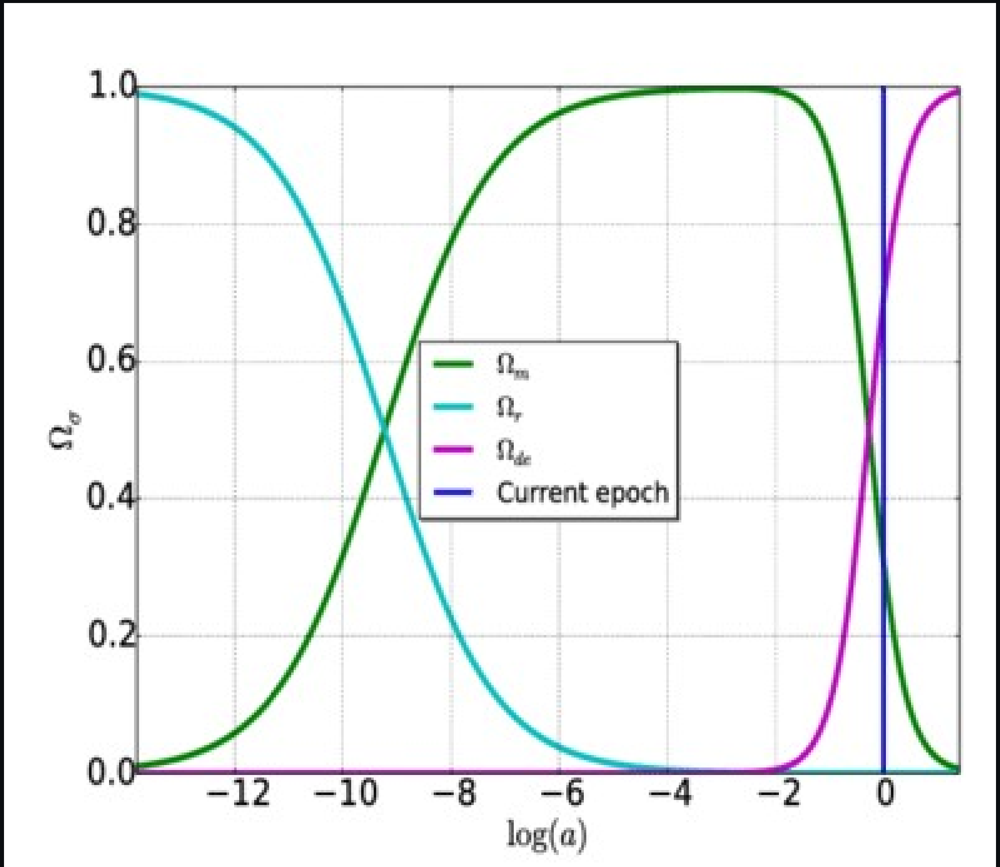
Wait for the signal

The goal is reasoning, not guessing

Today, dark matter and dark energy (Λ) make up about 25% and 70% of the cosmic energy budget. In the future, these fractions will be

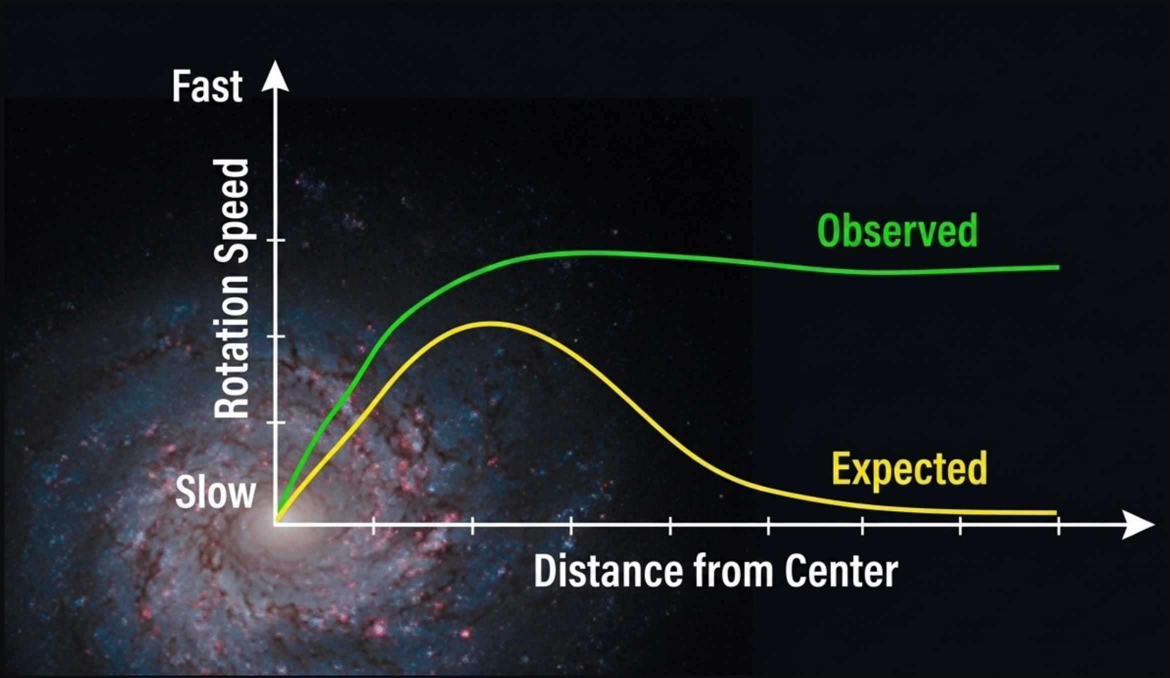
A. the same for both
B. higher for both
C. smaller for both
D. smaller for DM, the same for DE
E. smaller for DM, higher for DE
F. higher for DM, smaller for DE


Radiation density
Matter-radiation crossover point
DARK ENERGY-DOMINATED
MATTER-DOMINATED
RADIATION-DOMINATED
Matter density
Dark energy density
Density (kg/m^3)
1
10^{-5}
10^{-10}
10^{-15}
10^{-20}
10^{-25}
10^{-30}
10^2
10^4
10^6
10^8
10^{10}
Time since Big Bang (yr)


1.0
0.8
0.6
0.4
0.2
0.0
Ω_σ
Ω_m
Ω_r
Ω_{de}
Current epoch
−12
−10
−8
−6
−4
−2
0
$\log(a)$

The evidence for dark matter is overwhelming

1. Galaxies



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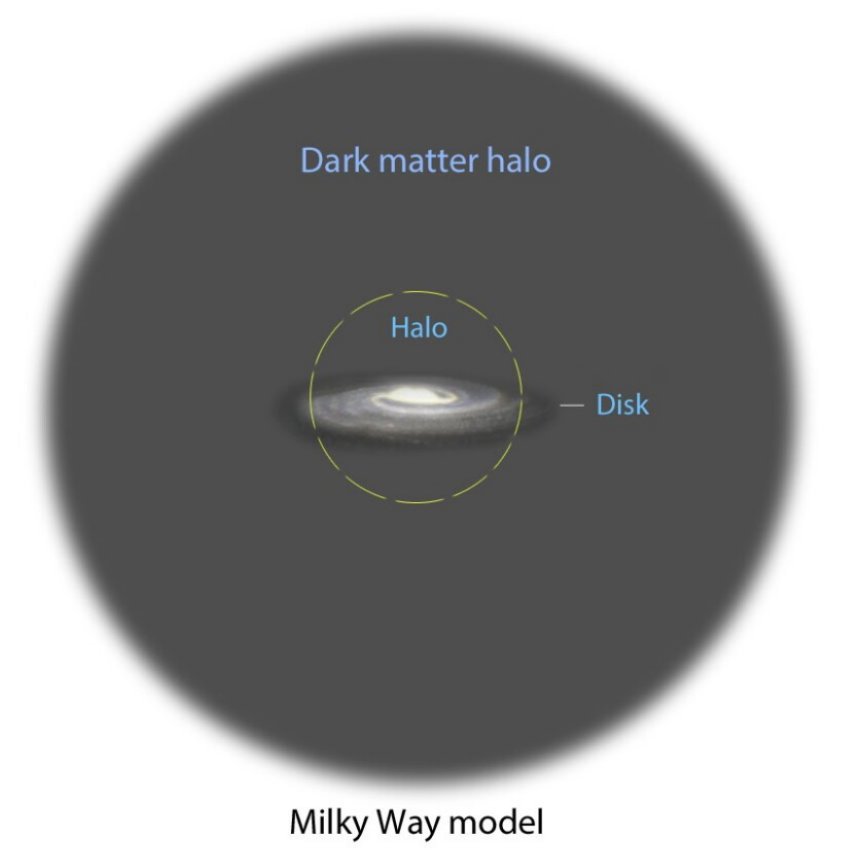
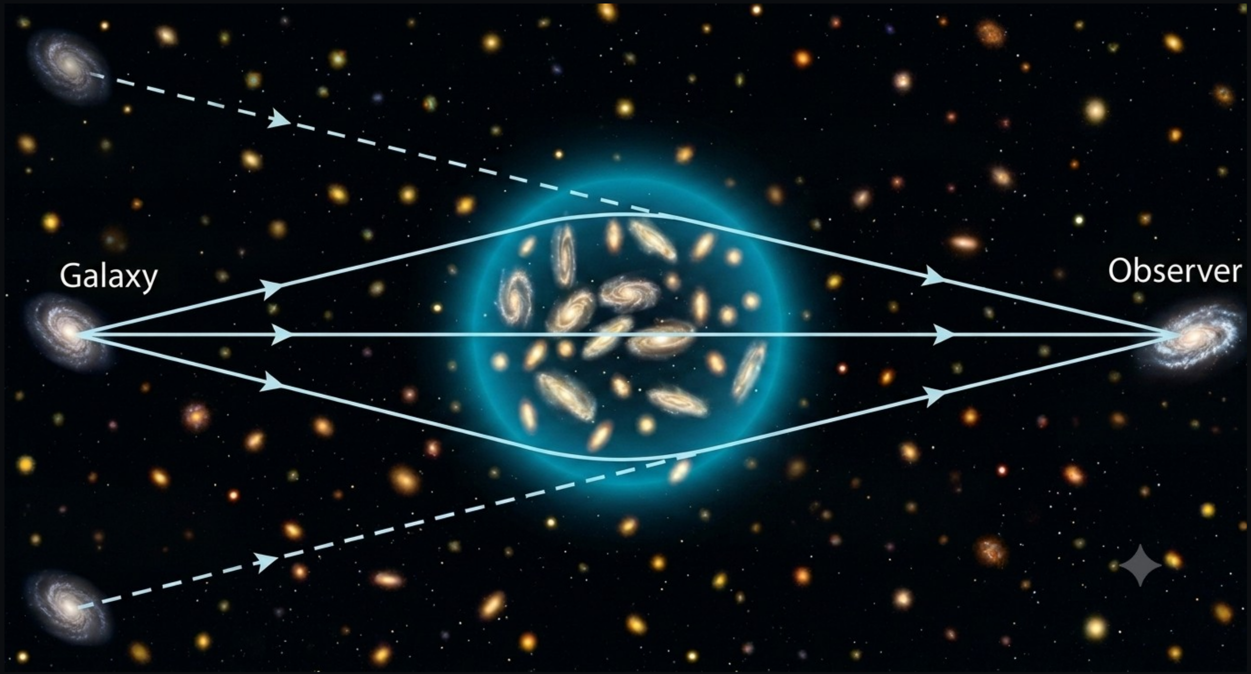


The evidence for dark matter is overwhelming

1. Galaxies

2. Clusters



The evidence for dark matter is overwhelming

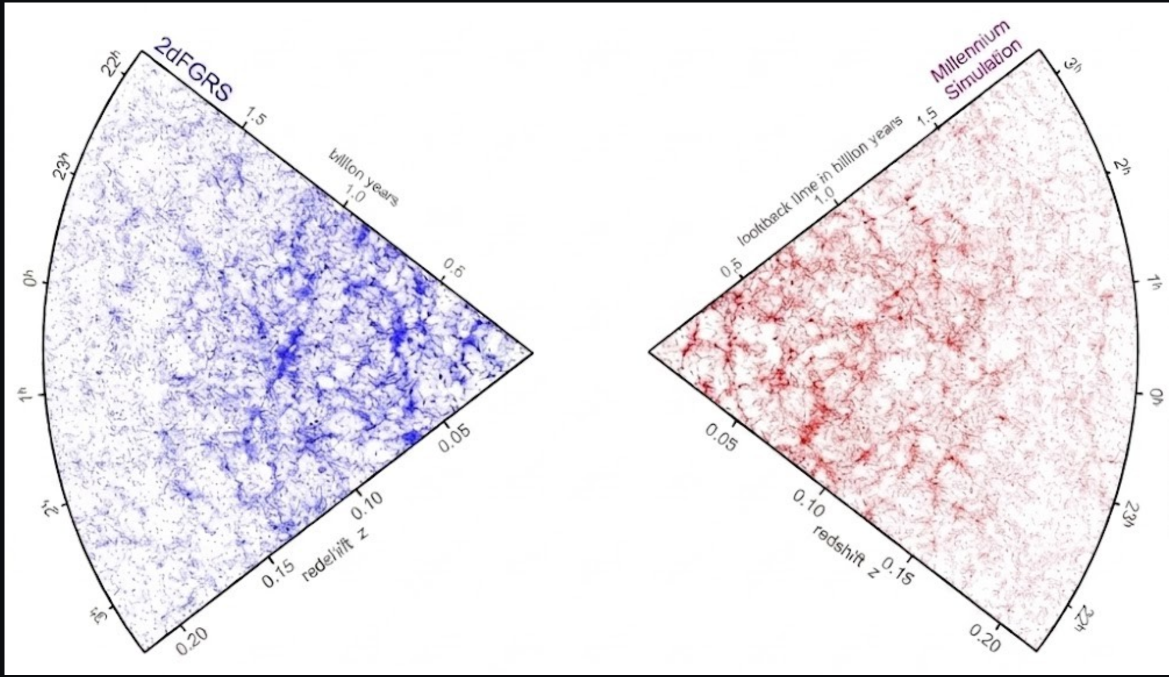
1. Galaxies

2. Clusters

3. Cosmic structure

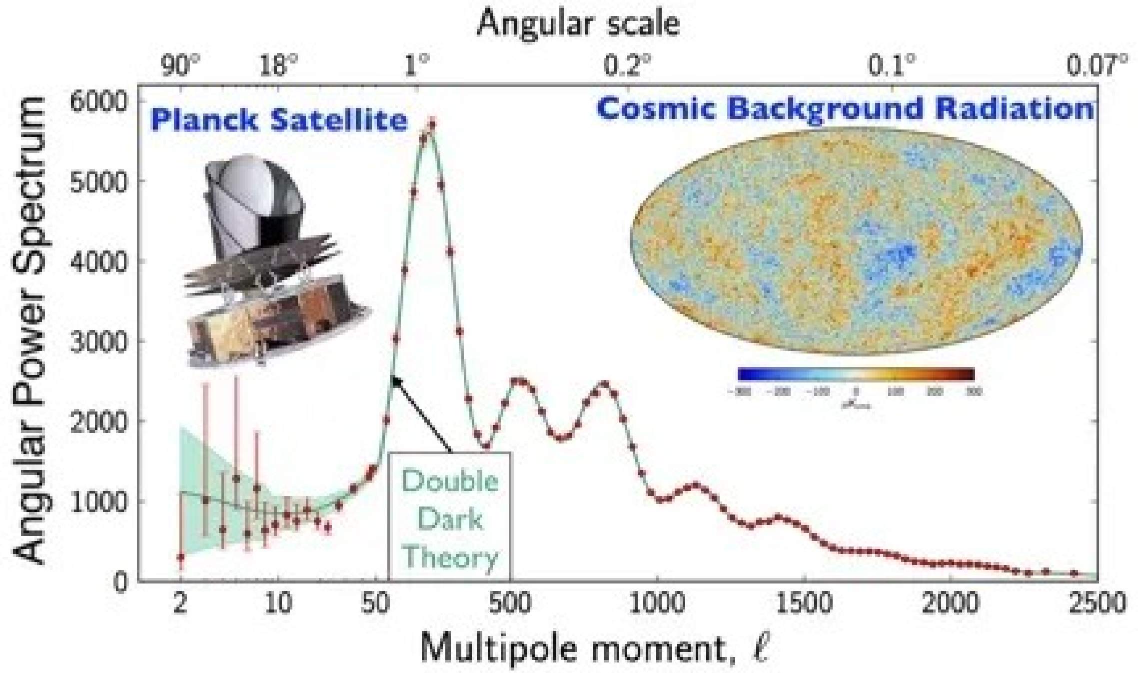
Observations

DM simulation



The evidence for dark matter is overwhelming

1. Galaxies
2. Clusters
3. Cosmic structure
4. CMB



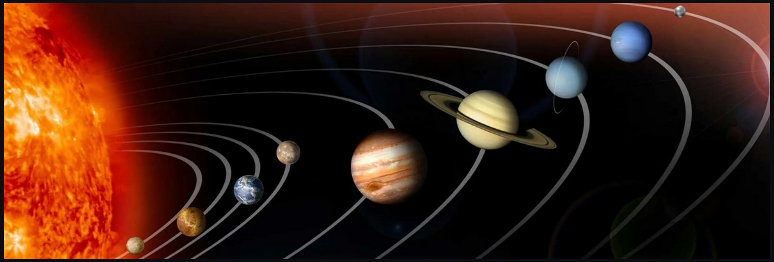
$$\Omega_{\rm DM} h^2 = 0.1200 \pm 0.0012.$$

The evidence for dark matter is overwhelming

1. Galaxies
2. Clusters
3. Cosmic structure
4. CMB

But it is all gravitational

Gravity does not reveal the physical nature of dark matter

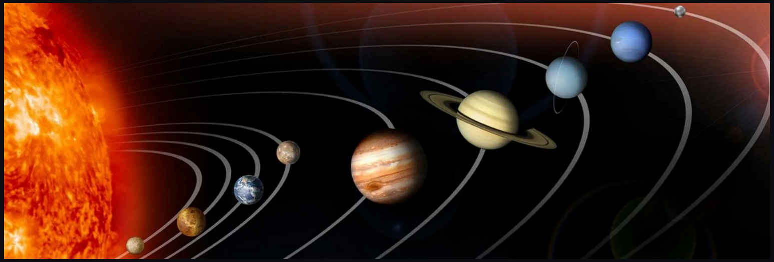


Planetary Motion → M_{Sun}

Not from gravity:

- Age
- Radius
- Temperature
- Composition

Gravity does not reveal the physical nature of dark matter



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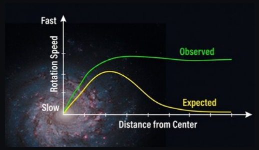
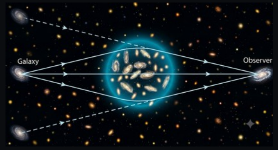
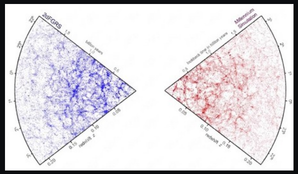
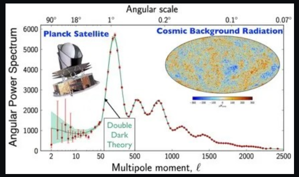








DM evidence → Ω_{DM}

Still unknown:

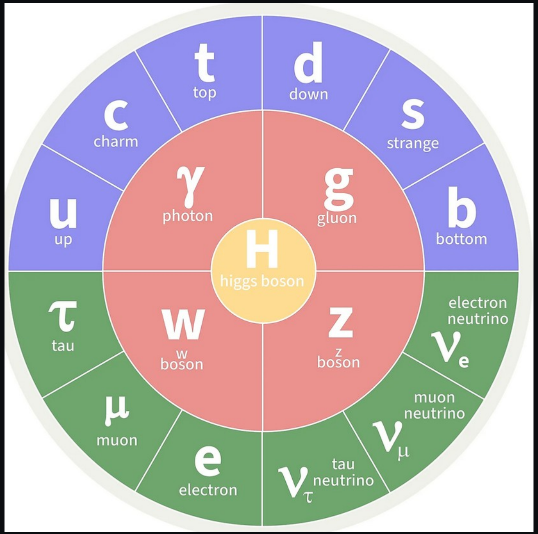
- Origin
- Mass scale
- Interactions
- Composition

As we saw, the orbital velocity of stars remains constant at large distances (r) from the galactic center. Assuming these stars are in circular orbits dominated by a dark matter halo, how must the enclosed mass M(r) scale with r?

A. $M(r) \propto$ constant
B. $M(r) \propto r$
C. $M(r) \propto 1/r$
D. $M(r) \propto r^2$
E. $M(r) \propto 1/r^2$
F. none of the above

The microscopic nature of dark matter is still unknown

Ordinary Matter:



Known particles and interactions

Dark Matter:

DM	$I(J^{PC}) = ?(?^{??})$
DM MASS $= ? \pm ?$	
DM WIDTH $= ? \pm ?$	

Couplings to quarks and leptons

$g_V^l = ? \pm ?$	$g_A^l = ? \pm ?$
$g_V^q = ? \pm ?$	$g_A^q = ? \pm ?$

DM DECAY MODES

Mode	Fraction (Γ_i/Γ)
Γ_1 STABLE ?	?

Unknown physical properties

Any viable dark matter candidate must satisfy several constraints

Charge

Lifetime

Kinematics

Interactions

Abundance

Any viable dark matter candidate must satisfy several constraints

Charge
Neutral

Lifetime
Cosmologically stable

Kinematics
Cold DM

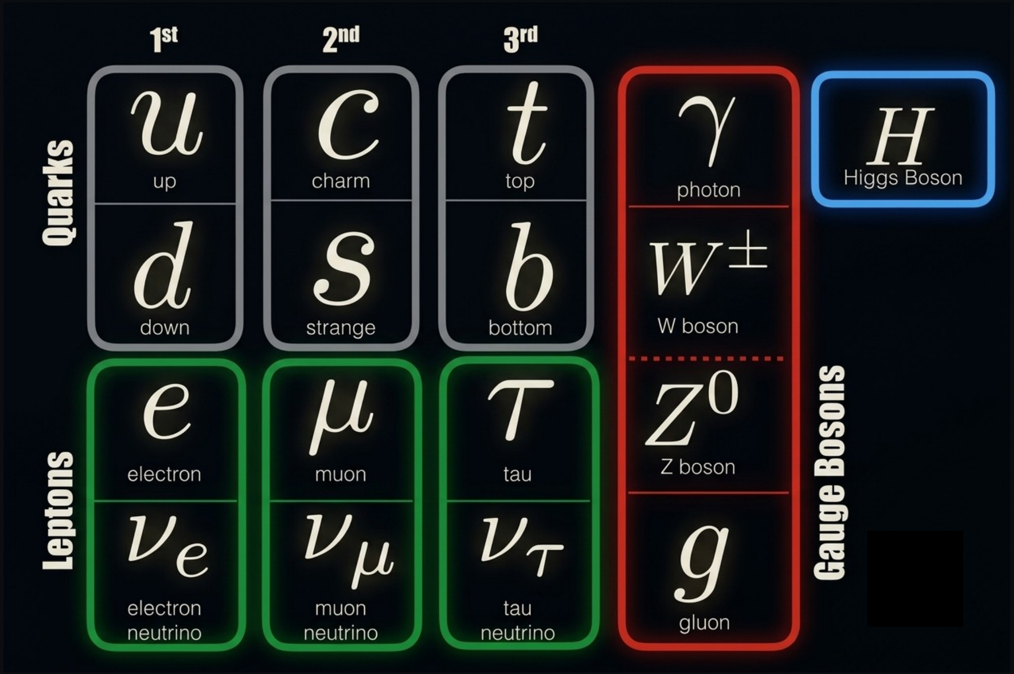
Interactions
Consistent with bounds

Abundance
$\Omega_{DM}h^2 \approx 0.12$

The Standard Model has no viable dark matter candidate

Most SM particles are charged or unstable

ν's fail on kinematics and abundance

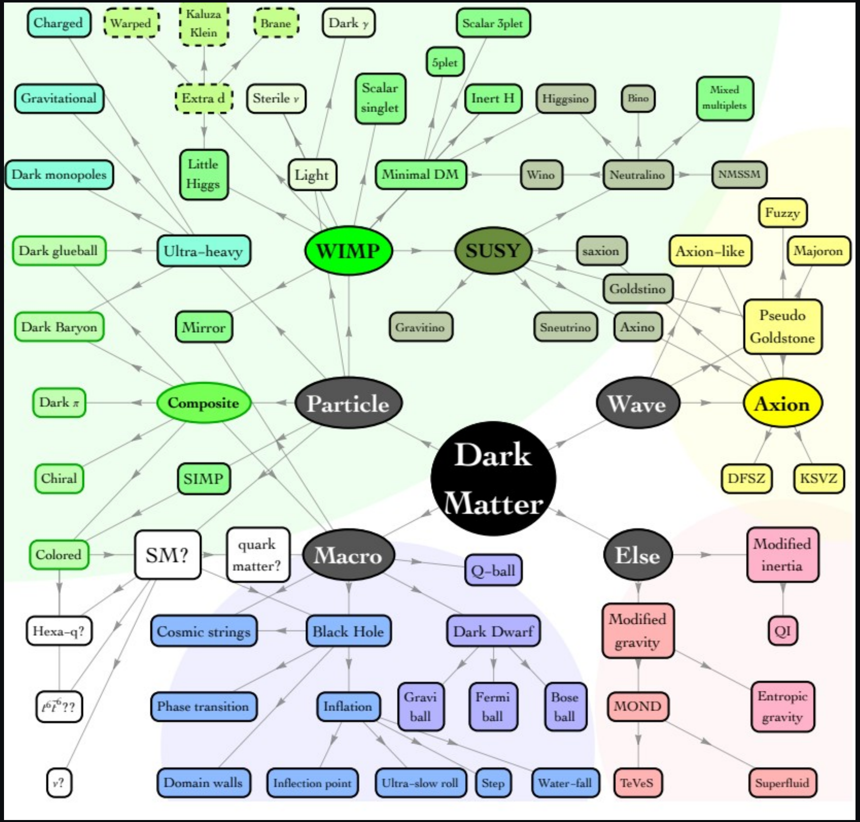


New physics is required

Hundreds of models have been proposed to explain dark matter

Dark matter is a major driver of BSM physics

The candidate landscape keeps expanding

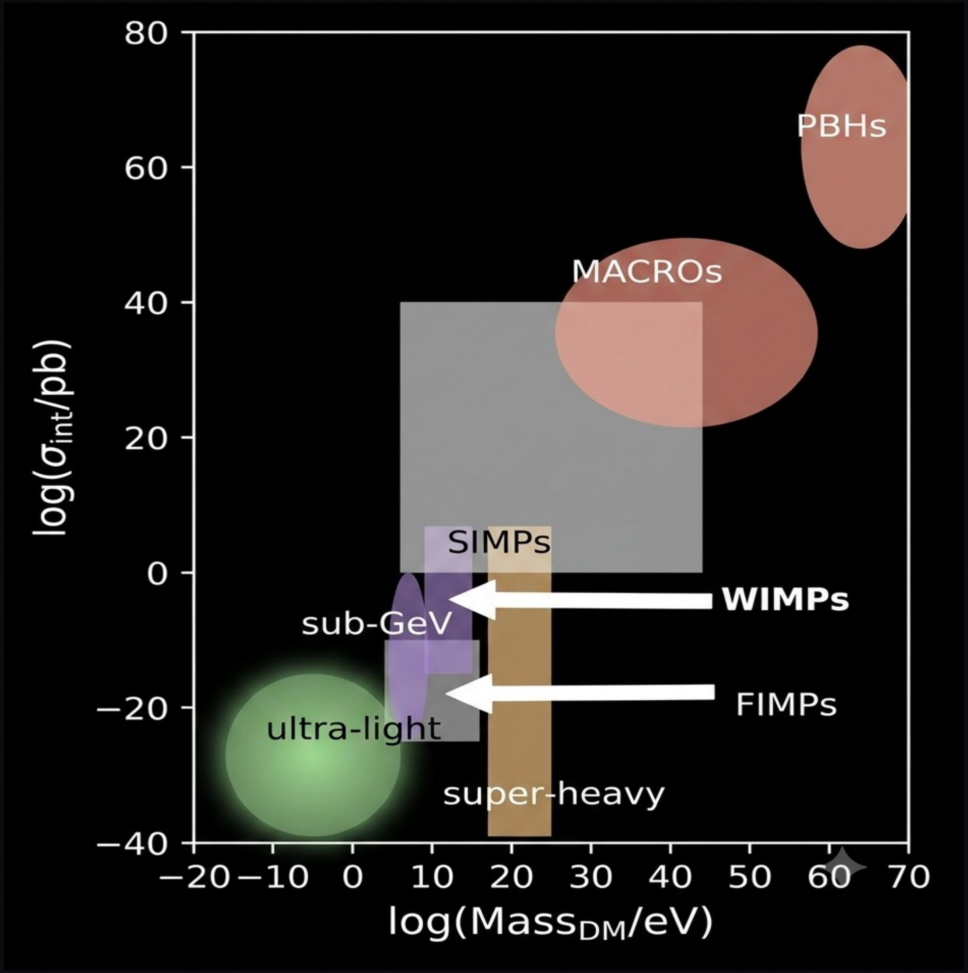


Cirelli et al, 2024

Dark matter candidates occupy a broad parameter space

M and σ span many orders of magnitude

Specific models work only in limited regions



WIMPs are the classic paradigm for particle dark matter

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Neutral and stable

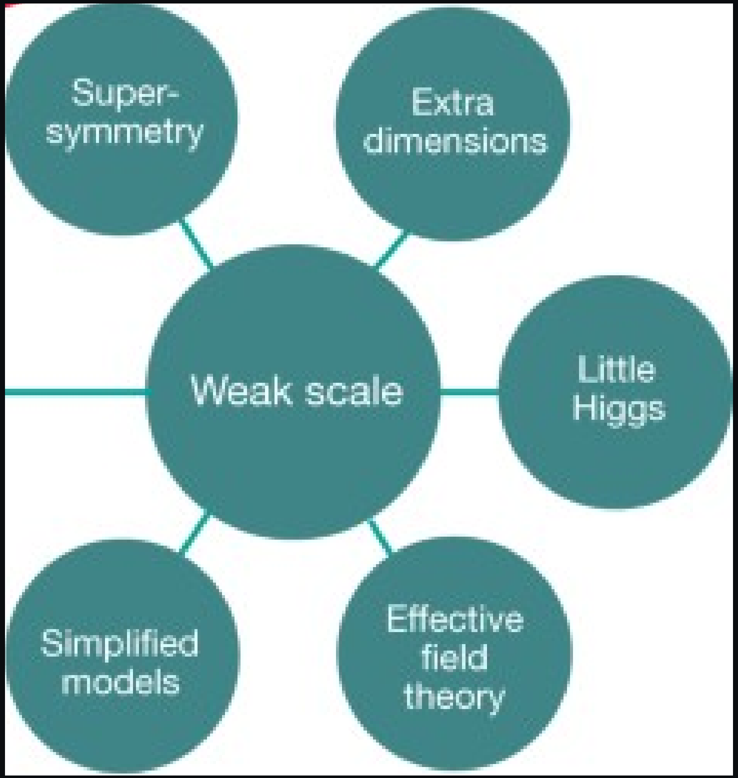
Weakly
Interacting
Massive
Particle

$\sigma_{WIMP} \sim \sigma_{Weak}$

$M_{WIMP} \sim$ 100 GeV - 1 TeV

WIMPs are the classic paradigm for particle dark matter

Natural in many BSM theories



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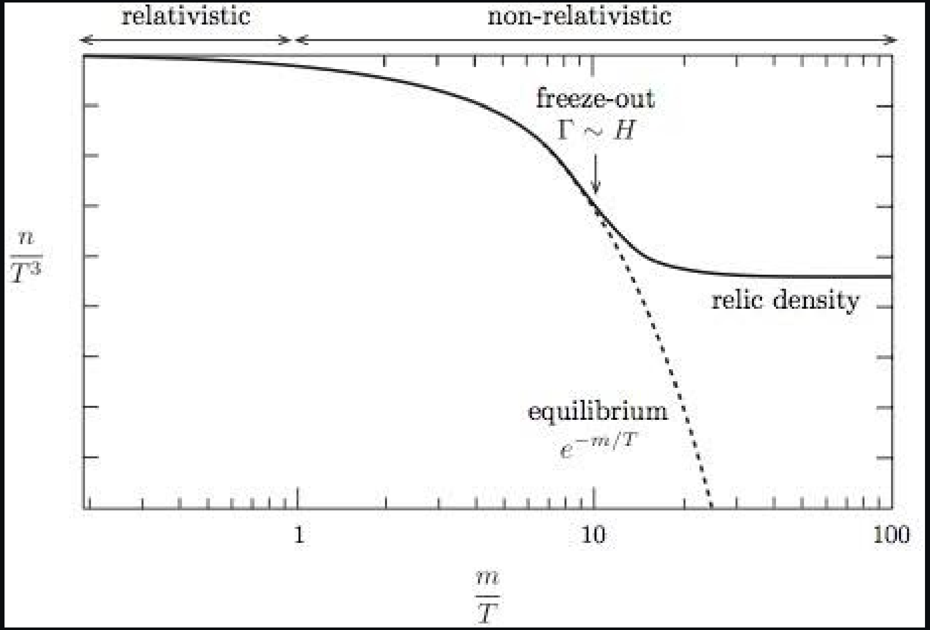
Natural in many BSM theories

Thermal origin in the early Universe

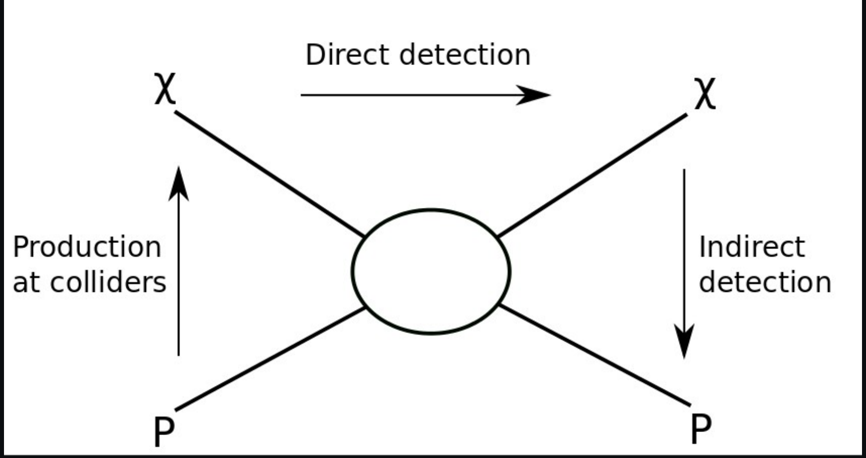


WIMPs are the classic paradigm for particle dark matter

Natural in many BSM theories

Thermal origin in the early Universe

Testable through multiple searches



Thermal freeze-out leaves a relic population of WIMPs

Equilibrium at high T: $\chi\bar{\chi} \leftrightarrow \mathrm{SM}\;\overline{\mathrm{SM}}$

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Freeze-out: $\Gamma_{ann} = n_{\chi} \langle \sigma v \rangle \sim H$

Thermal freeze-out leaves a relic population of WIMPs

Equilibrium at high T: $\chi\bar{\chi} \leftrightarrow \mathrm{SM}\,\overline{\mathrm{SM}}$

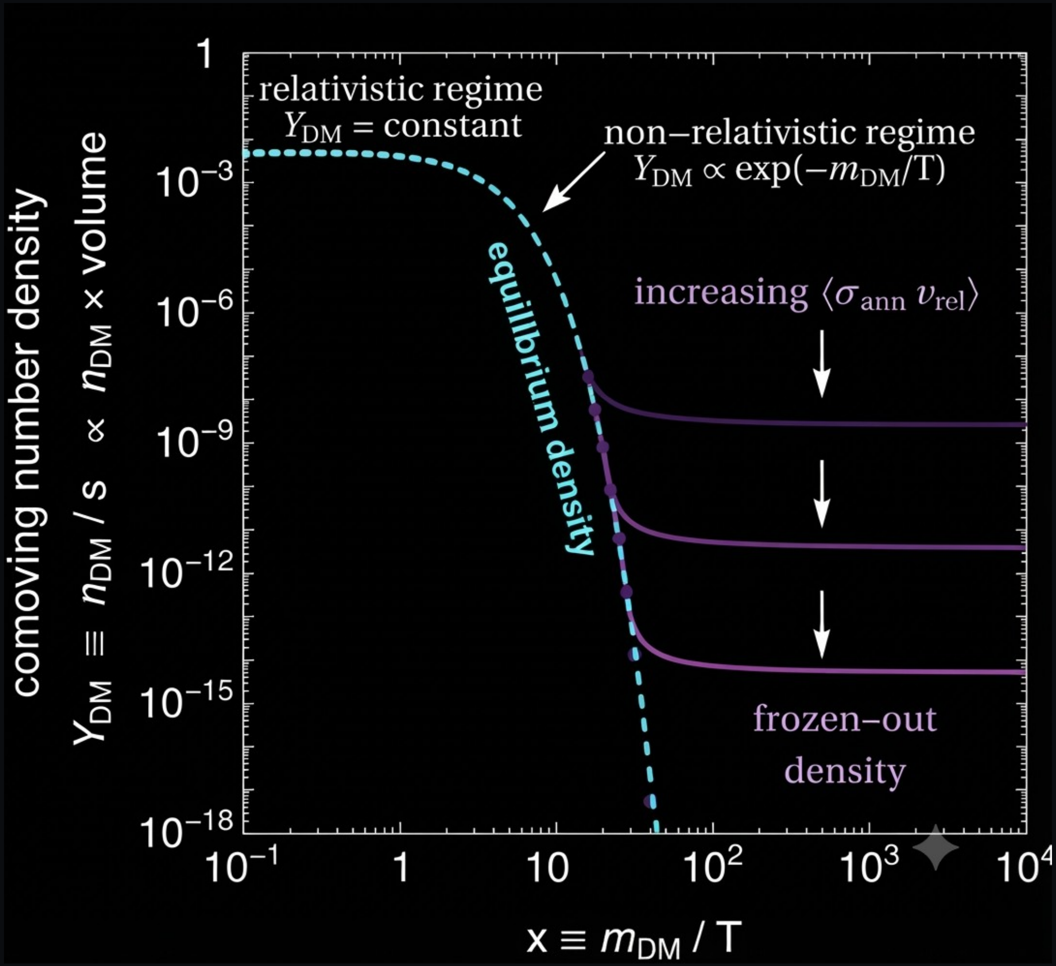
Freeze-out: $\Gamma_{ann} = n_\chi \langle \sigma v \rangle \sim H$

Relic abundance: $\Omega_\chi h^2 \propto 1/\langle \sigma v \rangle$

Efficient annihilation leaves less dark matter

Freeze-out follows from the Boltzmann equation

$$\frac{dn_\chi}{dt} = -3Hn_\chi - \langle \sigma v \rangle \left(n_\chi^2 - n_{\mathrm{eq}}^2\right)$$



The WIMP miracle links the observed DM abundance to weak-scale physics

m_χ~100 GeV – 1 TeV
and $g \sim g_W$

→

$\langle\sigma v\rangle \sim (\alpha_W/m_\chi)^2$
$\sim 10^{-26}\ cm^3/s$

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Freeze-out gives $\Omega_\chi h^2 \propto 1/\langle \sigma v \rangle$ → $\Omega_\chi h^2 \sim 0.1$

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Freeze-out gives
$\Omega_\chi h^2 \propto 1/\langle\sigma v\rangle$

→

$\Omega_\chi h^2 \sim 0.1$

Remarkably close to the observed value!

Consider a 1 TeV stable particle whose interactions are set by a free coupling λ. What do you think will happen to its relic density as λ goes from 1 to 0?

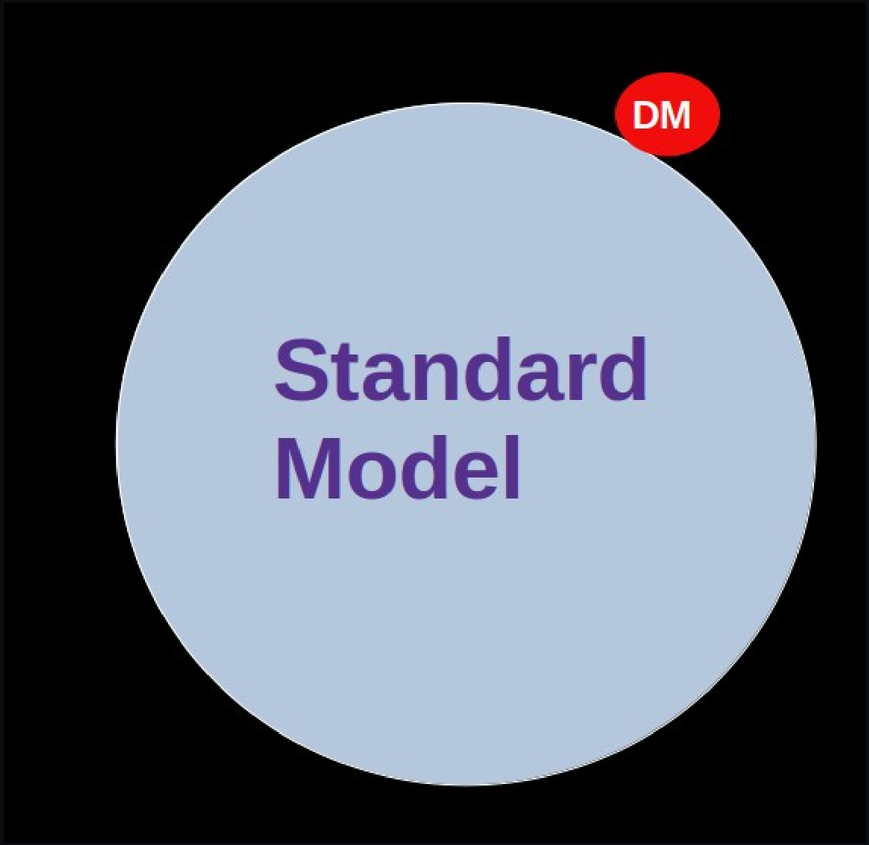
A. goes up indefinitely
B. goes to zero monotonically
C. first increases, then goes to 0
D. first decreases, then goes to ∞
E. it does not change

Minimal WIMP models are an appealing solution to the dark matter problem

Extend the SM, but minimally

Few new fields and symmetries

Simple and testable framework



WIMP models often need a new symmetry to ensure DM stability

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Discrete symmetries

Z_2: odd and even particles
e.g. R-parity in SUSY

The lightest odd particle is stable

Z_N: multiple stable particles

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Discrete symmetries

Z_2: odd and even particles
e.g. R-parity in SUSY

The lightest odd particle is stable

Z_N: multiple stable particles

Gauge symmetries

U(1): DM particle is charged
Charge conservation can forbid its decay

B-L, L_μ-L_τ, $U(1)_{Dark}$

GUTs?

We add a real scalar singlet ϕ to the SM. The new scalar potential contains

$$V \supset \frac{1}{2} m_\phi^2 \phi^2 + \frac{\mu_3}{3}\phi^3 + \frac{\lambda_\phi}{4}\phi^4 + \mu_{H\phi}\phi H^\dagger H + \frac{\lambda_{H\phi}}{2}\phi^2 H^\dagger H$$

with H the Higgs doublet. For ϕ to be a DM particle, which term should be absent?

A. none
B. ϕ^2
C. ϕ^3
D. ϕ^4
E. $\phi H^\dagger H$
F. $\phi^2 H^\dagger H$
G. C, E
H. D, F

The simplest DM model is probably the singlet scalar

Just one new field

A real scalar singlet, S

Odd under a Z_2

$S \rightarrow -S, \quad \langle S \rangle = 0$

The simplest DM model is probably the singlet scalar

Just one new field — A real scalar singlet, S

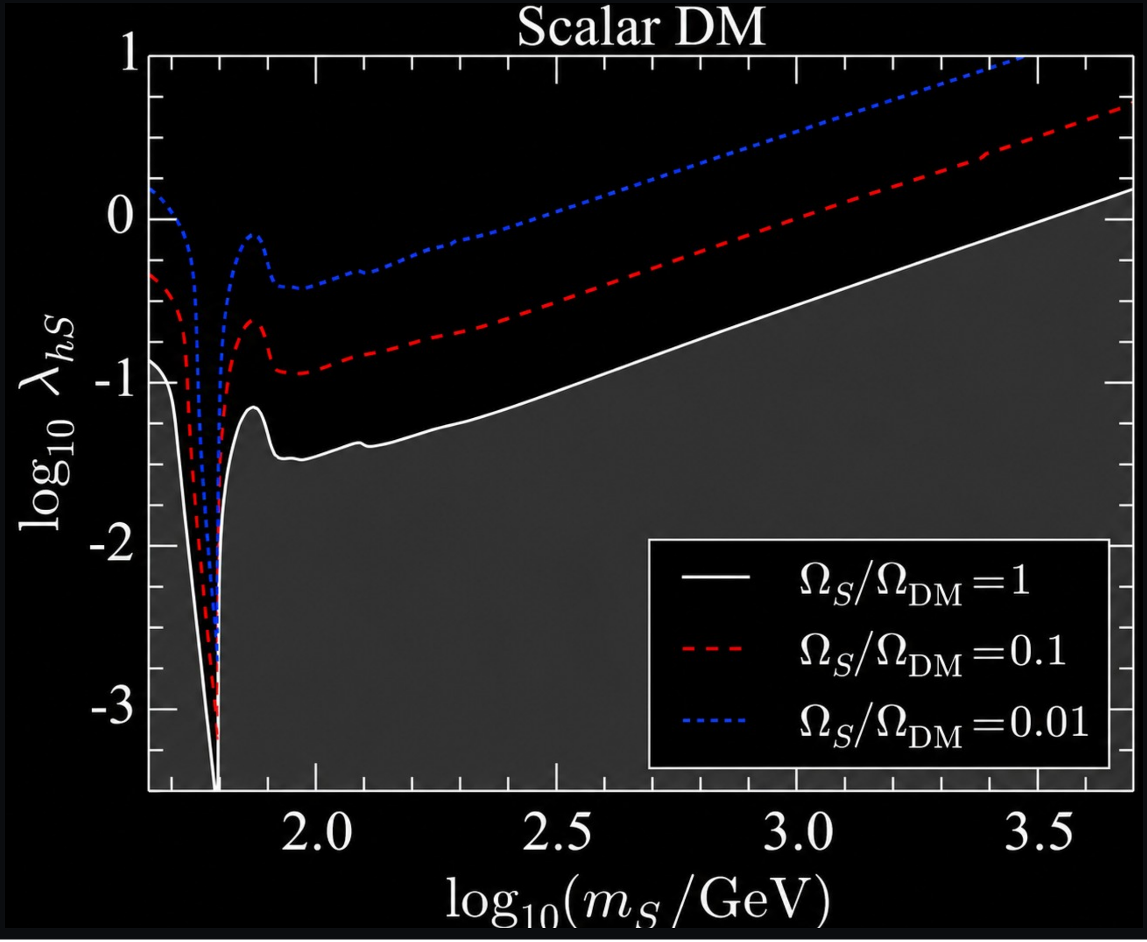
Odd under a Z_2 — $S \to -S$, $\langle S \rangle = 0$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S\,\partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{\lambda_S}{4}S^4 - \frac{\lambda_{HS}}{2}S^2 H^\dagger H$$

We can now compute the S relic density via thermal freeze-out

It depends only on m_S and λ_{HS}

Requiring $\Omega_{DM}h^2 \approx 0.12$ selects a curve



Other models can be constructed along similar lines

Model class	Symmetry	New fields	DM candidate
Scalar singlet	Z_2	real scalar S	scalar S
Inert Higgs doublet	Z_2	second Higgs doublet H_2	neutral scalar
Singlet fermion portal	Z_2	fermion χ + mediator	fermion χ
Scotogenic model	Z_2	inert doublet η, fermions N_i	scalar or fermion
Z_N dark sectors	Z_N	scalars and fermions	multiple stable particles
Gauged $B - L$	$U(1)_{B-L}$	Z', scalar, fermions	scalar or fermion
Dark gauge sector	$U(1)_D$	dark photon/Z', scalar or fermion	scalar or fermion

Let us now answer our opening questions

1. What is dark matter?

2. Why do we need it?

3. What makes a particle viable as dark matter?

4. Why are WIMPs a classic benchmark?

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Dark Matter

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Yesterday we answered the following questions

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Gravity reveals dark matter's presence, not its particle identity

Gravitational evidence

Galaxies, clusters, CMB, etc

Ω_{DM}, M(r), ρ_{DM}

Particle searches

Sky and laboratory signals

Mass, spin, interactions, etc

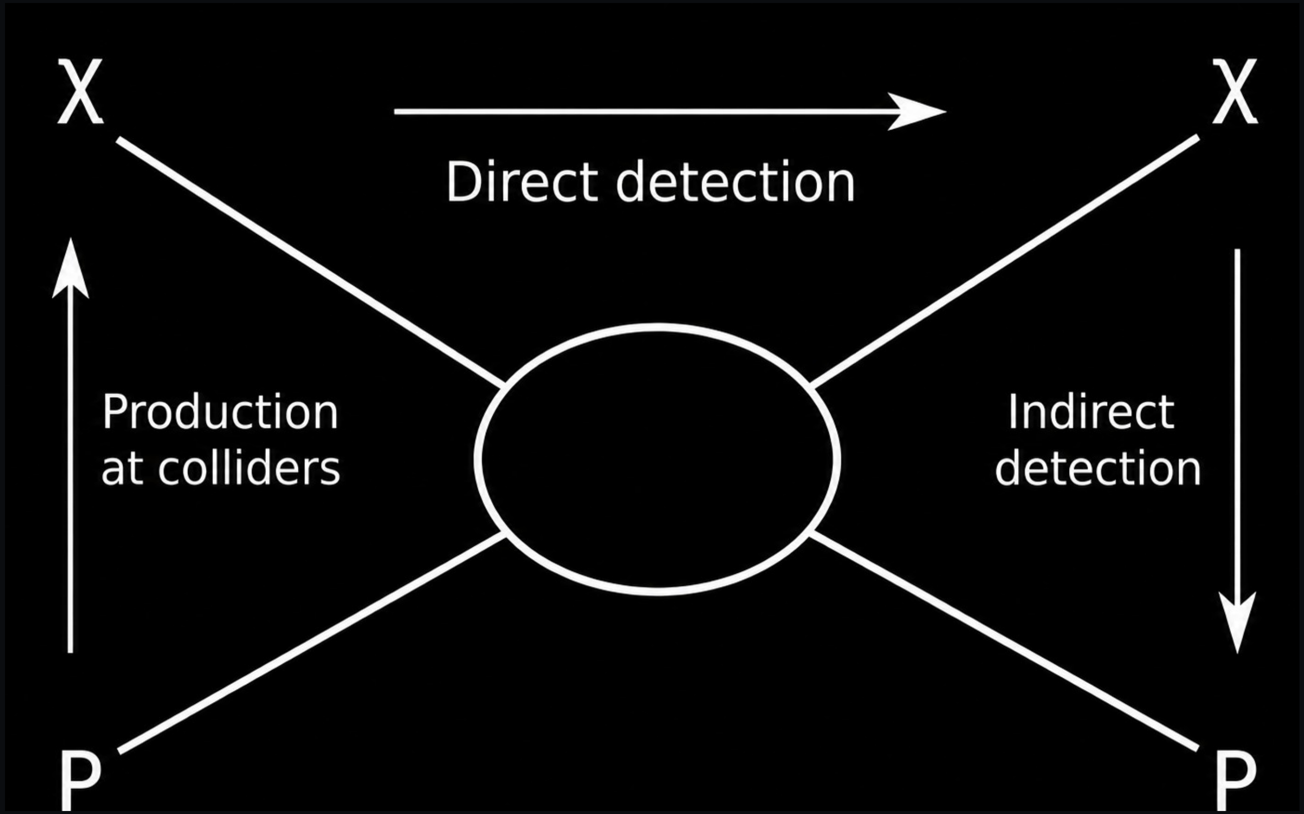
Detection means looking for non-gravitational fingerprints

WIMP dark matter could be detected in different ways

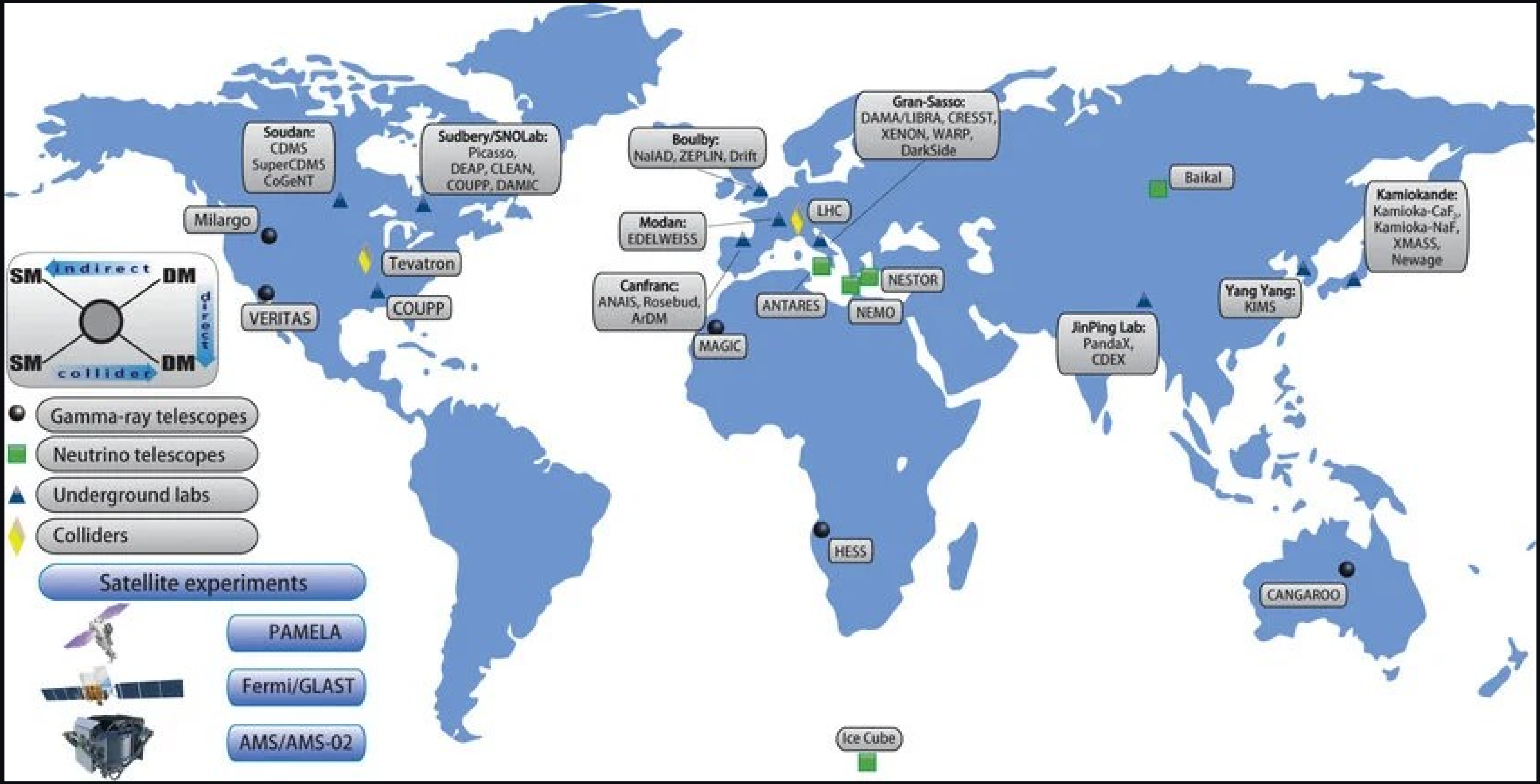
No confirmed signals so far

Just strong constraints

Future signals?



The search for dark matter is a worldwide effort



Direct and indirect searches look for different signals

Indirect detection

DM annihilation:

$\chi\bar{\chi} \rightarrow W^+W^-, b\bar{b}, hh, e^+e^-, \ldots$

Products from the sky

Direct detection

DM scattering:

$\chi N \rightarrow \chi N, \ \chi e^- \rightarrow \chi e^-$

Recoils in the lab

Complementary signals, different techniques

Which search strategy is closely related to thermal freeze-out?

A. Direct detection
B. Indirect detection
C. Production at colliders
D. A and B
E. A, B and C

Indirect detection

Indirect detection relies on four basic principles

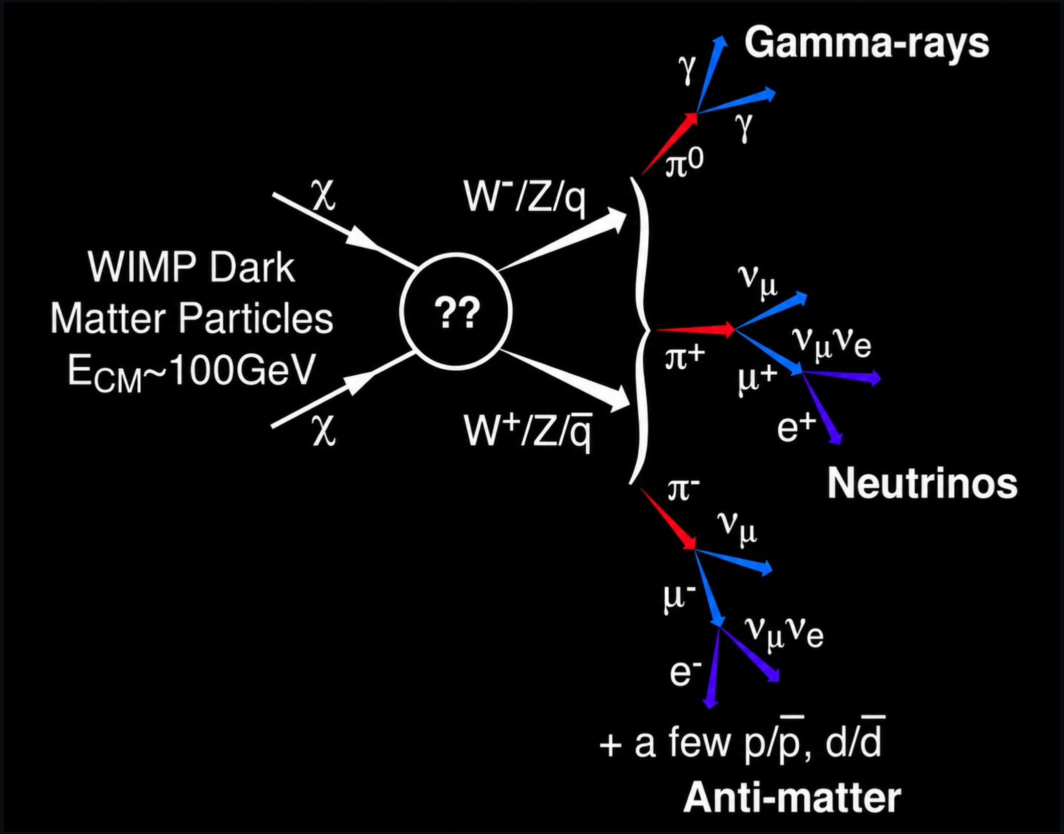
Annihilation today	$\chi\bar{\chi} \rightarrow$ SM particles, $\langle\sigma v\rangle$
Density squared	$\Gamma_{ann} \propto \rho_{DM}^2$
Visible messengers	γ, $e^{\pm}$, ν, $\bar{p}$
Signal vs background	Dense, nearby, quiet targets

The messengers are usually secondary products of DM annihilations

Gamma rays

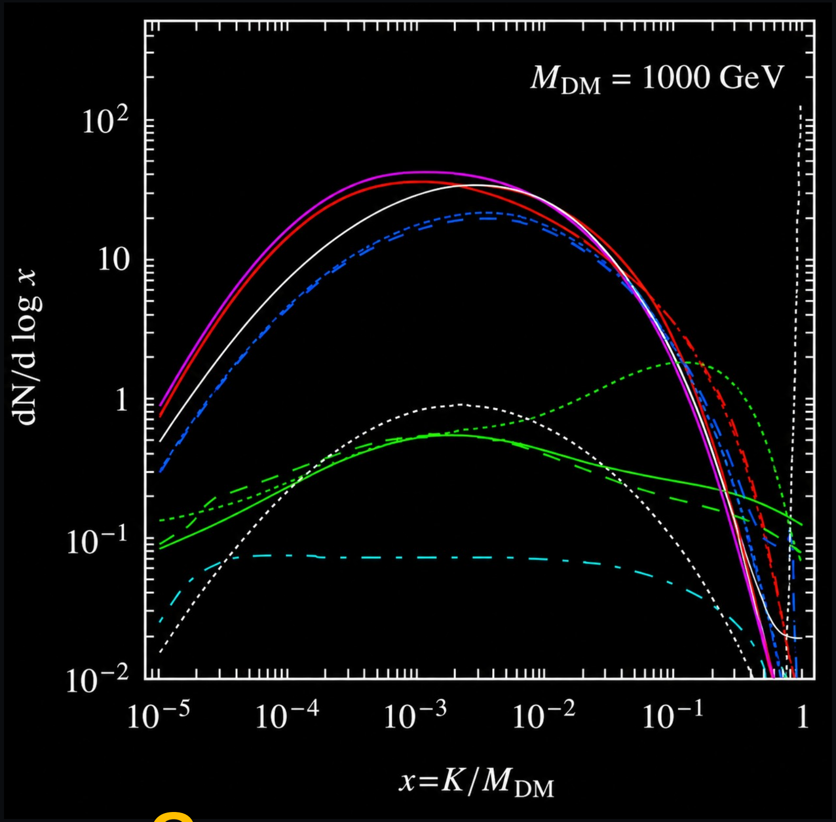
Antimatter

Neutrinos

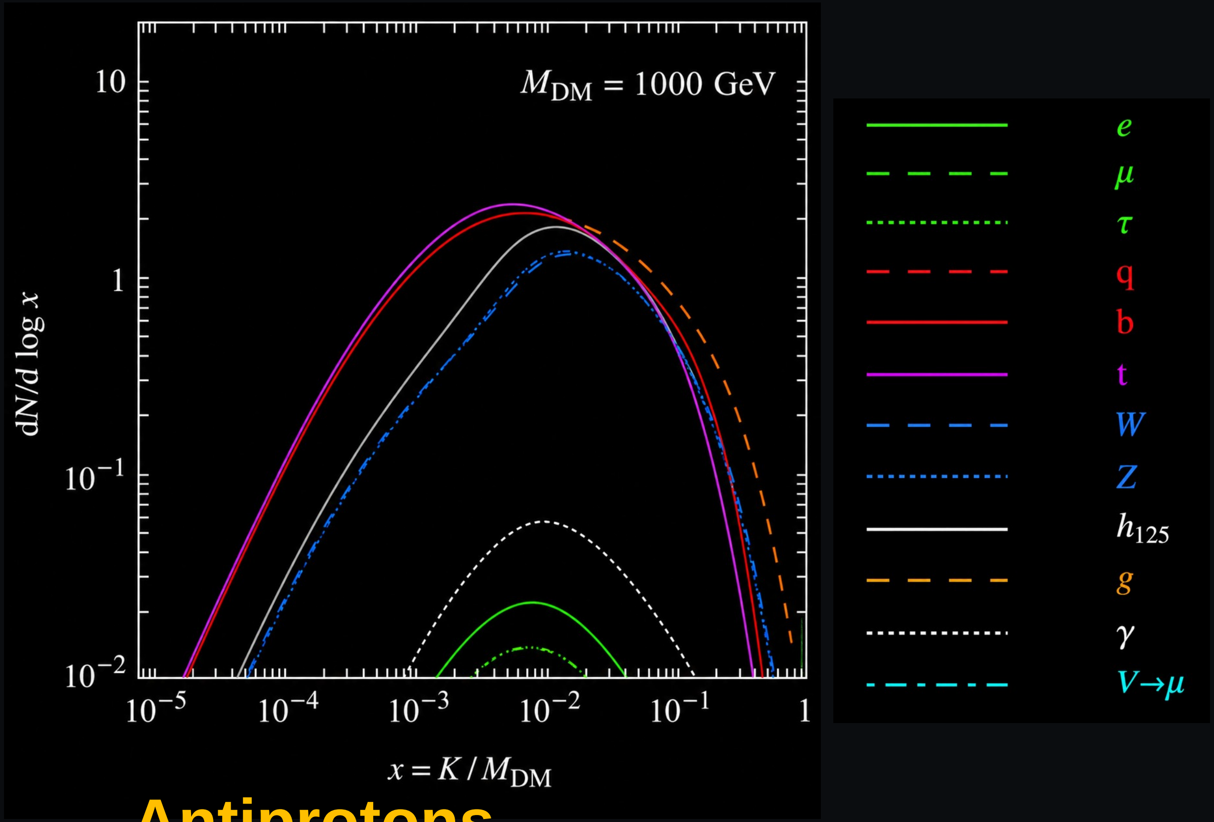


Each messenger requires a different kind of experiment

Each annihilation channel predicts a characteristic messenger spectrum



Gamma rays



Antiprotons

The expected γ-ray flux factorizes into three ingredients

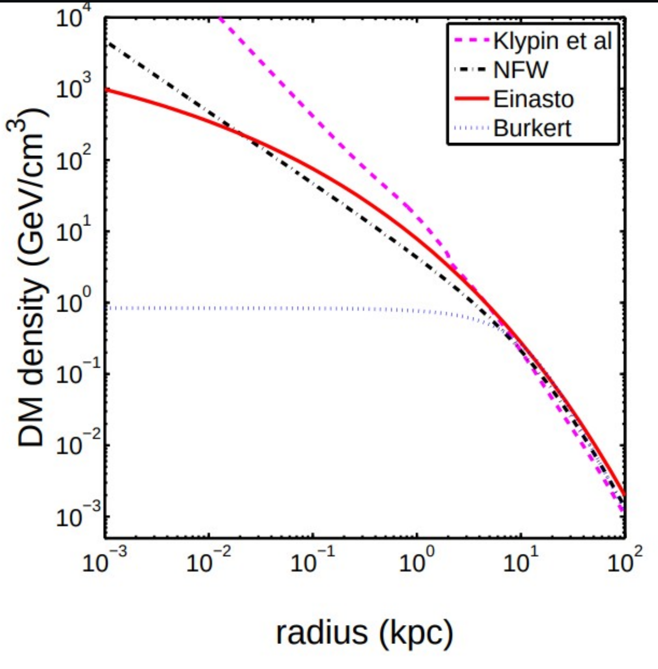
Final-state spectrum

$$\frac{\mathrm{d}\Phi(\Delta\Omega, E_\gamma)}{\mathrm{d}E_\gamma} = \frac{1}{4\pi}\,\frac{\langle\sigma_{\mathrm{ann}}\,v\rangle}{2\,m_\chi^2} \times \sum_i \mathrm{BR}_i\,\frac{dN_\gamma^i}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\mathrm{los}} ds\,\rho^2(s,\Omega)$$

DM properties

Astrophysics: J-factor

J-factors depend on the unknown dark matter distribution



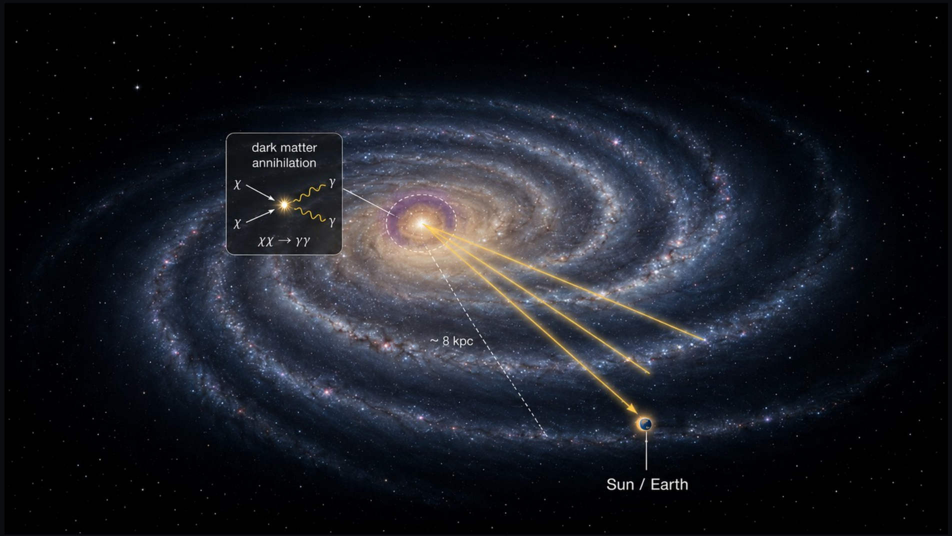
Halo profiles

Region	$\bar{J}_{\mathrm{ann}}$		
	NFW	Ein	Bur
'GC 0.1°'	11579	3579	6.21
'GC 0.14°'	8255	3206	6.21
'GC 1°'	1118	1196	6.21
'GC 2°'	542	711	6.19

Same region, different J-factors

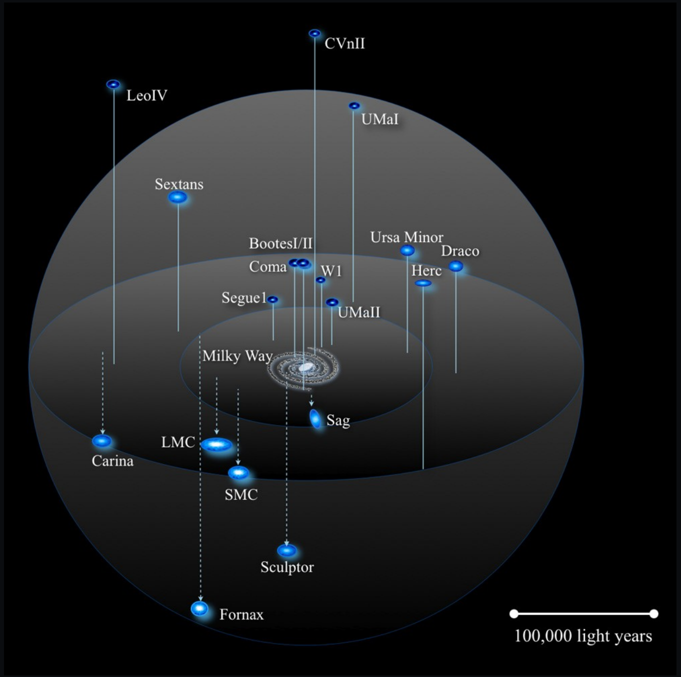
A larger J-factor does not automatically make a better target

Galactic Center



Larger J, messy region

Dwarfs

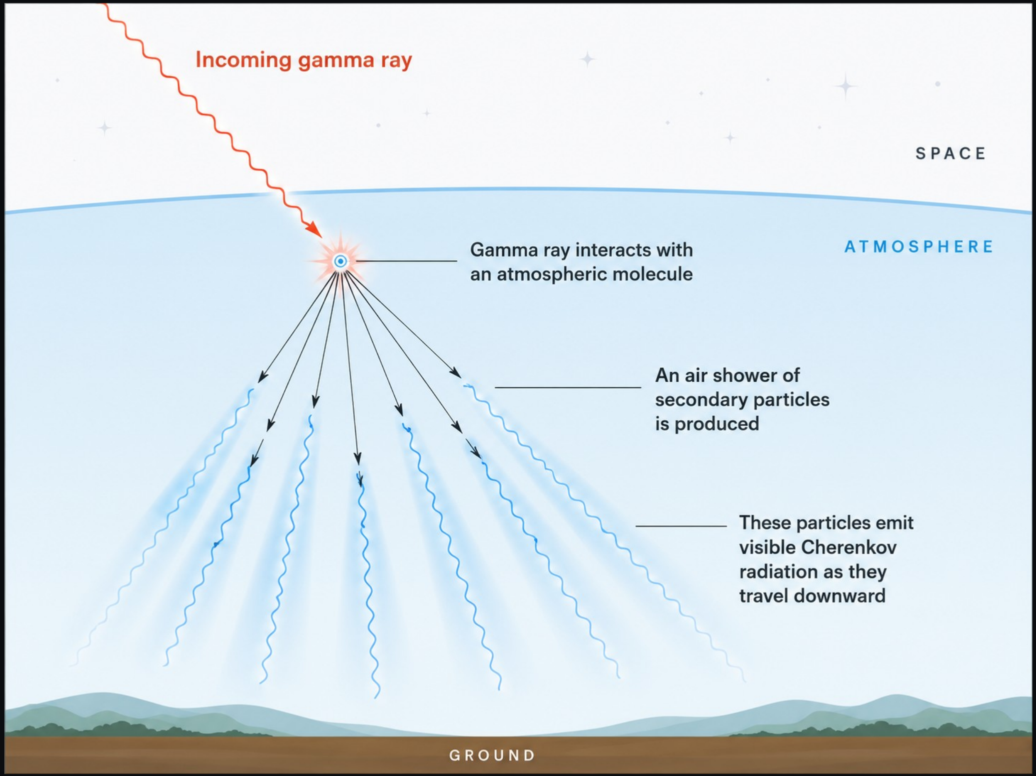


Smaller J, cleaner target

γ-rays point back to their sources, but the atmosphere block them

Targets can be selected

How do we detect them?



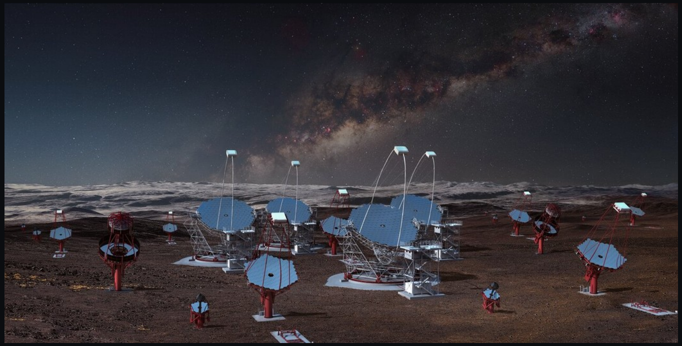
Gamma rays are observed in two complementary ways

Space telescopes

Detect photons directly
MeV-GeV energies

Ground telescopes

Detect air-showers
GeV-TeV energies



Several dwarf galaxies show γ-ray excesses with the same spectrum, but no corresponding excess is identified toward the Galactic Center. What is the most reasonable conclusion?

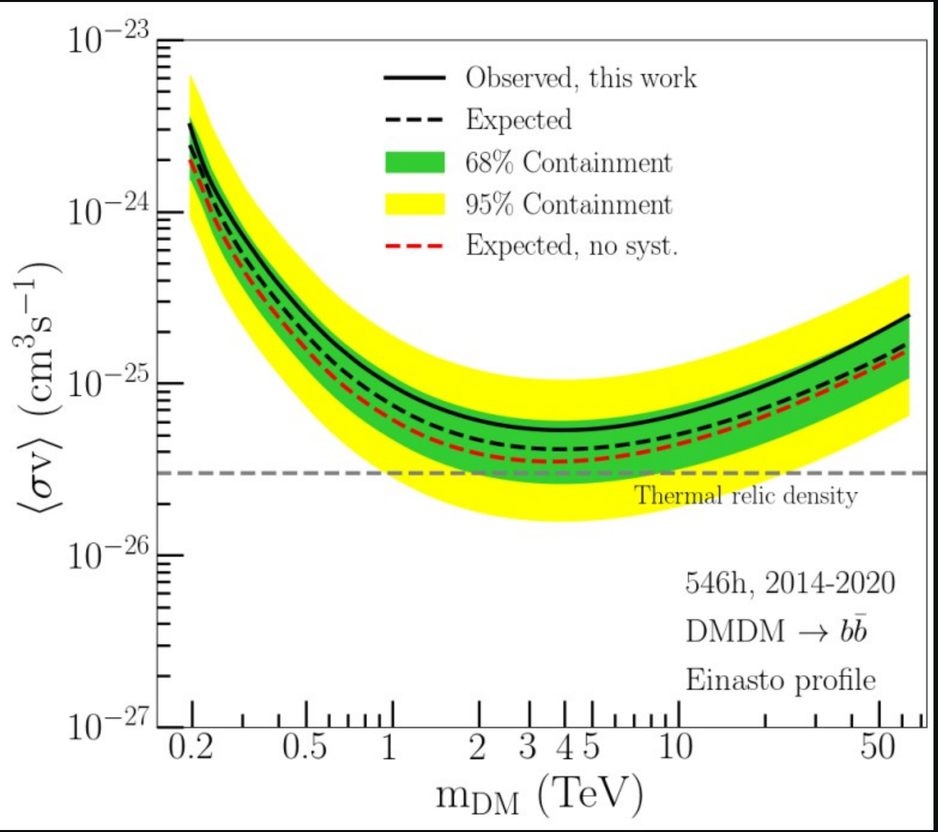
A. Dwarfs have larger J-factors than the GC
B. Dark matter cannot explain the excesses
C. The excesses confirm dark matter
D. The GC signal may be hidden by backgrounds
E. The GC contains too little dark matter

Gamma-ray limits constrain the DM annihilation cross section

One annihilation channel at a time

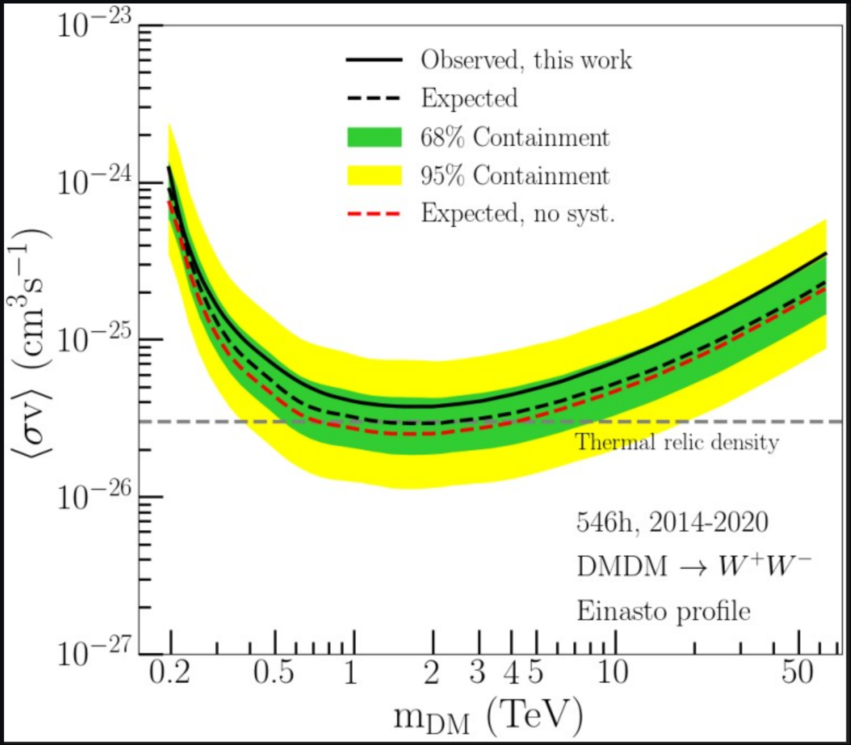
A halo profile is assumed

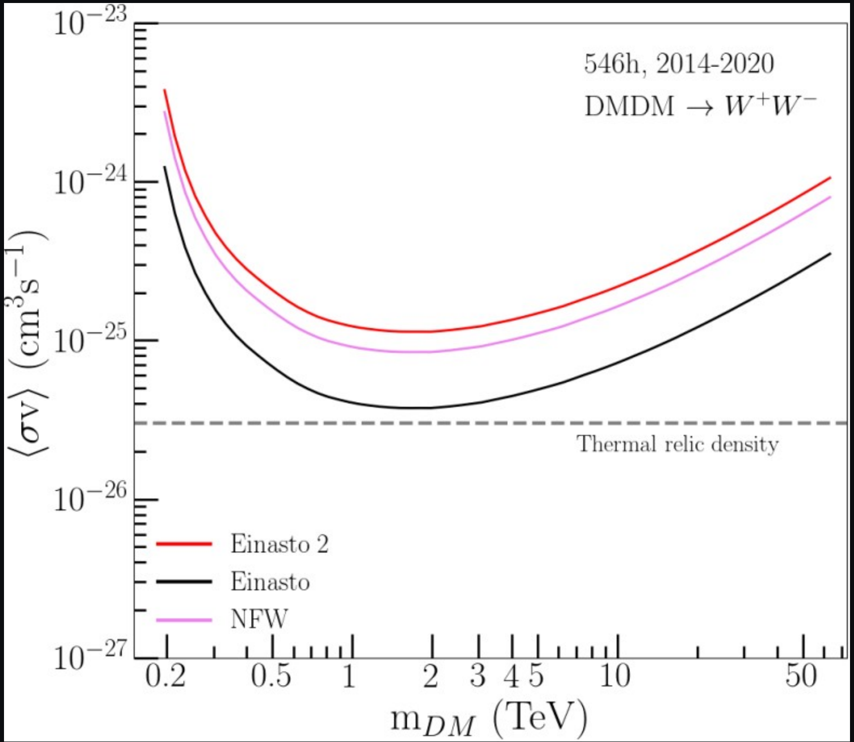
Above the curve is excluded



Galactic Center, H.E.S.S., 2022

Gamma-ray limits depend on the annihilation channel and halo profile



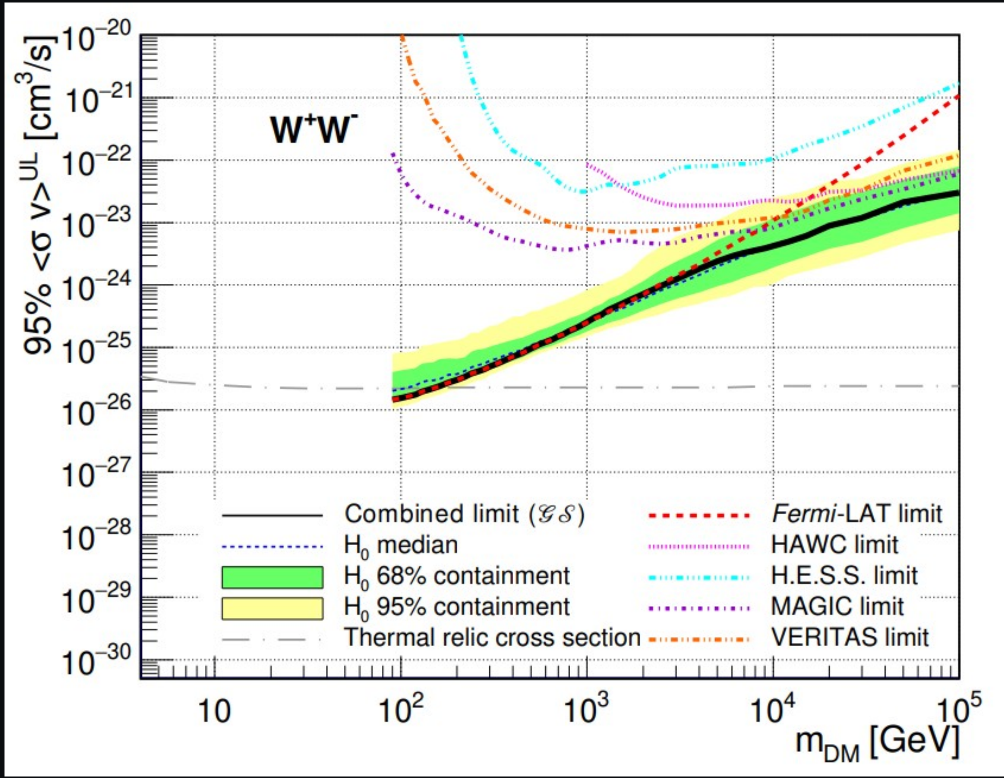


Different channel **Different halo profiles**

Dwarf spheroidals are clean targets for combined gamma-ray searches

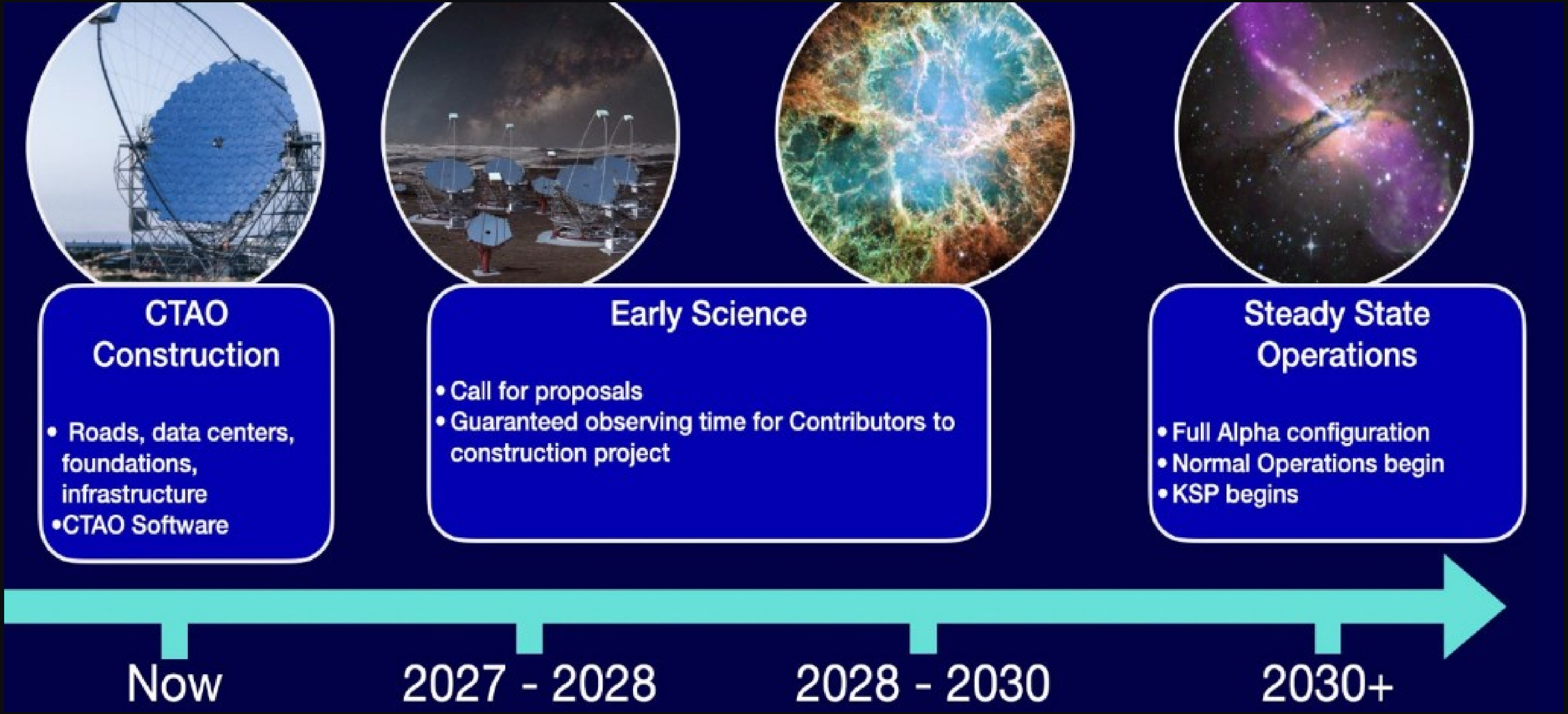
Low masses: Fermi-LAT dominates

High masses: ground observatories take over



The combined limit is stronger than individual ones

CTAO will be the next major step for gamma-ray dark matter searches

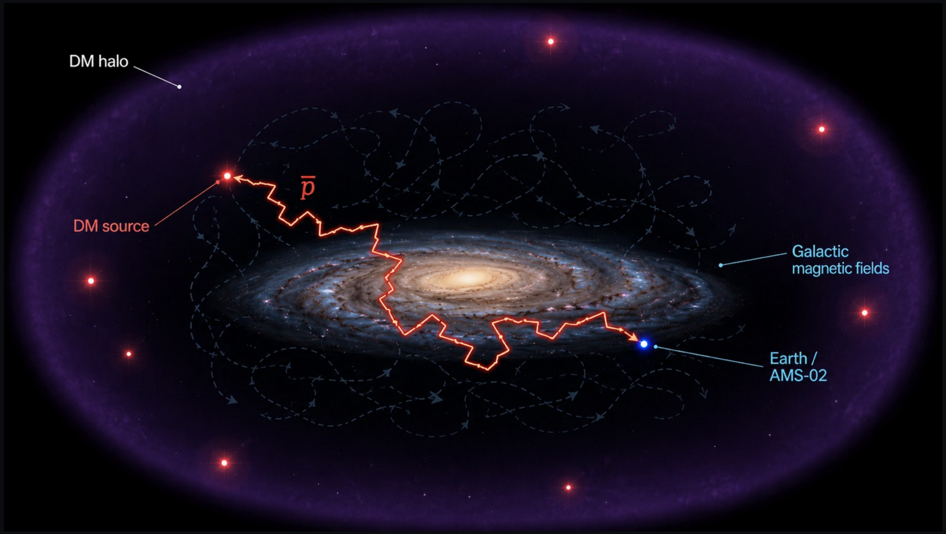


Its improved sensitivity is an opportunity for dark matter discovery

Antiproton limits depend strongly on Galactic propagation

Antiprotons do not point back to their source

Space or balloon detectors: AMS-02, PAMELA, BESS



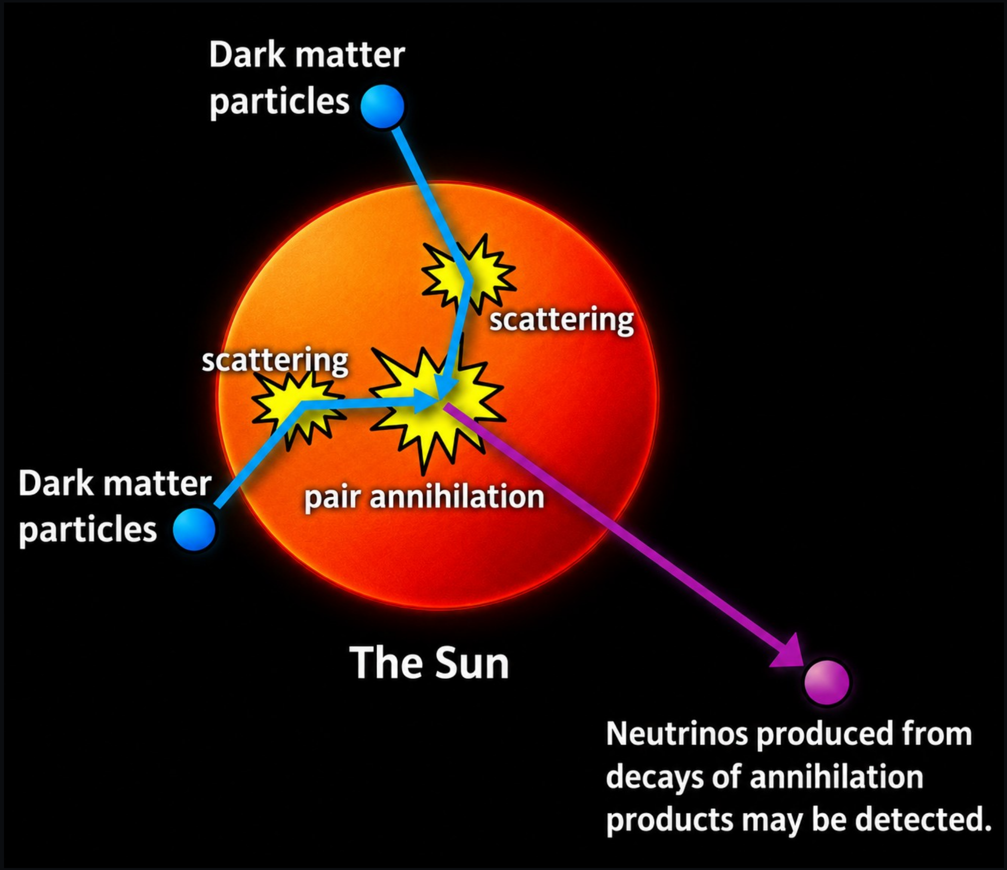
The measured spectrum is propagation-dependent

Neutrino telescopes search for dark matter captured in the Sun

DM scatters in the Sun

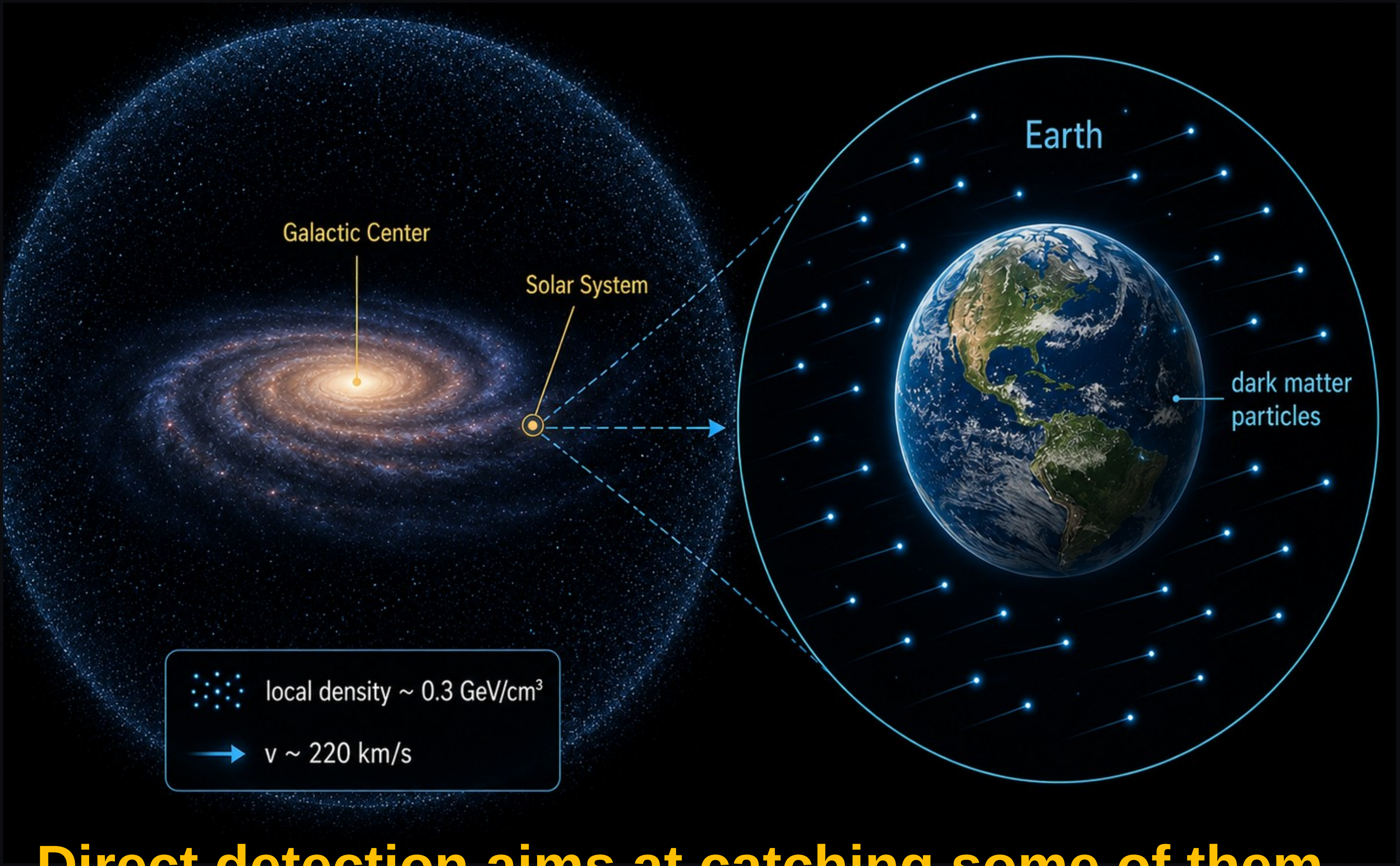
Captured DM annihilates

Only neutrinos can escape



Direct detection

Dark matter particles are all around us



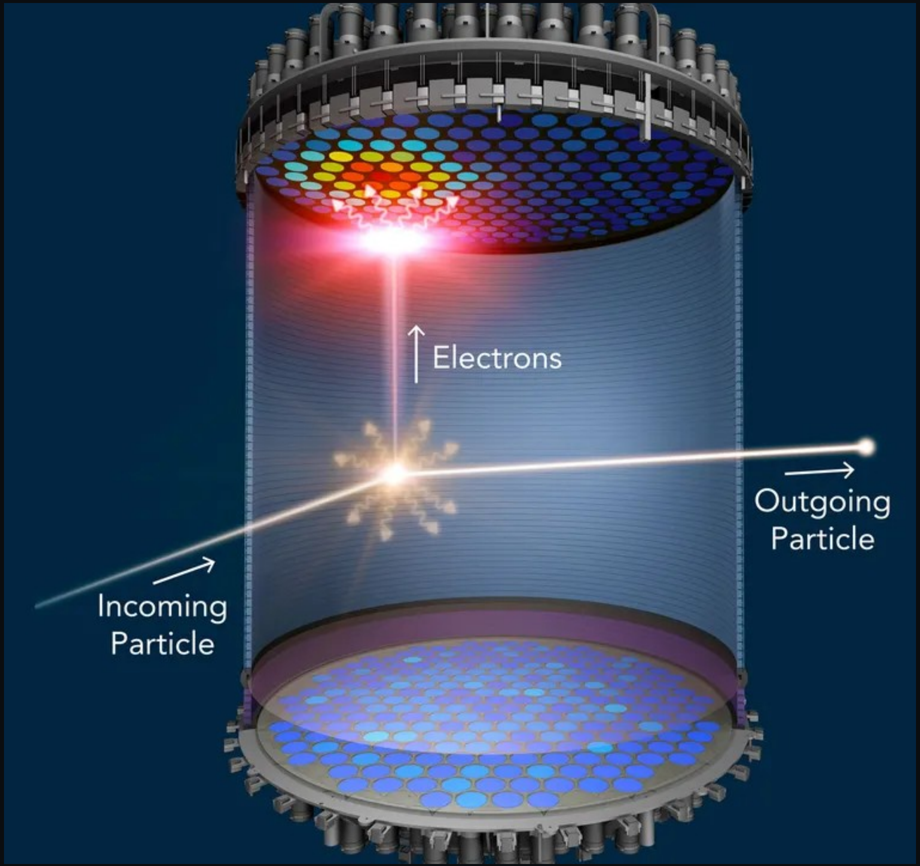
Direct detection aims at catching some of them

Direct detection looks for tiny nuclear recoils in underground detectors

A rare $\chi + N \rightarrow \chi + N$ event

Tiny nuclear recoil: $E_R \sim$ keV

Deep underground: low backgrounds



The recoil spectrum carries information about dark matter properties

$$\frac{dR}{dE_R} = \frac{\rho_0}{m_\chi m_N} \int_{v > v_{\min}(E_R)} \mathrm{d}^3 v \; v \; f(\mathbf{v}, t) \, \frac{\mathrm{d}\sigma_{\chi N}}{dE_R}(v, E_R)$$

Astrophysics

ρ_0, $f(v,t)$

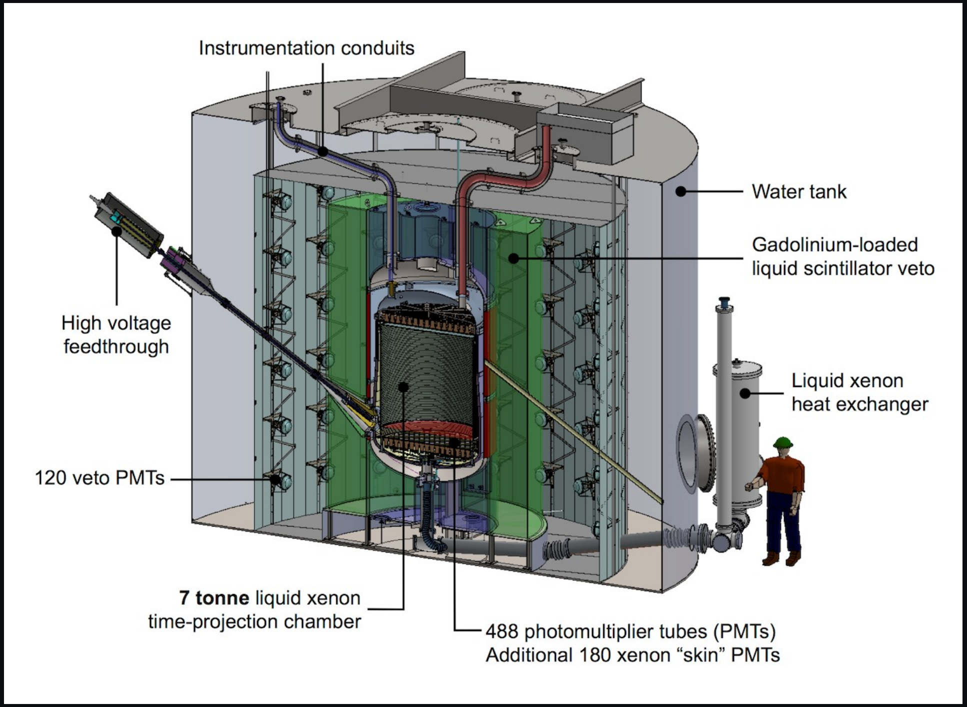
Detector

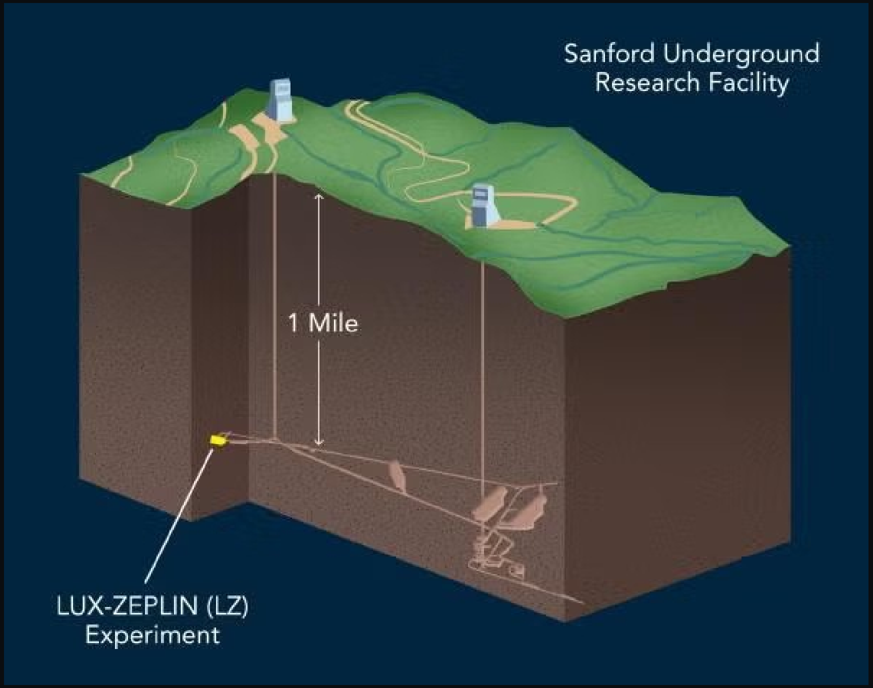
m_N, E_R

Dark matter

m_χ, $\sigma_{\chi N}$

LZ currently sets the most stringent WIMP-nucleon scattering limits





7-ton Xenon target

Deep underground

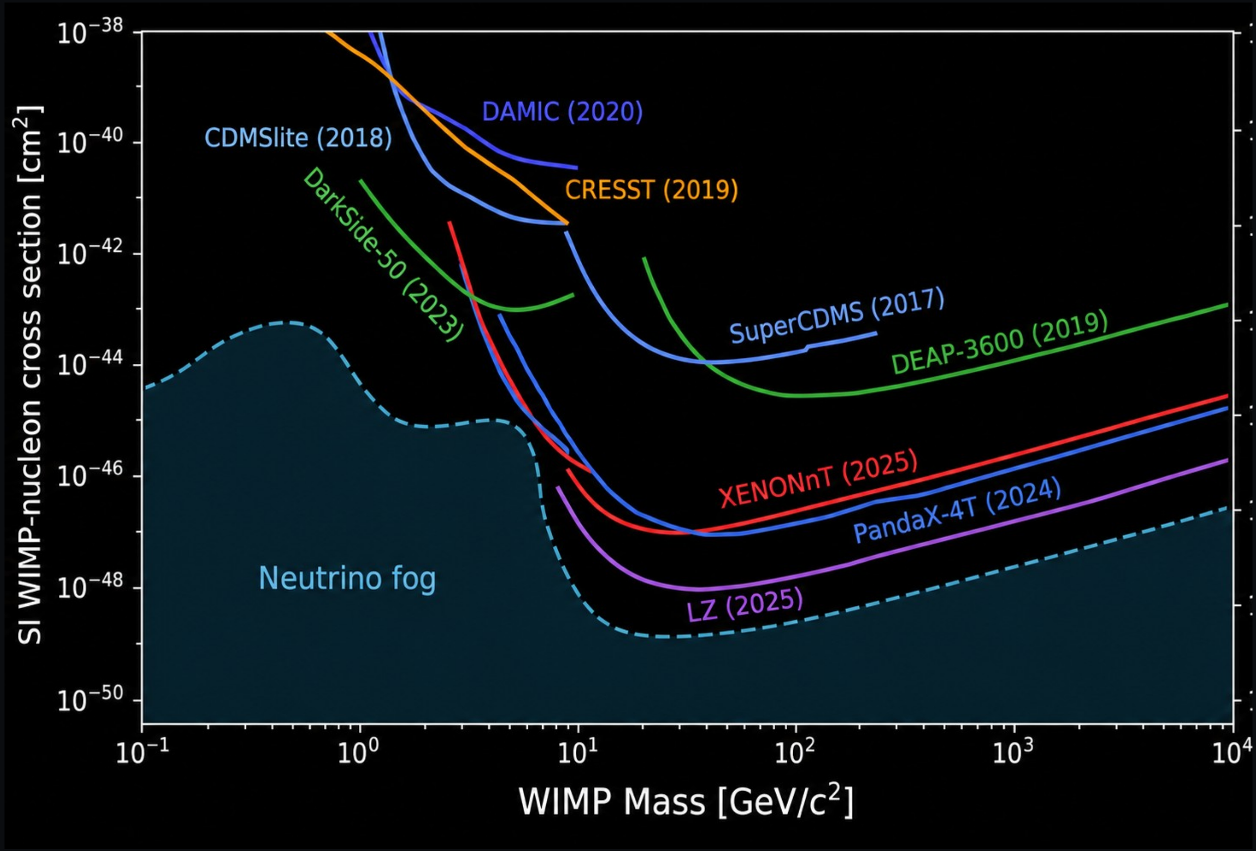
Direct detection limits have improved significantly over the past decades

Larger exposures

Lower backgrounds

New technologies

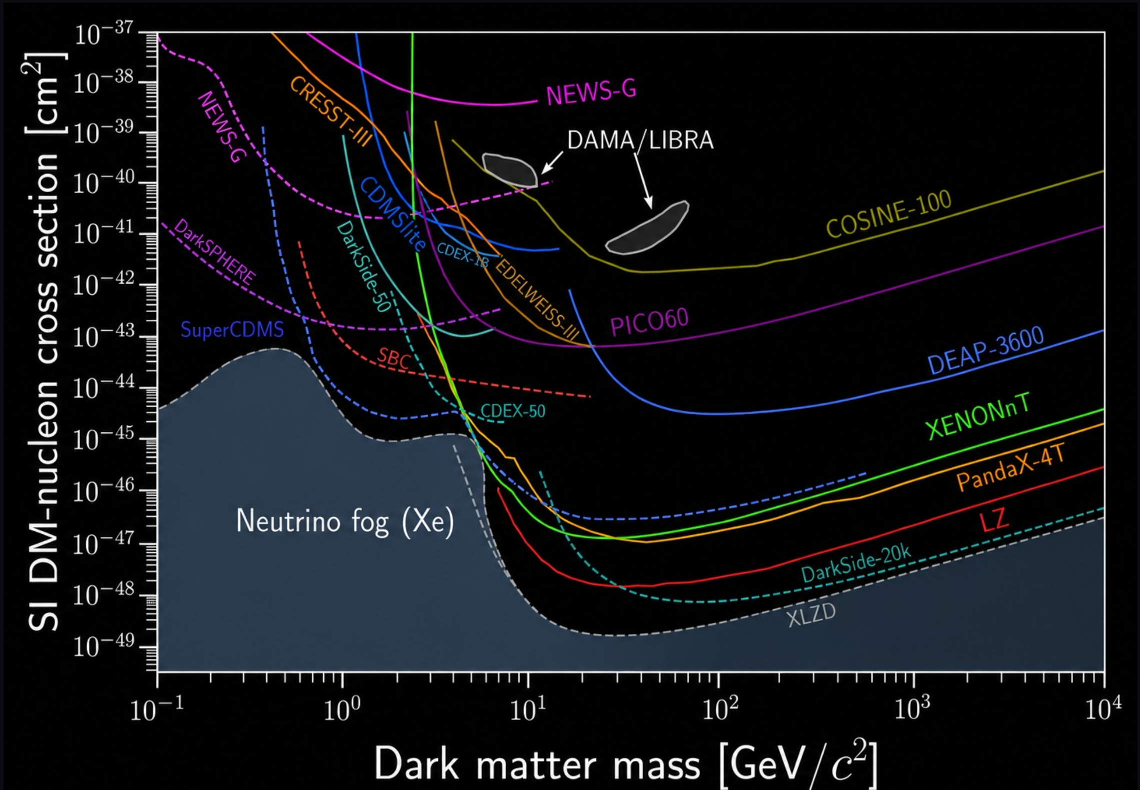
Lower thresholds



Future experiments will probe even smaller cross sections

Larger Xe and Ar detectors

Lower-threshold experiments



There is still room for discovery

Today we answered the following questions

1. In what ways can dark matter be detected?

2. Which signals do dark matter searches look for?

3. What determines the sensitivity of a DM experiment?

4. Which kinds of experiments are searching for DM?

5. What can DM searches teach us about its fundamental properties?