The Physics of Dark Matter

Theory and Phenomenology

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Theoretical High Energy
Physics & Astrophysics

TCAP Preworkshop, NARIT

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Theoretical High Energy Physics & Astrophysics

Outline

What is Dark Matter?

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Dark matter

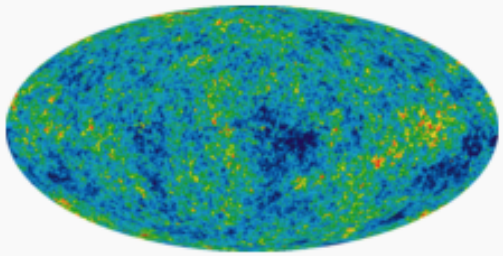
From Wikipedia, the free encyclopedia

Not to be confused with antimatter, dark energy, dark fluid, or dark flow. For other uses, see Dark Matter (disambiguation).

Dark matter is a hypothetical type of matter distinct from ordinary matter such as protons, neutrons, electrons, and neutrinos.

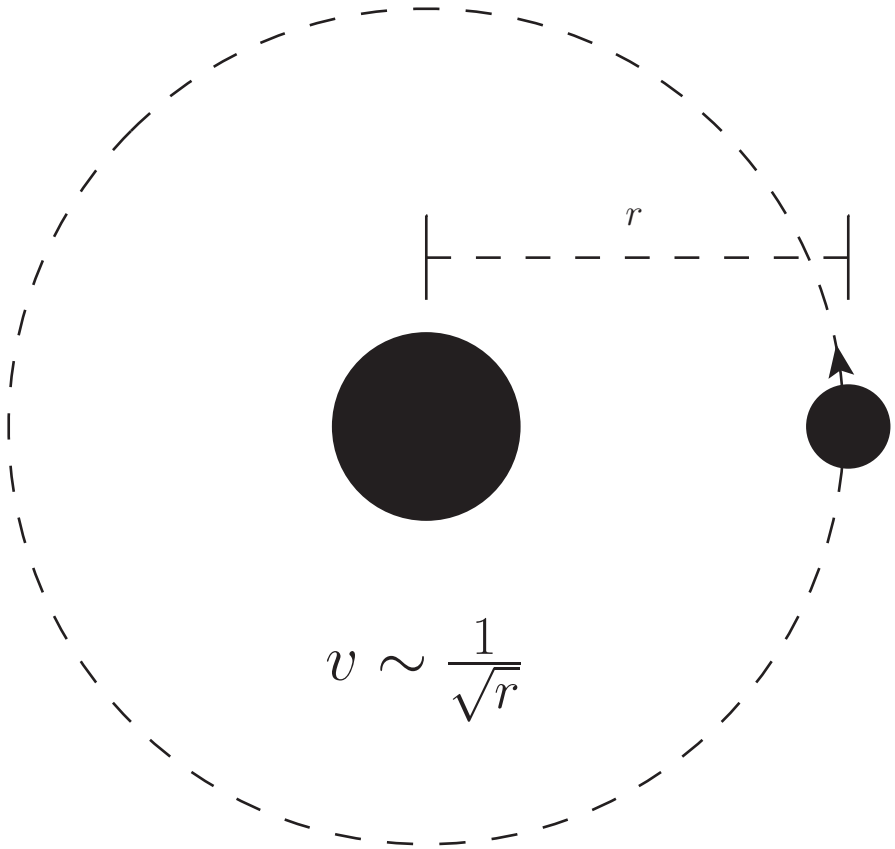
Dark matter has never been directly observed; however, its existence would explain a number of otherwise puzzling astronomical observations.[1][2] The name refers to the fact that it does not emit or interact with observable electromagnetic radiation, such as light, and is thus invisible to the entire electromagnetic spectrum.[3]

Part of a series on
Physical cosmology



Big Bang · Universe
Age of the universe
Chronology of the universe

Orbital Velocity: Warm Up



Apply this to a star orbiting a galaxy.

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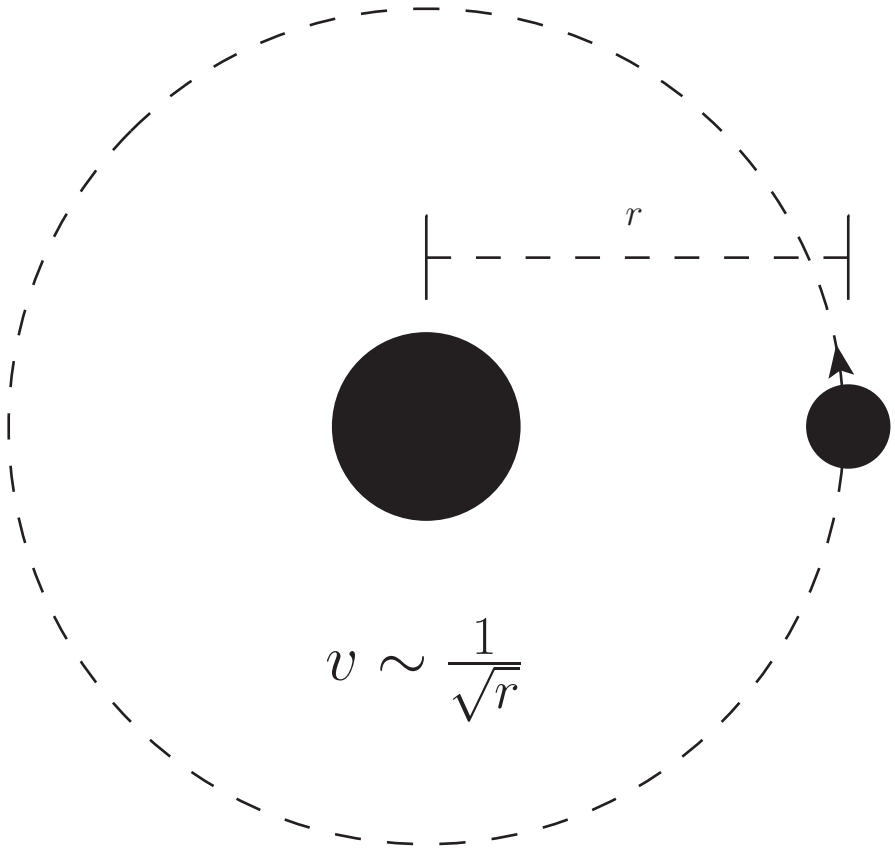

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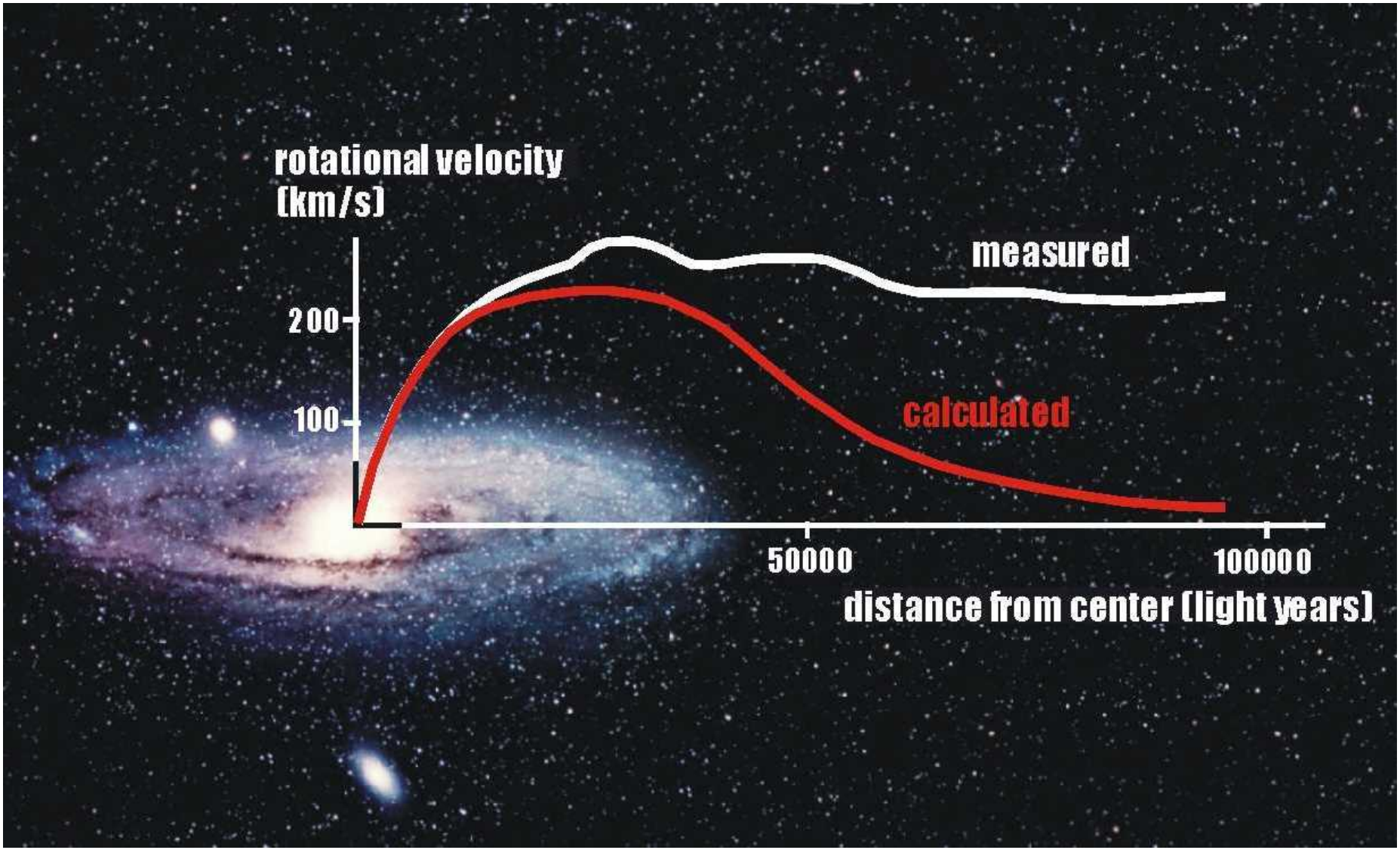
Orbital Velocity: Real Galaxy



The Rotational Curve Resolutions

There are 2 options:

1. Gravity behave differently at large distance. (Modified gravity)

2. The galaxy must contains more mass than we can see. (Dark matter)

As you can guess from the title, we'll take option #2!

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Theoretical High Energy Physics & Astrophysics

Why Dark Matter (I)?

Theoretical High Energy Physics & Astrophysics

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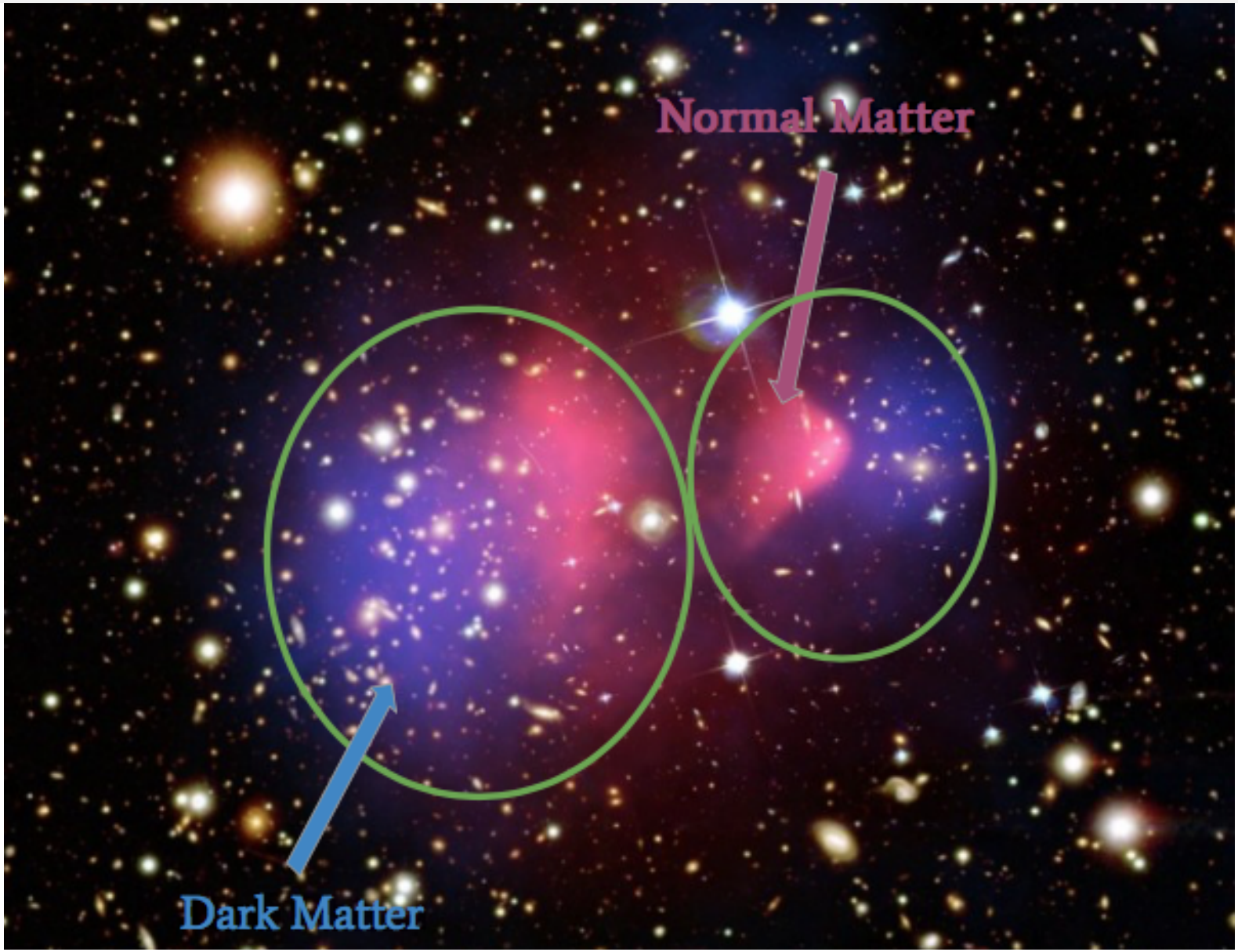
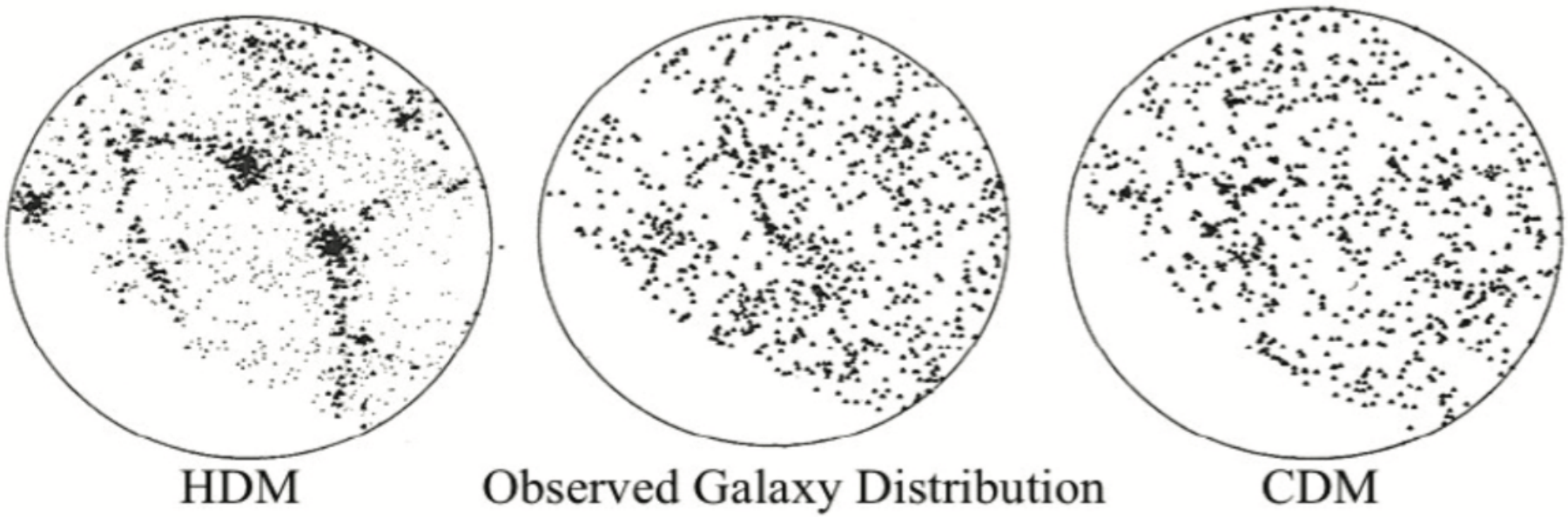


Why Dark Matter (II)?



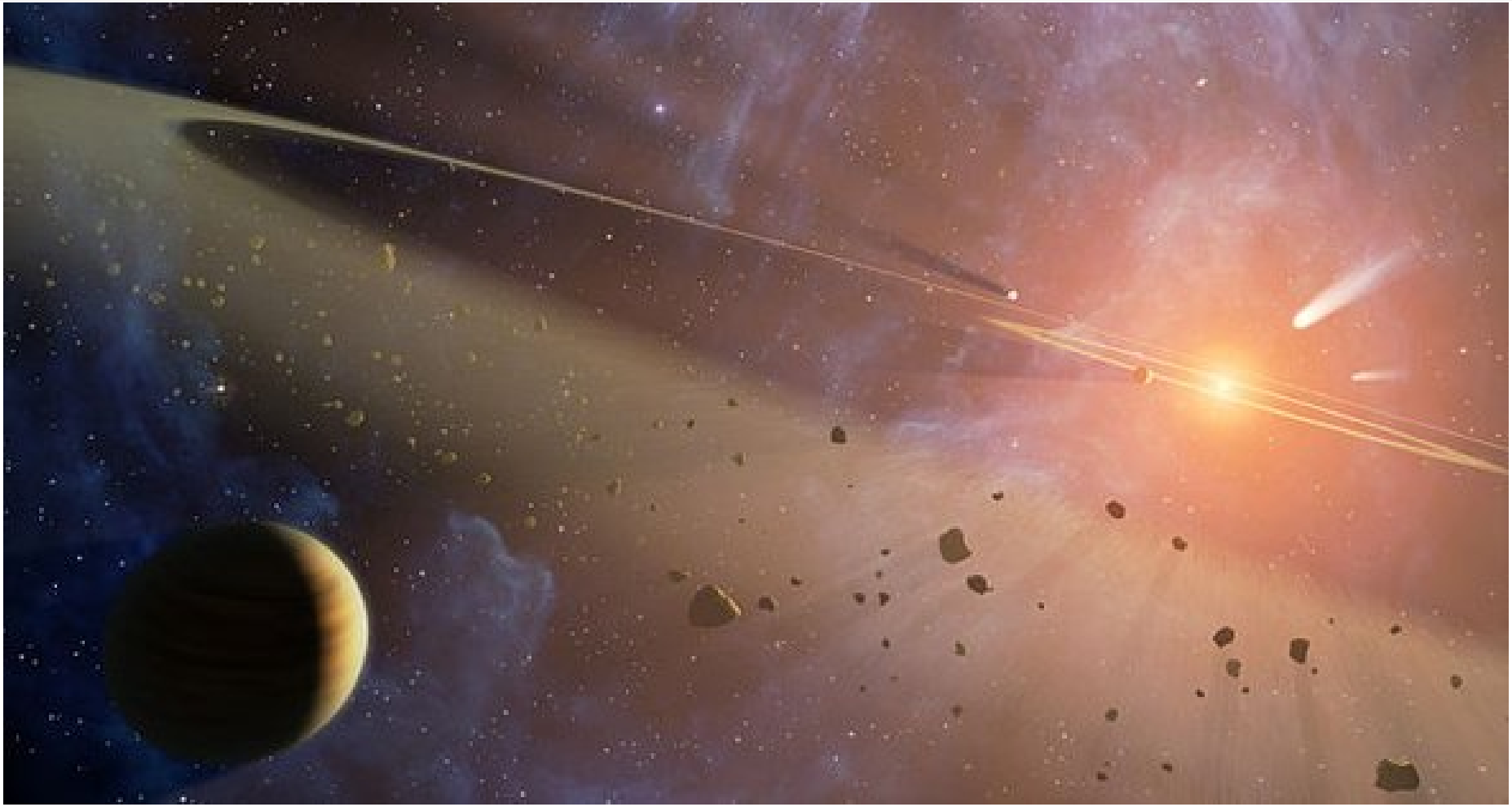
[Kolb et al '86]

- At the end of inflation, DM provided gravitational pull so that matter can clump.
- Simulation favors non-relativistic dark matter.

Theoretical High Energy Physics & Astrophysics

Dark Matter Could Potentially Explain a Long Standing Mystery!!!

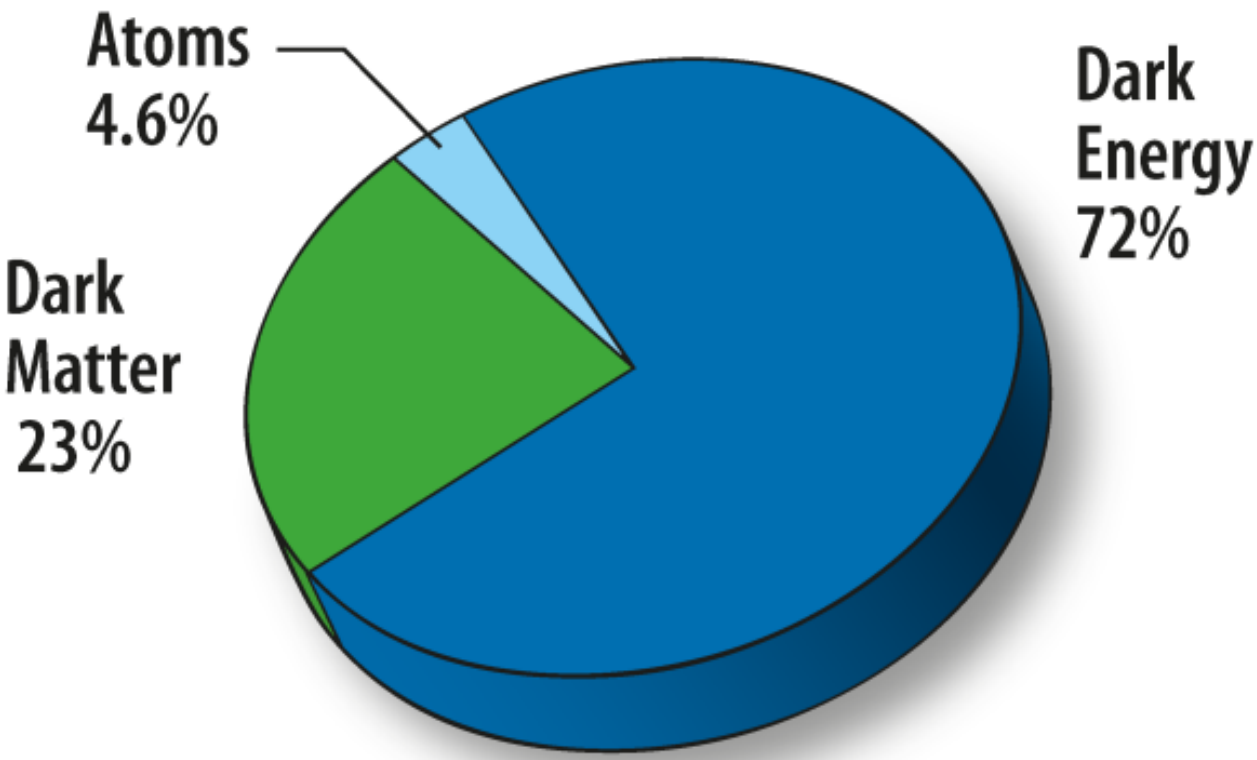
What Kill Dinosaurs?



DM triggers periodic commet impacts [Randall & Reece '14]

Image credit: NASA/JPL-Caltech

The Universe Today



Dark matter accounts for $\gtrsim 80\%$ of the mass of the universe.

Image credit: NASA/WMAP Science Team

Theoretical High Energy Physics & Astrophysics

Outline

Properties of Dark Matter

- Massive (duh).
- Does not interact electromagnetically (electrically neutral particle).
- Stable.

Possible properties:

- Interact weakly with regular matters.
- Some could interact strongly among themselves.

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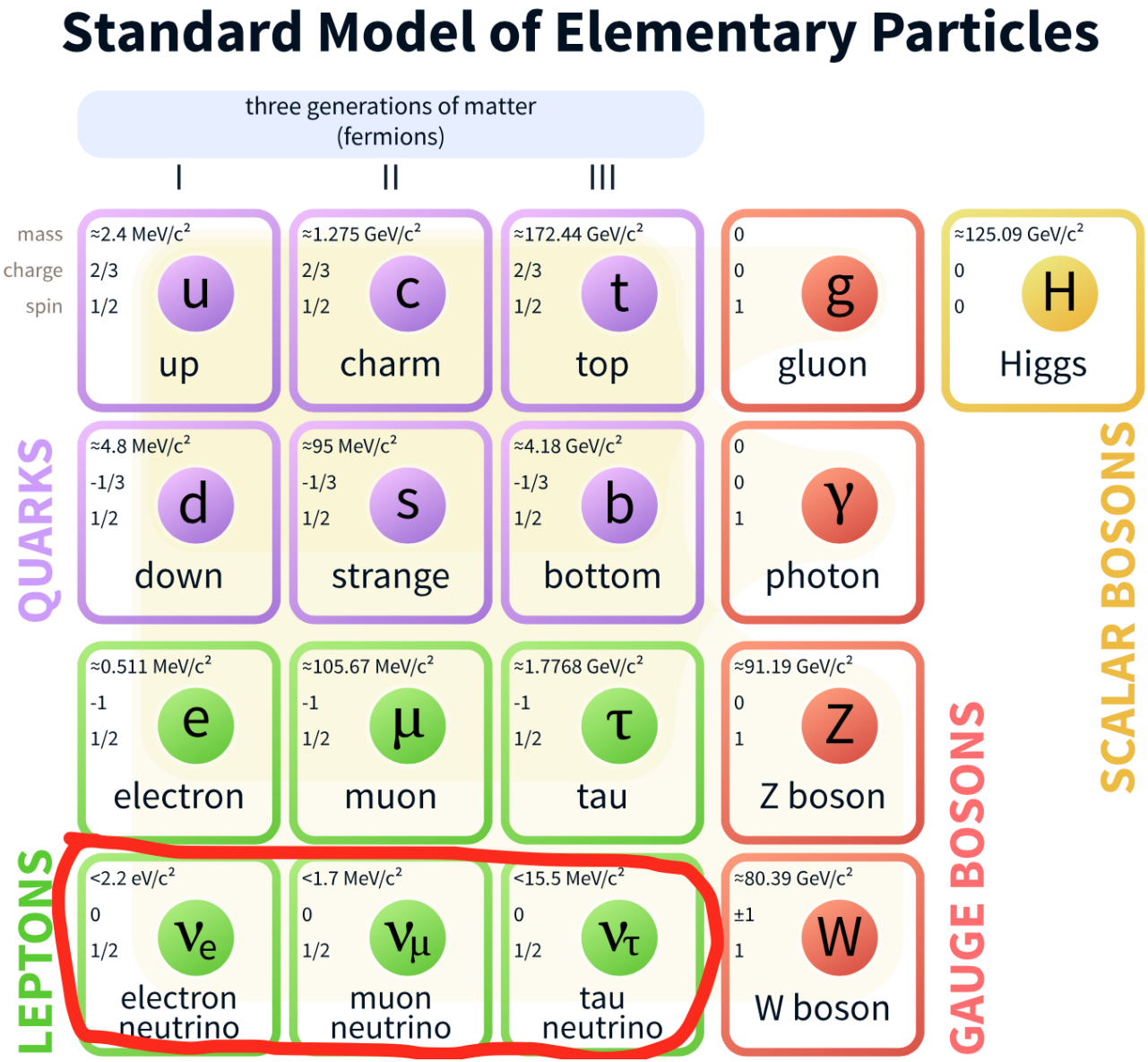
Regular Matters



Dark Matter = New Physics

Zoo of Dark Matter Candidates

A (well) motivated new physics scenario usually contains dark matter (incomplete list).

- Sterile neutrino $\Leftrightarrow$ neutrino mass generation.
- Supersymmetric particle $\Leftrightarrow$ the hierarchy problem.
- Axion $\Leftrightarrow$ the strong CP problem.
- Kaluza-Klein particle $\Leftrightarrow$ extra-dimension.
- Dark photon $\Leftrightarrow$ the fifth force.
- ...

We will not be worried about a specific scenario.

A Unified Approach

Working assumptions

- Stable particle.
  - Scalar (spin-0): Axion, ...
  - Fermion (spin-1/2): SUSY, KK, ...
  - Vector (spin-1): Dark photon, ...
- Interacts weakly (and non-gravitationally) with SM.
  - Typically involve 2 DM and 2 SM particles.

WIMP Paradigm.

We can probe their properties!

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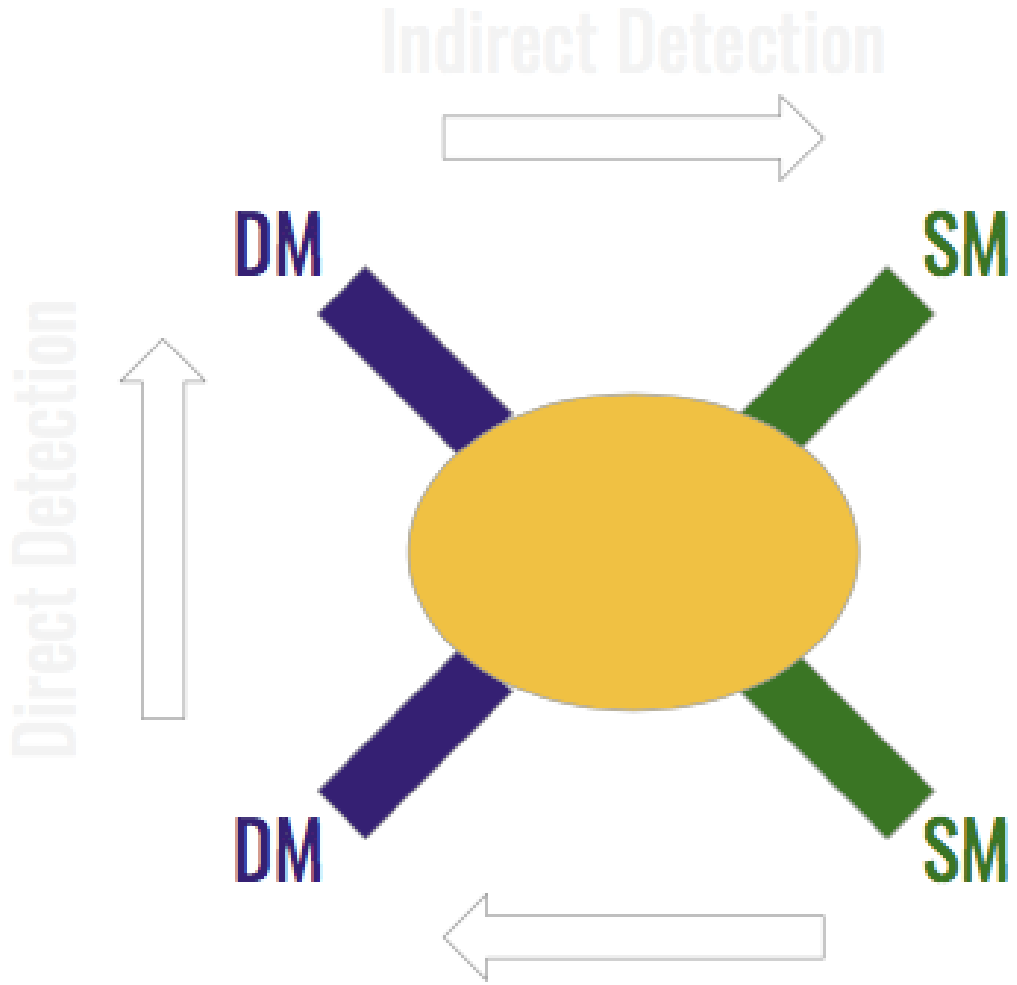
Dark Matter Phenomenology in a Nutshell



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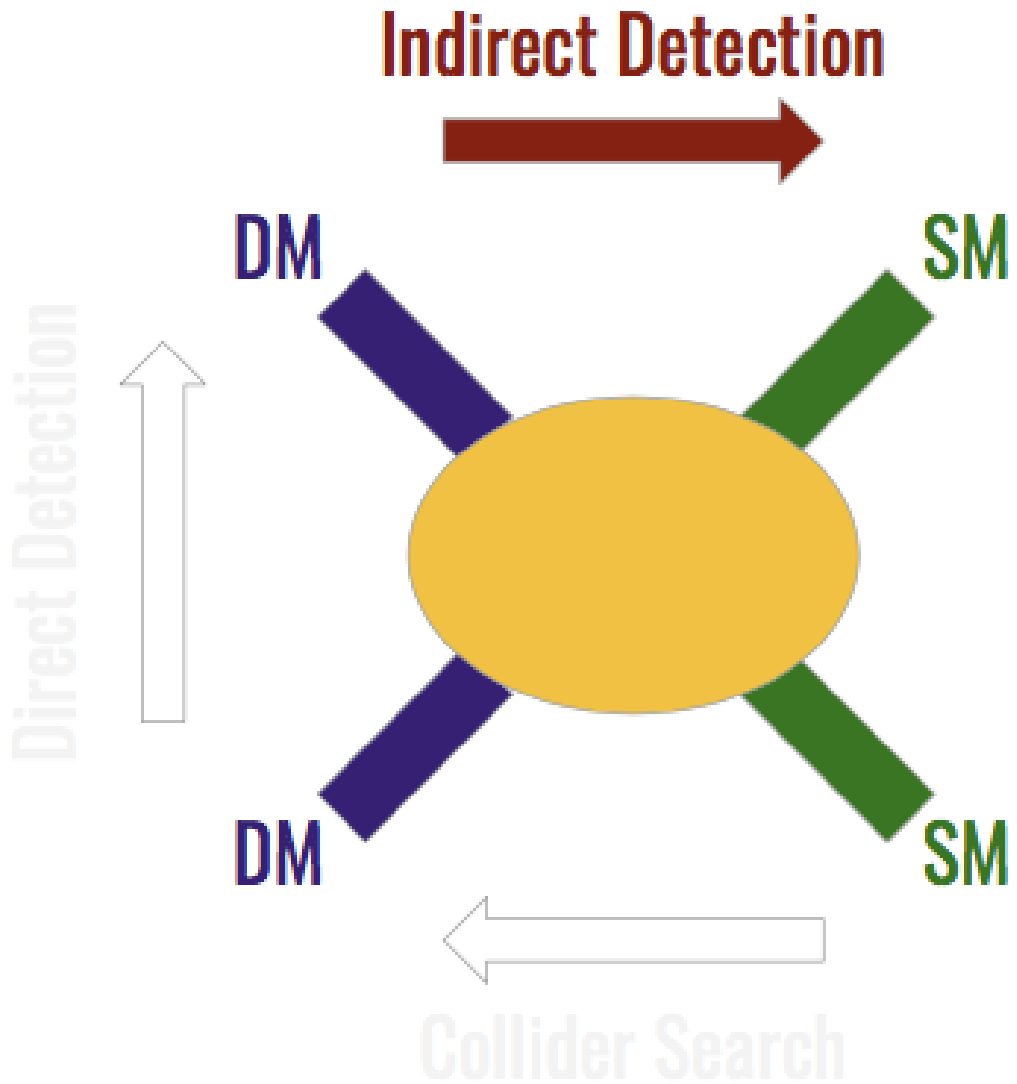

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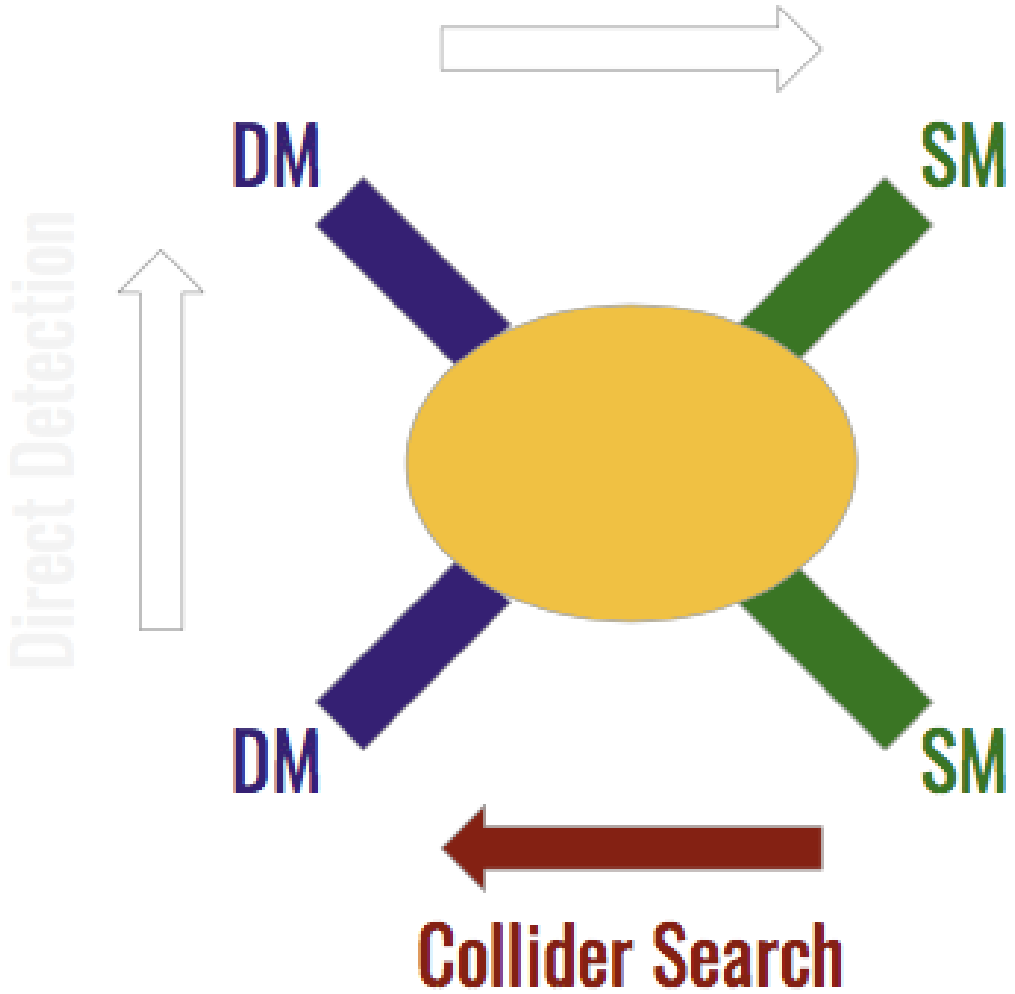

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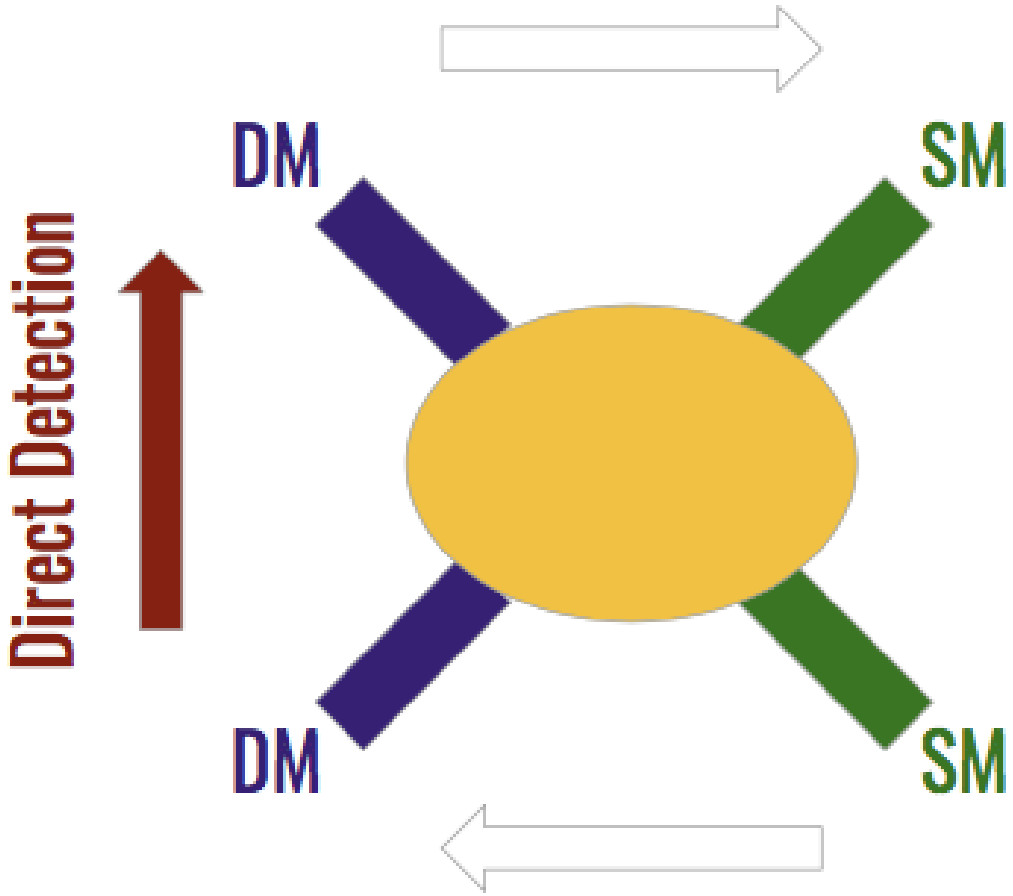
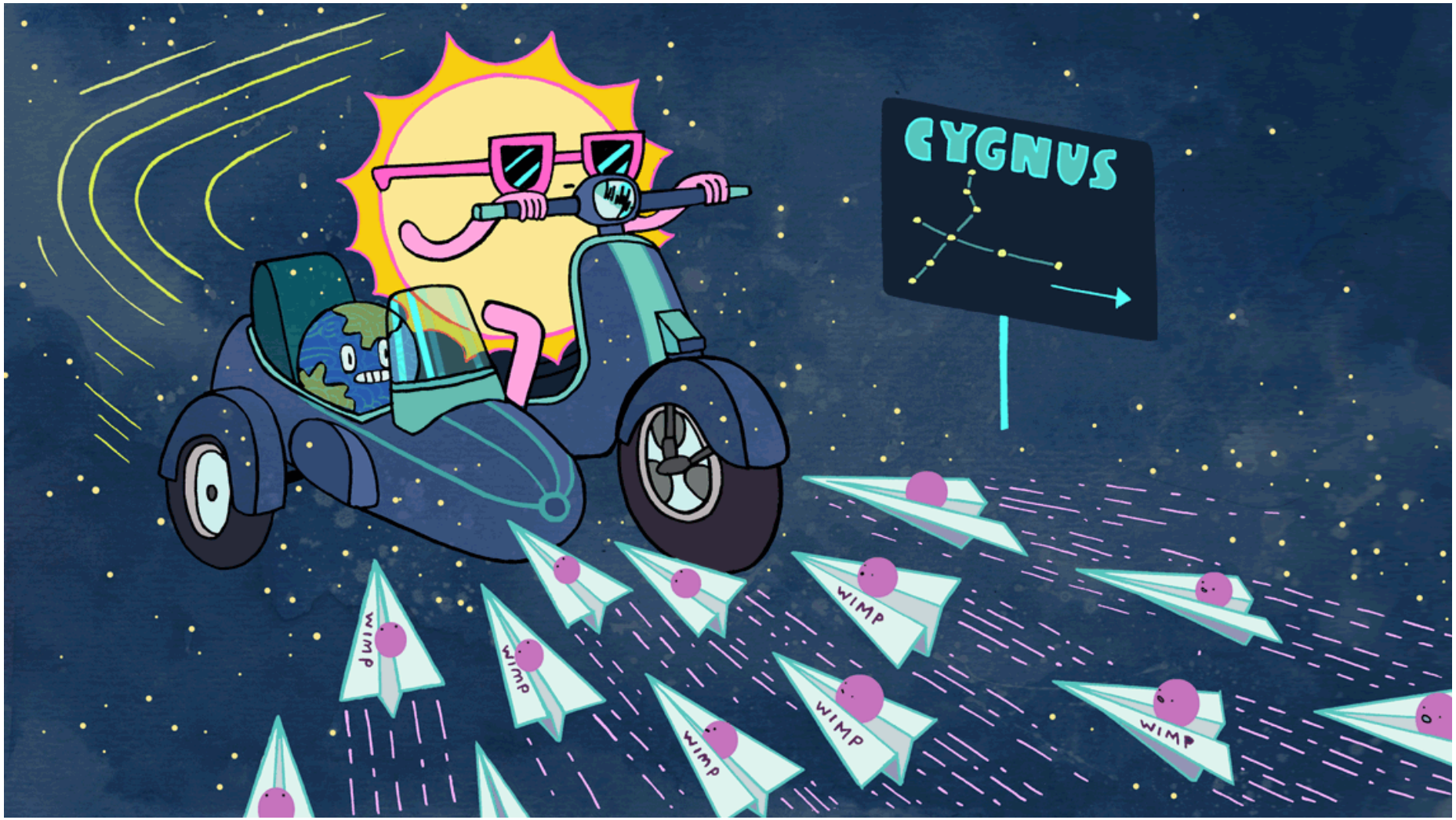


Theoretical High Energy Physics & Astrophysics

The Earth is being bombarded with DM



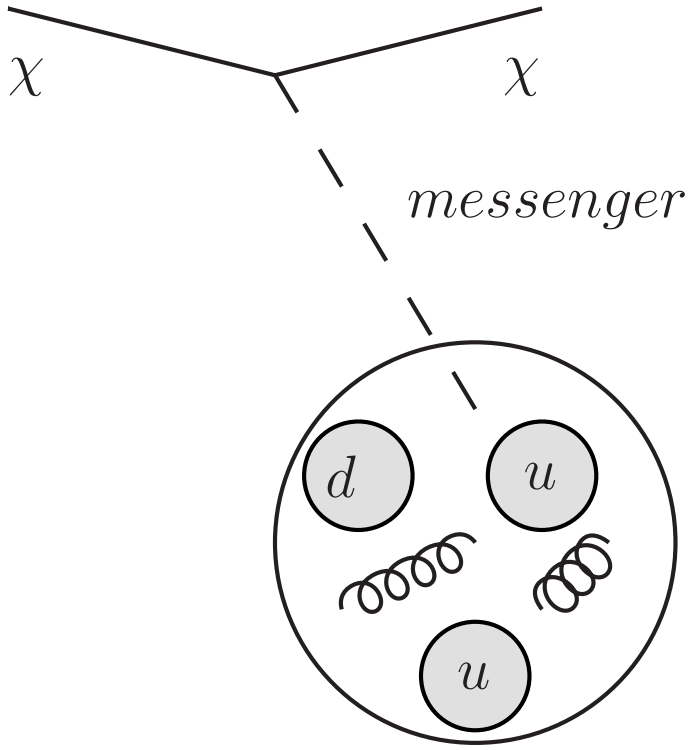
Cr: Corinne Mucha, Sandbox Studio Chicago

Direct Detection of DM

Sit and wait for DM to come interacts with the detector.
Signal is buried in SM background!

2 Different Approaches:

- Zero background
  - CDMS, LUX, XENON, ...
  - Absolute number of events.
  - Current status: negative.
- Anual modulation
  - CRESST, COGENT, DAMA, ...
  - Relative number of events.
  - Current status: positive.



Data $\Longrightarrow$ DM-nucleon cross-section

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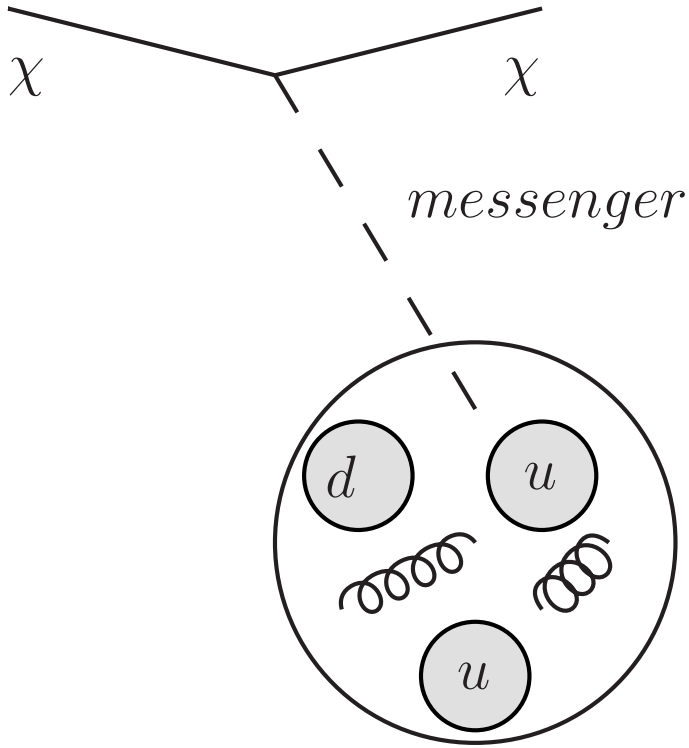

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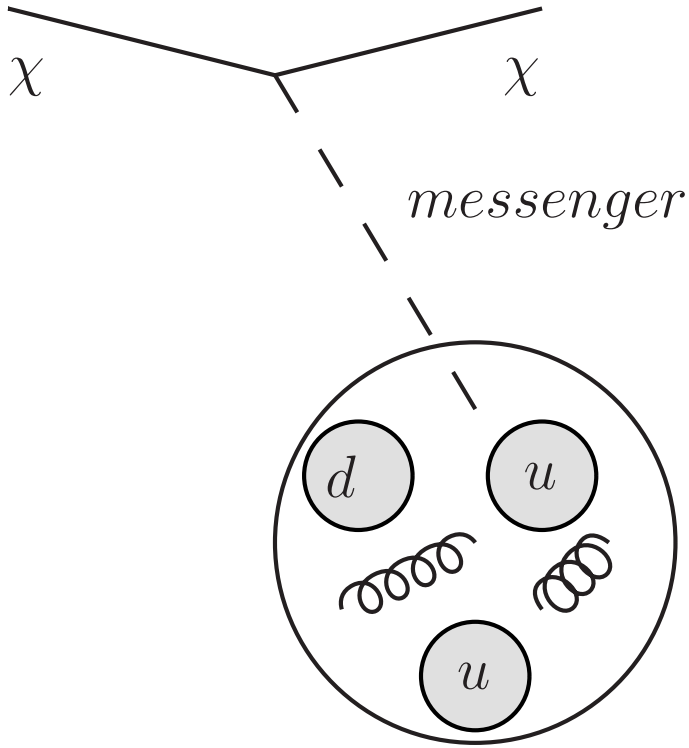

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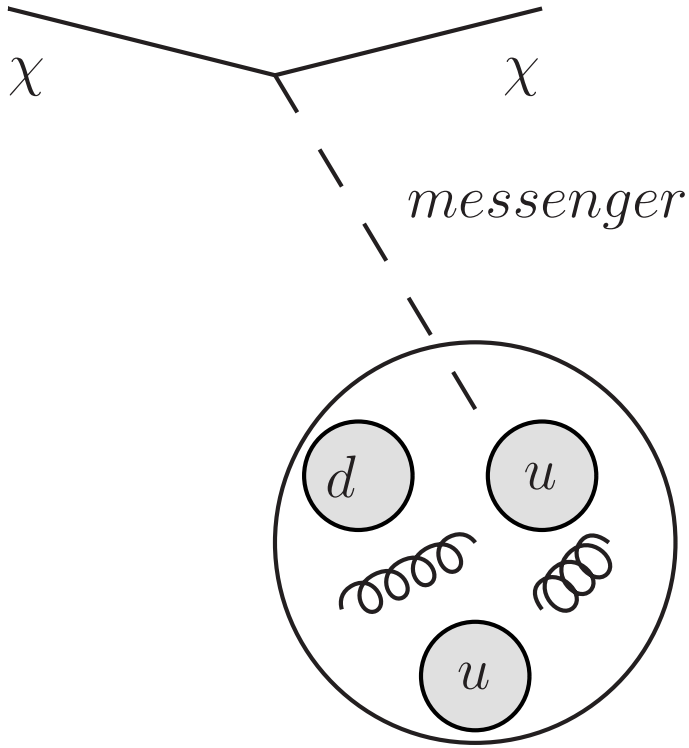

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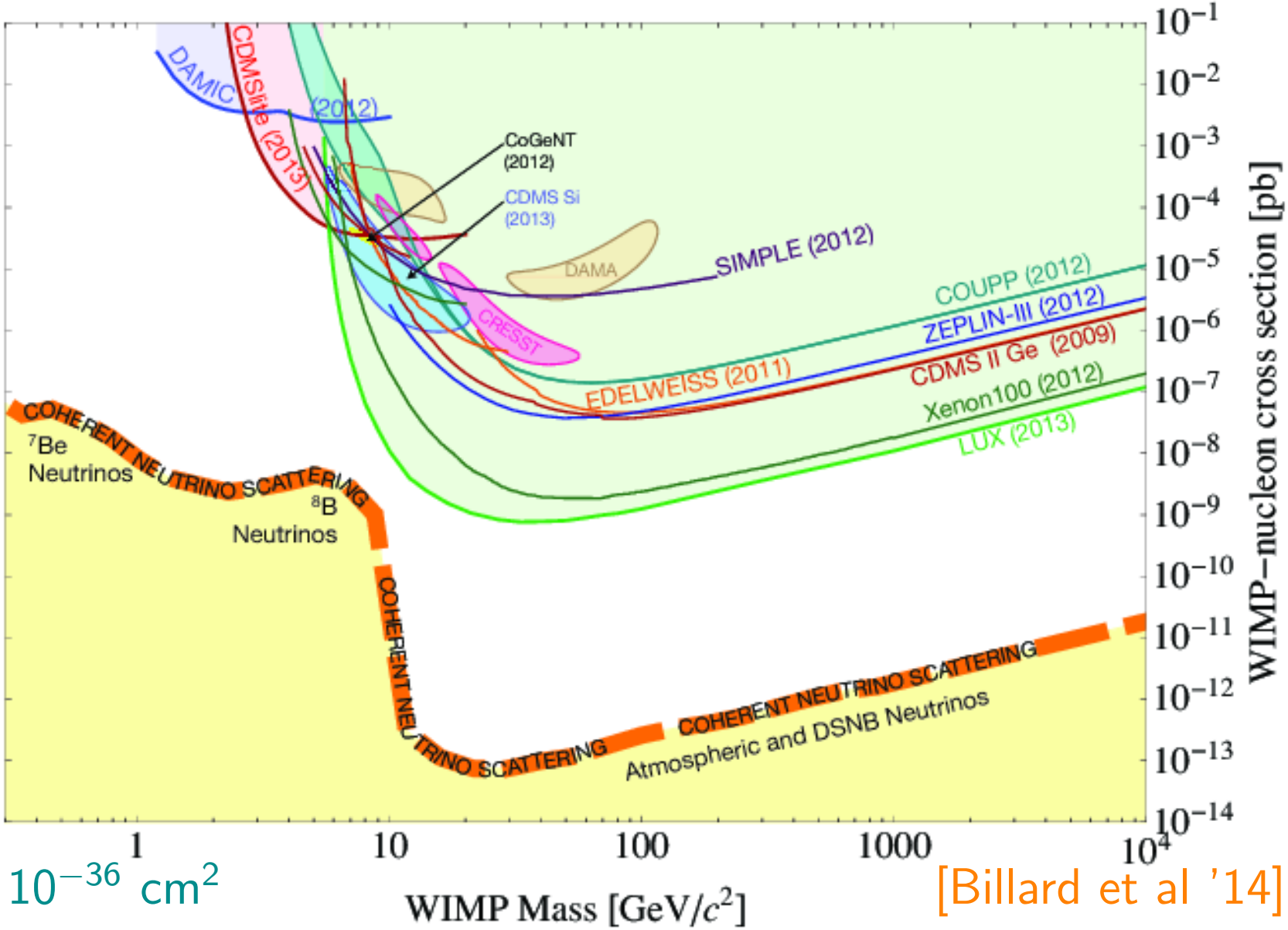
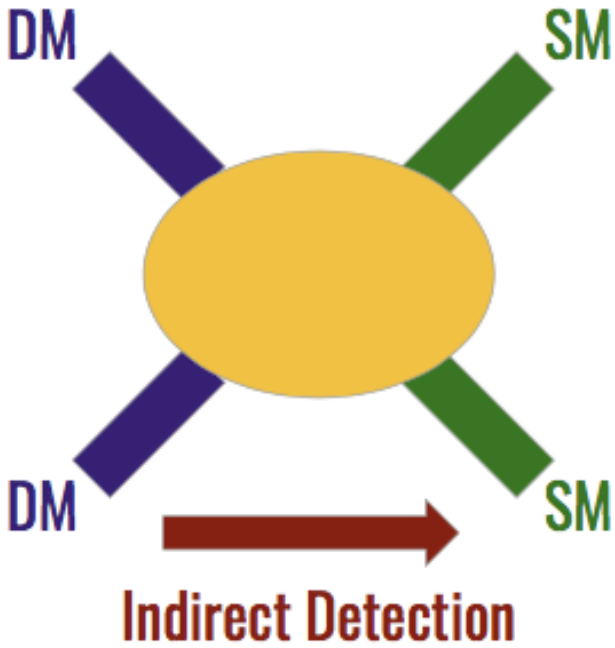
State of Direct Detection



1pb $= 10^{-36}$ cm^2

[Billard et al '14]

Essence of Indirect Detection



DM annihilate in space.

- SM particles (flux) reach Earth.
- Typical SM states: γ, $e^{\pm}$, ν, etc.

$$\frac{d\Phi}{dE\,d\Omega} = \frac{1}{4\pi}\frac{1}{2m_\chi^2} J \left[\langle \sigma v \rangle \frac{dN}{dE}\right].$$

Indirect Detection Experiment

γ, $e^{\pm}$ interact with the Earth's atmosphere, ν doesn't.

- Ground based telescopes:
  - Neutrino directly from DM annihilation: IceCUBE, Super(Hyper)K, KamLAND, etc.
  - γ from Cherenkov radiation: HESS, VERITAS, CTA etc.
- Space based telescopes:
  - γ: Fermi-LAT, DAMPE, etc.
  - $e^{\pm}$: PMELA, AMS, etc.

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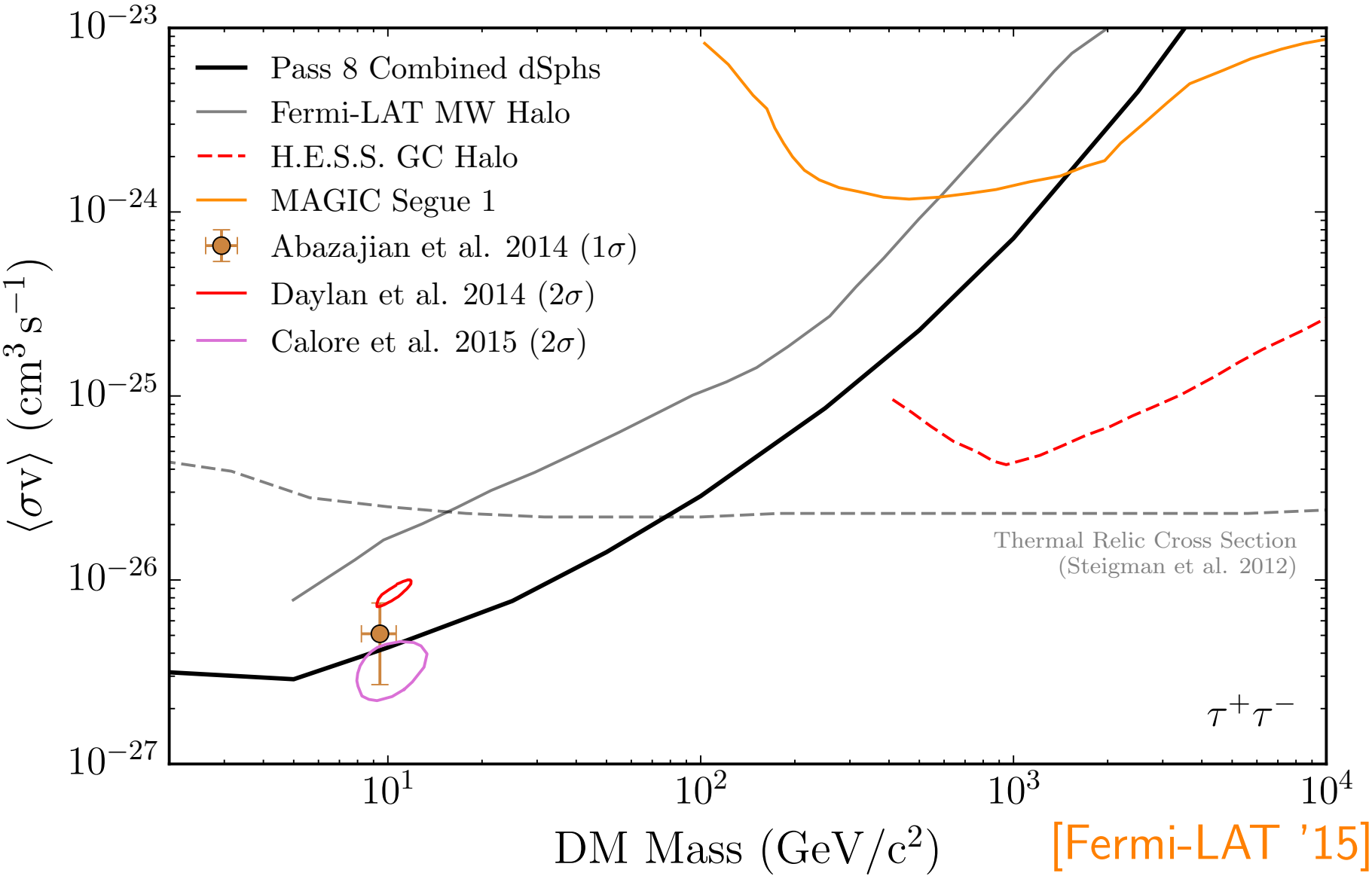
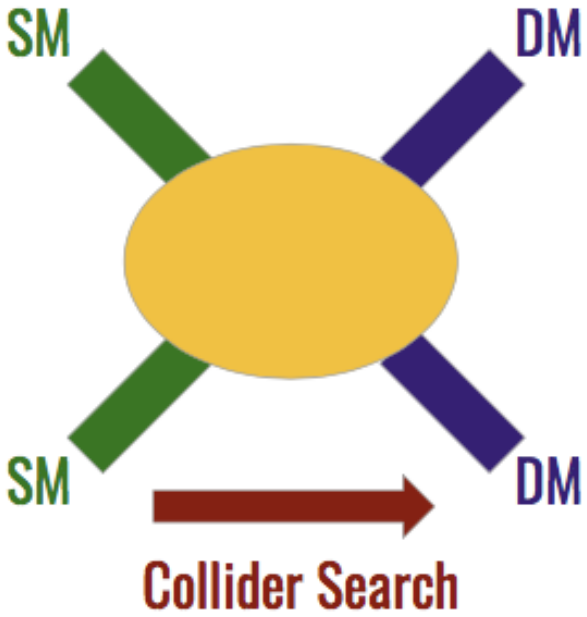
Indirect Detection Result, γ-channel



[Fermi-LAT '15]

Collider Search (naively)



Experimental procedures:

- Collide SM particles (pp, $p\bar{p}$, e^+e^-)
- Look for DM(s) that were created from the collision.

Drawback?

- DM does not interact with detector!

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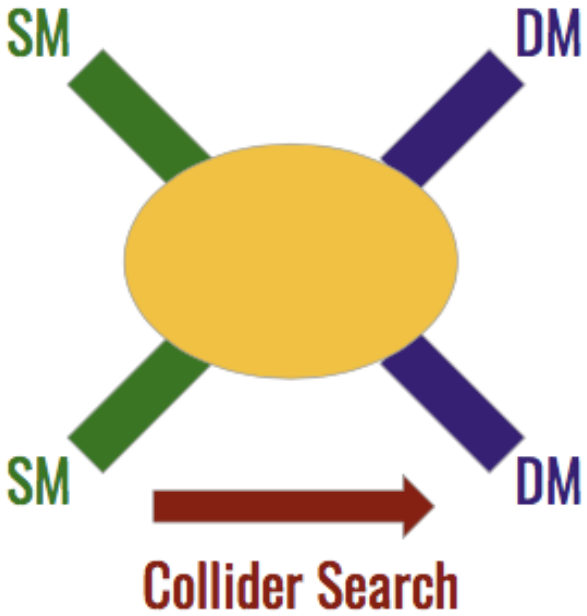

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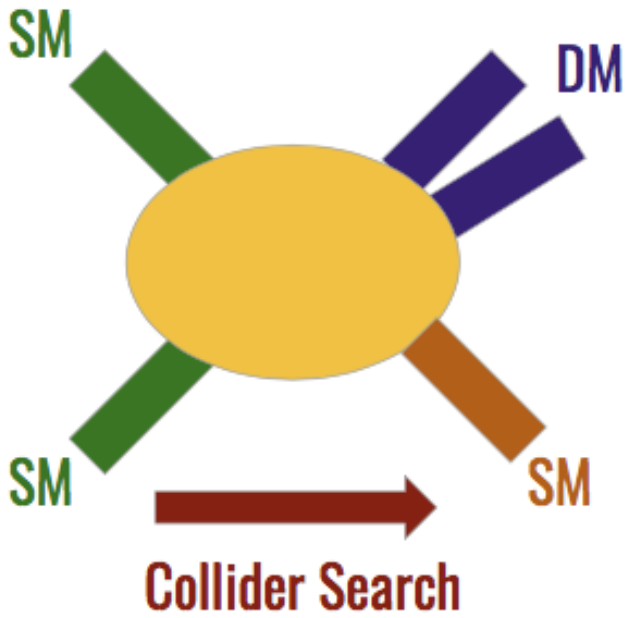

Need SM in the final state for DM to recoils against.

- Still cannot detect DM.
- But now they appears as imbalanced (missing) momentum.
- Simplest case: 1 SM (photon, jet, lepton, ...) a.k.a *mono-X* search.

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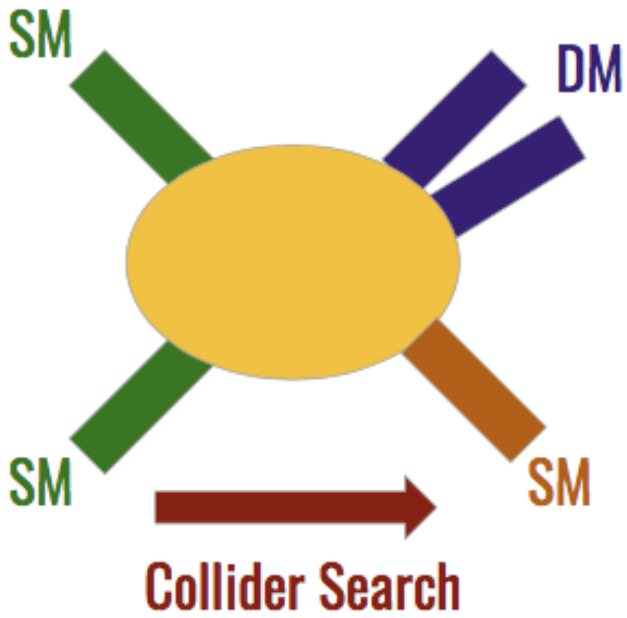

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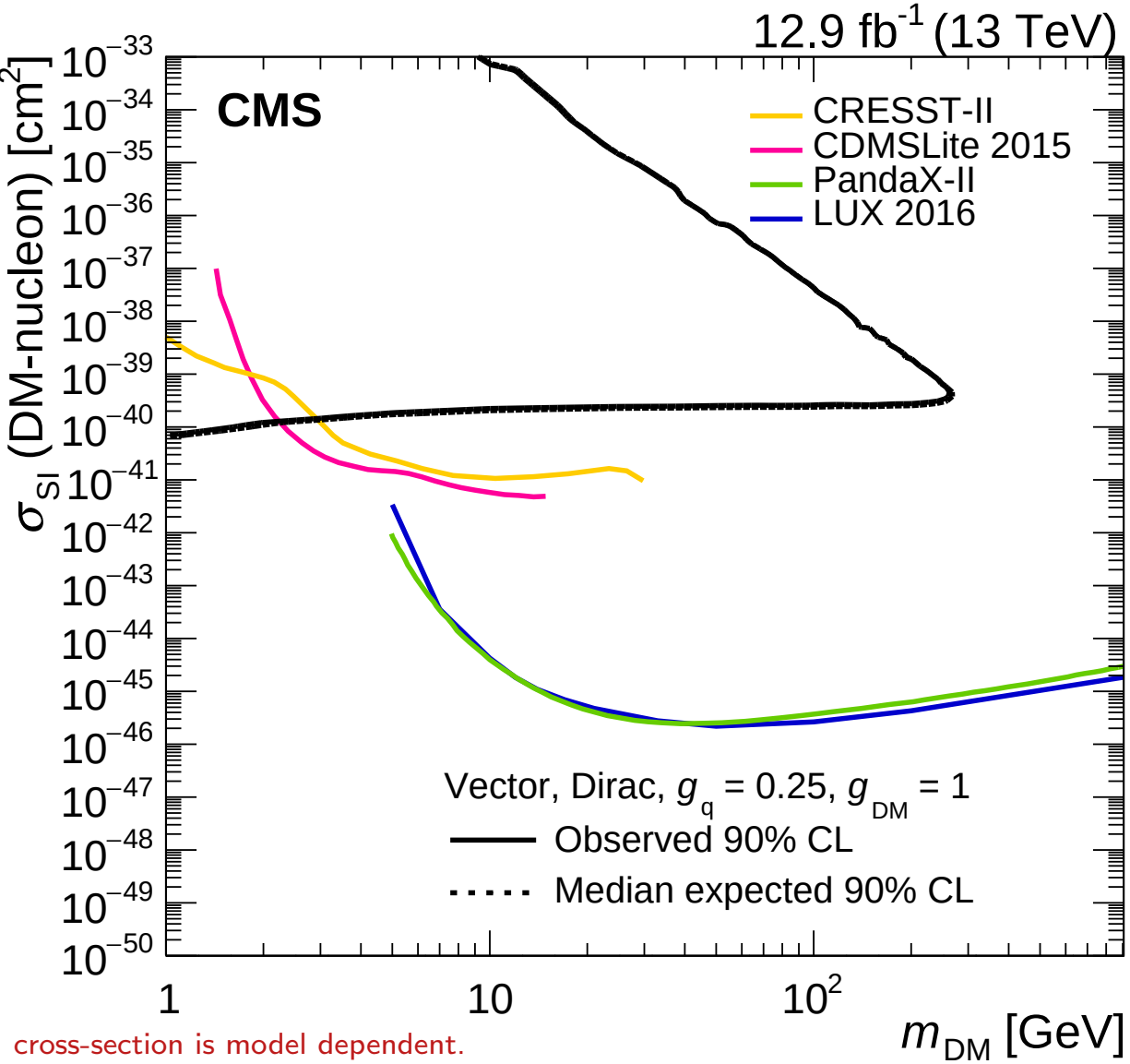
Ex: CMS Mono-Photon Result



LHC data → DM cross-section is model dependent.

Outline

Higgs Portal Dark Matter

Working assumptions:

- Only Higgs boson couples to DM.
- DM can be spin-0, spin-1/2 or spin-1.

$$\mathcal{L}_\chi = \begin{cases} g_\chi \chi^\dagger \chi H^\dagger H\,, & \text{scalar DM;} \\ \dfrac{g_\chi + i\tilde{g}_\chi}{\Lambda} \bar{\chi}_L \chi_R H^\dagger H + \text{h.c.}, & \text{fermion DM;} \\ \dfrac{g_\chi}{2} \chi^\mu \chi_\mu H^\dagger H, & \text{vector DM.} \end{cases}$$

Very predictive. DM phenomenology depends on DM–Higgs coupling, g_χ, and DM mass, m_χ.

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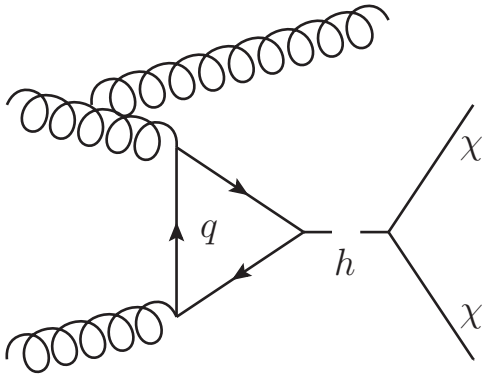
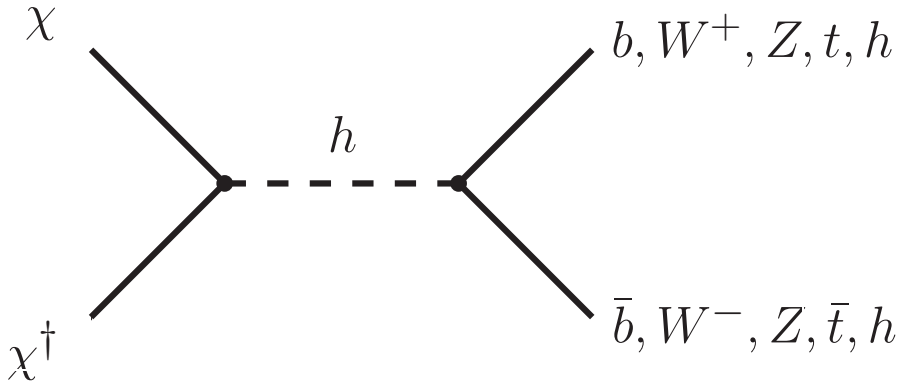
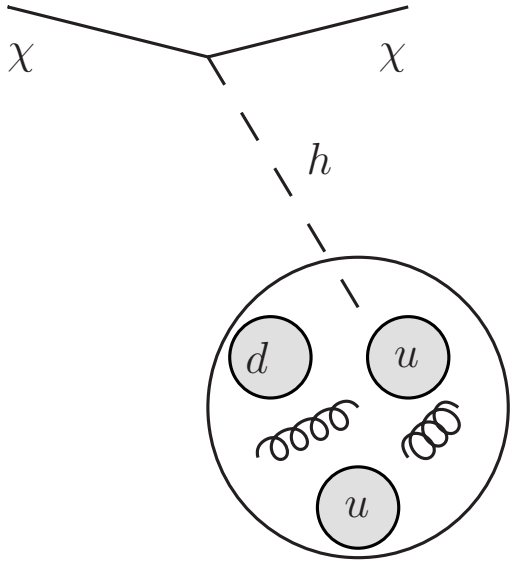
Higgs Portal Phenomenology



Collider

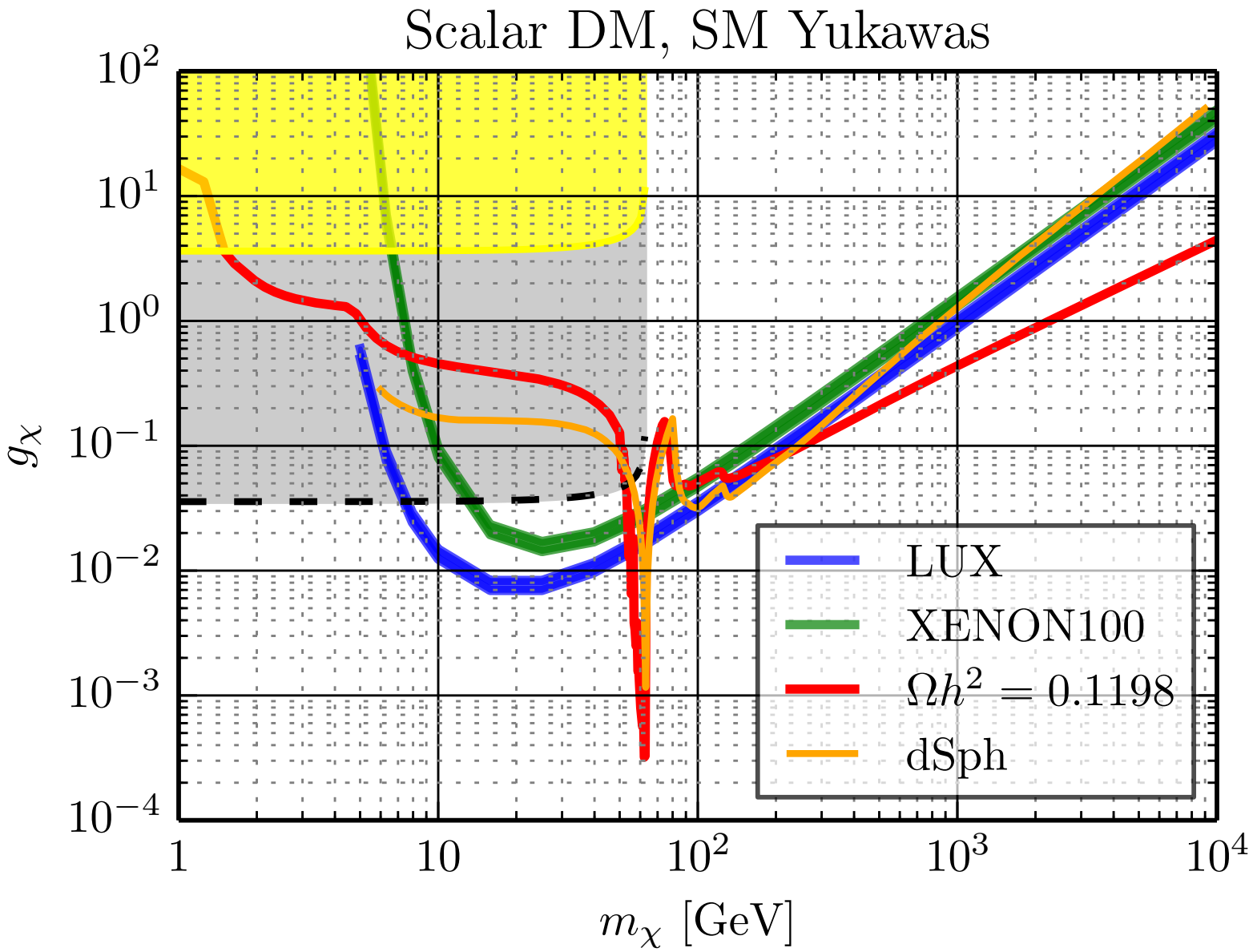


Indirect Detection

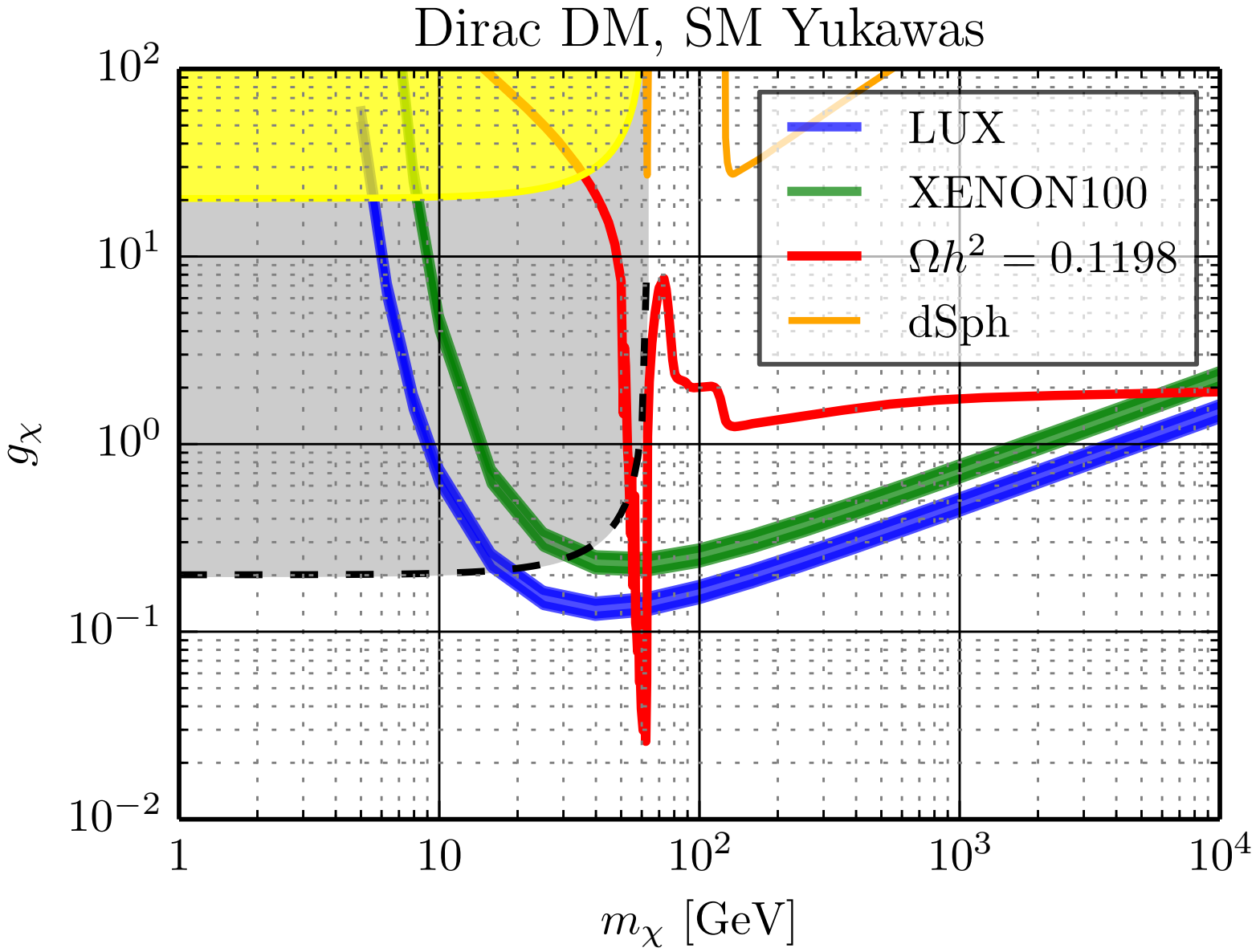


Direct Detection

Higgs Portal: Scalar DM



Higgs Portal: Fermionic DM



DM-neutrino Interactions

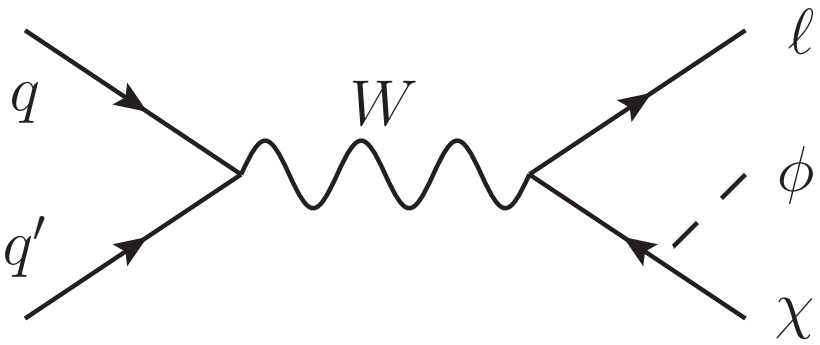
Working assumptions:

- DM interacts with a neutrino and a messenger.
- Other interactions of DM are negligible.
- DM can be a scalar or a fermion.

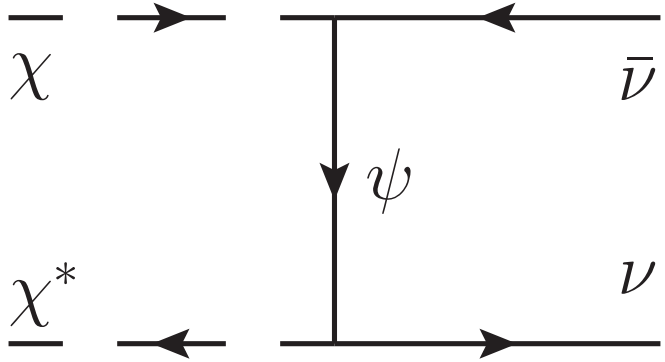
$$\mathcal{L}_{int} = \begin{cases} y\,\bar{\chi} P_L \nu \phi + \text{h.c.}, & \text{fermionic DM}, \\ y\,\bar{\psi} P_L \nu \chi + \text{h.c.}, & \text{scalar DM} \end{cases}$$

$\chi =$ DM, $\phi(\psi) =$ messenger.
Slightly less predictive, phenomenology depends on 3 parameters: y, m_χ, $m_{\phi(\psi)}$.

Phenomenologies

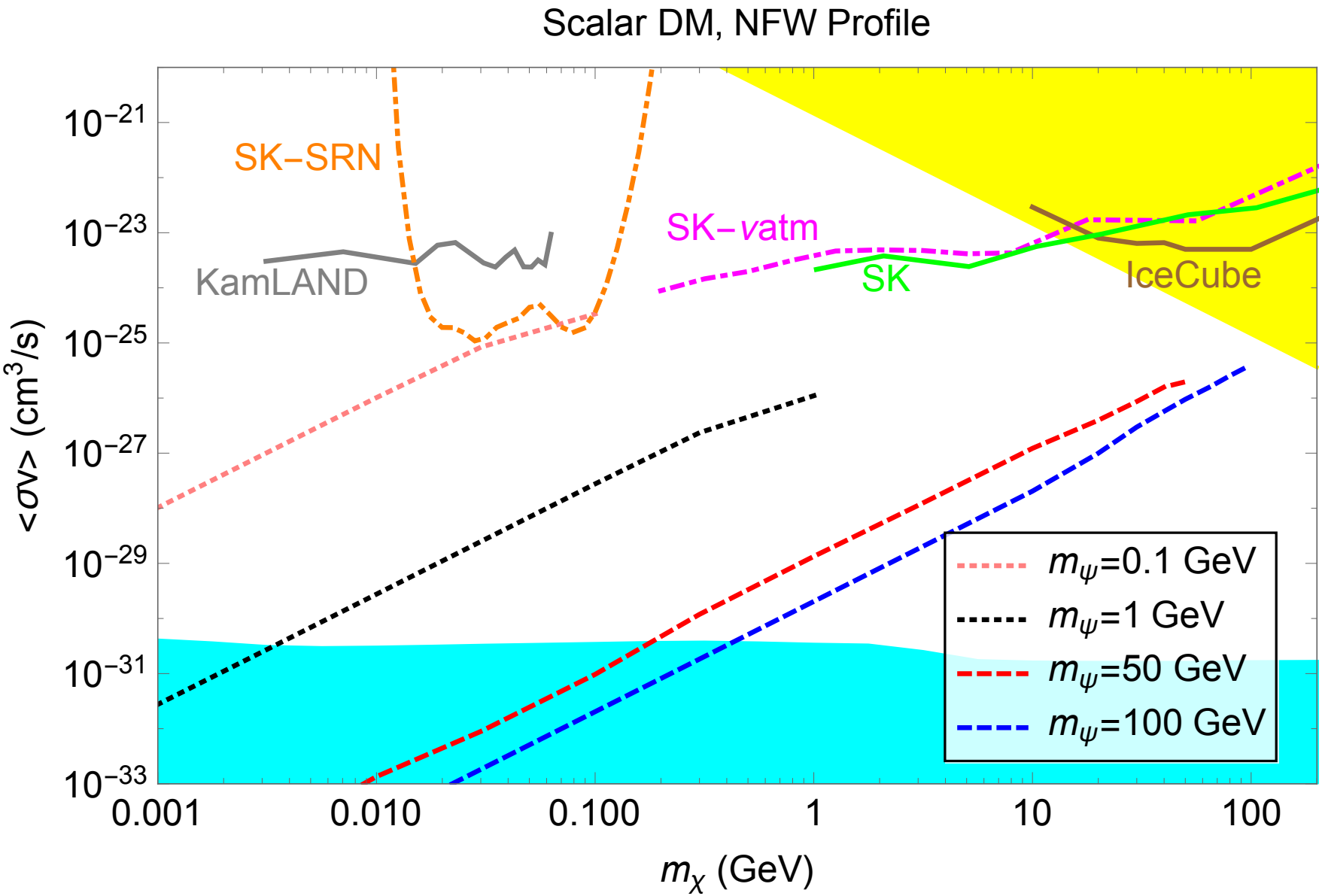


Collider

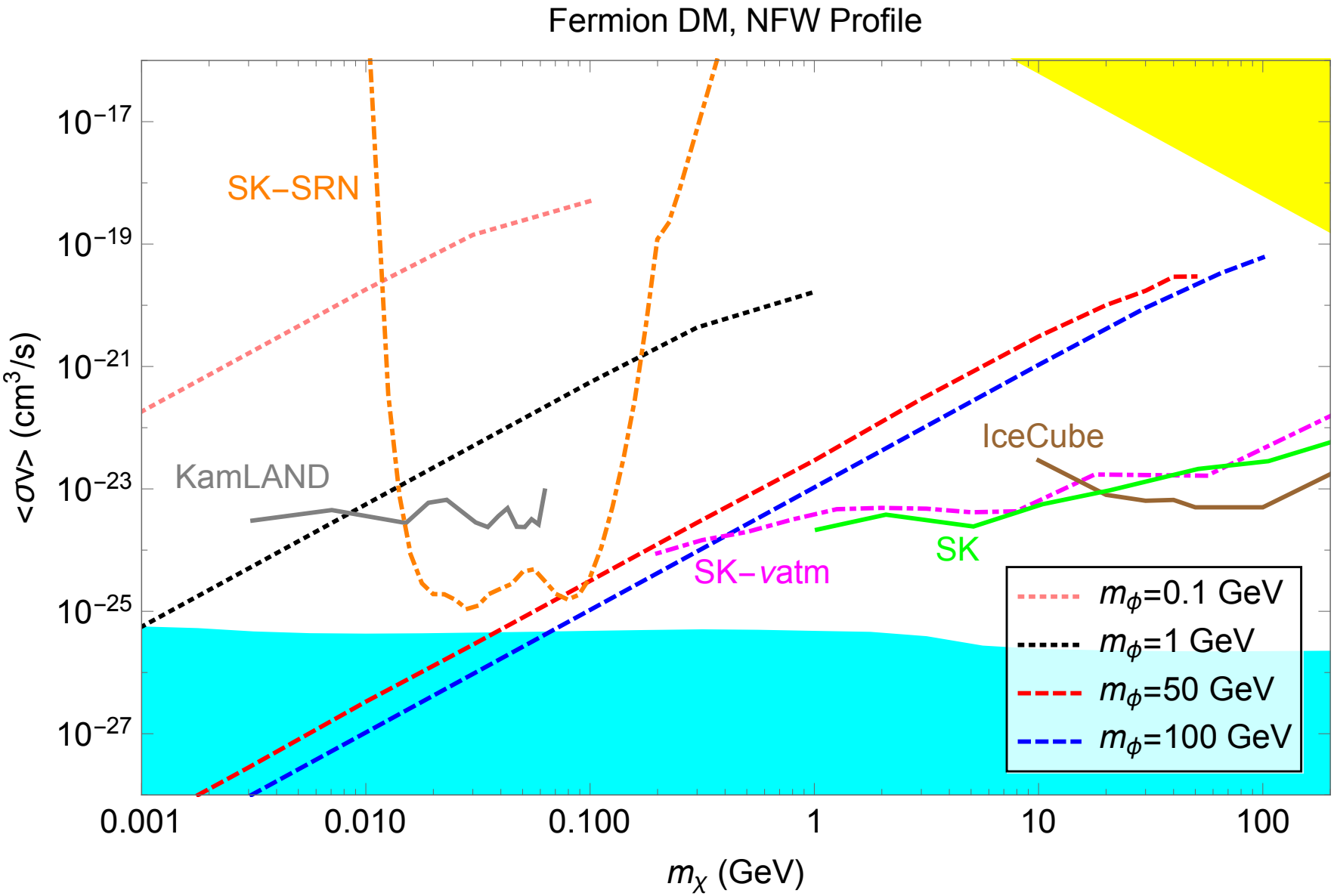


Indirect Detection

Scalar DM: Viable Parameter Space



Fermionic DM: Viable Parameter Space



Take Home Messages

- DM is a new particle (*new physics*).
  It interacts weakly with SM.
- Many well motivated scenarios of NP contain DM.
- In a particular scenario, we can learn quite a lot of DM properties.
- DM is interdisciplinary.
  - Astrophysics. (telescopes, DM profile, etc)
  - Particle physics. (models, detectors, etc)
  - Cosmology. (evolution of the universe, etc)

Omitted Topics

- How DM was generated.
  - Thermal relic
  - Freeze out vs. freeze in.
- DM distribution.
- Impacts of DM on the evolution of the Universe.
  - Large scale structure.
  - CMB spectrum.
  - Cosmic dawn (21 cm spectrum line).
- Strongly interacting DM.
- DM and the matter–antimatter asymmetry.
- DM stars.

Theoretical High Energy Physics & Astrophysics

Thank you for your attention.


"I'm searching for my keys."
Callander