COSMIC FRONTIER

Summary of Snowmass Activities

Jonathan Feng and Steve Ritz

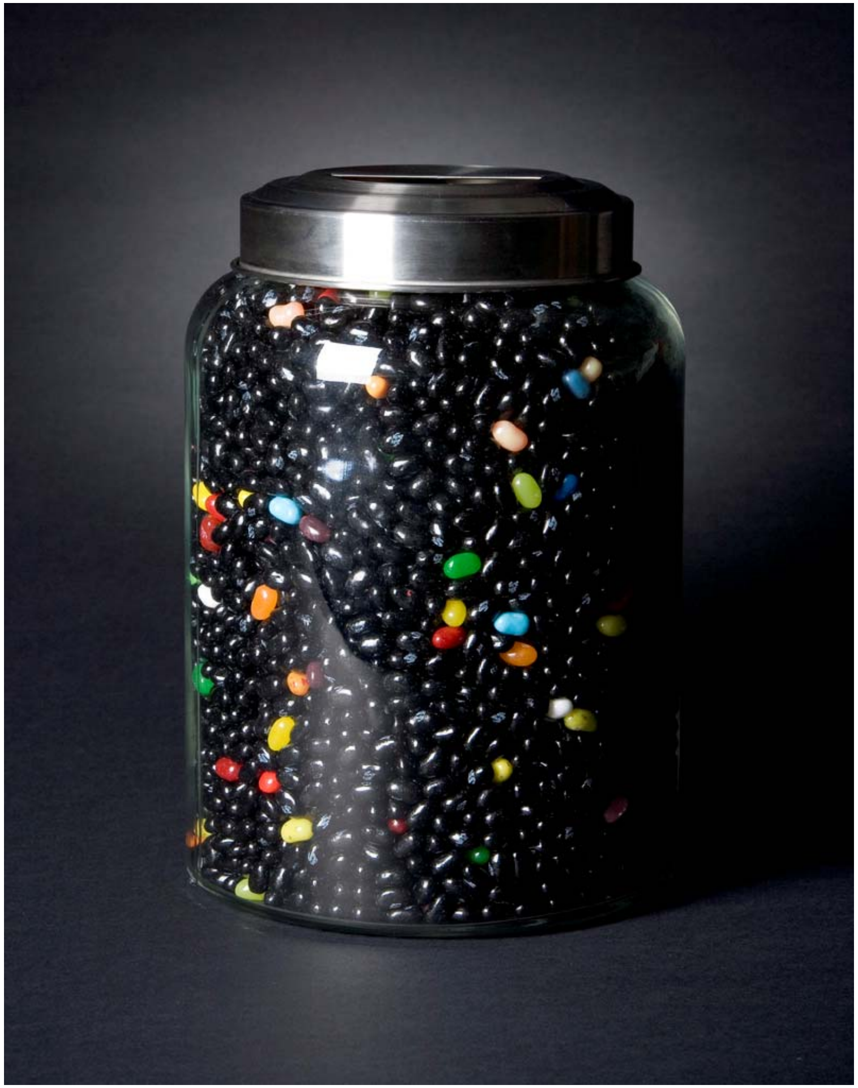
for the Cosmic Frontier Group

INTRODUCTION

Our understanding of the Universe has been transformed in recent years.

With the other Frontiers, the Cosmic Frontier now provides overwhelming evidence for new physics and powerful approaches to address many of our most fascinating questions:

- What is dark matter?
- What is dark energy?
- Why more matter than anti-matter?
- How did the Universe begin?
- What are the neutrinos' properties?
- What is the physics of the Universe at the highest energies?



COSMIC FRONTIER STRUCTURE

For references and more than can possibly be covered here, see
http://www.snowmass2013.org/tiki-index.php?page=Cosmic%20Frontier

- CF1: WIMP Dark Matter Direct Detection (Priscilla Cushman, Cristian Galbiati, Dan McKinsey, Hamish Robertson, Tim Tait)
    - A: Status and Science Case (Dan Bauer)
    - B: Defining the Parameter Space (Tim Tait)
    - C: Enabling Technology and Infrastucture (Bob Jacobsen)
- CF2: WIMP Dark Matter Indirect Detection (Jim Buckley, Doug Cowen, Stefano Profumo)
- CF3: Non-WIMP Dark Matter (Alex Kusenko, Leslie Rosenberg)
- CF4: Dark Matter Complementarity (Dan Hooper, Manoj Kaplinghat, Konstantin Matchev)

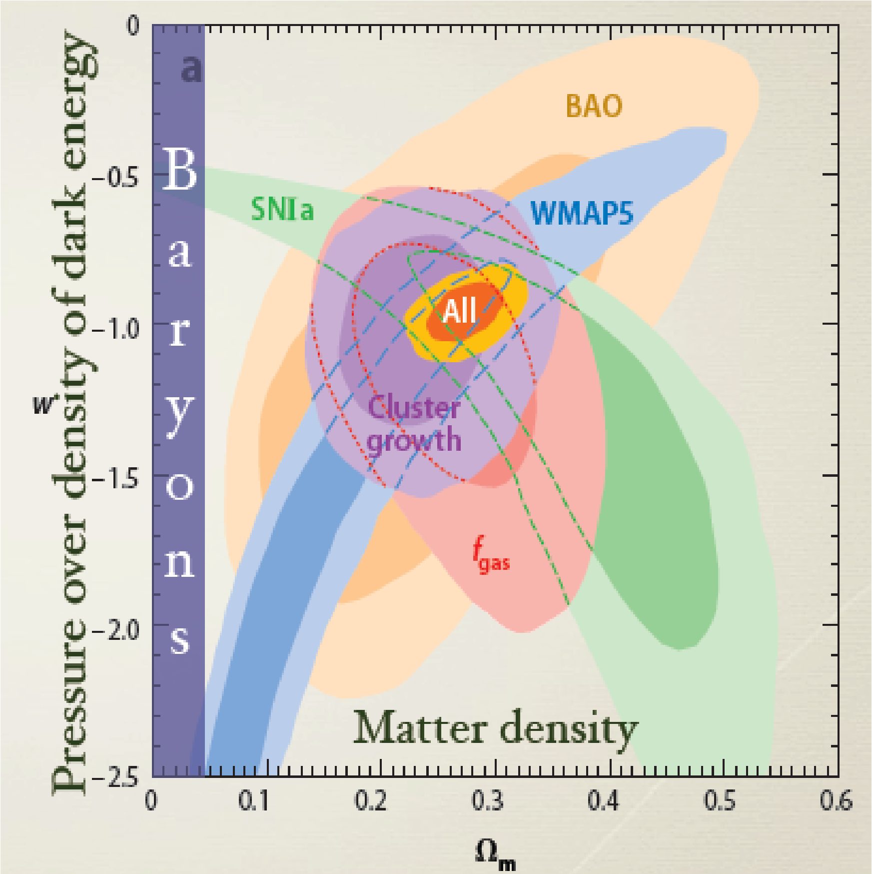
COSMIC FRONTIER STRUCTURE

- CF5: Dark Energy and CMB (Scott Dodelson, Klaus Honscheid)
  - Distances (Alex Kim, Nikhil Padmanabhan)
  - Growth of Cosmic Structure (Dragan Huterer, David Kirkby)
  - Cross-Correlations (Jason Rhodes, David Weinberg)
  - Novel Probes of Gravity and Dark Energy (Bhuvnesh Jain)
  - Inflation Physics from CMB and Large Scale Structure (John Carlstrom, Adrian Lee)
  - Neutrino Physics from CMB and Large Scale Structure (Kev Abazajian, John Carlstrom, Adrian Lee)
  - Dark Energy Facilities (David Weinberg)

- CF6: Cosmic Particles and Fundamental Physics (Jim Beatty, Ann Nelson, Angela Olinto, Gus Sinnis)
  - A: Cosmic Rays, Gamma Rays and Neutrinos (Gus Sinnis, Tom Weiler)
  - B: The Matter of the Cosmological Asymmetry (Ann Nelson)
  - C: Exploring the Basic Nature of Space and Time (Aaron Chou, Craig Hogan)

DARK MATTER

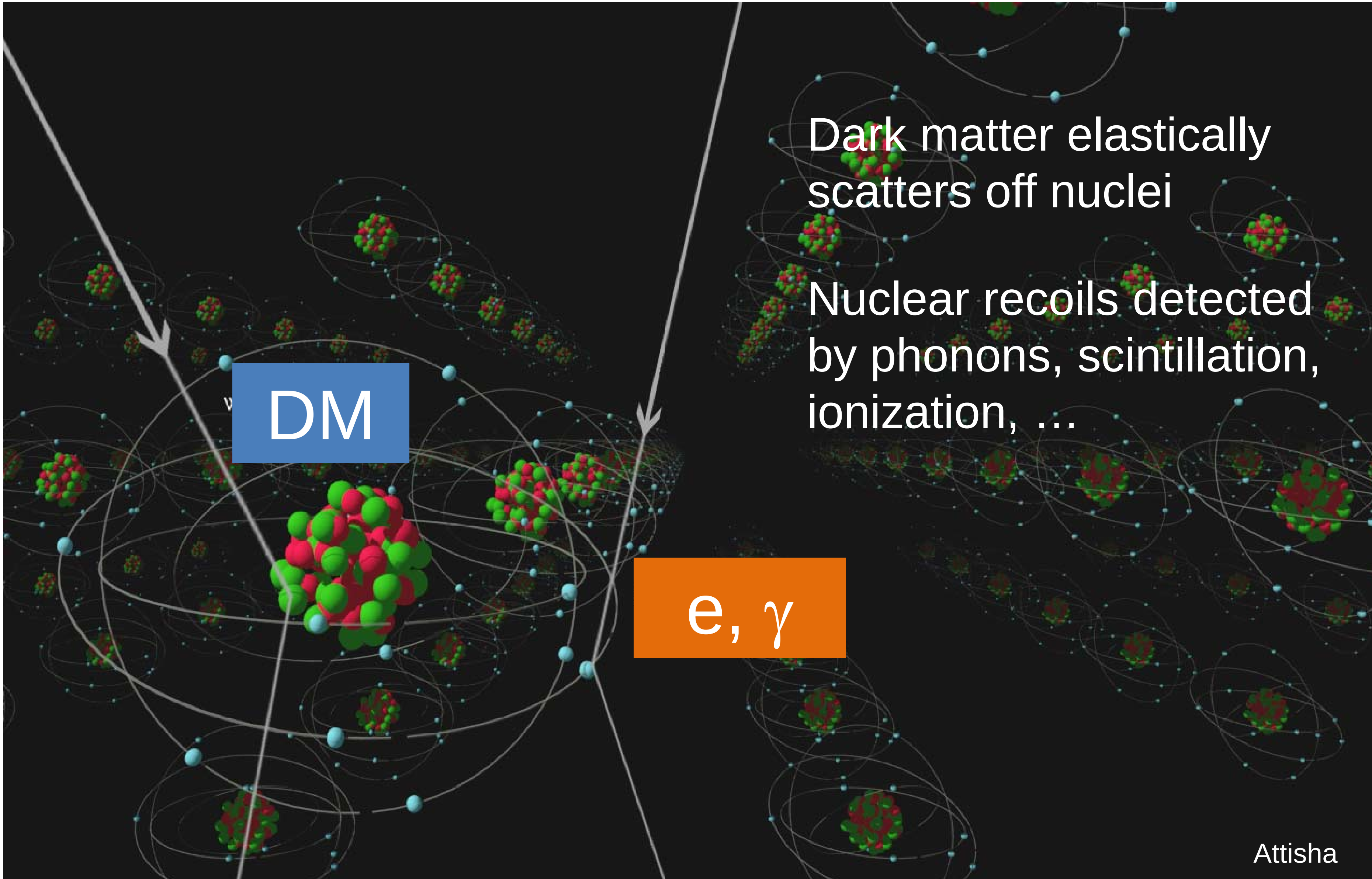
- Dark matter has **already been discovered** through
  - Galaxy clusters
  - Galactic rotation curves
  - Weak lensing
  - Strong lensing
  - Hot gas in clusters
  - Bullet Cluster
  - Supernovae
  - CMB
- We are entering the **decade of dark matter identification**



Allen et al, Annual Review of Astronomy and Astrophysics, vol. 49, pp. 409-470 (2011)

Mantz et al, Monthly Notices of the Royal Astronomical Society, Volume 406, Issue 3, pp. 1759-1772 (2010)

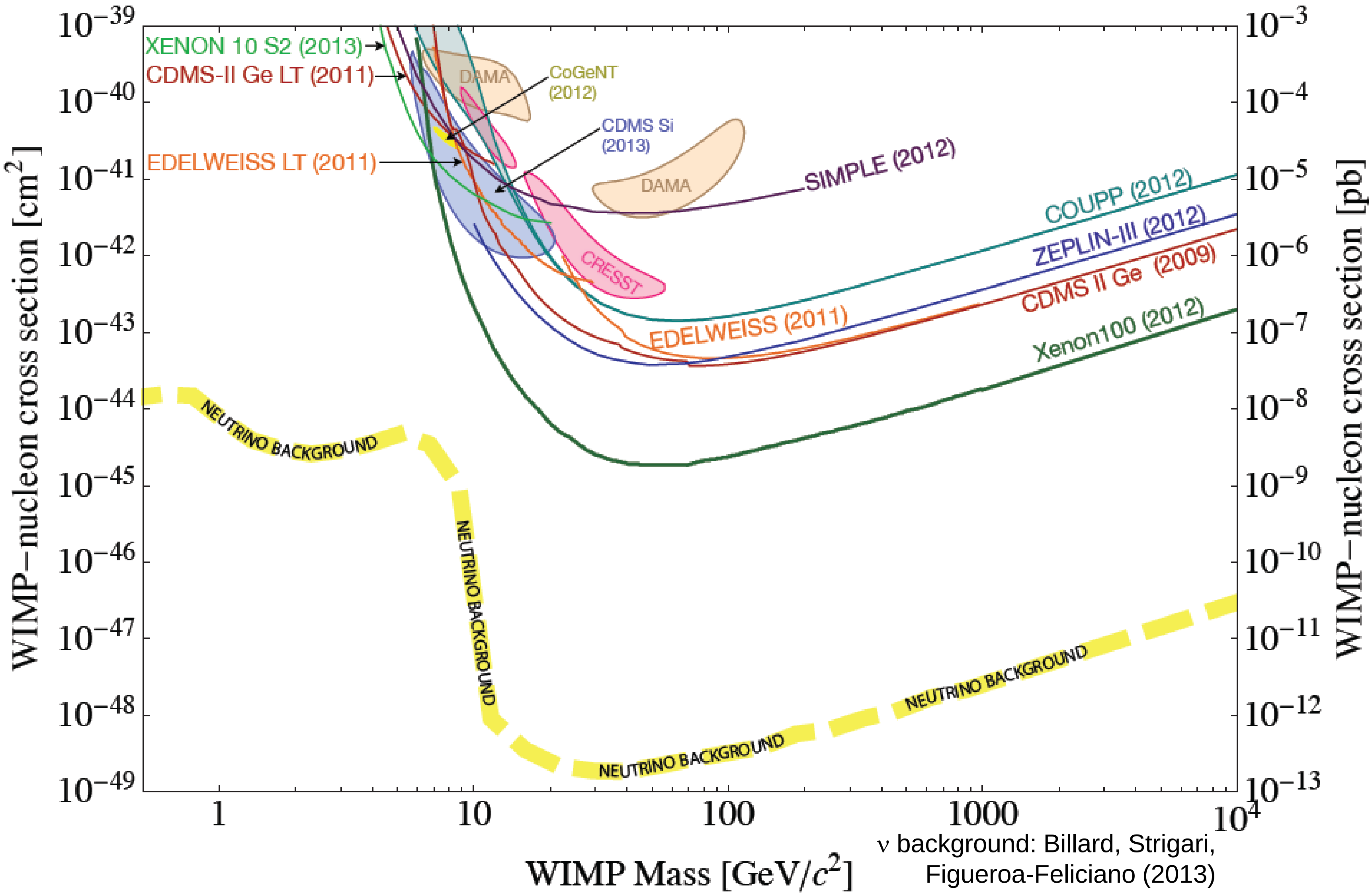
DIRECT DETECTION



Dark matter elastically scatters off nuclei

Nuclear recoils detected by phonons, scintillation, ionization, …

CURRENT STATUS AND FUTURE PROSPECTS



ν background: Billard, Strigari, Figueroa-Feliciano (2013)

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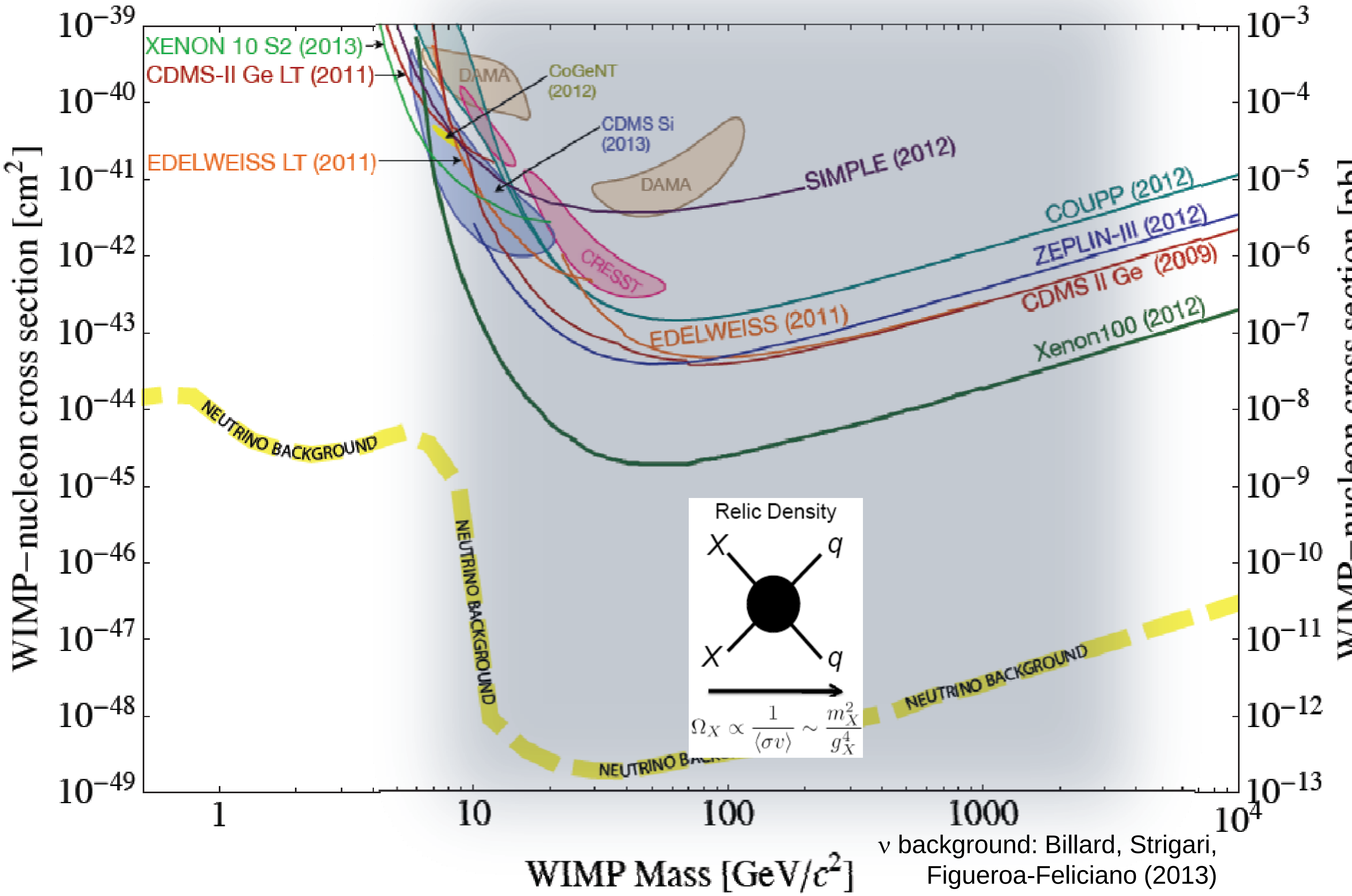

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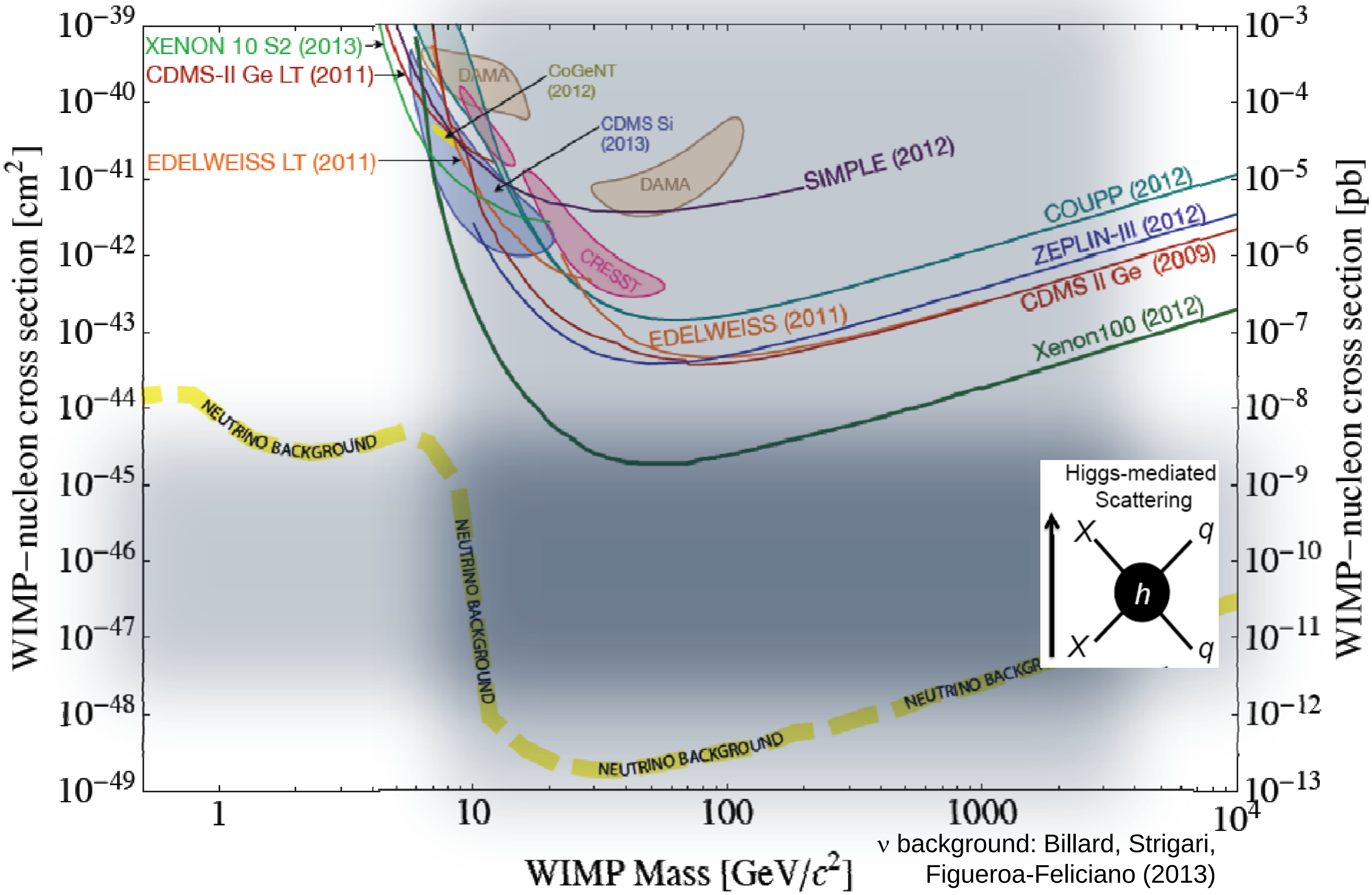

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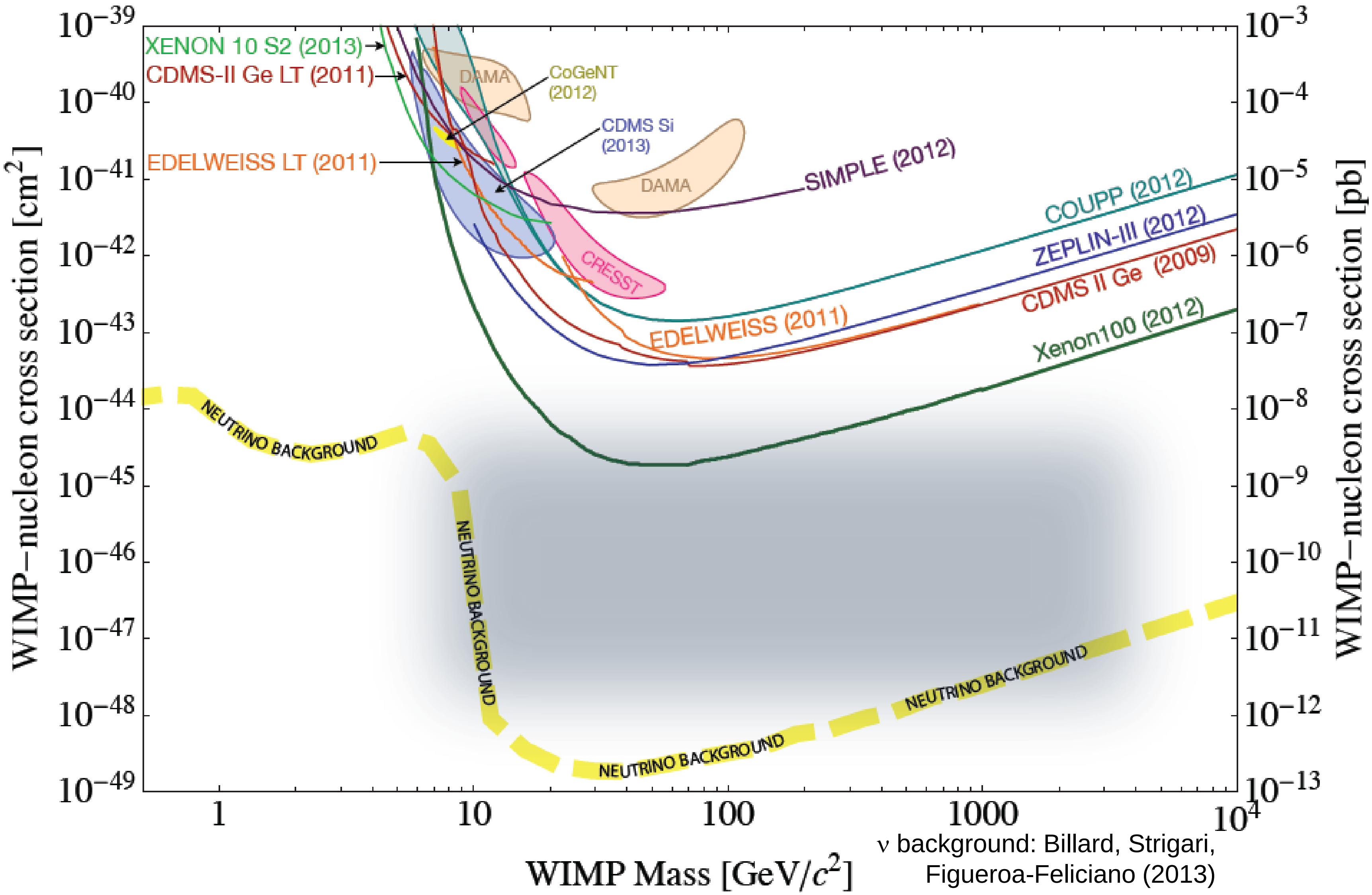

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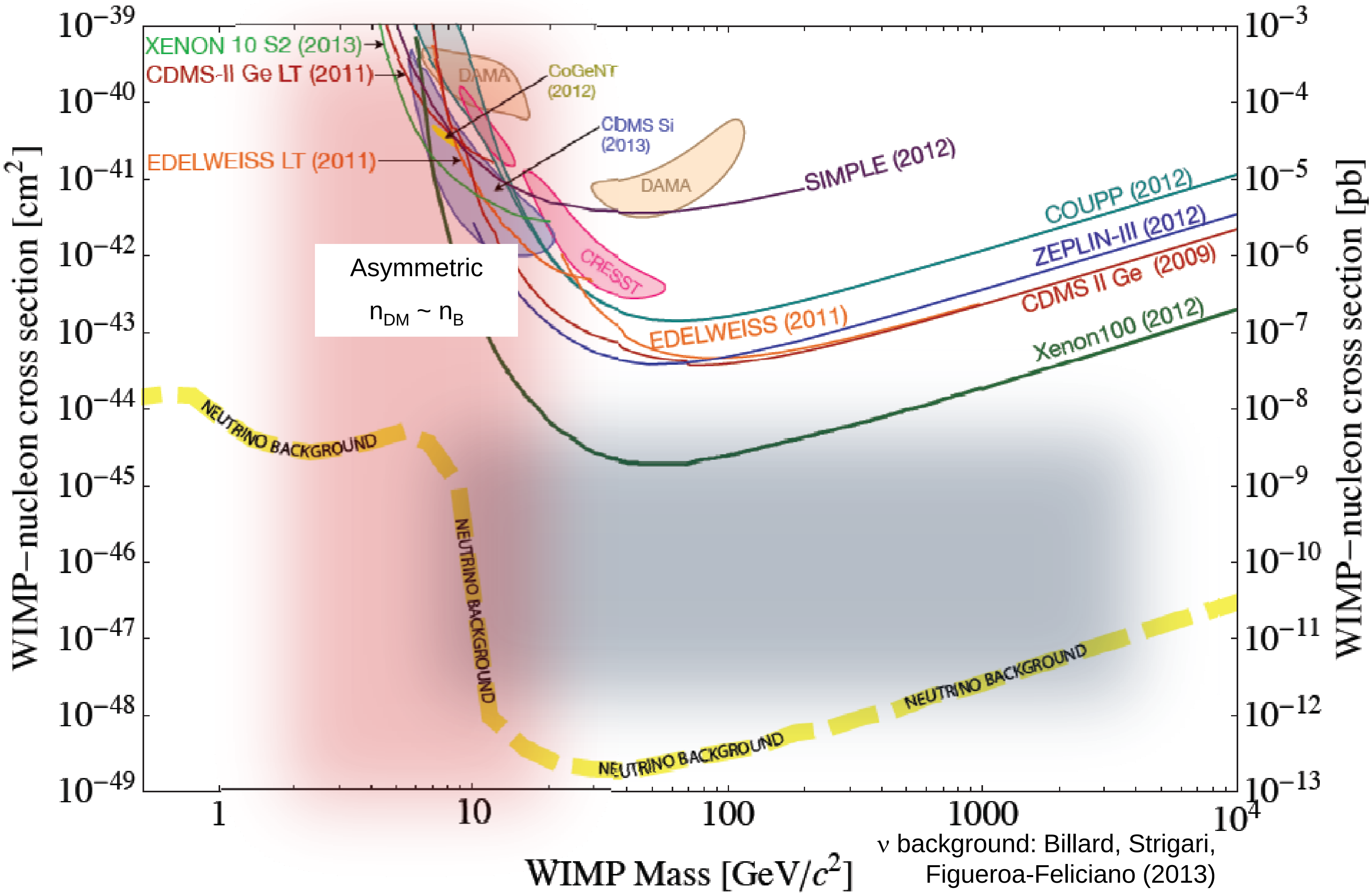

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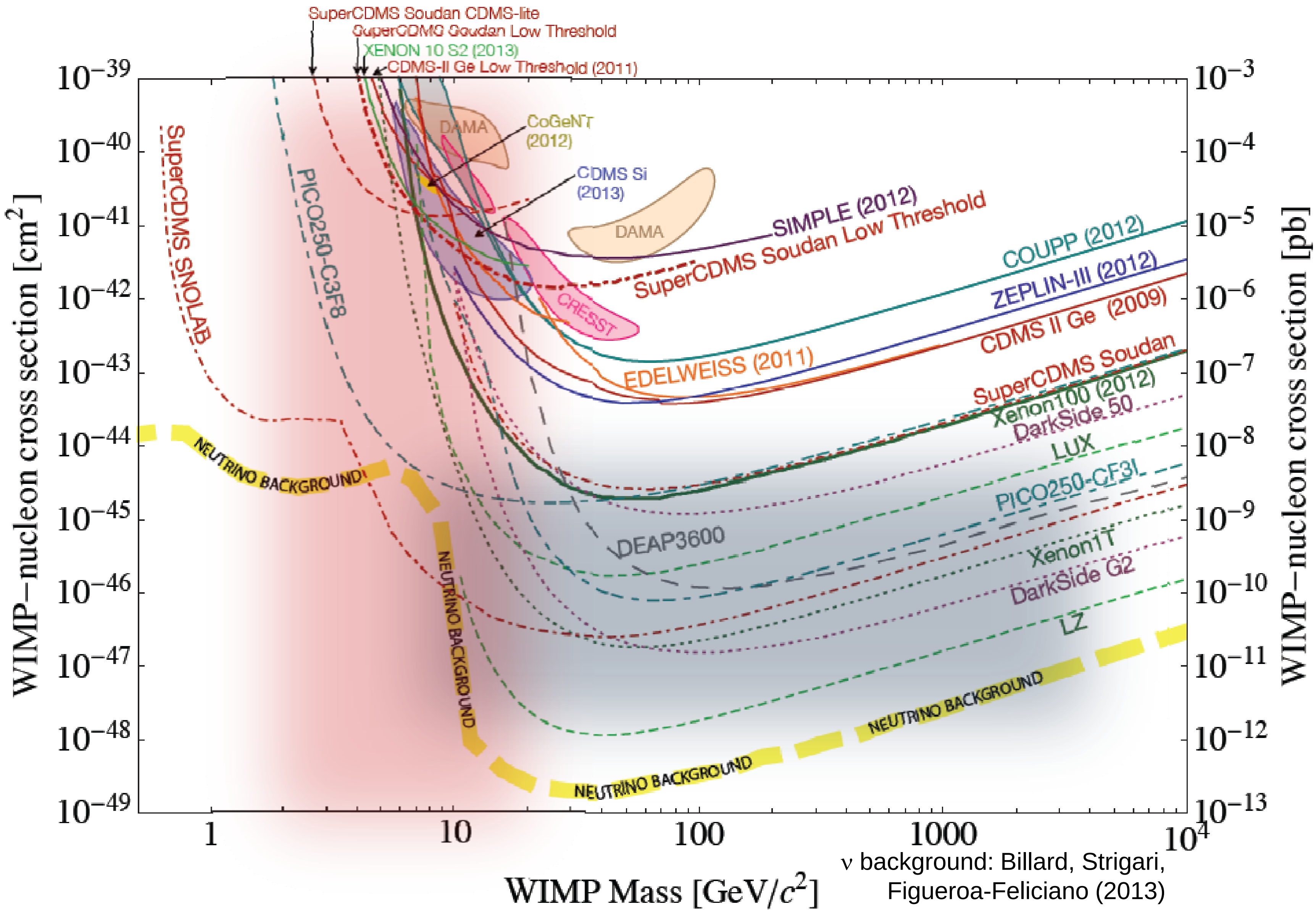

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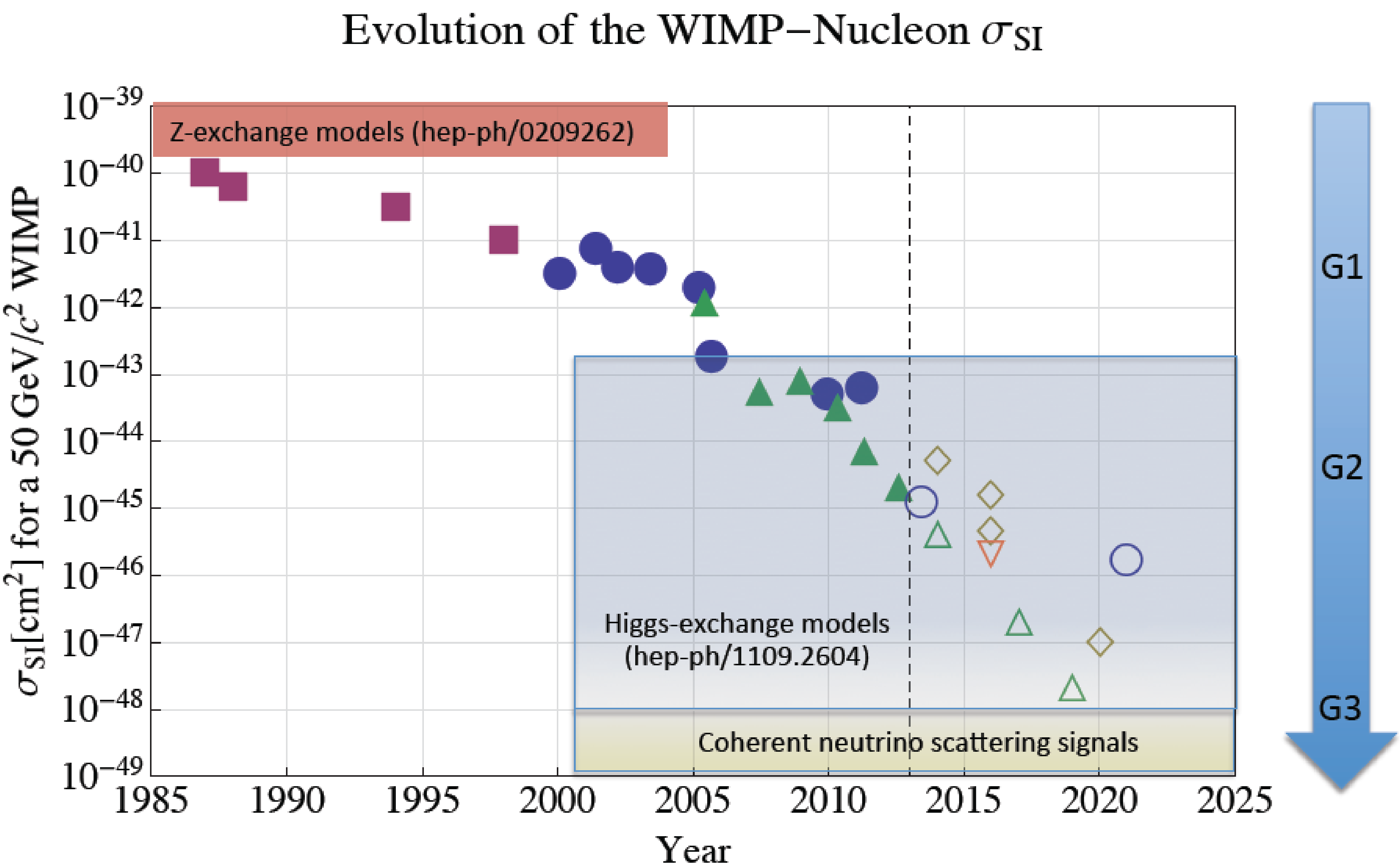
MOORE'S LAW FOR DARK MATTER



DIRECT DETECTION ROADMAP

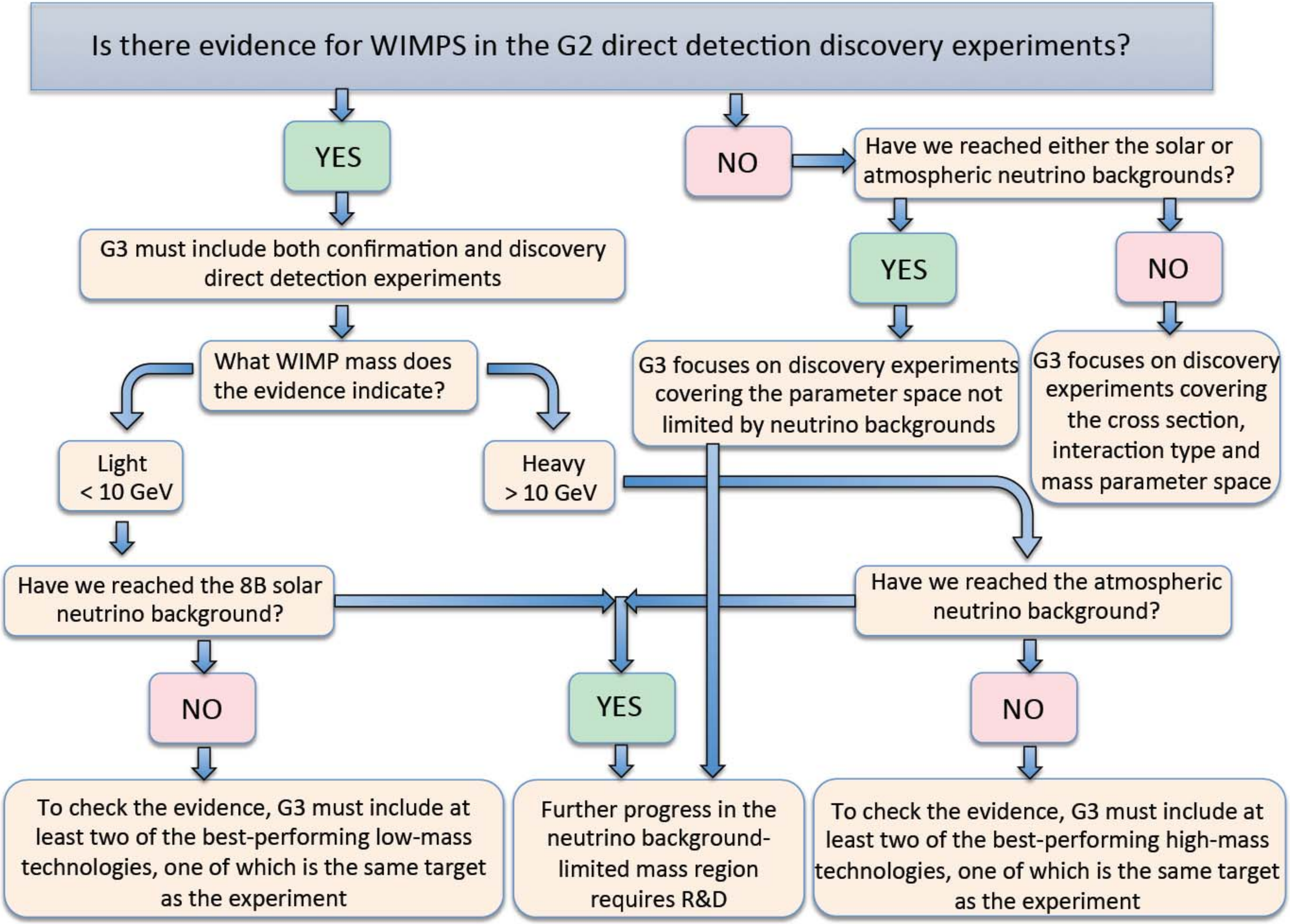
Discovery: Search for WIMPS over a wide mass range (1 GeV to 100 TeV), with at least an order of magnitude improvement in sensitivity in each generation, until we encounter the coherent neutrino scattering signal that will arise from solar, atmospheric and supernova neutrinos.

Confirmation: Check any evidence for WIMP signals using experiments with complementary technologies, and also with an experiment using the original target material, but having better sensitivity.

Study: If a signal is confirmed, study it with multiple technologies in order to extract maximal information about WIMP properties.

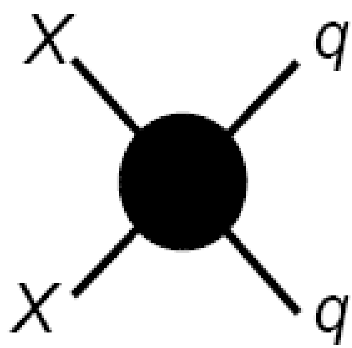
R&D: Maintain a robust detector R&D program on technologies that can enable discovery, confirmation and study of WIMPs.

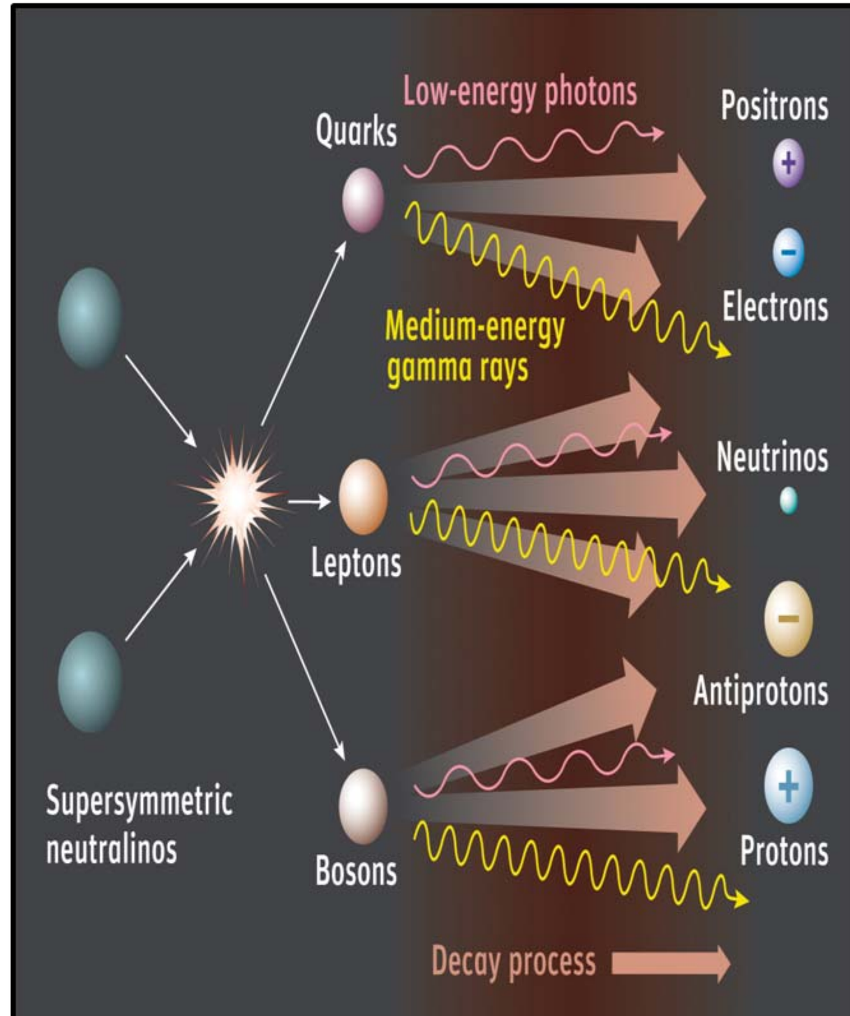
DIRECT DETECTION ROADMAP



INDIRECT DETECTION

- Dark matter may pair annihilate in our galactic neighborhood to
  - Photons
  - Neutrinos
  - Positrons
  - Antiprotons
  - Antideuterons



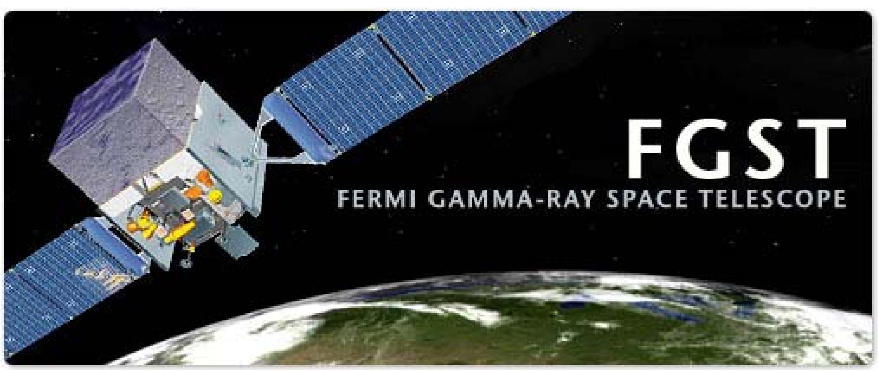


- The relic density provides a target annihilation cross section

$$\langle \sigma_A v \rangle \sim 3 \times 10^{-26}\ \mathrm{cm^3/s}$$

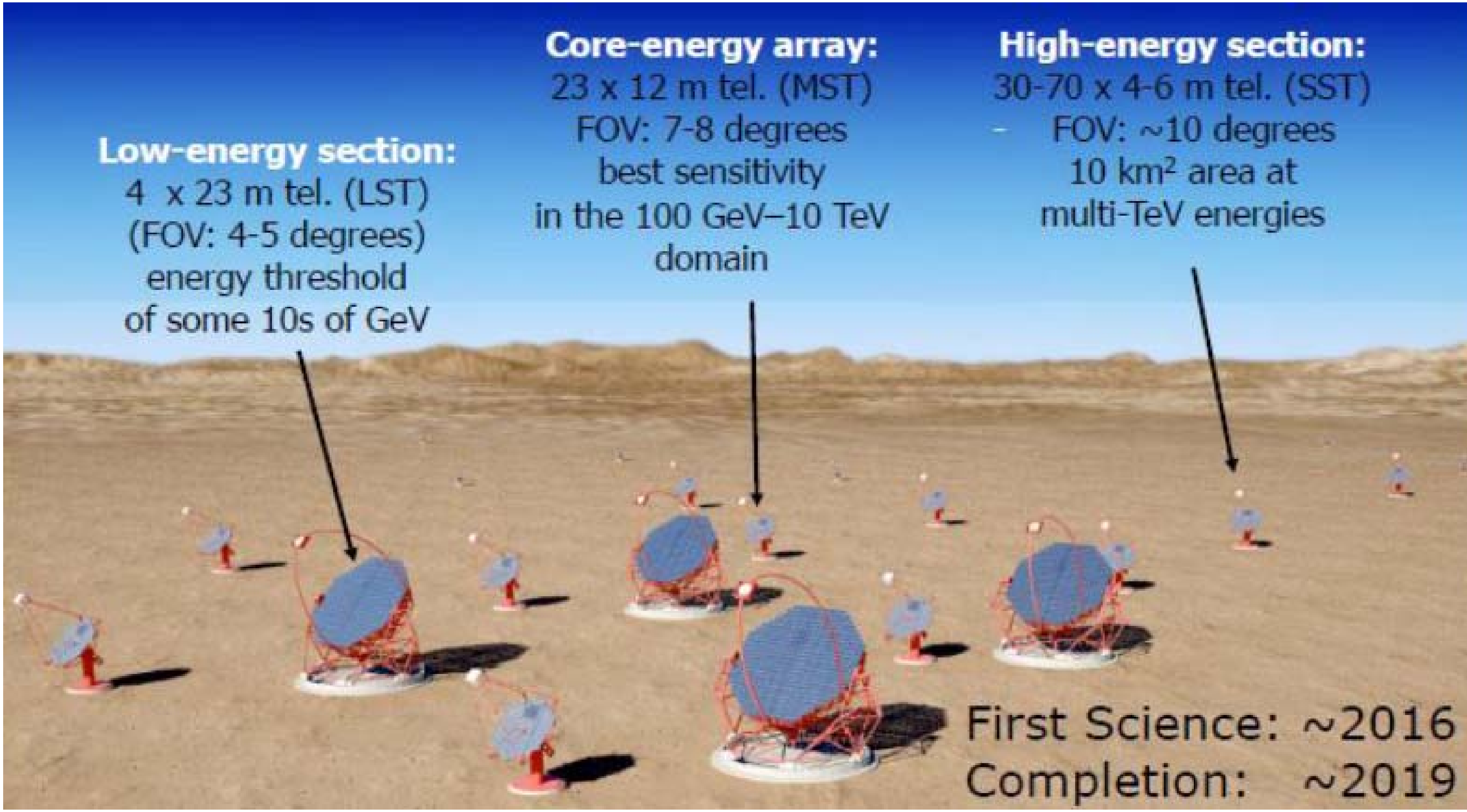
INDIRECT DETECTION: PHOTONS

Current: Veritas, Fermi-LAT, HAWC, and others

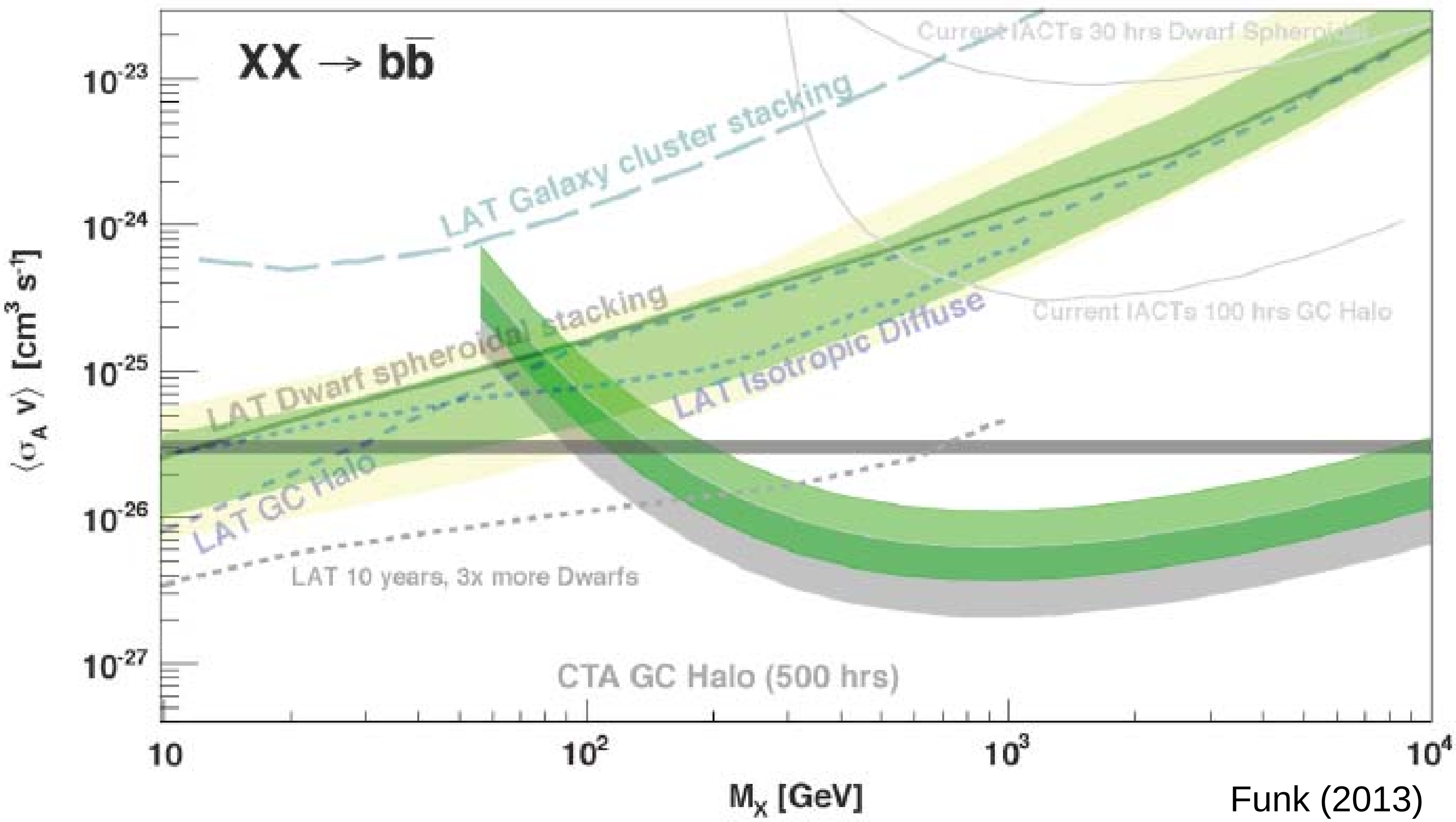


INDIRECT DETECTION: PHOTONS

Future: Cerenkov Telescope Array



INDIRECT DETECTION: PHOTONS



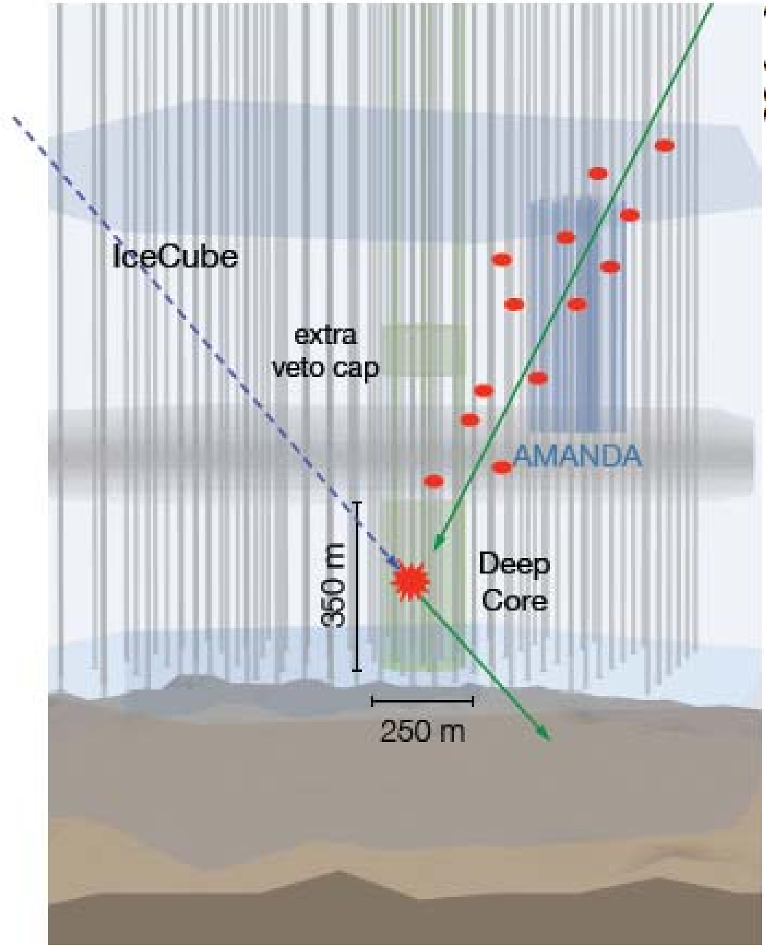
Funk (2013)

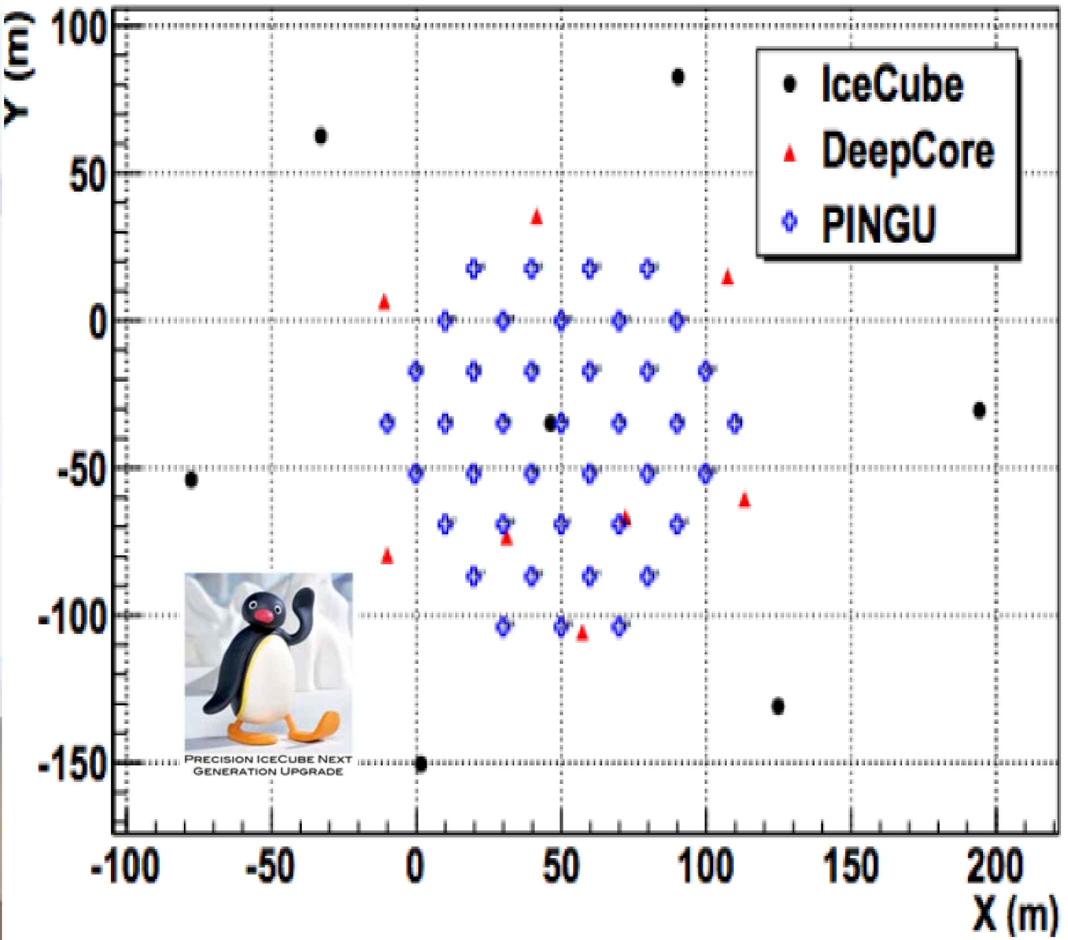
- Fermi-LAT has excluded a light WIMP with the target annihilation cross section for certain annihilation channels
- CTA extends the reach to WIMP masses ~ 10 TeV

INDIRECT DETECTION: NEUTRINOS

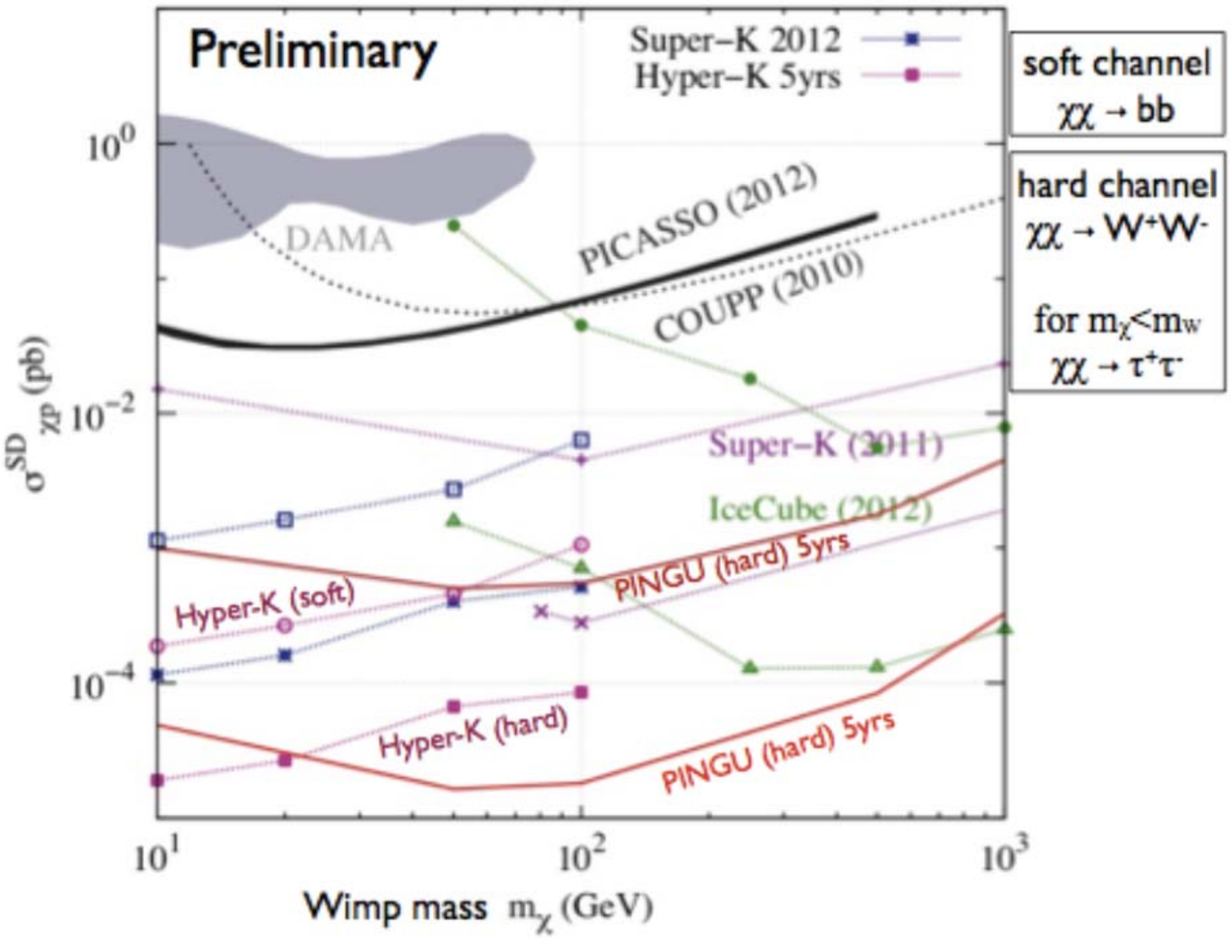
Current: IceCube/DeepCore, ANTARES

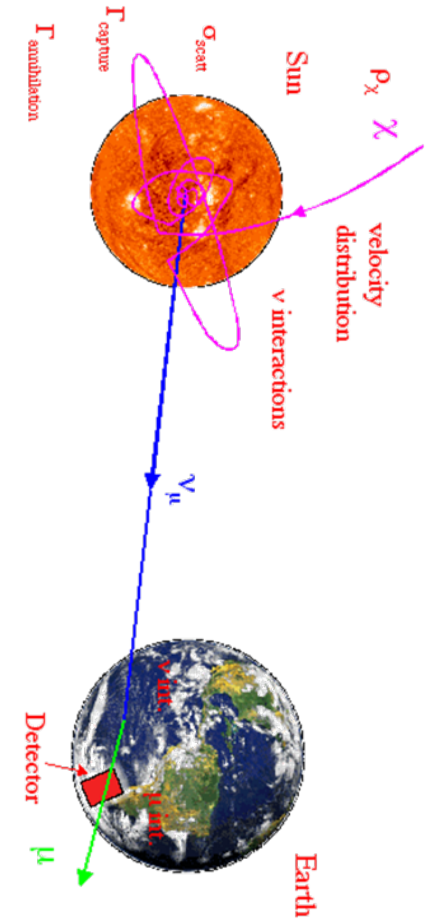
Future: PINGU





INDIRECT DETECTION: NEUTRINOS

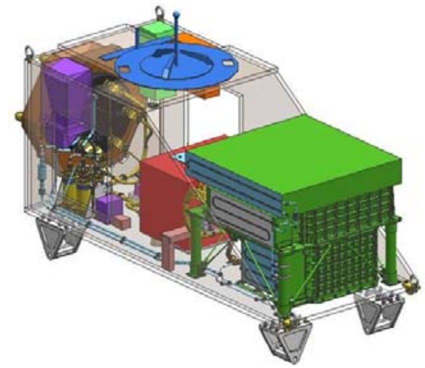


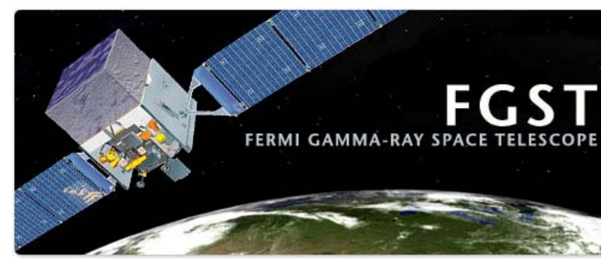


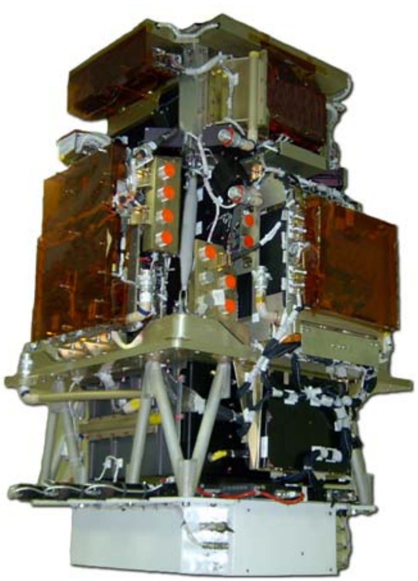
Future experiments like PINGU may discover the smoking-gun signal of HE neutrinos from the Sun, or set stringent σ_{SD} limits, extending the reach of IceCube/DeepCore

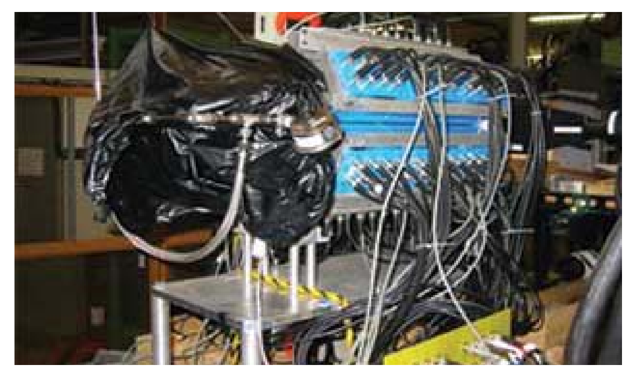
INDIRECT DETECTION: ANTI-MATTER

- Positrons (PAMELA, Fermi-LAT, AMS, CALET)
- Anti-Protons (PAMELA, AMS)
- Anti-Deuterons (GAPS)

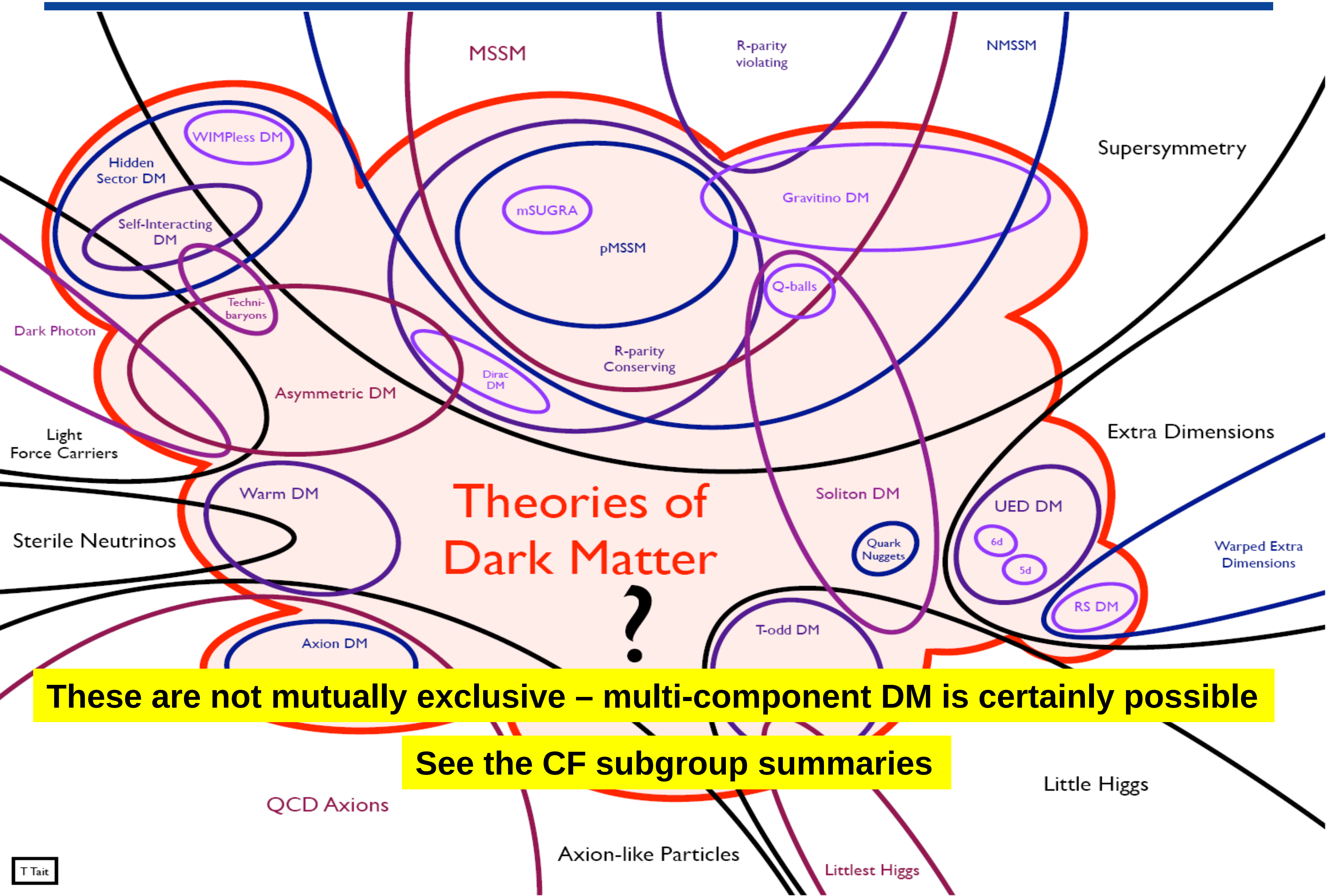








NON-WIMP DARK MATTER



These are not mutually exclusive – multi-component DM is certainly possible

See the CF subgroup summaries

AXIONS

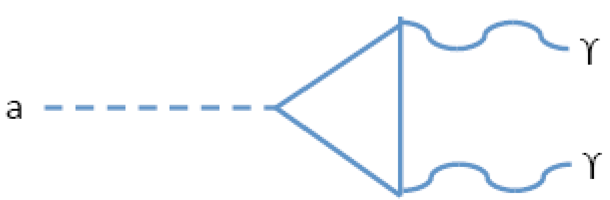
- Strongly motivated by the strong CP problem

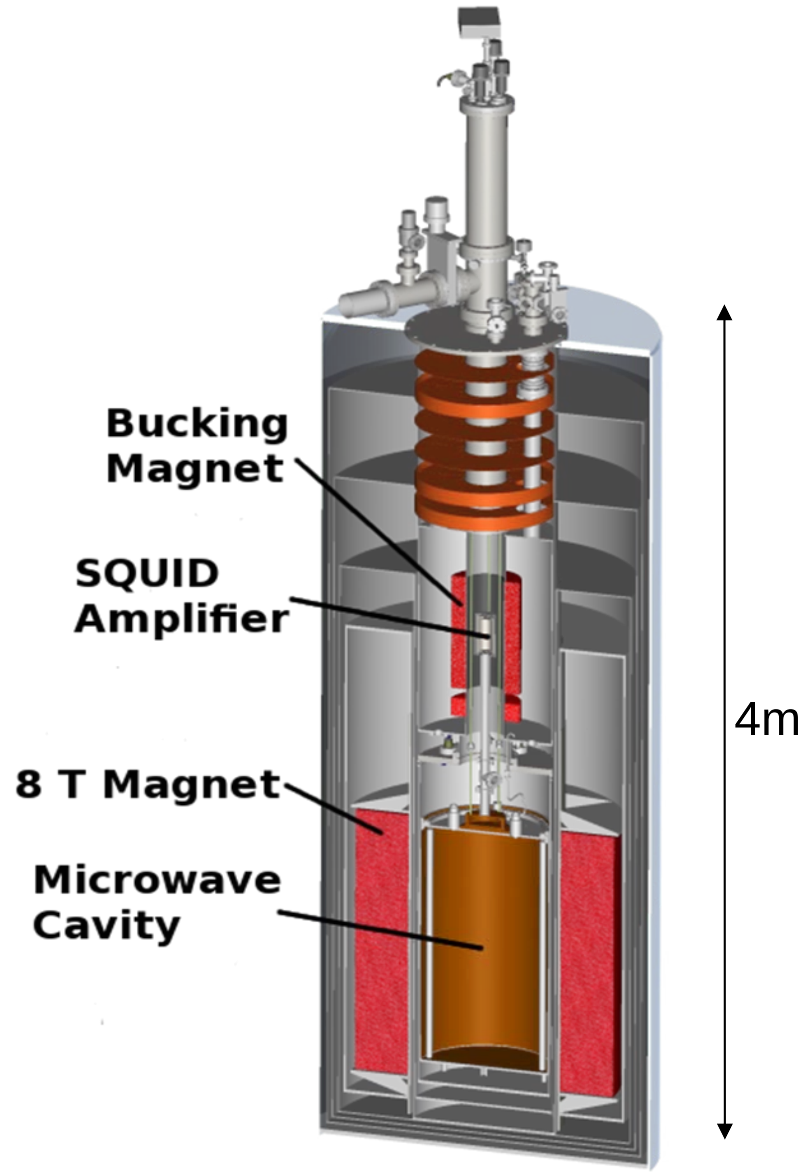
$$\theta_{\mathrm{CP}} \frac{g_3^2}{32\pi^2} \epsilon^{\mu\nu\rho\sigma} G^{\alpha}_{\mu\nu} G^{\alpha}_{\rho\sigma}$$

- Current bound from electric dipole moments is

$$\theta_{\mathrm{CP}} < 10^{-10}$$

- Motivates introduction of the axion field, which couples to two photons

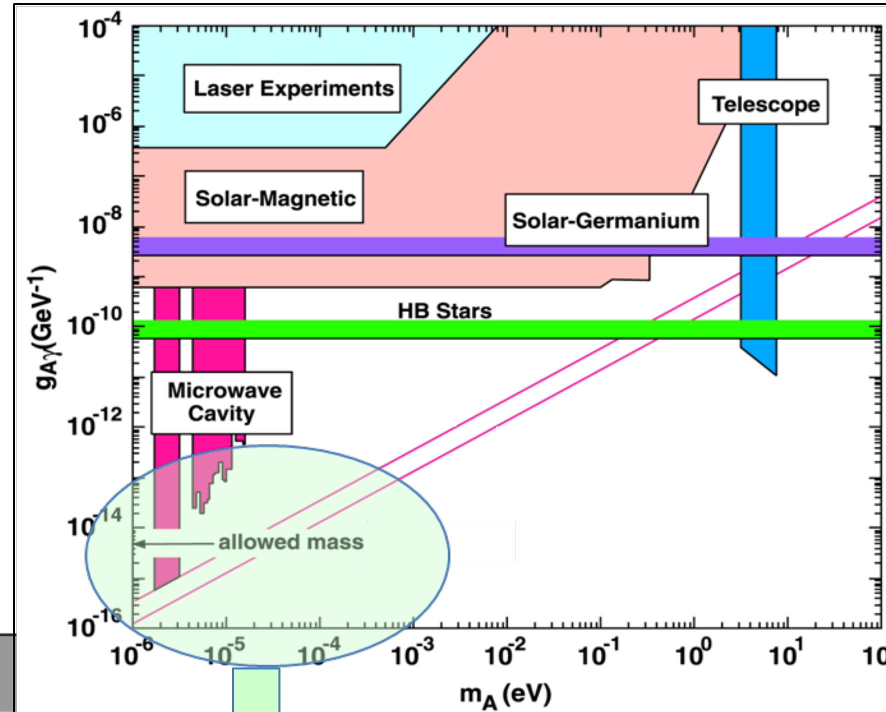


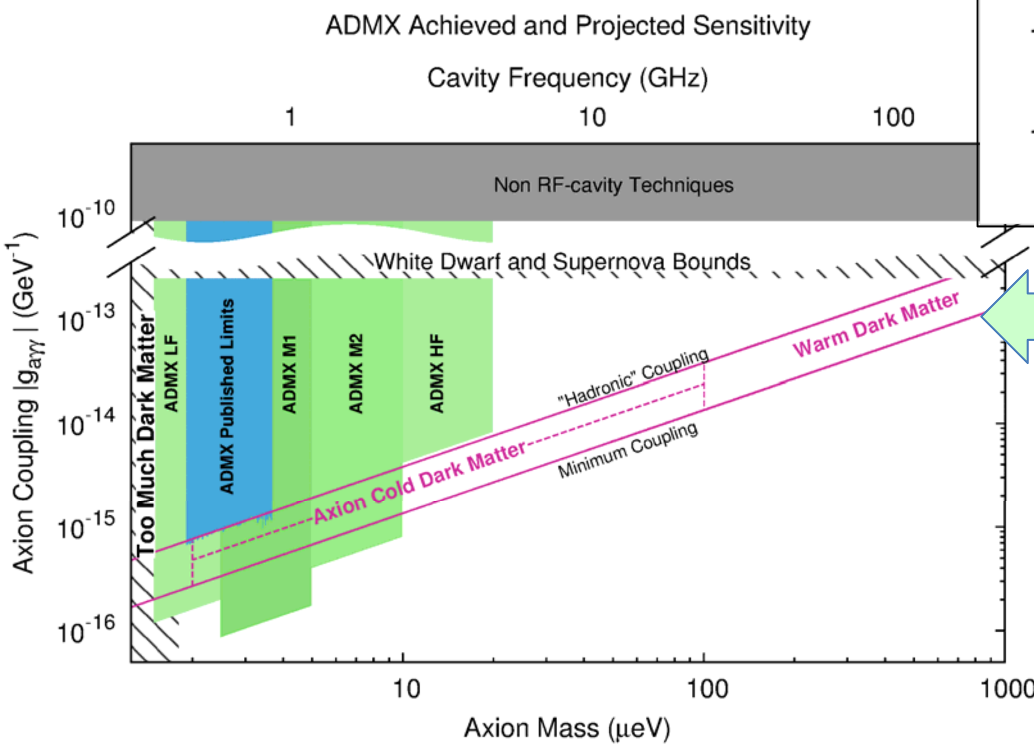


AXION FUTURE PROSPECTS

Parameter space constrained by

- Supernova cooling
- White dwarf cooling
- Red giant energy transport
- Relic density
- Direct detection constraints



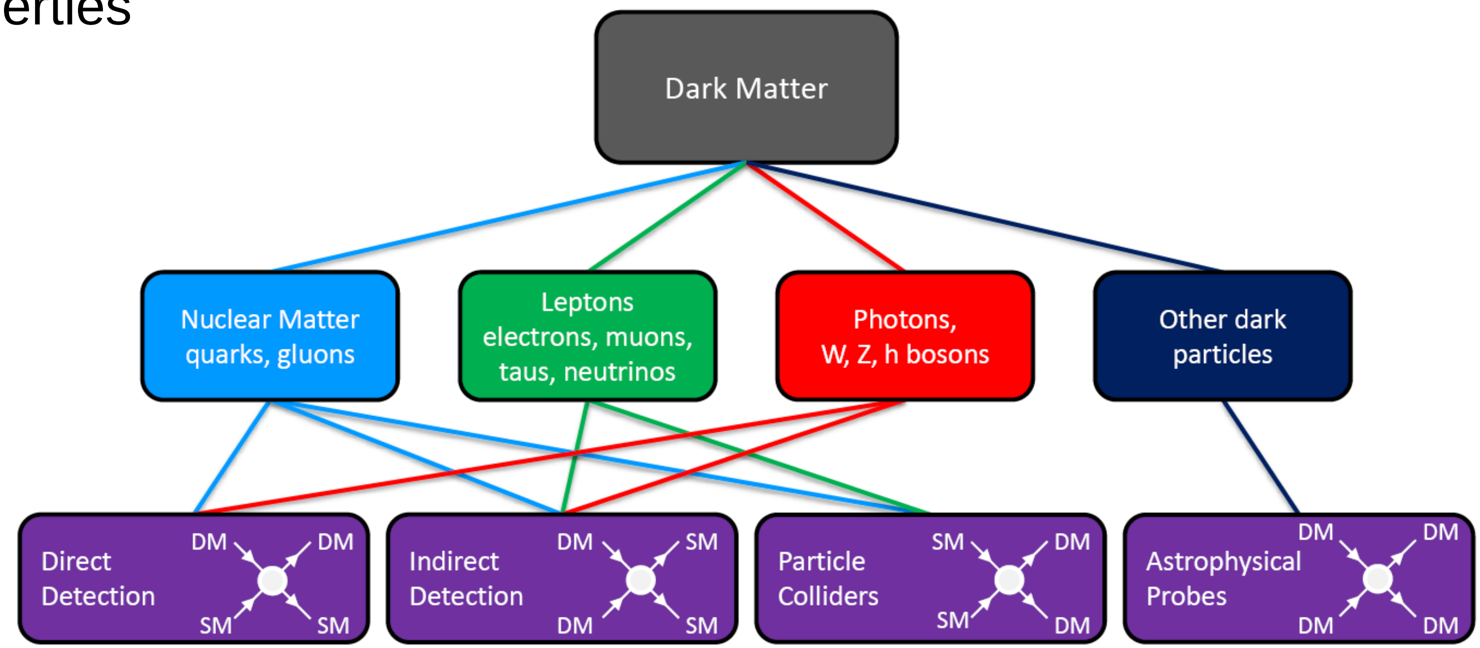


- Favored mass: μeV to meV
- ADMX is projected to cover the first of these three decades in its first year of operations, and the second decade over the following two years

DARK MATTER COMPLEMENTARITY

- Before a signal: Different experimental approaches are sensitive to different dark matter candidates with different characteristics, and provide us with different types of information – complementarity!

- After a signal: we are trying to identify a quarter of the Universe: need high standards to claim discovery and follow-up studies to measure properties



Mass measurement for m > 500 GeV?

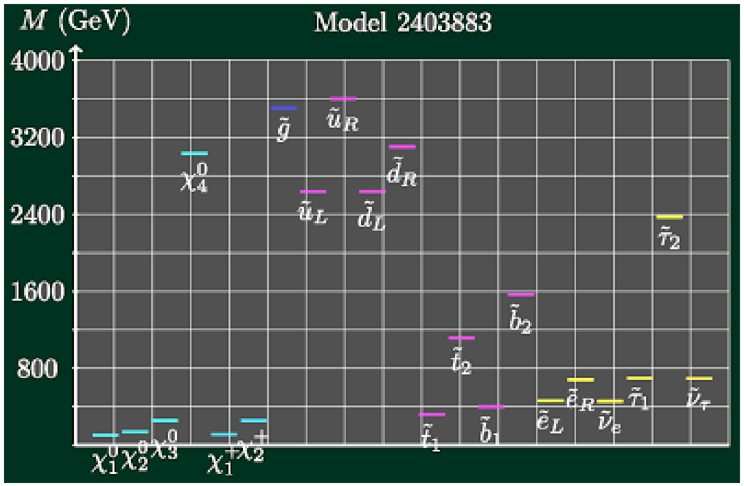
Asymmetric DM?

Lifetime: 10^{-7} s → 10^{17} s?

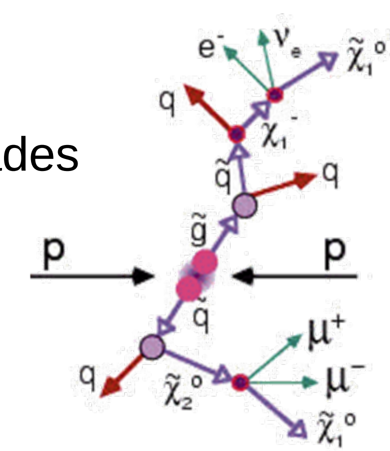
Detailed particle properties?

COMPLEMENTARITY: MODELS

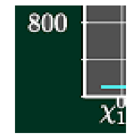
- Full Models (e.g., pMSSM Supersymmetry)



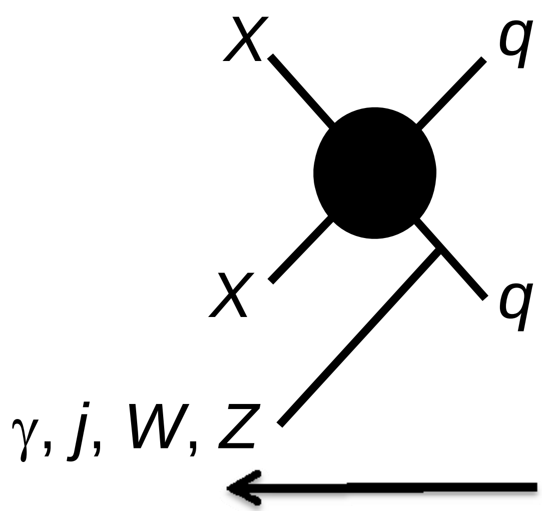
Cascades



- DM Effective Theories (Bare Bones Dark Matter)

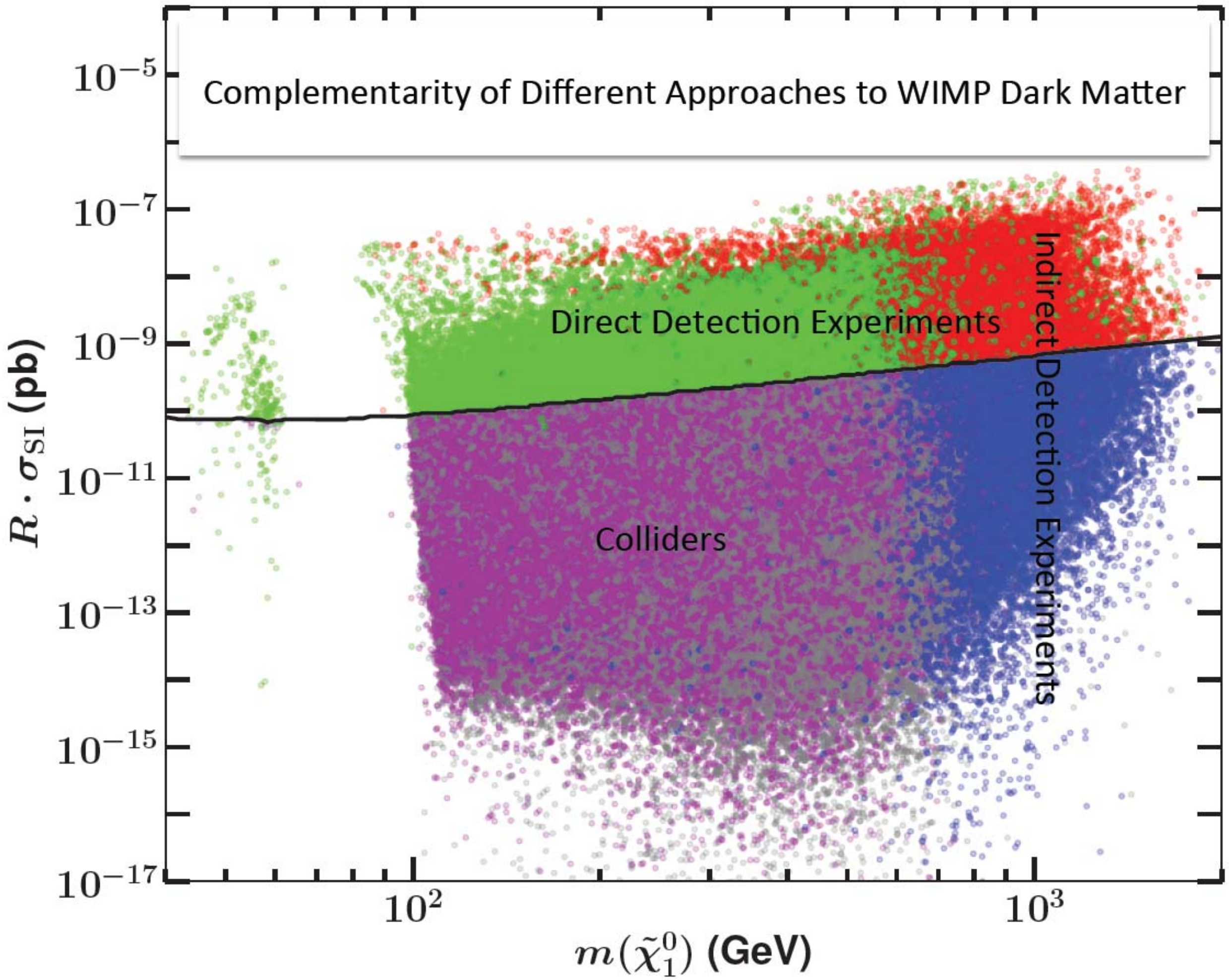


Mono-whatever



COMPLEMENTARITY: FULL MODELS

pMSSM 19-parameter scan of SUSY parameter space



Cahill-Rowley et al. (2013)

Different SUSY models are probed by different experiments

COMPLEMENTARITY: DM EFFECTIVE THEORIES

- Consider dark matter interacting only with leptons

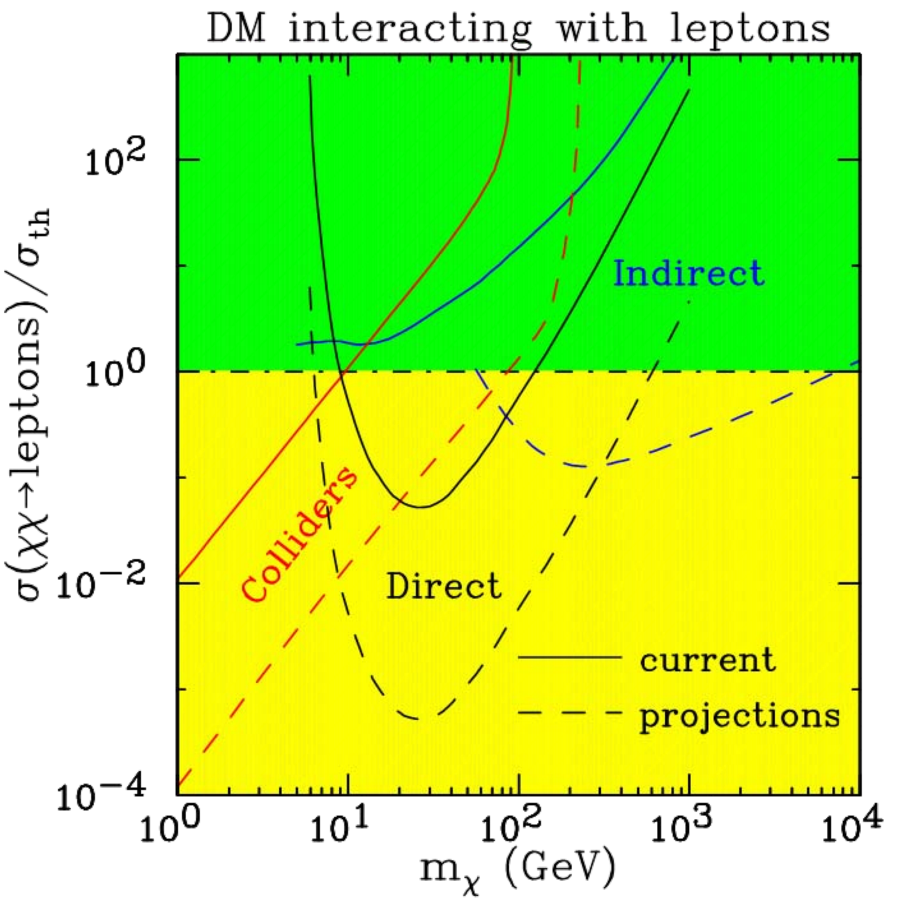
- Best probes:

  Low mass: colliders

  Moderate mass: direct

  High mass: indirect

- Results differ for other assumed interactions, but complementarity remains



Bauer et al. 1305.1605

- Many promising approaches to dark matter, and any compelling signal will have far-reaching implications

DARK MATTER SUMMARY