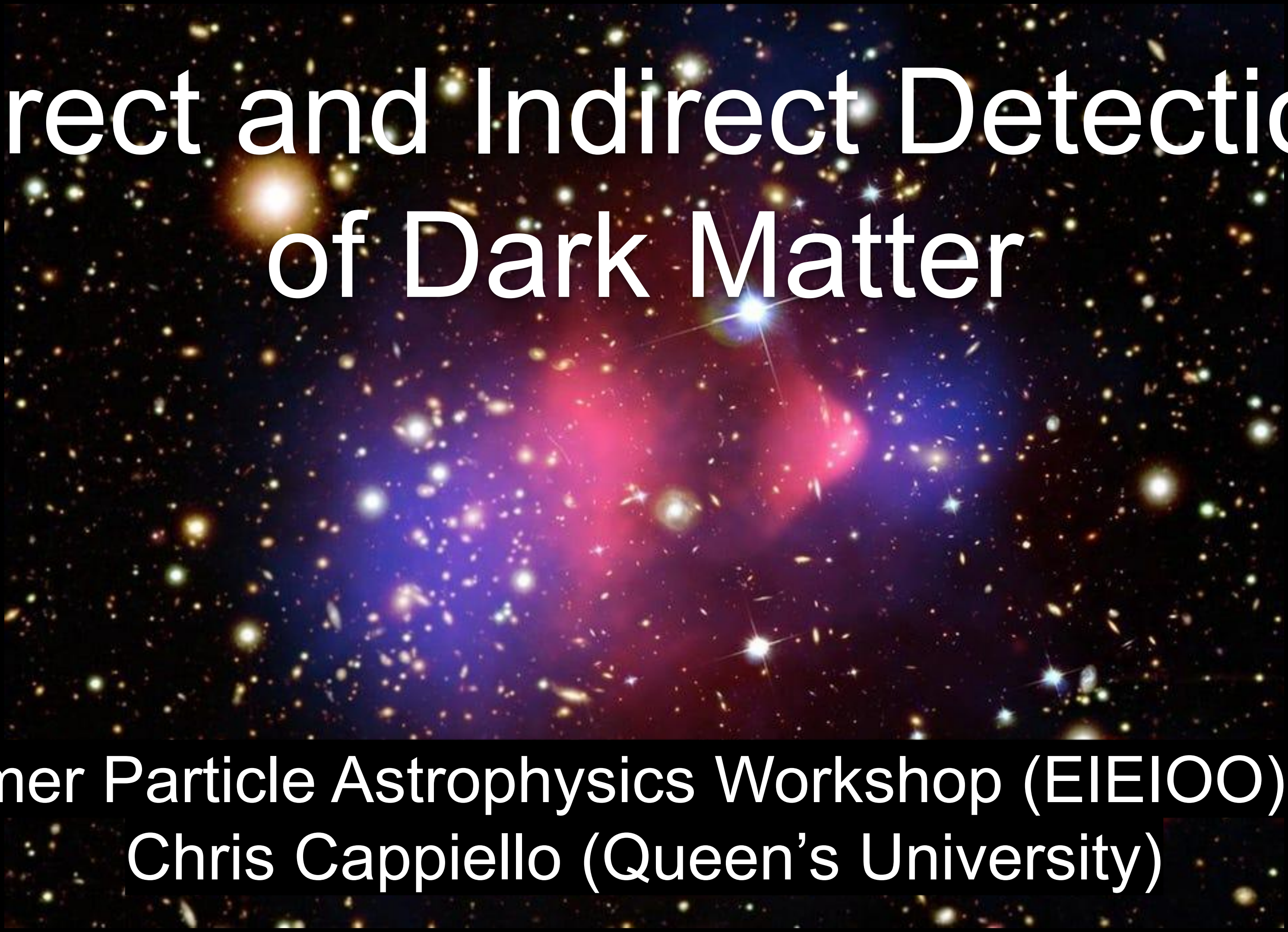
Direct and Indirect Detection of Dark Matter



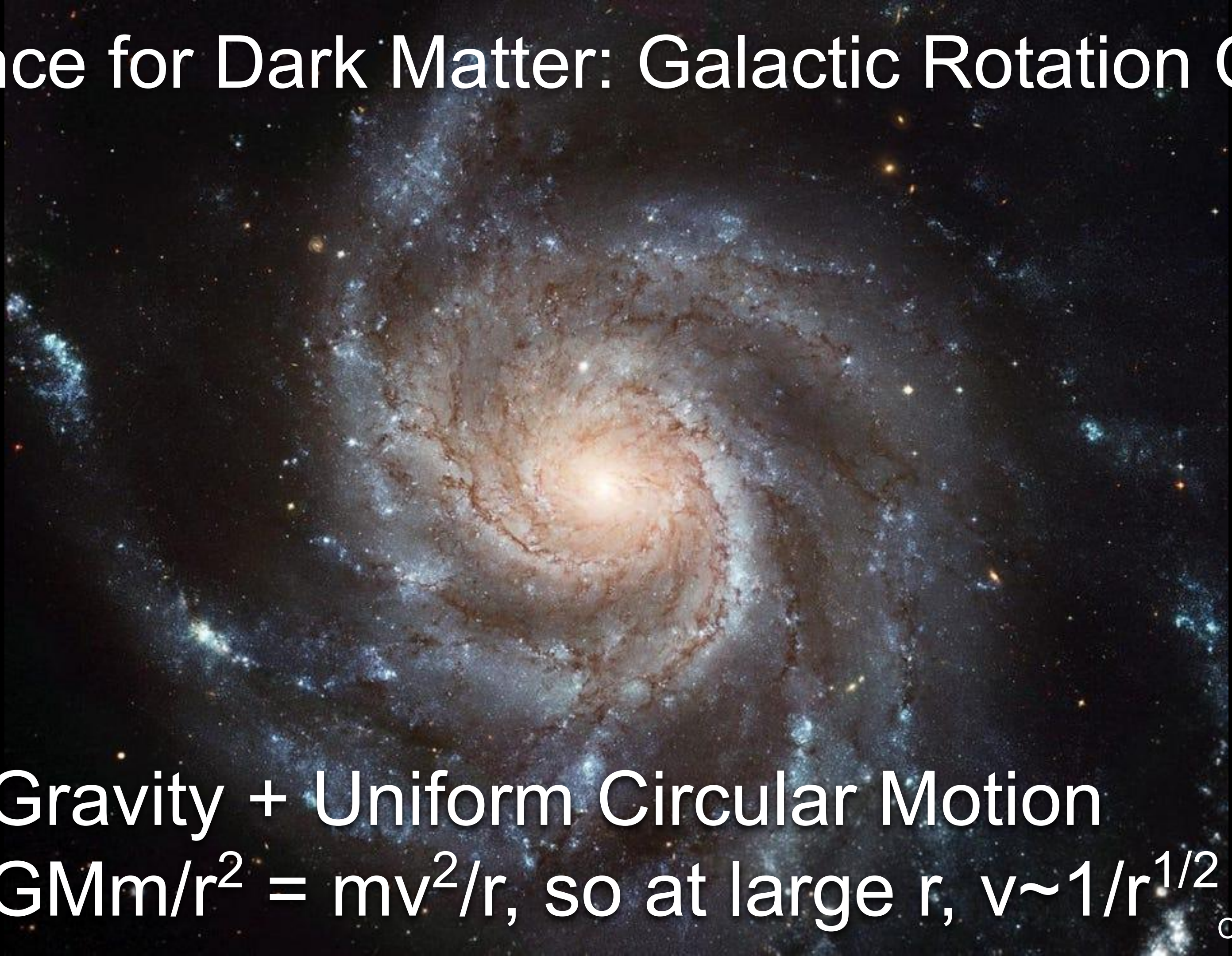
Summer Particle Astrophysics Workshop (EIEIOO) 2023

Chris Cappiello (Queen's University)

Evidence for Dark Matter: Galactic Rotation Curves

Credit: ESA/NASA

Evidence for Dark Matter: Galactic Rotation Curves

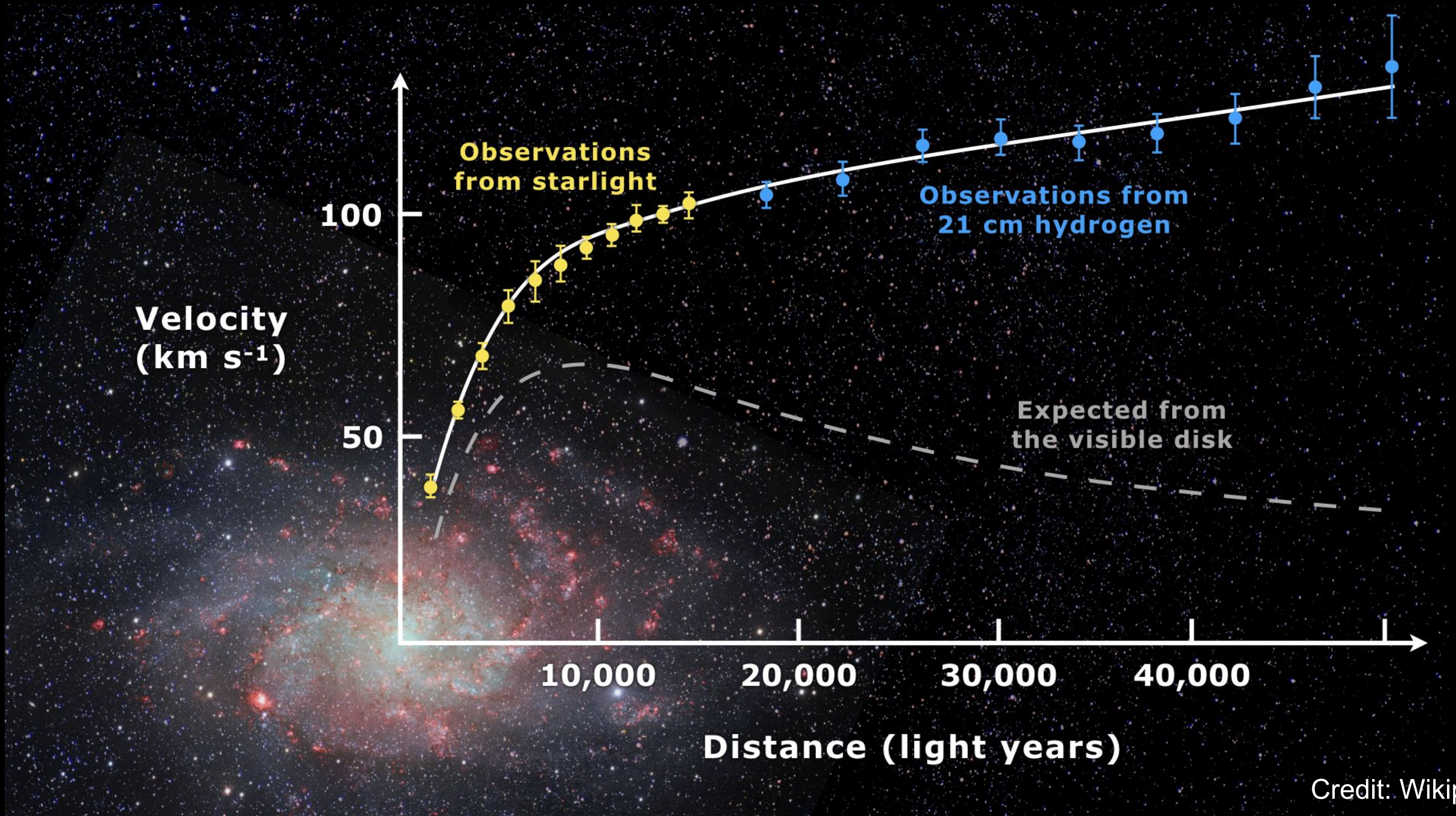


Gravity + Uniform Circular Motion

$GMm/r^2 = mv^2/r$, so at large r, $v \sim 1/r^{1/2}$

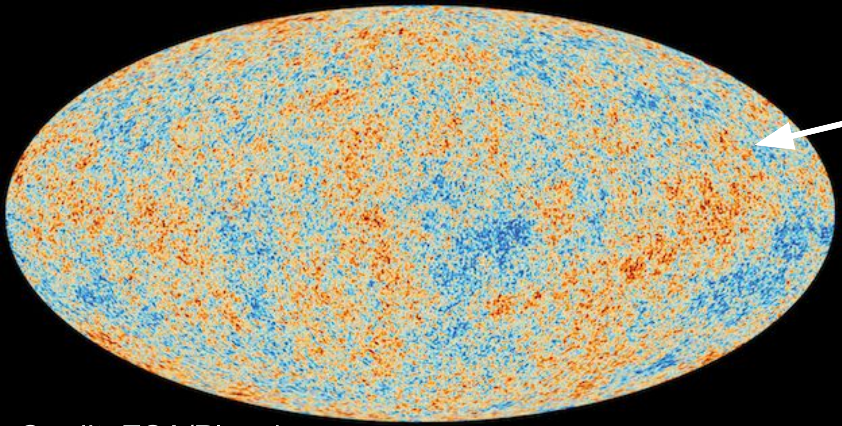
Credit: ESA/NASA

Evidence for Dark Matter: Galactic Rotation Curves



Credit: Wikipedia

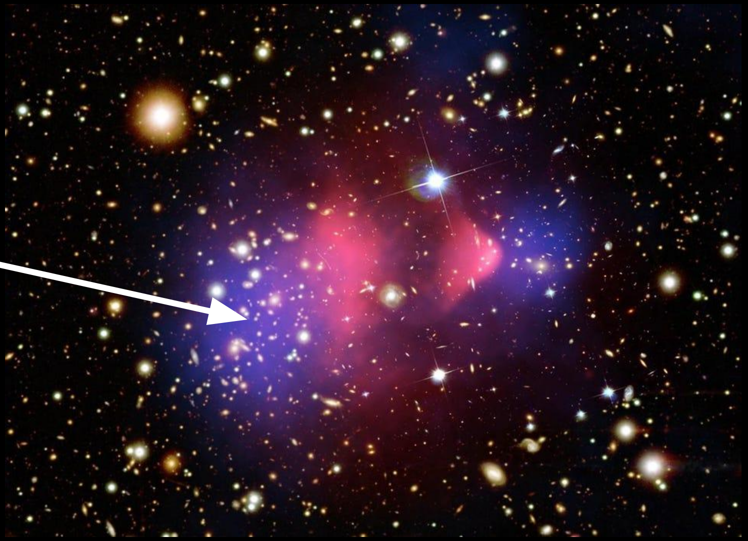
Evidence for Dark Matter: Other Observations



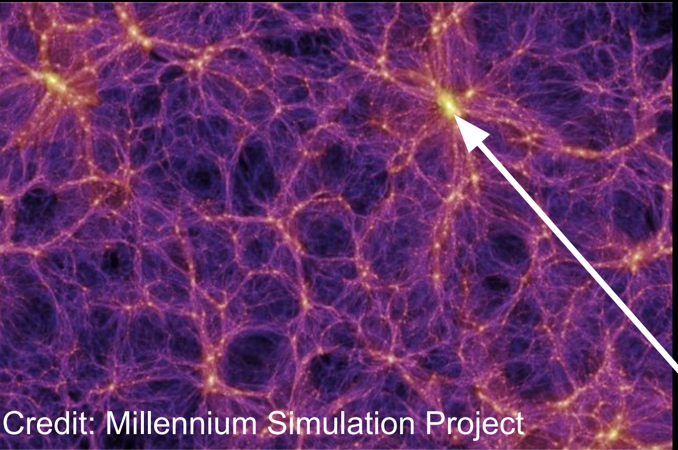
Cosmic Microwave Background (CMB)

Credit: ESA/Planck

Gravitational Lensing



Credit: X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

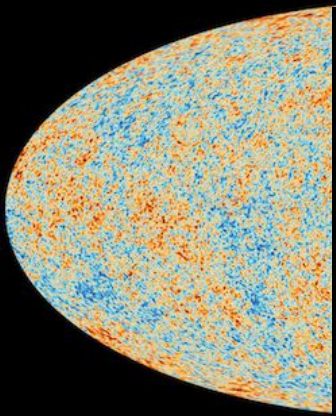


Credit: Millennium Simulation Project

Large Scale Structure

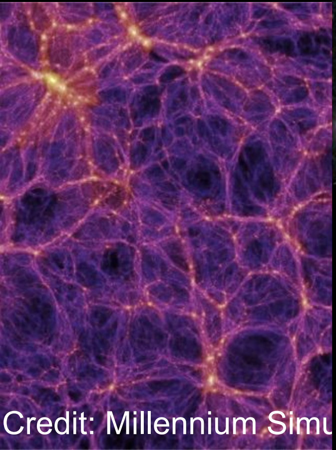
And more…

Evidence for Dark Matter: Other Observations

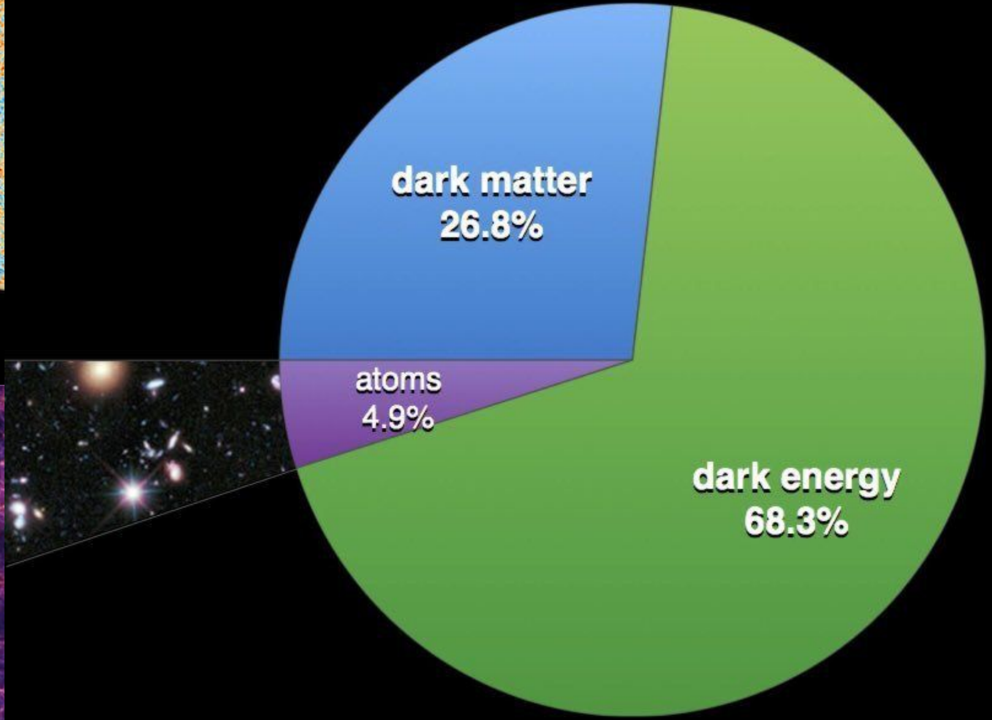


Credit: ESA/Planck

ıd (CMB)



Credit: Millennium Simu



@AstroKatie/Planck13

:VITCH ET AL.; LENSING MAP:
RIZONA/D.CLOWE ET AL.;
RIZONA/D.CLOWE ET AL.

And more…

Why Haven’t We Detected Dark Matter?

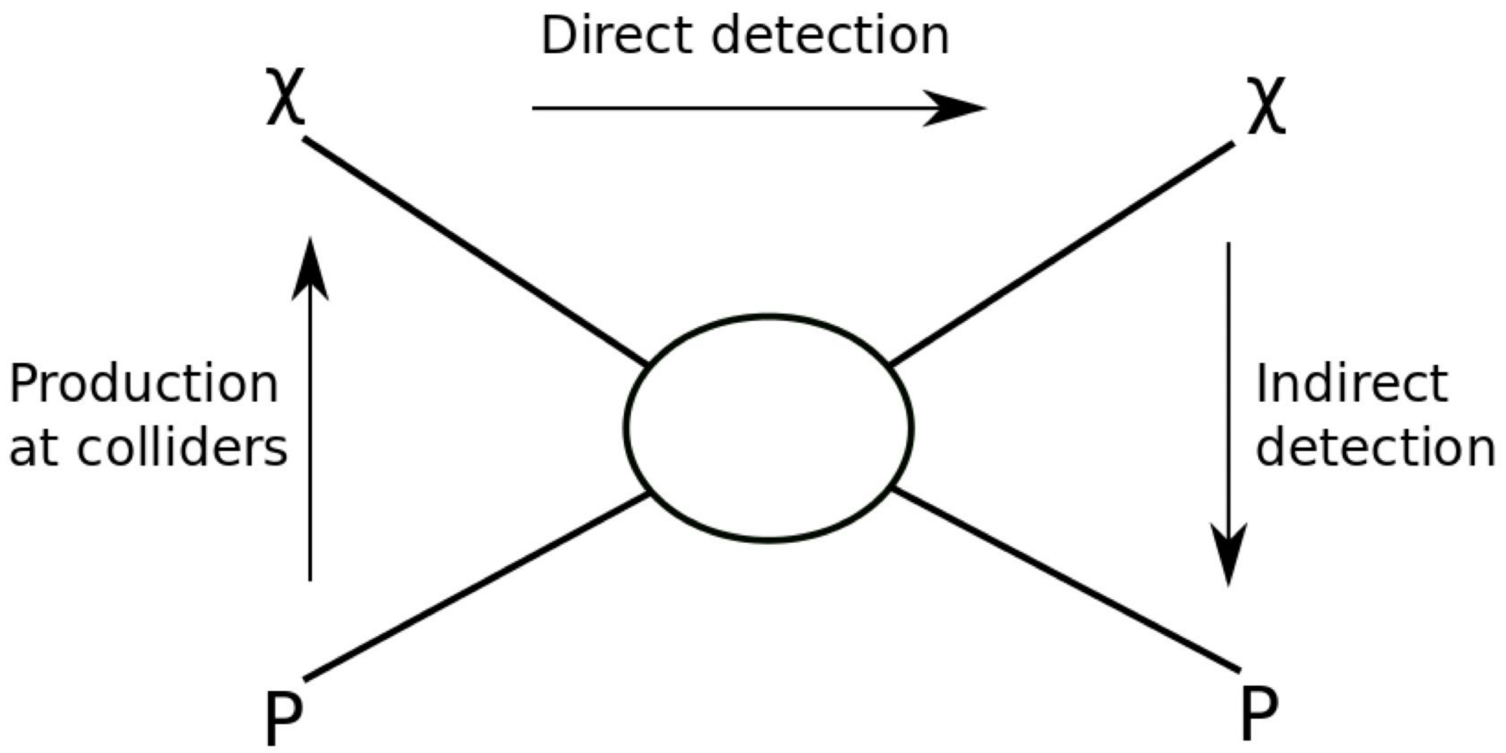
Why Haven’t We Detected Dark Matter?

Option 1: Very weakly interacting (WIMP?)

Why Haven’t We Detected Dark Matter?

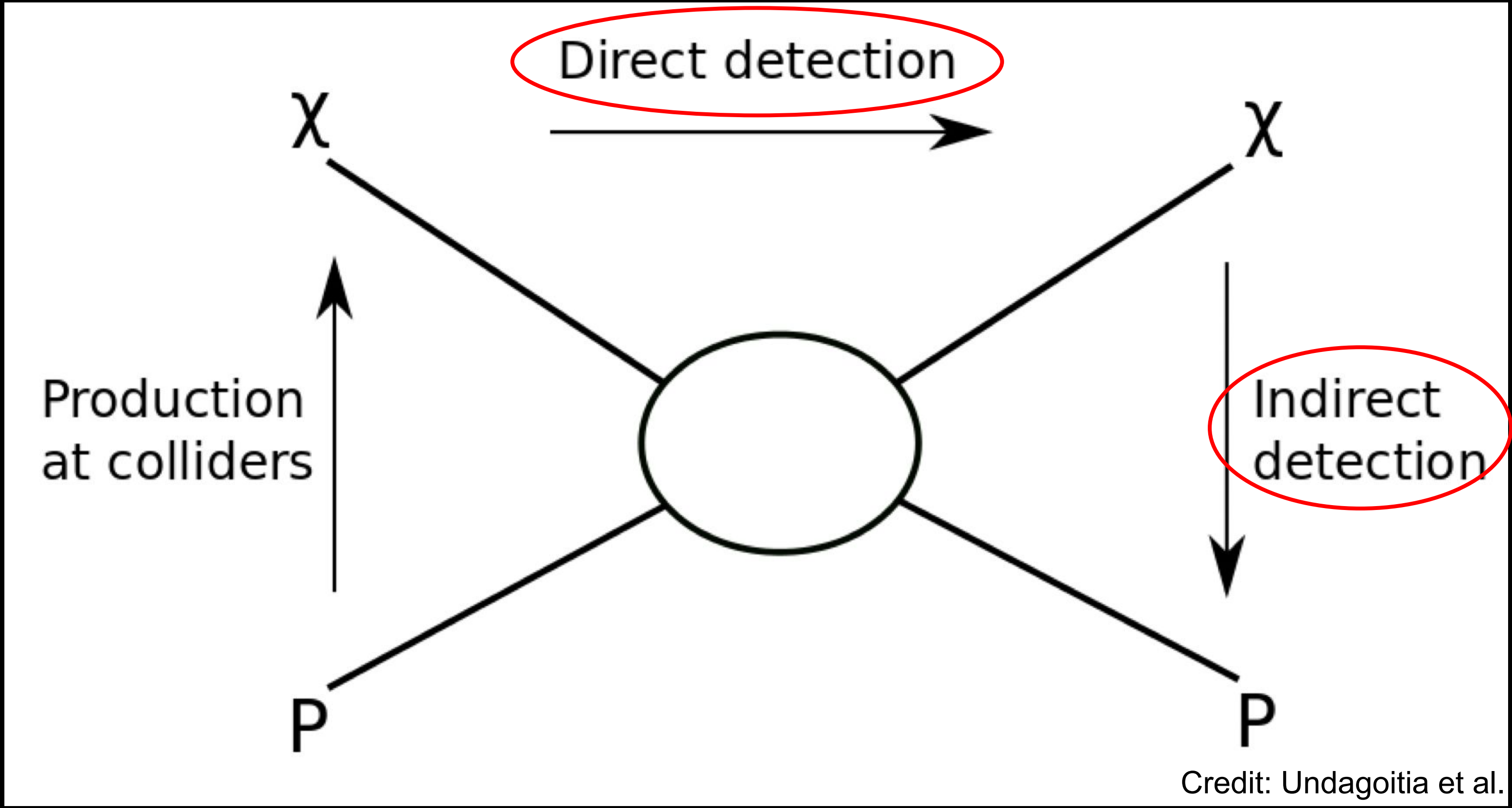
Option 1: Very weakly interacting (WIMP?)
Option 2: Too light to detect (Axions/ALPs)
Option 3: Too rare to detect (Black holes?)
And more…

Searching for Dark Matter

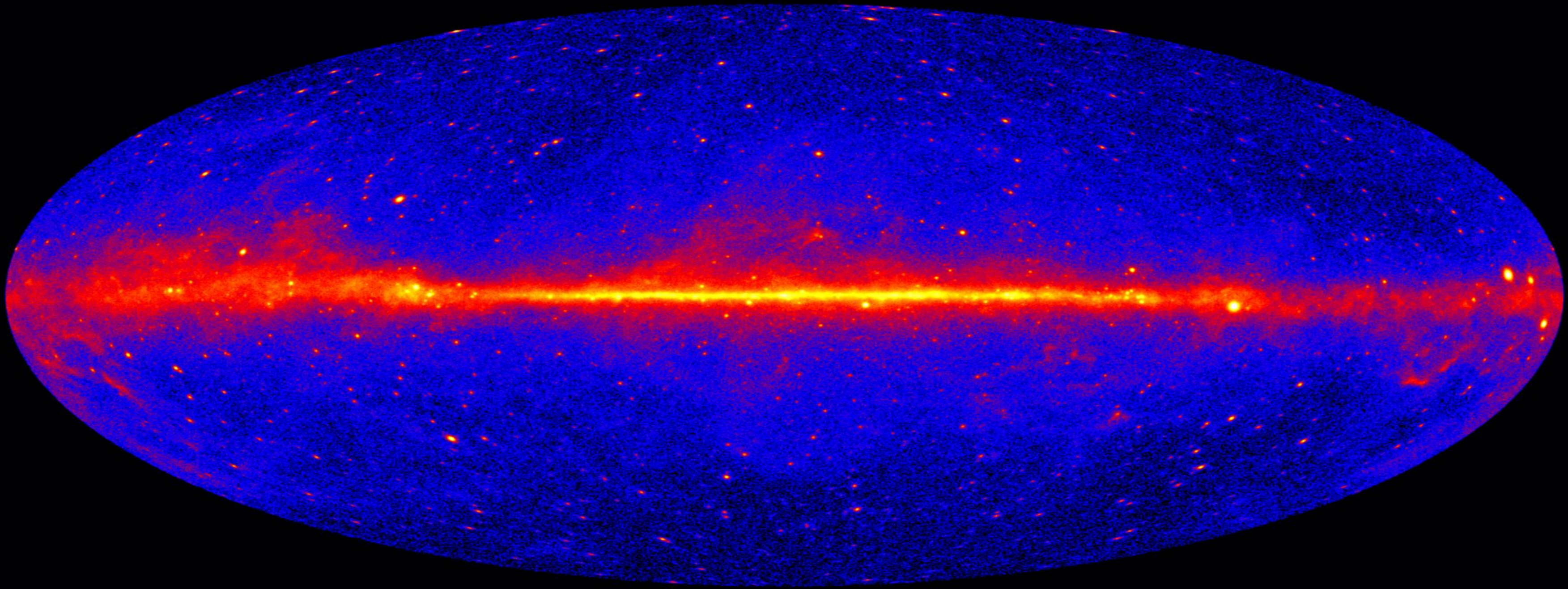


Credit: Undagoitia et al.

Searching for Dark Matter

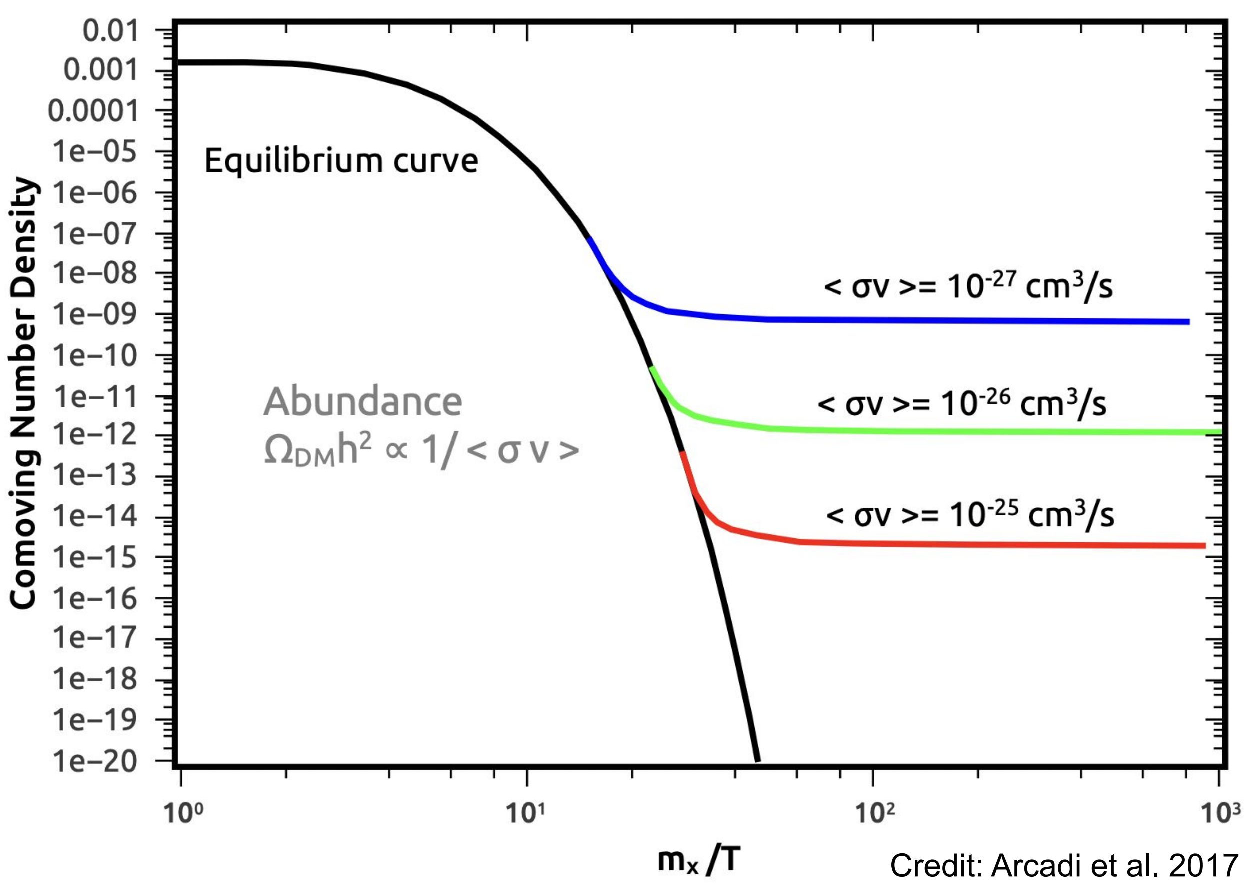


Dark Matter Indirect Detection



Credit: NASA/DOE/Fermi-LAT

Dark Matter Annihilation: The WIMP Miracle



Credit: Arcadi et al. 2017

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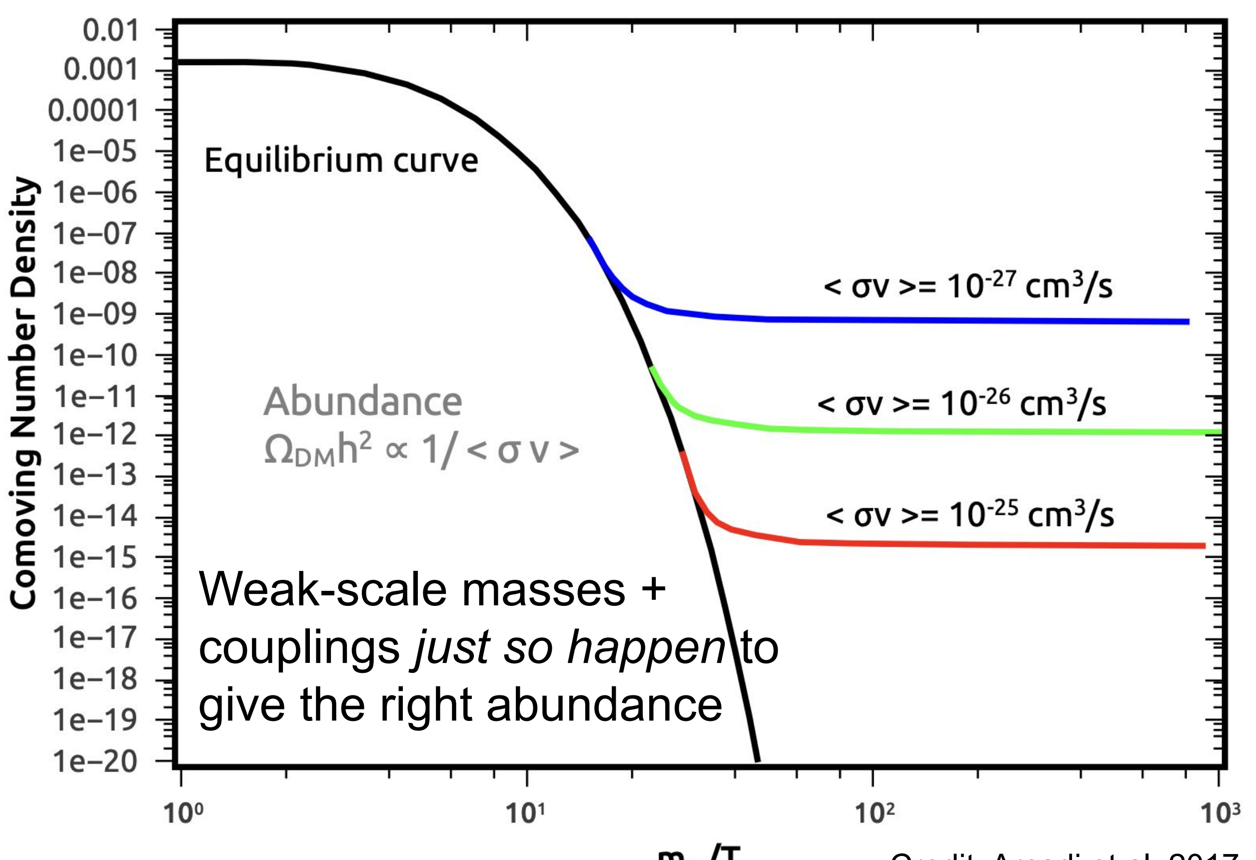


Credit: Arcadi et al. 2017

If dark matter annihilation took place in the early universe, it could still be happening today!

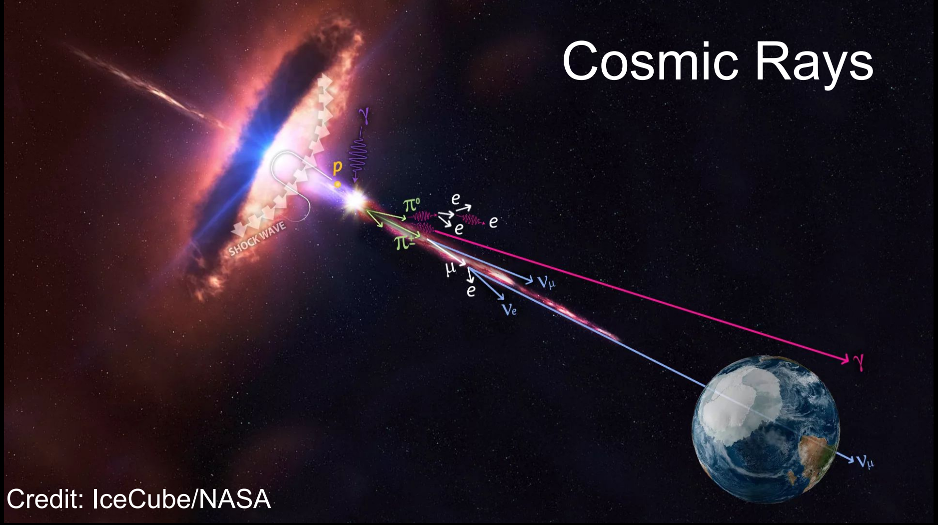
If dark matter annihilation took place in the early universe, it could still be happening today!

$\Gamma = n_x^2 \langle \sigma v \rangle$ so look for places where $n_x \sim \rho_x$ is large

Galaxy Clusters

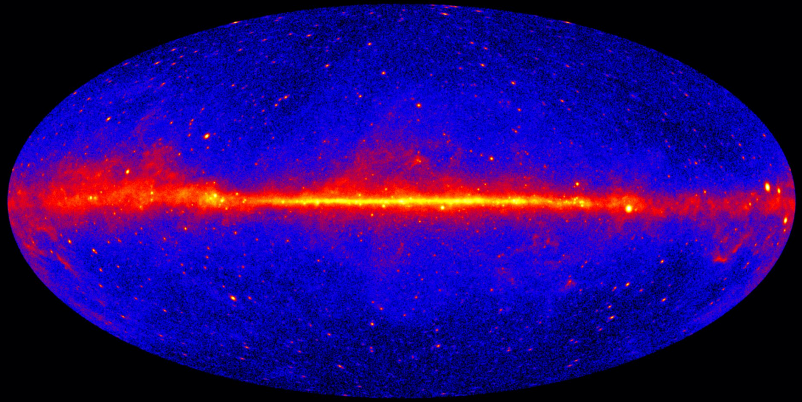
Credit: X-RAY: NASA/CXC/CFA/M.MARKEVITCH ET AL.; LENSING MAP: NASA/STSCI; ESO WFI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.; OPTICAL: NASA/STSCI; MAGELLAN/U.ARIZONA/D.CLOWE ET AL.

Cosmic Rays



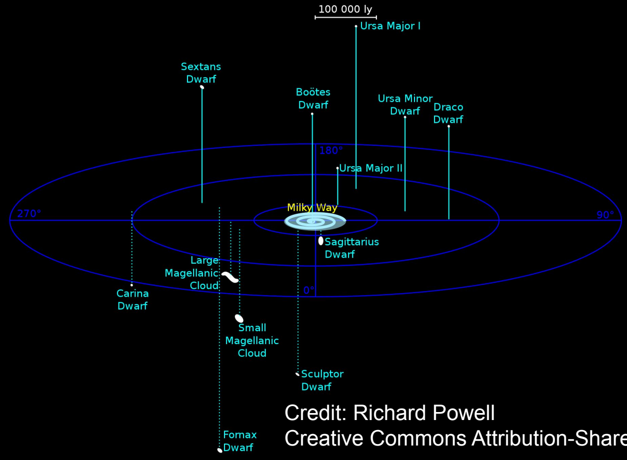
Credit: IceCube/NASA

Galactic Center



Credit: NASA/DOE/Fermi-LAT

Dwarf Galaxies



Credit: Richard Powell
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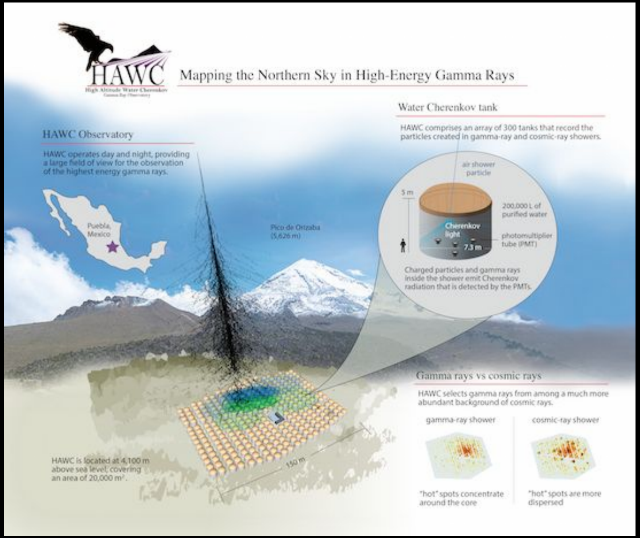
Dark Matter Annihilation/Decay to Photons

Credit: NASA/Fermi-LAT



Credit: Wisconsin IceCube Particle Astrophysics Center

Credit: ESA

Why Would Dark Matter Annihilate or Decay to Photons?

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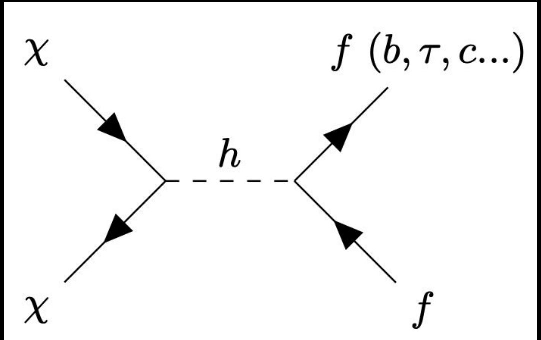

Heavy quarks and leptons decay producing pions and gamma rays

Credit: Foster et al. 2022

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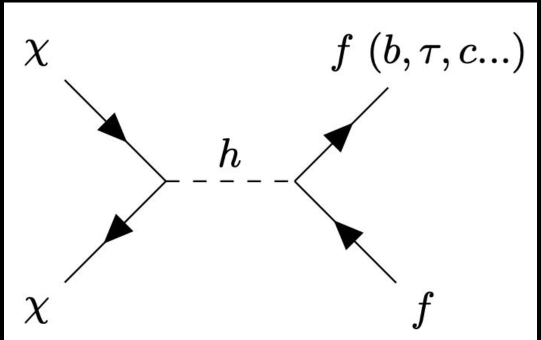

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Stable particles annihilate, produce final state radiation, Inverse Compton emission…

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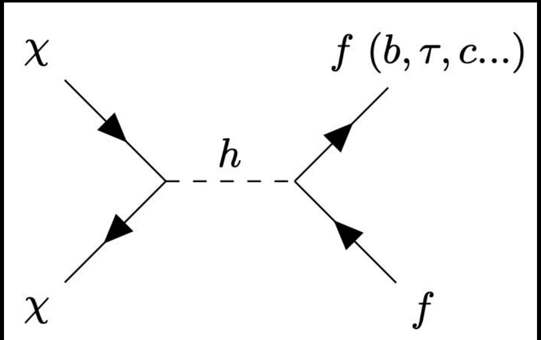
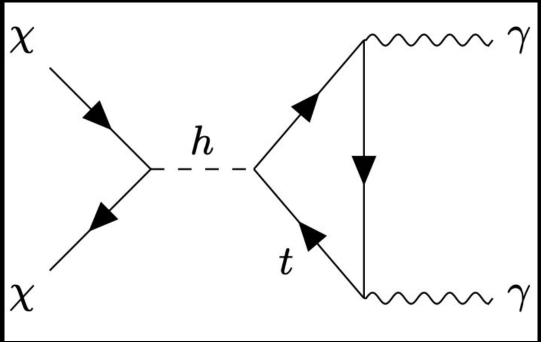


Heavy quarks and leptons decay producing pions and gamma rays

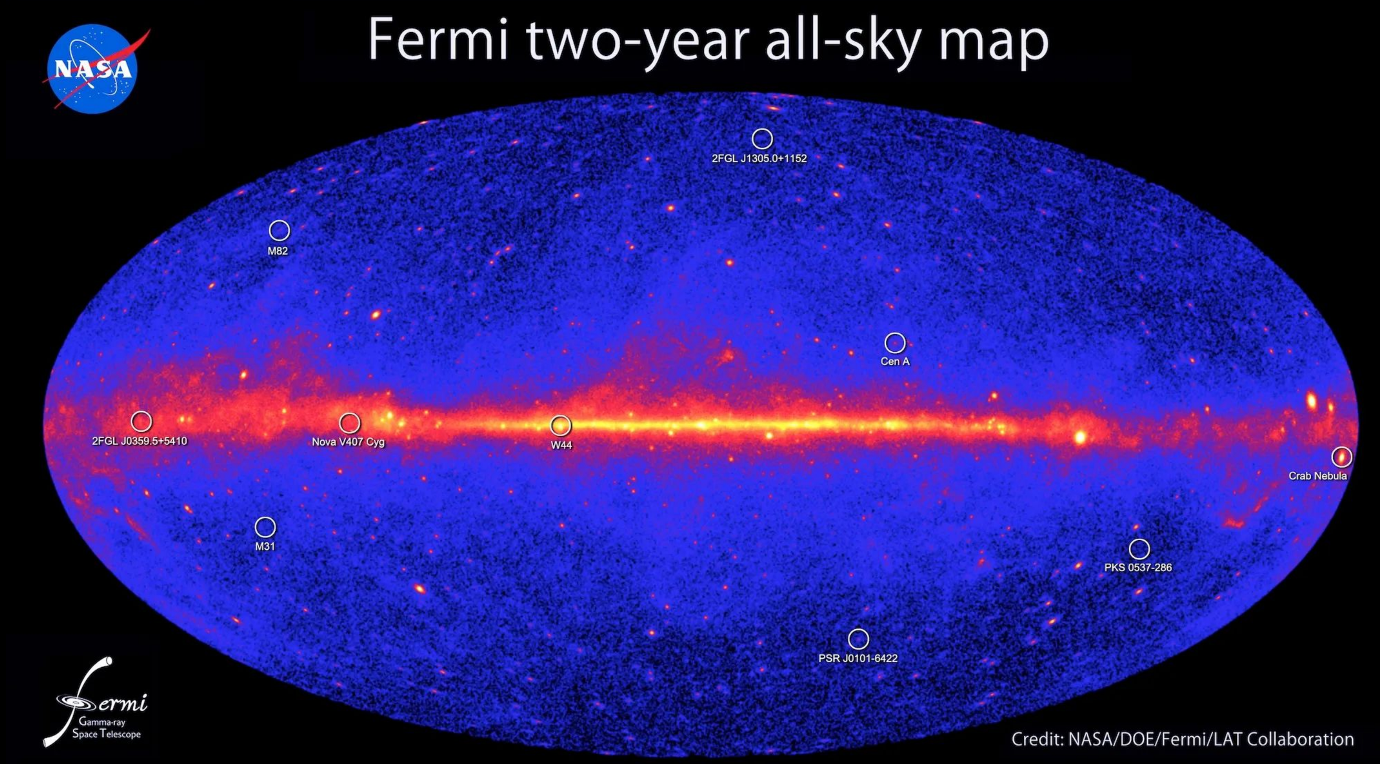
Stable particles annihilate, produce final state radiation, Inverse Compton emission…

Loop-induced decay to gamma ray lines

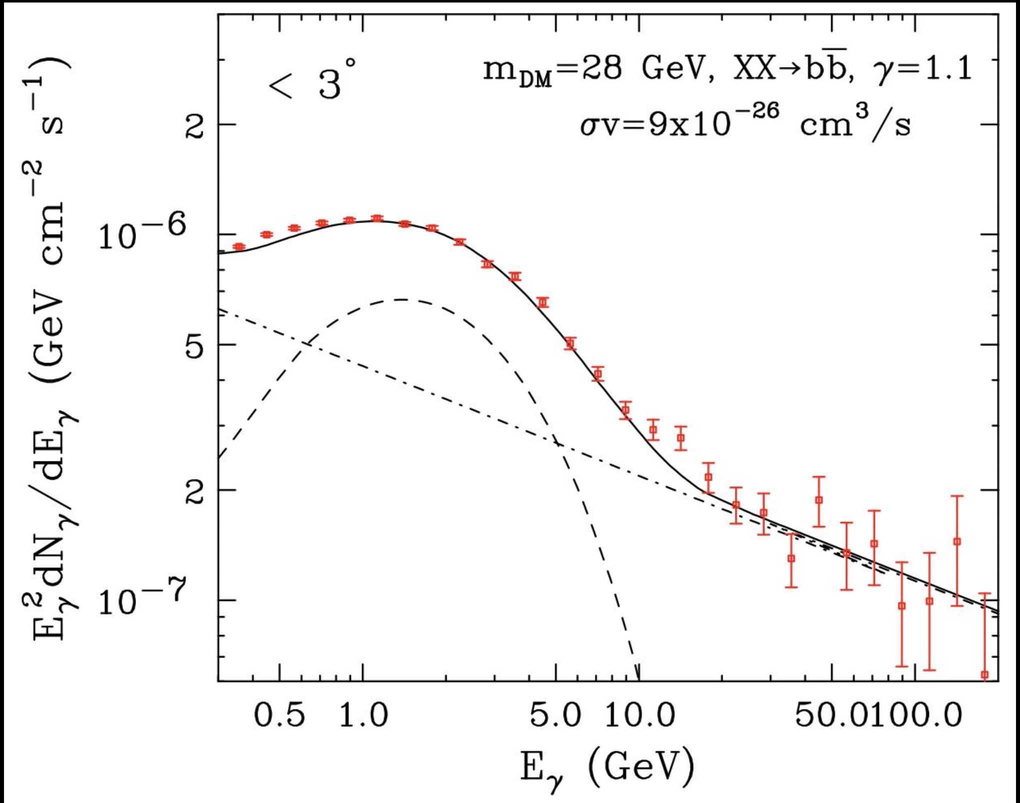


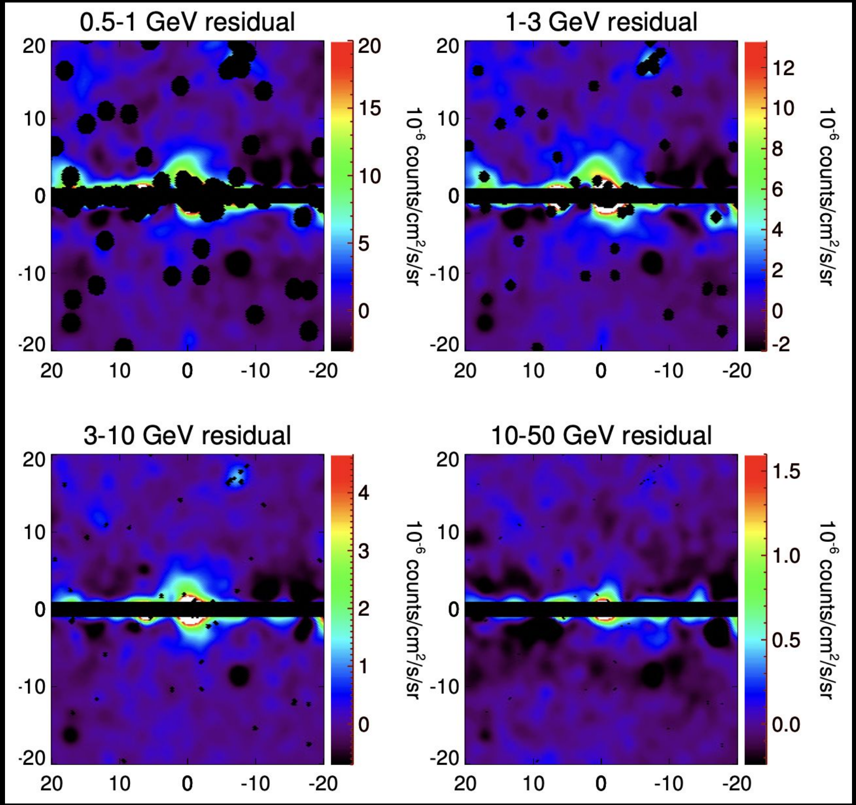
Credit: Foster et al. 2022

Fermi-LAT Observations of the Galactic Center



Fermi GeV Excess (Since 2009)



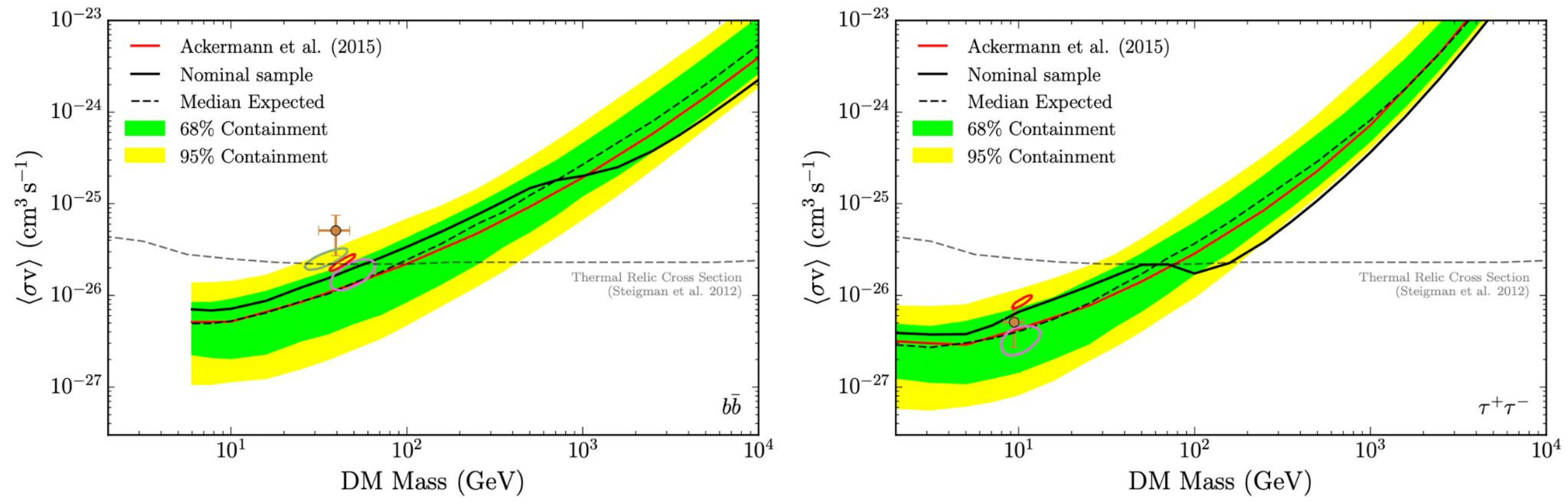


Credit: Goodenough & Hooper 2009

Credit: Daylan et al. 2016

Dwarf Galaxies with Fermi

- Dwarf galaxies smaller than the Milky Way, but have much less background
- Slight tension with galactic center excess, but not conclusive
- Dwarfs can test WIMP models by excluding the required relic cross section

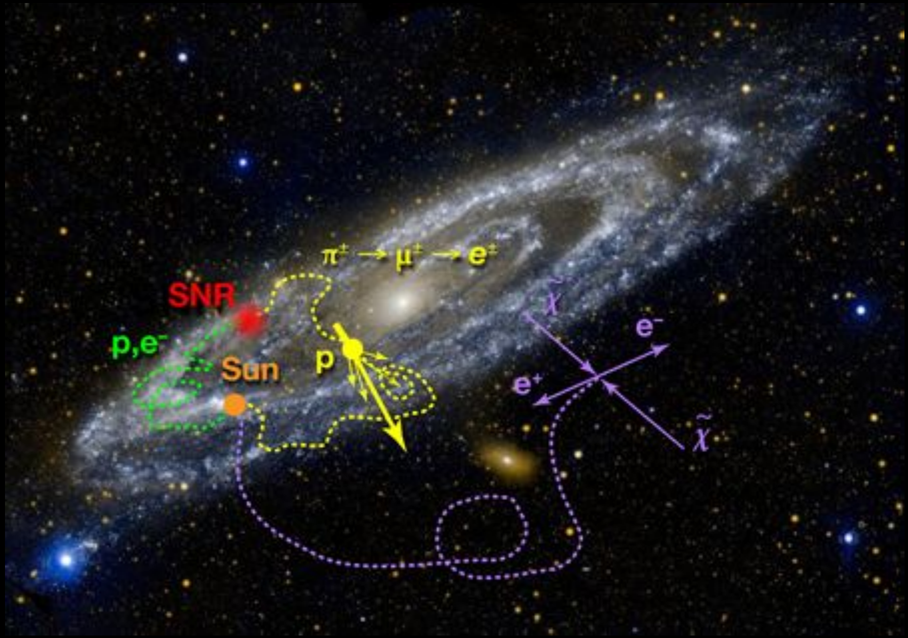


Credit: Albert et al. 2017

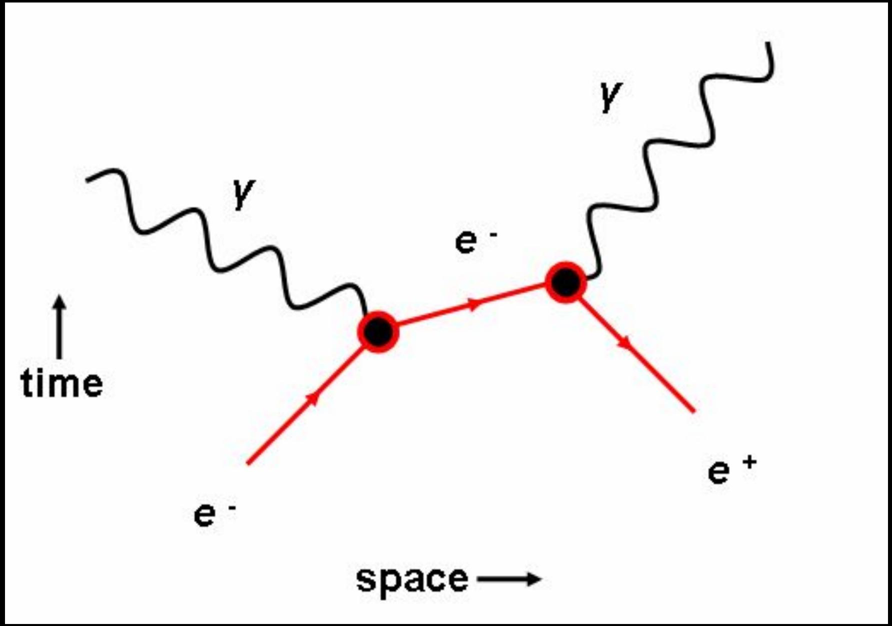
Annihilation to Electrons

Search for positrons in CR spectra

Search for 511 keV photons from electron-positron annihilation

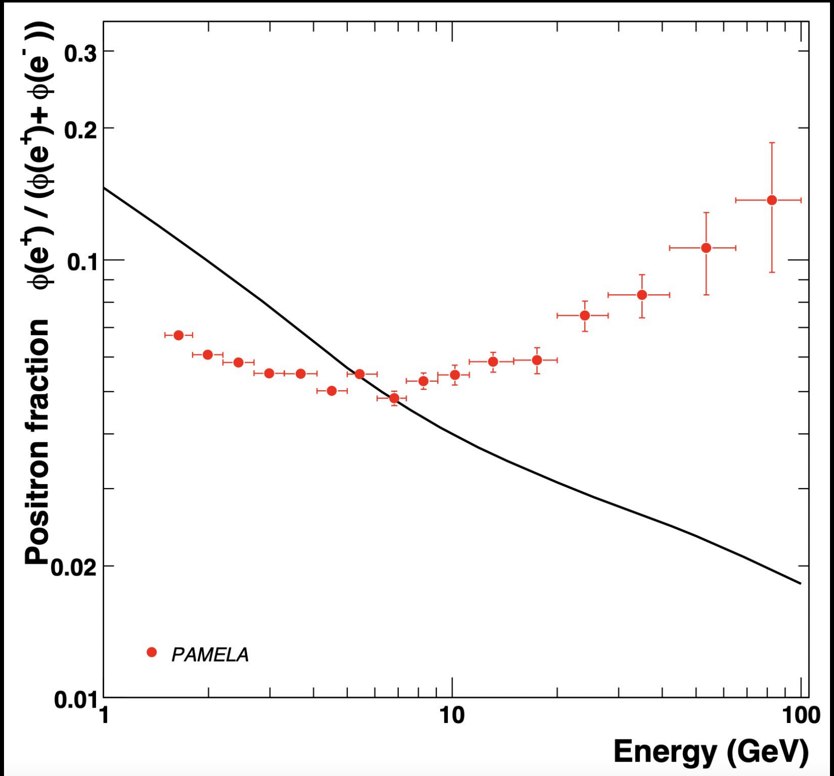


Credit: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker



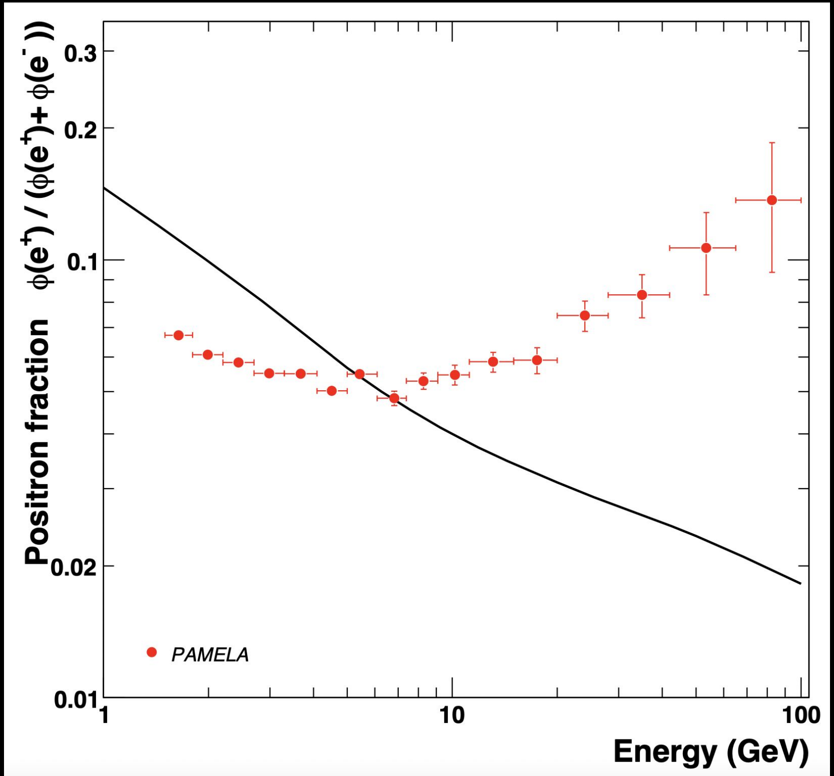
Credit: Wikipedia

Cosmic Ray Positron Excess

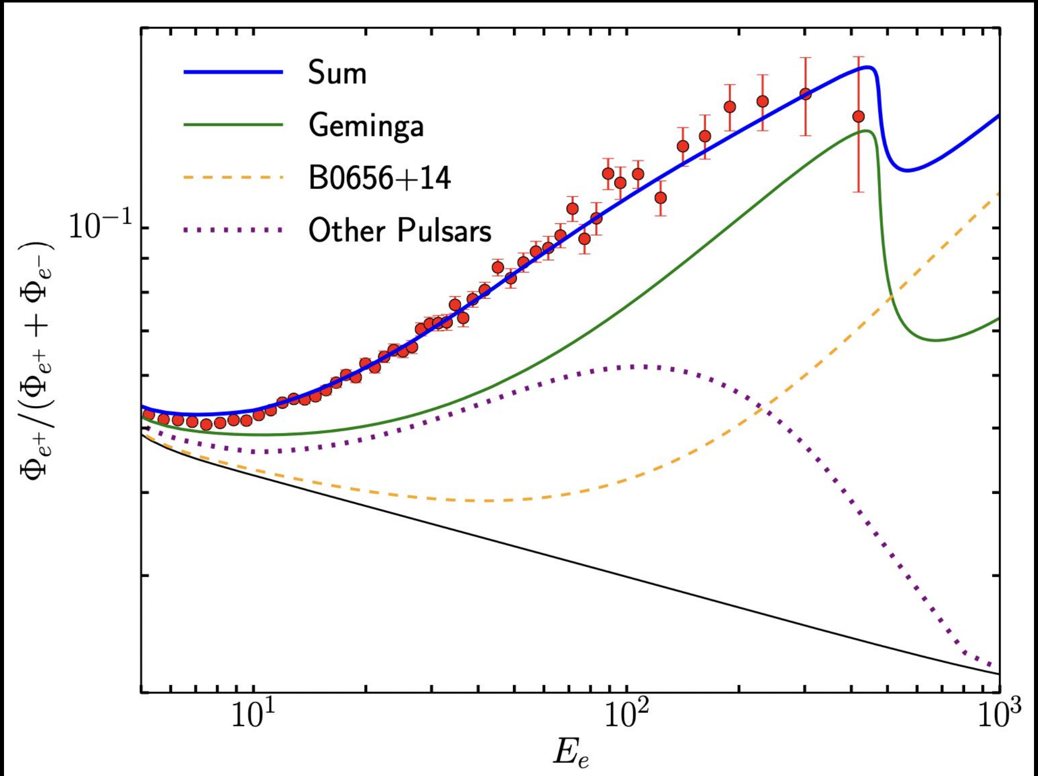


Credit: Adriani et al. 2008

Cosmic Ray Positron Excess



Credit: Adriani et al. 2008



Credit: Hooper et al. 2017

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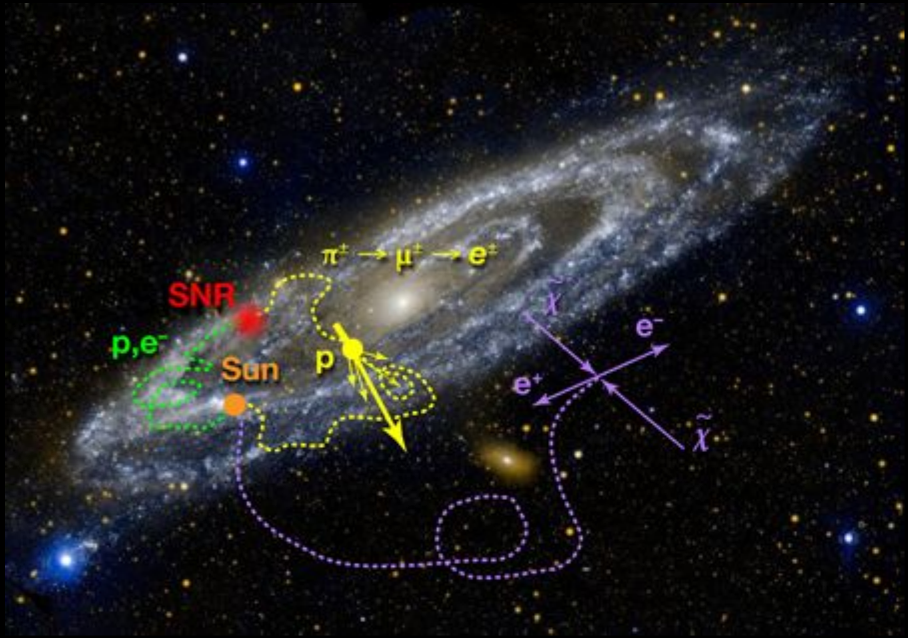

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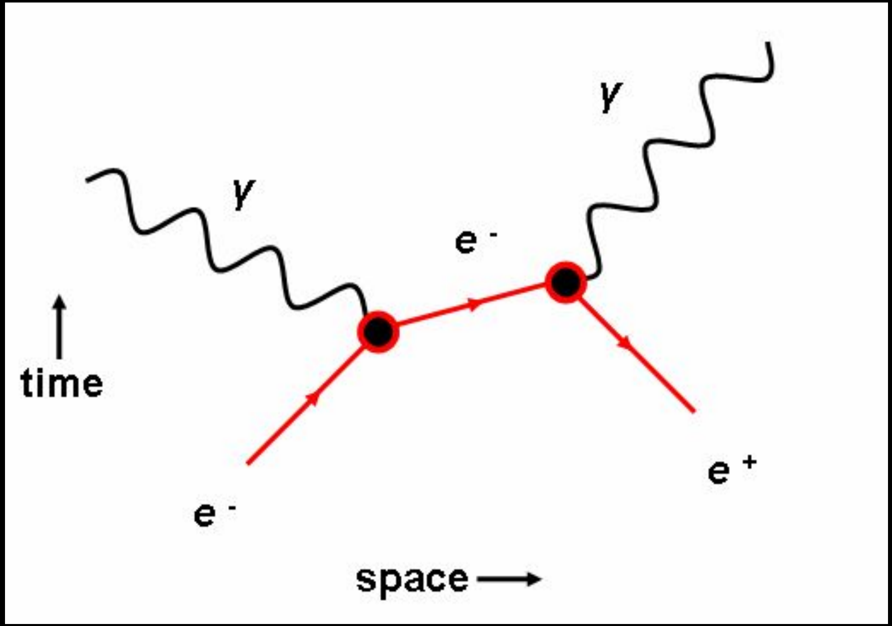
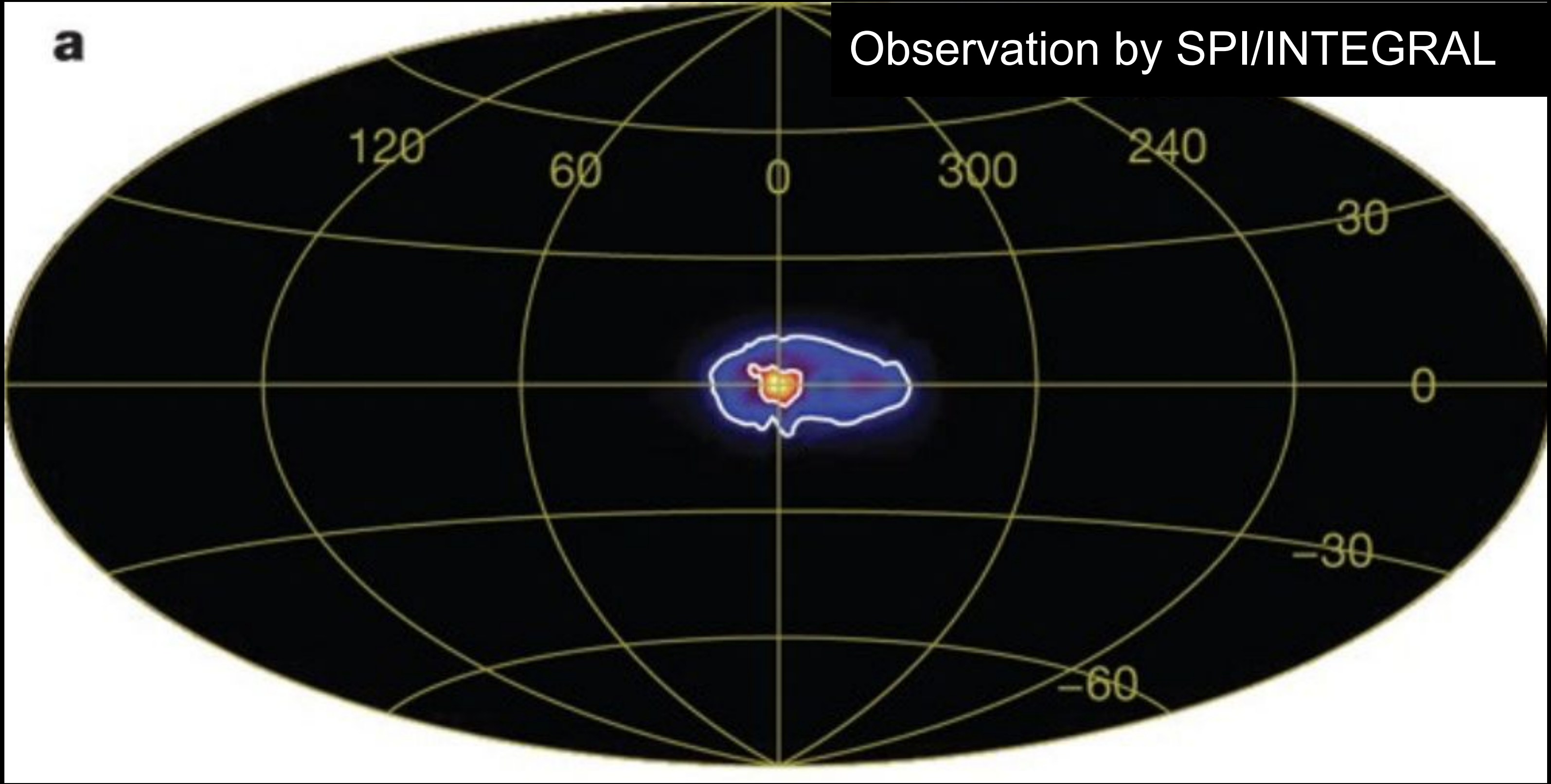


Credit: Wikipedia

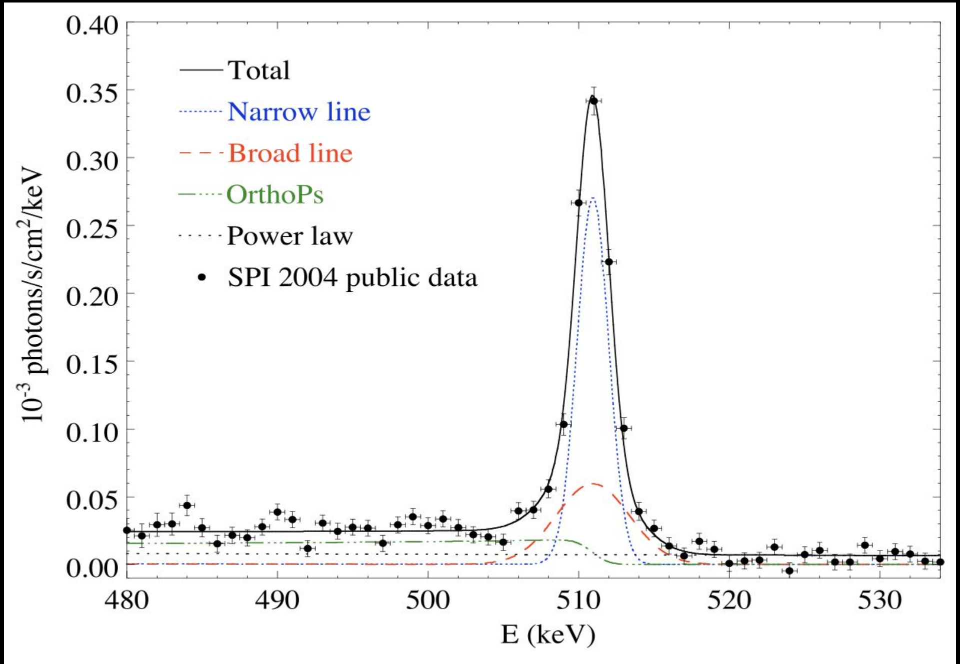
511 keV Excess (Since 1972)



Observation by SPI/INTEGRAL

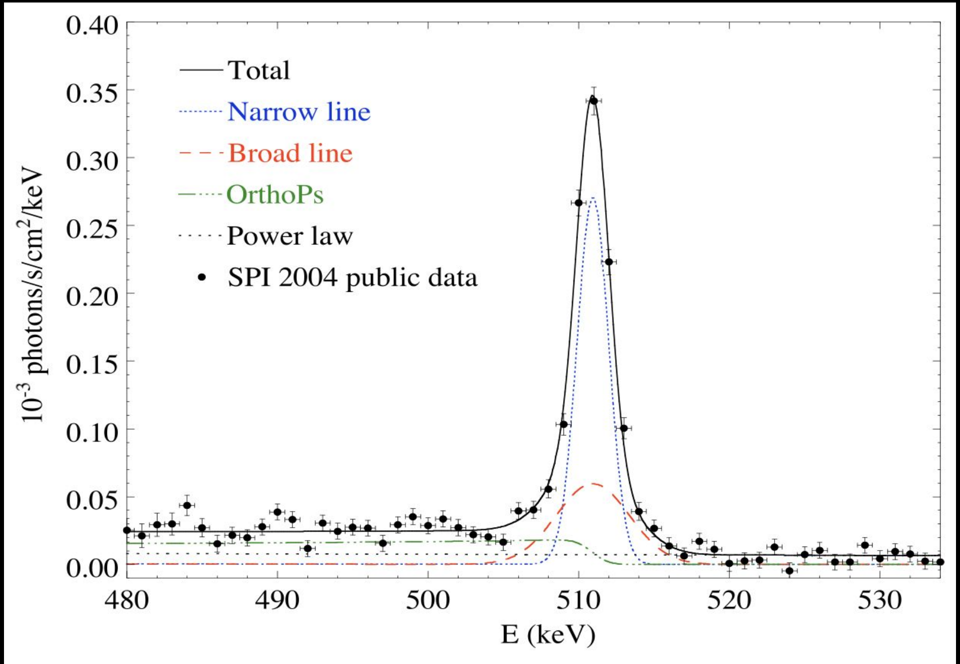
Credit: Weidenspointner et al. 2008

511 keV Excess (Since 1972)



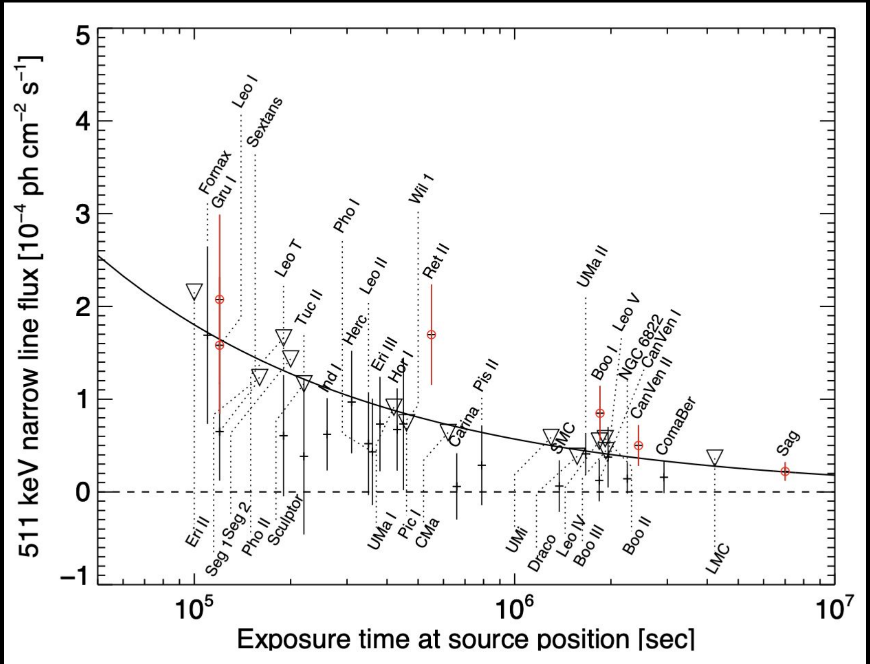
Credit: Jean et al. 2006

511 keV Excess (Since 1972)



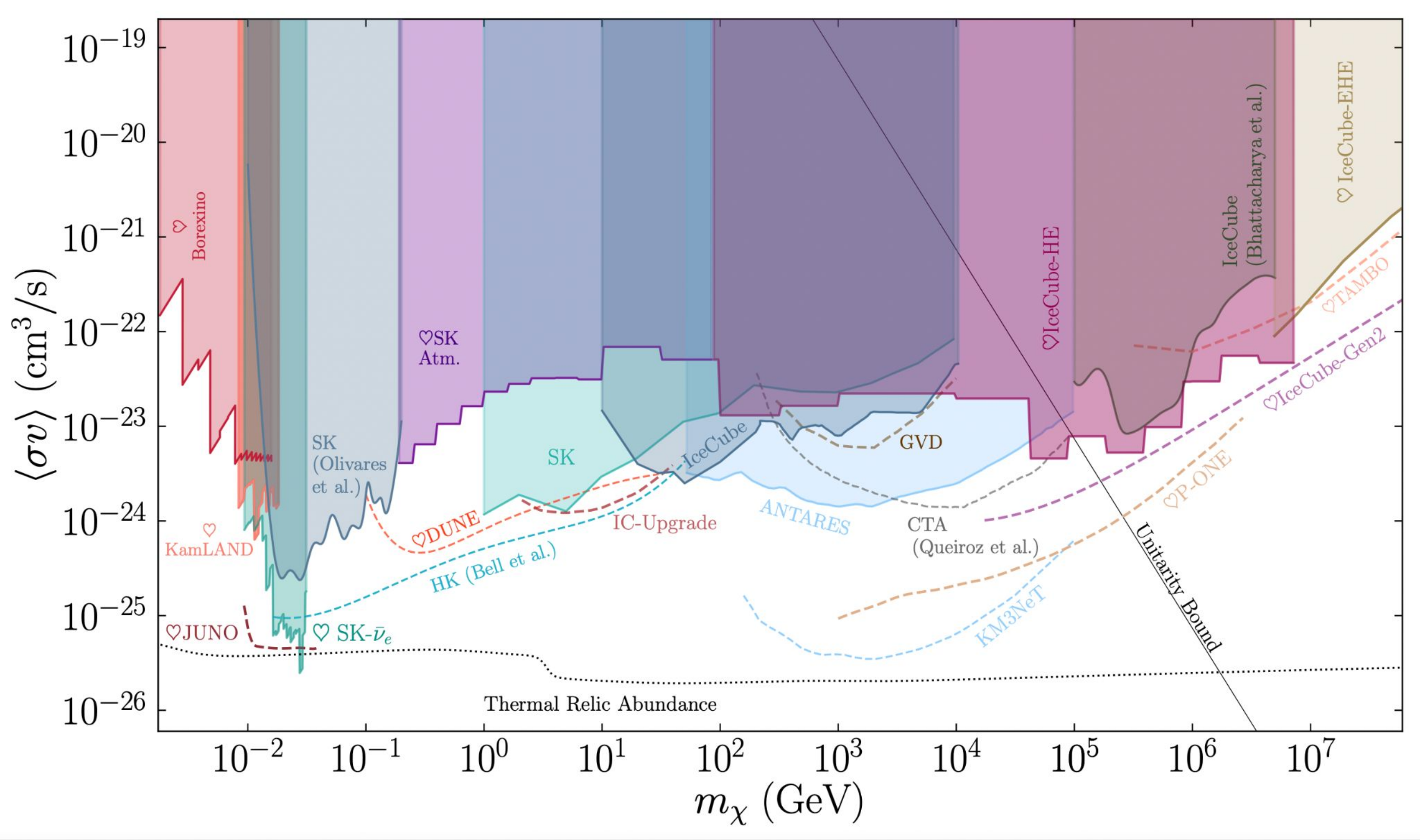
Credit: Jean et al. 2006

Dwarf Galaxy Observations (INTEGRAL)



Credit: Siegert et al. 2016

Annihilation to Neutrinos

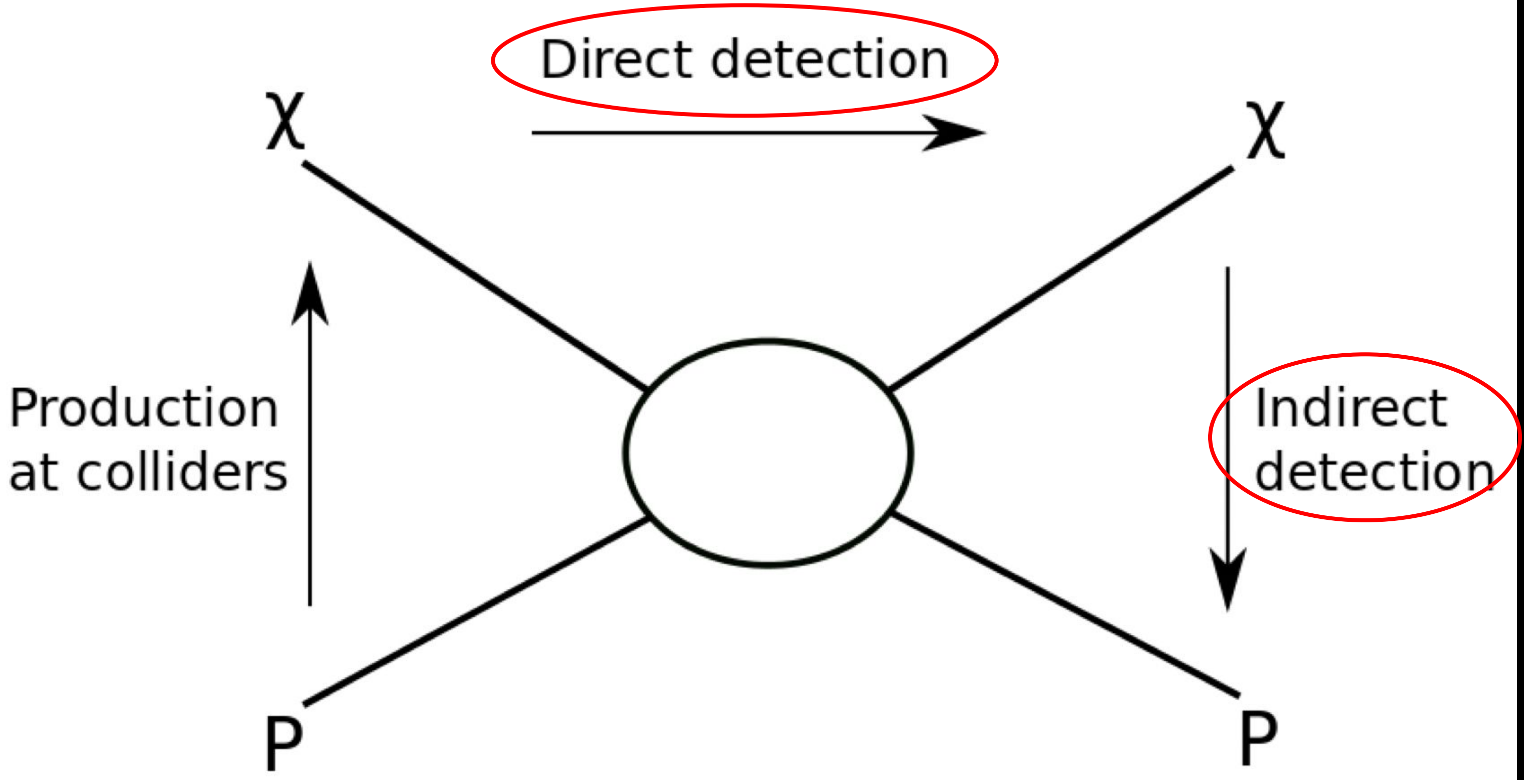


Credit: Argüelles et al. 2021

Indirect Detection: Key Takeaways

- Can search for dark matter annihilation to various products across many orders of magnitude in mass/energy
- Several excesses seen in e.g. gamma rays, cosmic rays
- Standard Model backgrounds can mimic a dark matter signal–modeling backgrounds is crucial
- Can look at different galaxies to try to understand signals coming from our own galaxy

Searching for Dark Matter



Credit: Undagoitia et al.

Dark Matter Direct Detection

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

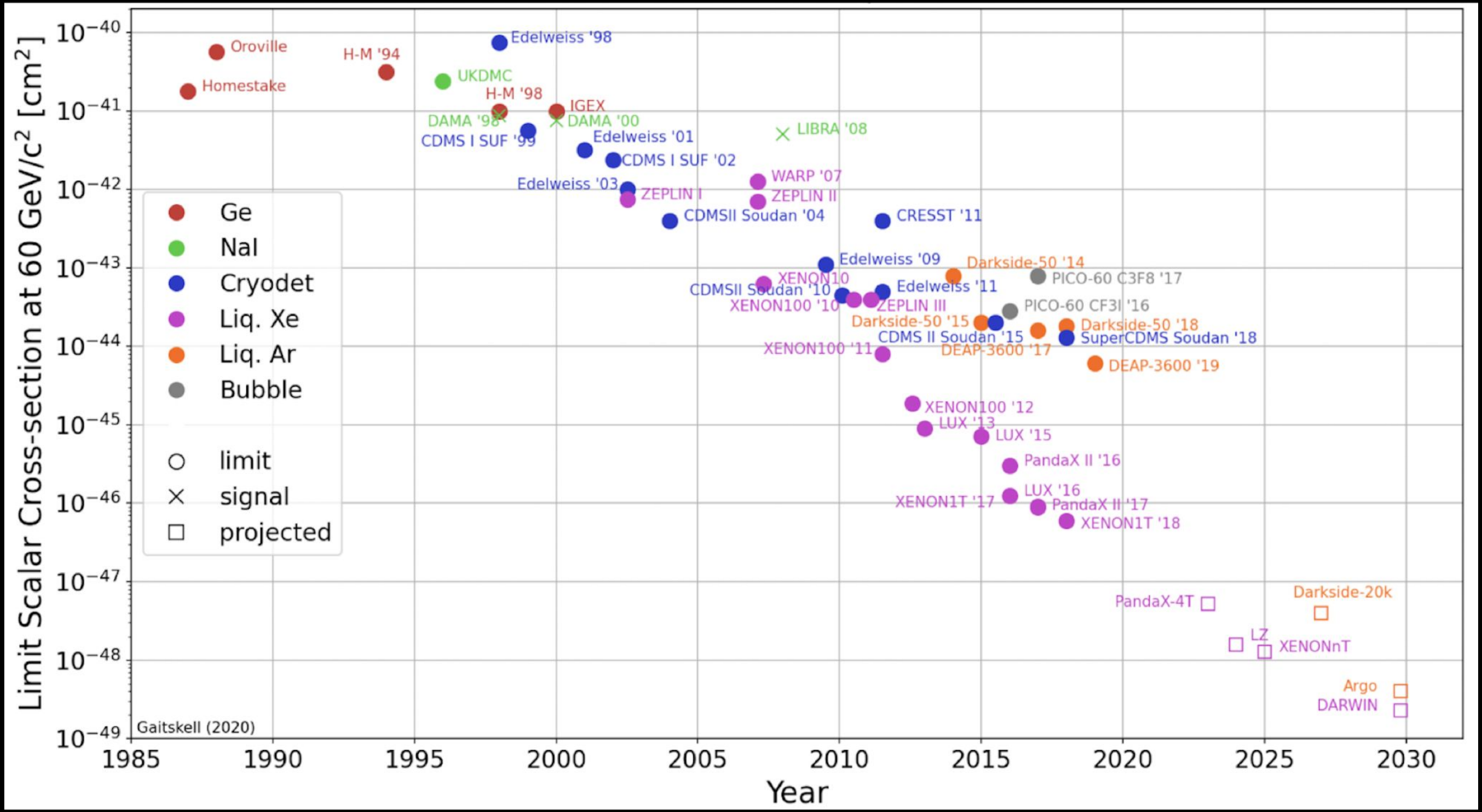
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

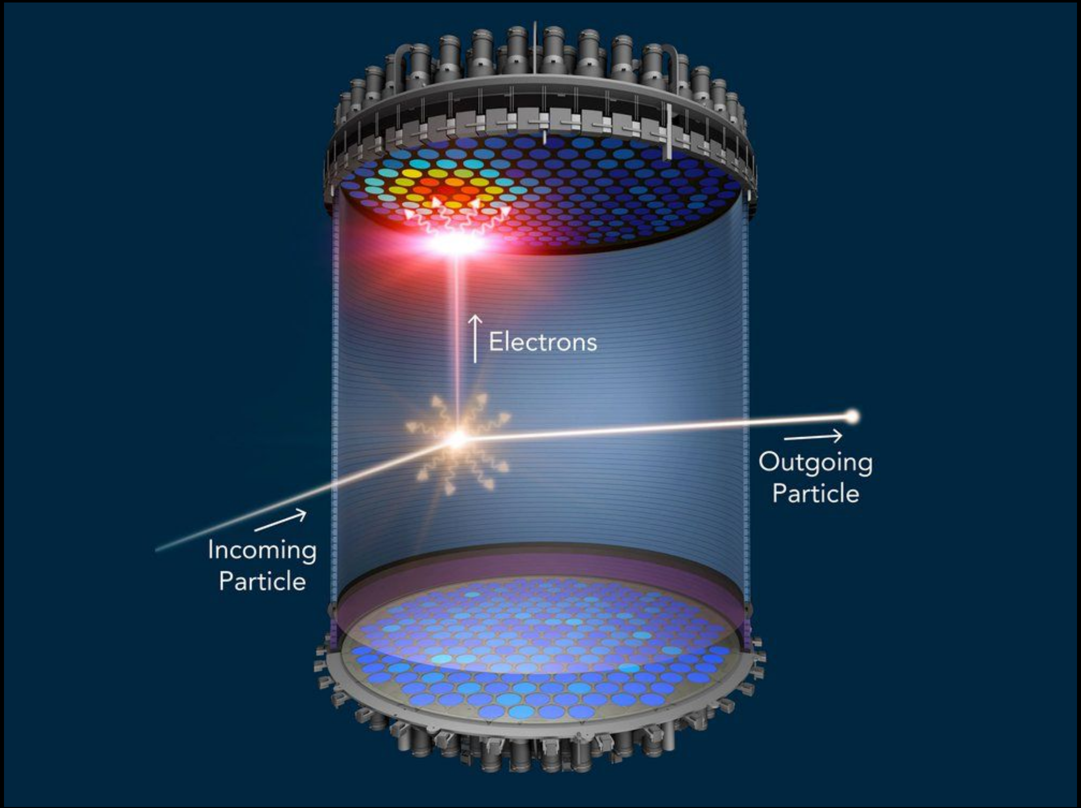
See also Wasserman, 1986

Dark Matter Direct Detection



Credit: Rick Gaitskell / Laura Baudis

Dark Matter Direct Detection



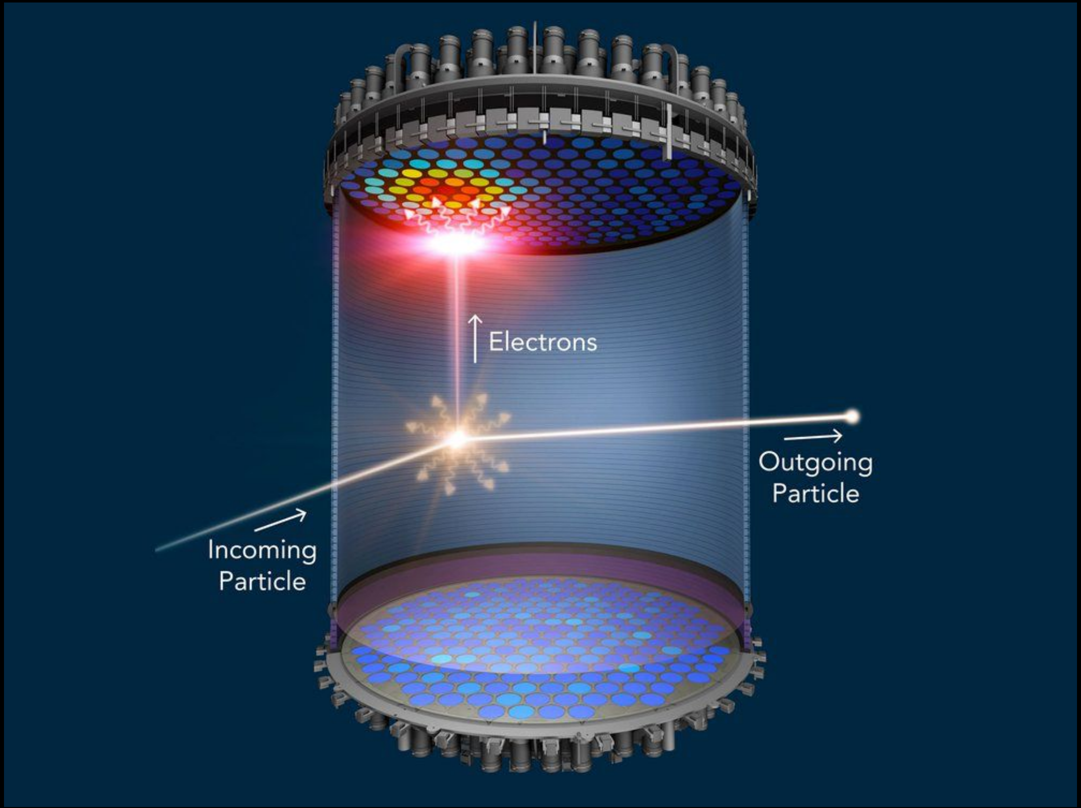
Credit: SLAC National Accelerator Laboratory

Dual-phase xenon time projection chamber (TPC)

- XENON1T, XENONnT
- LUX, LUX-ZEPLIN
- PandaX-II, Pandax-4T

Search for 2 signals: scintillation light (s1), plus ionized electrons (s2)

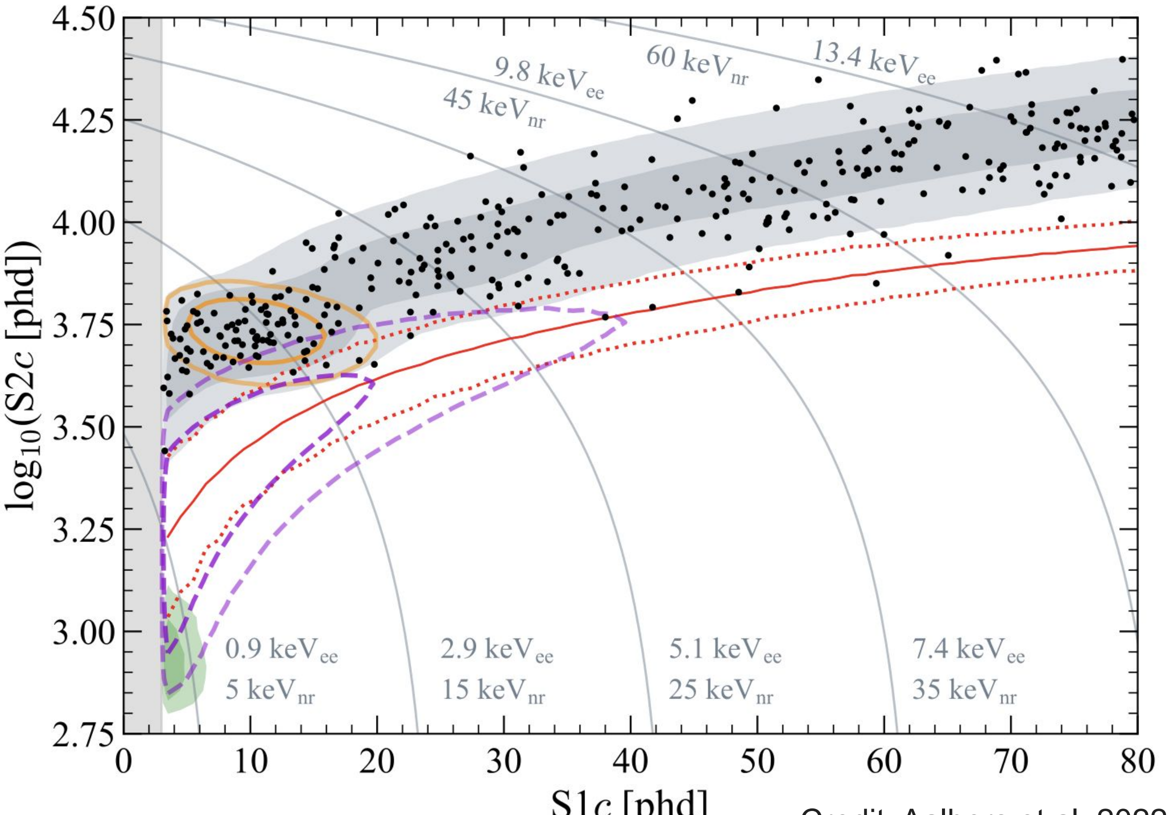
LUX-ZEPLIN (LZ) Experiment



Credit: SLAC National Accelerator Laboratory

Credit: Akerib et al. (LUX-ZEPLIN) 2020

Backgrounds in LZ



Credit: Aalbers et al. 2022

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}(E_R)} \mathrm{d}v\; v f_\chi(v)\frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R}$$

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{1}{m_N}\frac{\rho_\chi}{m_\chi}\int_{v>v_{\min}(E_R)} \mathrm{d}v \, v f_\chi(v) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R}$$

Number Density

Velocity Distribution

Cross Section

$$\frac{\mathrm{d}R}{\mathrm{d}E_R} = \frac{1}{m_N} \frac{\rho_\chi}{m_\chi} \int_{v>v_{\min}(E_R)} \mathrm{d}v \; v f_\chi(v) \frac{\mathrm{d}\sigma_N}{\mathrm{d}E_R}$$

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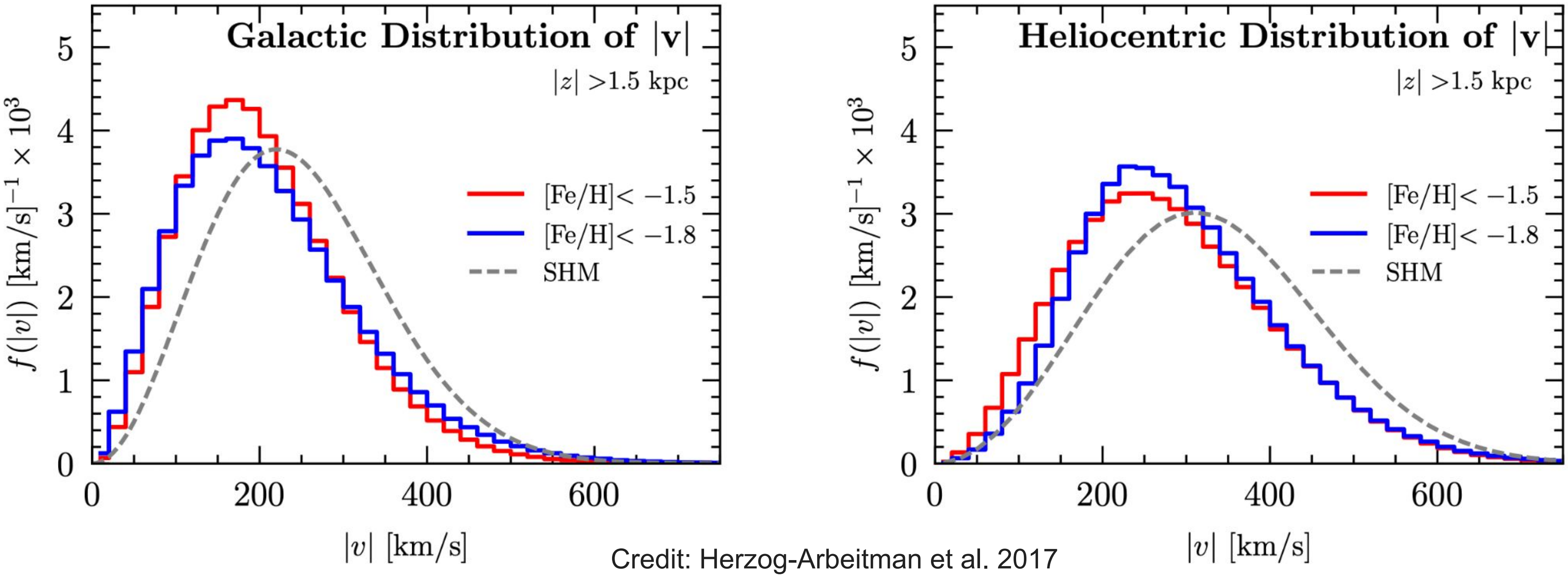

Credit: Herzog-Arbeitman et al. 2017

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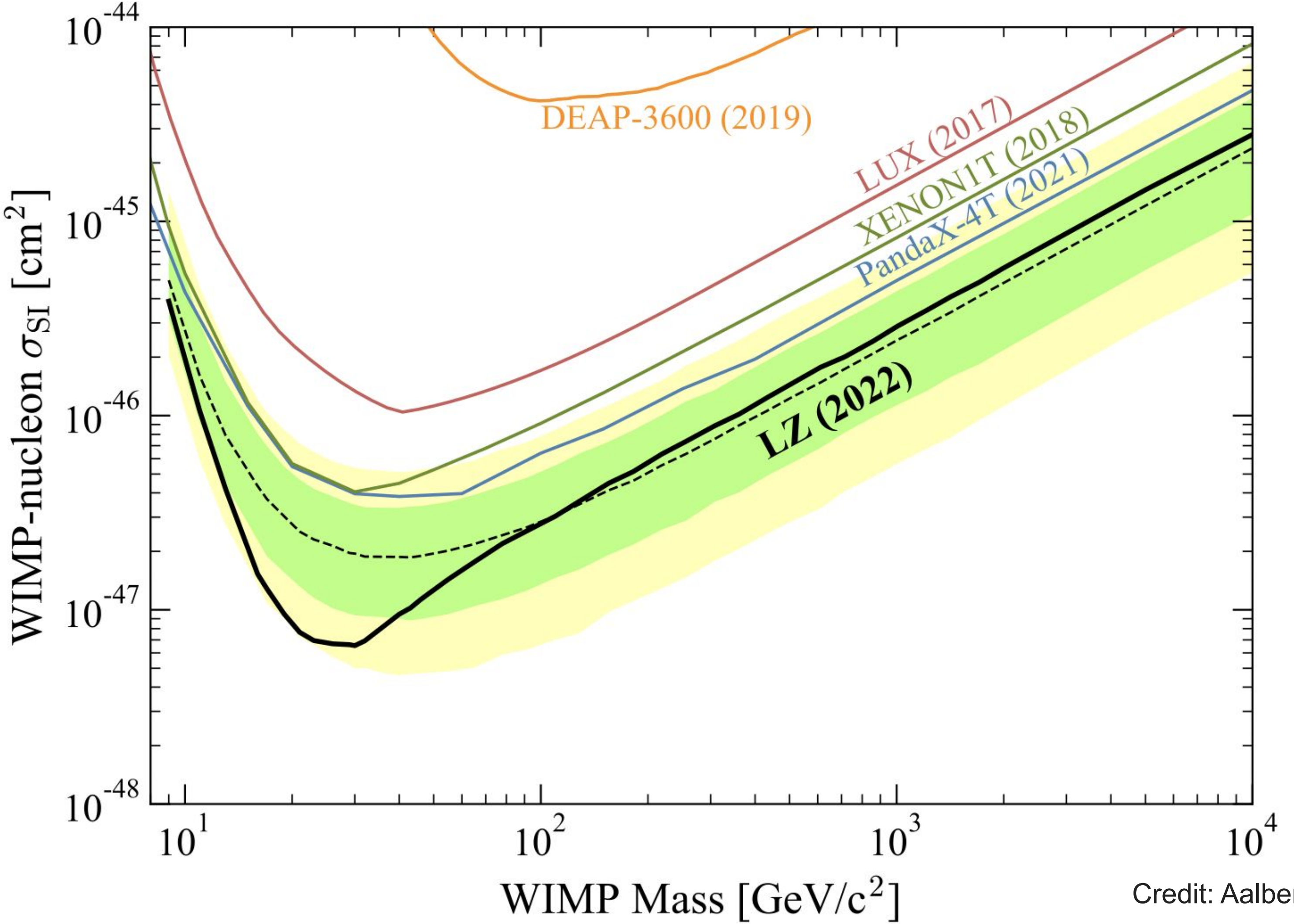
Number Density — Velocity Distribution — Cross Section

Many, many dark matter models, but two standard benchmark types of model for direct detection:

$$\frac{d\sigma}{dE_R} = \frac{2m_N}{\pi v^2}\left[Z f_p + (A-Z) f_n\right]^2 F^2(q)$$ ← Spin-Independent

$$\frac{d\sigma}{dE_R} = \frac{16m_N}{\pi v^2} G_F^2 J(J+1)\Lambda^2 F_{\mathrm{SD}}^2(q)$$ ← Spin-Dependent



Credit: Aalbers et al. 2022

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Velocity Distribution

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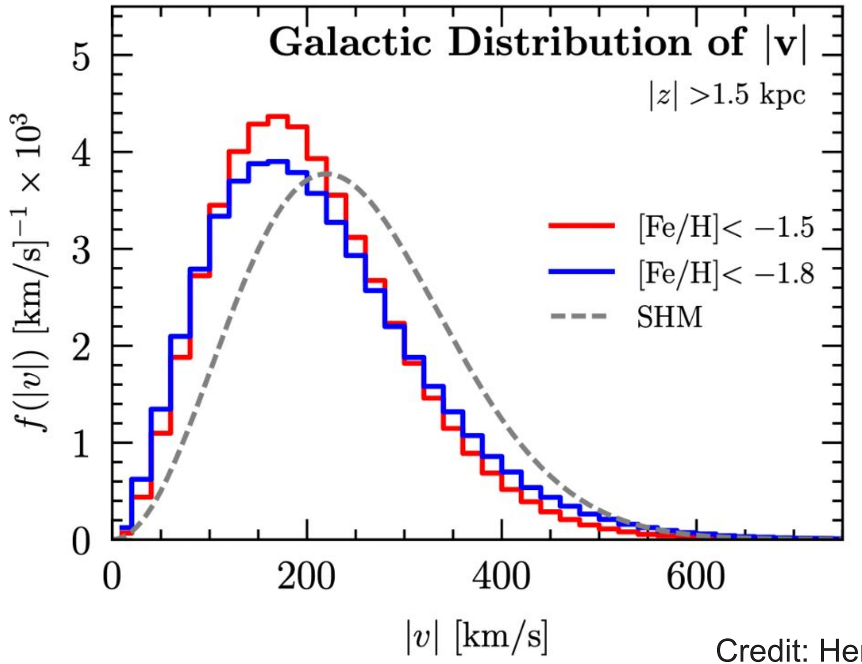
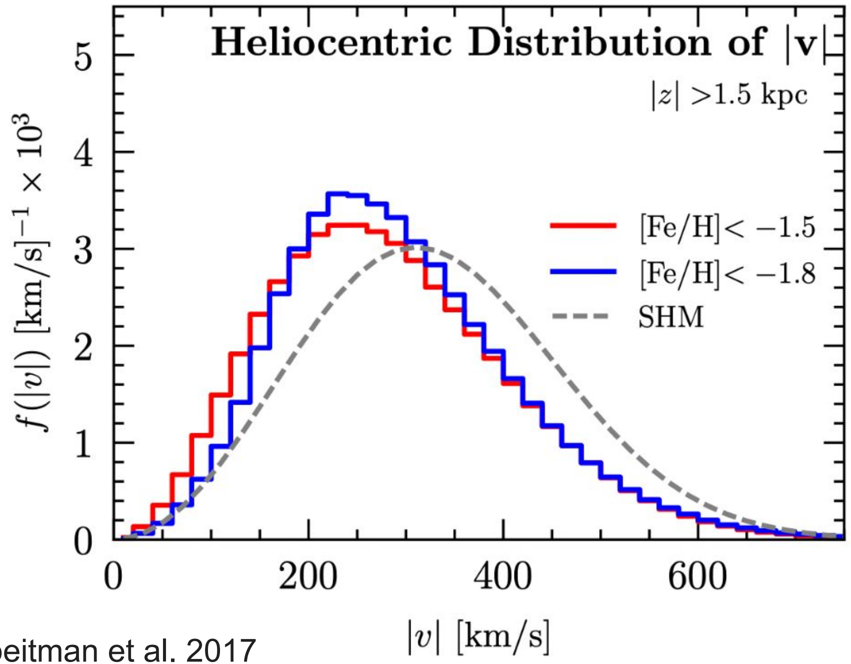
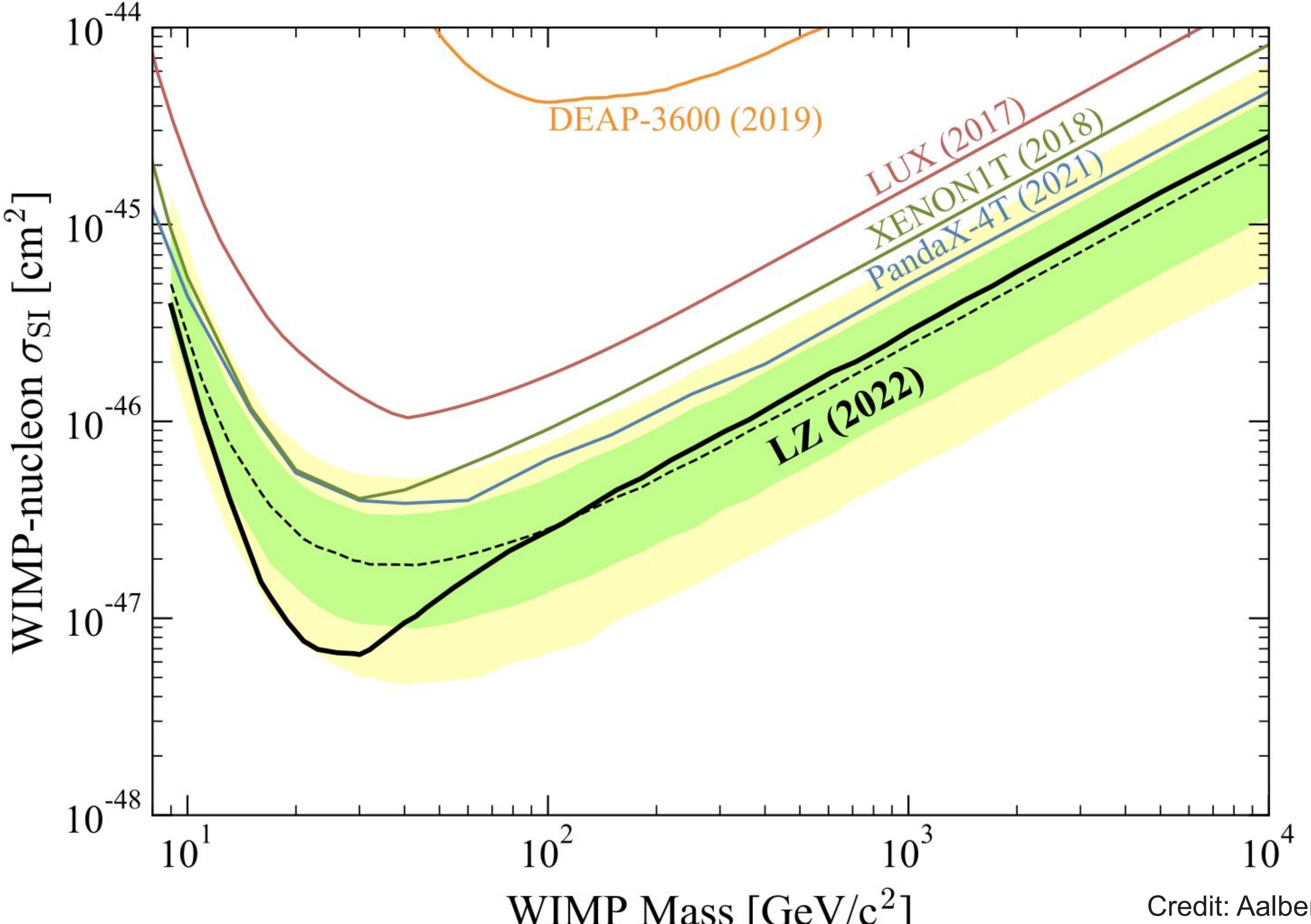




Credit: Herzog-Arbeitman et al. 2017



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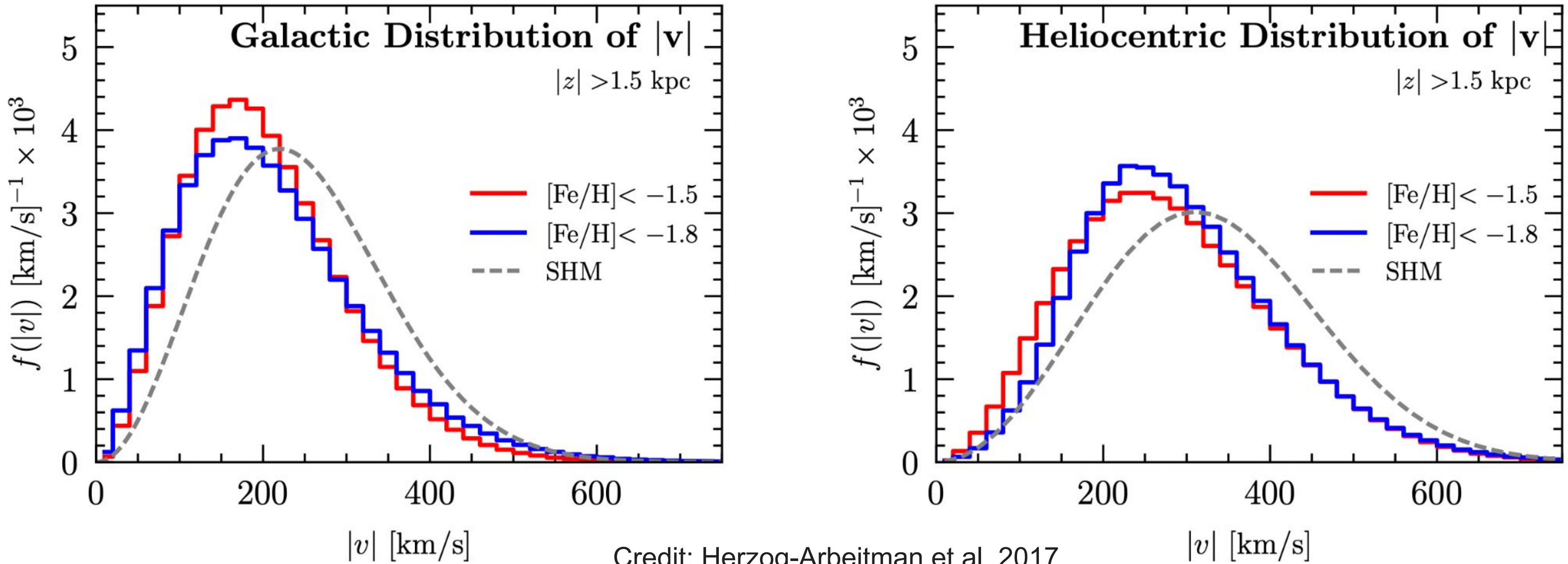
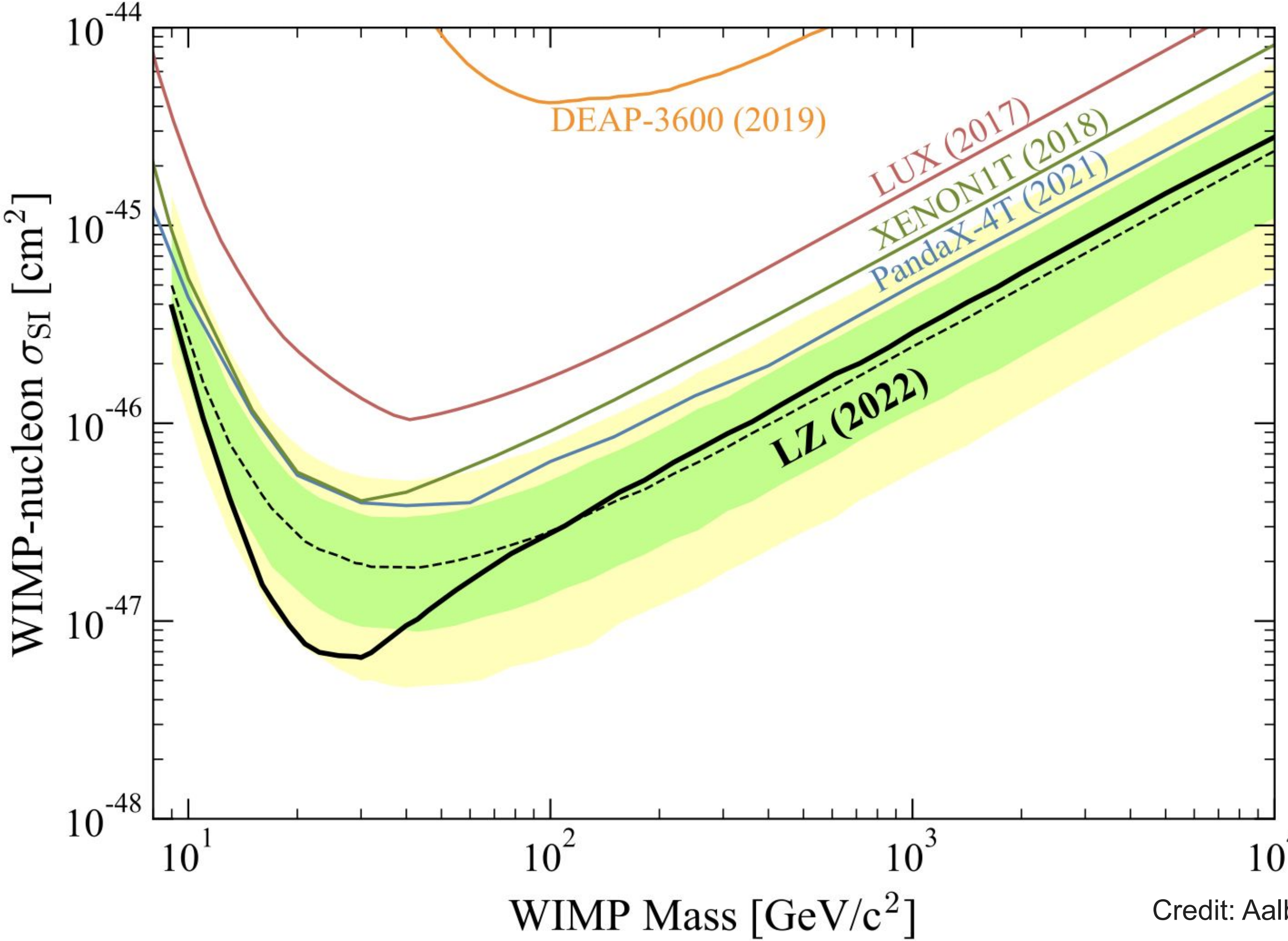
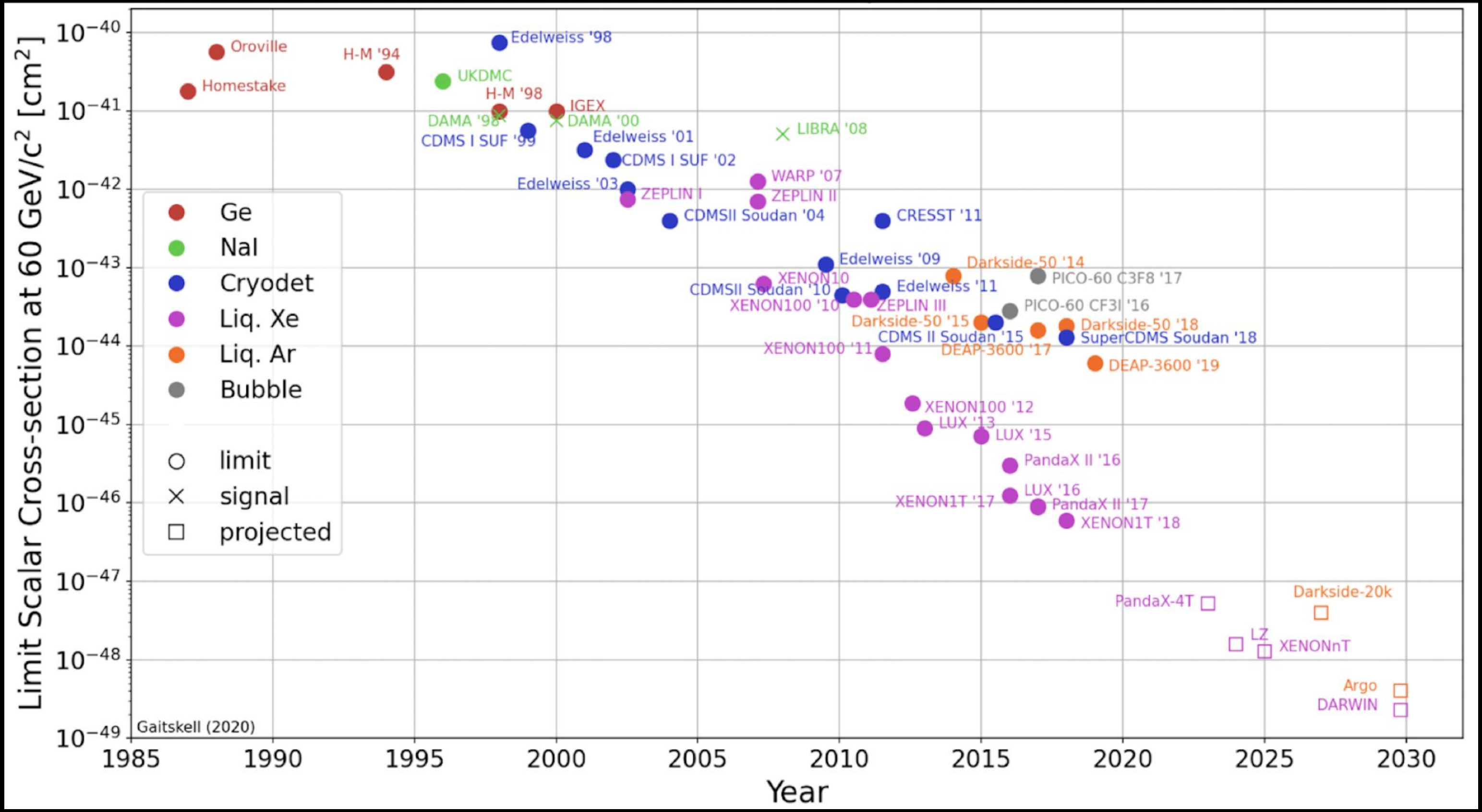


Credit: Herzog-Arbeitman et al. 2017



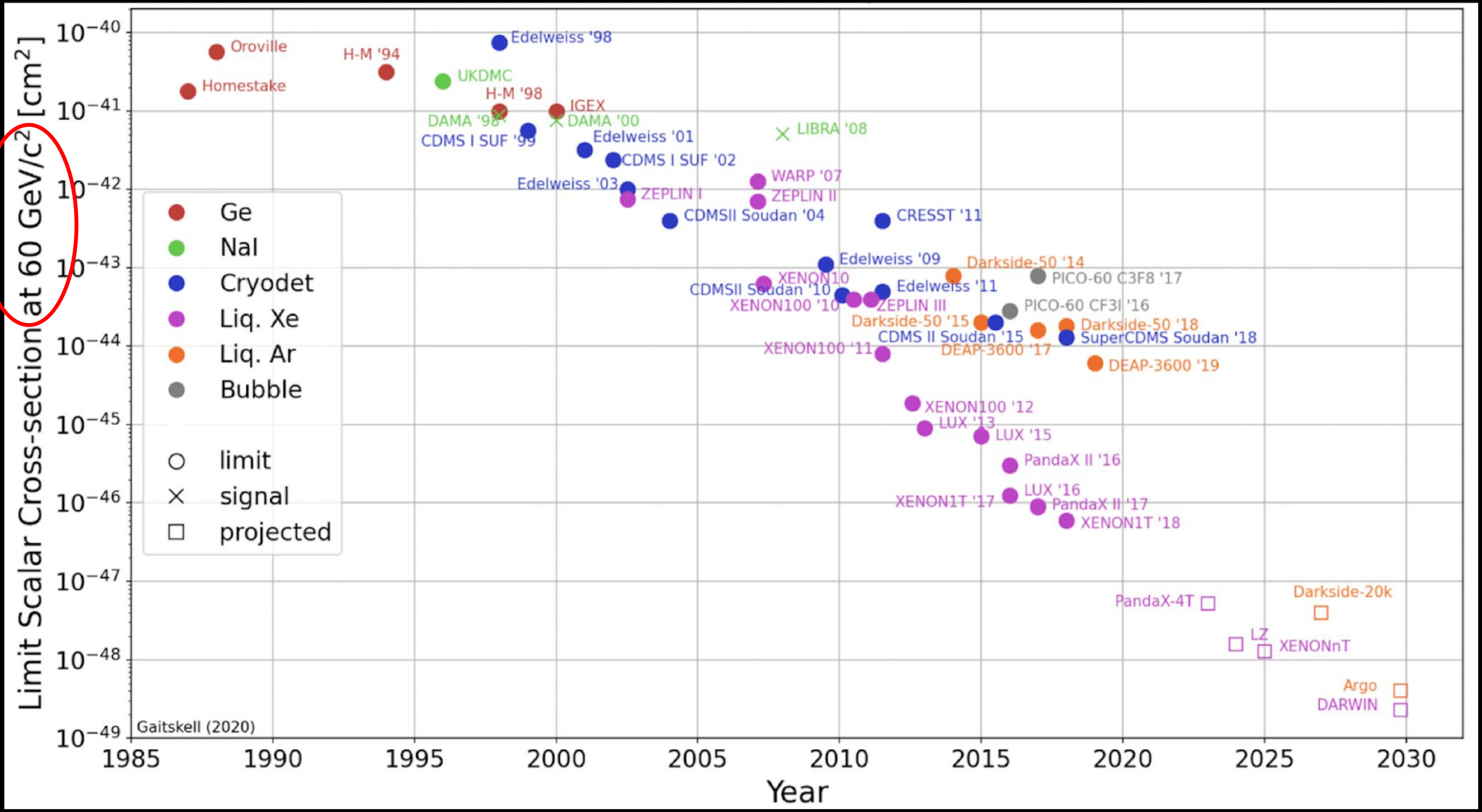
Credit: Aalbers et al. 2022

Comparing Experimental Limits



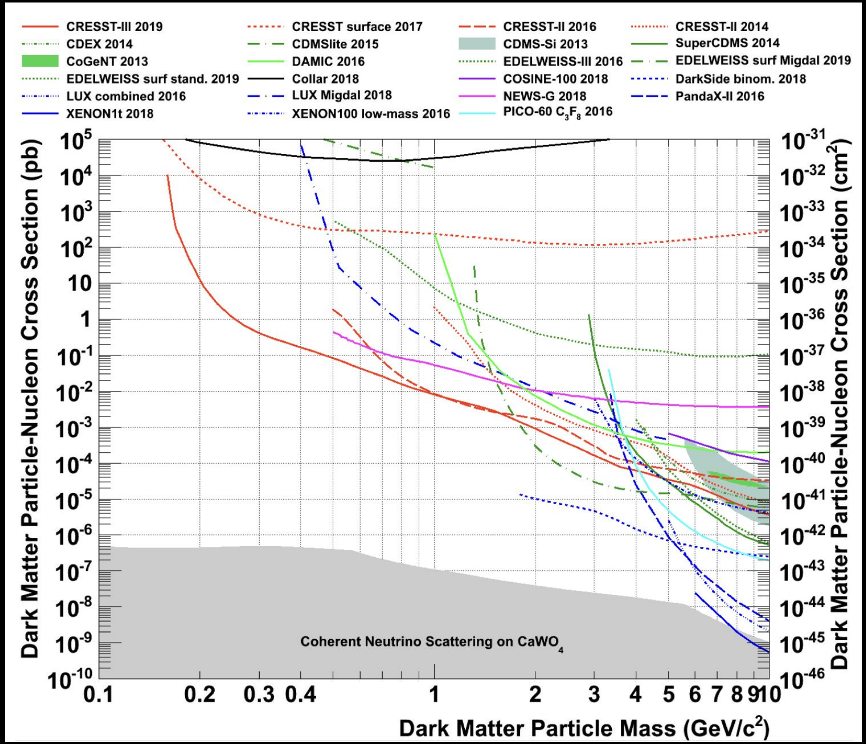
Credit: Rick Gaitskell / Laura Baudis

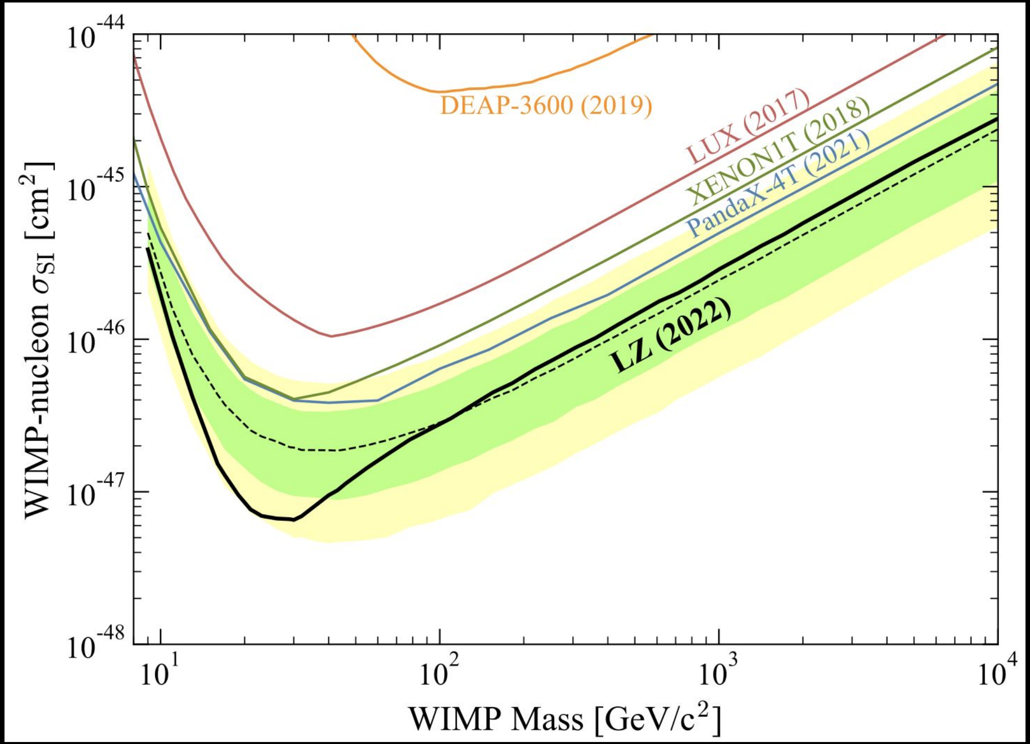
Comparing Experimental Limits



Credit: Rick Gaitskell / Laura Baudis

Comparing Experimental Limits

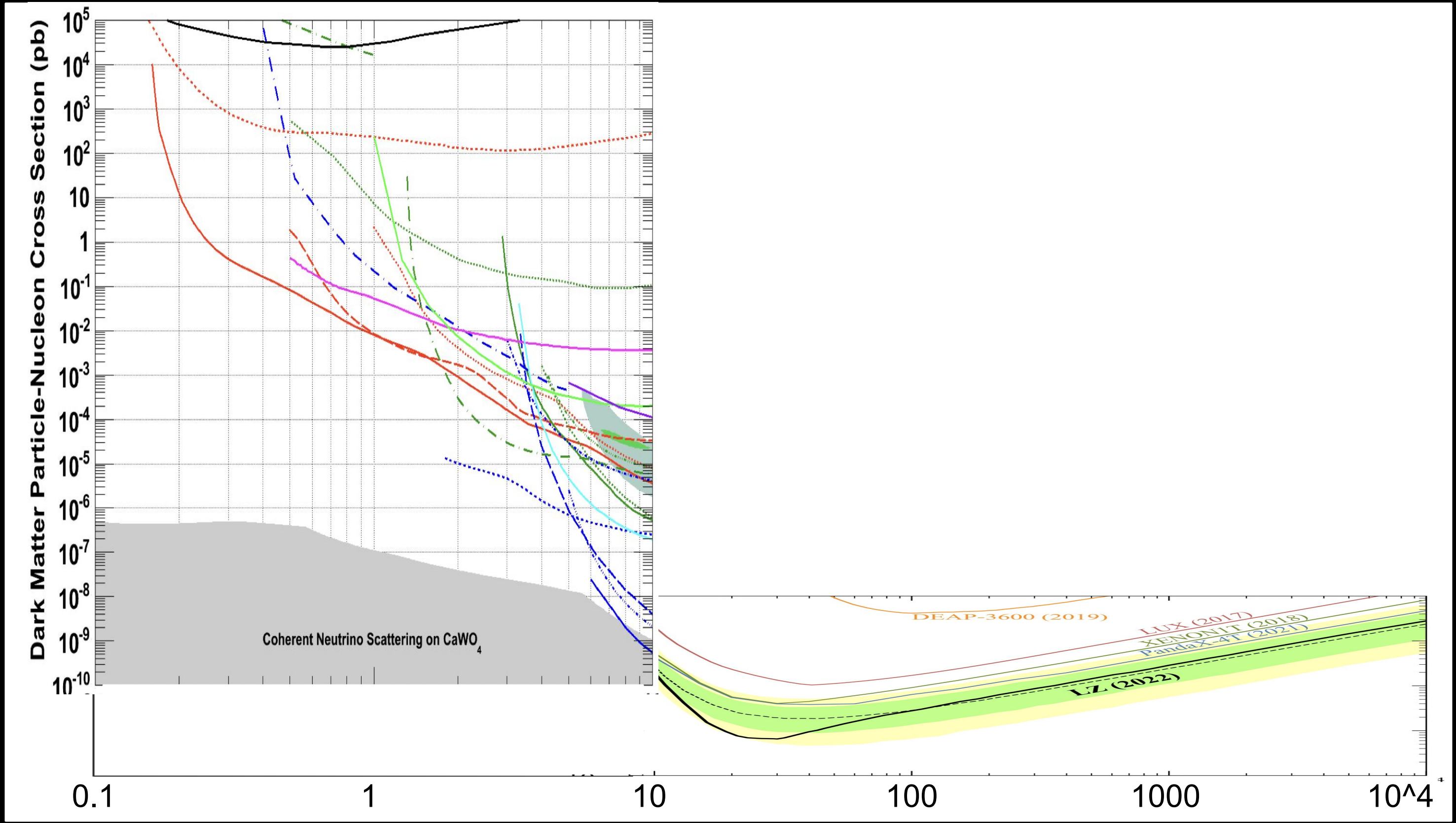




Credit: Abdelhameed et al. 2019

Credit: Aalbers et al. 2022

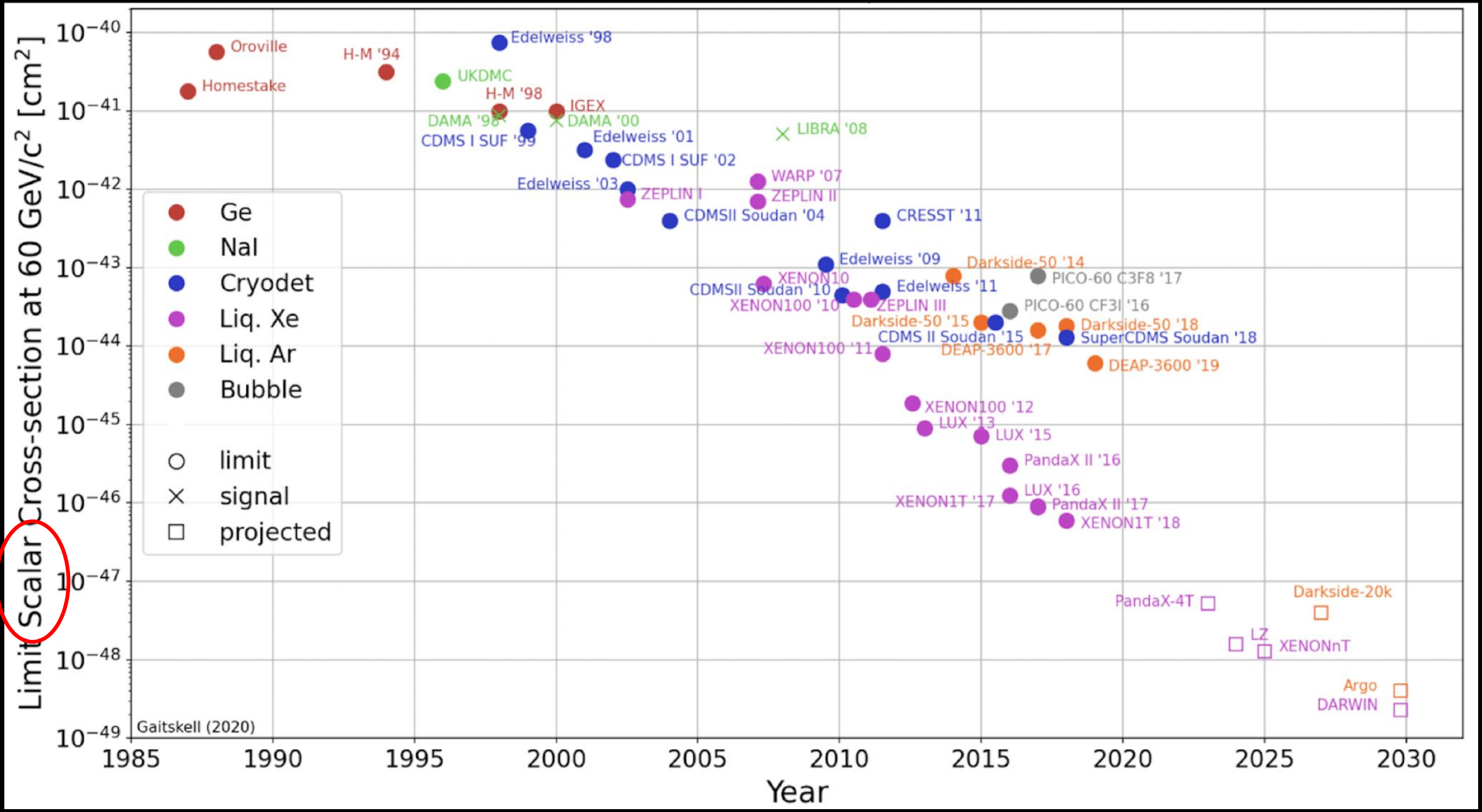
Comparing Experimental Limits



Credit: Abdelhameed et al. 2019

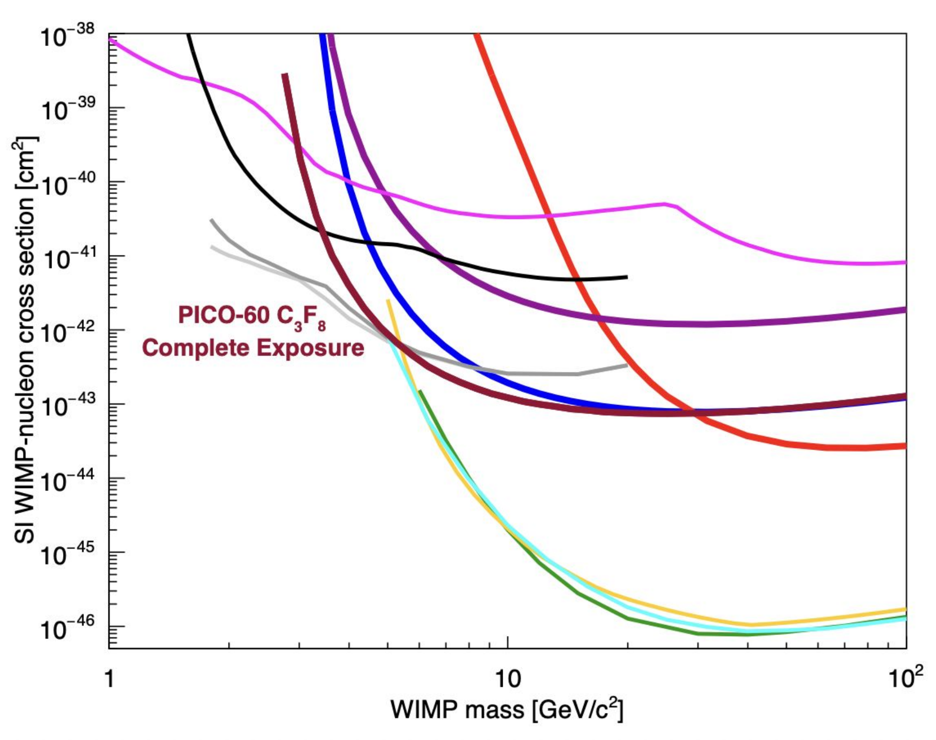
Credit: Aalbers et al. 2022

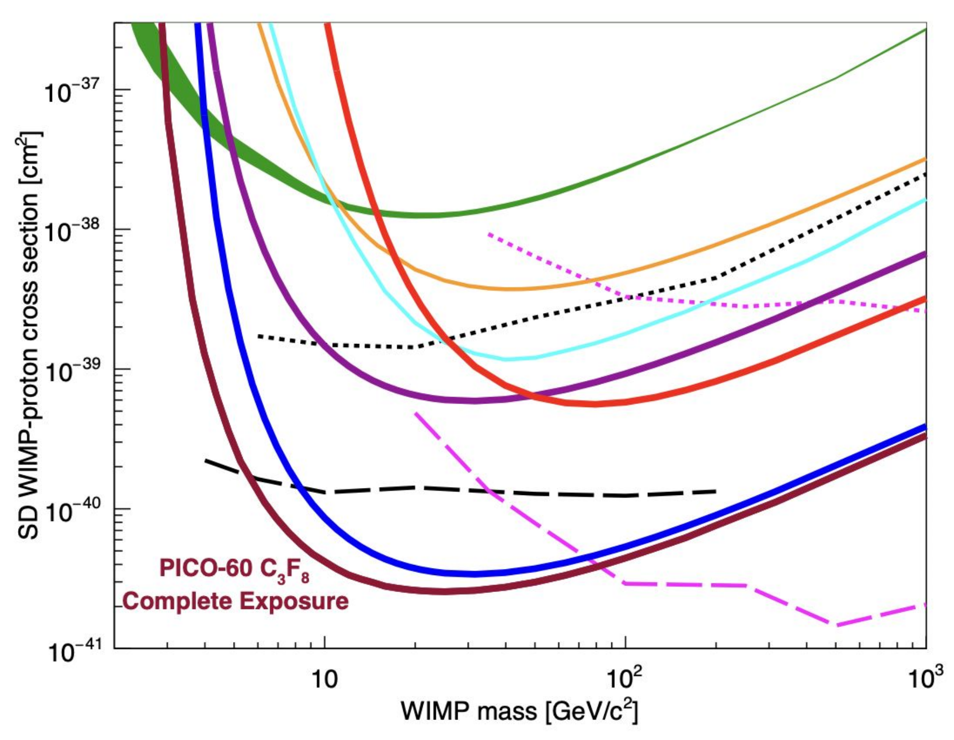
Comparing Experimental Limits



Credit: Rick Gaitskell / Laura Baudis

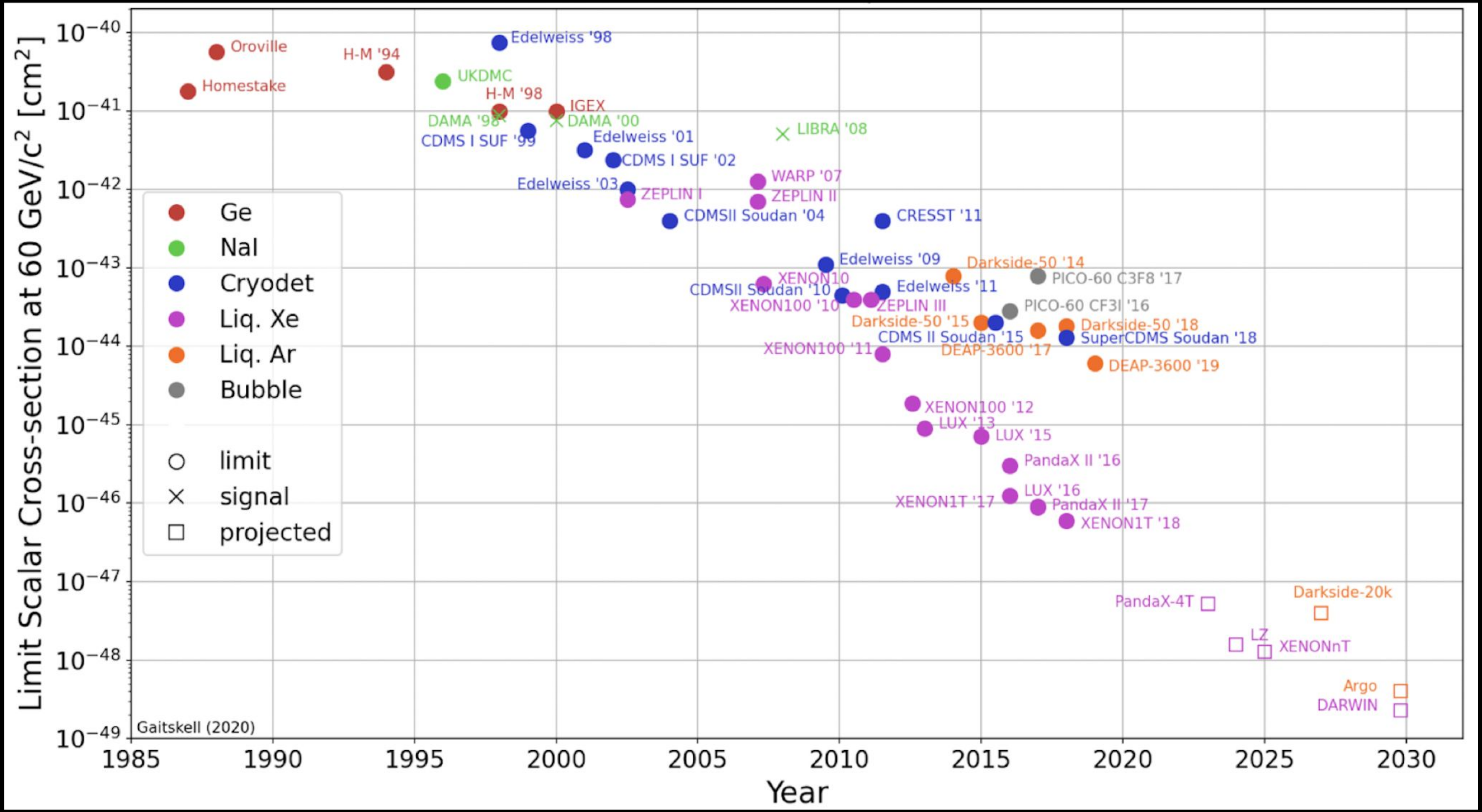
Comparing Experimental Limits





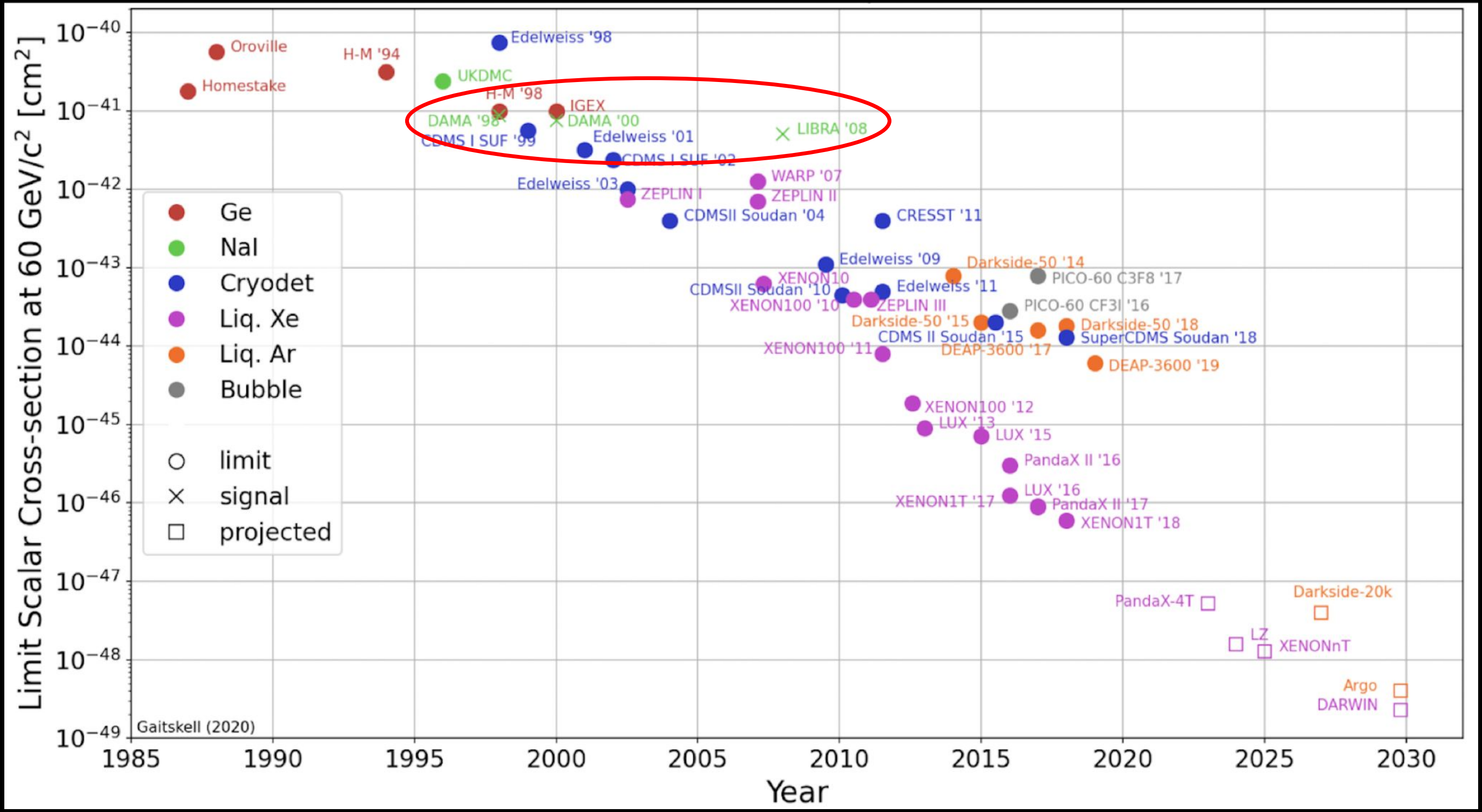
Credit: Amole et al. 2019

Signals? Excesses?



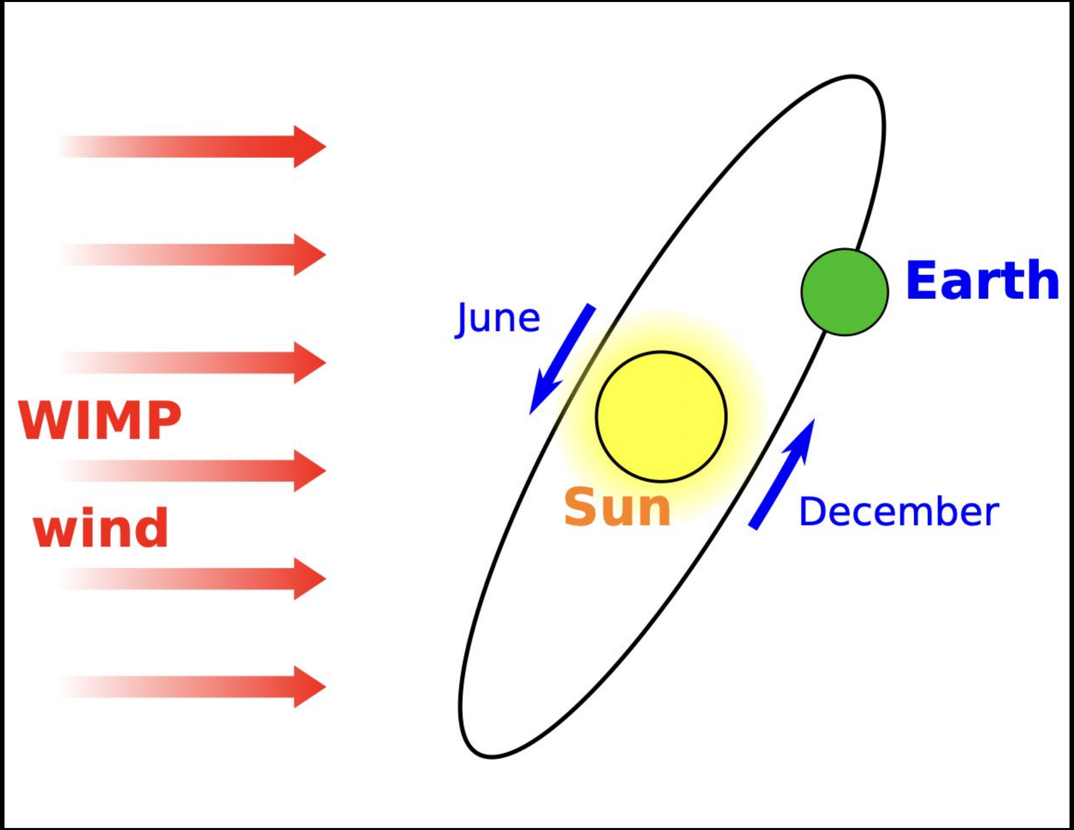
Credit: Rick Gaitskell / Laura Baudis

Signals? Excesses?



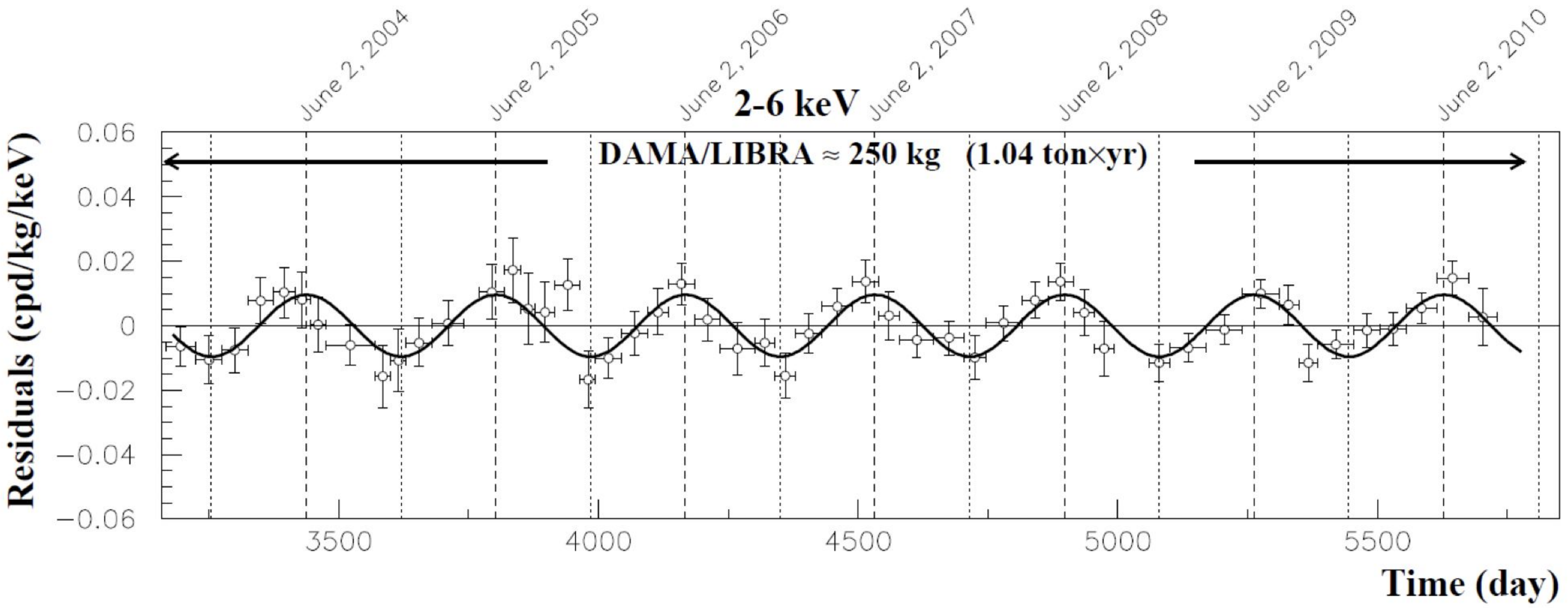
Credit: Rick Gaitskell / Laura Baudis

Annual Modulation



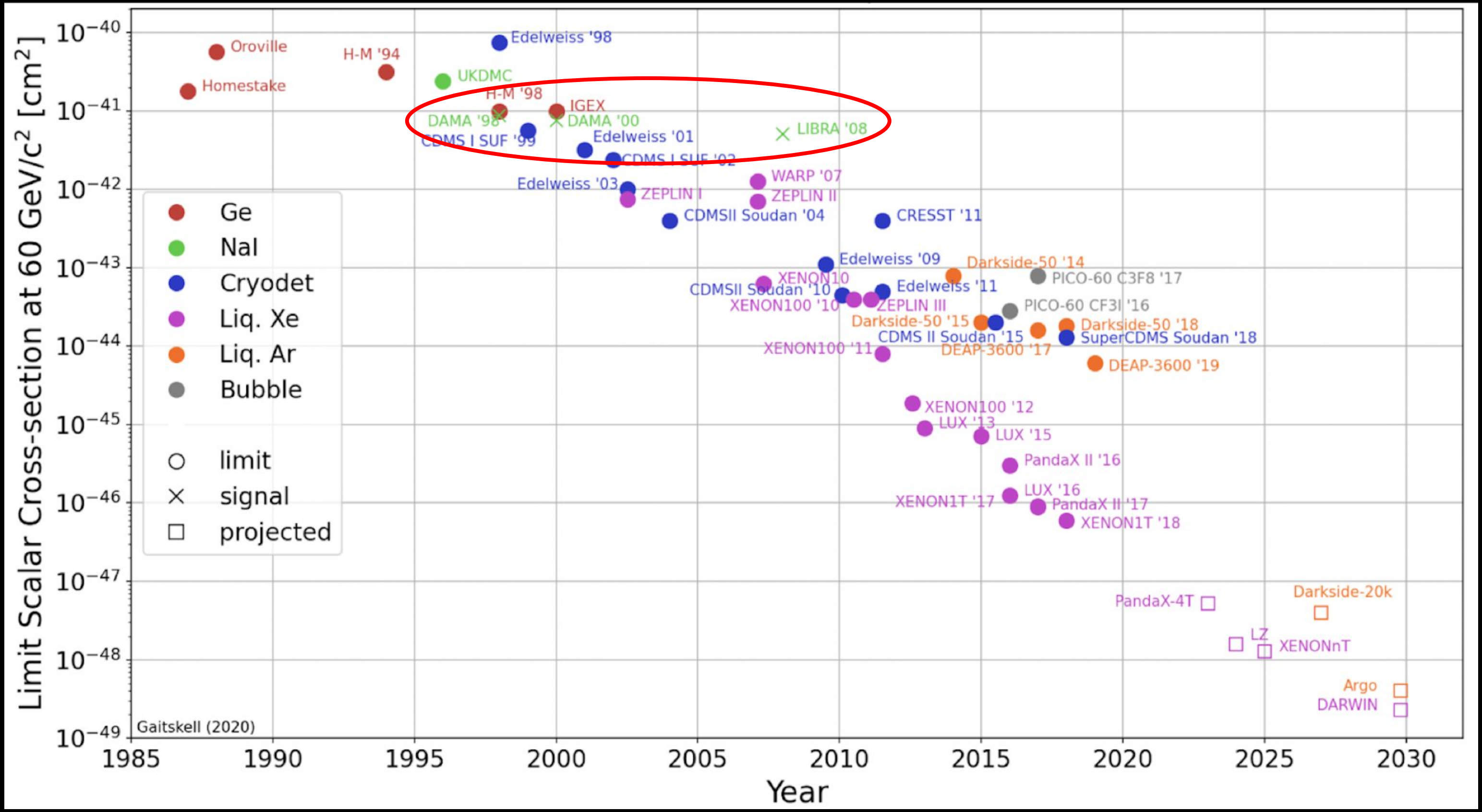
Credit: Freese et al. 2012

Annual Modulation



Credit: Bernabei et al. 2017

Annual Modulation



Credit: Rick Gaitskell / Laura Baudis

Direct Detection: Key Takeaways

- Direct detection limits have improved by nearly 7 orders of magnitude over ~40 years
- Searching for extremely rare events requires the ability to identify and remove backgrounds extremely efficiently
- Different detectors are optimized for different dark matter models and masses