DARK MATTER

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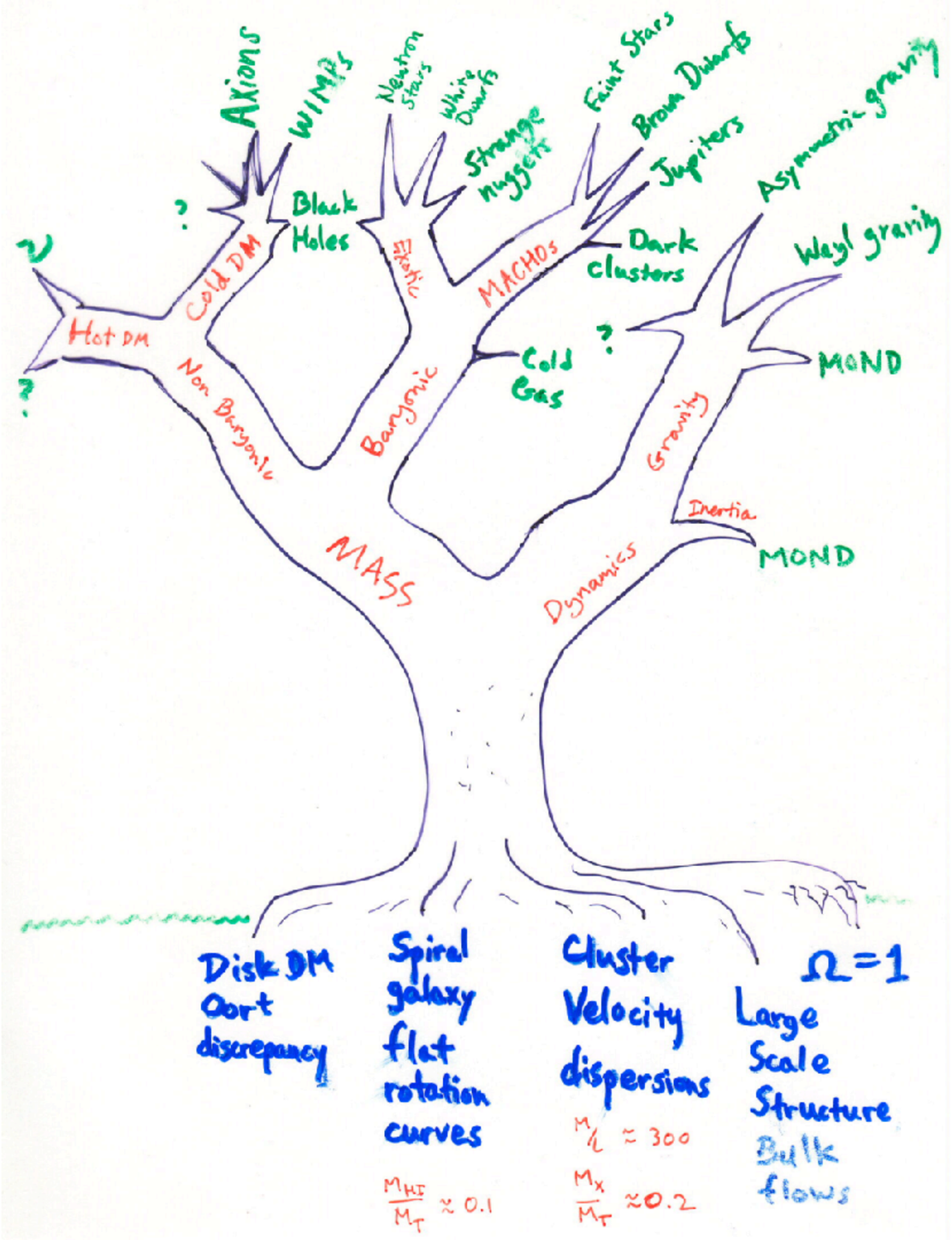

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Things we know for sure in cosmology:

"Cosmologists are often wrong, but never in doubt"
- Lev Landau

Cosmological parameters over time

Quantity	circa 1990	circa 2000	WMAP5 2008	Planck 2018
Ω_m	1	0.3	0.258 ± 0.027	0.315 ± 0.007
Ω_Λ	0	0.7	0.742	0.685
$\Omega_b h^2$	0.0125 ± 0.0025 Light element abundances	0.019 ± 0.001 Deuterium	0.02273 ± 0.00062 CMB fit	0.02237 ± 0.00015 CMB fit
H_o	50	72 ± 8	71.9 ± 2.7	67.4 ± 0.5
dark matter	CDM	CDM	CDM	CDM

Experimental results to date (2024): nada

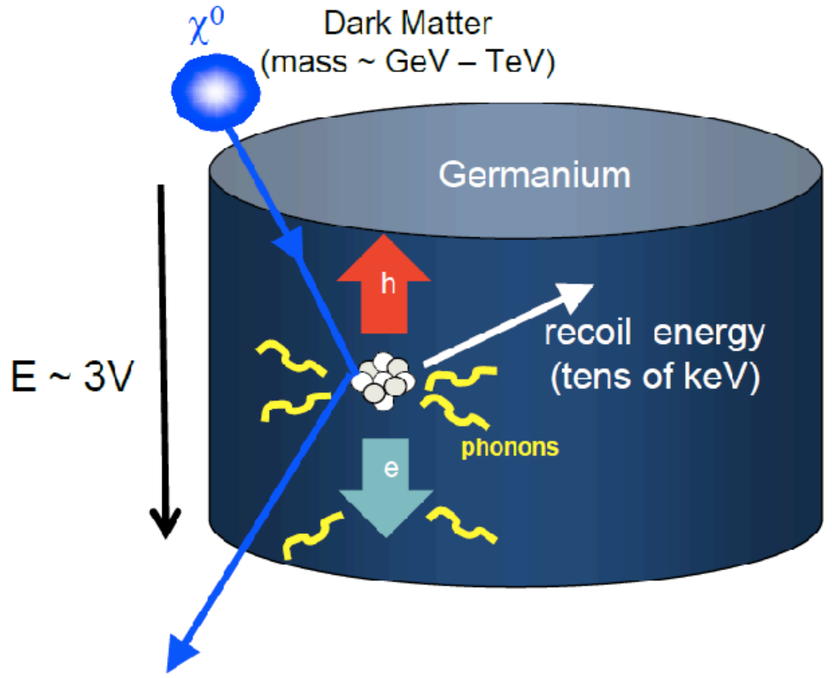
Direct detection

Many, *many* experiments
CDMS, LUX, XENON, DAMA, etc., etc.

Basic idea: WIMP passing through detector interacts via weak force; scatters off nucleus.
Detect deposited energy of recoil. (analogous to neutrino detection).

Fraction of the initial kinetic energy T_i transferred from a WIMP of mass m_X to a nucleus of mass M:

$$f_T = \frac{T_f}{T_i} = \frac{4 m_X M}{(m_X + M)^2} \cos^2 \theta$$



Experimental Approaches

Cryogenic crystal detectors – A technique used by the Cryogenic Dark Matter Search (CDMS) detector at the Soudan Mine relies on multiple very cold germanium and silicon crystals. The crystals (each about the size of a hockey puck) are cooled to about 50 mK. A layer of metal (aluminium and tungsten) at the surfaces is used to detect a WIMP passing through the crystal. This design hopes to detect vibrations in the crystal matrix generated by an atom being "kicked" by a WIMP. CRESST, CoGeNT, and EDELWEISS run similar setups.

Noble gas scintillators – Another way of detecting WIMPs scattering off nuclei is to use scintillating material, so that light pulses are generated by the moving atom and detected, often with PMTs. Experiments such as DEAP at SNOLAB and DarkSide at the LNGS instrument a very large target mass of liquid argon for sensitive WIMP searches. ZEPLIN, and XENON used xenon.

Crystal scintillators – Instead of a liquid noble gas, a simpler approach is the use of a scintillating crystal such as NaI(Tl). This approach is taken by DAMA/LIBRA, an experiment that observed an annular modulation of the signal consistent with WIMP detection. DM-Ice is deploying NaI crystals with the IceCube detector at the South Pole. KIMS is approaching the same problem using CsI(Tl) as a scintillator.

Bubble chambers – The PICASSO experiment is a direct dark matter search experiment that is located at SNOLAB in Canada. It uses bubble detectors with Freon as the active mass. PICASSO is predominantly sensitive to spin-dependent interactions of WIMPs with the fluorine atoms in the Freon.

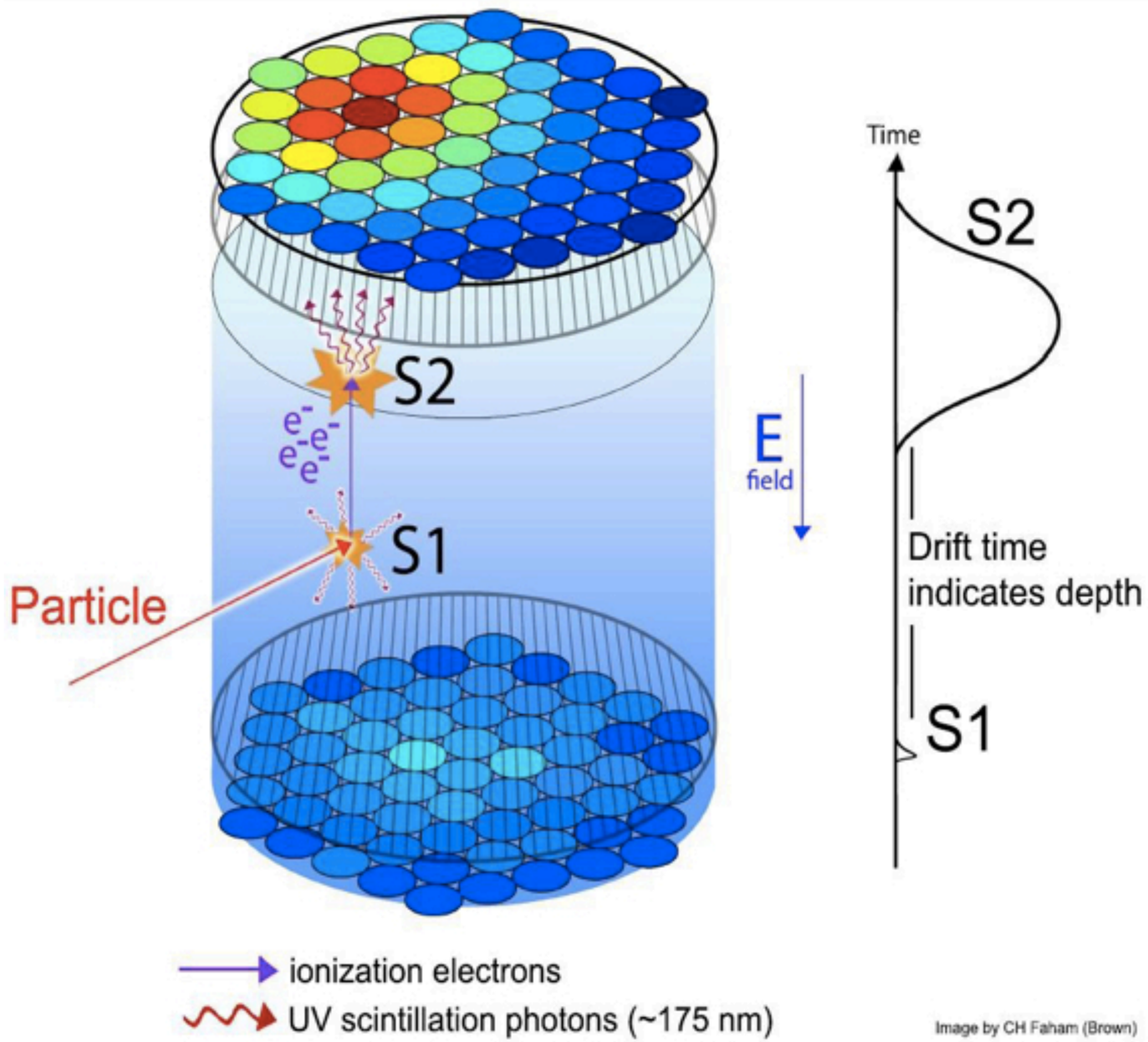
XENON type detectors

Direct detection

Cool detection medium to near absolute zero to minimize thermal noise.

Must shield experiments from cosmic rays, natural radioactivity, self-radioactivity, etc., etc.

Bury them deep in mines.

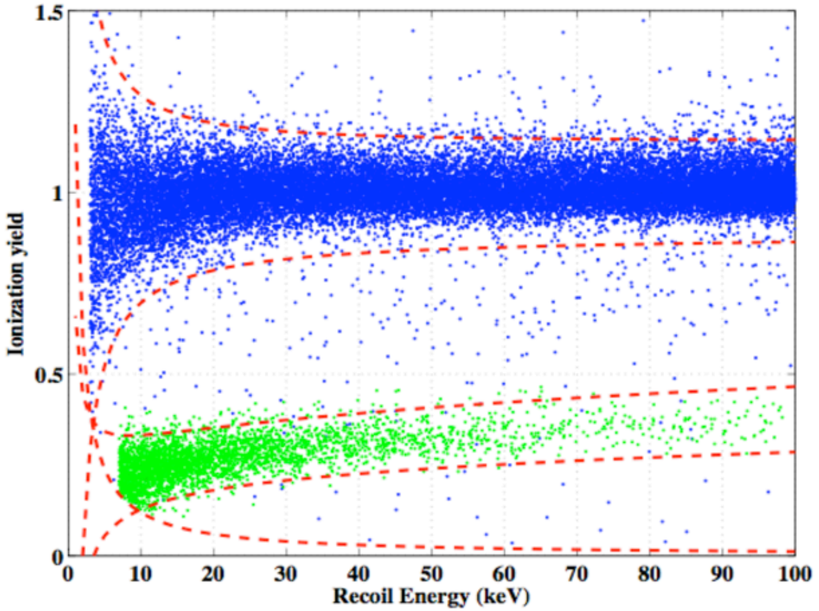


Discrimination between atomic and nuclear scale events

Cool detection medium to near absolute zero to minimize thermal noise.

Must shield experiments from cosmic rays, natural radioactivity, self-radioactivity, etc., etc.

Bury them deep in mines.

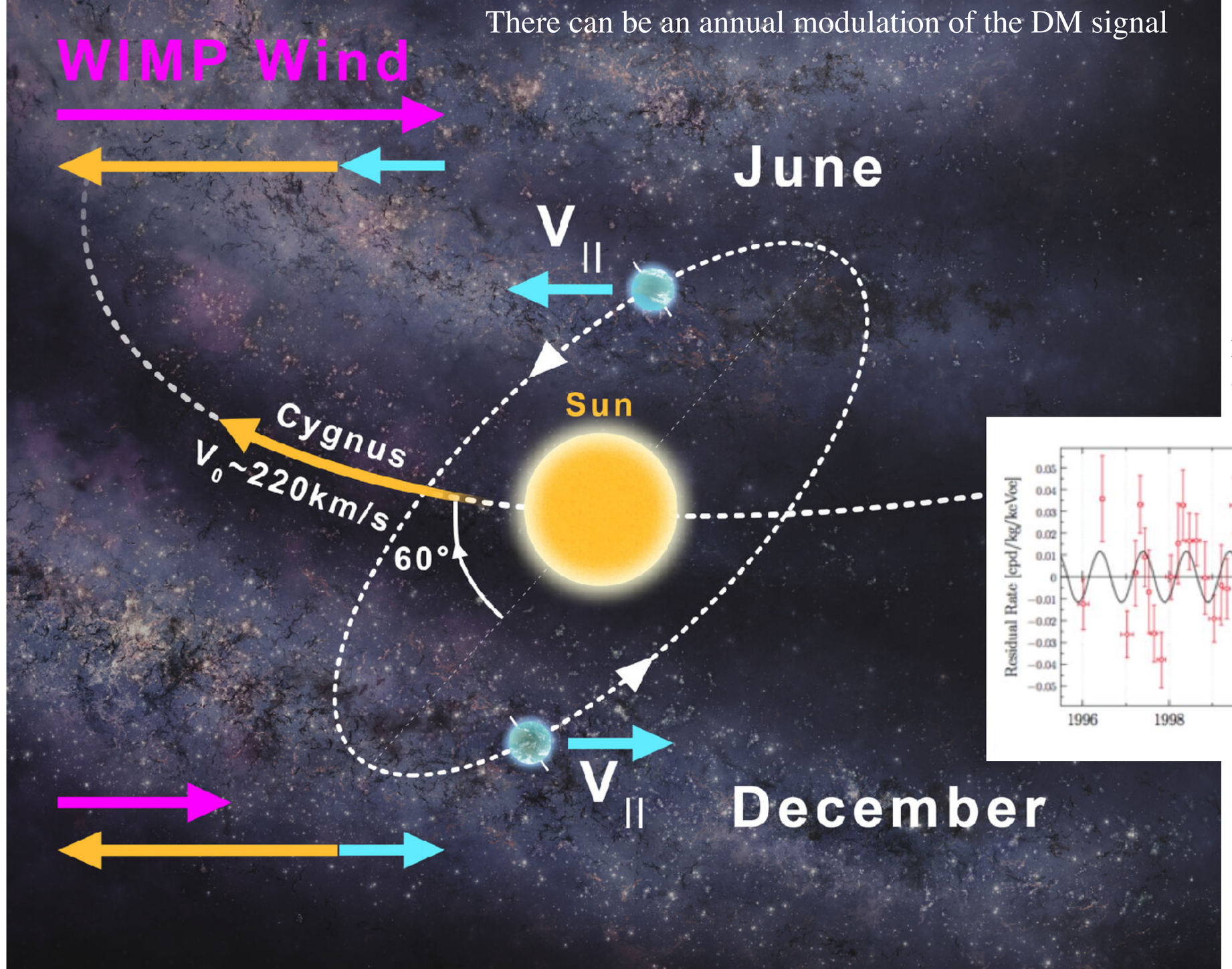


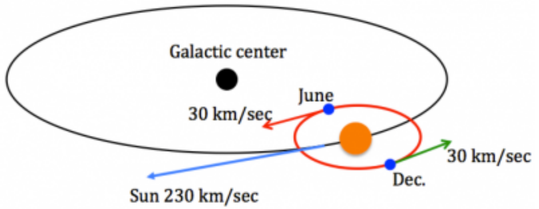
Atomic scale: electrons, photons

Nuclear scale: neutrons, WIMPs?

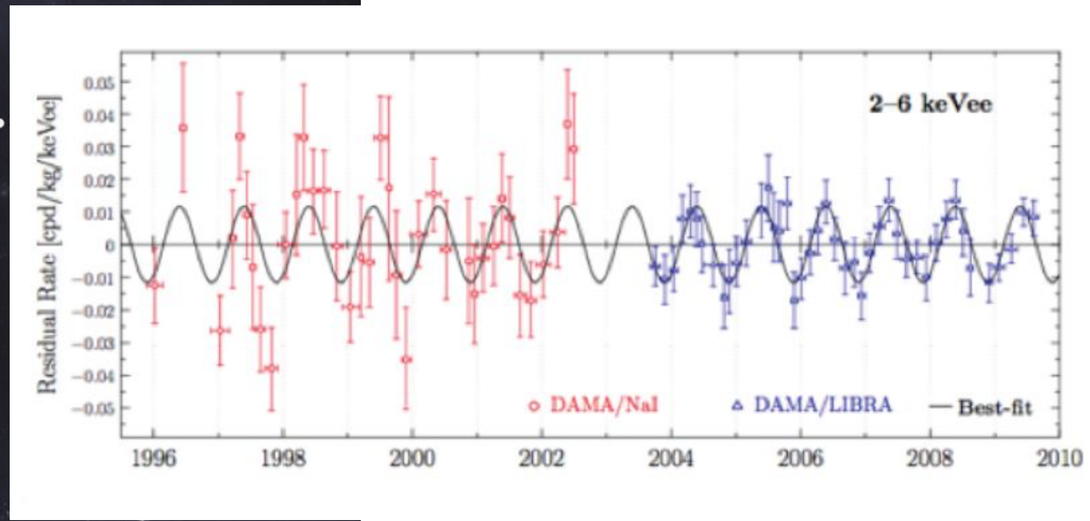
Figure 10. *Example from the CDMS II experiment of the response to gamma rays (blue) and neutrons (green), showing the difference in ionization versus phonon energy deposition for electron and nuclear recoils.*

There can be an annual modulation of the DM signal





DAMA/LIBRA claimed a 9 σ detection of annual modulation consistent with WIMPs.

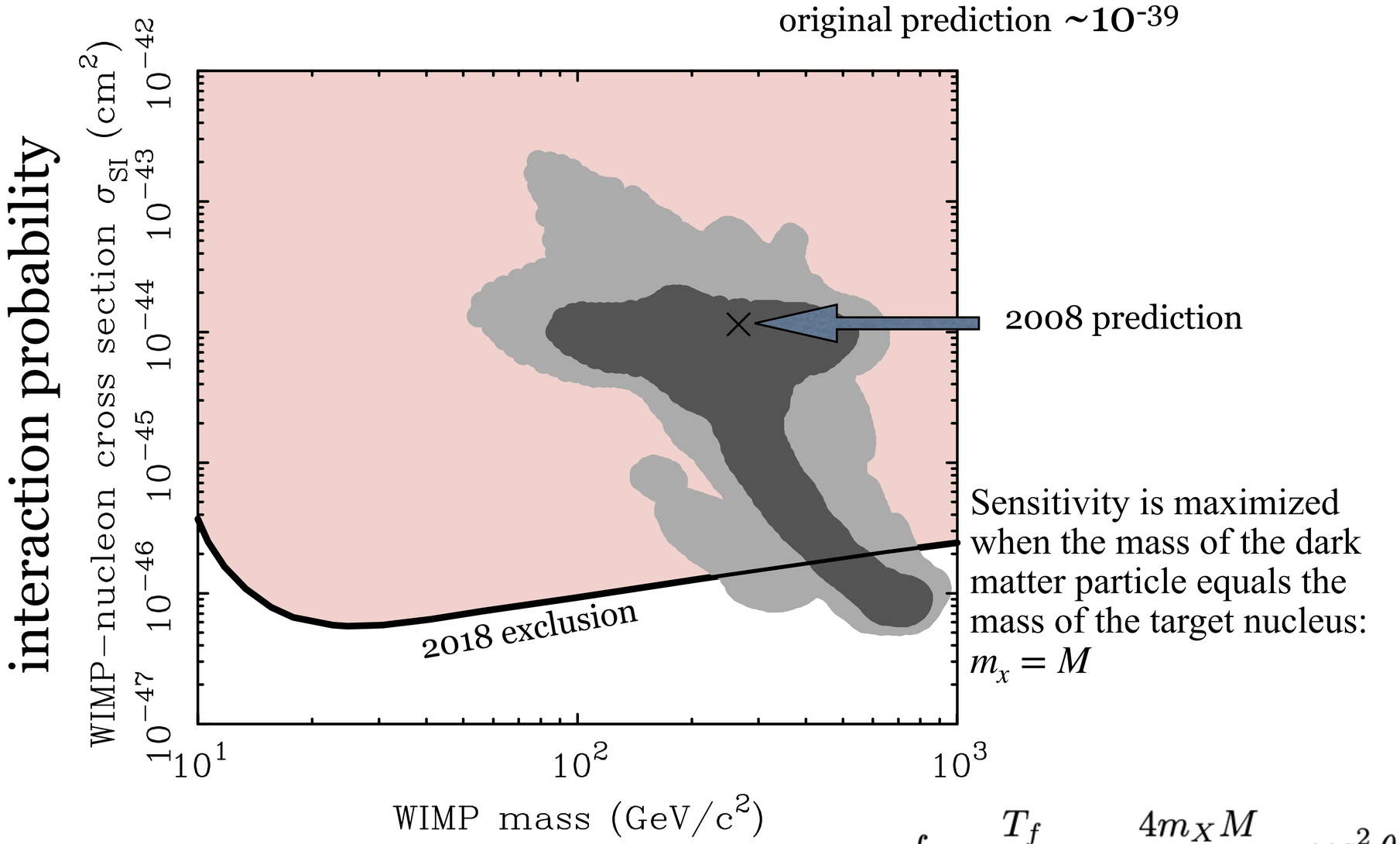


Bernabei et al., *Bled Workshops Phys*. **14**, 13 (2013) [*Nucl. Instrum. Meth.* A **742**, 177 (2014)] [arXiv:1403.1404].

Direct detection experiments have repeatedly excluded predicted WIMP properties

The original prediction of $\sigma \sim 10^{-39}$ cm^2 is off scale, having been excluded long ago, BUT we can still get away with the "right" thermal cross-section $\langle \sigma v \rangle$ for the WIMP miracle if the mass is high enough for the velocity to be low.

Current data are exceedingly grim for the WIMP, but we stick with it out of habit and for lack of a better idea.



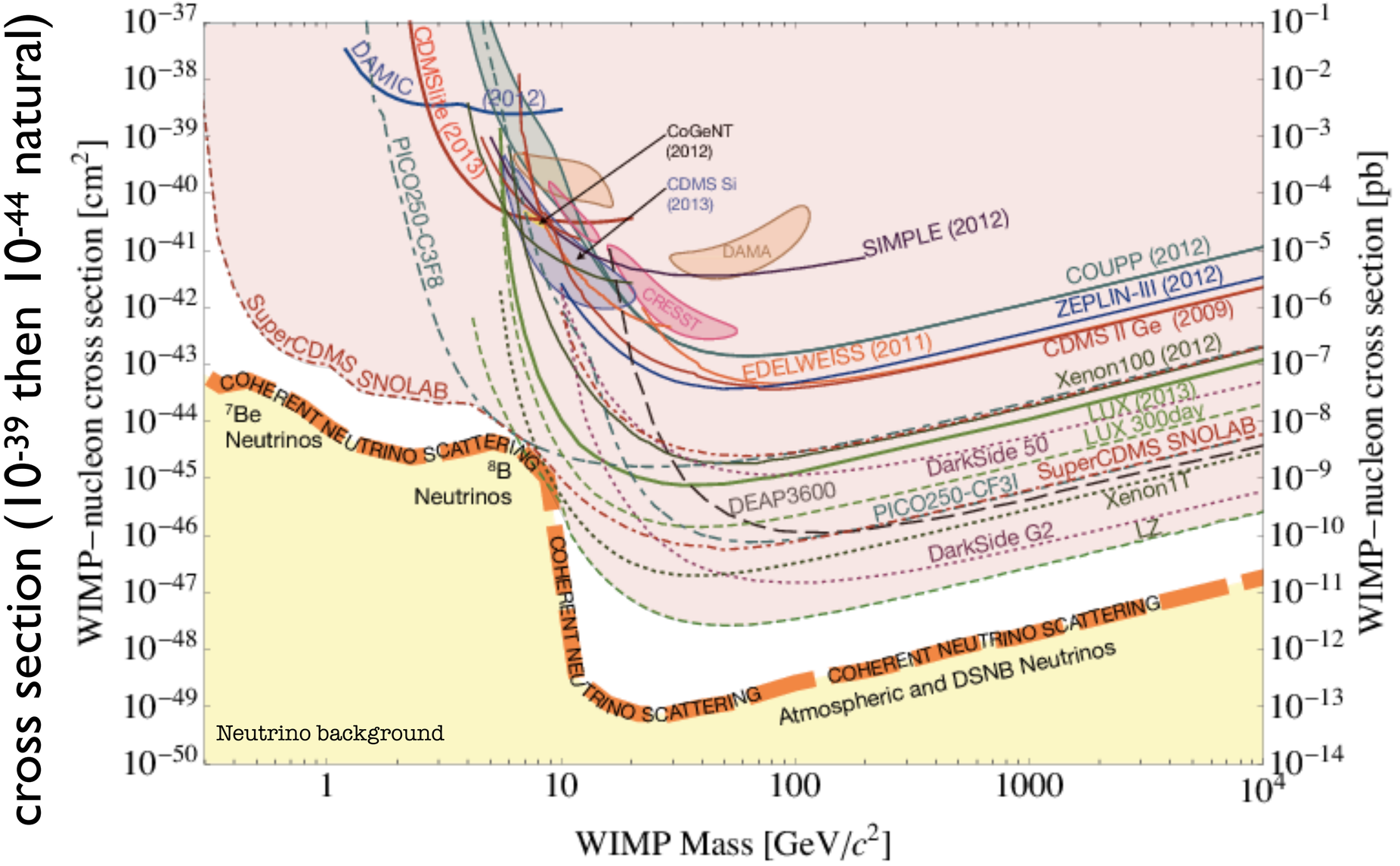
Sensitivity is maximized when the mass of the dark matter particle equals the mass of the target nucleus: $m_x = M$

$$f_T = \frac{T_f}{T_i} = \frac{4 m_X M}{(m_X + M)^2} \cos^2 \theta$$

WIMP detection experiments

Experimental goals have been reached; the neutrino background looms

http://astroweb.case.edu/ssm/darkmatter/WIMPexperiments.html



cross section (10^{-39} then 10^{-44} natural)

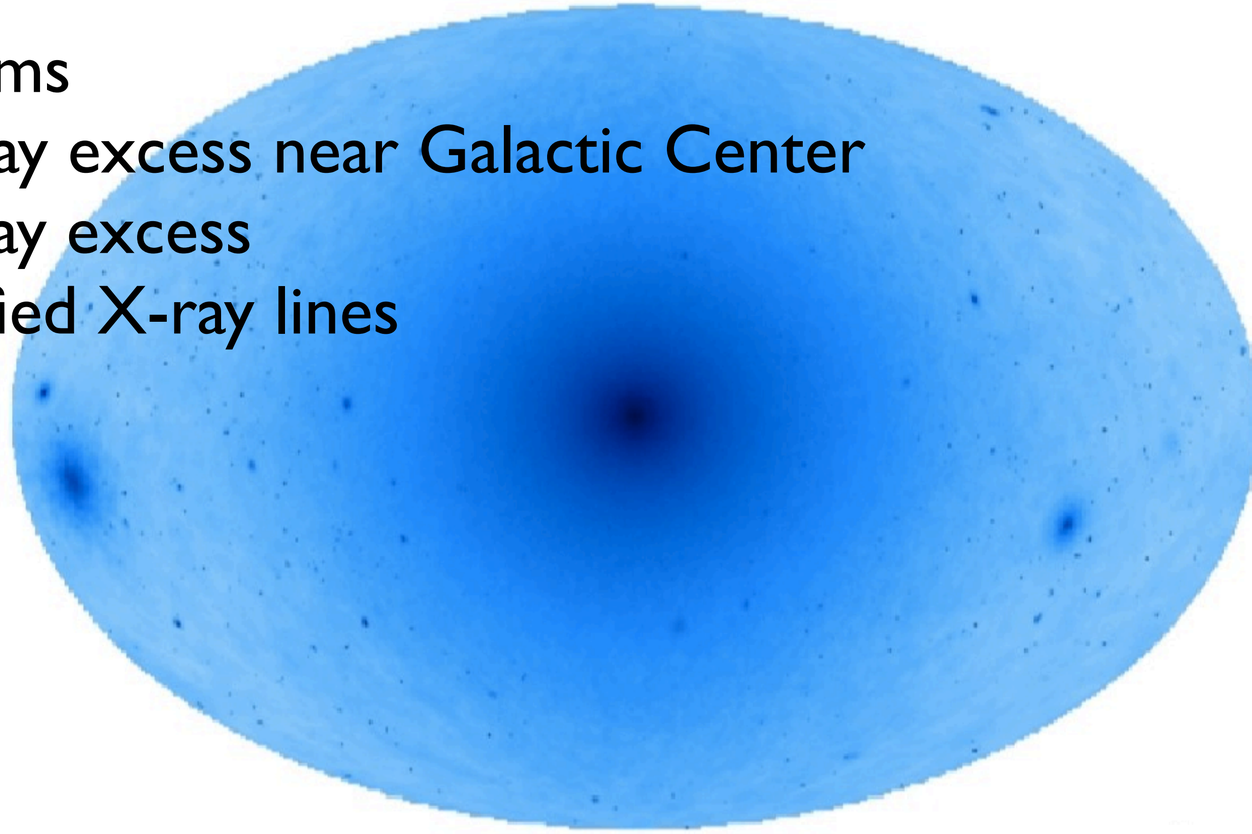
WIMP mass (~100 GeV natural)

Experimental results to date (2024): nada

LHC: the LHC sees no indication of dark matter
or even supersymmetry

Direct Detection: Nothing so far
(DAMA claims a detection that no one can reproduce)

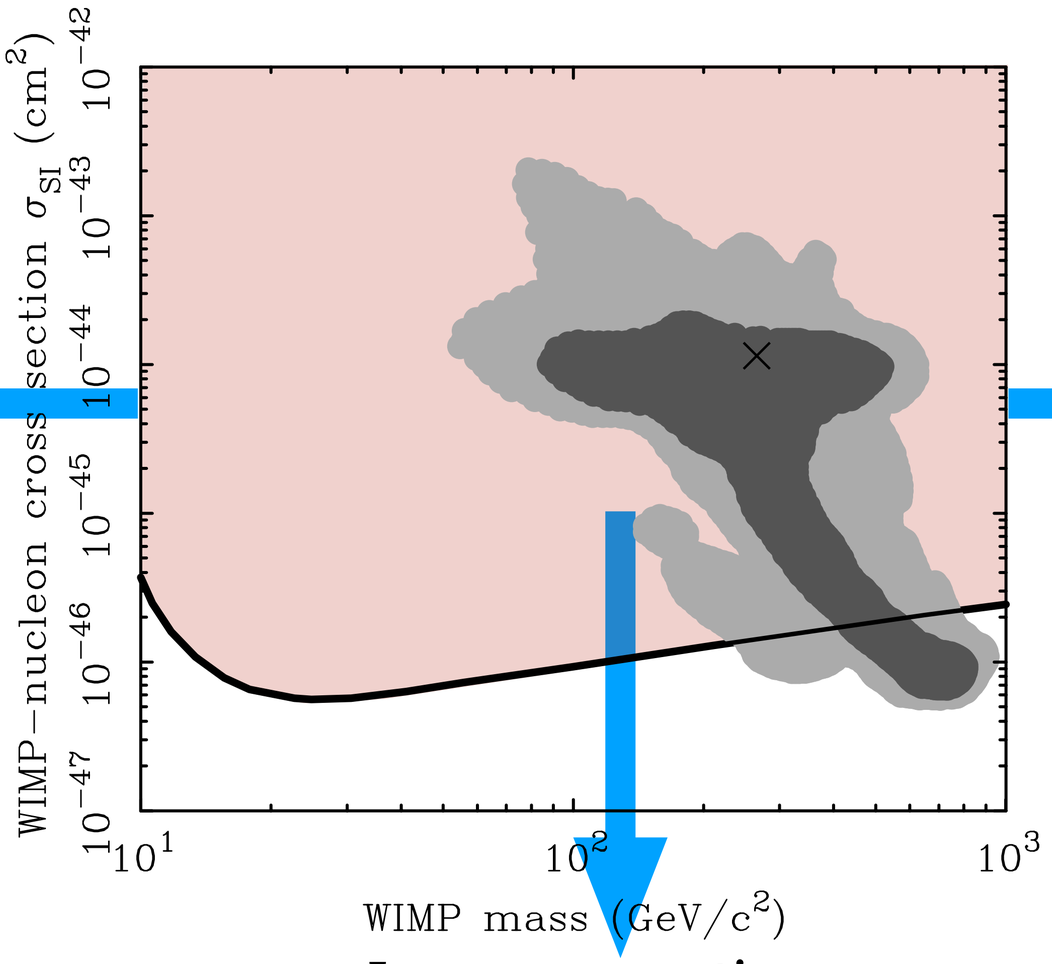
Indirect Detection: Various claims
gamma ray excess near Galactic Center
cosmic ray excess
unidentified X-ray lines



As yet: nothing credible.

WIMPs, *as originally expected*,
have been thoroughly falsified

- where are the WIMPs?



Light DM
(violate Lee-Weinberg bound: m > 2 GeV)

TeV DM
(WIMPzillas)
(because why not? Unitarity bound not till 100 TeV)

Low cross-section
(weak scale, strongly suppressed)

How do we decide when we've looked hard enough?