

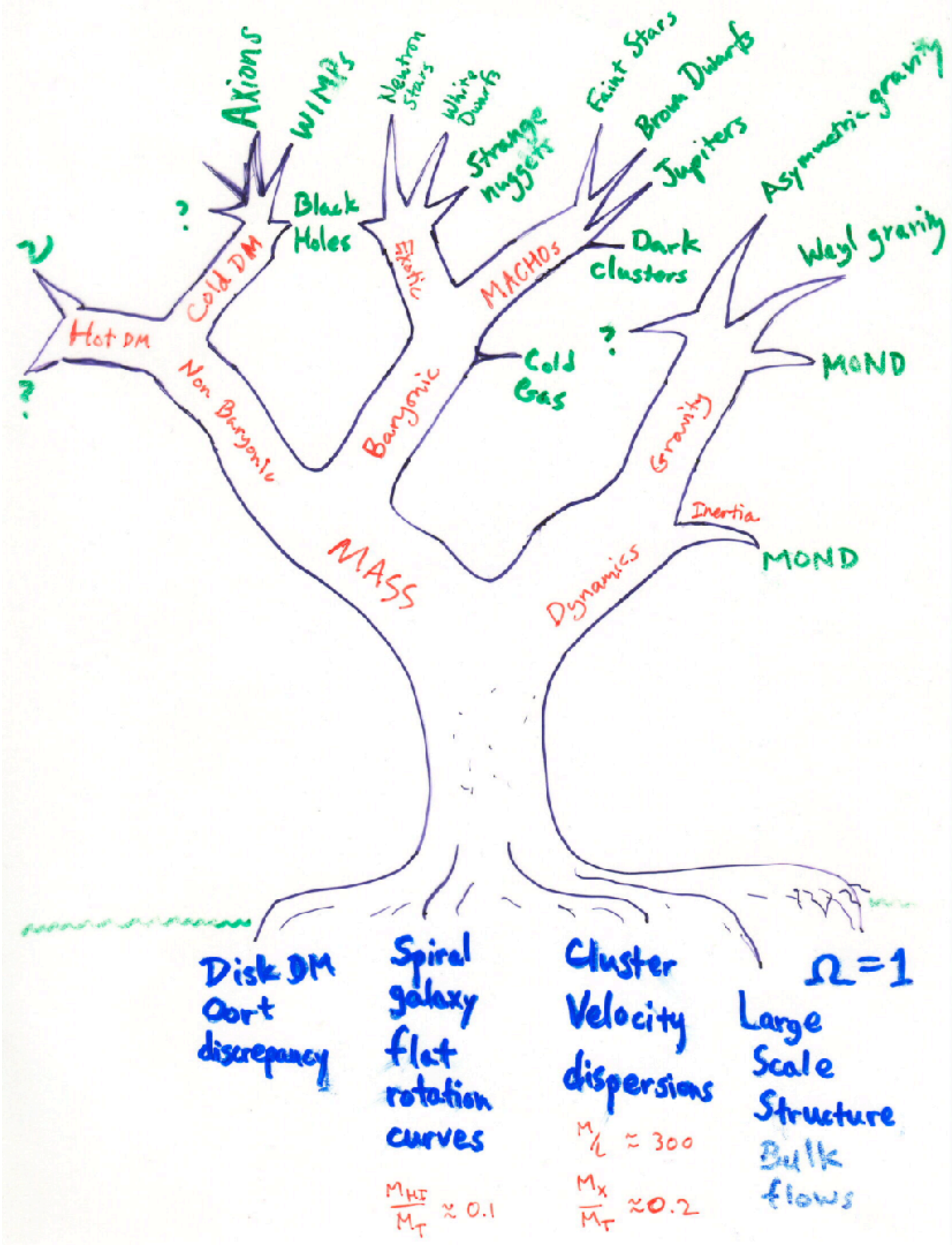
# DARK MATTER

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TR 11:30AM-12:45PM  
SEARS 552

<http://astroweb.case.edu/ssm/ASTR333/>

PROF. STACY MCGAUGH  
SEARS 558  
368-1808

[stacy.mcgaugh@case.edu](mailto:stacy.mcgaugh@case.edu)

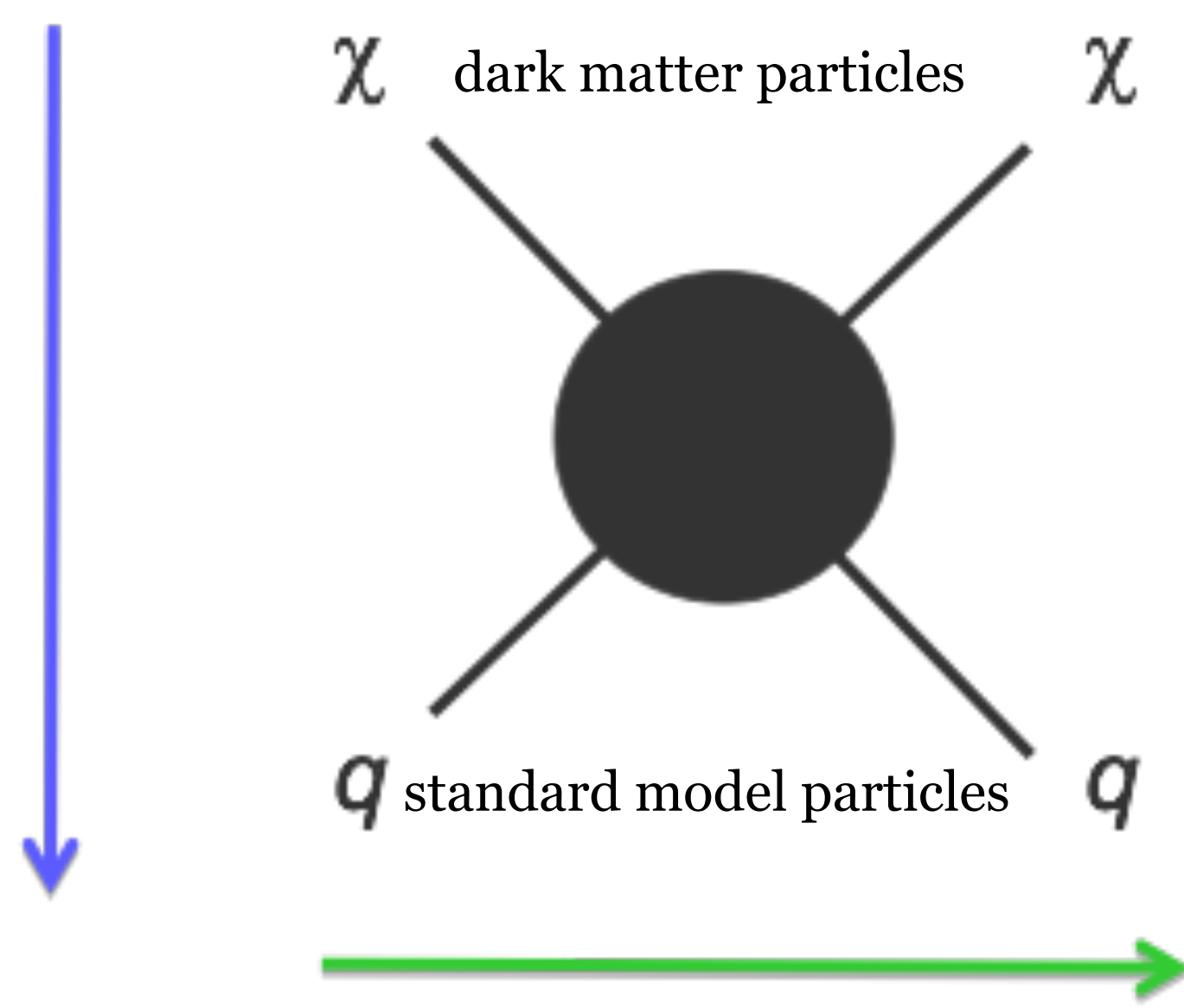


# WIMP DETECTION

Correct relic density  $\rightarrow$  Lower bound on DM-SM interaction

WIMPs decay into  
standard model particles  
(gamma rays, cosmic rays)

Efficient annihilation now  
(Indirect detection)



Efficient scattering now  
(Direct detection)

Efficient production now  
(Particle colliders)

WIMPs created in particle  
colliders (like the LHC)

WIMPs scatter off nuclei in  
underground laboratory  
experiments

# Experimental results to date: nada

## Particle production

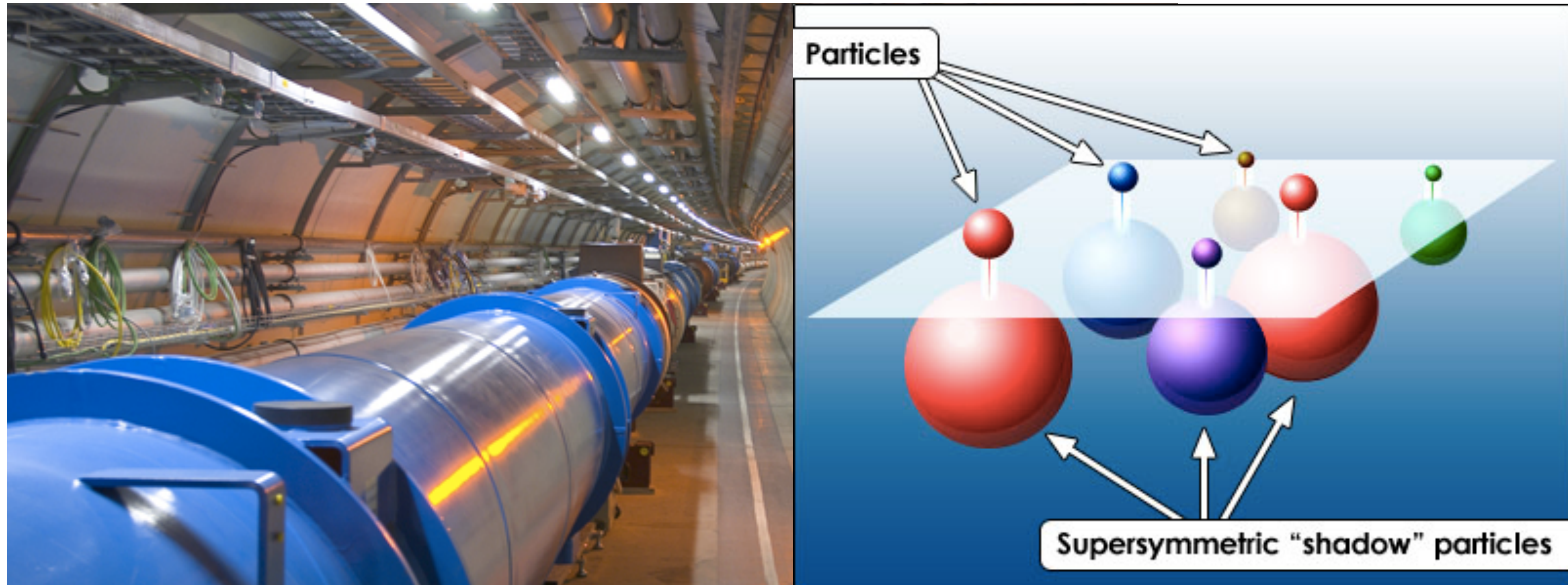
the LHC has discovered the Higgs

- a necessary ingredient for SUSY
- too “normal” for MSSM (minimal SUSY)

the LHC has NOT observed excess Bs meson decay

- the Golden Test for SUSY
- looking grim for MSSM, SUSY in general

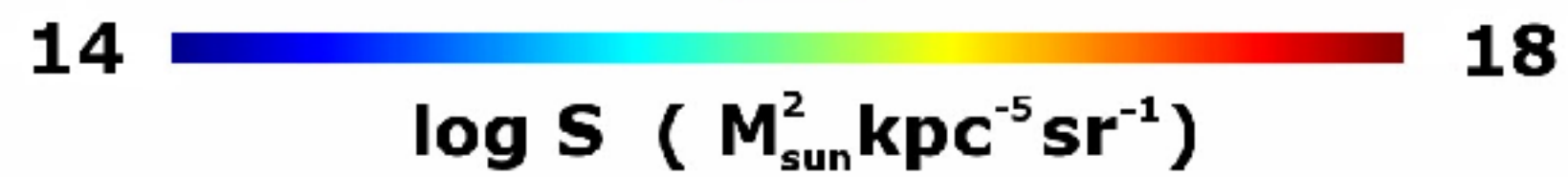
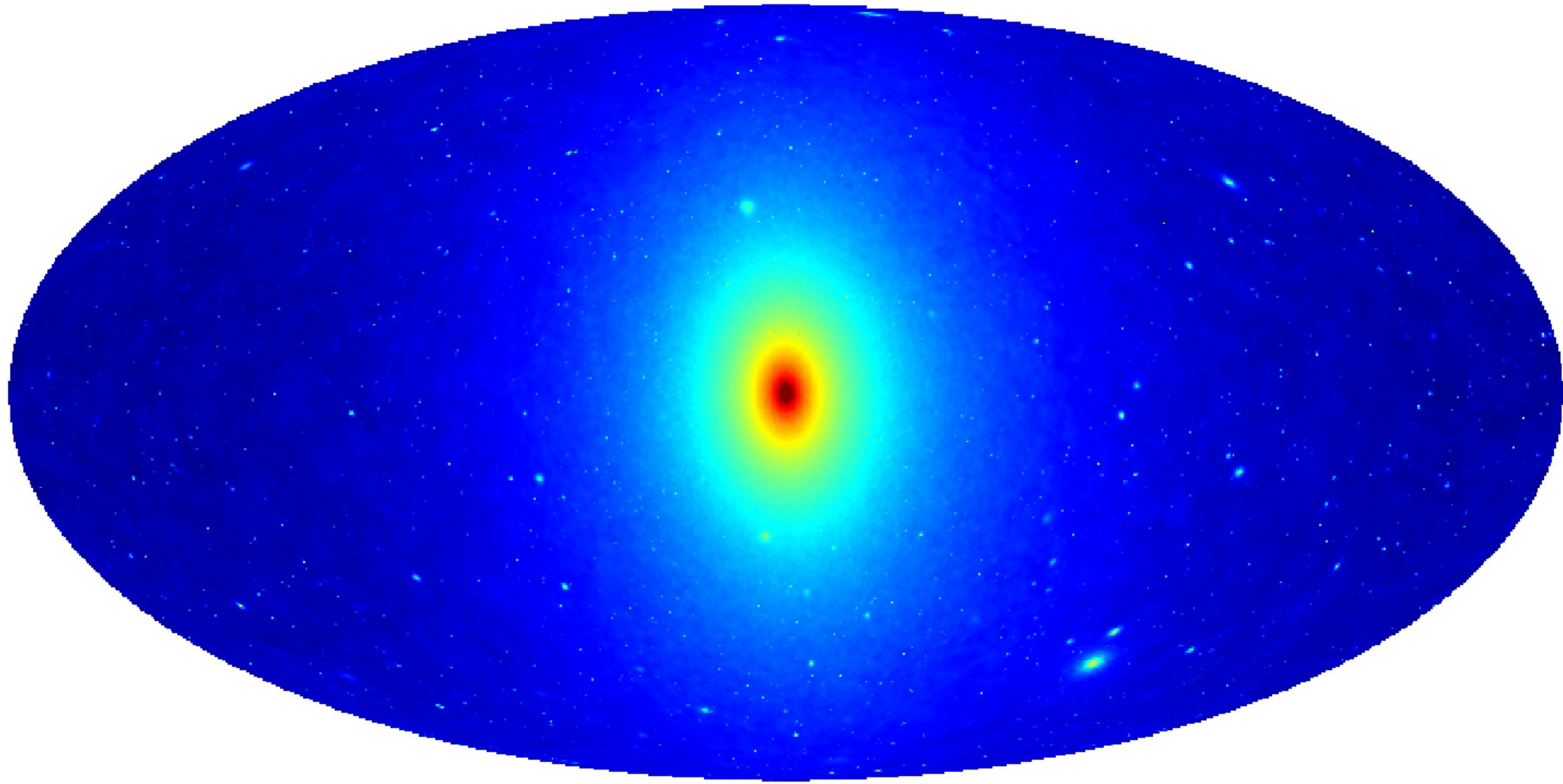
DM created in the LHC would escape like a neutrino; would be noticed by non-conservation of mass-energy



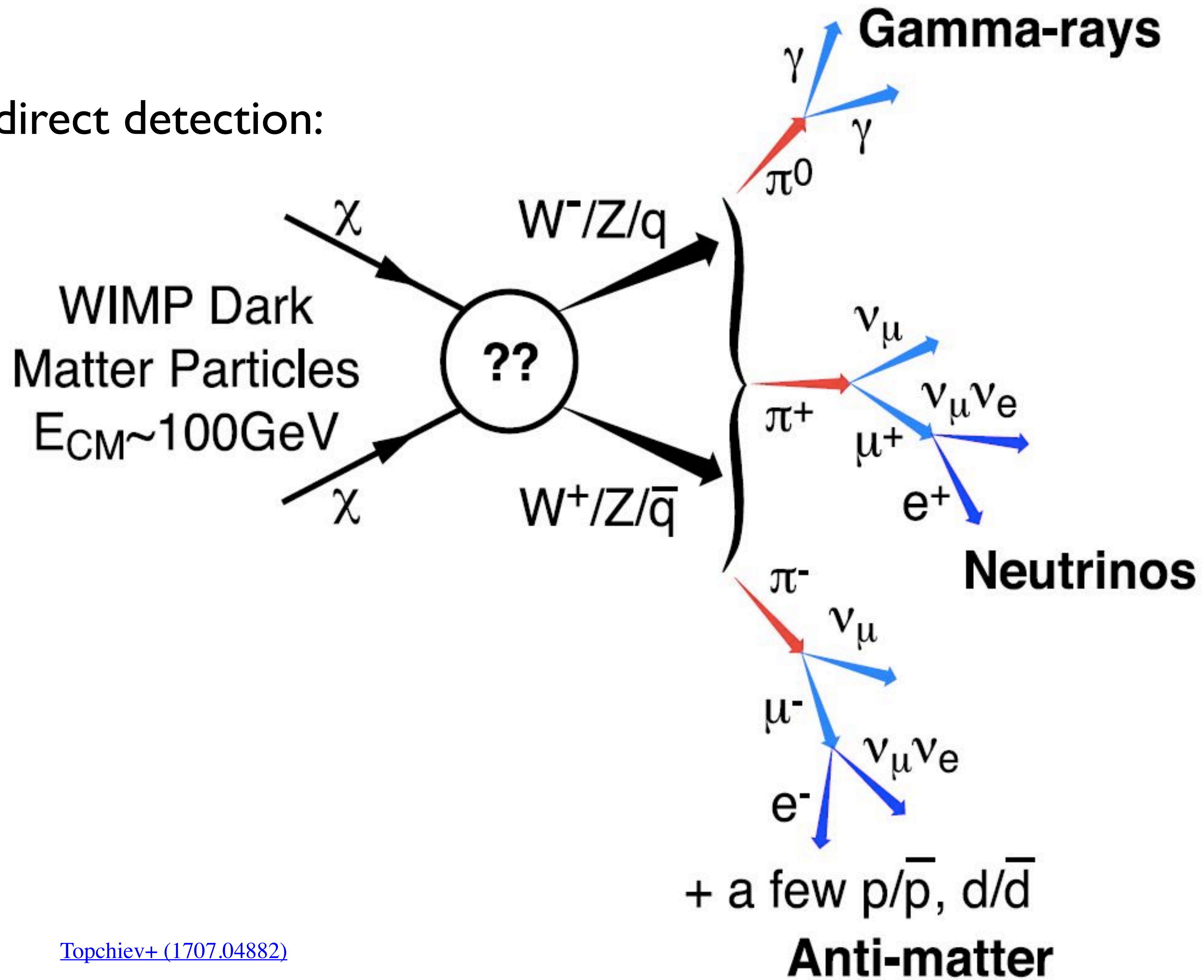
Experimental results to date: nada

## Indirect detection

predicted gamma ray sky



Indirect detection:



## Working out the expected gamma ray flux

Strigari (2018) Reviews of Modern Physics, 81, e6901

averaged annihilation  
cross-section

$$\langle \sigma v \rangle = \int d^3 v P(v) \sigma(v)$$

$\sigma$  here is the interaction cross-section  
(not velocity dispersion)  
 $\sigma$  often assumed to be velocity  
independent, but doesn't have to be.

Probability of a dark matter particle having velocity  $v$

$$P(v) = \frac{\text{distribution function } f_{DM}(x, v)}{\text{dark matter density } \rho_{DM}(x)}$$

photon flux

$$\frac{dF}{dE}$$

DM particle mass

$$= \frac{1}{4\pi m^2}$$

DM particle mass

photon spectrum

$$\frac{dN}{dE}$$

$$\int d\Omega$$

solid angle

$$\int d\ell$$

line-of-sight integral

$$\langle \sigma v \rangle [\rho_{DM}(r(\ell, \Omega))]^2$$

dark matter density squared as projected on the sky

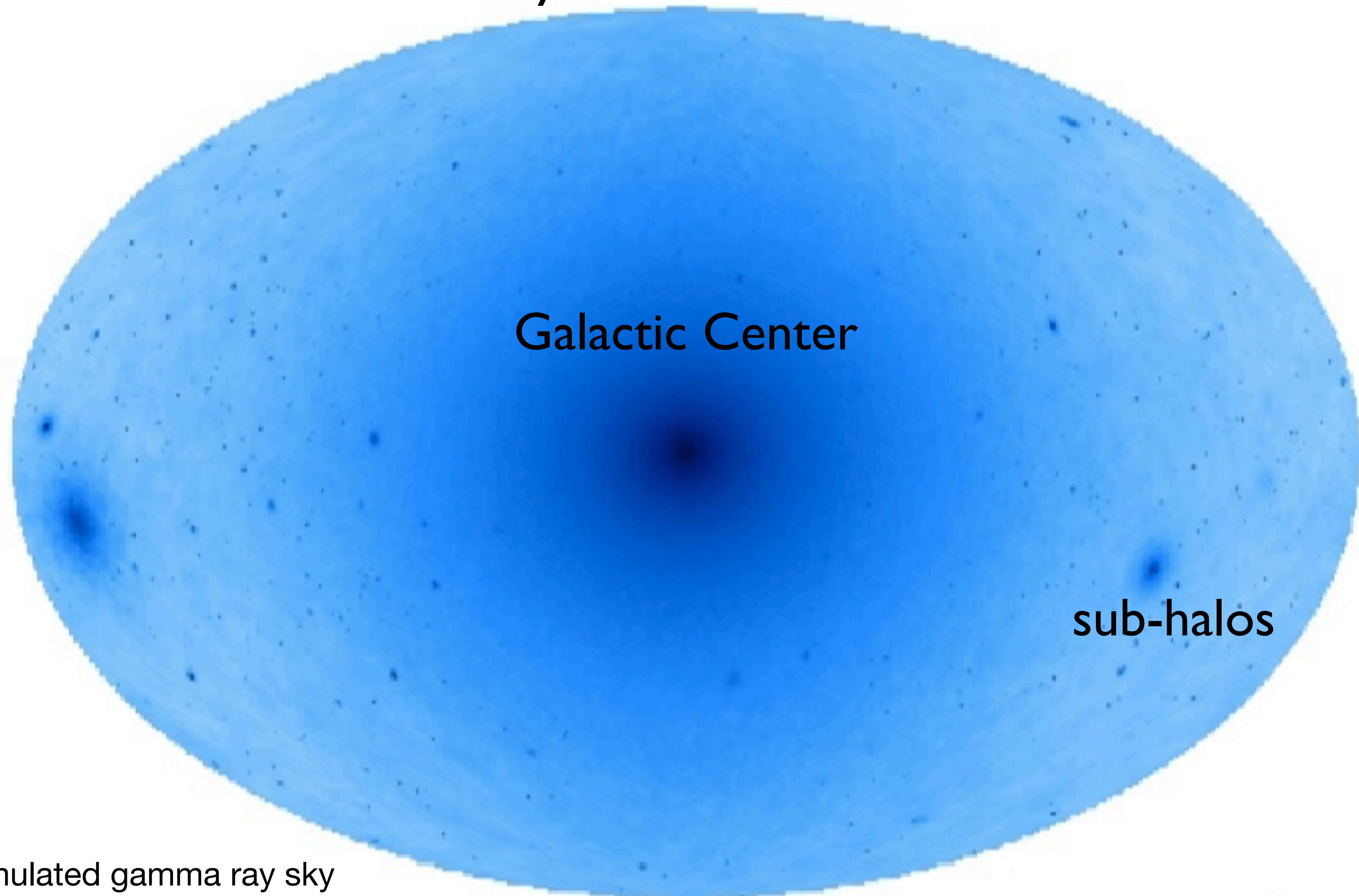
“ $J$  factor”

$$J = \int d\Omega \int d\ell [\rho_{DM}(r(\ell, \Omega))]^2$$

If the interaction cross-section is not velocity-dependent,  
then the flux depends only on the DM density profile.

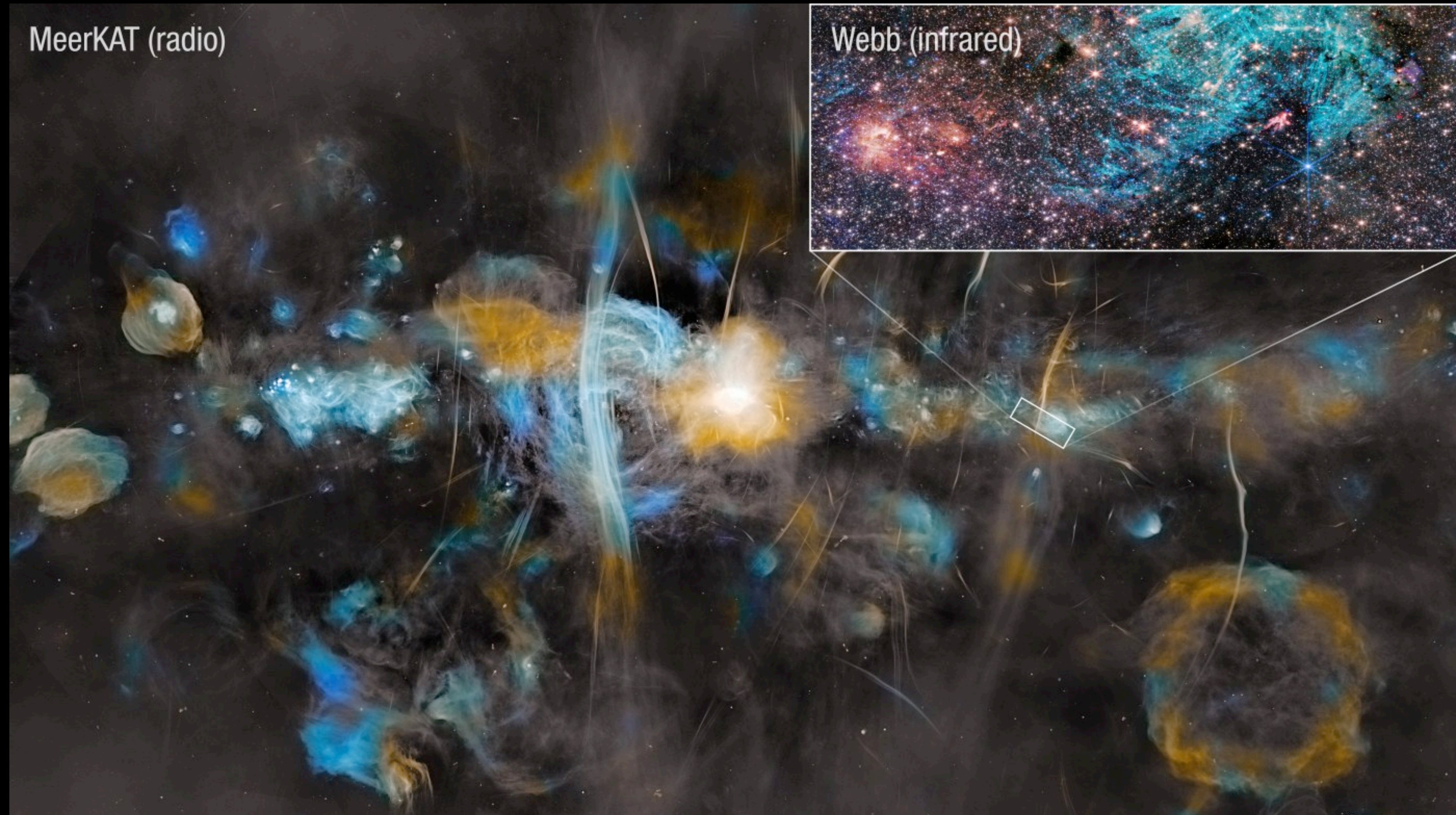
Experimental results to date: nada

gamma ray flux from WIMP self-annihilation scales as the square of the dark matter density.

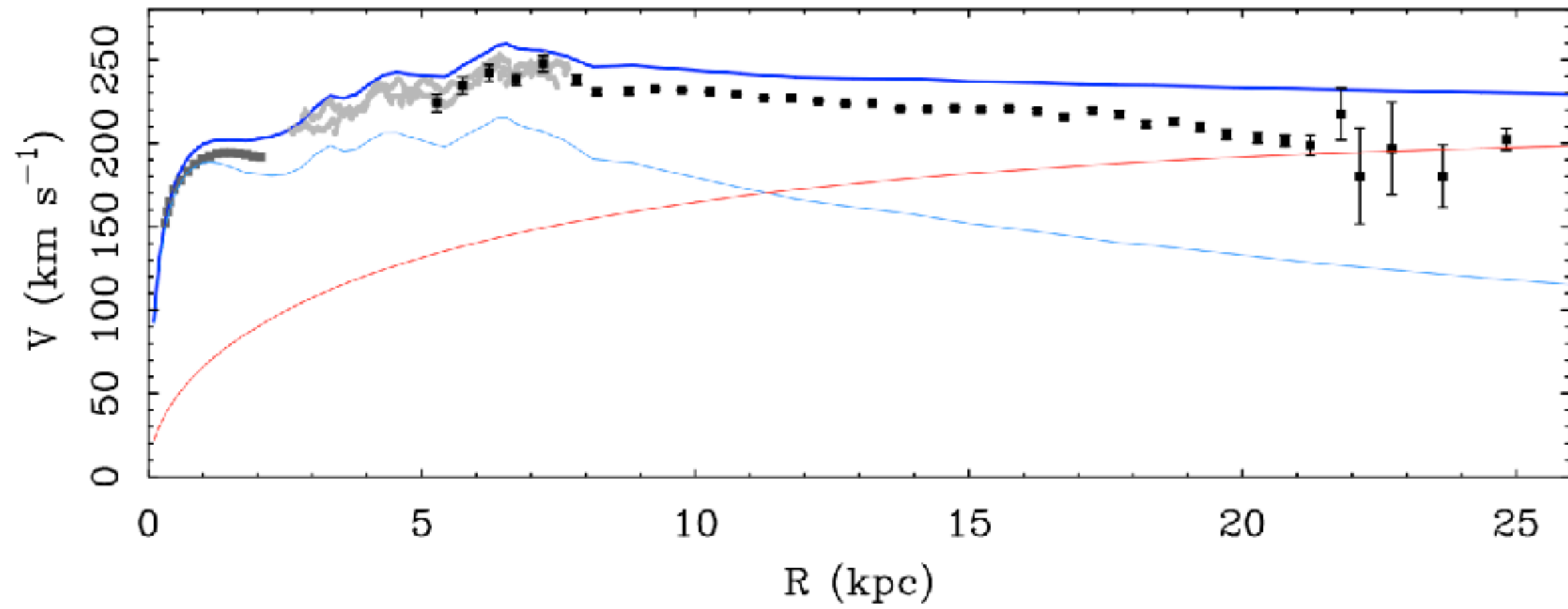


simulated gamma ray sky

# The center of the Milky Way is a busy place with lots of astrophysical sources



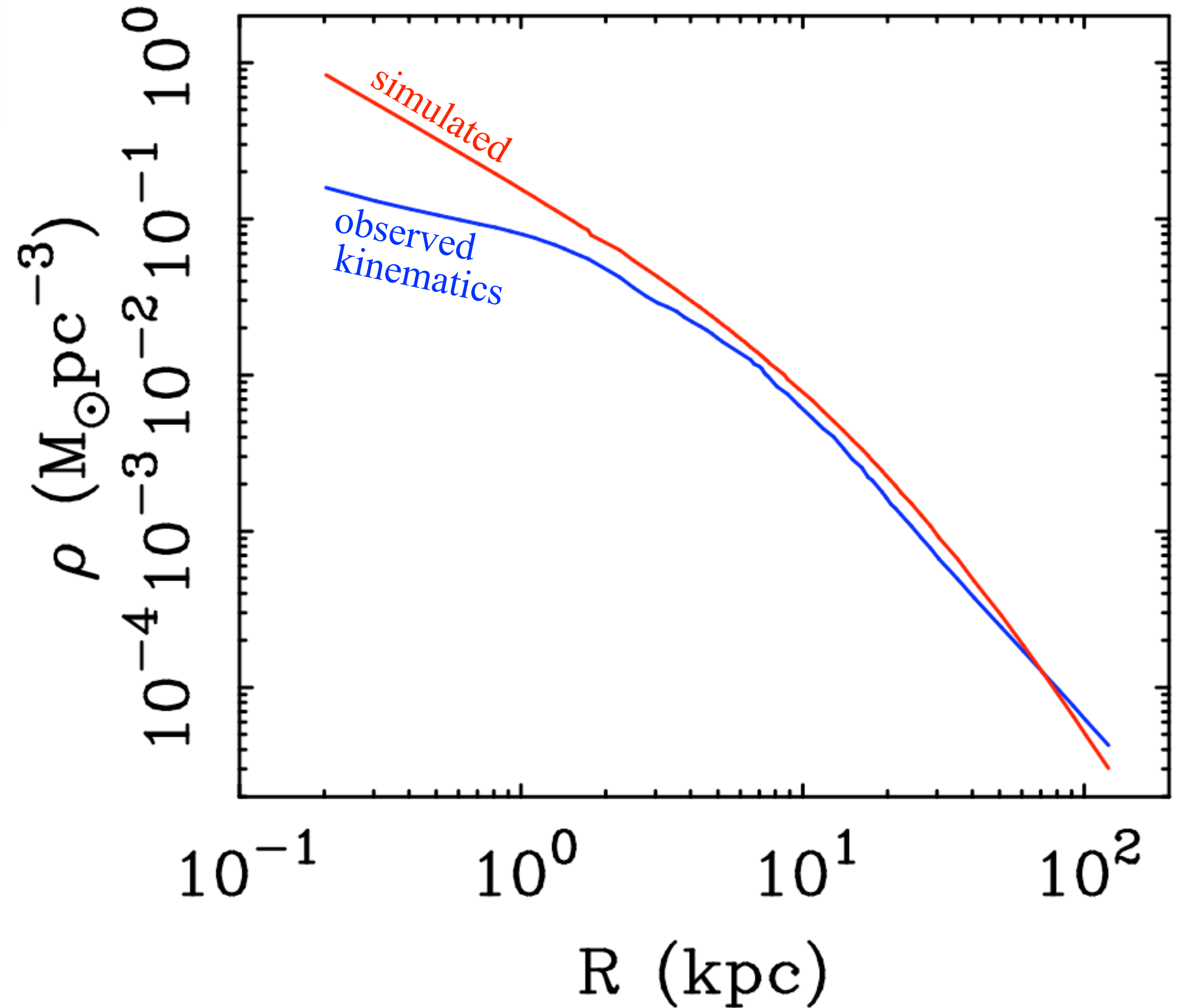
The center of the Milky Way as seen by the [South African MeerKAT radio telescope](#) with a close up from [JWST](#).  
Image credit: NASA, ESA, CSA, STScI, SARA0, S. Crowe (UVA), J. Bally (CU), R. Fedriani (IAA-CSIC), I. Heywood (Oxford).



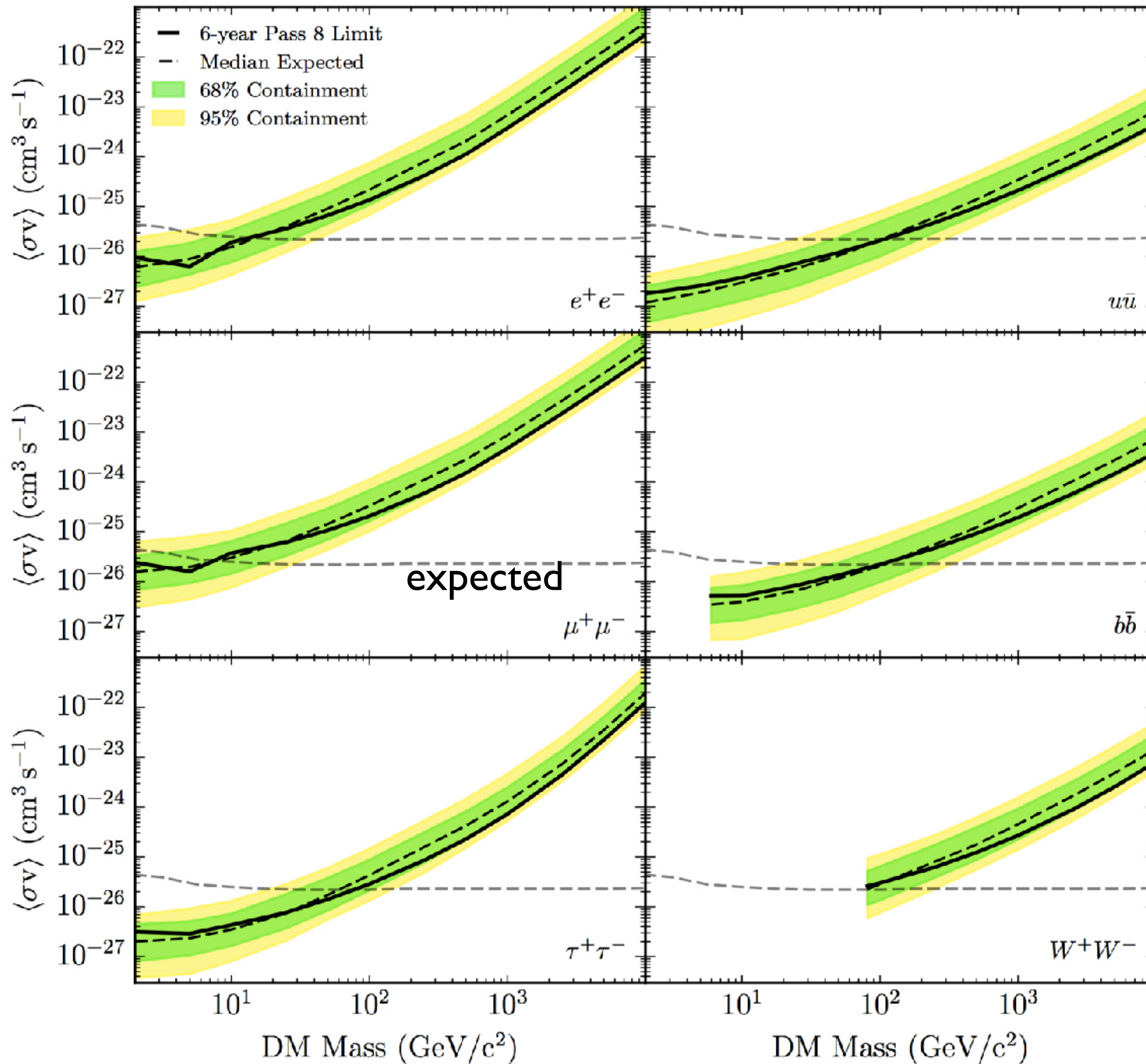
There is a recent claim of an indirect detection of Milky Way dark matter in  $\gamma$ -rays by [Totani \(2025\)](#).

[Totani \(2025\)](#) assumes a DM profile from a simulation that is more dense than observed.

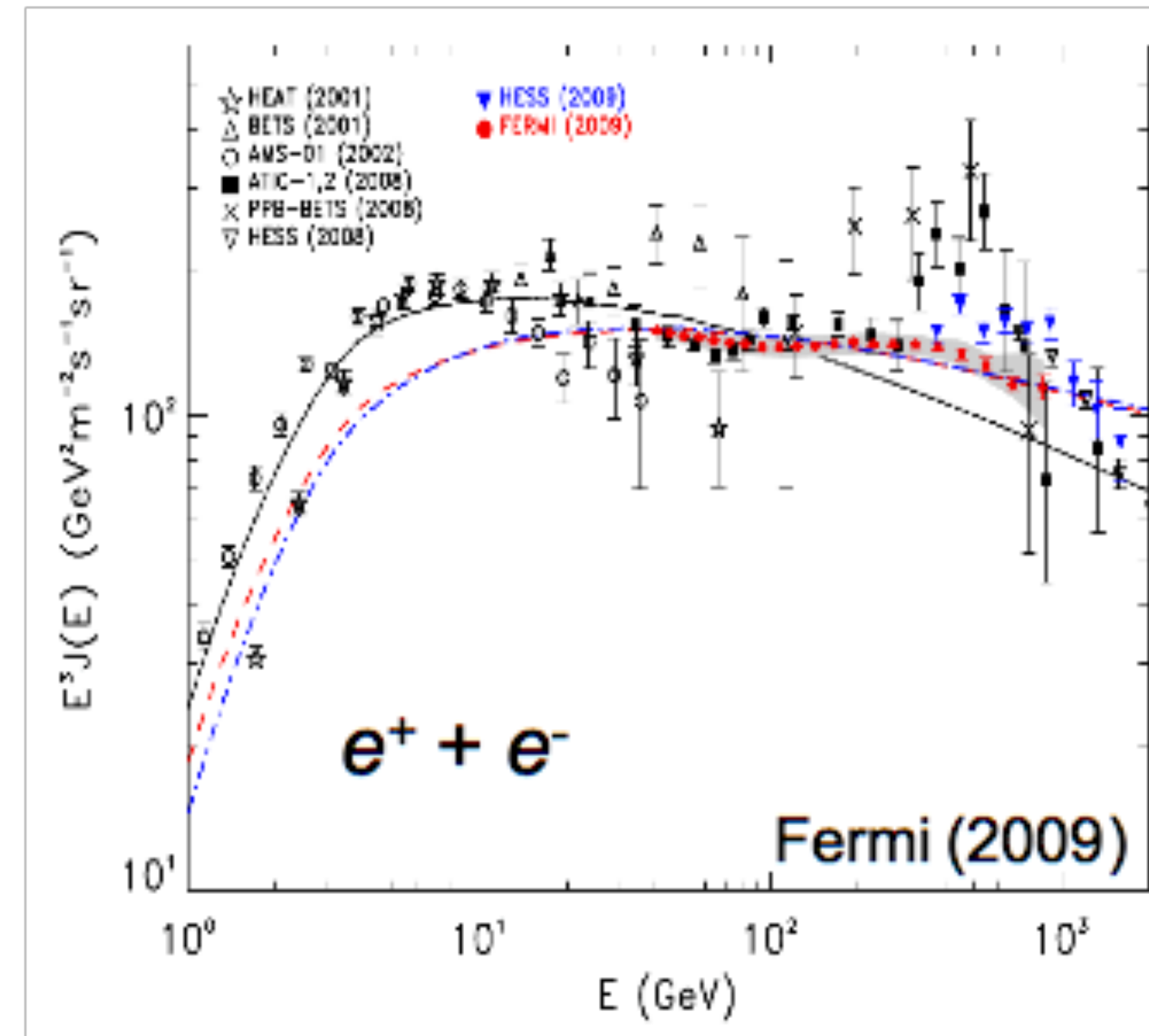
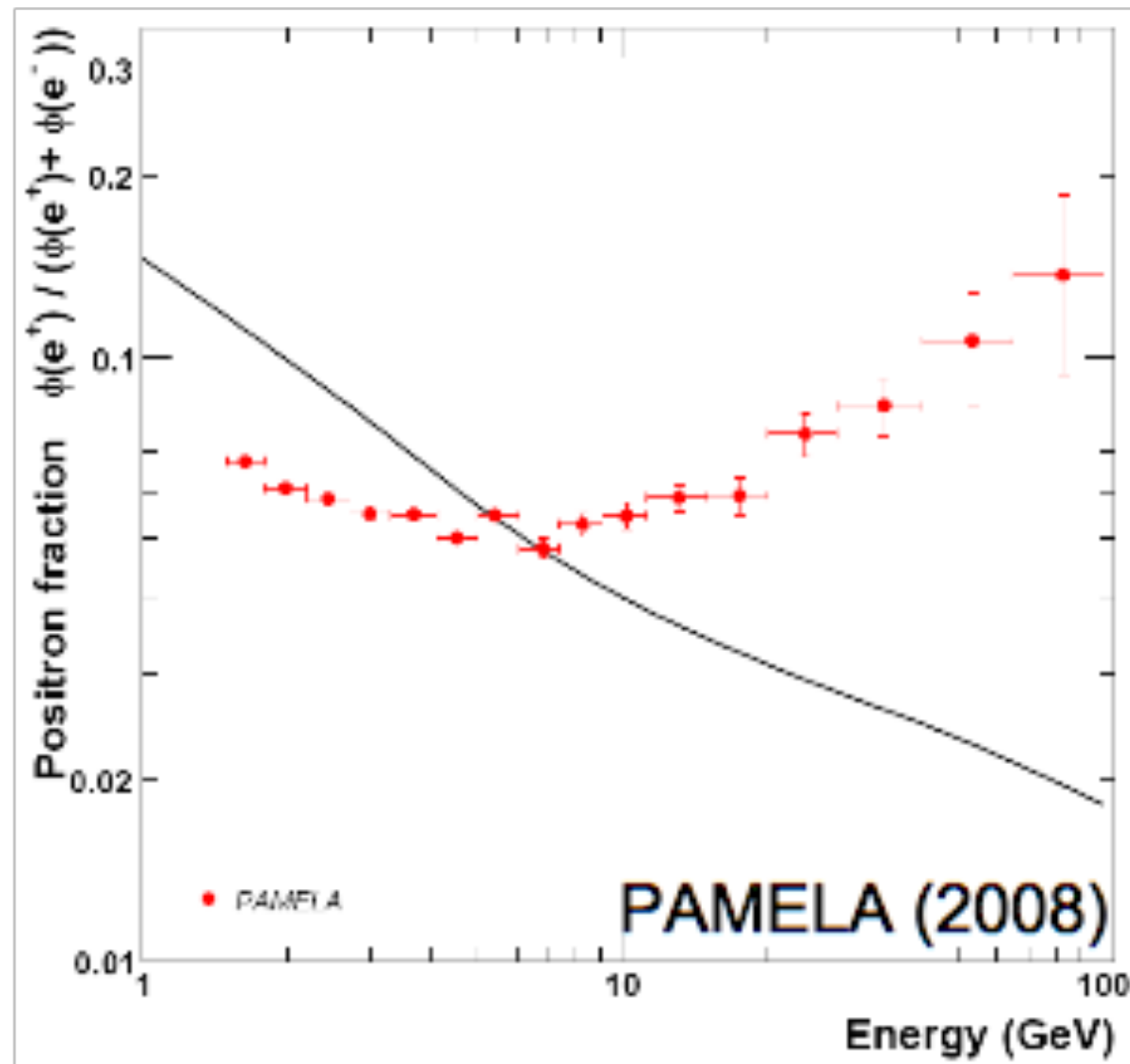
This has a large impact on the predicted  $\gamma$ -ray flux, which depends on the square of the DM density,  $\rho^2$ .



Low mass  
WIMPs  
excluded  
for  
various  
decay  
channels



# INDIRECT DETECTION



Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

*One must exclude astrophysical sources  
before claiming a detection of dark matter.*

# ARE THESE DARK MATTER?

- Pulsars can explain PAMELA

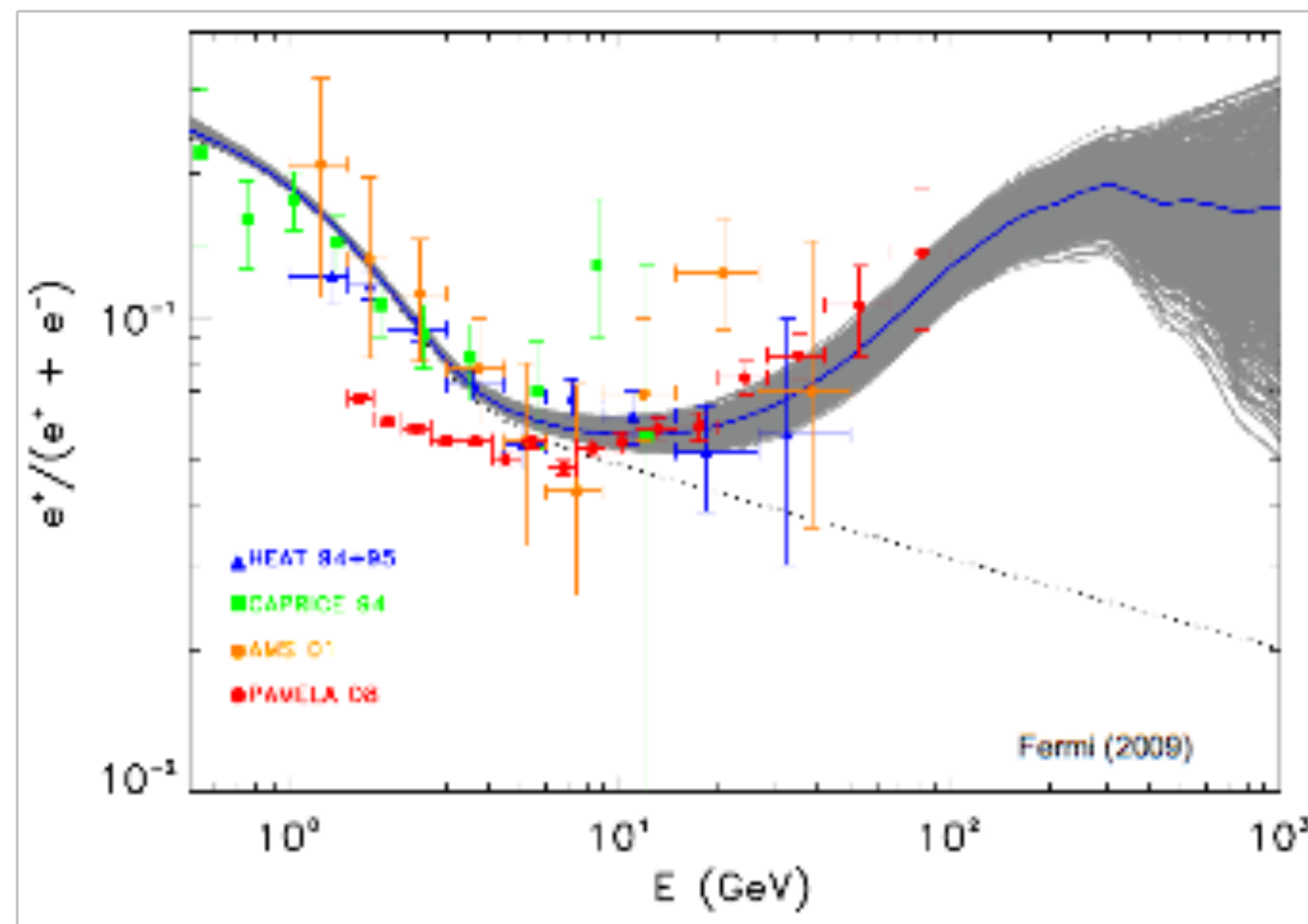
Zhang, Cheng (2001); Hooper, Blasi, Serpico (2008)

Yuksel, Kistler, Stanev (2008)

Profumo (2008) ; Fermi (2009)

- For dark matter, there is both good and bad news

- Good: the WIMP miracle motivates excesses at  $\sim 100$  GeV – TeV



- Bad: the WIMP miracle also tells us that the annihilation cross section should be a factor of 100-1000 too small to explain these excesses. Need enhancement from

- astrophysics (very unlikely)
- particle physics (also very unlikely)

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The canonical WIMP cross-section is pretty well specified (Steigman et al. 2012: <https://arxiv.org/abs/1204.3622>)

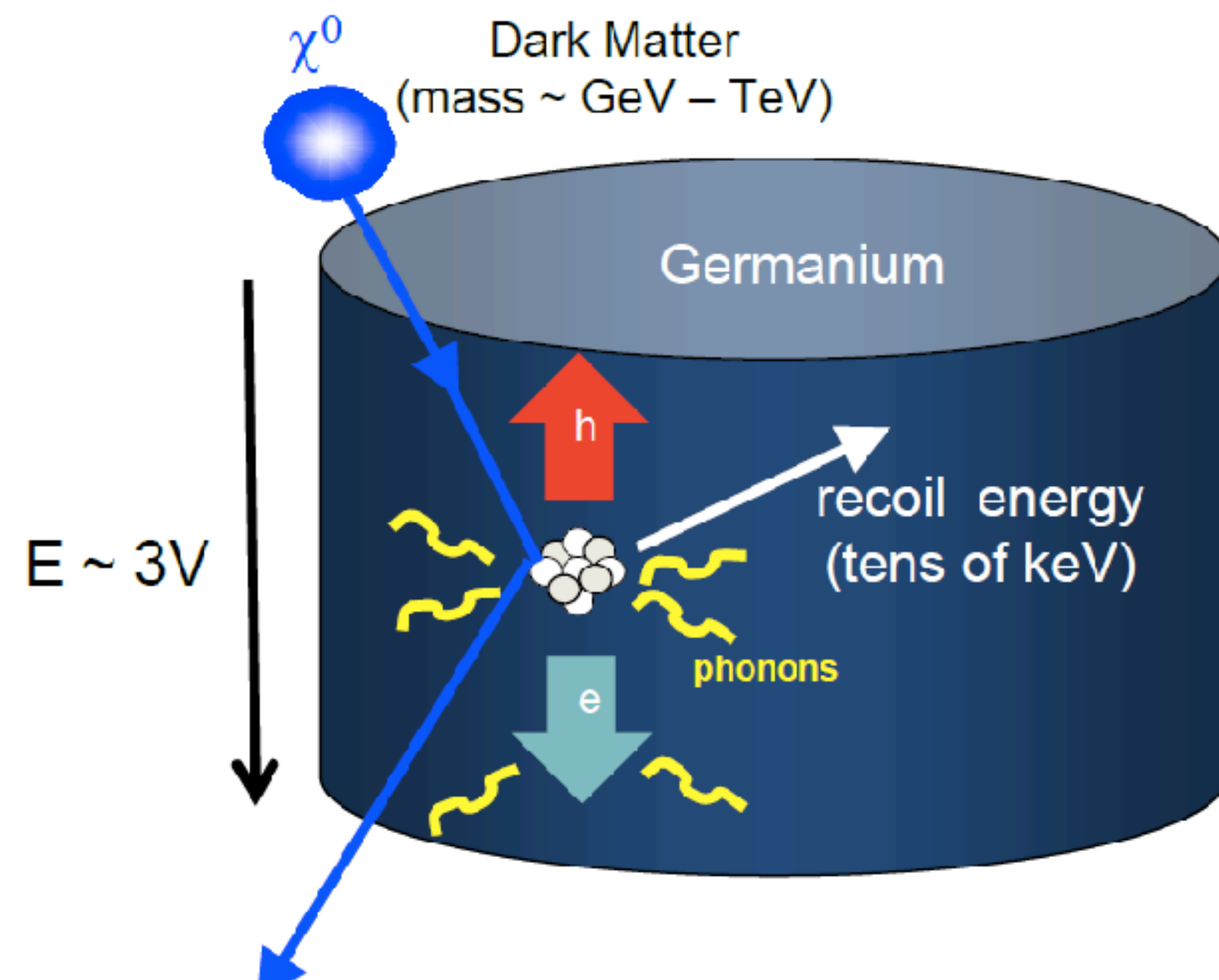
Experimental results to date: nada

## 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).



## 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.

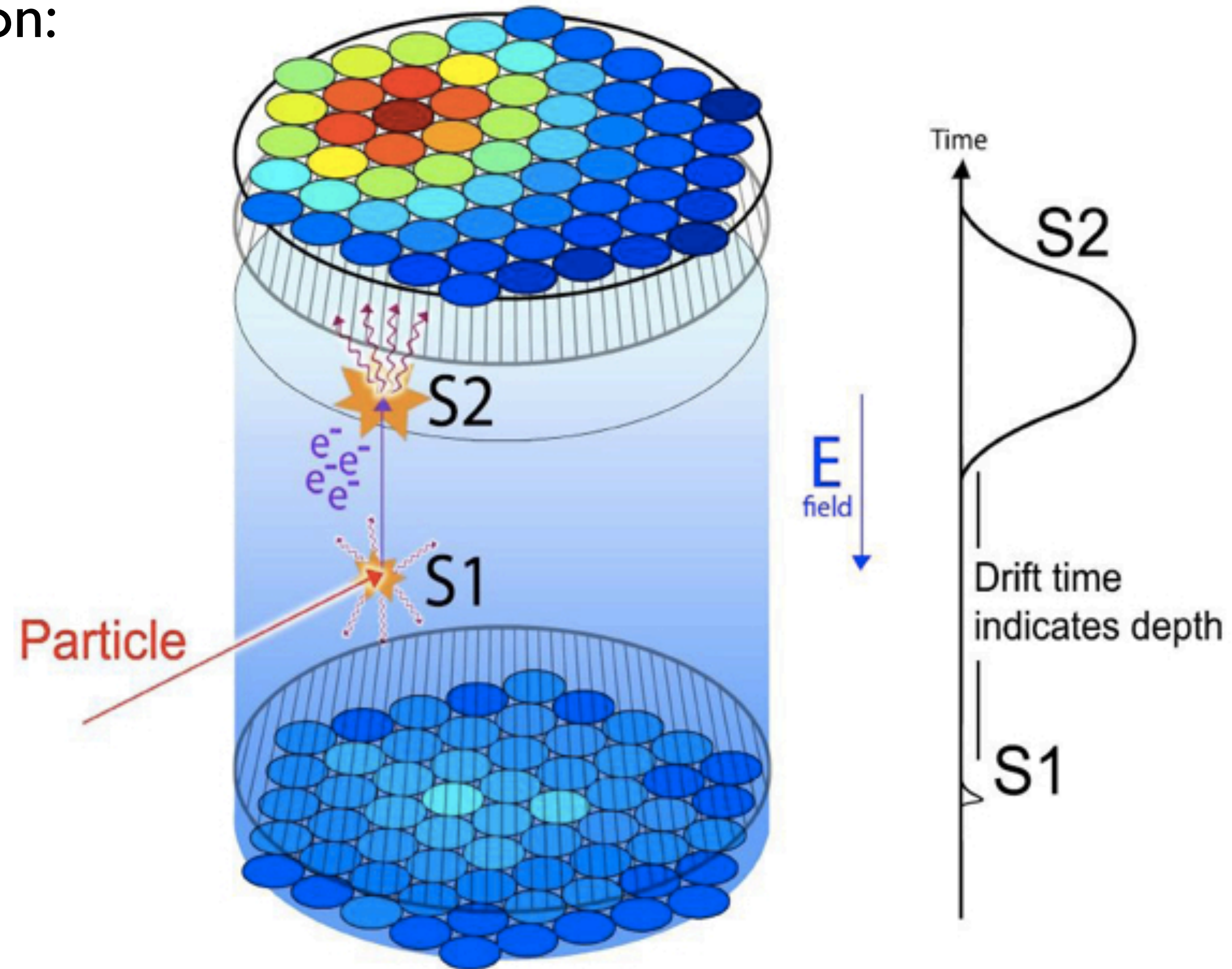
**Bubble chambers** – The [PICASSO](#) experiment is a direct dark matter search experiment that is located at [SNOLAB](#) in Canada. It uses bubble detectors with [Freon](#) as the active mass. PICASSO is predominantly sensitive to spin-dependent interactions of WIMPs with the fluorine atoms in the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

# XENON type detectors

Direct detection:

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

Bury them deep in mines.



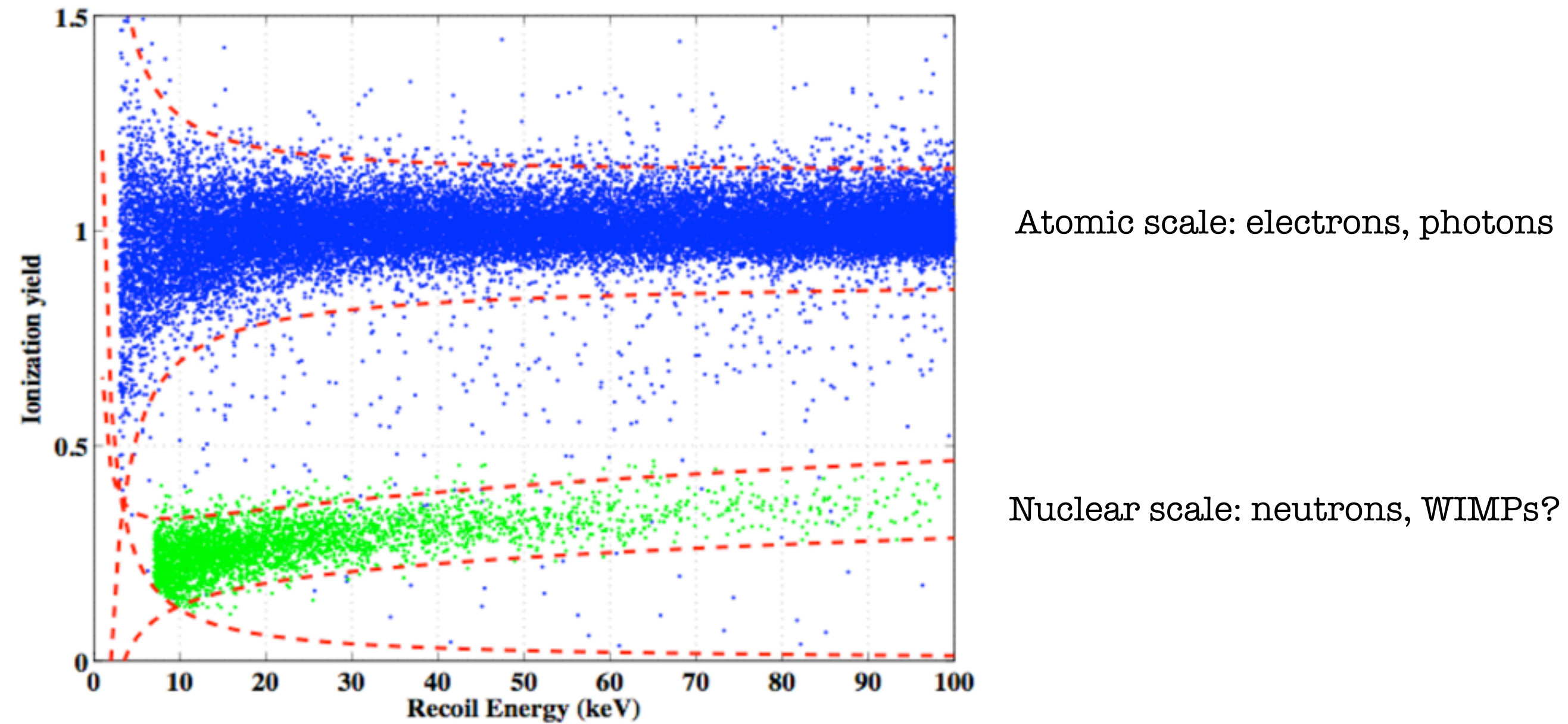
- ionization electrons
- UV scintillation photons (~175 nm)

# 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.



**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

**WIMP Wind**



**June**



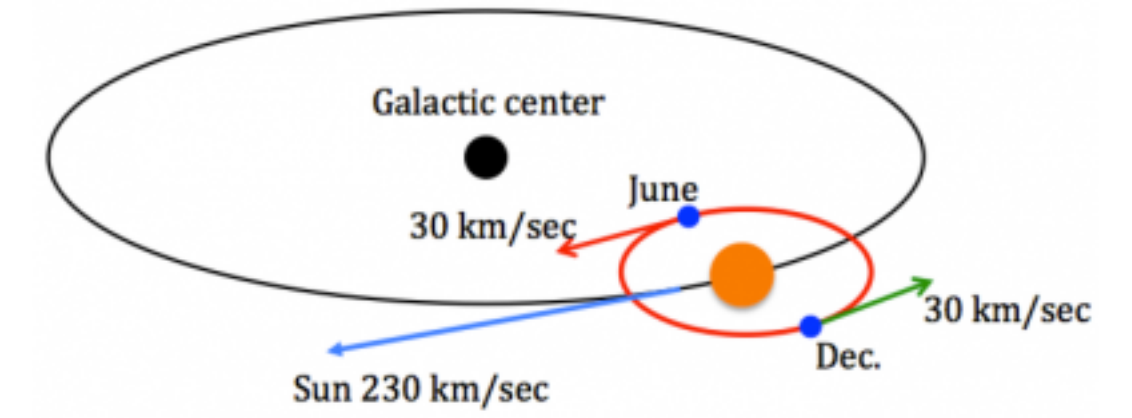
**Sun**

Cygnus  
 $V_0 \sim 220 \text{ km/s}$

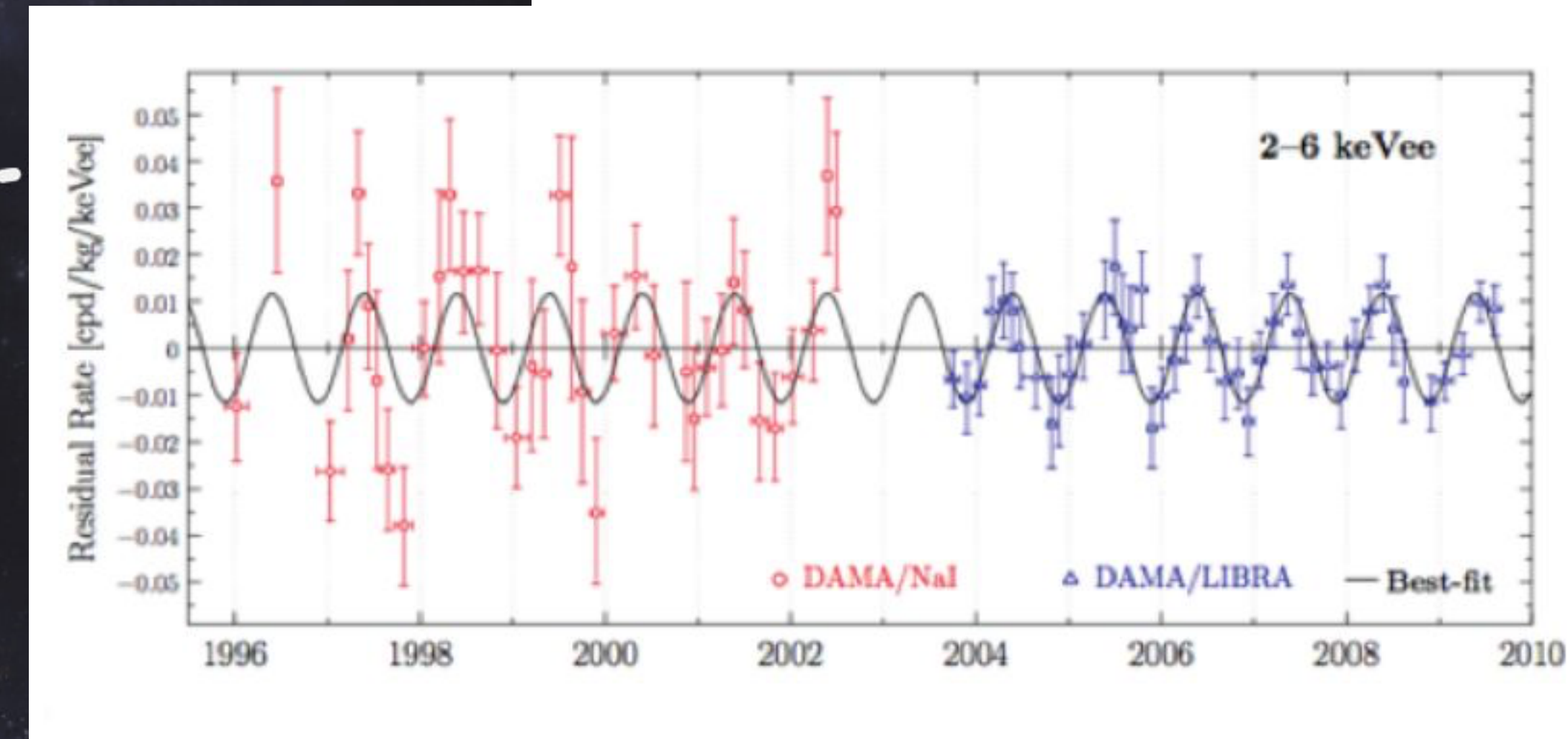
$60^\circ$



**December**



DAMA/LIBRA claimed a  $9 \sigma$  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](https://arxiv.org/abs/1403.1404)].

This is the same sort of signal Michelson & Morley sought for aether

# WIMPs are hiding

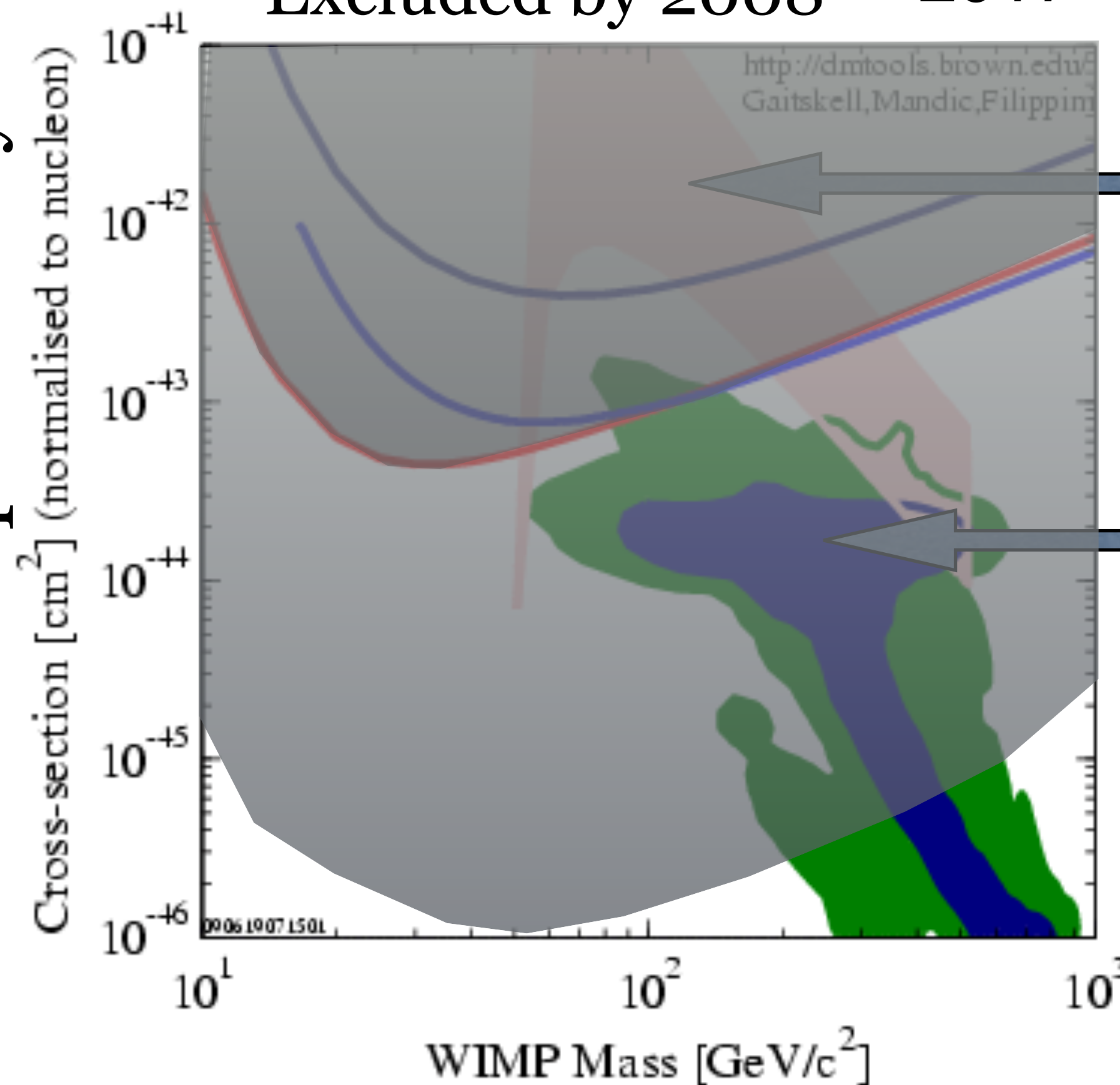
original prediction  $\sim 10^{-39}$

Excluded by 2008 2017

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

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

interaction probability



Early prediction

2008 prediction

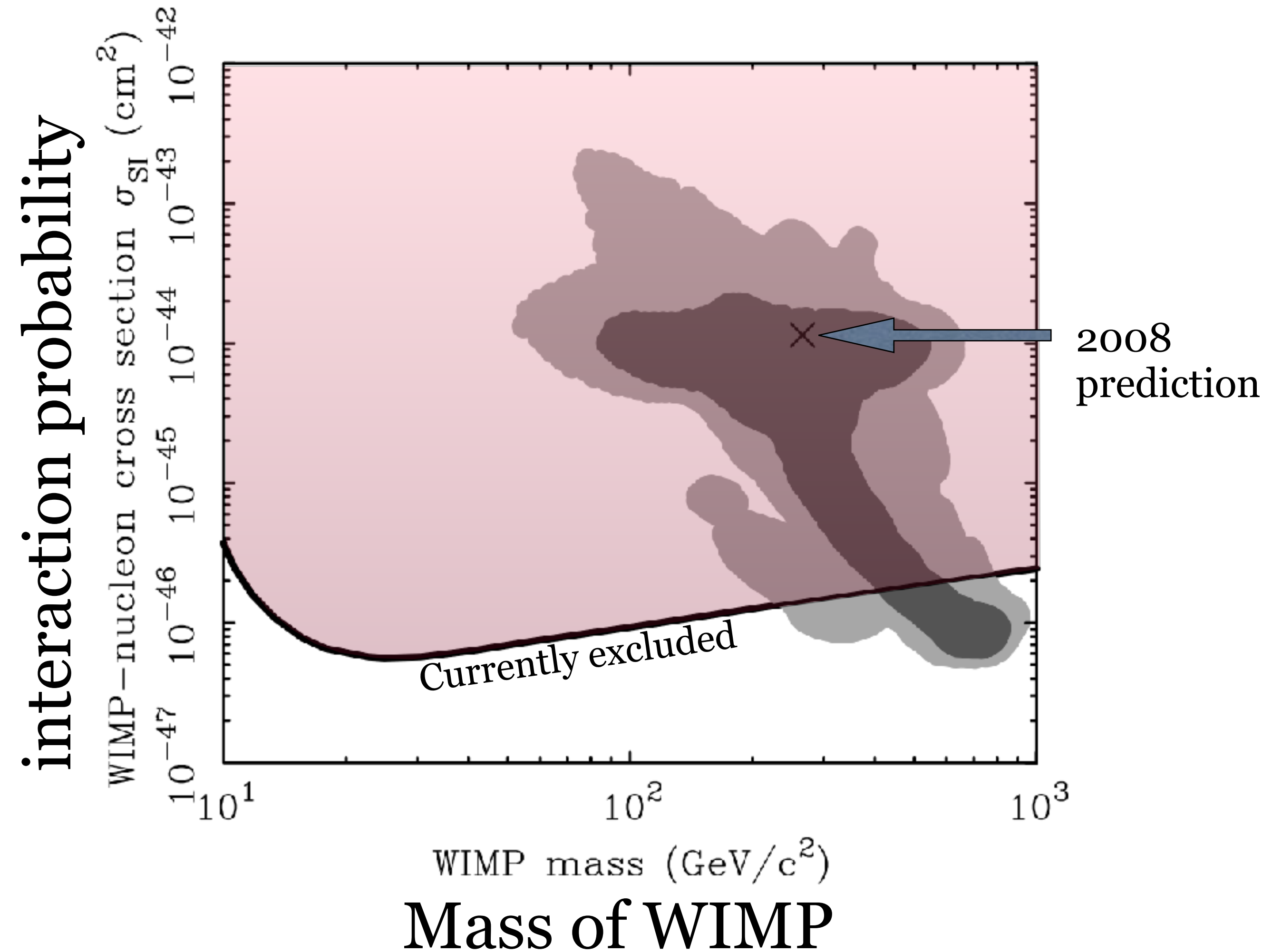
Mass of WIMP

WIMP detection experiments

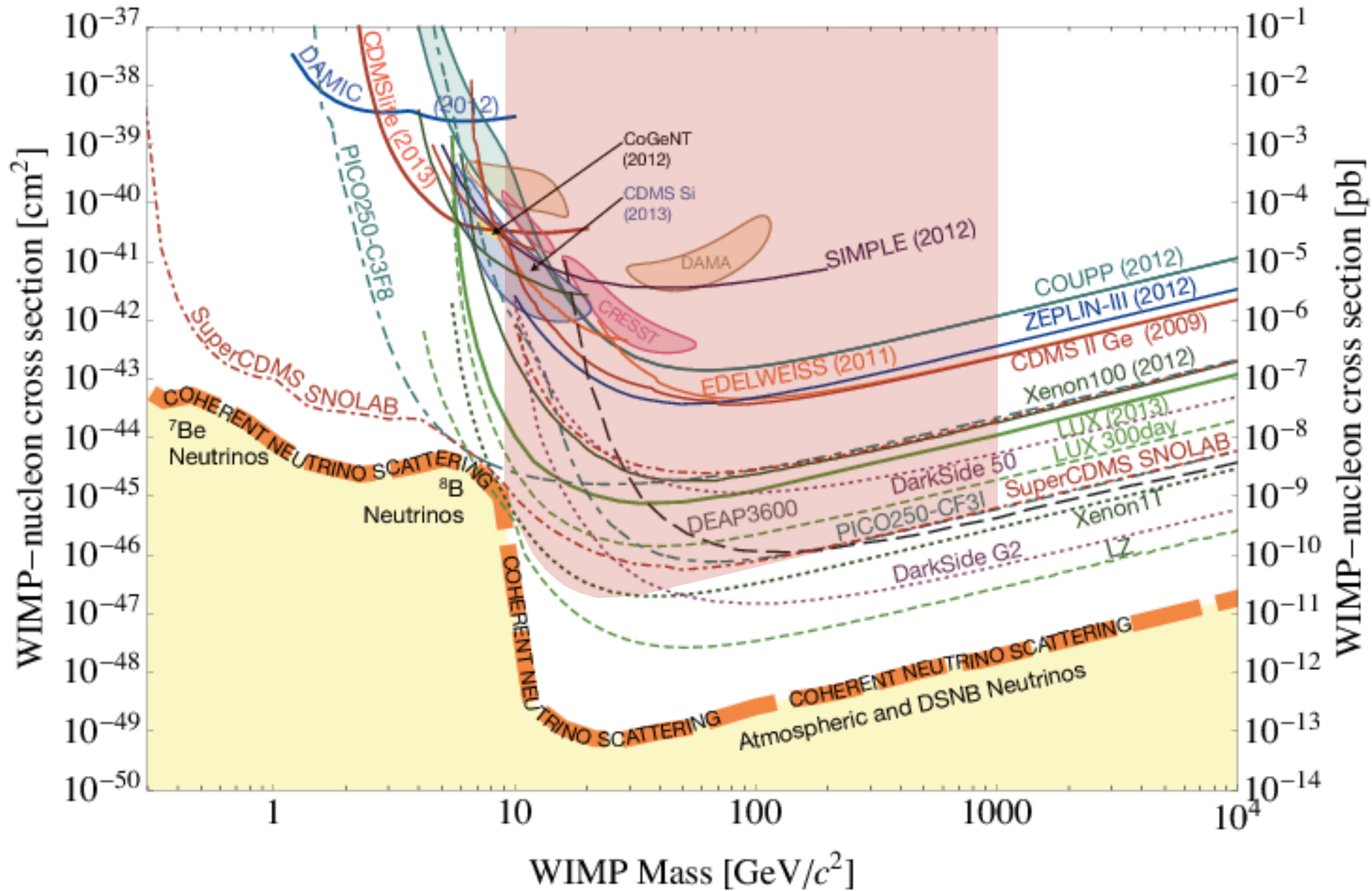
# Direct detection experiments have repeatedly excluded predicted WIMP properties

The original prediction of  $\sigma \sim 10^{-39}$  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.



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



WIMP mass ( $\sim 100 \text{ GeV}$  natural)

## Experimental results to date: nada

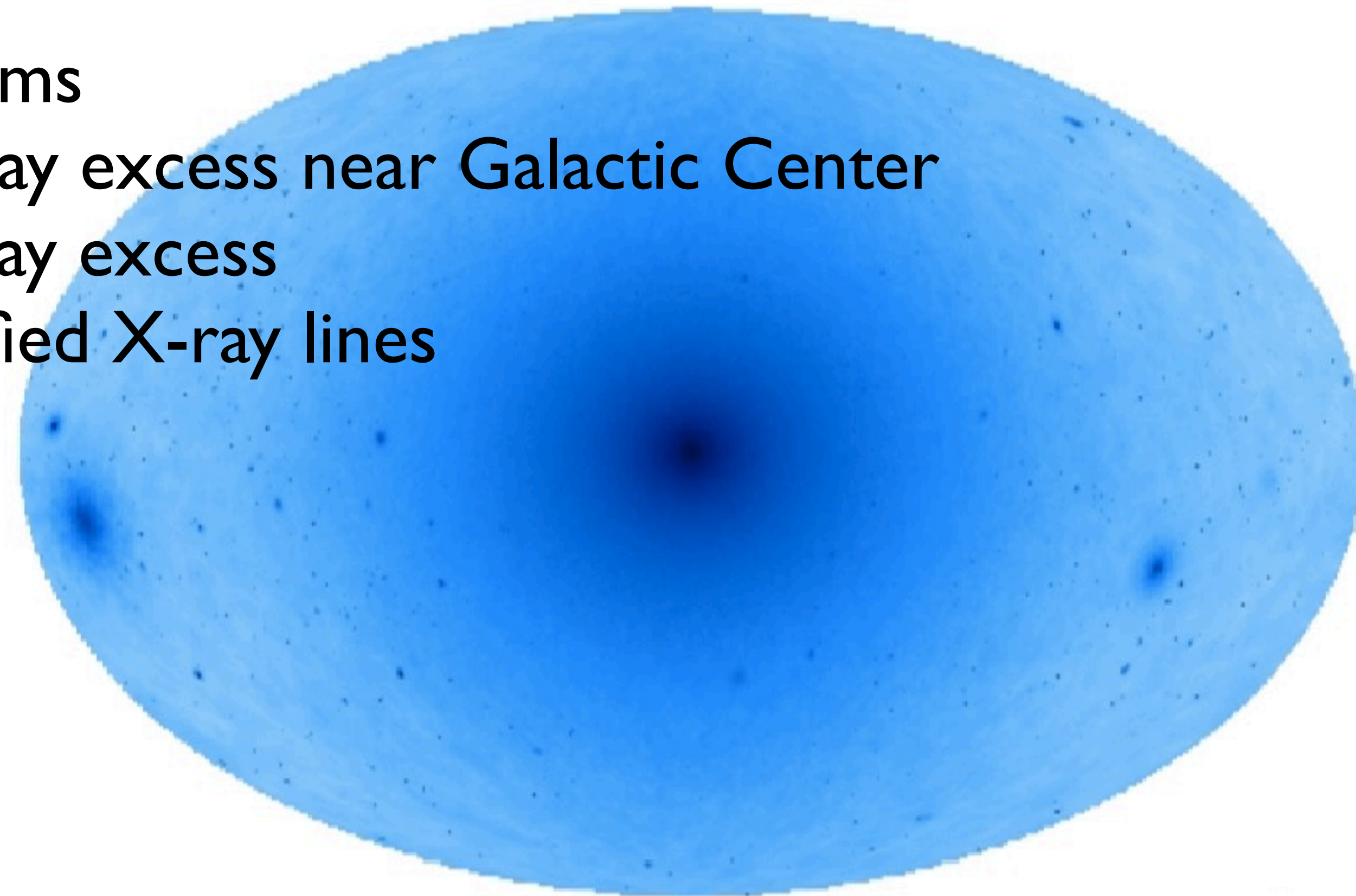
LHC: the LHC sees no indication of dark matter  
or even supersymmetry

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

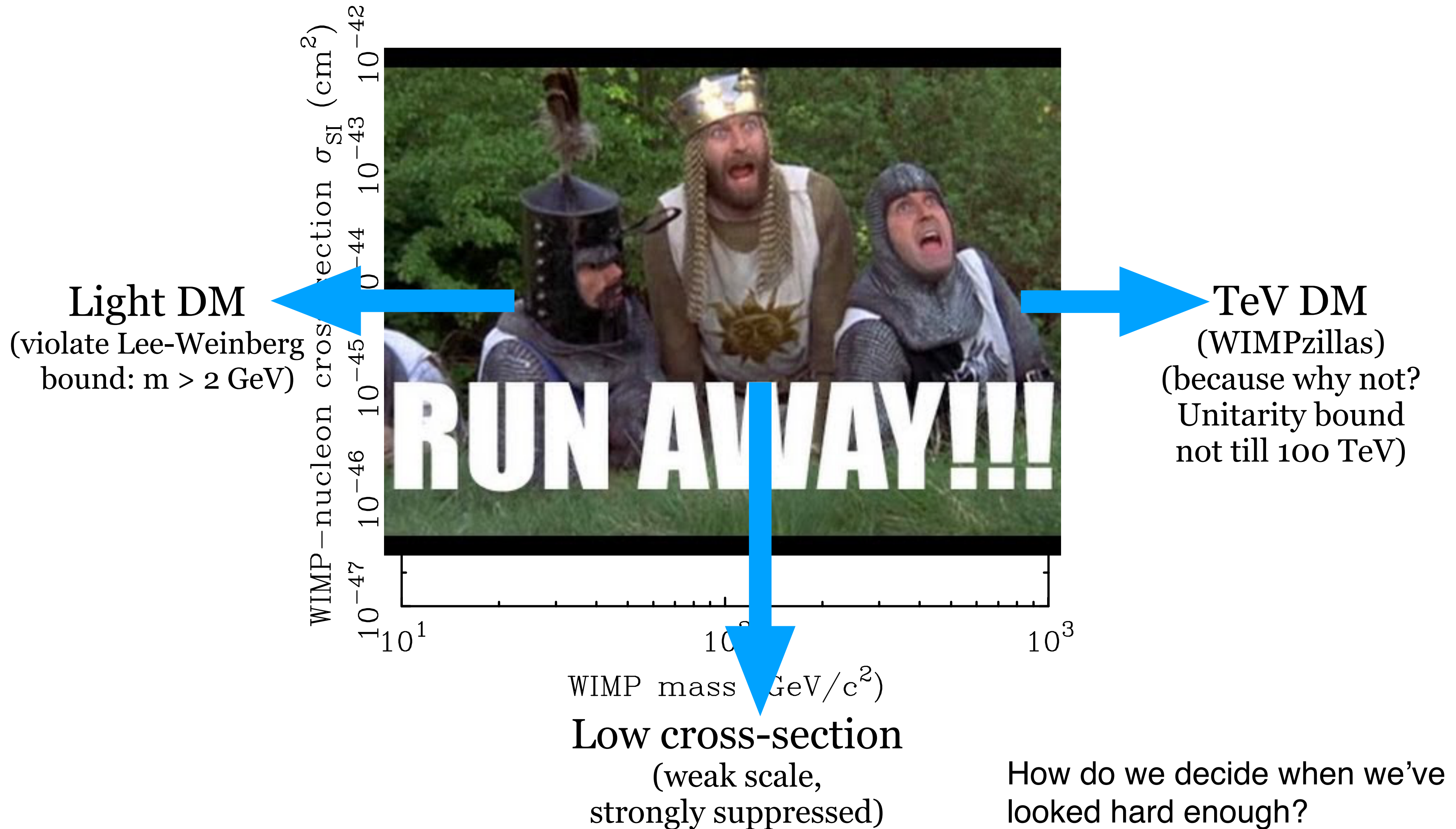
Indirect Detection: Various claims  
gamma ray excess near Galactic Center  
cosmic ray excess  
unidentified X-ray lines

As yet: nothing credible.

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



- where are the WIMPs?



Lots of particle candidates for CDM:

WIMPs

Axions

Light dark matter

wimpzillas

etc.

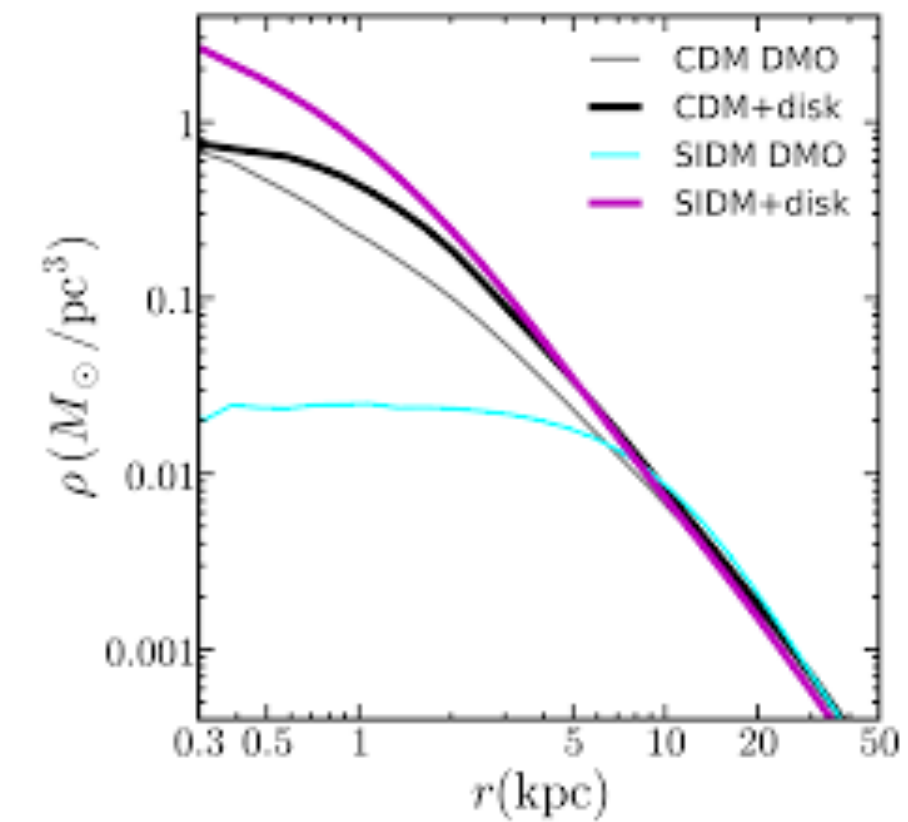
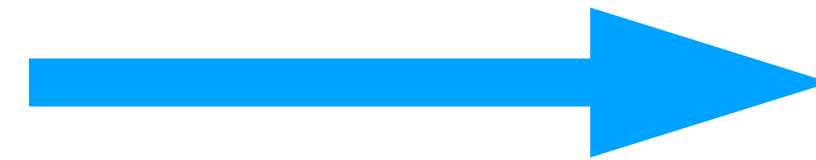
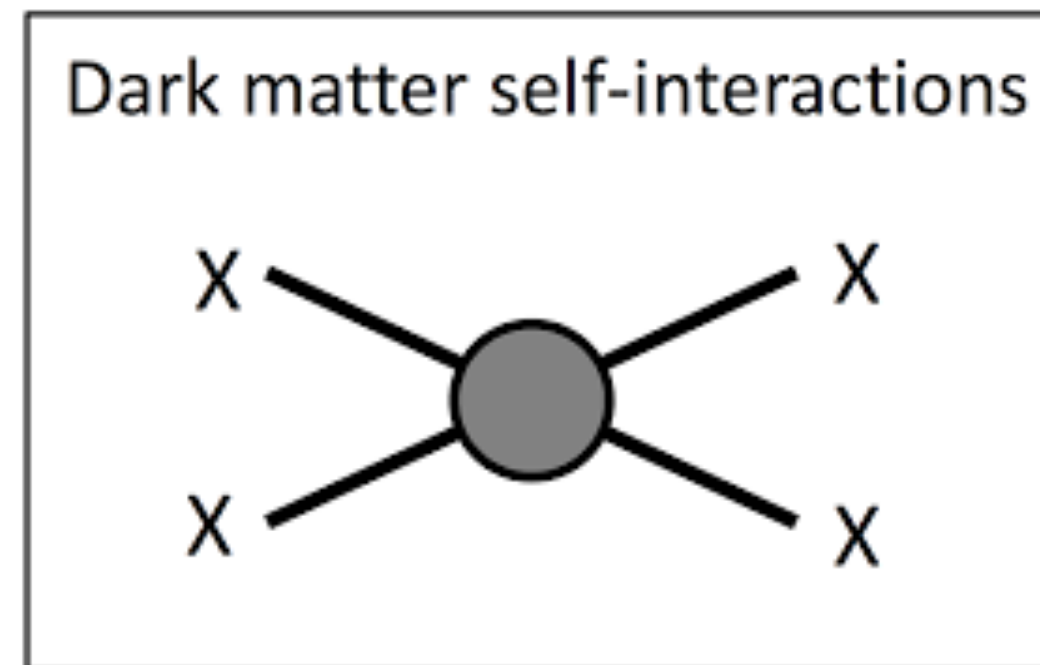
Can imagine other candidates as well:

Warm DM

Self-interacting DM

etc.

# Self-Interacting Dark Matter (SIDM)

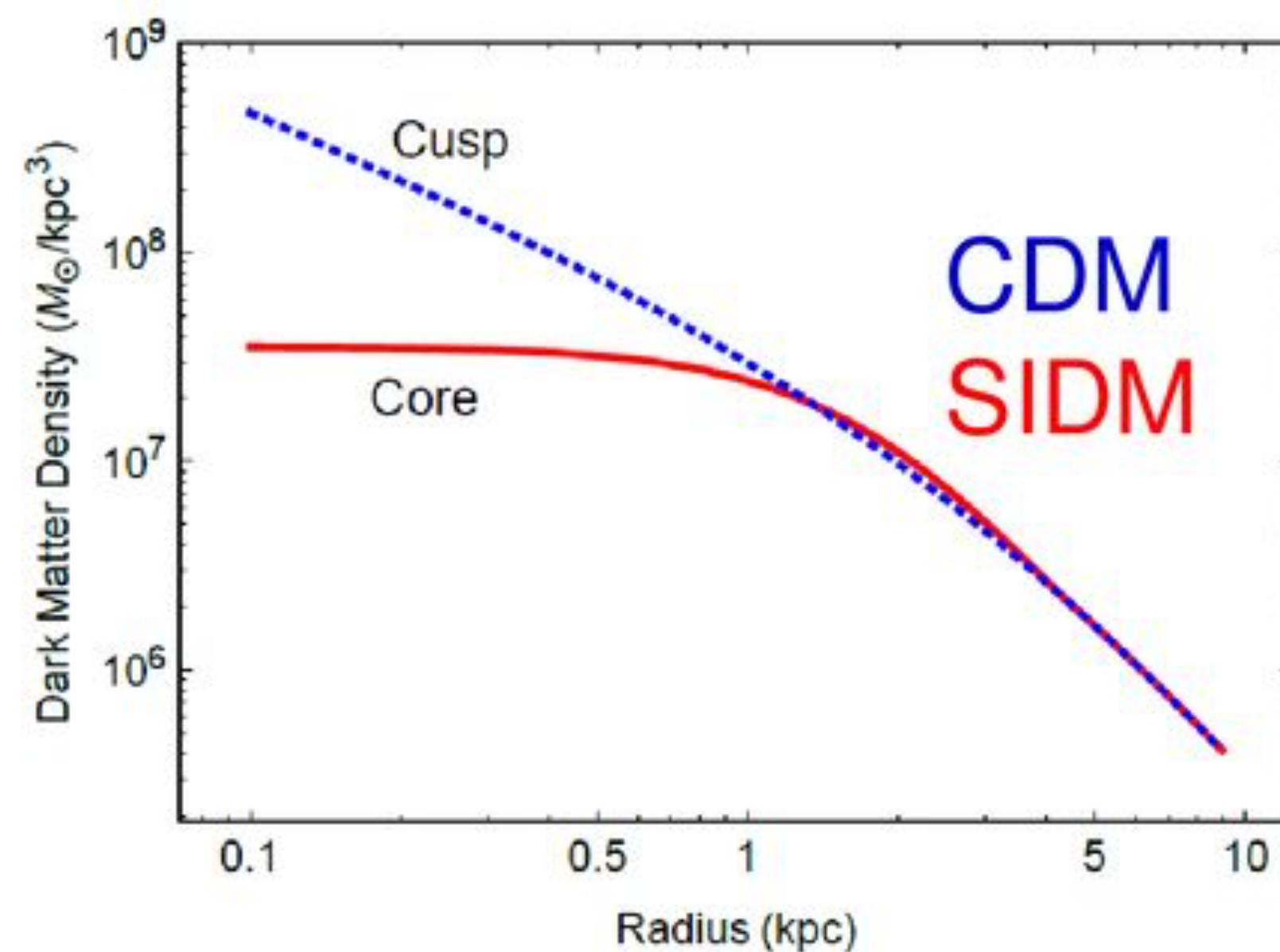
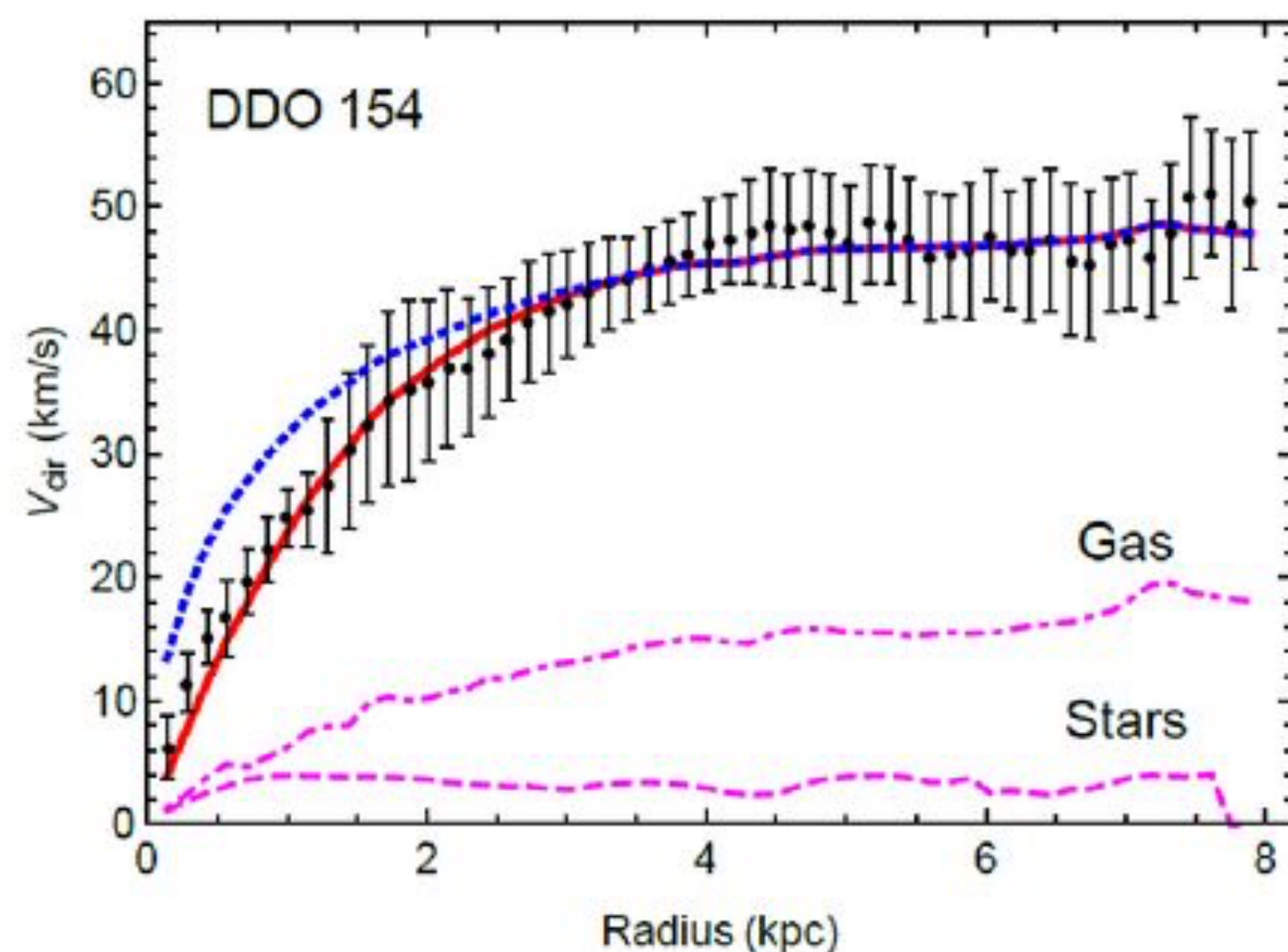


What if dark matter interacts with itself?

Simulations with SIDM suggest it might create cores rather than cusps

In order for dark matter to self-interact, there needs to be a new force that is only active in the dark sector (mediated, e.g., by dark photons). The interaction cross section needs to be a function of velocity in order to make cores in galaxies but not huge ones in clusters of galaxies.

*Phys.Rept. 730 (2018) 1-57*



- Collisionless CDM-only simulations predict “cuspy” DM density profiles, while observation prefer “core”.
- Others: Missing satellites problem, Rotation curve diversity problem, Too-big-to-Fail problem.
- SIDM is leading candidate to solve these issues.

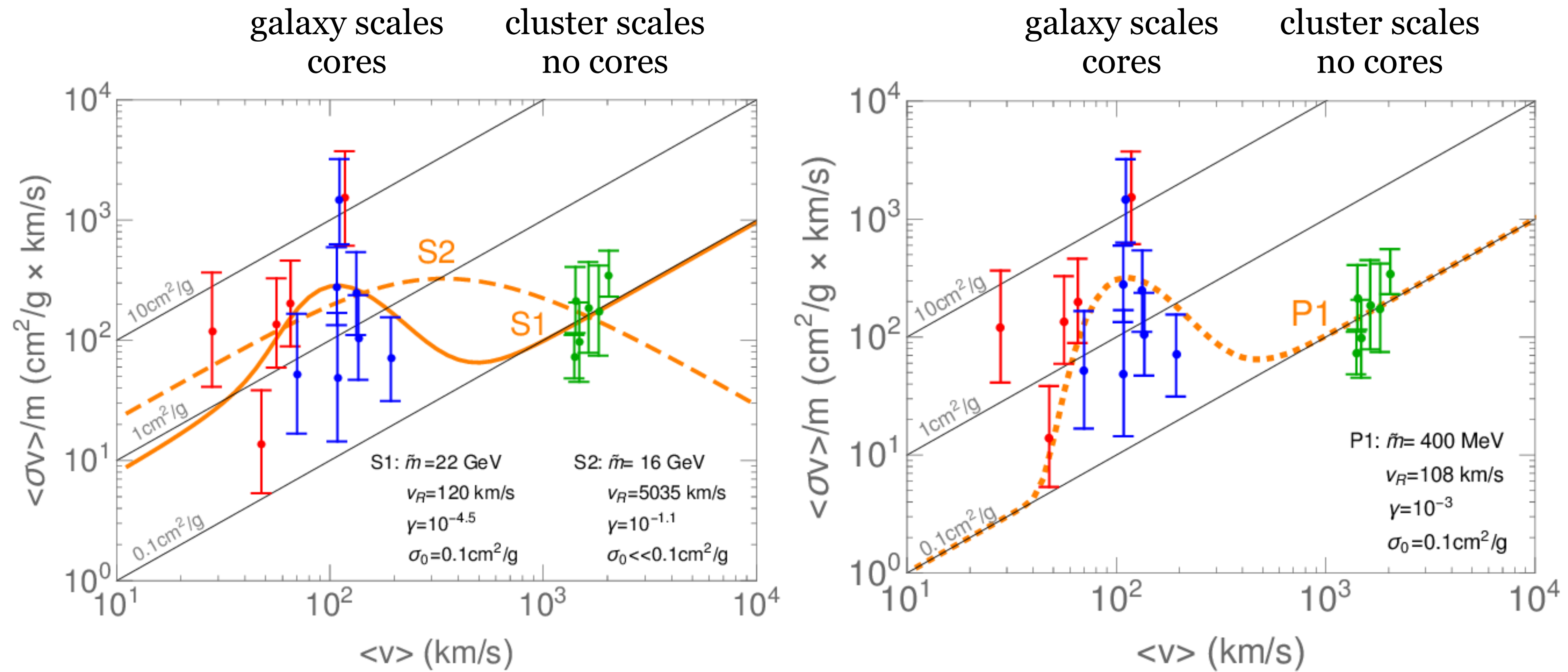


Figure 1: RSIDM cross section per unit of mass as a function of the velocity. Best-fit curves to data [15] for S-wave (left) and P -wave scatterings (right). The latter is also the best-fit curve for  $L > 1$  after rescaling  $\tilde{m} = mS^{-1/3}$ .

