Dark Matter

ASTR 333/433
Spring 2024
TR 11:30am–12:45pm
Sears 552

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

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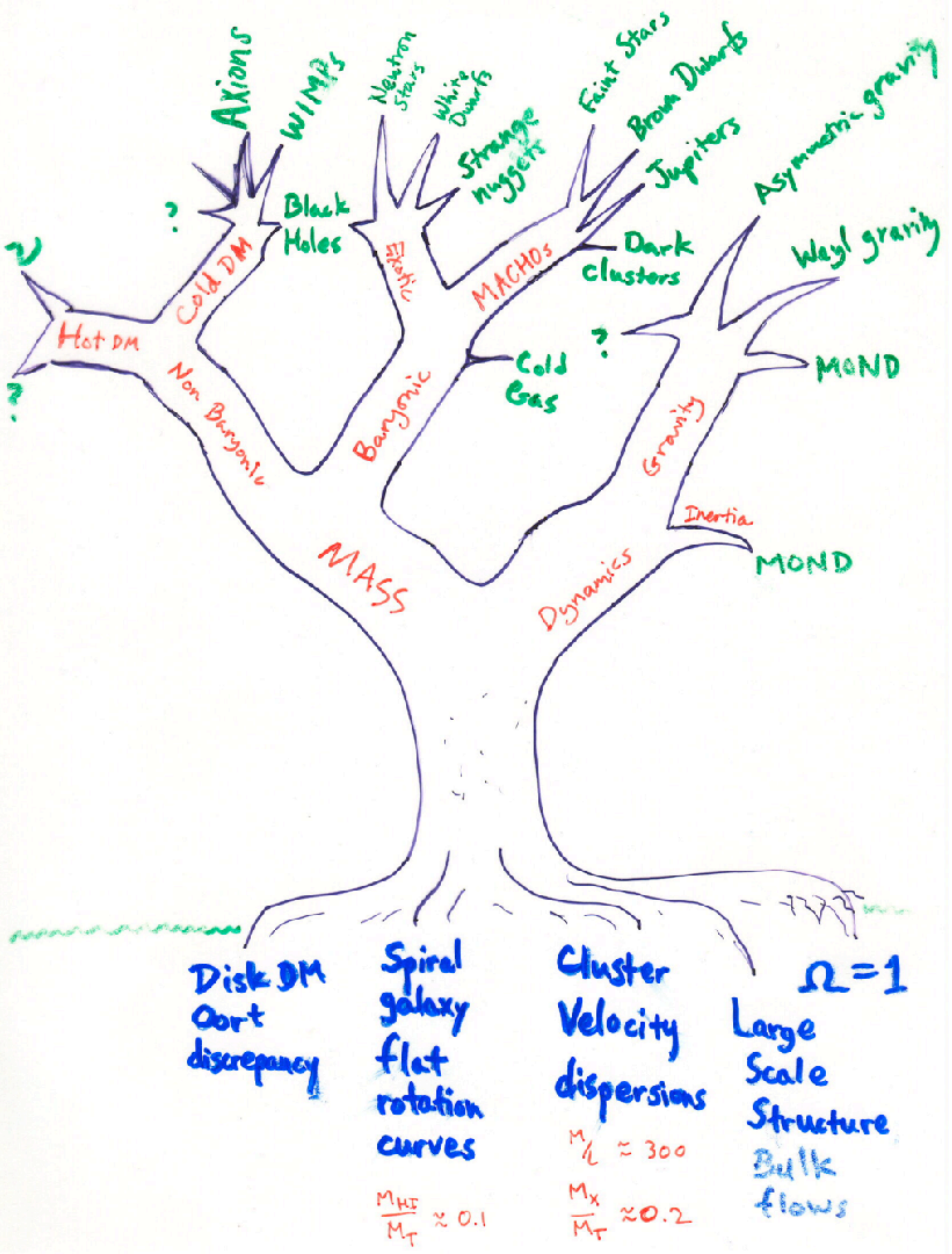


Measurements of the gravitating mass density

- Cluster M/L $\Omega_m \approx 0.25$ Bahcall et al. (1995)
  - measure M/L of a cluster, combine with measured luminosity density of universe.
- Weak lensing $\Omega_m \approx 0.18 \pm 0.04$ Dark Energy Survey arxiv:2002.11124
  - measure shear over large scales
- Peculiar Velocity Field $\Omega_m = 0.25 \pm 0.05$ Tonry & Davis (1980)
  - measure deviations from Hubble flow
- Power spectrum of galaxies
- CMB fits

$\Omega_m h = 0.213 \pm 0.023$

$\Omega_m = 0.3$ for $h = 0.71$

Tegmark et al. (2004)

$\Omega_m = 0.315 \pm 0.007$ Planck Collaboration (2018)

also gives $h = 0.674 \pm 0.005$

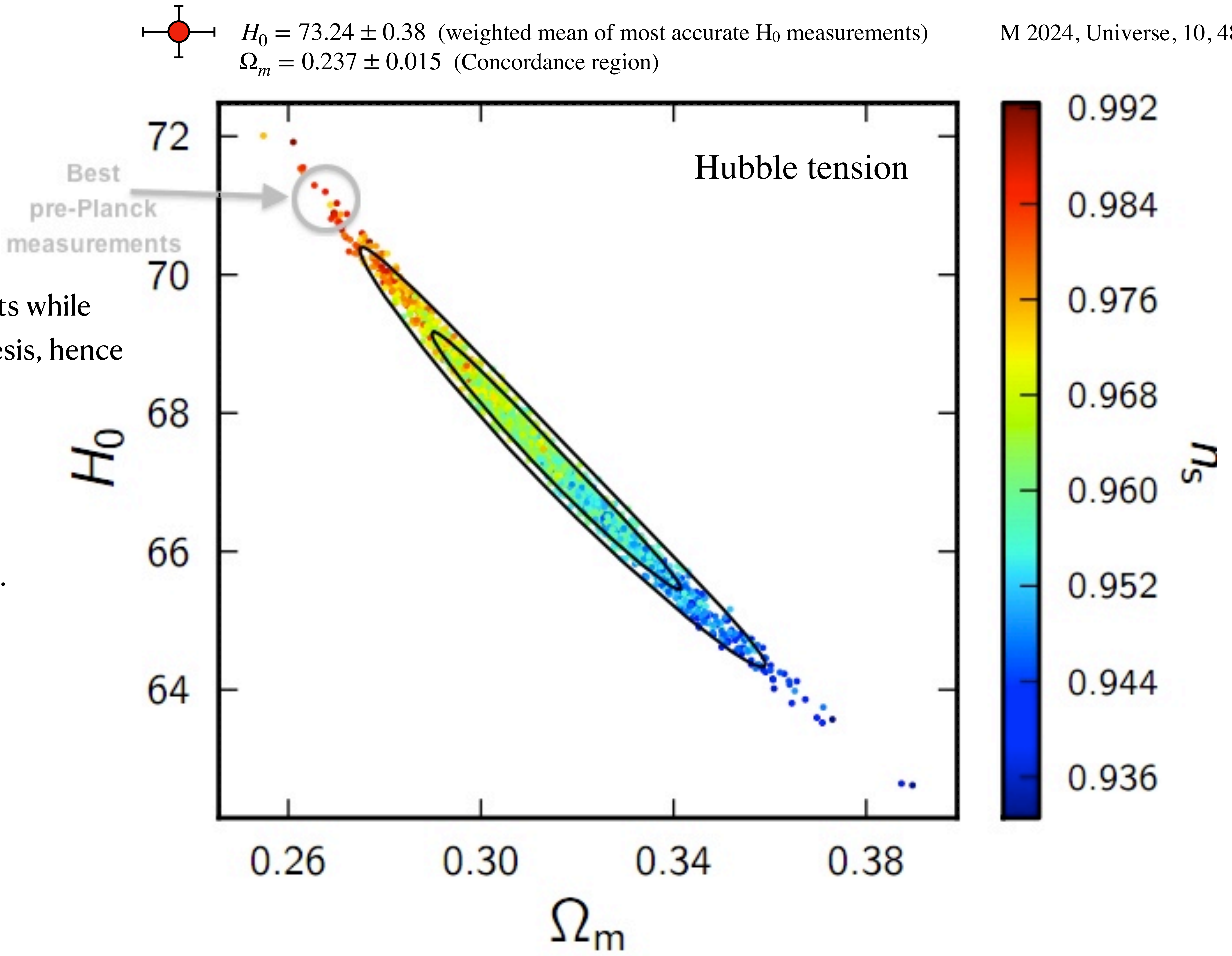
So:

$\Omega_m \approx 0.30$ from dynamical measurements while
$\Omega_b \approx 0.05$ from primordial nucleosynthesis, hence
$\Omega_m > \Omega_b$ for sure and we need

non-baryonic dark matter…

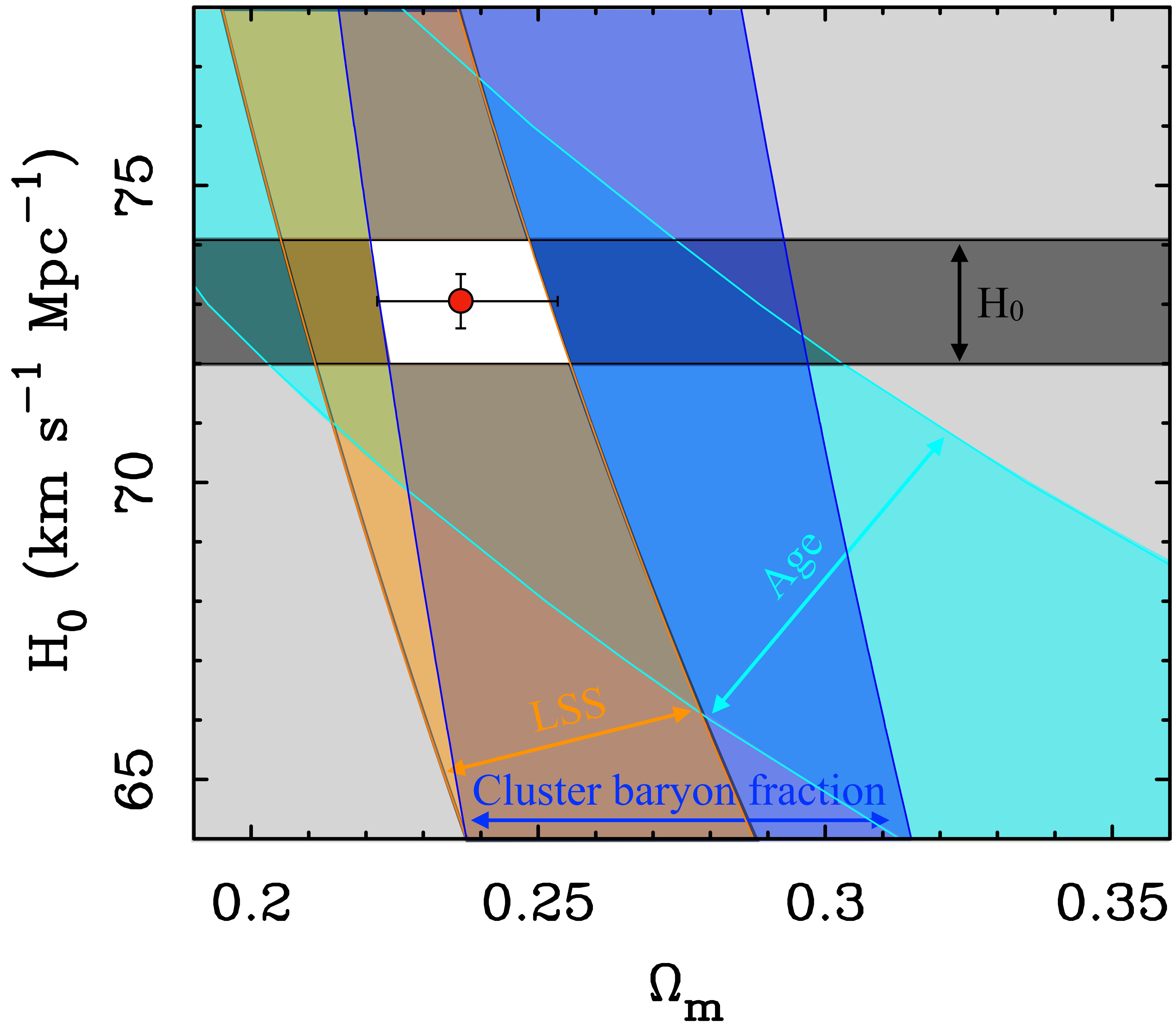
assuming the FLRW cosmology is correct.

M 2024, Universe, 10, 48



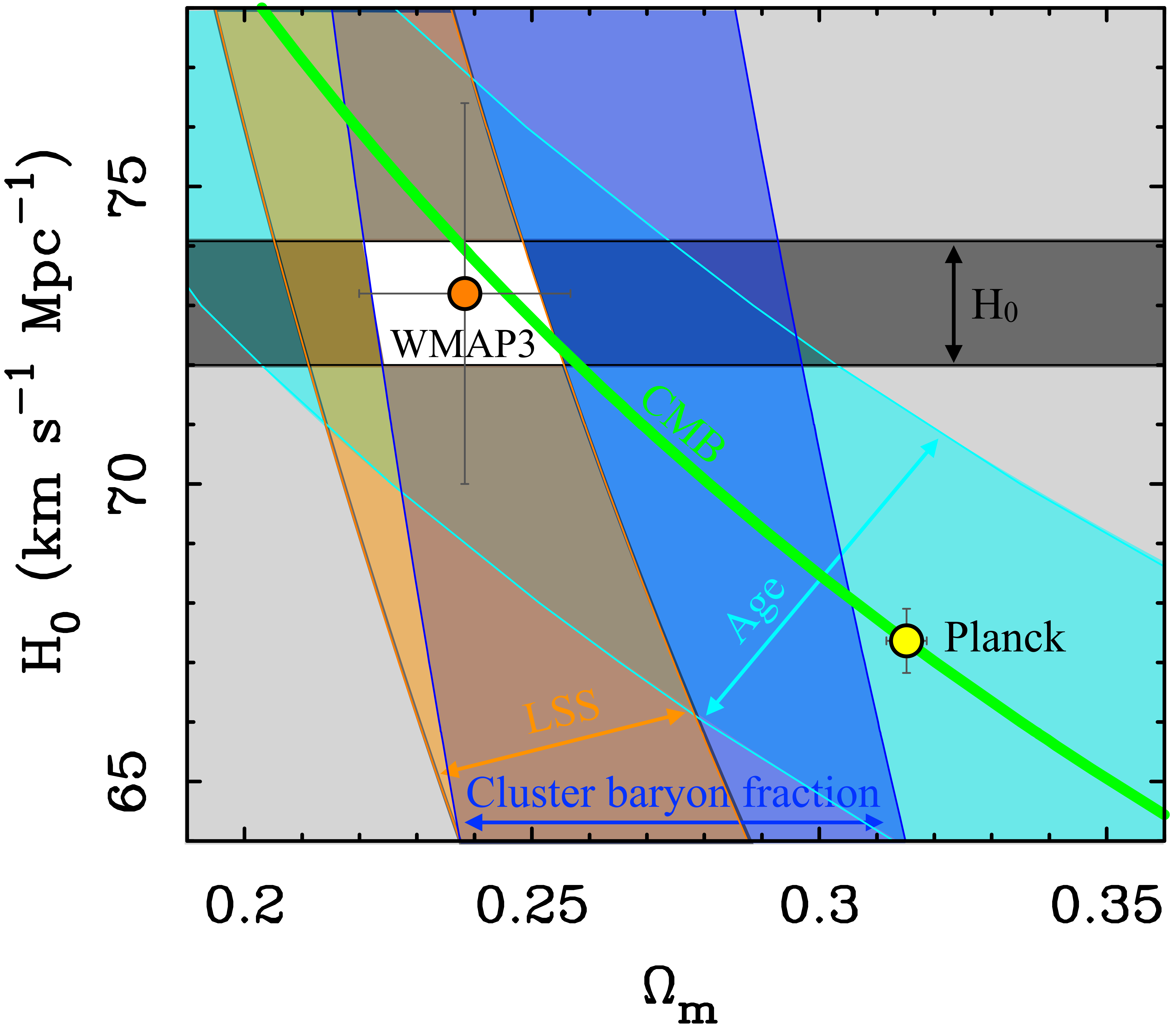
Concordance LCDM without CMB

M 2024, Universe, 10, 48



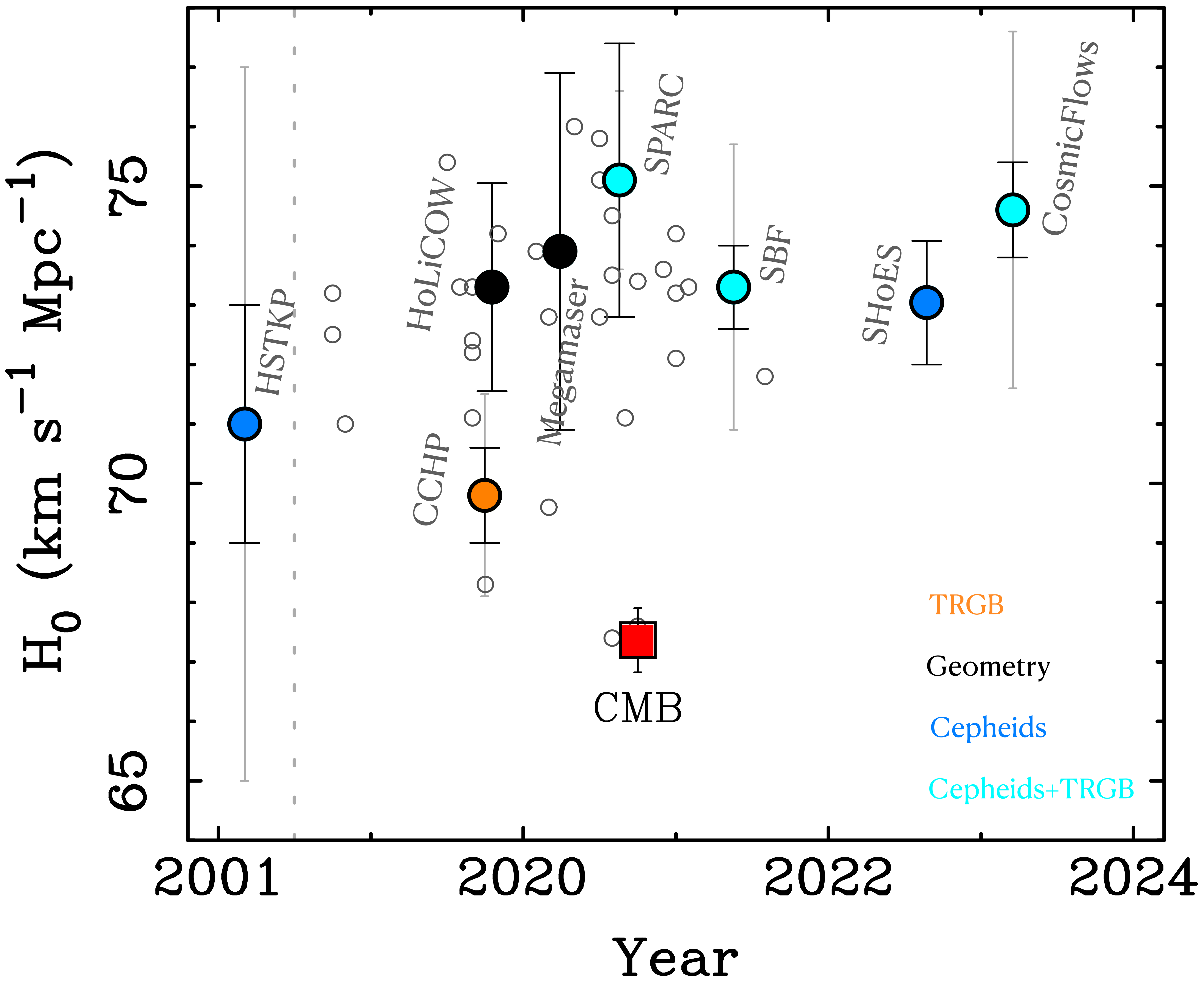
Concordance(?) LCDM with CMB

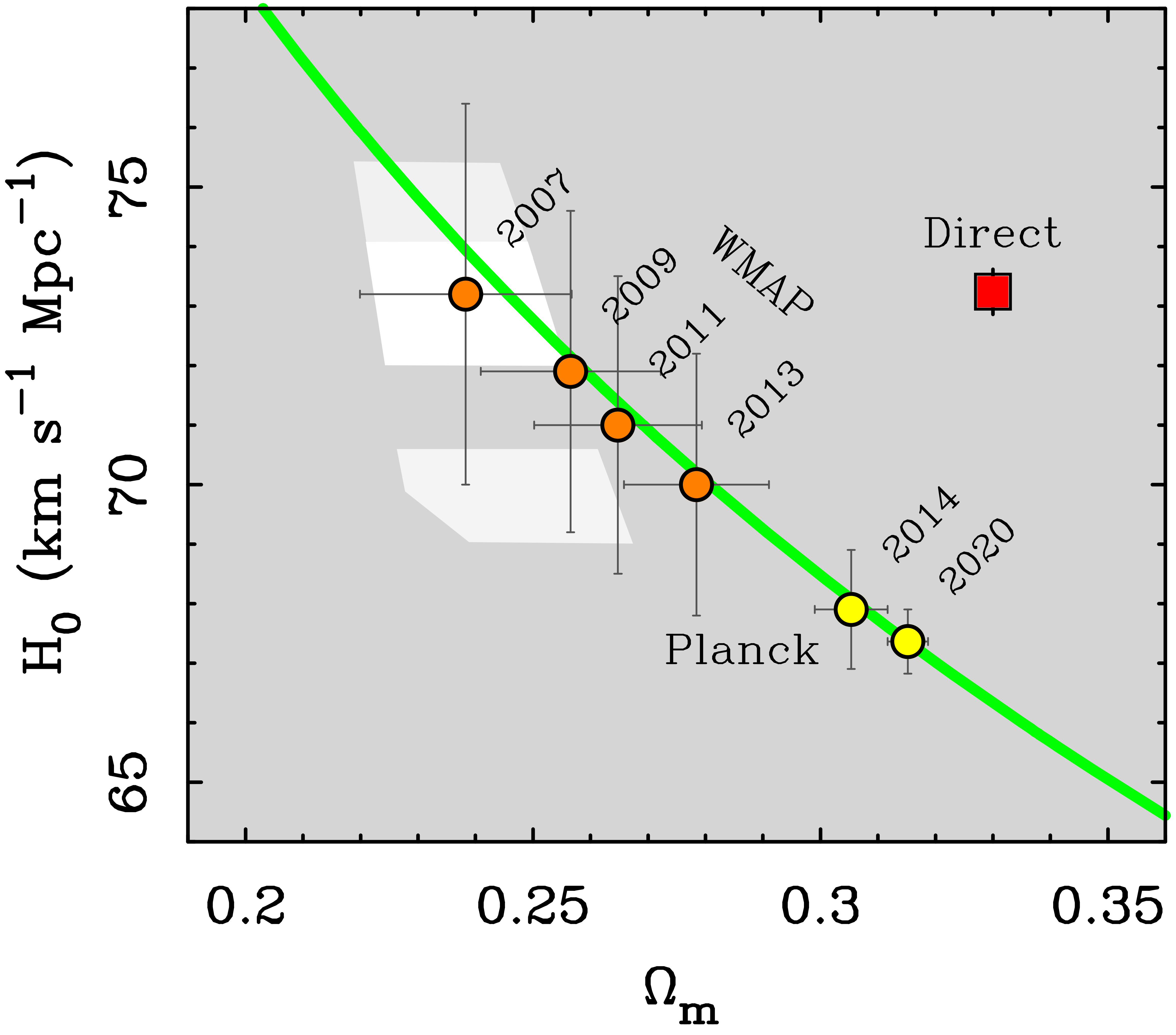
M 2024, Universe, 10, 48



The Hubble tension appears to be real, and a result of time variation in the CMB best fit.

M 2024, Universe, 10, 48





FLRW cosmology works if and only if there is non-baryonic cold dark matter (and dark energy).

Cosmologically, the only requirement to be CDM is

- dynamically cold (slow moving)
- non-baryonic (no E&M interactions)

could be

WIMPS

(or some other particle, but there are lots of extra particle-physics constraints on new particles)

or

Black Holes

(primordial BHs with masses of ~ 30 $M_{\odot}$ are conceivable, but most mass ranges have been excluded by gravitational lensing observations)

WIMPs are considered the odds-on favorite CDM candidate because of the so-called `WIMP miracle': the relic density of a new weakly interacting particle is about right to explain the mass density.

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WIMPS

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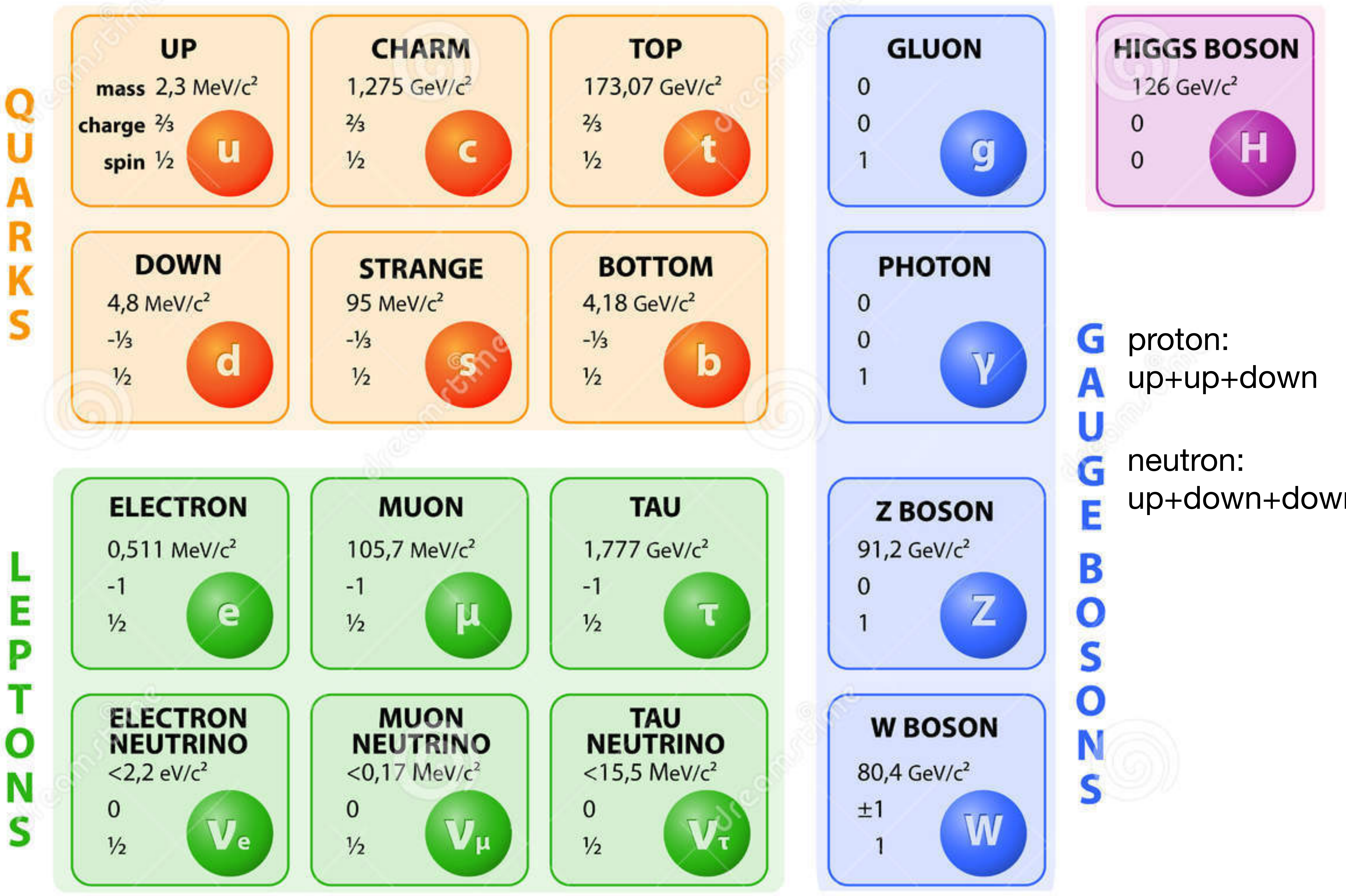
WIMPS, or whatever it is, represent new physics beyond the Standard Model of particle physics.

WIMPs are not just a new particle to discover.
Their existence requires entirely new physics
outside the Standard Model of particle physics;
e.g., something like SuperSymmetry.

STANDARD MODEL OF ELEMENTARY PARTICLES

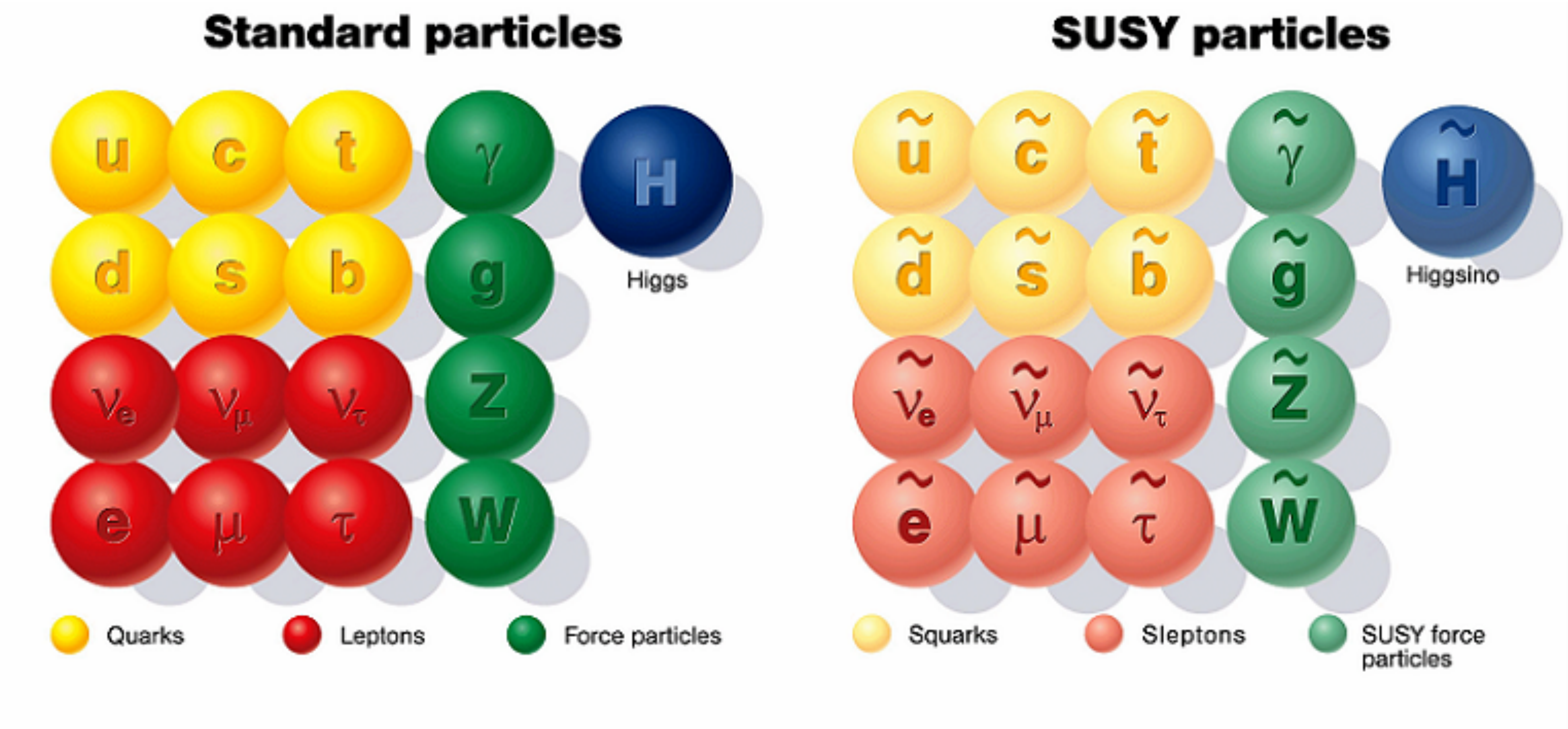


proton:
up+up+down

neutron:
up+down+down

Supersymmetry: a hypothetical new symmetry of nature

arxiv.org/abs/hep-ph/9606414



Every Standard Model particle has a superpartner.
The lightest stable massive superparticle is the most favored WIMP candidate. Usually the neutralino (theory dependent).

Relic density of particles determined by when they freeze out

number density x cross-section = expansion rate

Freeze out condition: $n\sigma \approx H$

HOT (relativistic)
e.g., neutrino

$T_\nu \gg m_\nu$ so number still around just depends on the photon density

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{91.5 \text{ eV}}$$

current limits

$$0.06 \leq \sum m_\nu \leq 0.12$$

neutrino oscillations — structure formation

COLD (non-relativistic)
e.g., WIMP

$T_X \ll m_X$ particle-antiparticle pairs have time to annihilate, so

$$n \sim (m_X T)^{3/2} e^{-\frac{m_X}{T}}$$

$$\frac{\Omega_X}{0.2} \approx \frac{x_{fo}}{20} \left(\frac{10^{-8} \text{ GeV}^{-2}}{\sigma} \right)$$

$$20 \lesssim x_{fo} < 50$$

annoying quantum factor

$$\sigma \sim \frac{g^4}{m_X^2}$$

where **g** is the coupling strength
(e.g., the weak nuclear force)

Lee-Weinberg limit: $m_X > 2$ GeV to not over-produce cosmic mass density

THE WIMP MIRACLE

- Fermi's constant G_F introduced in 1930s to describe beta decay

$$n \rightarrow p\, e^- \bar{\nu}$$

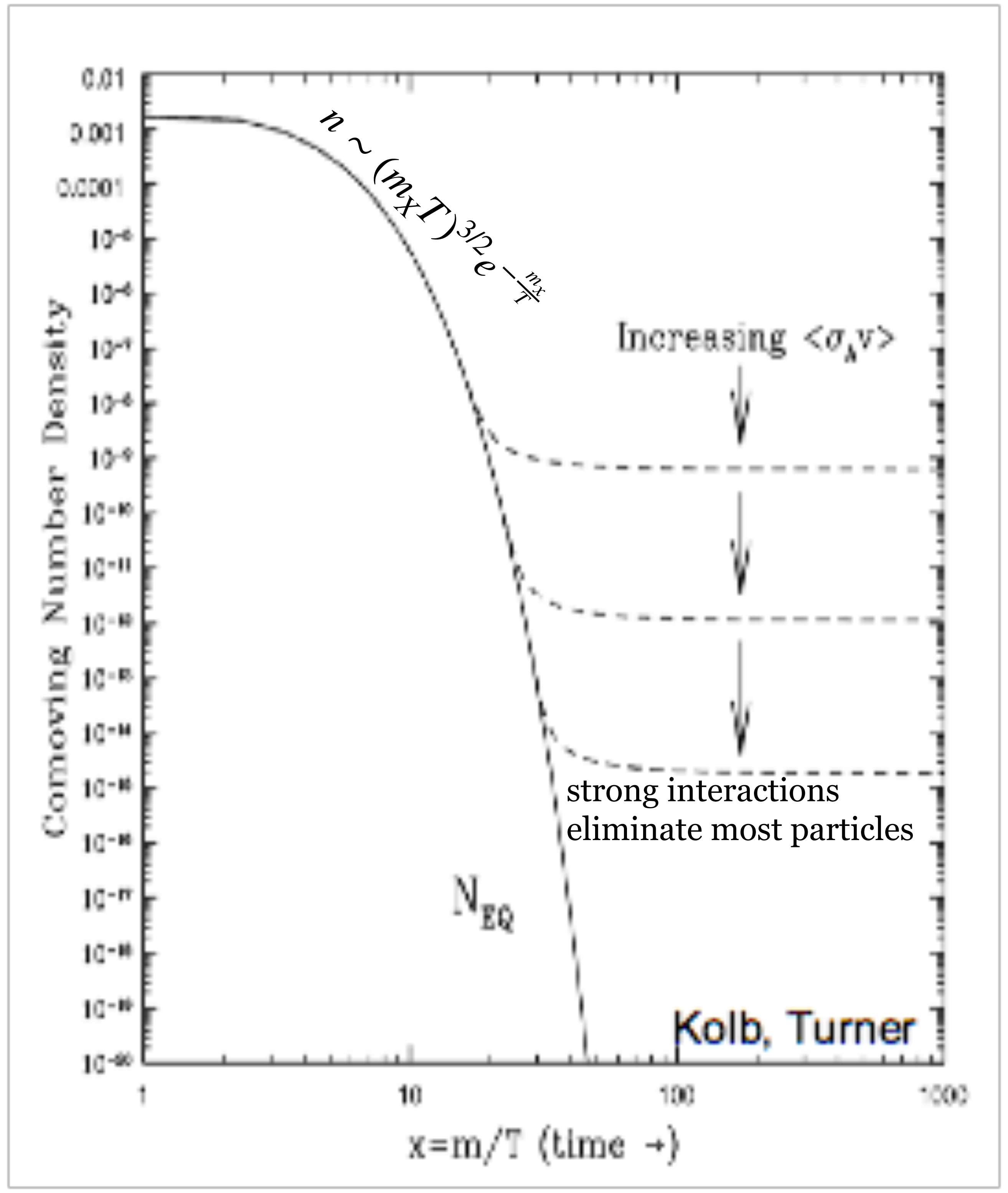
- $G_F \approx 1.1\ 10^5\ \text{GeV}^{-2} \rightarrow$ a new mass scale in nature

$$m_{weak} \sim 100\ \text{GeV}$$

- We still don't understand the origin of this mass scale, but every attempt so far introduces new particles at the weak scale

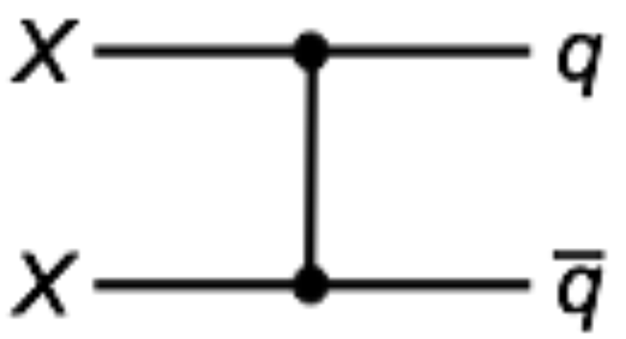
From review by Feng et al. linked from course review literature page.
Original idea goes back to Peebles (1984) & Steigmann & Turner (1985).
See also the cosmology textbook by Kolb & Turner.

THE WIMP MIRACLE



- Assume a new (heavy) particle X is initially in thermal equilibrium
- Its relic density is

$$\Omega_X \propto \frac{1}{\langle \sigma v \rangle} \sim \frac{m_X^2}{g_X^4}$$



- $m_X \sim 100$ GeV, $g_X \sim 0.6 \rightarrow \Omega_X \sim 0.1$

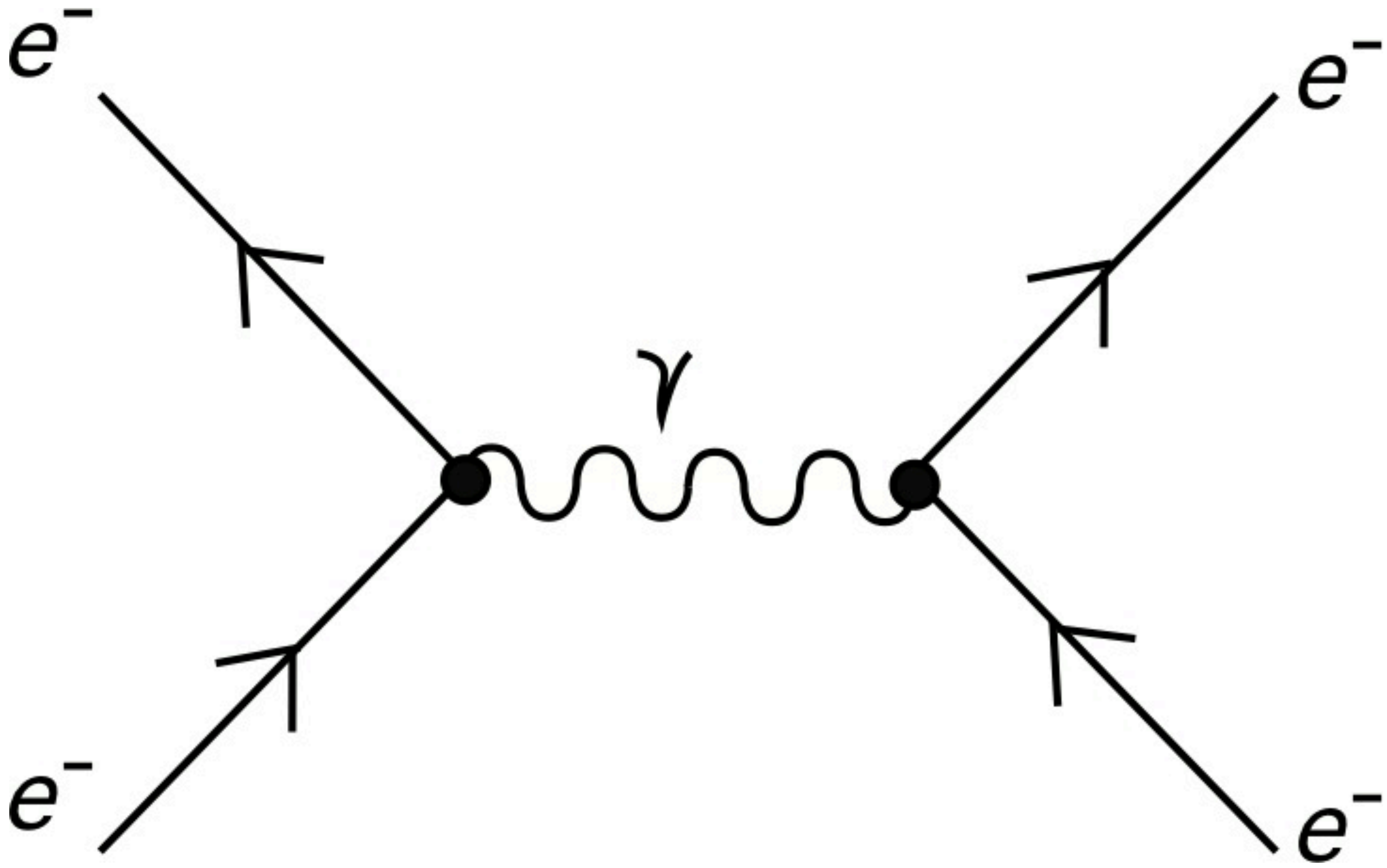
$\langle \sigma v \rangle$ "thermal cross-section"

- Remarkable coincidence: particle physics independently predicts particles with the right density to be dark matter

Originally expected $\sigma \sim 10^{-39}\ \mathrm{cm}^{-2}$, but only the thermal cross-section $\langle \sigma v \rangle$ matters here.

From review by Feng et al. linked from course review literature page.

Feynman diagram



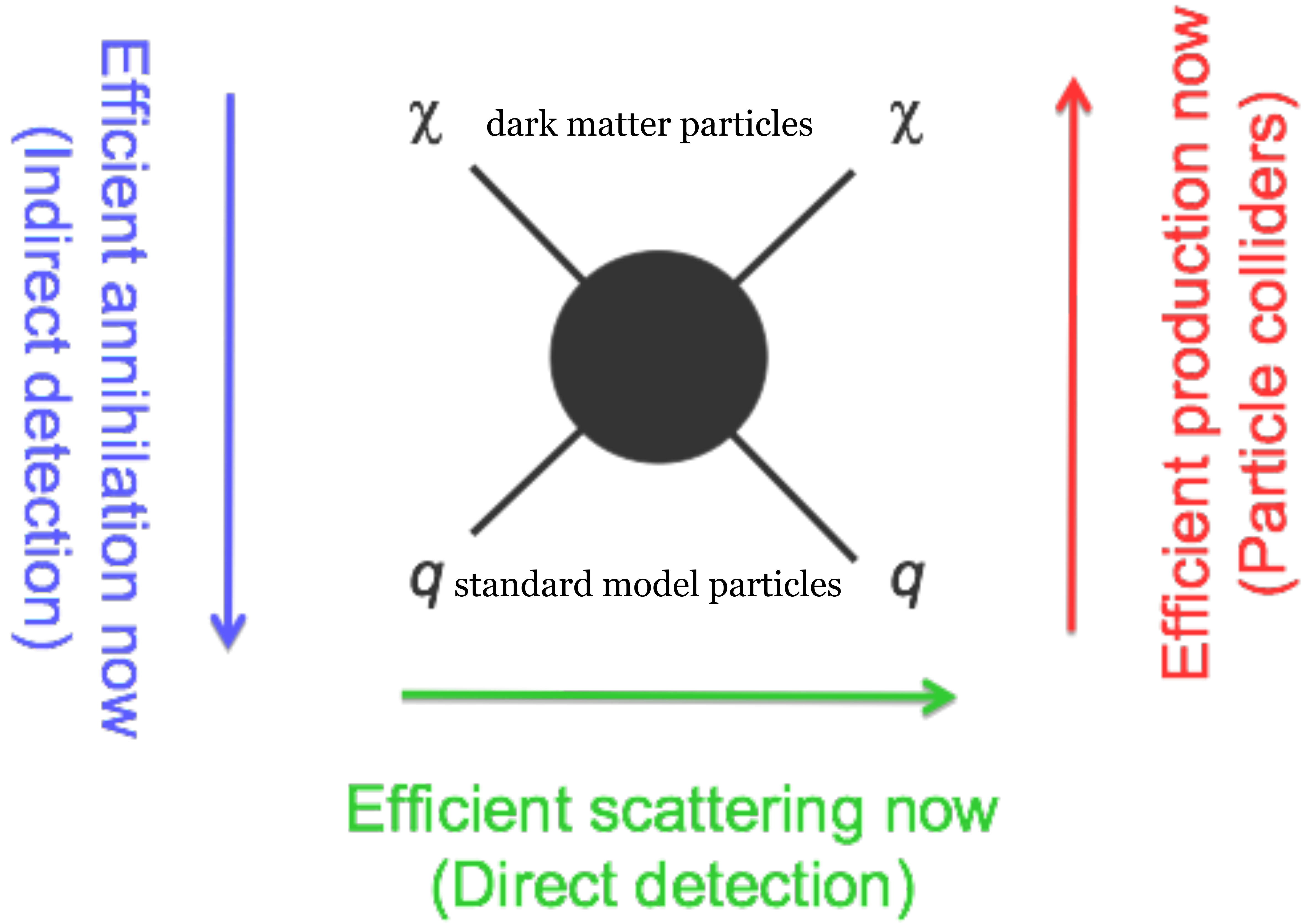
Illustrates the interaction of particles by the exchange of force carriers - in this case, electrons scatter by photon exchange

(electrostatic repulsion: two negatively charged particles repel each other)

WIMP DETECTION

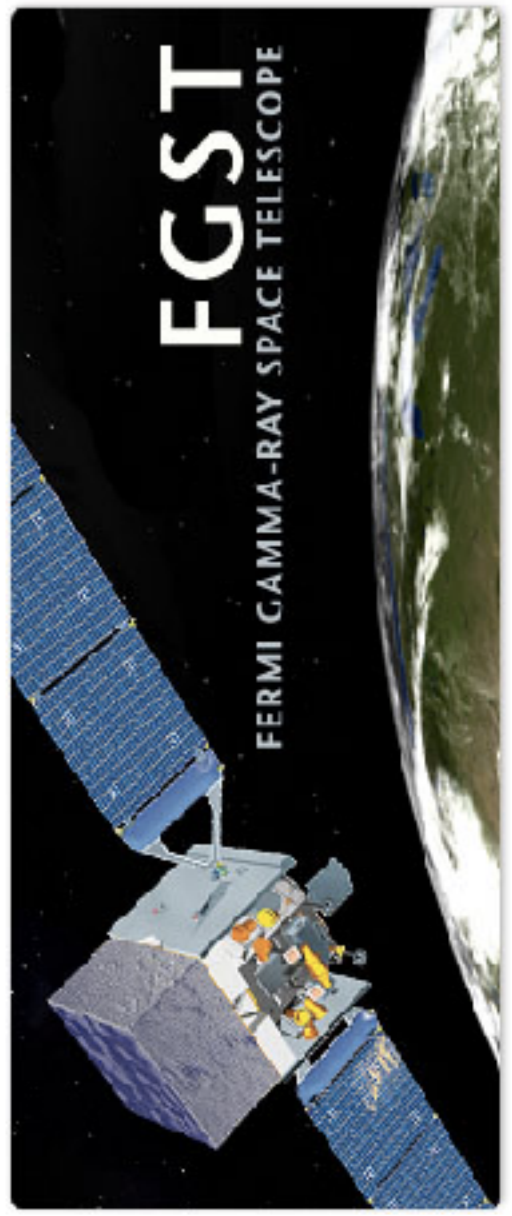
Correct relic density → *Lower* bound on DM-SM interaction

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

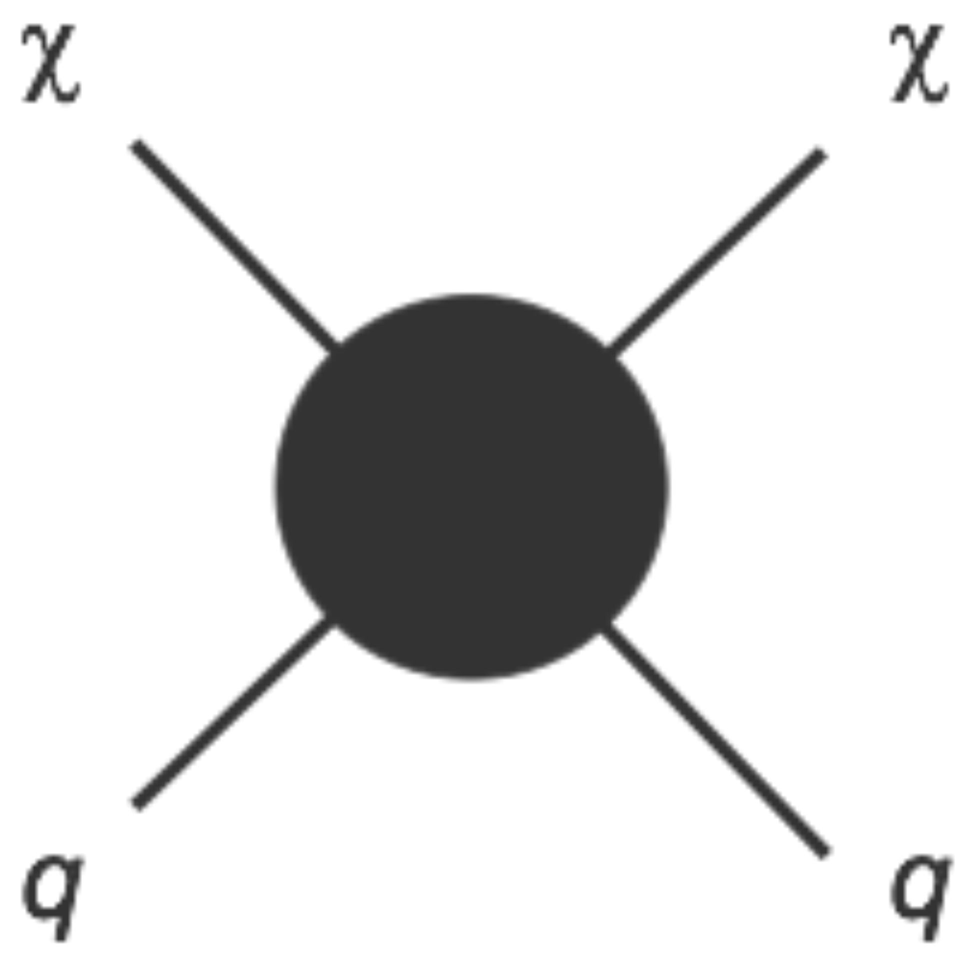


WIMPs created in particle colliders (like the LHC)

WIMPs scatter off nuclei in underground laboratory experiments



Efficient annihilation now
(Indirect detection)



Efficient production now
(Particle colliders)

Efficient scattering now
(Direct detection)

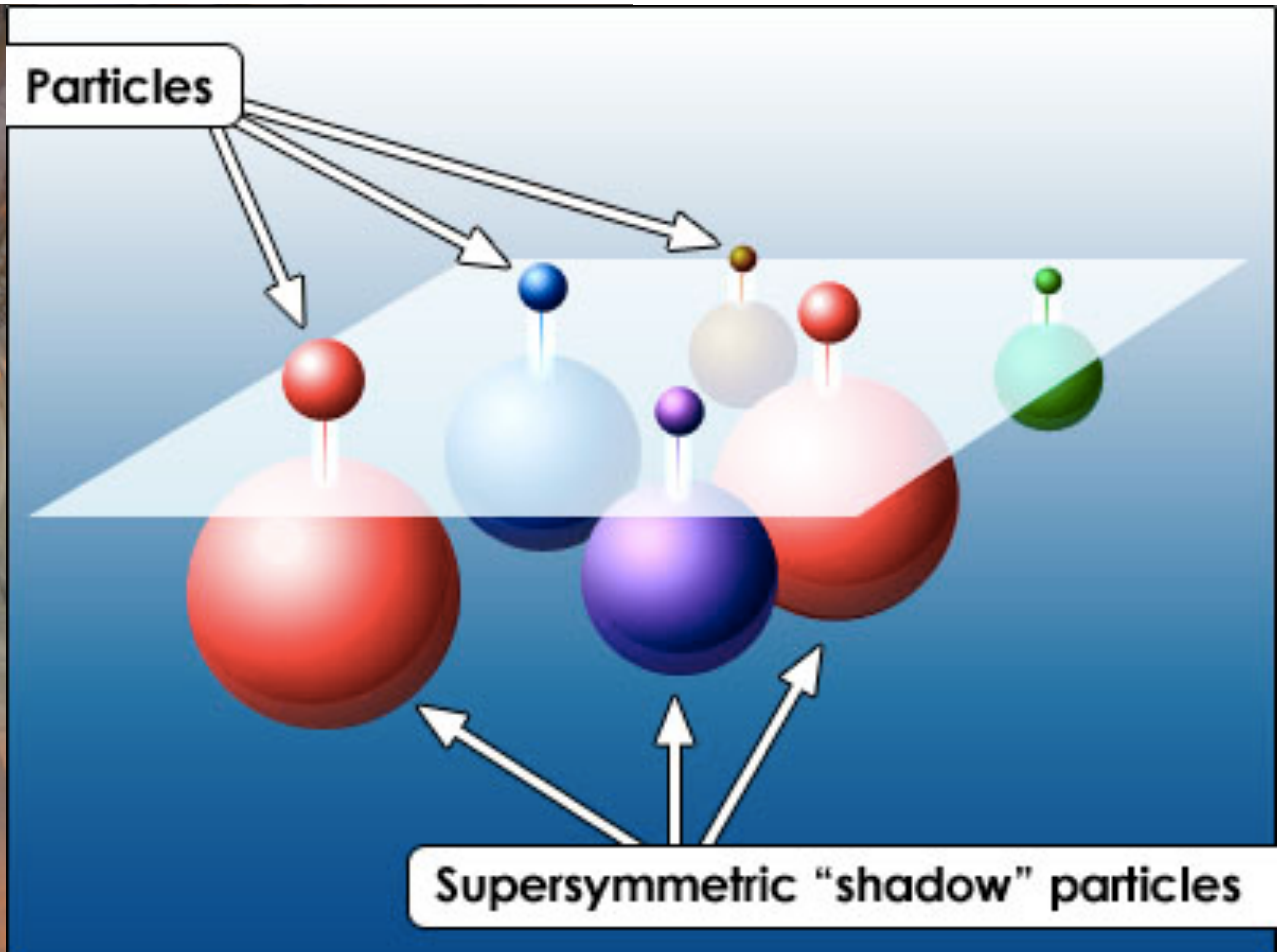
Experimental results to date (2024): nada

Particle production

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

the LHC has discovered the Higgs
- a necessary ingredient for SUSY
- too "normal" for MSSM (minimal SUSY)

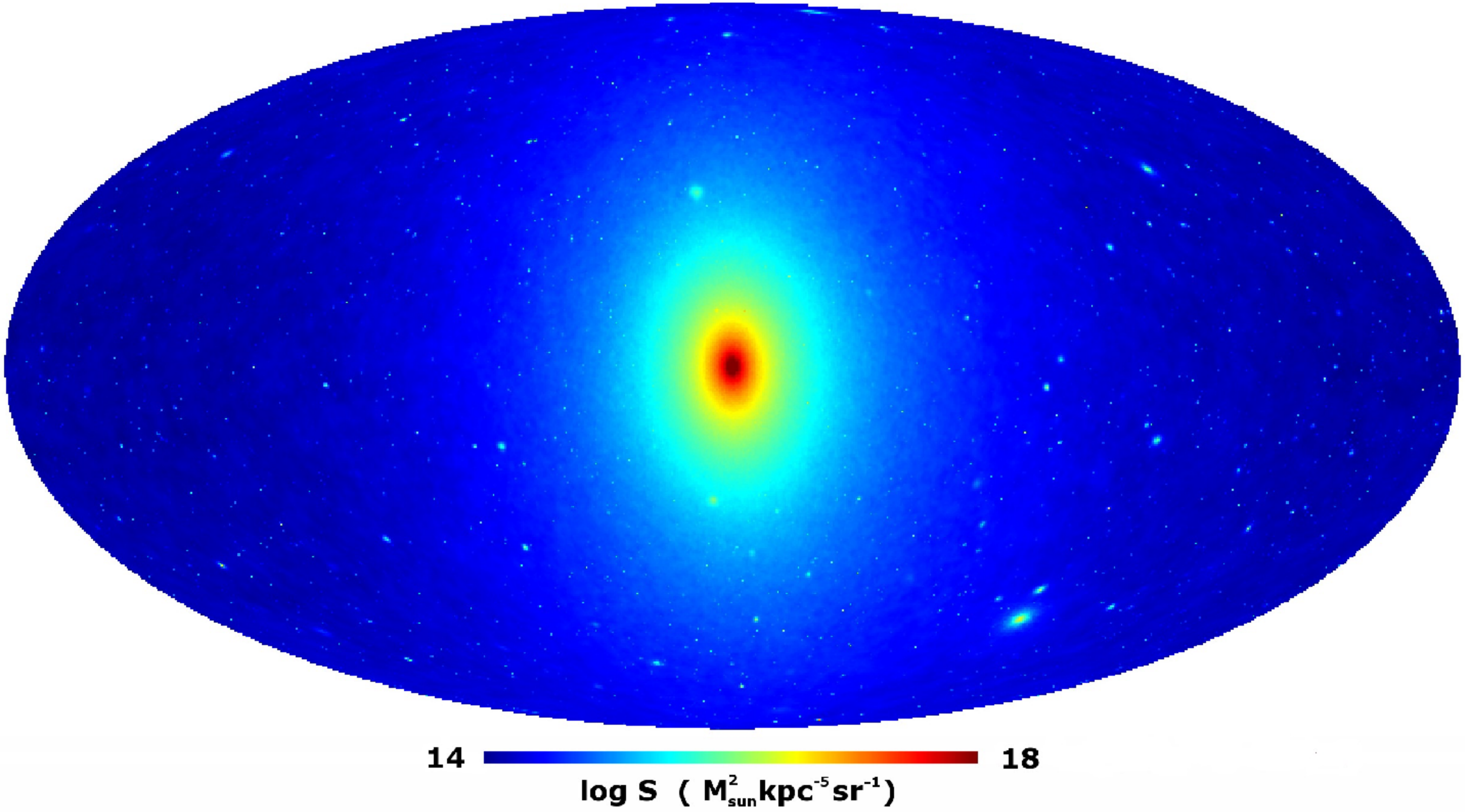
the LHC has NOT observed excess Bs meson decay
- the Golden Test for SUSY
- looking grim for MSSM, SUSY in general



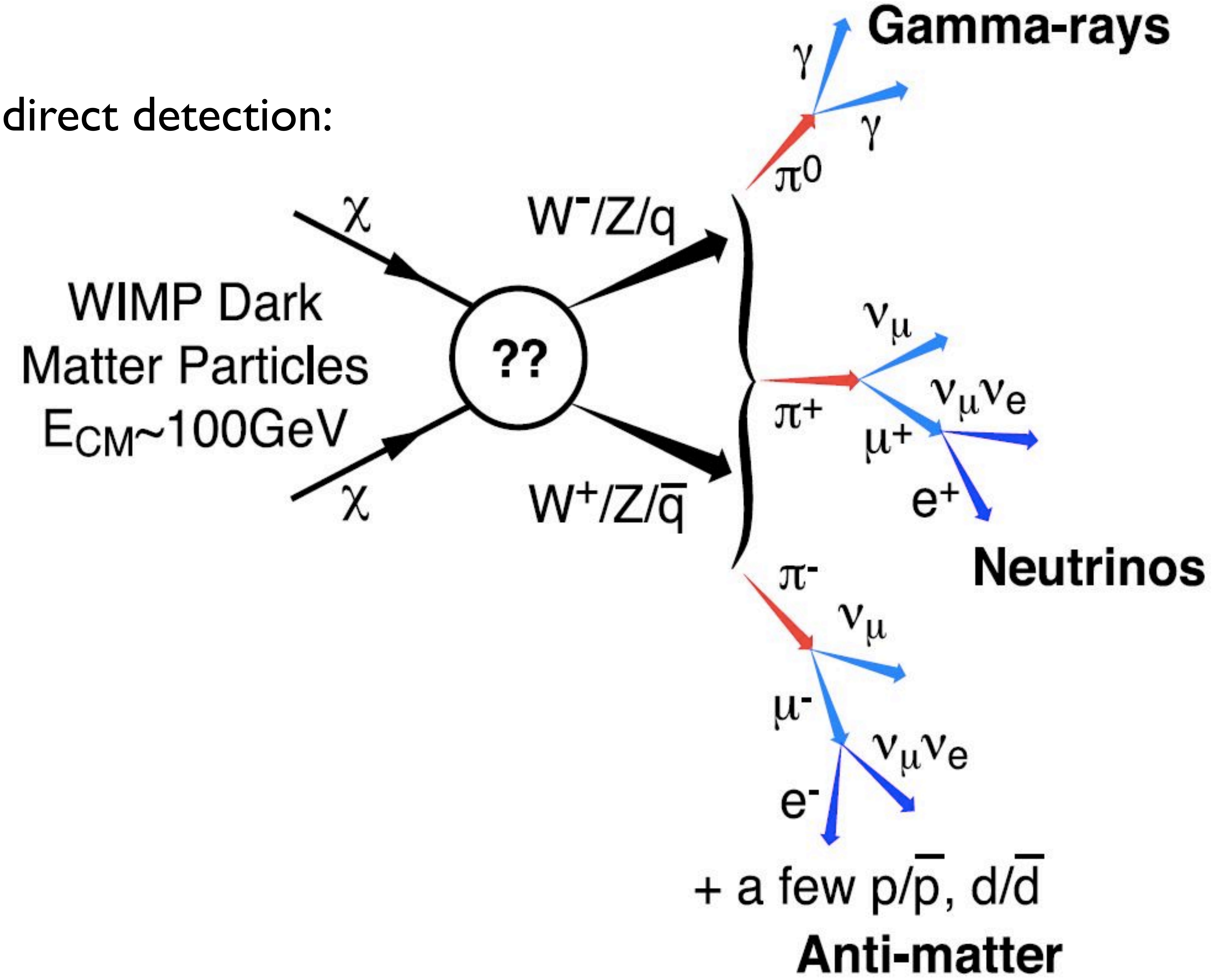
Experimental results to date (2024): nada

Indirect detection

predicted gamma ray sky

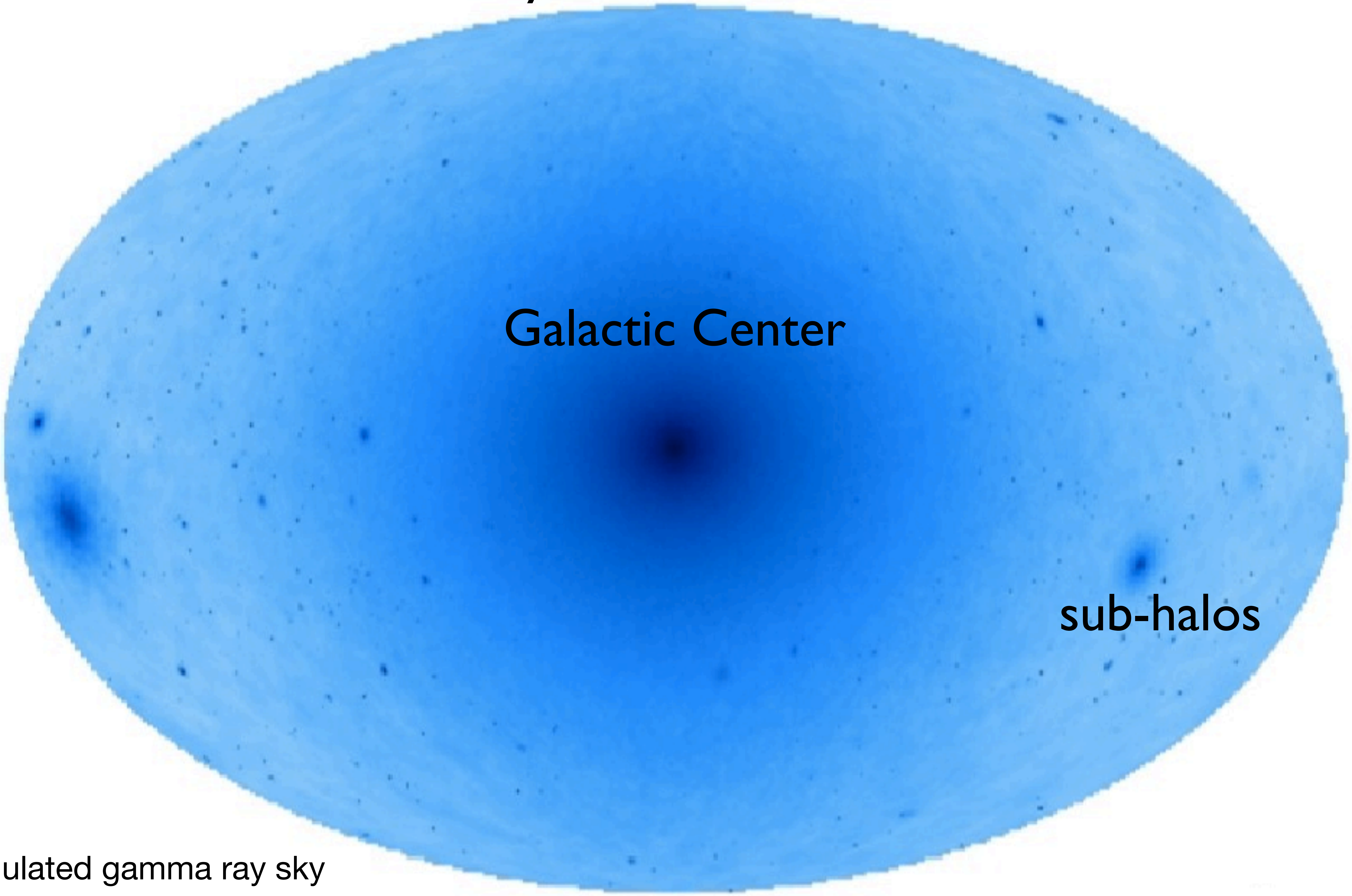


Indirect detection:



Experimental results to date (2024): nada

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



simulated gamma ray sky

Working out the expected gamma ray flux

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

averaged annihilation cross-section

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

σ here is the interaction cross-section (not velocity dispersion)

σ often assumed to be velocity independent, but doesn't have to be.

Probability of a dark matter particle having velocity v

distribution function

$$P(v) = \frac{f_{DM}(x, v)}{\rho_{DM}(x)}$$

dark matter density

photon flux, photon spectrum

$$\frac{dF}{dE} = \frac{1}{4\pi m^2} \frac{dN}{dE} \int d\Omega \int d\ell \langle \sigma v \rangle [\rho_{DM}(r(\ell, \Omega))]^2$$

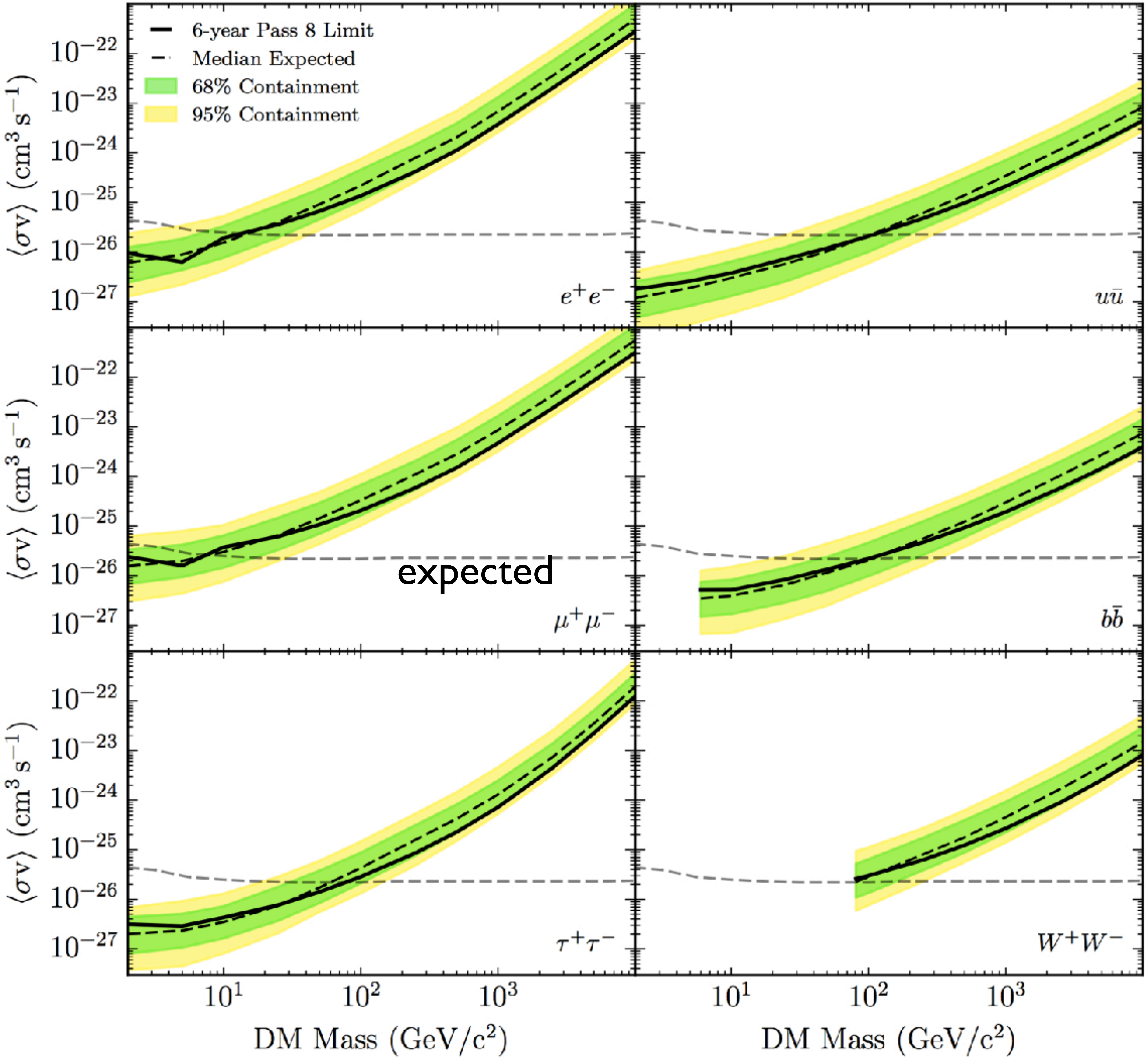
DM particle mass; solid angle; line-of-sight integral; dark matter density squared as projected on the sky

"*J* factor"

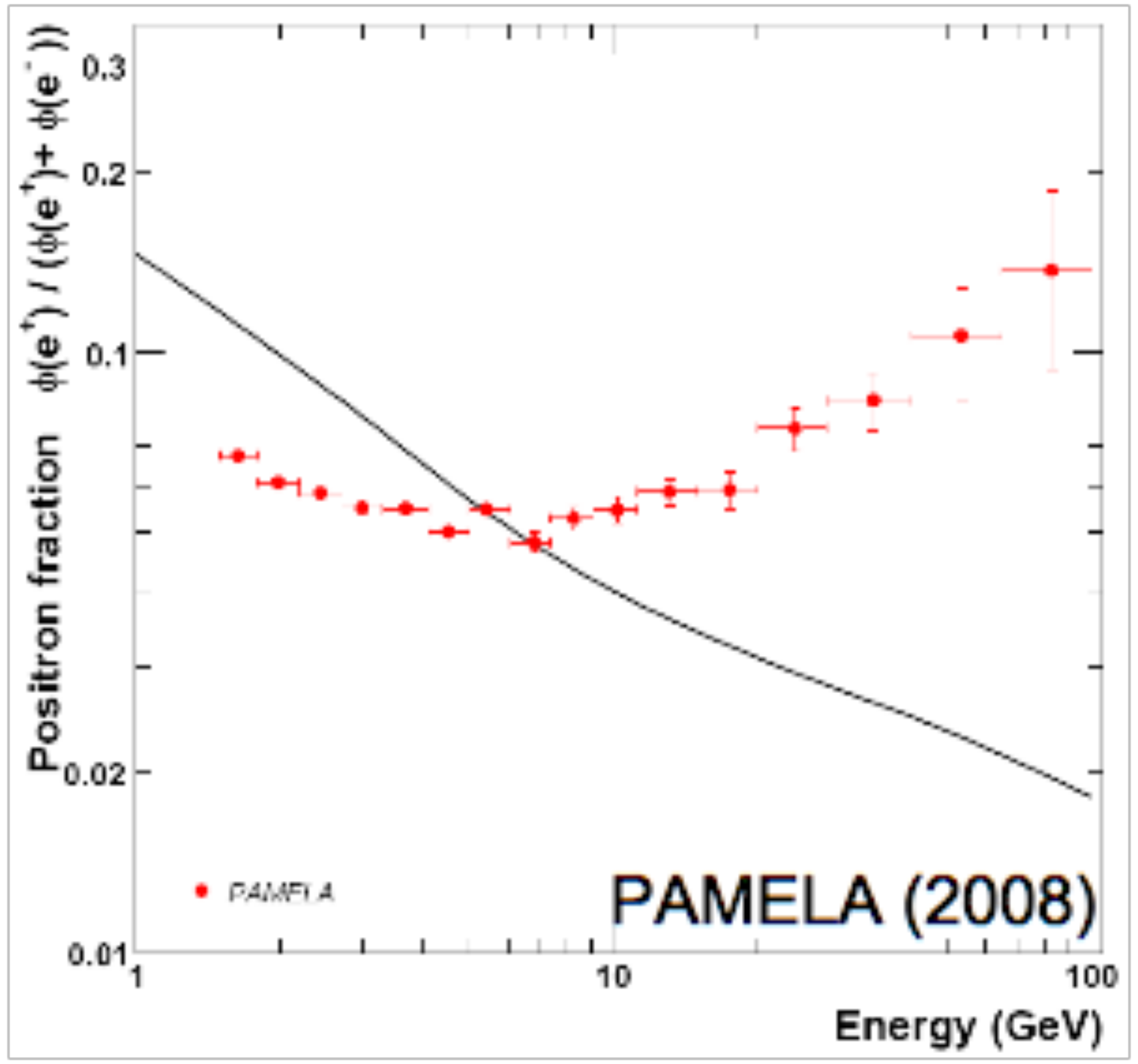
$$J = \int d\Omega \int d\ell [\rho_{DM}(r(\ell, \Omega))]^2$$

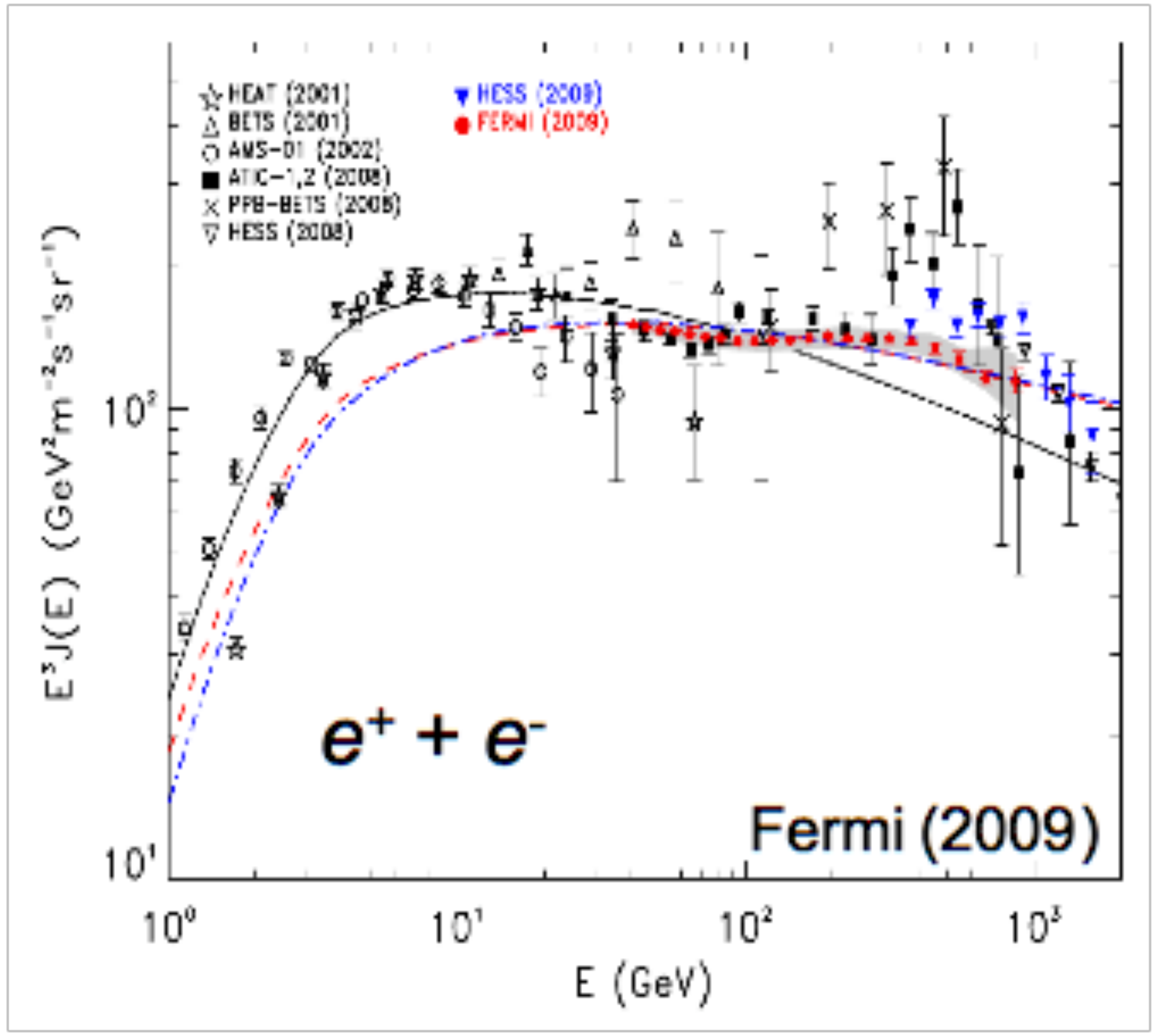
If the interaction cross-section is not velocity-dependent, then the flux depends only on the DM density profile.

Low mass WIMPs excluded for various decay channels



INDIRECT DETECTION





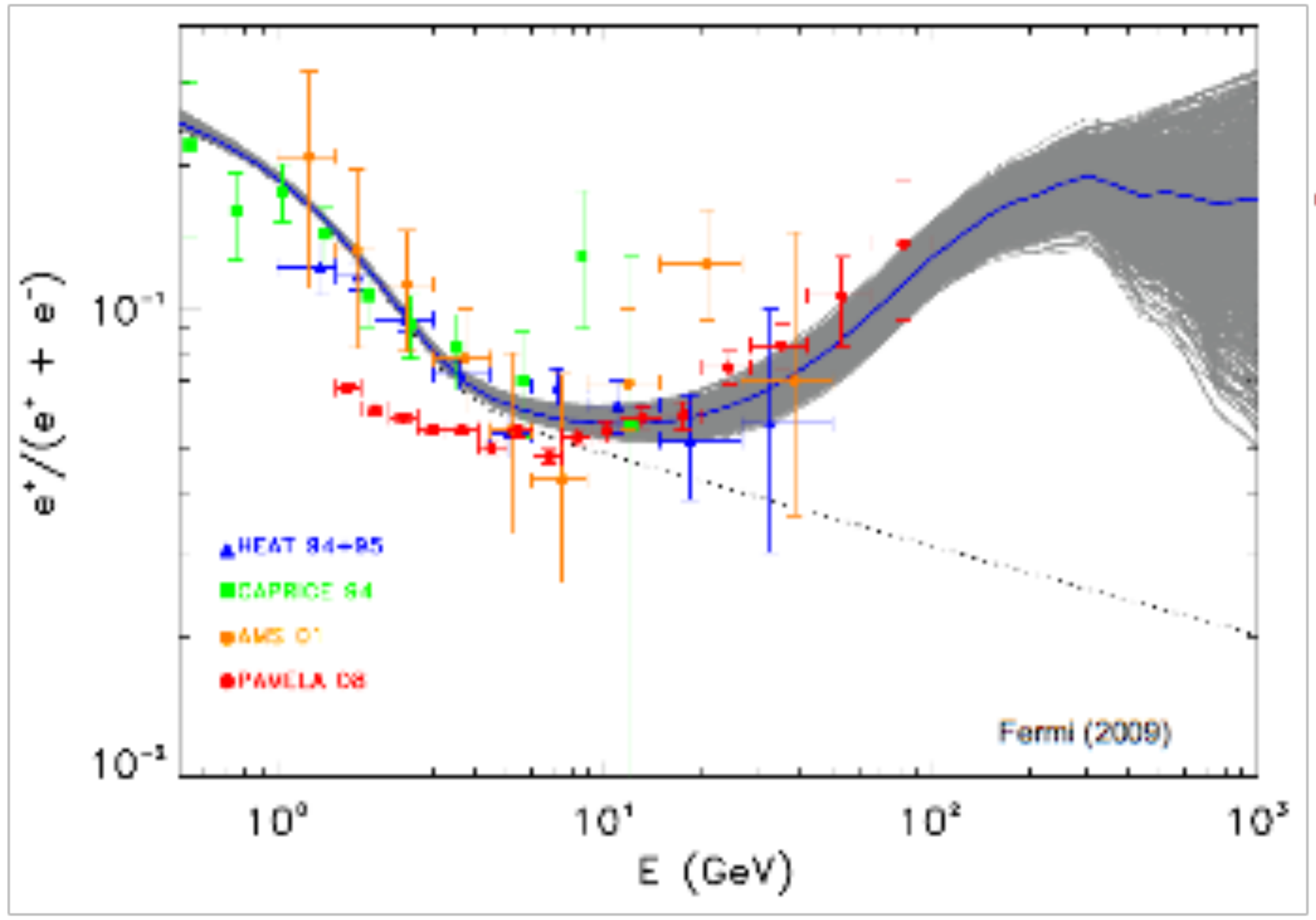
Solid lines are the predicted spectra from GALPROP (Moskalenko, Strong)

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 ~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

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).