우주입자와 21세기 물리학

physics beyond the standard theory

박성찬

Colloquium @ 원주입자물리스쿨, 4/14 2015

there are things, which just happen to be true…

The Ratio of Proton and Electron Masses

FRIEDRICH LENZ
Düsseldorf, Germany

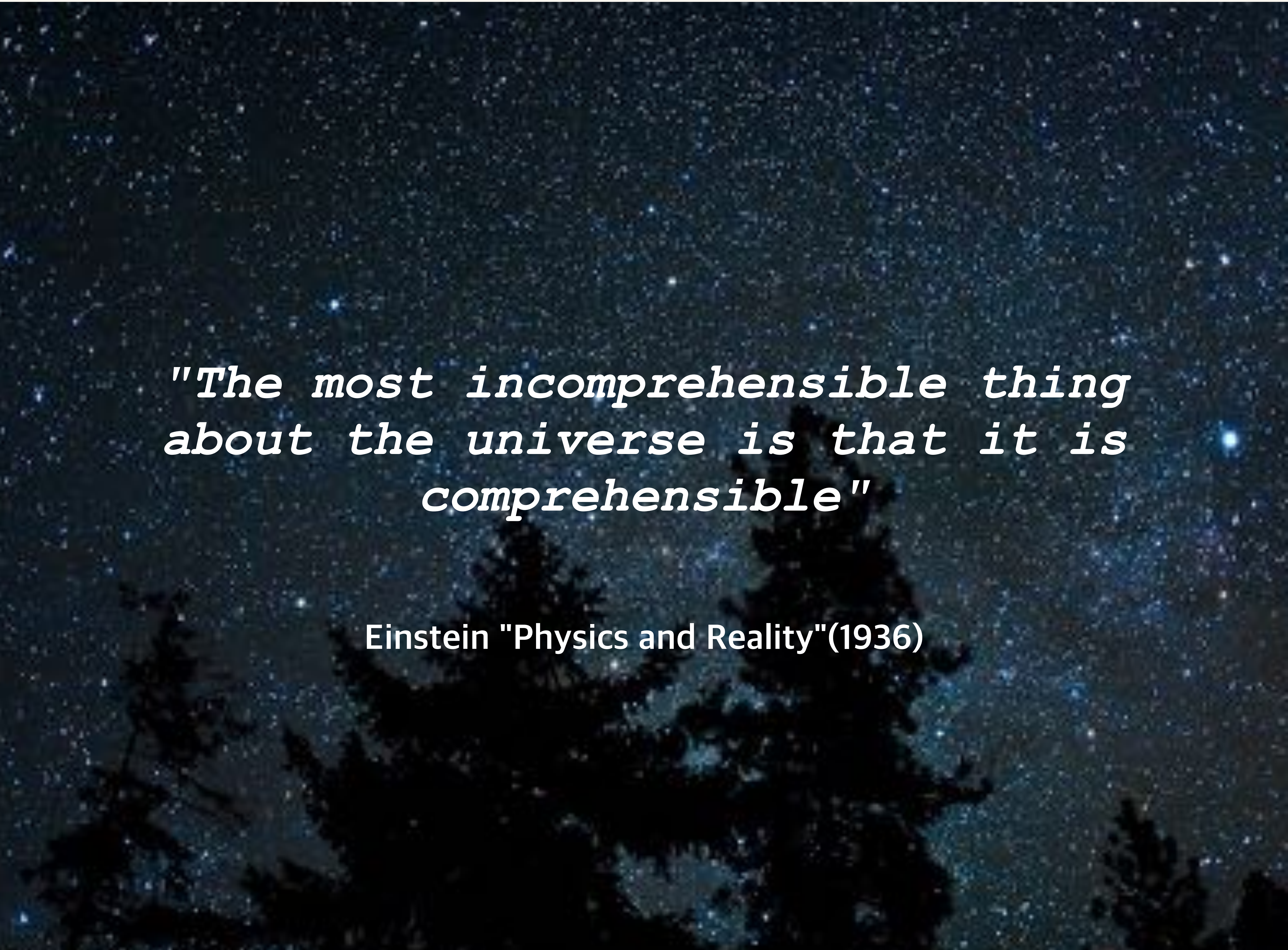
(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12 ± 0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

now 1836.15

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

But there are truly amazing things ??


"The most incomprehensible thing about the universe is that it is comprehensible"
Einstein "Physics and Reality"(1936)

Planck 2015: Lambda CDM + inflation

Planck Collaboration Cosmological parameters[5]

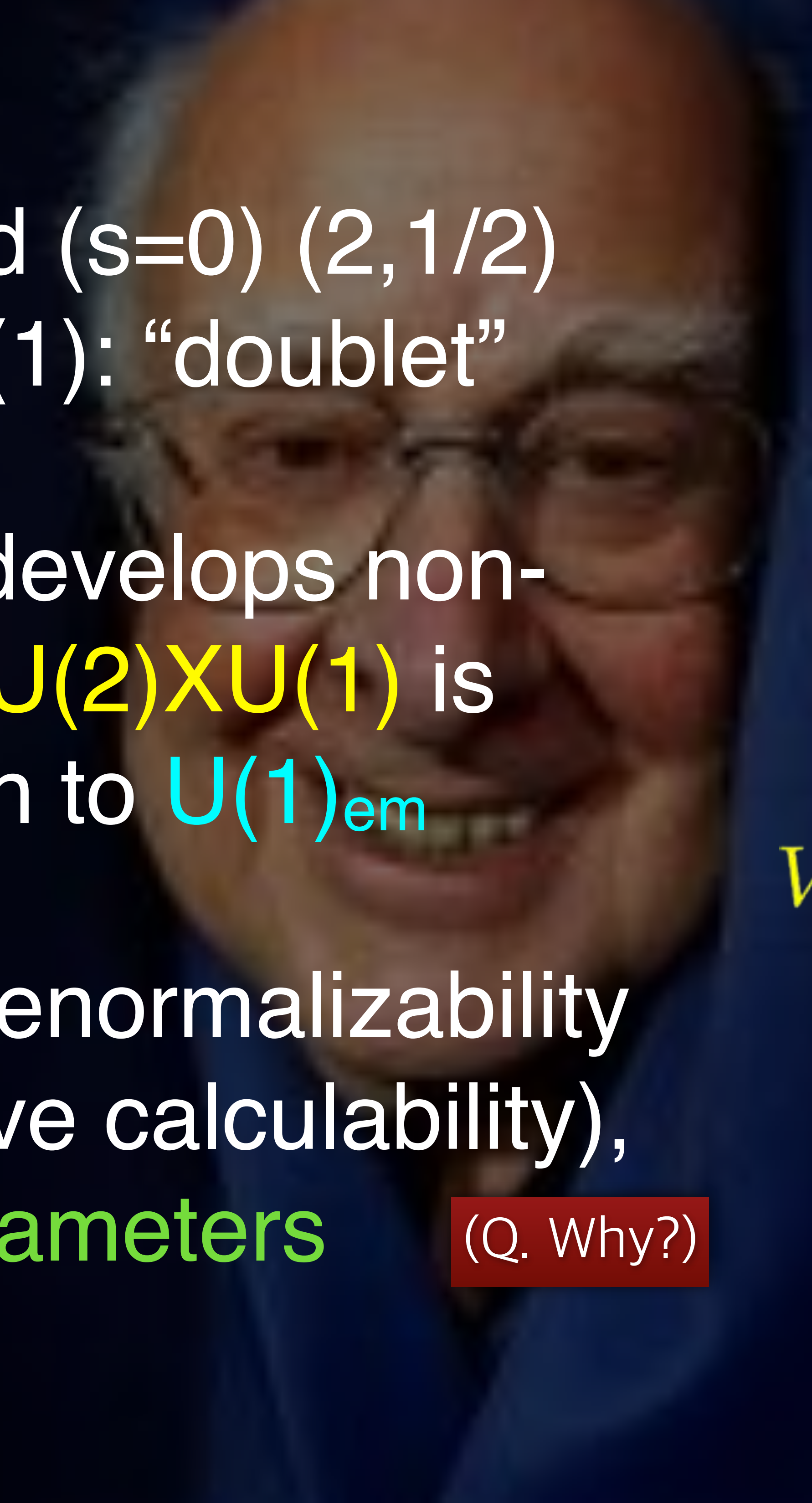
	Description	Symbol	Value
Independent parameters	Physical baryon density[note 1]	$\Omega_b h^2$	0.022 30 ±0.000 14
	Physical dark matter density[note 1]	$\Omega_c h^2$	0.1188 ±0.0010
	Age of the universe	t_0	13.799 ±0.021 × 10^9 years
	Scalar spectral index	n_s	0.9667 ±0.0040
	Curvature fluctuation amplitude	Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$, $k_0 = 0.002$ Mpc^{-1}
	Reionization optical depth	τ	0.066 ±0.012
Fixed parameters	Total density	Ω_{tot}	1
	Equation of state of dark energy	w	−1
	Sum of three neutrino masses	$\Sigma\, m_\nu$	negligible
Calculated values	Hubble constant	H_0	67.74 ±0.46 km s^{-1} Mpc^{-1}
	Matter density	Ω_m	0.3089 ±0.0062
	Dark energy density	Ω_Λ	0.6911 ±0.0062
	Fluctuation amplitude at $8h^{-1}$ Mpc	σ_8	0.8159 ±0.0086
	Redshift at decoupling	z_*	1 089.90 ±0.23
	Age at decoupling	t_*	377 700 ±3 200 years[8]
	Redshift of reionization	z_{re}	$8.8^{+1.7}_{-1.4}$

2013 :

The year of elementary scalars

- Planck 2013 data suggests “a single scalar field inflaton”
- March 2013, the CERN officially announced “a Higgs boson” is discovered.

The Higgs in the SM



- A scalar field (s=0) (2,1/2) of SU(2)XU(1): “doublet”

$$H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

- Tachyonic, develops non-zero VEV SU(2)XU(1) is broken down to $U(1)_{em}$

$$V(H) = \lambda(|H|^2 - v^2/2)^2$$

- Requiring Renormalizability (=perturbative calculability), two free parameters

(Q. Why?)

Higgs in the SM

- W-mass and gauge coupling measurement or equivalently GF :
- vev =246 GeV
- Mass=125 GeV from the LHC!

$$v = \frac{2m_W}{g}$$

$$\lambda = \frac{m_H^2}{2v^2} \approx 1/8$$

Now, all the parameters in the Higgs sector

are experimentally measured!

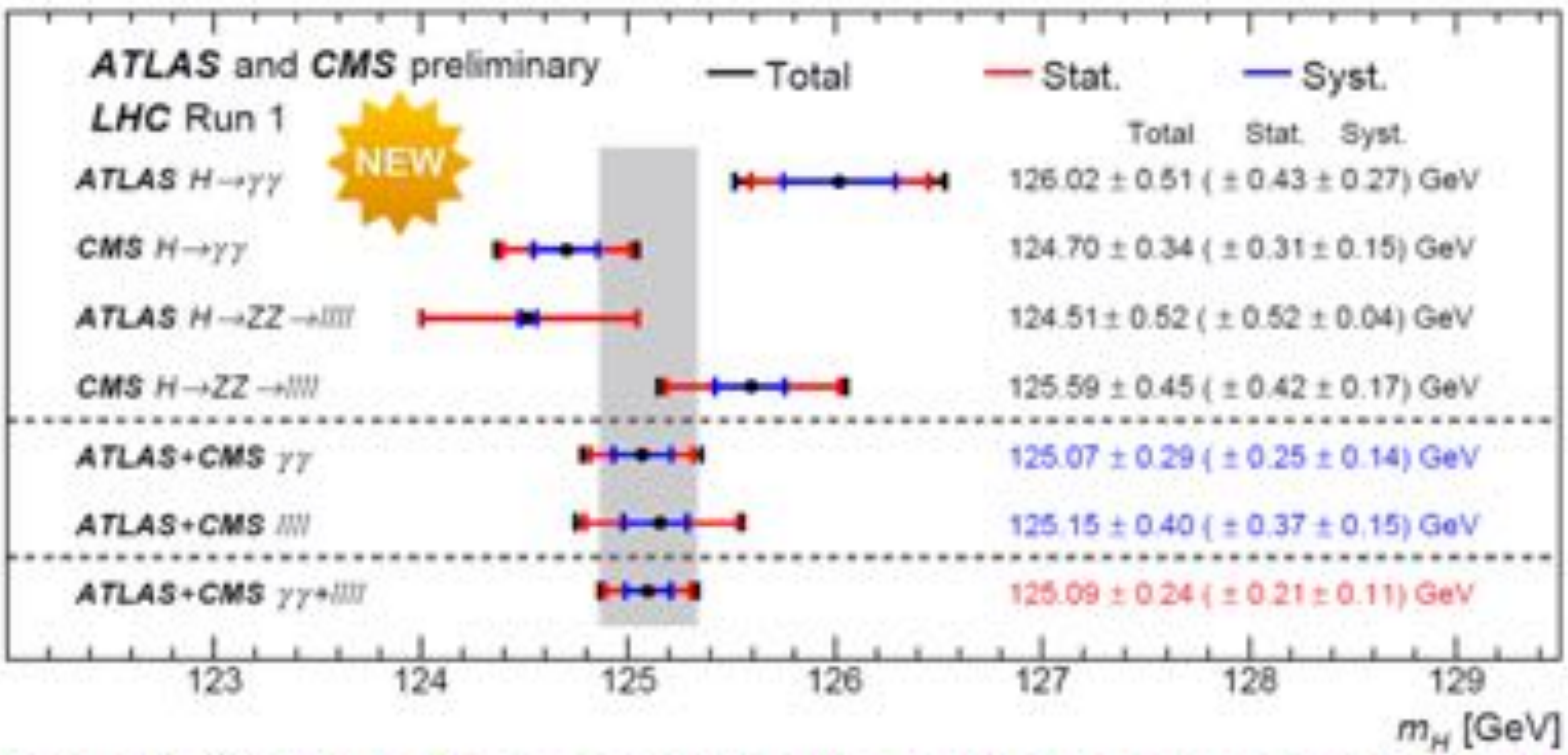
Moriónde 2015, some weeks ago!

ATLAS+CMS Higgs mass combination

… and the ATLAS+CMS combined Higgs boson mass is:

$$m_H = 125.09 \pm 0.24 \text{ GeV}$$ **(0.19% precision!)**

$$= 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{syst.}) \text{ GeV}$$

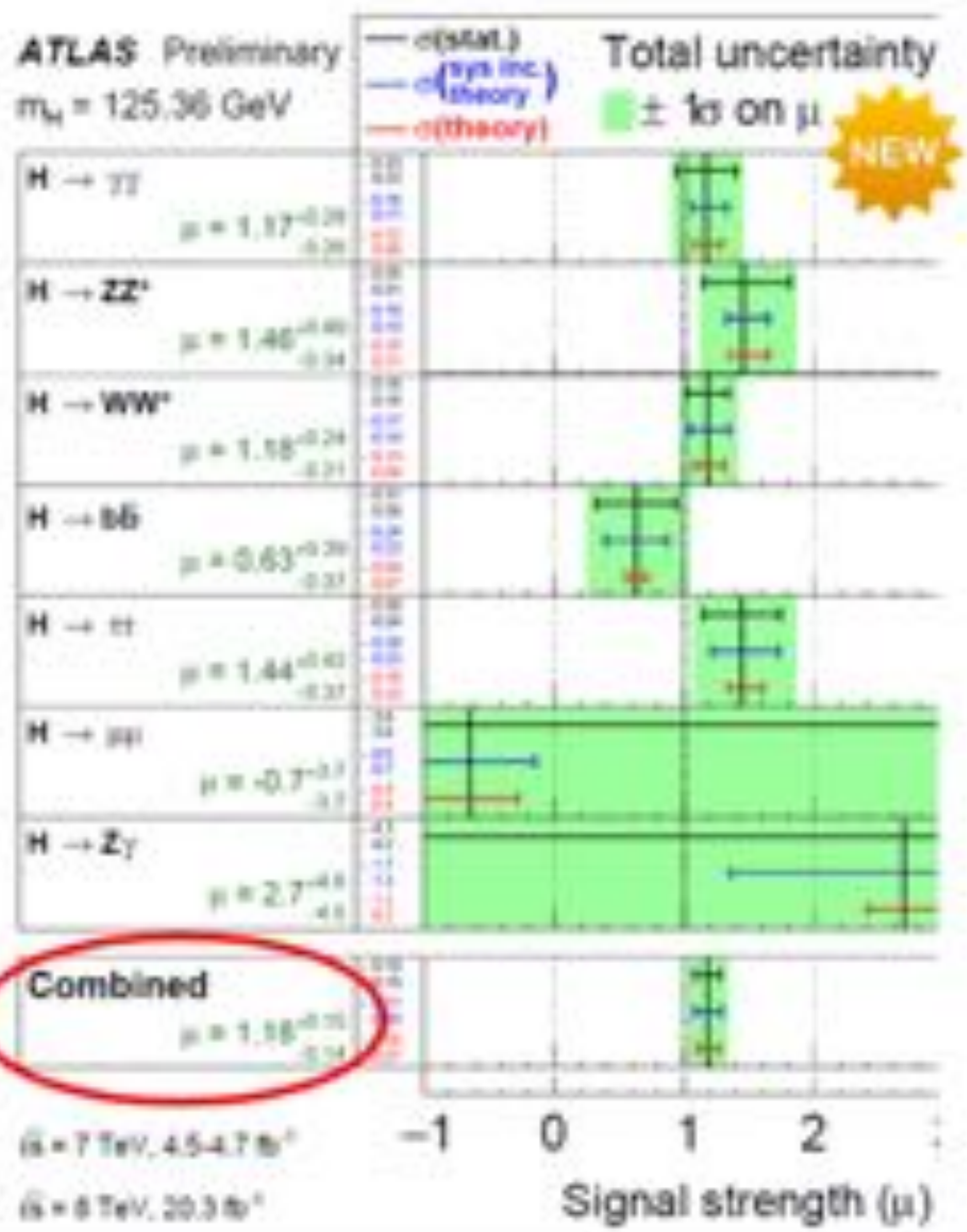


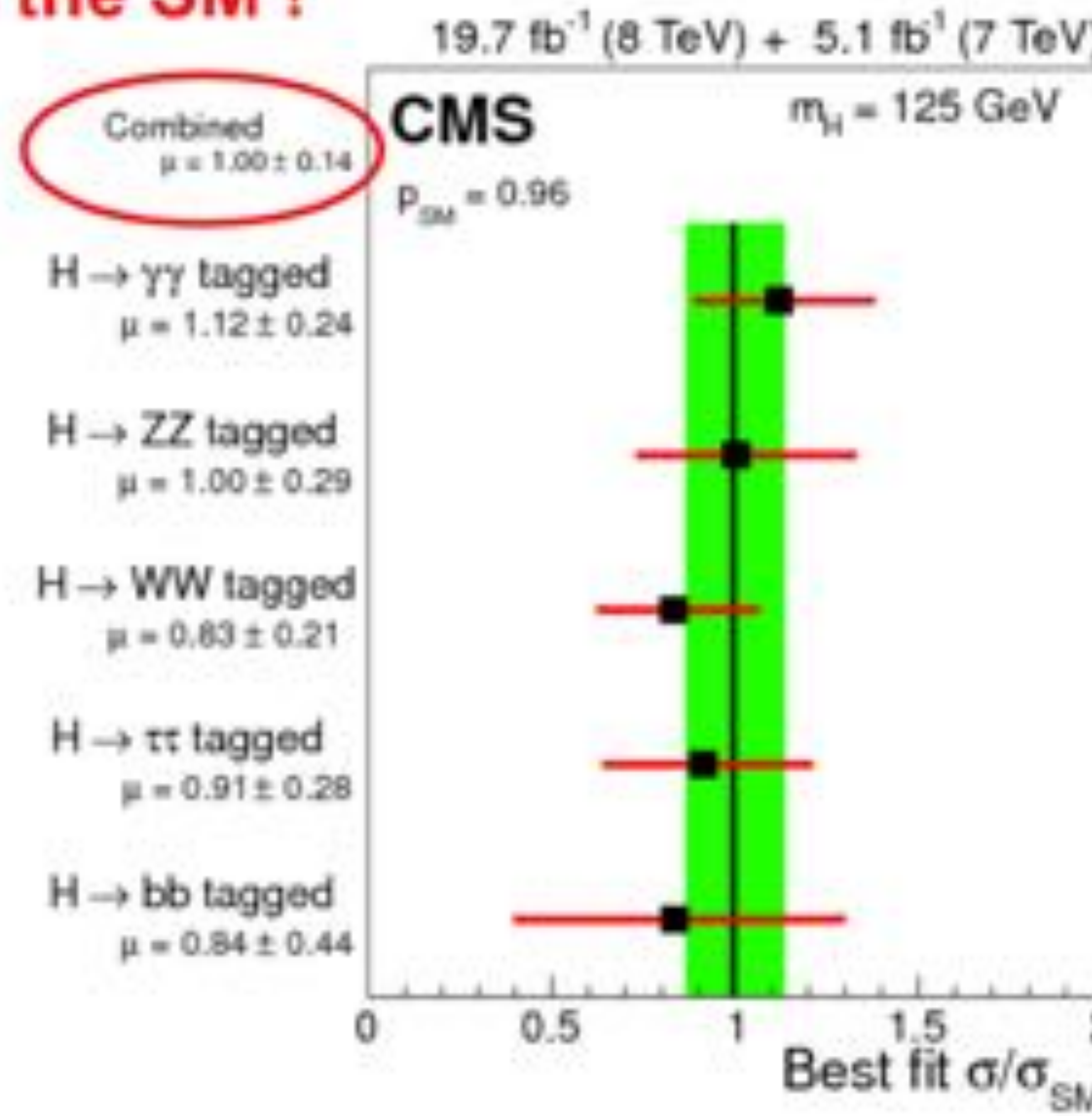
Compatibility of the 4 m_H measurements with the combined mass: 7-10%

Morionde 2015, some weeks ago!

Signal strength: grouping by decay

- SM values for ratios between different production cross sections are assumed
- **Results are consistent with the SM !**

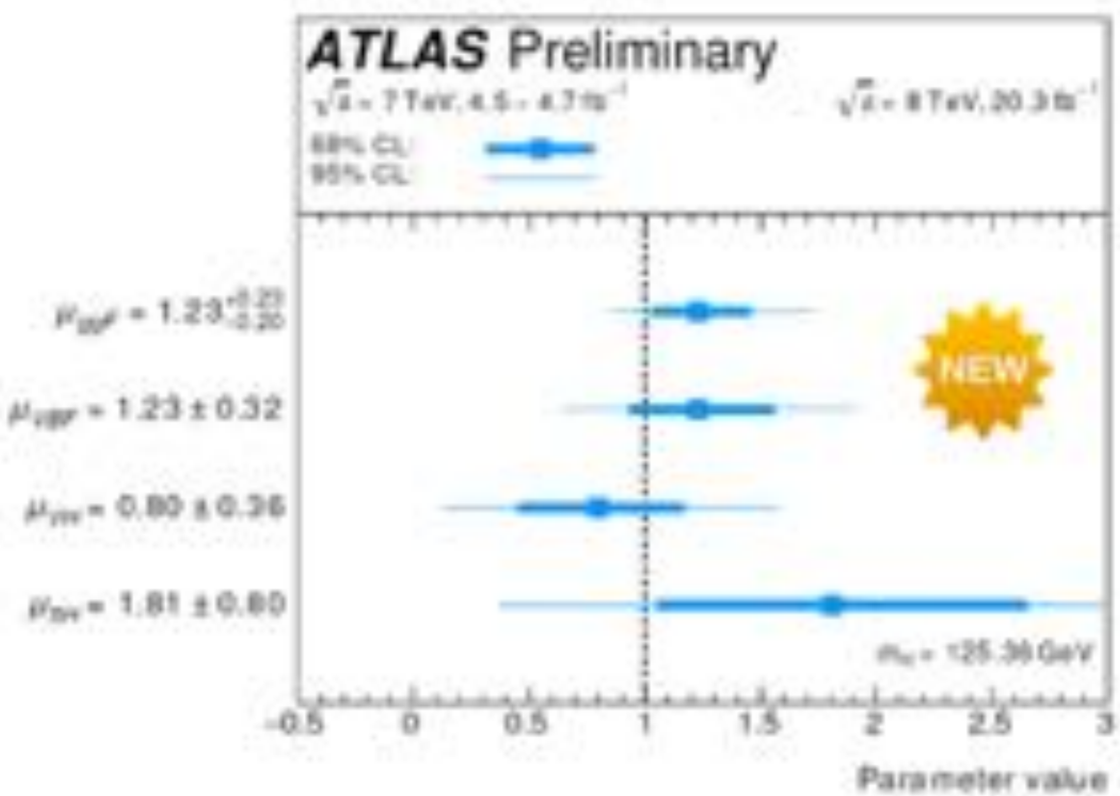


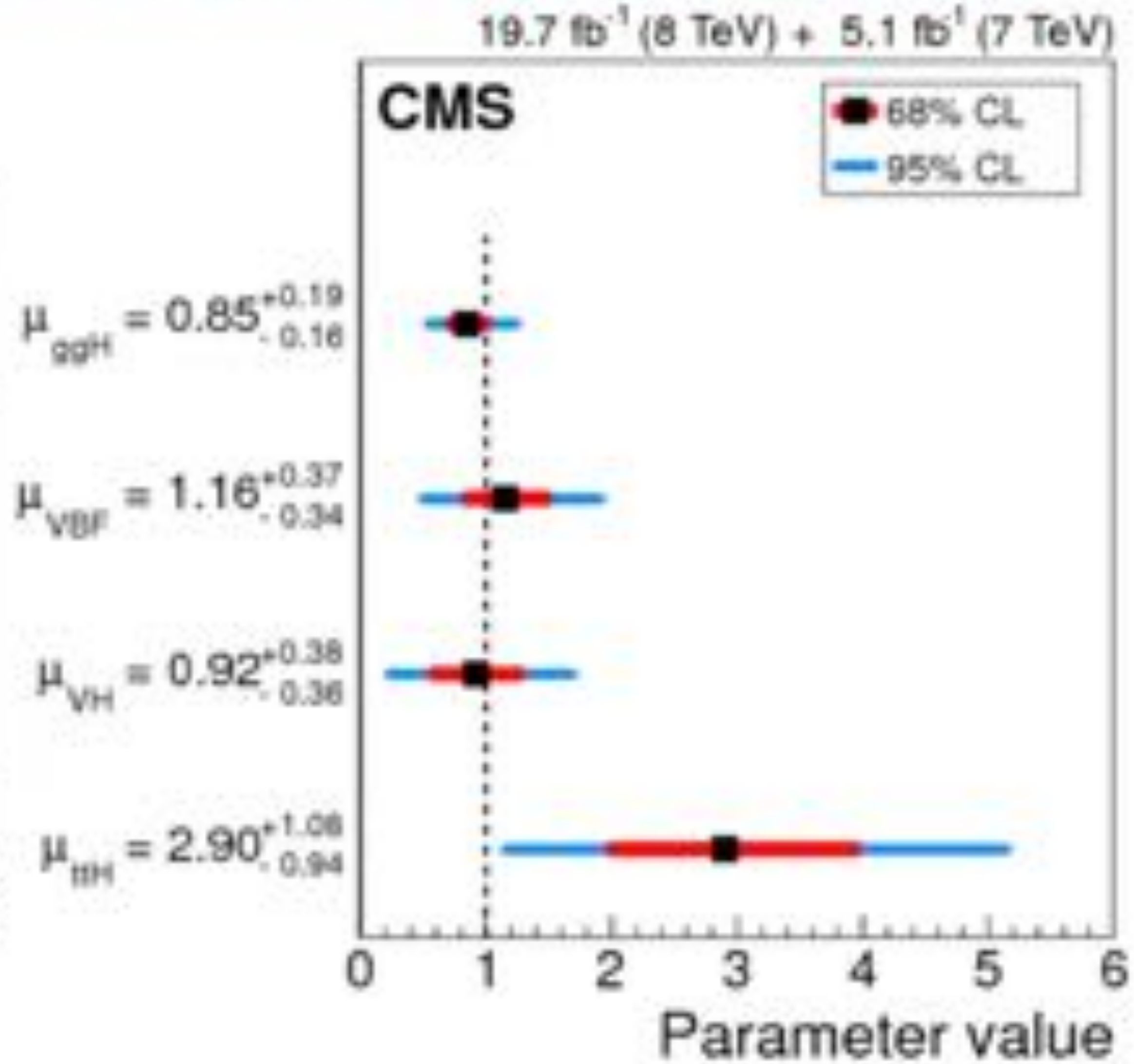


Morionde 2015, some weeks ago!

Signal strength: grouping by production

- **SM values for ratios between different branching fractions are assumed**
- **Results are consistent with the SM !**
  (but we can keep hoping for a ttH excess beyond the SM)





The SM is confirmed!

- all constituents of matter are discovered
- all gauge interactions are observed
- all parameters are now measured (Q. how many parameters?)

- In principle, the SM, a renormalizable QFT, can be valid up to very high energy as Planck energy.
- Do we really need BSM??

Yes, we need BSM!

- SM: many whys
  - ✳ why SU(3)XSU(2)XU(1)?
  - ✳ if effective theory, why renormalizable?
  - ✳ why 3 generations/ 6 flavors?
  - ✳ how 18 parameters are given as we measured?
  - ✳ (why so strong compared to gravity?)

Also, cosmological problems

- DM problem
- DE problem
- Baryogenesis problem
- Causality problem
- …and many others…
- what's yours?

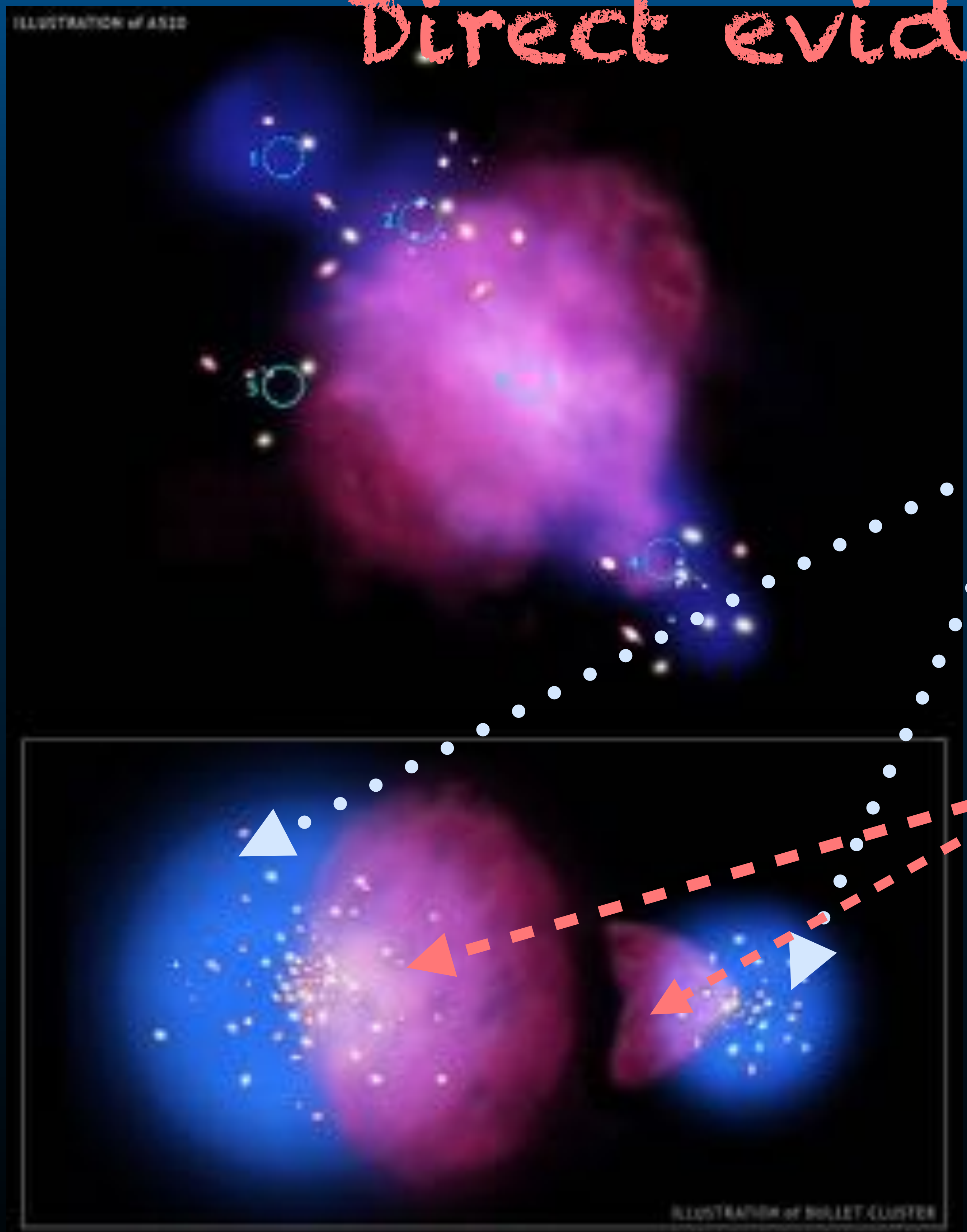
총알은하

S. Randall etal 0704.026

Two colliding galaxies

http://chandra.harvard.edu/photo/2007/a520/

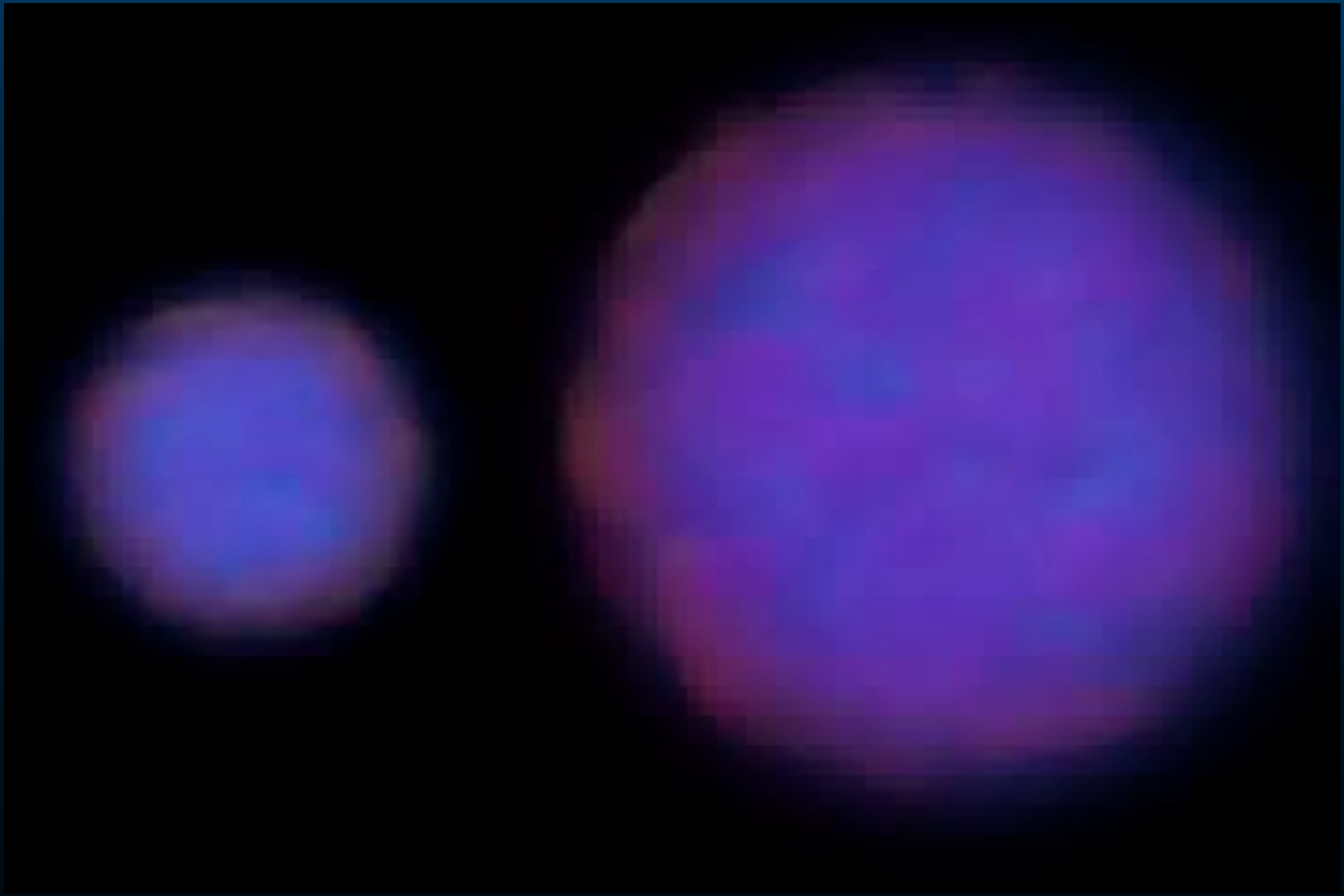
Direct evidence for DM!



Blue:
gravitational potential
seen by lensing

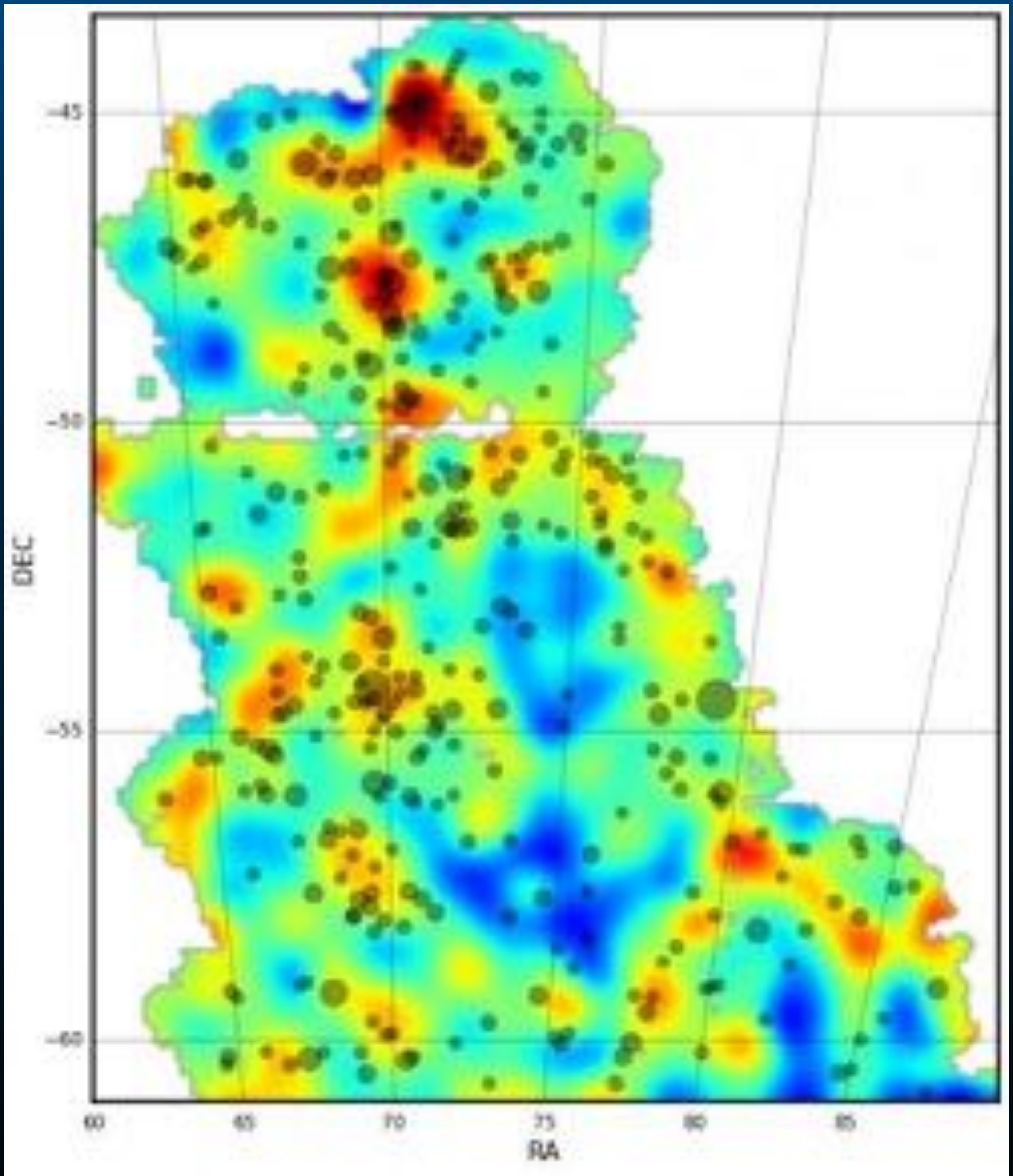
Red:
visible matter
seen by X-ray

http://chandra.harvard.edu/photo/2006/1e0657/1e0657_bullett_anim_lg.mpg



APS Aprl 2015, now going on!

암흑 물질 지도



red:dense region
blue:avg region
dots:galaxies, clusters

Dark Energy Surveys(DES) at APS, April meeting, 2015

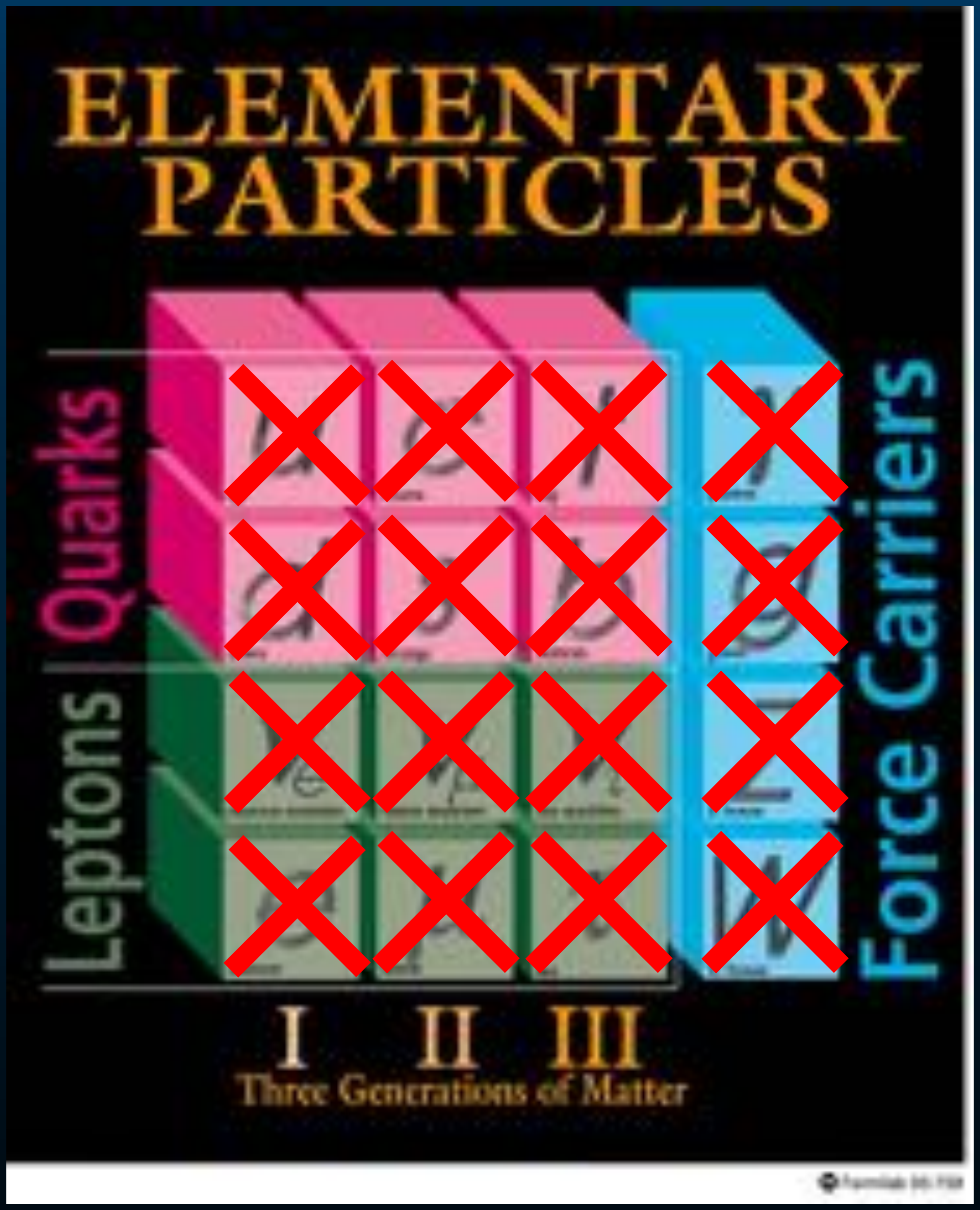
Cosmic Smily Face

more evidences

- Galactic rotation curve + Galaxy formation (CDM)
- Gravitational lensing
- Bullet cluster
- CMBR
- Cosmological acceleration

- 암흑 물질의 '존재 증명'은 이미 이루어 졌다.
- 그런데 그 '정체'를 이해하는 것은 또 다른 수준의 이해를 필요로 한다.

Q. DM in the SM?



Known DM properties

- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

Unambiguous evidence for new particles!

A big irony

- After many years’ digging into particle physics, we end up with a conclusion that we only know about 5% of the energy budget of Universe.

- Revealing the nature of DM is our mission now

Modern view of Galaxy

What DM is not.

- Astronomical search excludes $(10^{-7}, 10)$ solar mass "dark astronomical objects"

  [Afonso *et. al.* (EROS Collaboration) 2003 *Astron. Astrophys.* **400** 951]

- CMB excludes "Baryonic dark matter"

$$\Omega_b h^2 = 0.024 \pm 0.001$$

Spergel D N *et al* (WMAP Collaboration) 2003 *Astrophys. J.* Suppl. **148** 175

$$\Omega_m h^2 = 0.14 \pm 0.02$$

- gravitational Bohr radius < galaxy scale otherwise a halo wouldn't form.

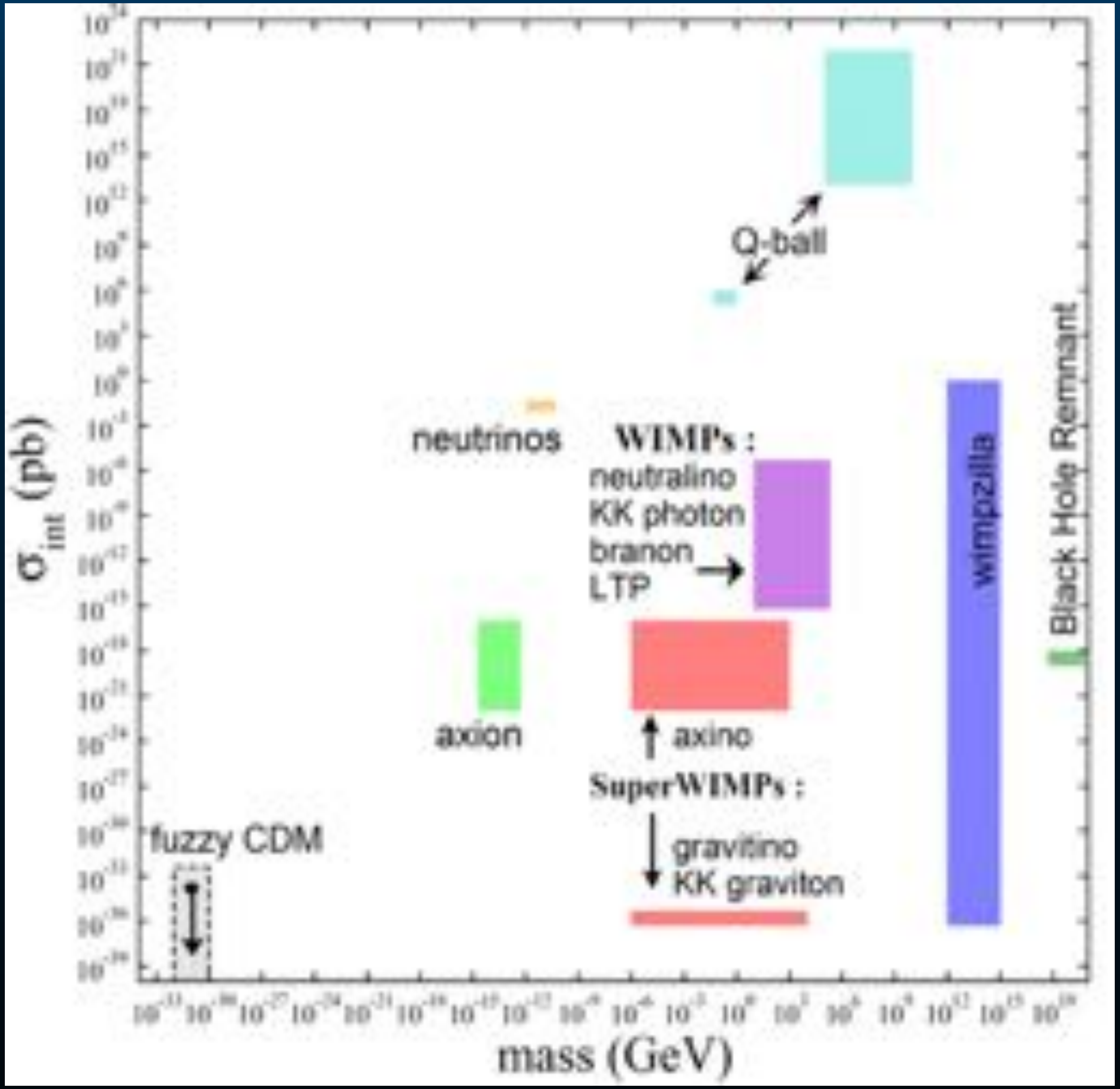
  Hu W, Barkana R and Gruzinov A 2000 *Phys. Rev. Lett.* **85** 1158

Dark matter mass?

- $M=(10^{-31}, 10^{50})$ GeV (if fermion, bound tighter due to the Pauli pressure)
- Still a window with 81 orders magnitude is open for DM··· not very precise :-(
- ···but certainly improved since the first proposal by Fritz Zwicky in 1930s: $v \sim \langle T \rangle \sim$ Mass (virial motion of astronomical objects)

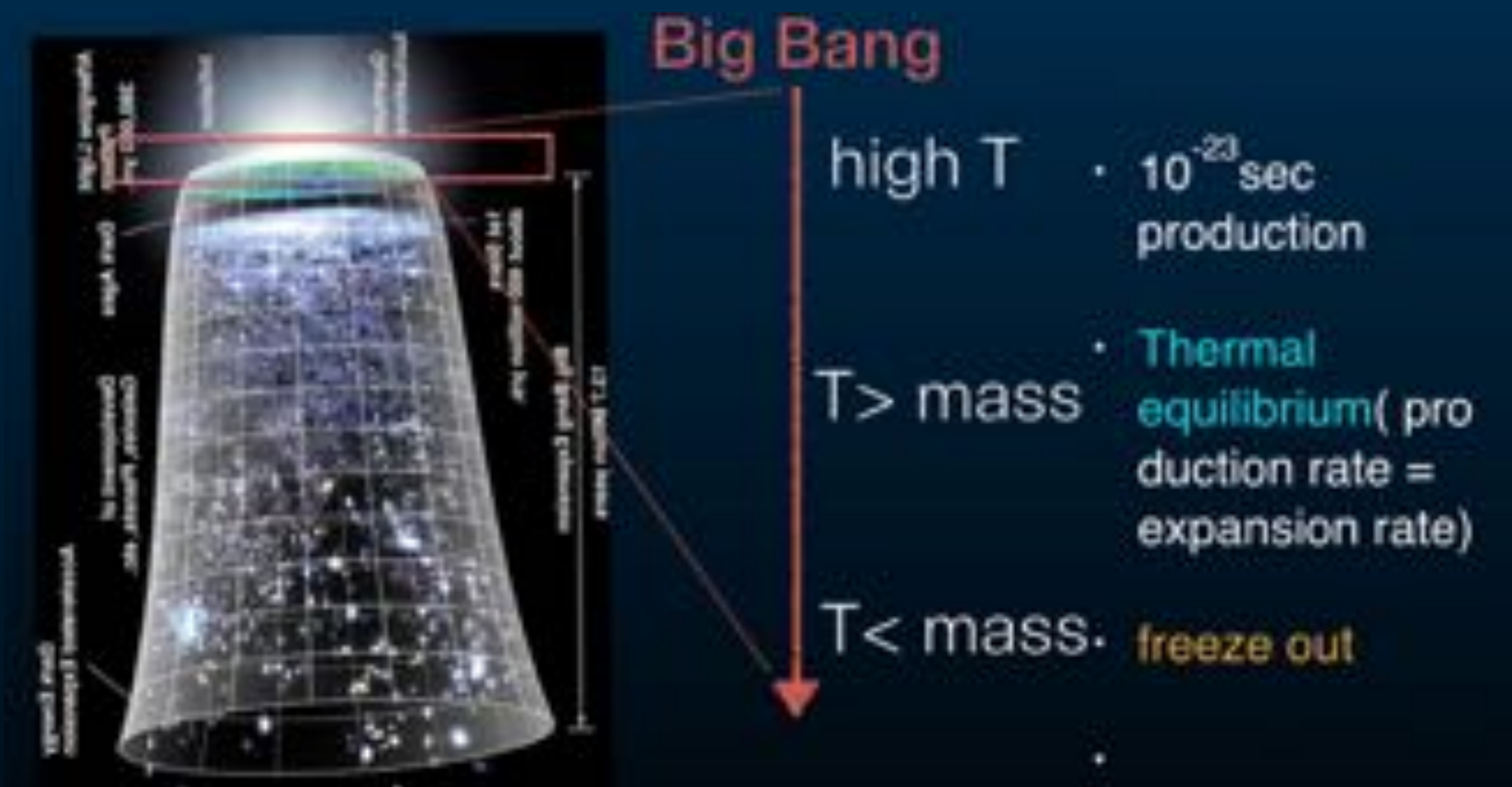
DARK MATTER CANDIDATES

- There are many candidates
- Masses and interaction strengths span many, many orders of magnitude,
- **WIMP is the most popular candidate due to WIMP-miracle.**



Baer, KY Choi, JE Kim, Roszkowski, Phys.Rept. 555 (2014)

WIMP miracle



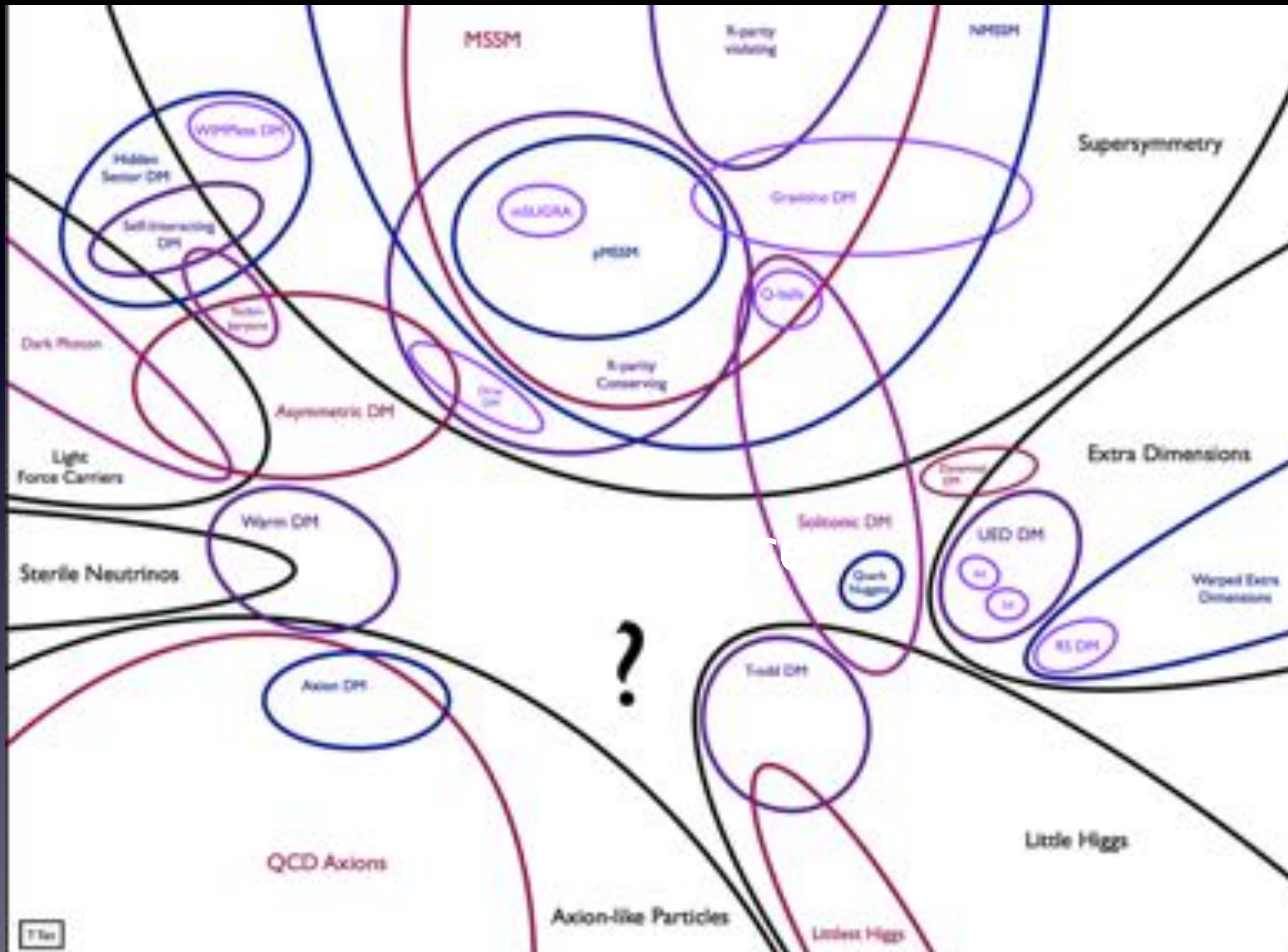
Lee-Weinberg (1977)

$$\Omega_\chi h^2 \approx \frac{0.1\text{pb} \cdot c}{\langle \sigma_A v \rangle}$$

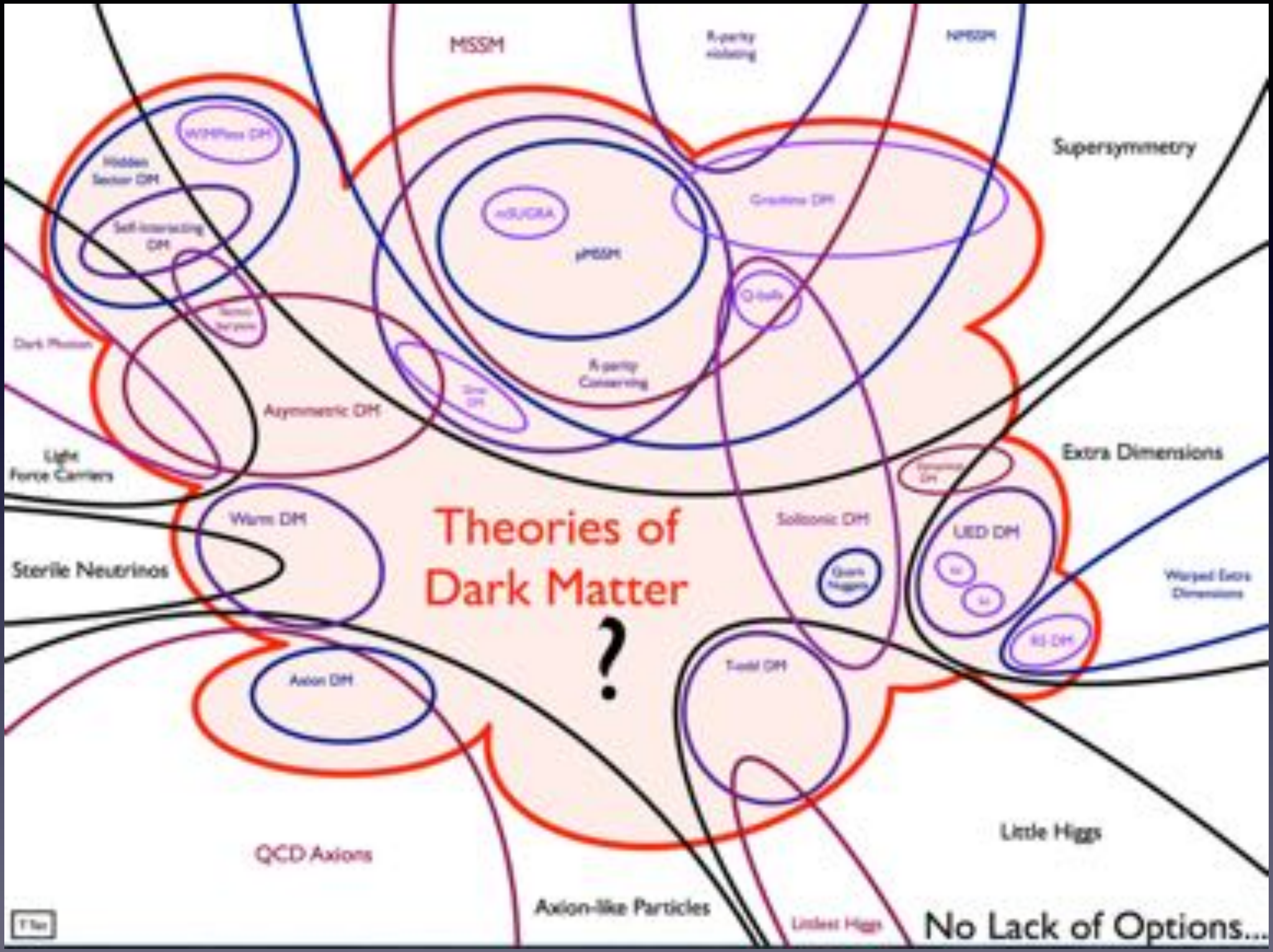
$$\therefore \langle \sigma \frac{v}{c} \rangle \simeq 1\text{pb}$$

Typical weak interaction!

But···don't forget the huge theory space for BSM

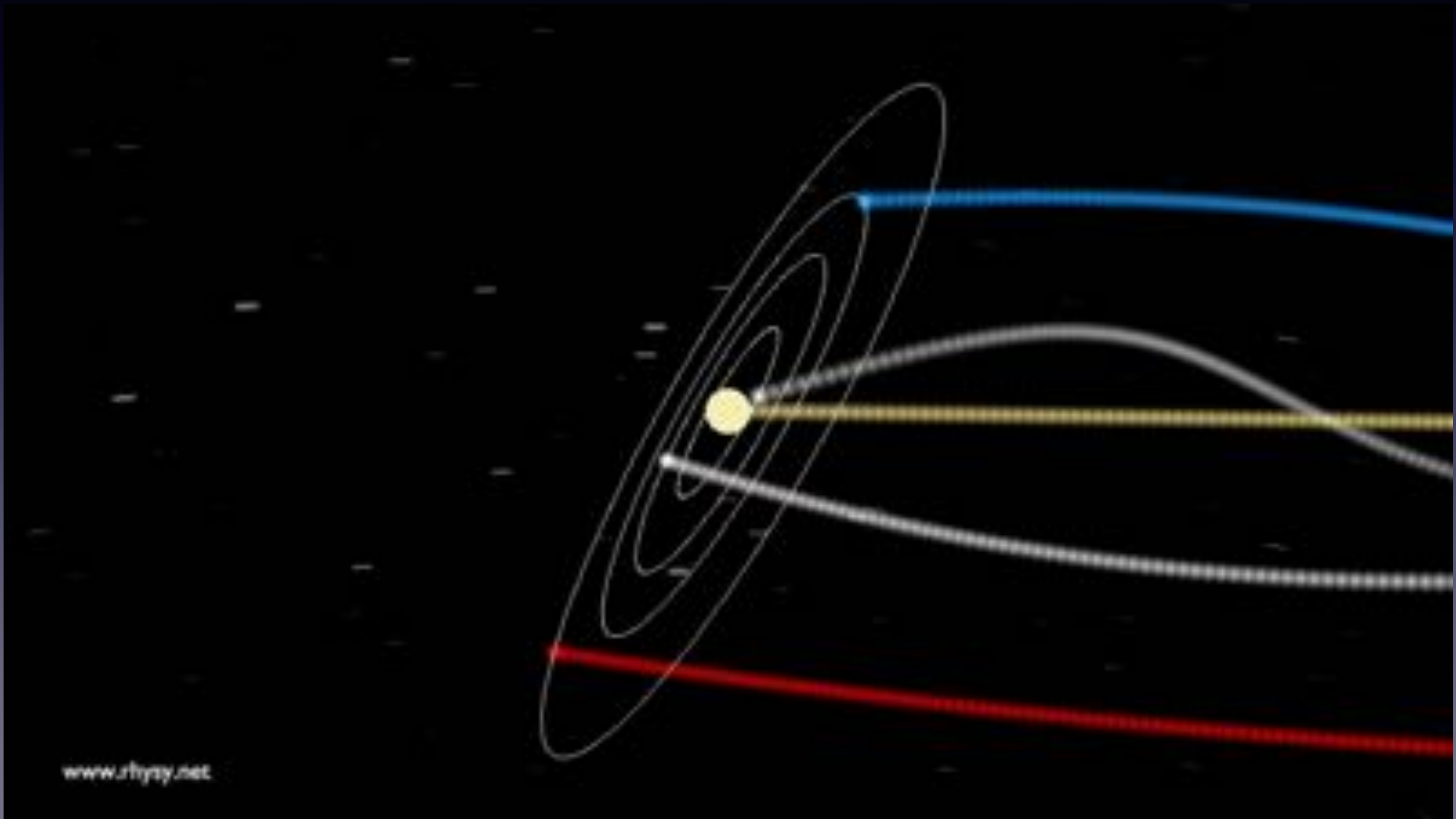


There are many candidates in the market



One obvious search strategy

- We are always facing the DM wind
- Why don't we detect this wind?


www.rhysy.net

from N-body simulation
+ observational inputs

$$\rho_{DM} = 0.3 - 0.4\mathrm{GeV}/\mathrm{cm}^3$$

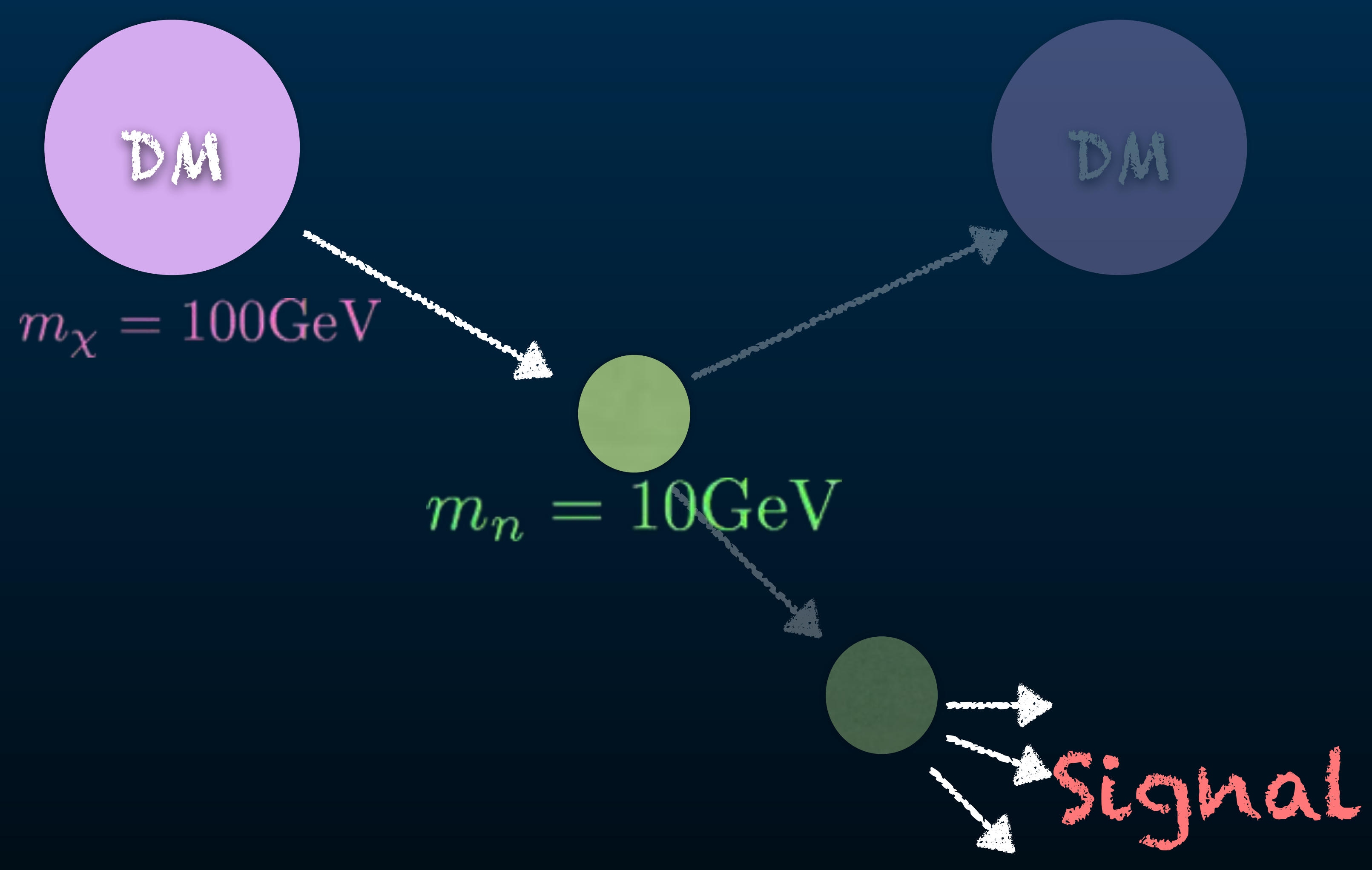
$$v = 240\mathrm{km}/\mathrm{s}$$

from the motion of solar system
in DM halo

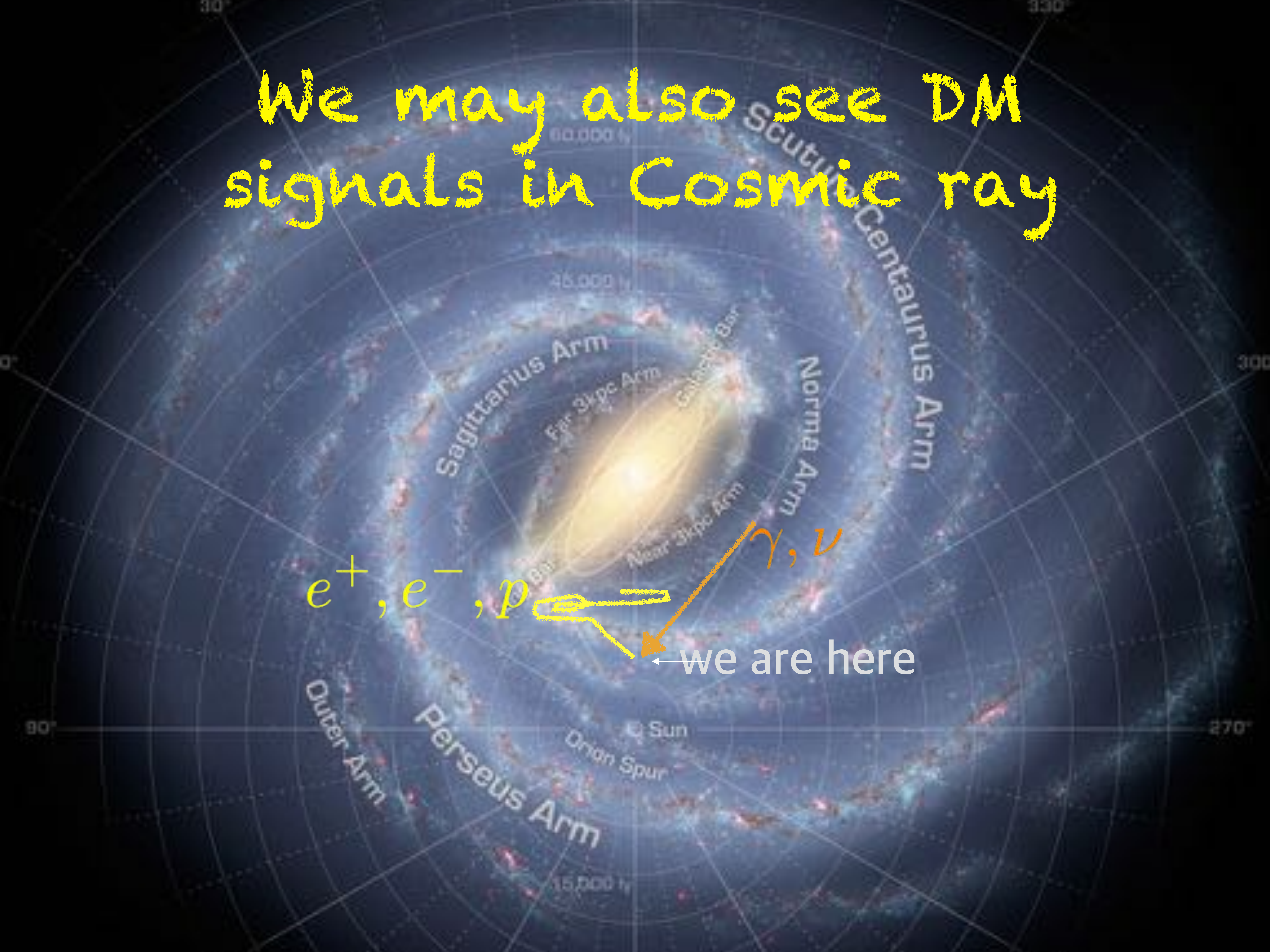
$$j = n_{DM} v = \frac{0.3}{\mathrm{cm}^3}\frac{240km}{\mathrm{s}} \cdot \frac{\mathrm{GeV}}{M_{DM}} \approx 7.2 \times 10^7/\mathrm{cm}^2$$

Difficulties in direct detection

- Like fishing in the sea, we can wait for the moment of DM-N interaction. There are many on-going projects including one in Korea.
- If we are lucky, we may able to detect DM flux directly!
- Local clump of DM sub halo can change the estimation orders of magnitude
- WIMP-Nucleon recoil energy~1-100keV if DM~ GeV-TeV but much less if DM is lighter (sensitive detector with large volume helps)
- Below cosmic neutrino interaction cross section, the background will dominate over the signal.

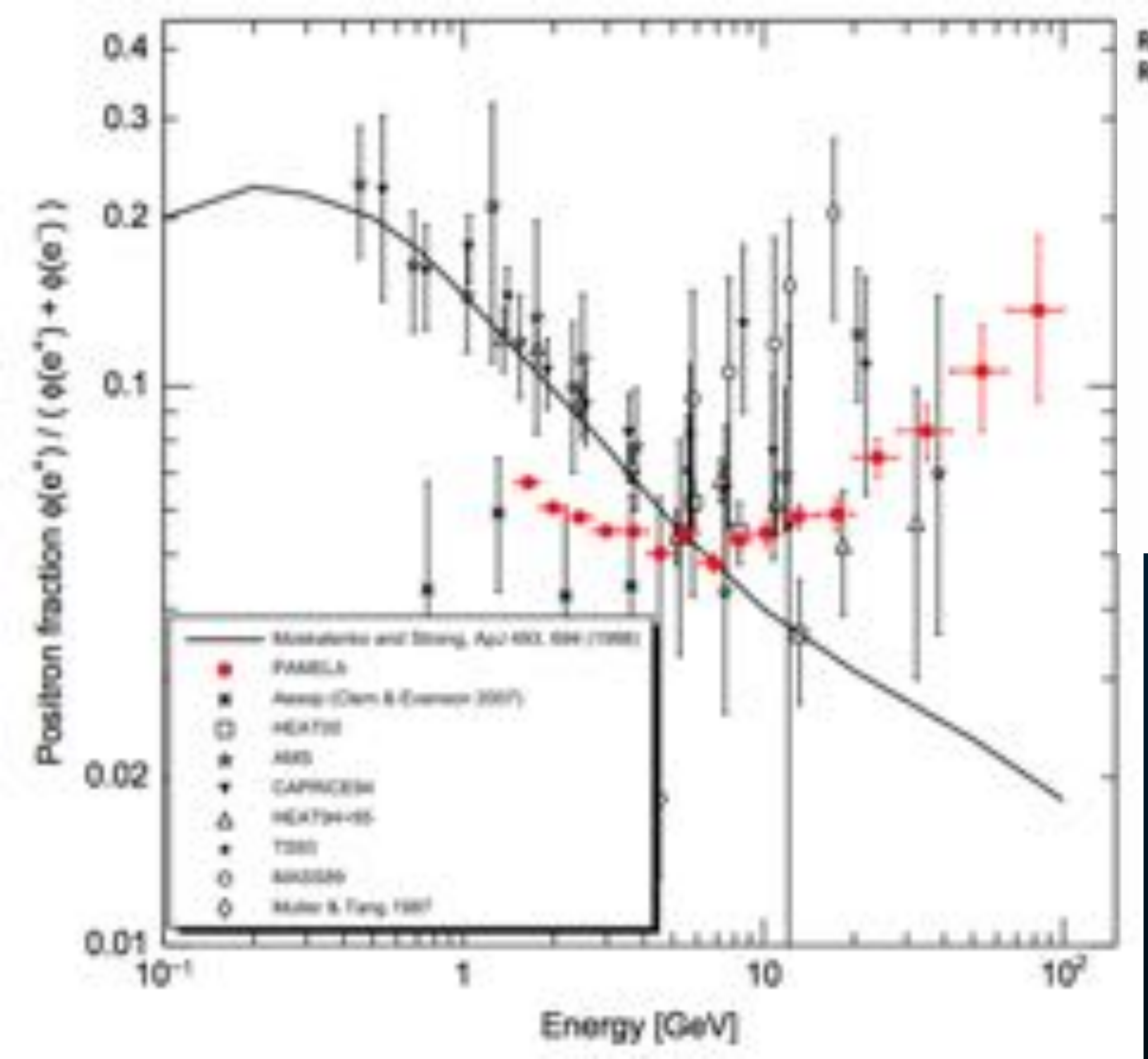

DM
DM
$m_\chi = 100\mathrm{GeV}$
$m_n = 10\mathrm{GeV}$
Signal

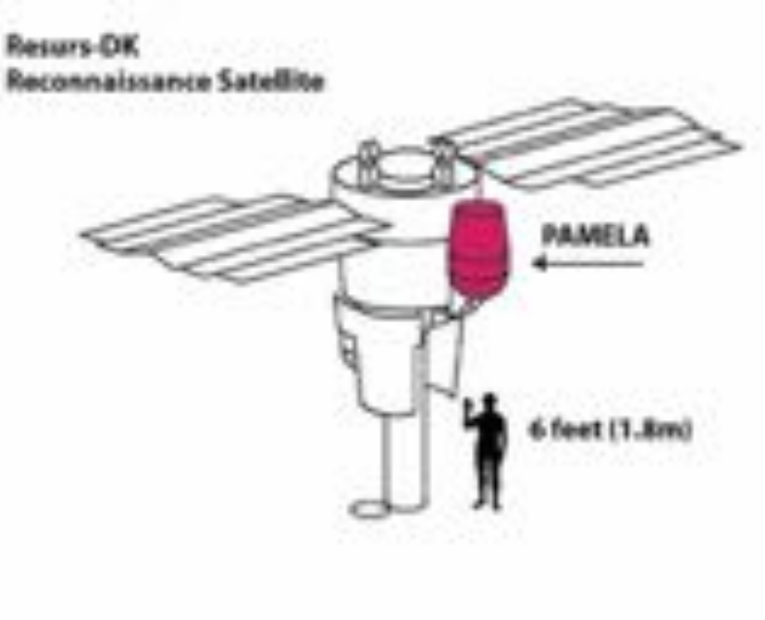
We may also see DM signals in Cosmic ray



- DM can pair annihilate into visible but stable standard model particles. The rate ~ rho^2 in the case of annihilating, ~rho for decaying DM.
- Naturally more signature is expected from the Galactic center.
- Charged particles bump into Galactic magnetic field and lose its initial energy and diffuse. Diffuse signals of e+,e-, p, p- are good targets to be seen.
- Indeed, the beginning of 21st century is full of surprises in cosmic-ray physics

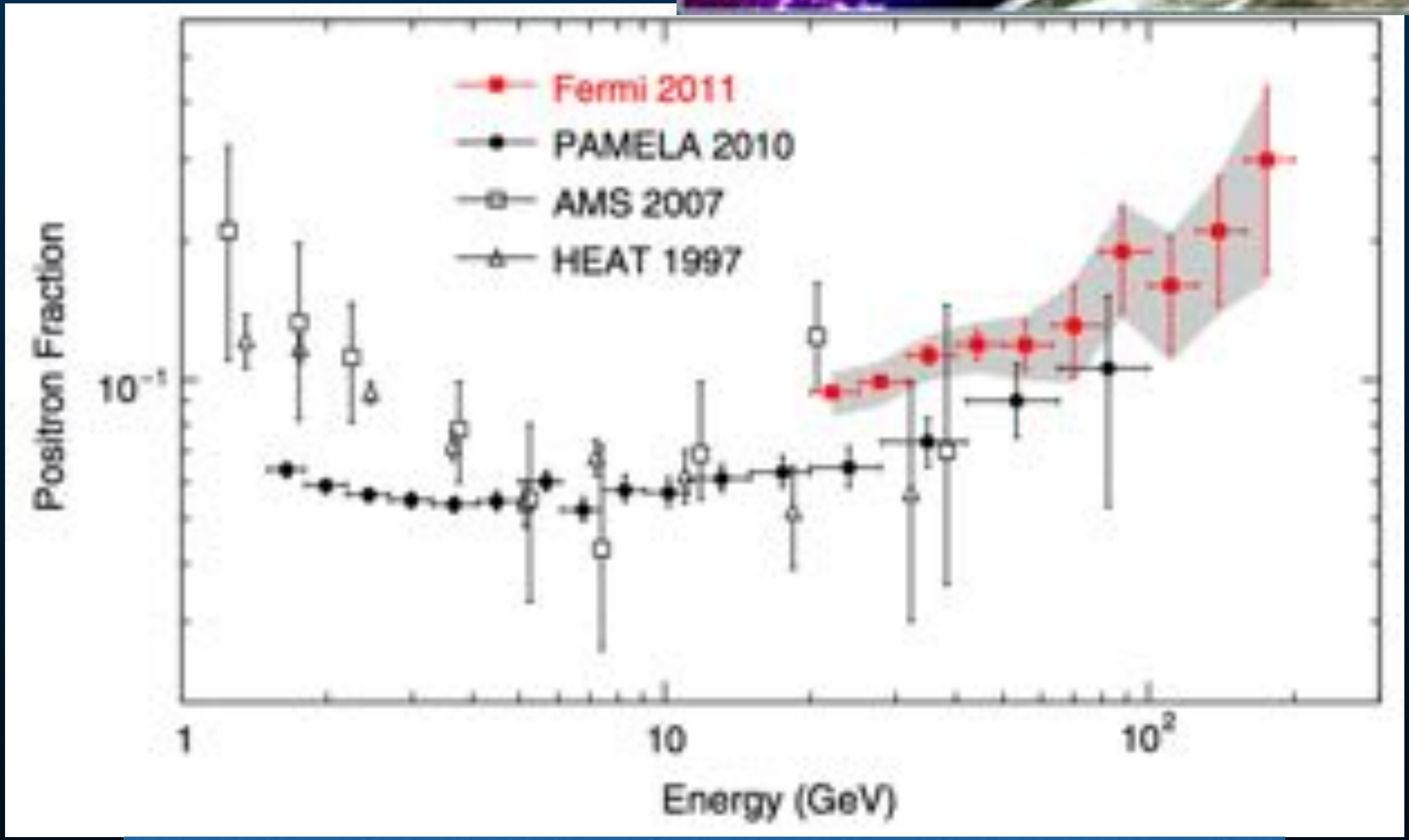
Pamela e+/(e−+E+)





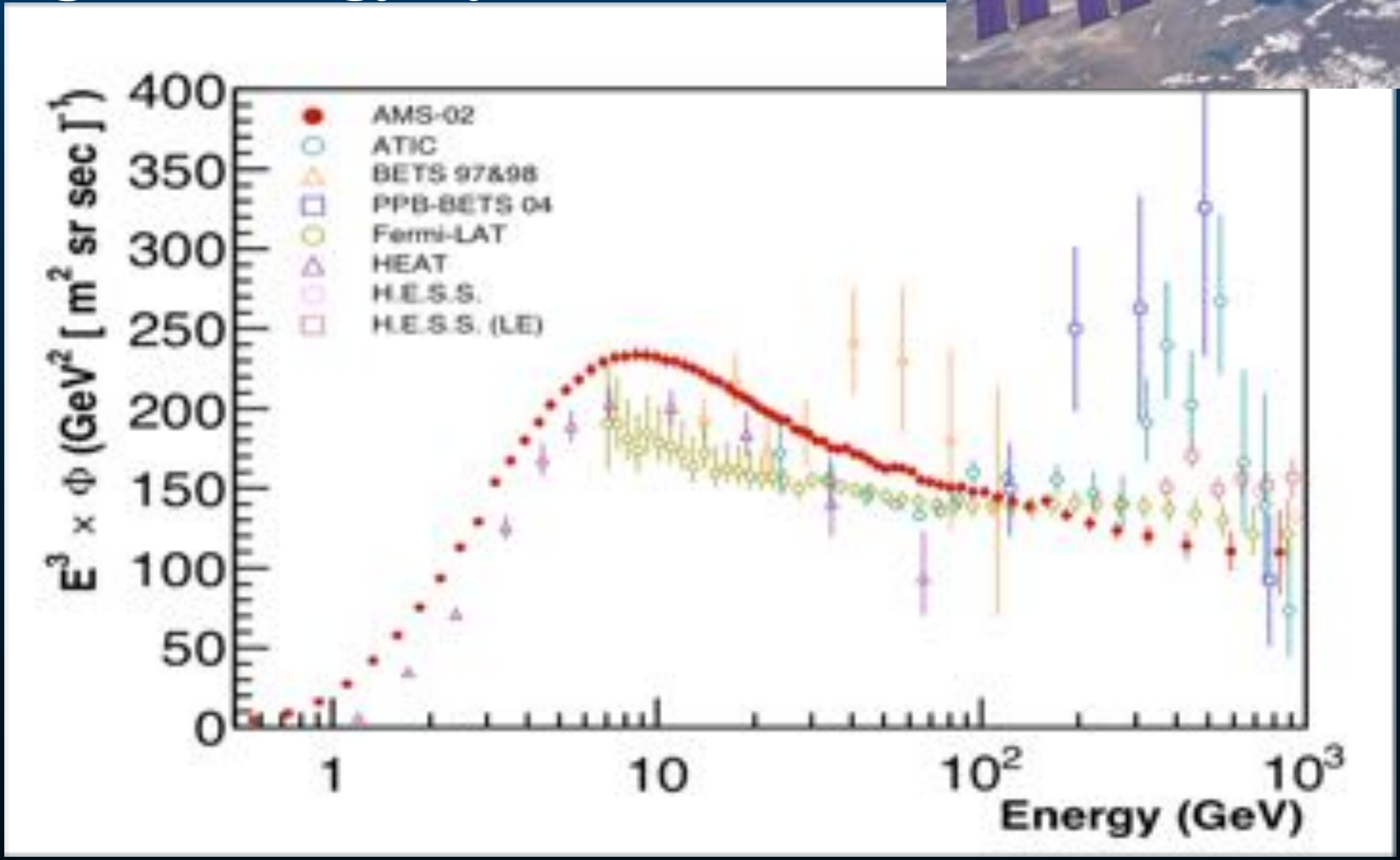
O. Adriarini et. al. [PAMELA] Nature (458) 607, (2009)

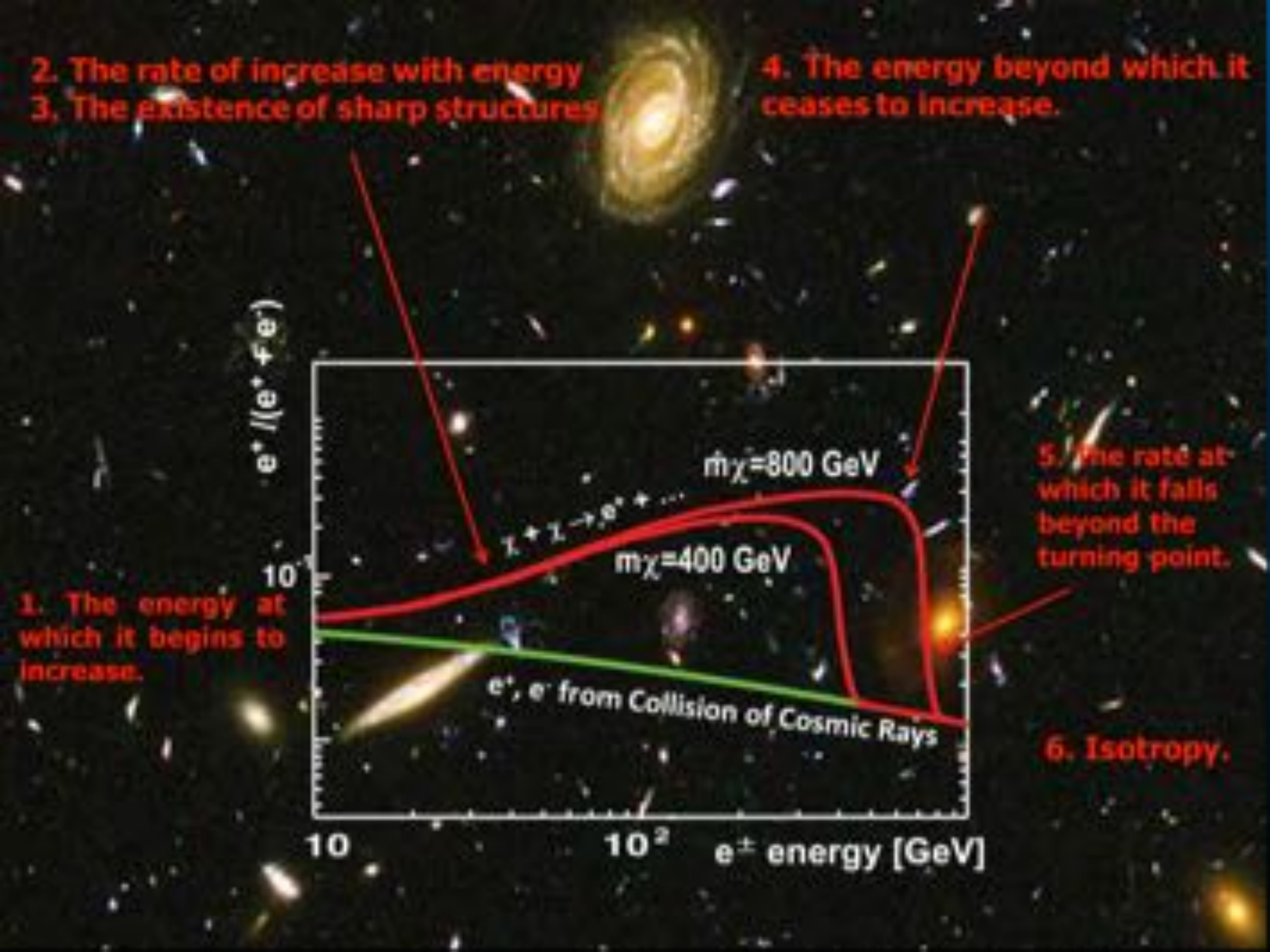
Confirmed by Fermi-LAT



M. Ackermann [Fermi-LAT] PRL 108, 011103 (2012)

Re-confirmed and extended to higher energy by AMS02

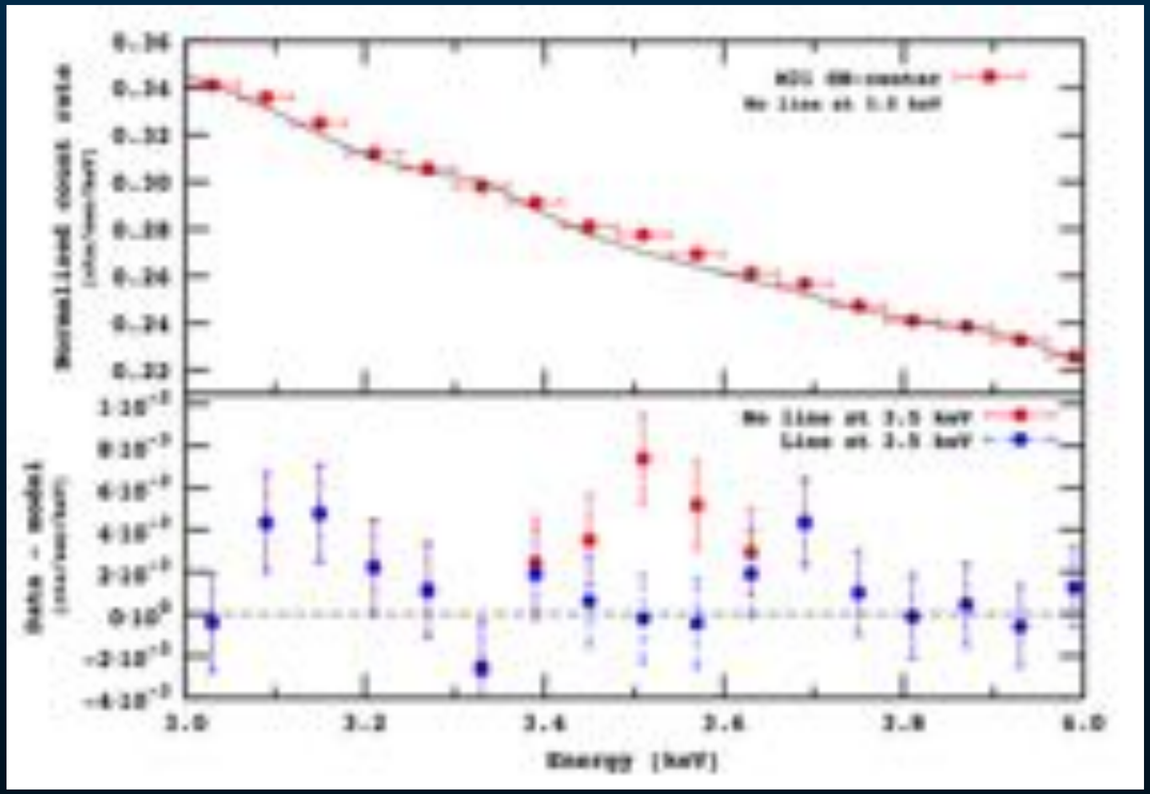




2. The rate of increase with energy
3. The existence of sharp structures
4. The energy beyond which it ceases to increase.
$e^+/(e^+ + e^-)$
m_χ=800 GeV
$\chi + \chi \to e^+ + \ldots$
m_χ=400 GeV
10^{-1}
5. The rate at which it falls beyond the turning point.
1. The energy at which it begins to increase.
e^+, e^- from Collision of Cosmic Rays
6. Isotropy.
10
10^2
$e^\pm$ energy [GeV]

3.5 keV 'line' from the stack of galactic clusters
Boyarsky etal. 1402.4119

Hot topic of the season

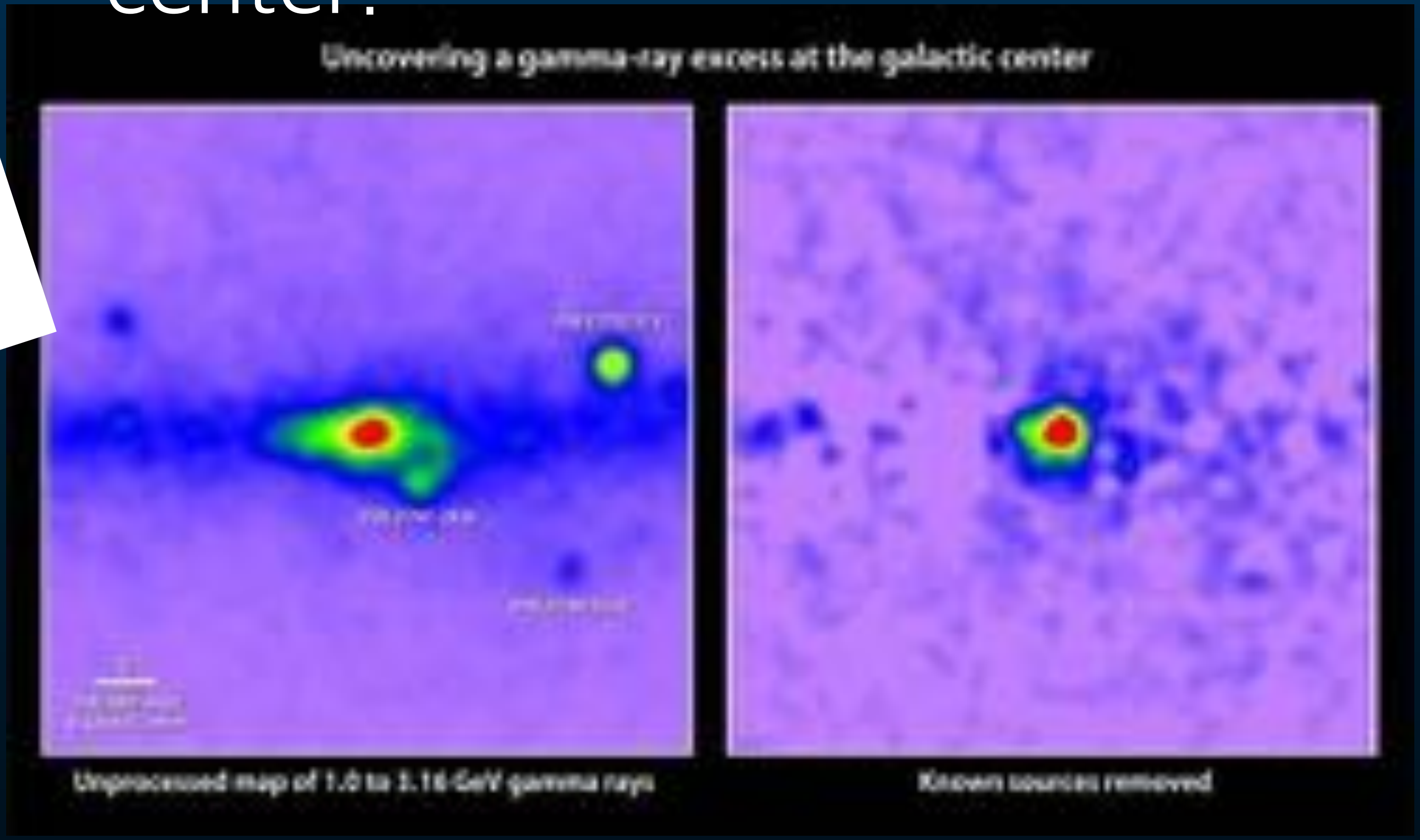


from keV DM?
Amino DM: J.C.Park, K.Kong, SCP (2014)
Axion-like DM: H.M.Lee, W.Park, SCP (2014)

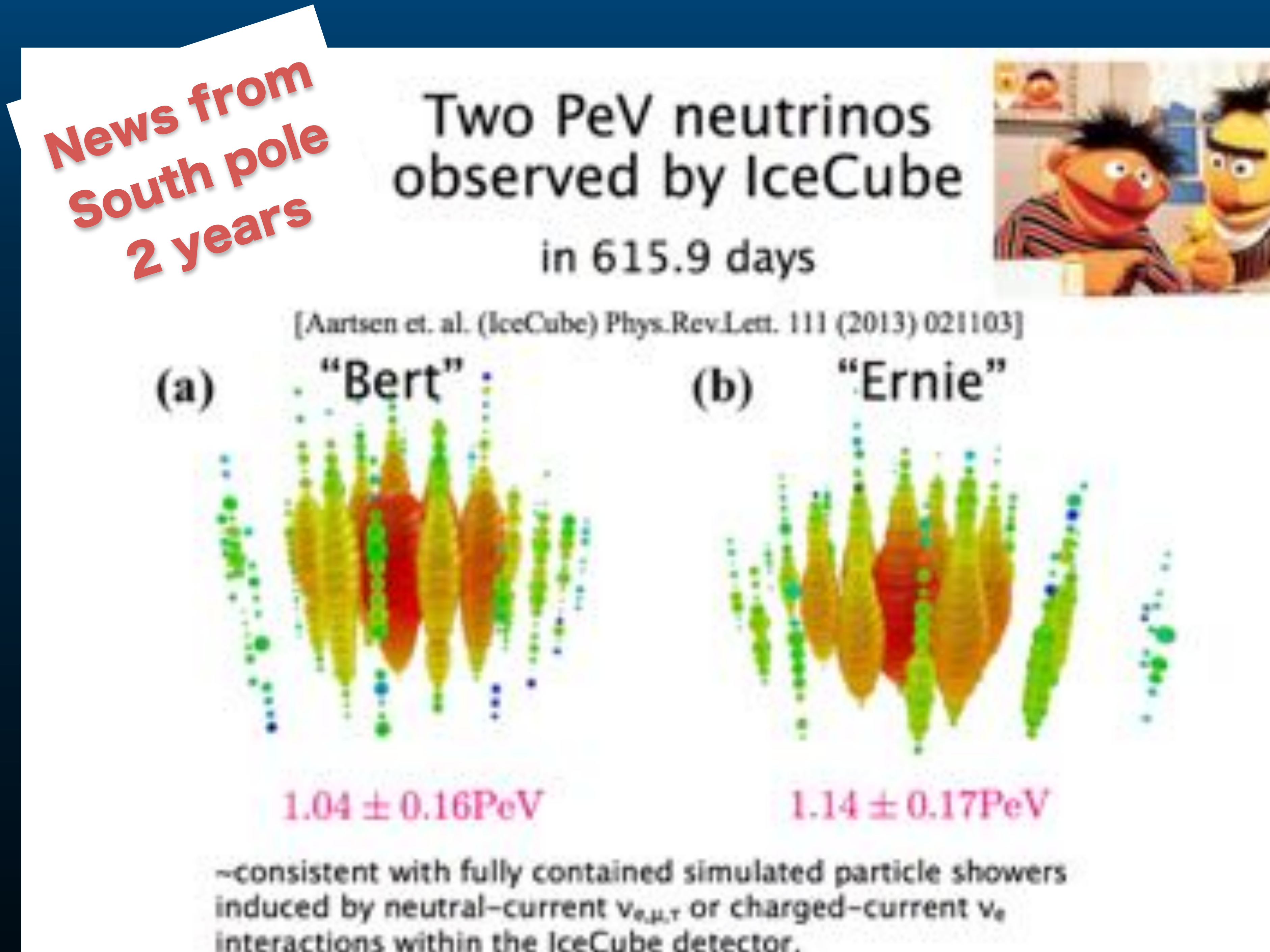
Fermi-LAT gamma-ray excess at "GeV" at the Galactic center!

Hooper, Linden 2014

Hot topic of the season

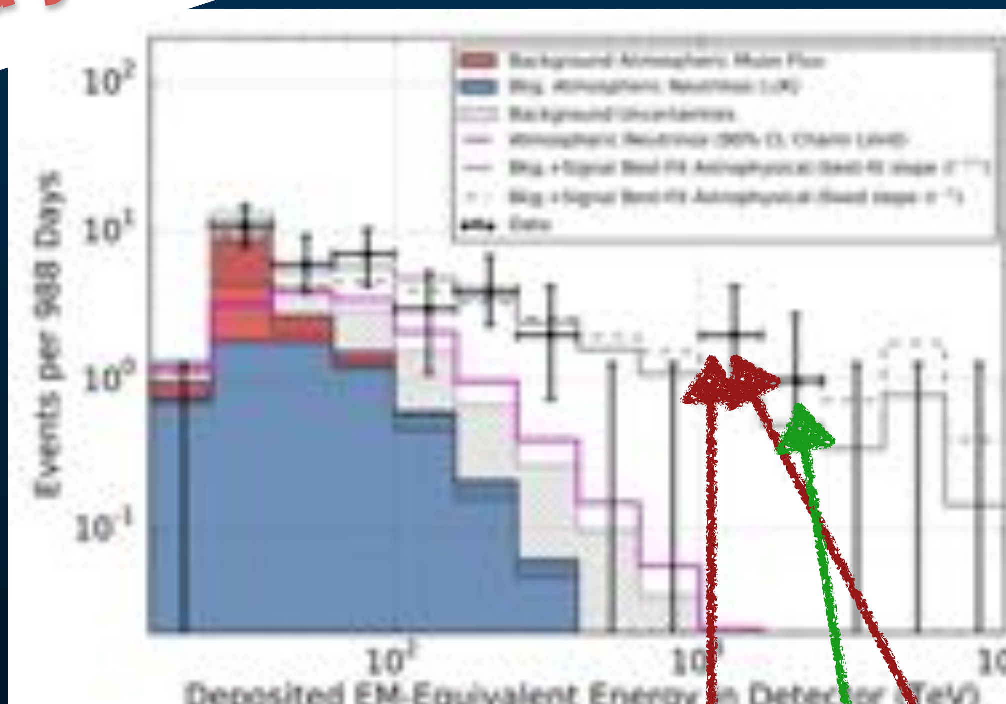


PeV Dark Matter??

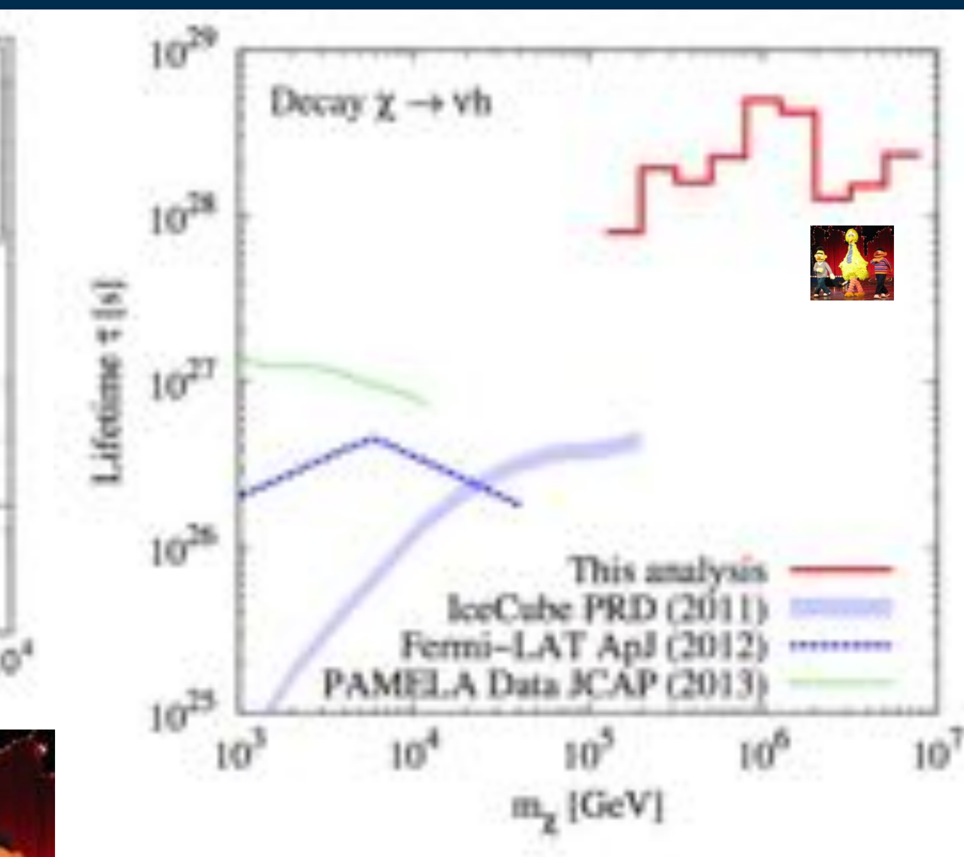


News from South pole 3rd year

IceCube PeV neutrinos



IceCube 3yr arXiv:1405.530



Rott, Kohri, SCP;1408.4864
to appear in PRL

perspectives

“…in this field, almost everything is already discovered, and all that remains is to fill a few unimportant holes…”

When Philip Jolly met Max Planck in 1878

However, there were hints for ‘NP’

- Blackbody radiation
- Atomic spectra and Periodic table of atoms
- Precession of the orbit of Mercury
- (Hidden) symmetries in Maxwell’s theory
- …
- People knew the phenomena but did not understand underlying physics.

Fifth Solvay conference participants, 1927.

A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. de Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin;

P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr;

I. Langmuir, M. Planck, M. Skłodowska-Curie, H.A. Lorentz, A. Einstein, P. Langevin, Ch.-E. Guye, C.T.R. Wilson, O.W. Richardson

There are hints for ‘NP’ now!

- Dark Matter and Dark Energy, Causality of Universe and inflation (today’s topics)
- The weakness of gravity
- Periodic table of quarks and leptons
- Baryogenesis
- Strong CP problem
- …
- We know all these phenomena for a long time but do not understand the physics behind them

There are a lot more new things out there.

Let's find them!

A. Piccard, E. Henriot, P. Ehrenfest, E. Herzen, Th. de Donder, E. Schrödinger, J.E. Verschaffelt, W. Pauli, W. Heisenberg, R.H. Fowler, L. Brillouin;

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I. Langmuir, M. Planck, M. Skłodowska-Curie, H.A. Lorentz, A. Einstein, P. Langevin, Ch.-E. Guye, C.T.R. Wilson, O.W. Richardson

Thank you!

노벨상 2015 ?

- bottom (1977), top (1995), tau neutrino (2000) discoveries ?
- Cosmological inflation Guth, Starobinski, Albrecht, Sato, Linde (1980-1981) ?
- Dark matter by V. Rubin (1970s) ?
- Congratulations to **Bjorken, Altarelli, Dokshitzer, Lipatov, Parisi** for the prestigious EPS High Energy Physics prize !

Next we consider a 6-plet model, another interesting model of *CP*-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{weak}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \tag{13}$$

Then, we have *CP*-violating effects through the interference among these different current components. An interesting feature of this model is that the *CP*-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

Weinberg's model. However, other schemes of underlying gauge groups and/or scalar fields are possible. Georgi and Glashow's model[4] is one o
can easily see that *CP*-violation is incorporated into their model with
ing any other fields than (many) new fields which they have introd

Kobayashi-Maskawa (1972)
Nobel Prize 2008

References

1) S. Weinberg, Phys. Rev. Letters **19** (1967), 1264; **27** (1971), 1688.
2) Z. Maki and T. Maskawa, RIFP-146 (preprint), April 1972.
3) P. W. Higgs, Phys. Letters **12** (1964), 132; **13** (1964), 508.
G. S. Guralnik, C. R. Hagen and T. W. Kibble, Phys. Rev. Letters **13** (1964), 585.
4) H. Georgi and S. L. Glashow, Phys. Rev. Letters **28** (1972), 1494.