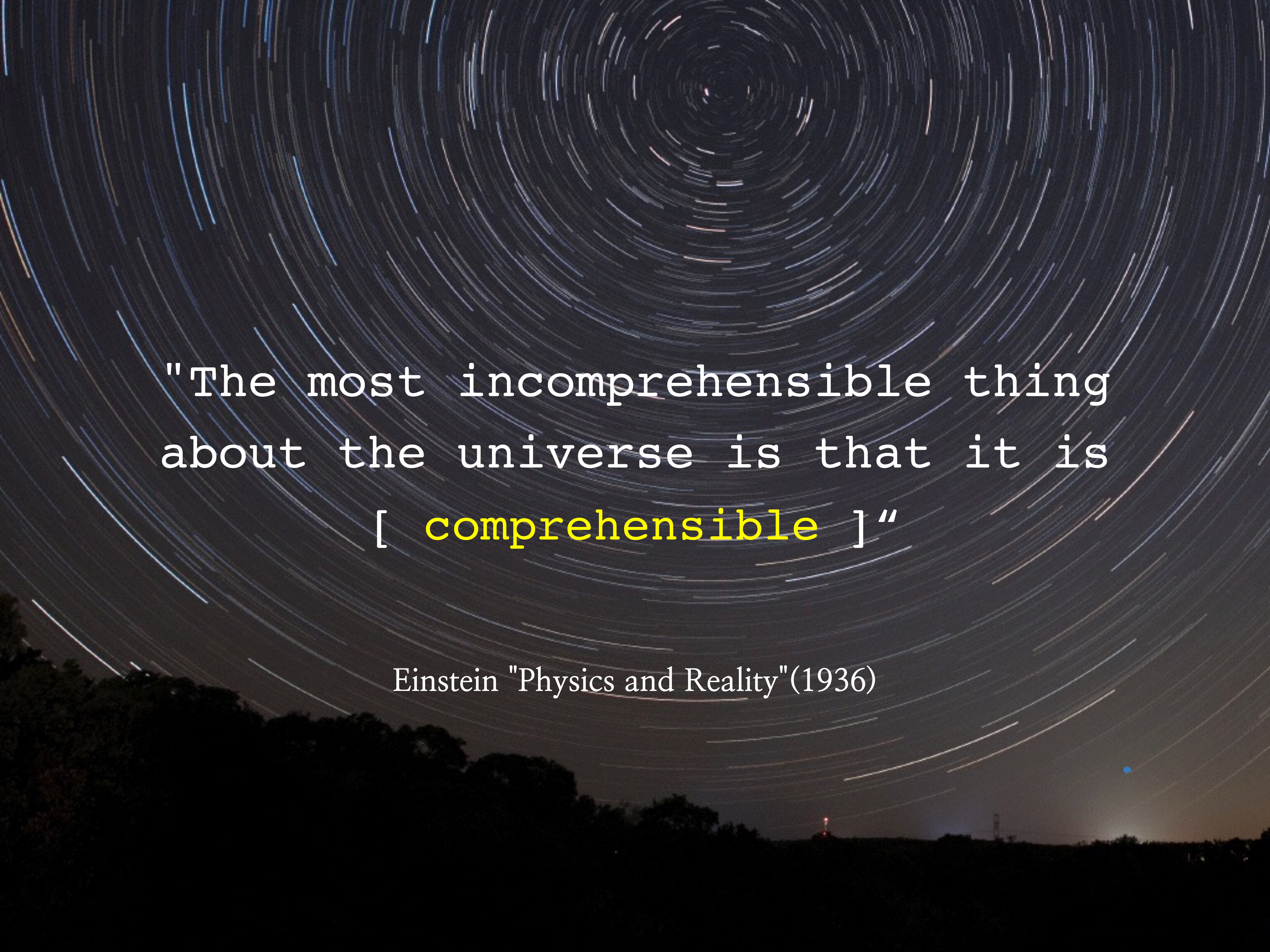
New messages from the sky

on physics beyond the standard theory

s.c.park

Colloquium for Yonsei-BRL workshop
Exotic Phenomena of Gauge Theory @ “토지 문화원” 15.06.06


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

Fundamental questions

- We physicists are brave enough to ask really fundamental questions and try to find the answers
  - Where are we from? Where are we going to?
  - What are we made of?
  - How does the Universe work?
- Let me report you some of notable progresses in those questions and my perspectives.

The Starry Night

is an oil on canvas painting by the Dutch post-impressionist painter Vincent van Gogh. Painted in June, 1889, it depicts the view from the east-facing window of his asylum room at Saint-Rémy-de-Provence, just before sunrise.

What is this?

Moon

Stars

Venus

Hills

Olive Trees

Idealized Village (added)

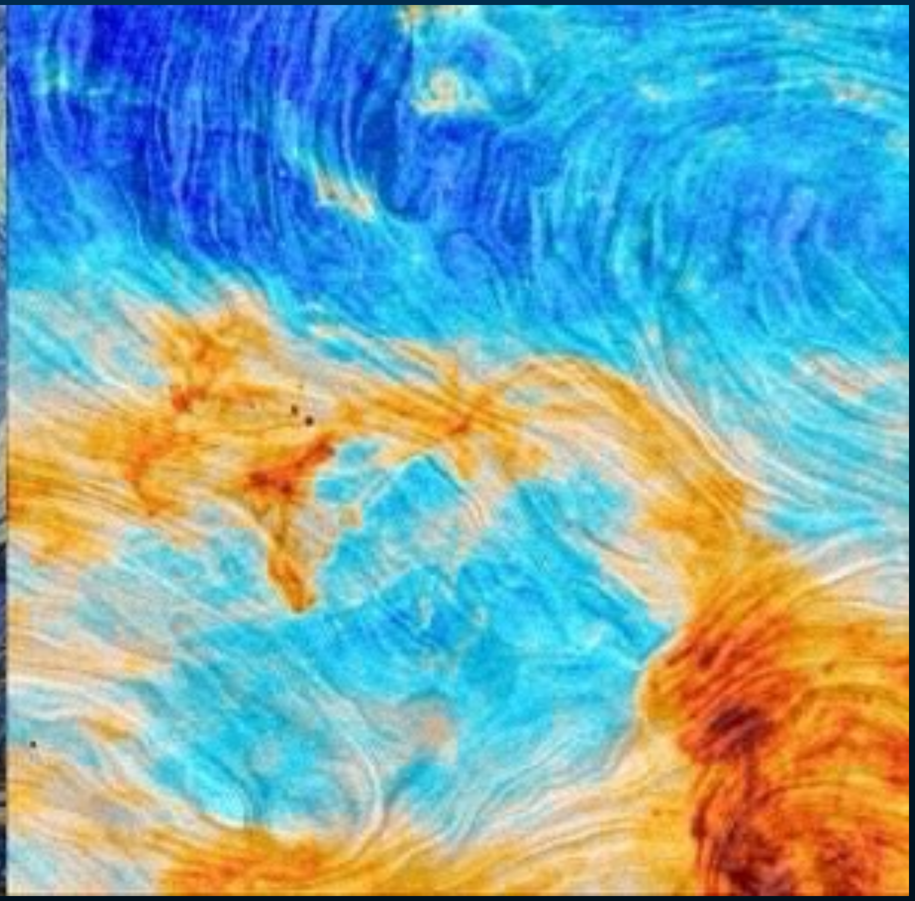
The standard interpretation is whirlpool galaxy.

Sketch of the Whirlpool Galaxy by Lord Rosse in 1845, 44 years before Van Gogh's painting

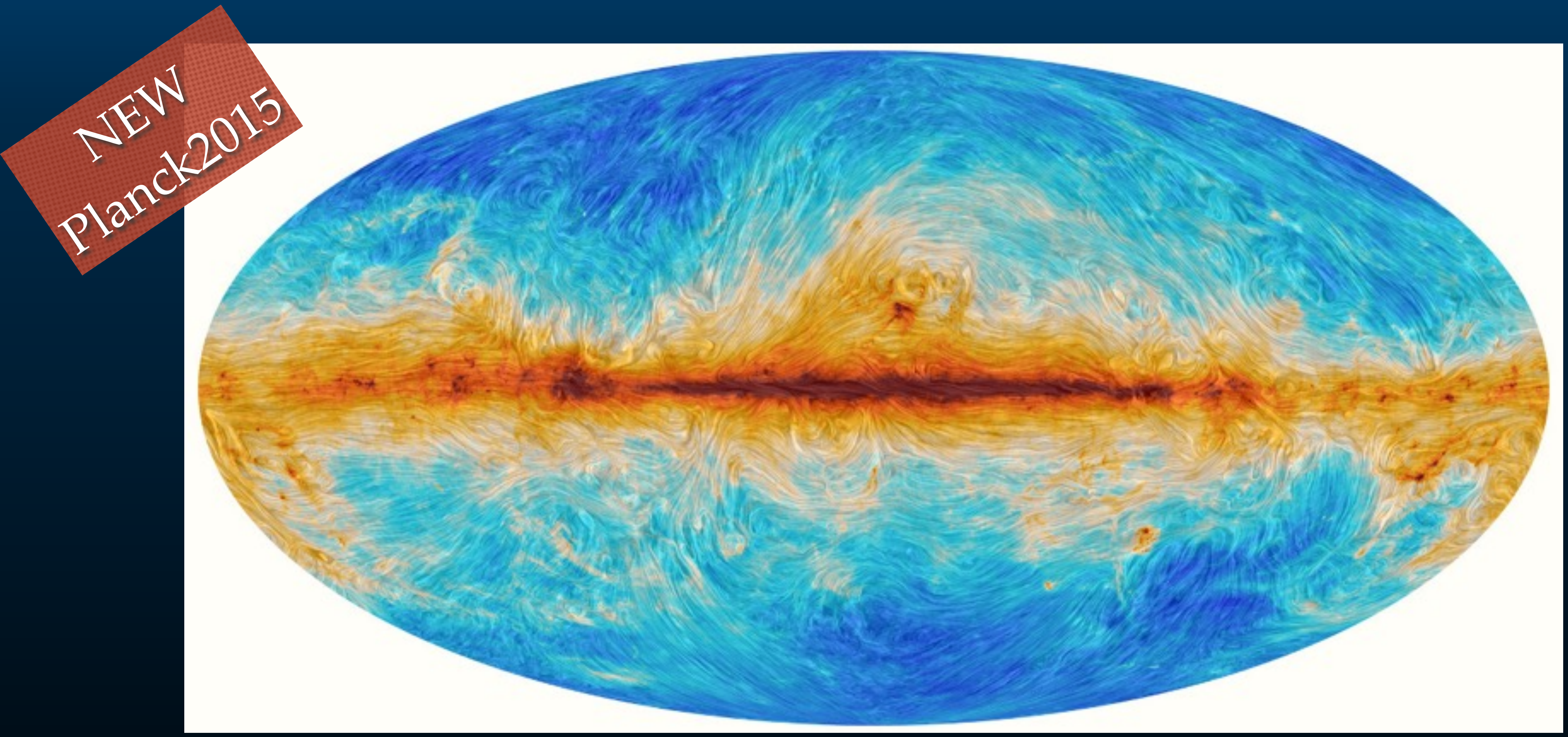
But the scale does not seem quite correct.

Vincent Van Gogh(1889)

Planck (2015)

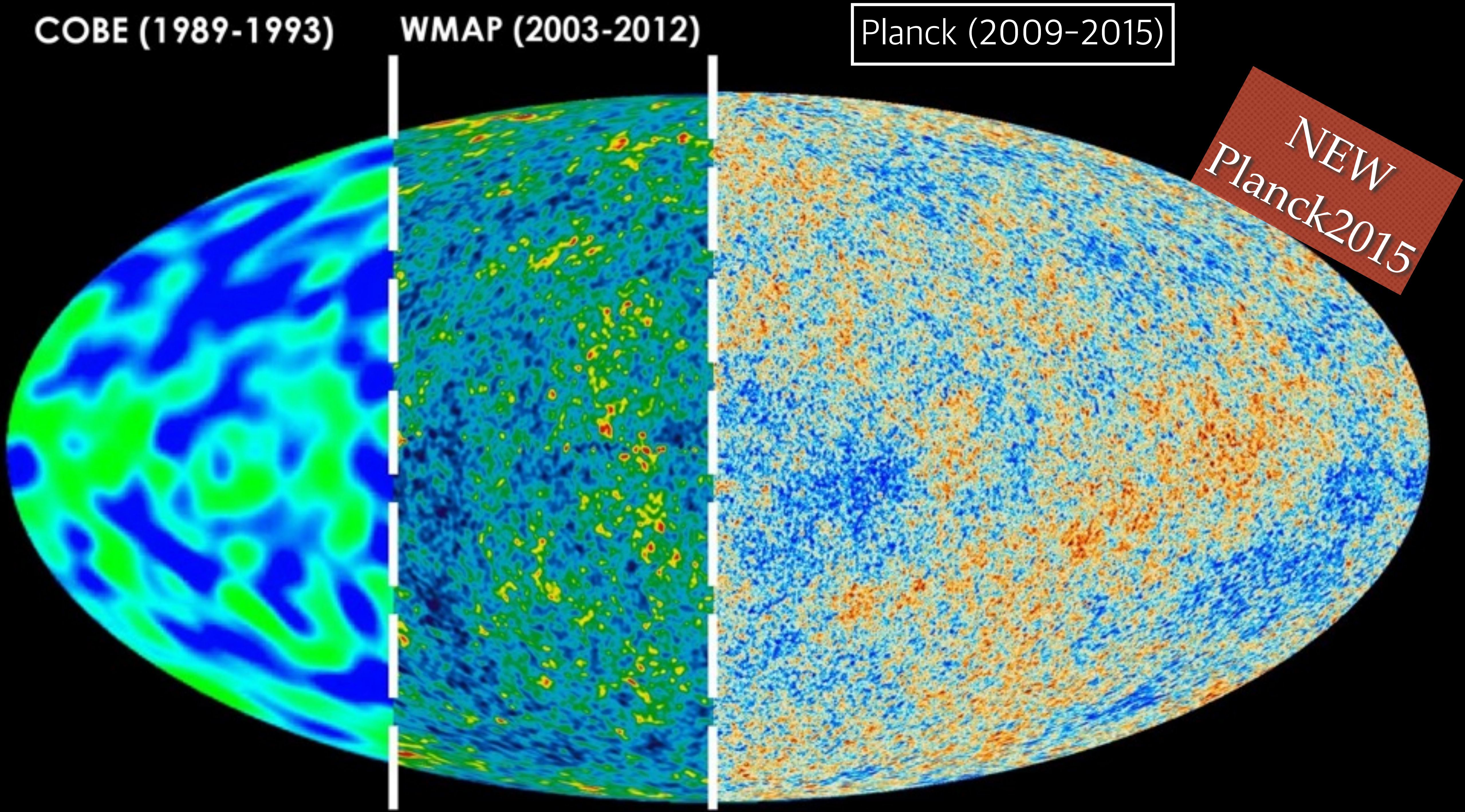


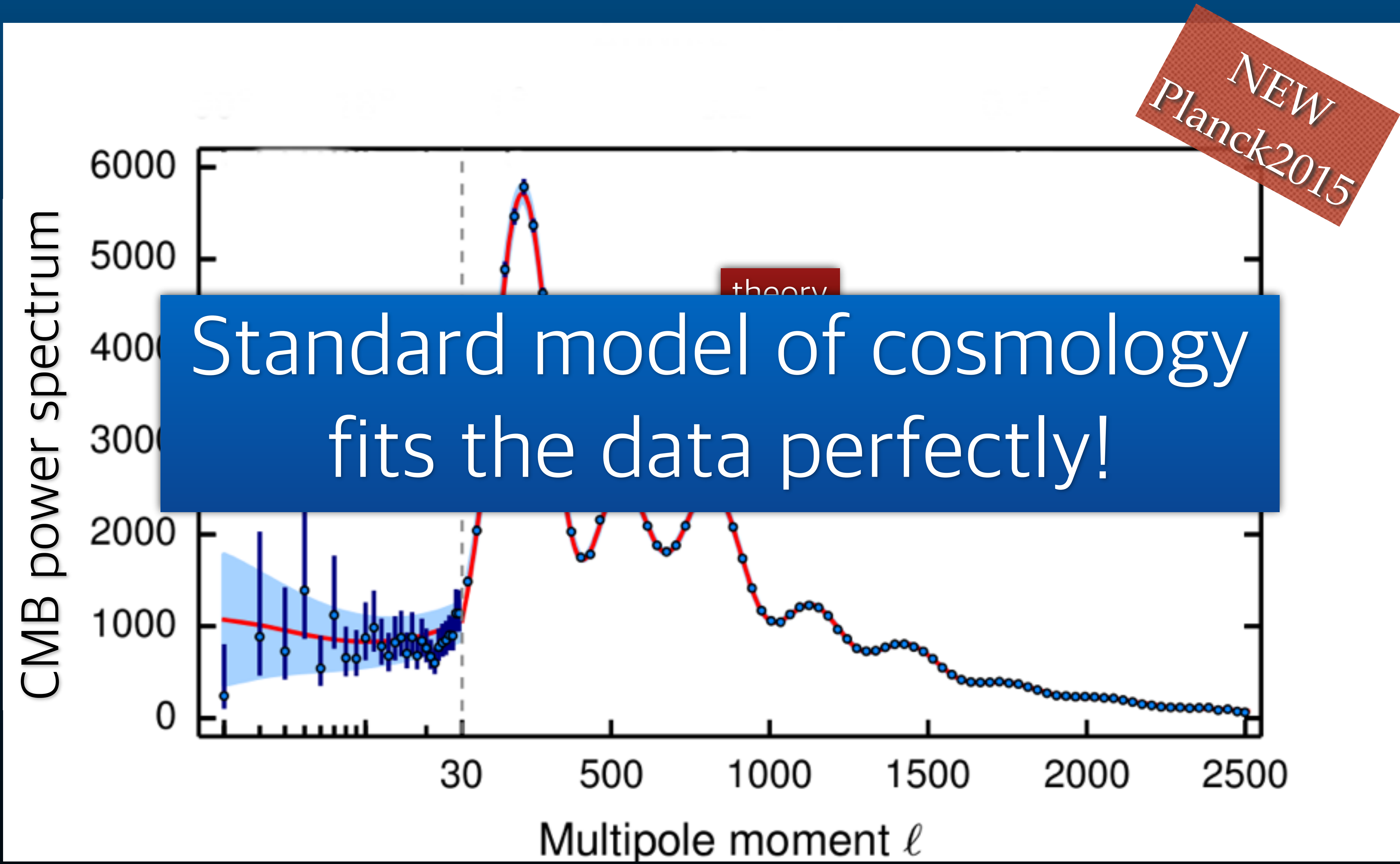
The interaction between interstellar dust in the Milky Way and the structure of our Galaxy's magnetic field



- The dust map will eventually help us to observe the primordial gravitational wave from the inflationary era.

CMBR


COBE (1989-1993)
WMAP (2003-2012)
Planck (2009-2015)
NEW
Planck2015



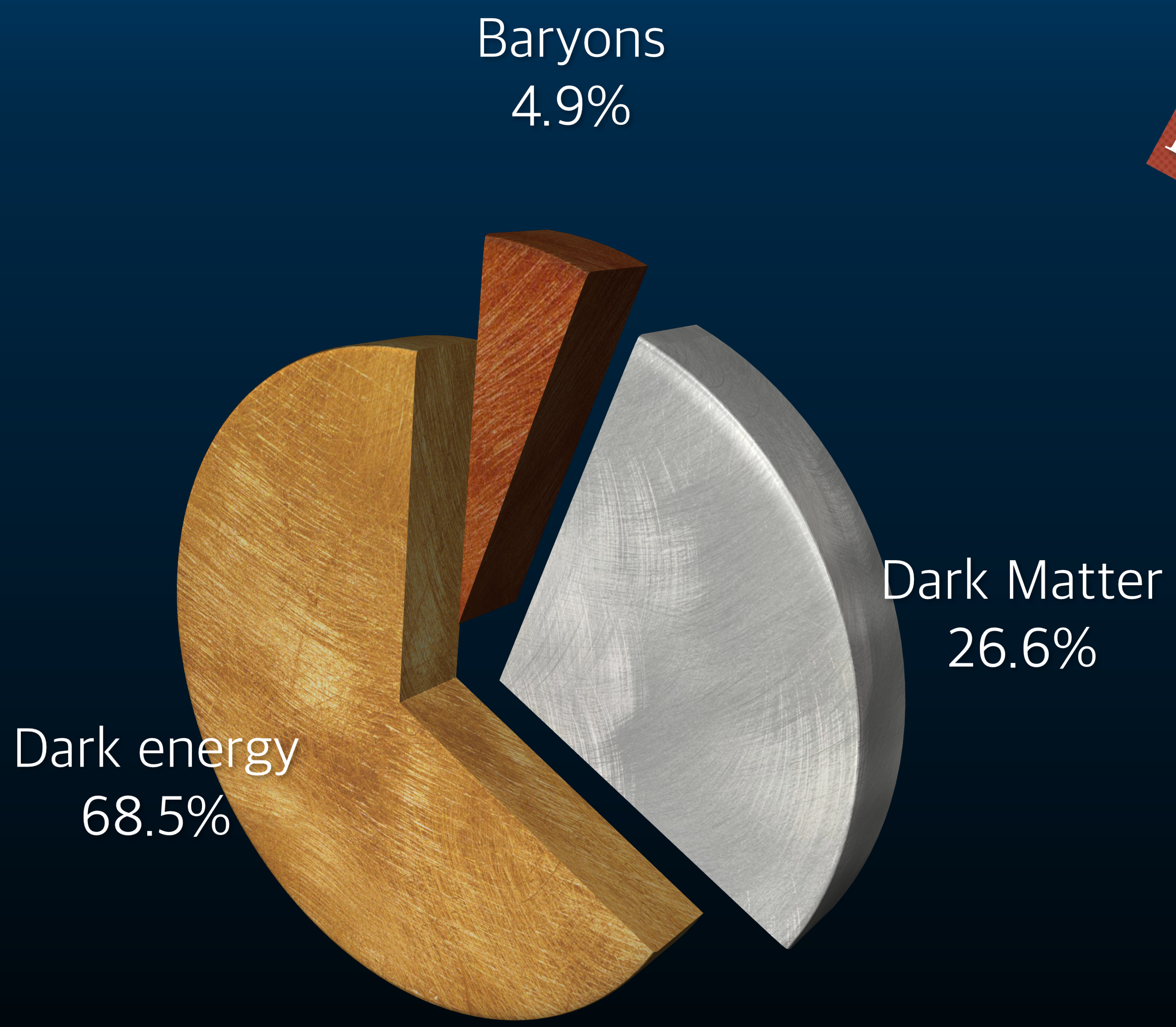
Standard model of cosmology fits the data perfectly!

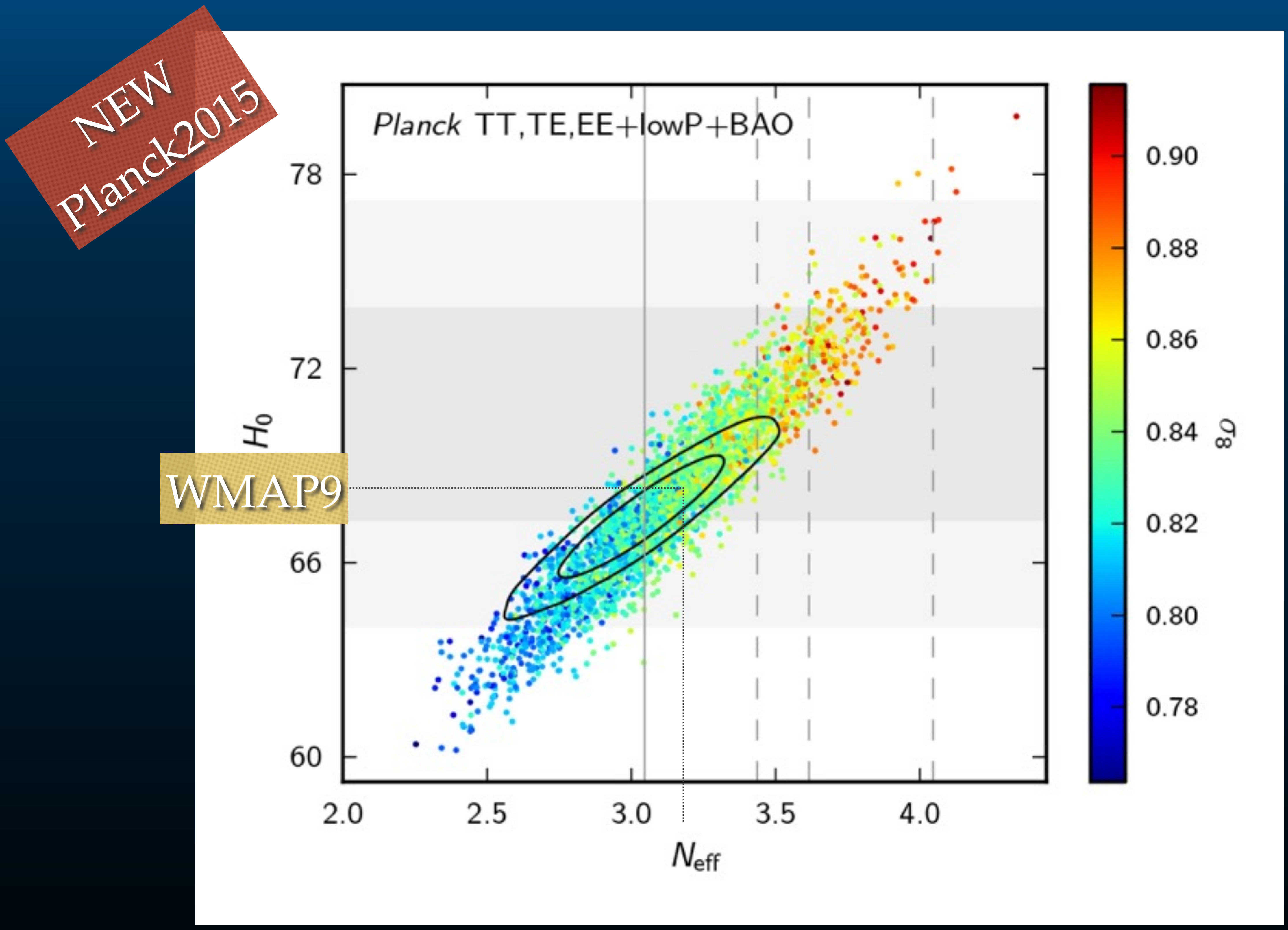
Theory= SM of cosmology

- For the first time in history of science, we now have a well established framework to describe our universe from the (almost) beginning to the end.

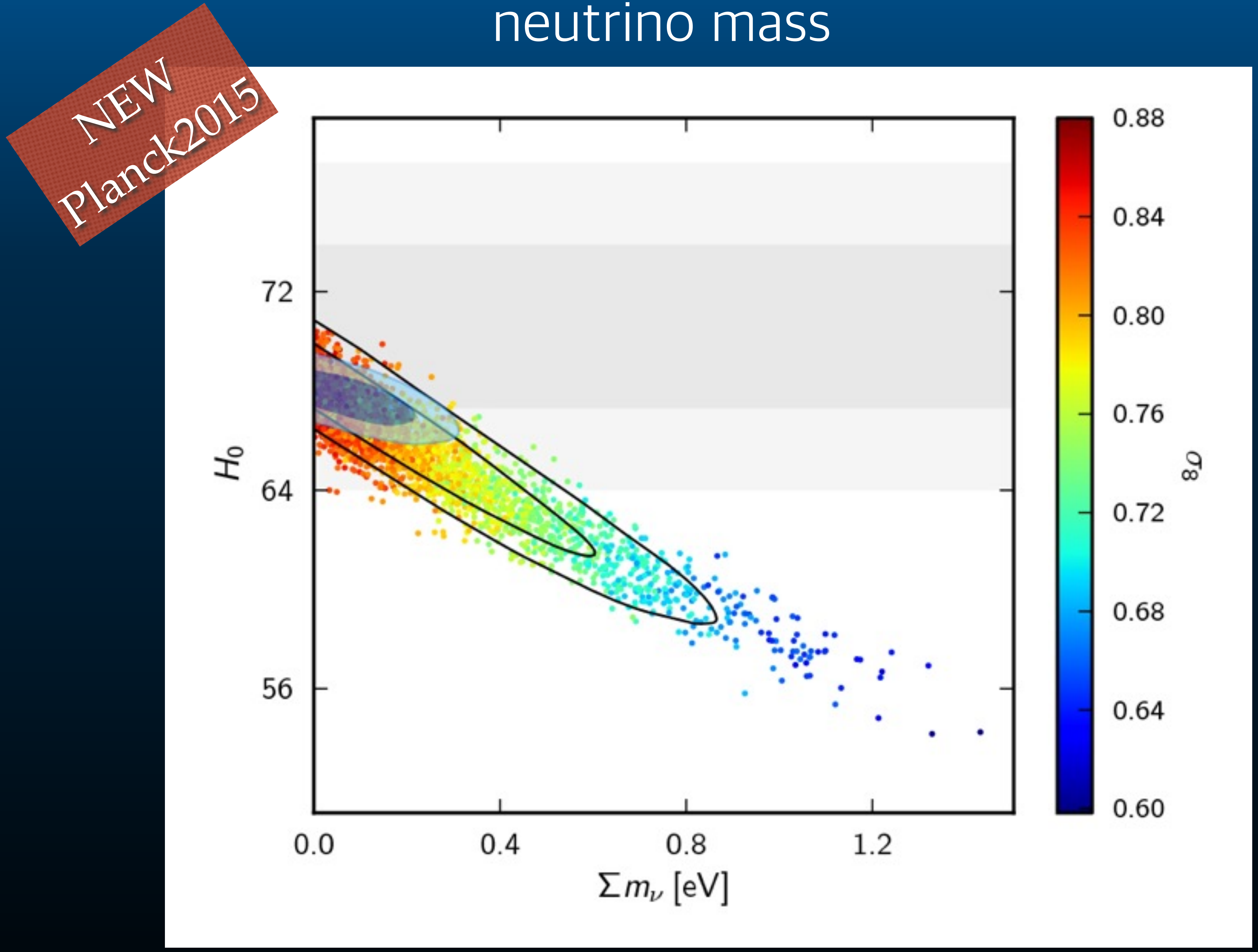
cosmic pie updated

NEW
Planck2015




NEW
Planck2015
WMAP9
Planck TT,TE,EE+lowP+BAO
78
72
66
60
H_0
2.0
2.5
3.0
3.5
4.0
$N_{\rm eff}$
0.90
0.88
0.86
0.84
0.82
0.80
0.78
σ_8

neutrino mass



cosmology vs particle physics

- Cosmology is for large scale physics…
- Why many particle physicists are doing cosmology?

fundamental duality

Time ~ 1/ Energy

Distance ~1/Momentum

Physics in early universe

=Physics in small universe

=Physics in high energy

How early time we can see?

=How small scale can we see?

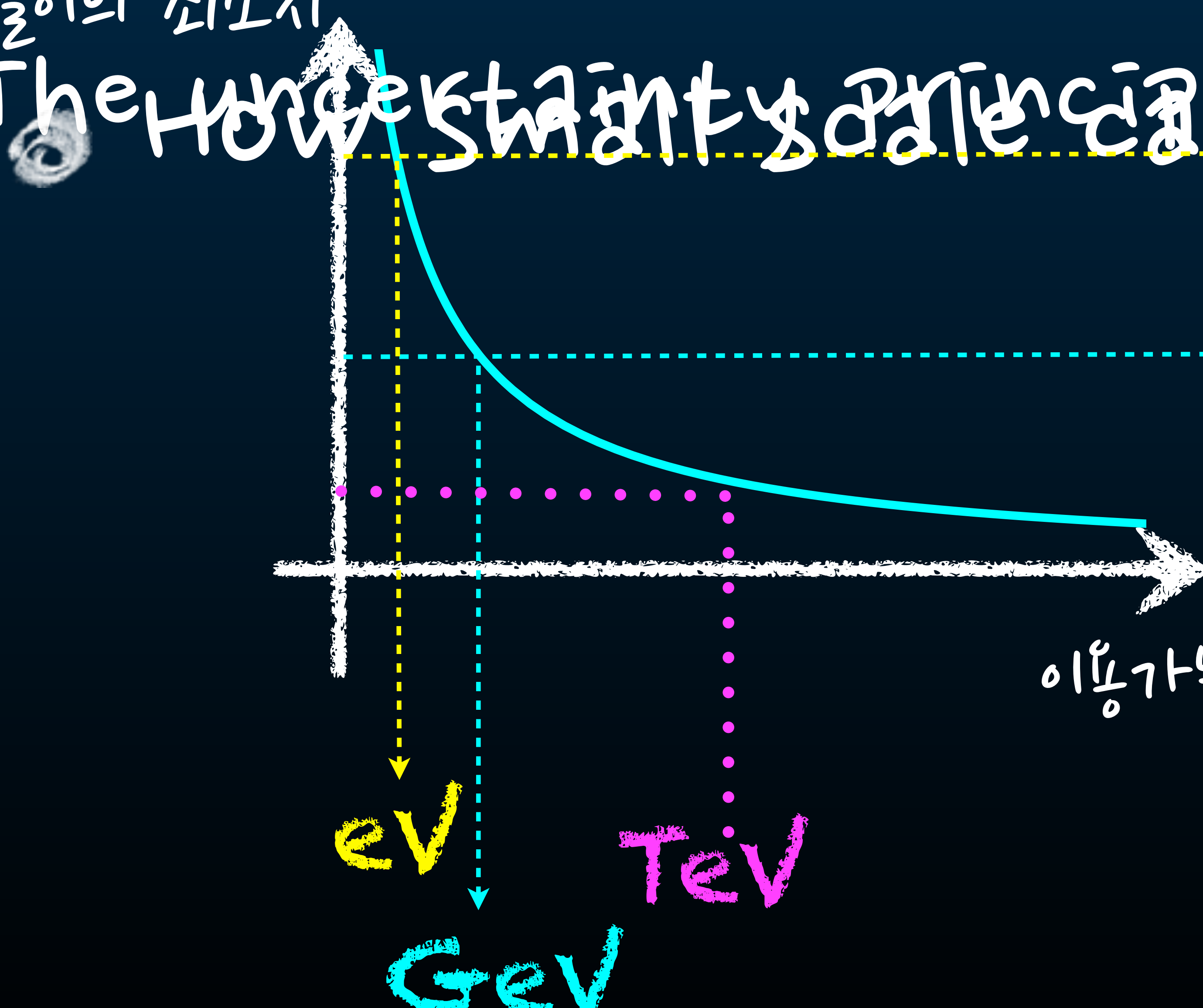
The uncertainty principle

How small scale can we see?

★~1900 reached atomic scale 10^{-8}cm$\approx 1/(\alpha^2 m_e)$

★~1970 reached strong scale 10^{-13}cm$\approx 1/(m\, e^{-2\pi/\alpha_s b_0})$

★~2013 reach weak scale 10^{-17}cm ⟸LHC here!



10^{-17} cm

- The scale first found by E. Fermi in 1933
- The scale where electroweak symmetry breaking takes place
- Excitation of Higgs field (=Higgs particle) can be seen

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 VEV
SU(2)XU(1) is broken down to $U(1)_{em}$

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

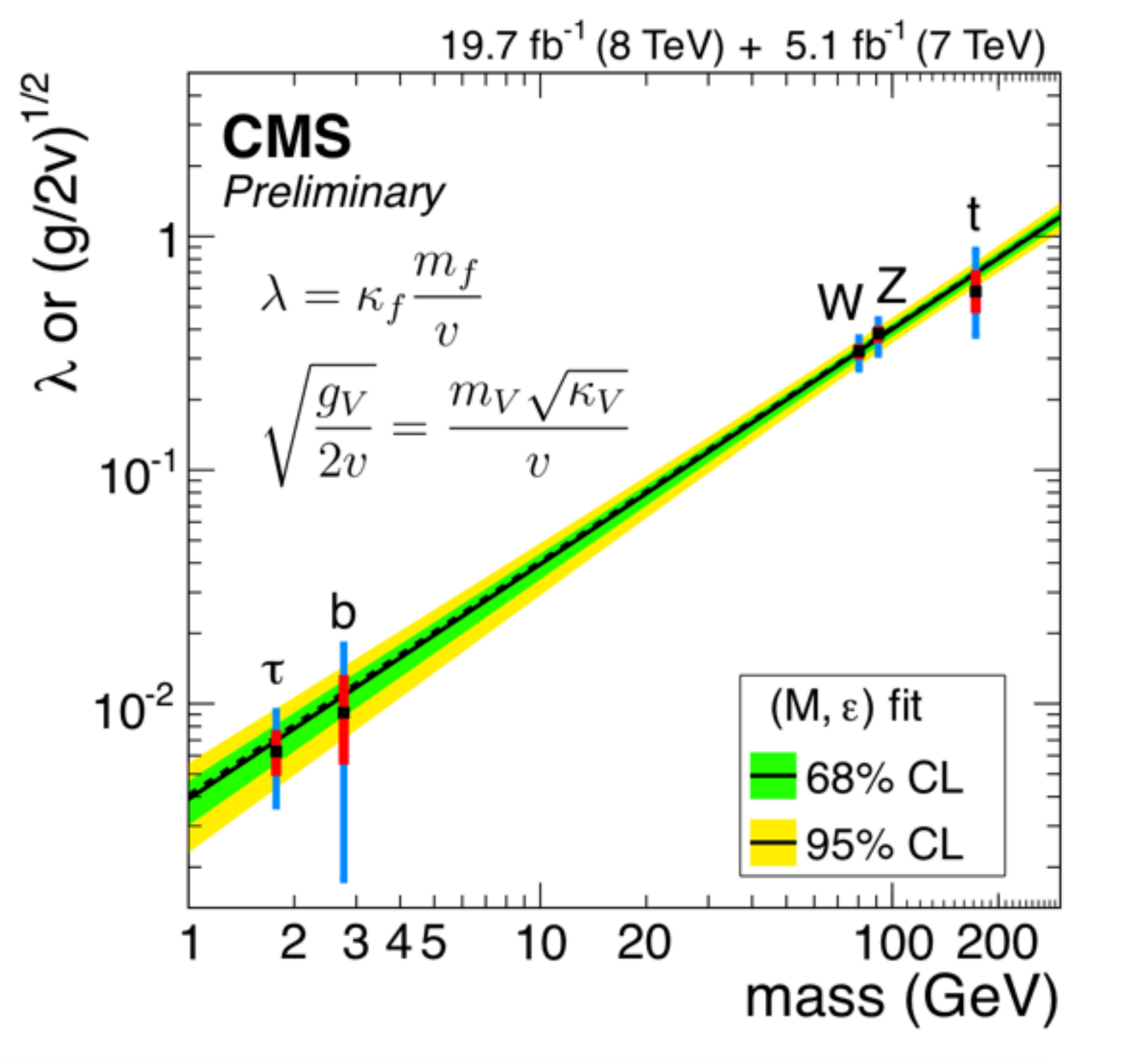
- Requiring Renormalizability, two free parameters in the general renormalizable action

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

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

Now, all the parameters are experimentally measured!

- The observed Higgs is very consistent with the SM



The SM is confirmed!

- all constituents of matter are discovered and their properties have been measured
- all gauge interactions are observed and measured with a great precision
- all parameters are now measured (in total 18 free parameters in the SM)

- This is a great story of success in scientific research.
- In principle, the SM, a renormalizable QFT, could be valid up to very high energy ~Planck energy.
- however, we already know that the SM is not the end of the story.

Hints for BSM from the sky

- Dark matter is 5 times more abundant than what we know in the SM. We want to know what it is. (DM problem)

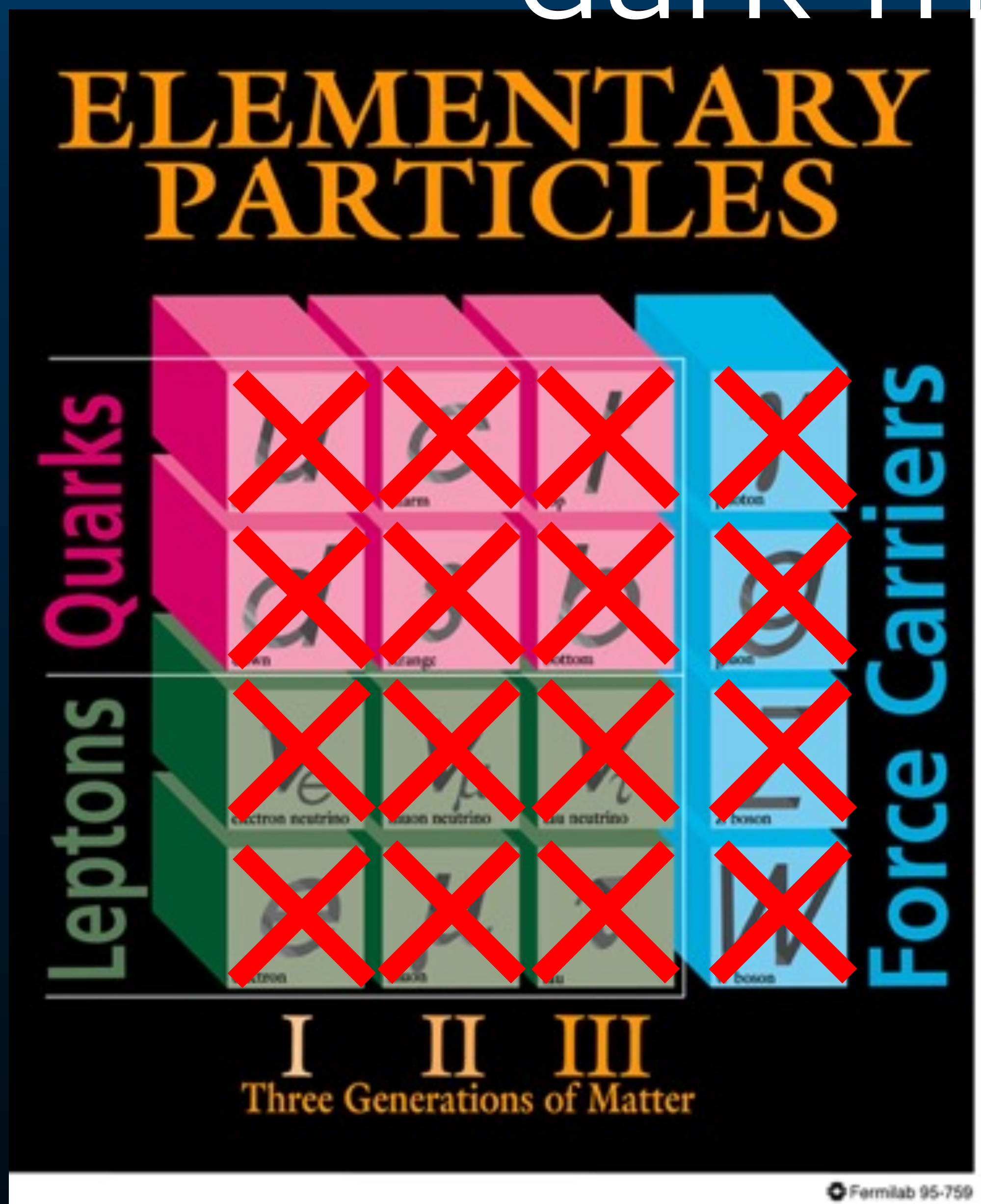
- Dark energy component dominates the total energy budget of universe ~70%. We want to know what it is (Dark energy problem)

- Apparently Universe looks acausal but it shouldn't be. We want to know why. (causality problem)

- more …

New message-#1

dark matter problem



Known DM properties

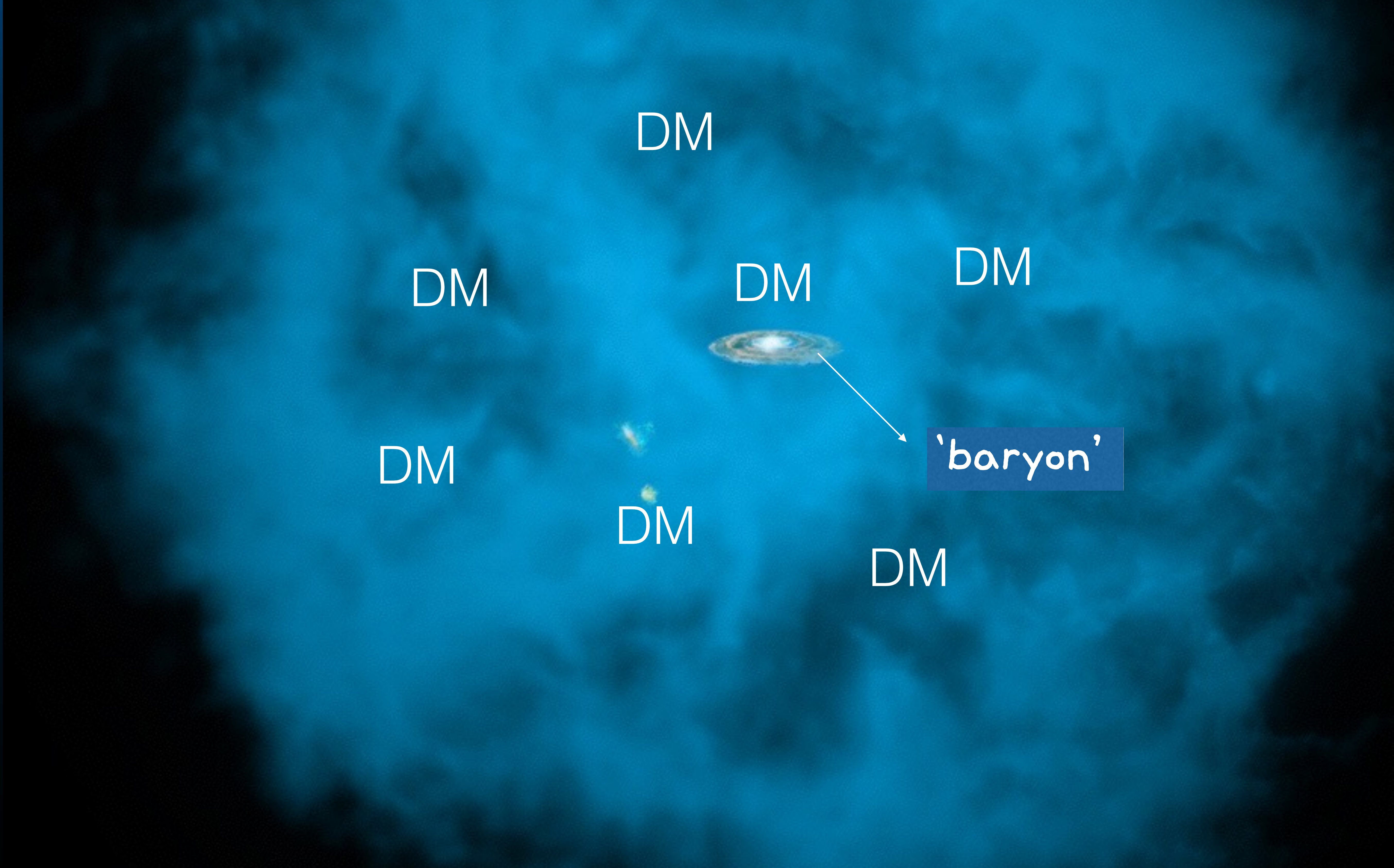
- Gravitationally interacting
- Not short-lived
- Not hot
- Not baryonic

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.

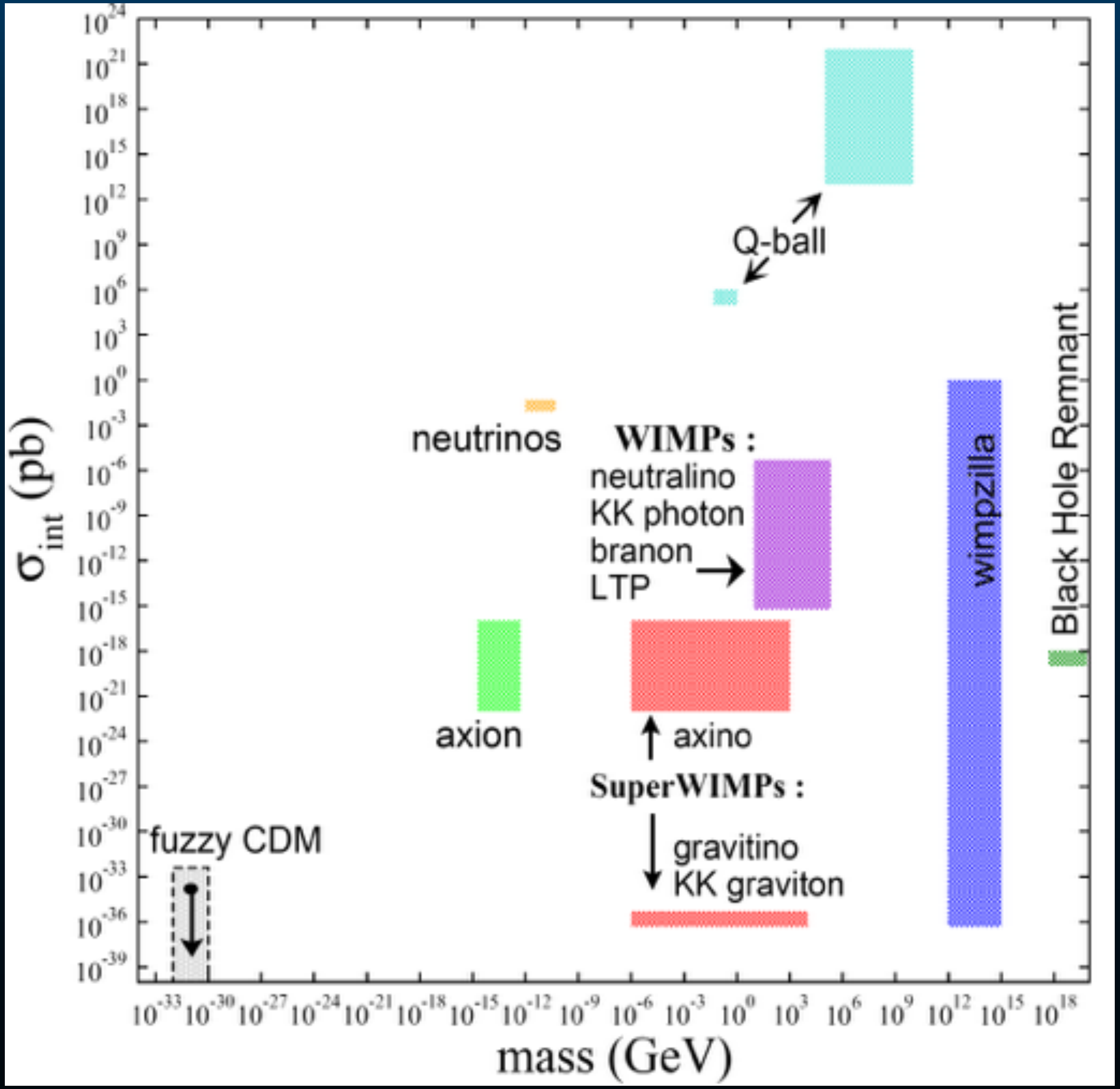
  Hu W, Barkana R and Gruzinov A 2000 *Phys. Rev. Lett.* **85** 1158

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 :-(

DARK MATTER CANDIDATES

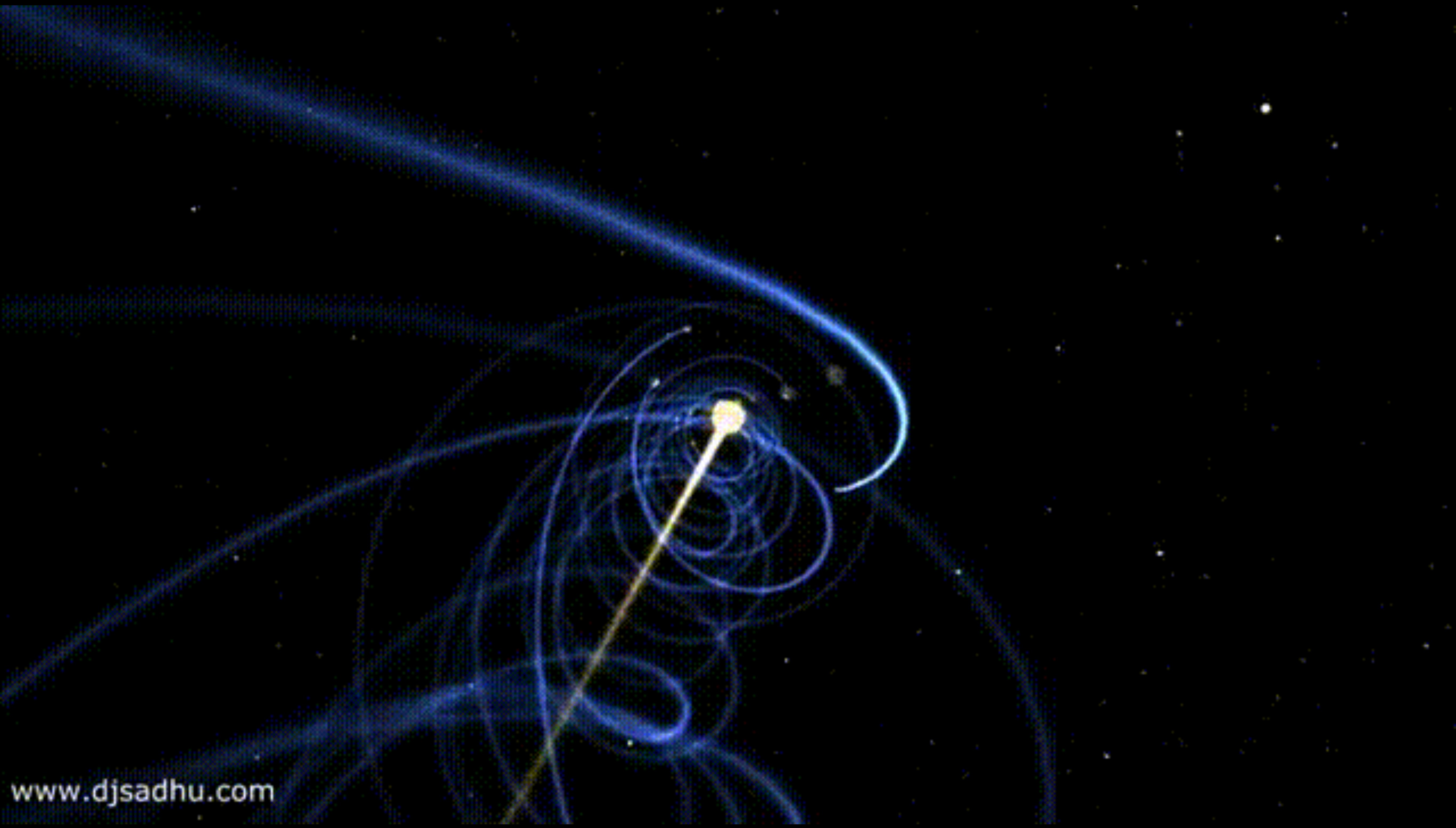
- Masses and interaction strengths span many, many orders of magnitude,
- **WIMP is just one of many candidates**



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

One obvious search strategy

- We are always facing the DM wind
- If the DM wind can interact strongly enough with the SM particles (e.g. quarks), we may observe them!


www.djsadhu.com

from N-body simulation
+ observational inputs

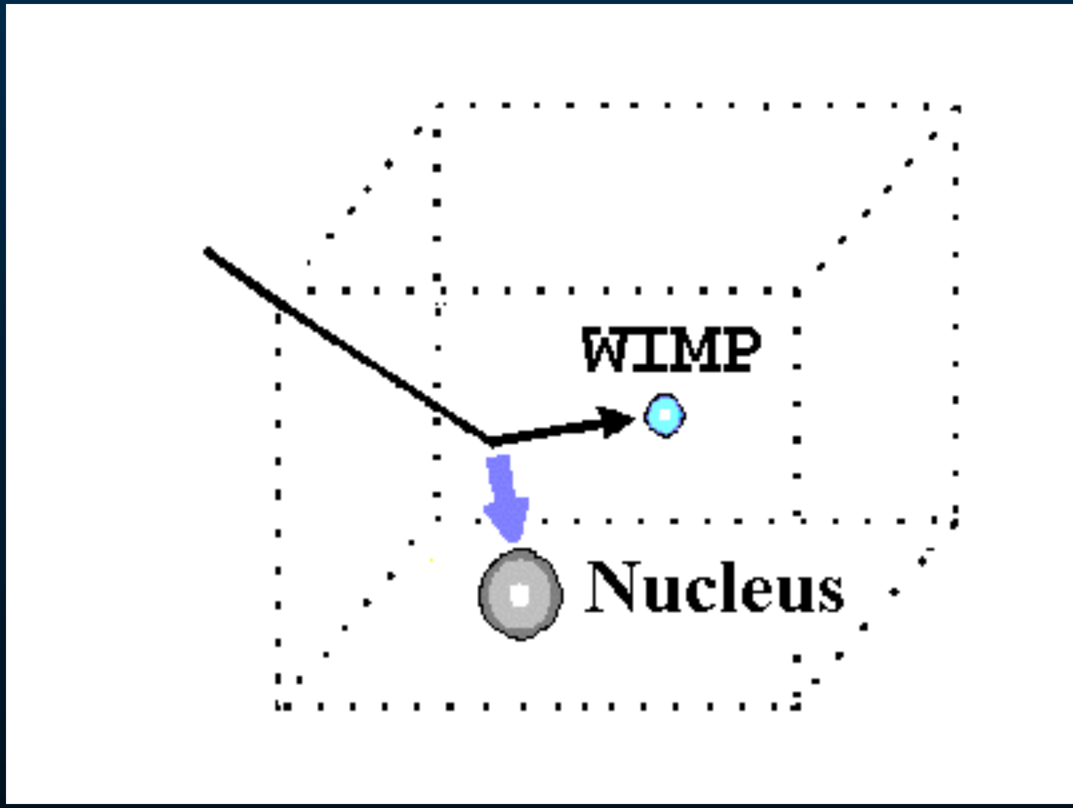
$$\rho_{DM} = 0.3 - 0.4\mathrm{GeV}/\mathrm{cm}^3$$

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

from the motion of solar system
in DM halo

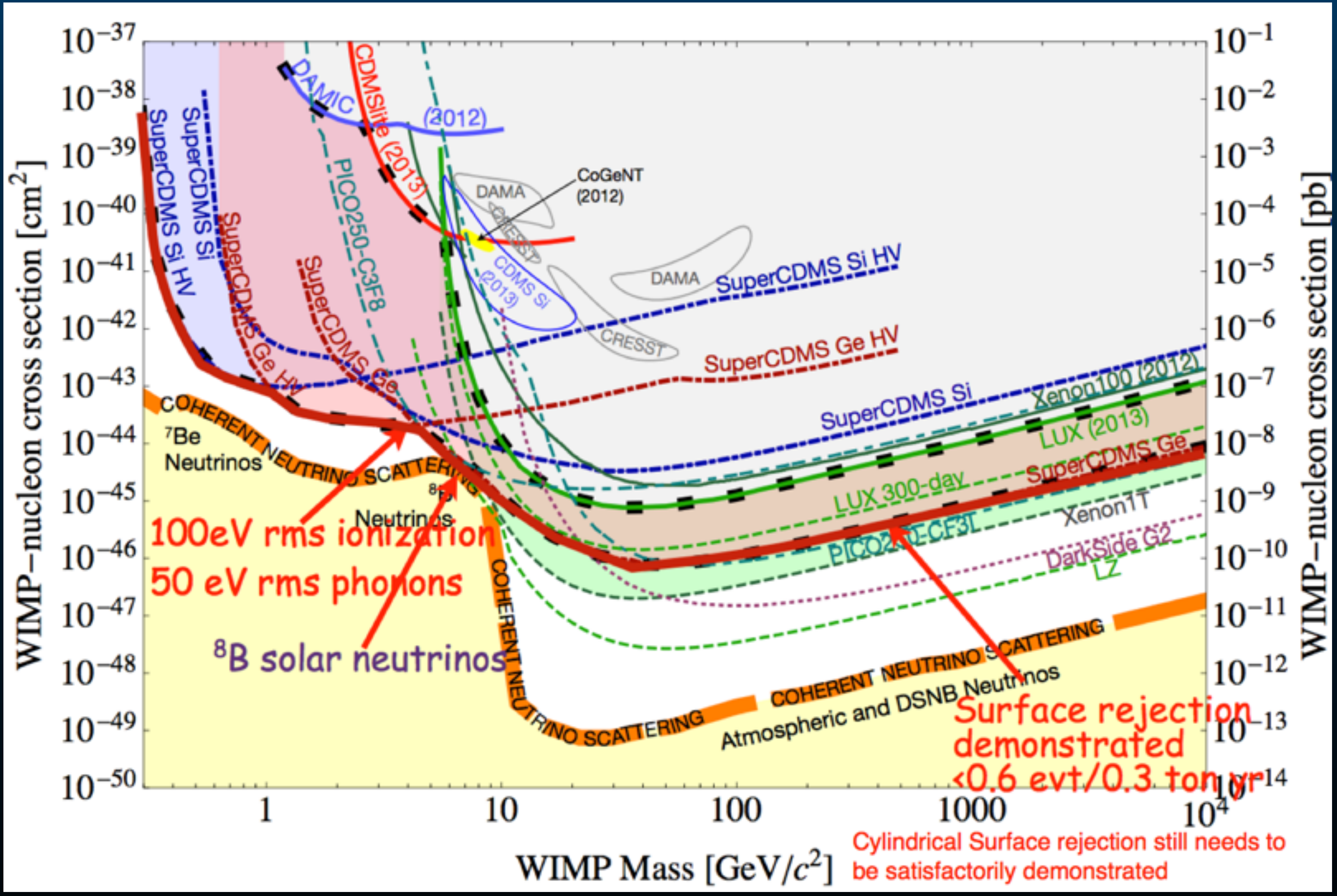
$$j = n_{DM} v = \frac{0.3}{\mathrm{cm}^3} \frac{240km}{\mathrm{s}} \cdot \frac{\mathrm{GeV}}{M_{DM}}$$

$$\approx 7.2 \times 10^7/\mathrm{cm}^2/\mathrm{sec}$$


WIMP
Nucleus

- Like a fisher man, we wait for the moment of DM-N interaction…

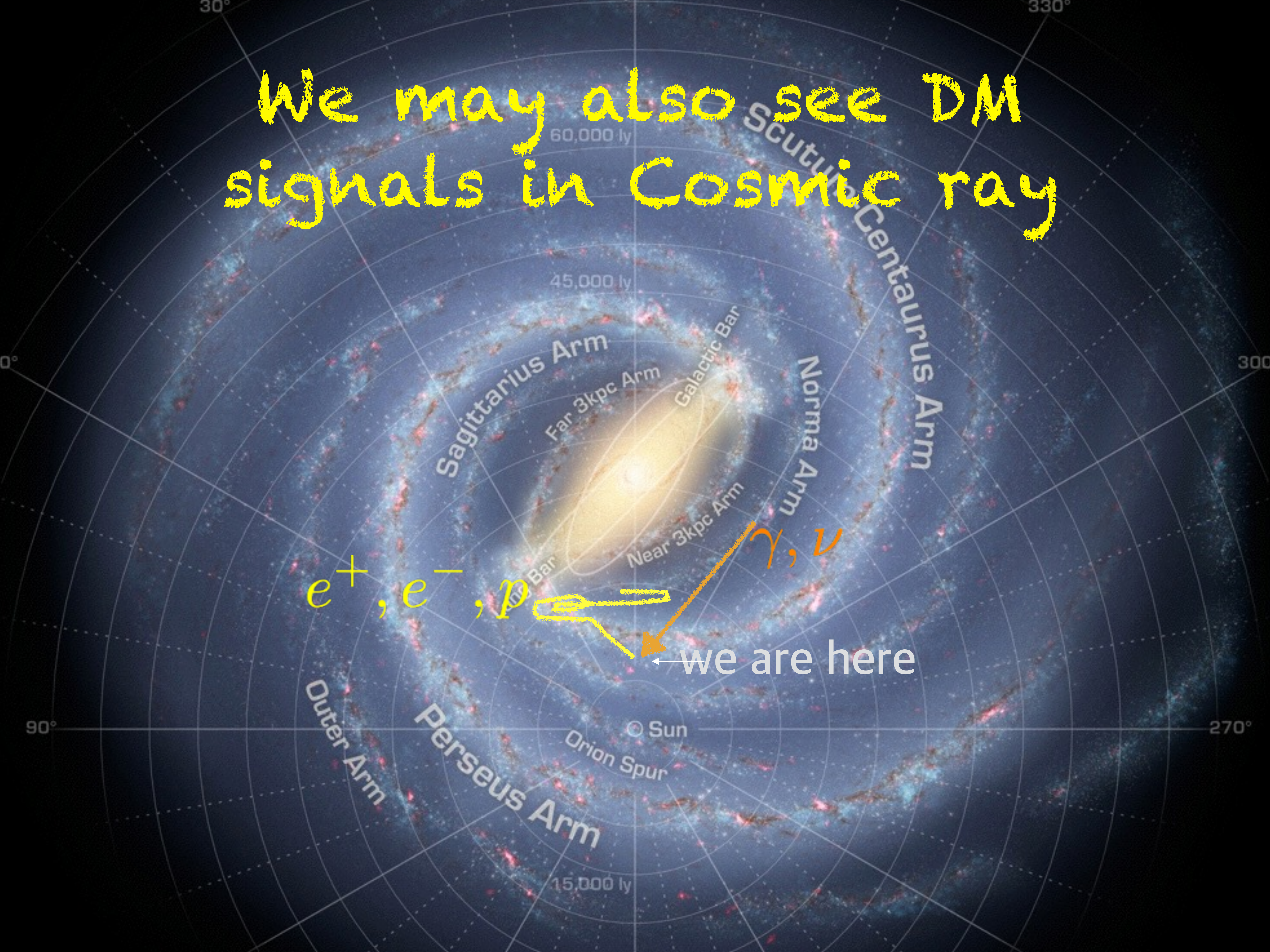
Like an unlucky fisherman, many experimentalists have have failed to find DM-N scattering so far…



difficulties and uncertainties

- 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.

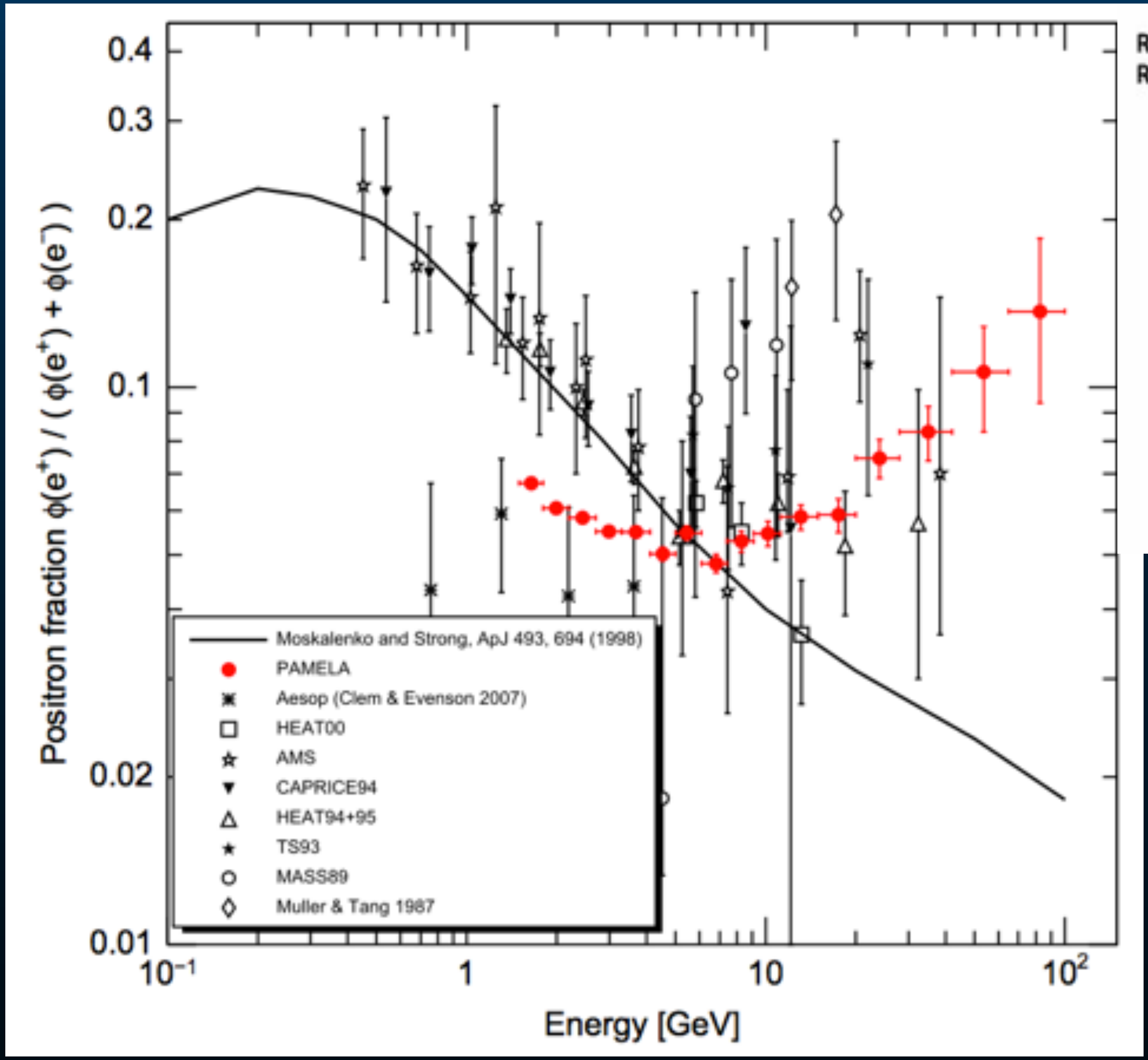
We may also see DM signals in Cosmic ray

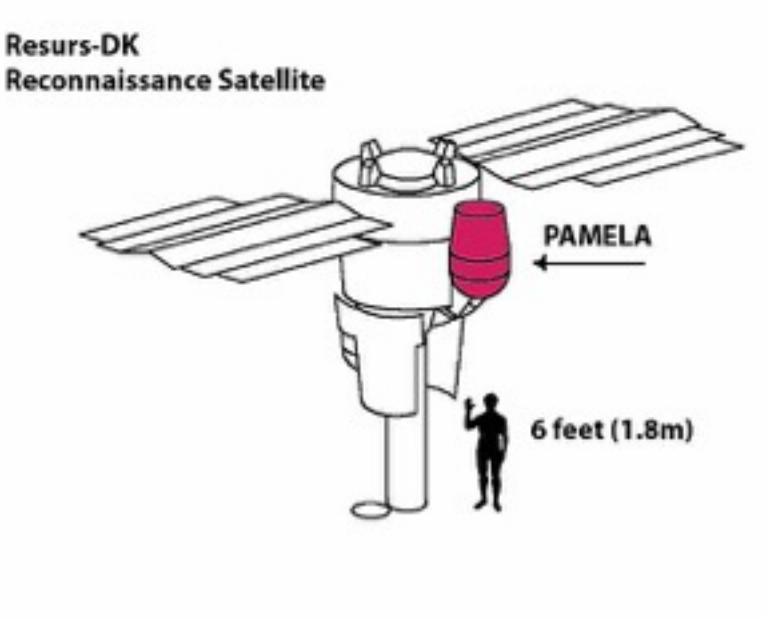


Indirect detection of DM

- 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

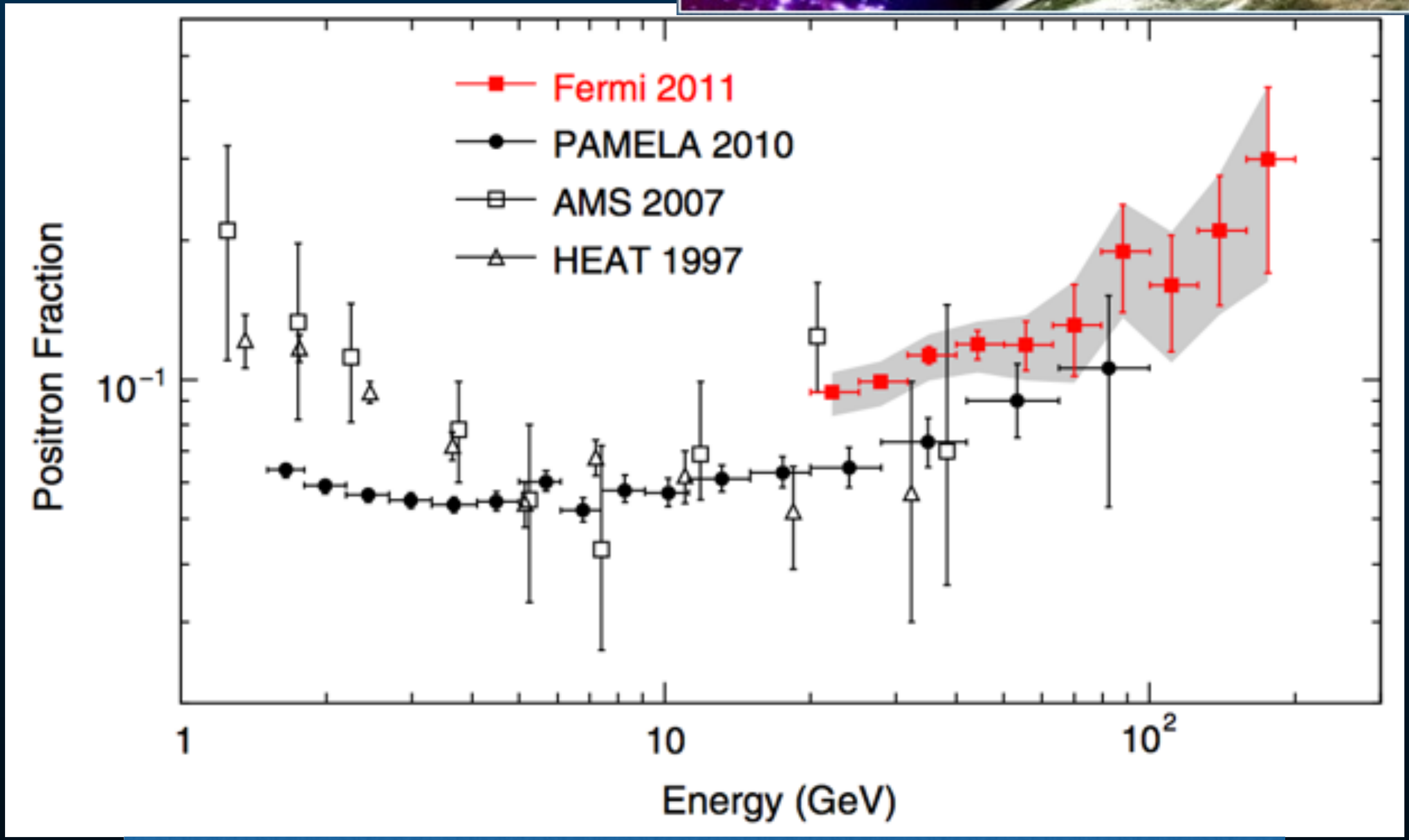
Pamela e+/(e−+E+)





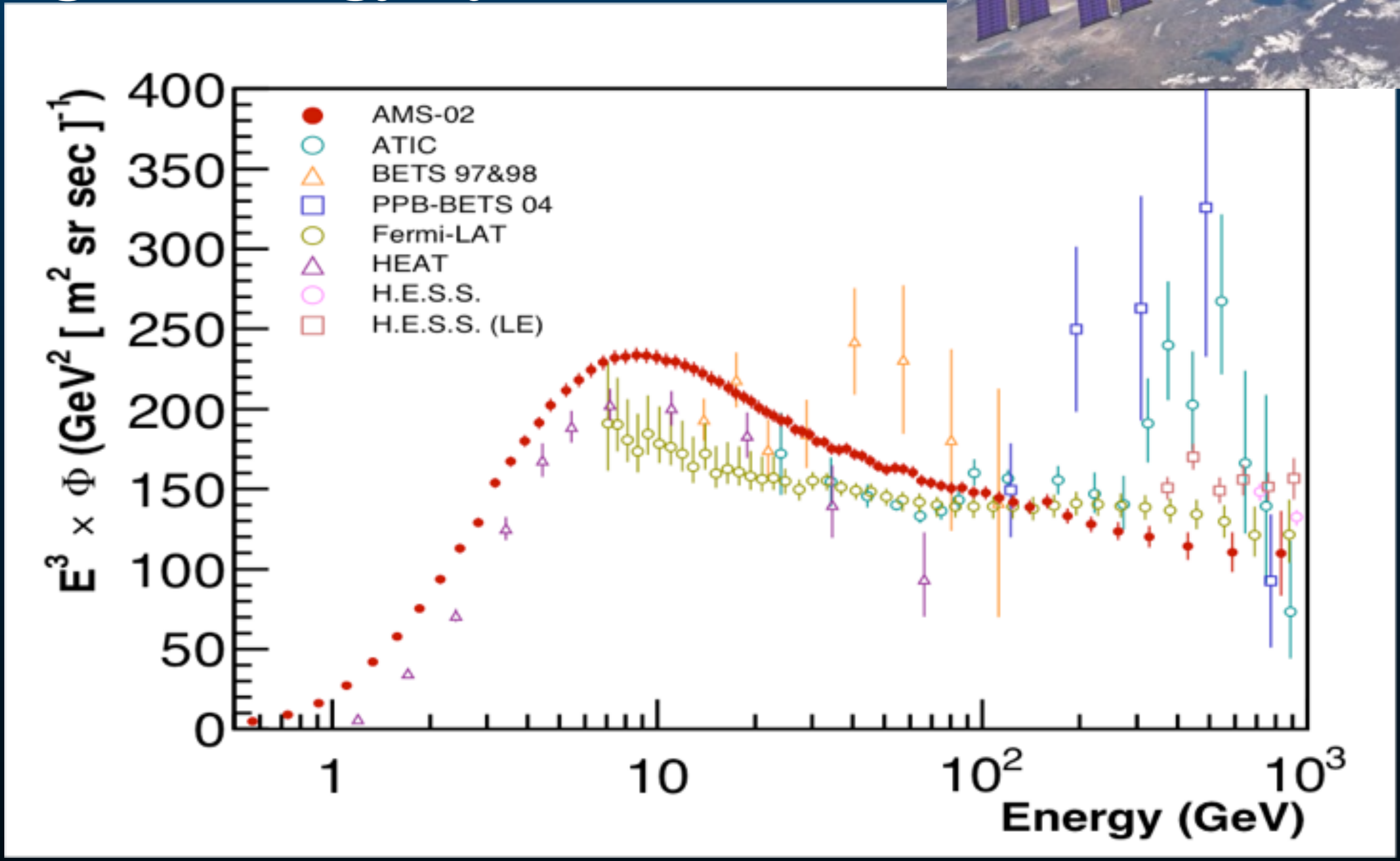
O. Adriarini et. al. [PAMELA] Nature (458) 607, (2009)

Confirmed by Fermi-LAT



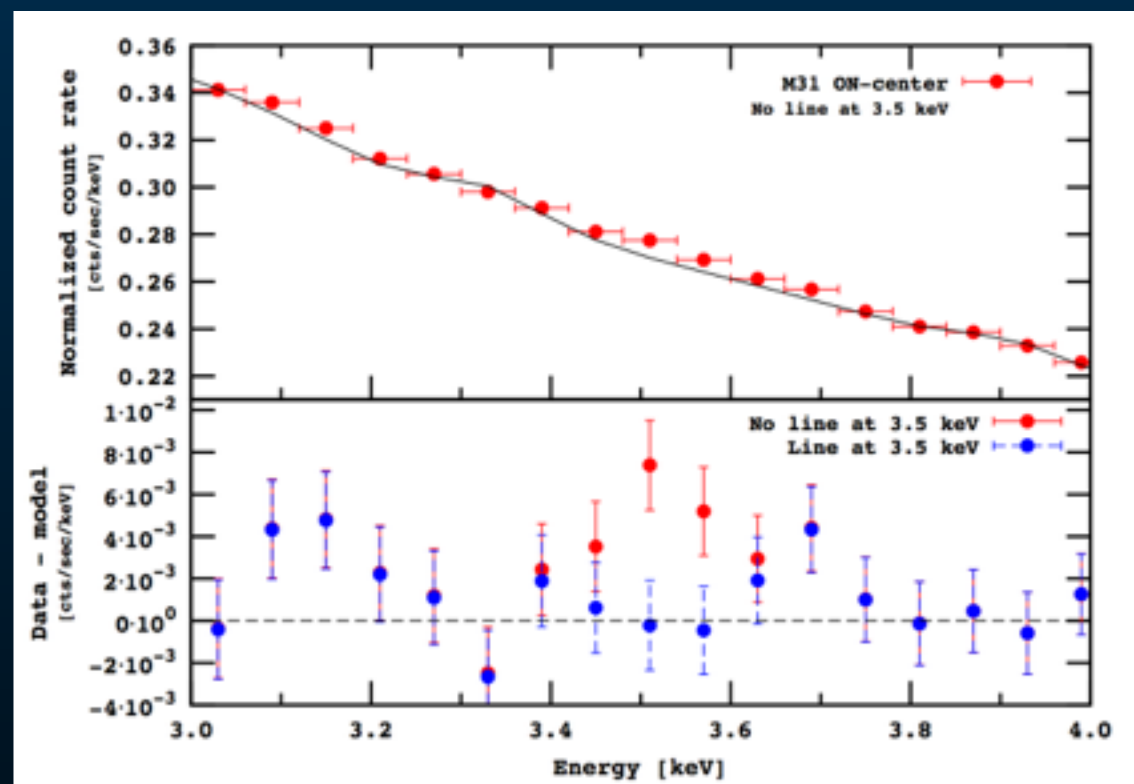
M. Ackermann [Fermi-LAT] PRL 108, 011103 (2012)

Re-confirmed and extended to higher energy by AMS02



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

Hot topic of the season



from keV DM?

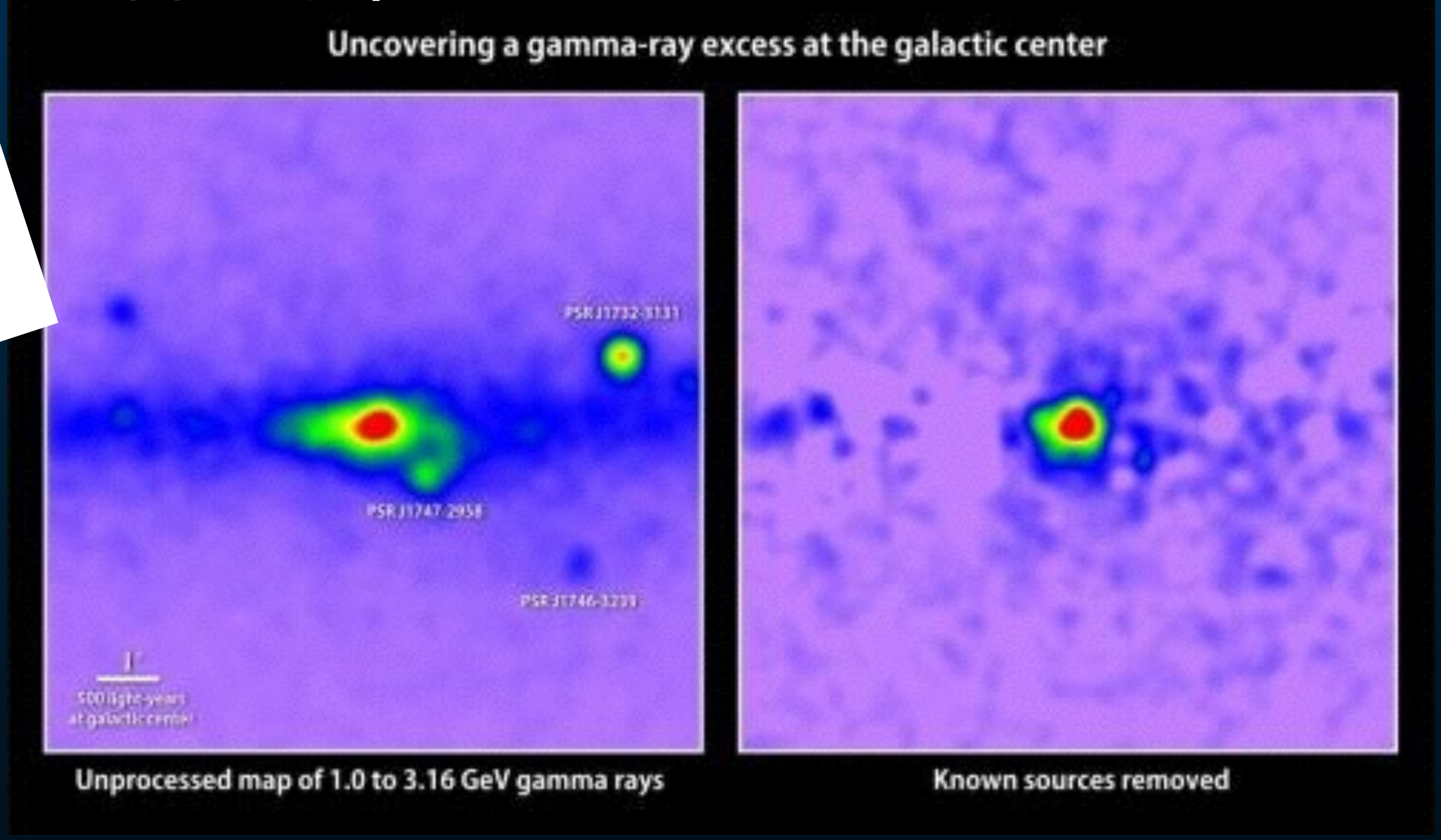
Amino DM: J.C.Park, K.Kong, SCP (2014)

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



J-C. Park, J. Kim, SCP (2015)

PeV Dark Matter??

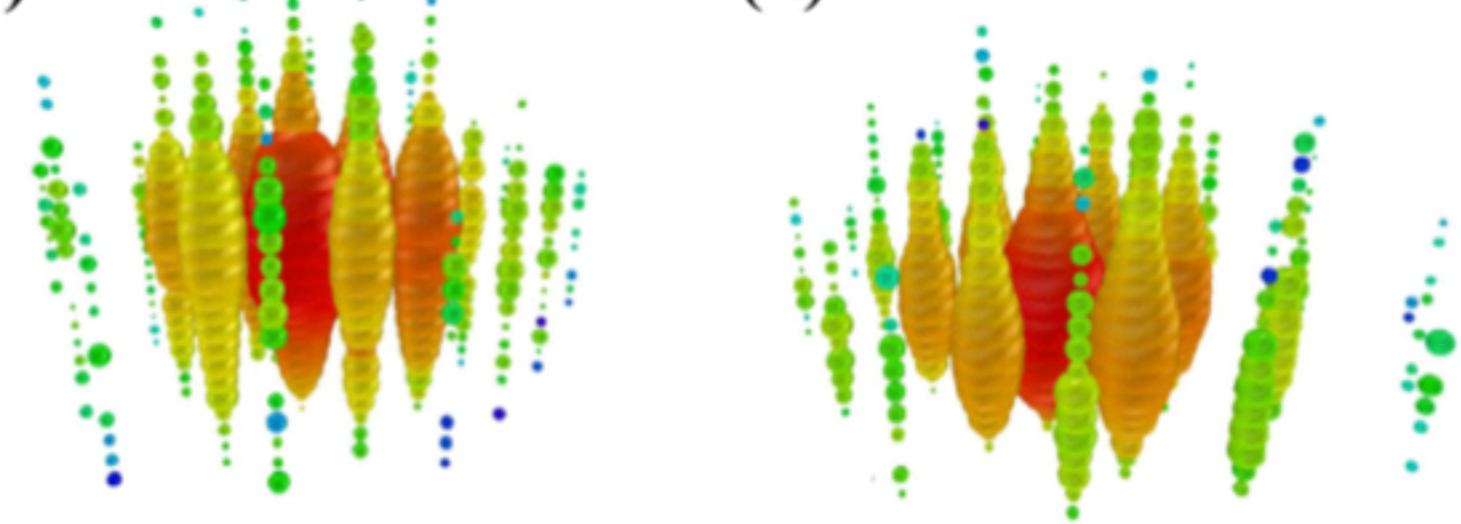
News from South pole 2 years

Two PeV neutrinos observed by IceCube

in 615.9 days

[Aartsen et. al. (IceCube) Phys.Rev.Lett. 111 (2013) 021103]

(a) "Bert" (b) "Ernie"

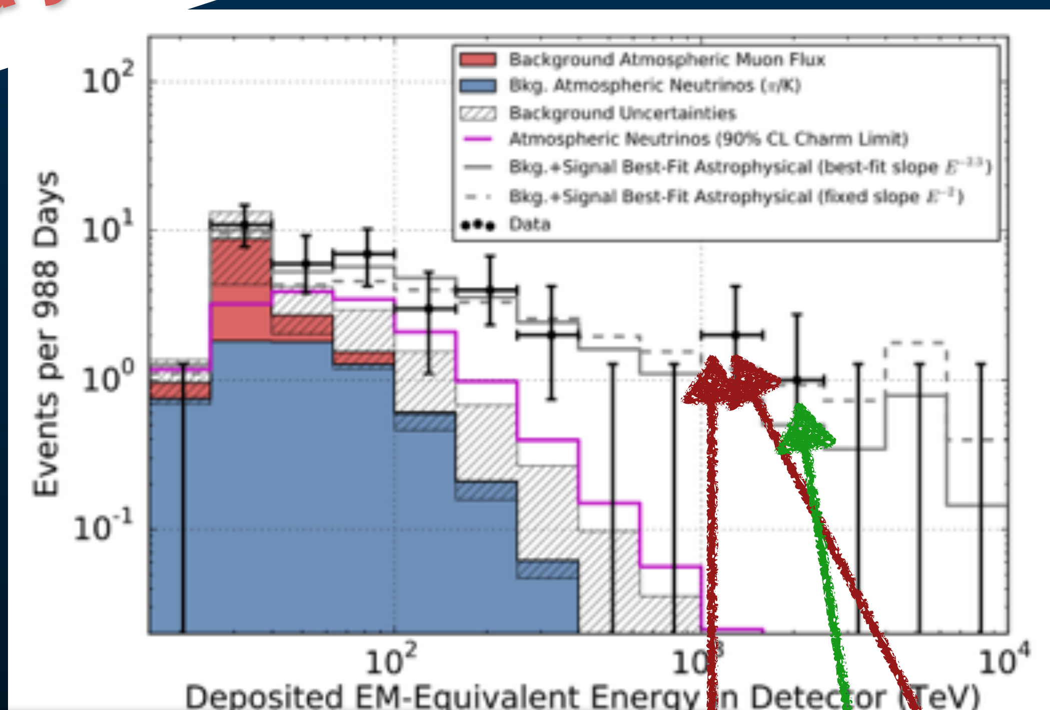


$1.04 \pm 0.16\mathrm{PeV}$ $1.14 \pm 0.17\mathrm{PeV}$

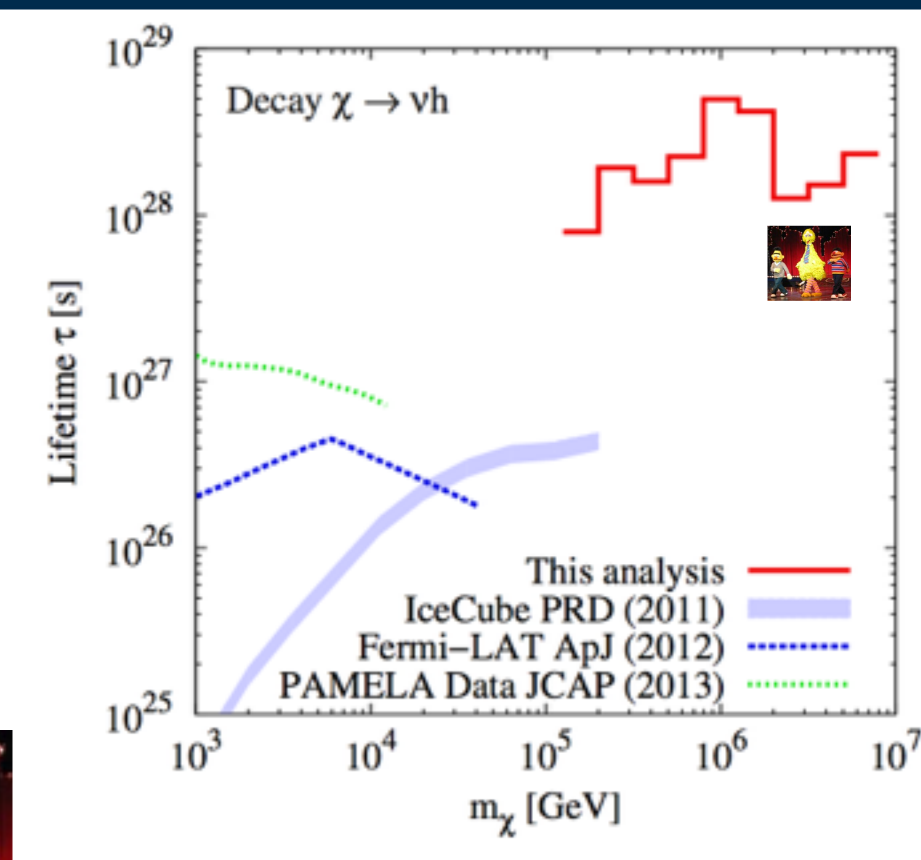
~consistent with fully contained simulated particle showers induced by neutral-current $\nu_{e,\mu,\tau}$ or charged-current ν_e interactions within the IceCube detector.

News from
South pole
3rd year

IceCube PeV neutrinos



IceCube 3yr arXiv:1405.530



Rott, Kohri, SCP (2015)

New message-#2
Dark energy problem

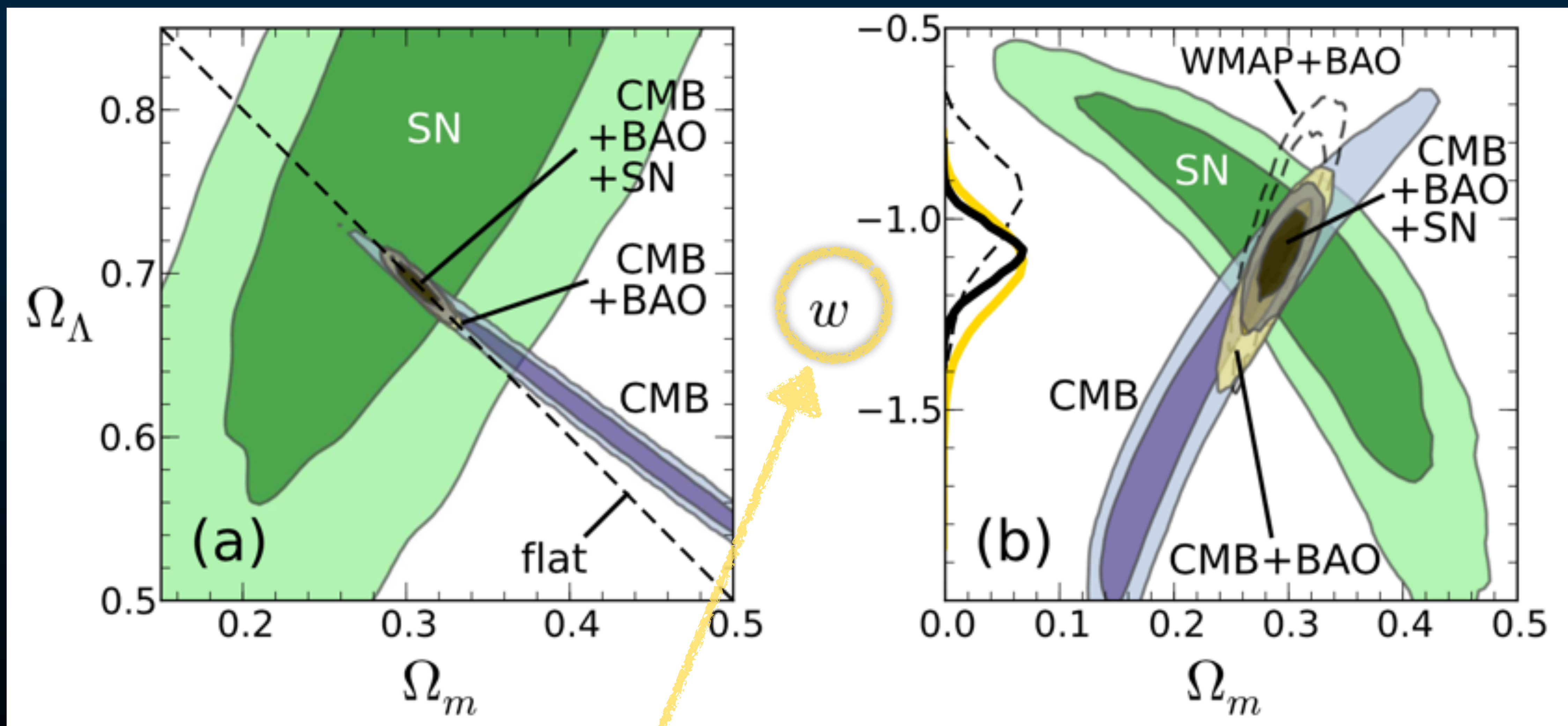
- Accelerated expansion of universe is directly observed with SNs Type1a, a standard candle due to its absolute luminosity is decided by Chandrasekhar limit

- The expansion rate is consistent with the `Dark energy' component about ~70% of energies.

Perlmutter S *et al* (Supernova Cosmology Project Collaboration) 1999 *Astrophys*. *J*. **517** 565
Riess A G *et al* (Supernova Search Team Collaboration) 1998 Astron. J. **116** 1009

Dark energy

- The data are consistent with cosmological constant, which gives $p_\Lambda = -\rho_\Lambda$



$w = -1.10 \pm 0.08$ at 68.3% CL

$$p = \omega \rho$$

(PDG 2014)

Naïve estimation of Lambda

$$\mathcal{L}_\Lambda = \sqrt{g}\Lambda$$

SM fields: $\Lambda \sim (300\mathrm{GeV})^4$

GUT: $\Lambda \sim (10^{14}\mathrm{GeV})^4$

Planck scale physics: $\Lambda \sim (10^{19}\mathrm{GeV})^4$

The worst miserable failure in theoretical physics

$$\rho_{measure} = (1.35 \pm 0.15) \times 10^{-123} M_p^4$$

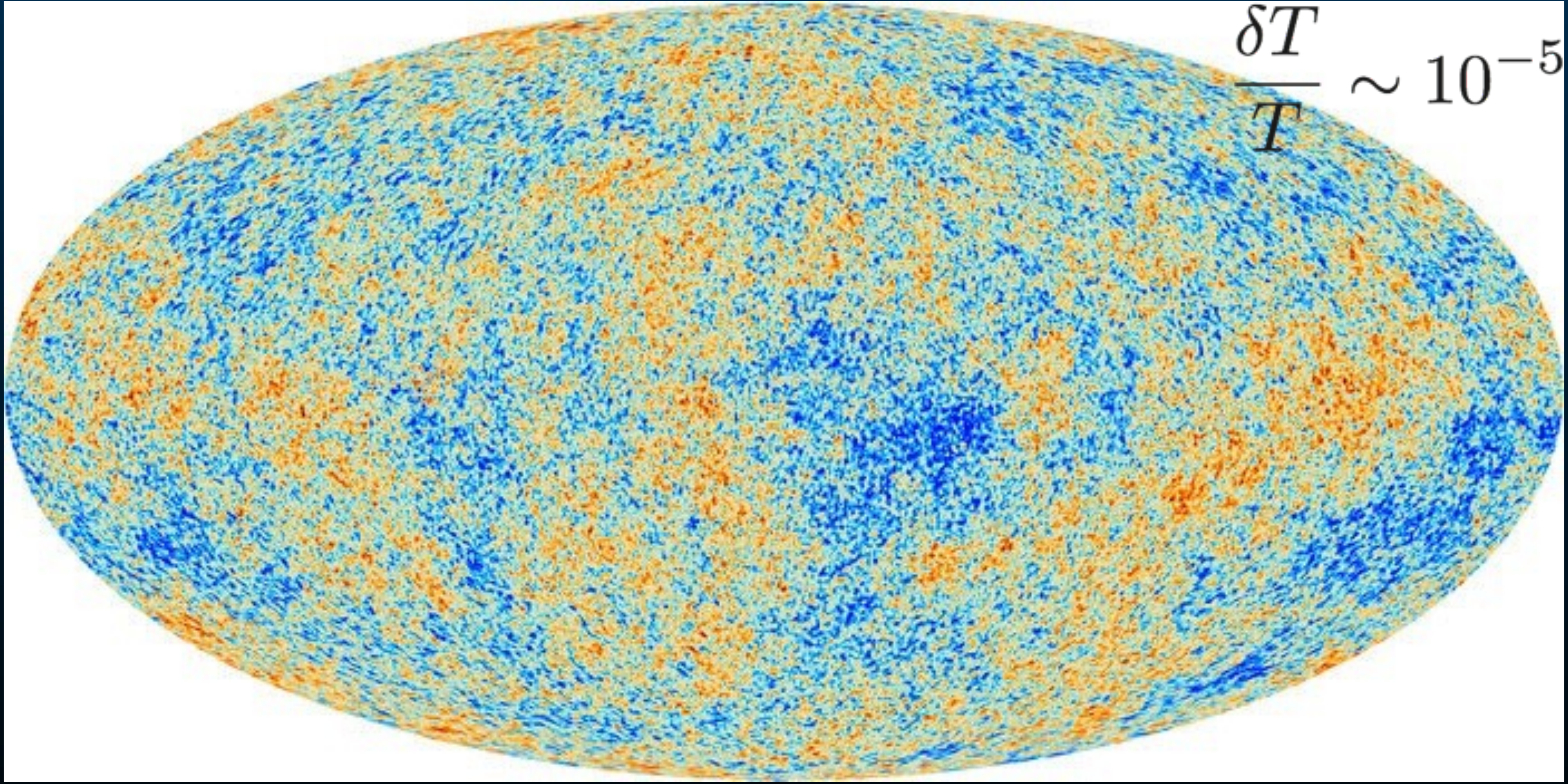
J.D.Barrow, D.J. Show Gen.Rel.Grav. 43 (2011) 2555-2560

Partial solution

- With SUSY, the CC cancelation takes place by symmetry··· but with SUSY breaking at TeV, cc~$(\text{TeV})^4$
- There could be some dynamical reason why cc should be vanishingly small but again quantum fluctuation should be cancelled by some reason which is not simple
- Anthropic argument, for now, seems the only argument giving an acceptable precision in cc estimation but it is hard to get tested (hard to swallow..)
- New idea should come out!

New message-#3

Acausality in CMBR



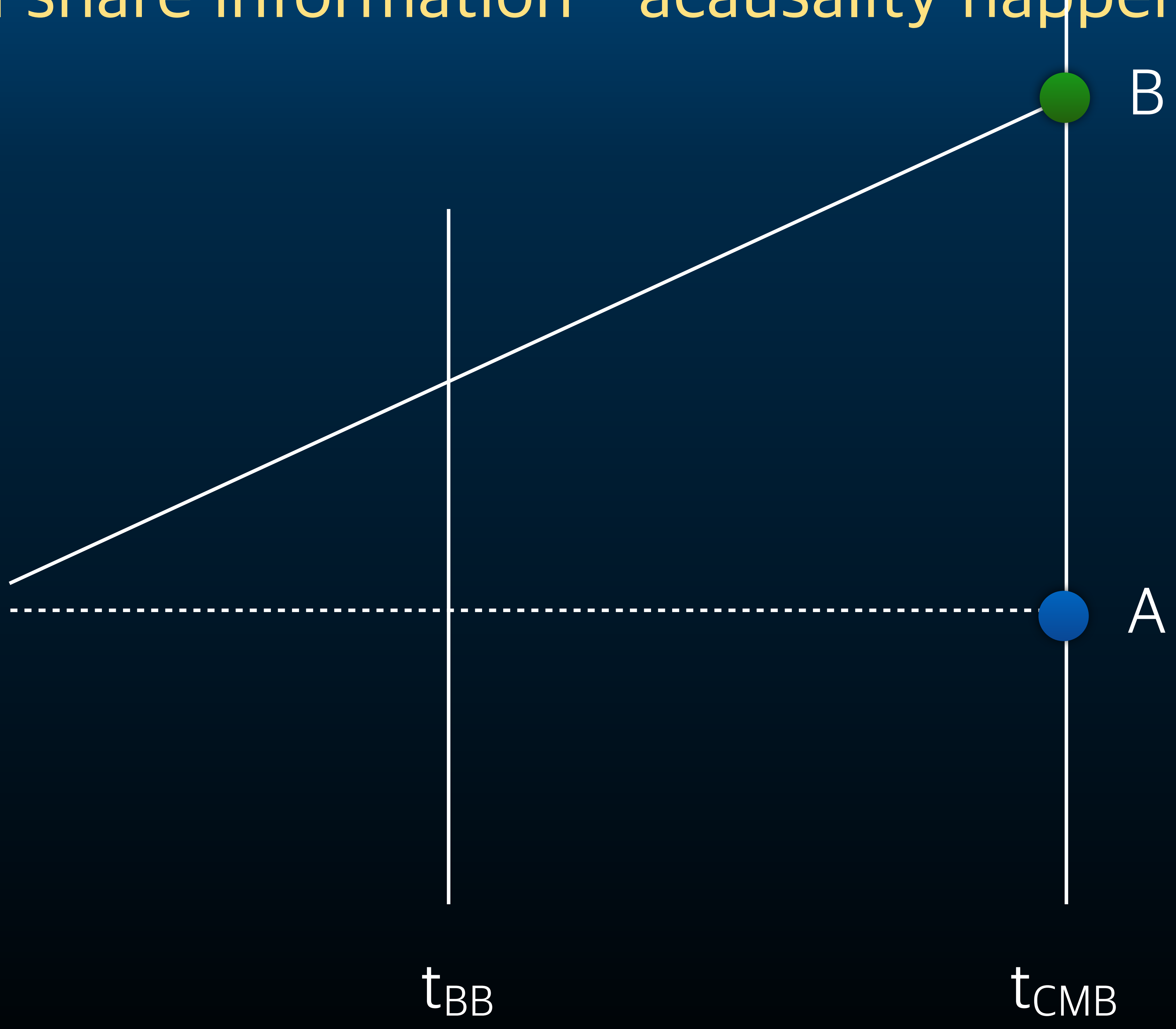
Acausality in CMBR

- CMBR is pretty homogeneous and isotropic. Fluctuation is only 10^{-5} level. (much smother than billiard ball!)

- CMBR formed after 380,000 years after "hot big bang" but there was no time for different part of universe had communication before.

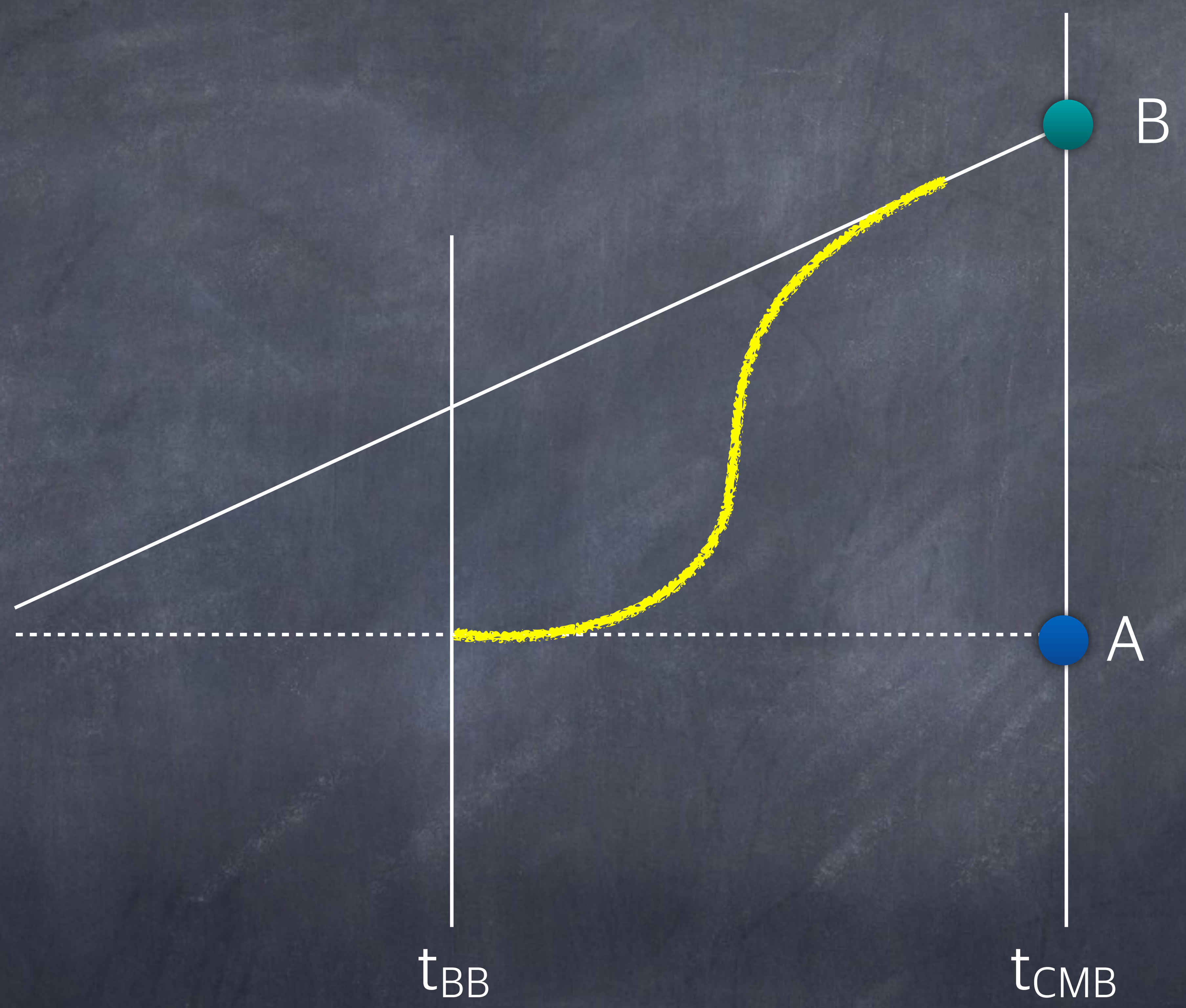
- This is truly weird!

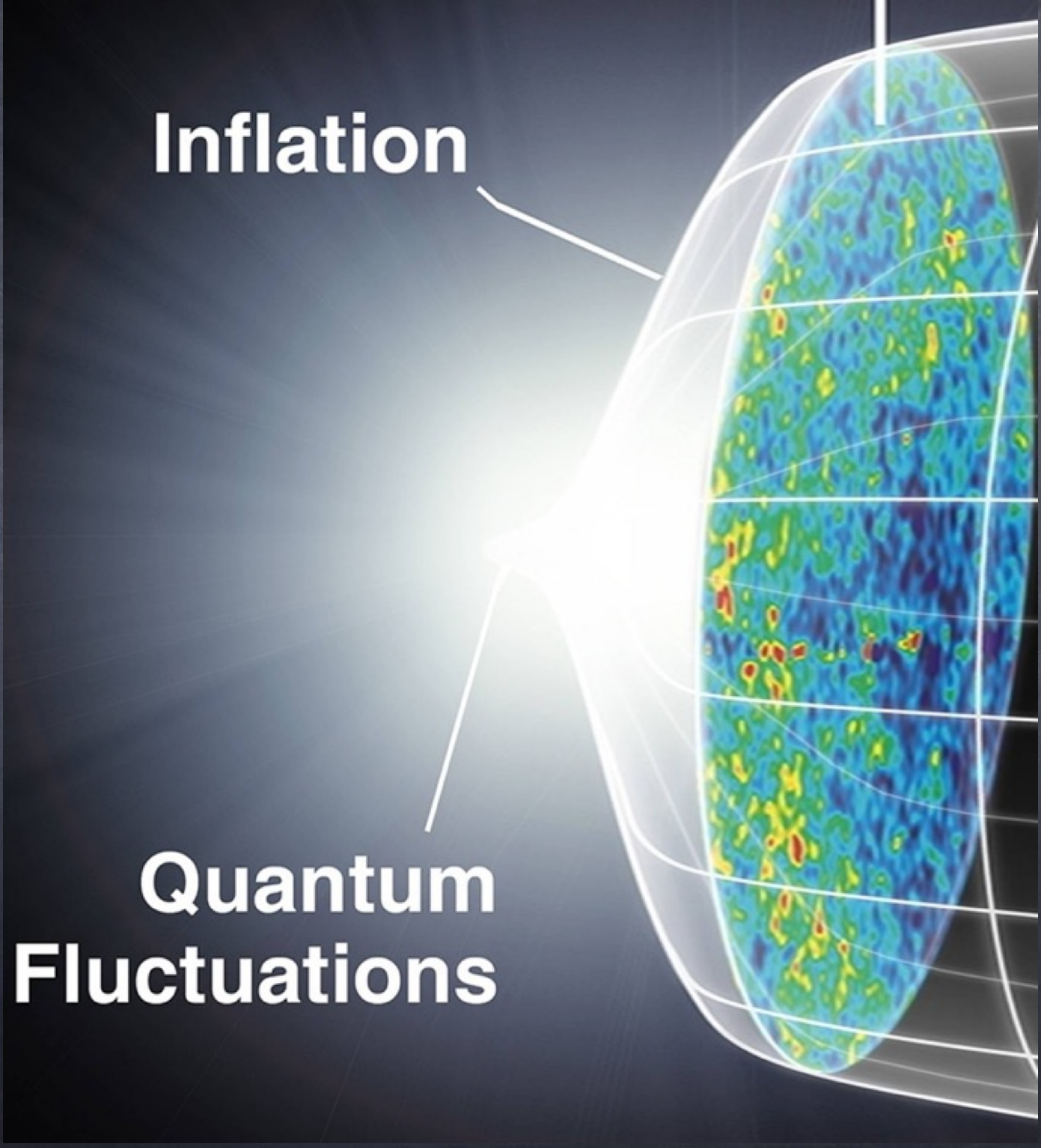
They never have talked before but still share information···acausality happened?



solutions?

- Causality violation in early universe :-(
- Seemingly separate parts of universe were actually in contact before conventional BB expansion :-)
- r => e^{60} r in a short time explains the phenomena. (Inflation!)

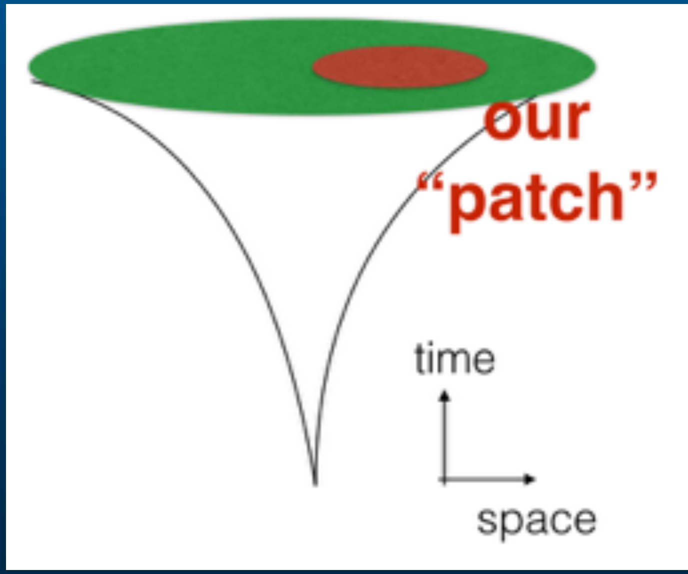

B
A
t_{BB}
t_{CMB}


Inflation
Quantum
Fluctuations

inflation

- make space flat and isotropic
- solves horizon problem
- set the IC for hot BB universe

In particle physics, inflation is driven by a scalar field (inflaton)



This is what we want:

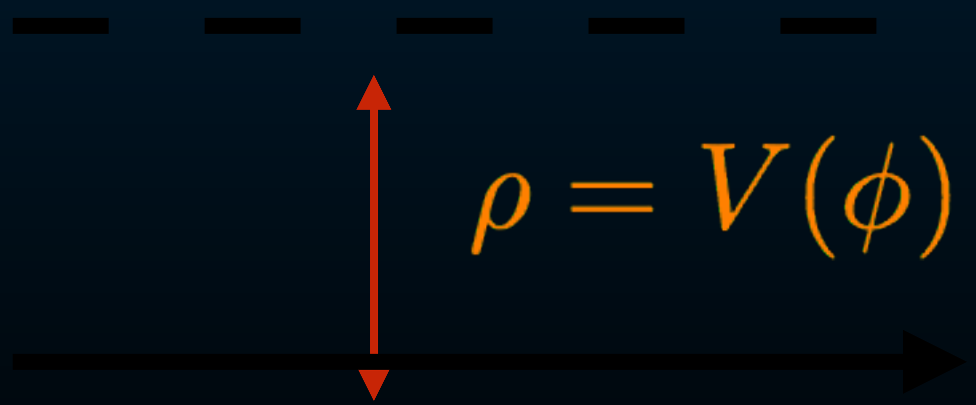
$$ds^2 = dt^2 - a(t)^2 d\vec{x} \cdot d\vec{x}$$

$$a(t) = a_0 e^{H(t-t_0)}$$

This is the equation:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{\rho}{3M_p^2}$$

It is realized if the potential is "flat"



"slow-roll conditions"

$$(V'/V)^2 \ll 1$$
$$V''/V \ll 1$$

(ex) $V = \lambda \phi^4, \lambda \sim 10^{-12}$

N.B. This guy is not be a vector or fermion unless it makes a composite state with s=0.

Q. Can Higgs be Inflaton?

Higgs	vs	Chaotic Inflation
$V(H) \approx \frac{1}{8}(\lvert H\rvert^2 - v^2)^2$		$V(\phi_{\text{inf}}) \approx 10^{-12}\phi_{\text{inf}}^4$

apparently looks very different…

But!

The Higgs potential becomes flat at high energy by RGE!

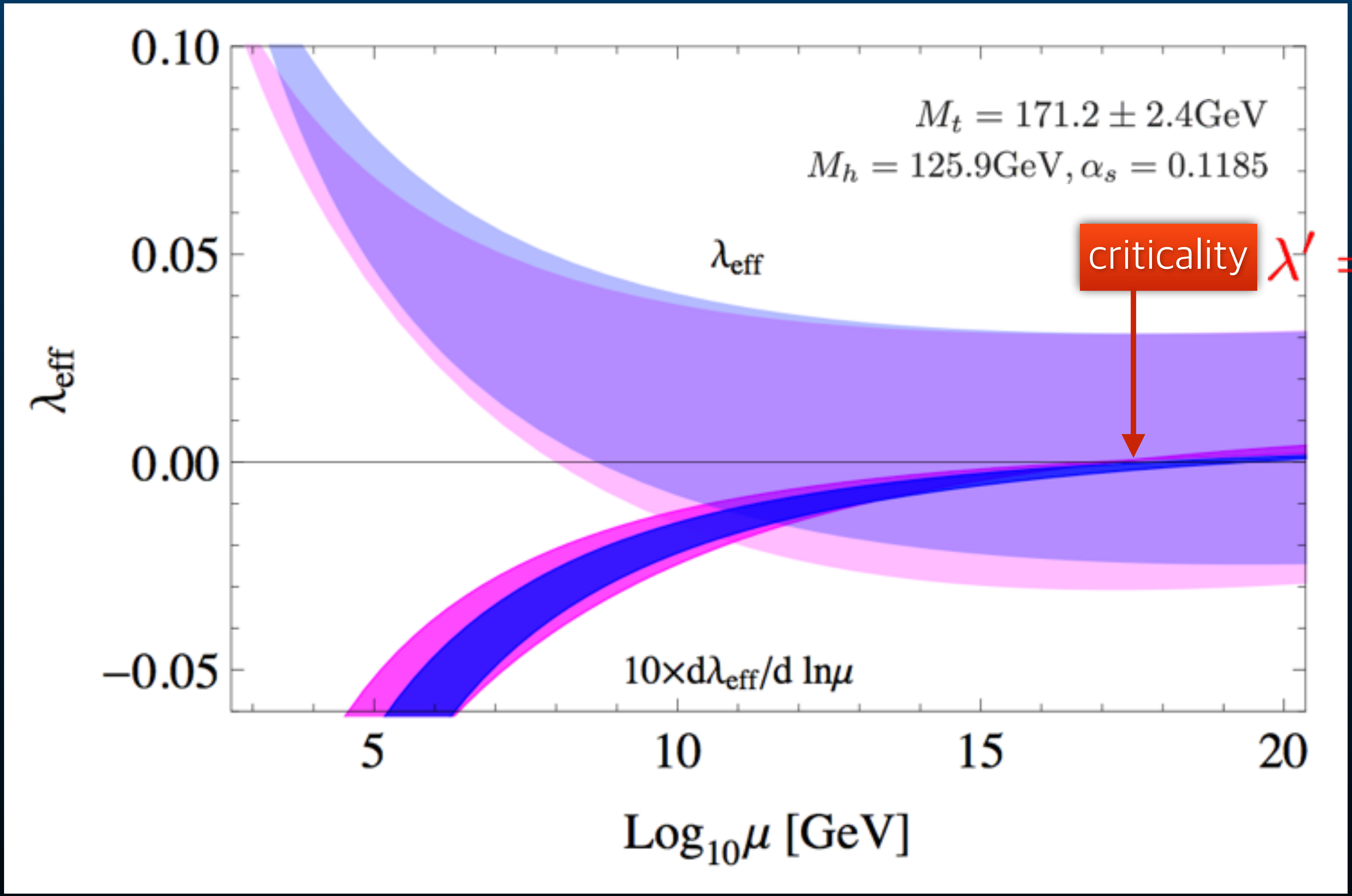
The SM Higgs quartic coupling

$$\lambda(\mu_{\rm EW}) \sim \mathcal{O}(1)$$

$$\lambda(\mu_{\rm Inflation}) \ll \mathcal{O}(1)$$

MITP

arXiv:1405.4781



〔Hamada, Kawai, Oda, SCP, Phys.Rev.Lett. 112 (2014) 24, 241301〕

〔Hamada, Kawai, Oda, SCP, Phys.Rev. D91 (2015) 5, 053008〕

perspectives

- After Higgs discovery, we now ask what would be the next.

“…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;

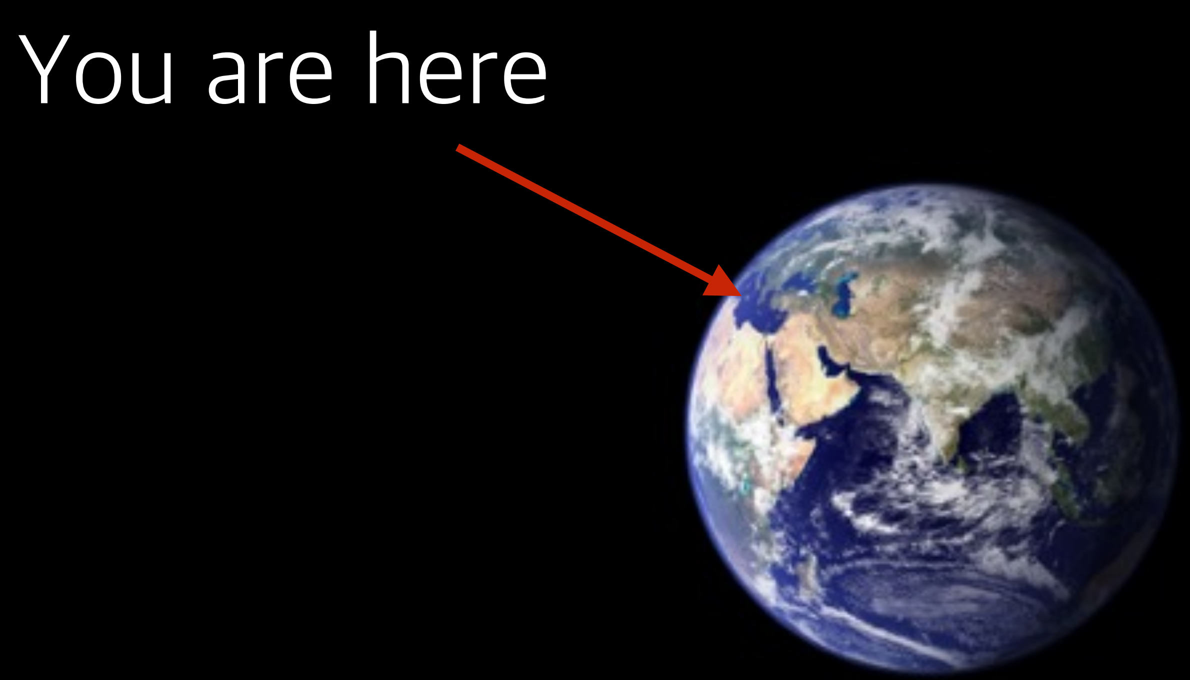
P. Debye, M. Knudsen, W.L. Bragg, H.A. Kramers, P.A.M. Dirac, A.H. Compton, L. de Broglie, M. Born, N. Bohr;

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

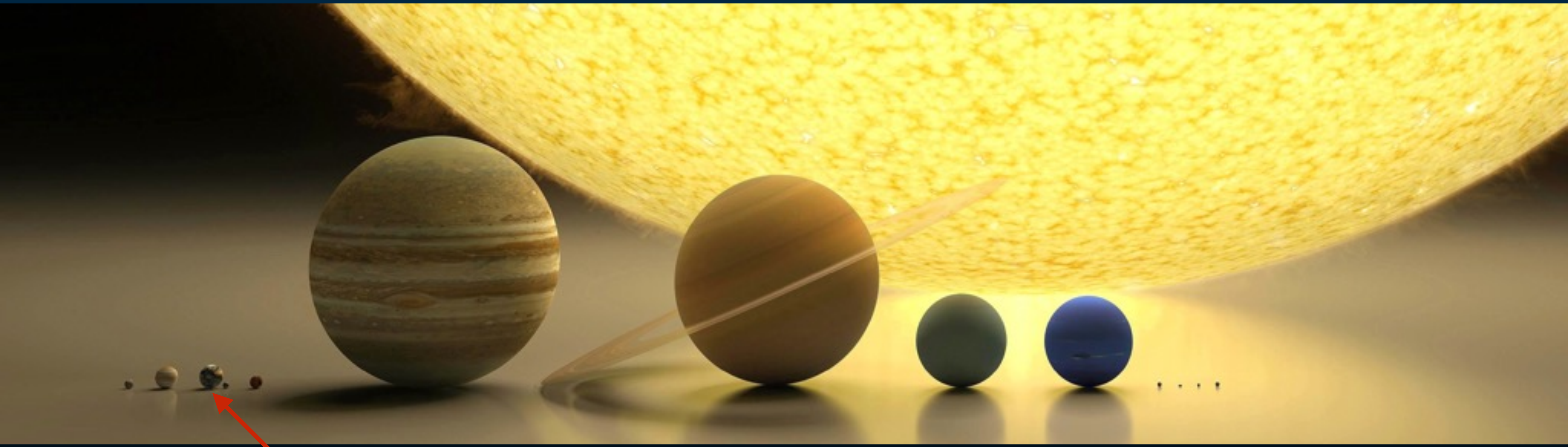
There are hints for 'NP' now!

- 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

The Copernican Evolution



The Copernican Evolution



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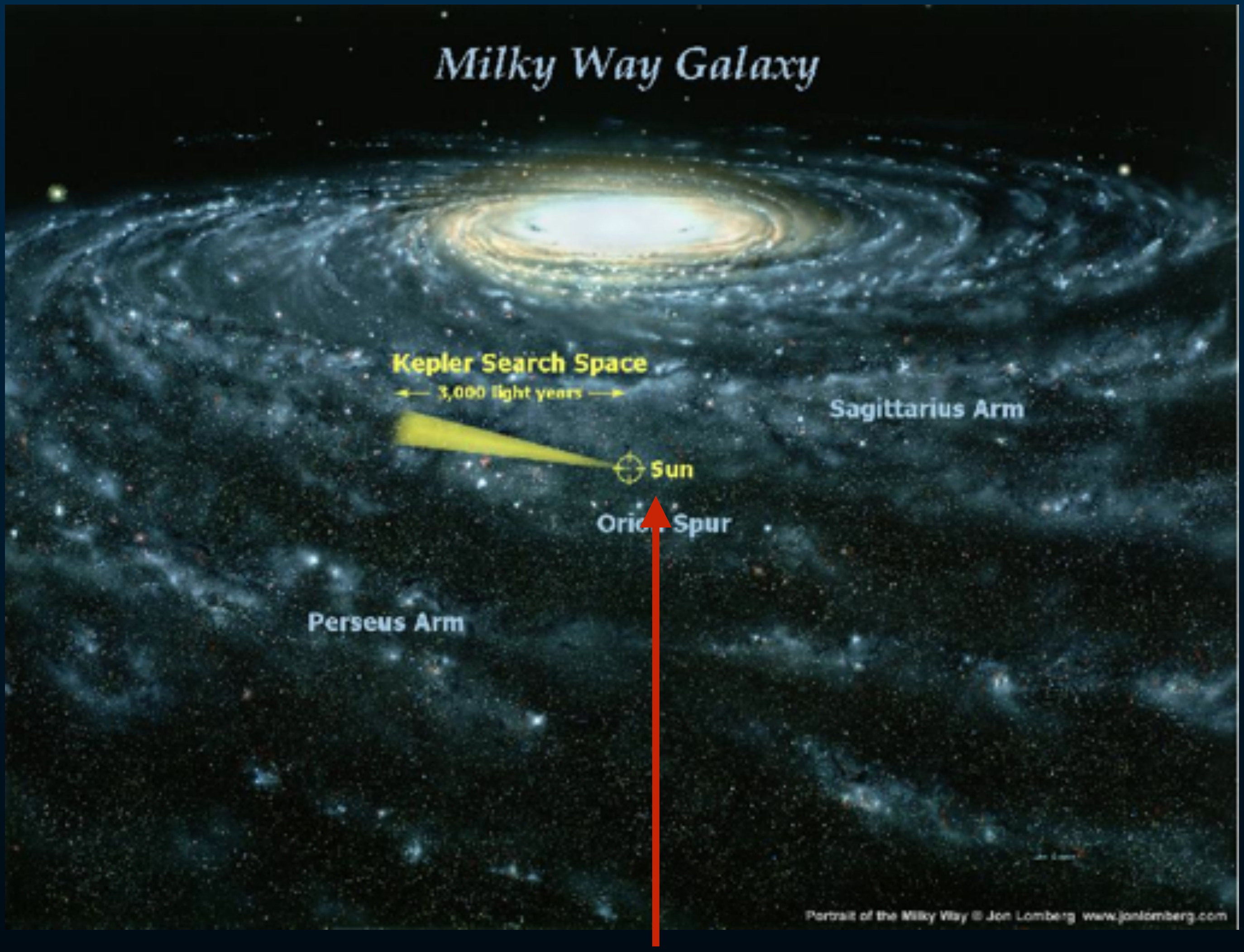
The Copernican Evolution



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The Copernican Evolution

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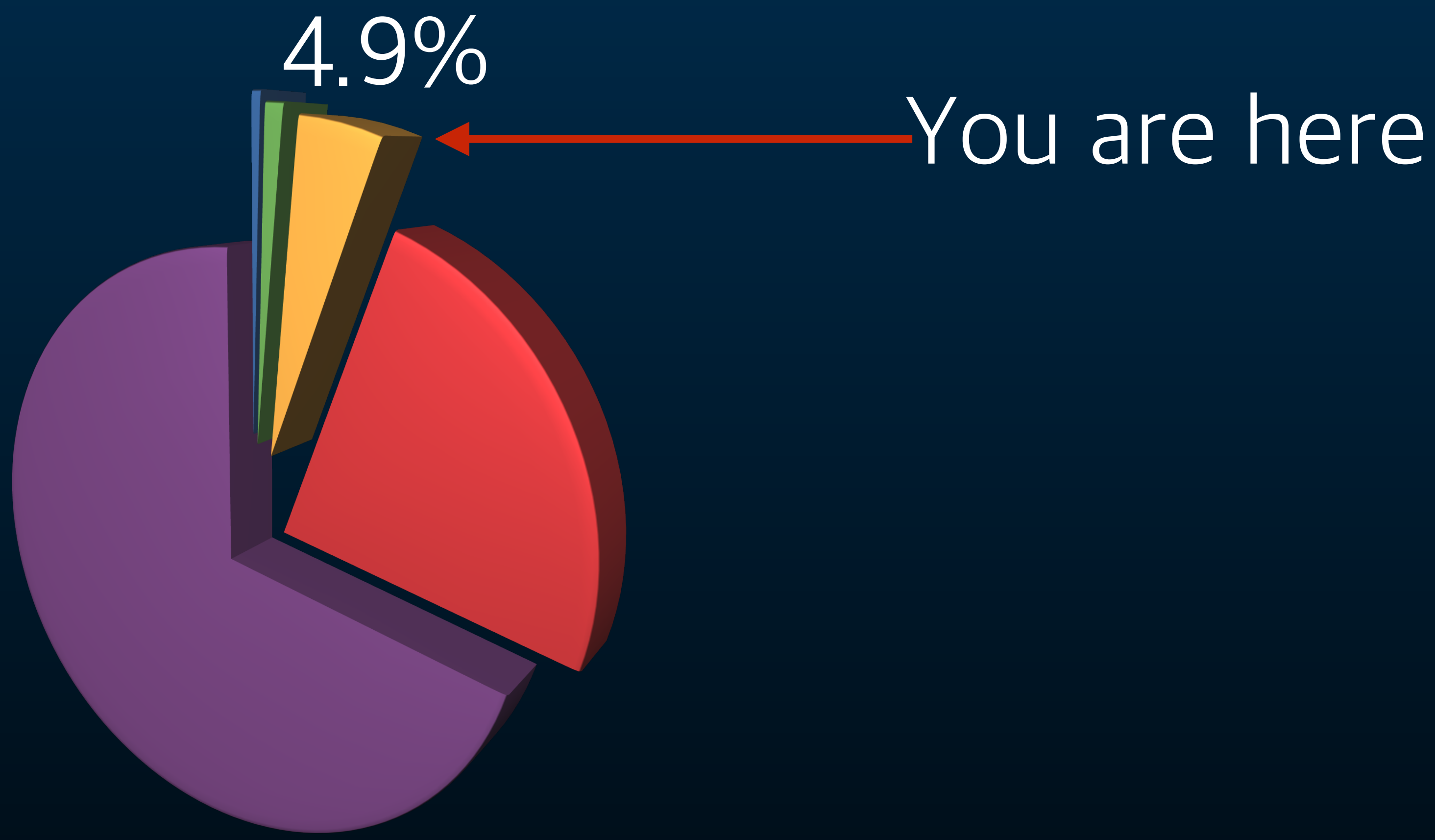

The Copernican Evolution

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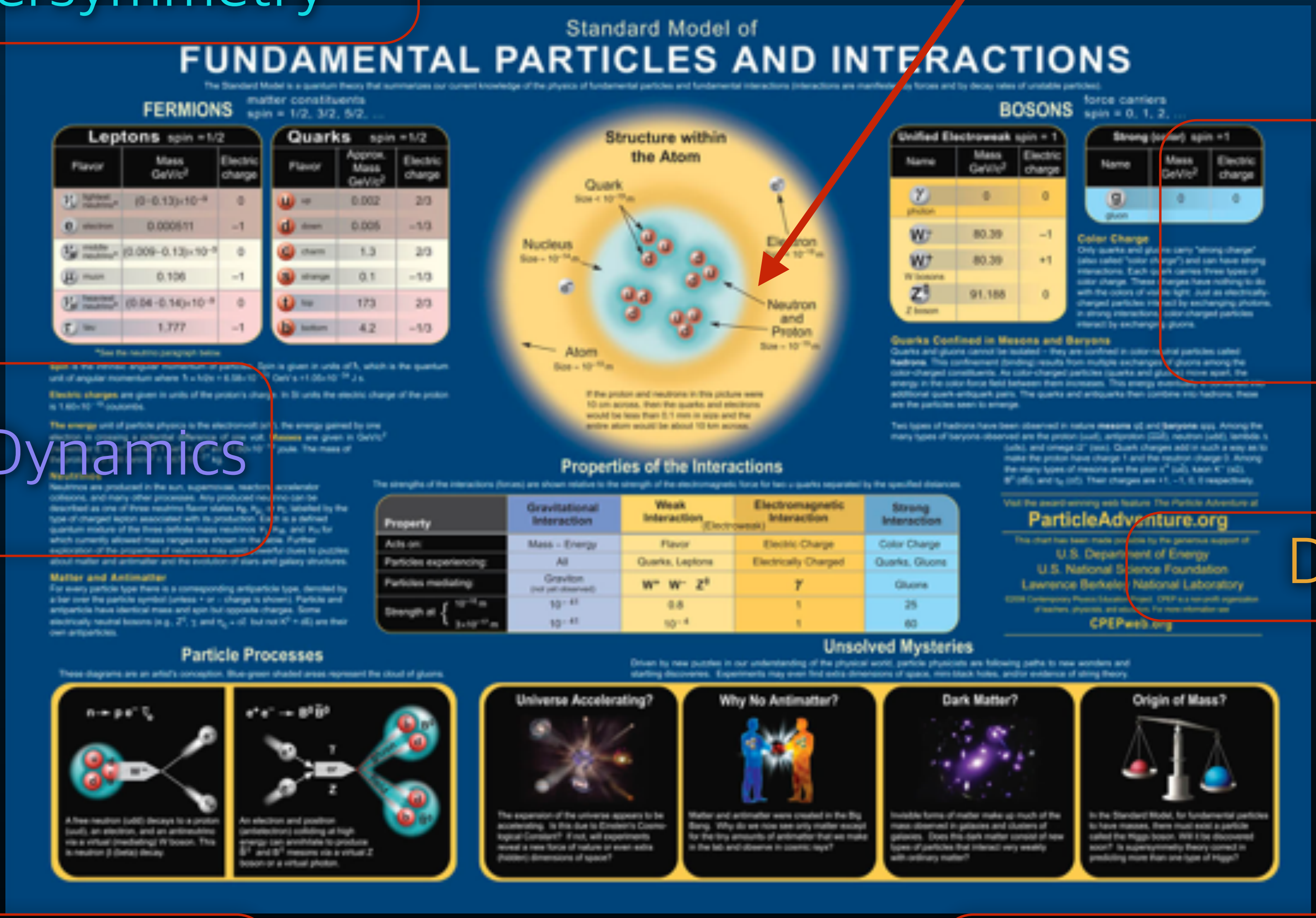
Supersymmetry

Large Extra Dimensions

Conformal Dynamics

Dark Force



Strong Dynamics

Hidden Sector

There are a lot more new things out there.

Let’s find them!

Thank you!