Review of Neutrino Physics

Hitoshi Murayama
(Kavli IPMU & Berkeley)

DBD 2018, Waikoloa, Oct 21, 2018

東京大学
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Neutrinos as Superheroes

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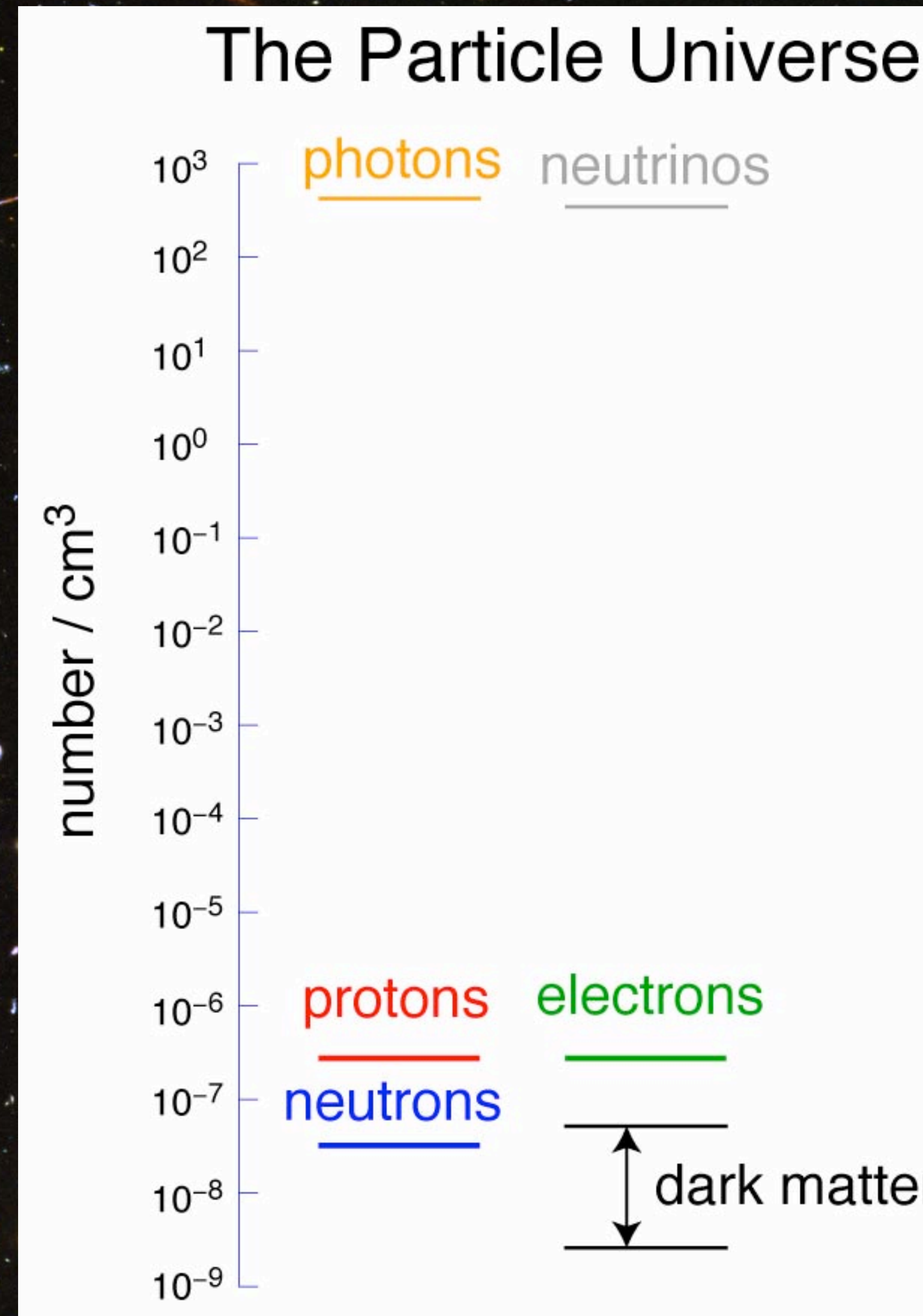
DBD 2018, Waikoloa, Oct 21, 2018

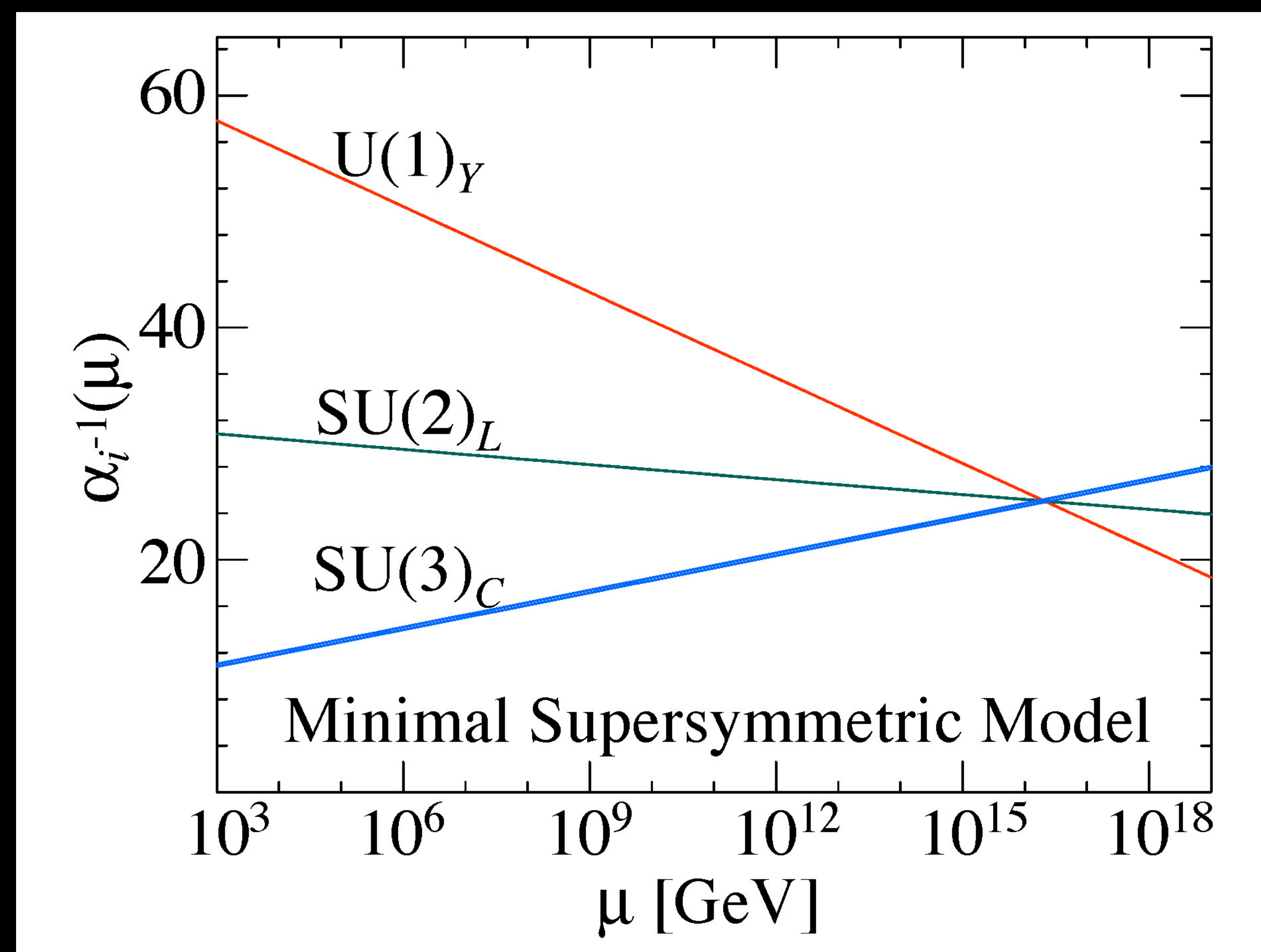
Why Neutrinos?

There are a lot of neutrinos out there



Einstein’s Dream

- Einstein dreamed to come up with a *unified* description of vast phenomena in Nature



Rare effects from high energies

- Effects of high-energy physics mostly disappear by power suppression

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W^{a\mu}_{\nu}W^{b\nu}_{\lambda}W^{c\lambda}_{\mu}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

unique role of m_ν

- Lowest order effect of physics at short distances
- tiny effect: $(m_\nu/E_\nu)^2 \approx (0.1\,\mathrm{eV}/\mathrm{GeV})^2 \approx 10^{-20}$!
- interferometry (e.g. Michaelson-Morley)
  - need a coherent source
  - need a long baseline
  - need interference (i.e. large mixing angle)
- Nature was kind to provide them all!
- neutrino interferometry (a.k.a. oscillation) a unique tool to study physics at very high E
- probing up to $\Lambda \approx 10^{14}$ GeV

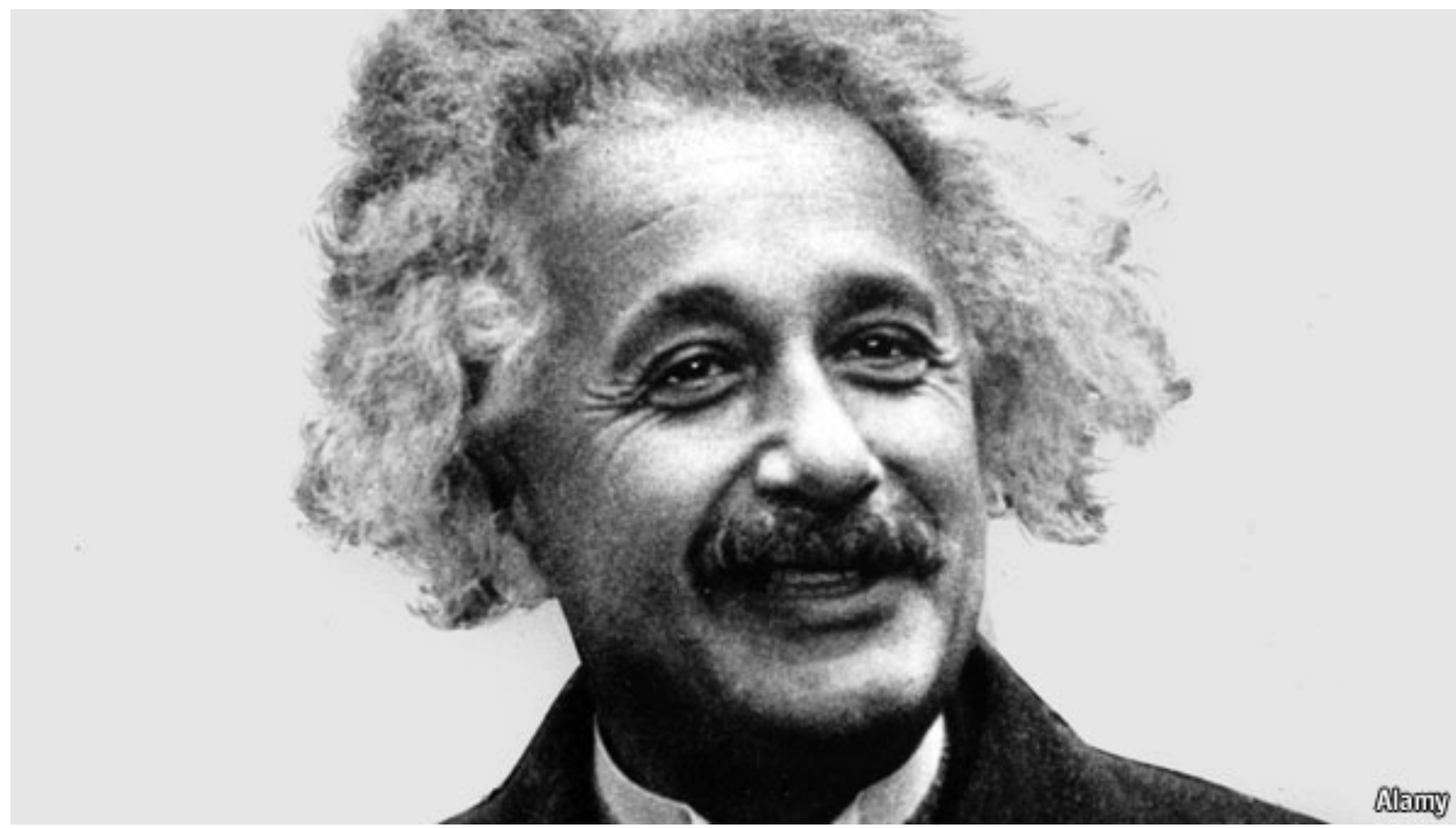
The Economist

Neutrinos and relativity

Faster than the speed of light

What does an experiment that seems to contradict Einstein's theory of relativity really mean?

Oct 1st 2011 | from the print edition

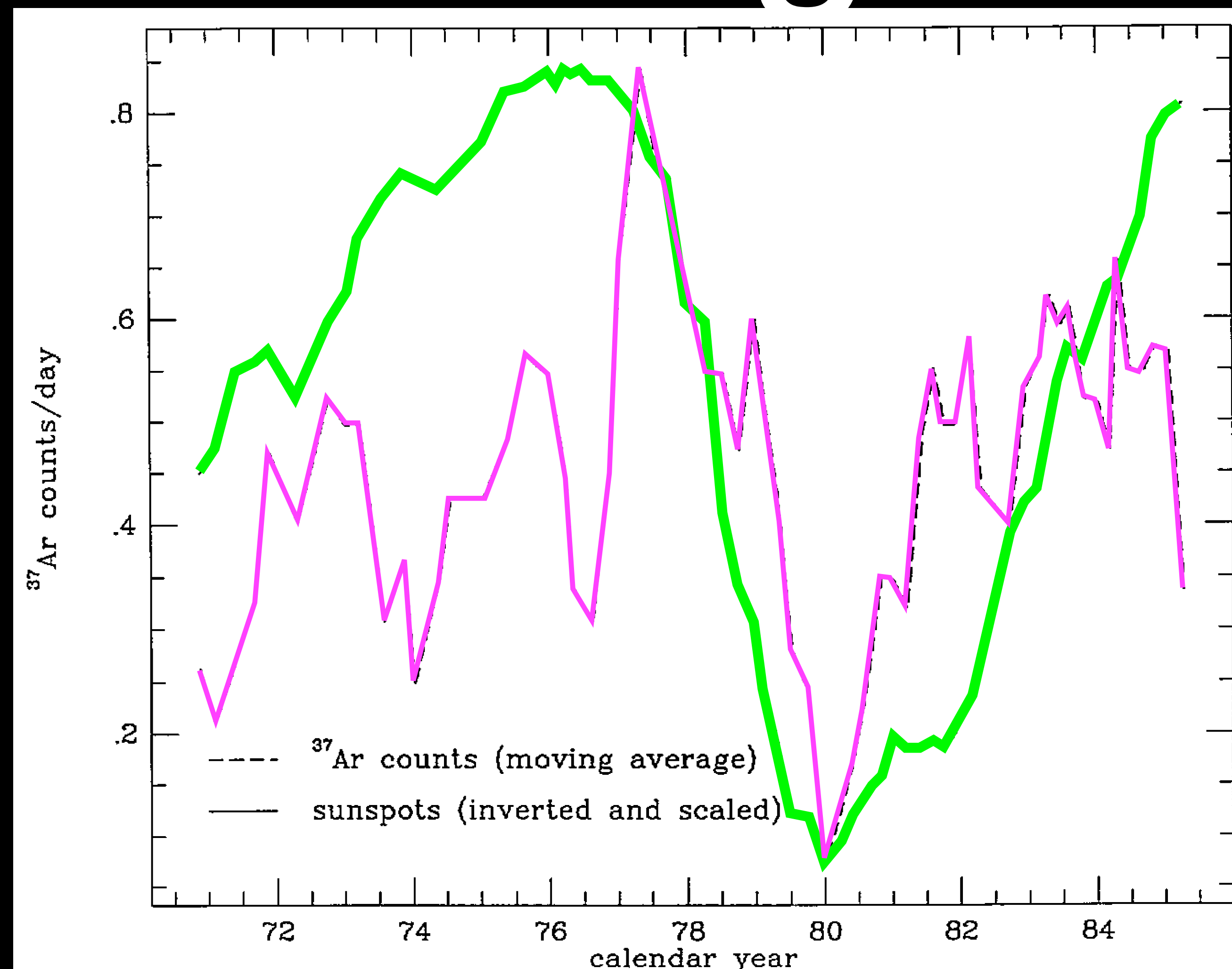


IN 1887 physicists were feeling pretty smug about their subject. They thought they understood reality well, and that the future would just be one of ever more precise measurements. They could not have been more wrong. The next three decades turned physics on its head, with the discovery of electrons, atomic nuclei, radioactivity, quantum theory and the theory of relativity. But the grit in the pearl for all this was a strange observation made that year by two researchers called Albert Michelson and Edward Morley that the speed of light was constant, no matter how fast the observer was travelling.

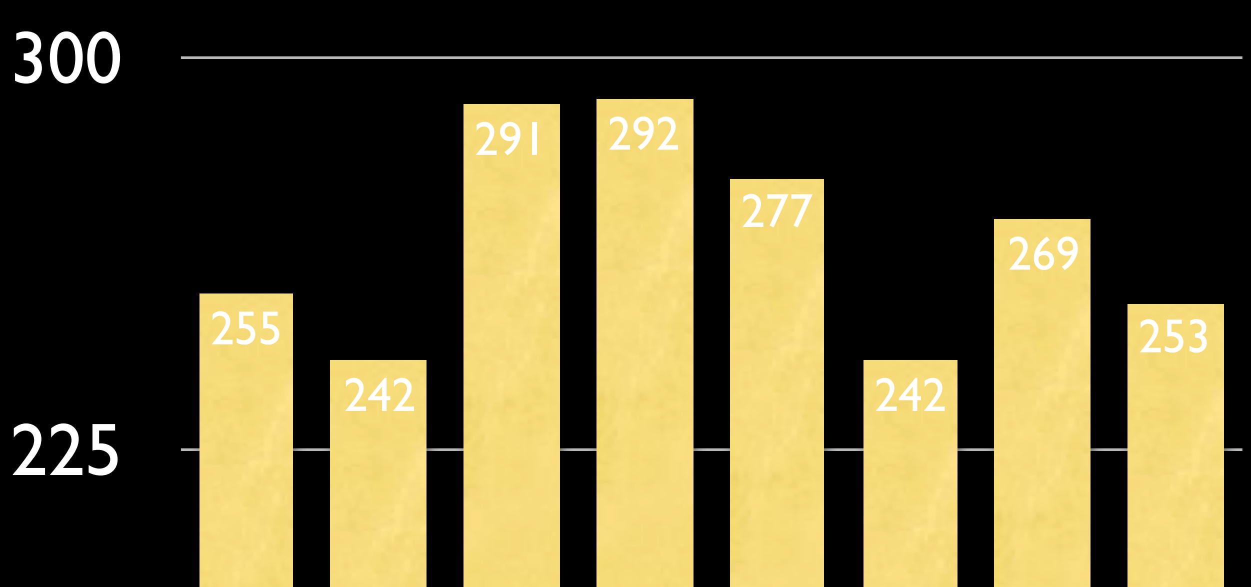
Confusing data

–#sunspot

Homestake



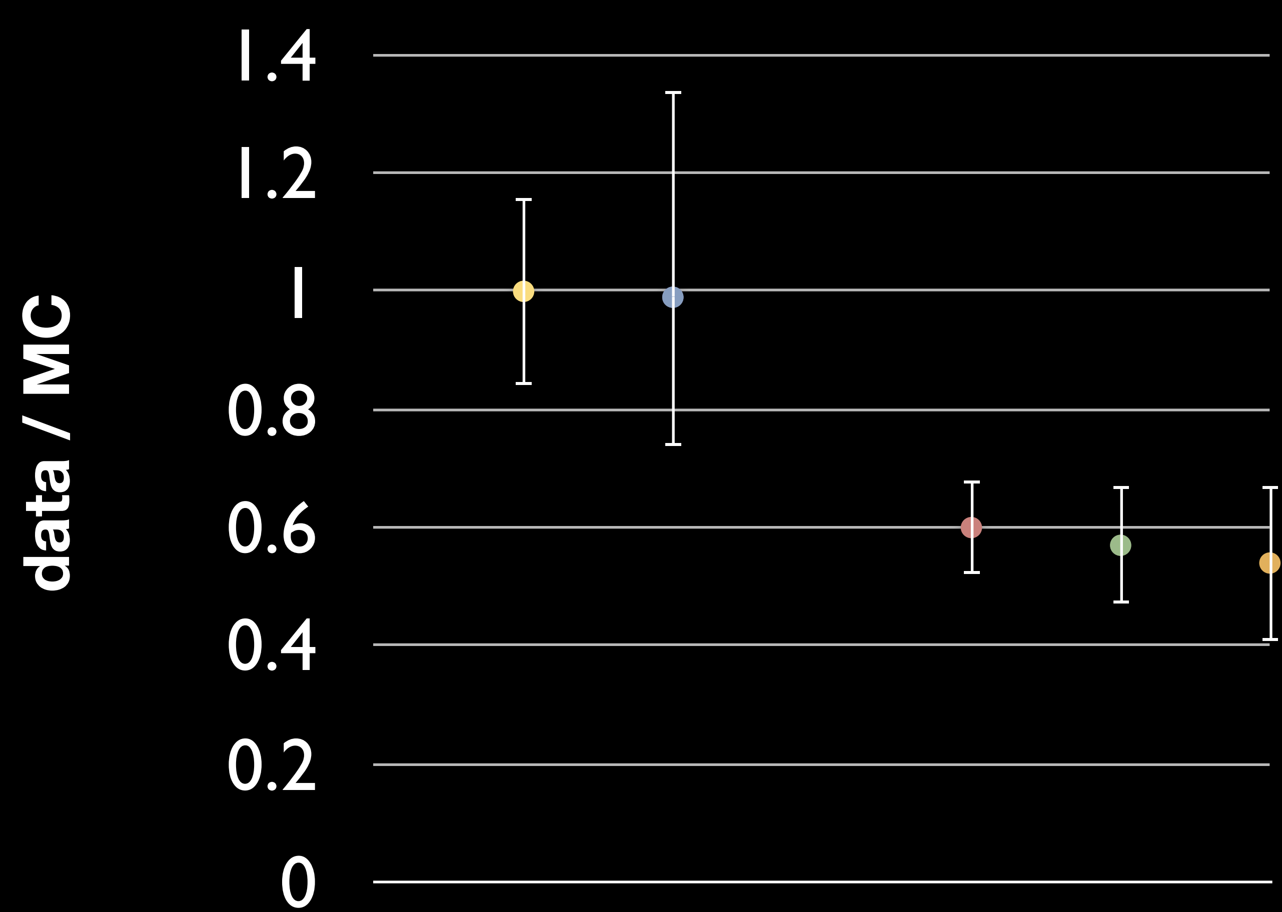
#Democrates in the House



Atmospheric neutrinos

1988

- mu/e ratio
  - problem w/ Water Ch?
  - neutron BG?
  - particle ID?
  - proton decay?



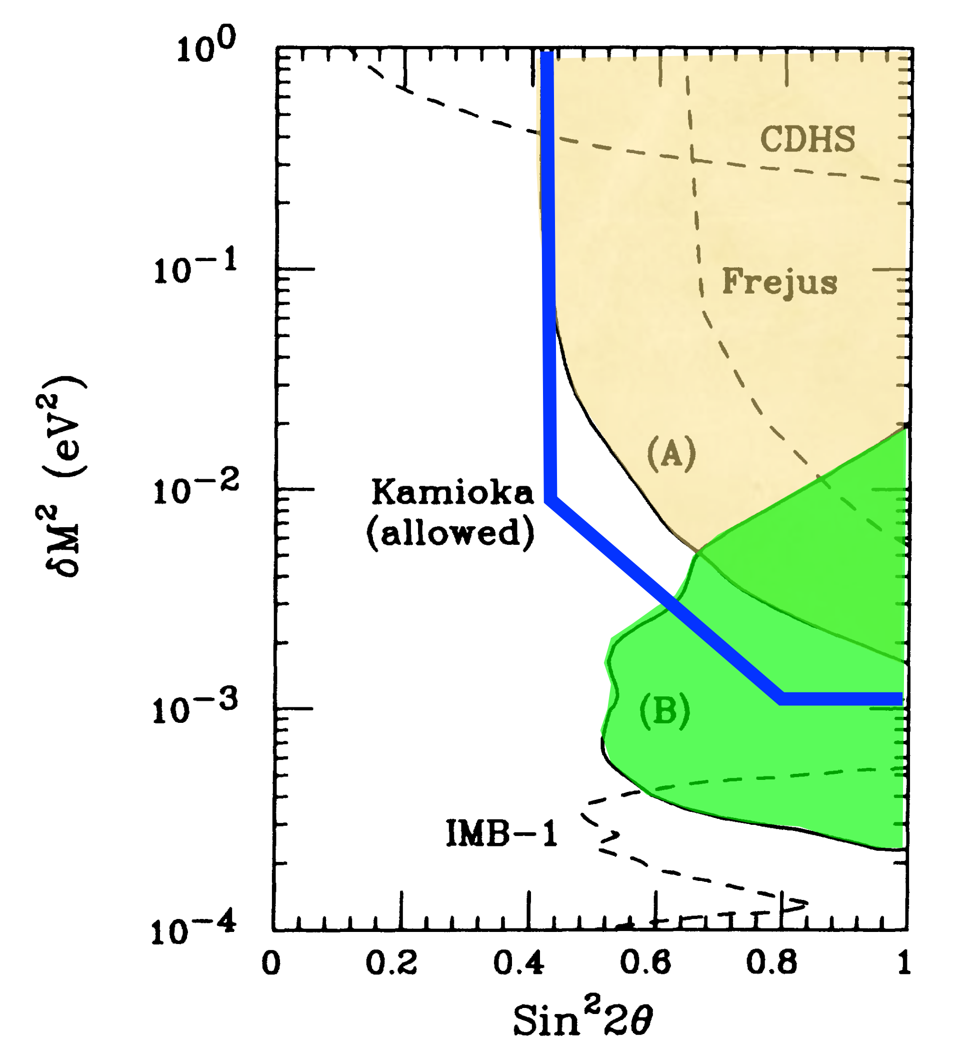
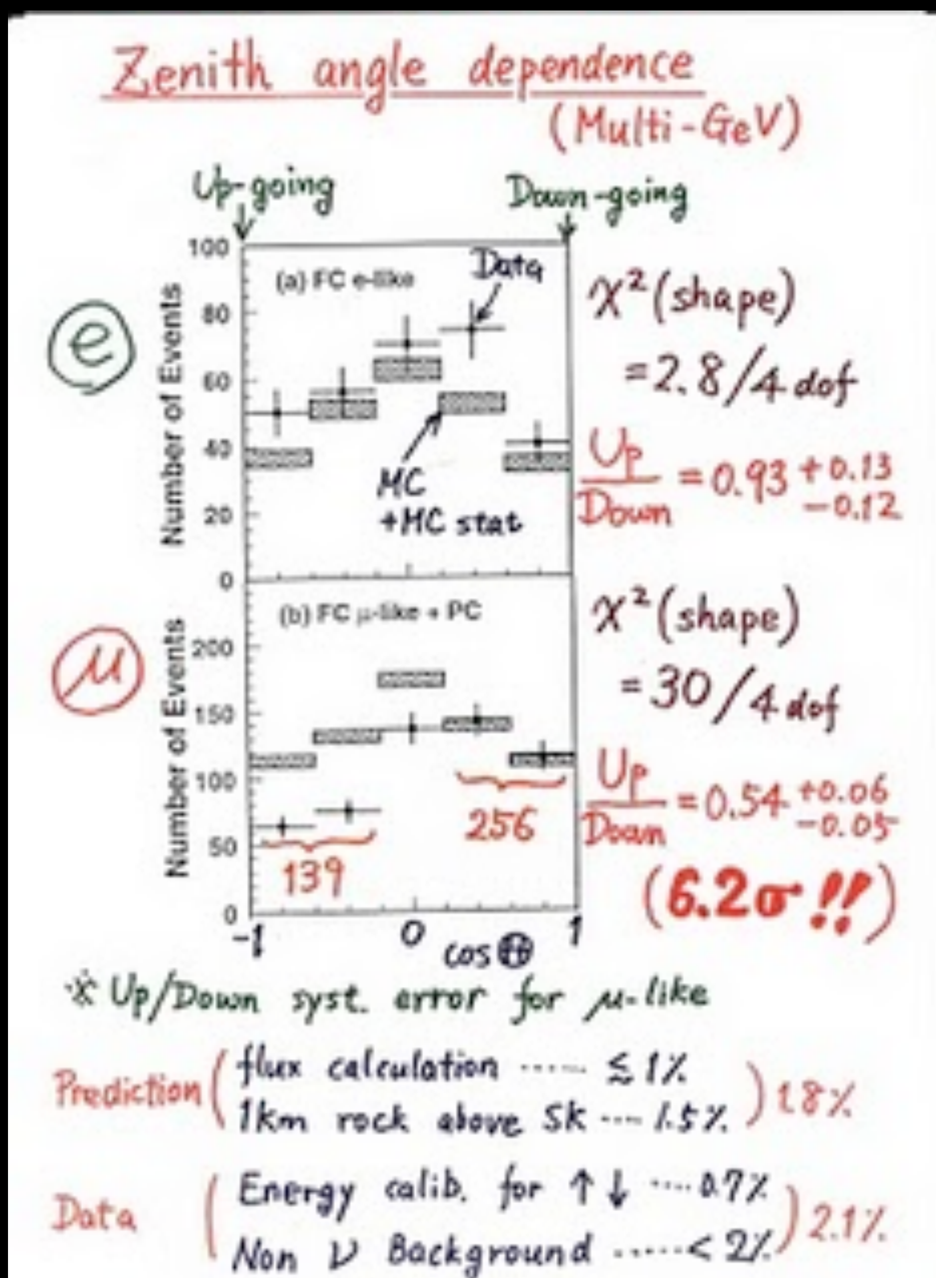


FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

IMB, PRL 69, 1010 (1992)

nospheric neutrinos

1998



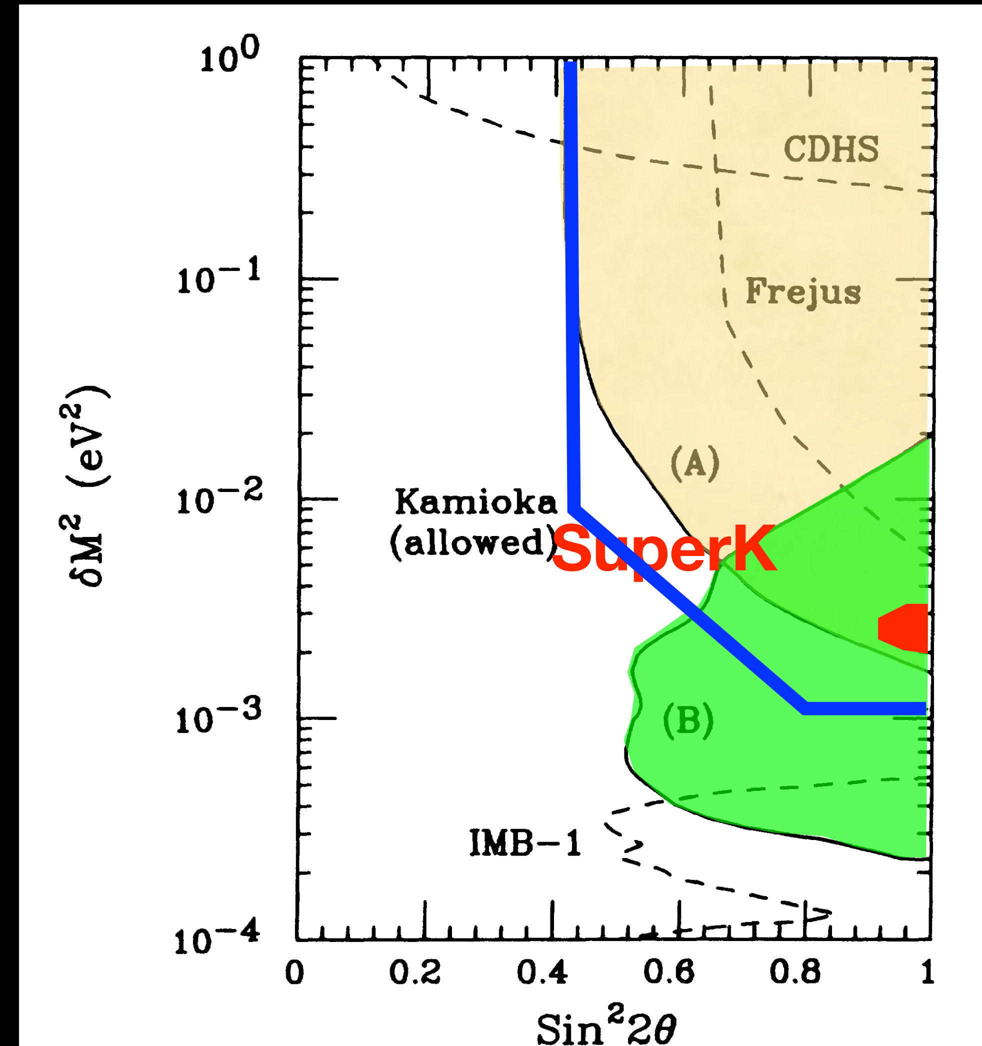


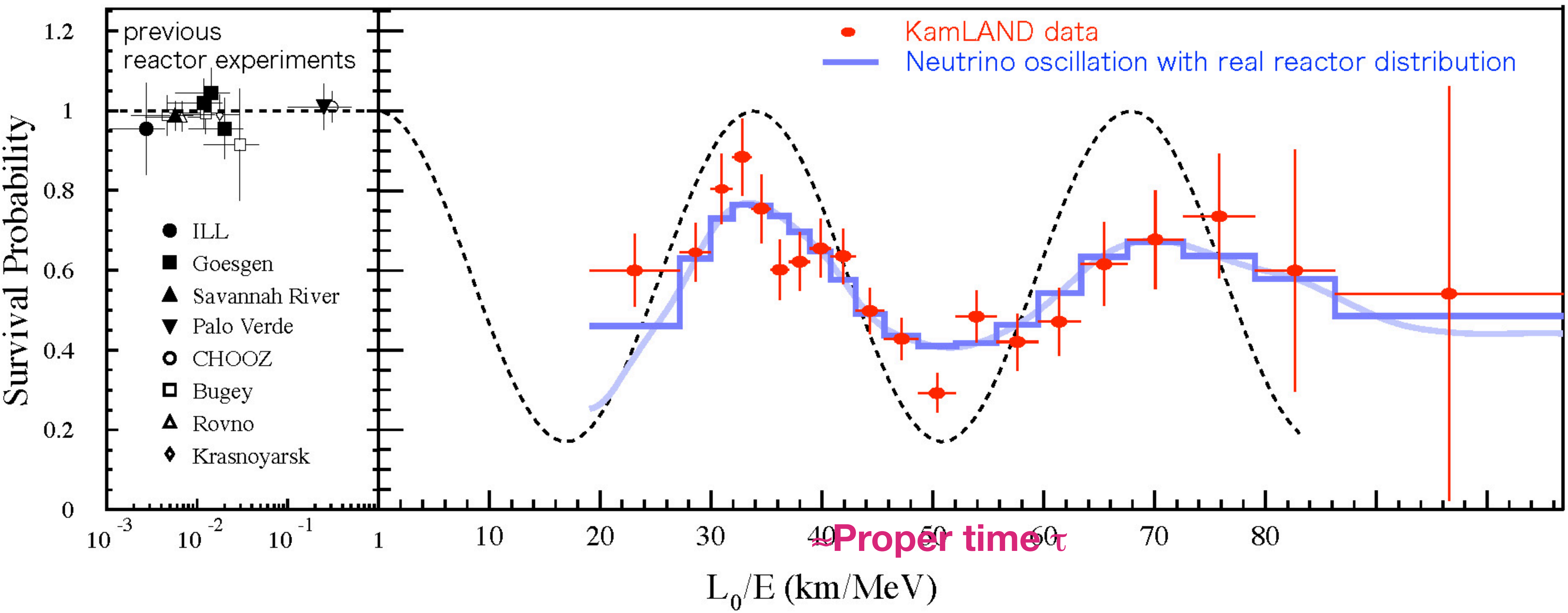
FIG. 2. 90% C.L. limits on ν_μ to ν_τ oscillations from rate (A) and stopping fraction (B). Dashed curves show limits from IMB-1 [14], Frejus [3], and CERN-Dortmund-Heidelberg-Saclay (CDHS) [15]. Dotted curve shows the allowed region from Kamiokande [16]. The Frejus limit is 95% C.L.; others are 90%.

IMB, PRL 69, 1010 (1992)

Typical Theorist's View ca. 1990

- Solar Neutrino Problem must be solved by Small Angle MSW solution because it is so beautiful Wrong!
- Important scale for oscillation is $\Delta m^2 \approx 10\text{-}100$ eV^2 because it is cosmologically relevant Wrong!
- θ_{23} must be about $\theta_{23} \approx V_{cb} \approx 0.04$ Wrong!
- atmospheric neutrino anomaly must go away because it requires large mixing angle Wrong!

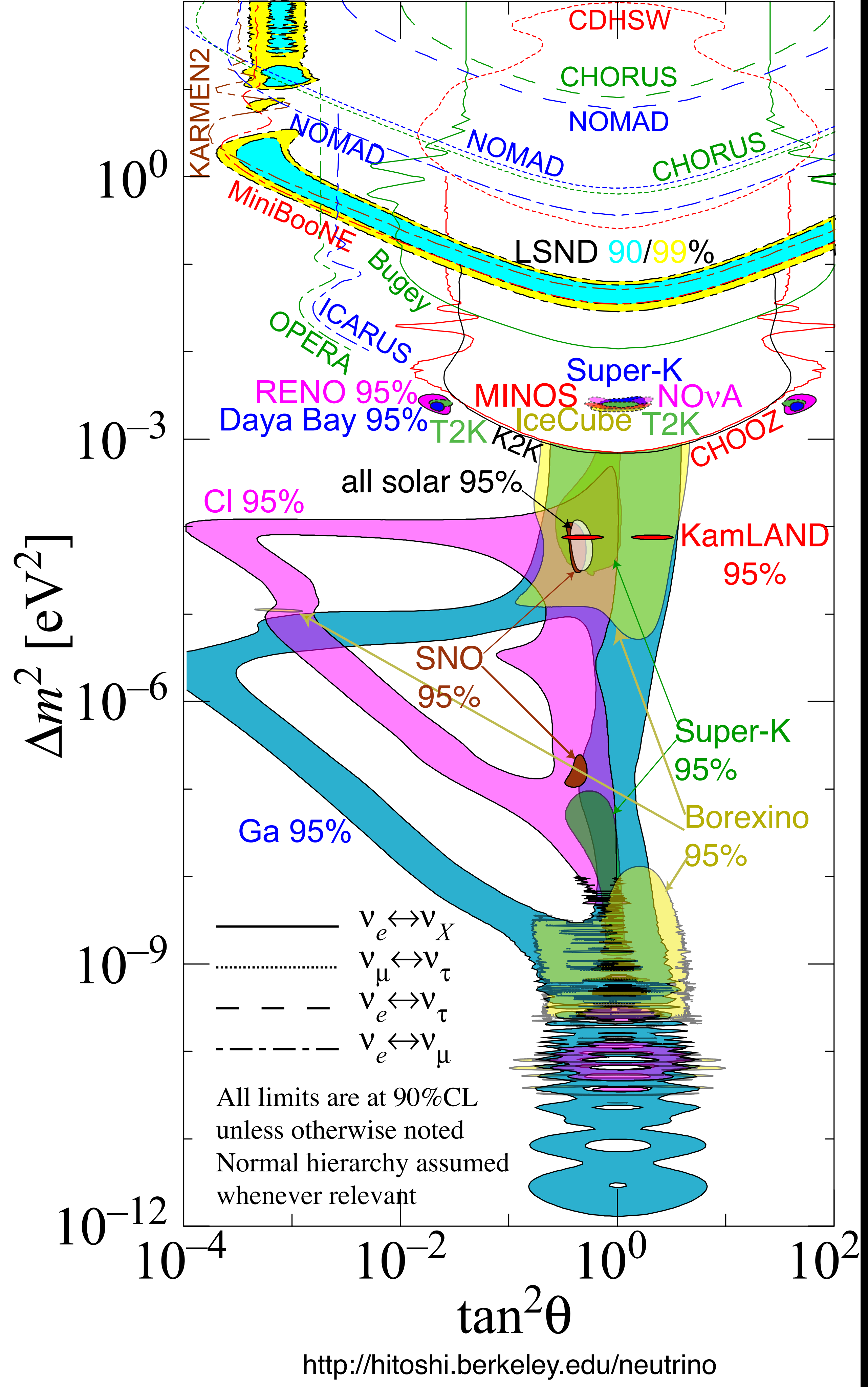
KamLAND
neutrinos do oscillate!



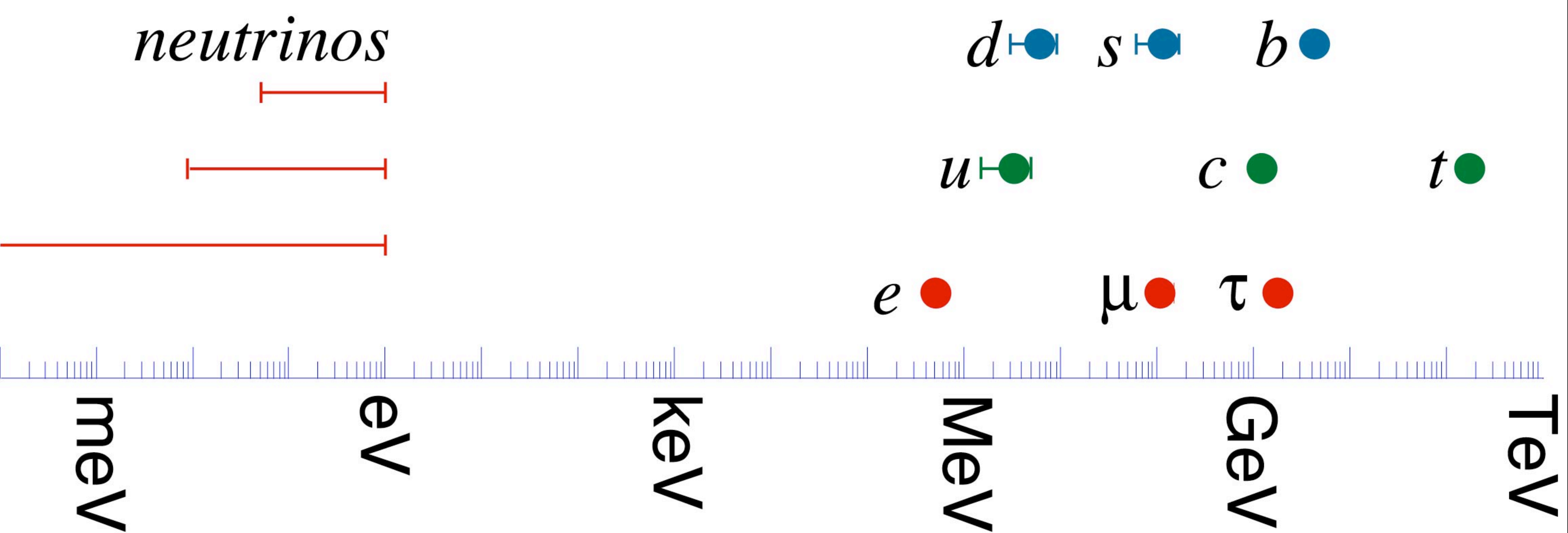
L_0=180 km

Lot of effort since '60s

Now we know *Neutrinos have tiny but finite mass*

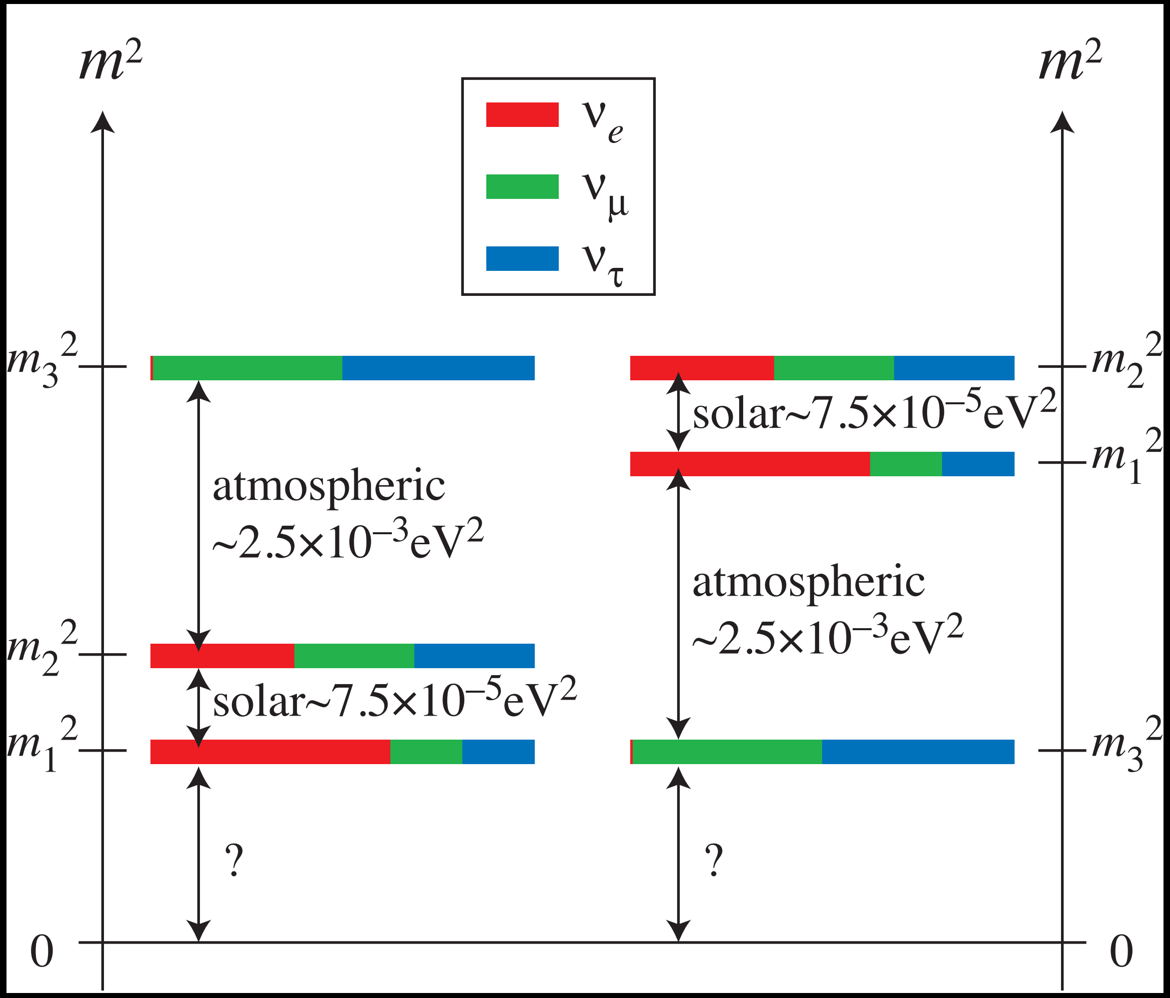


Neutrino Mass Beyond the Standard Model



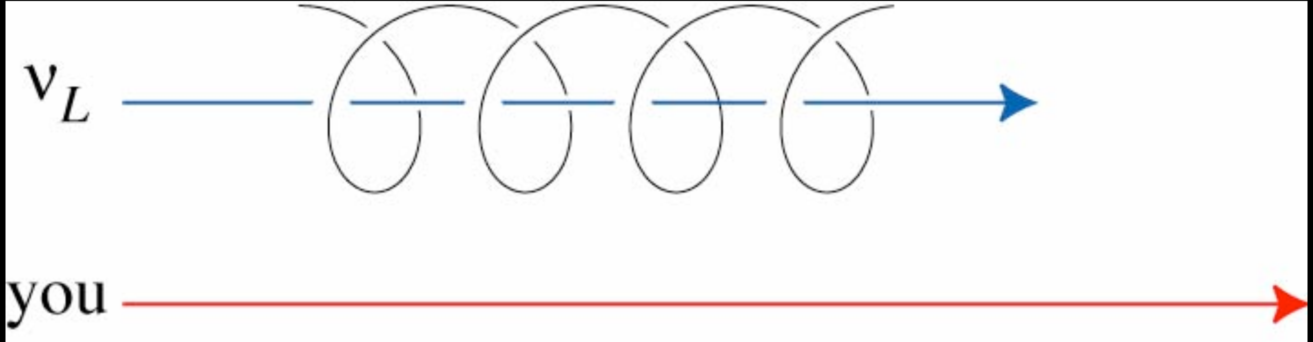
Questions

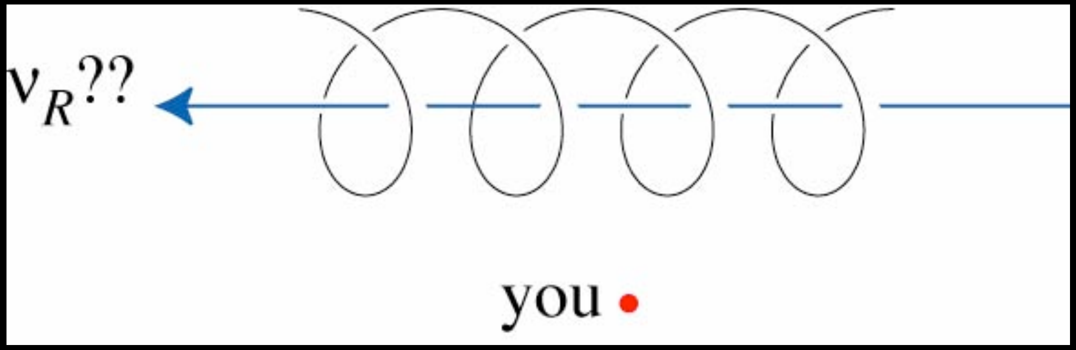
- mass hierarchy?
- mass scale?
- which octant?
- Is θ_{23} maximal?
- CP violation?
- Dirac or Majorana?
- sterile neutrinos?
- non-std interactions?
- origin of neutrino mass?
- seesaw? which type?
- leptogenesis?
- dark matter?



Neutrinos have mass

- They have mass. Can't go at speed of light.



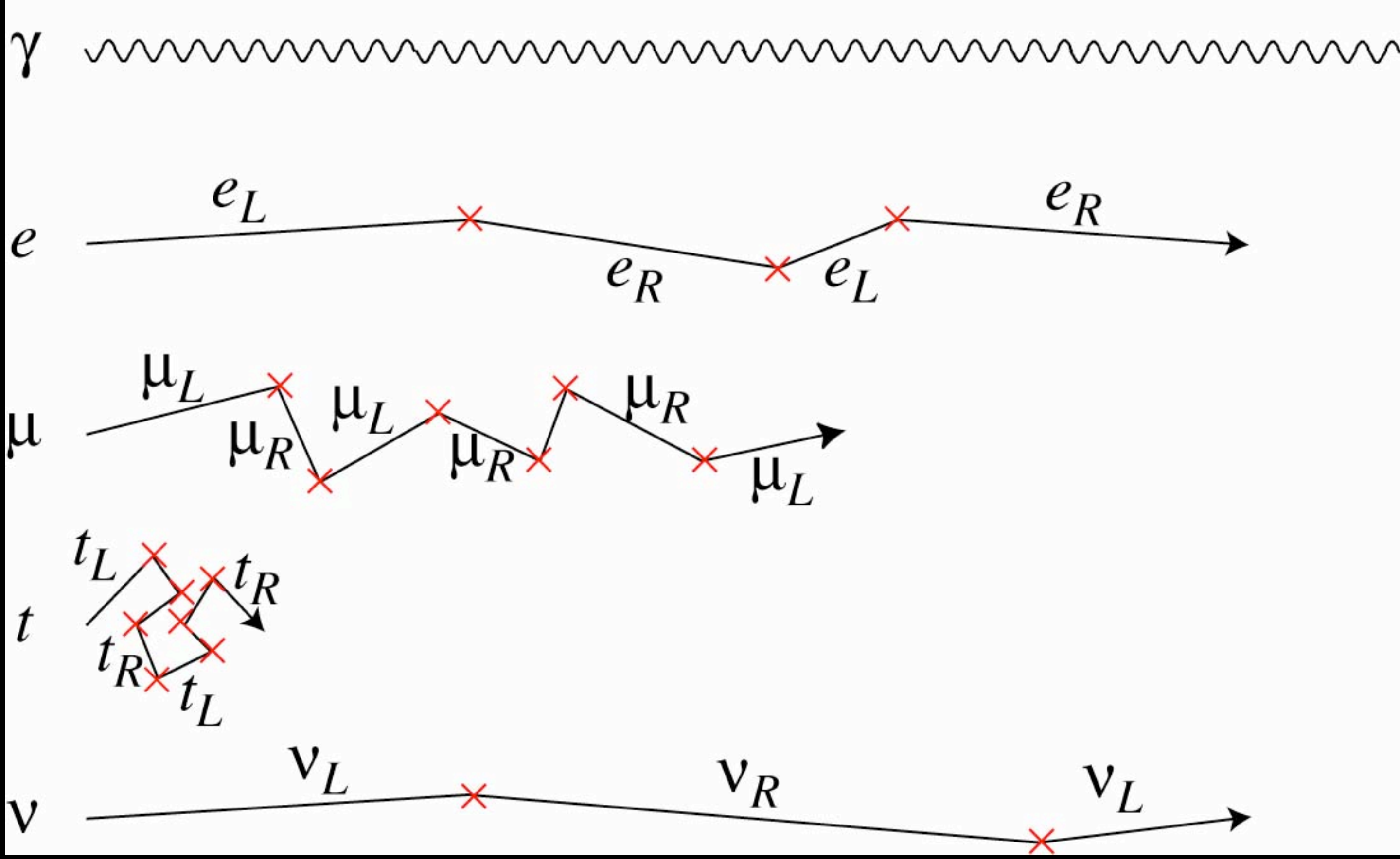


- **What is this right-handed particle?**
  - **New particle: right-handed neutrino (Dirac)**
  - **Old anti-particle: right-handed anti-neutrino (Majorana)**

Two ways to go

(1) Dirac Neutrinos:

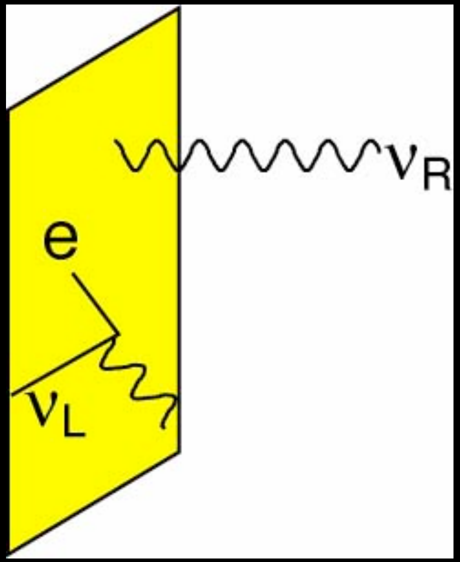
- **There are new particles, right-handed neutrinos, after all**
- **Why haven't we seen them?**
- **Right-handed neutrino must be *very very weakly coupled***
- **Why?**



Extra Dimension

- All charged particles are on a 3-brane
- Right-handed neutrinos SM gauge singlet

  ⇒ Can propagate in the "bulk"



- Makes neutrino mass small

  (Arkani-Hamed, Dimopoulos, Dvali, March-Russell; Grossman, Neubert; Barbieri, Strumia)

- Or SUSY breaking

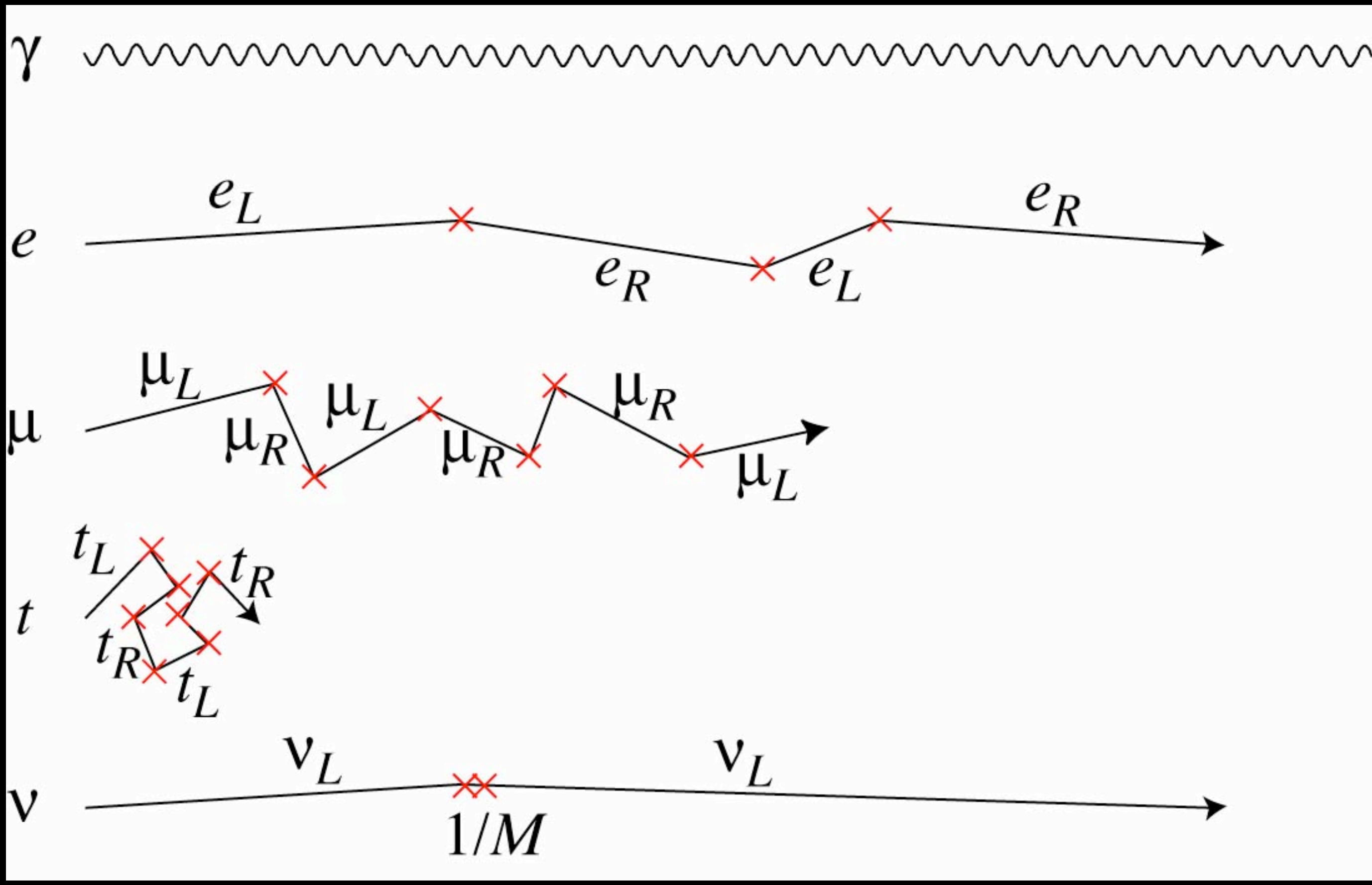
  (Arkani-Hamed, Hall, HM, Smith, Weiner; Arkani-Hamed, Kaplan, HM, Nomura)

- Or very low-scale physics??

Two ways to go

(2) Majorana Neutrinos:

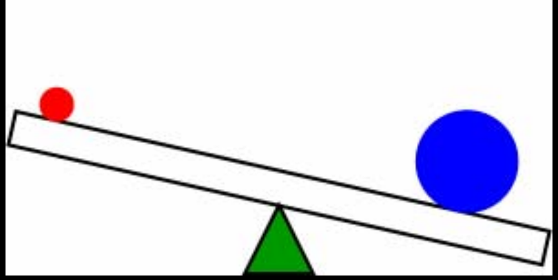
- **There are no new light particles**
- **What if I pass a neutrino and look back?**
- **Must be right-handed *anti*-neutrinos**
- **No fundamental distinction between neutrinos and anti-neutrinos!**



Seesaw Mechanism

- Why is neutrino mass so small?
- Need right-handed neutrinos to generate neutrino mass , but ν_R SM neutral

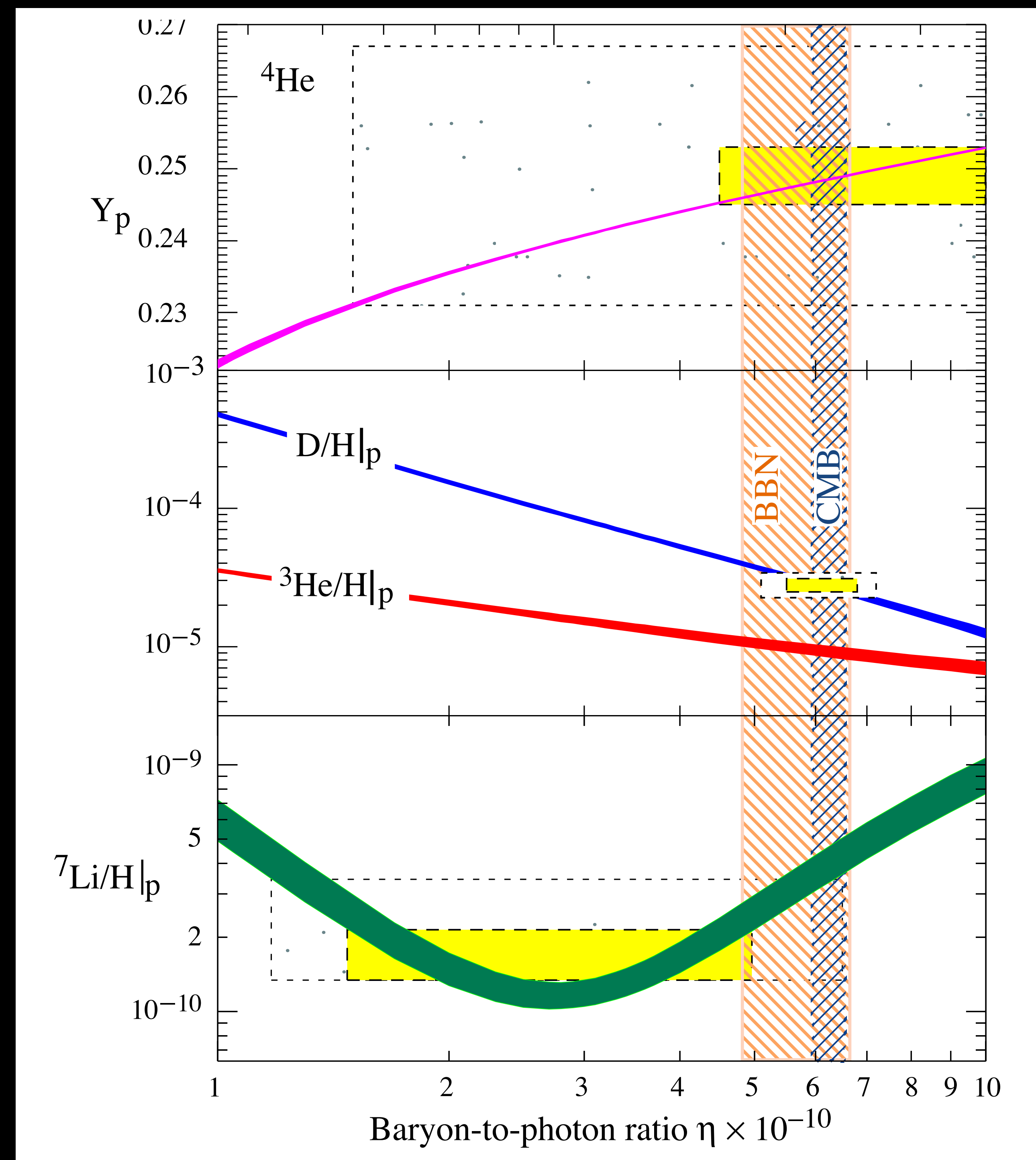
$$\begin{pmatrix} \nu_L & \nu_R \end{pmatrix} \begin{pmatrix} & m_D \\ m_D & M \end{pmatrix} \begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix} \qquad m_\nu = \frac{m_D^2}{M} << m_D$$



To obtain $m_3 \sim (\Delta m^2_{\mathrm{atm}})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

BBN & CMB

- At T>MeV, the soup of $e^+, e^-, \nu, \bar{\nu}$
- small amount of p, n
- they start to fuse, forming light elements
- abundance of light elements depends on amount of baryon
- baryon asymmetry consistent with T~MeV and T~0.3eV



Early Universe

matter	anti-matter
1,000,000,002	1,000,000,000

Current Universe

2

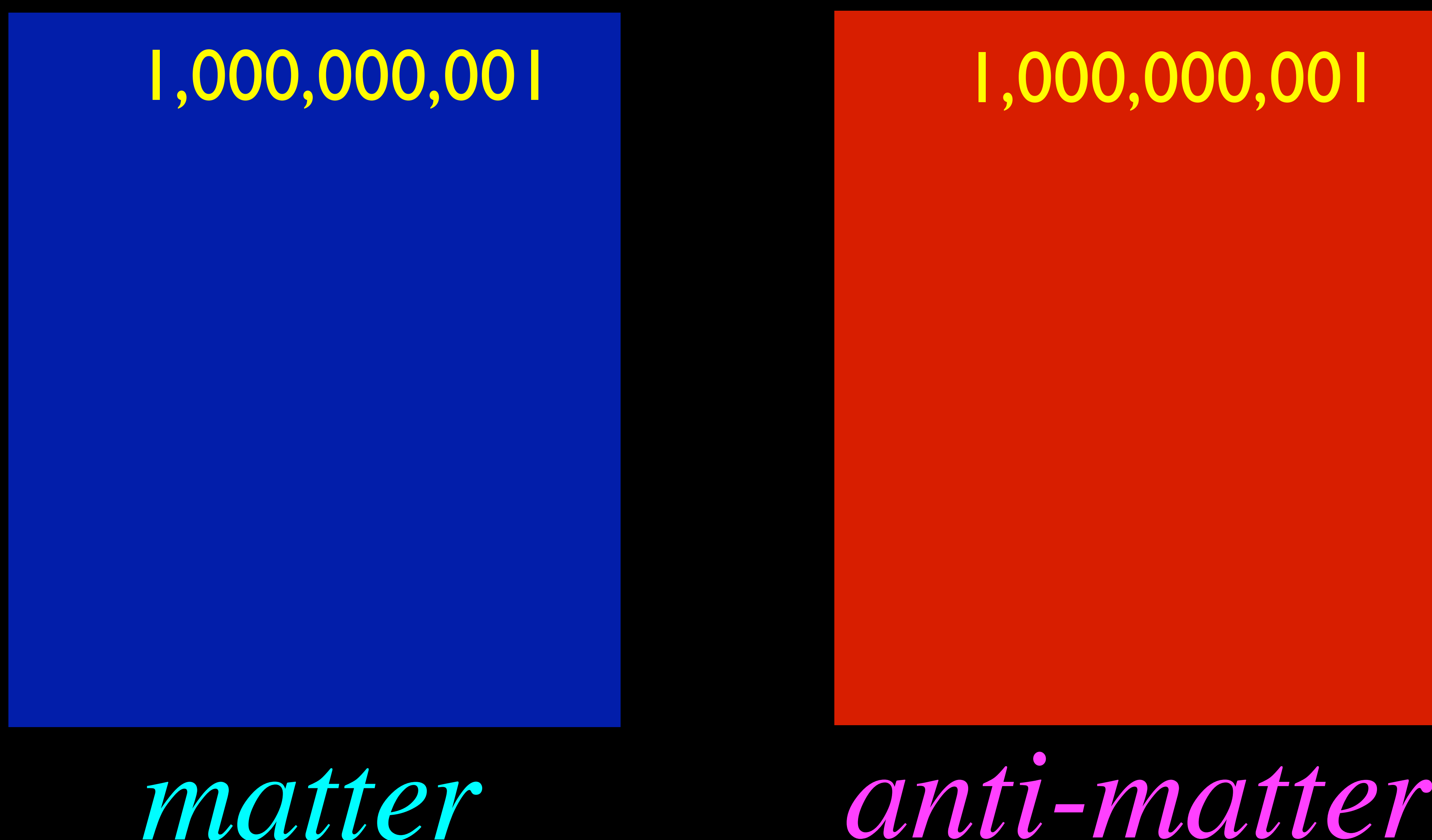
•

us

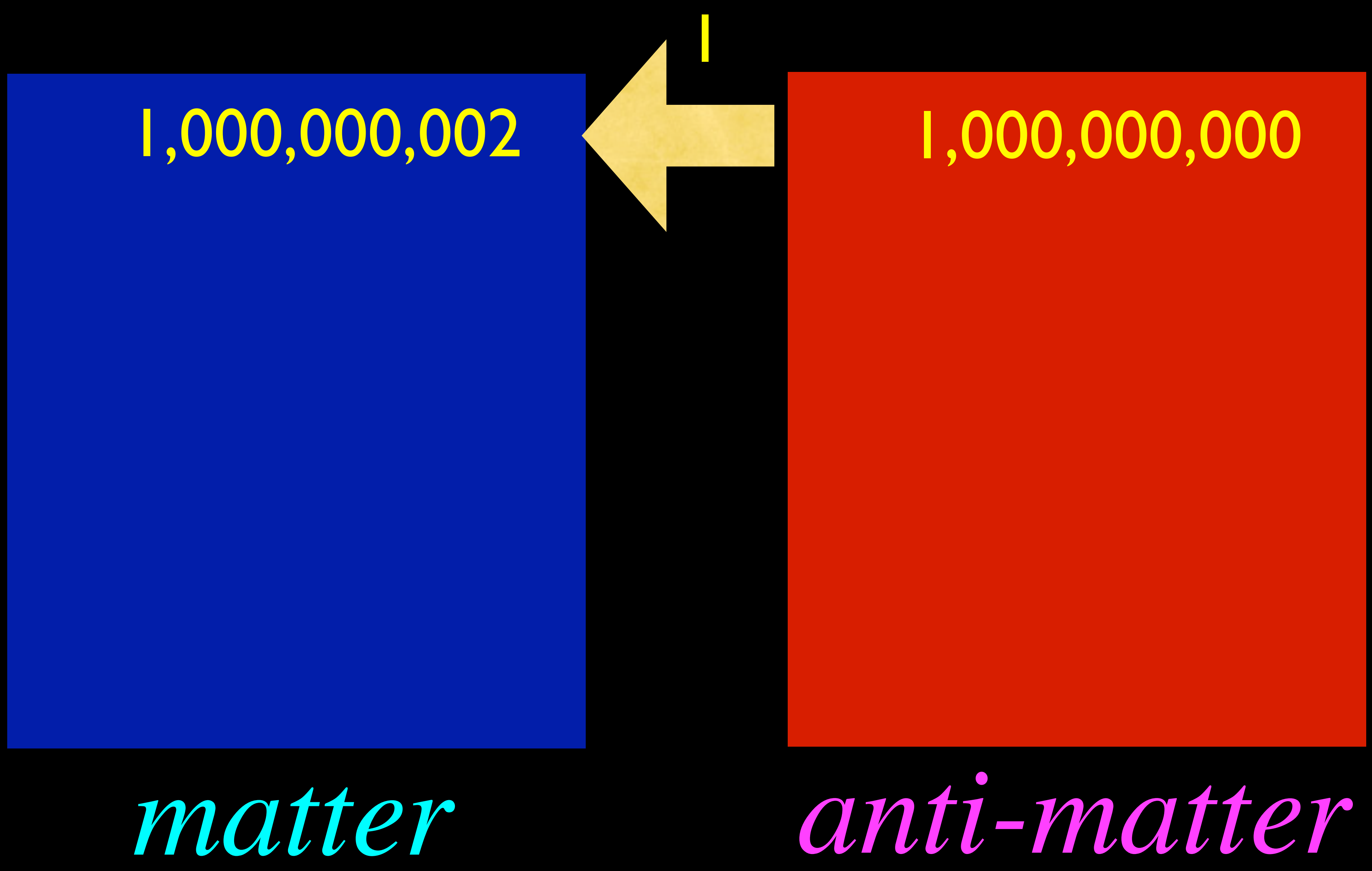
matter *anti-matter*

We won! But *why?*

Beginning of Universe



fraction of second later



turned an anti-matter out of a billion to matter

Universe Now

2

us

matter

anti-matter

This must be how we survived the Big Bang!

2008 Nobel Prize

CP Violation

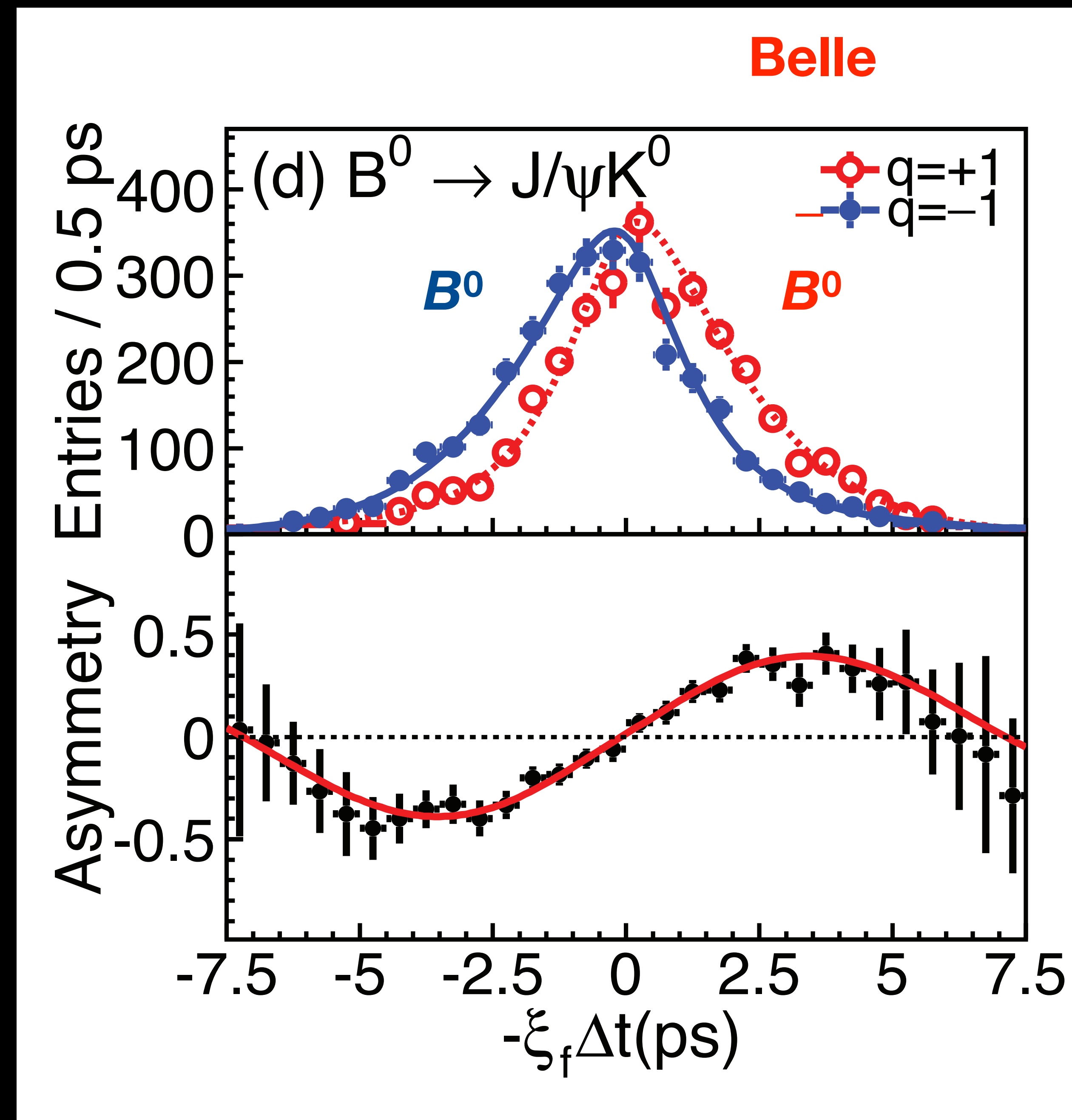
- Is anti-matter the exact mirror of matter?

1964 discovery of CP violation

- But only one system, hard to tell what is going on.

2001, 2002 Two new CP-violating phenomena

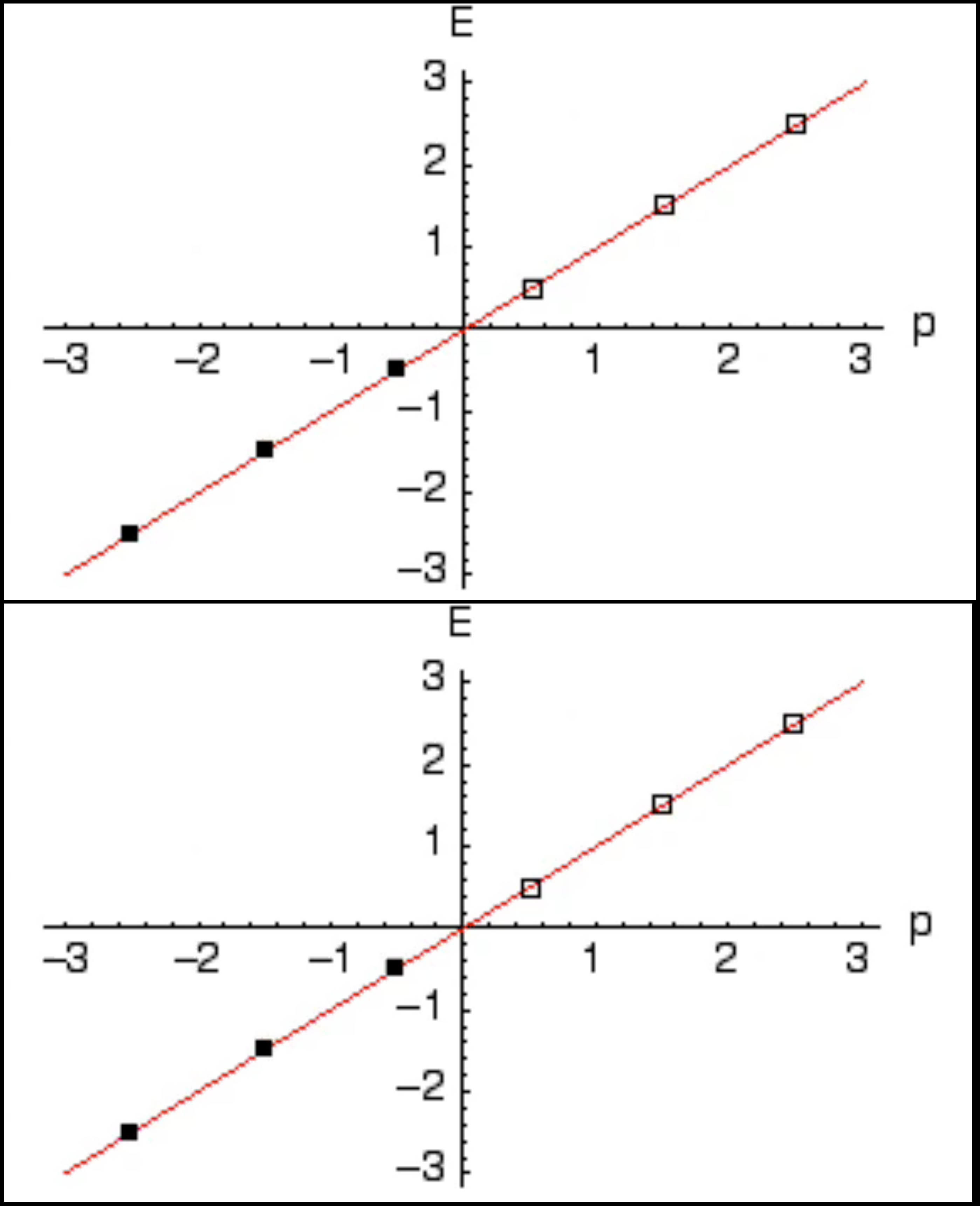
- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
- doesn't look like quarks are important here



Anomaly!

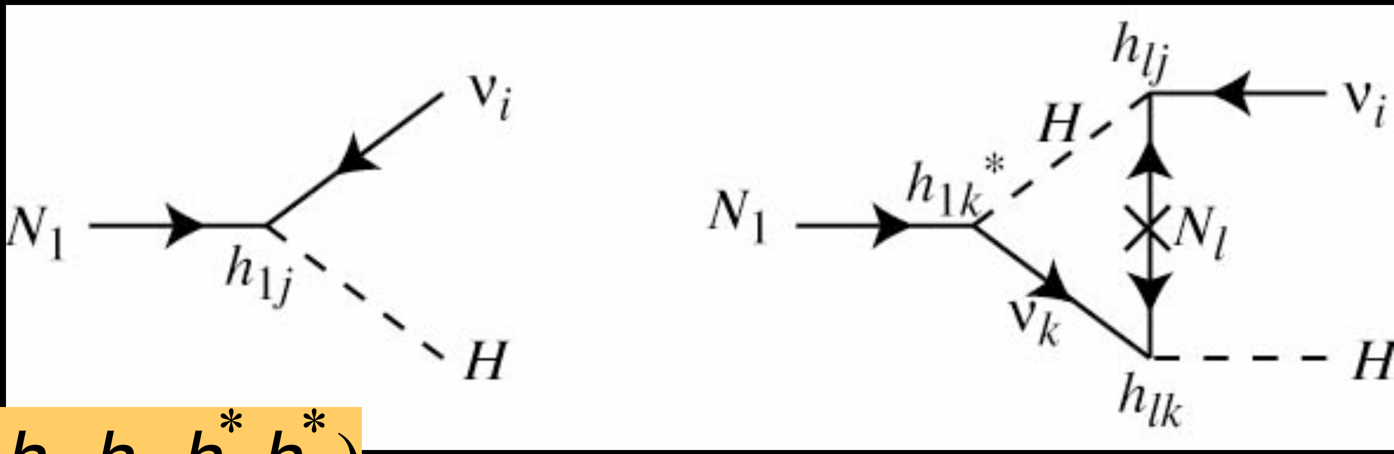
- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field

$\Delta q = \Delta q = \Delta q = \Delta L$



Leptogenesis

- You generate *Lepton Asymmetry* first.
- Generate *L* from the direct CP violation in right-handed neutrino decay
- *Like ε'/ε!*



$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H) \propto \mathrm{Im}(h_{1j} h_{1k} h_{lk}^* h_{lj}^*)$$

- *L* gets converted to *B* via EW anomaly

  ⇒ More matter than anti-matter

  ⇒ *Neutrinos saved us from complete annihilation*


DISNEY PRESENTS A PIXAR FILM
THE IνCREDIBLES
NOW PLAYING
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Excitement

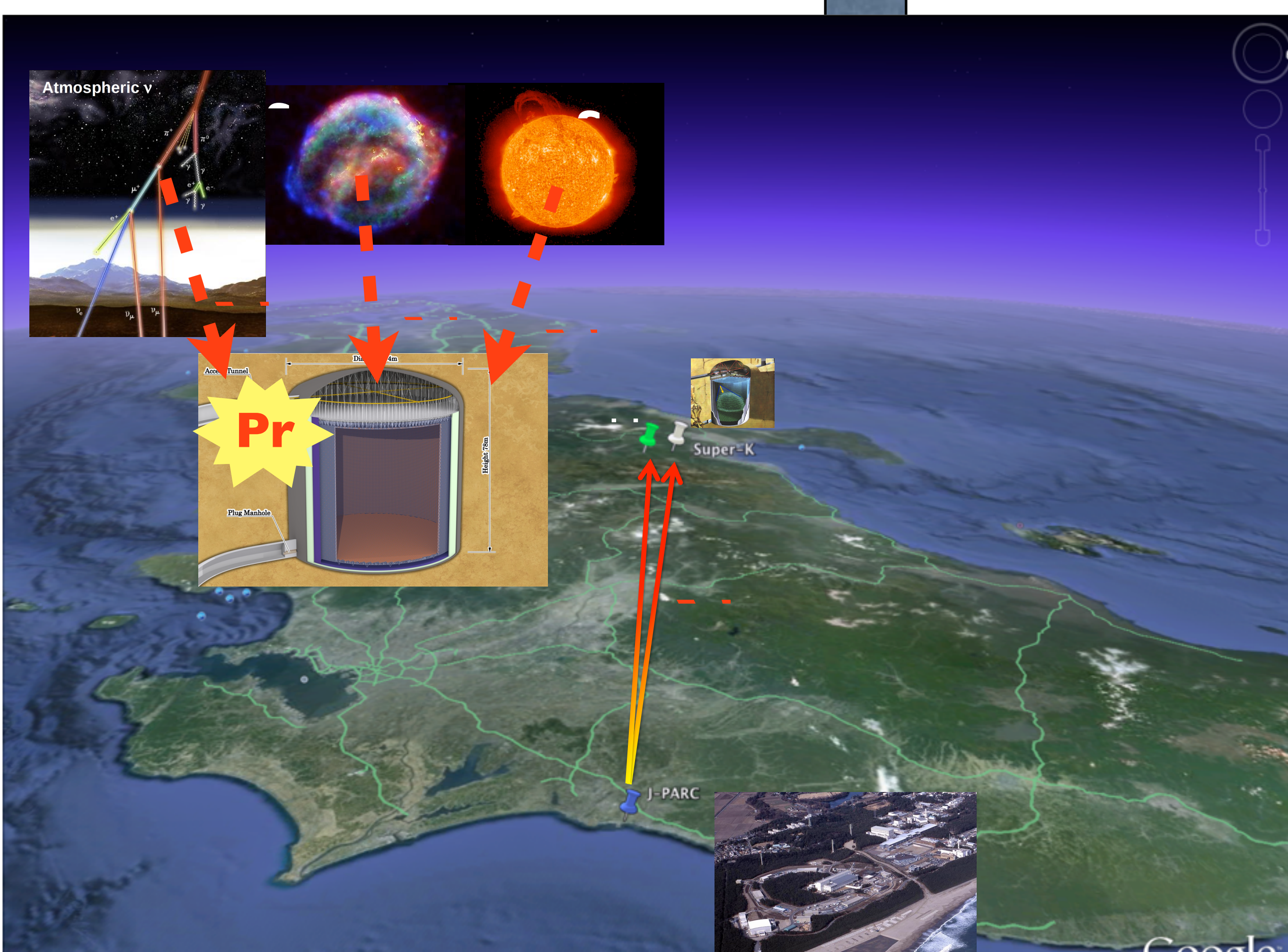
- CP violation in neutrino sector may be observable with conventional technique

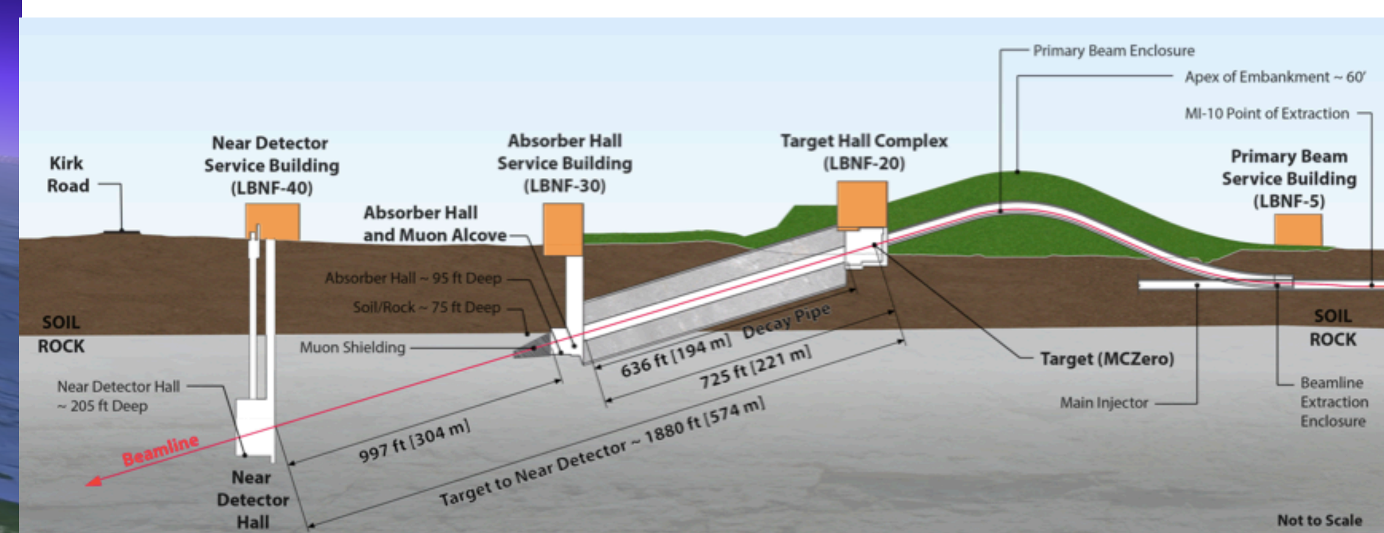
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16\boxed{s_{12}}c_{12}\boxed{s_{13}}c_{13}^2\boxed{s_{23}}c_{23}\sin\delta\sin\frac{\boxed{\Delta m^2_{12}}L}{4E}\sin\frac{\boxed{\Delta m^2_{13}}L}{4E}\sin\frac{\boxed{\Delta m^2_{23}}L}{4E}$$

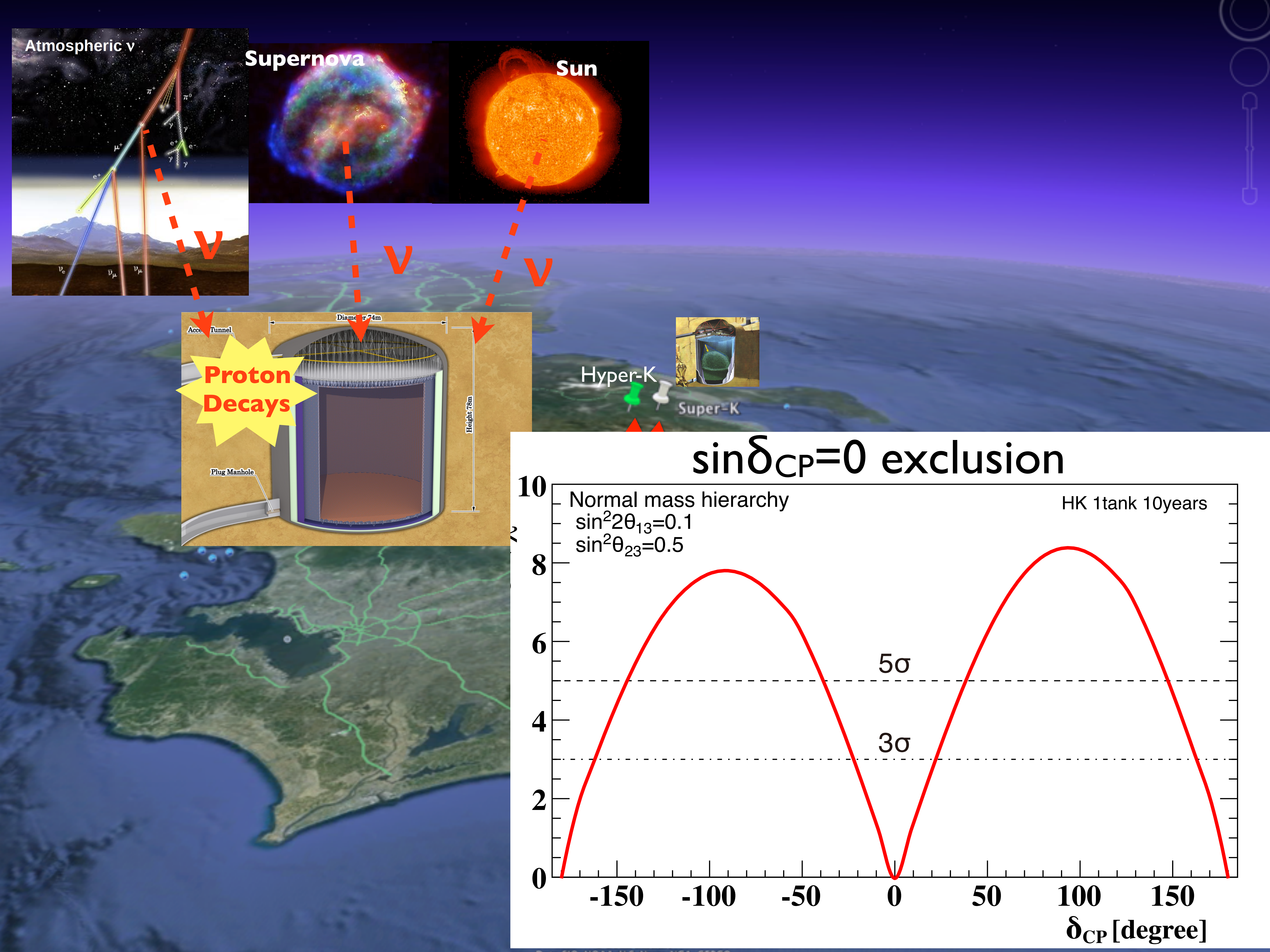
2002
KamLAND
SNO

2012
Daya
Bay

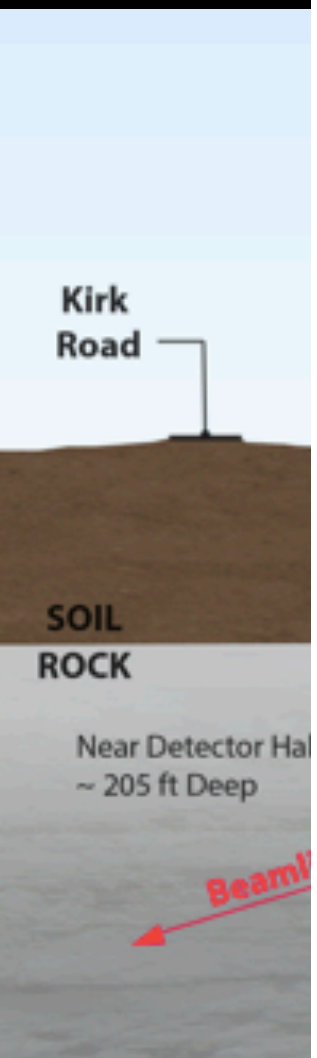
1998
Super-K

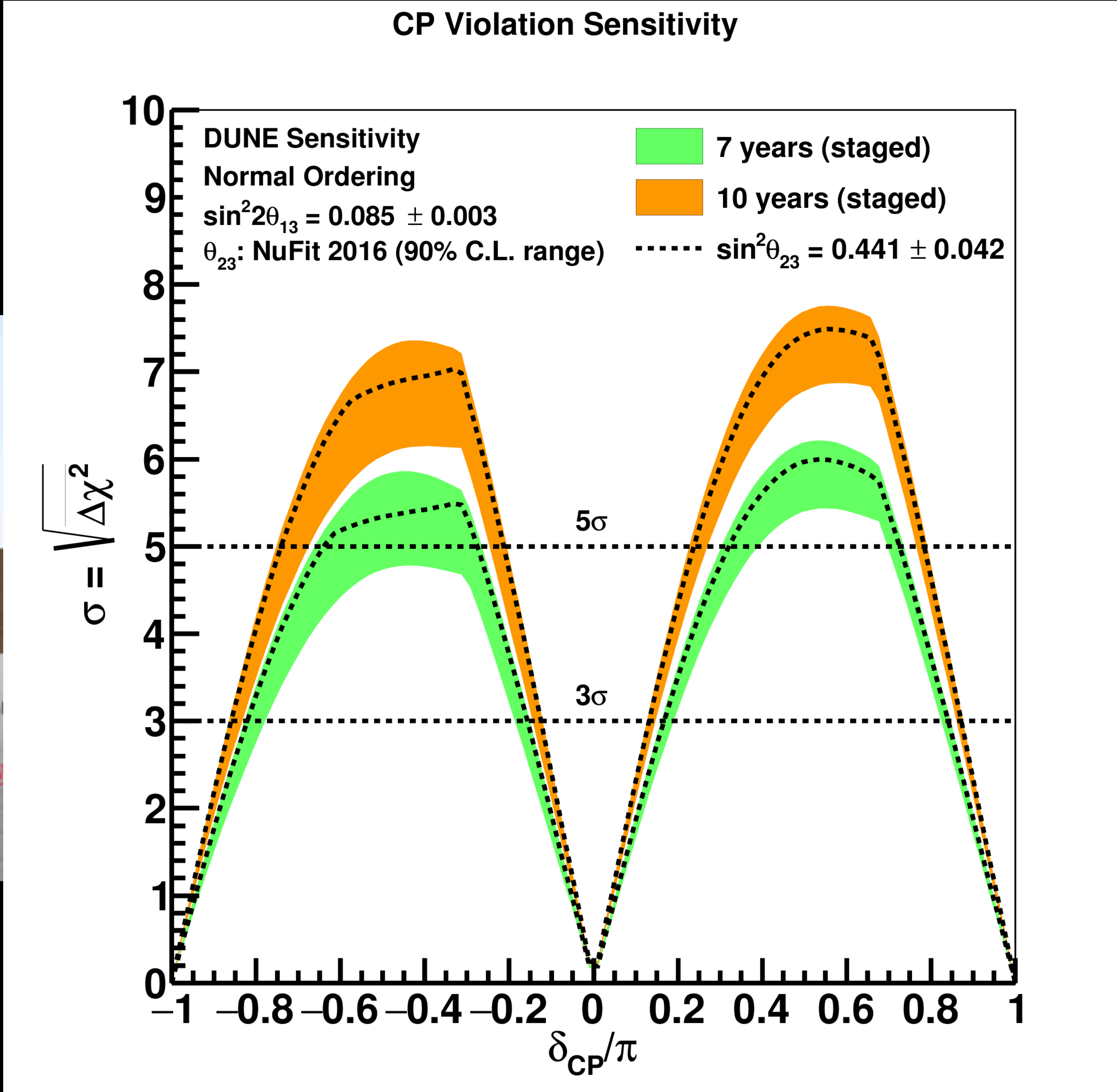


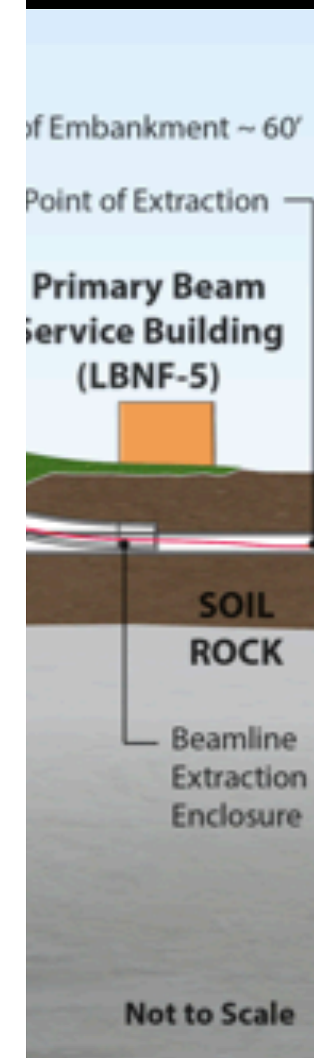




Atmospheric ν
Supernova
Sun
ν
ν
ν
Proton Decays
Plug Manhole
Hyper-K
Super-K
sinδCP=0 exclusion
Normal mass hierarchy
sin²2θ13=0.1
sin²θ23=0.5
HK 1tank 10years
5σ
3σ
0
2
4
6
8
10
-150
-100
-50
0
50
100
150
δCP [degree]


Kirk
Road
SOIL
ROCK
Near Detector Hal
~ 205 ft Deep


CP Violation Sensitivity
DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
θ_{23}: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
$\sin^2\theta_{23} = 0.441 \pm 0.042$
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
δ_{CP}/π
0
1
2
3
4
5
6
7
8
9
10
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1


Point of Extraction
Primary Beam
(LBNF-5)
SOIL
ROCK
Beamline
Extraction
Enclosure
Not to Scale

東京大学
THE UNIVERSITY OF TOKYO

The University of Tokyo

Hongo, Bunkyo-ku, Tokyo 113-8654, Japan

September 12th, 2018

Concerning the Start of Hyper-Kamiokande

Seed funding towards the construction of the next-generation water Cherenkov detector Hyper-Kamiokande has been allocated by the Ministry of Education, Culture, Sports, Science and Technology (MEXT) within its budget request for the 2019 fiscal year. Seed fundings in the past projects usually lead to full funding in the following year, as it was the case for the Super-Kamiokande project.

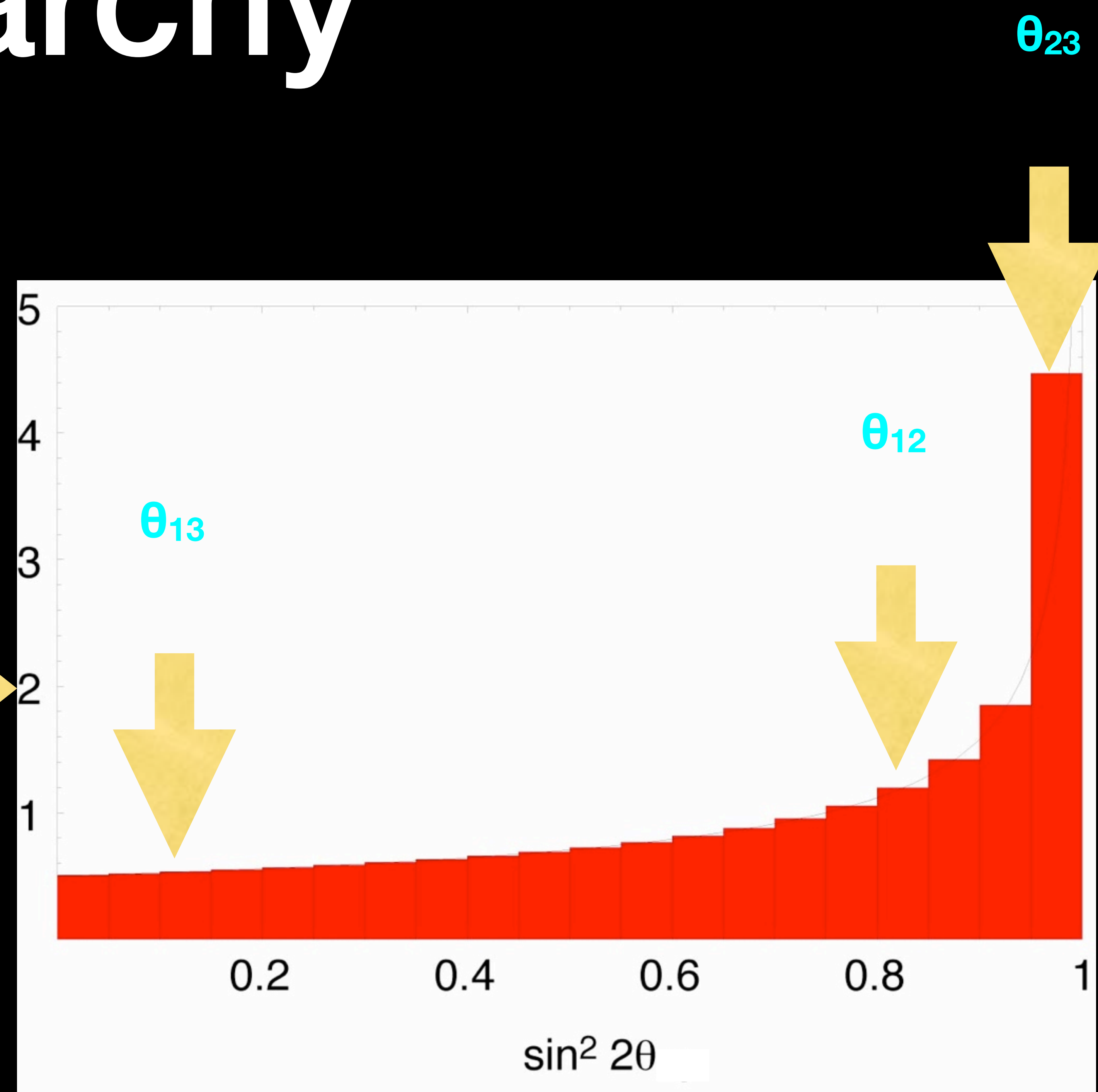
The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

The neutrino research that lead to Nobel prizes for Special University Professor Emeritus Koshiba and Distinguished University Professor Kajita has entered a new era. The international community has demonstrated the need for Hyper-Kamiokande. The considerable expertise and achievements of the University of Tokyo and Japan, and unique and invaluable contributions from national and international collaborators will ensure the project will make significant contributions to the intellectual progress of the world.

Makoto Gonokami

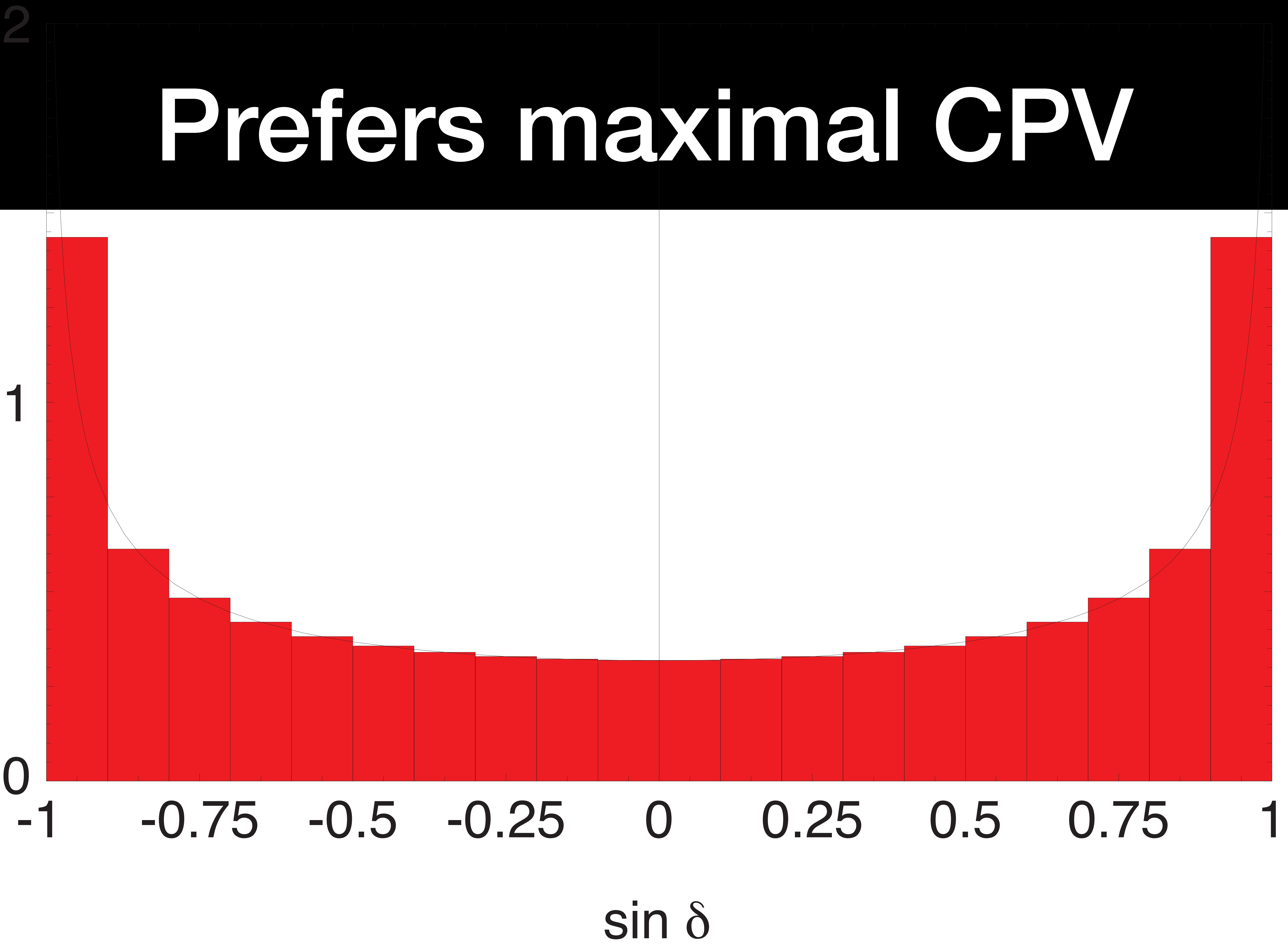
Makoto Gonokami
President, The University of Tokyo

anarchy



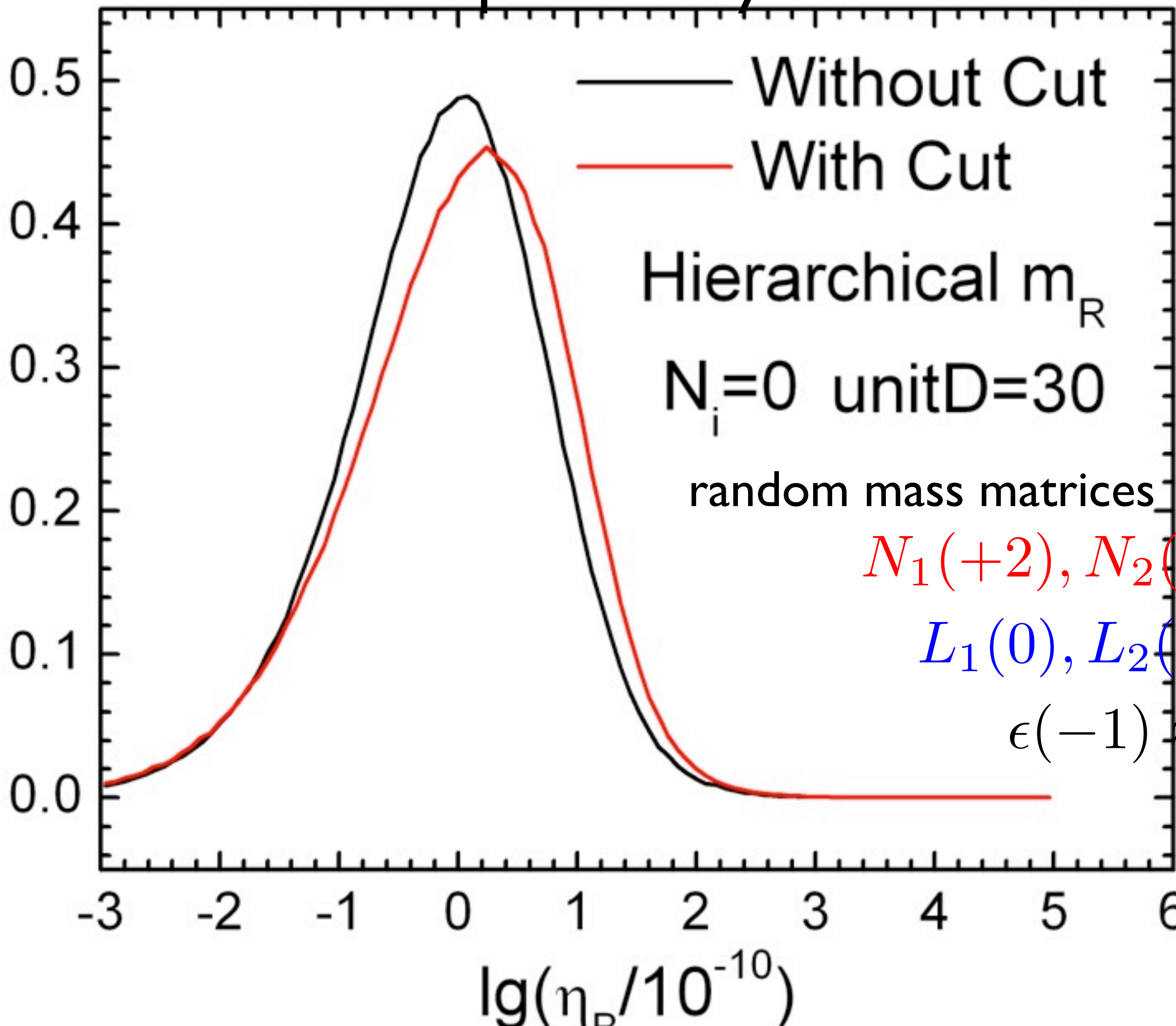
Kolmogorov-Smirnov test (de Gouvêa, HM)
nature has 47% chance to choose this kind of numbers

Prefers maximal CPV



no direct connection to CP violation in oscillation

but a plausibility test



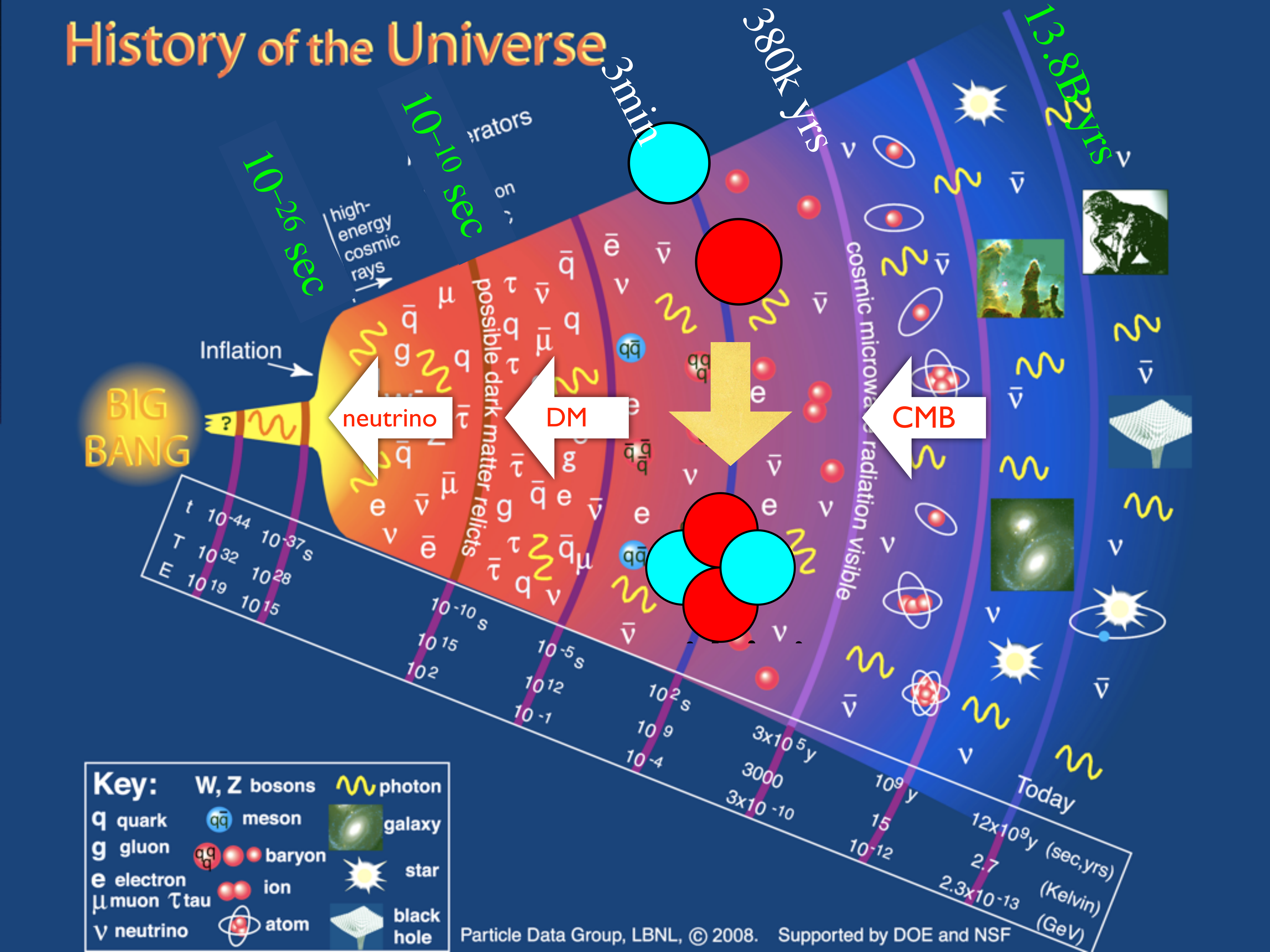
random mass matrices

$N_1(+2), N_2(+1), N_3(0)$

$L_1(0), L_2(0), L_3(0)$

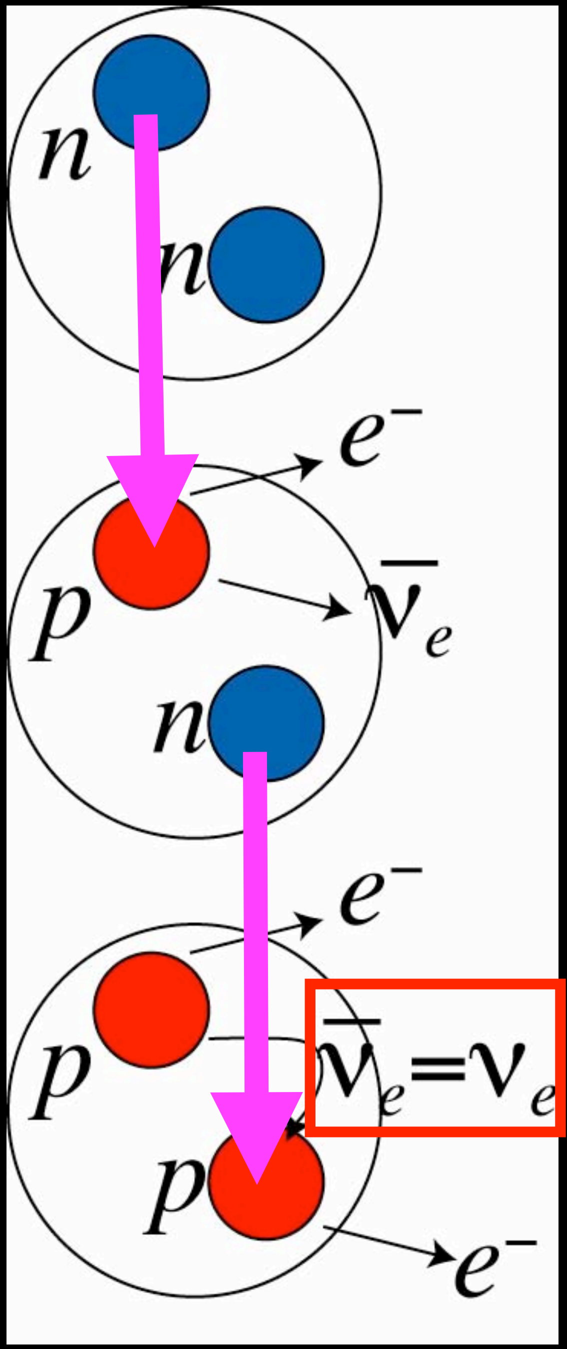
$\epsilon(-1) \approx 0.1$

Xiaochuan Lu, Murayama


History of the Universe
10−26 sec
10−10 sec
3min
380k yrs
13.8Byrs
high-energy cosmic rays
Inflation
BIG BANG
neutrino
DM
CMB
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10-12 2.3x10-13 (GeV)
Today
Key:
q quark
g gluon
e electron
µ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

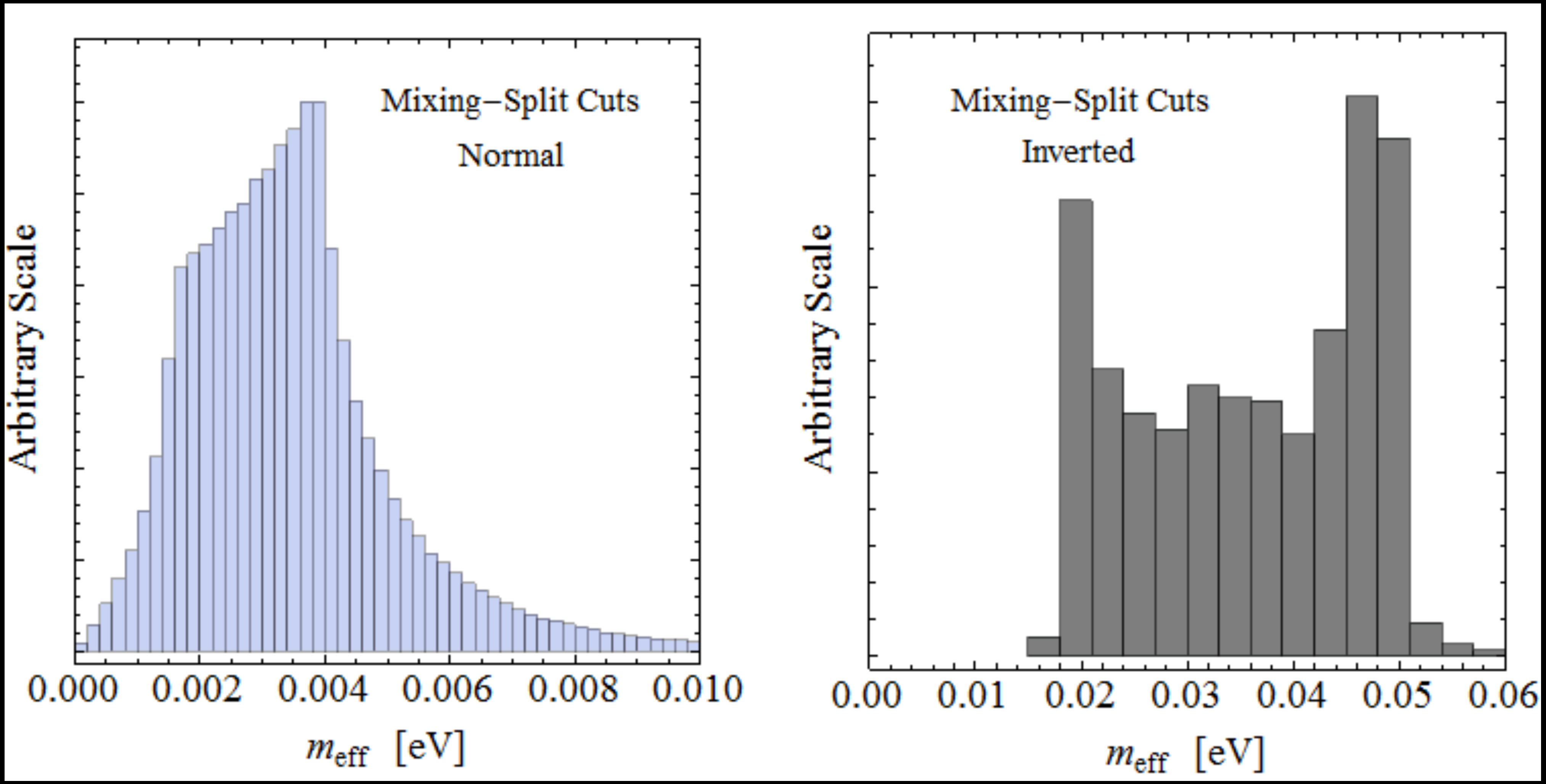
Can anti-matter turn into matter?

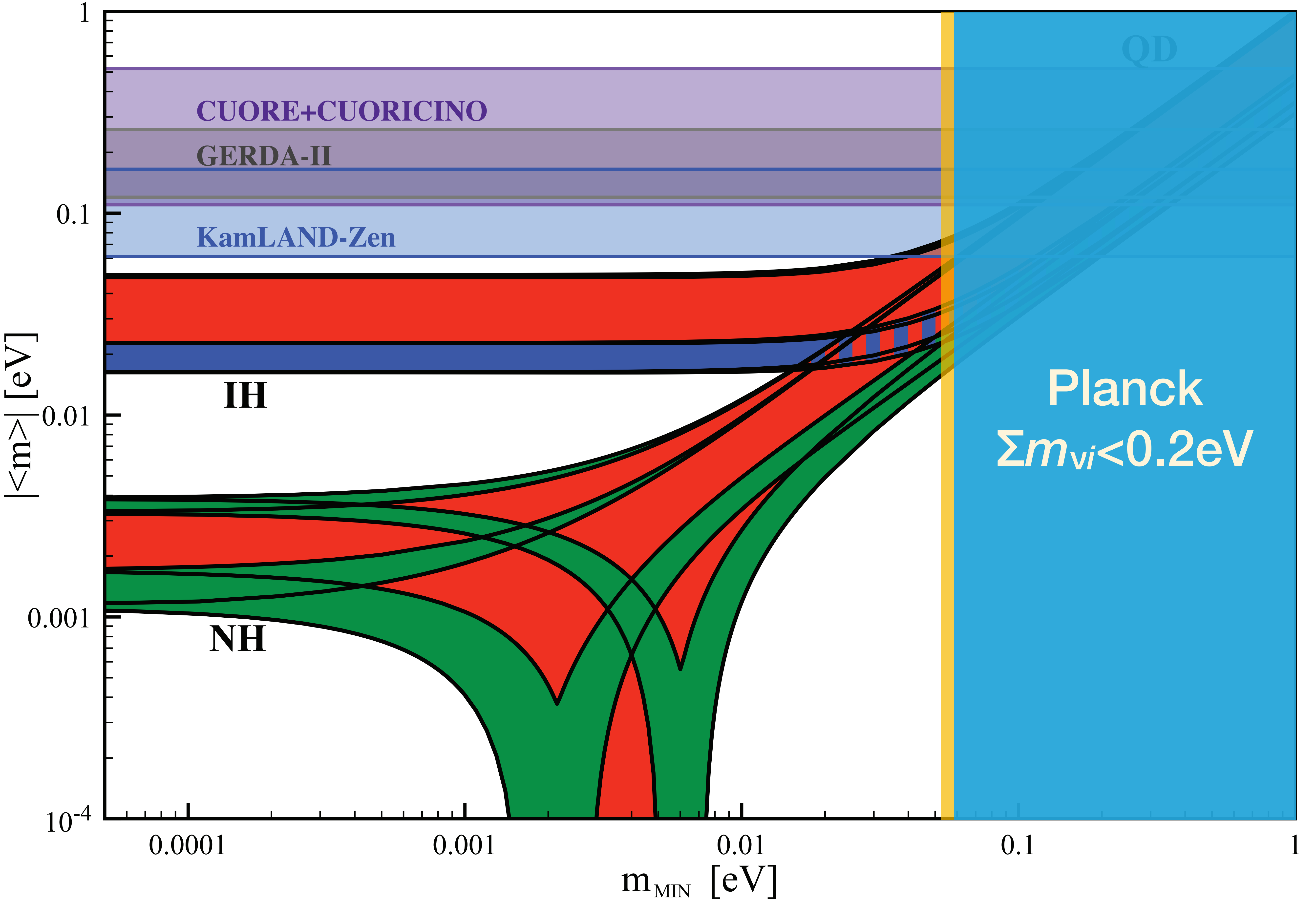
- proton is positively charged, anti-proton negatively
- can never turn into each other
- But neutrinos or anti-neutrinos do not have electric charge
- neutrinoless double beta decay: $nn \to ppe^- e^-$
- can we look for anti-matter turning into matter?



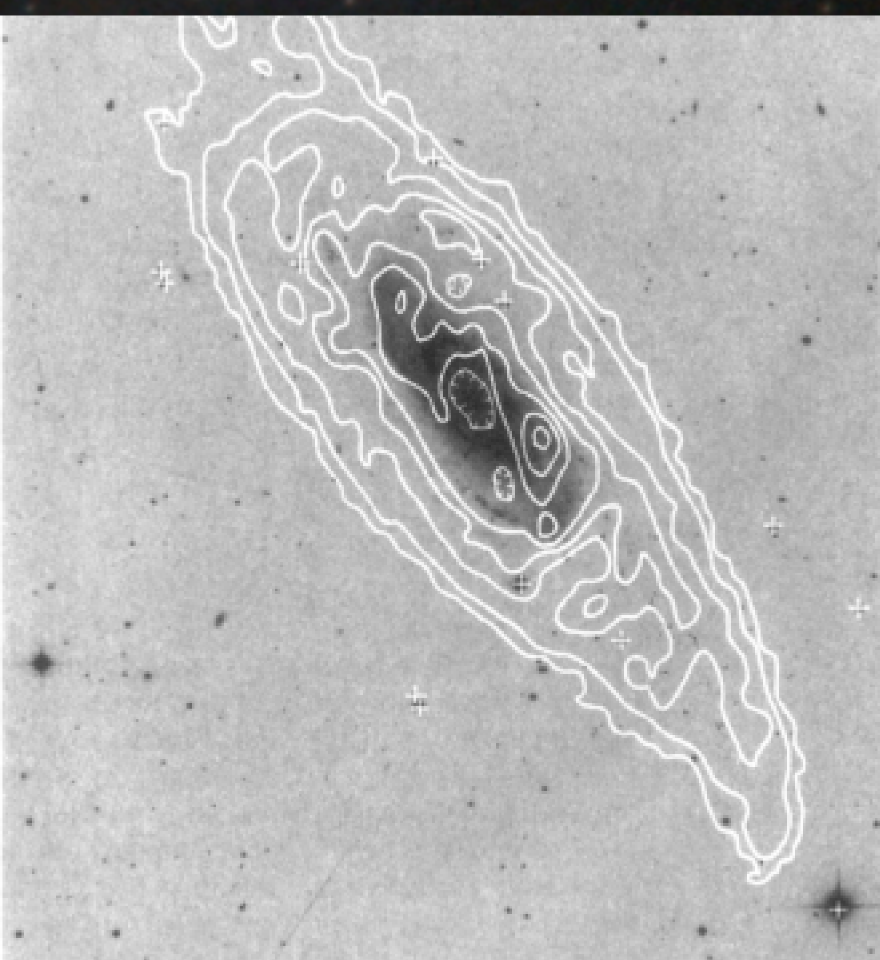
Not easy

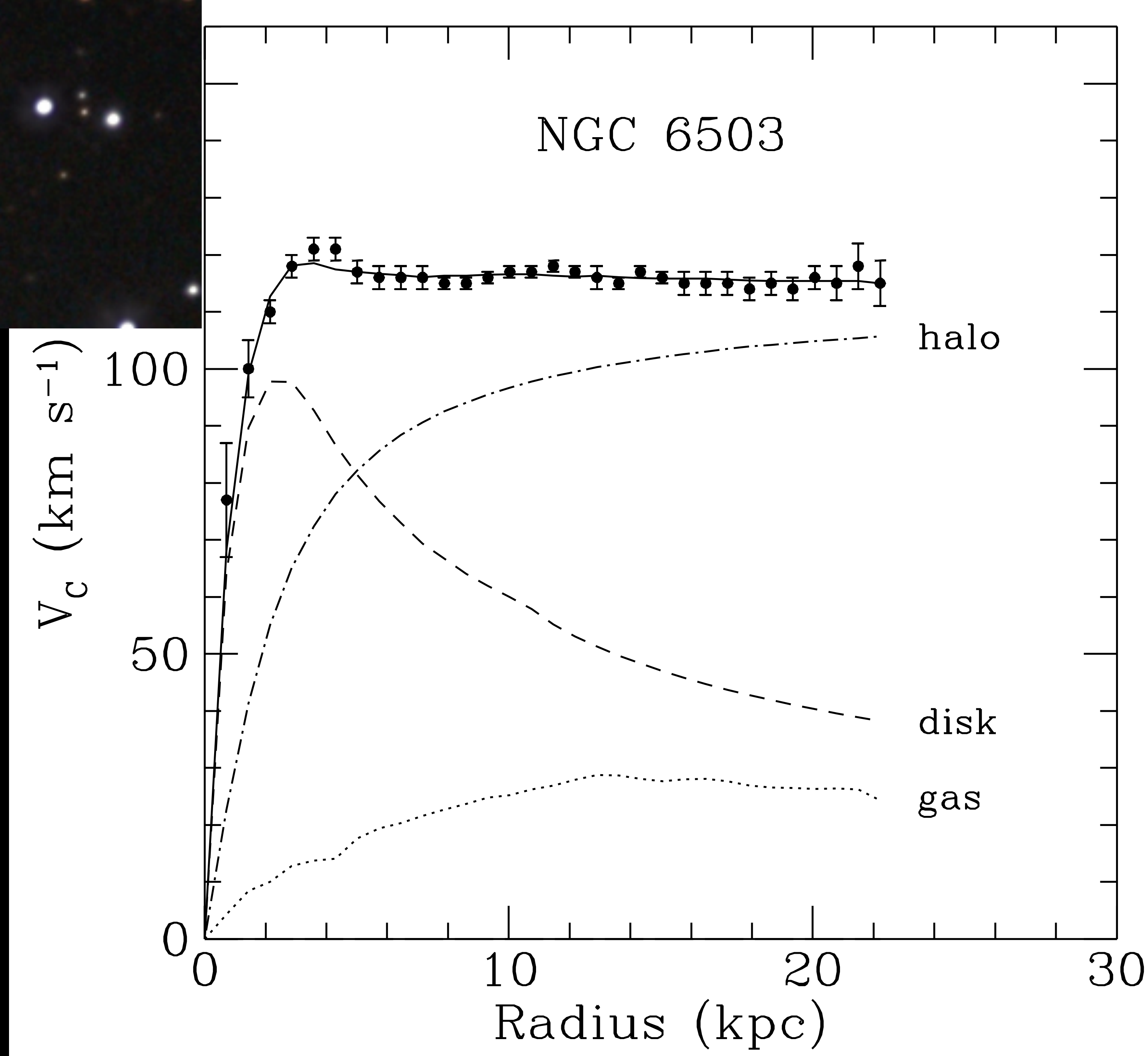
- anarchy prefers normal hierarchy
- quite difficult to reach the sensitivity levels
- but if LBL discovers inverted hierarchy, it is in a much better shape!



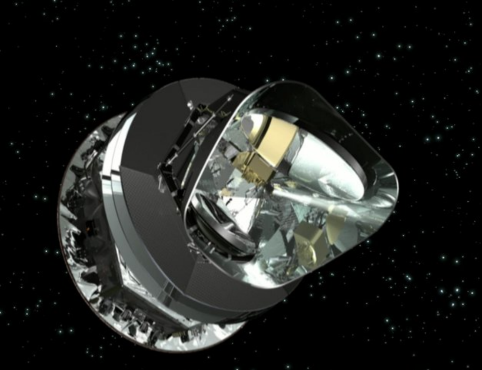


CUORE+CUORICINO
GERDA-II
KamLAND-Zen
QD
IH
NH
Planck
Σ$m_{\nu i}$<0.2eV
|<m>| [eV]
m_{MIN} [eV]
1
0.1
0.01
0.001
10^{-4}
0.0001
0.001
0.01
0.1
1




NGC 6503
halo
disk
gas
V_c (km s^{-1})
0
50
100
0
10
20
30
Radius (kpc)


cluster of galaxies
Abell 2218
2.1B lyrs

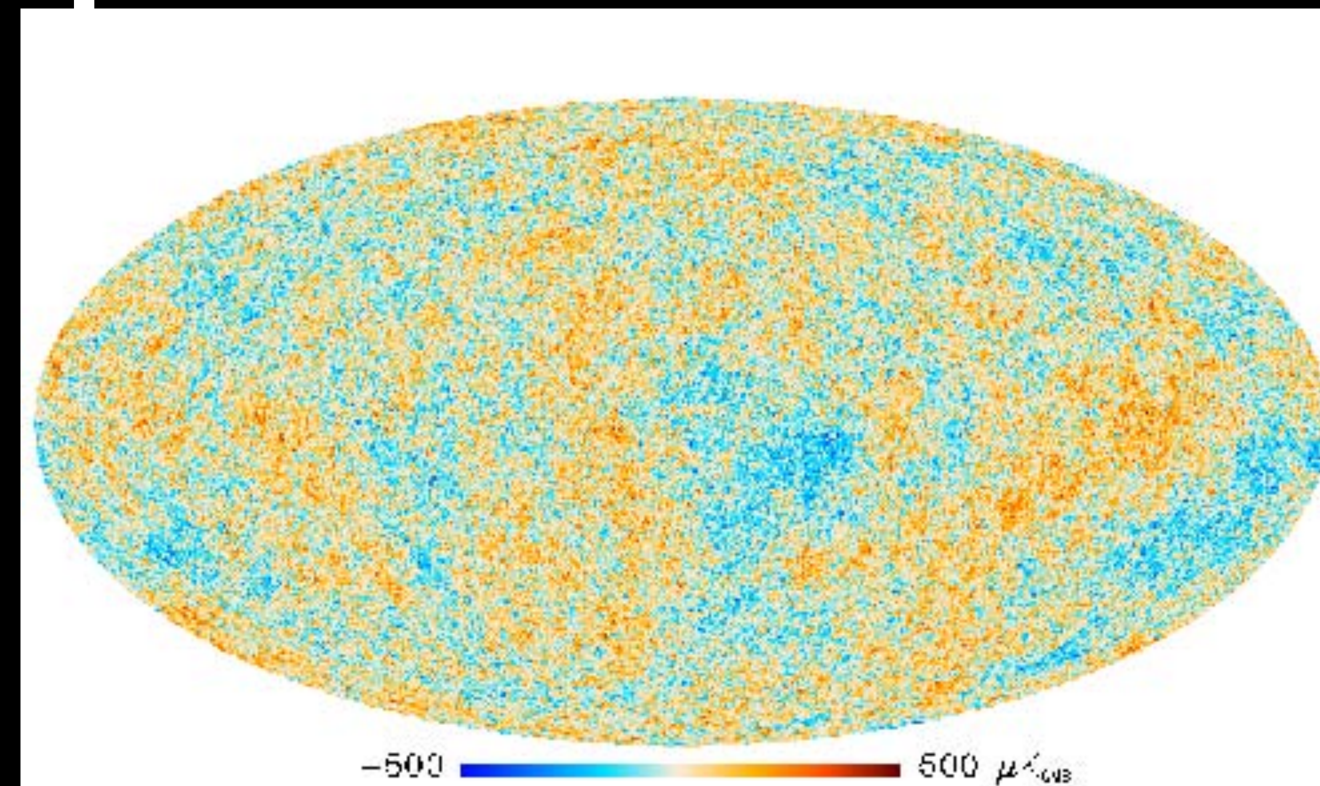


assumption

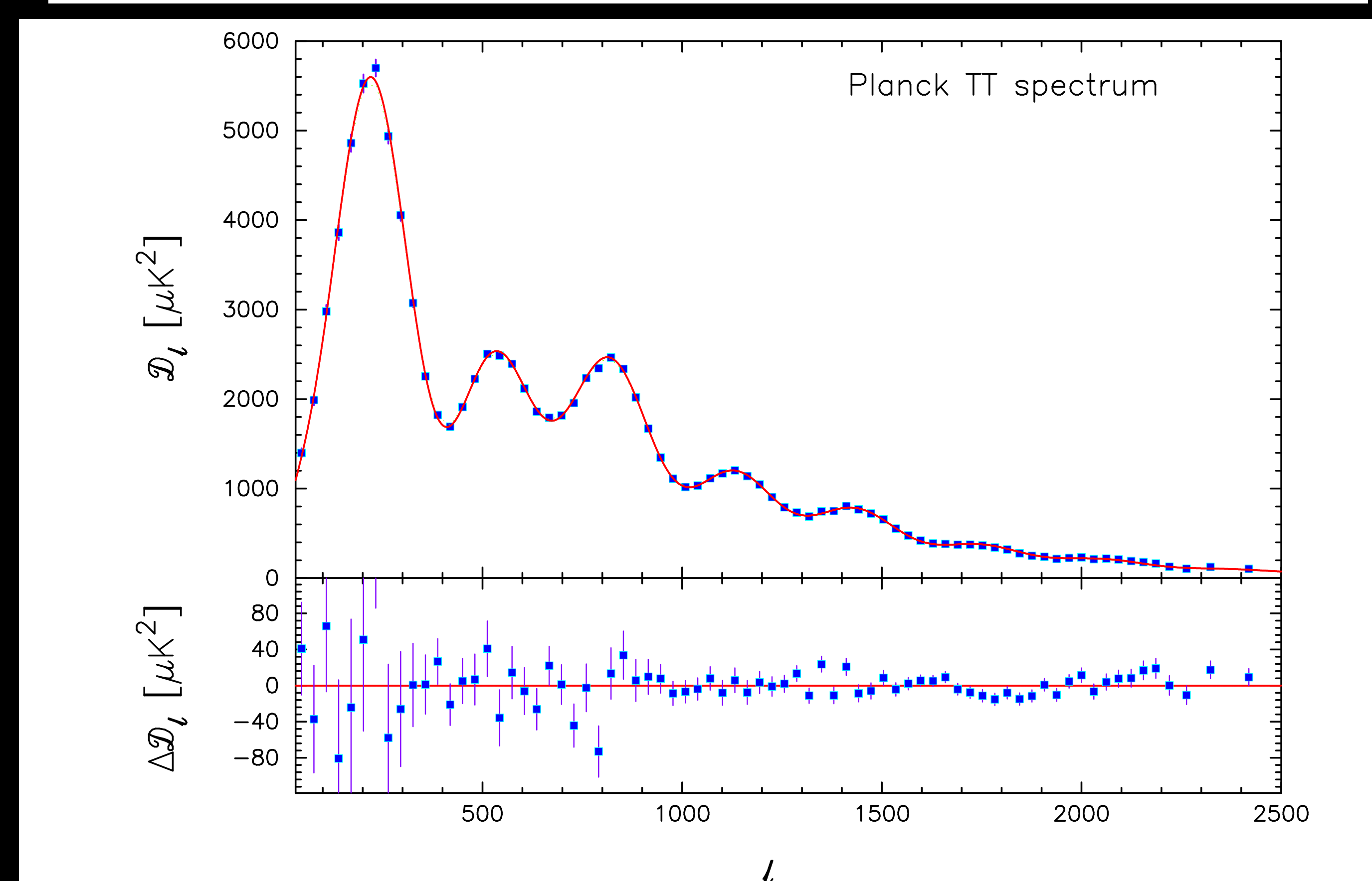
- a random density fluctuations ~O(10^{-5}) more-or-less scale invariant $P(k) \propto k^{n_s-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between $0<z<1300$

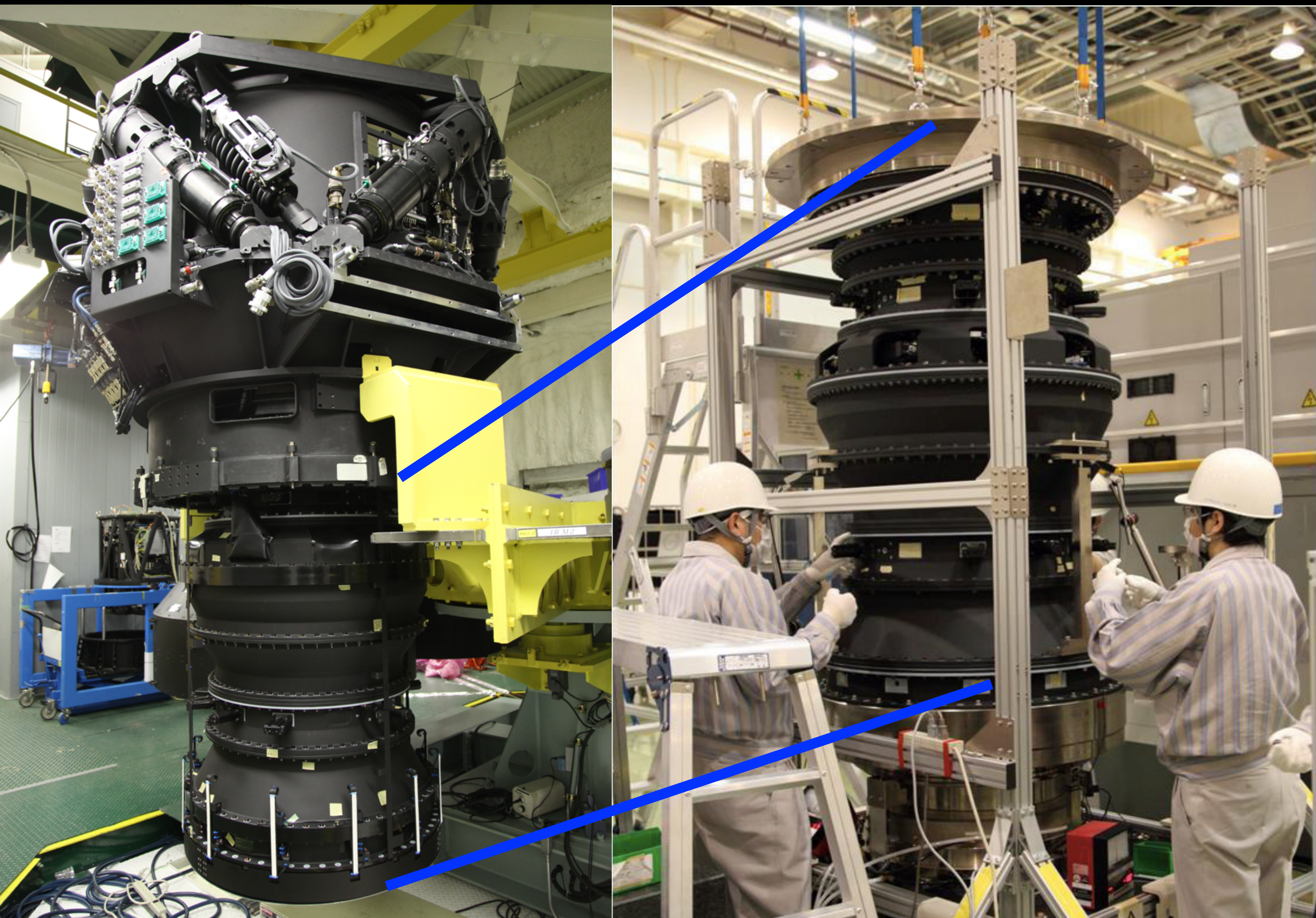
$$\delta T/T = a_{lm}\, Y_l^m$$

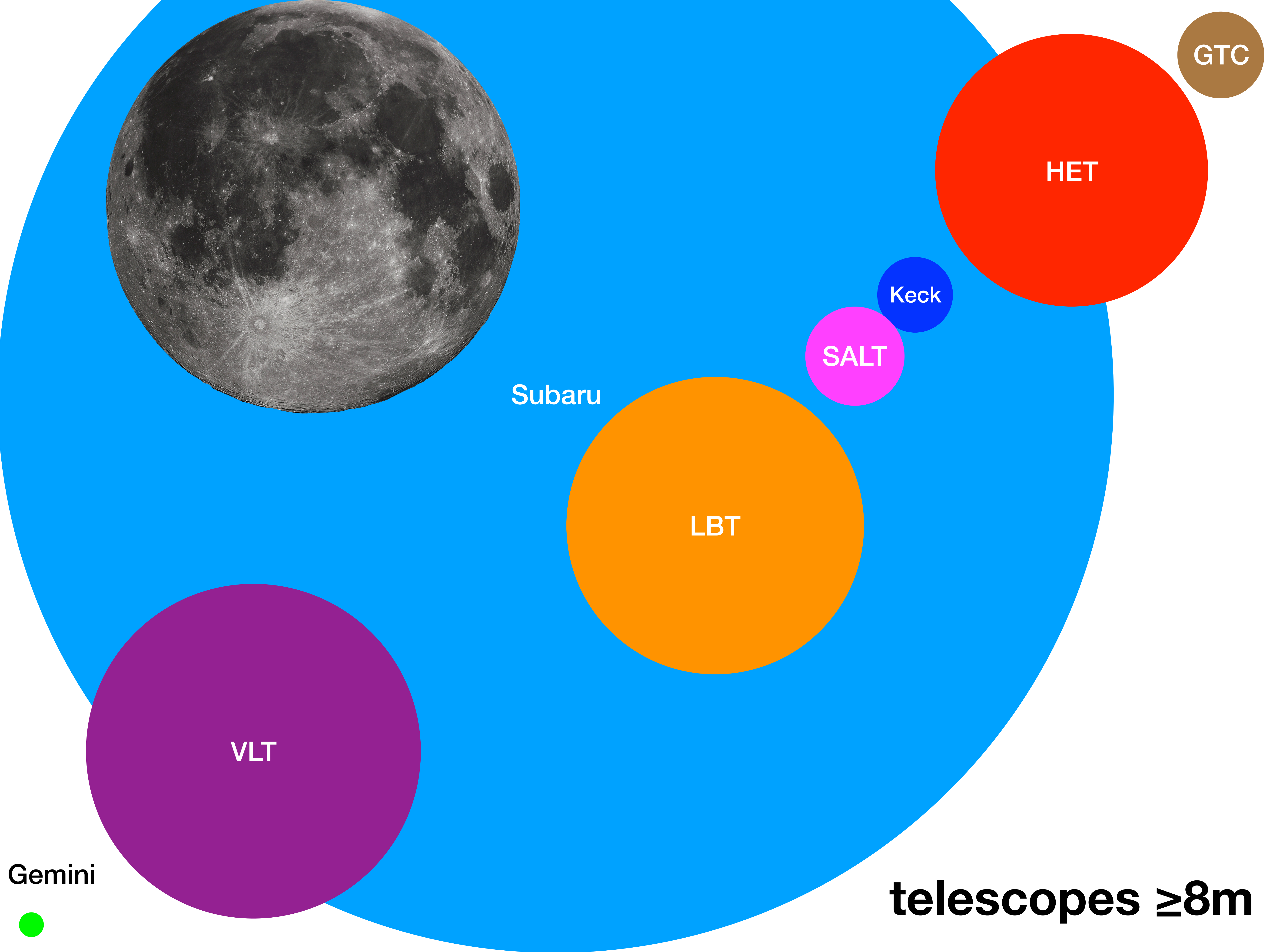
$$(2l+1)c_{lm} = \Sigma_m\, a_{lm}{}^* a_{lm}$$



Planck Collaboration: Cosmological parameters



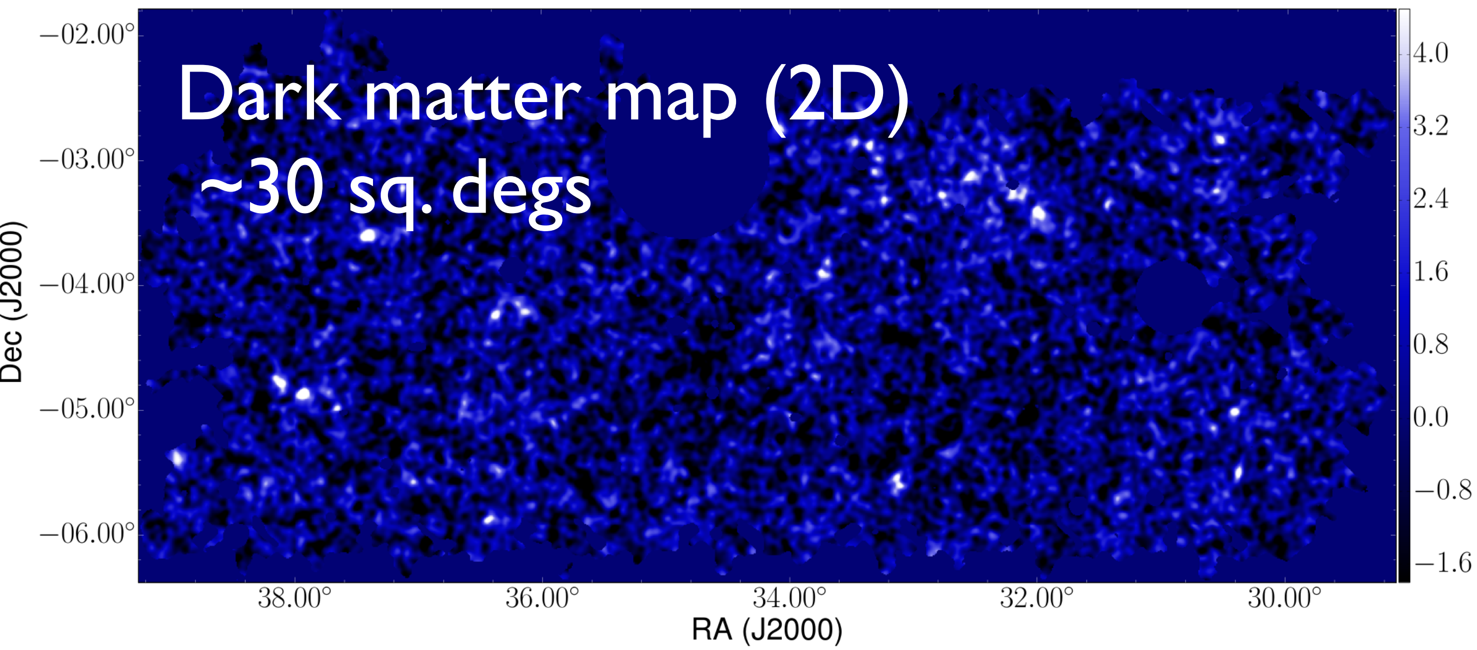


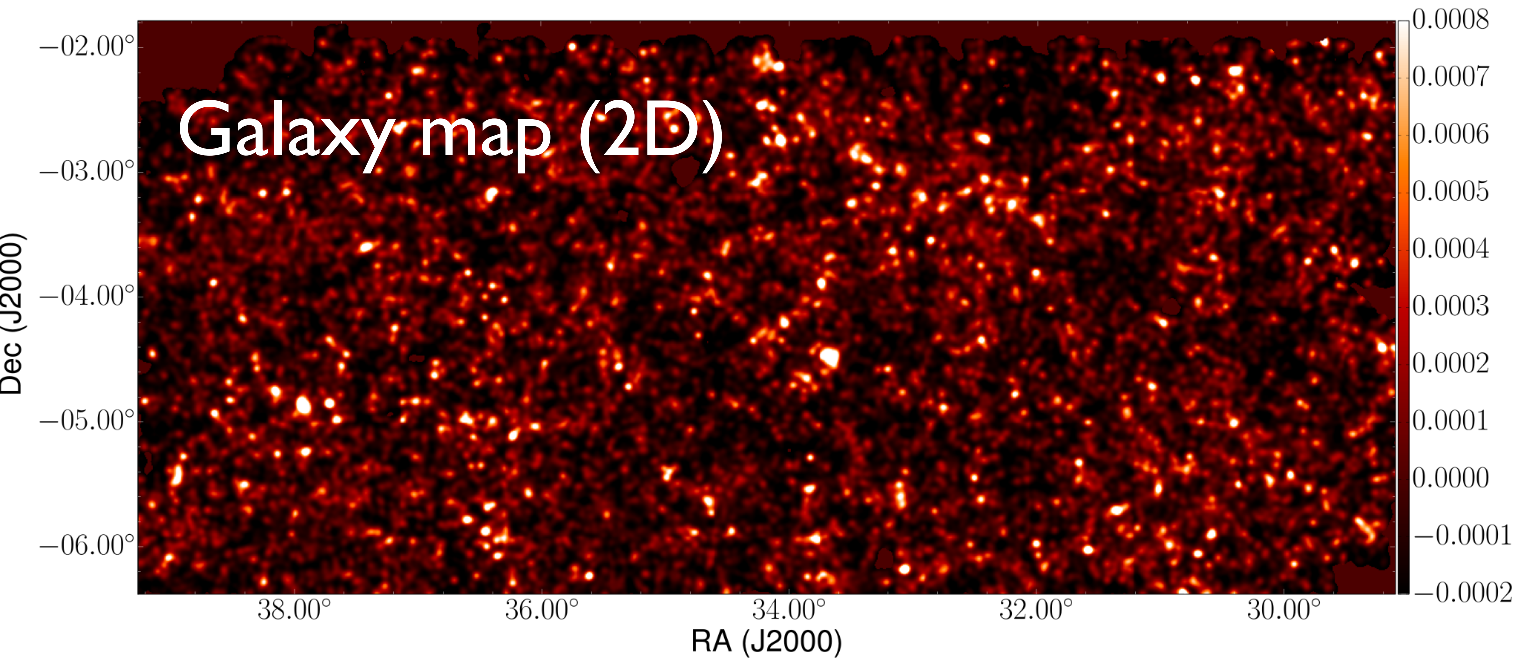

GTC
HET
Keck
SALT
Subaru
LBT
VLT
Gemini
telescopes ≥8m

Largest 3D map of dark matter

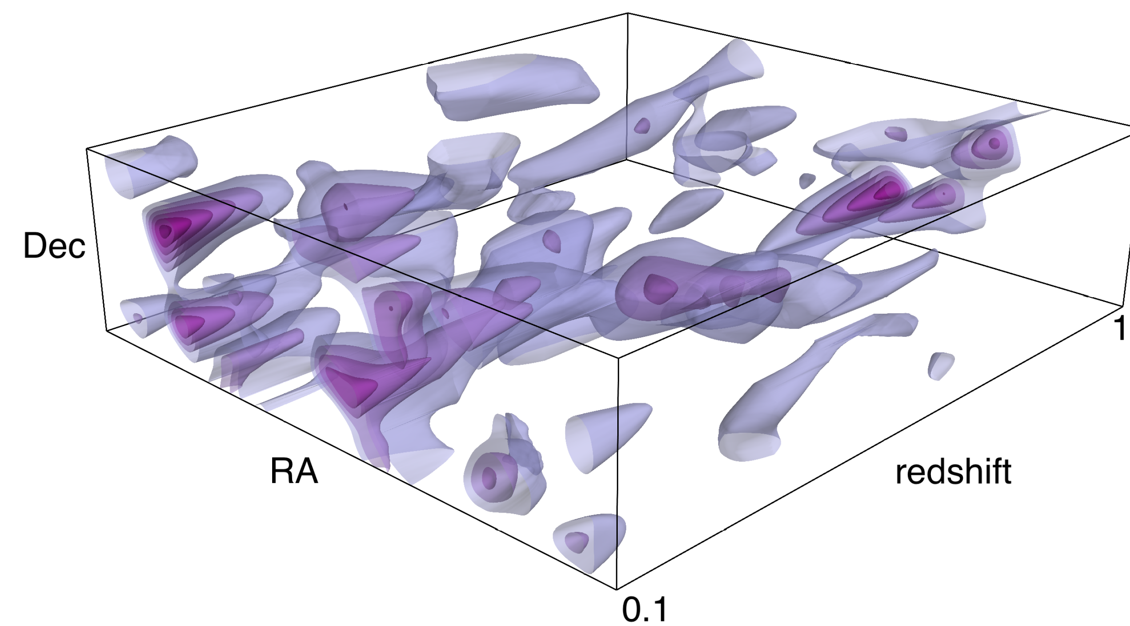
- Galaxy shape catalog now fixed (Mandelbaum, Miyatake + 17)
- Galaxy shapes + Photoz of gals → 3D mass & galaxy maps
- Strong correlations between DM and galaxy distributions

Oguri et al. arXiv:1705.06792

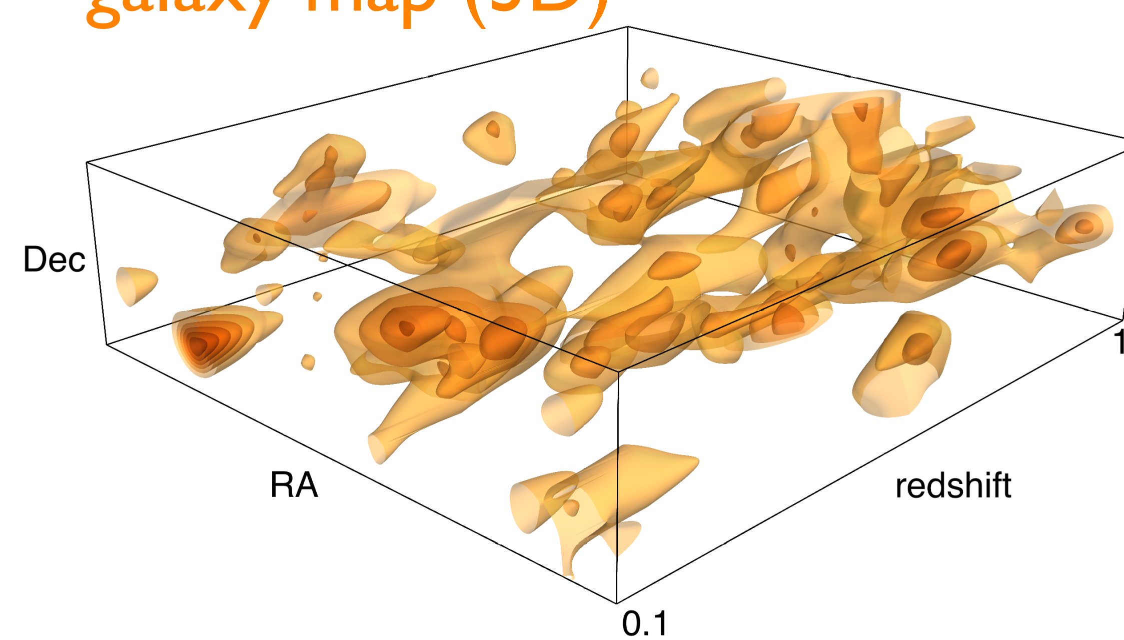




Dark matter map (3D)



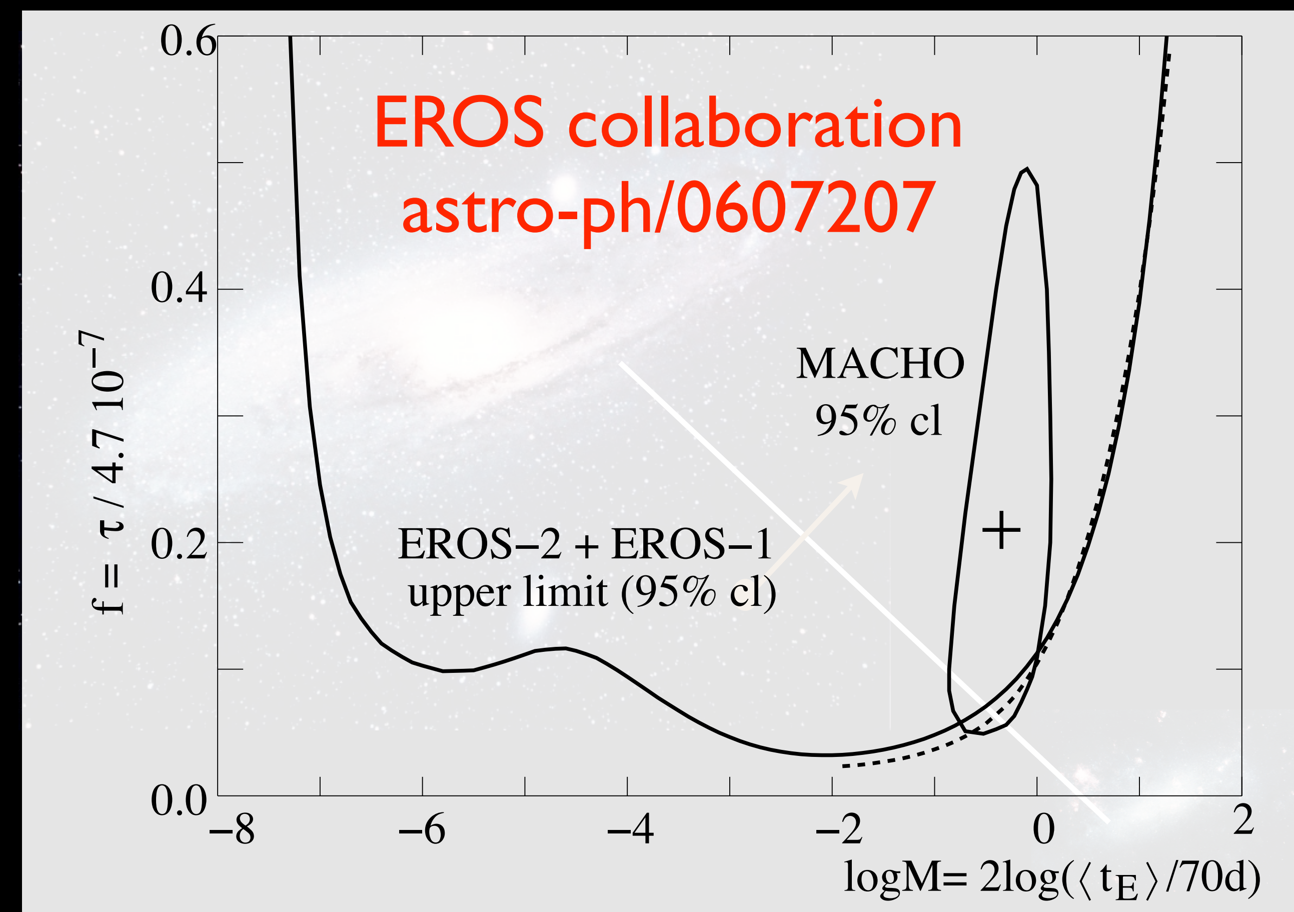
galaxy map (3D)

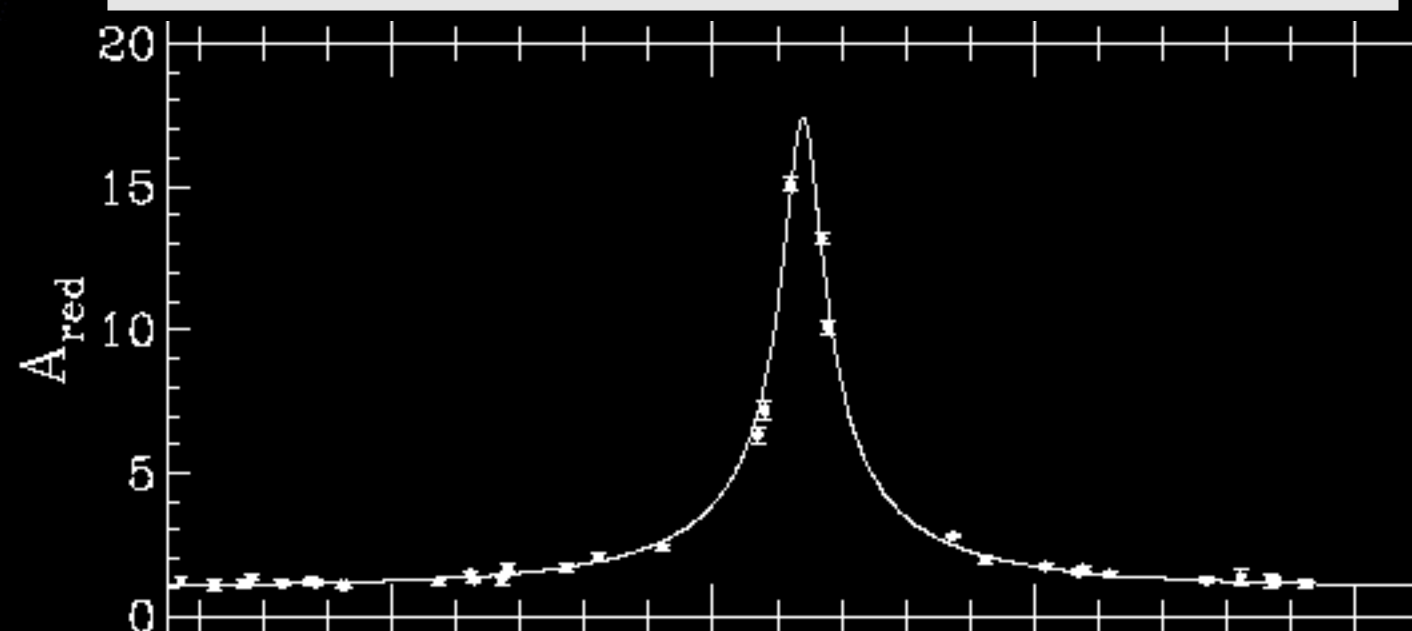


Dim Stars?

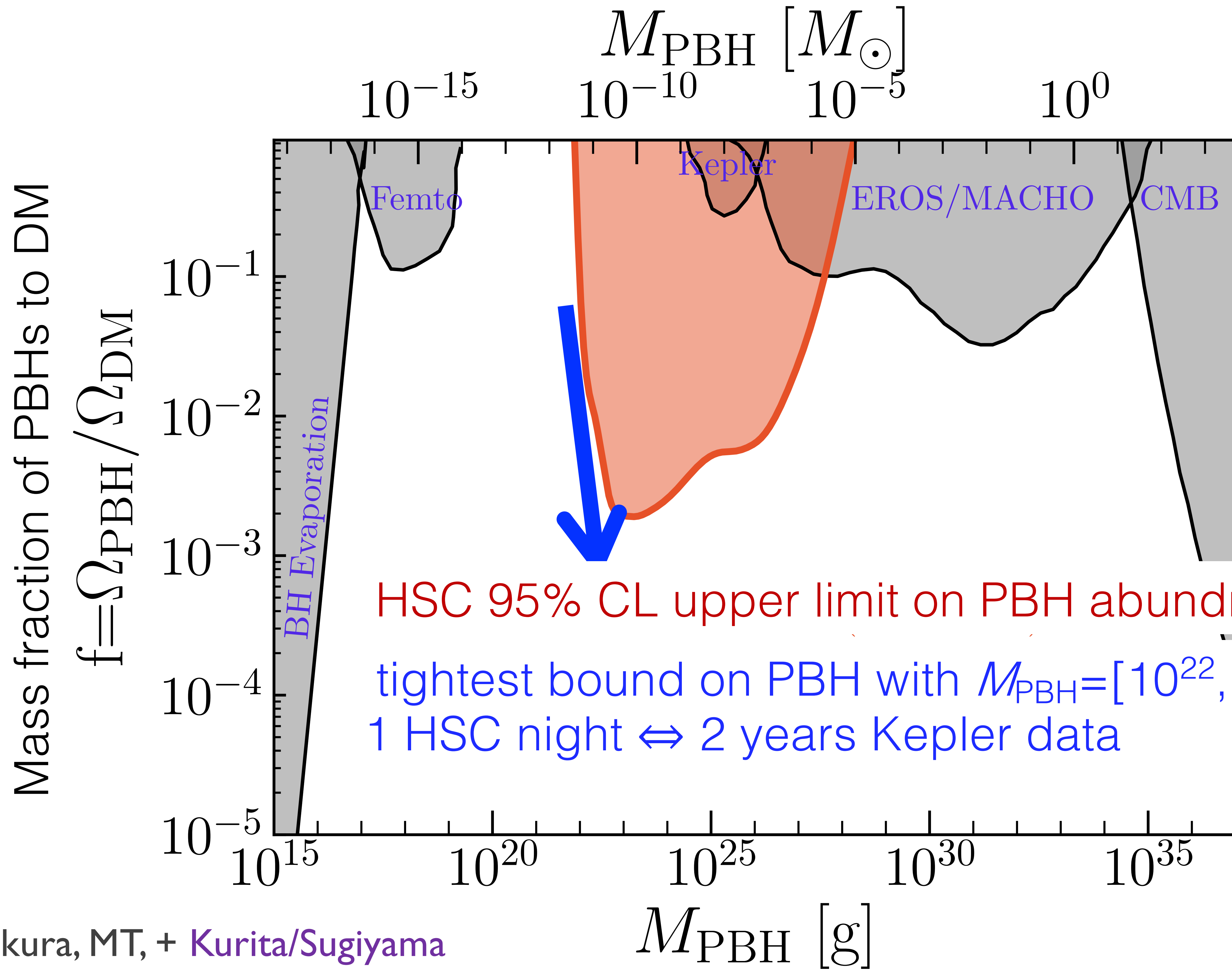
Search for MACHOs
(Massive Compact Halo Objects)

Not enough of them!





Results: New bound on PBH abundance



HSC 95% CL upper limit on PBH abundnace

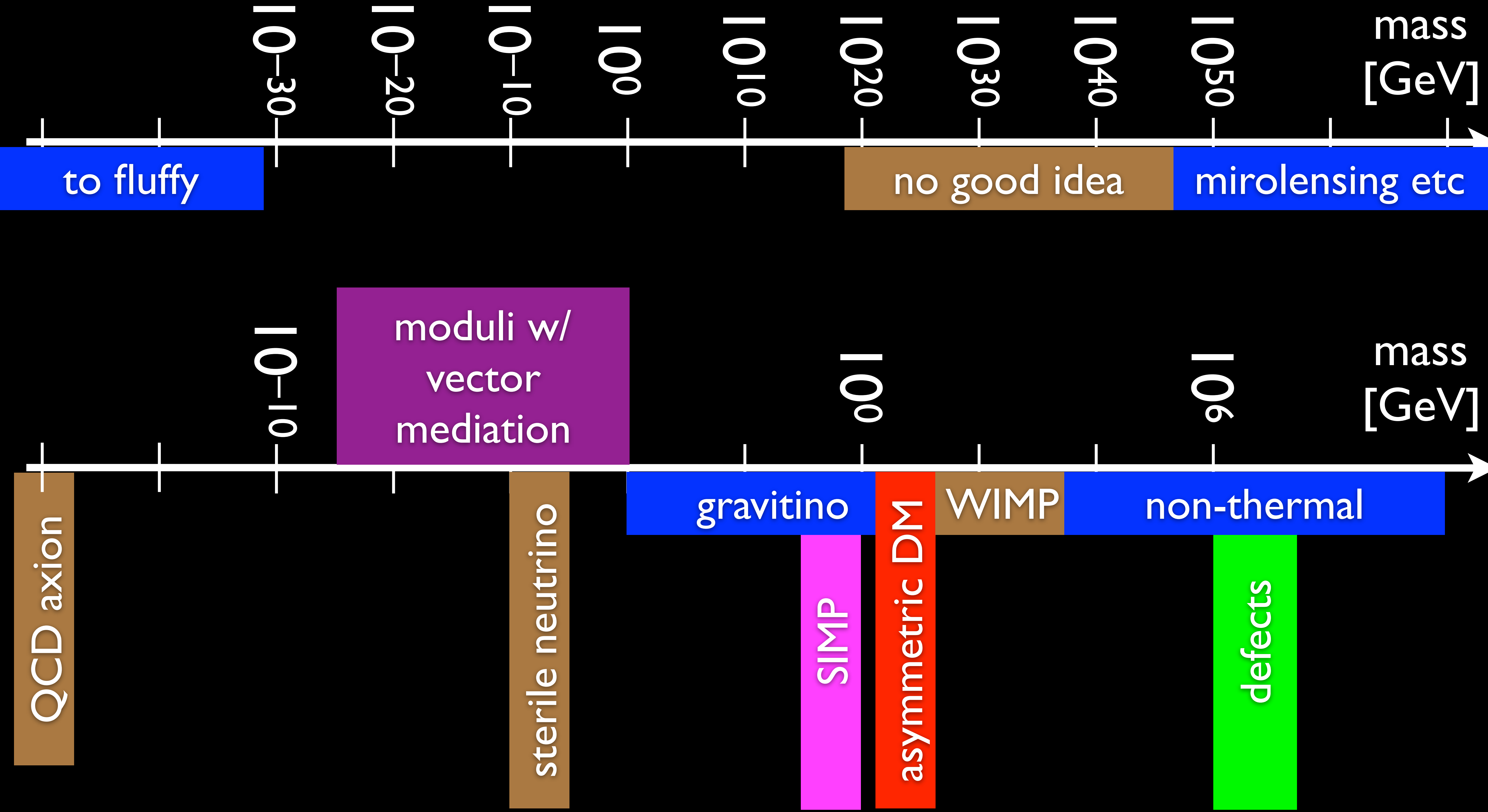
tightest bound on PBH with $M_{\rm PBH}=[10^{22},10^{28}]$g

1 HSC night ⇔ 2 years Kepler data

Niikura, MT, + Kurita/Sugiyama

Mass Limits
"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)



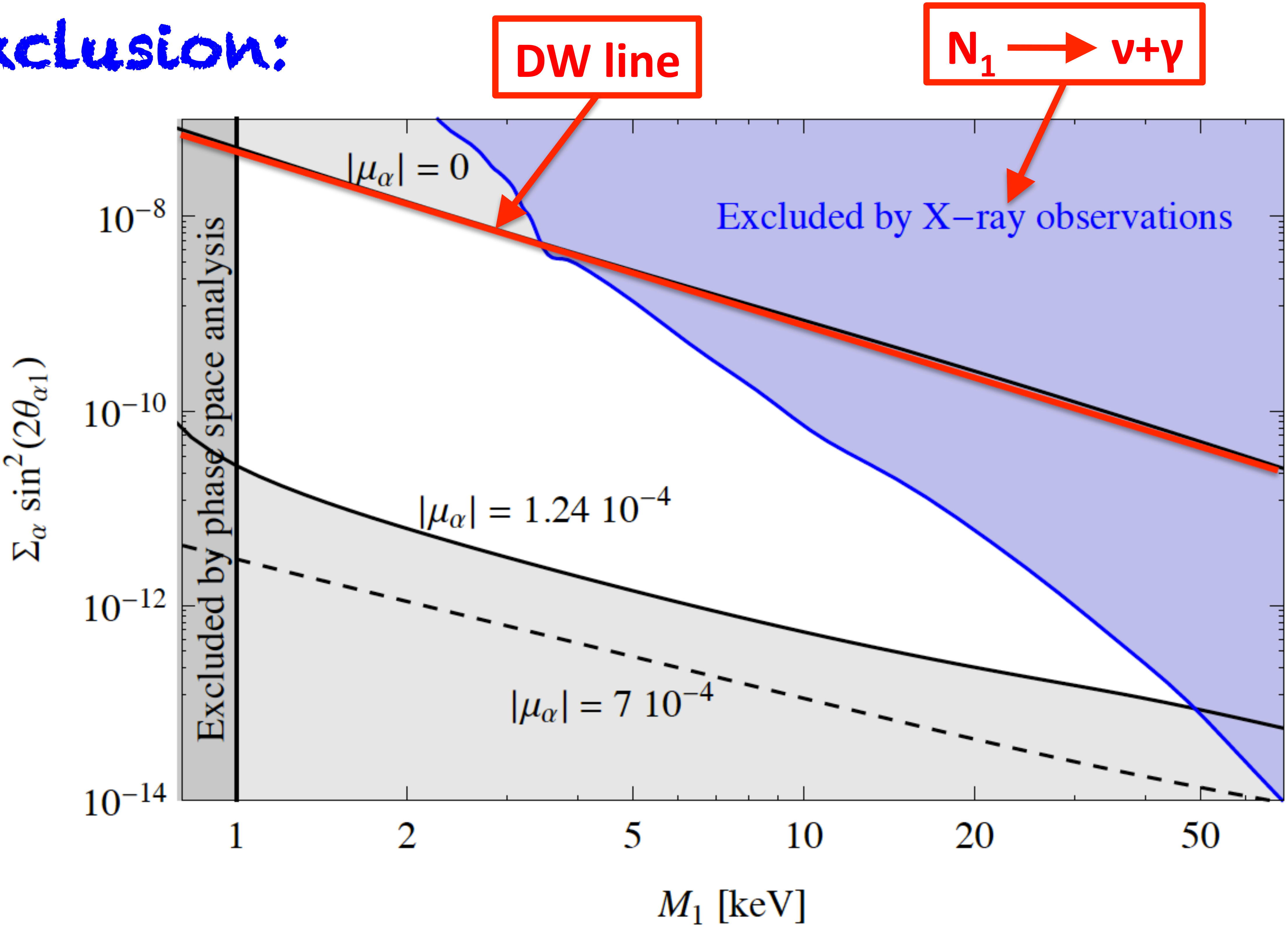
10−30
10−20
10−10
100
1010
1020
1030
1040
1050
mass [GeV]
to fluffy
no good idea
mirolensing etc
moduli w/ vector mediation
10−10
100
106
mass [GeV]
QCD axion
sterile neutrino
gravitino
SIMP
asymmetric DM
WIMP
non-thermal
defects

sterile neutrinos

- keV-scale sterile neutrinos could be dark matter
- >0.4keV because of the Pauli exclusion principle
- <50keV to avoid too rapid decay
- created by oscillation
- typically very small mixing angles
- requires non-zero asymmetry

2. Production Mechanisms

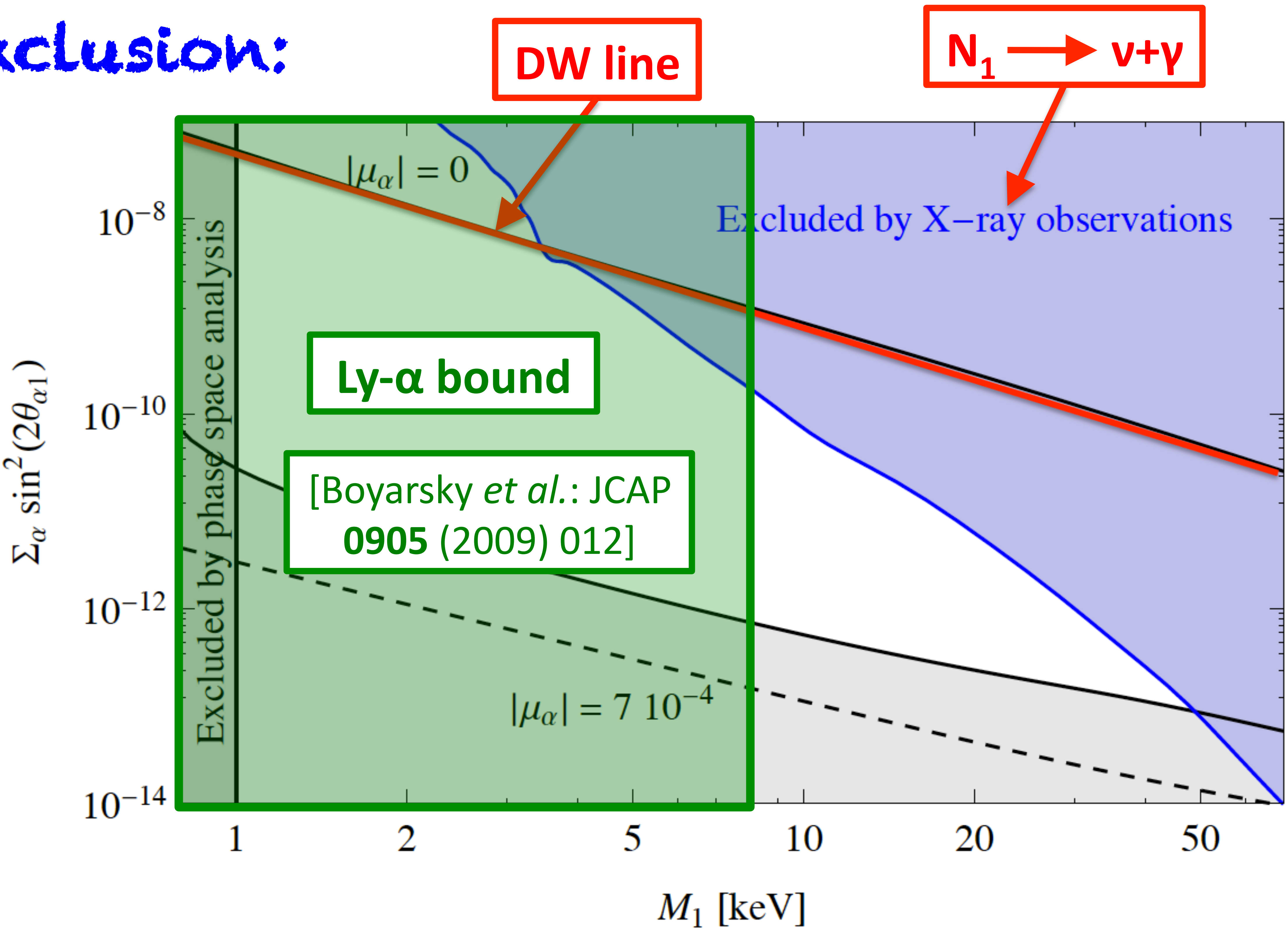
Exclusion:



[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

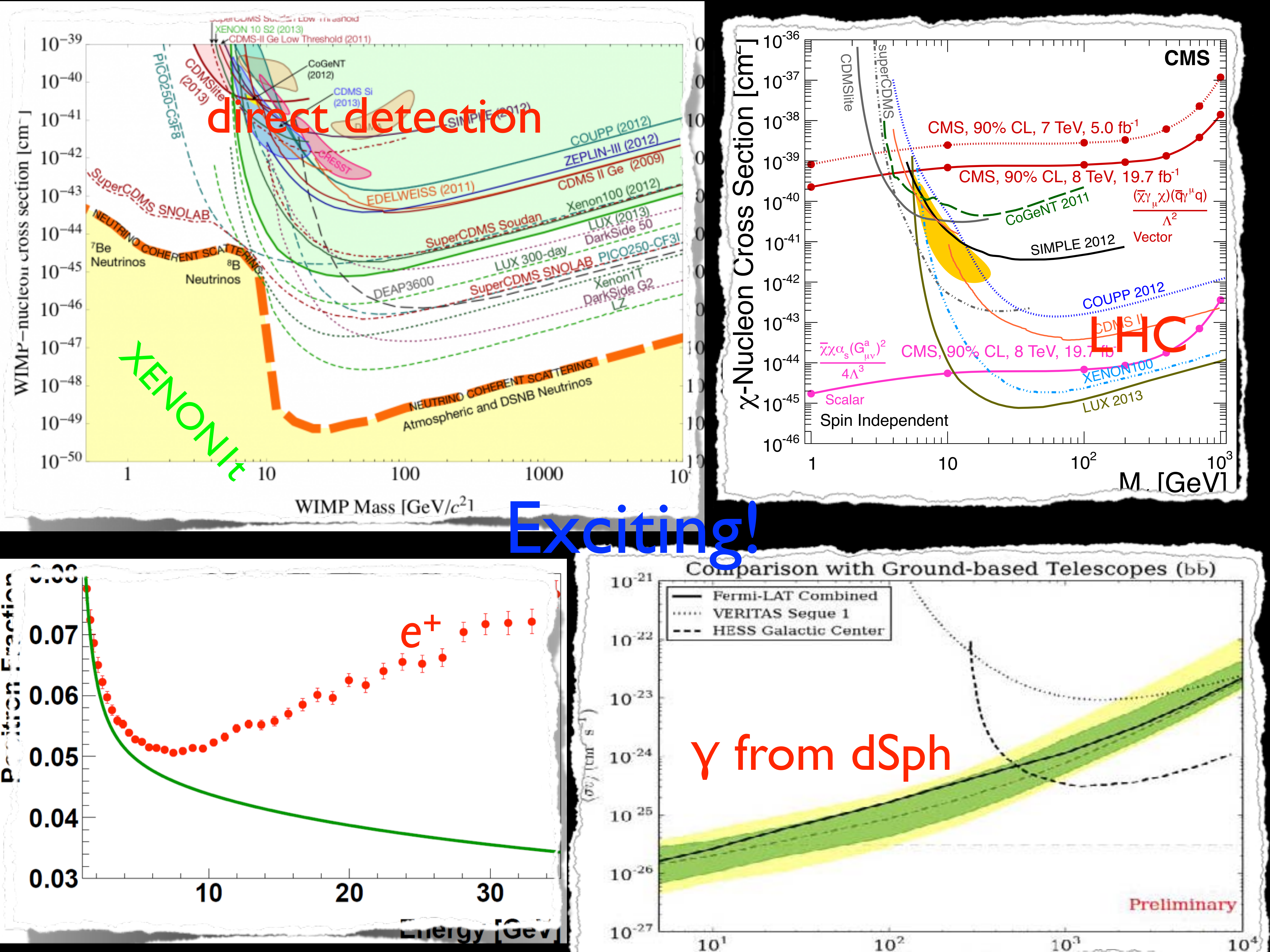
2. Production Mechanisms

Exclusion:

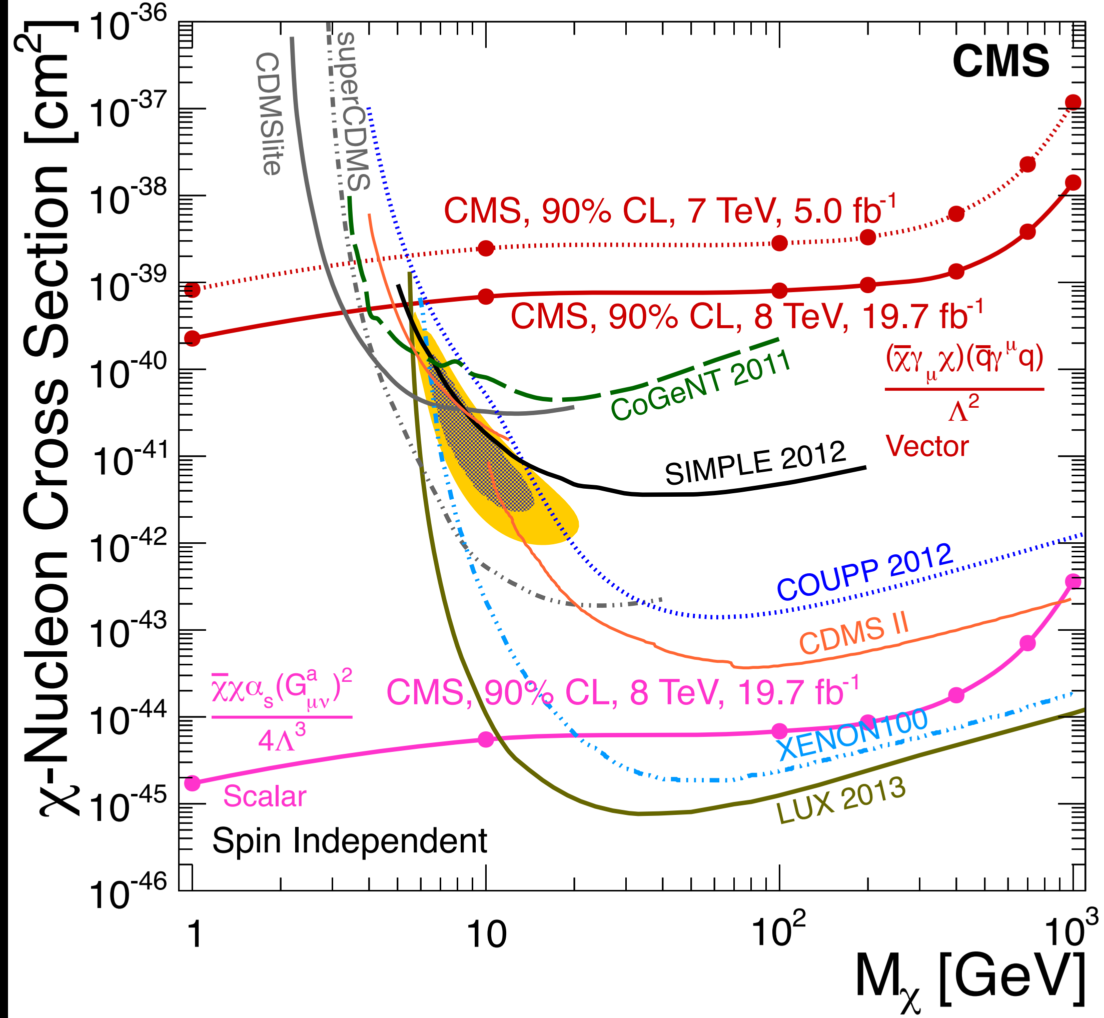


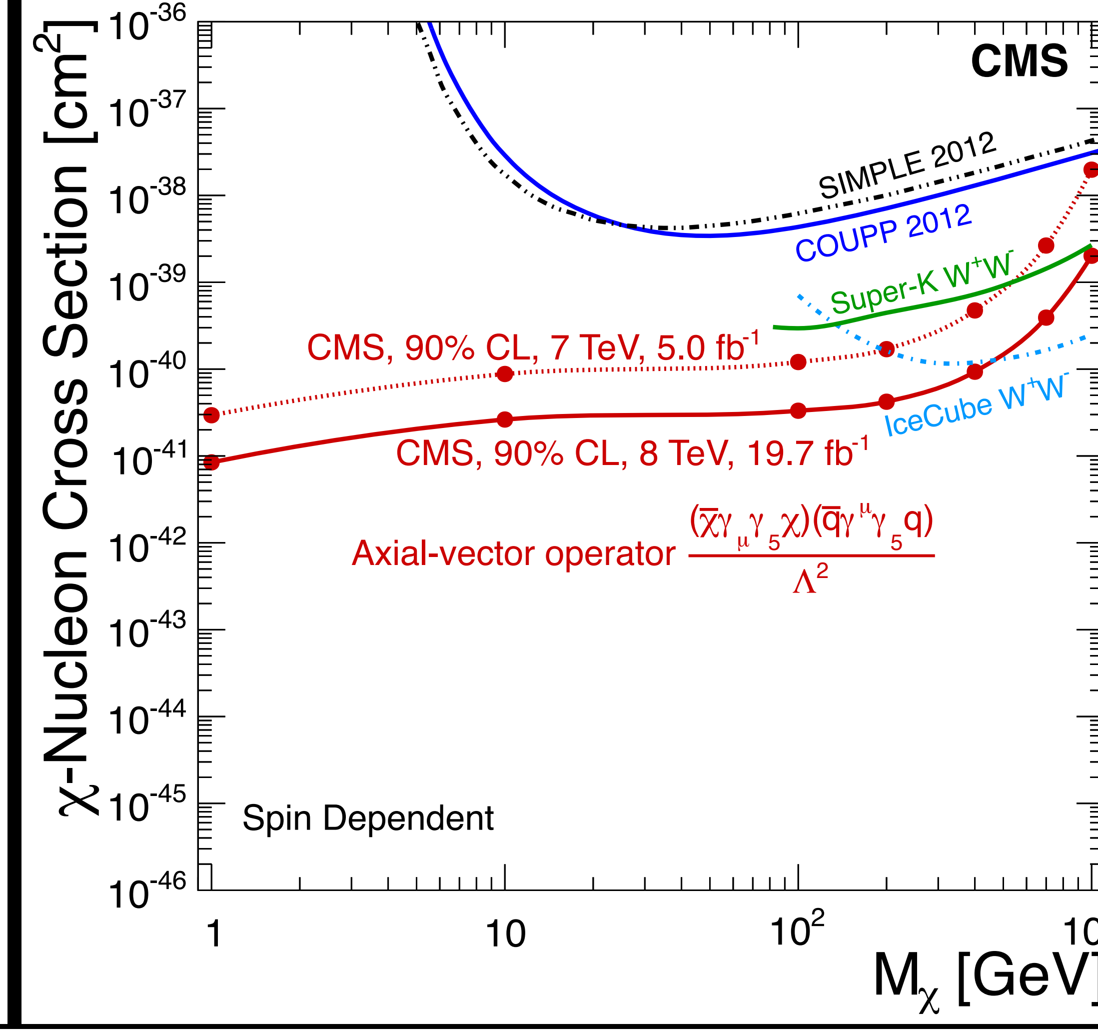
[Canetti *et al.*: Phys. Rev. **D87** (2013) 093006]

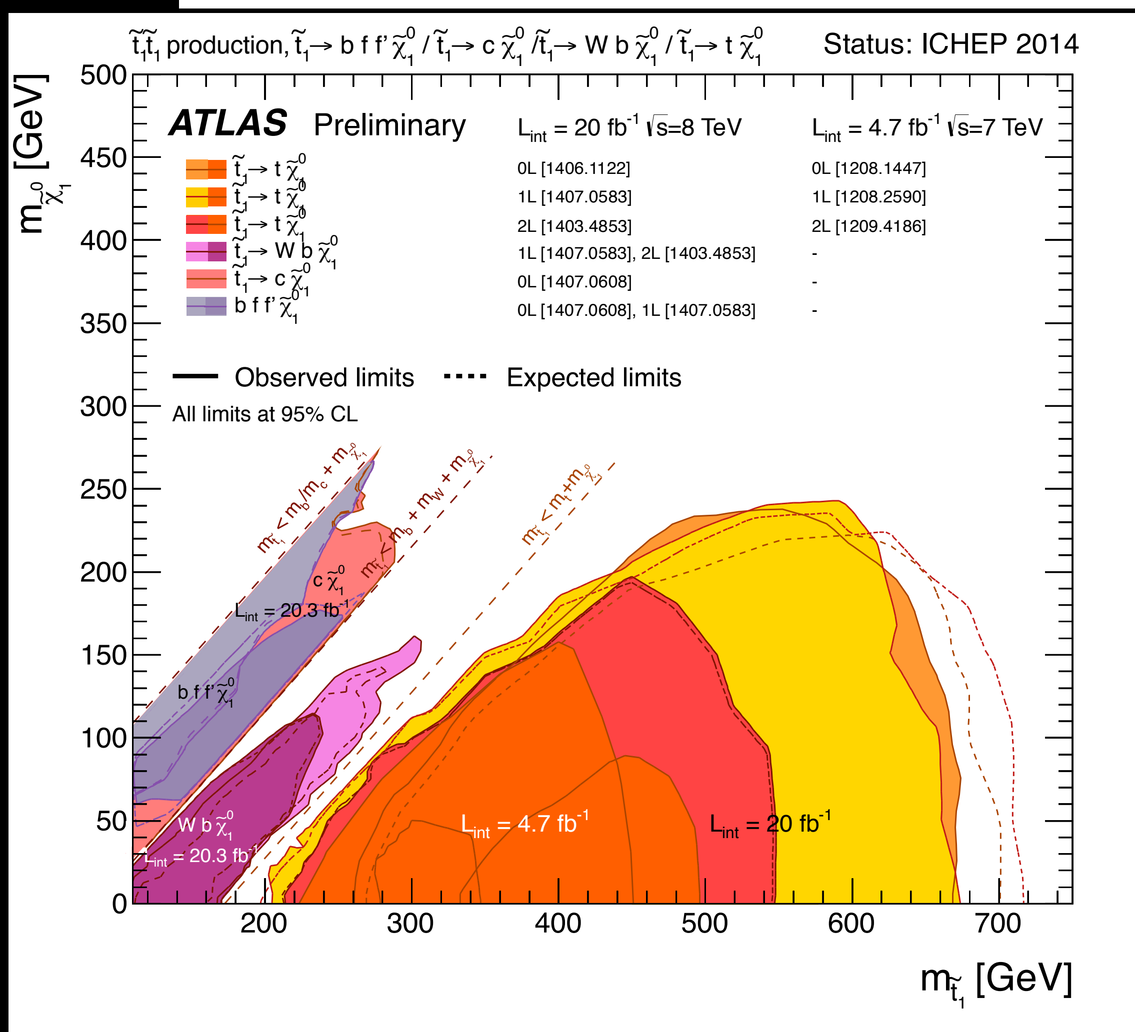
Alexander Merle

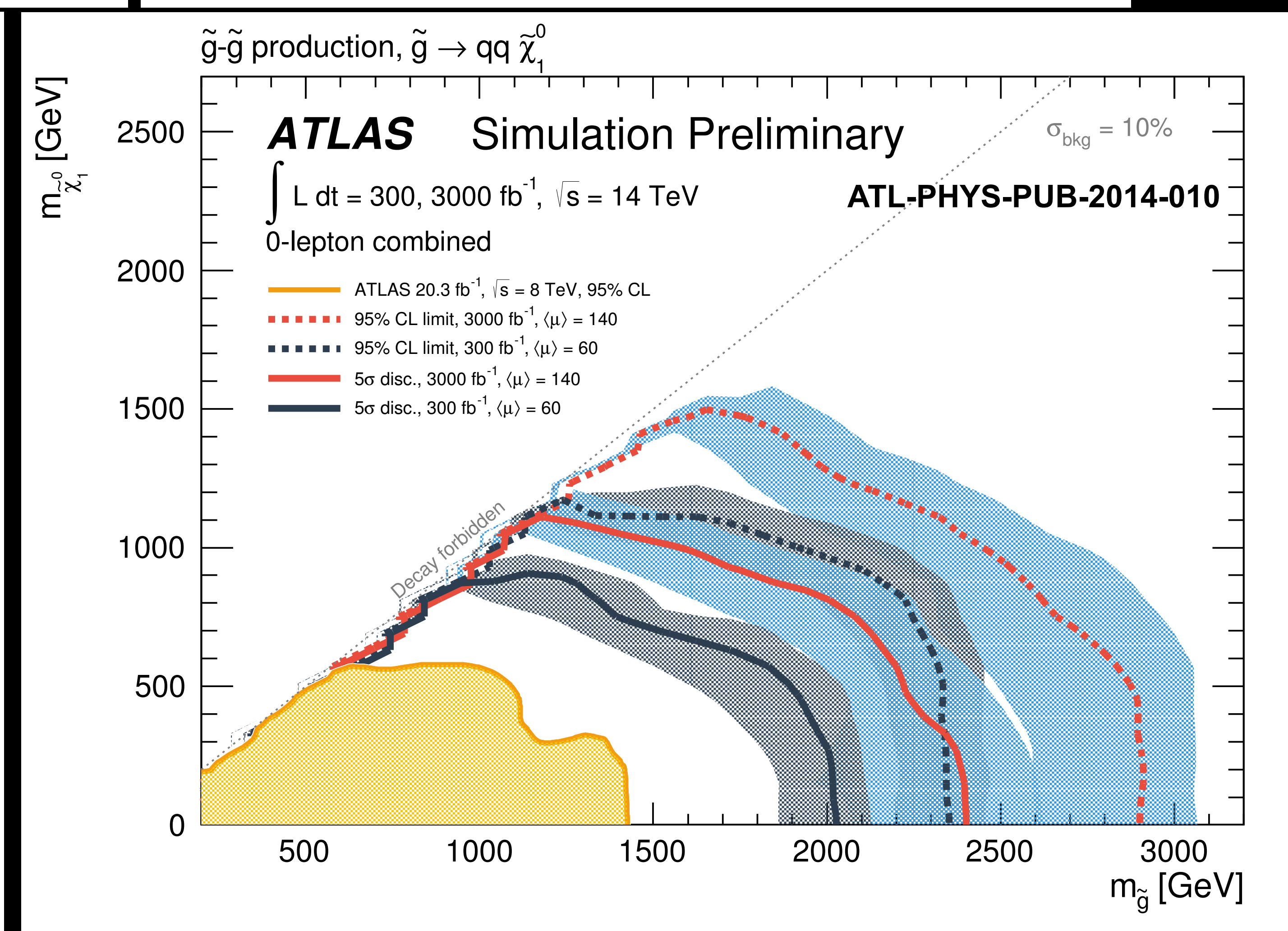


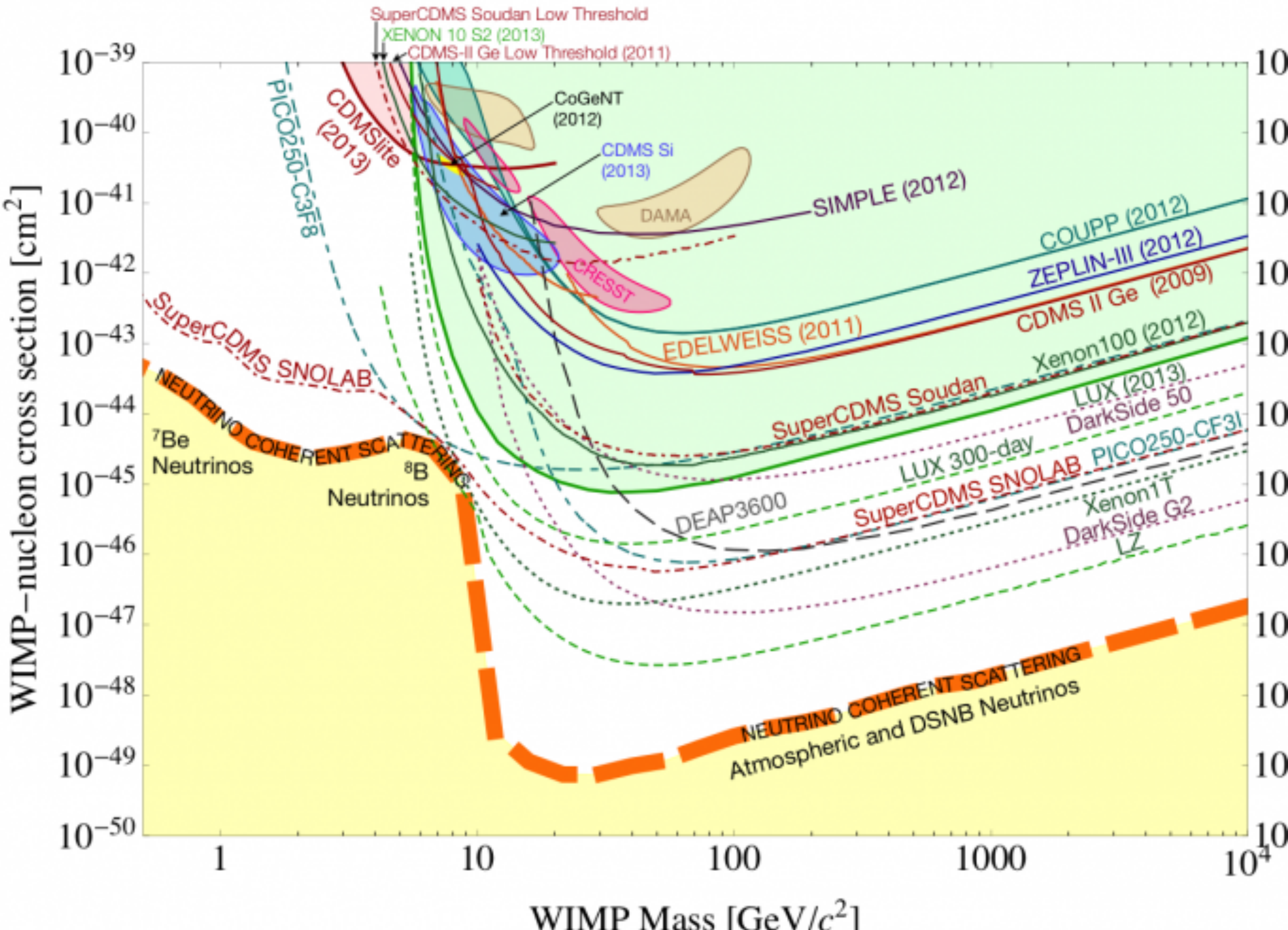
direct detection
XENON1t
LHC
Exciting!
e+
γ from dSph
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
CRESST
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
SuperCDMS SNOLAB
LUX 300-day
PICO250-CF3I
DEAP3600
Xenon1T
DarkSide G2
LZ
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
CDMS-II Ge Low Threshold (2011)
XENON 10 S2 (2013)
CMS
χ-Nucleon Cross Section [cm²]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
Vector
COUPP 2012
CDMS II
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
XENON100
Scalar
LUX 2013
Spin Independent
Positron Fraction
Energy [GeV]
Comparison with Ground-based Telescopes (bb)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
Preliminary


CMS
χ-Nucleon Cross Section [cm²]
CDMSlite
superCDMS
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
CoGeNT 2011
SIMPLE 2012
Vector
COUPP 2012
CDMS II
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
XENON100
LUX 2013
Scalar
Spin Independent
M_χ [GeV]


CMS
χ-Nucleon Cross Section [cm²]
SIMPLE 2012
COUPP 2012
Super-K W⁺W⁻
CMS, 90% CL, 7 TeV, 5.0 fb⁻¹
IceCube W⁺W⁻
CMS, 90% CL, 8 TeV, 19.7 fb⁻¹
Axial-vector operator
Spin Dependent
M_χ [GeV]


Status: ICHEP 2014
ATLAS Preliminary
L_int = 20 fb⁻¹ √s=8 TeV
L_int = 4.7 fb⁻¹ √s=7 TeV
0L [1406.1122]
1L [1407.0583]
2L [1403.4853]
1L [1407.0583], 2L [1403.4853]
0L [1407.0608]
0L [1407.0608], 1L [1407.0583]
0L [1208.1447]
1L [1208.2590]
2L [1209.4186]
Observed limits
Expected limits
All limits at 95% CL
L_int = 4.7 fb⁻¹
L_int = 20 fb⁻¹
L_int = 20.3 fb⁻¹
m_t̃₁ [GeV]


g̃-g̃ production, g̃ → qq χ̃⁰₁
ATLAS Simulation Preliminary
σ_bkg = 10%
∫ L dt = 300, 3000 fb⁻¹, √s = 14 TeV
ATL-PHYS-PUB-2014-010
0-lepton combined
ATLAS 20.3 fb⁻¹, √s = 8 TeV, 95% CL
95% CL limit, 3000 fb⁻¹, ⟨μ⟩ = 140
95% CL limit, 300 fb⁻¹, ⟨μ⟩ = 60
5σ disc., 3000 fb⁻¹, ⟨μ⟩ = 140
5σ disc., 300 fb⁻¹, ⟨μ⟩ = 60
Decay forbidden
m_g̃ [GeV]



SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
CDMSlite (2013)
PICO250-C3F8
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
CRESST
EDELWEISS (2011)
Xenon100 (2012)
SuperCDMS Soudan
LUX (2013)
DarkSide 50
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PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
Xenon1T
DarkSide G2
LZ
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]

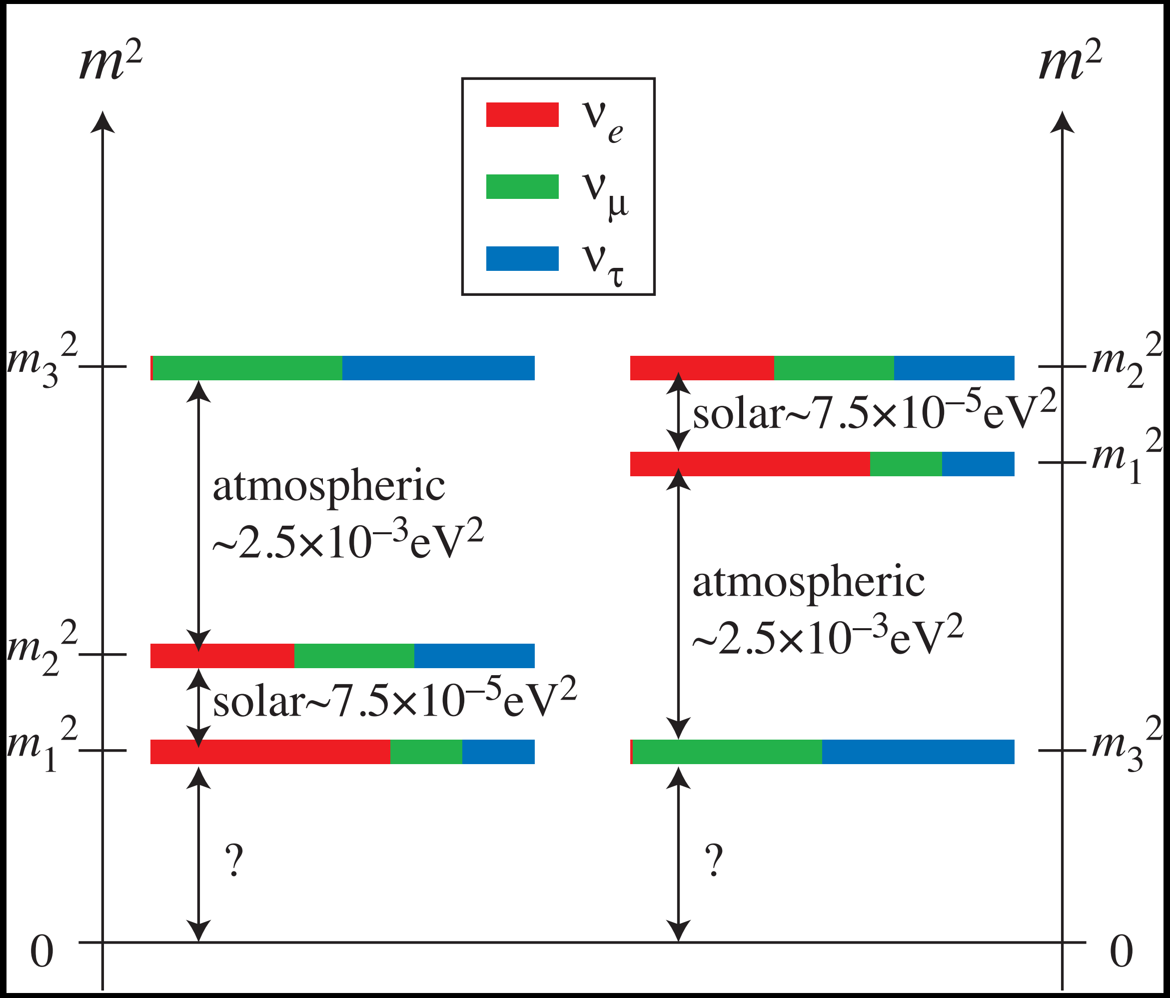
neutrinos & dark matter

- Line is drawn for convenience of funding agencies in a ridiculous way
- e.g., underground expts supported by US DOE

Energy	Nuclear	HEP
~1-100 GeV		accelerator ν
~5-12 MeV	solar ν	
~2-8 MeV	reactor ν	reactor ν
~10-100 keV		dark matter

Questions

- mass hierarchy?
- mass scale?
- which octant?
- Is θ_{23} maximal?
- CP violation?
- Dirac or Majorana?
- sterile neutrinos?
- non-std interactions?
- origin of neutrino mass?
- seesaw? which type?
- leptogenesis?
- dark matter?

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