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KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Baryogenesis

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Pre-SUSY Summer School

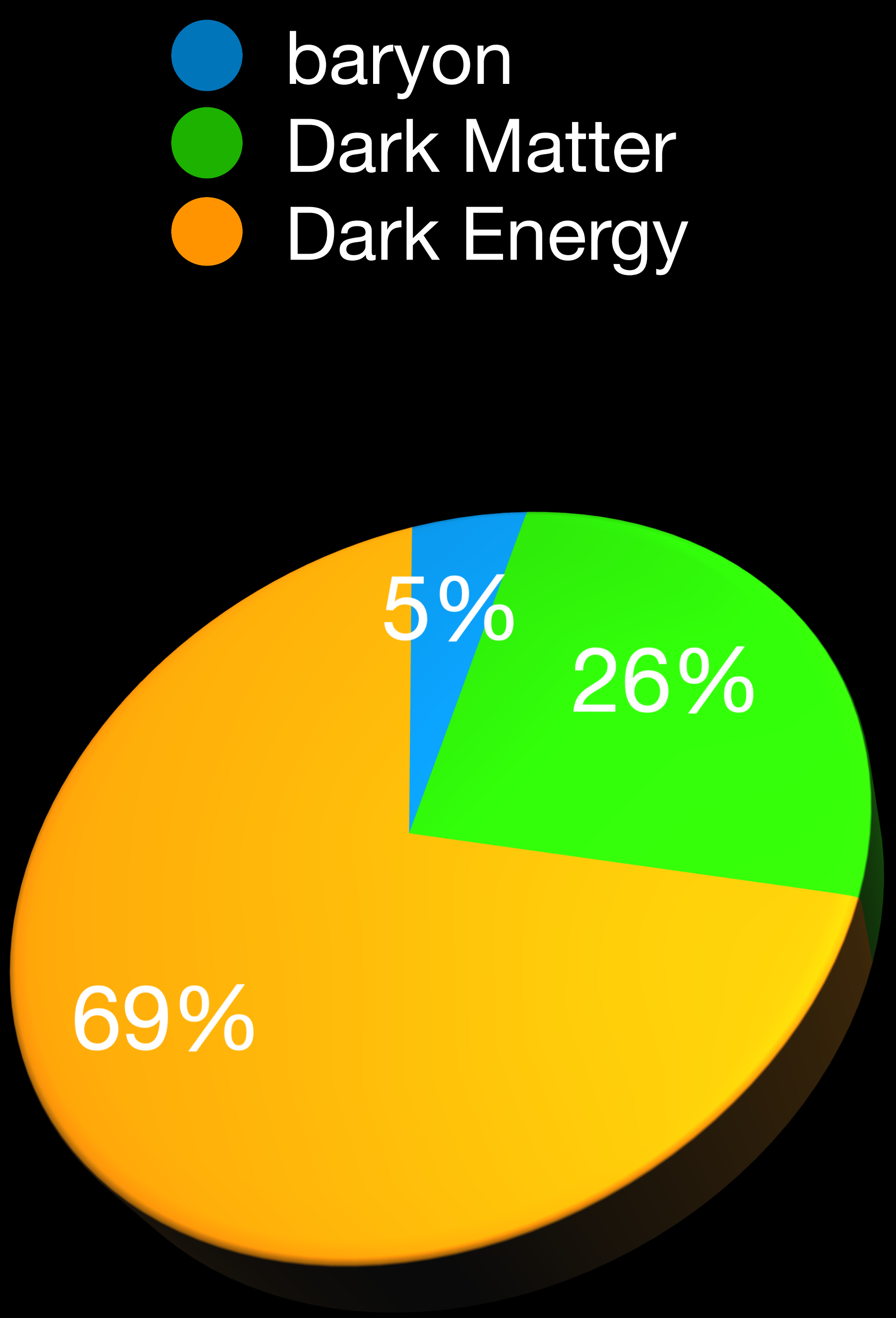
August 19, 2021

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Cosmic mysteries

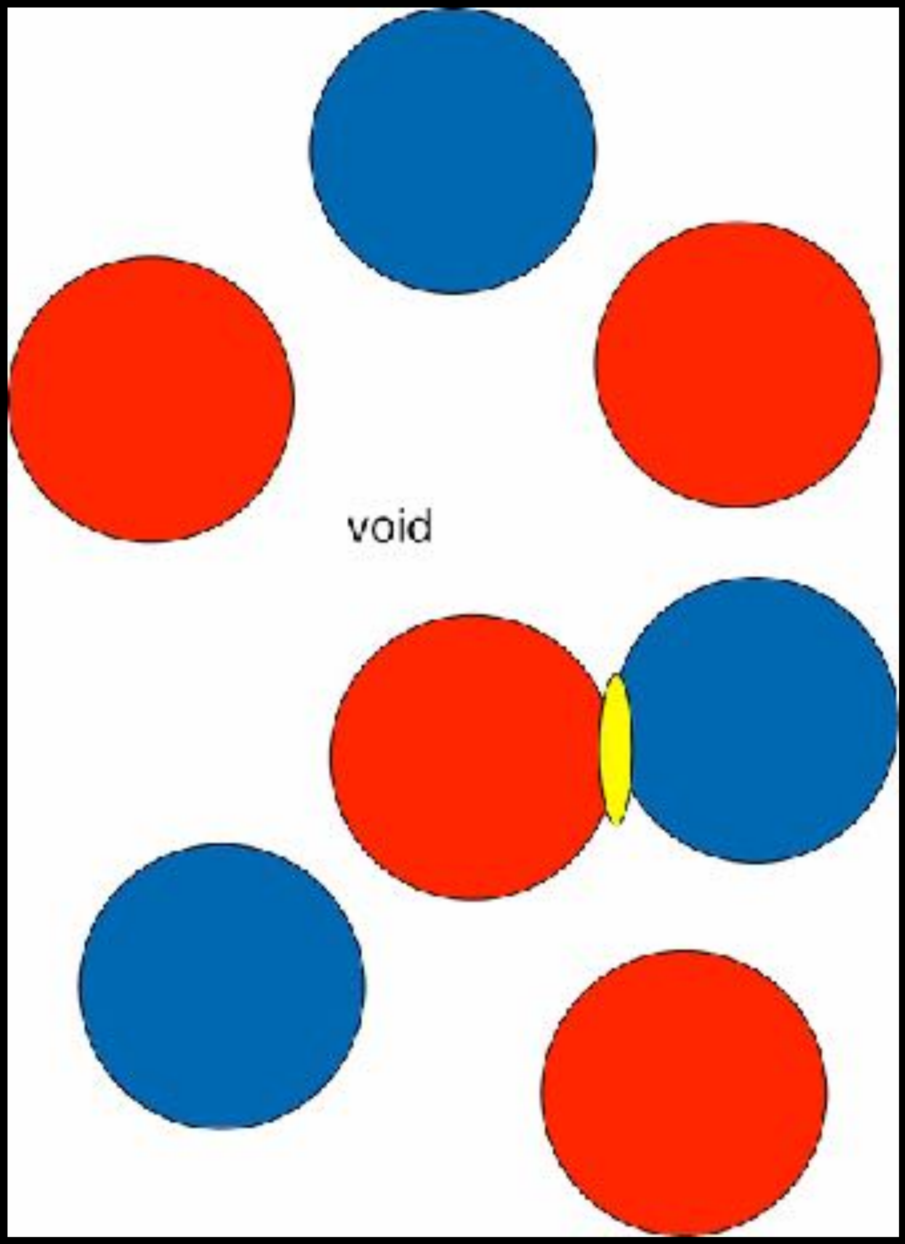
- We don't know what dark energy is
- We don't know what dark matter is
- We don't know why baryons exist
- why are they all within an order of magnitude now?



baryosymmetric Universe?

The Question

- We are made of matter
- Berkeley made anti-matter
- Big Bang made presumably both matter and anti-matter, too
- Where did it go?
- Are there anti-matter domains in the universe?
- Could the universe be *baryosymmetric*?



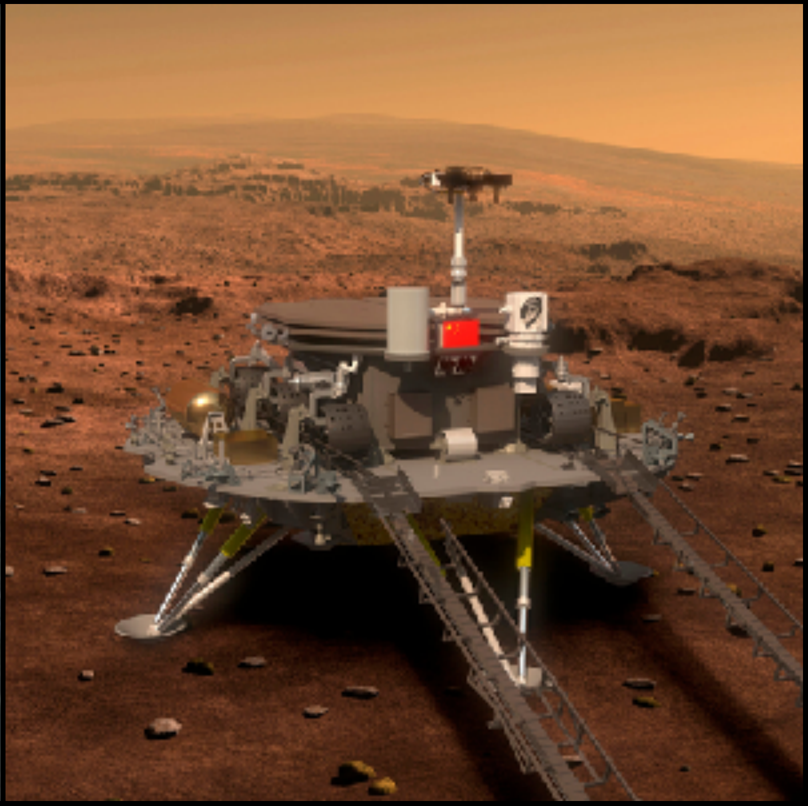
Basic premise

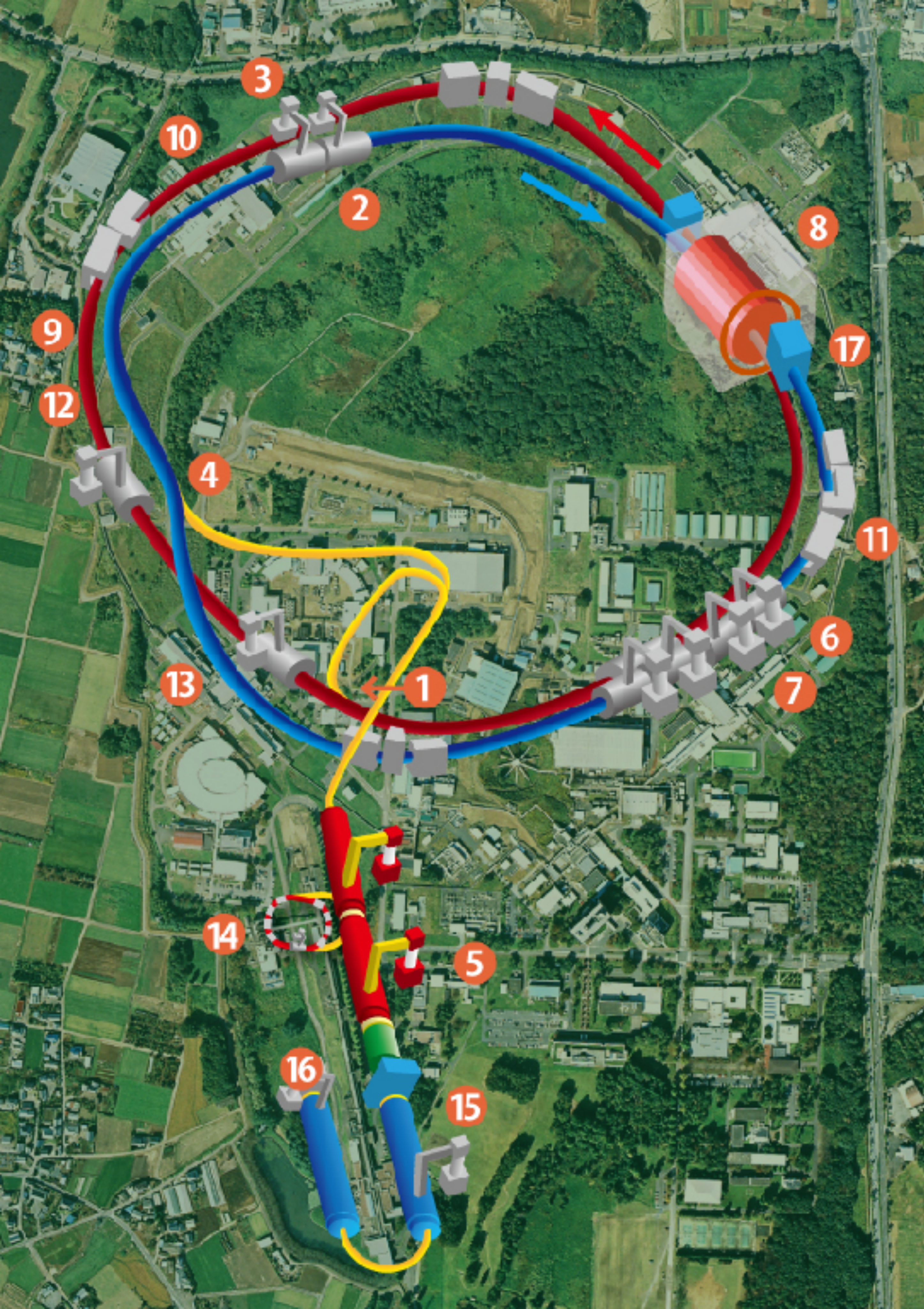
- Short answer: *no!*
- Universe is not empty
  - Structured at various levels
  - interstellar medium, intracluster gas
- Anti-matter shouldn't be close to matter
  - Otherwise they annihilate
  - Produce gamma rays
  - Cosmic microwave background, diffuse gamma rays
- How did anti-matter get separated to begin with?
  - Need to violate causality

Anti-matter
in Solar System

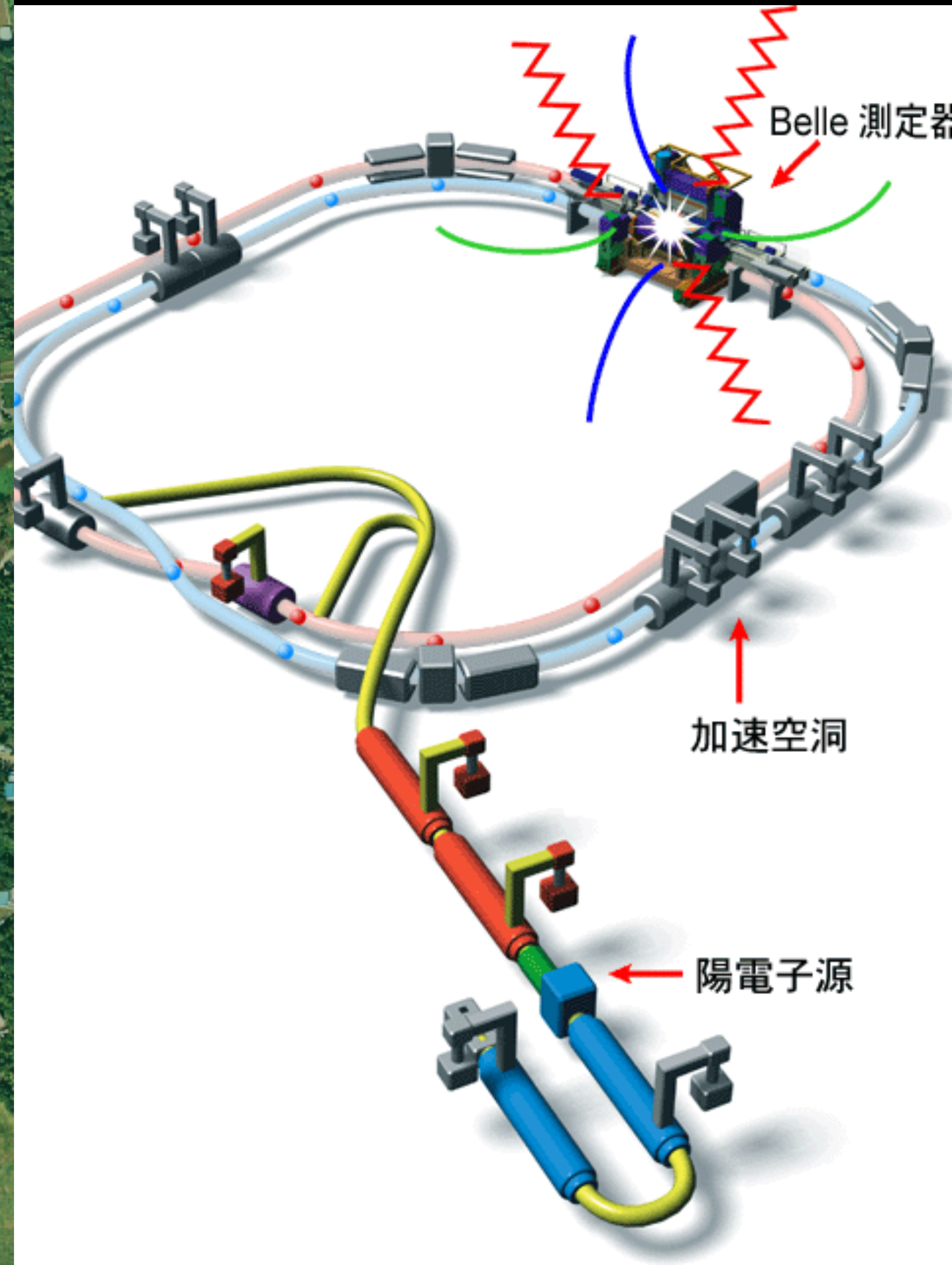
No

- Landing on the moon
- Past asteroid/meteor impact
- Solar cosmic rays
- Voyager spacecraft





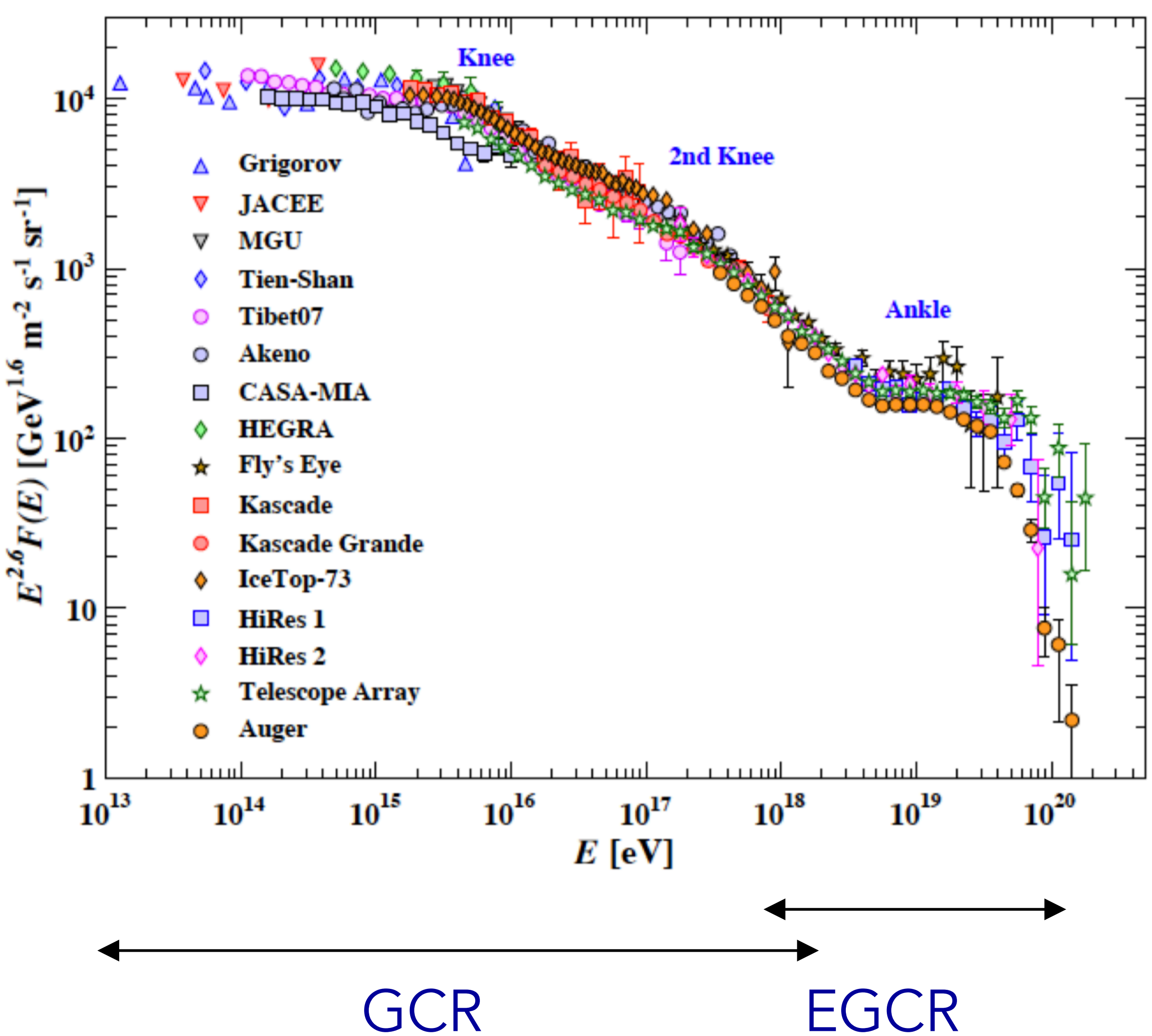
Biggest concentration 200 trillion positrons



Anti-matter in Our Milky Way Galaxy

GCR/EGCR transition: a key issue!

- Immediate consequences
  - EGCRs must go as low in energy as the transition!
  - GCRs must go as high in energy as the transition!



- Forget PeVatrons: think EeVatrons!
  - Galactic sources must accelerate particles to much high energies than the knee → crucial constraint!
- Magnetic confinement
  - Galactic magnetic field should confine particles up to the ankle!
- Magnetic horizon
  - Extragalactic magnetic field should not prevent ankle particles from reaching us from extragalactic sources
- EGCR flux level & UHECR spectrum!

BESS

Supe

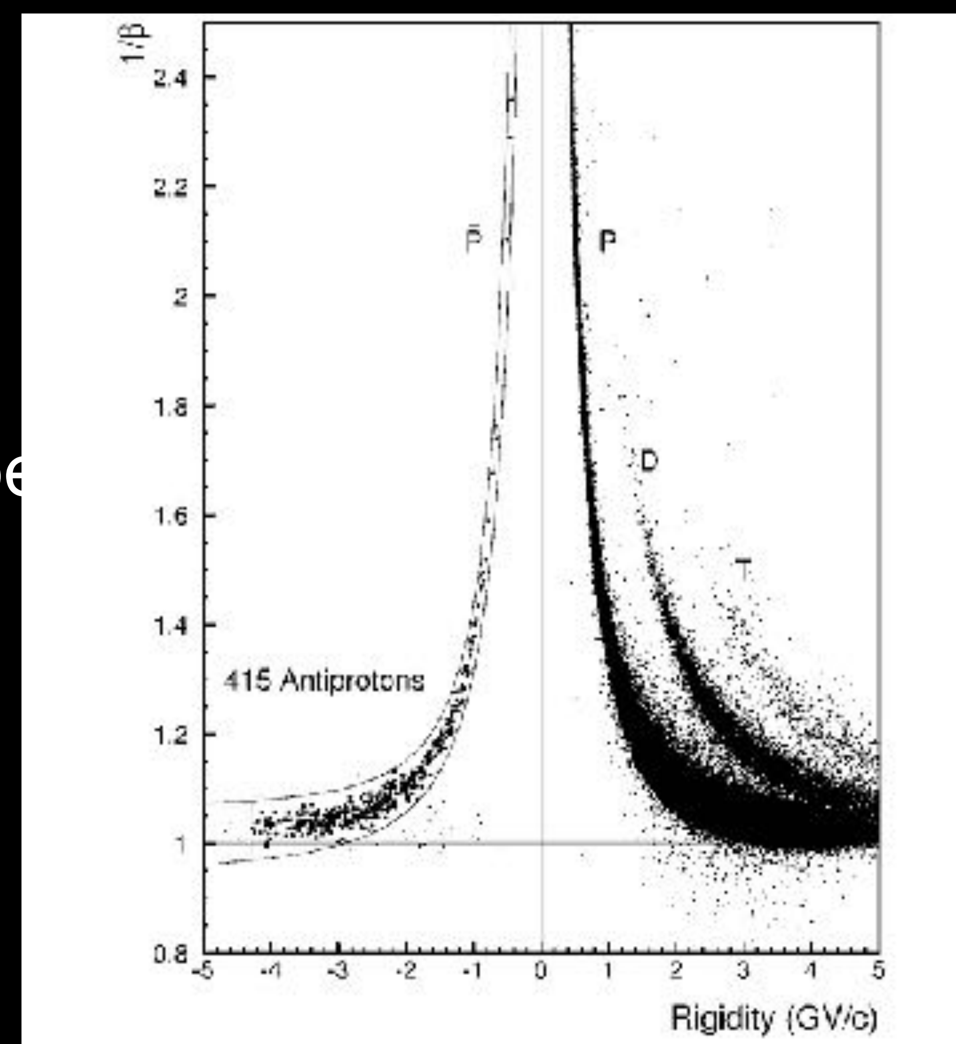


FIG. 2. The identification of $\bar{p}$ events. The solid lines define the $\bar{p}$ mass band used for the spectrum measurement.

Anti-protons

- There are anti-protons in cosmic rays
- ~10^{-4} of protons
- Consistent as secondaries due to the interaction of cosmic-ray protons in the ISM (InterStellar Medium)
- Certainly not 1:1

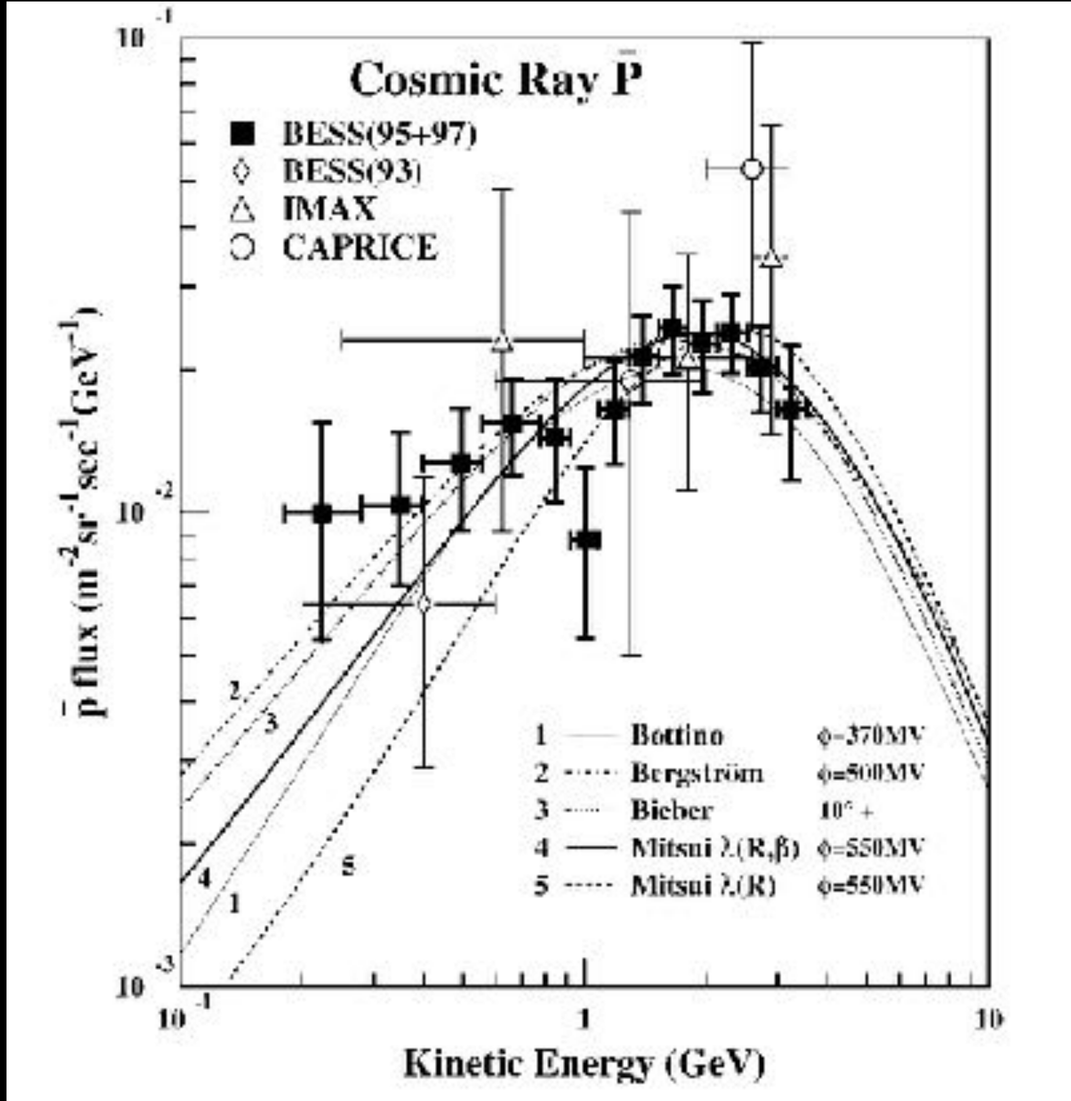


FIG. 3. BESS 1995 + 1997 (solar minimum) antiproton fluxes at the top of the atmosphere together with previous data. The error bars represent the quadratic sums of the statistical and systematic errors. The curves are recent calculations of the secondary $\bar{p}$ spectra for the solar minimum period.

Anti-Helium

- Anti-nuclei unlikely form as secondaries
- Anti-helium product of BBN in anti-matter domains
- Extragalactic anti-matter within ~10Mpc should give ~10^{-6} anti-helium flux (Stecker)
- BESS 2002 excluded this level
- Curious: AMS-02 reported 6 anti-^{3}He and 2 anti-^{4}He events (2018)

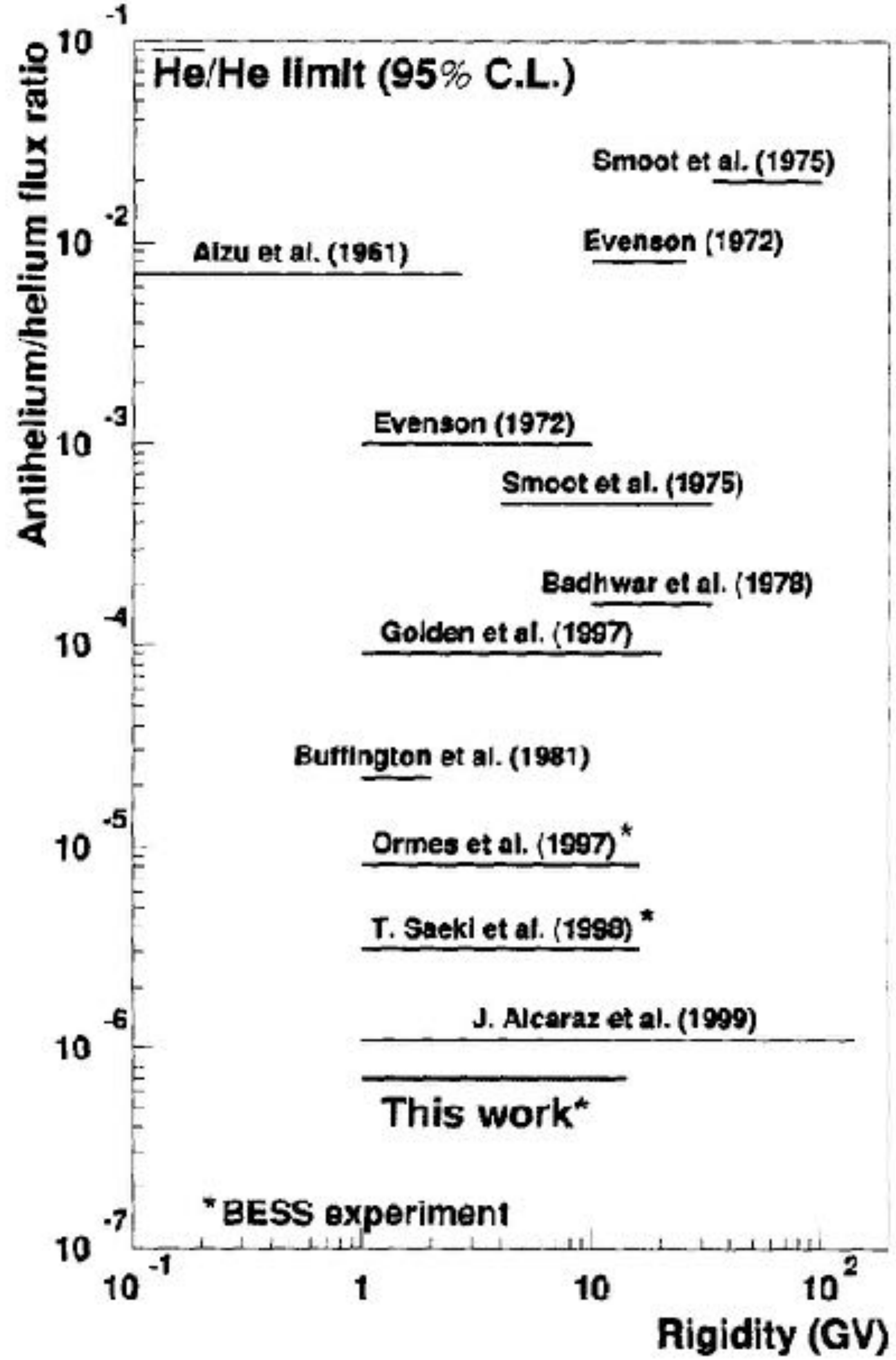
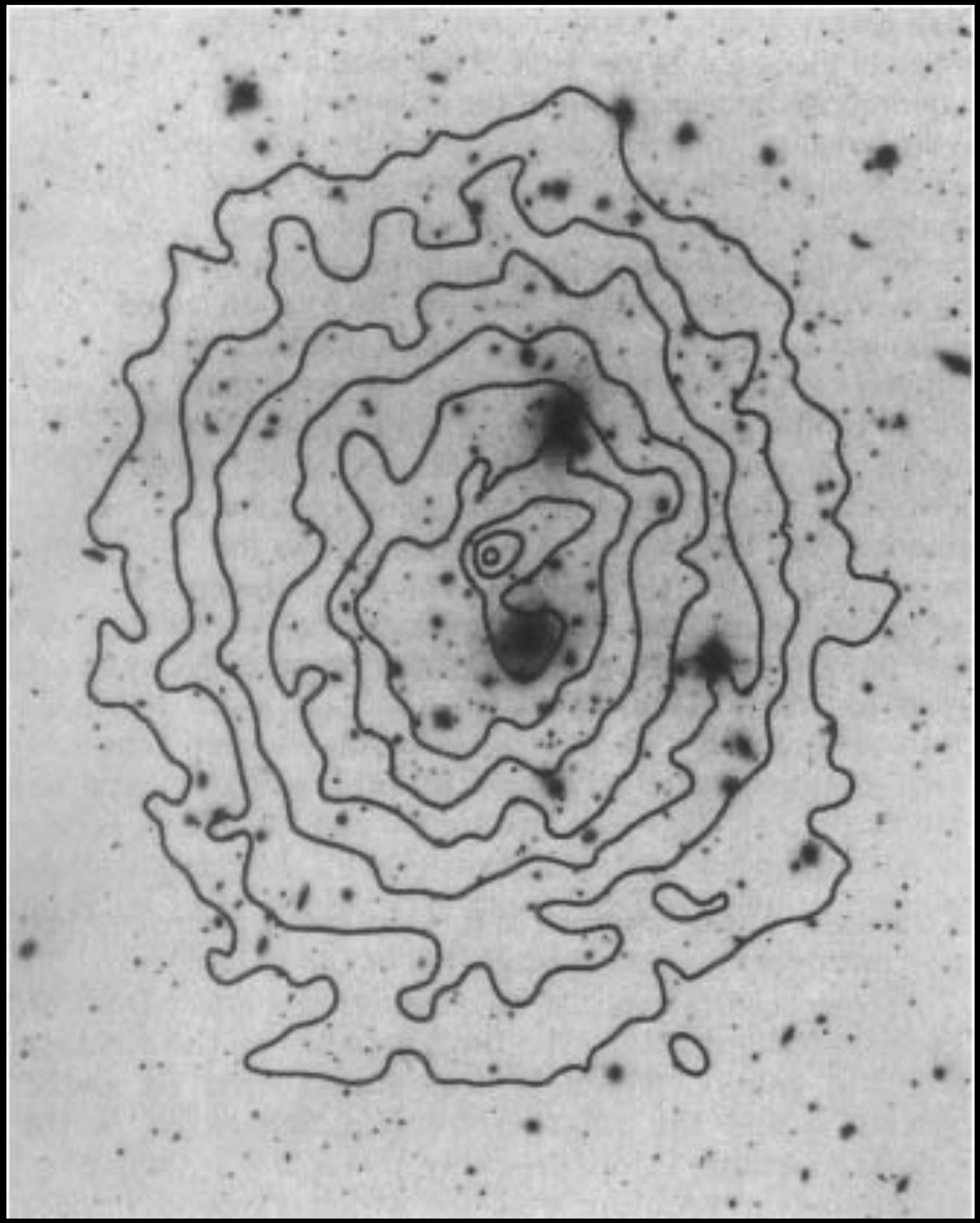


Figure 6. New upper limit of $\overline{He}$/He obtained in this work shown with previous BESS results(BESS 1993-1995 and 1997-2000), and with other experiment results.

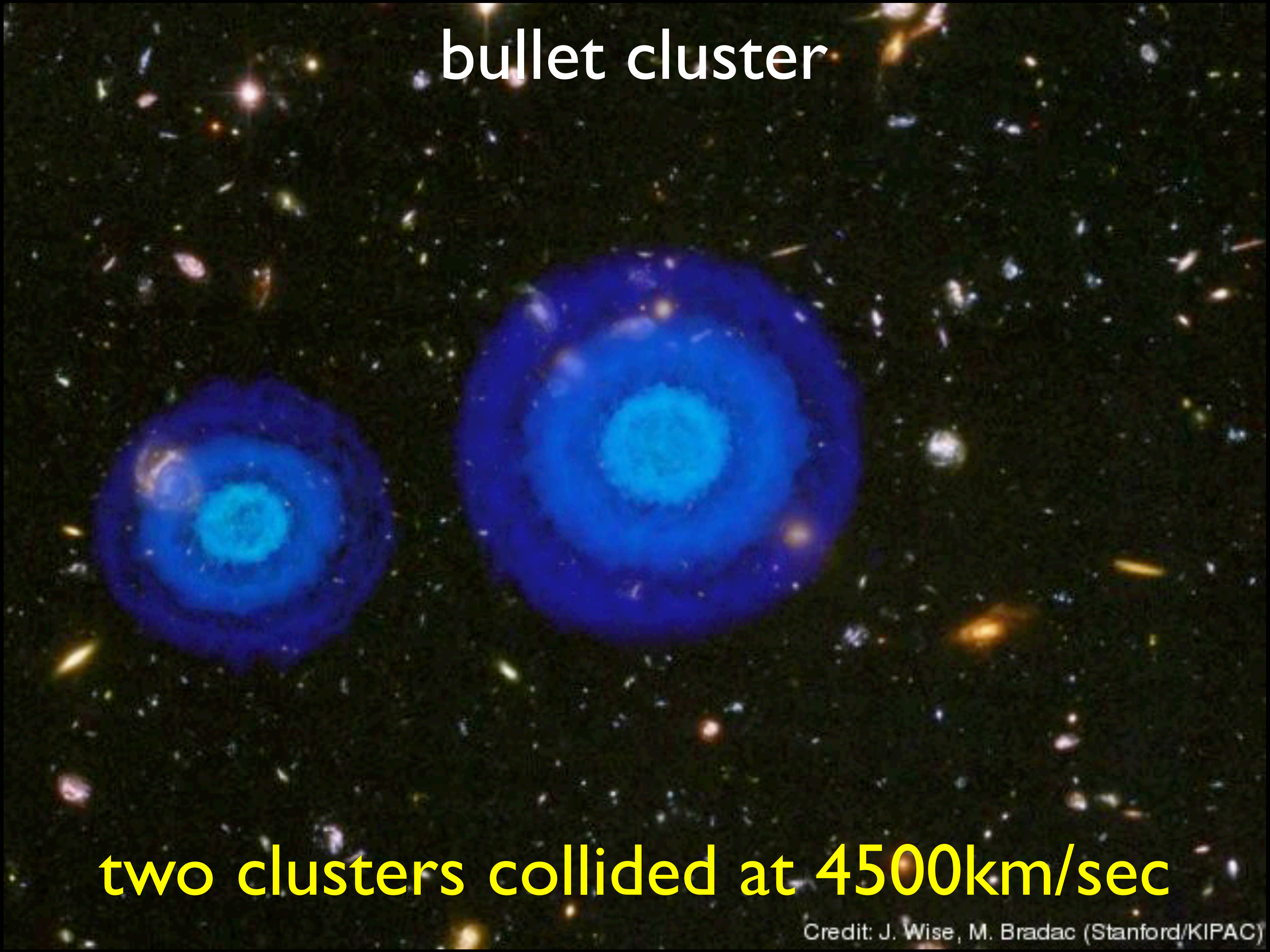
Anti-matter in Cluster

Galaxy Clusters

- No gamma rays from other X-ray emitting clusters (sure to have intracluster gas)
- No coexistence of matter and anti-matter within ~20Mpc scale
- $>10^{13}$–$10^{14} M_\odot$ only matter, little anti-matter



Good not to be here



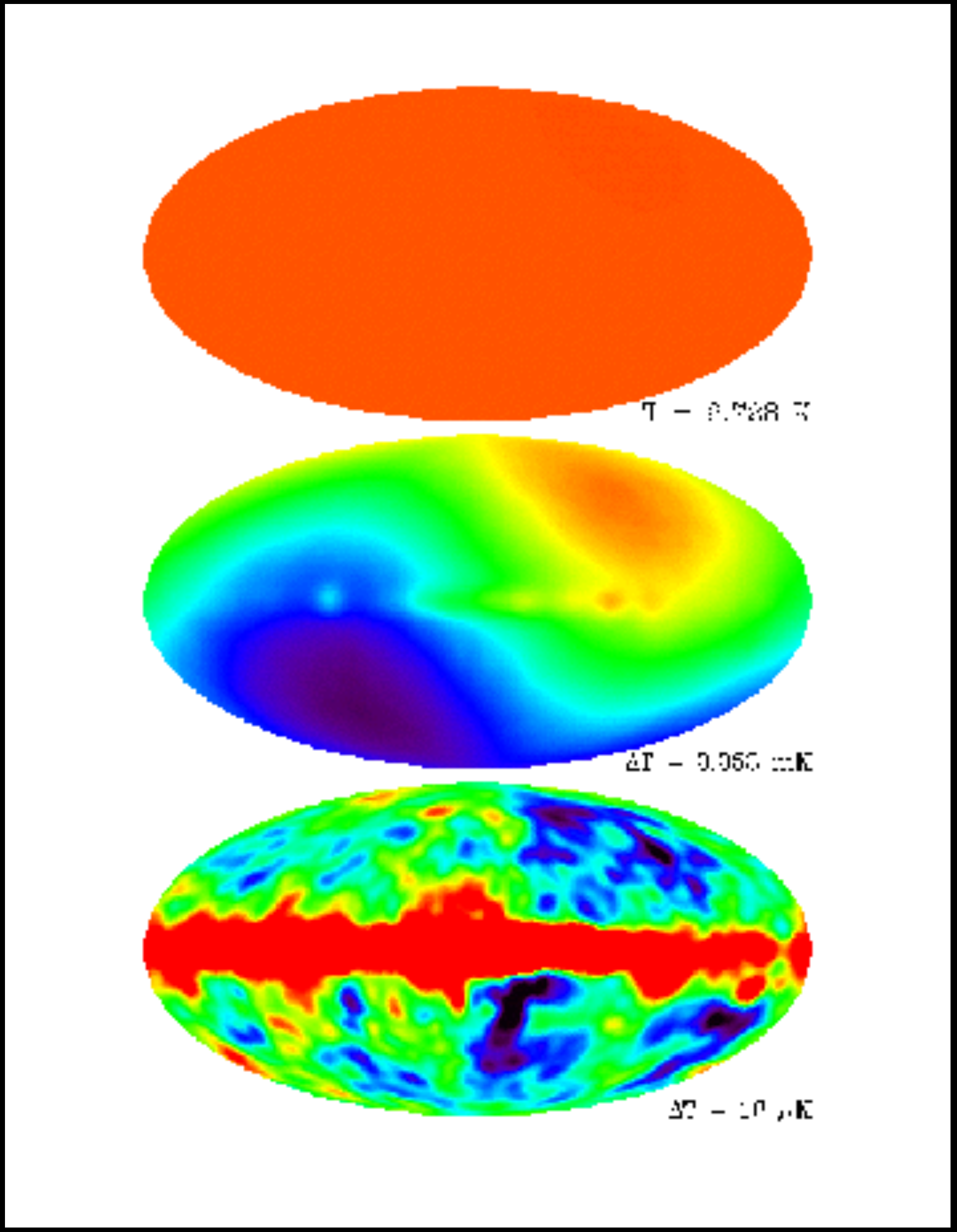
4B lyrs away

Anti-matter on Cosmological Scales

Cohen, De Rujula, Glashow (1997)

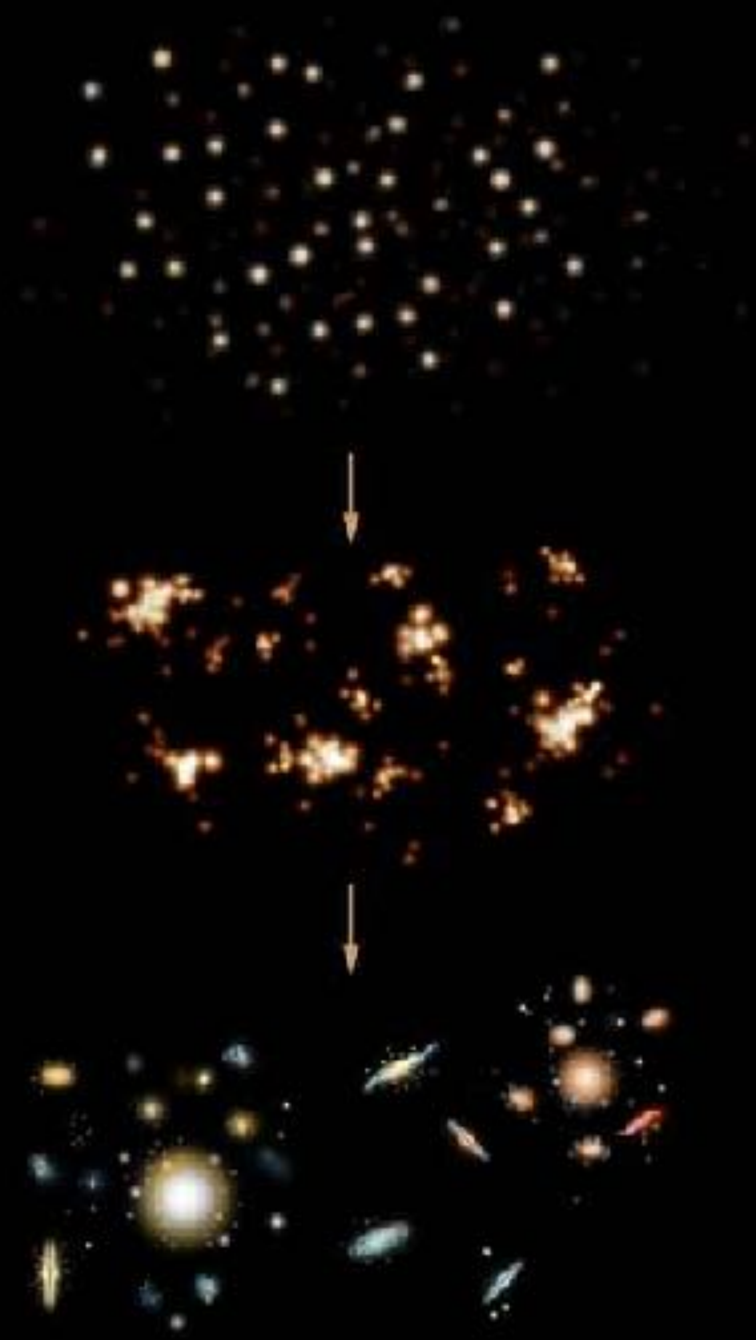
Before Recombination (z>1100)

- To avoid annihilation, need void between galaxies and anti-galaxies (or clusters)
- O(1) density fluctuations!
- unacceptably large anisotropies in CMB $\sim 10^{-2}$-$10^{-1} \gg 10^{-5}$
- Only way out: make voids very small within the resolution of CMB <15Mpc at the time of recombination
- However, the photon pressure moves domains closer and fills the void up to ~16Mpc



Structure Formation (z<20)

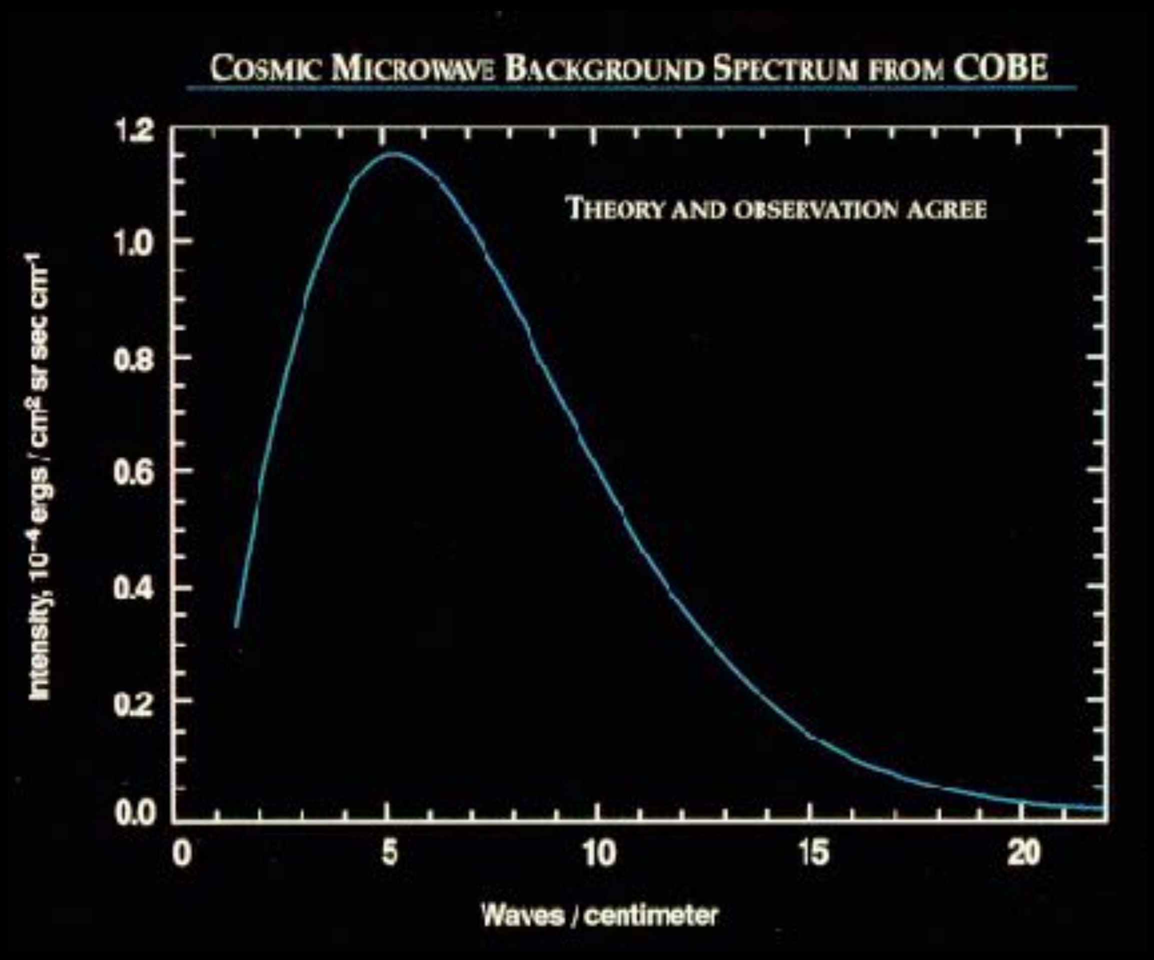
- Density fluctuation grows by gravity
- It could well form structure with both matter and anti-matter, leading to intense annihilation
- However, the annihilation leads to gamma rays and the photon pressure may stop the gravitational collapse
- Assume that the mixed structure does not form
- Conservative assumption that minimizes the annihilation gamma rays
- Do not discuss non-linear regime (*e.g.*, z>20)



Unavoidable Annihilation

- It leaves 1100>z>20 for annihilation
- Density must be smooth, void must be filled
- Domains touch each other and annihilation takes place at the interface
- CMB distortion?
- Diffuse gamma ray background?

COBE/FIRAS



CMB distortion

- Annihilation photons Compton scatter, making the CMB spectrum harder
- Significant effect only on high-energy tail
- Current limits do not exclude this

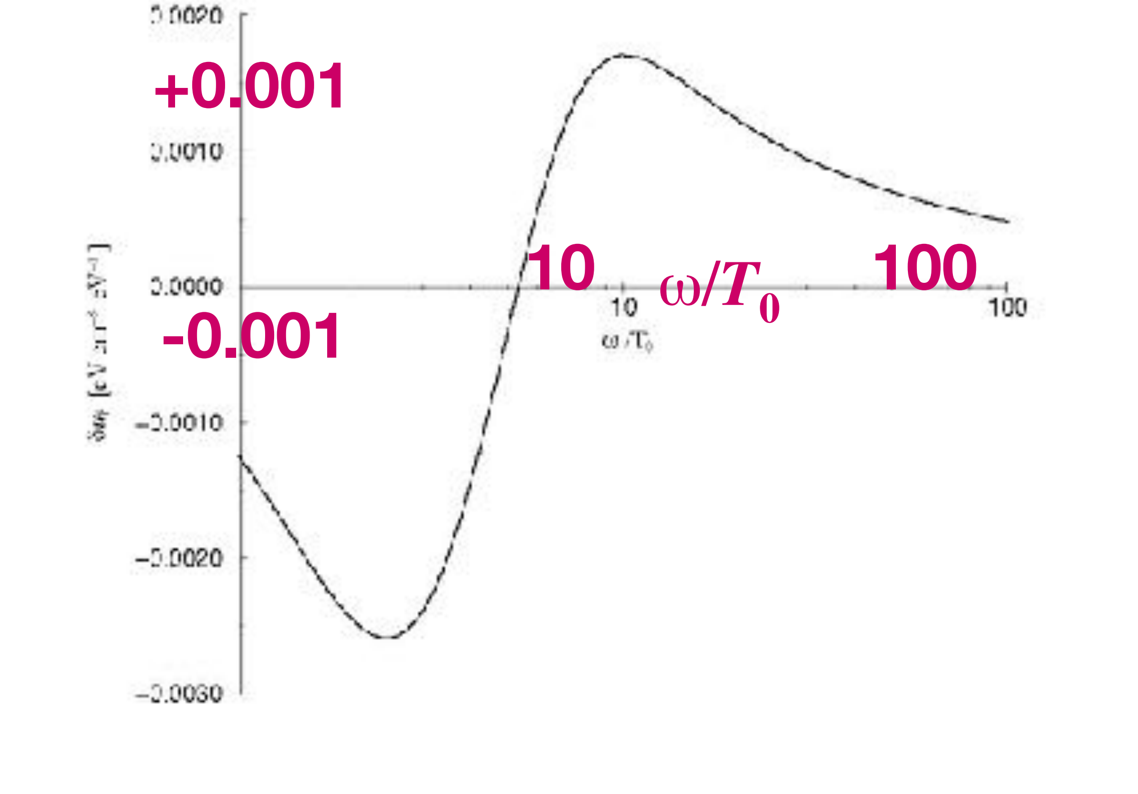


Figure 4: The CBR spectral distortion. Beyond the range shown, $\delta u_\omega \propto 1/\sqrt{\omega}$, up to $\omega/T_0 \sim 10^4$.

Diffuse Gamma Ray Background

- Most of the gamma rays from π^0 are still around
- Contributing to the diffuse gamma ray background
- d_0<1Gpc excluded

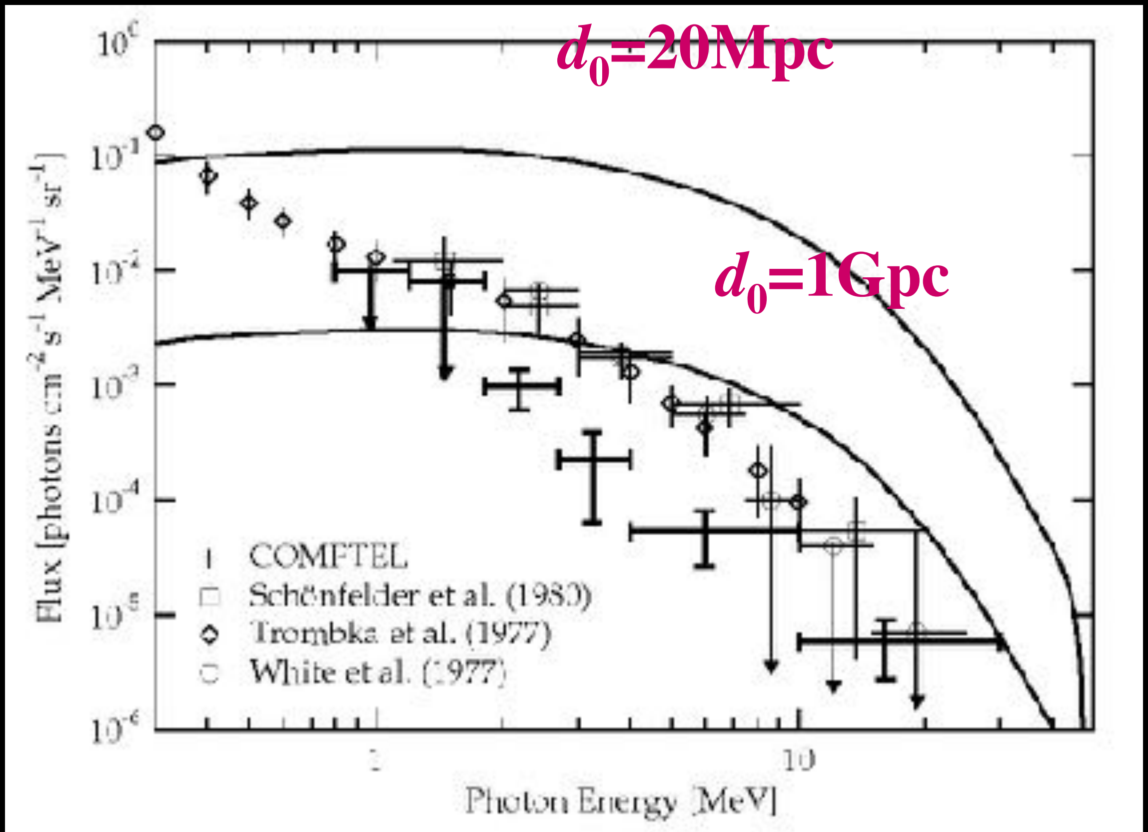


Figure 5: Data [23] and expectations for the diffuse γ-ray spectrum.

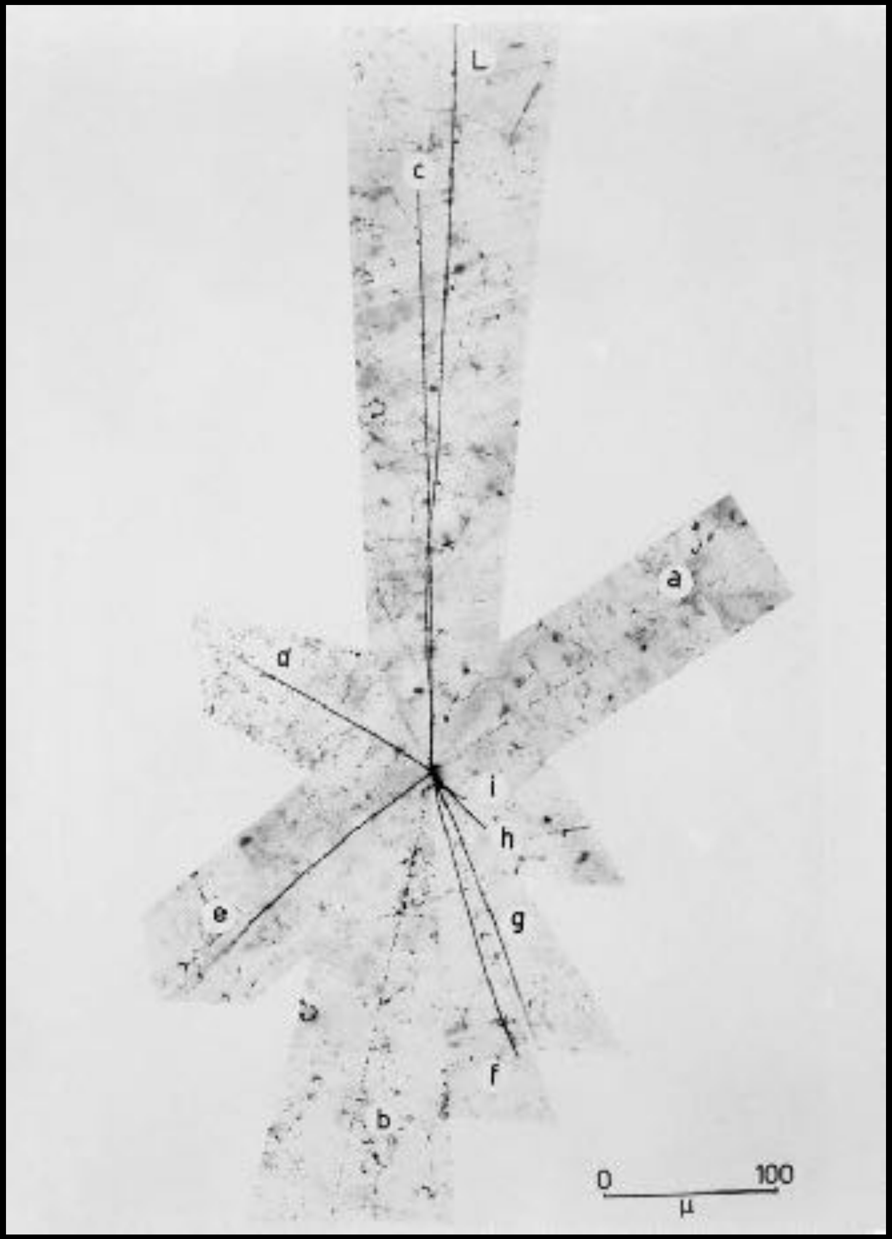
Causality

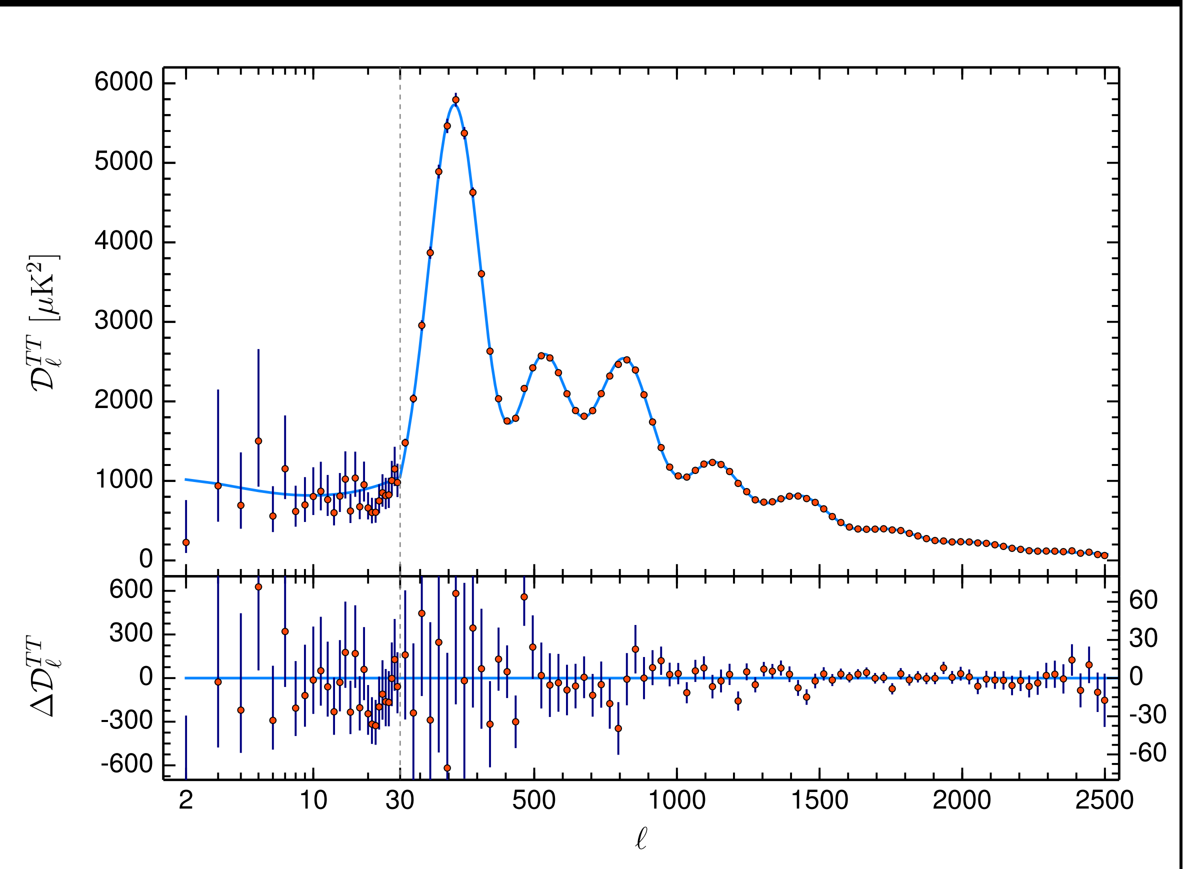
No communication

- We learned that matter and anti-matter domains (if they exist) must be separated beyond >1Gpc, basically the size of the visible universe now.
- A new force that repels matter and anti-matter?
- Distance of ~1Gpc has just come to see each other
- No causal mechanism could separate them
- Think what could have happened in earlier universe well before recombination

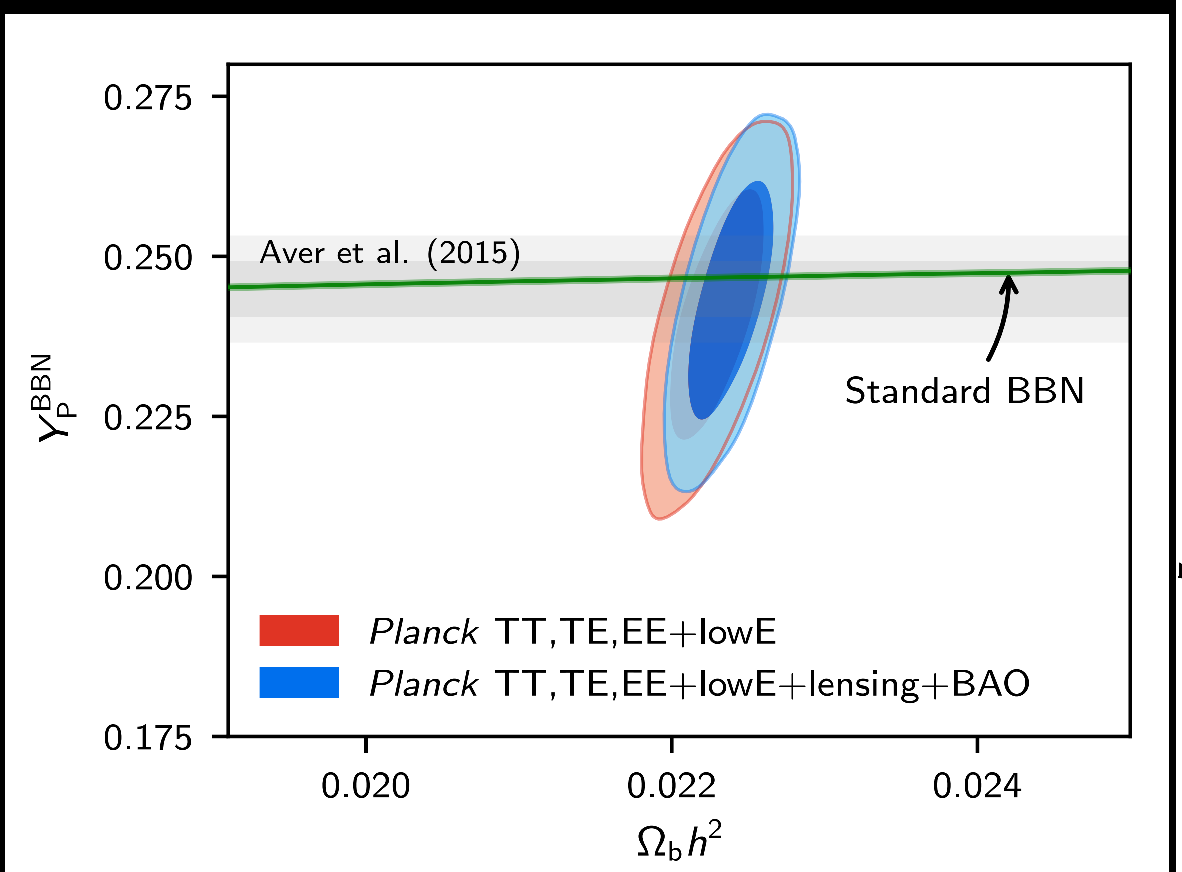
QCD phase transition

- In early universe above the QCD phase transition (kT>100MeV), both q and anti-q produced by gluons
- Once the $T<T_c$, they all hadronize
- Gas of baryons, anti-baryons, and mesons
- Baryons and anti-baryons annihilate immediately
- End up with $n_B/n_\gamma \sim 10^{-20}$ everywhere in universe

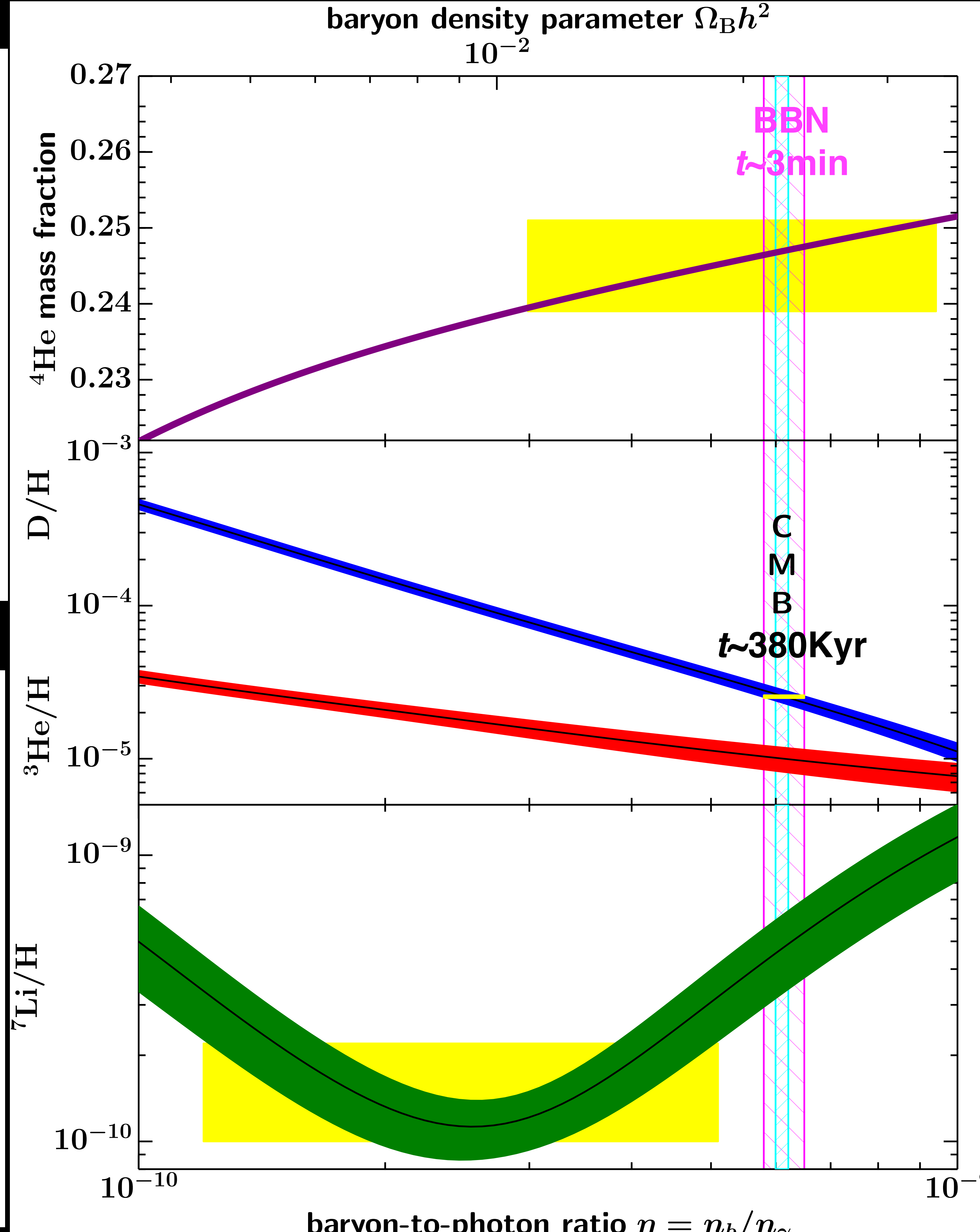




$\mathcal{D}_\ell^{TT}$ [μK^2]
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ



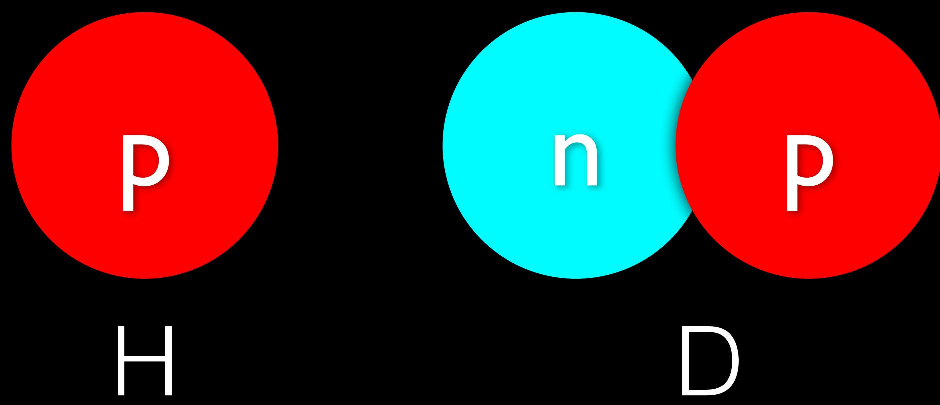
Y_P^{BBN}
0.275
0.250
0.225
0.200
0.175
Aver et al. (2015)
Standard BBN
Planck TT,TE,EE+lowE
Planck TT,TE,EE+lowE+lensing+BAO
0.020
0.022
0.024
$\Omega_b h^2$



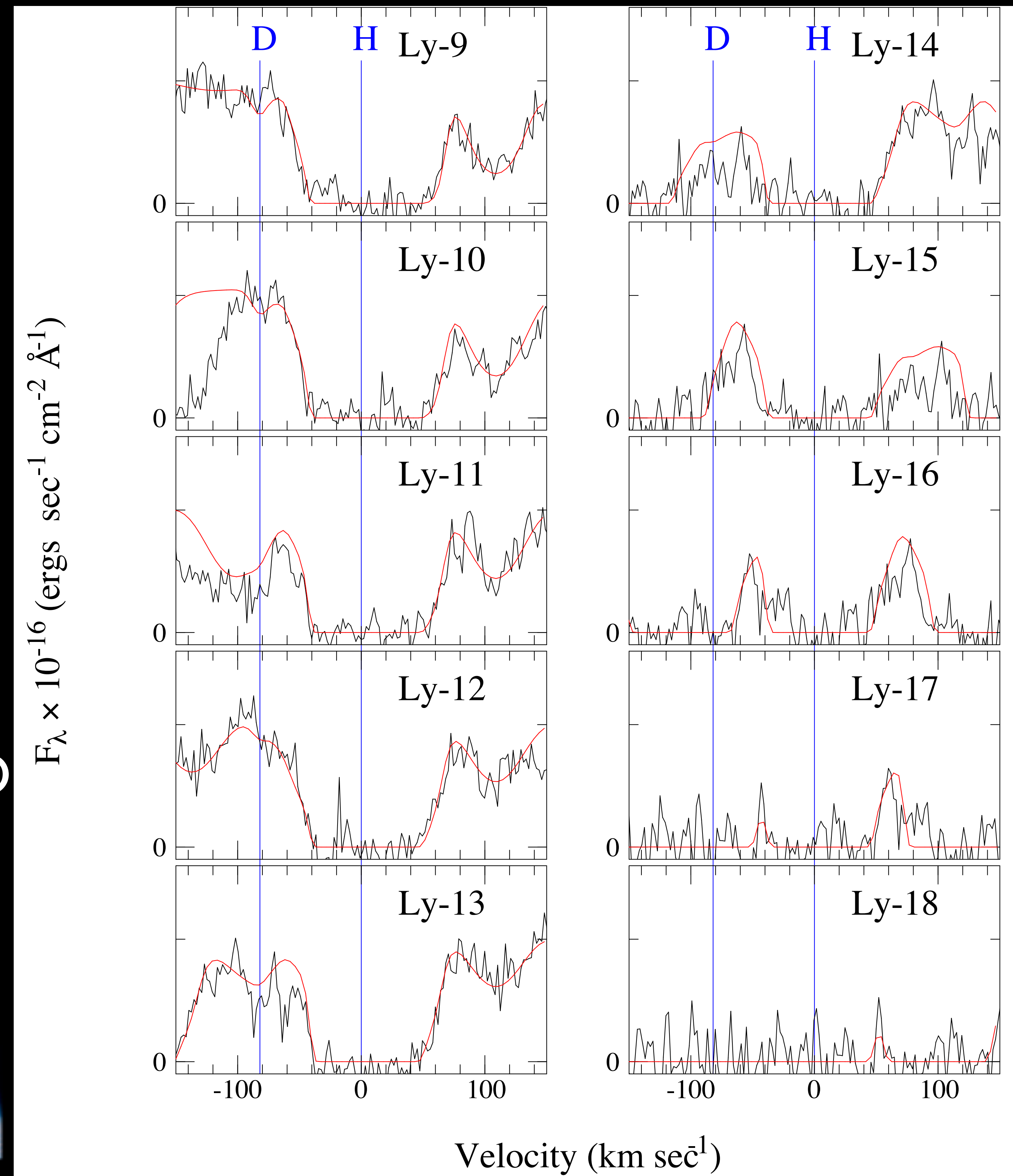
baryon density parameter $\Omega_B h^2$
10^{-2}
0.27
0.26
0.25
0.24
0.23
^{4}He mass fraction
BBN
t~3min
10^{-3}
D/H
10^{-4}
^{3}He/H
10^{-5}
C
M
B
t~380Kyr
10^{-9}
^{7}Li/H
10^{-10}
10^{-10}
10^{-9}
baryon-to-photon ratio $\eta = n_b/n_\gamma$

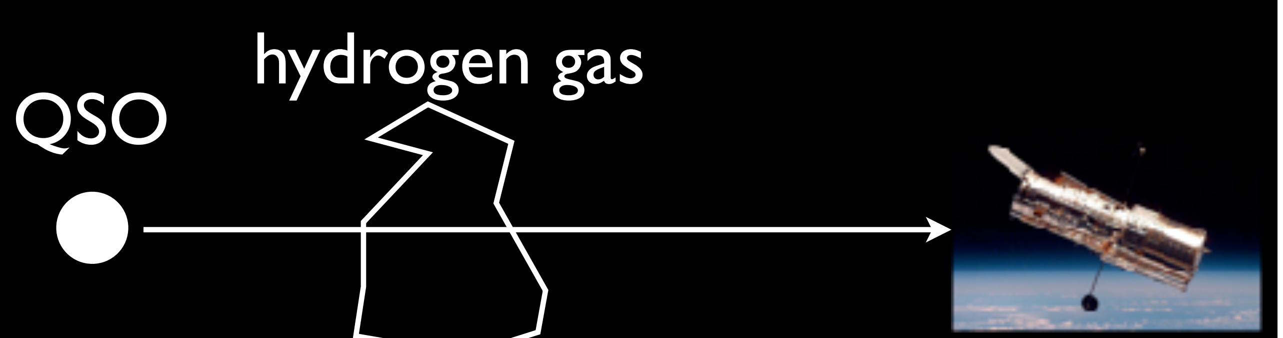
deuterium

Kirkman, Tytler, Suzuki, O'Meara, Lubin



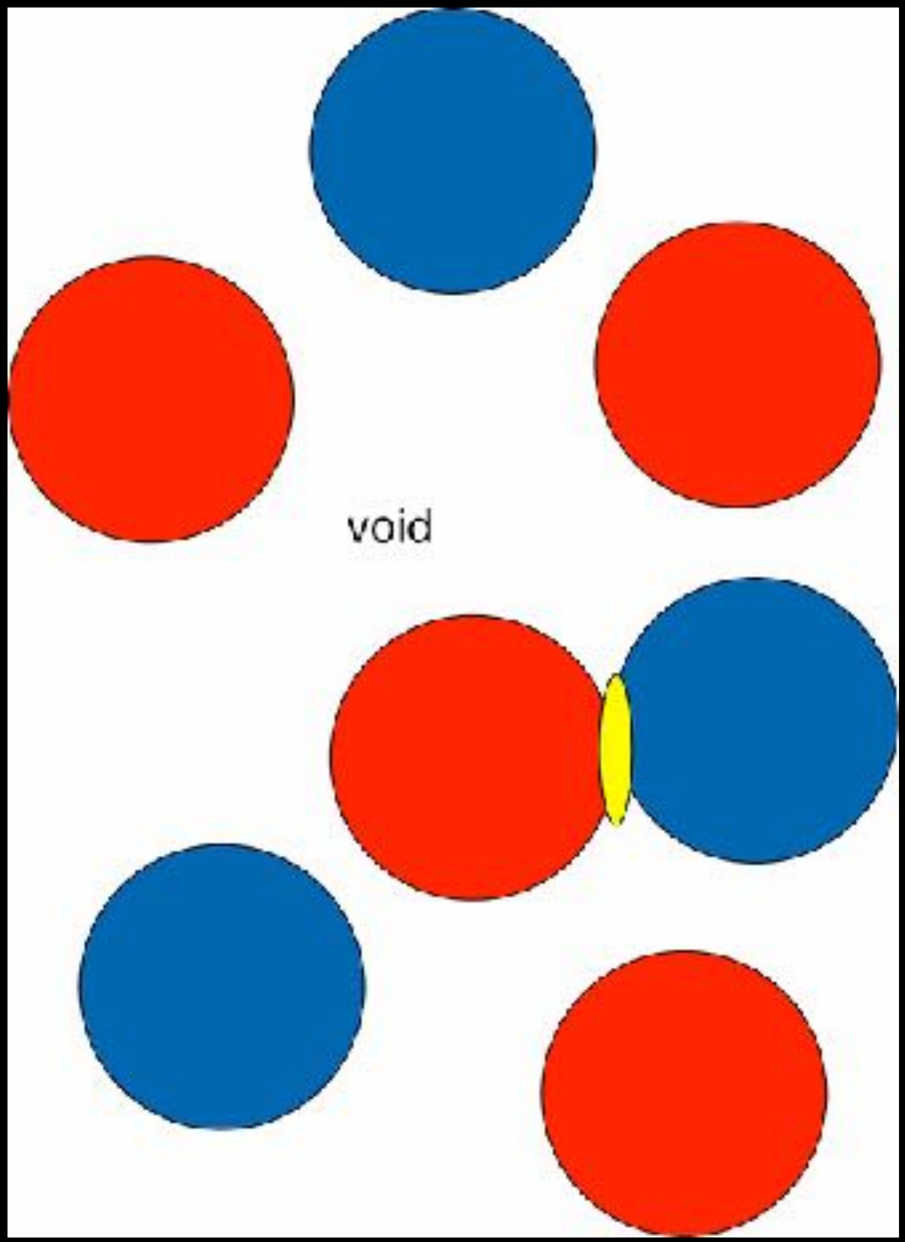
- the same chemically
- energy levels
  $E_n = -\alpha^2 \mu c^2/2$
- reduced mass differs by ~1/4000 between H & D





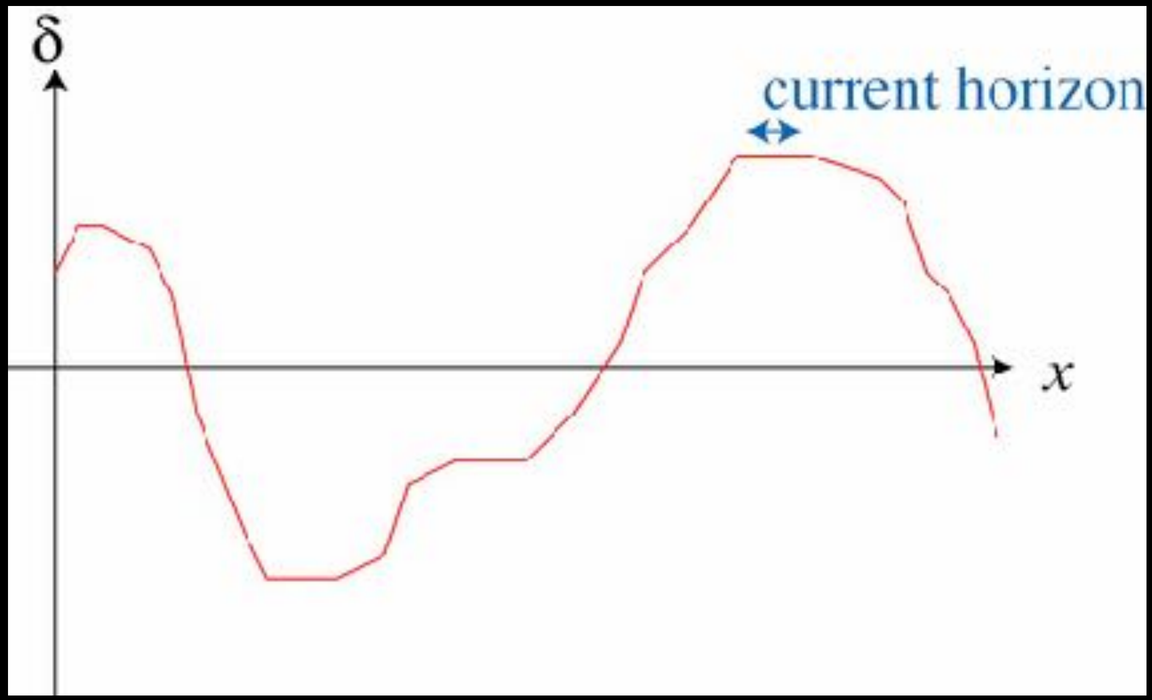
Requirement for separating domains

- Domains of matter and anti-matter must have been well separated *before* the QCD phase transition to avoid this near-total annihilation
- Horizon size back then $\sim 10^{-7} M_\odot$
- Need to separate $>> 10^{13} M_\odot$
- Need *acausal* mechanism



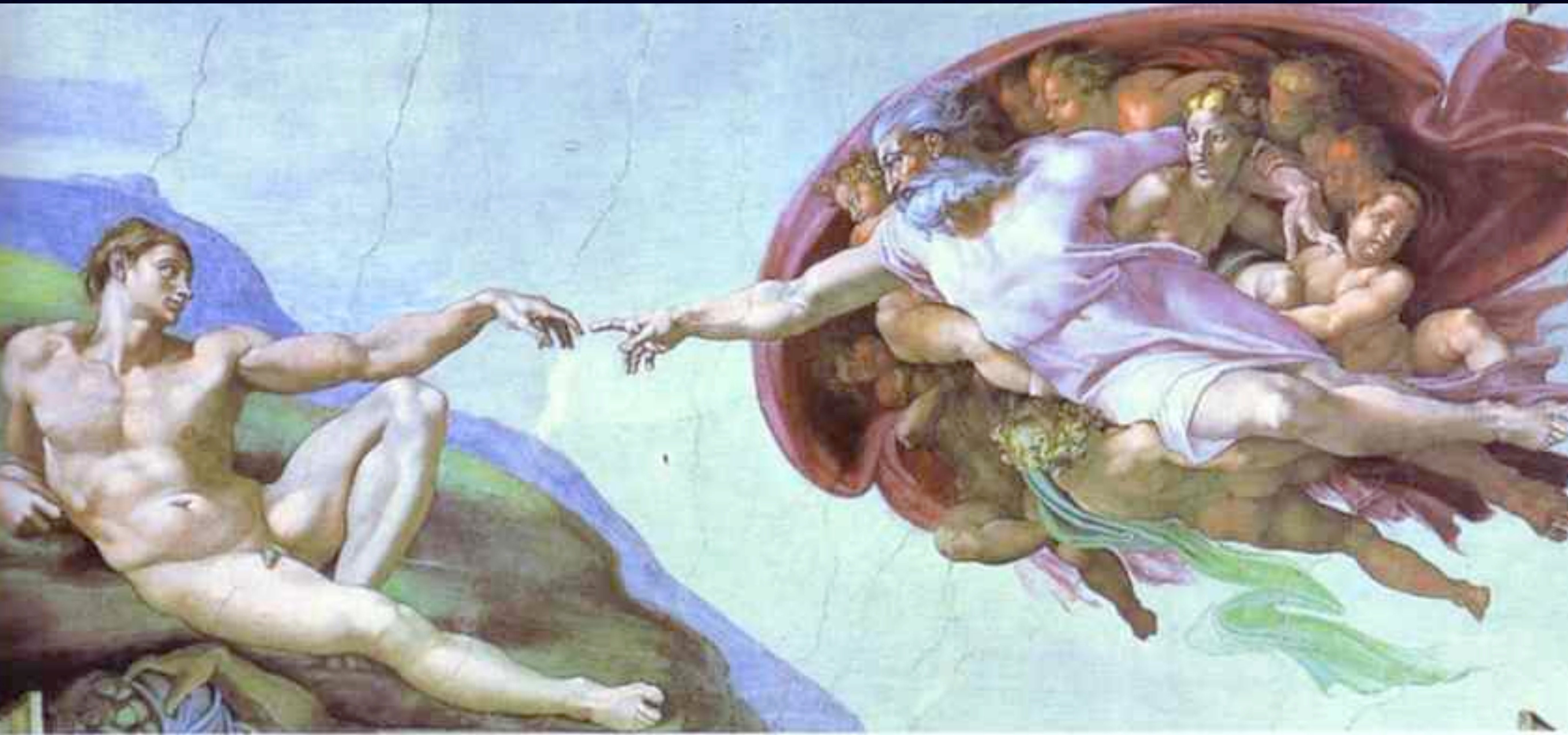
Spontaneous CP violation
(Cohen, Kaplan)

- Assume a source of CP violation is determined by a VEV of a scalar field
- The field can vary from one horizon to another
- Inflation stretches it so that it is nearly constant, varies only on superhorizon scales
- The anti-matter domain could exist just beyond the current visible universe
- Not easy to do “just right”



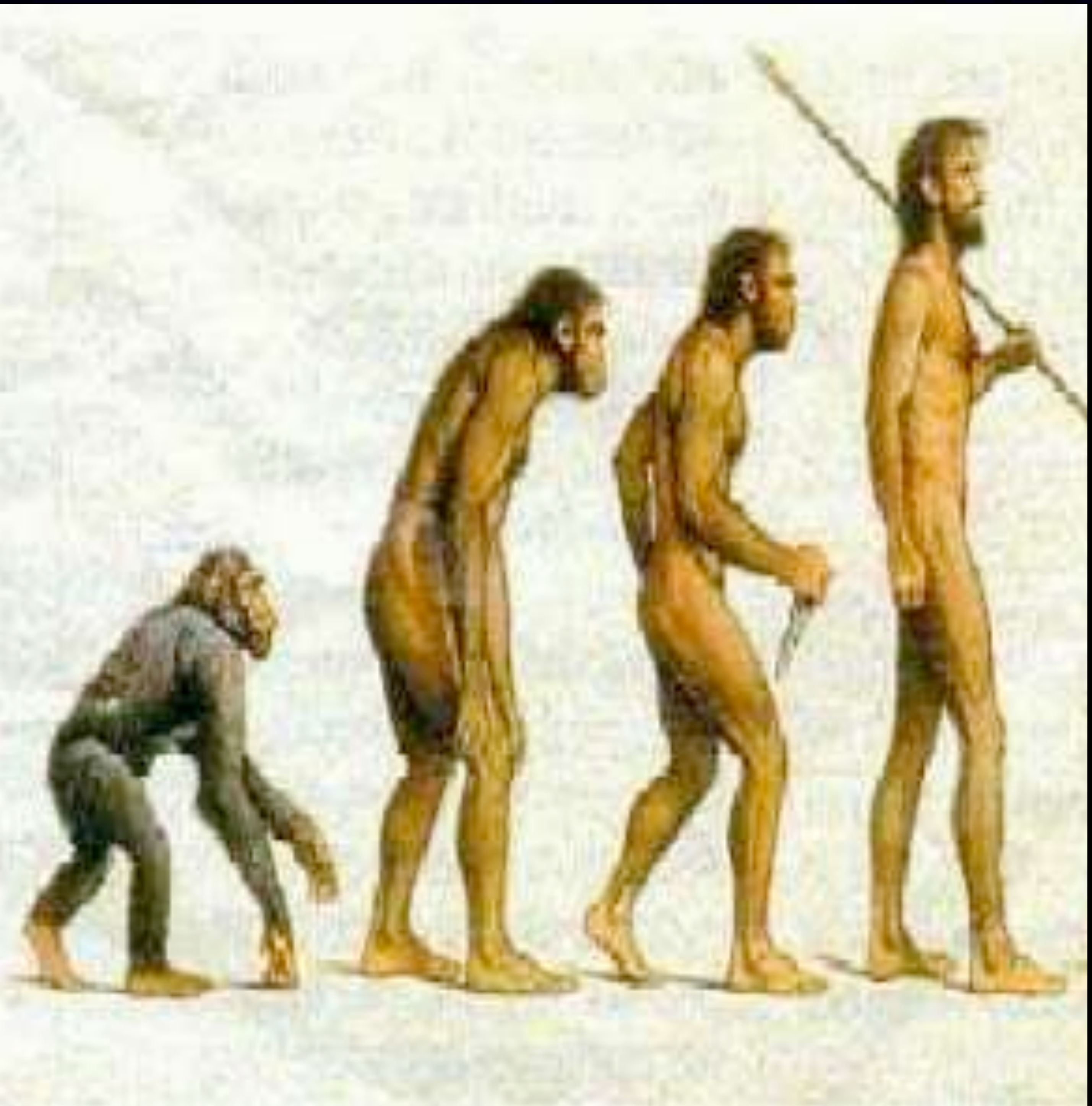
Creation

$n_b(t=0) \neq 0$

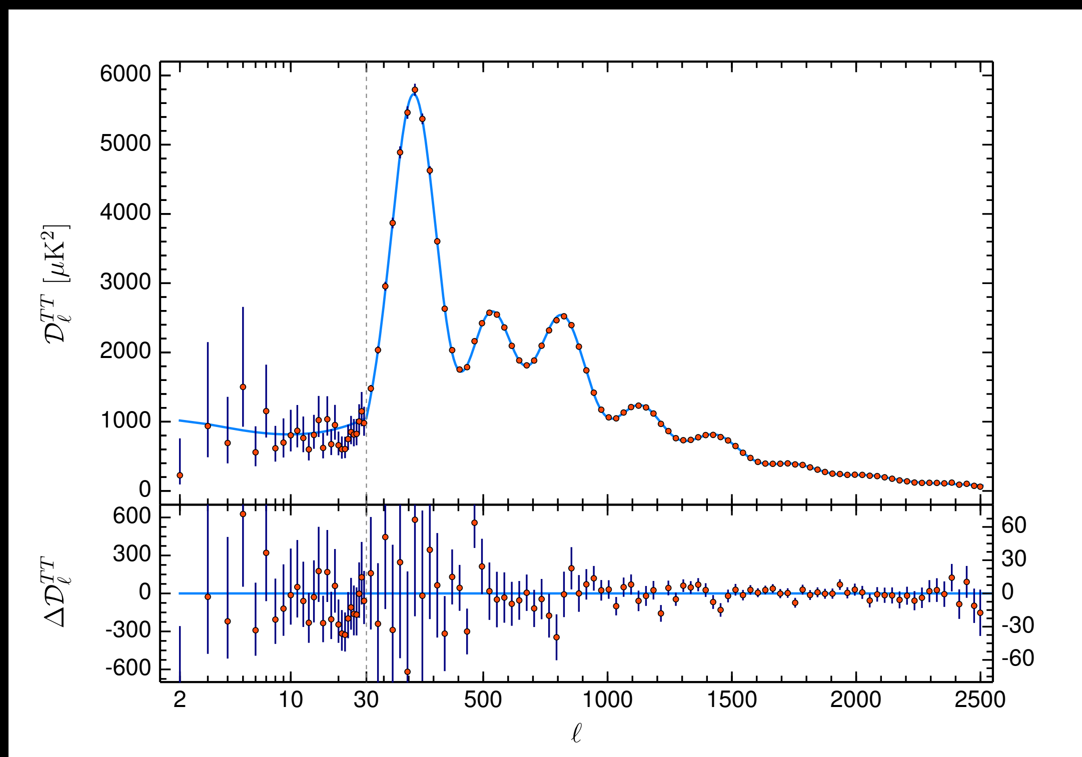


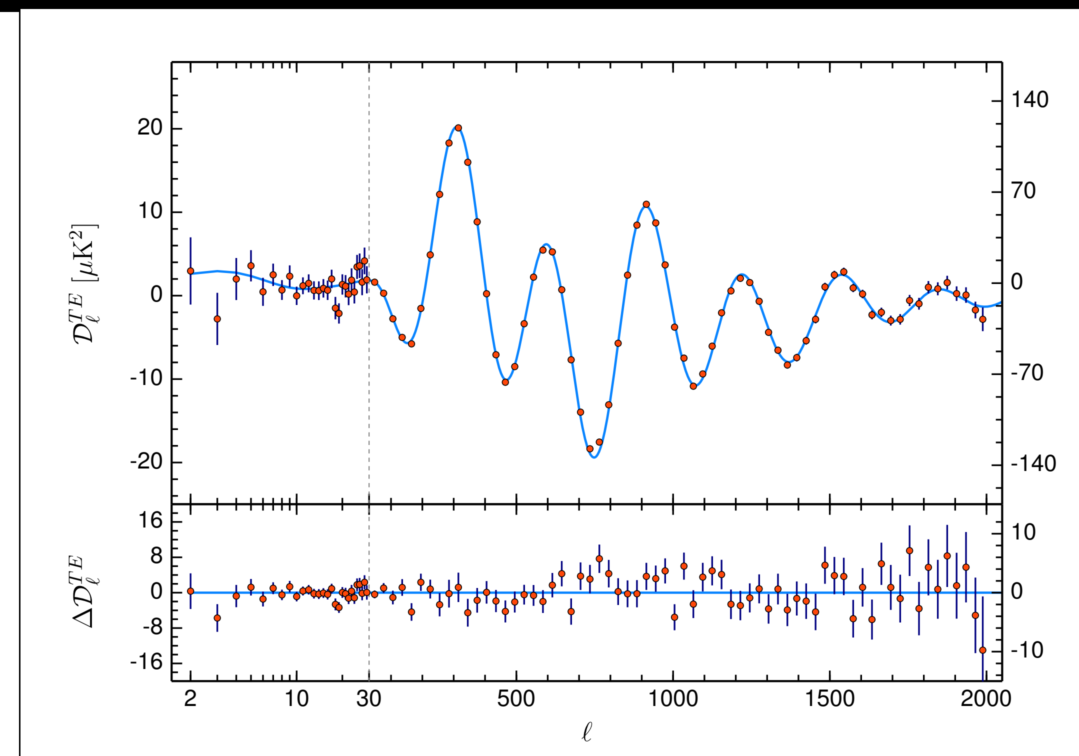
Or Evolution?

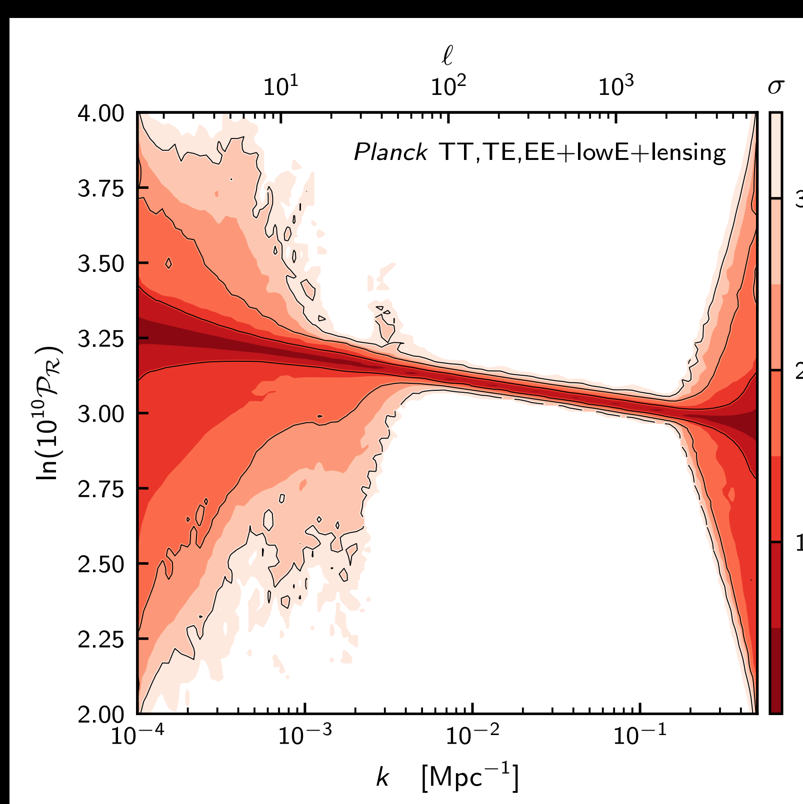
$$n_b(t=0)=0 \Rightarrow n_b(t>t_b)\neq 0$$

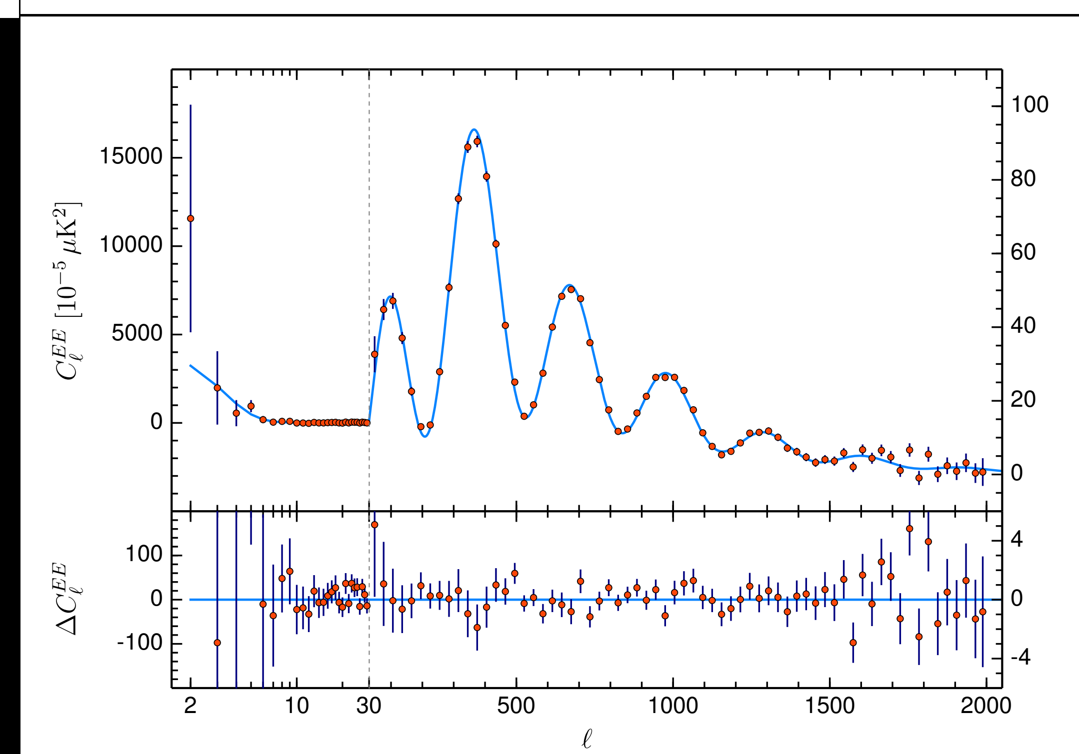


Inflation


$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
ℓ


$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$
ℓ


ℓ
σ
Planck TT,TE,EE+lowE+lensing
ln($10^{10}\mathcal{P}_\mathcal{R}$)
k [Mpc^{-1}]


C_ℓ^{EE} [$10^{-5}\,\mu$K^2]
ΔC_ℓ^{EE}
ℓ

Basic Conclusion

- no anti-matter domain within the observable Universe
- causality does not allow separation of matter and anti-matter
  - unless “acausal” mechanism *e.g.* spontaneous baryogengesis
- need to generate baryon asymmetry after inflation
  - baryogengesis is now *required* in consistent cosmology

Beginning of Universe

1,000,000,000

matter

1,000,000,000

anti-matter

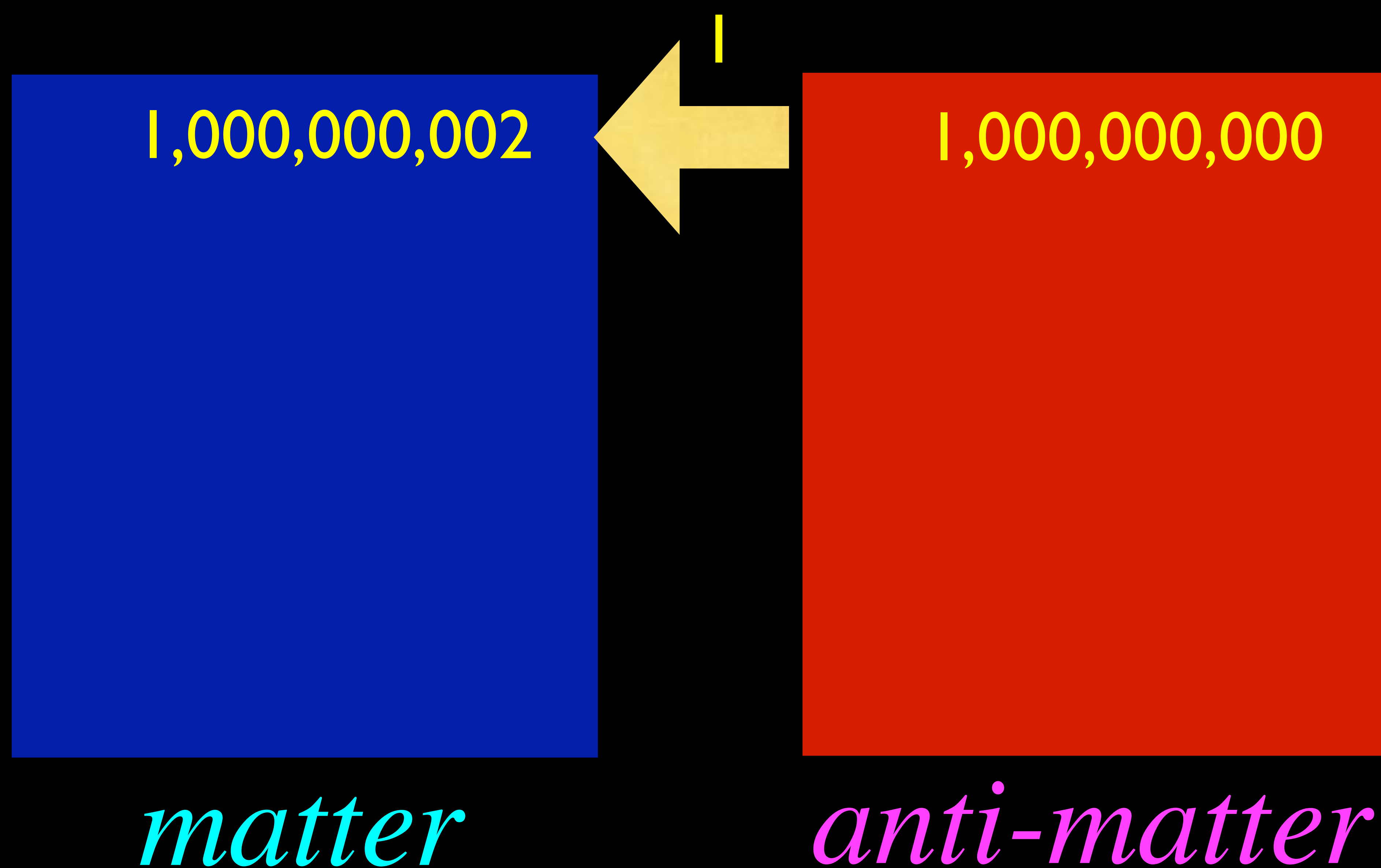
Beginning of Universe

matter	anti-matter
1,000,000,001	1,000,000,001

matter

anti-matter

fraction of second later



turned a billionth of anti-matter to matter

Universe Now

2

•

us

matter *anti-matter*

we were saved from the complete annihilation!


Who saved us from
a complete annihilation?

Sakharov's condition

- C and CP violation
  - which one is matter? we need distinction
- Baryon number violation
  - must be a way to change B=0 to B≠0
- Departure from equilibrium
  - no net gain as long as detailed balance

Sakharov Conditions

- We need to satisfy all three ingredients
- Baryon number violation
  - need a way to change B=0 to B≠0
- CP violation
  - which one is matter? we need distinction
- Departure from equilibrium
  - no net gain as long as detailed balance
- Where and when?

too many theories for a single number

Two tales

- Testing Leptogenesis with gravitational waves
  - +Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)
  - arXiv:1908.03227 accepted for PRL, *Editors' Suggestion*
- Asymmetric Matters from a dark first-order phase transition
  - +Eleanor Hall (Berkeley), Thomas Konstandin (DESY), Robert McGehee, Bethany Suter (Berkeley)
  - arXiv:1911.12342, 2107.03398

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Testing seesaw and leptogenesis by gravitational wave

Hitoshi Murayama (Berkeley, Kavli IPMU)
+Jeff Dror (Berkeley), Takashi Hiramatsu (ICRR), Kazunori Kohri (KEK), Graham White (TRIUMF)

arXiv:1908.03227,
Phys.Rev.Lett. 124 (2020) 4, 041804
Editor's Suggestion

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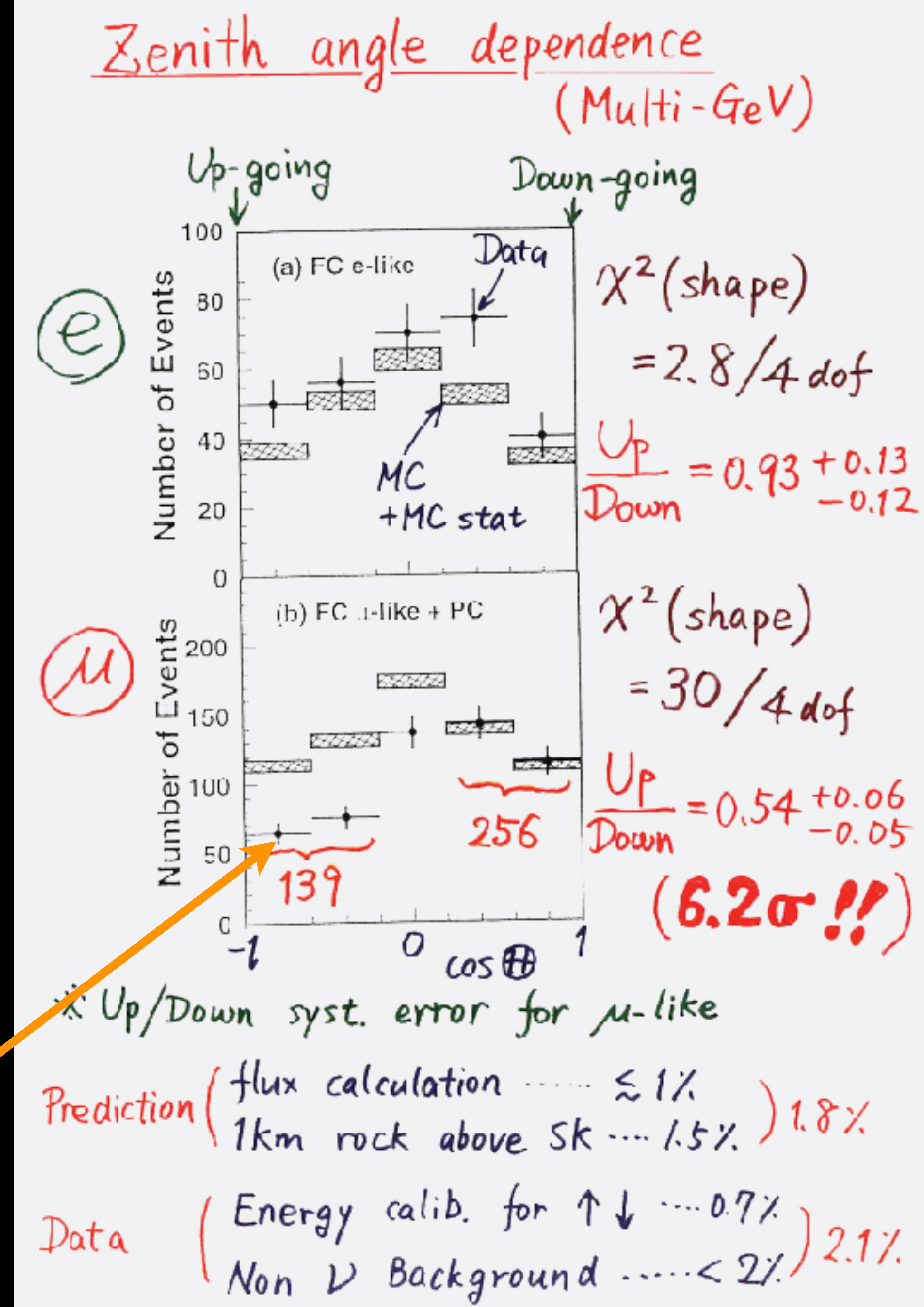
neutrinos oscillate

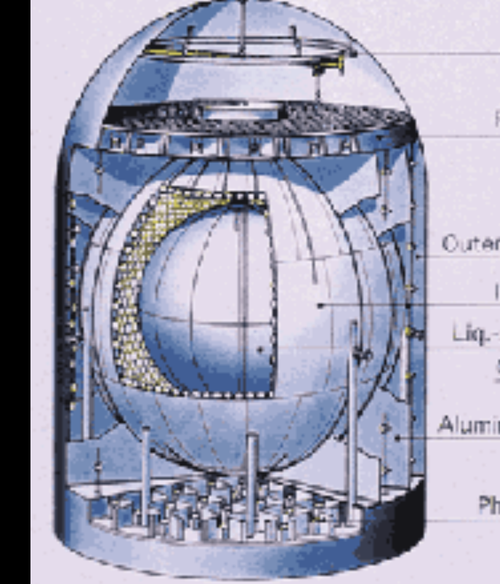
1998

a half of expected

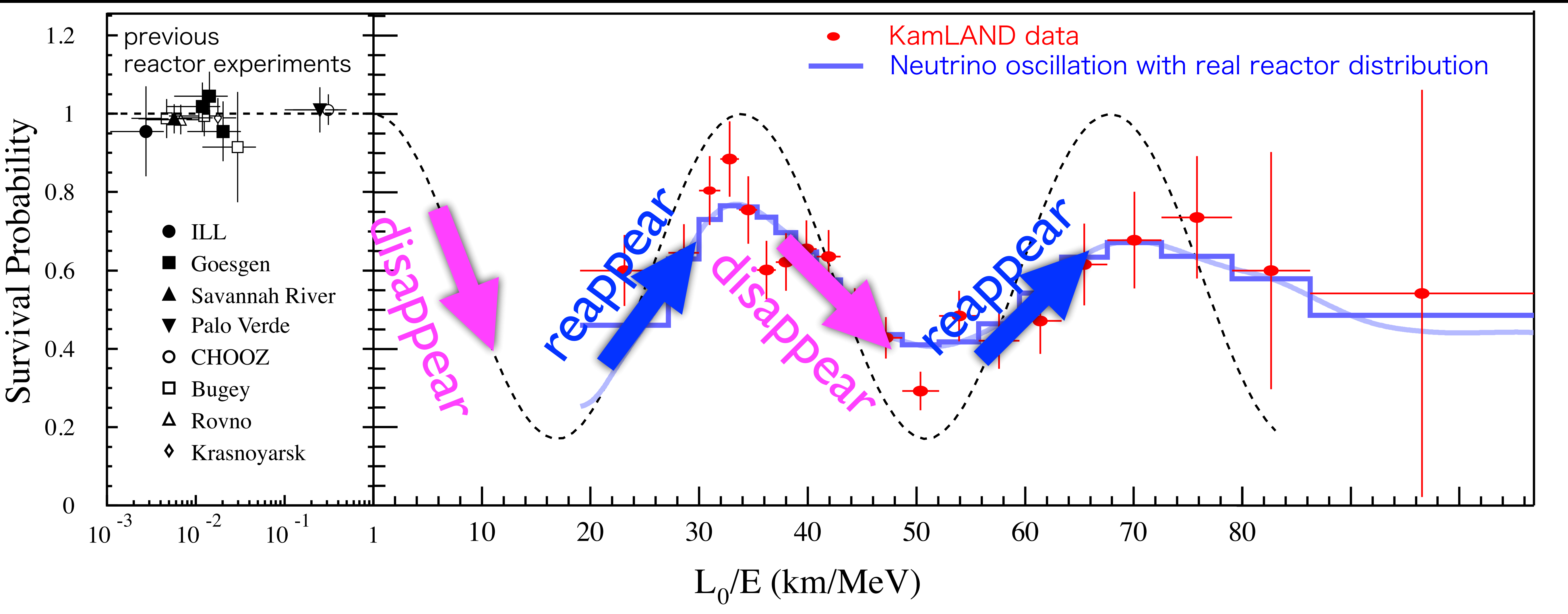


shift inside the mine for KamLAND

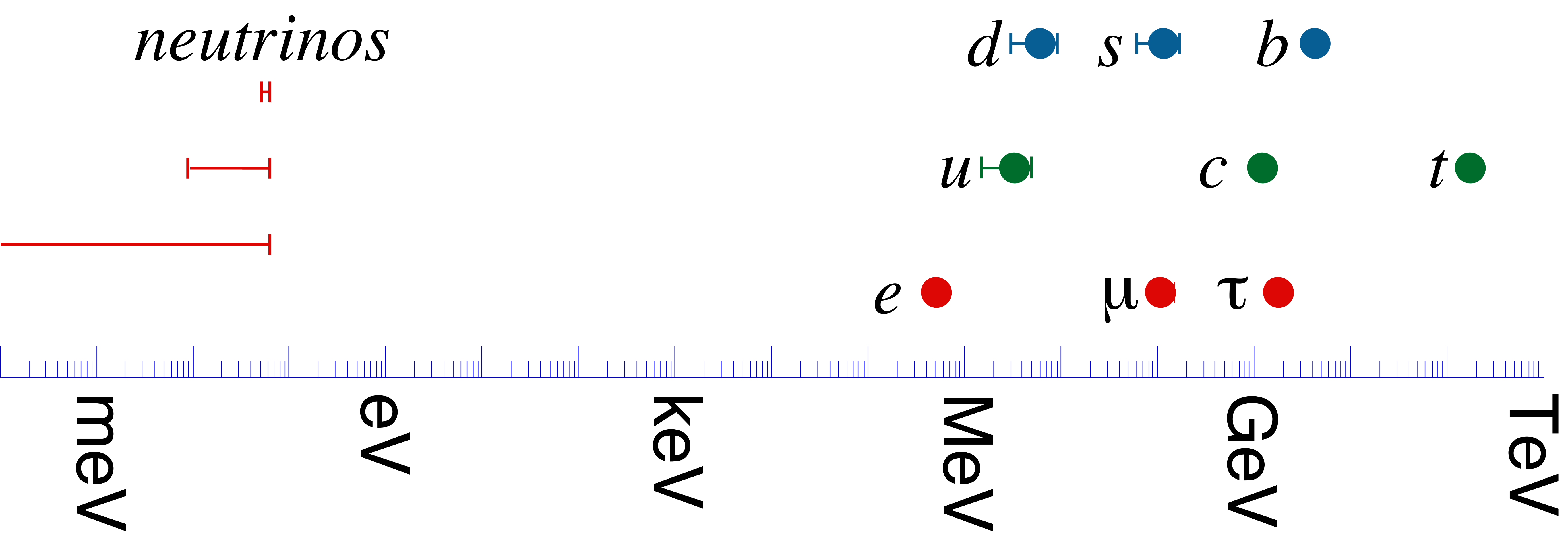
reactor neutrinos



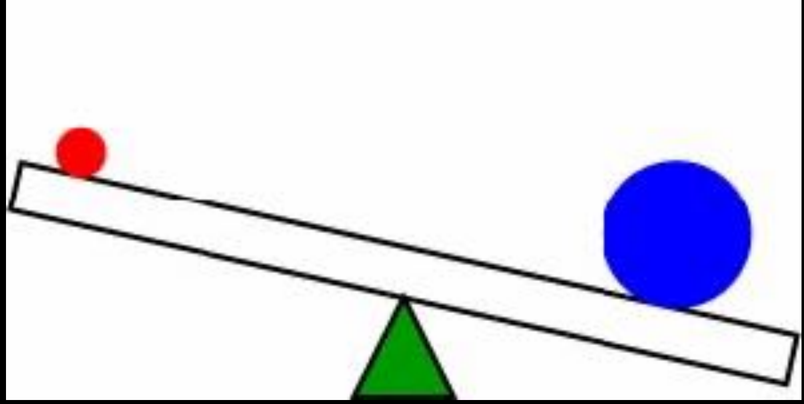
- KamLAND experiment
- a ring of reactors with average *L*~175 km



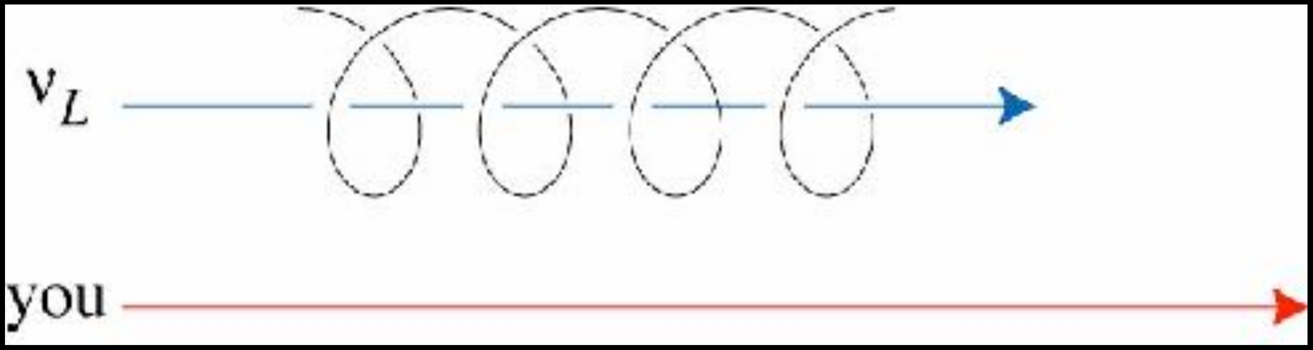
very light

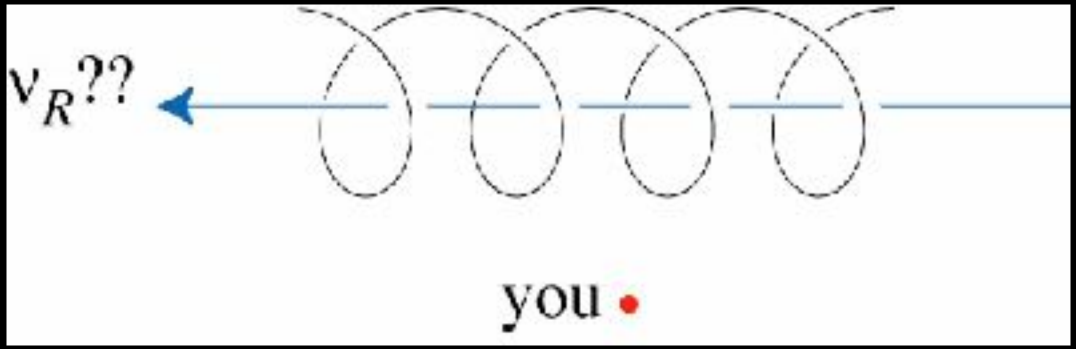


Seesaw



- Why is the neutrino mass so small?
  - neutrinos are left-handed
  - but now they have mass
  - we can overtake and look back
  - looks right-handed!
  - introduce right-handed neutrino
  - small but finite neutrino masses $m_\nu \sim (yv)^2 / M$
  - when you look back at a neutrino, you see anti-neutrino

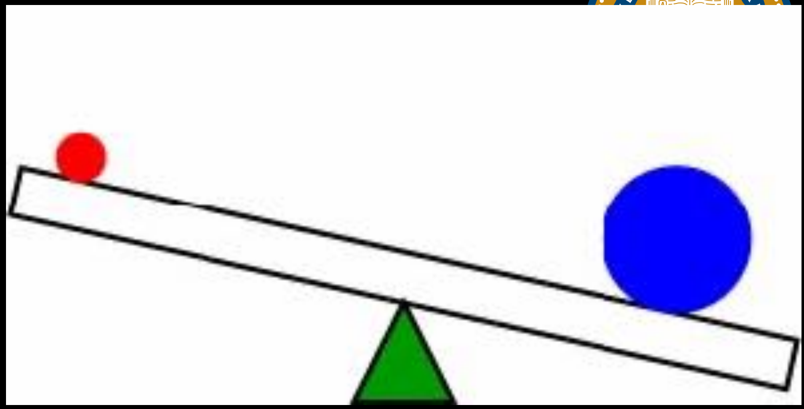




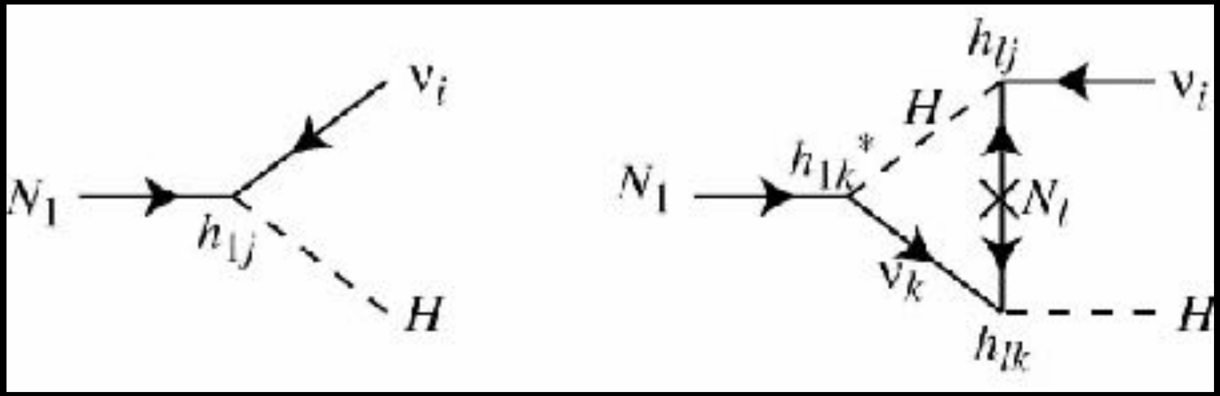
$$\mathcal{L} = -yLNH$$

$$\begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} -\frac{(yv)^2}{M} & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

Leptogenesis



- Right-handed neutrinos in early universe
- when they decay, produce *L*≠0



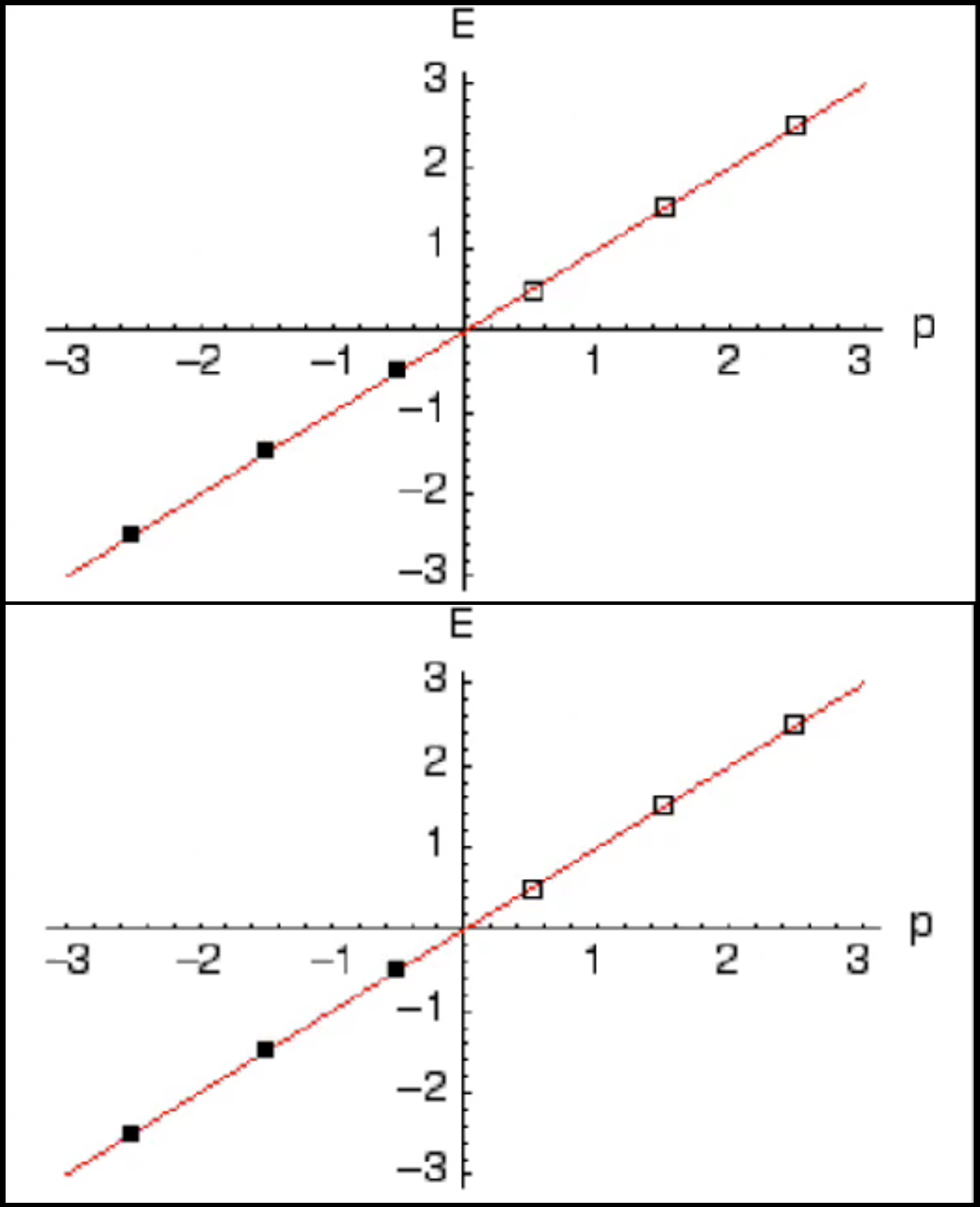
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

- the dominant paradigm in neutrino physics
- probe to very high-energy scale
- notoriously difficult to test

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

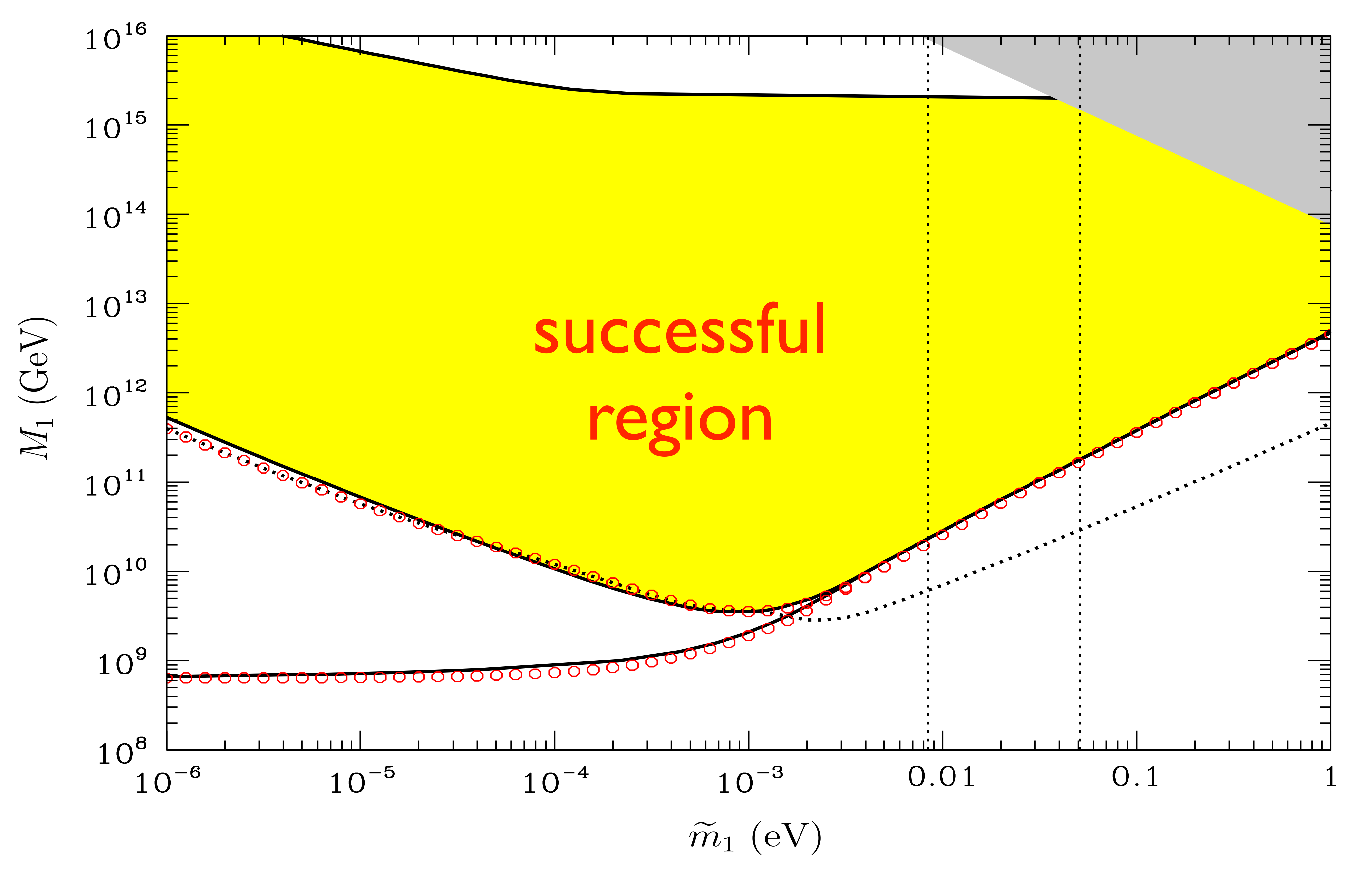
$\Delta q = \Delta q = \Delta q = \Delta L$



Sakharov Conditions

- all three ingredients satisfied
- Baryon number violation
  - lepton number violation + Electroweak anomaly (sphaleron effect)
- CP violation
  - Yukawa couplings $y_{i\alpha} L_i N_\alpha H + M_\alpha N_\alpha N_\alpha$
  - even two generations sufficient
- Departure from equilibrium
  - out-of-equilibrium decay of N_α due to long lifetimes

Leptogenesis



$$\tilde{m}_1 = \frac{(m_D^\dagger m_D)_{11}}{M_1}$$

di Bari, Plümacher, Buchmüller


Disney PRESENTS A PIXAR FILM
THE INCREDIBLES
NOW PLAYING
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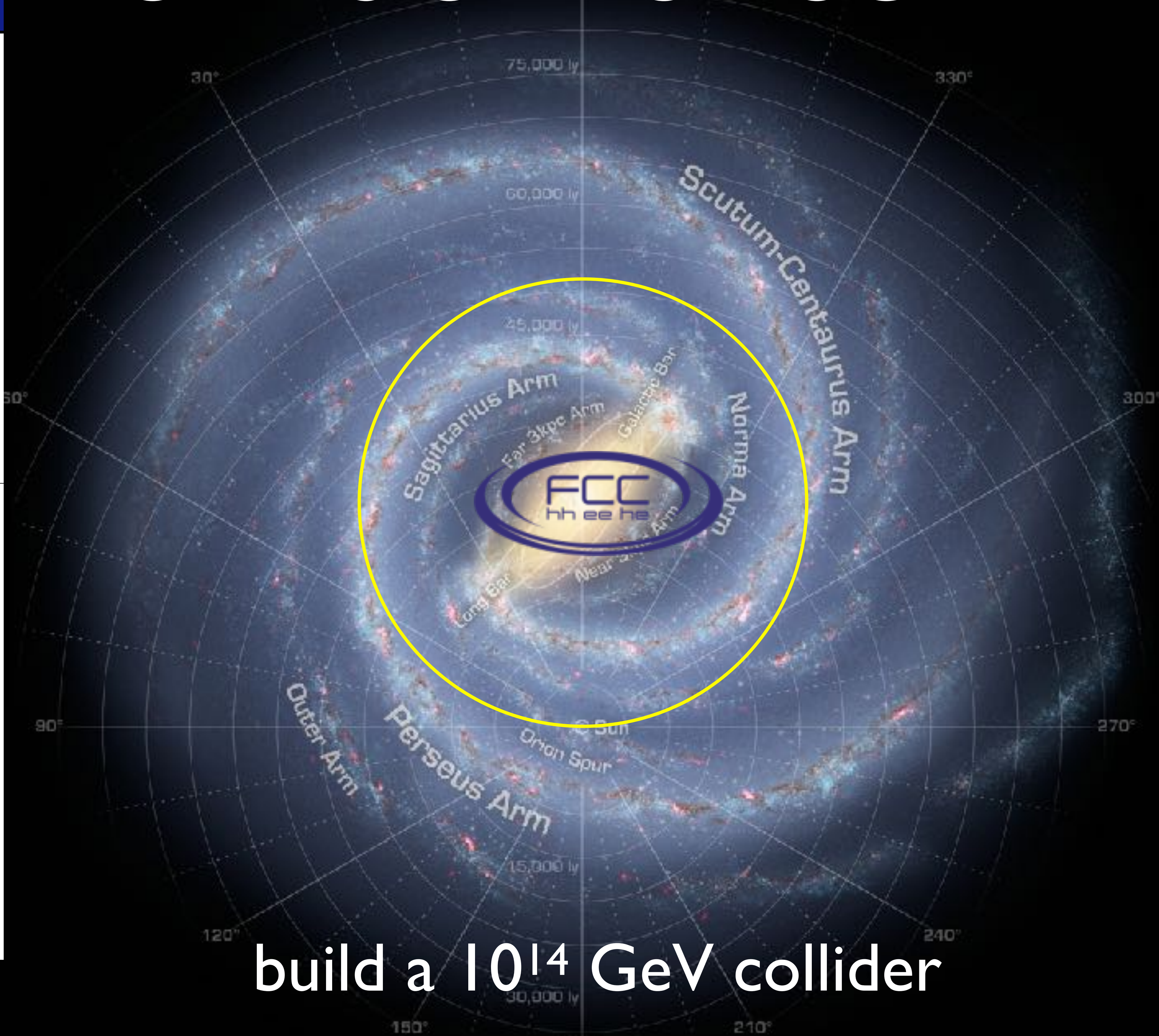
How do we test it?



build a 10^{14} GeV collider

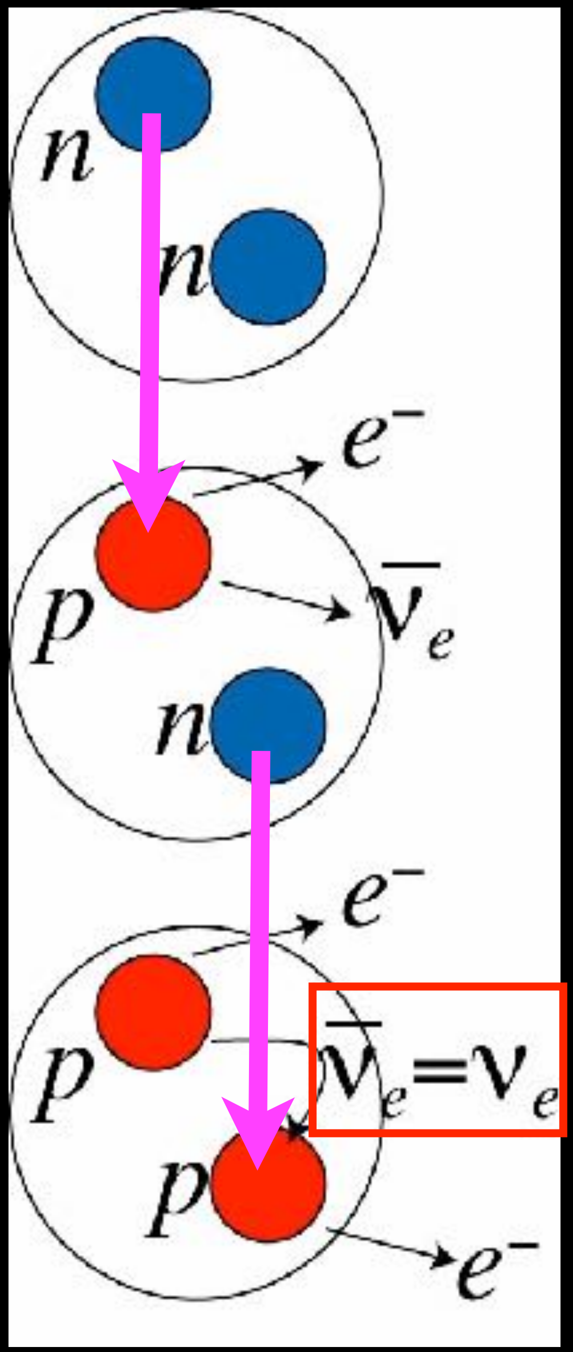
how do we test it?

- possible three circumstantial evidences
  - $0\nu\beta\beta$
  - CP violation in neutrino oscillation
  - other impacts e.g. LFV (requires new particles/interactions < 100 TeV)
- *archeology*
- *any more circumstantial evidences?*

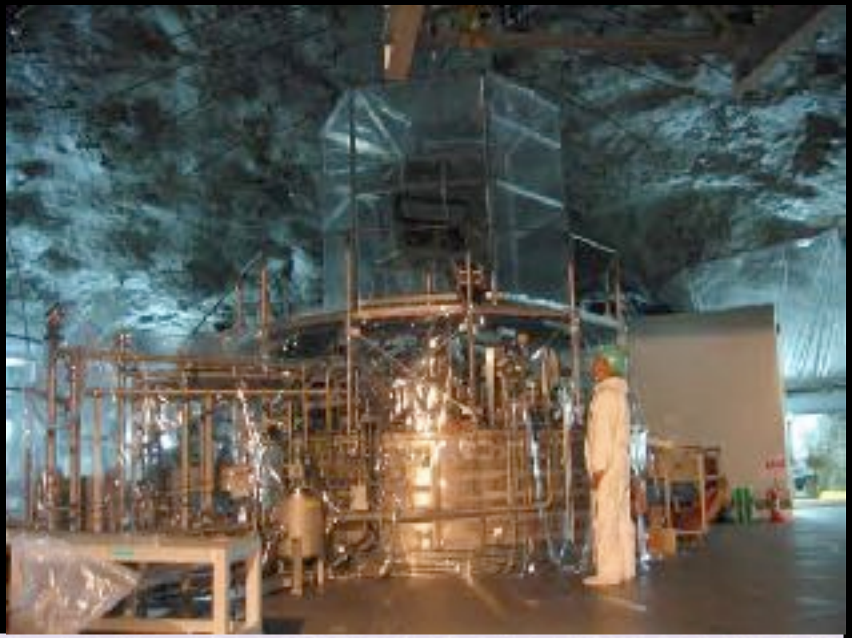
Turn anti-matter into matter

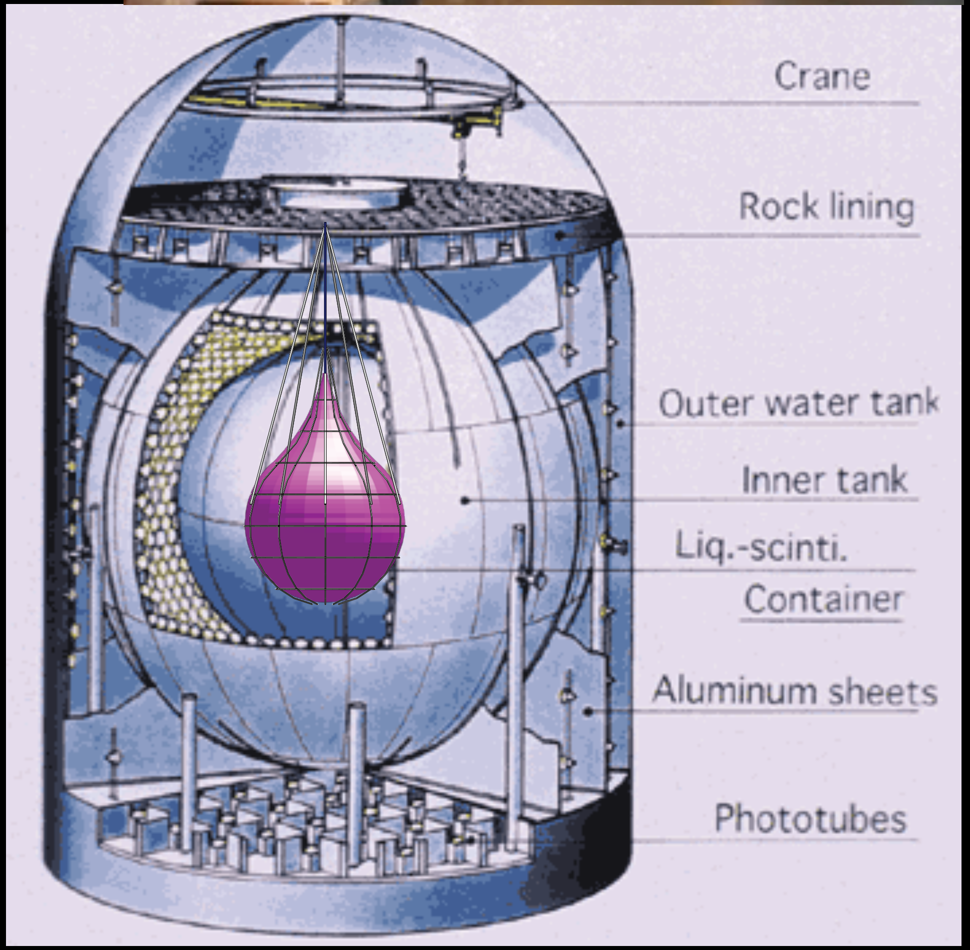
- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity
- $0\nu\beta\beta$: $nn \rightarrow ppe^{-}e^{-}$ with no neutrinos
- can happen only once 10^{24} (trillion trillion) years

patience!



Need big underground experiments

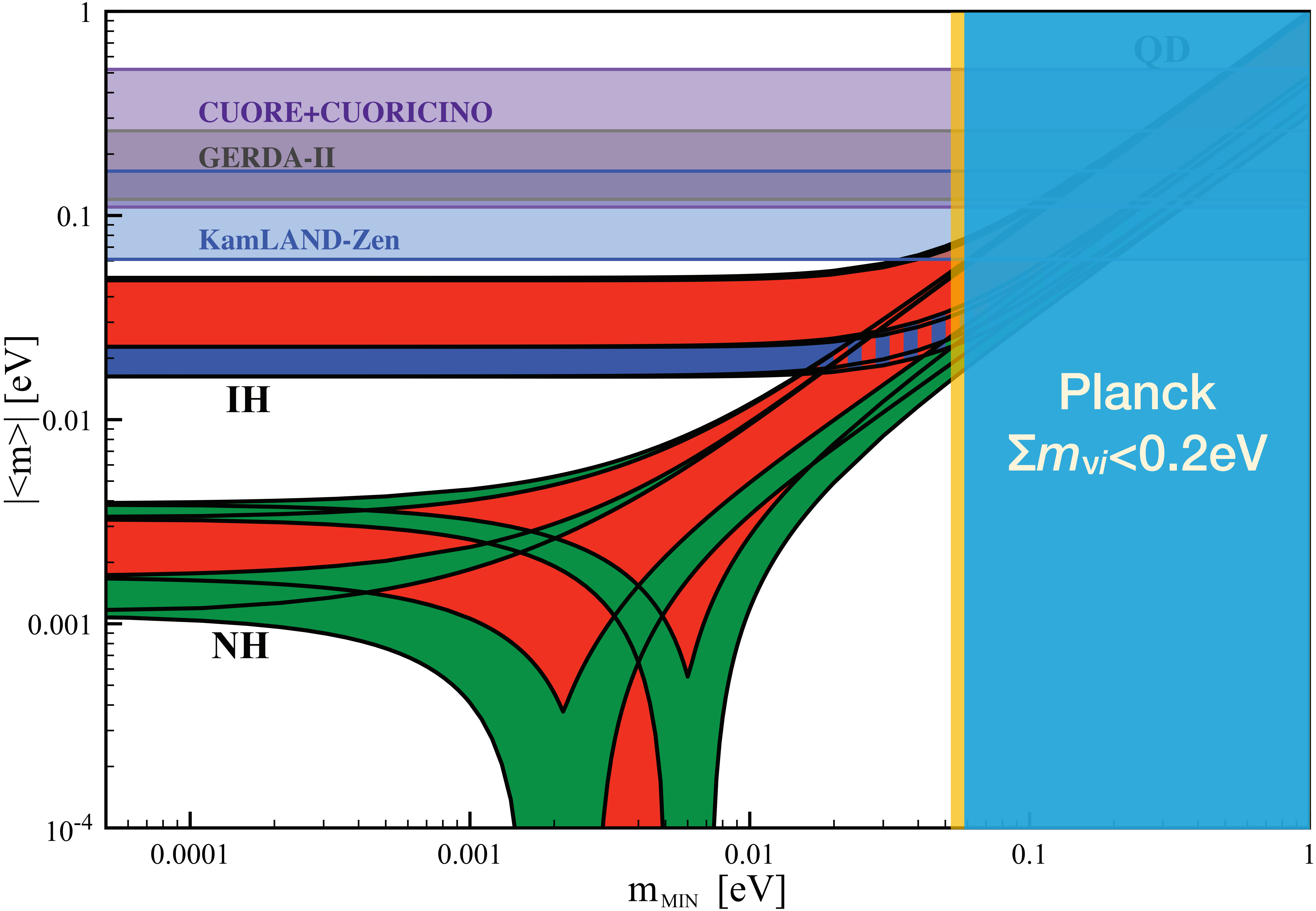




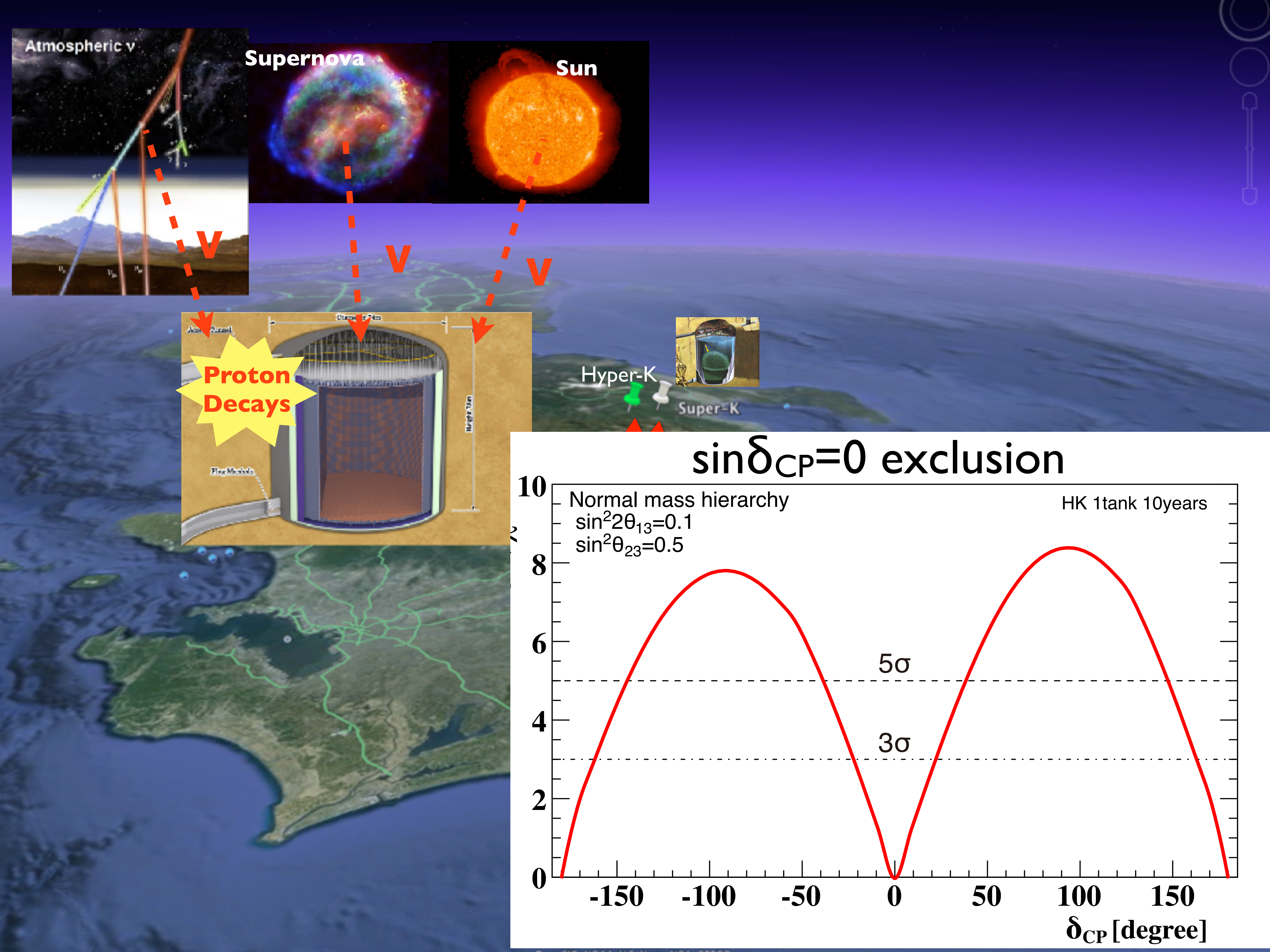
- look for $^{136}\mathrm{Xe} \to {}^{136}\mathrm{Ba}\ e^- e^-$
- dissolve gaseous xenon into liquid scintillator
- current 100kg of enriched xenon
- so far only upper limit

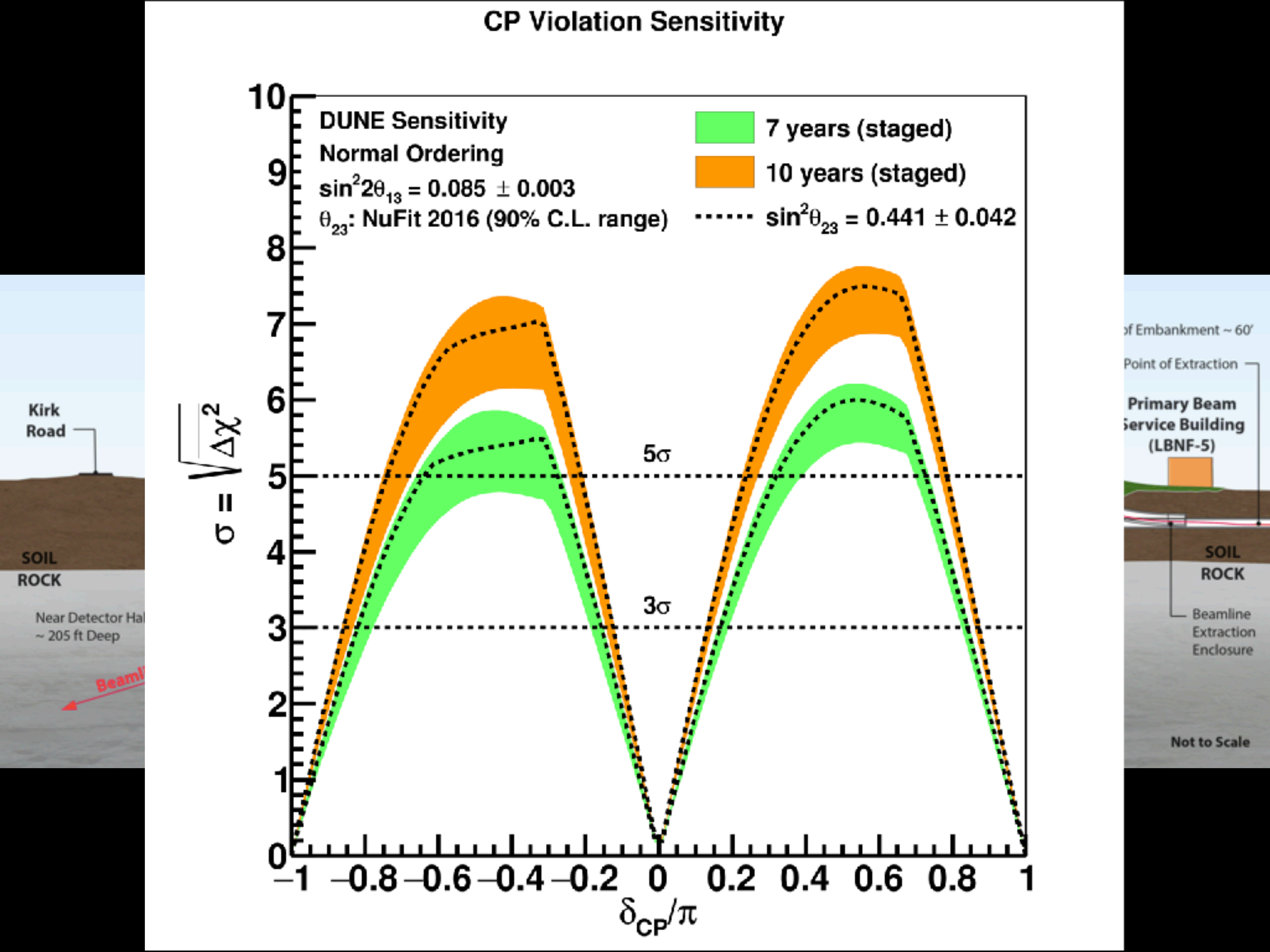
$\tau_{1/2} > 3.4 \times 10^{25}\mathrm{years}$

KamLAND=1000t



QD
CUORE+CUORICINO
GERDA-II
KamLAND-Zen
IH
NH
Planck
Σm_νi<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


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

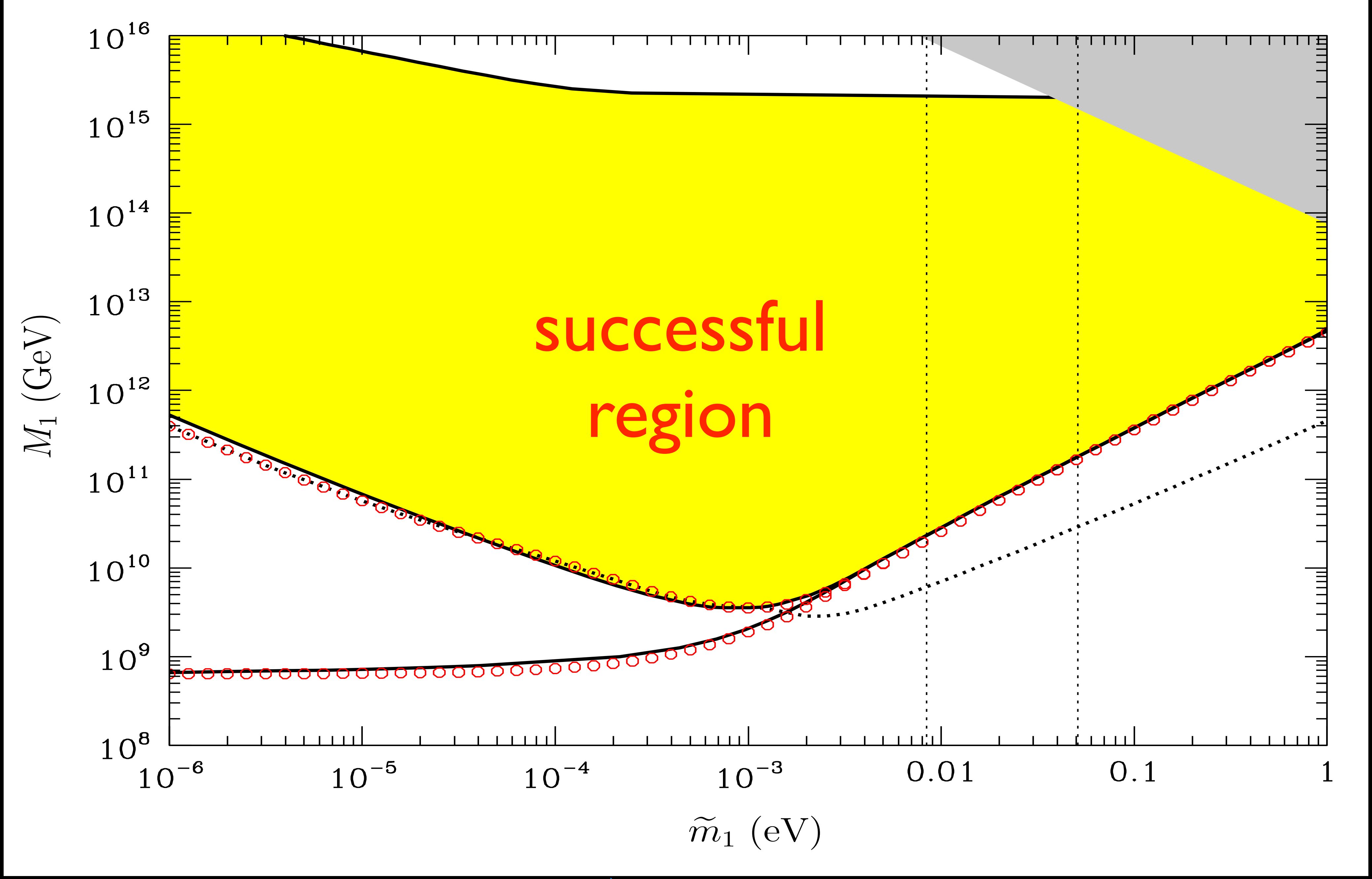


CP Violation Sensitivity
DUNE Sensitivity
Normal Ordering
$\sin^2 2\theta_{13} = 0.085 \pm 0.003$
θ_{23}: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
$\sin^2\theta_{23} = 0.441 \pm 0.042$
5σ
3σ
$\sigma = \sqrt{\Delta\chi^2}$
δ_{CP}/π
0
1
2
3
4
5
6
7
8
9
10
−1
−0.8
−0.6
−0.4
−0.2
0
0.2
0.4
0.6
0.8
1
Kirk
Road
SOIL
ROCK
Near Detector Hal
~ 205 ft Deep
of Embankment ~ 60'
Point of Extraction
Primary Beam
Service Building
(LBNF-5)
SOIL
ROCK
Beamline
Extraction
Enclosure
Not to Scale

M_{Pl}

Natural to think M is induced from symmetry breaking
e.g. $\mathcal{L}=-y\langle\varphi\rangle N\,N$

inflation



Phase Transition → Gravitational Waves?

energy scales

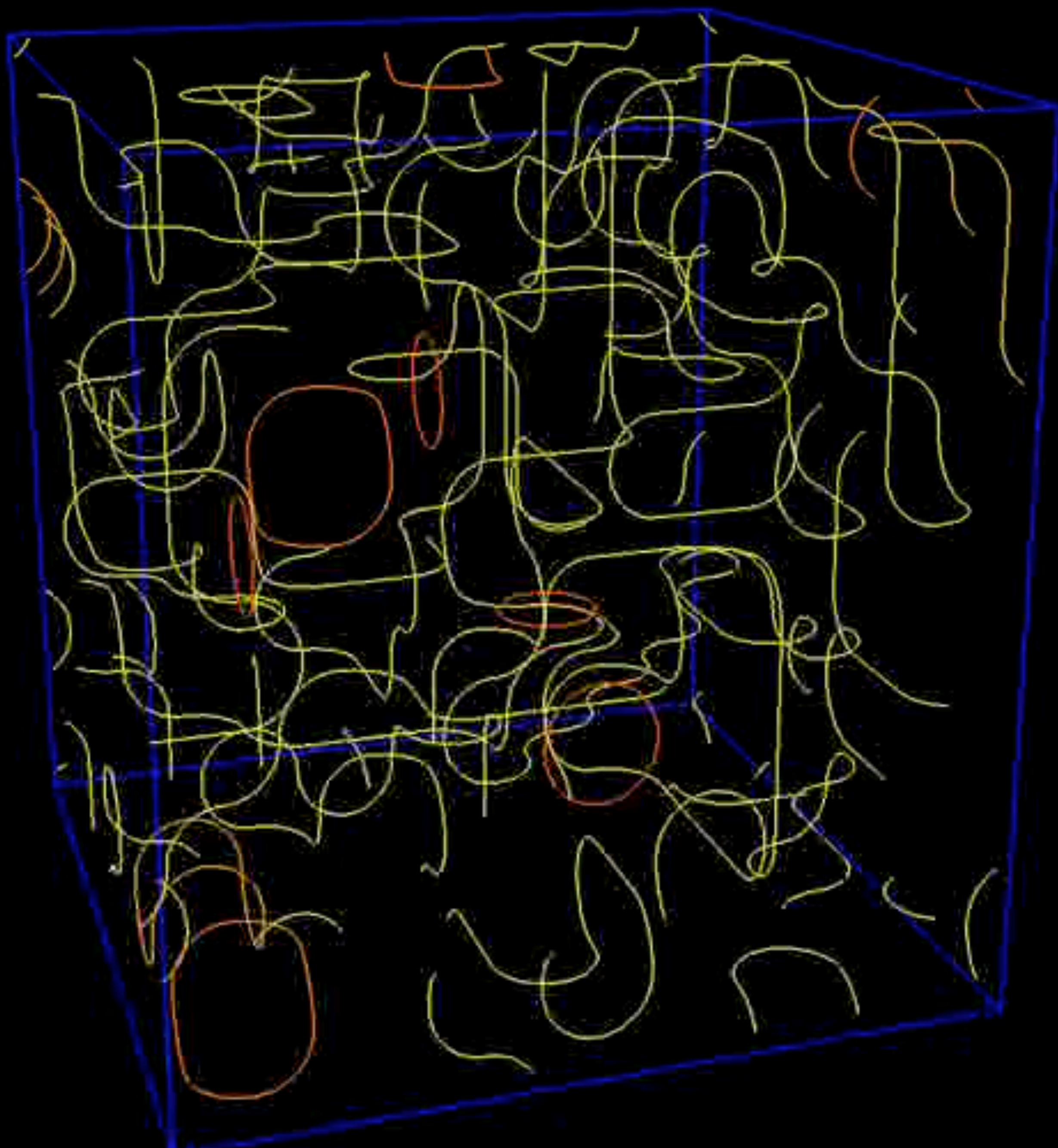
- to obtain the correct mass scale of light neutrinos, need $M_R < 10^{14}$ GeV
- to obtain the correct baryon asymmetry via leptogenesis, need $M_R > 10^9$ GeV
- natural that $M_R \gg v_{EW} = 250$GeV because M_R is allowed by SU(2)×U(1)
- but $M_R \ll M_{Pl}$
- Presumably some protection due to a new symmetry
  - e.g., $U(1)_{B-L}$ *s.t.* $\langle\phi\rangle v_R v_R$ or $\langle\phi^2\rangle v_R v_R / M_{Pl}$
- implies a phase transition at a high temperature
- any signatures?
- gravitational wave!

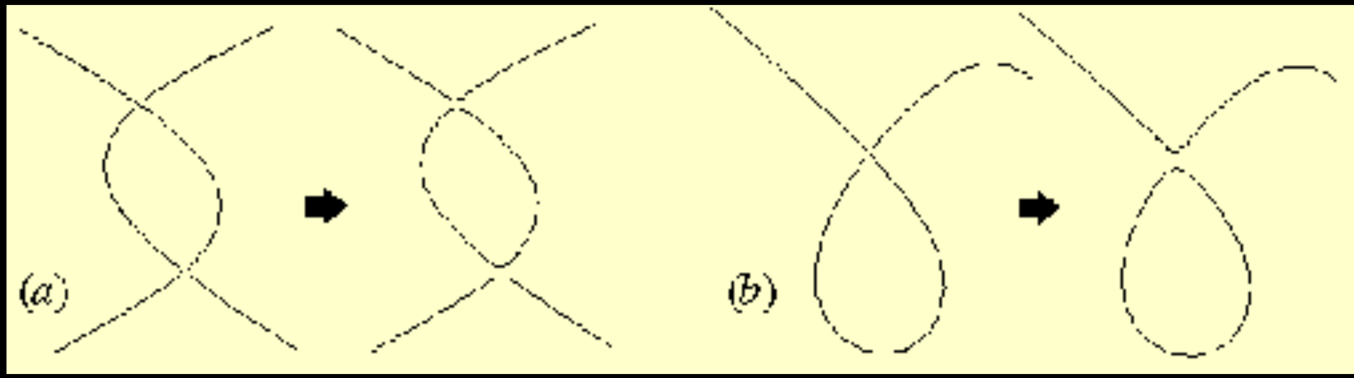
$U(1)_{B-L}$

- Consider $<\phi>\neq 0$
  - M_R from $<\phi>\nu_R\nu_R$
  - U(1) breaking produces cosmic strings because $\pi_1(U(1))=Z$
- nearly scale invariant spectrum
- simplification of the network produces gravitational waves
- stochastic gravitational wave background

https://www.ligo.org/science/Publication-S5S6CosmicStrings/index.php

cosmic strings





$G\mu \sim v^2/M_{Pl}^2$

classification

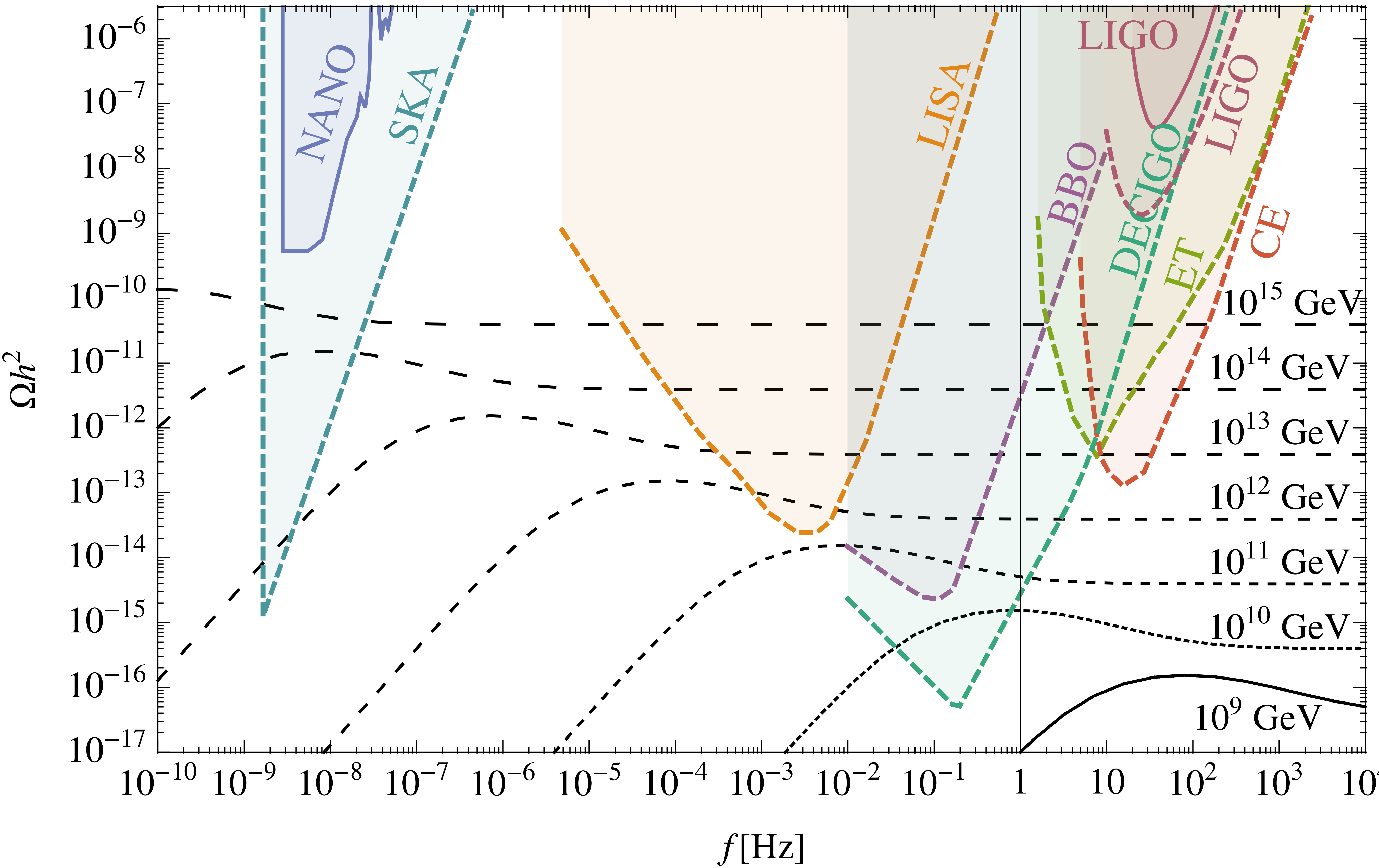
- possible gauge groups
  - forbids $M\,\nu_R\,\nu_R$
  - anomaly-free without additional fermions
  - no magnetic monopoles
  - rank ≤5
- possible Higgs
  - matter parity?
  - e.g. ϕ(+1) or ϕ(+2)
  - $H=G_{SM}$ or $G_{SM}\times Z_2$
- 5 out of 8 have strings

$$
\begin{aligned}
G_{\rm disc} &= G_{\rm SM} \times \mathbb{Z}_N\,, \\
G_{B-L} &= G_{\rm SM} \times U(1)_{B-L}\,, \\
G_{LR} &= SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}\,, \\
G_{421} &= SU(4)_{\rm PS} \times SU(2)_L \times U(1)_Y\,, \\
G_{\rm flip} &= SU(5) \times U(1)\,.
\end{aligned}
$$

$\langle\phi\phi\rangle\,\nu_R\nu_R/M_{Pl}$ $\langle\phi\rangle\,\nu_R\nu_R$

	$H = G_{\rm SM}$		$H = G_{\rm SM}\times\mathbb{Z}_2$	
G	**defects**	**Higgs**	**defects**	**Higgs**
$G_{\rm disc}$	domain wall*	$B-L=1$	domain wall*	$B-L=2$
G_{B-L}	abelian string*	$B-L=1$	$\mathbb{Z}_2$ string†	$B-L=2$
G_{LR}	texture*	$(\mathbf{1},\mathbf{1},\mathbf{2},\frac{1}{2})$	$\mathbb{Z}_2$ string	$(\mathbf{1},\mathbf{1},\mathbf{3},1)$
G_{421}	none	$(\mathbf{10},\mathbf{1},2)$	$\mathbb{Z}_2$ string	$(\mathbf{15},\mathbf{1},2)$
$G_{\rm flip}$	none	$(\mathbf{10},1)$	$\mathbb{Z}_2$ string	$(\mathbf{50},2)$

$$0 \to \pi_2(G) \to \pi_2(G/H) \to \pi_1(H) \to \pi_1(G) \to \boxed{\pi_1(G/H)} \to \pi_0(H) \to \pi_0(G) = 0$$



J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

Hybrid inflation

- $U(1)_{B\text{-}L}$ broken after inflation

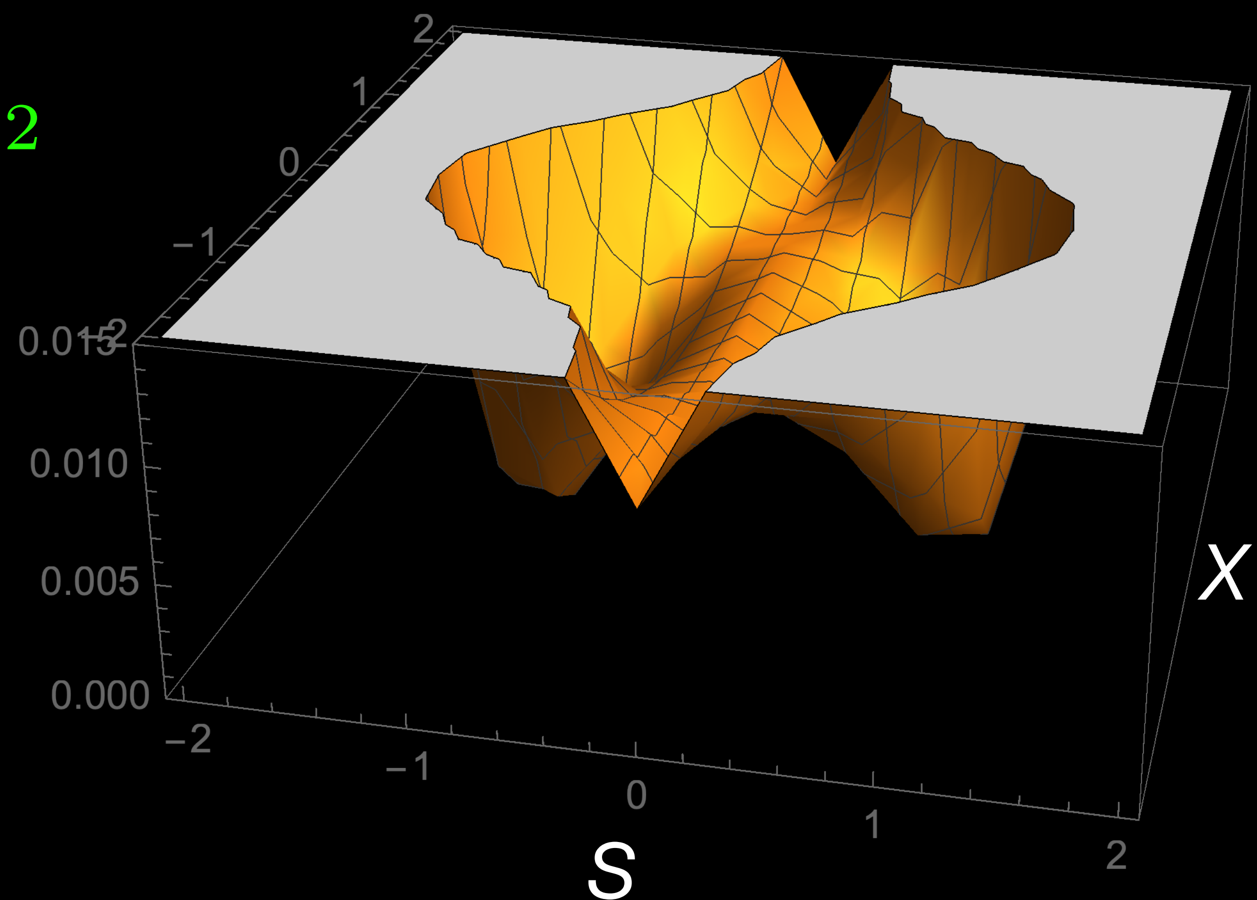
$$W = \lambda X (S^+ S^- - v^2)$$

$$V = \lambda^2 \left|S^+ S^- - v^2\right|^2 + \lambda^2 |X|^2 (|S^+|^2 + |S^-|^2) + \frac{e^2}{2}(|S^+|^2 - |S^-|^2)^2$$

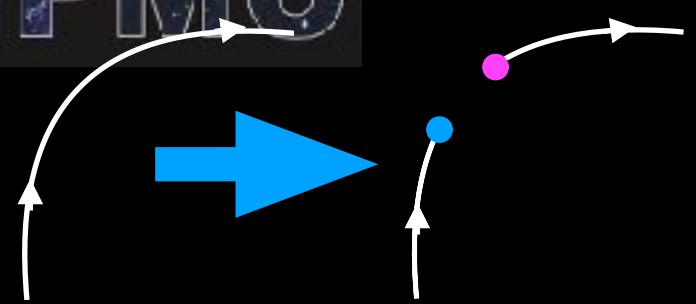
- *D*-flat direction $S=S^+=S^-$

$$V = \lambda^2 \left|S^2 - v^2\right|^2 + 2\lambda^2 |X|^2 |S|^2$$

- flat: $S=0$, $V=\lambda^2 v^2$
- falls down to $S=v$ near $X\sim 0$
- forms cosmic strings
- requires high $v \geq$ a few 10^{15} GeV
- *excluded* by Pulsar Timing Array?

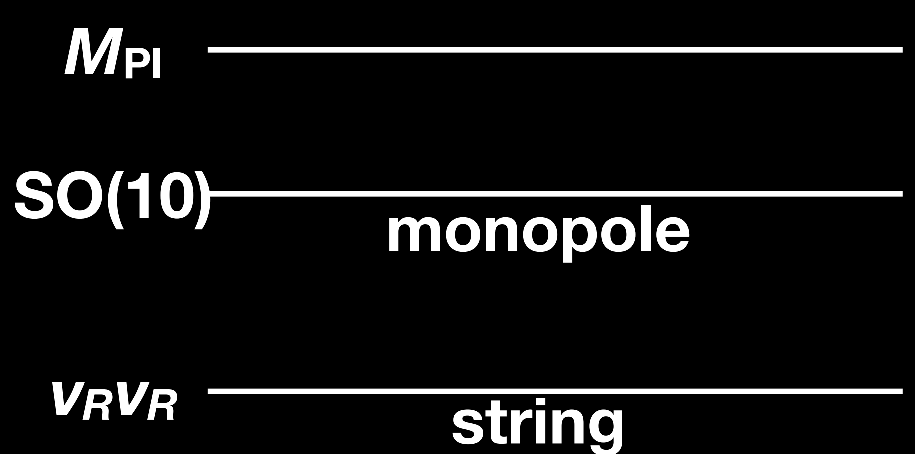


Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695



SO(10)

- All of them embeddable into SO(10)
- paradox: $\pi_1(SO(10)/G_{SM})=0$
- resolution:



$$G_{\rm disc} = G_{\rm SM} \times \mathbb{Z}_N \,,$$
$$G_{B-L} = G_{\rm SM} \times U(1)_{B-L} \,,$$
$$G_{LR} = SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L} \,,$$
$$G_{421} = SU(4)_{\rm PS} \times SU(2)_L \times U(1)_Y \,,$$
$$G_{\rm flip} = SU(5) \times U(1) \,.$$

	$\langle\phi\phi\rangle v_R v_R/M_{Pl}$		$\langle\phi\rangle v_R v_R$	
	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
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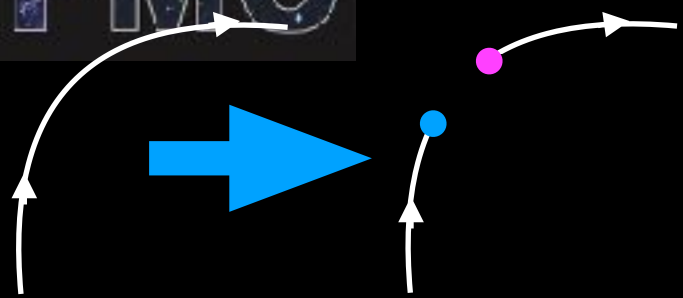
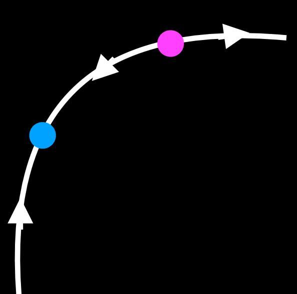


monopoles

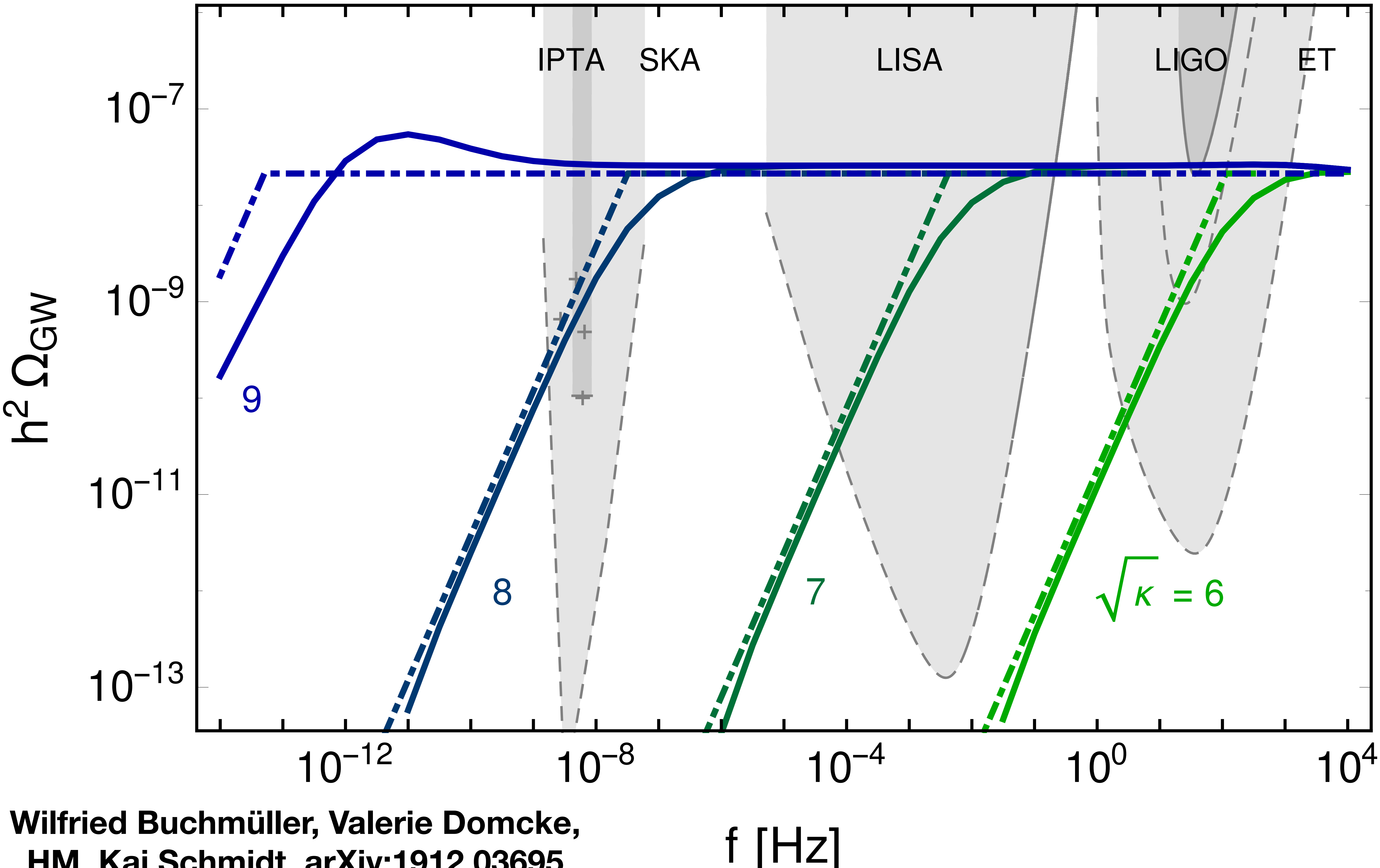
- string from $U(1)_{B-L}$ breaking is basically Abrikosov flux in a superconductor
  - For the Higgs $\phi(\pm Q)$
  - magnetic flux $2\pi\hbar/(e\,Q)$ × integer (Q=1, 2, …)
  - minimum monopole charge $2\pi\hbar/e$
  - If Q=1, monopole can saturate the flux and cut the string
  - If Q=2, the minimum string cannot be cut by monopoles
  - dual Schwinger process
- survives to date if $v < 10^{15}$GeV

$$\frac{\Gamma}{L} = \frac{eE}{4\pi^2}\sum_{n=1}^{\infty}\frac{1}{n}e^{-\pi m^2 n/eE}$$



hybrid inflation

$\kappa = m^2_{\rm monopole}/\mu$



Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695

Conclusions

- stochastic gravitational waves as another possible circumstantial evidence for seesaw+leptogenesis
- for rank≤5 gauge groups, more than a half of theories produce cosmic strings
- future missions promising to cover most range of seesaw scales
- if we do detect scale-invariant gravitational waves, a smoking gun for strings
- if strings appear to break, evidence for grand unification!
- *any experimental technique to probe gravitational waves of much higher frequencies?*

Asymmetric Matters from a dark first-order phase transition

Hitoshi Murayama (Berkeley, Kavli IPMU)
+Nell Hall (Berkeley), Thomas Konstandin (DESY), Robert McGehee (Berkeley)

arXiv:1911.12342

Sakharov Conditions

- Standard Model may have all three ingredients
- Baryon number violation
  - Electroweak anomaly (sphaleron effect)
- CP violation
  - Kobayashi–Maskawa phase

$$J \propto \det[M_u^\dagger M_u, M_d^\dagger M_d]/T_{EW}^{12} \sim 10^{-20} \ll 10^{-10}$$

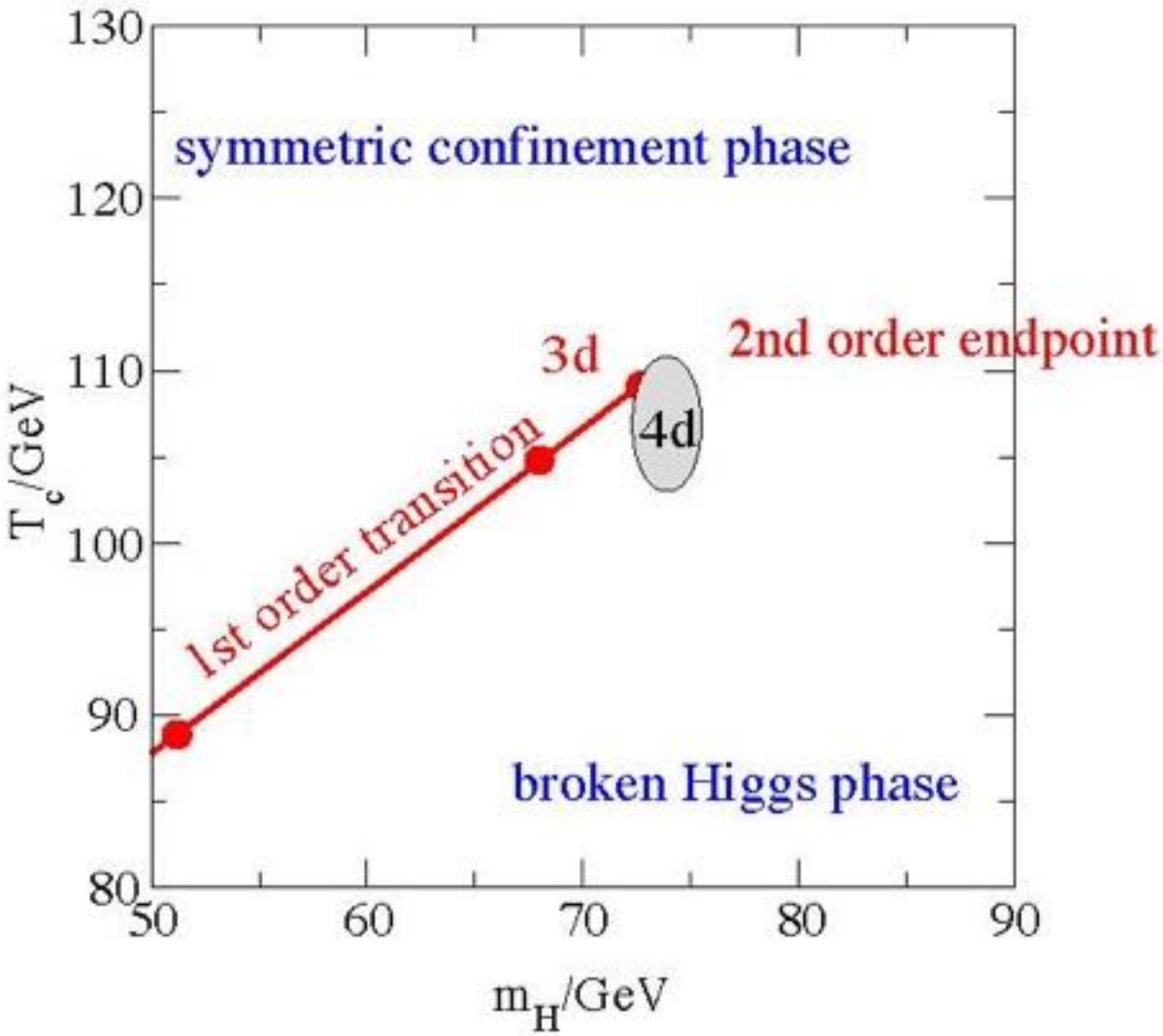
- Departure from equilibrium
  - First-order phase transition of Higgs

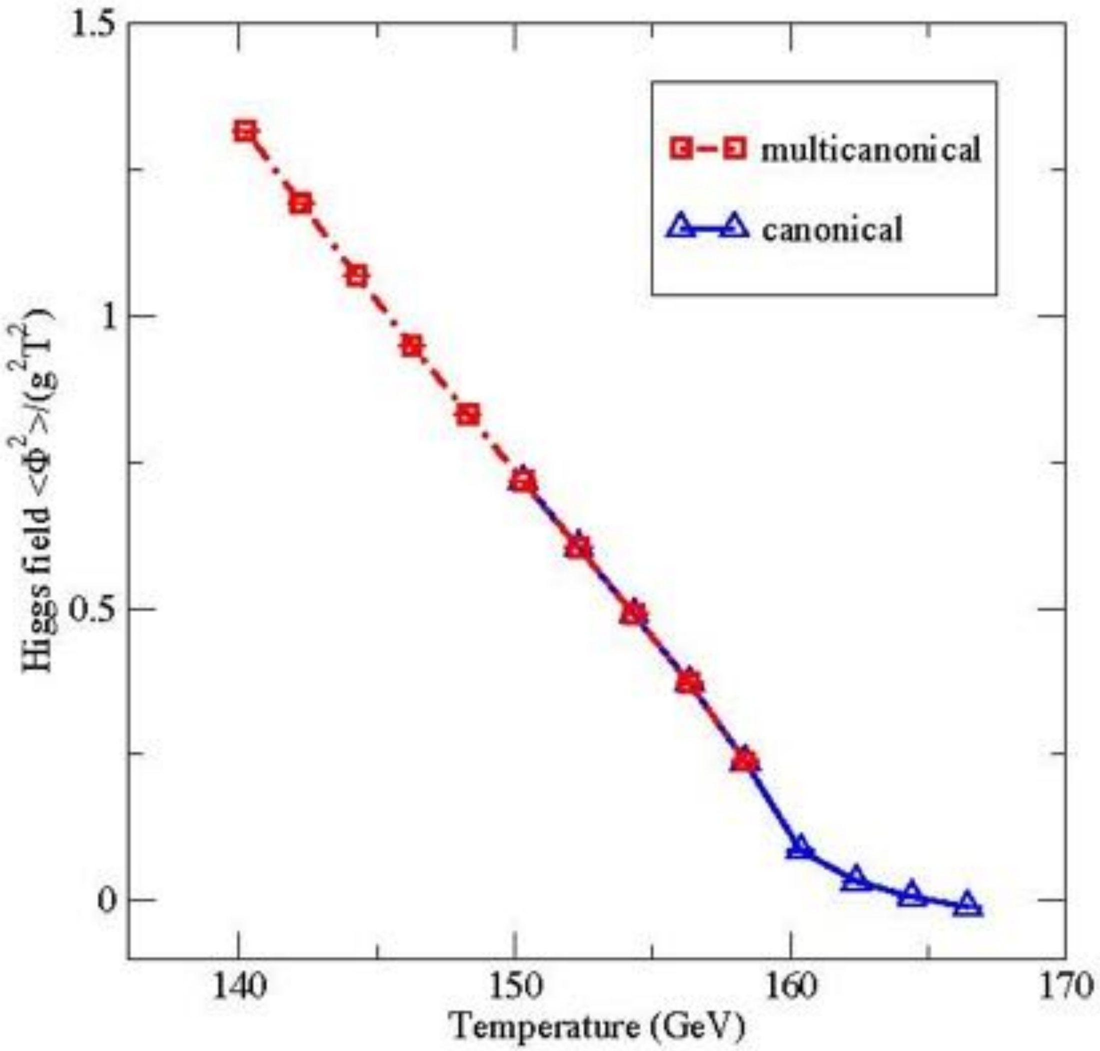
requires m_h < 75 GeV

- Experimentally testable?

Phase diagram for the Standard Model:

Mikko Laine (Bern)





$\langle H \rangle = 0$ from gauge invariance (Elitzur)

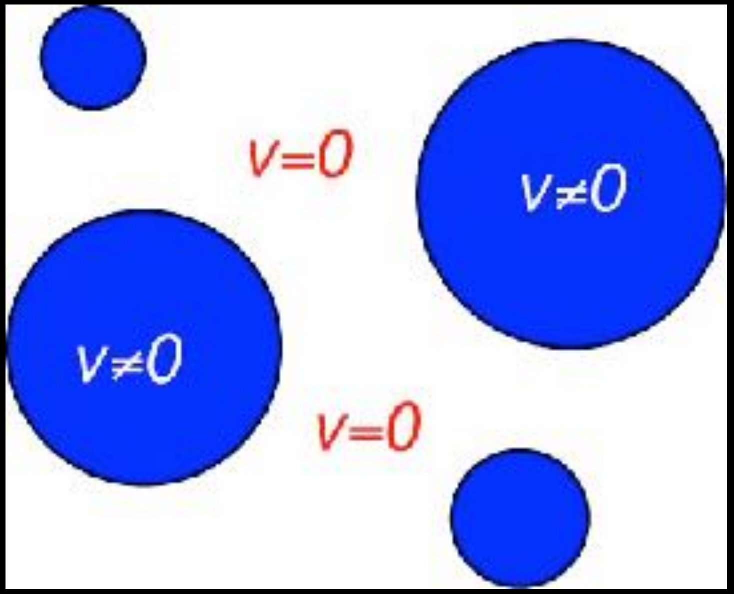
$\langle H^\dagger H \rangle$ is not an order parameter

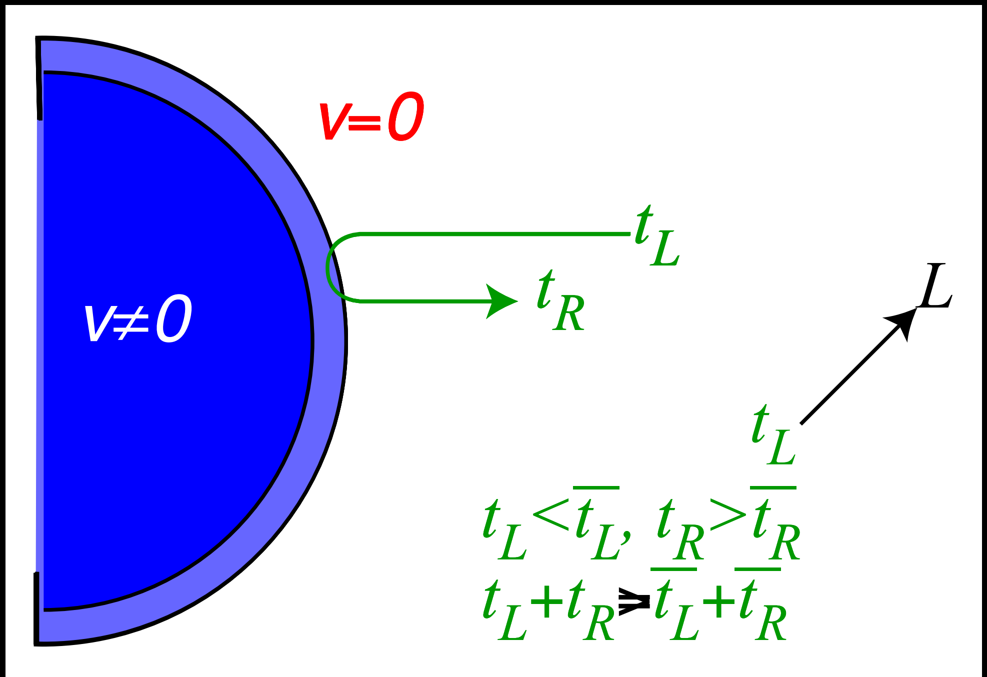
for m_h=125GeV, it is crossover

No phase transition in the Minimal Standard Model

Scenario
Cohen, Kaplan, Nelson

- First-order phase transition
- Different reflection probabilities for t_L, t_R
- asymmetry in top quark
- Left-handed top quark asymmetry partially converted to lepton asymmetry via anomaly
- Remaining top quark asymmetry becomes baryon asymmetry
- need *varying CP phase* inside the bubble wall (G. Servant)
- fixed KM phase doesn't help
- need CPV in Higgs sector





Electric Dipole Moment

- baryon asymmetry limited by the sphaleron rate
  $\Gamma \sim 20\, \alpha_W^5\, T \sim 10^{-6}\, T$

- Can't lose much more to obtain 10^{-9}

- need

  - new physics for 1st order PT at the Higgs scale v=250 GeV

  - CP violation×efficiency $\geq 10^{-3}$

Oct 2018

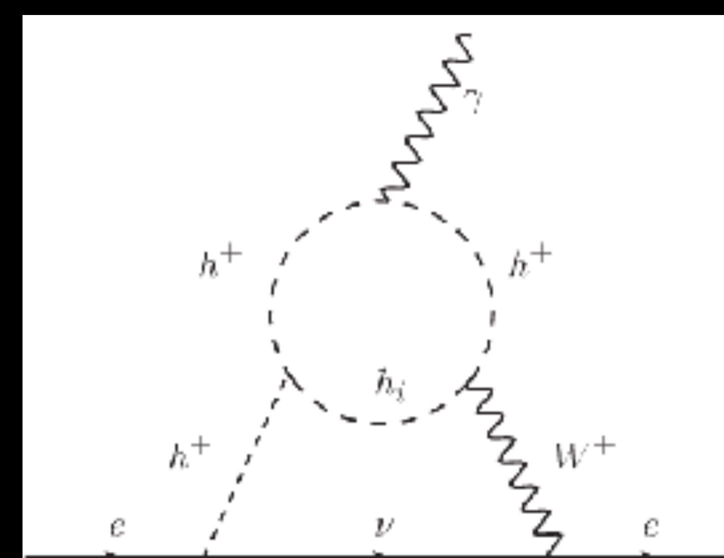
ARTICLE

https://doi.org/10.1038/s41586-018-0599-8

Improved limit on the electric dipole moment of the electron

ACME Collaboration*

$d_e \leq 1.1\times10^{-29}$ *e* cm

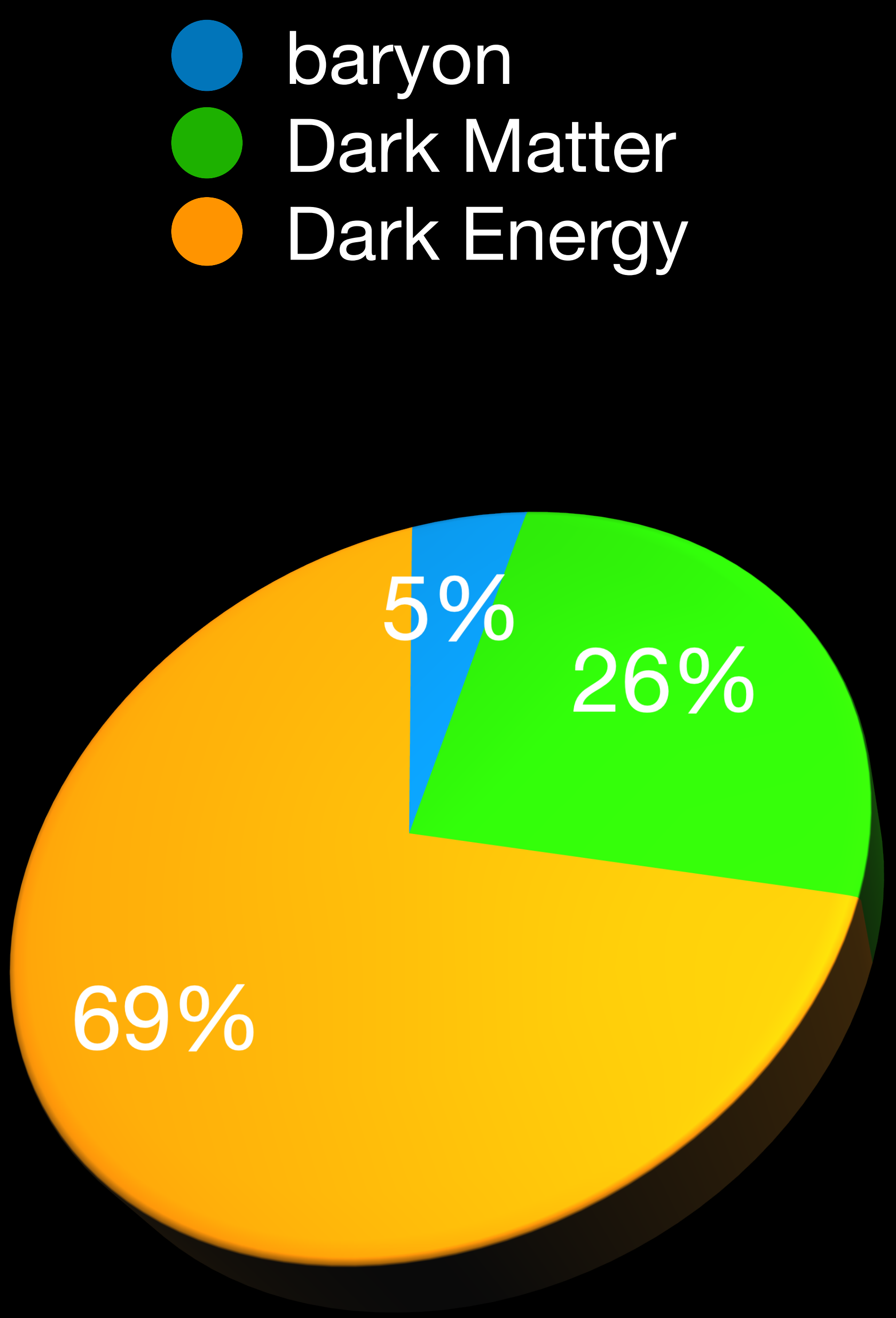


Barr-Zee diagrams

$$d_e \approx \frac{e m_e}{(16\pi^2)^2}\frac{1}{v^2}\sin\delta = 1.6\times10^{-22} e\mathrm{cm}\sin\delta$$

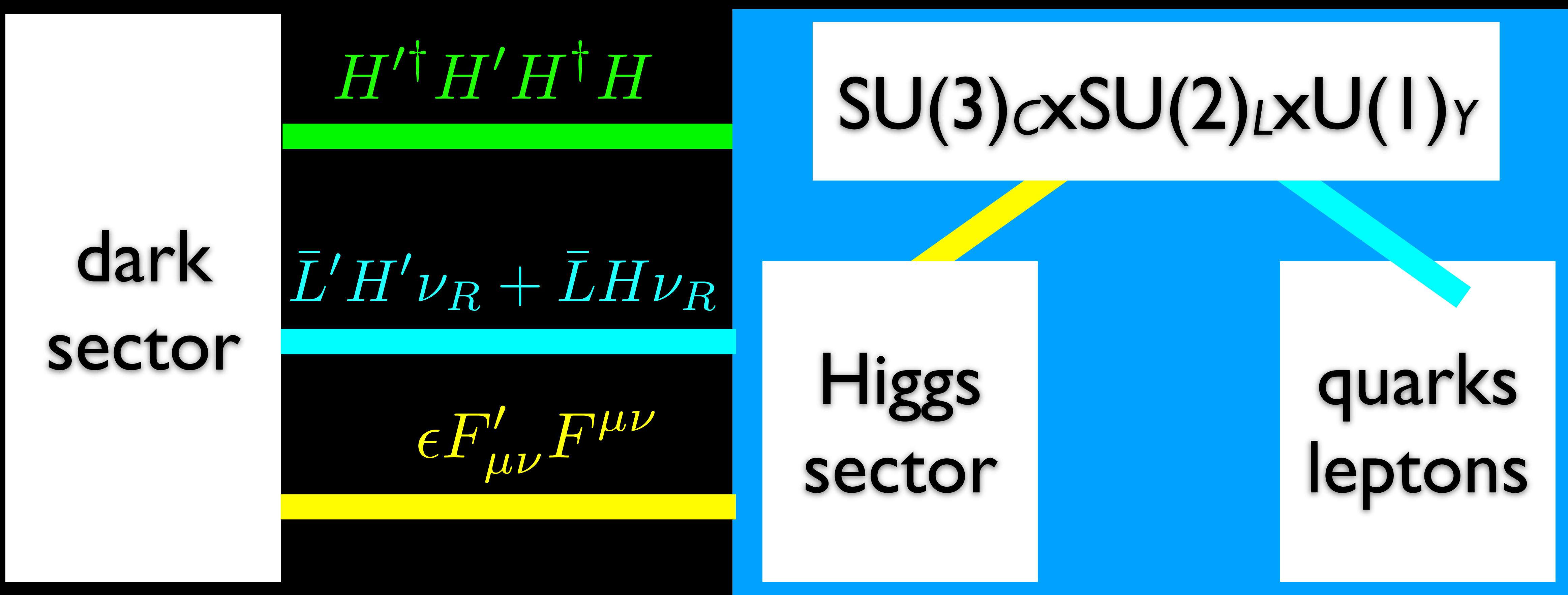
asymmetric dark matter

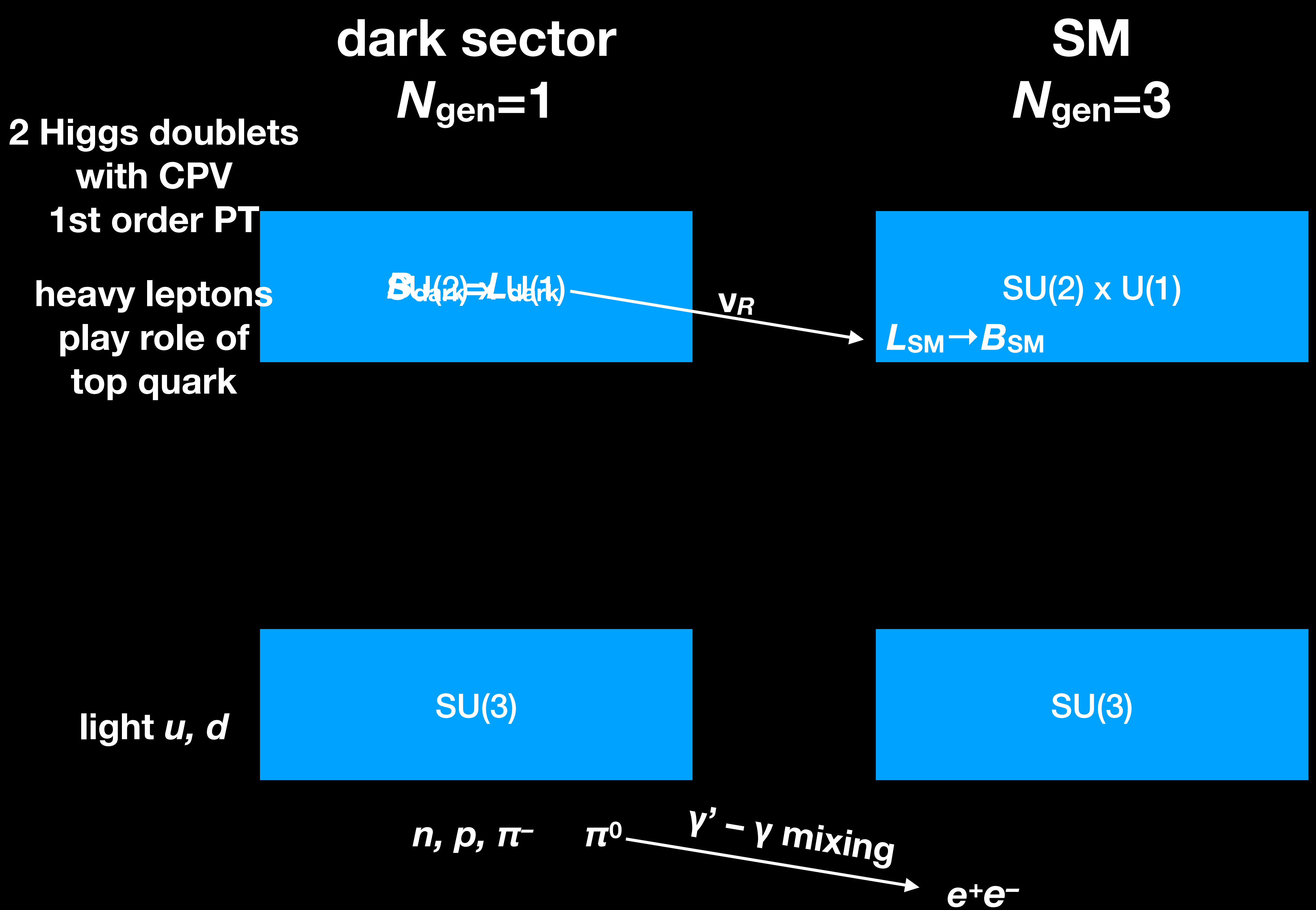
- may explain the coincidence between baryon and dark matter densities today
- need to efficiently get rid of symmetric component → strongly coupled?
- proton mass is dynamical. also “dark proton?”
- If the same asymmetries, m_{ADM}~6GeV, “light” dark matter
- need anomalies and non-anomalous gauge
  - simplest structure: copy of SM
- need equilibration mechanism between two asymmetries → neutrino portal

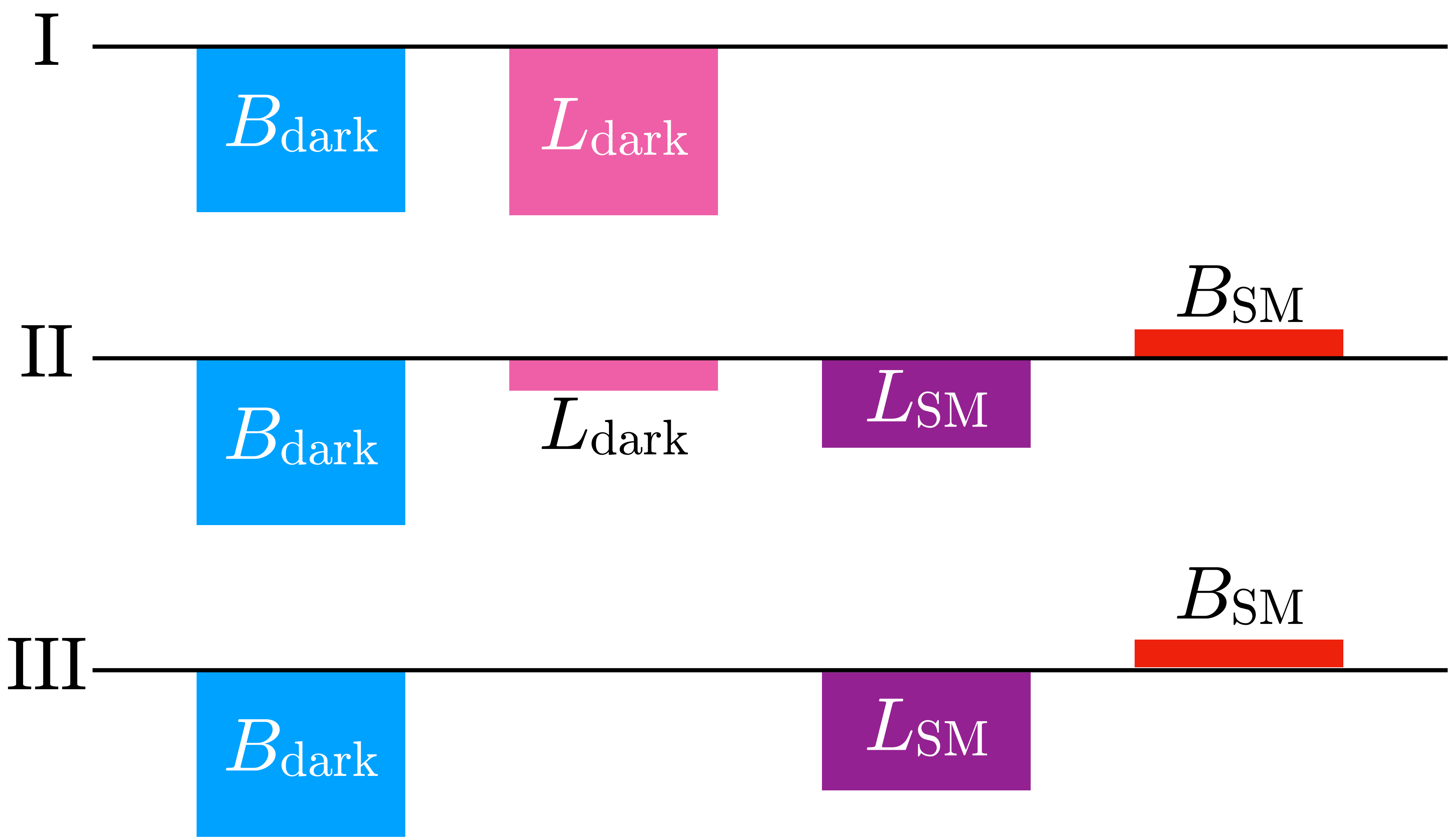


portals

three possible portals in renormalizable theories




dark sector
N_{gen}=1
SM
N_{gen}=3
2 Higgs doublets
with CPV
1st order PT
heavy leptons
play role of
top quark
SU(2) x U(1)
$B_{dark} \to L_{dark}$
ν_R
SU(2) x U(1)
$L_{SM} \to B_{SM}$
light u, d
SU(3)
SU(3)
n, p, π^-
π^0
$\gamma' - \gamma$ mixing
e^+e^-

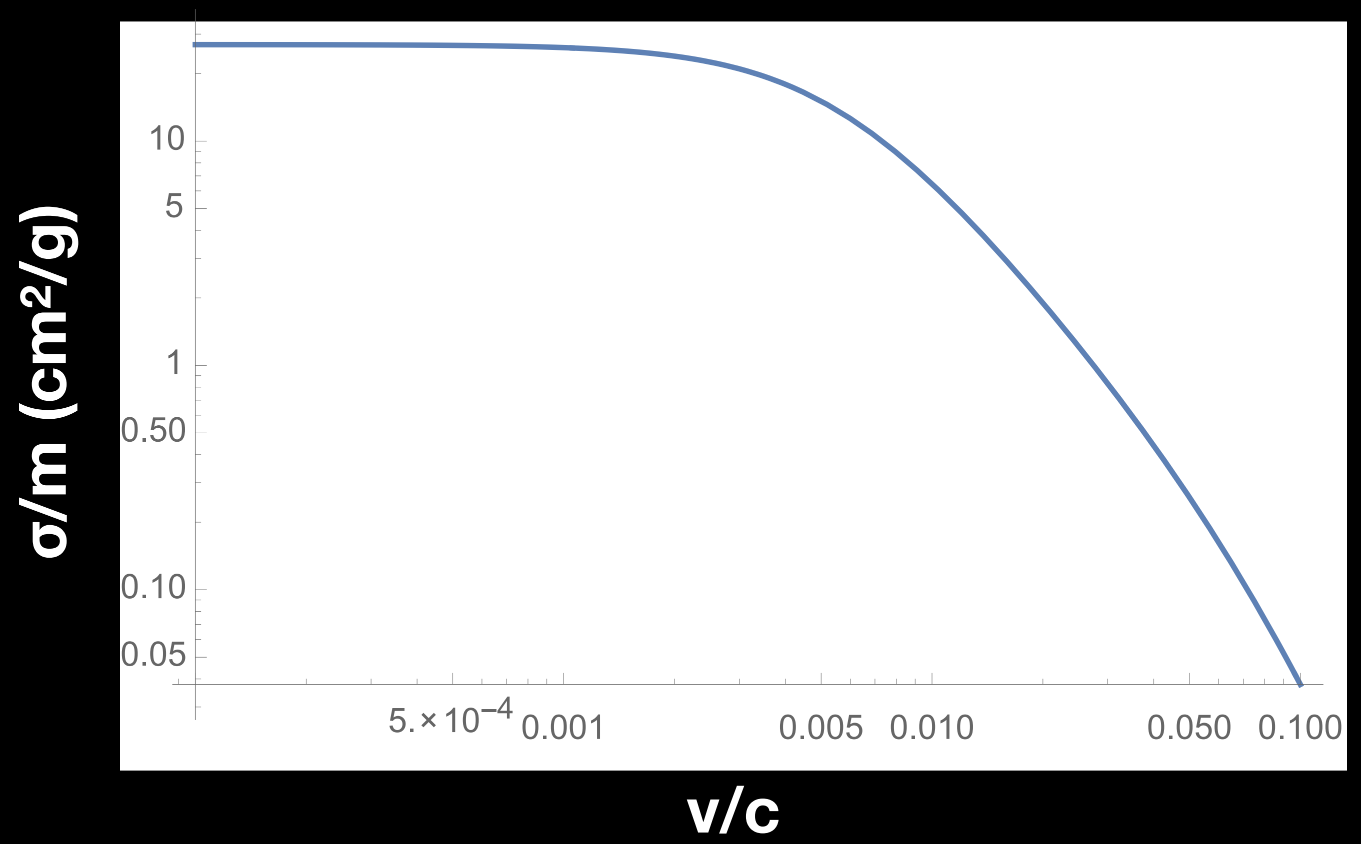


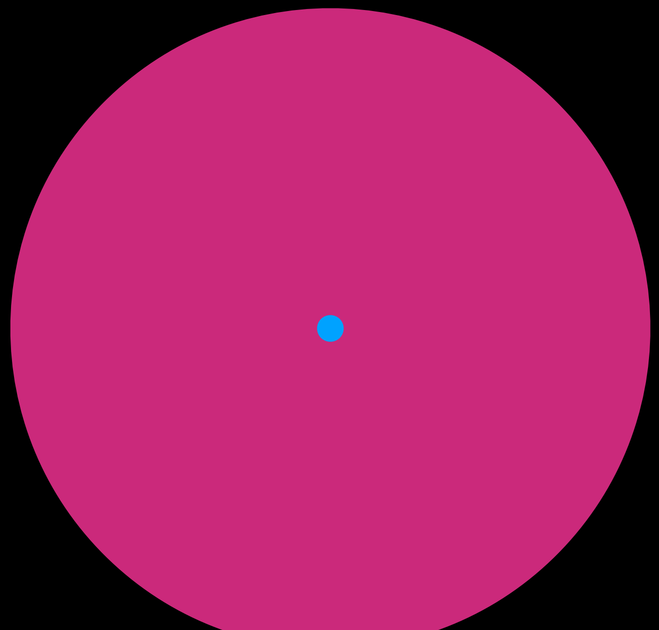
If $M_N > T_{\mathrm{sphaleron}}$ $B_{\mathrm{SM}} = \frac{36}{133} B_{\mathrm{dark}}, \quad L_{\mathrm{SM}} = -\frac{97}{133} B_{\mathrm{dark}}$ **$m_{n'}$=1.63 GeV**

If $M_N < T_{\mathrm{sphaleron}}$ $B_{\mathrm{SM}} = \frac{12}{37} B_{\mathrm{dark}}, \quad L_{\mathrm{SM}} = -\frac{25}{37} B_{\mathrm{dark}}$ **$m_{n'}$=1.36 GeV**

n-*n* scattering

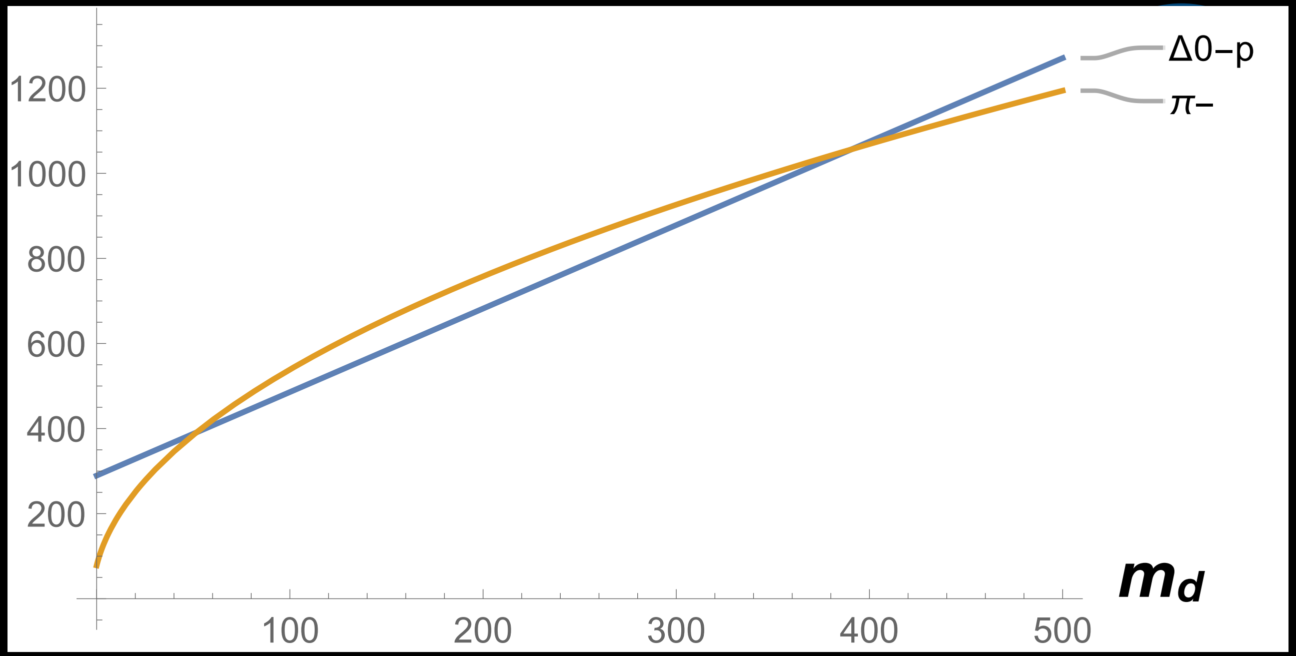
- *n*-*n* scattering has an anomalously large cross section a=18.9fm
- If so, it violates astrophysical bounds on self-interaction
- a fine cancellation between the bare and one-loop couplings in the pion-less EFT
- According to lattice simulations (HAL QCD), the cross section is more or less of the geometric size if pion mass is not special



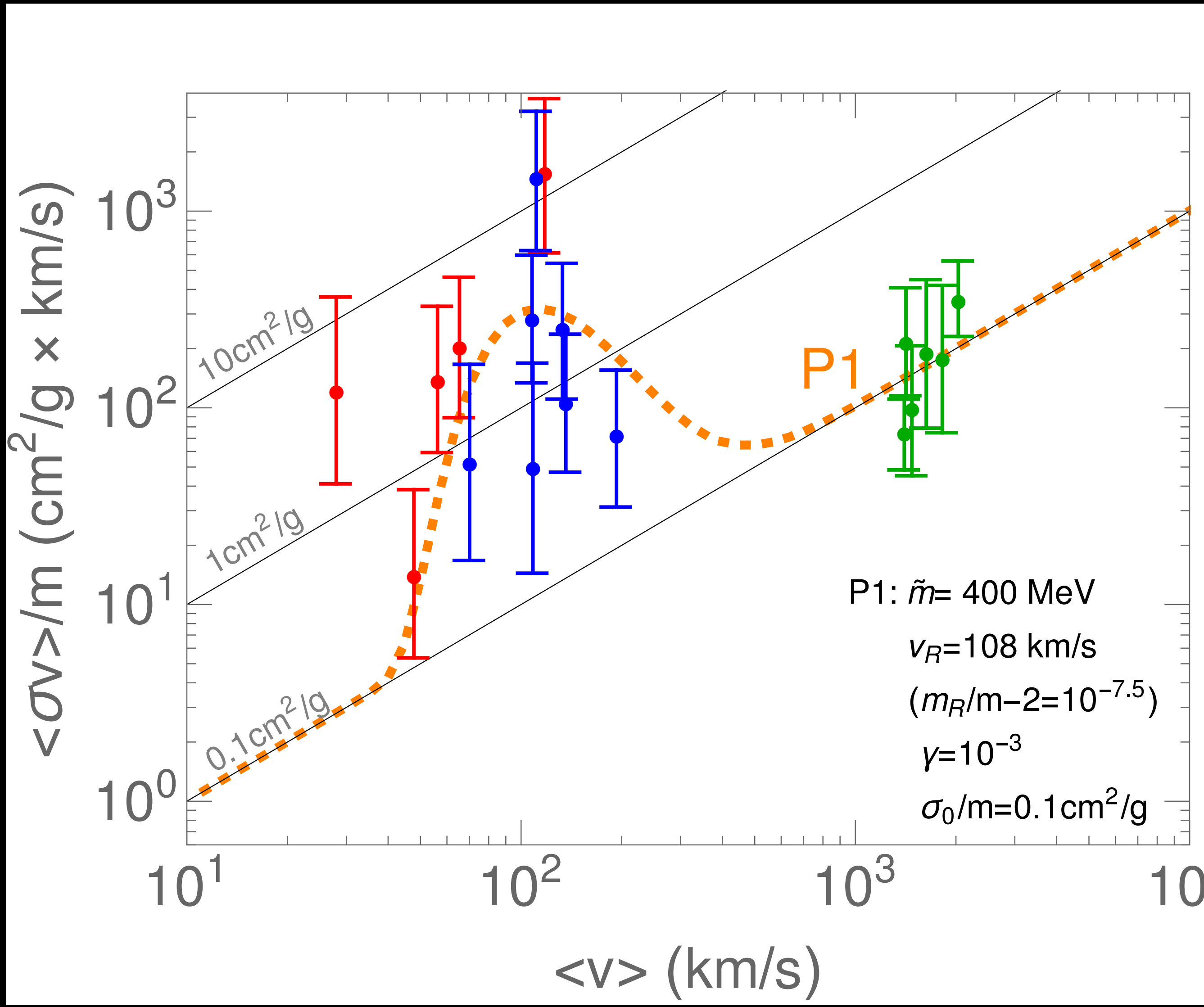


baryon spectrum

- m_u and m_d free parameters
- If $m_d \ll m_u \ll \Lambda_{QCD}$, n' dominates
- If $m_u \ll m_d \ll \Lambda_{QCD}$, p' dominates, together with π'^- for charge neutrality
    - possibly a resonant interaction $\pi'^- p' \to \Delta^0 \to \pi'^- p'$
    - may solve core/cusp problem



Robert McGehee, HM, Yu-Dai Tsai, in prep



Xiaoyong Chu, Camilo Carcia-Cely, HM, Phys.Rev.Lett. 122 (2019) no.7, 071103

some history

- asymmetric dark matter
  - S. Nussinov, PLB 165, 55 (1985) “technocosmology”
  - R. Kitano, HM, M. Ratz, arXiv:0807.4313, moduli decay
  - D.E. Kaplan, M. Luty, K. Zurek, arXiv:0901.4117
- darkogenesis (= “EW baryogenesis” in the dark sector)
  - J. Shelton, K. Zurek, arXiv:1008.1997

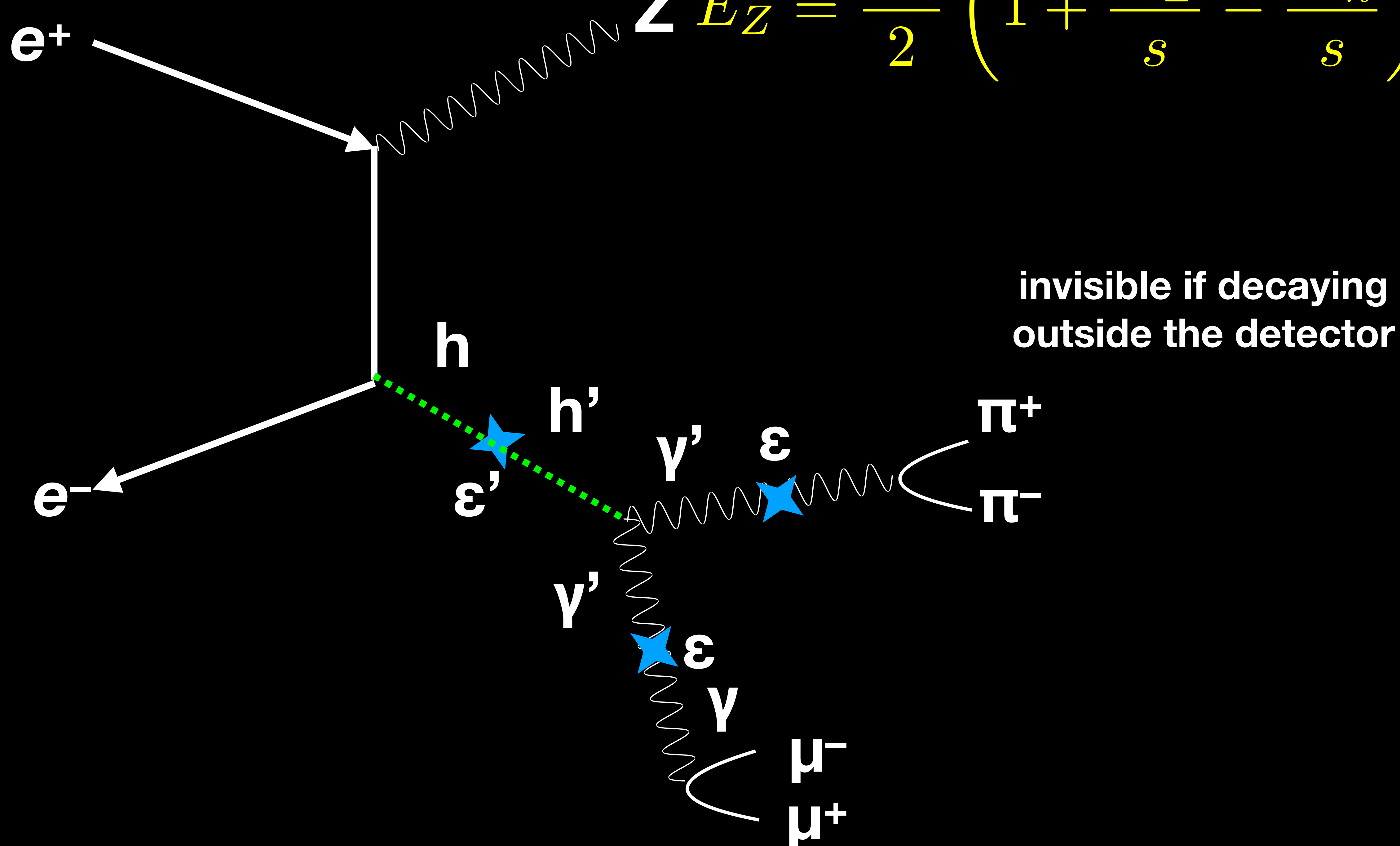
neutrino portal

$$\mathcal{L} = y' \bar{L}' H \nu_R + y_i \bar{L}_i H \nu_R$$

$$\epsilon_i = \frac{y_i}{\sqrt{(y')^2 + (y_i)^2}} \qquad M_\nu = \sqrt{(y')^2 + (y_i)^2} v$$

- charged current universality: $\varepsilon_i^2 < 10^{-3}$
- $\mu \to e\,\gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 4 \times 10^{-5}\, (G_F M_\nu)$
- $\tau \to \mu\,\gamma$ constraint: $\varepsilon_e\, \varepsilon_\mu < 0.03\, (G_F M_\nu)$
- If $M_\nu < 70$ GeV, $\varepsilon_i^2 < 10^{-5}$ (DELPHI: $Z \to \nu\, \nu_R$, $\nu_R \to l f f$)
- equilibration of asymmetries requires only $\varepsilon_i > 10^{-16}$ or so
- (orders of magnitude estimates so far)

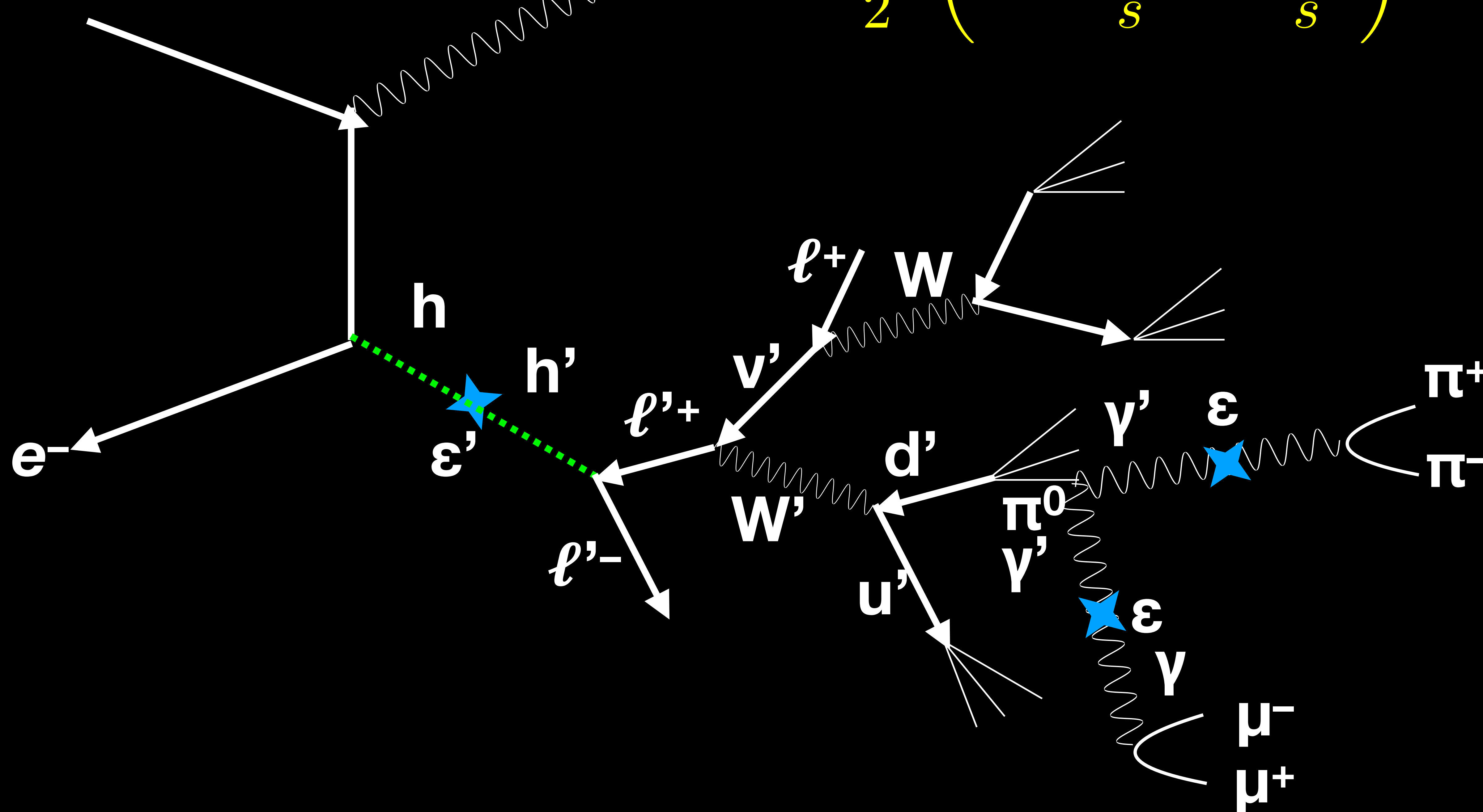
Higgs portal

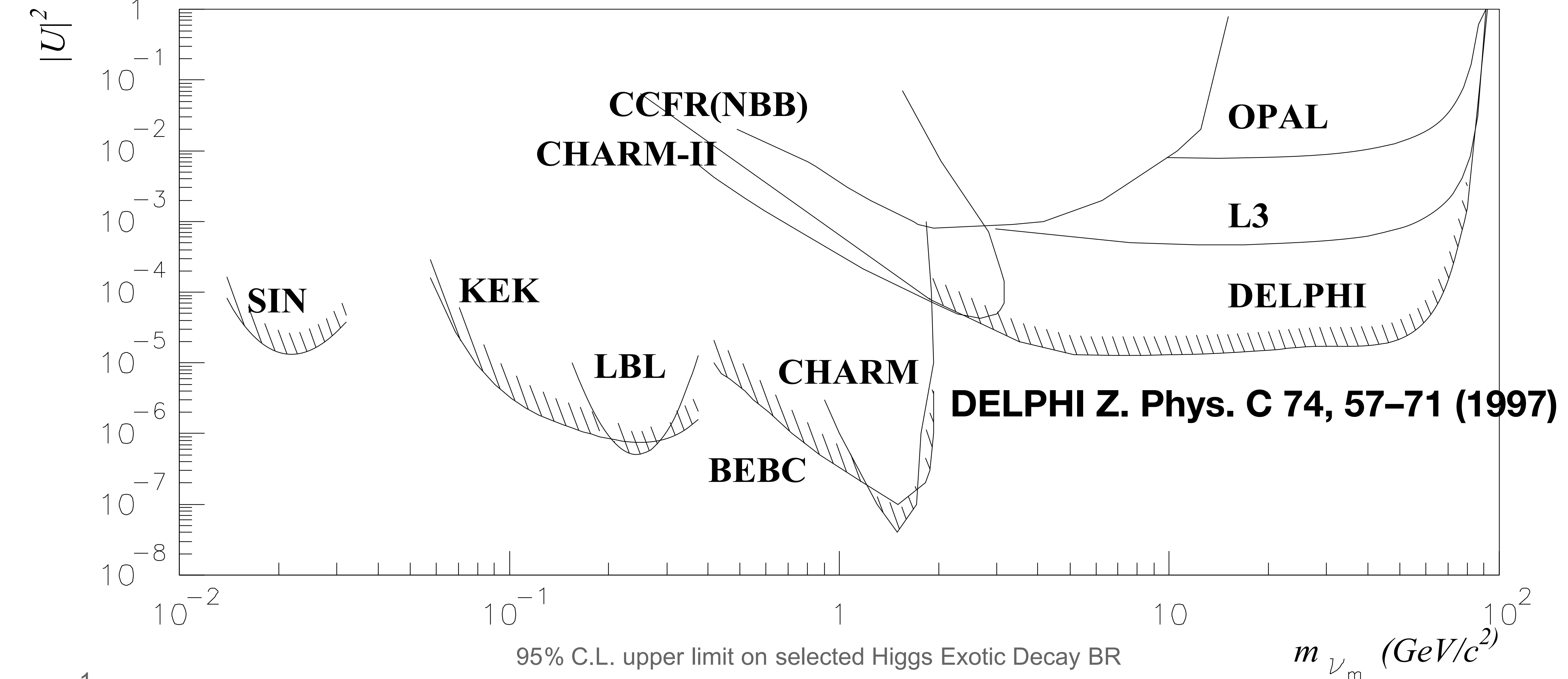


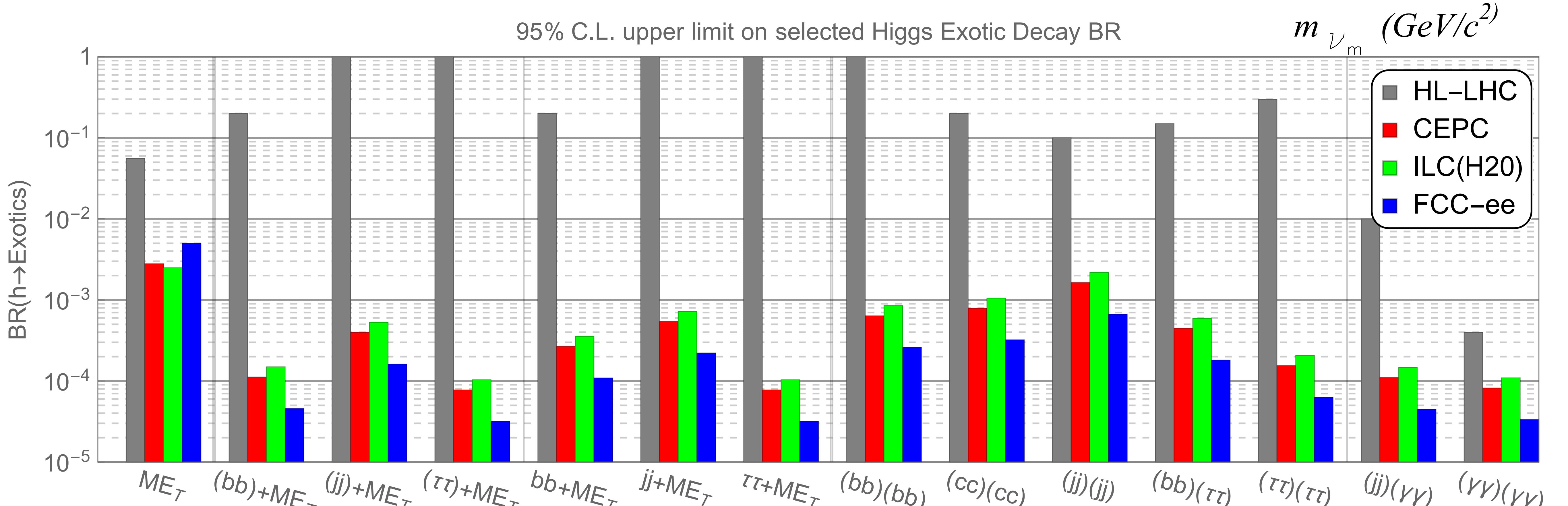
$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$

Higgs portal

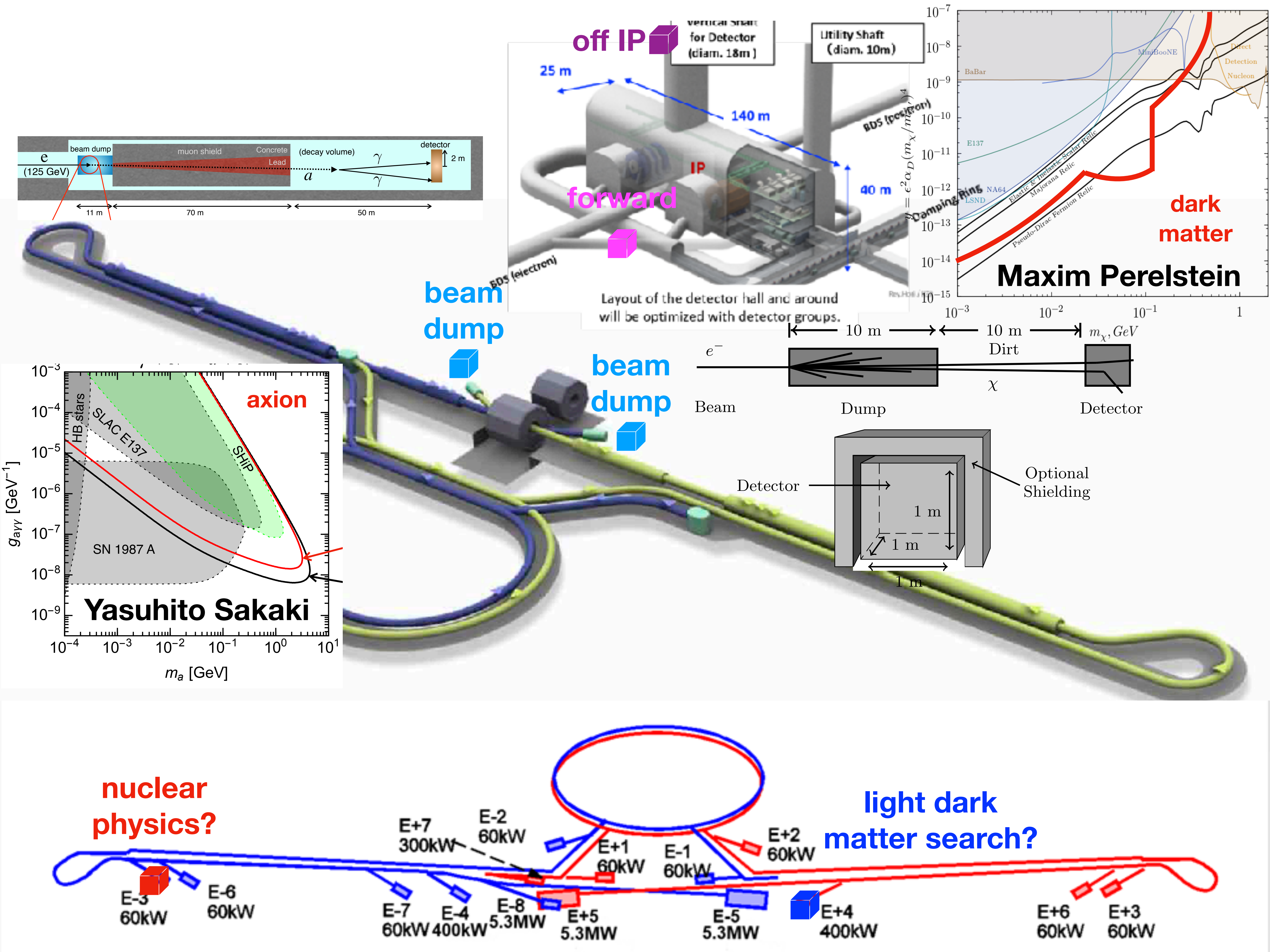
$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$



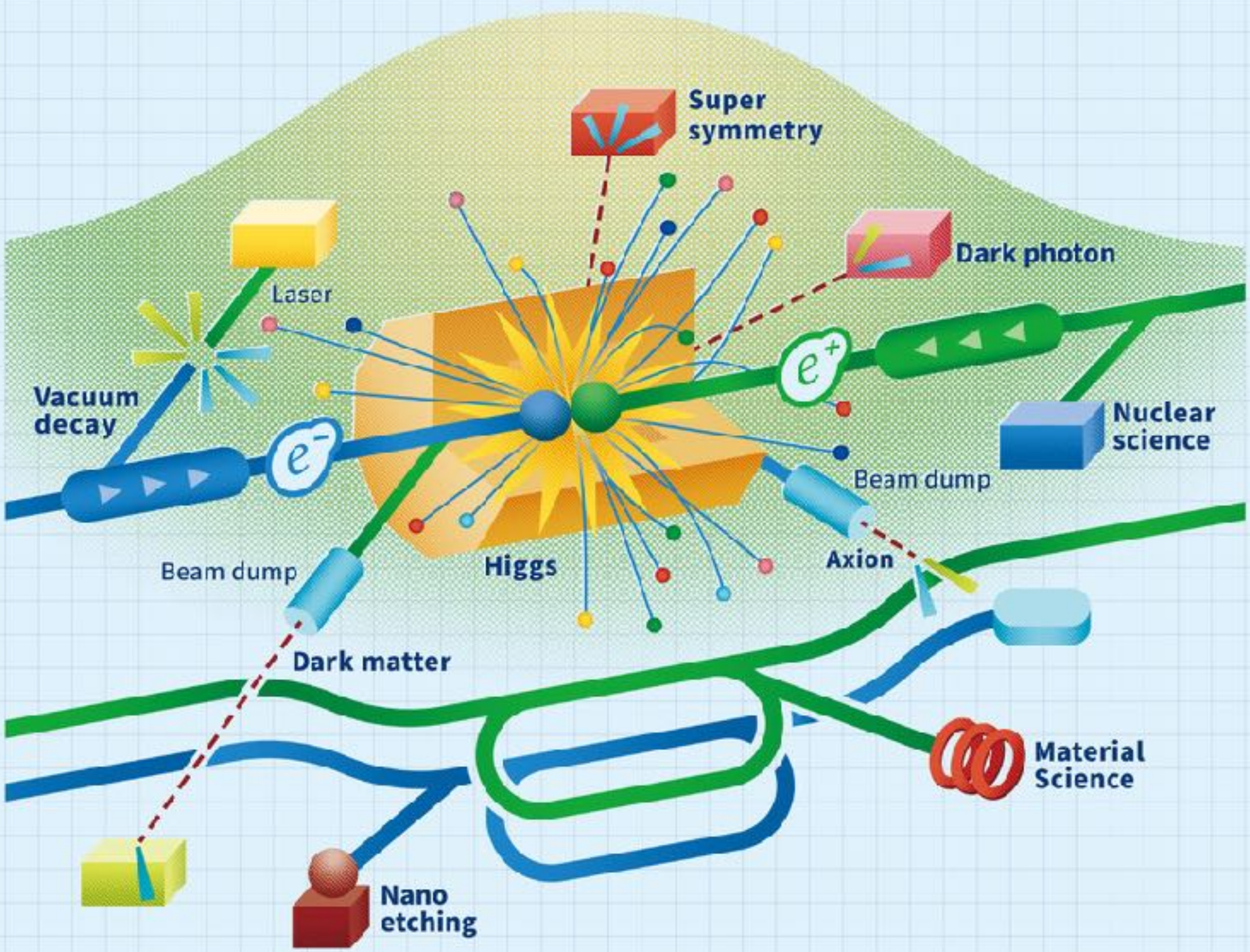




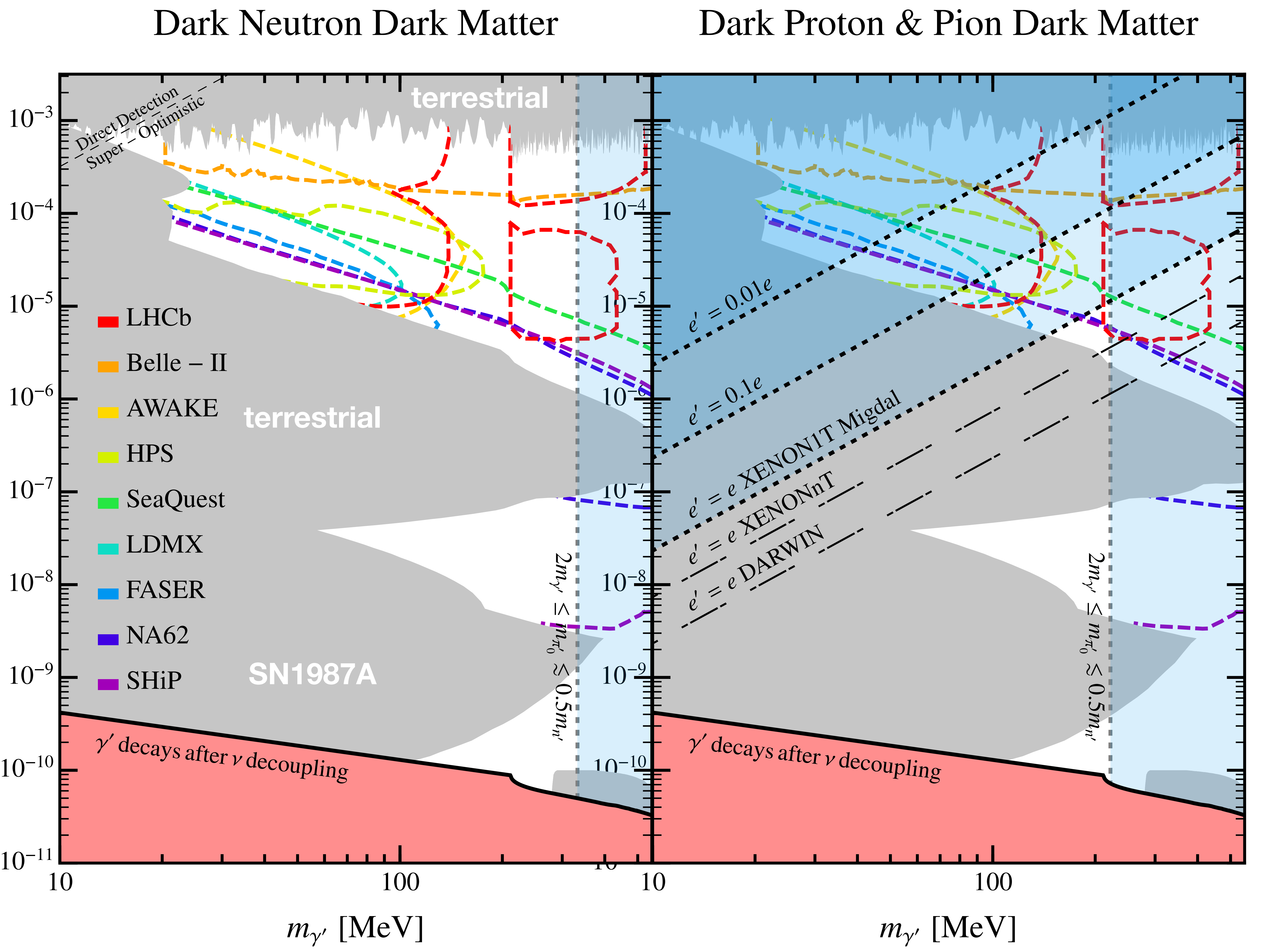
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284


off IP
Vertical Shaft for Detector (diam. 18m)
Utility Shaft (diam. 10m)
25 m
140 m
40 m
IP
forward
BDS (positron)
BDS (electron)
Damping Ring
Layout of the detector hall and around will be optimized with detector groups.
beam dump
detector
muon shield
Concrete
Lead
(decay volume)
e
(125 GeV)
a
γ
2 m
11 m
70 m
50 m
beam dump
beam dump
axion
HB stars
SLAC E137
SHiP
SN 1987 A
Yasuhito Sakaki
$g_{a\gamma\gamma}$ [GeV^{-1}]
m_a [GeV]
BaBar
MiniBooNE
Direct Detection Nucleon
E137
NA64
LSND
Elastic & Inelastic Scalar Relic
Majorana Relic
Pseudo-Dirac Fermion Relic
$y = \epsilon^2 \alpha_D (m_\chi/m_{A'})^4$
m_χ, GeV
dark matter
Maxim Perelstein
10 m
10 m
e^-
Dirt
χ
Beam
Dump
Detector
Detector
Optional Shielding
1 m
1 m
1 m
nuclear physics?
light dark matter search?
E+7 300kW
E-2 60kW
E+1 60kW
E-1 60kW
E+2 60kW
E-3 60kW
E-6 60kW
E-7 60kW
E-4 400kW
E-8 5.3MW
E+5 5.3MW
E-5 5.3MW
E+4 400kW
E+6 60kW
E+3 60kW

ILCX 2021 ILC Workshop on Potential Experiments

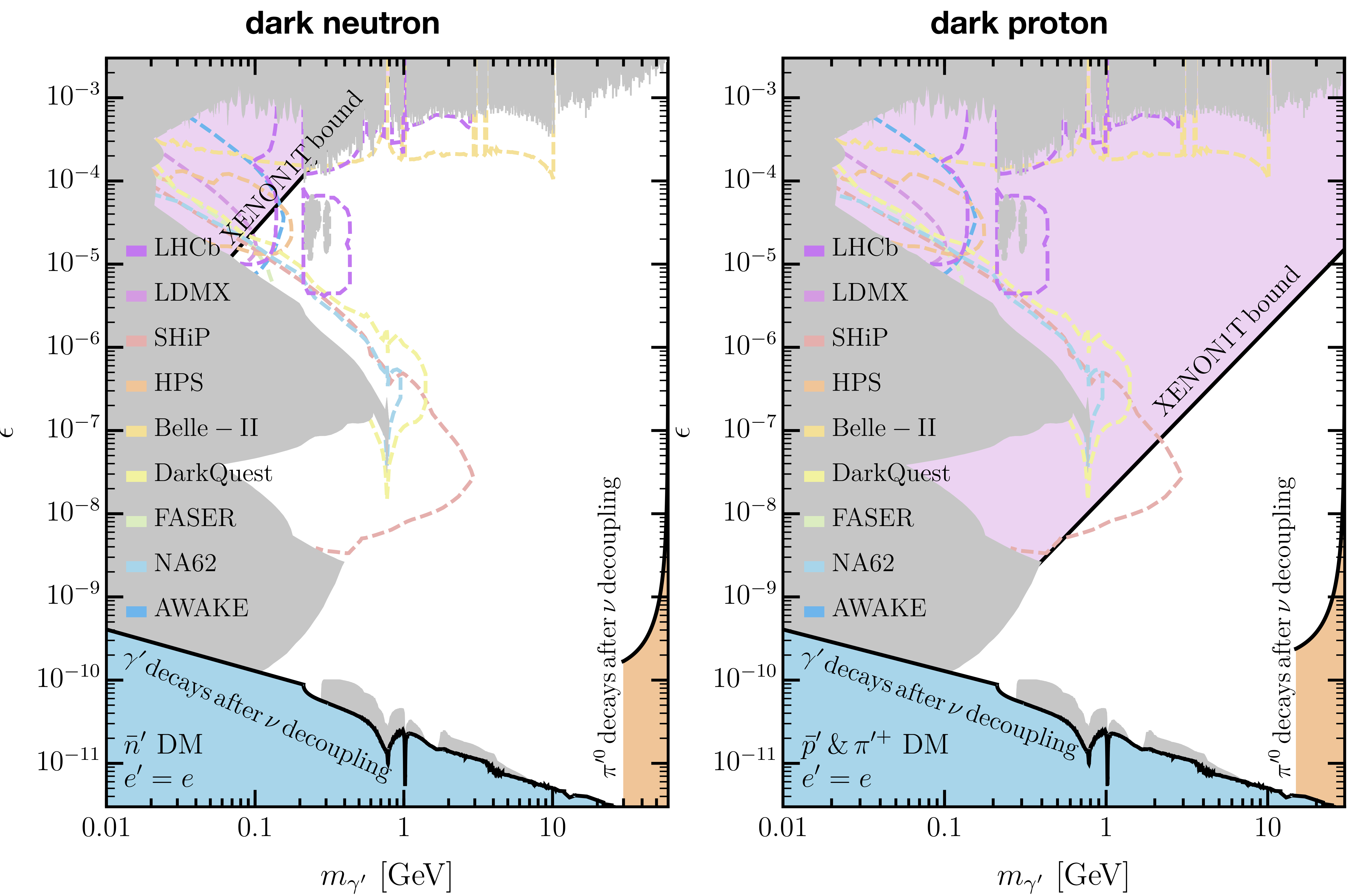


26–29 October 2021, Tsukuba, Japan



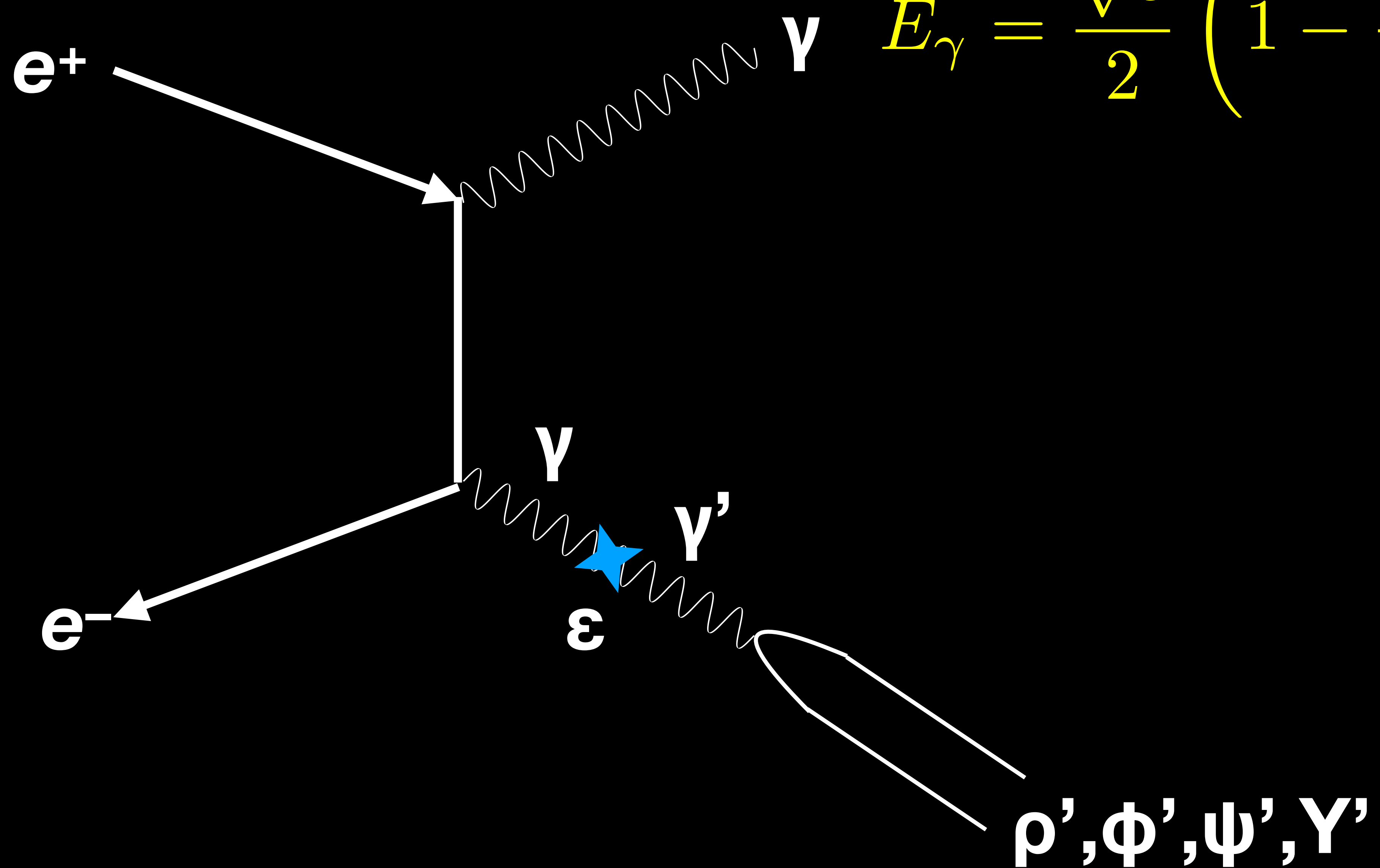
Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
terrestrial
Direct Detection
Super − Optimistic
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
$2m_{\gamma'} \leq m_{\pi'_0} \lesssim 0.5 m_{n'}$
γ' decays after ν decoupling
$e' = 0.01e$
$e' = 0.1e$
$e' = e$ XENON1T Migdal
$e' = e$ XENONnT
$e' = e$ DARWIN
$m_{\gamma'}$ [MeV]

If the asymmetry originates in the SM side transferred to the dark side



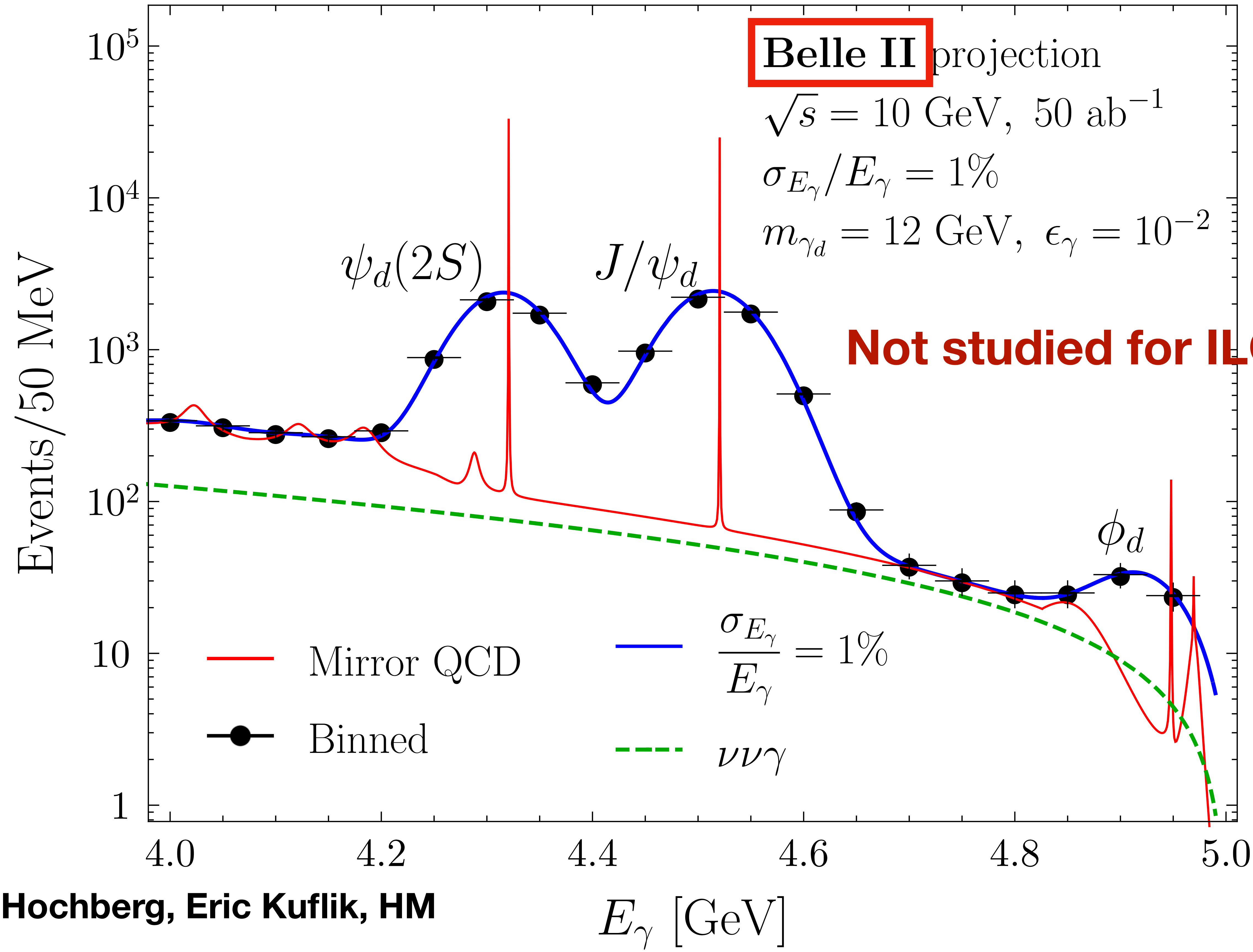
Dark Spectroscopy

$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\rm inv}^2}{s}\right)$$



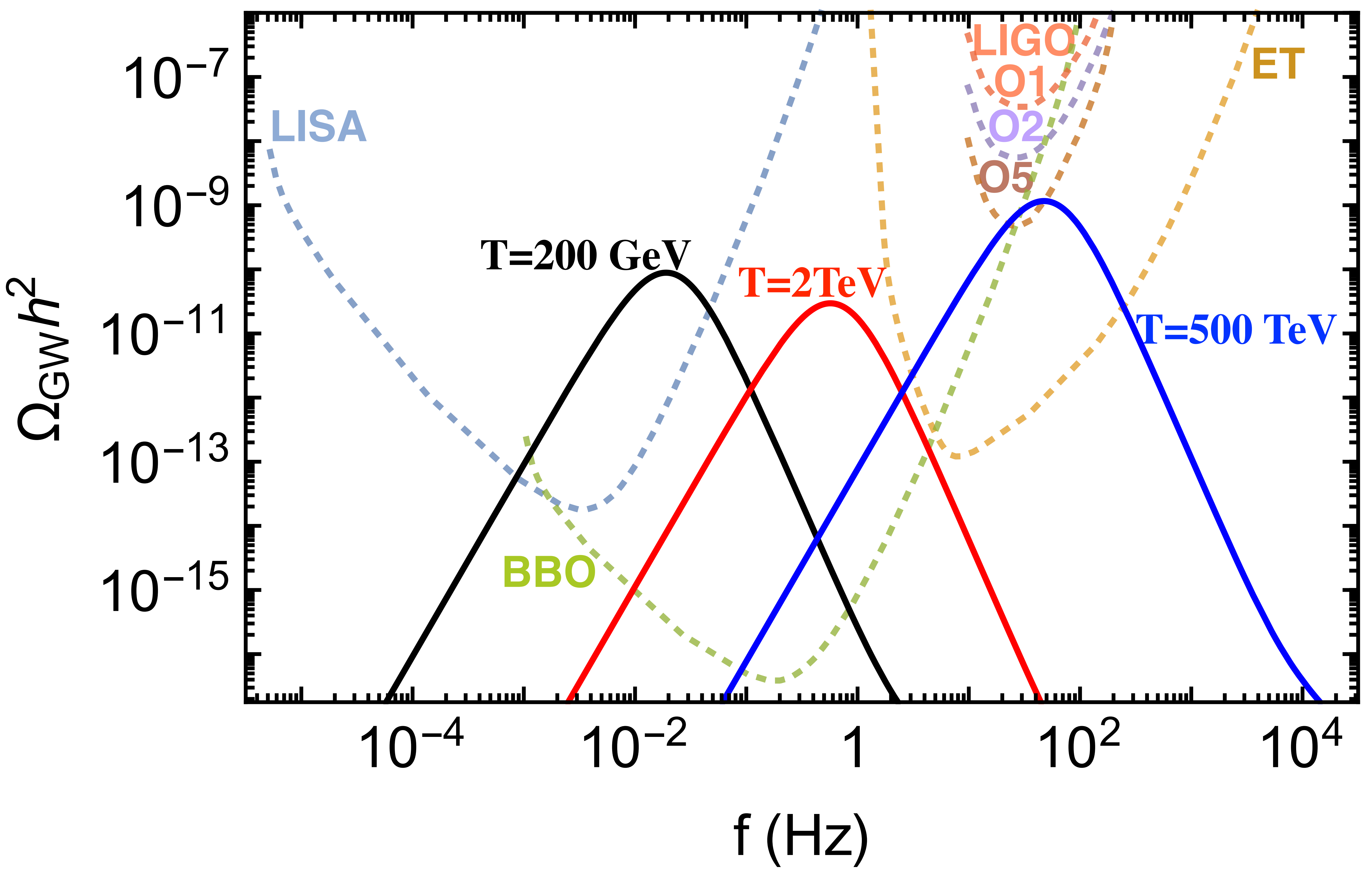
Yonit Hochberg, Eric Kuflik, HM, arXiv:1512.07917, 1706.05008

Dark Spectroscopy

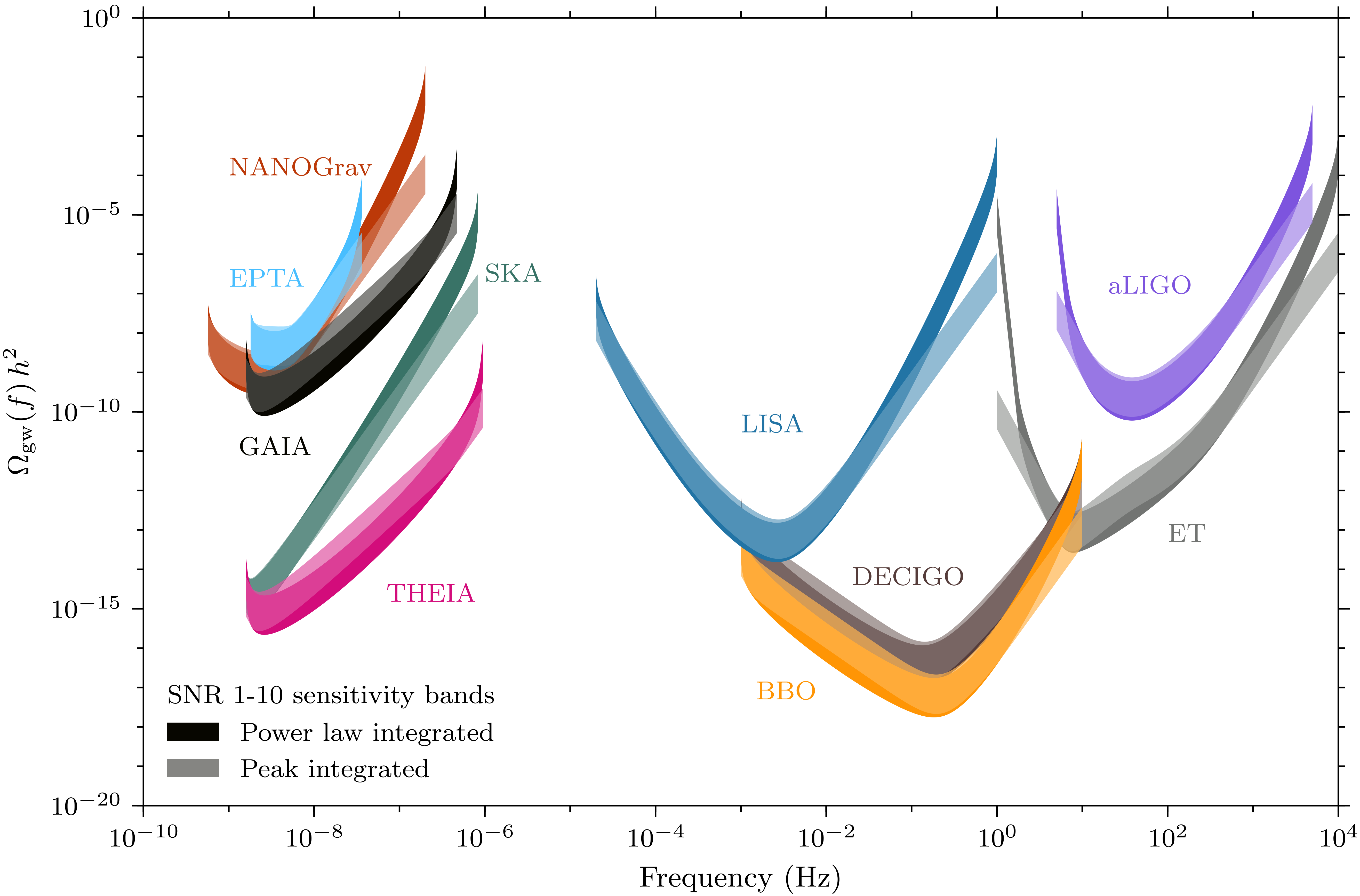


Not studied for ILC yet!

Yonit Hochberg, Eric Kuflik, HM



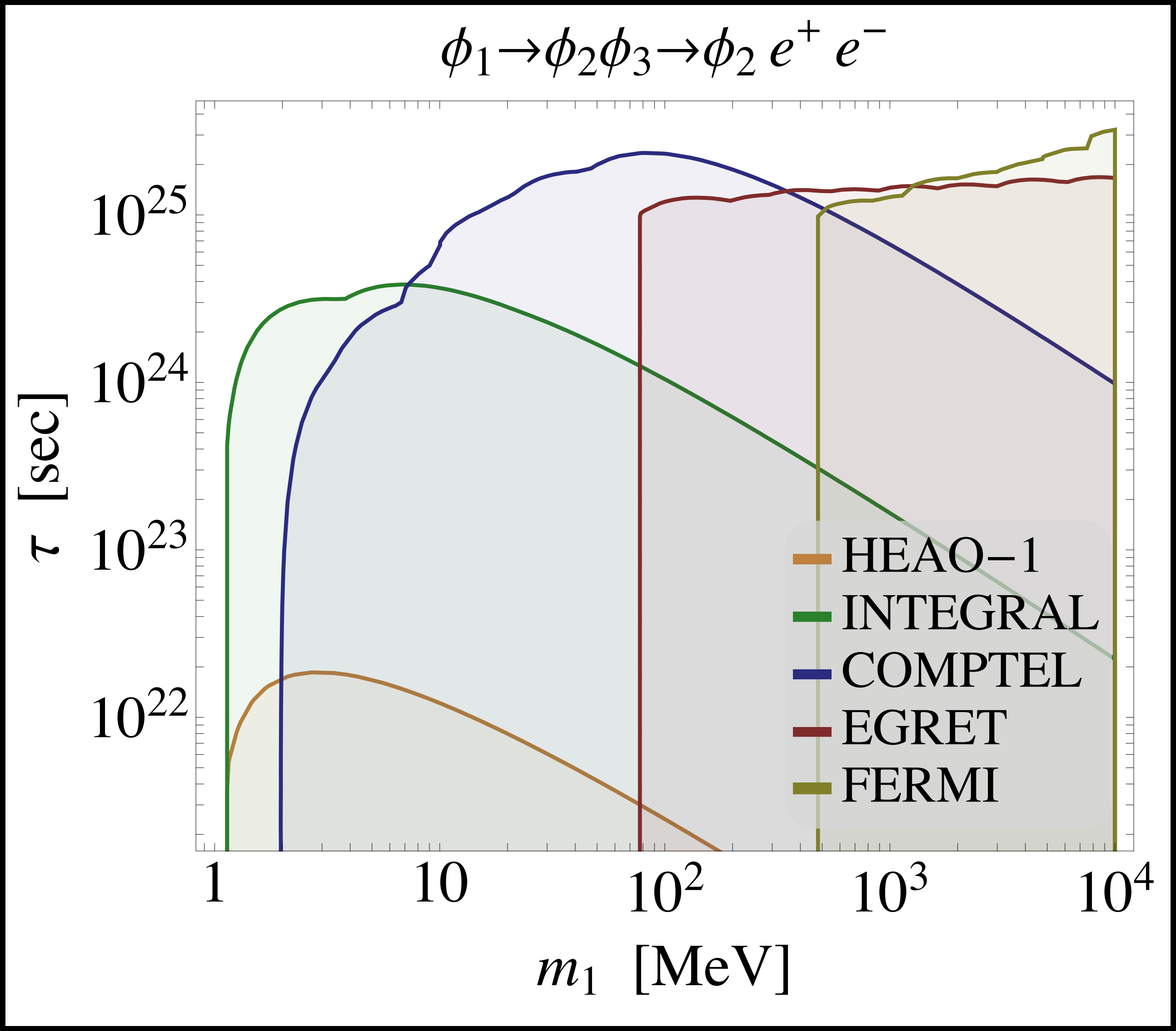
LIGO
O1
O2
O5
ET
LISA
T=200 GeV
T=2TeV
T=500 TeV
BBO
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
$\Omega_{GW}h^2$
10^{-4}
10^{-2}
1
10^{2}
10^{4}
f (Hz)



Juan Garcia-Bellido, Hitoshi Murayama, Graham White, arXiv:2104.04778

exotic signal

- SU(2)' instanton generates $u' d' d' \nu' e^{-8\pi^2/g^2} / v^2$
- dark neutron mixes to dark neutrino to neutrino portal to SM neutrino, decays into SM ℓ + (qqbar or $\ell\nu$)
- indirect detection of gamma's from galactic halos $\tau > 10^{25}$sec
- can happen if $\alpha'_W > 0.3$
- not possible when $N_{gen} > 1$



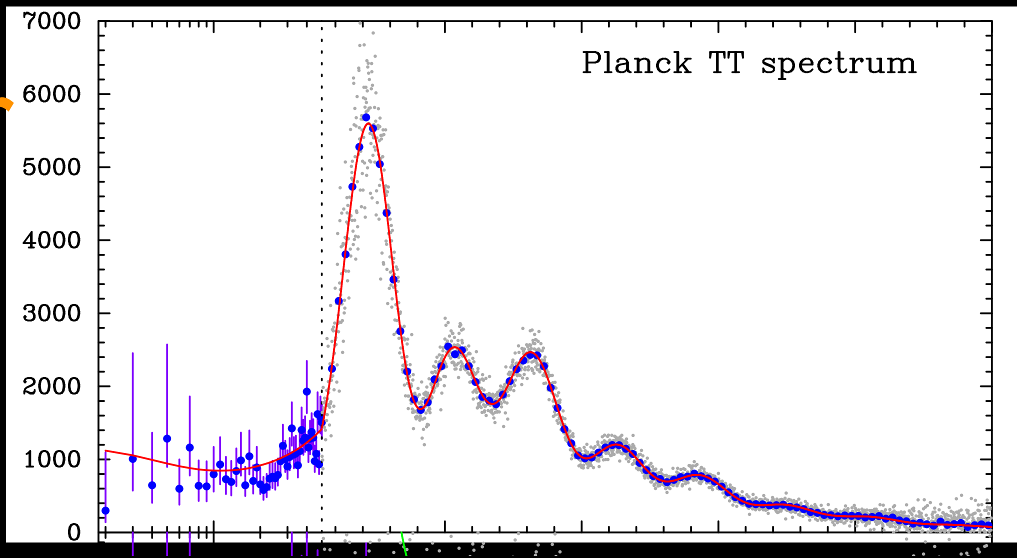
Essig, Kuflik, McDermott, Volansky, Zurek
aarXiv:1309.4091

Conclusions

- Electroweak baryogenesis *too testable*, very tight
  - do it in the dark sector
- dark SU(3)xSU(2)xU(1), one generation
  - two Higgs doublet CPV, 1st order phase transition
  - neutrino portal to transfer asymmetry to SM baryons
- dark neutron 1.33 or 1.58 GeV, or multi-component $p+\pi^-$
- amazingly wide array of experimental signatures
  - dark proton good target for direct detection
  - exotic Z-decay, h-decay (HL-LHC, ILC, CEPC, FCC-ee)
  - dark photon search at Belle II, LHC-b, beam dump
  - gravitational wave at LIGO, LISA, Einstein Telescope, etc
  - potential instanton-induced dark neutron decay in halos
- explain coincidence $\Omega_{DM} \sim \Omega_b$ if $N_{gen}=3$ and unification

Five evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - dark energy
  - apparently acausal density fluctuations
  - baryon asymmetry



We don't really know their energy scales...


many things
to look forward to!