Why don't we break apart?

—Higgs boson and Dark Matter—

Hitoshi Murayama (Berkeley & Kavli IPMU)

Summer Institute 2019 Gangneung

August 18, 2019


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—Higgs boson and Dark Matter–

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東京大学 THE UNIVERSITY OF TOKYO
BERKELEY CENTER FOR THEORETICAL PHYSICS
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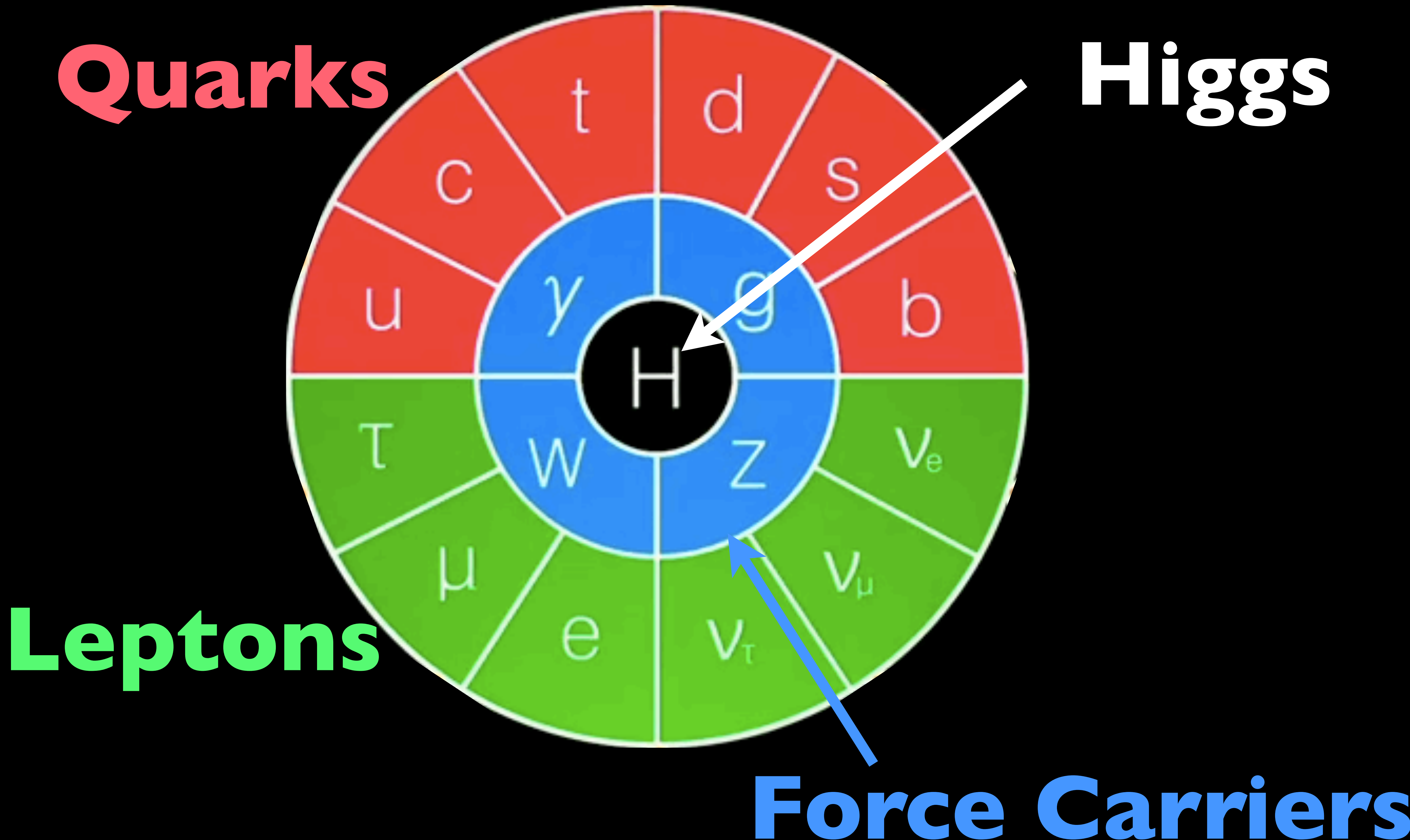
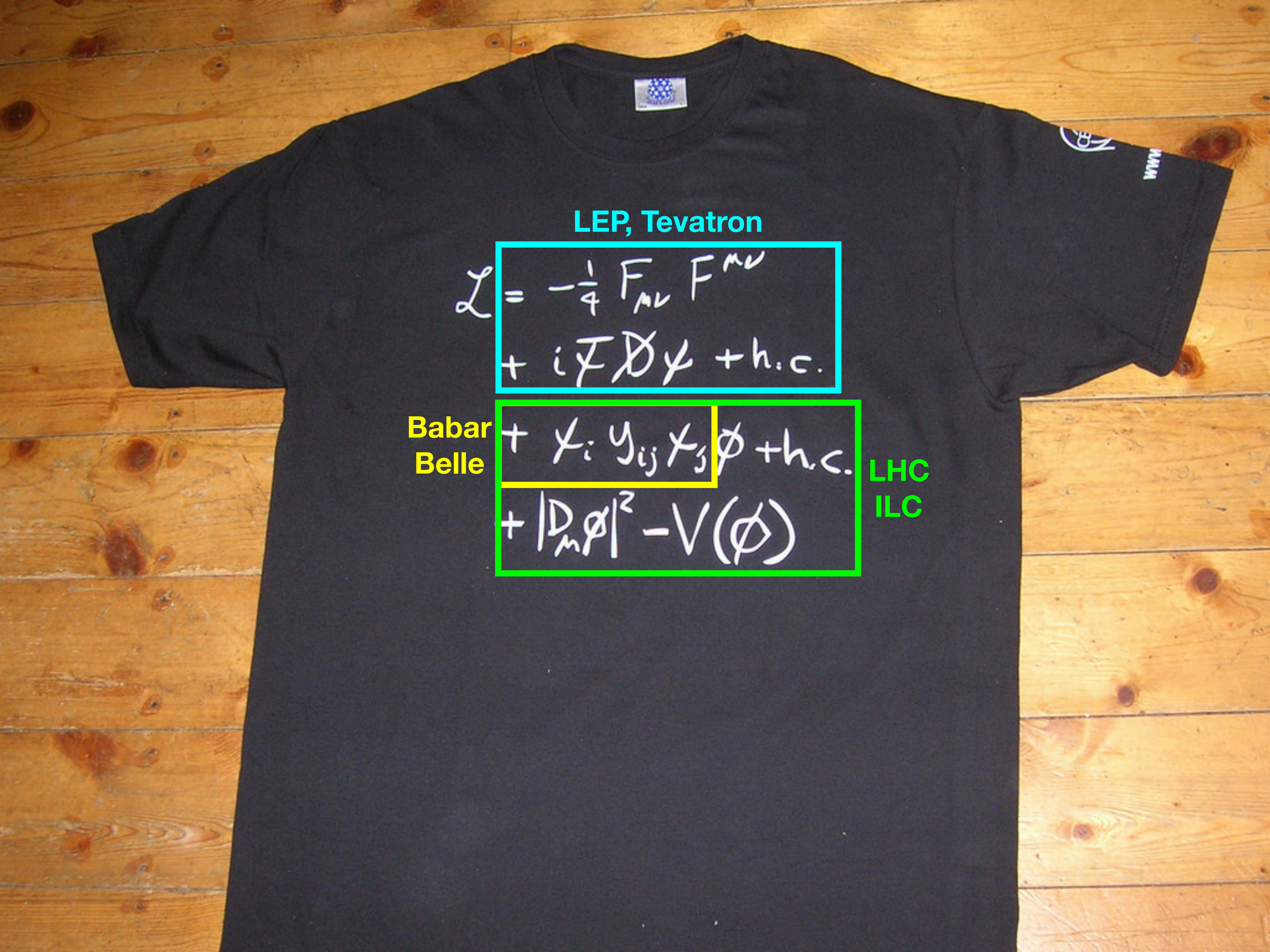
KAVLI IPMU

Standard Model



Standard Model


LEP, Tevatron
$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
Babar
Belle
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
LHC
ILC
$+ |D_\mu \phi|^2 - V(\phi)$

A Long History

- Since Fermi and Yukawa to the "Standard Model," it took almost 40 years to build
- Since deep inelastic scattering and *J*/ψ to precision measurements and Higgs, it took almost 40 years to test
- Now most ingredients experimentally verified except for Higgs couplings

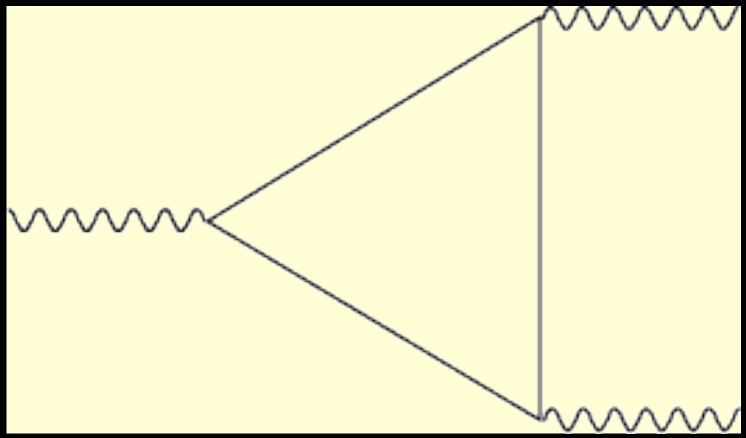
Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	*e*	*B*	*W*	*g*	*H*	*G*
$SU(3)_C$	3	3	3	1	1	1	1	8	1	1
$SU(2)_L$	2	1	1	2	1	1	3	1	2	1
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	1	0	0	0	-1/2	0
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1	1	1	0	2
flavor	3	3	3	3	3	1	1	1	1	1
seen?	Y	Y	Y	Y	Y	Y	Y	Y	Y	N

Anomaly Cancellation

- U(1)^3 $-6\left(\frac{1}{6}\right)^3+3\left(\frac{2}{3}\right)^3+3\left(\frac{-1}{3}\right)^3-2\left(\frac{1}{2}\right)^3+(1)^3=0$
- U(1)(gravity)^2 $-6\left(\frac{1}{6}\right)+3\left(\frac{2}{3}\right)+3\left(\frac{-1}{3}\right)-2\left(\frac{1}{2}\right)+(1)=0$
- U(1)(SU(2))^2 $-3\left(\frac{1}{6}\right)-2\left(\frac{1}{2}\right)=0$
- U(1)(SU(3))^2 $-2\left(\frac{1}{6}\right)+\left(\frac{2}{3}\right)+\left(\frac{-1}{3}\right)=0$
- (SU(3))^3 $-2+1+1=0$
- (SU(2))^3,(SU(3))^{2}SU(2),SU(3)(SU(2))^2 ,grav^3
- non-perturbative SU(2) 3+1=even



Non-trivial connection between q & l

General

- The most general renormalizable Lagrangian with the given particle content

$$
\begin{aligned}
\mathcal{L} \;=\; & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a} \\
& +\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i \\
& +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H \\
& -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}
\end{aligned}
$$

Parameters

- 3 gauge coupling constants + θ_{QCD}
- 2 parameters in the Higgs potential (G_F, m_H)

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a} \\ & +\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{e}_i i\not{D}e_i \\ & +Y_u^{ij}\bar{Q}_i u_j\tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H \\ & -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}\end{aligned}$$

g'~0.36, g~0.65, gs~1.2

G_F~(300 GeV)$^{-2}$, m_H=125 GeV, $\theta_{QCD}<10^{-10}$

Parameters

- 3x3 complex $Y_u^{ij}, Y_d^{ij}, Y_l^{ij}$: 54 real params
- reparameterization $SU(3)^5 \mathrm{x} U(1)$=41

$$\begin{aligned}\mathcal{L} \;=\;& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{\mu\nu a} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{\mu\nu a} \\ & +\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i \\ & +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H \\ & -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}\end{aligned}$$

$54-41=13=3_u+3_d+3_l+(3+1)_{CKM}$

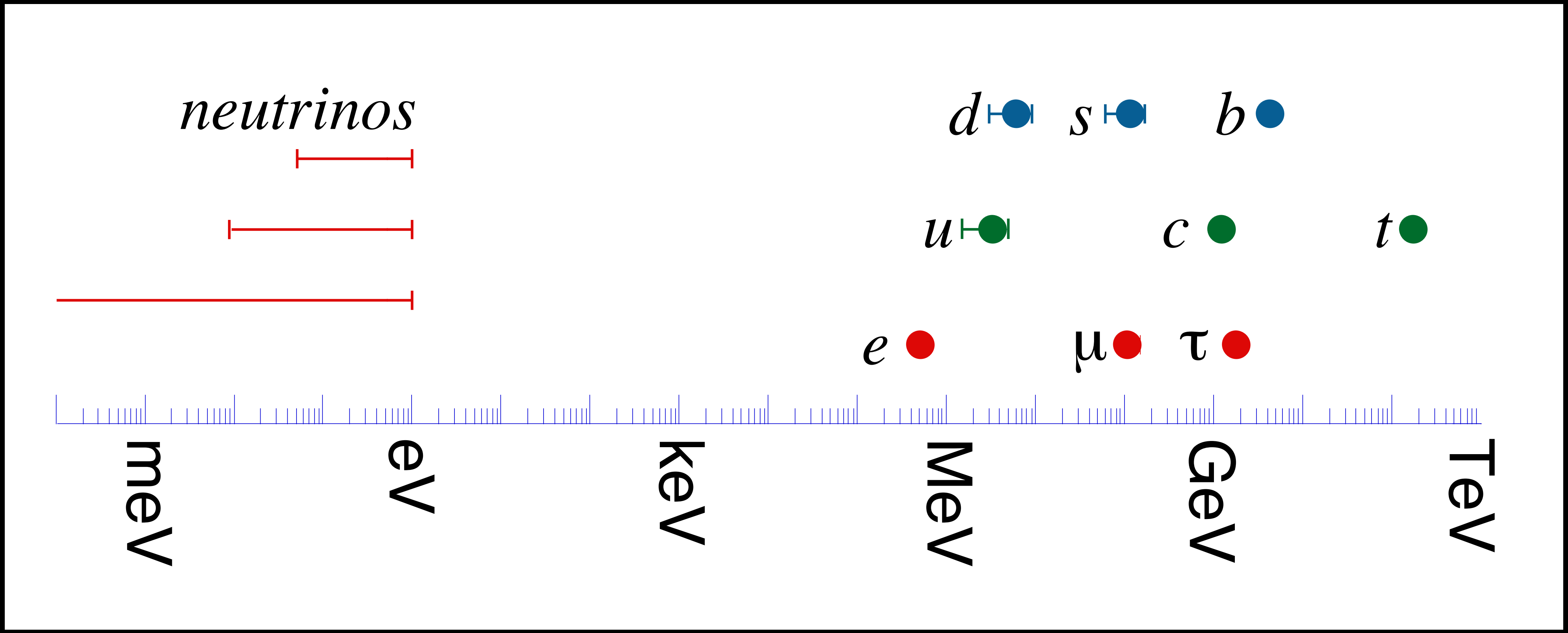
Masses and Mixings

- Choose masses and mixings as observed

$$V_{CKM} \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ -\lambda^3(1+\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

λ≈0.22

A, ρ, η≈O(1)



Standard Model is extreeemely successful

- Take Particle Data Group "Reviews of Particle Physics" with 400+ pages
- With only a few exceptions, all numbers in the book are consistent with the Standard Model with suitably chosen 19 parameters
- Some of them tested at 10^{-9}–10^{-12} level
- Many at 10^{-3} level

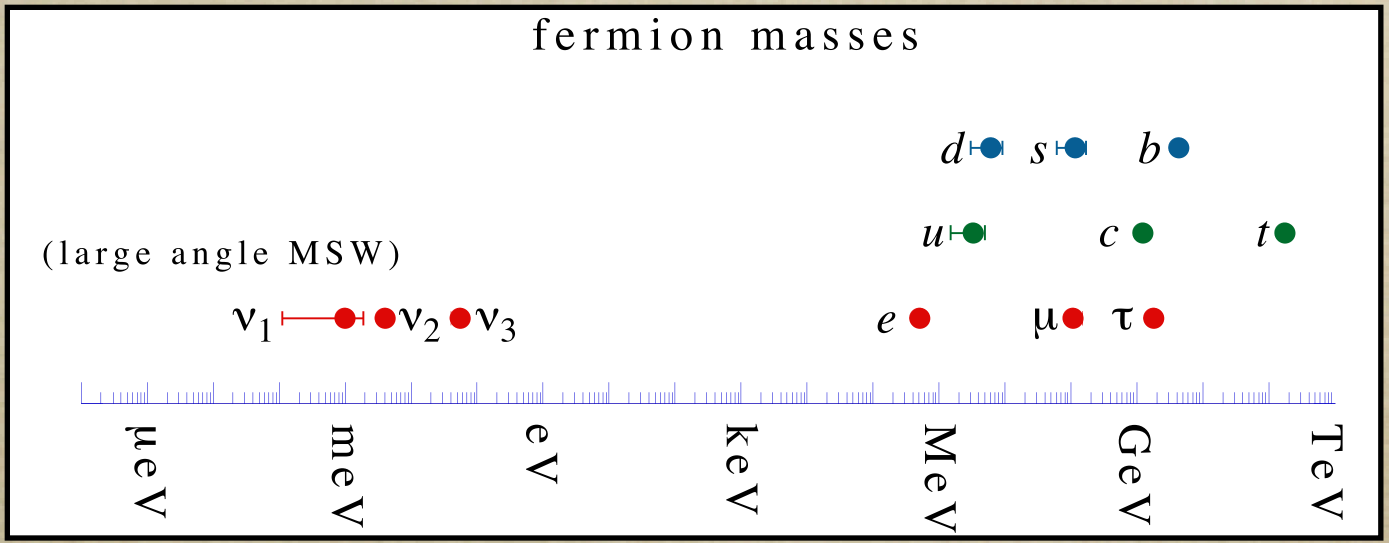
Standard Model is extreeemely successful

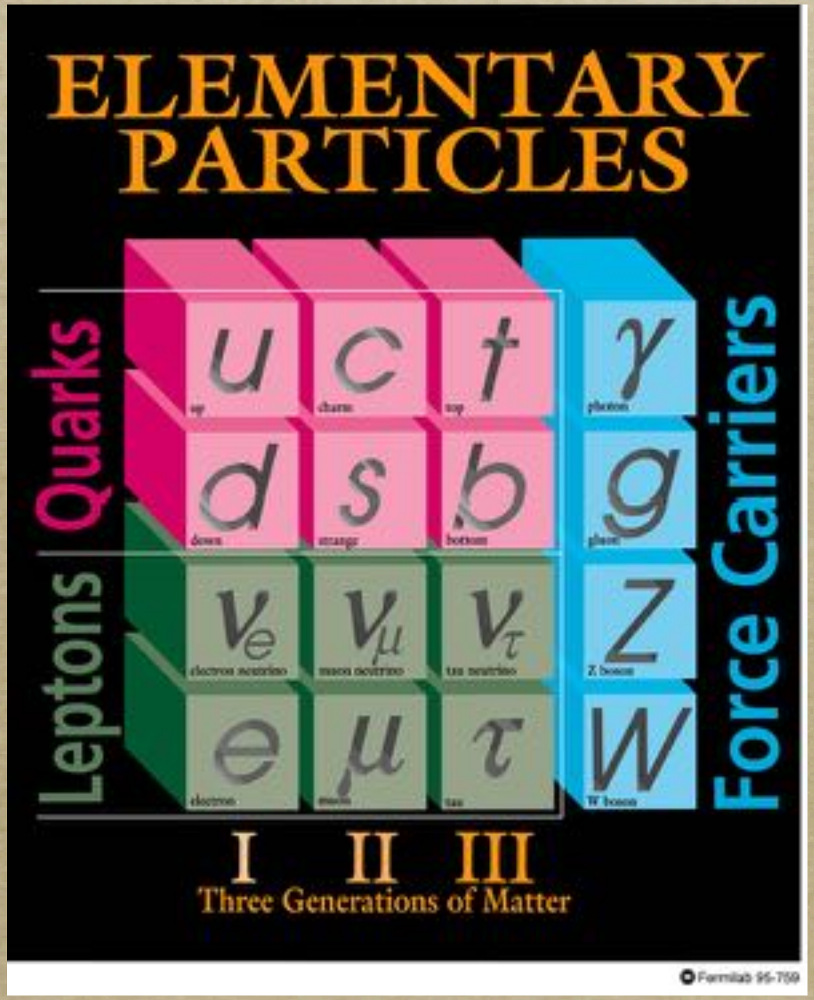
- baryon and lepton number conserved (apart from anomaly $\propto e^{-8\pi^2/g^2}$ giving rise to $^3He \to e^+ \mu^+ \bar{\nu}_\tau$)
- flavor approximately conserved (apart from small mixing in V_{CKM})
- especially flavor-changing neutral current small (e.g. $s \to d$ vanishes at tree-level, suppressed by m_c^2/m_W^2 at one-loop)

So, what’s the problem?

Big Questions –Horizontal–

- *Why are there three generations?*
- *What physics determines the pattern of masses and mixings?*
- *Why do neutrinos have mass yet so light?*
- *What is the origin of CP violation?*
- *What is the origin of matter anti-matter asymmetry in Universe?*

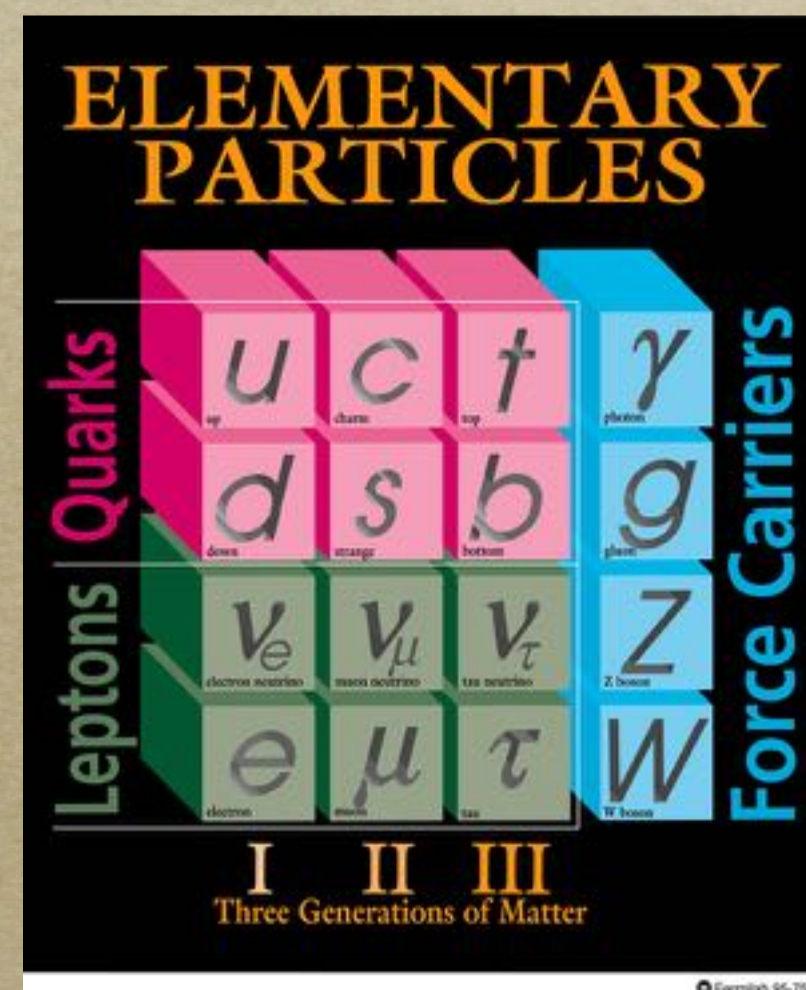




Big Questions –Vertical–

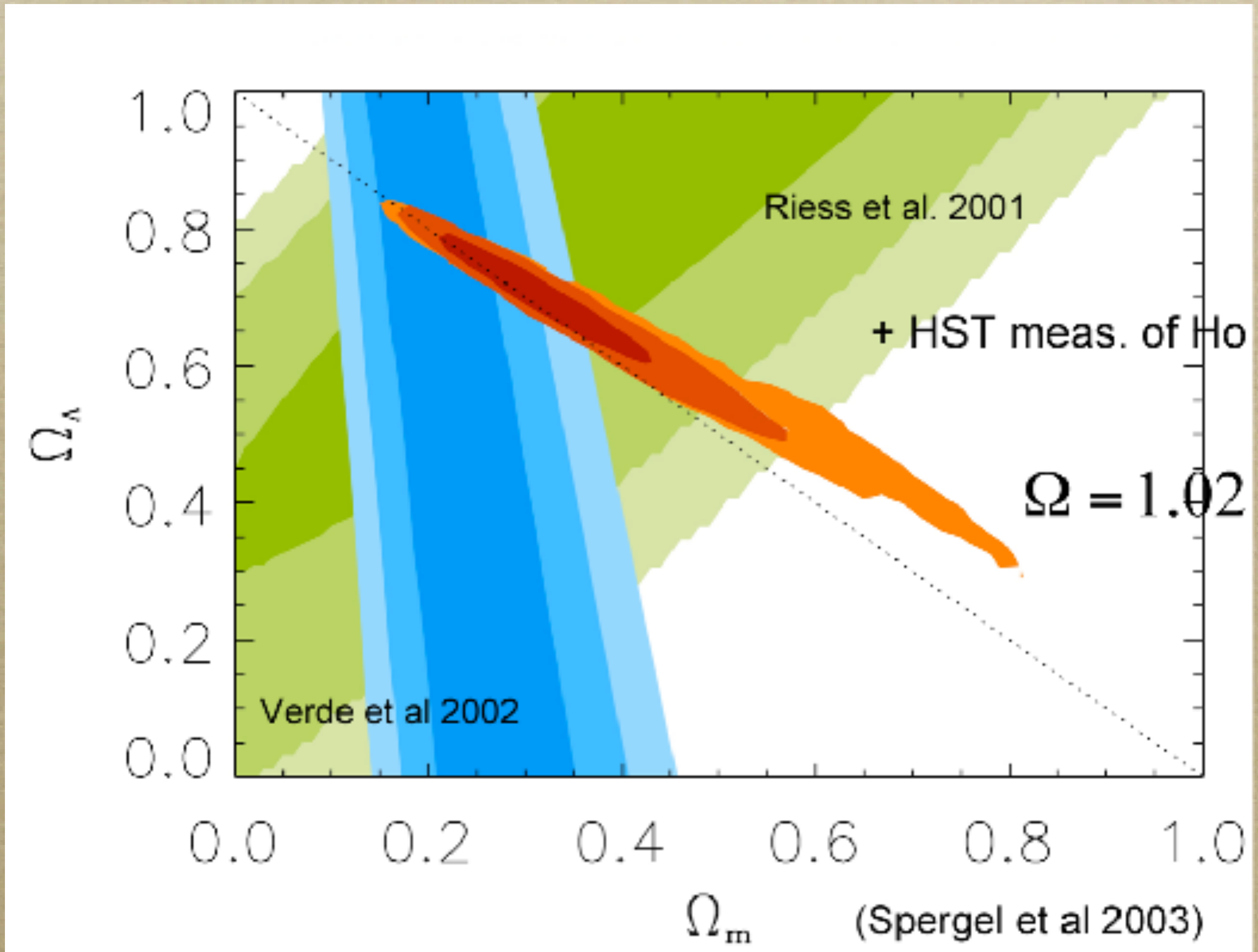
- *Why are there three unrelated gauge forces?*
- *Why is strong interaction strong?*
- *Charge quantization*
- *anomaly cancellation*
- *quantum numbers*
- *Is there a unified description of all forces?*
- *Why is* $m_W \ll M_{Pl}$ *?* *(Hierarchy Problem)*

$$Q(\mathbf{3},\mathbf{2},+\frac{1}{6}),\quad u(\mathbf{3},\mathbf{1},+\frac{2}{3}),\quad d(\mathbf{3},\mathbf{1},-\frac{1}{3}),$$
$$L(\mathbf{1},\mathbf{2},-\frac{1}{2}),\quad e(\mathbf{1},\mathbf{1},-1)$$

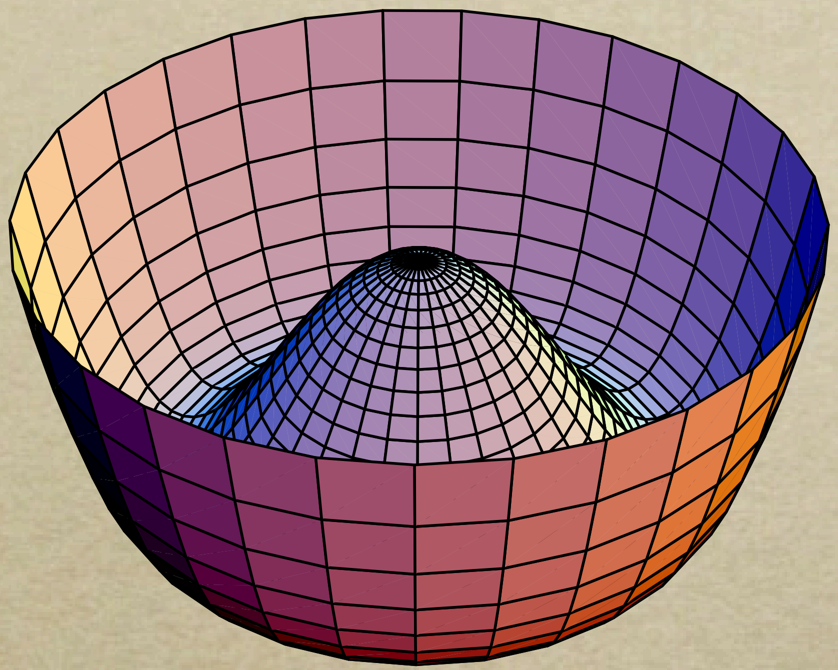


Big Questions
–From the Heaven–

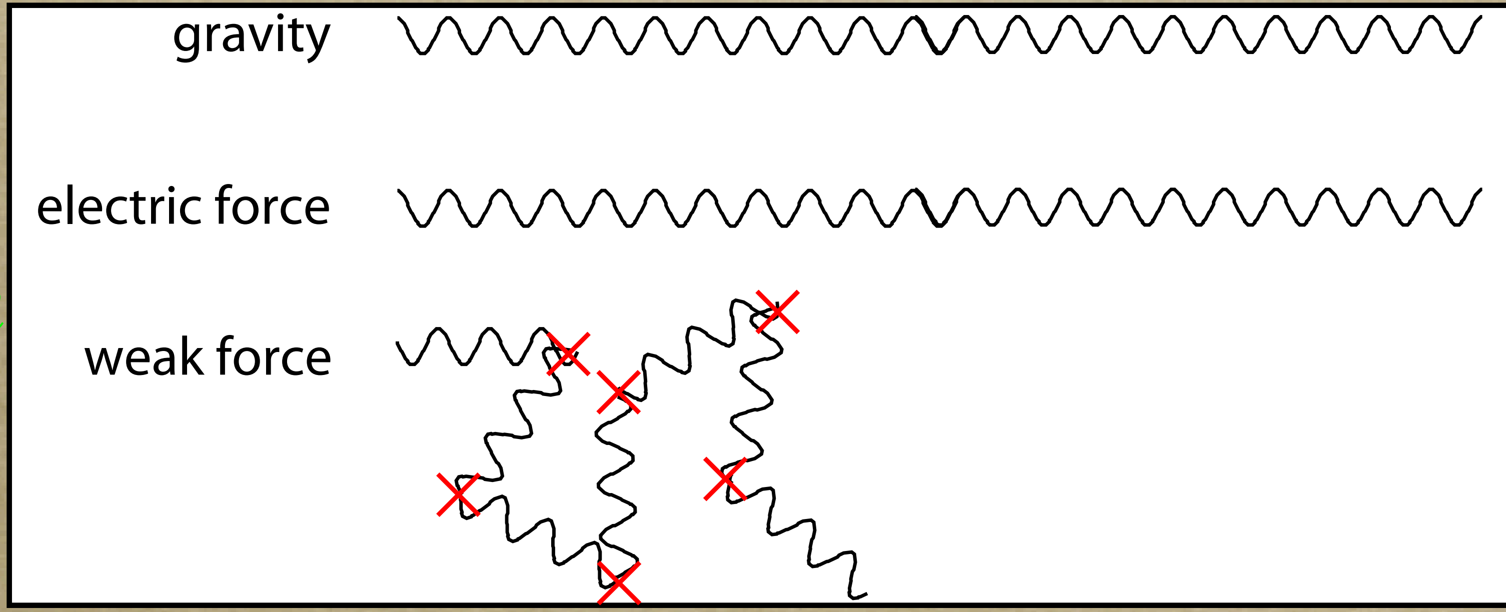
- *What is Dark Matter?*
- *What is Dark Energy?*
- *Why now? (Cosmic coincidence problem)*
- *What was Big Bang?*
- *Why is Universe so big? (flatness problem, horizon problem)*
- *How were galaxies and stars created?*



Big Questions –From the Hell–



- *What is the Higg boson?*
- *Why does it have negative mass-squared?*
- *Why is there only one scalar particle in the Standard Model?*
- *Is it elementary or composite?*
- *Is it really condensed in our Universe?*



HM, *Outlook*, Lepton Photon 2003

Standard Model is fragile

- The minute you allow for additional fields and/or gauge groups, much of the success is destroyed
- suppressed flavor-changing neutral currents
- no proton decay
- no neutrino mass either (good&bad)
- consistency with precise electroweak data
- no excessive CP violation (e/n EDM)
- no charge/color breaking

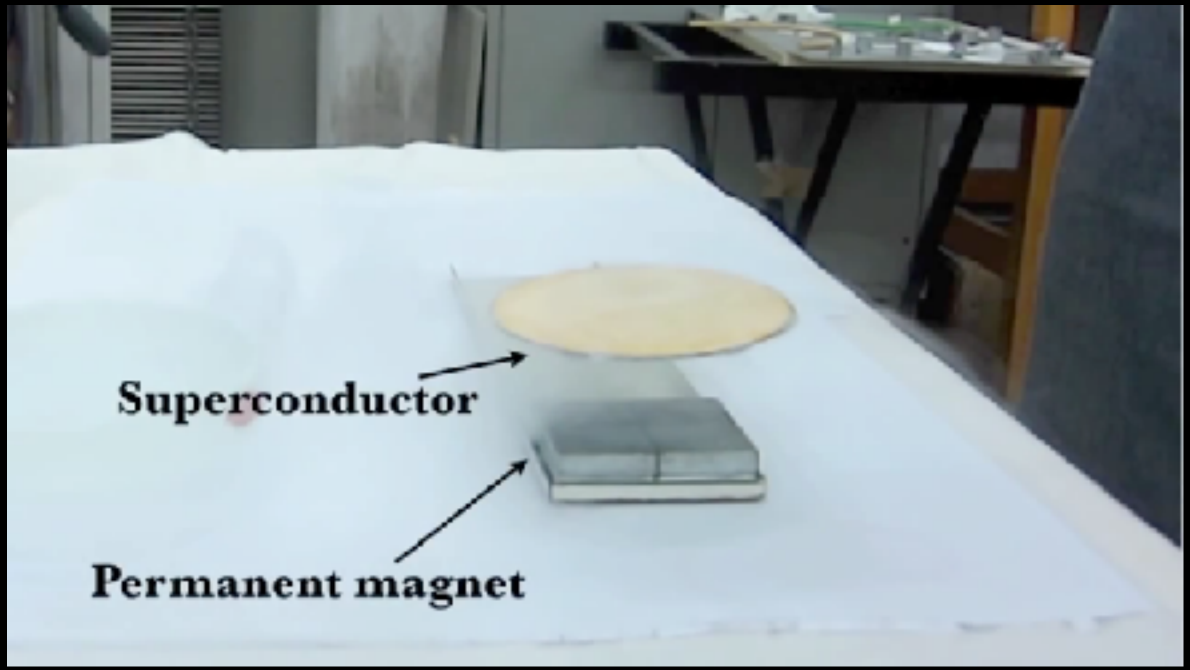
Standard Model is fragile

- The minute you allow for parameters to vary, it exhibits very different physics
- take $m_d < m_u$, all protons decay to neutrons and there are no atoms
- take $m_e > 4m_p - m_\alpha$, Sun doesn't burn
- if $m_H^2 > 0$, EWSB still occurs by QCD, but the world is too radioactive to live
- If $m_c \sim m_t$, no J/ψ before the end of cold war and no high-energy physics funding by now

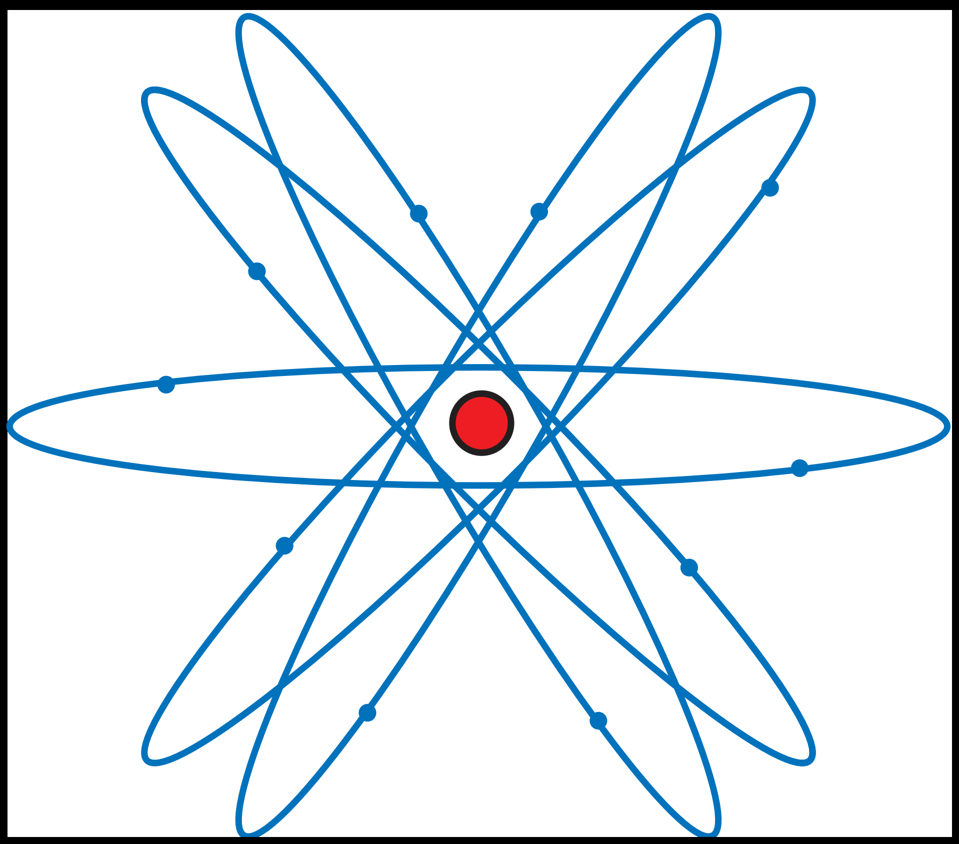
Higgs

Mystery

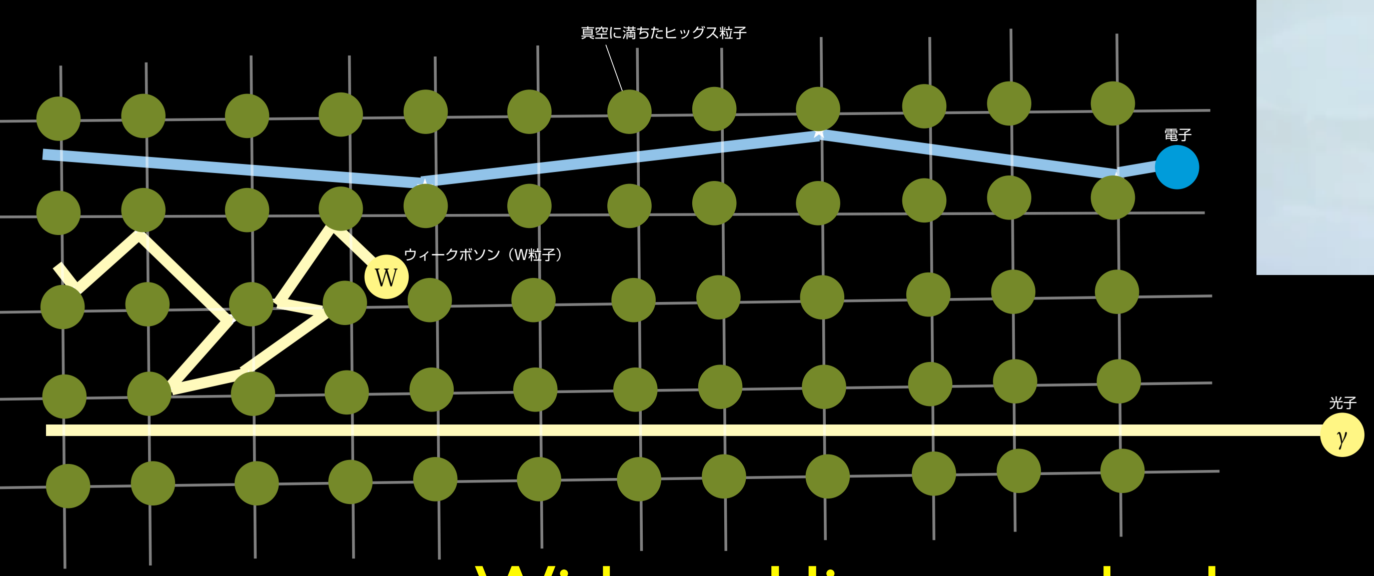
- Weak force is basically the same kind as the electromagnetism
- But then why is its range much shorter than the size of nuclei?



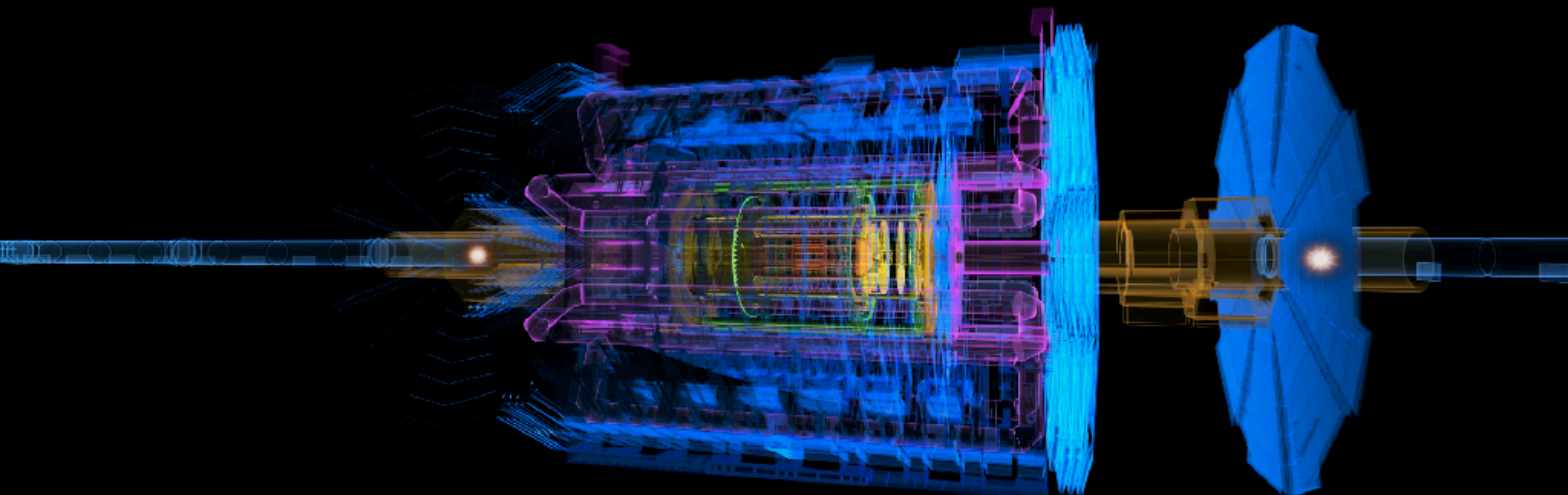
Higgs is frozen in our Universe



The whole Universe is a kind of superconductor
This is why weak interaction is short-ranged
All elementary particles masses come from Higgs



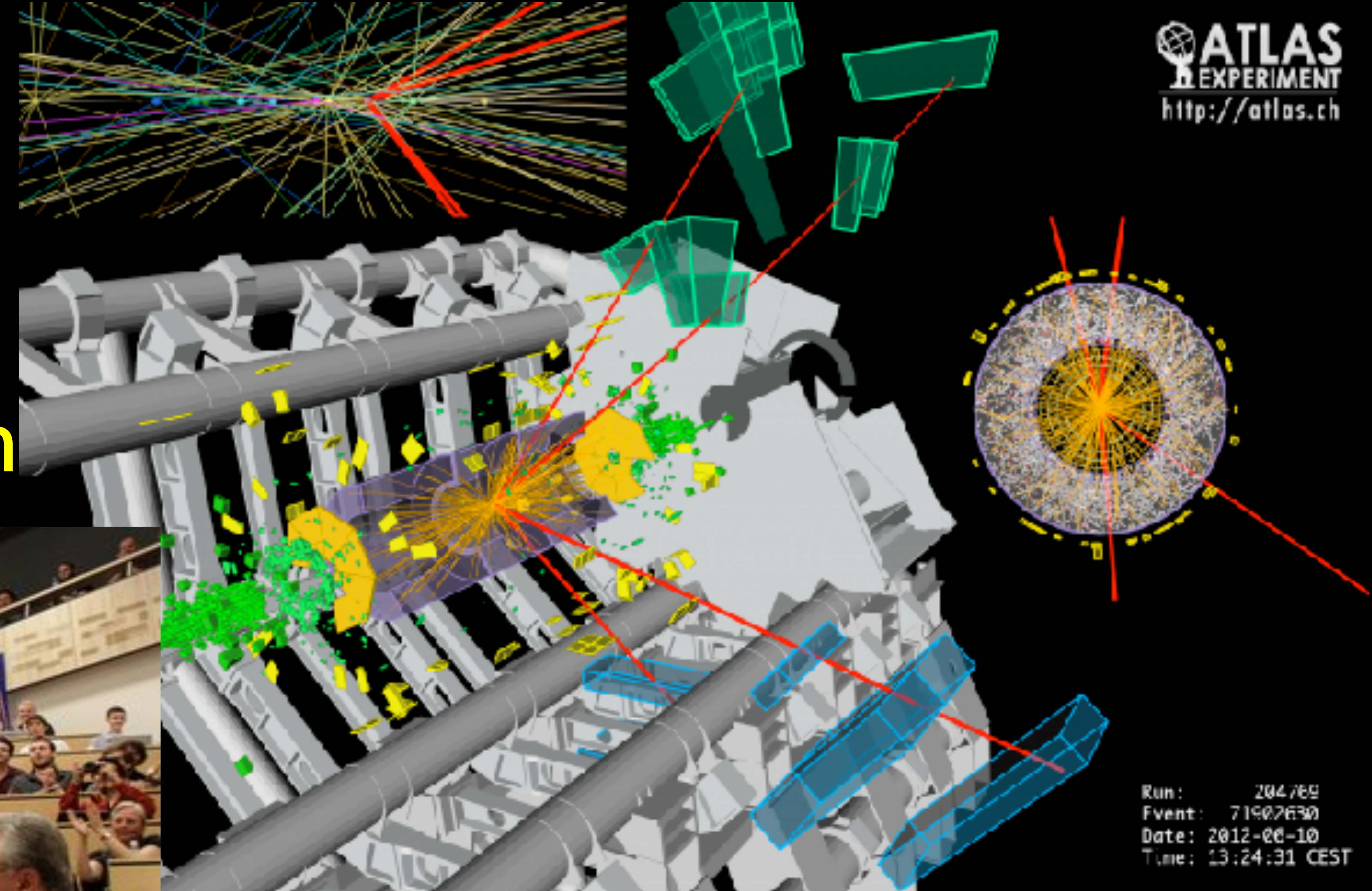
Without Higgs, our body evaporates in a nanosecond!

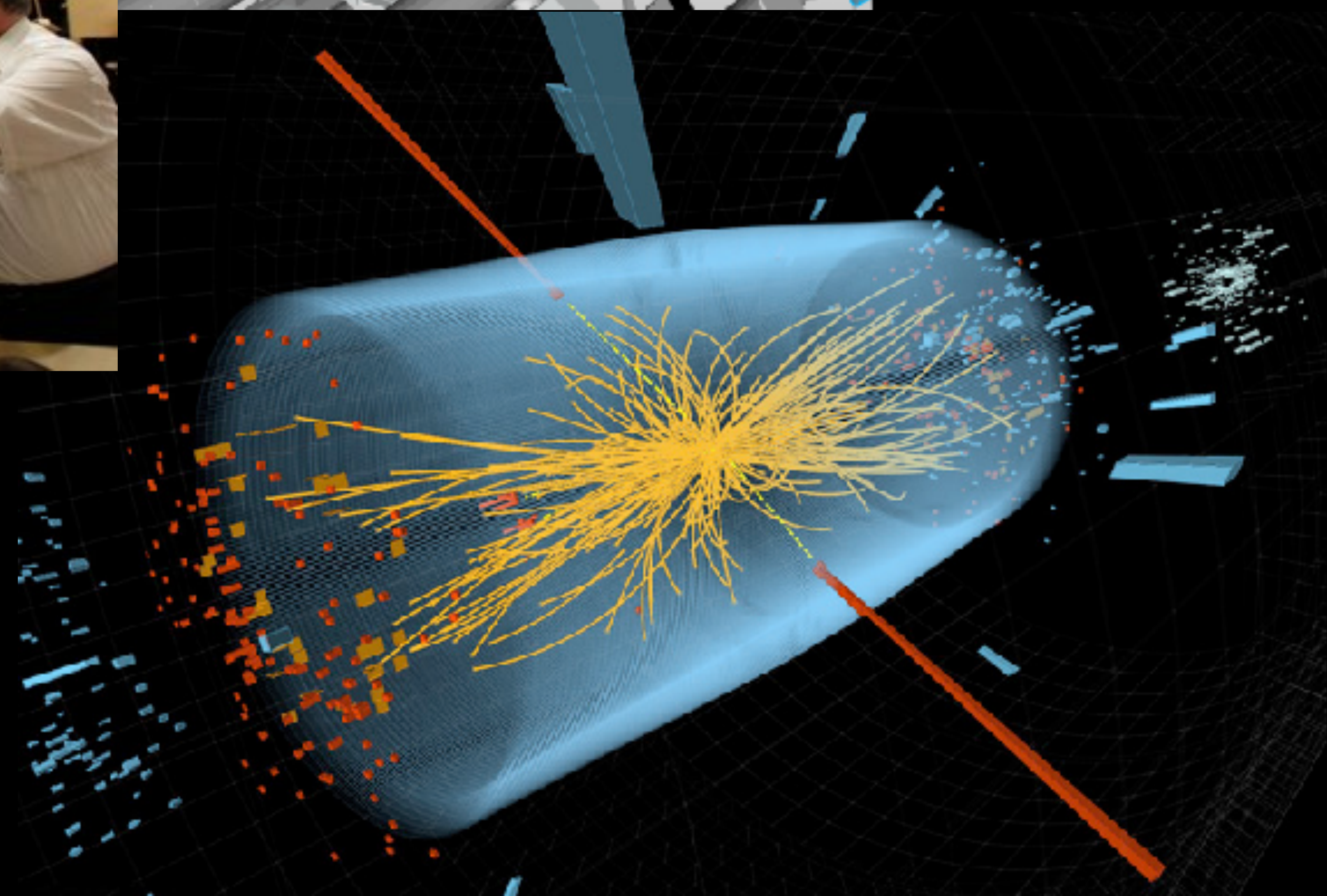


Higgs boson decays into two photons

2012.7.4

discovery of Higgs boson



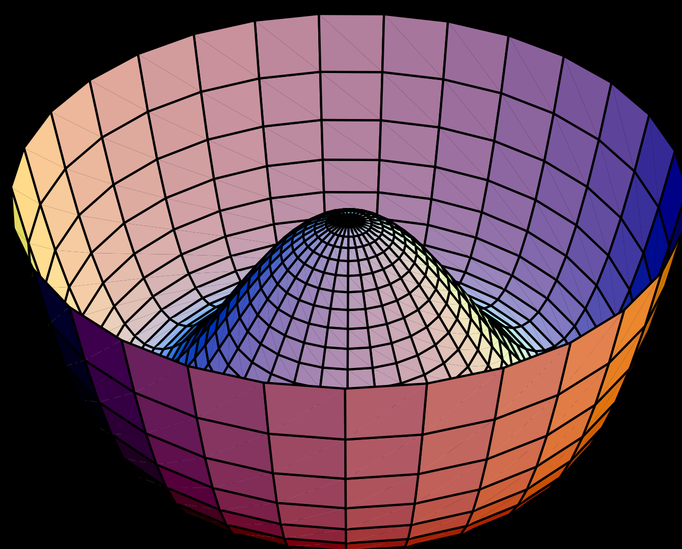


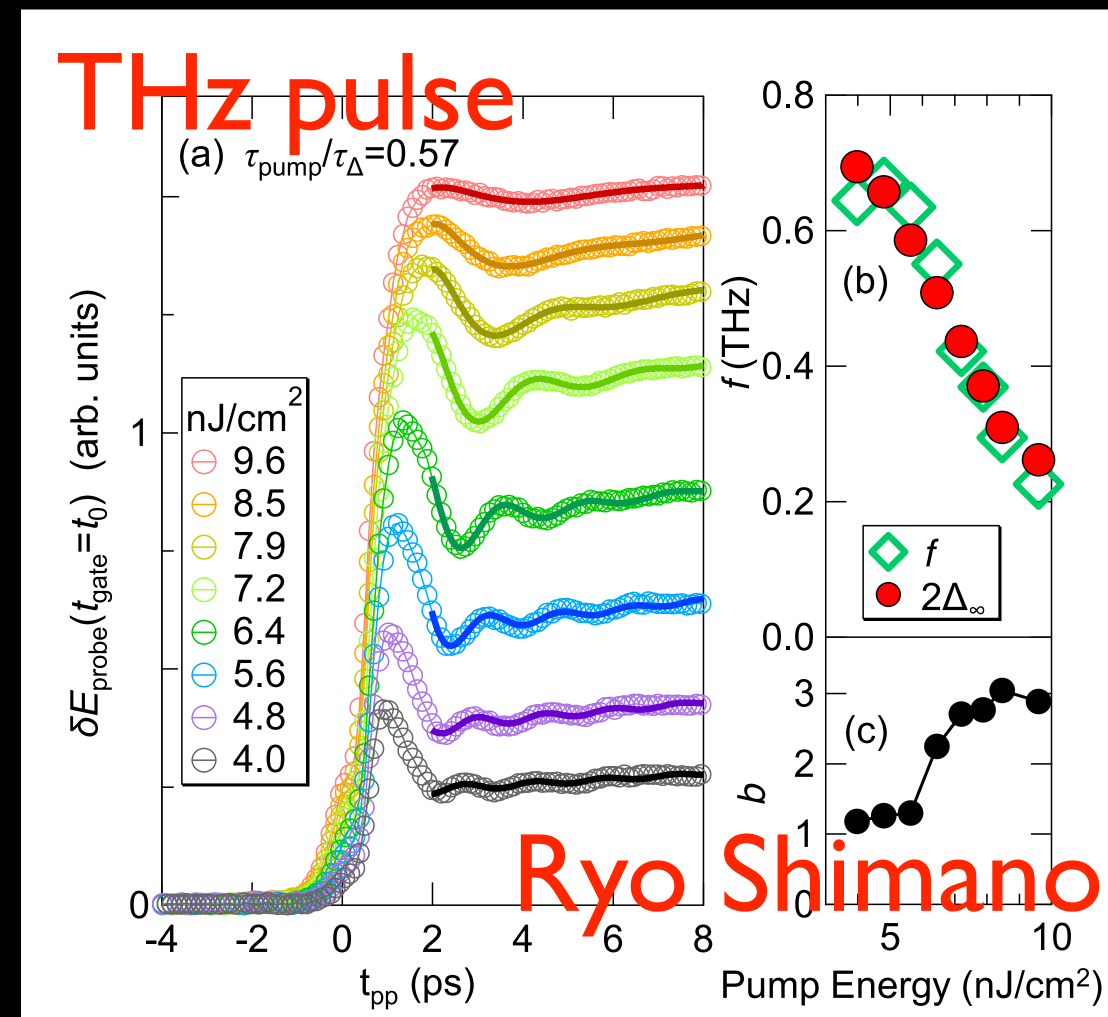
theory : 1964

design : 1984

construction : 1998

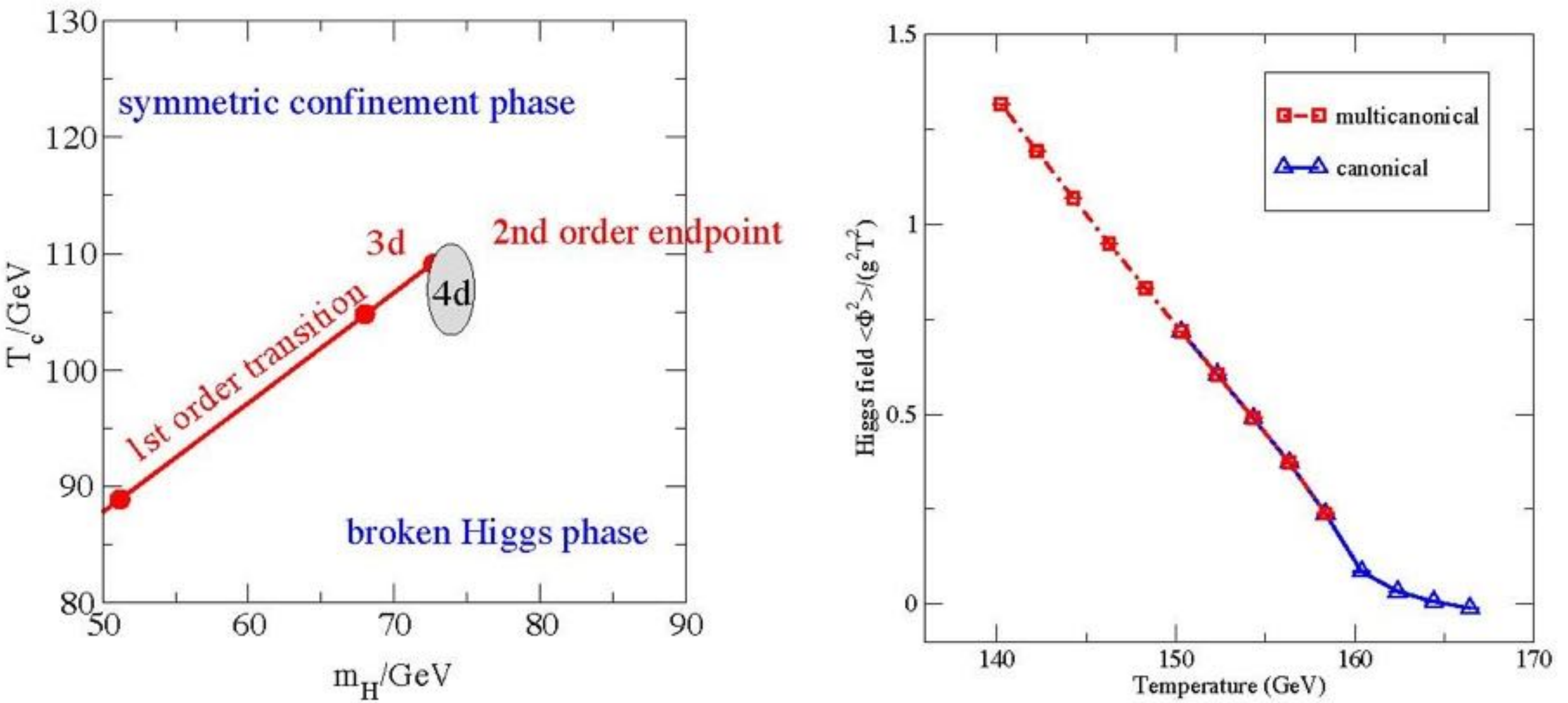
superconductors





Phase diagram for the Standard Model:

Mikko Laine (Bern)



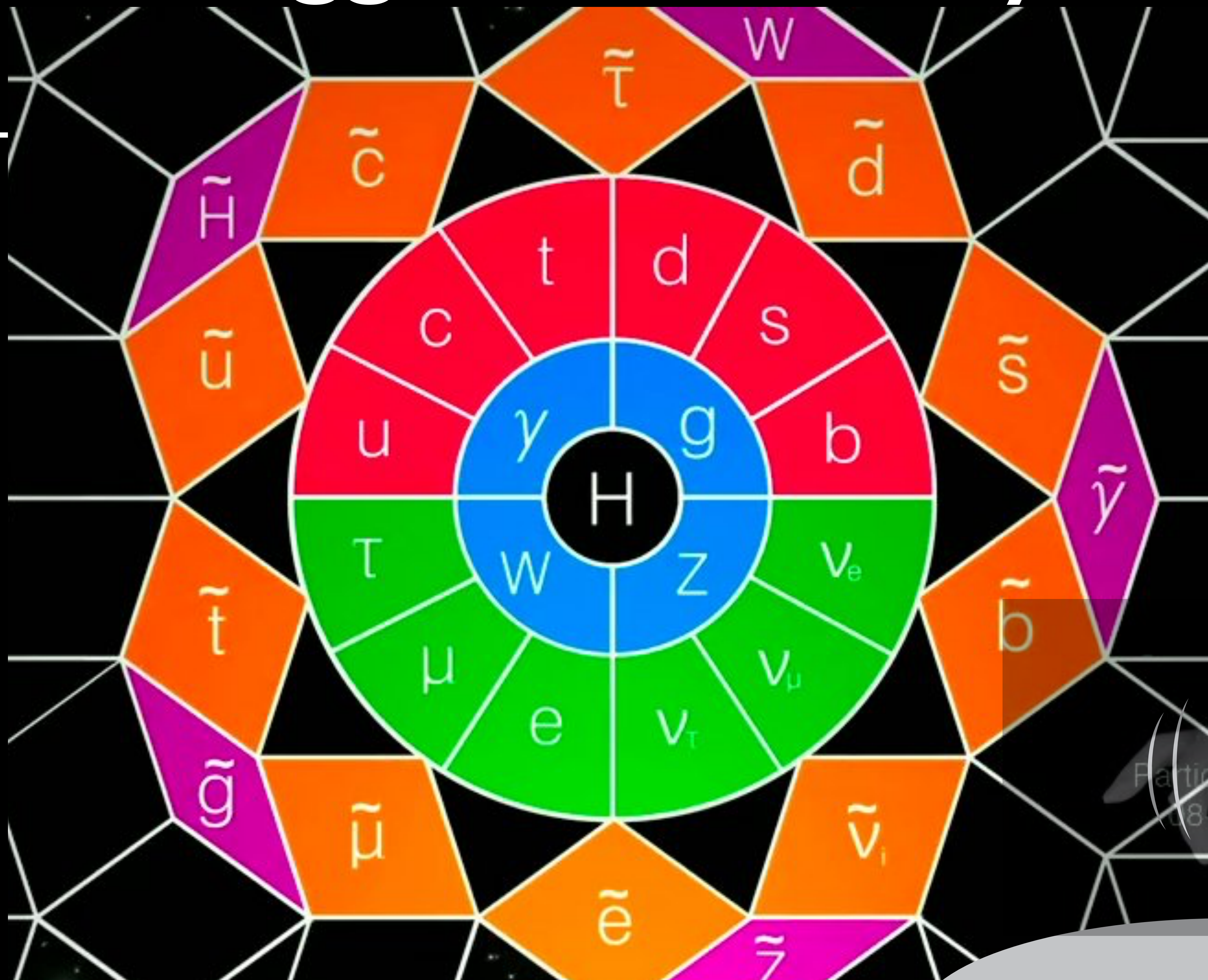
<H>=0 from gauge invariance (Elitzur)

<H†H> is not an order parameter

for m_h=126GeV, it is crossover

No phase transition in the Minimal Standard Model

Higgs is too testy



503
378
125

supersymmetry

Electron mass is natural by doubling #particles

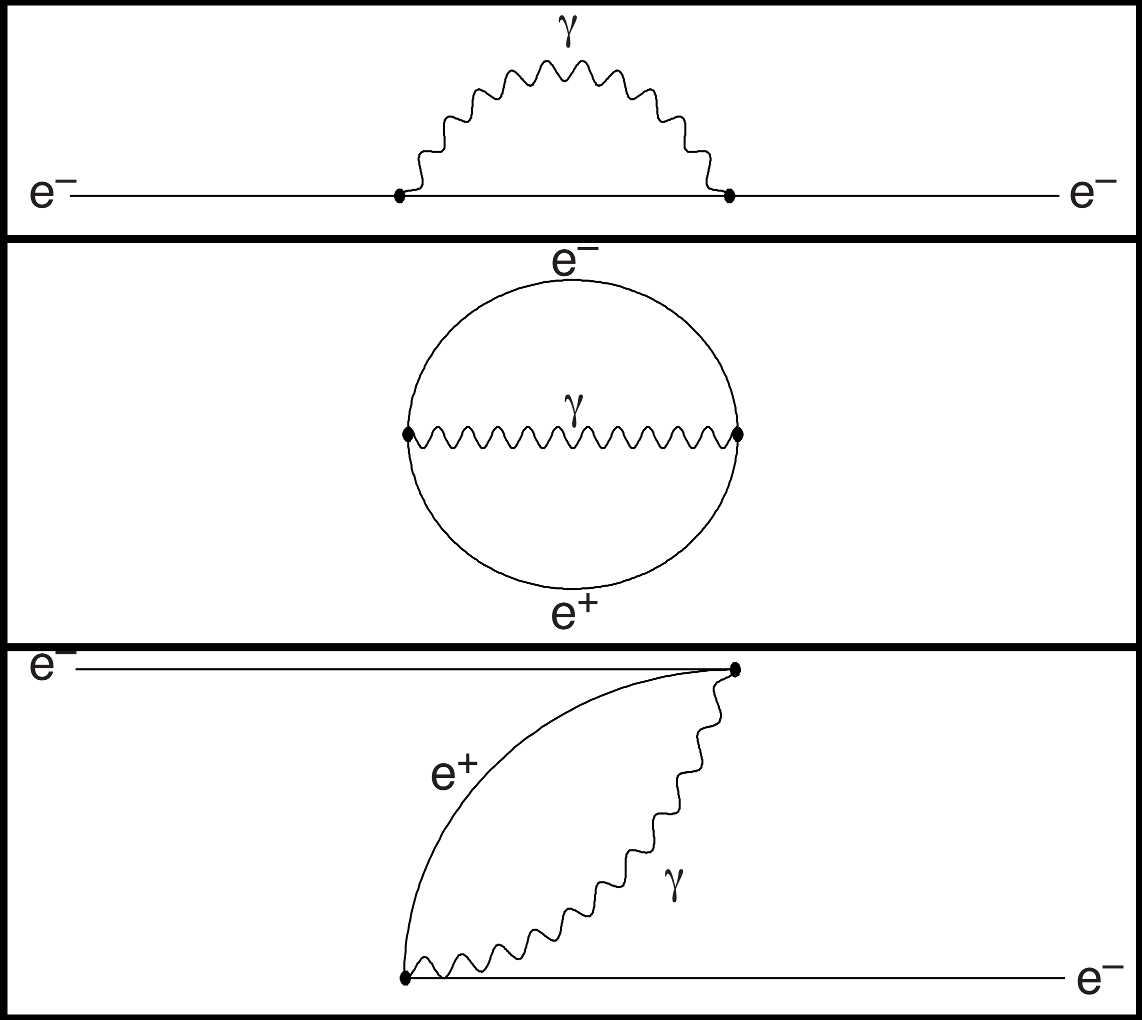
- Electron creates a force to repel itself

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \text{GeV}\frac{10^{-17}\text{cm}}{r_e}$$

- quantum mechanics and anti-matter

⇒ only 10% of mass even

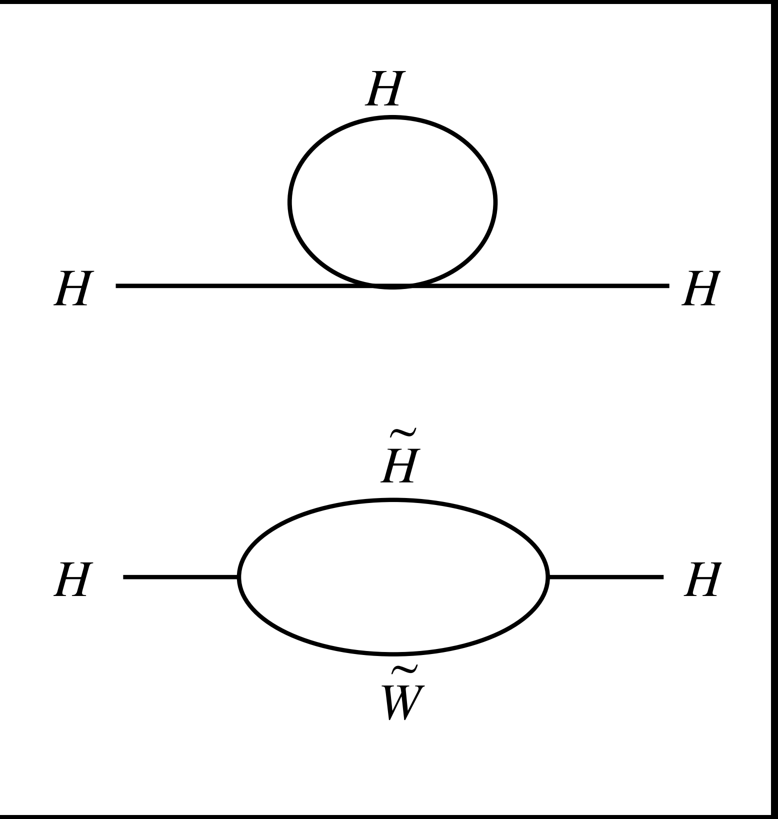
for Planck-size $r_e \sim 10^{-33}$cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs mass is natural by doubling #particles?

- Higgs also repels itself
- Double #particles again $\Rightarrow$ superpartners
- only log sensitivity to UV
- Standard Model made consistent up to higher energies

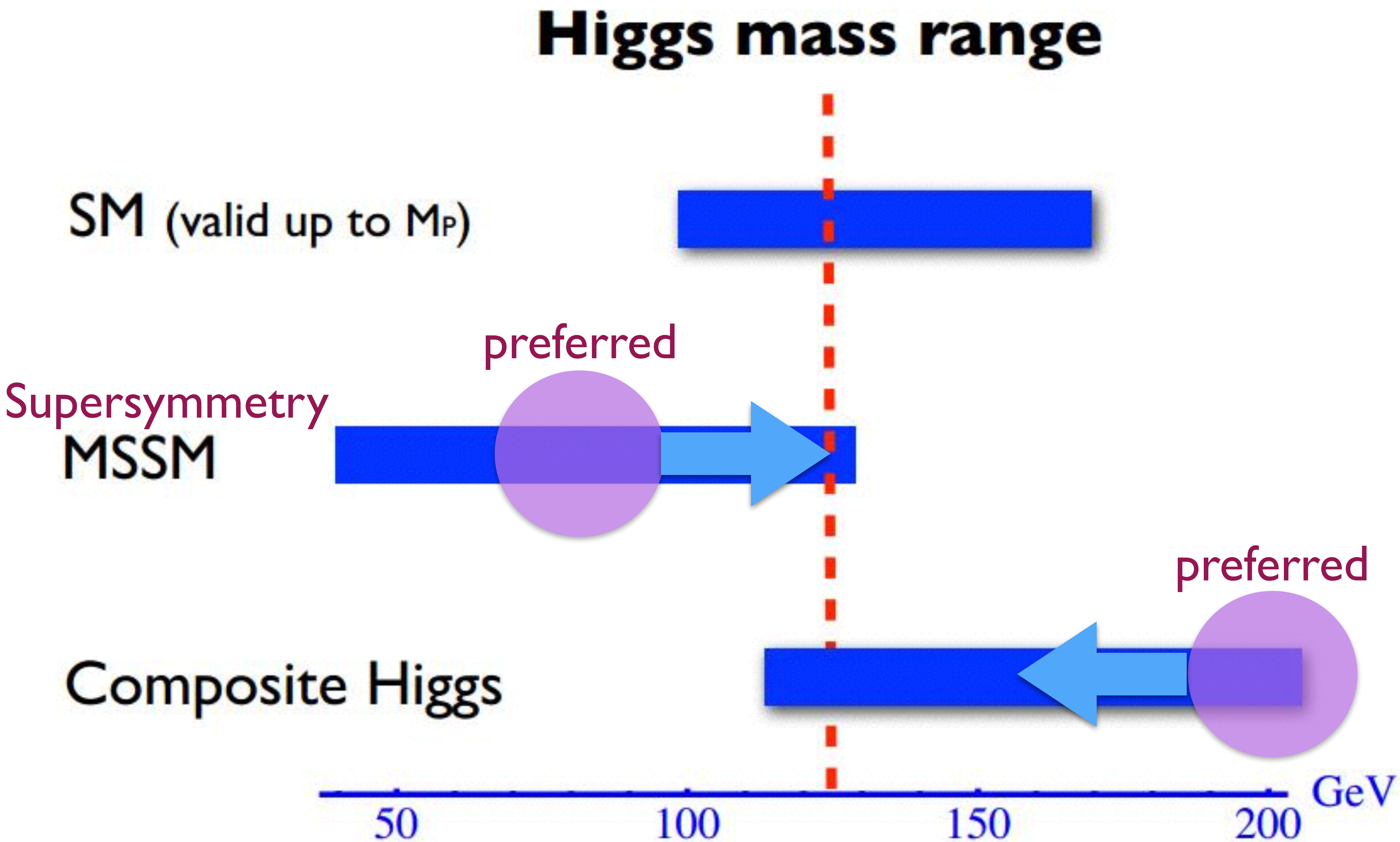


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

I still take it seriously

Scalar

- every elementary particles have spin
- electrons, photons, quarks, ...
- only Higgs boson doesn't spin
- Faceless! A *spooky particle*
- I had proposed "Higgsless theories"
- *Is it the only one?*
- *does it have siblings? relatives?*
- *Maybe it's spinning in extra dimensions?*
- *maybe composite?*
- *why did it freeze in?*

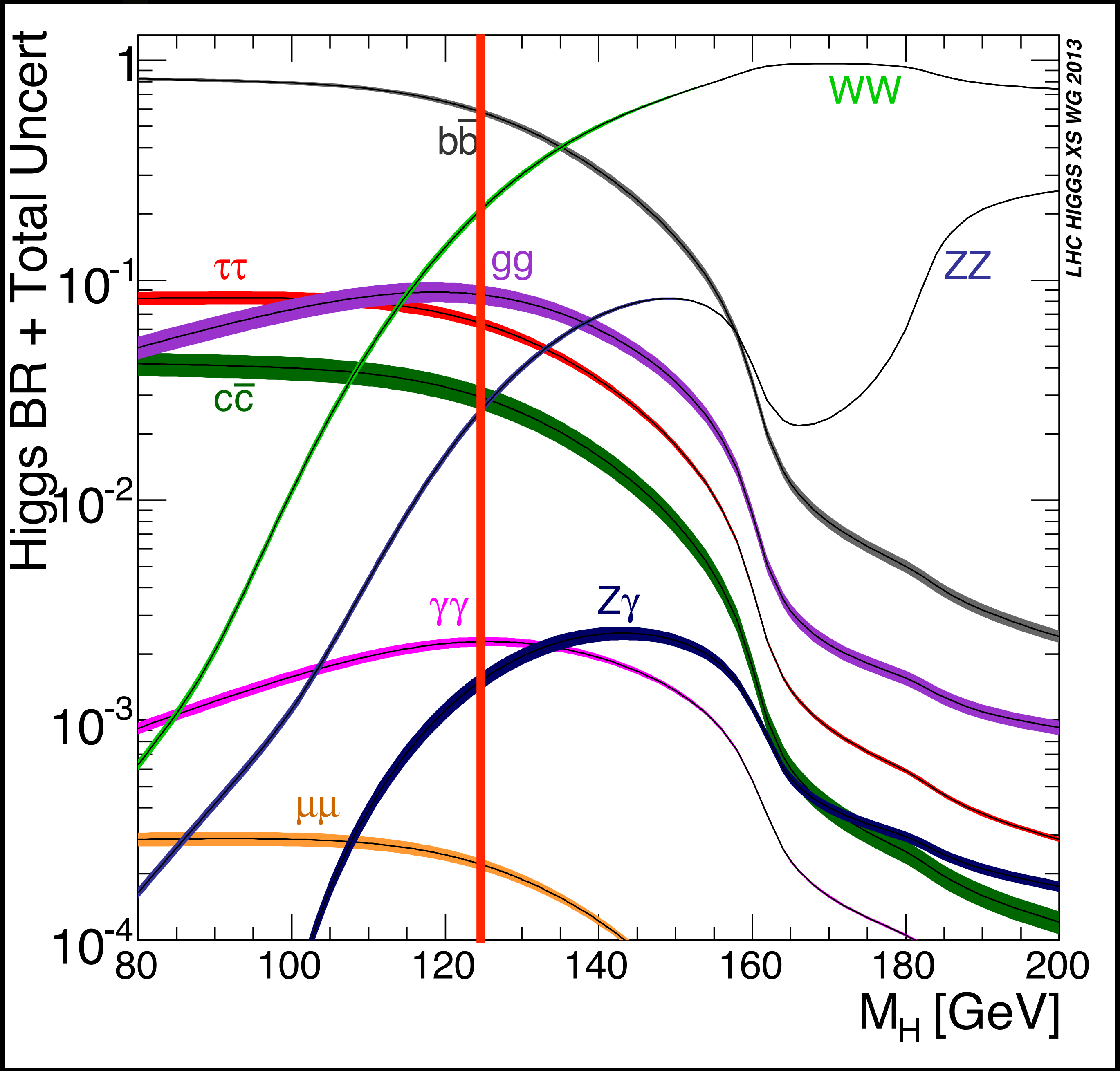

Higgs mass range
SM (valid up to MP)
preferred
Supersymmetry
MSSM
preferred
Composite Higgs
50
100
150
200
GeV

By A Pomarol

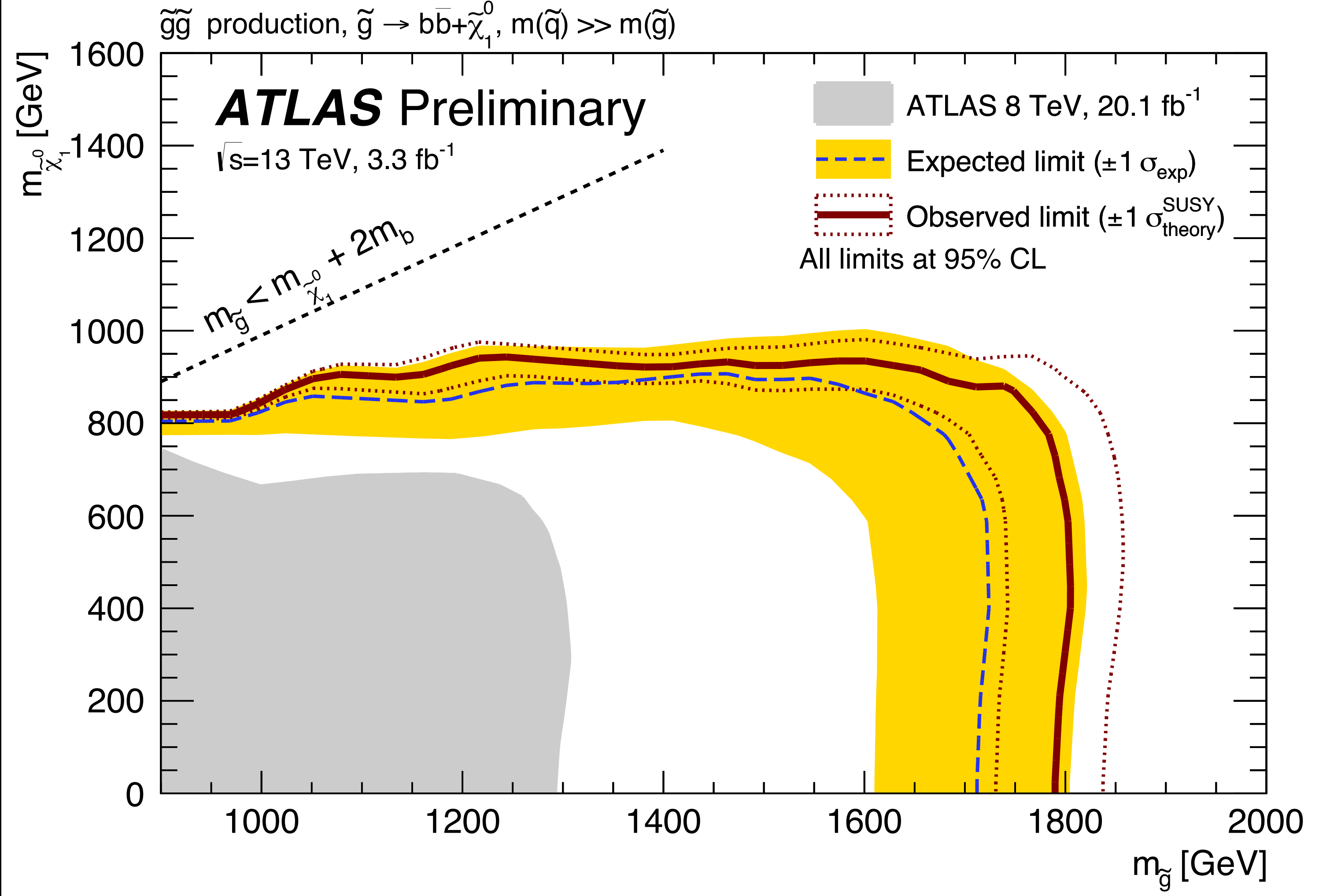
Nima's anguish

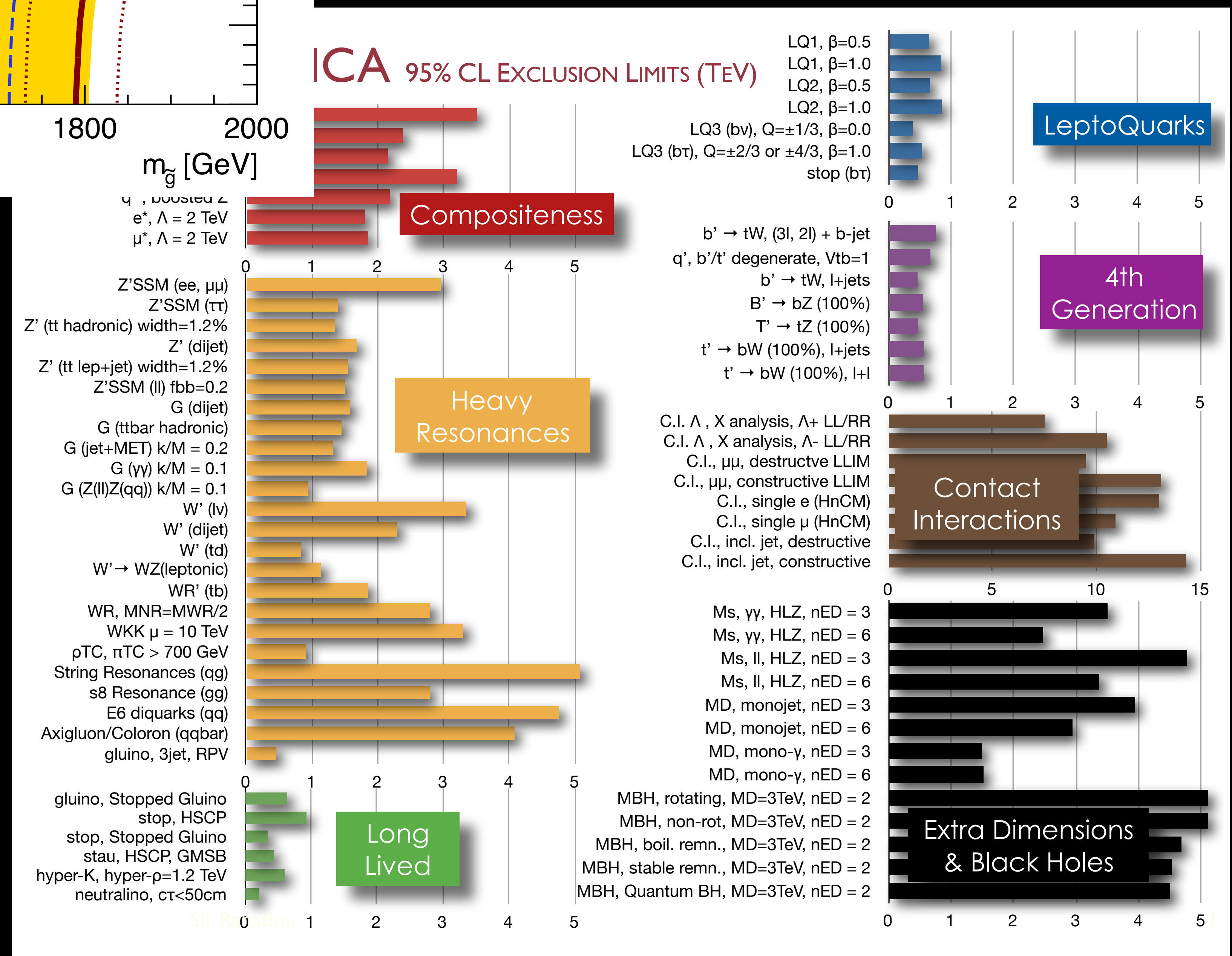
m_H=125 GeV seems almost maliciously designed to prolong the agony of BSM theorists….

dream case for experiments



stupid not to do this!





no sign of
new physics
that explains Higgs!

LHC score card

- origin of EWSB
  - Higgs discovery: but only a partial answer
- naturalness
  - None
- dark matter
  - None
- EW baryogenesis
  - No new CP violation
- unexpected
  - Perhaps??? 750 GeV diphoton???

Supersymmetry

ENGINEERING
Machines That Change Shape

MEDICINE
An Off Switch for Cancer

NEUROSCIENCE
How to Reach "Vegetative" Patients

SCIENTIFIC AMERICAN

ScientificAmerican.com

A

IF SUPERSYMMETRY

CRISIS

DOESN'T PAN OUT,

IN

SCIENTISTS NEED A NEW WAY

PHYSICS

TO EXPLAIN THE UNIVERSE

?

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The New York Times

Science

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ENVIRONMENT

315 Physicists Report Failure In Search for Supersymmetry

By MALCOLM W. BROWNE

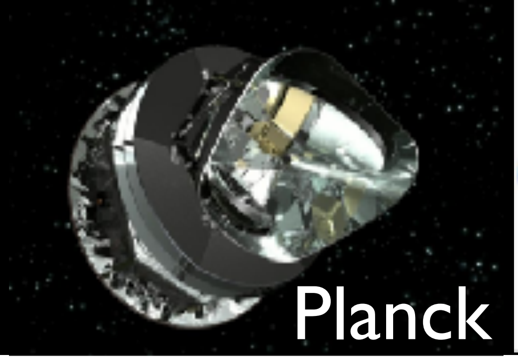
Published: January 5, 1993

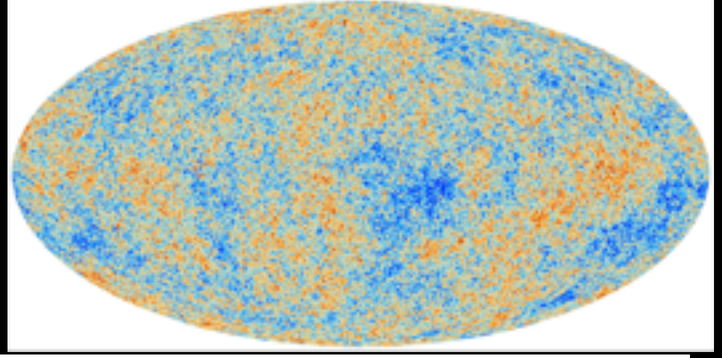
Three hundred and fifteen physicists worked on the experiment.

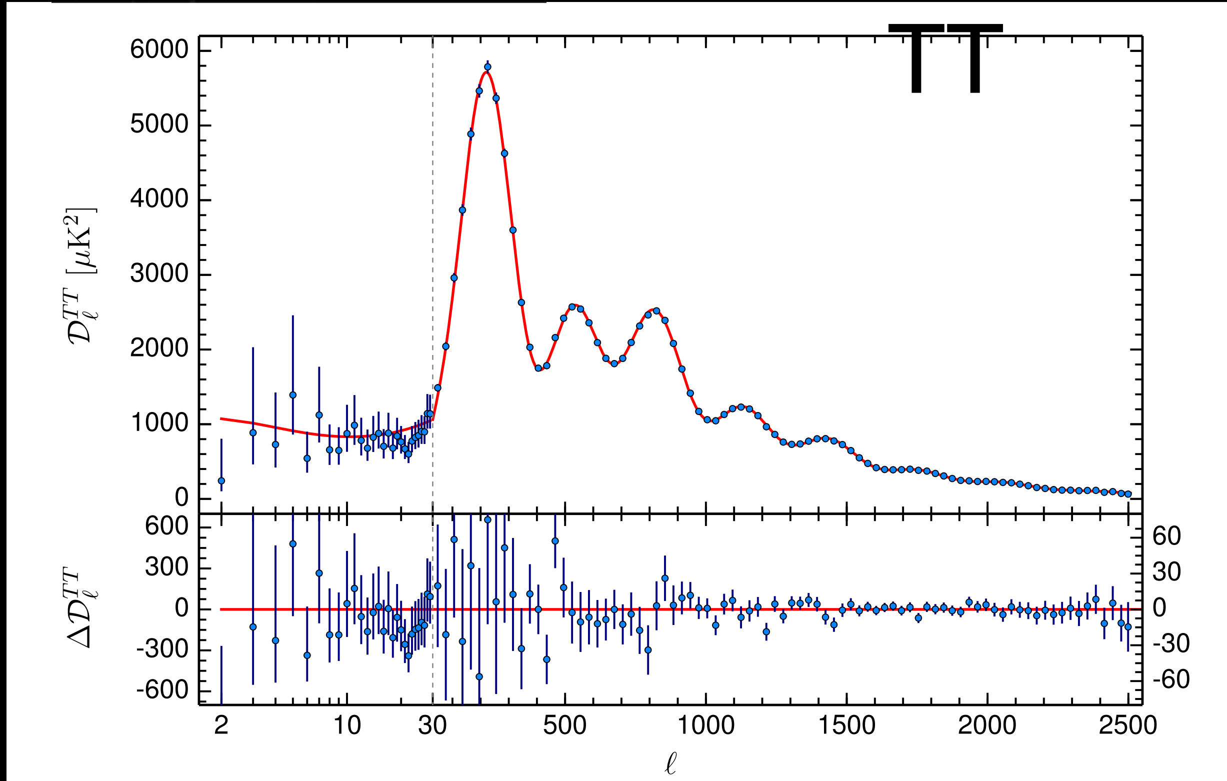
Their apparatus included the Tevatron, the world's most powerful

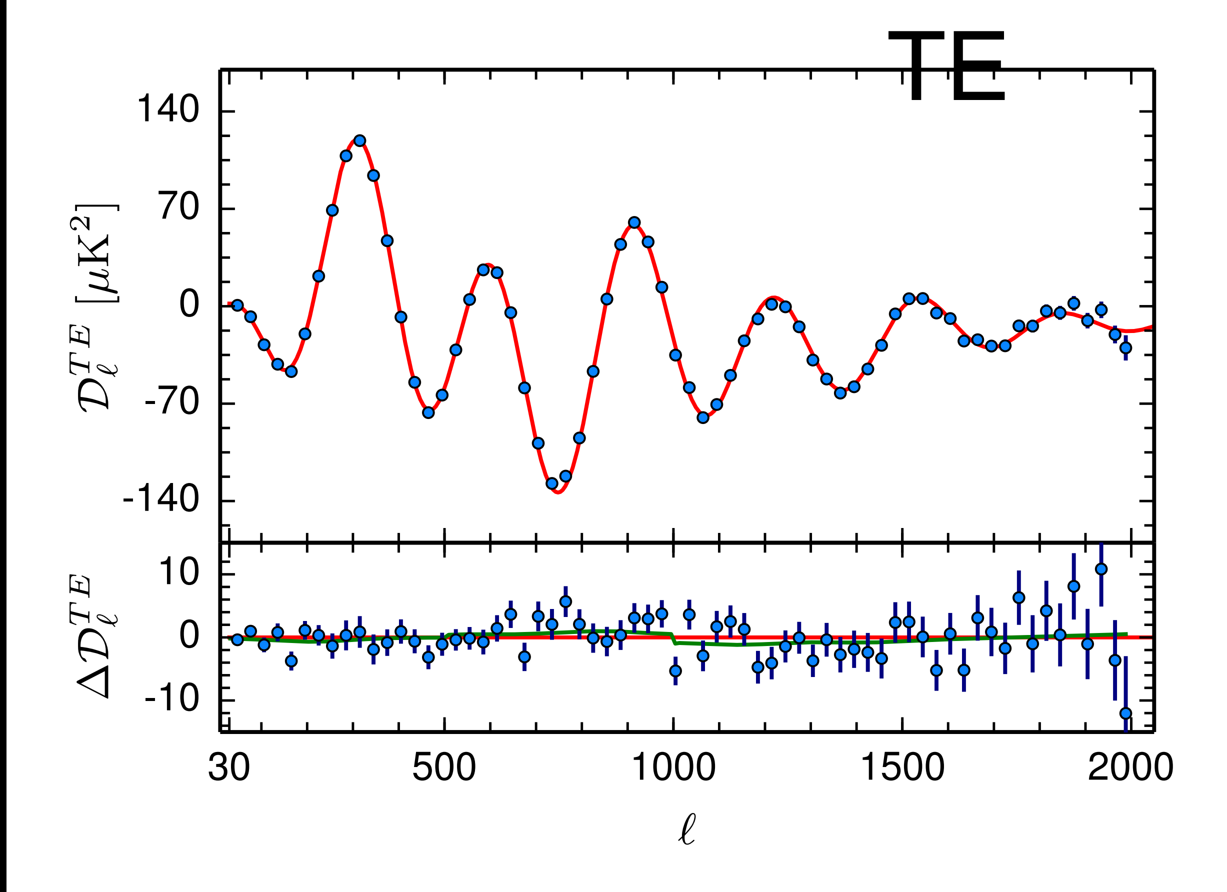
Naturalness works!

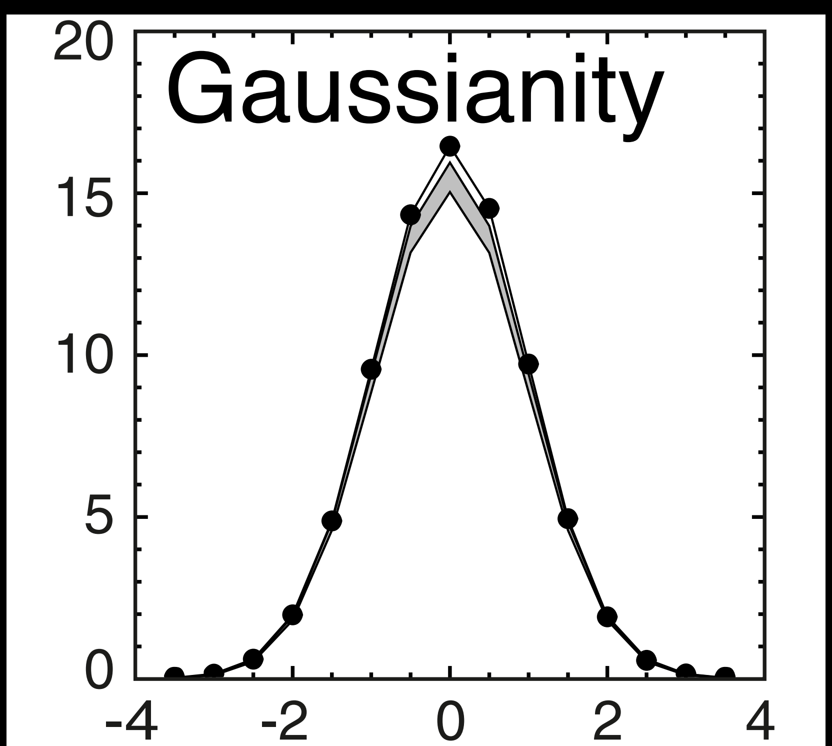
- Why is the Universe big?
- Inflation
  - horizon problem
  - flatness problem
  - large entropy







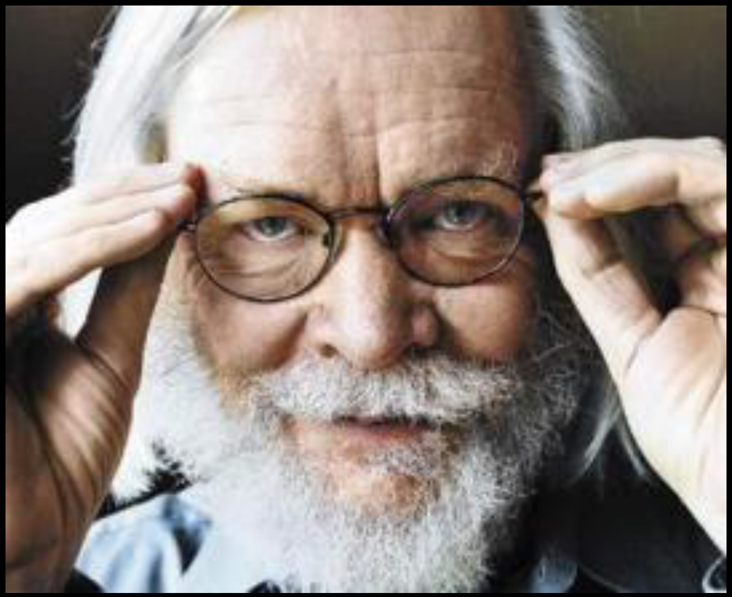




scalar top mass ≥ 10 TeV preferred

Giudice and Strumia, arXiv:1108.6077

assumption: MSSM

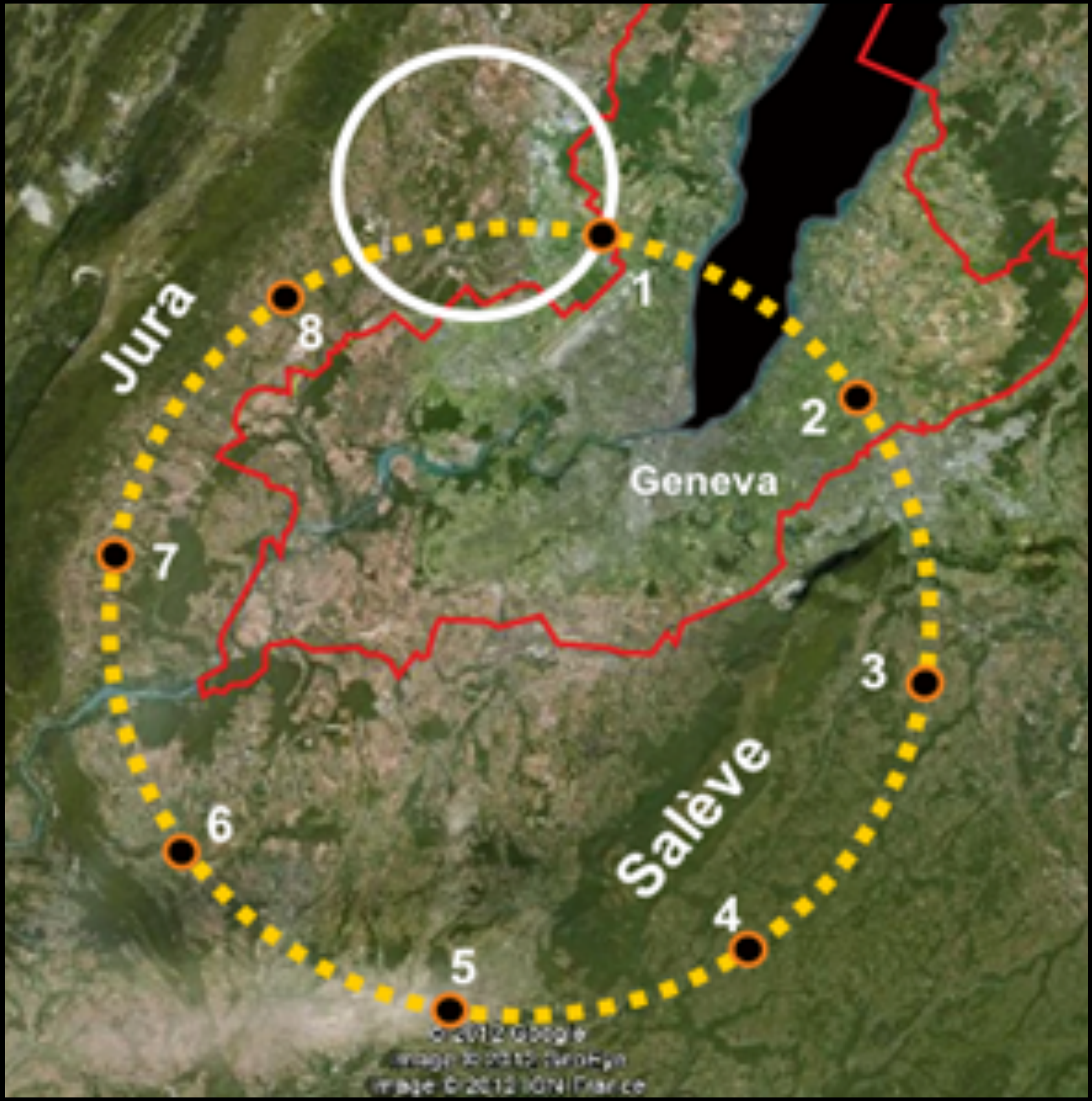


Better Late Than Never

Even m_{SUSY}~10 TeV ameliorates fine-tuning from 10^{-36} to 10^{-4}

higher energies?

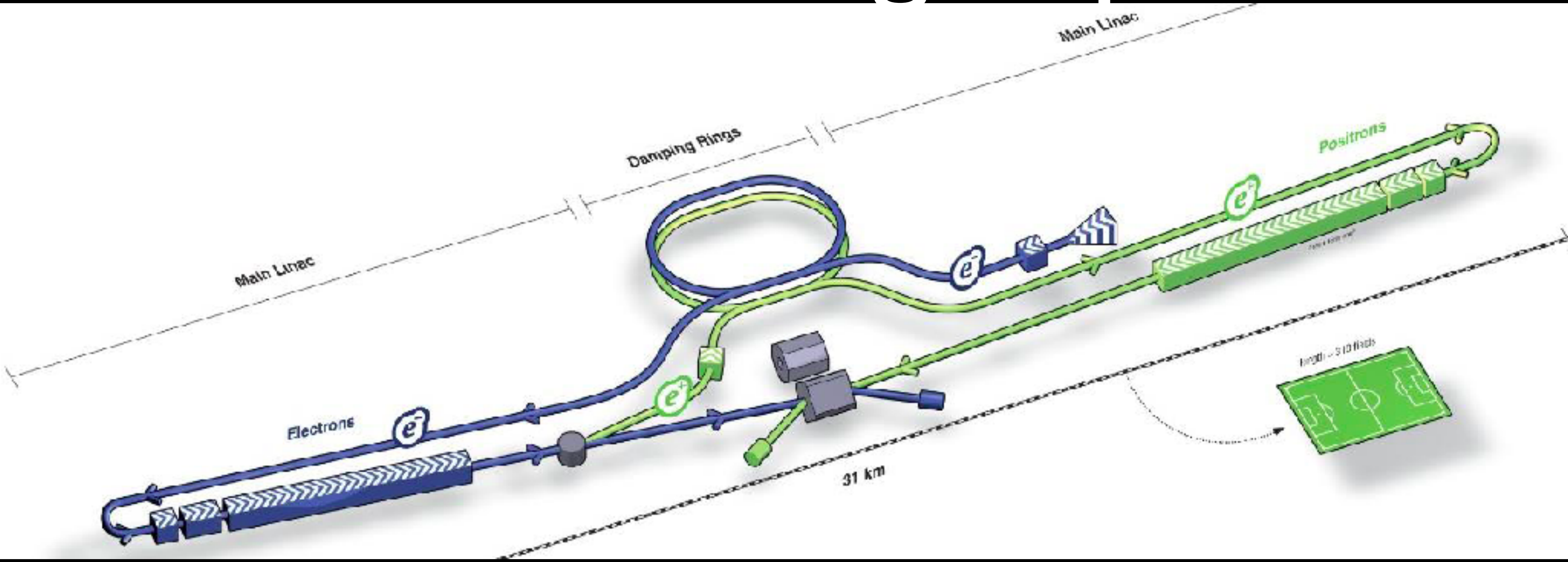
- Need to explore
- HL-LHC boosts reach
- We believe we should keep aiming at higher energies
- HE-LHC?
- *100 TeV pp would be great!*
- Need to continue magnet R&D
- Possible first stage: FCCee from m_Z upto 365 GeV



History of Colliders

1. precision measurements of neutral current (*i.e.* polarized e+d) predicted m_W, m_Z
2. UA1/UA2 discovered *W*/*Z* particles
3. LEP *nailed* the gauge sector
1. precision measurements of *W* and *Z* (*i.e.* LEP + Tevatron) predicted m_H
2. LHC discovered *a Higgs particle*
3. LC *nails* the Higgs sector?
1. precision measurements at LC predict ???

Another staged path

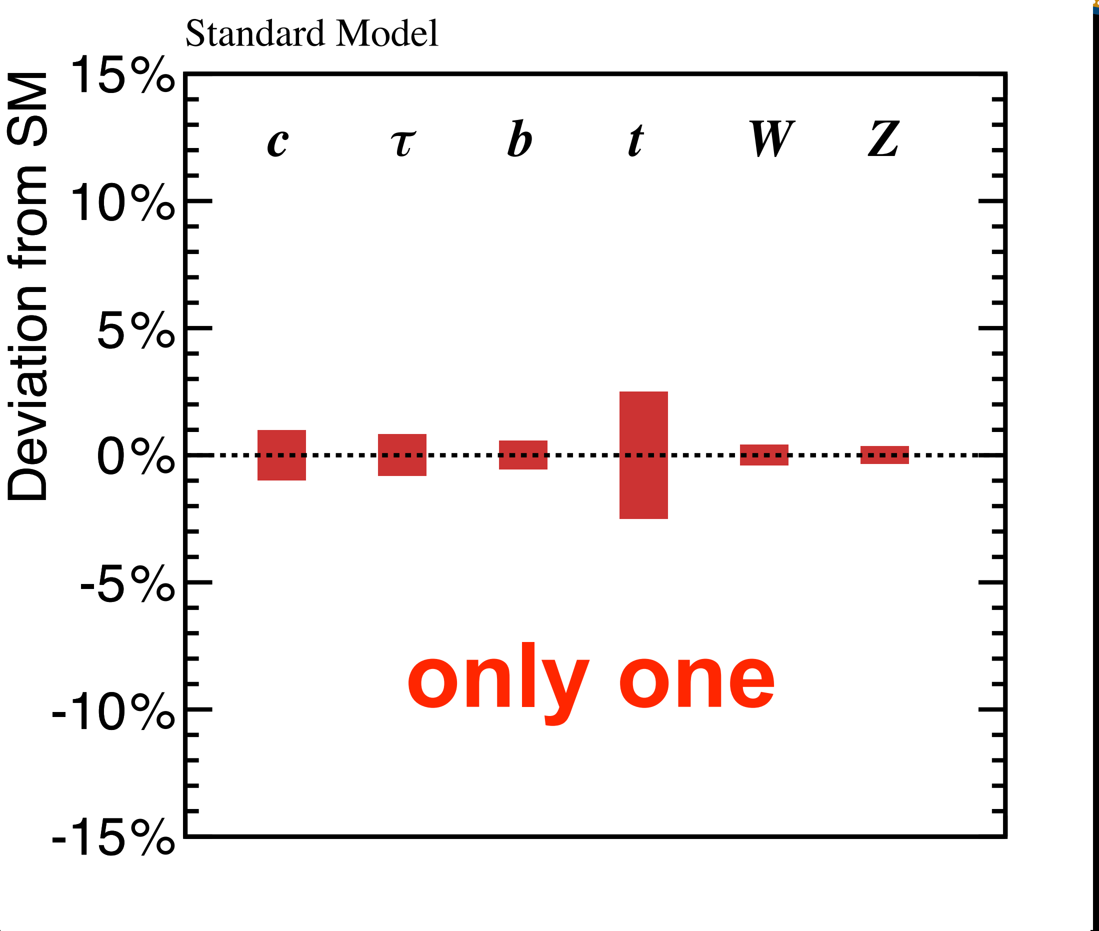


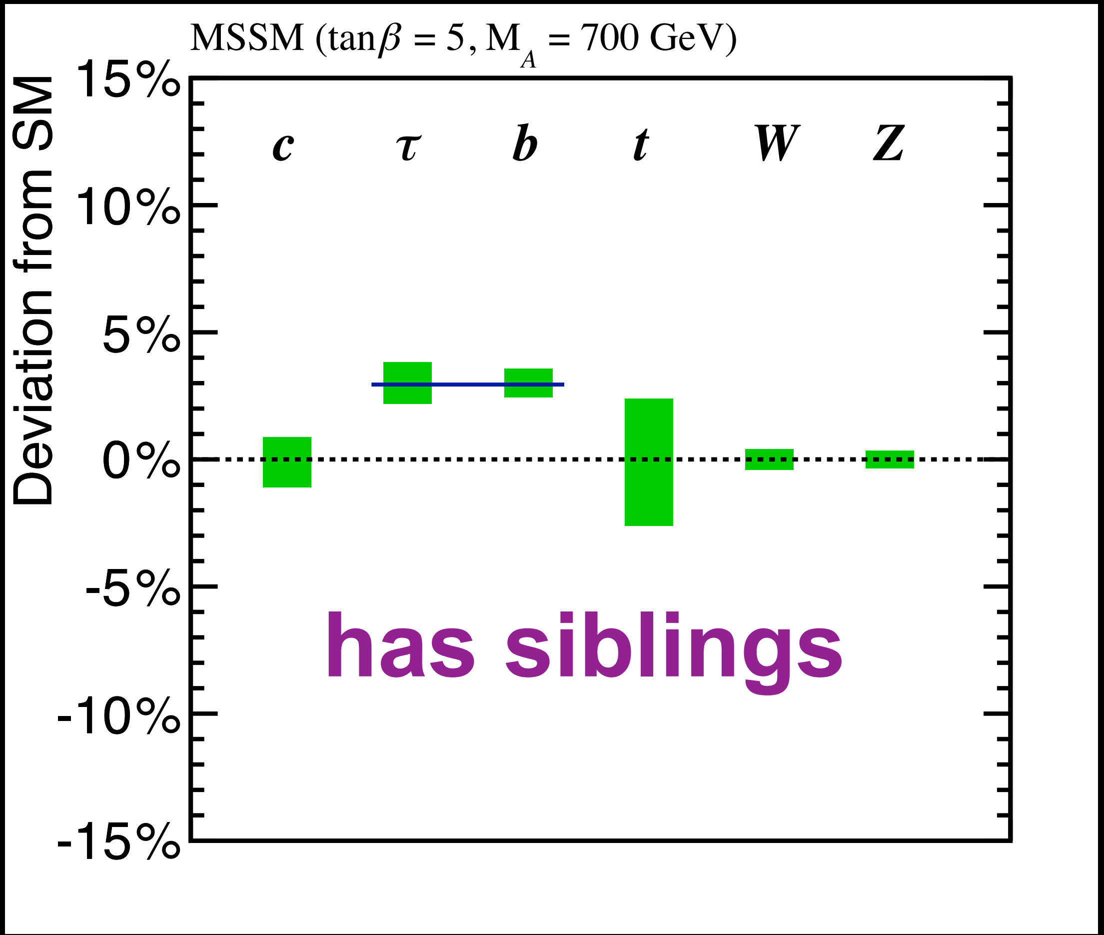
- Start with 250 GeV
- guaranteed precision Higgs and top physics
- extendable 500 GeV to 1 TeV
- TDR exists

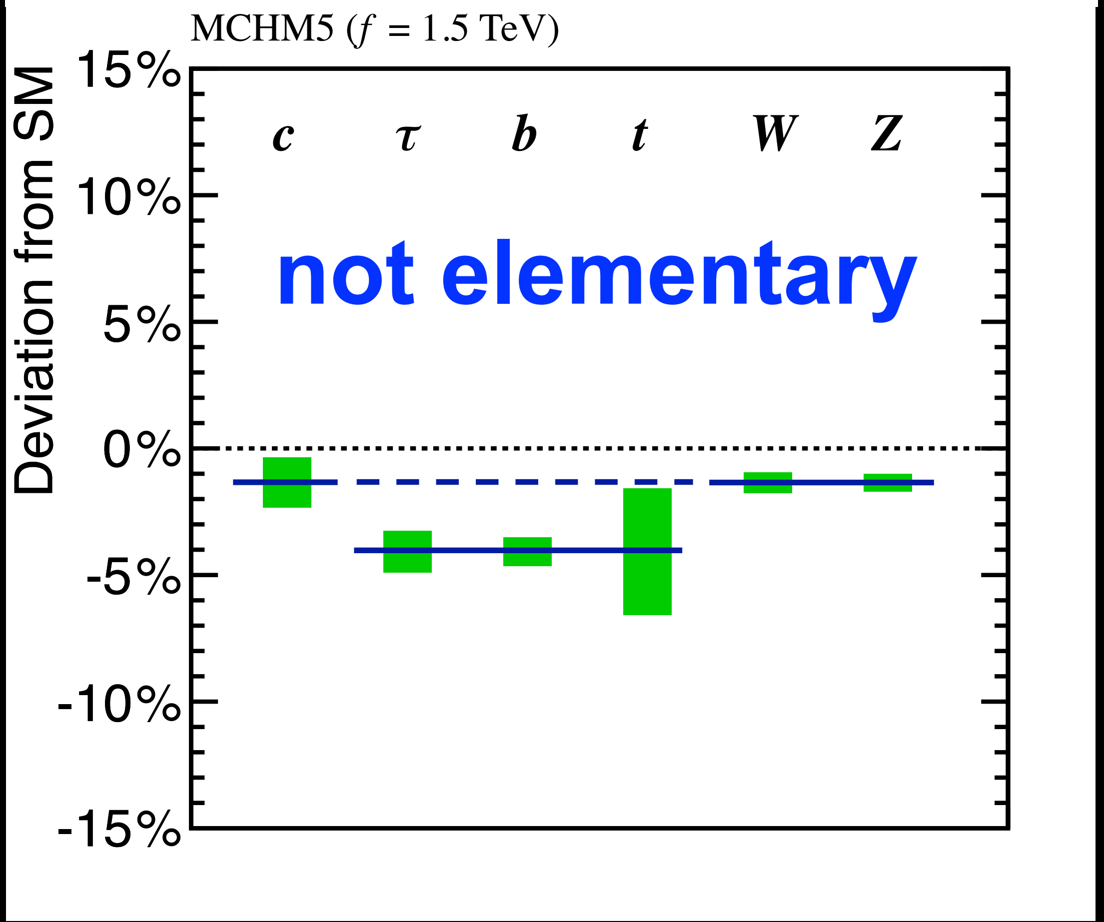
What is Higgs really?

Only one? (SM)
has siblings? (2DHM)
not elementary?

Lumi 1920 fb-1, sqrt(s) = 250 GeV
Lumi 2670 fb-1, sqrt(s) = 500 GeV







Higgs as a portal

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors"

$SU(3)_C xSU(2)_L xU(1)_Y$

hidden sector — Higgs sector — quarks leptons

$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

Twin Higgs

- Take two mirror copies of the SM:

$$(SM_A) \times (SM_B)$$

$\mathbb{Z}_2$ An exchange symmetry. $A \leftrightarrow B$.

- Assume Higgs potential has an SU(4) or SO(8) global symmetry in the UV.

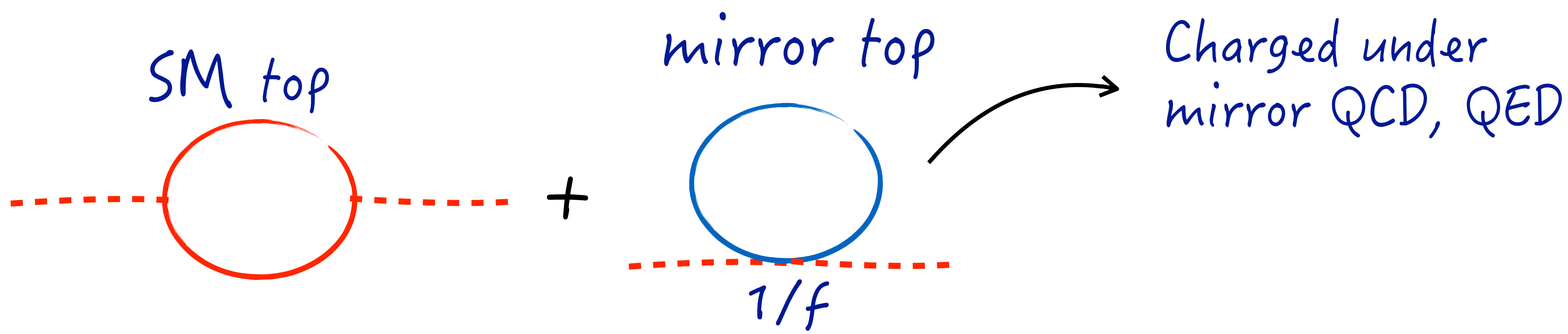
- Take a small hierarchy of Higgs vevs:

$$\langle H_A \rangle = v \qquad \langle H_B \rangle = f \qquad \text{with } v < f.$$

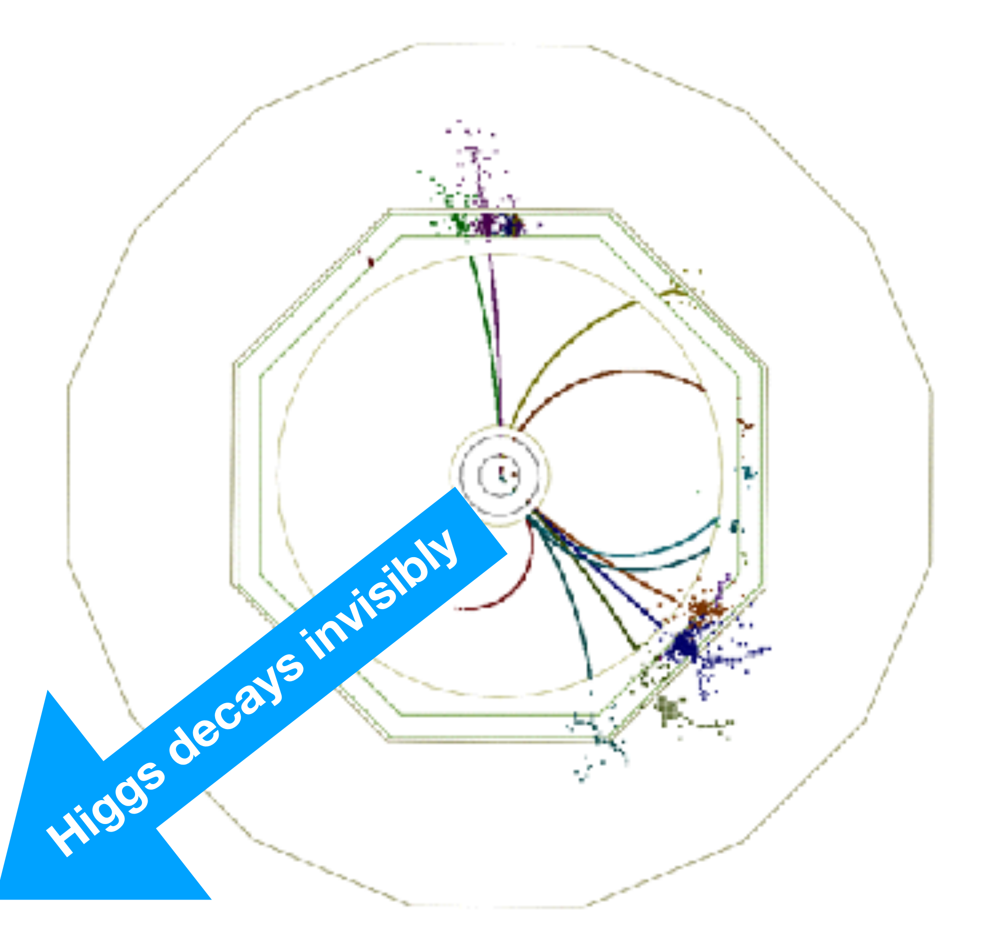
Chacko, Goh, RH (2005)

Twin Higgs

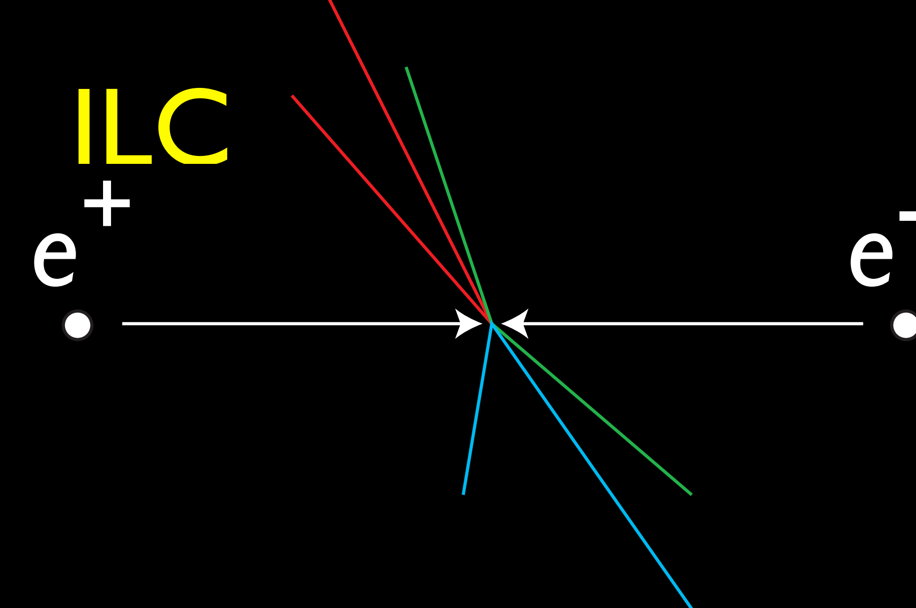
- All NP within LHC reach is SM neutral.
- PNGB Higgs, cancelation ...



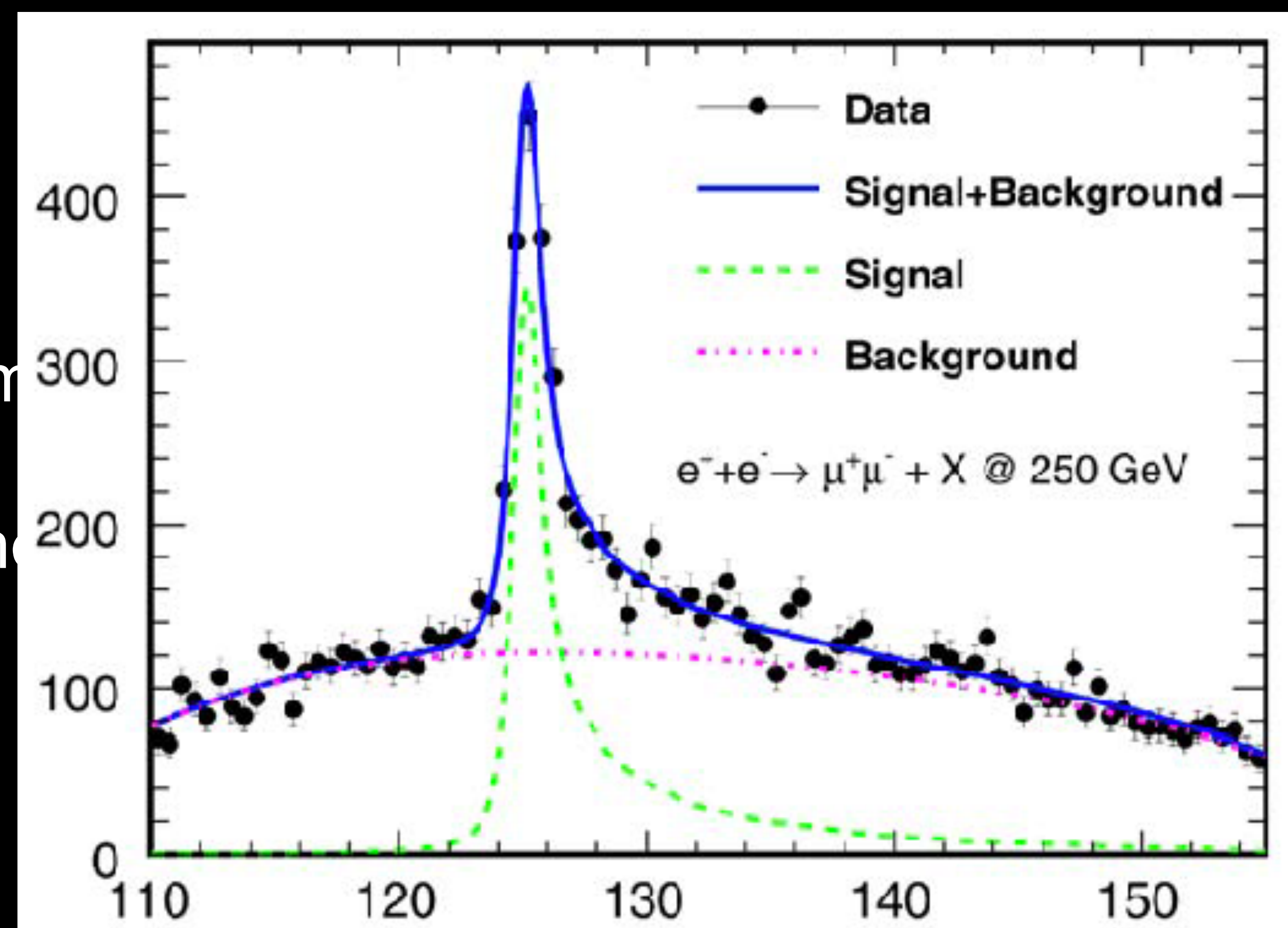
Roni Harnik and Zackaria Chacko, JHU workshop 2017 in Budapest



holistic

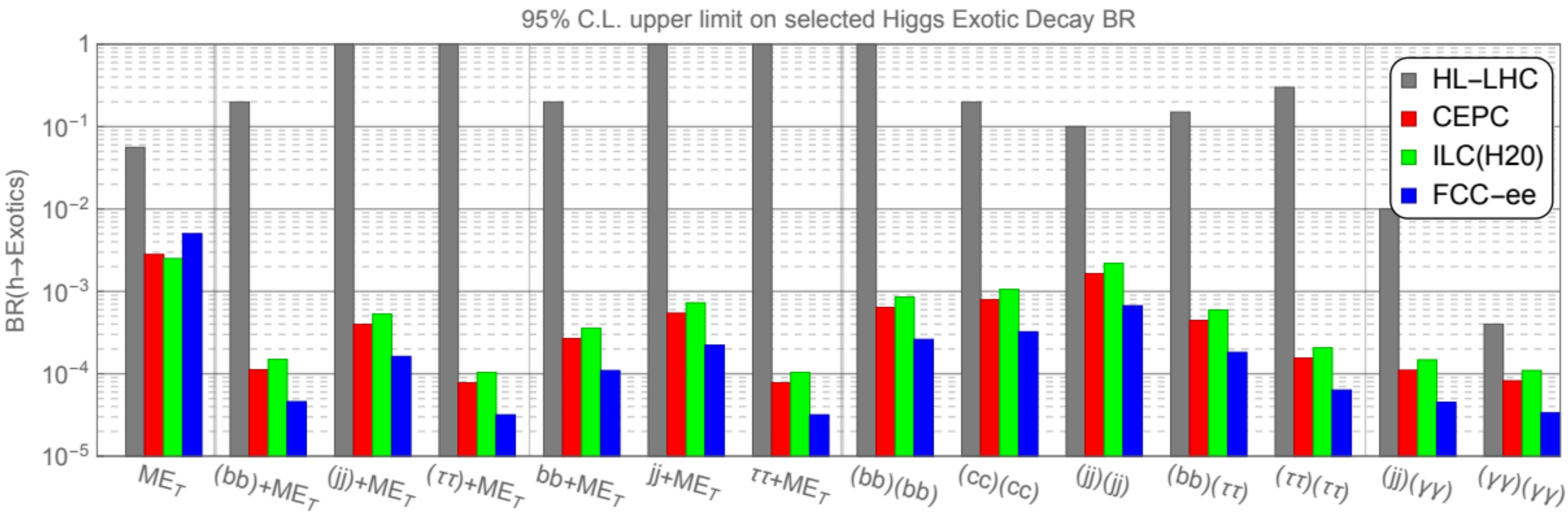


$$m^2_{\text{recoil}} = m^2_Z + s - 2\sqrt{s}E_Z$$



- Fully exploit energy-momentum conservation
- Don't lose information along the beam line
- Can use all final states
- Can "see" invisible states
- holistic use of all information

Higgs exotic decay



Complementary to hadron collider searches

Liantao Wang, GRC 2019

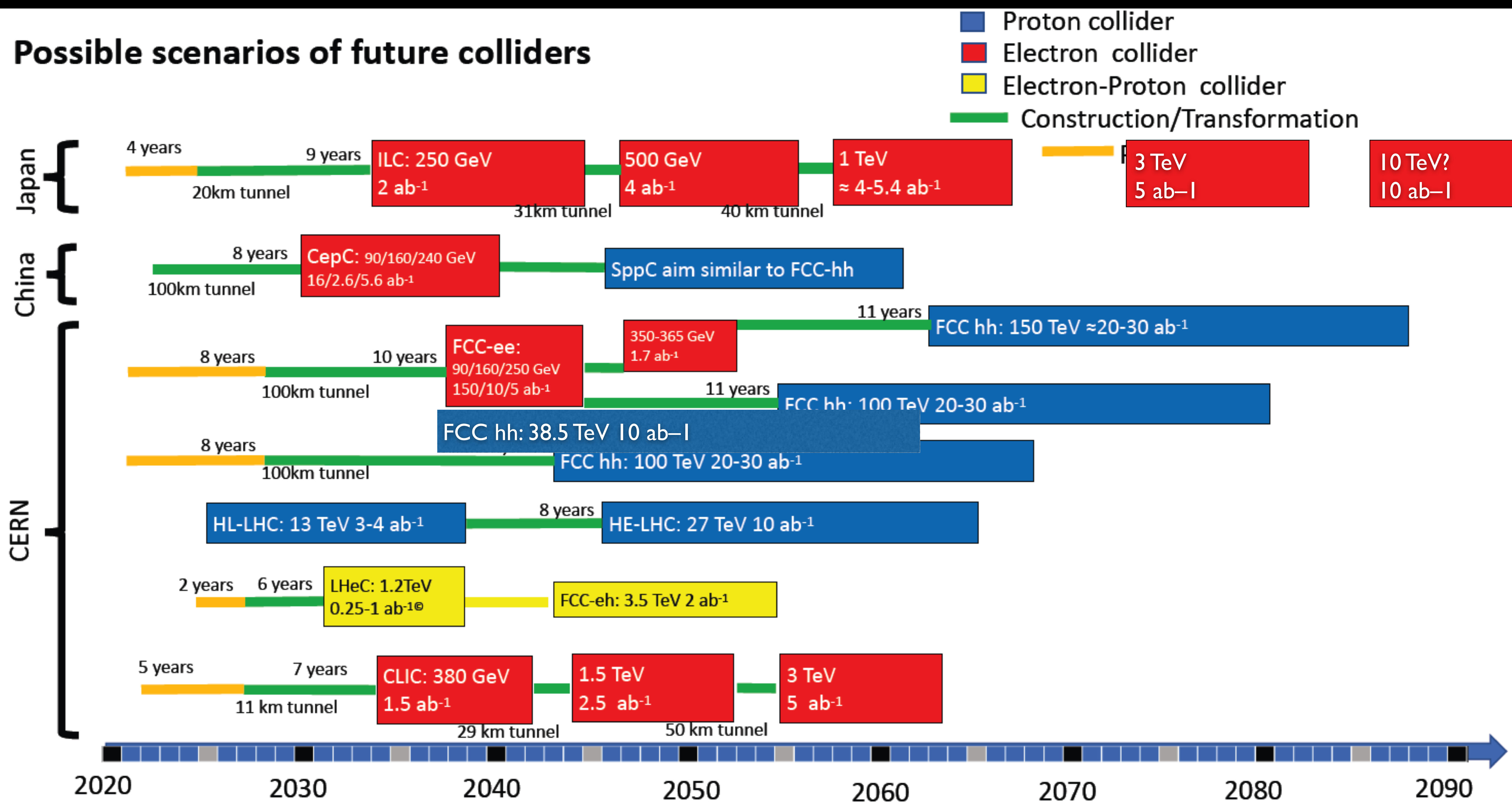
Timelines

Akira Yamamoto
@ Granada

Personal View on Relative Timelines

Timeline	~ 5	~ 10	~ 15	~ 20	~ 25	~ 30	~ 35
Lepton Colliders							
SRF-LC/CC	Proto/pre-series	Construction		Operation		Upgrade	
NRF—LC	Proto/pre-series	Construction		Operation		Upgrade	
Hadron Collier (CC)							
8~(11)T NbTi /(Nb3Sn)	Proto/pre-series	Construction		Operation			Upgrade
12~14T Nb_3Sn	Short-model R&D	Proto/Pre-series		Construction		Operation	
14~16T Nb_3Sn	Short-model R&D		Prototype/Pre-series			Construction	

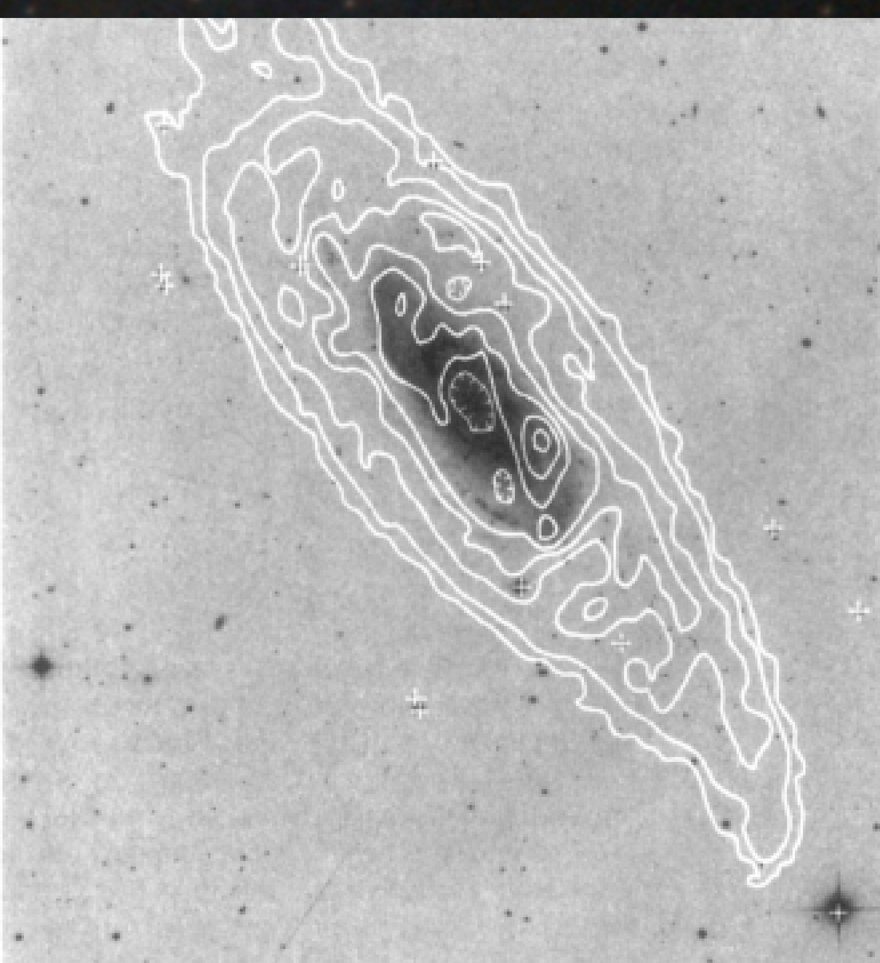
Possible scenarios of future colliders

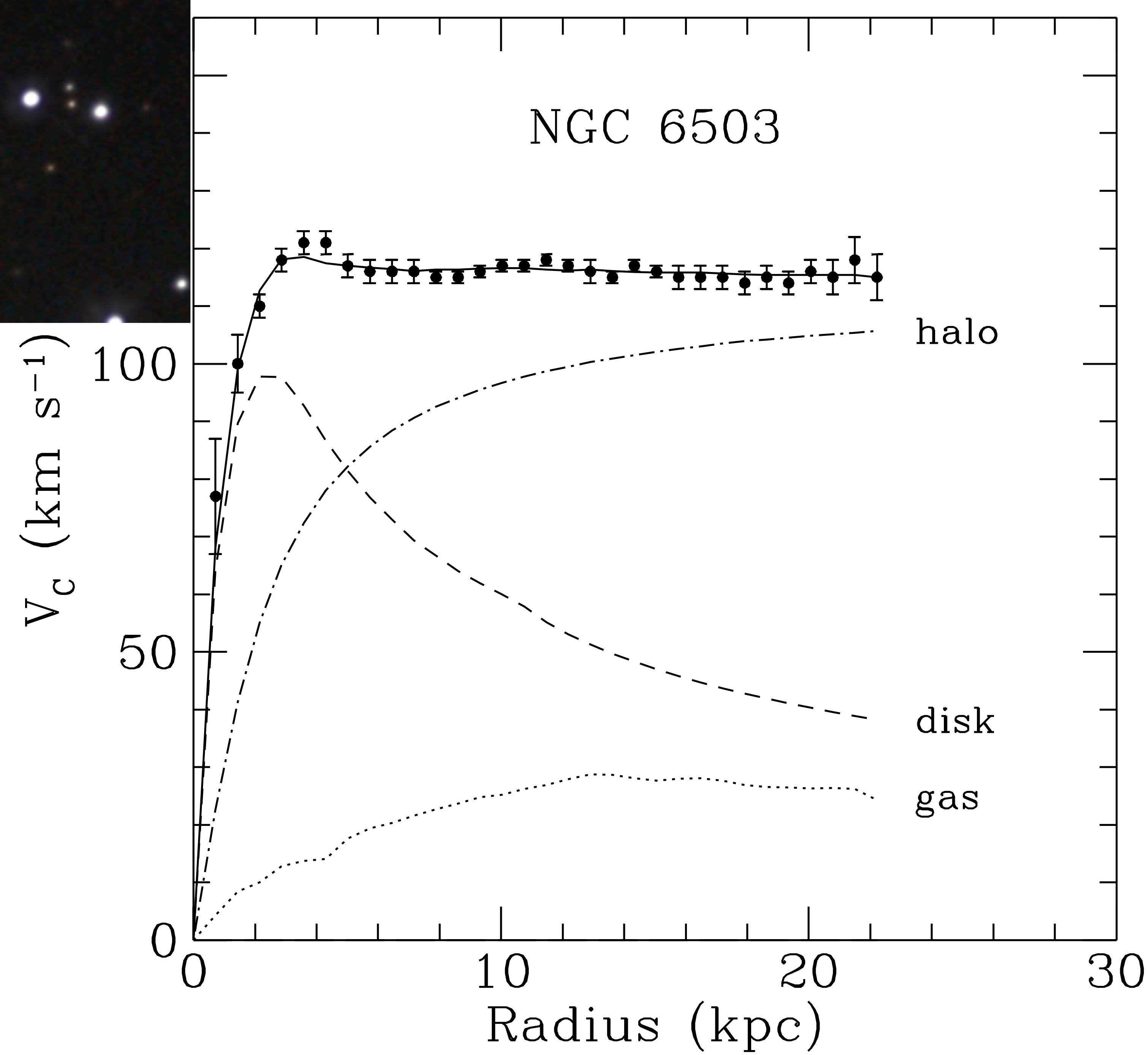


Ursula Bassler @ Granada

Multiverse

Dark Matter




NGC 6503
Vc (km s−1)
Radius (kpc)
0
10
20
30
0
50
100
halo
disk
gas

cluster of galaxies

Abell 2218
2.1B lyrs

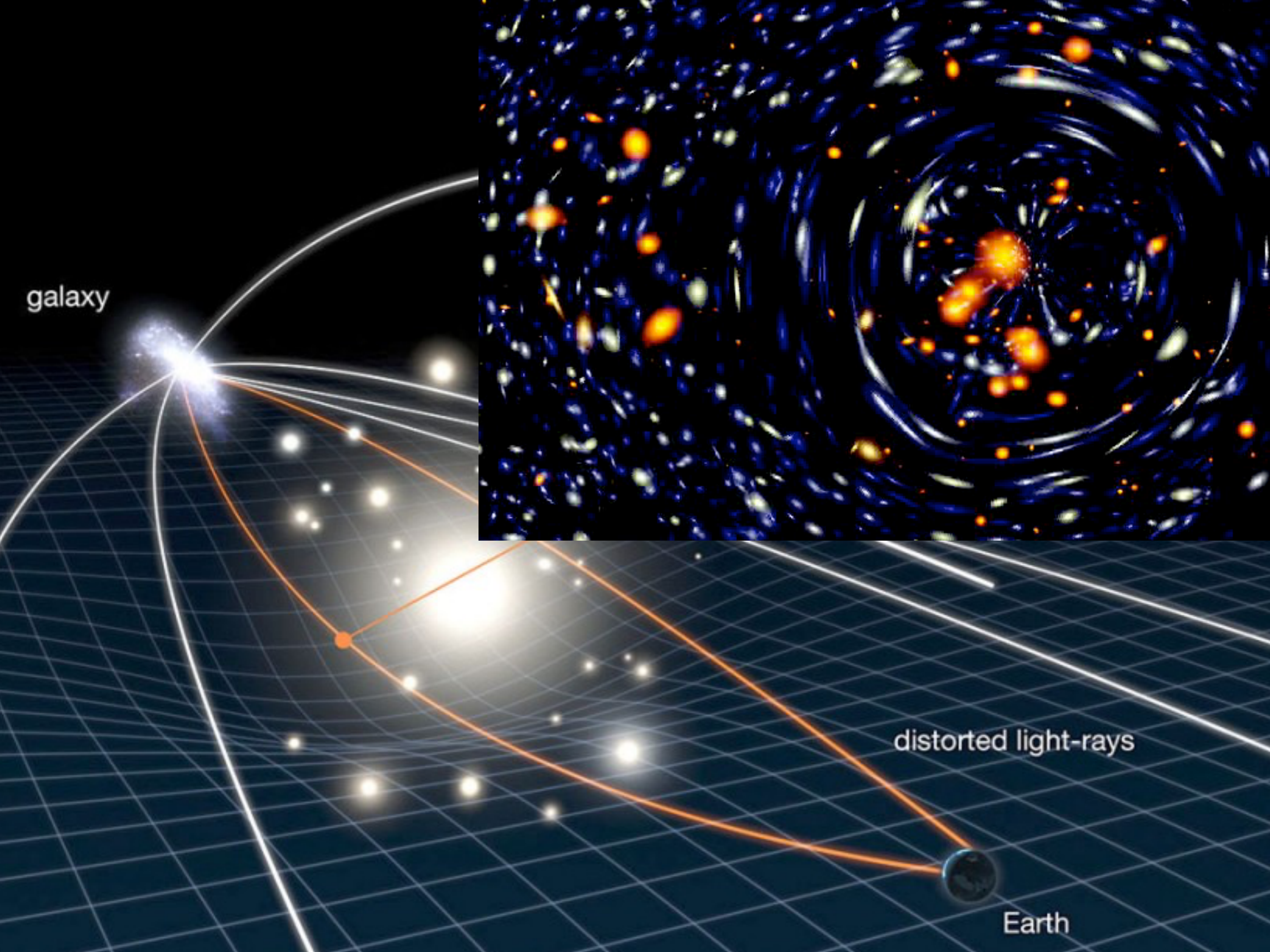
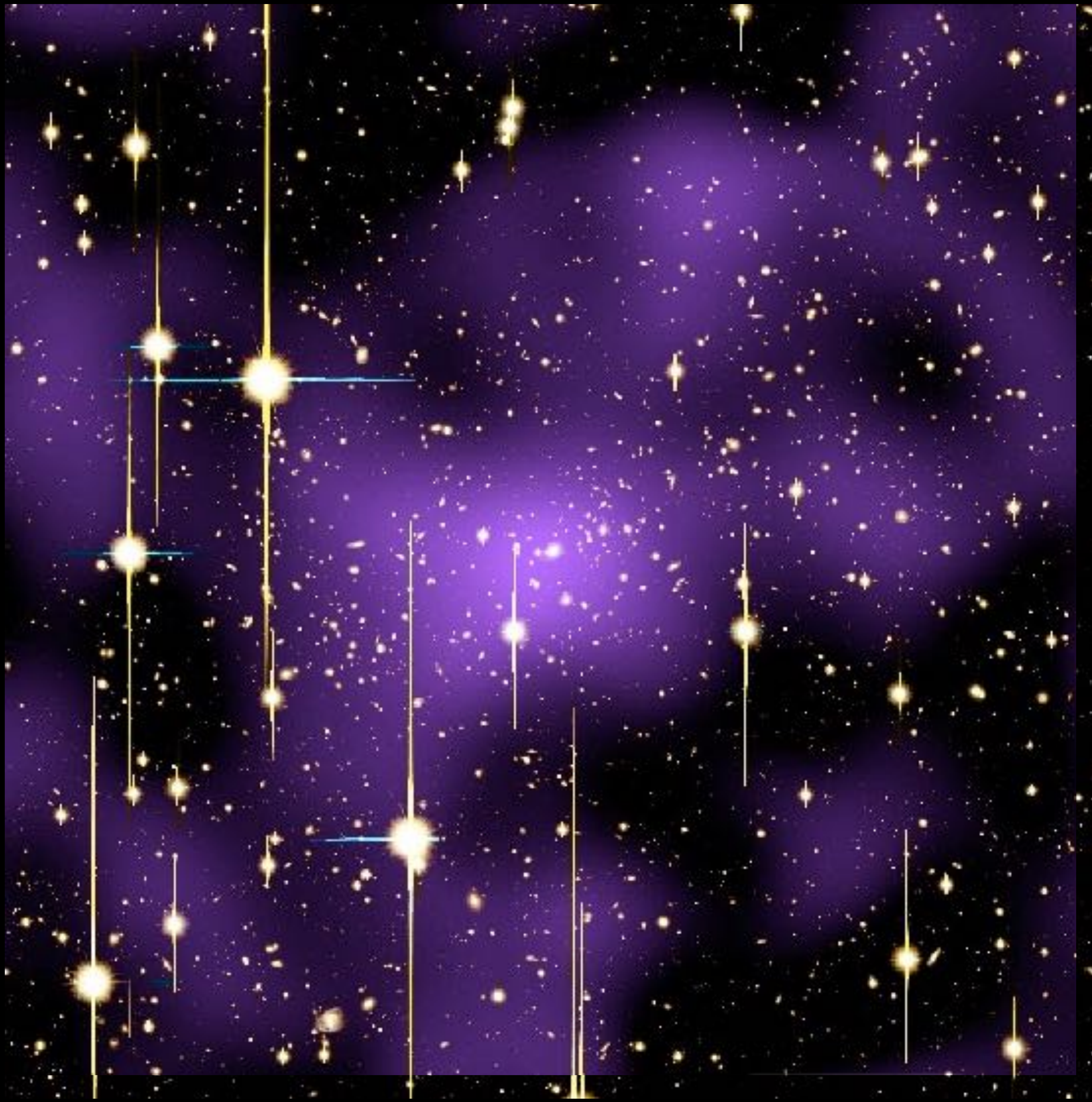
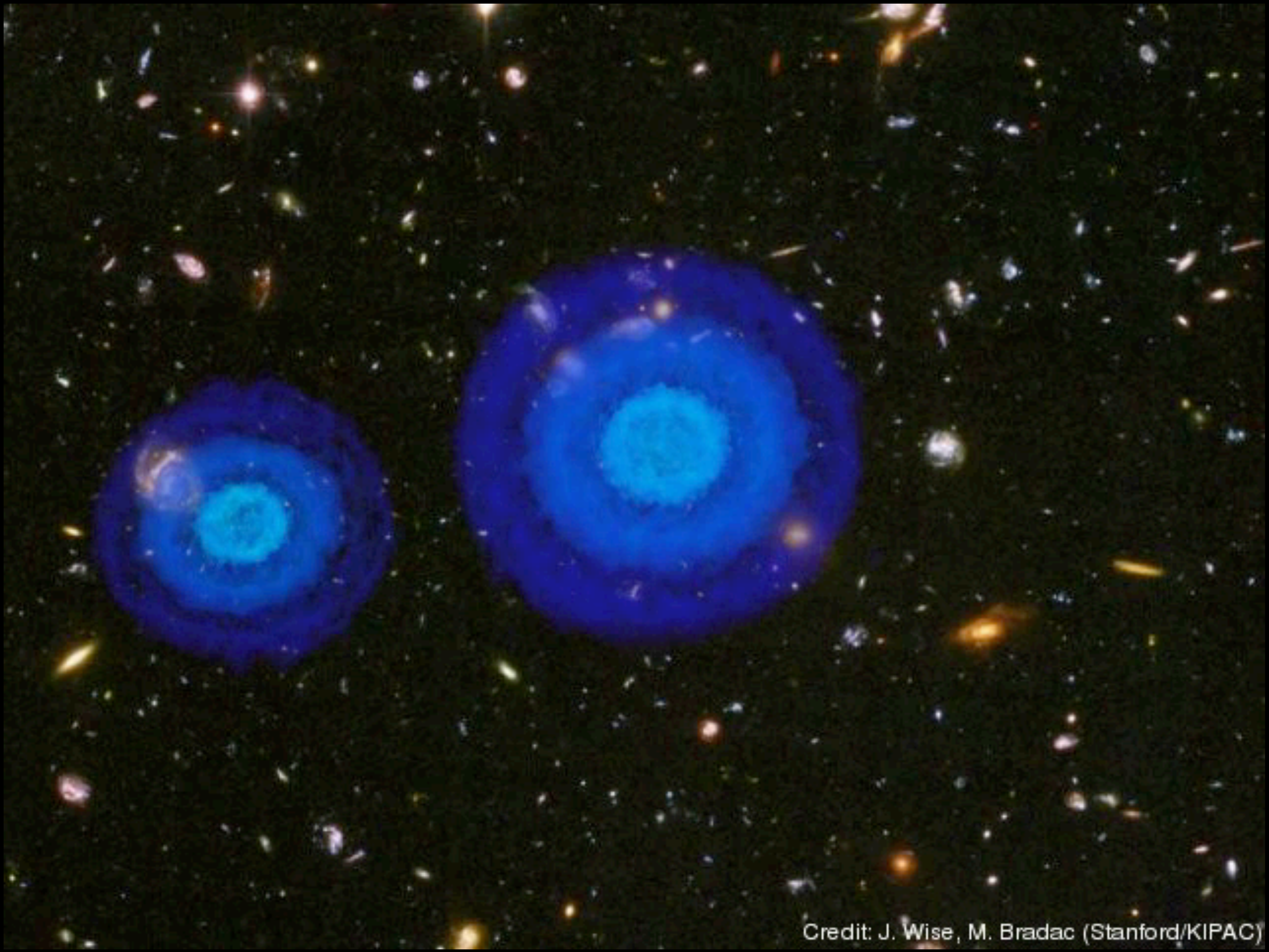

galaxy
distorted light-rays
Earth

image invisible dark matter



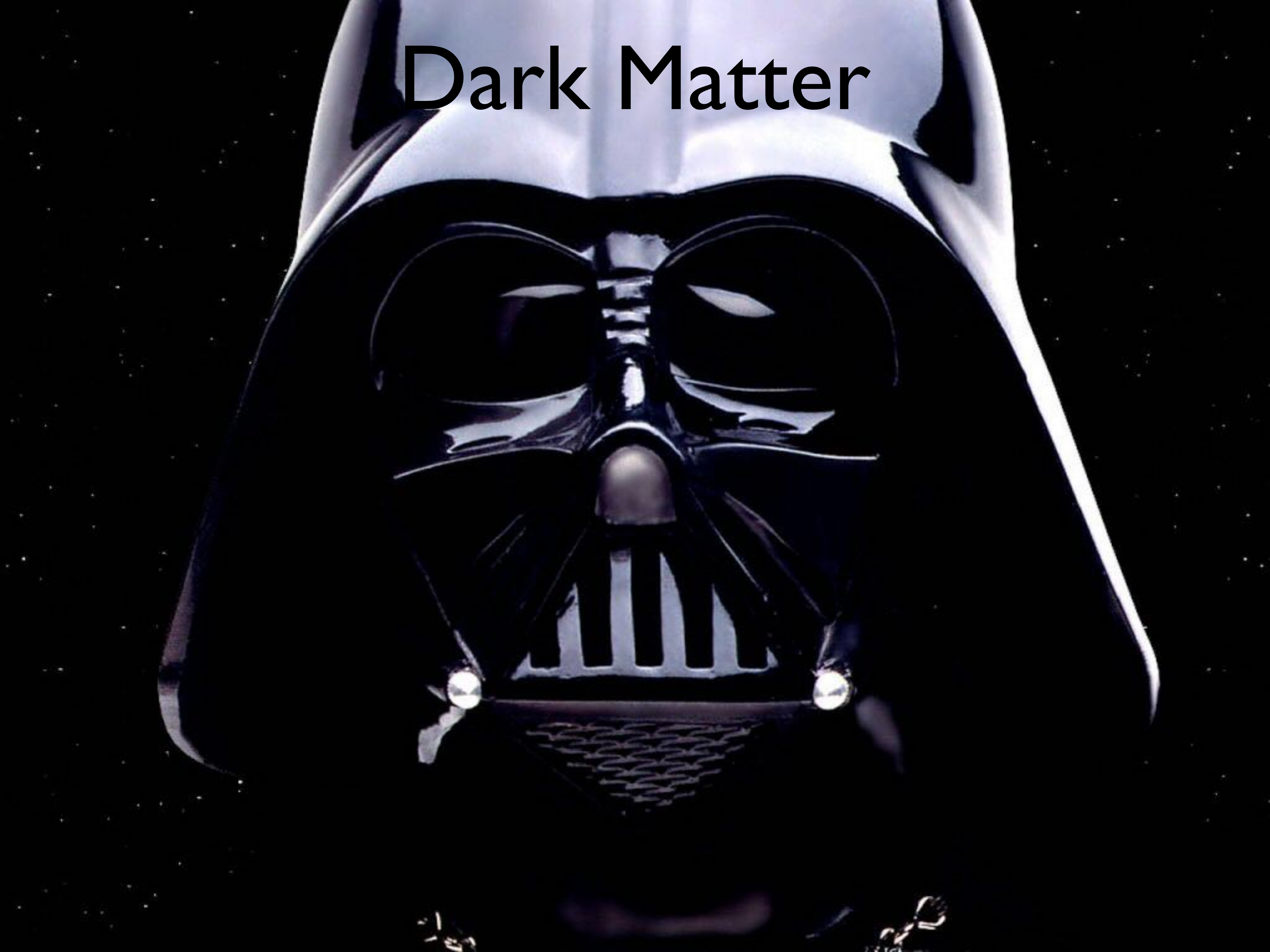
more than 80% of matter in the Universe is not atoms

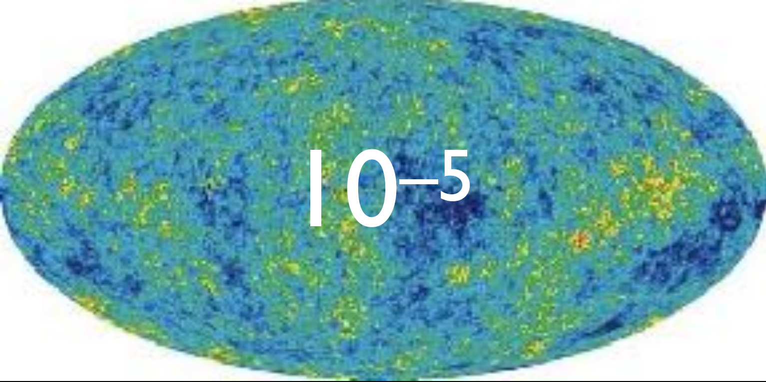


two clusters collided at 4500km/sec

4B lyrs away

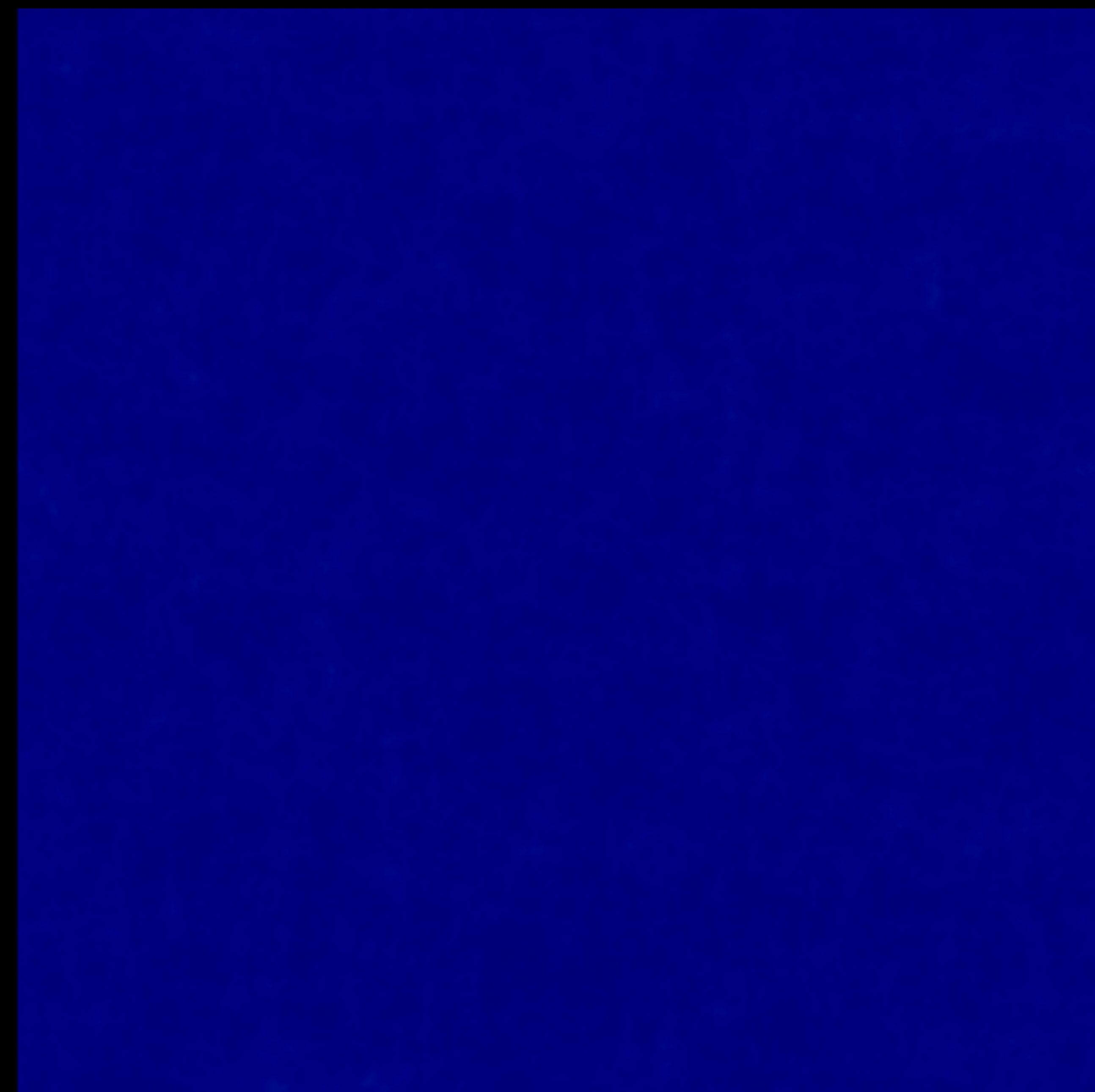
Dark Matter





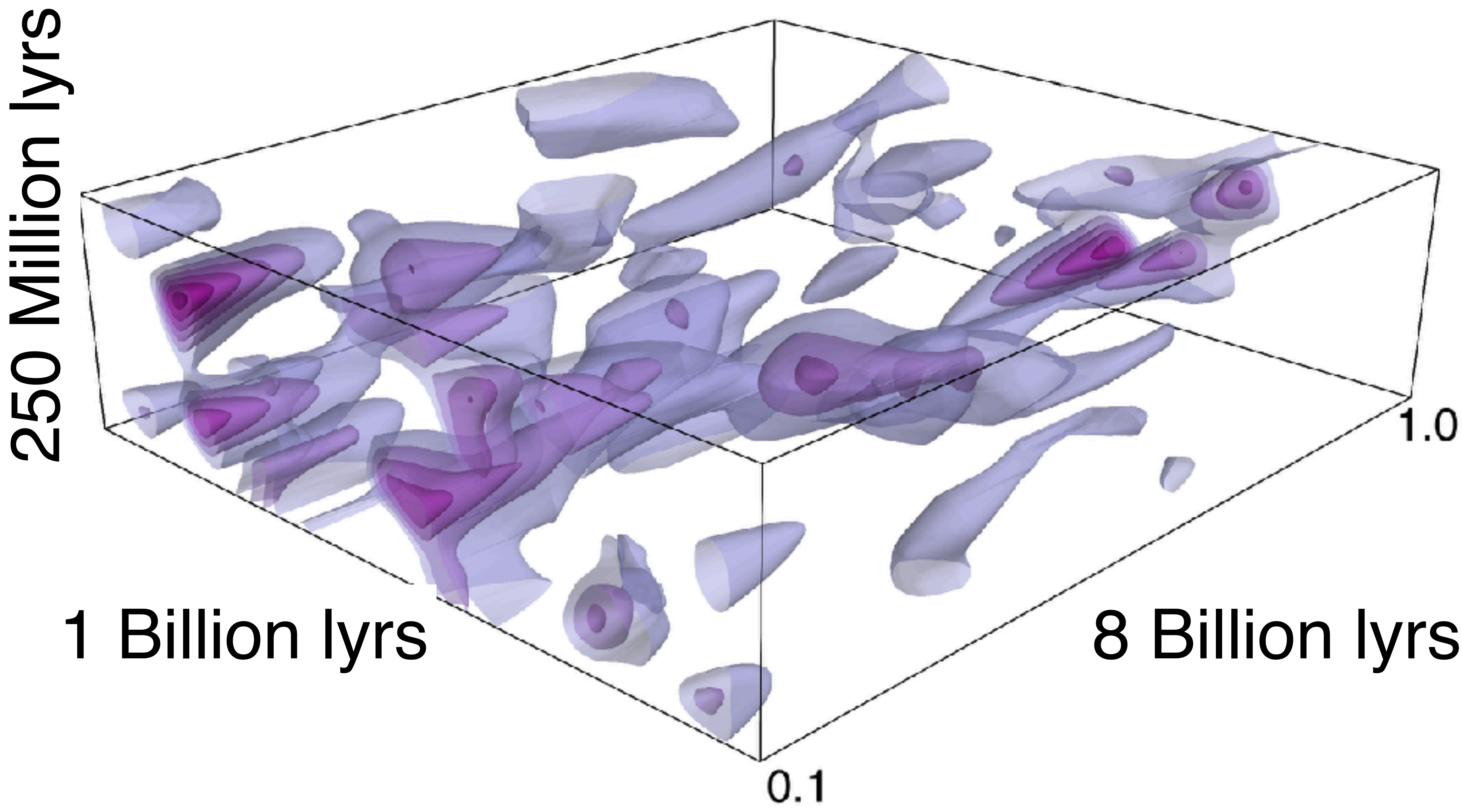
Dark Matter is our Mom

without dark matter

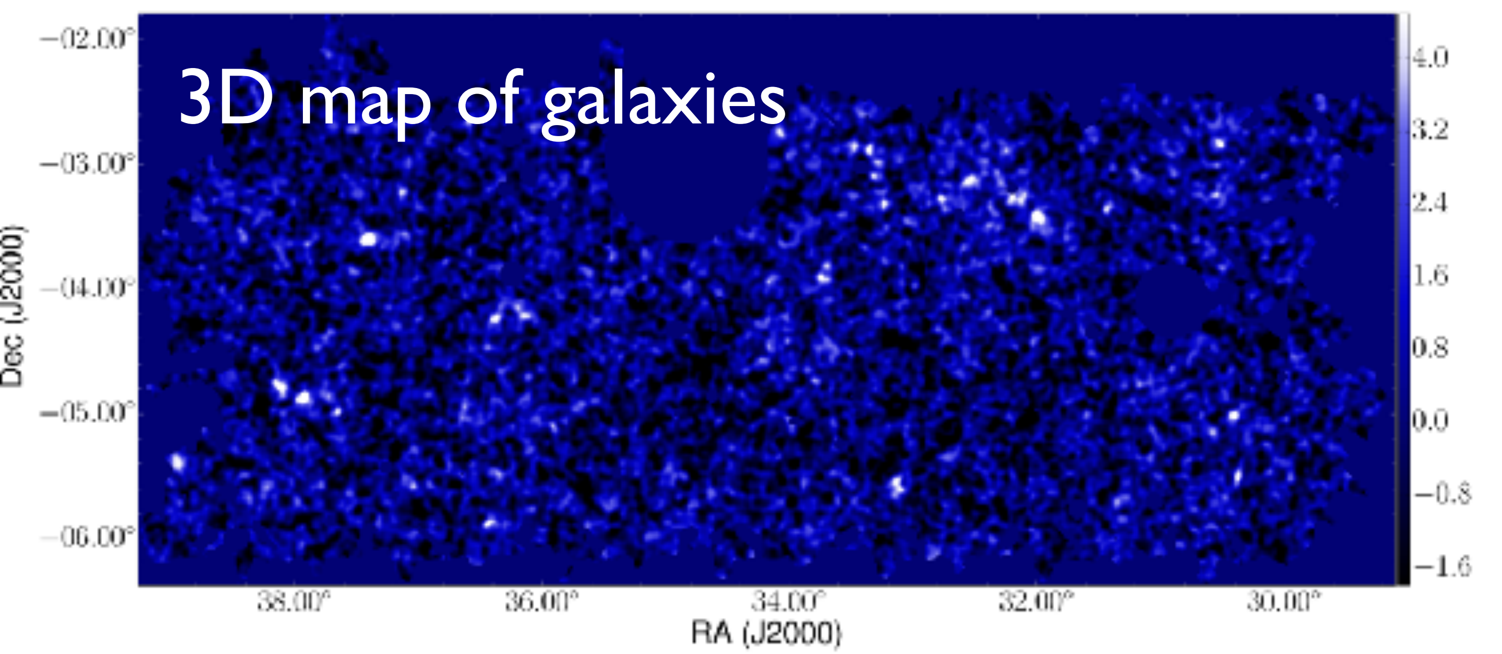


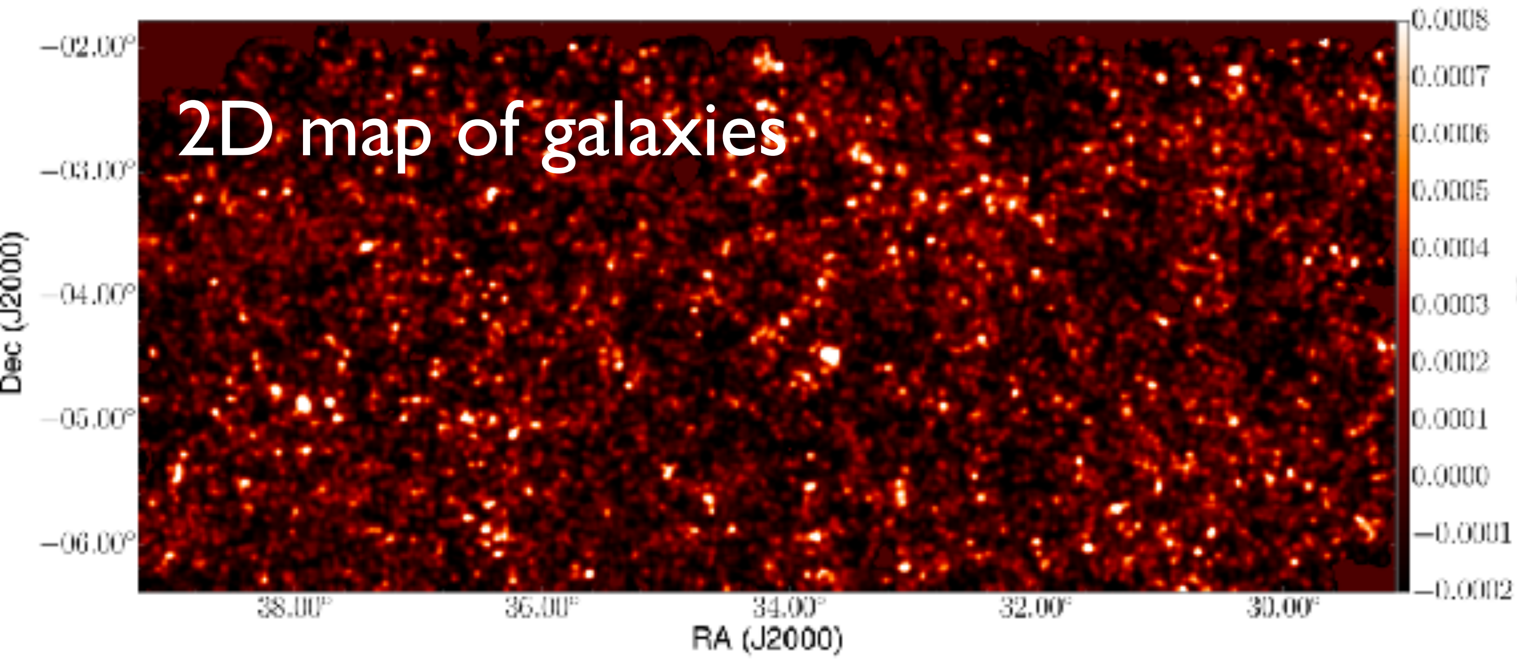
with dark matter

largest 3D map ever

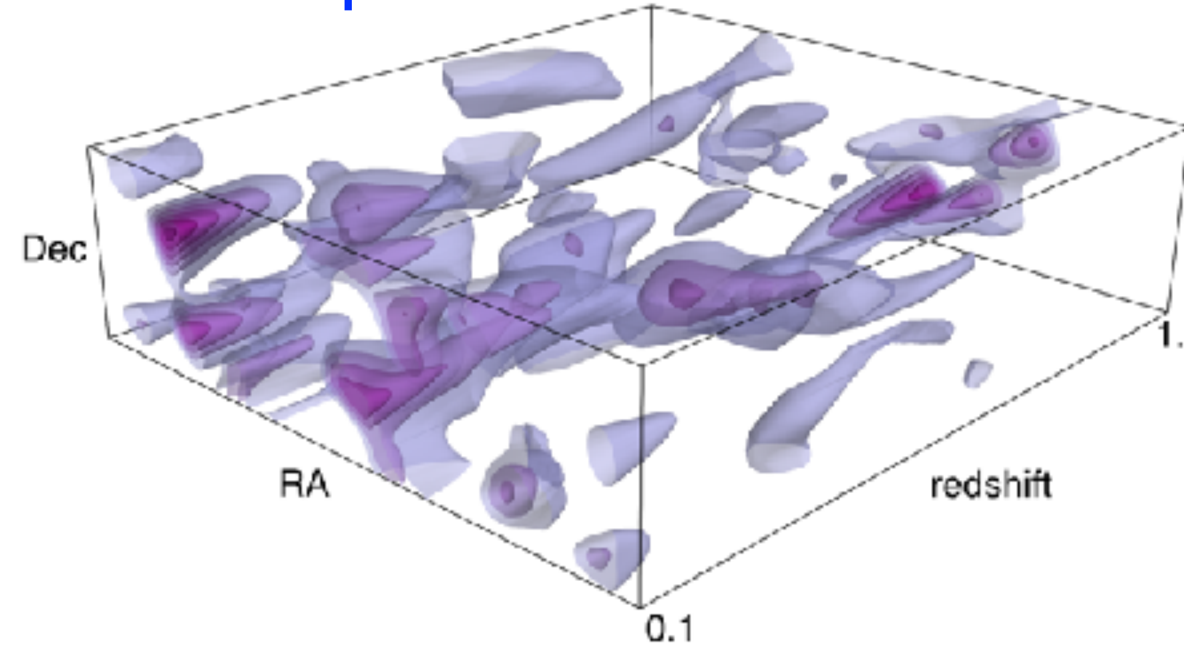


Indeed,
dark matter is our Mom!

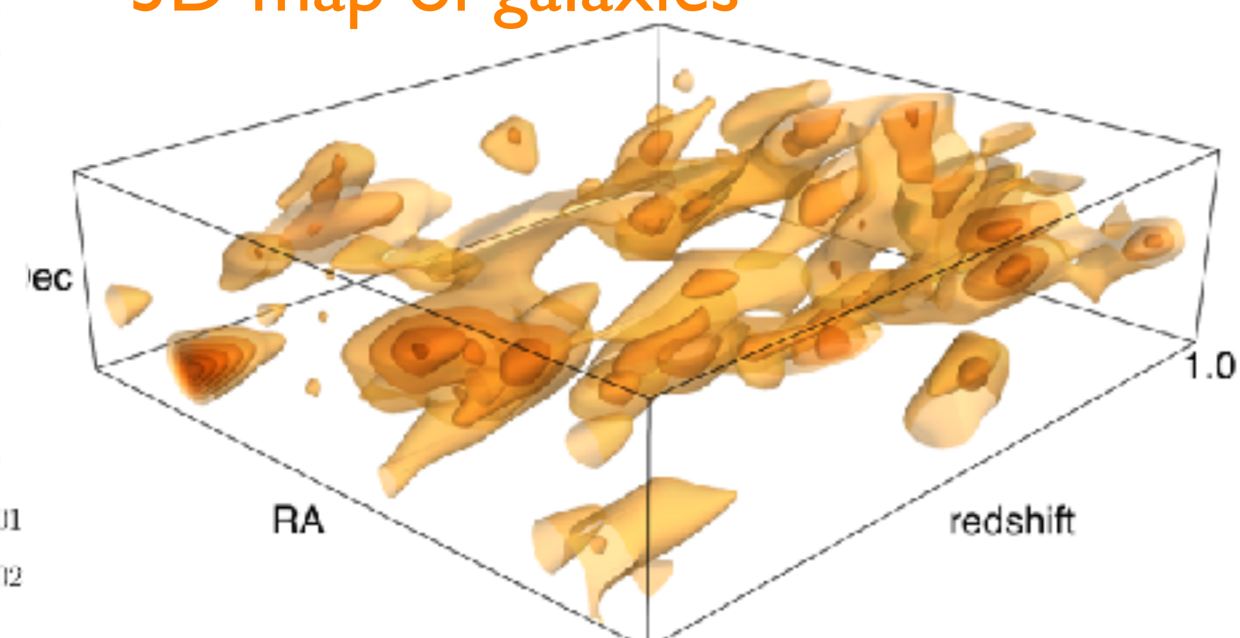




3D map of dark matter



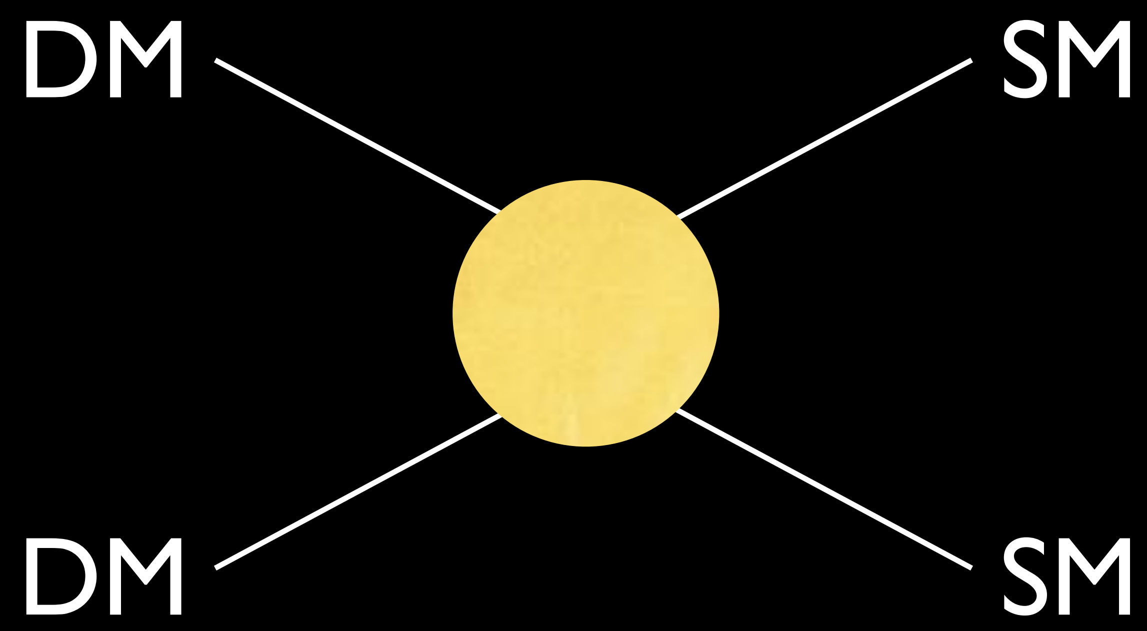
3D map of galaxies



Reenacting the Big Bang with Cal Marching Band

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles



$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \text{ GeV}$$

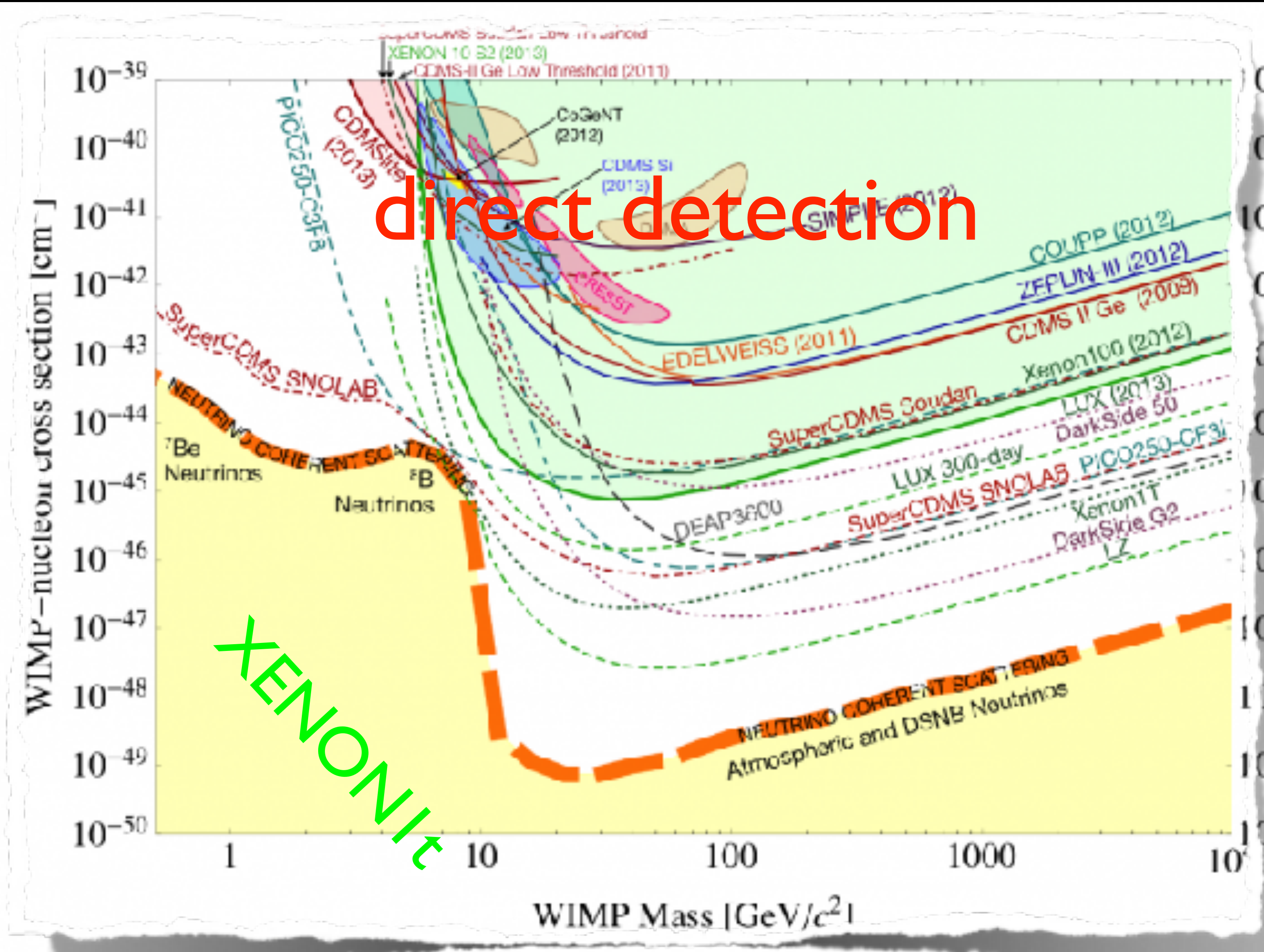
WIMP miracle^2

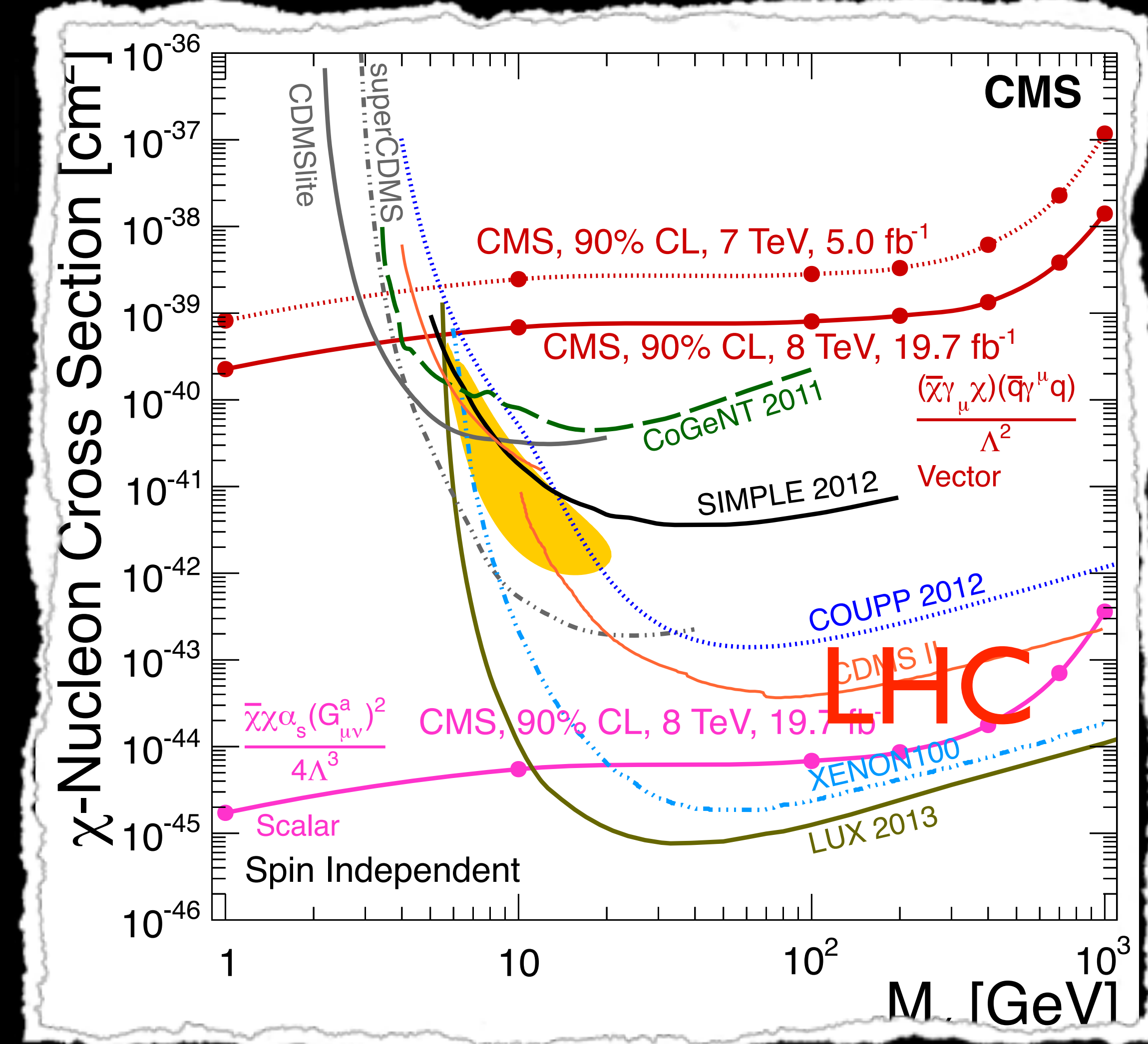
We wanted new particles at this energy scale to address the naturalness problems anyway.

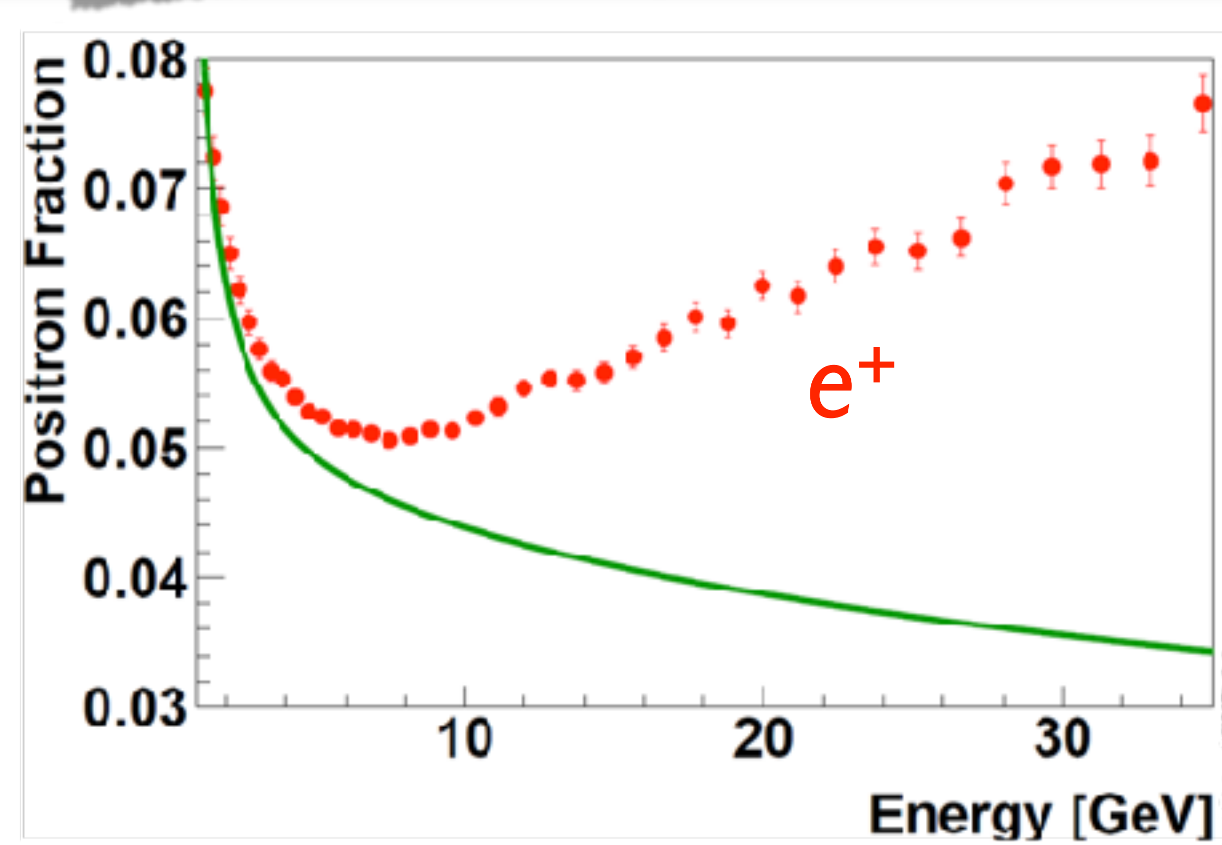
Supersymmetry

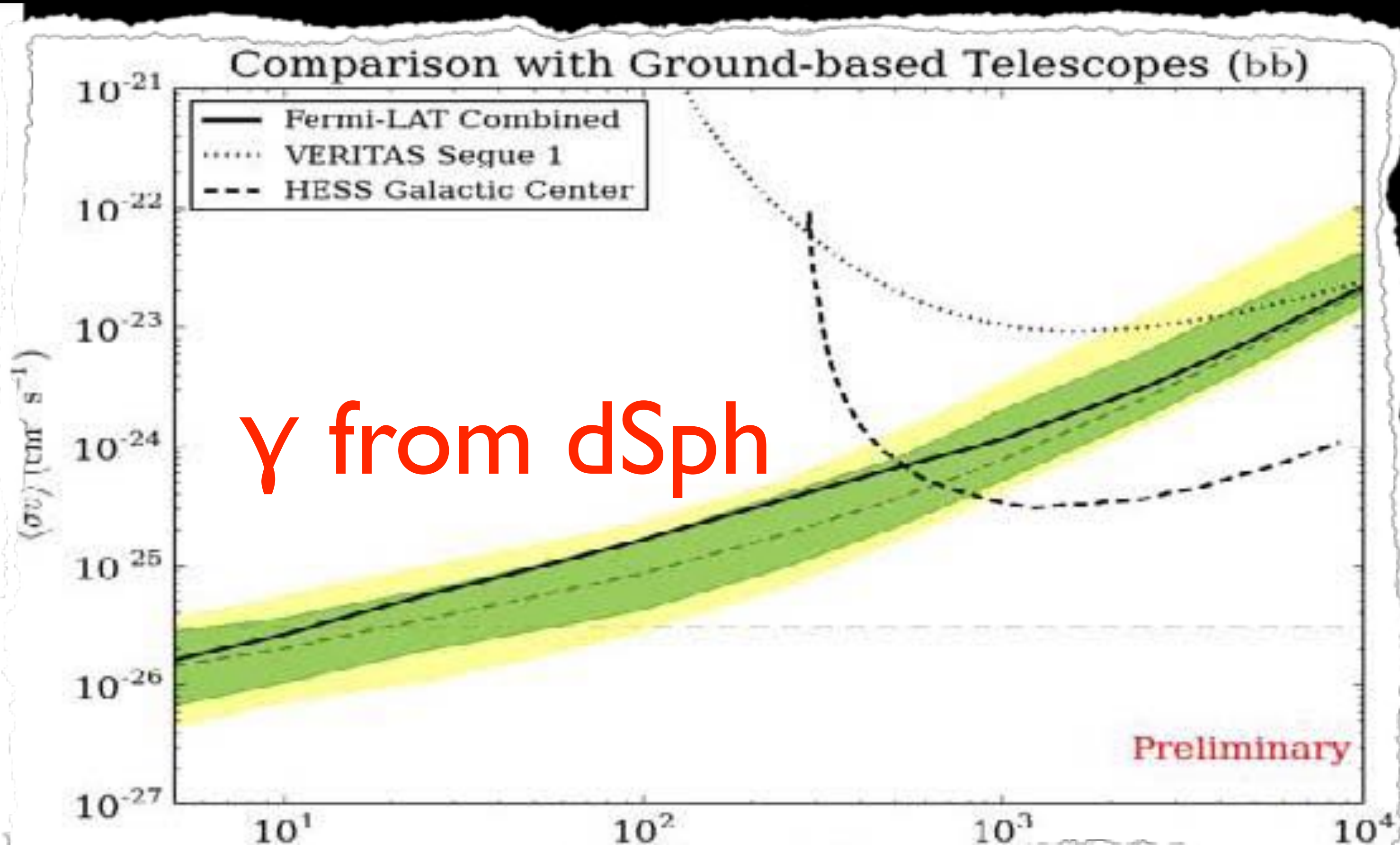
Extra dimensions

Composite models


direct detection
XENON1t
WIMP–nucleon cross section [cm²]
WIMP Mass [GeV/c²]
CoGeNT (2012)
CDMS Si (2013)
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
DEAP3600
XenonIT
DarkSide G2
LZ
CRESST
CDMSlite (2013)
PICO250-C3F8
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
⁷Be Neutrinos
⁸B Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos


LHC
CMS
χ-Nucleon Cross Section [cm²]
M [GeV]
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


e⁺
Positron Fraction
Energy [GeV]

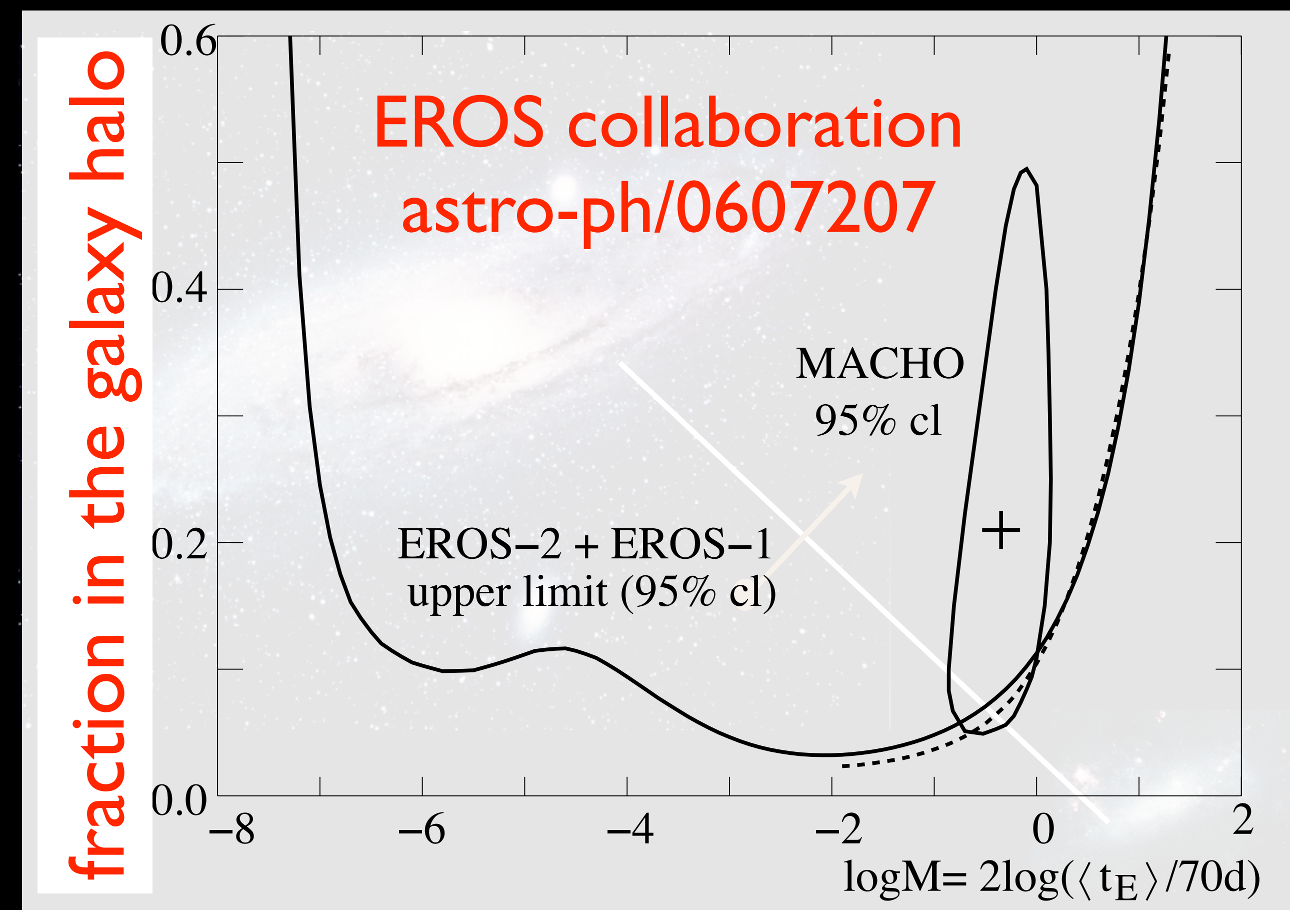

Comparison with Ground-based Telescopes (bb̄)
Fermi-LAT Combined
VERITAS Segue 1
HESS Galactic Center
γ from dSph
Preliminary

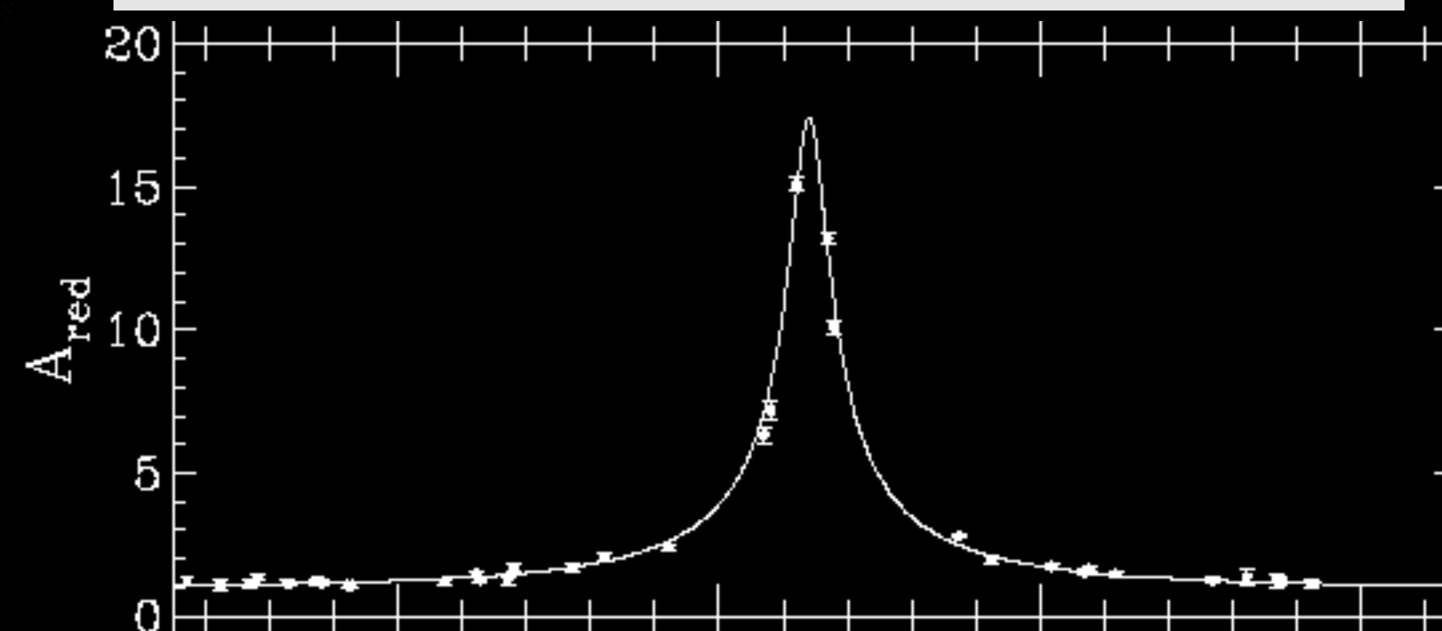
sociology

- in 1980s, dark matter was not as clear
- people tried to solve big problems in particle physics, i.e. naturalness, strong CP
- dark matter was optional, *i.e.* WIMP
- in 2010s, dark matter is a glaring problem
- but no sign of solution to naturalness
- perhaps naturalness is optional?
- rethinking: be more open-minded

Dim Stars? Black Holes?

Search for MACHOs
(Massive Compact Halo Objects)



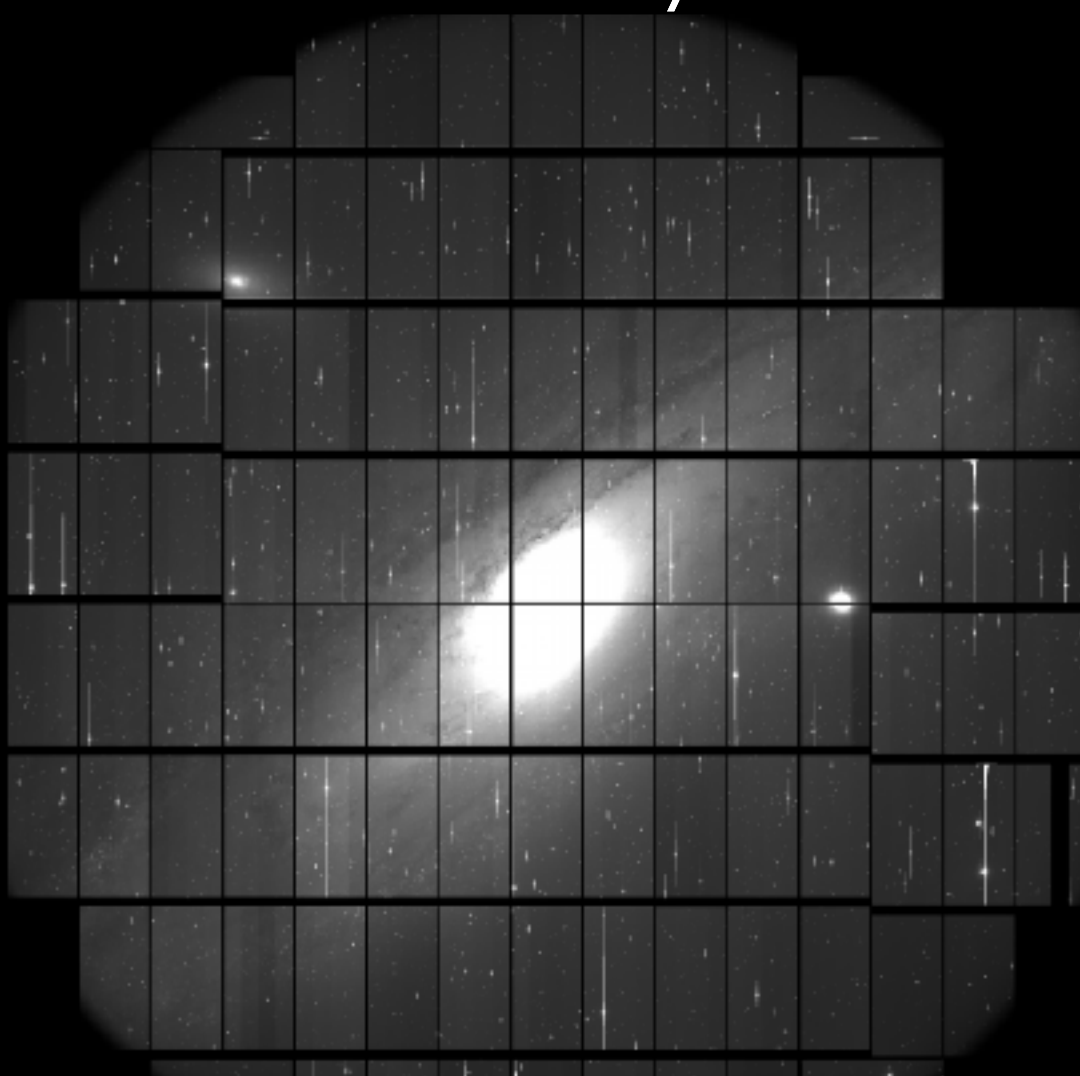


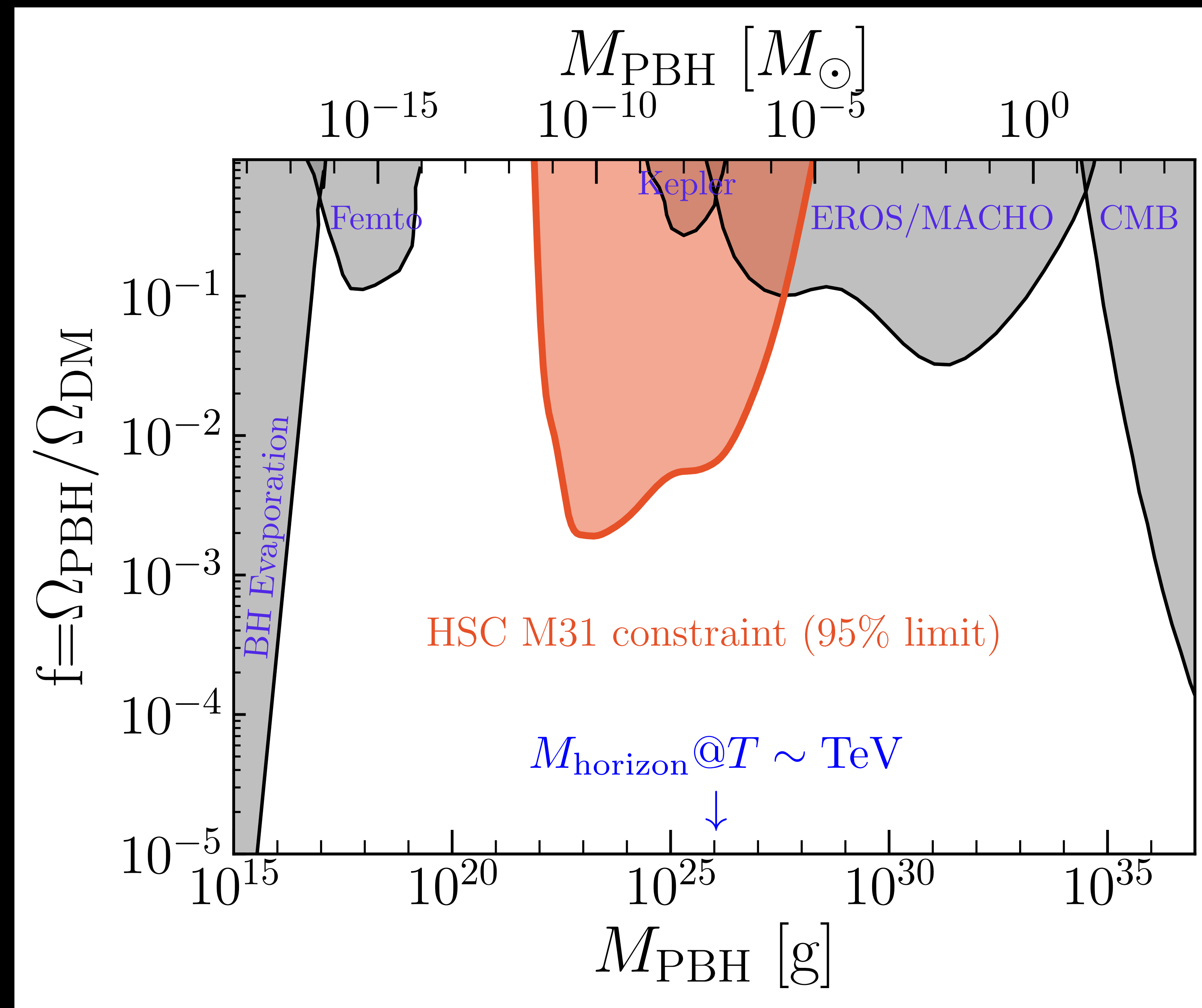
Not enough of them!

Best limit on Black Hole dark matter

Niikura, Takada et al., Nature Astronomy

observe Andromeda for one night
read out CCDs every 2 min

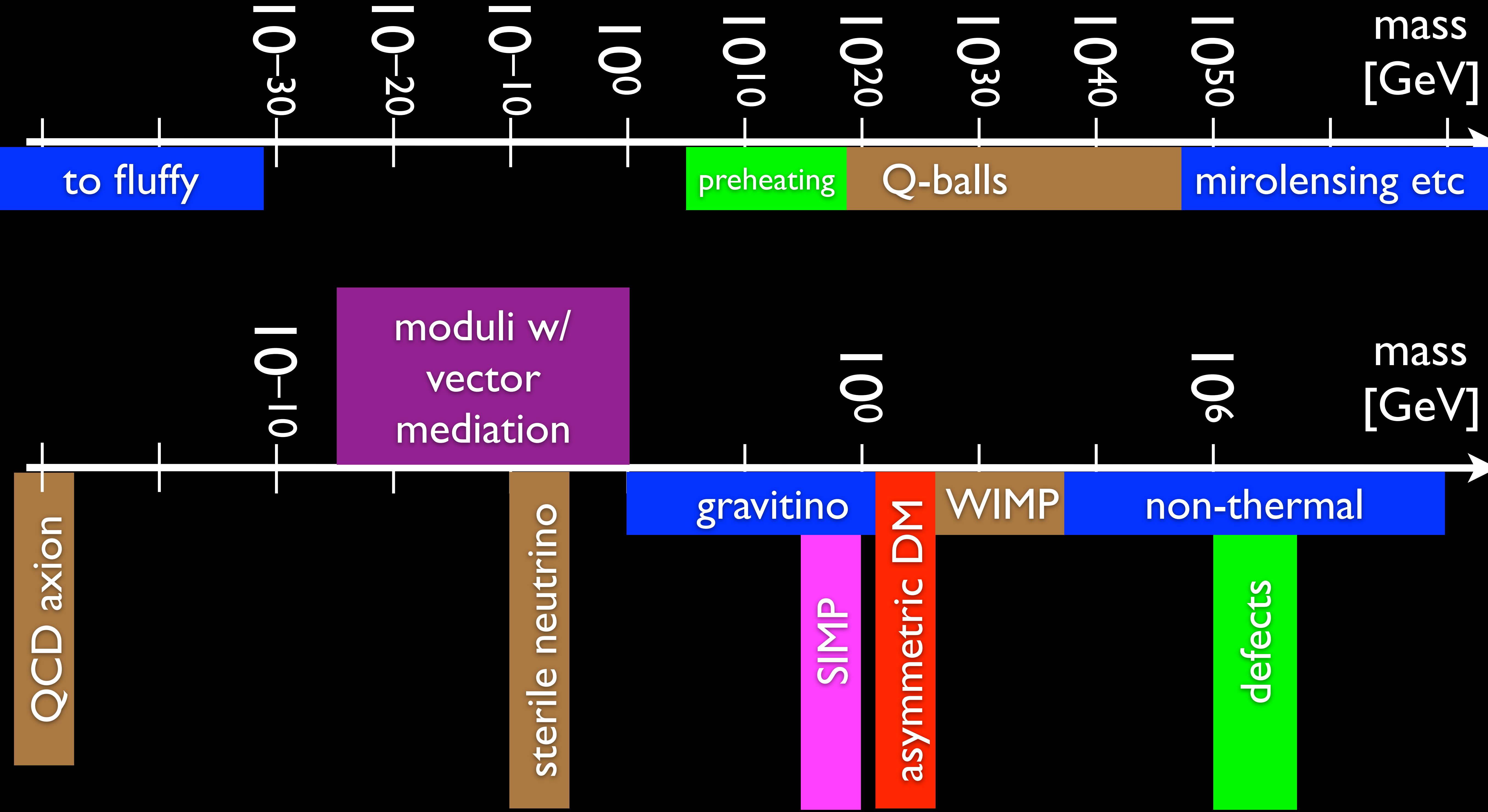




No detection ⇒ more stringent upper bound, than 2yr Kepler data (Griest et al.)

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)



SIMP: dark hadrons

m~0.3GeV, σ~10^{-24}cm^2

Conclusions

- Particle Physics: exciting as ever!
- Higgs: need to understand it better
  - HL-LHC, ILC, CEPC, FCCee
- naturalness: higher energies, precision
  - HE-LHC, FCChh, CLIC, PWFA, μμ
- dark matter: open mind, broad search
  - cosmology, direct, indirect, collider
  - “table top” experiments

experiments

healthy field!

Why do we exist at all?

—Baryogenesis and Inflation–

Hitoshi Murayama (Berkeley & Kavli IPMU)

Summer Institute 2019 Gangneung

August 19, 2019

東京大学 THE UNIVERSITY OF TOKYO
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB
KAVLI IPMU

Why don't we break apart?

—Higgs boson and Dark Matter—

Hitoshi Murayama (Berkeley & Kavli IPMU)

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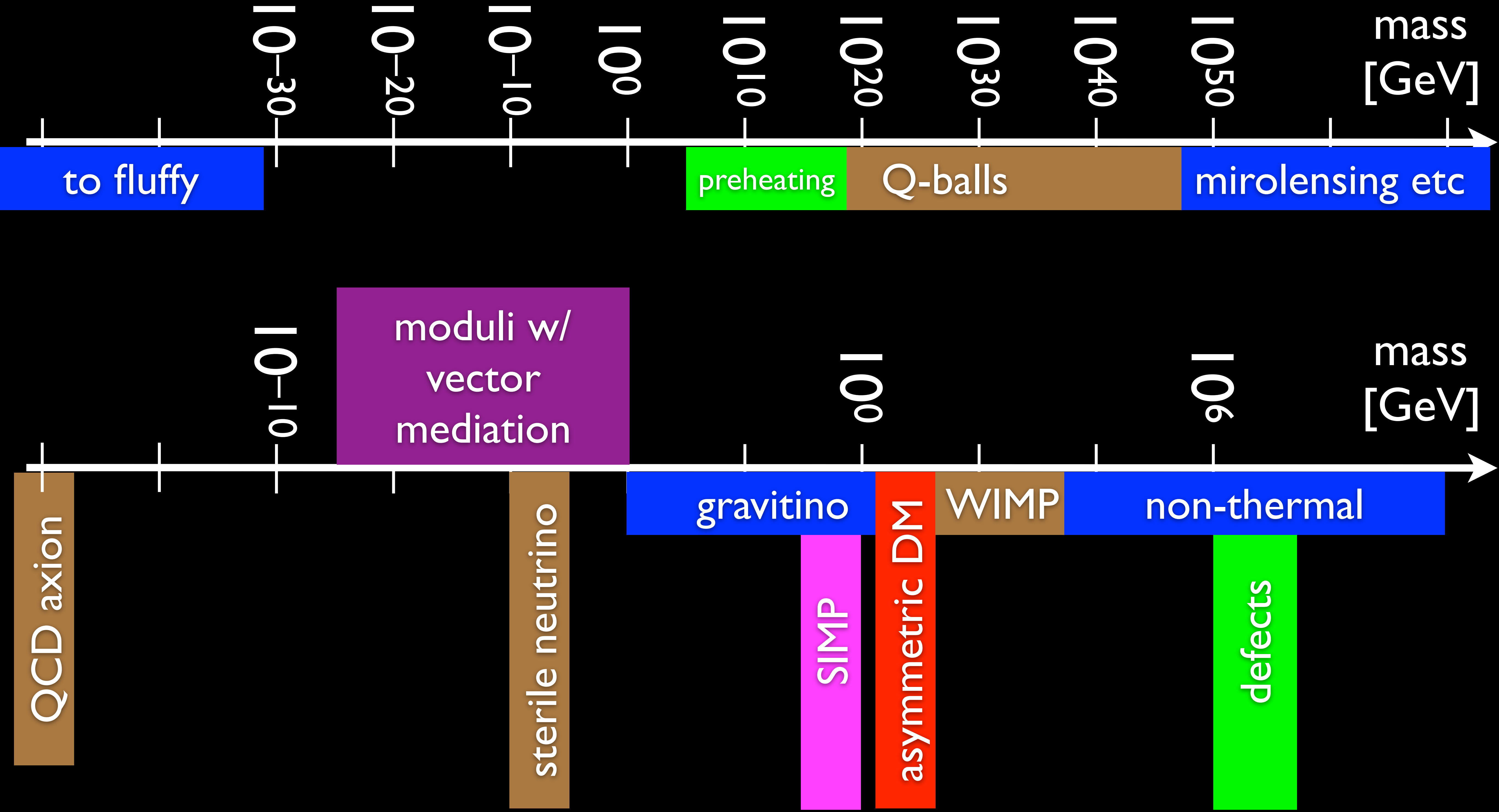


SIMP: dark hadrons

m~0.3GeV, σ~10^{-24}cm^2

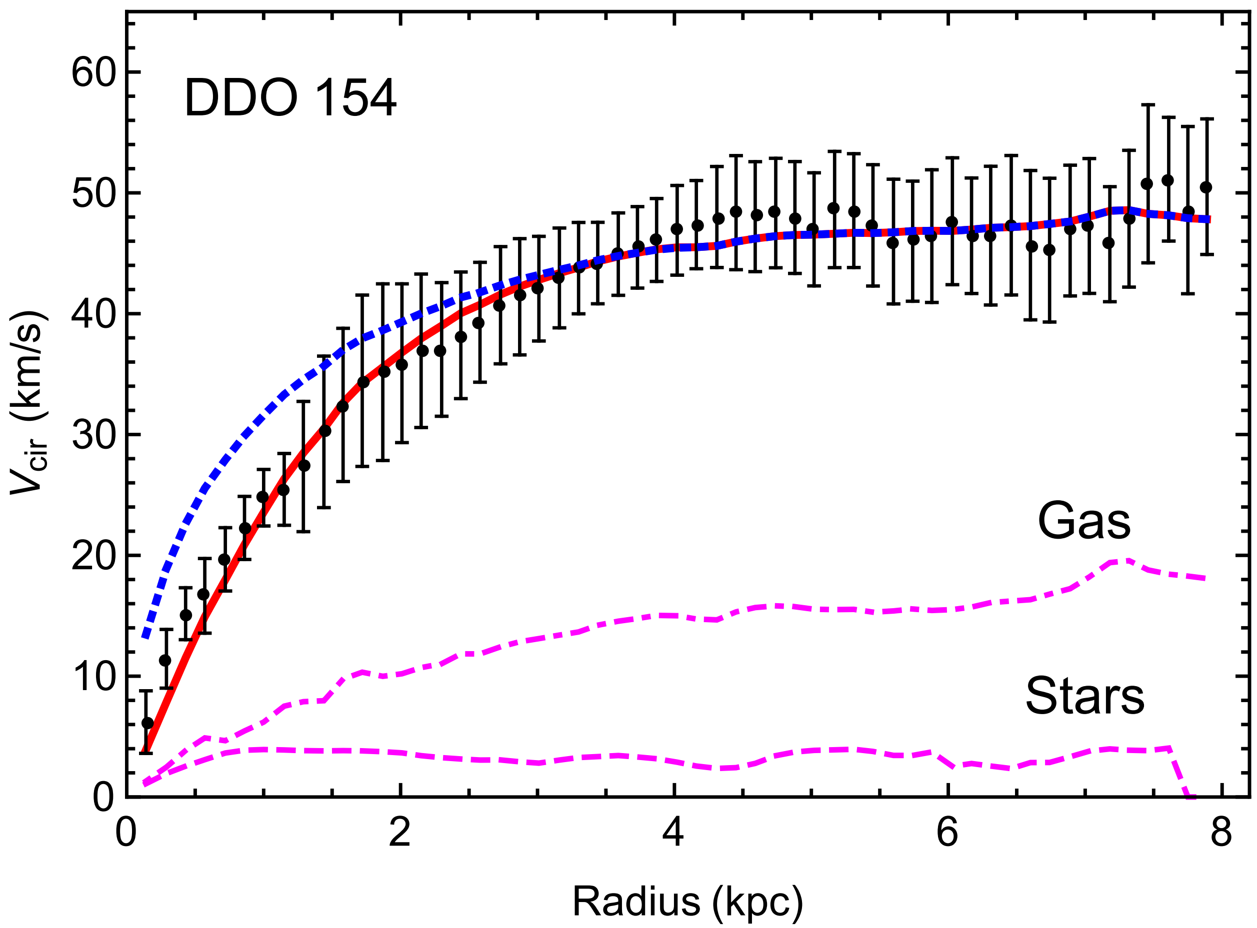
What to choose?

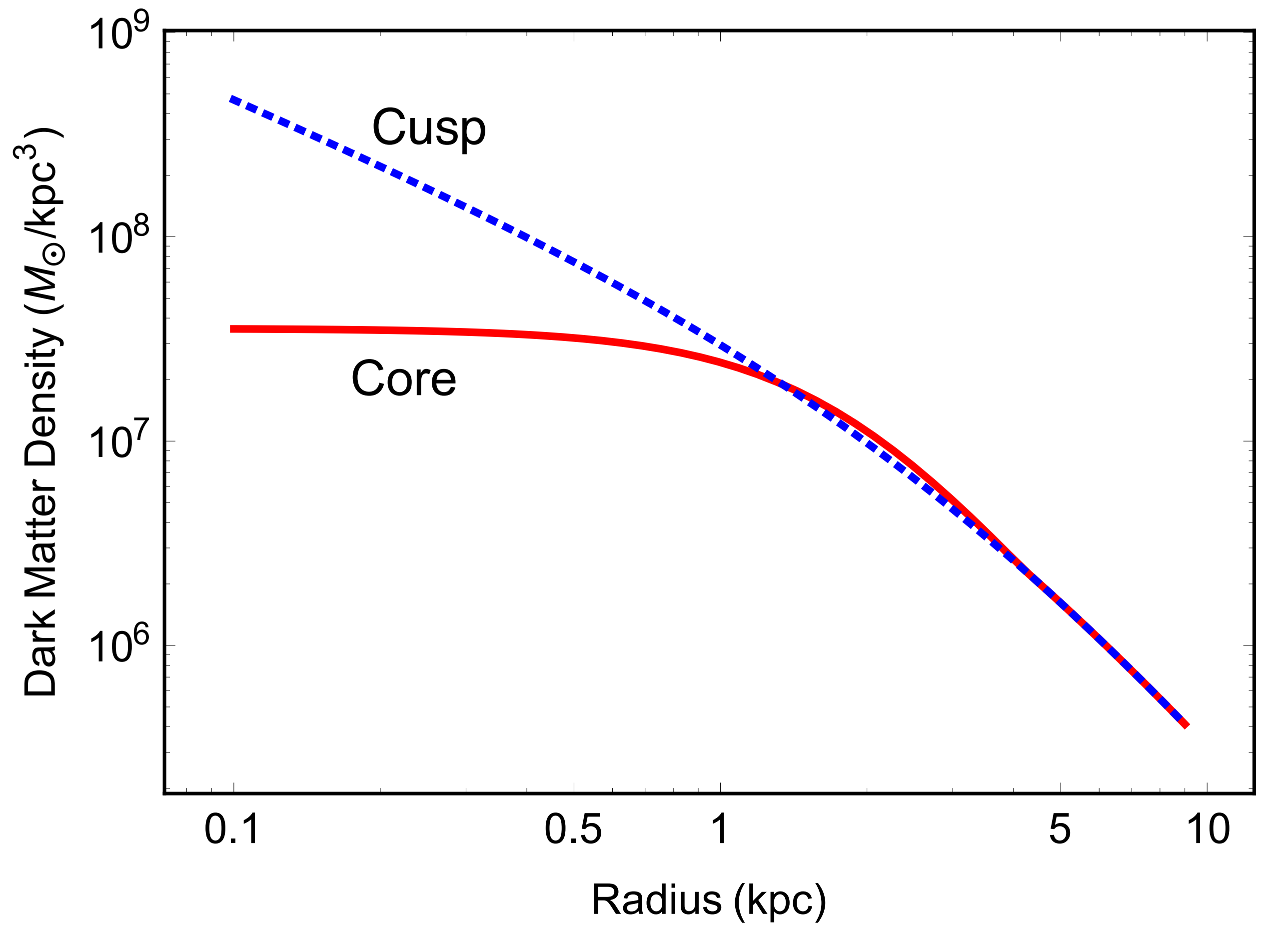
- We need a broad experimental search
- for me, I need some guidance from data
- the only one astrophysical data that points to nature of dark matter is issue with small-scale structure

  ➡ self-interacting dark matter (Spergel & Steinhardt 2000)
- still controversial
  - baryonic feedback?

DDO 154 dwarf galaxy

DDO 154 dwarf galaxy



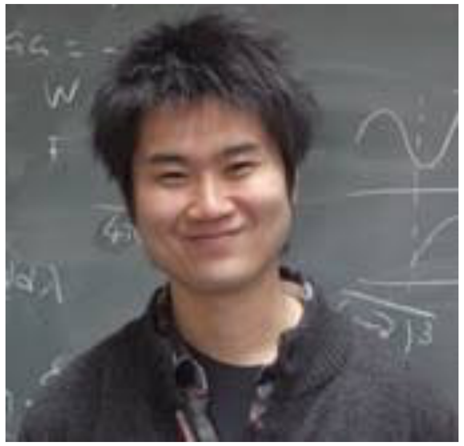


can be explained if dark matter scatters against itself

Need $\sigma/m \sim 1$b / GeV

only astrophysical information beyond gravity

Diversity in stellar distribution

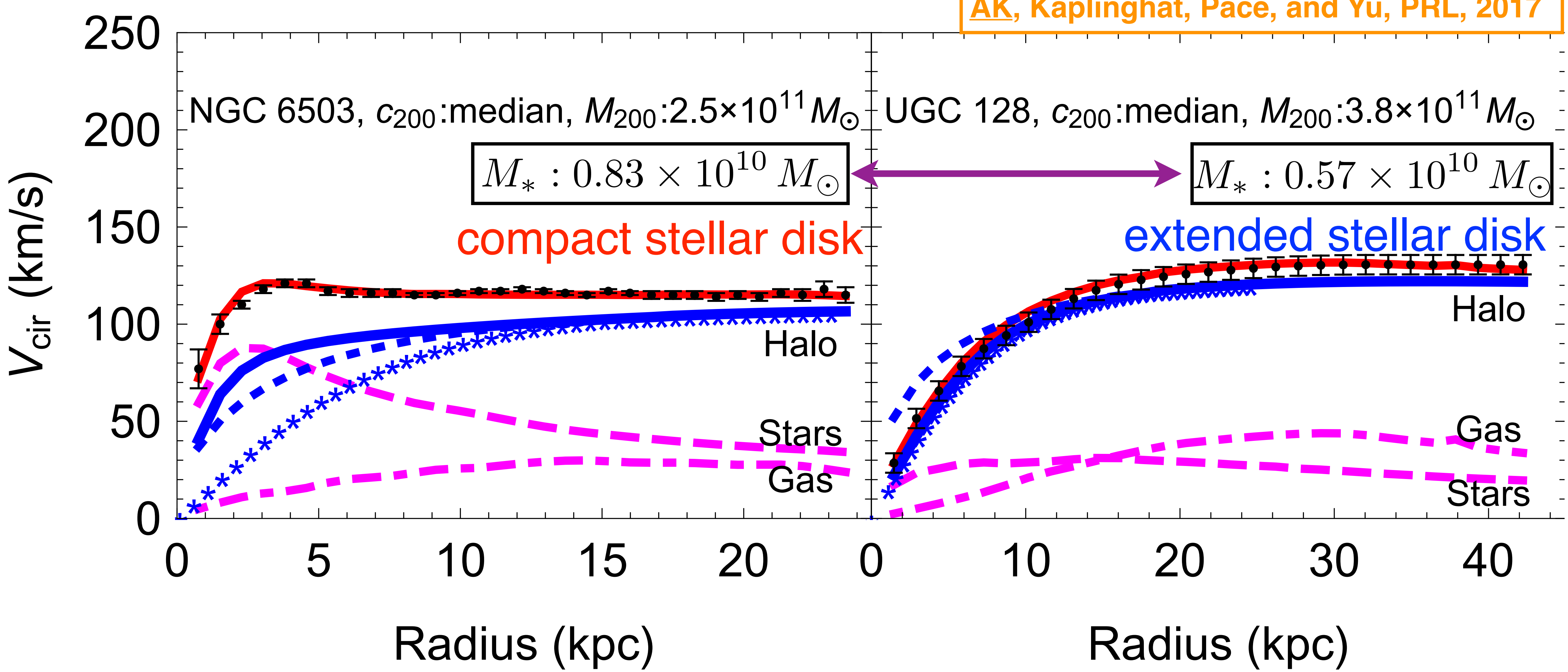


Ayuki Kamada

Similar outer circular velocity and stellar mass,
but different stellar distribution

- compact → redistribute SIDM significantly
- extended → unchange SIDM distribution

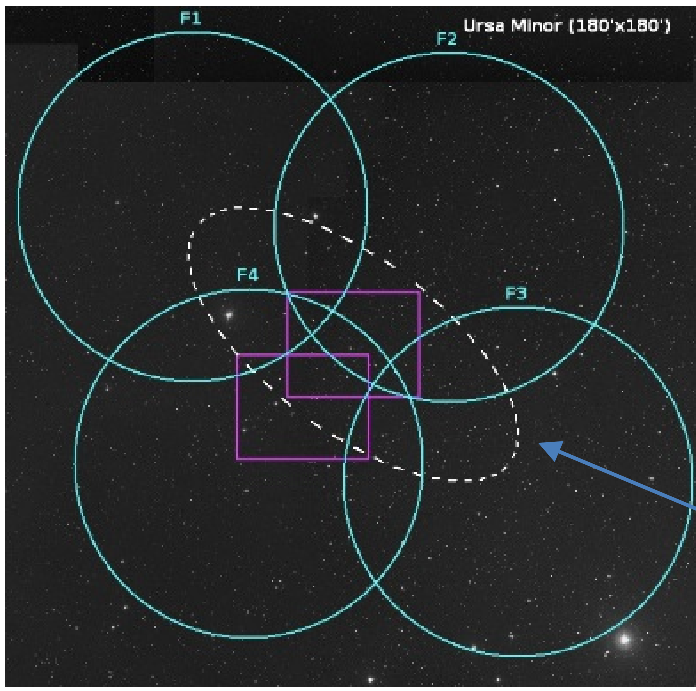
AK, Kaplinghat, Pace, and Yu, PRL, 2017



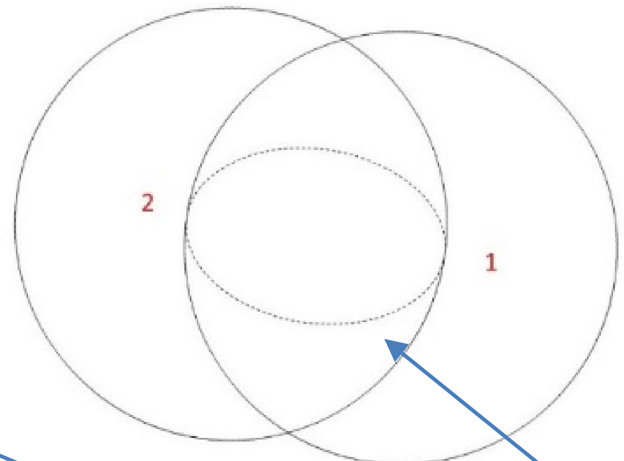
PFS pointings for MW satellites

~ HSC imaging data are available for all samples ~

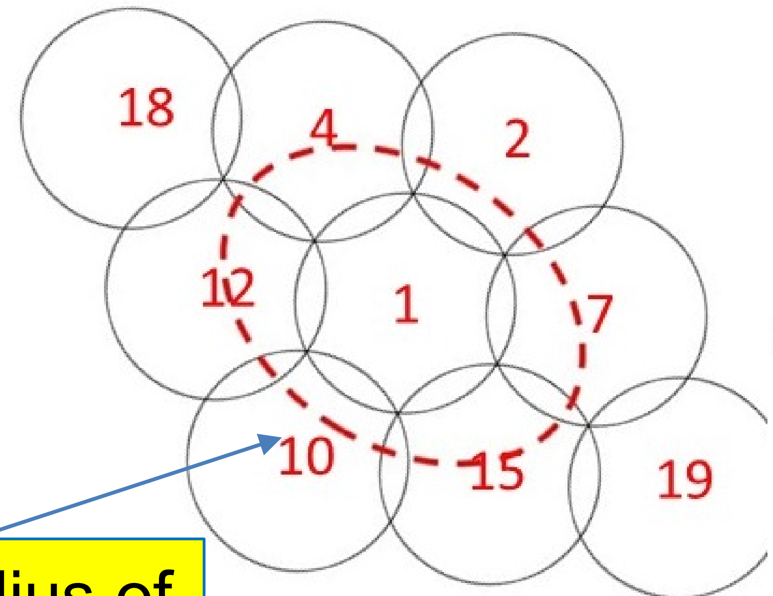
Ursa Minor



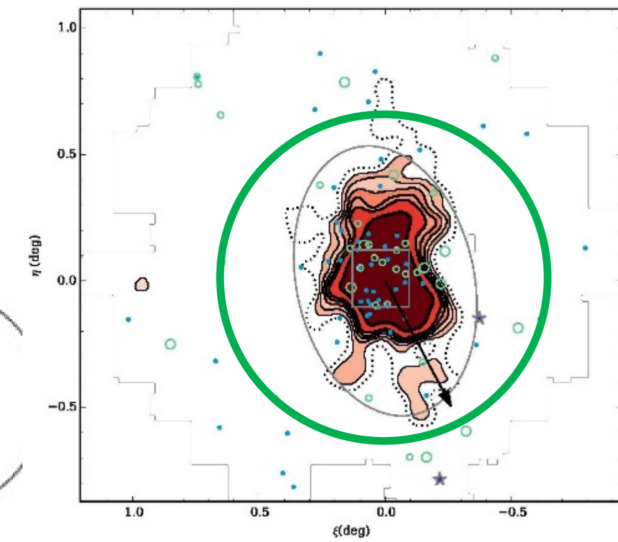
Draco



Sextans

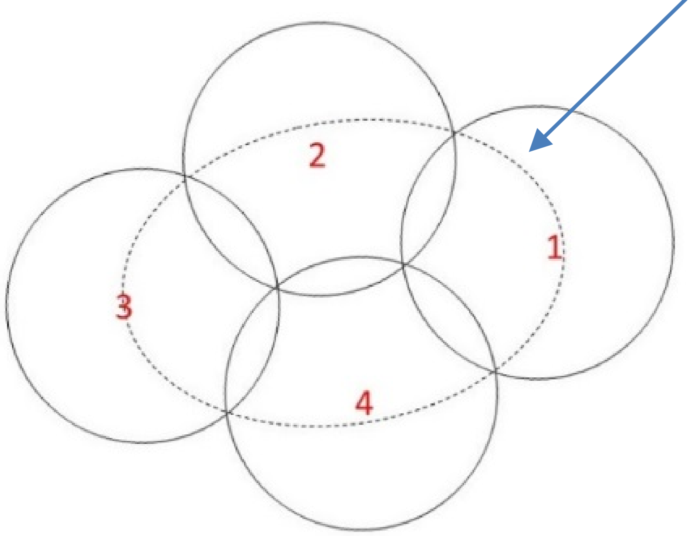


Bootes I

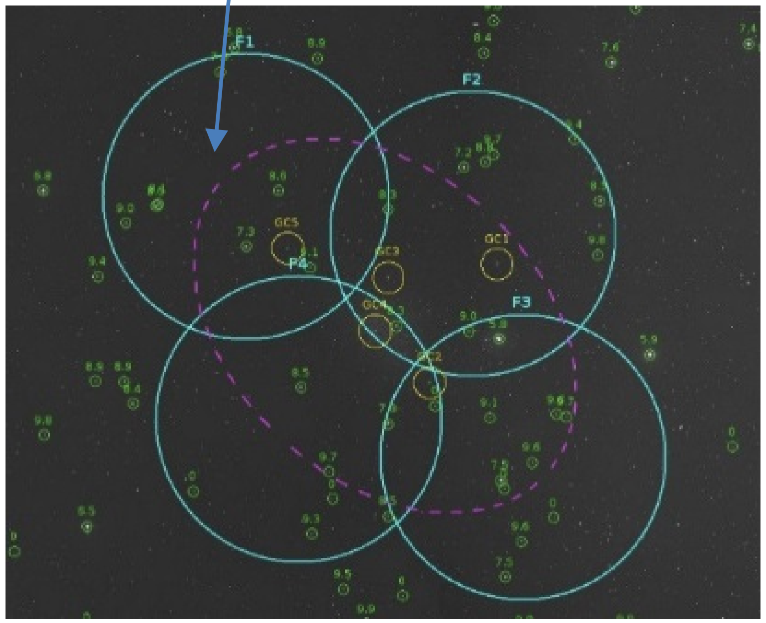


tidal radius of stellar comp.

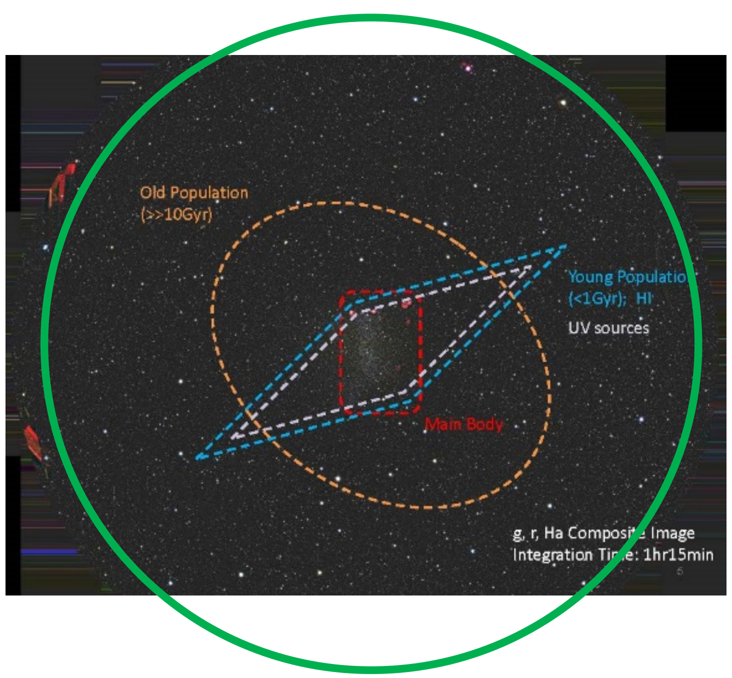
Sculptor



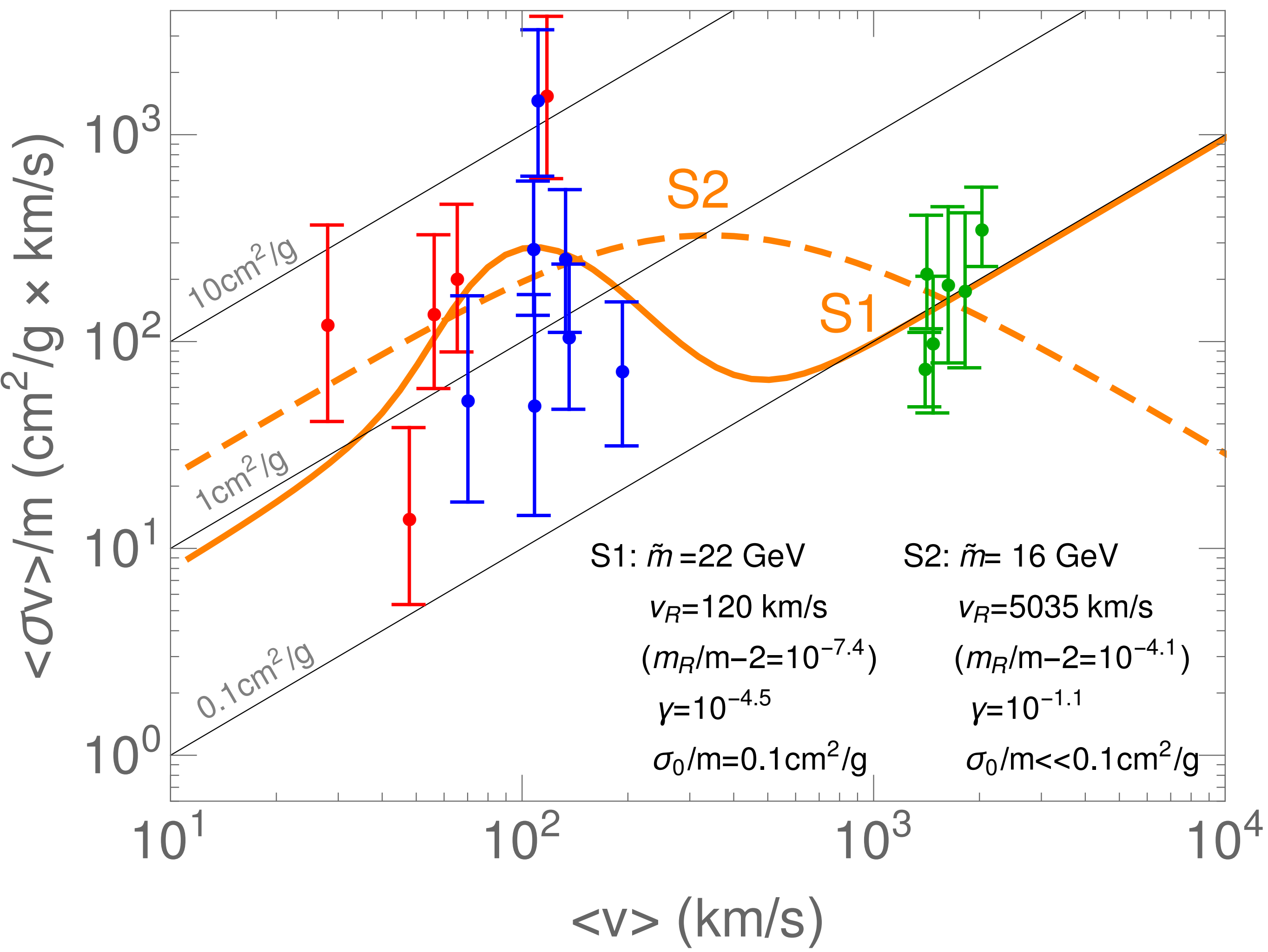
Fornax

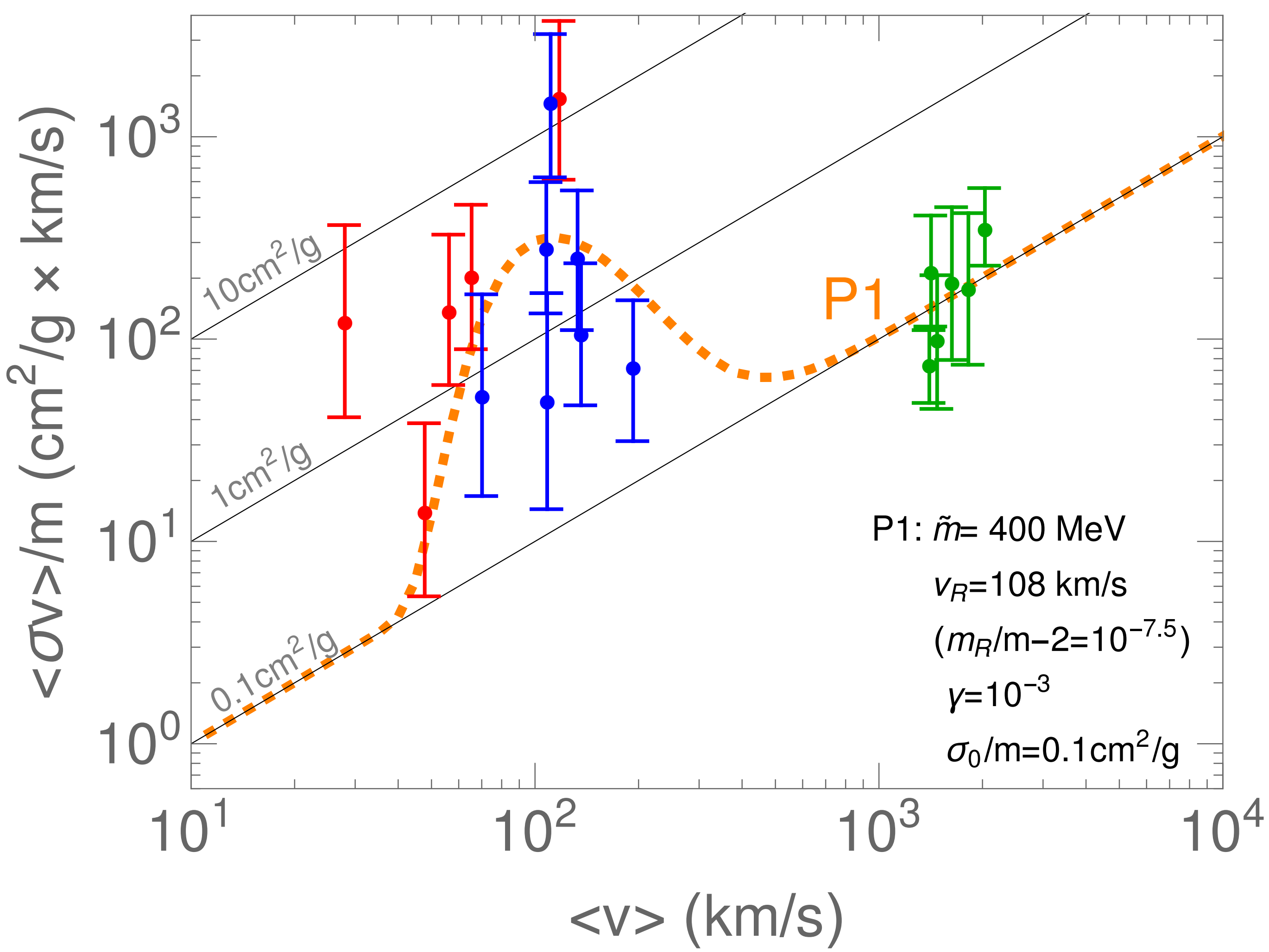


NGC6822



velocity dependence





Self interaction classical regime

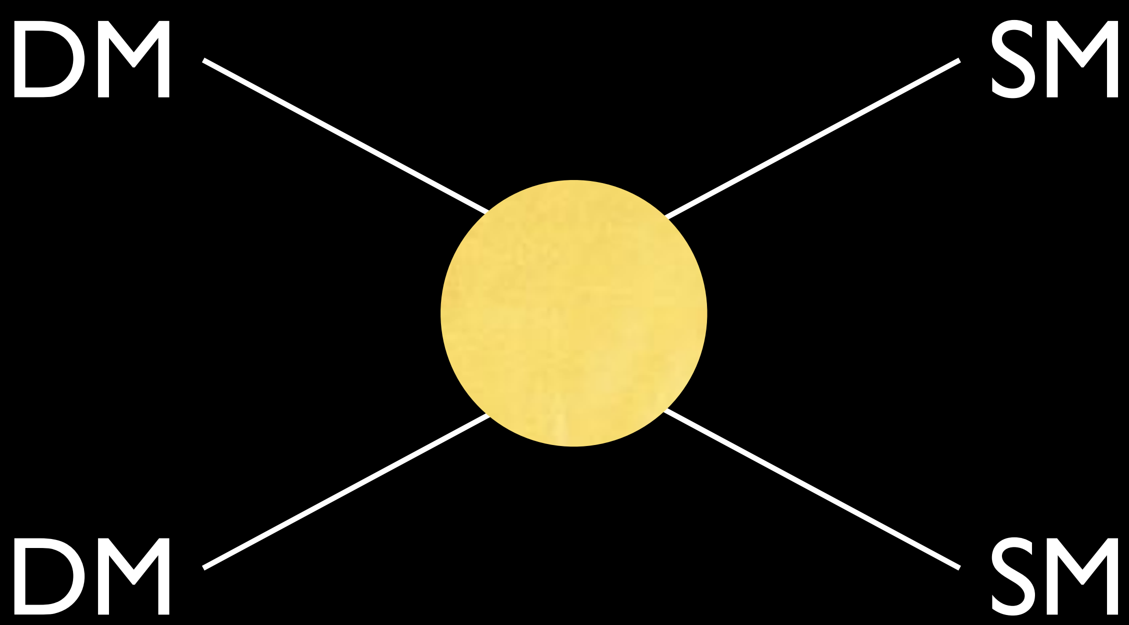
- (semi-)long-range force with light mediator
  - analog of Rutherford scattering (classical regime)
  - cross section can be large with many partial waves
  - but annihilation of dark matter into light mediator
  - asymmetric dark matter?

Self interaction quantum regime

- low-energy scattering typically dominated by *S*-wave ($\sigma \sim k^{2l}$)
- unitarity limit $\sigma_0 \leq 4\pi/k^2 \sim 4\pi/(mv)^2$ (quantum regime)
- to have $\sigma_0/m \sim 1 \text{cm}^2/\text{g}$ for $v \sim 100$km/s, we need $m < 30$ GeV
- typically light dark matter with strong interaction preferred
- a new strongly interacting sector?

$$\frac{n_{\rm DM}}{s} = 4.4 \times 10^{-10} \frac{\rm GeV}{m_{\rm DM}}$$

Miracles

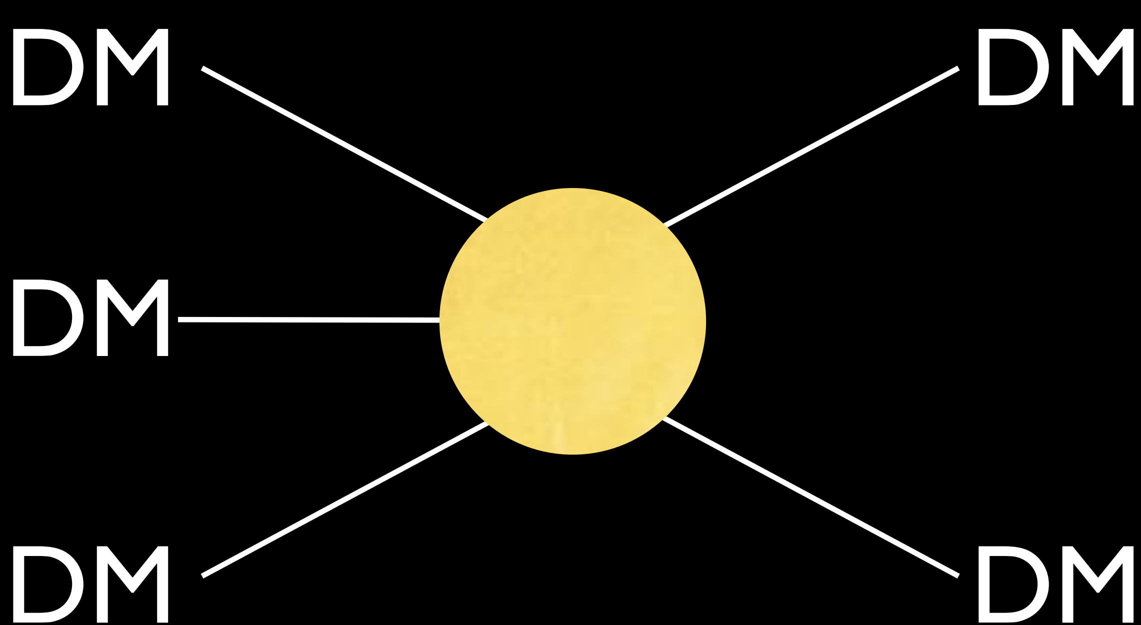


$$\langle \sigma_{2\to 2} v \rangle \approx \frac{\alpha^2}{m^2}$$

$$\alpha \approx 10^{-2}$$

$$m \approx 300 \text{ GeV}$$

WIMP miracle²



$$\langle \sigma_{3\to 2} v^2 \rangle \approx \frac{\alpha^3}{m^5}$$

$$\alpha \approx 4\pi$$

$$m \approx 300 \text{MeV}$$

Hochberg, Kuflik, Volansky, Wacker arXiv:1402.5143

SIMP miracle²

SIMPlest Miracle

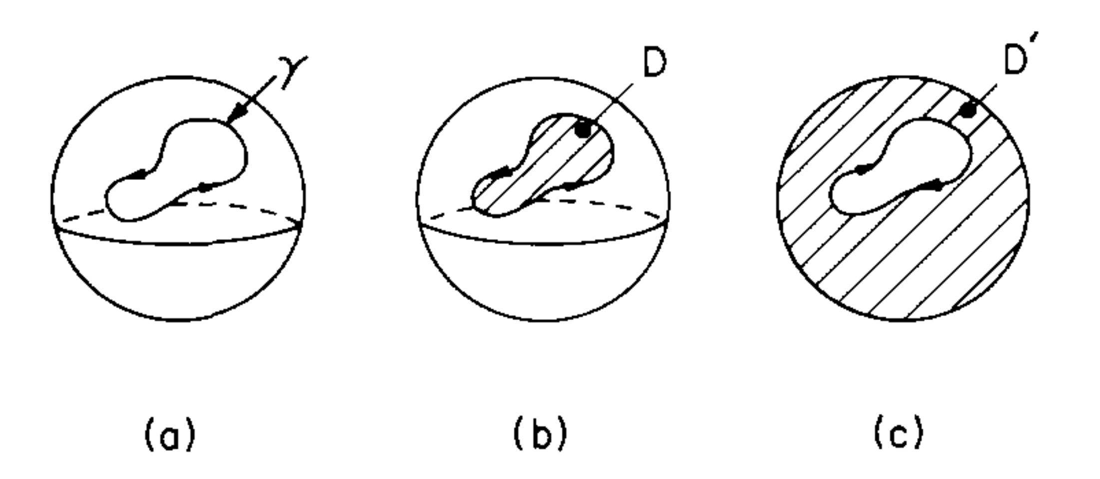
Yonit Hochberg, Eric Kuflik, HM, Tomer Volansky, Jay Wacker

- SU(2) gauge theory with four doublets
- SU(4)=SO(6) flavor symmetry
- $\langle q^i q^j \rangle \neq 0$ breaks it to Sp(2)=SO(5)
- coset space SO(6)/SO(5)=S^5
- 5 stable pions
- $\pi_5(S^5)=Z \Rightarrow$ Wess-Zumino term
  - $L_{WZ}=\varepsilon_{abcde}\, \varepsilon^{\mu\nu\rho\sigma}\, \pi^a \partial_\mu \pi^b \partial_\nu \pi^c \partial_\rho \pi^d \partial_\sigma \pi^e$

SIMP miracle^3

Wess-Zumino term

- SU(N_c) gauge theory
  - $\pi_5(SU(N_f))=\mathbb{Z}$ ($N_f \geq 3$)
- Sp(N_c) gauge theory
  - $\pi_5(SU(2N_f)/Sp(N_f))=\mathbb{Z}$ ($N_f \geq 2$)
- SO(N_c) gauge theory
  - $\pi_5(SU(N_f)/SO(N_f))=\mathbb{Z}$ ($N_f \geq 3$)



Witten

also vector SIMP Soo-Min Choi, Yonit Hochberg, Eric Kuflik, Hyun Min Lee, Yann Mambrini, Hitoshi Murayama, Mathias Pierre

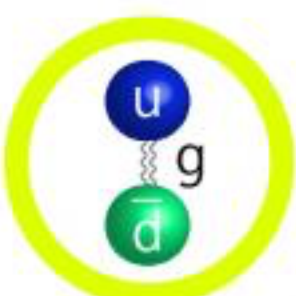
LAGRANGIANS

Quark theory

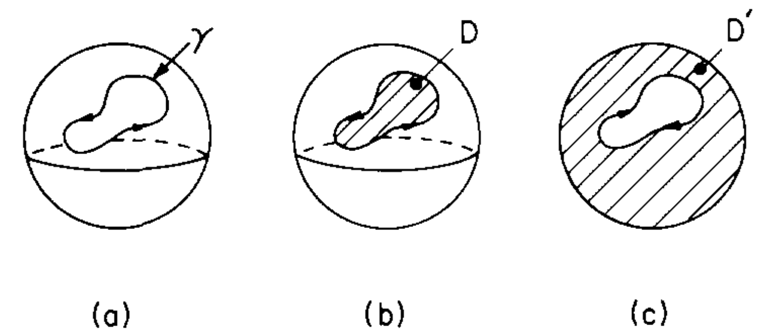
$$\mathcal{L}_{\text{quark}} = -\frac{1}{4}F^{a}_{\mu\nu}F^{\mu\nu a} + \bar{q}_i i\not{D} q_i \; -\frac{1}{2}m_Q \; J^{ij}q_i q_j + h.c.$$

Sigma theory

$$\mathcal{L}_{\text{Sigma}} = \frac{f_\pi^2}{16}\text{Tr}\partial_\mu\Sigma\,\partial^\mu\Sigma^\dagger - \frac{1}{2}m_Q\mu^3\text{Tr}J\Sigma + h.c. - \frac{iN_c}{240\pi^2}\int \text{Tr}(\Sigma^\dagger d\Sigma)^5$$



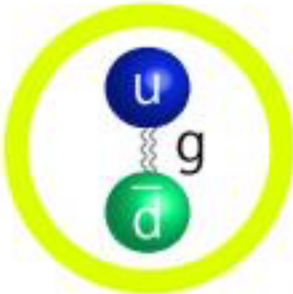
Pion theory

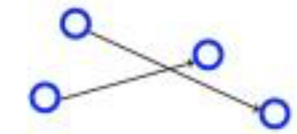


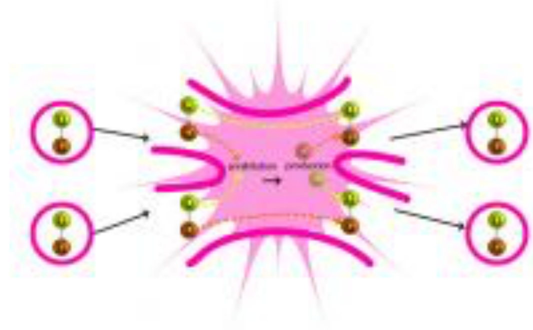
$$\mathcal{L}_{\text{pion}} = \frac{1}{4}\text{Tr}\partial_\mu\pi\partial^\mu\pi - \frac{m_\pi^2}{4}\text{Tr}\pi^2 + \frac{m_\pi^2}{12f_\pi^2}\text{Tr}\pi^4 - \frac{1}{6f_\pi^2}\text{Tr}\left(\pi^2\partial^\mu\pi\partial_\mu\pi - \pi\partial^\mu\pi\pi\partial_\mu\pi\right)$$

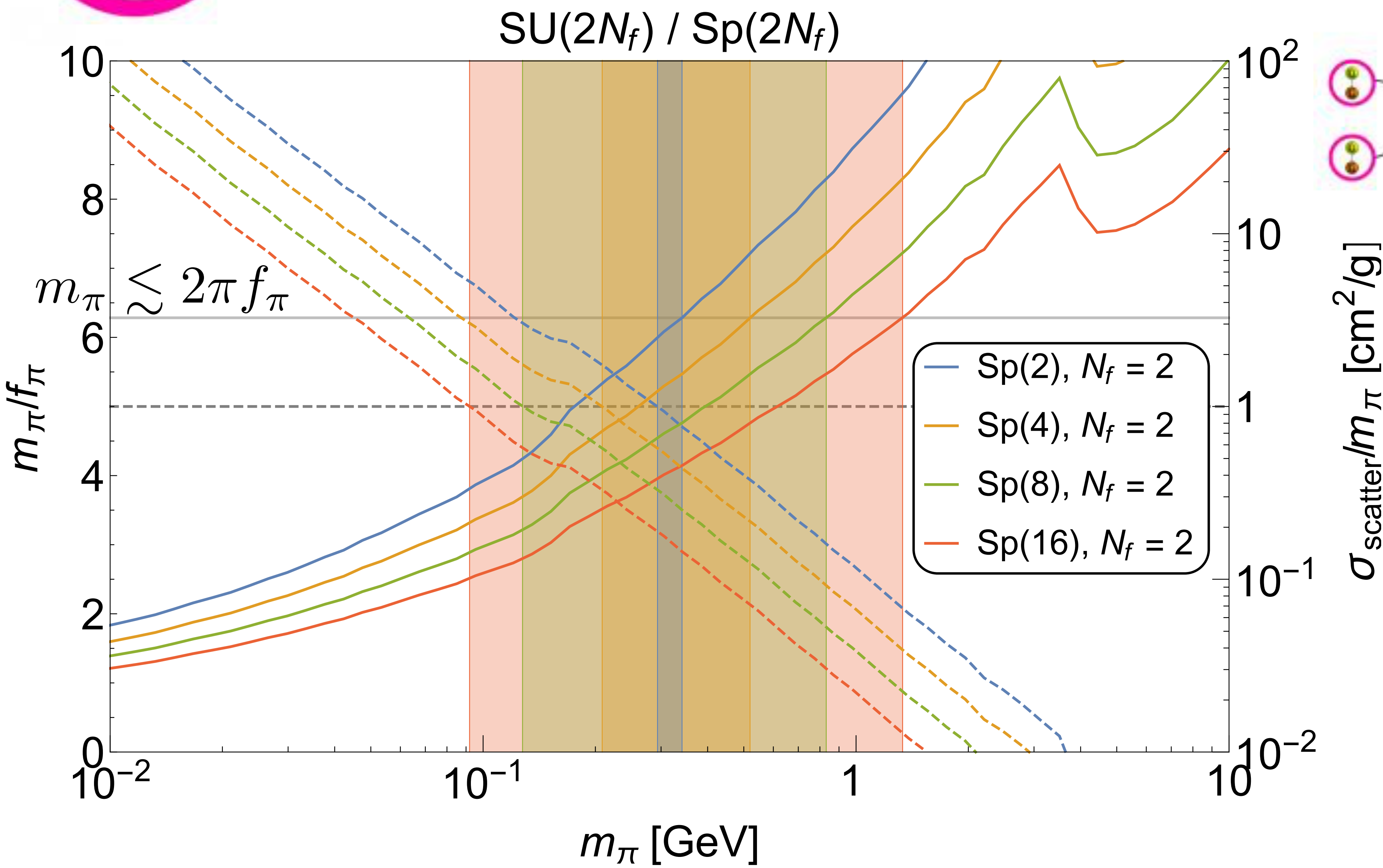
$$+\frac{2N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}\text{Tr}\left[\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right] + \mathcal{O}(\pi^6)$$

The Results









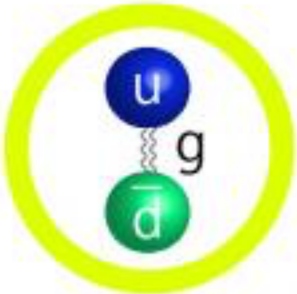
Solid curves: solution to Boltzmann eq.

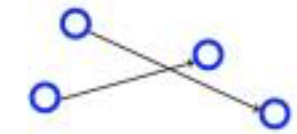
Dashed curves: along that solution

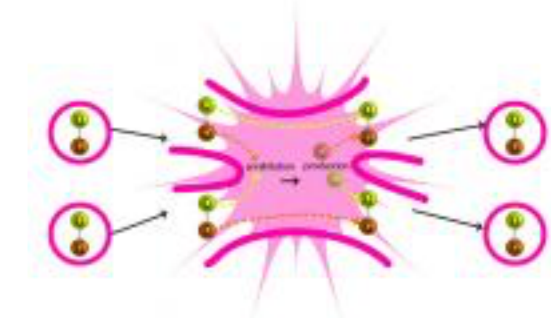
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

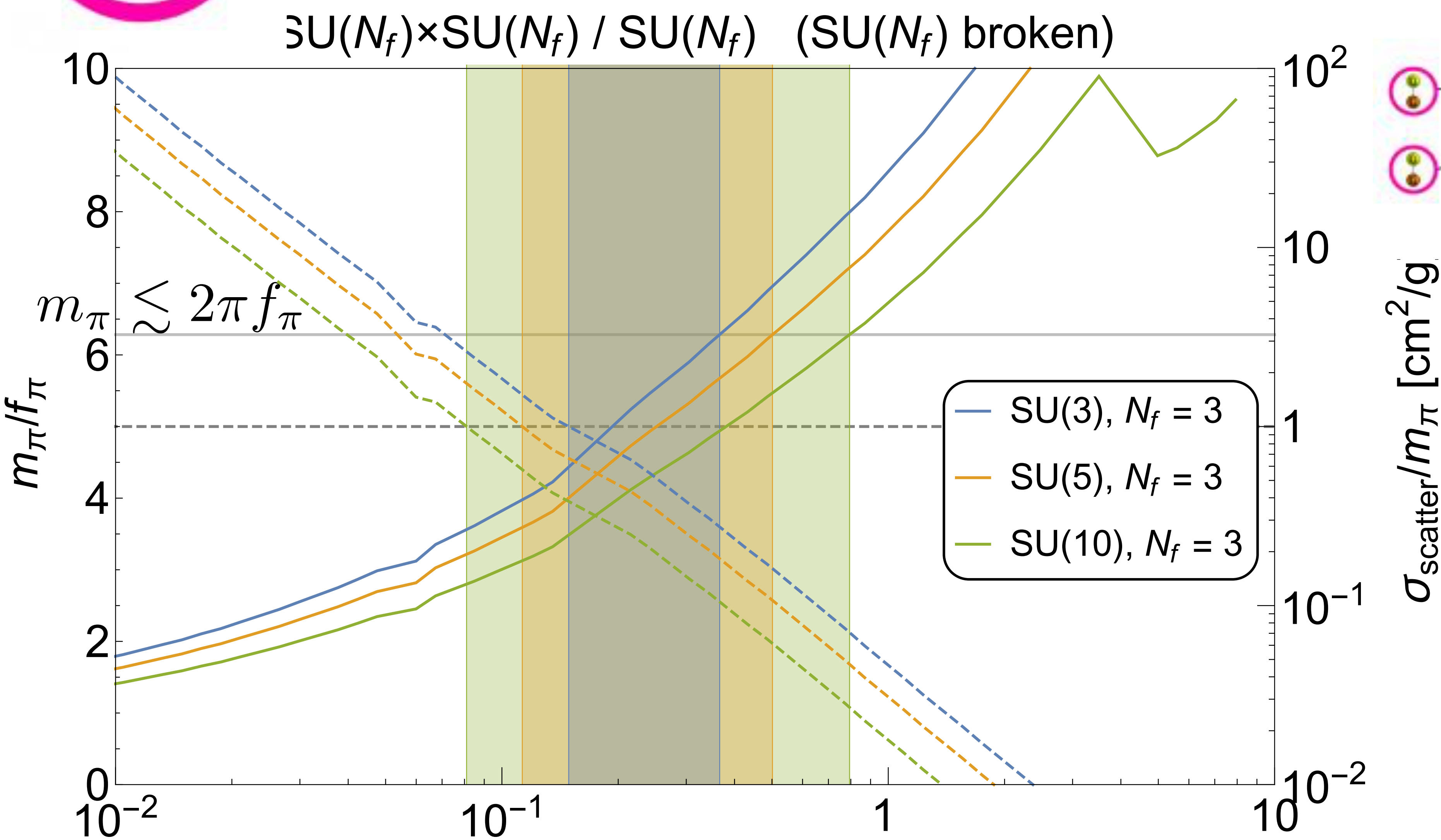
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

The Results









can be a part of twin QCD with N_f=4

Hochberg, Kuflik, HM, arXiv:1805.09345

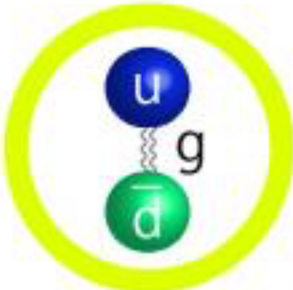
Solid curves: solution to Boltzmann eq.

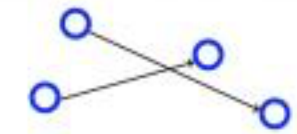
Dashed curves: along that solution

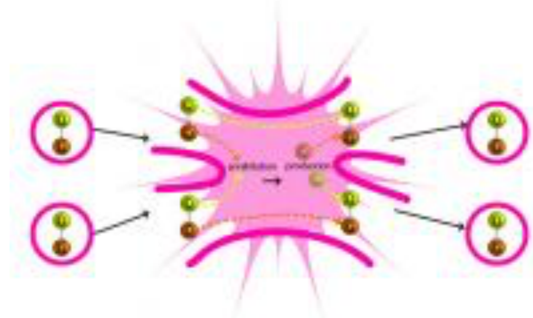
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

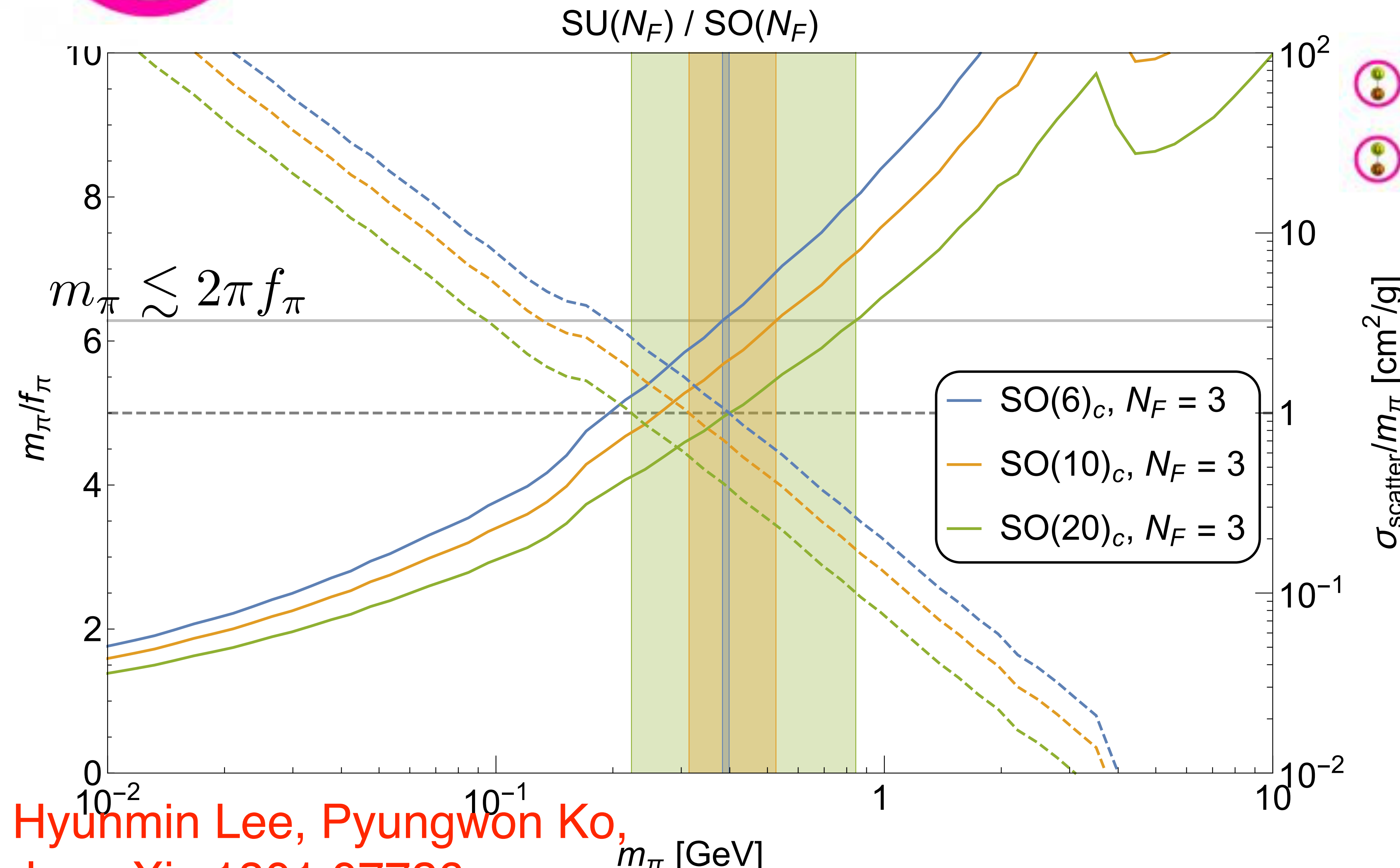
$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

The Results









Soo-Min Choi, Hyunmin Lee, Pyungwon Ko, Alexander Natale, arXiv:1801.07726,
vector mesons help enlarge parameter space

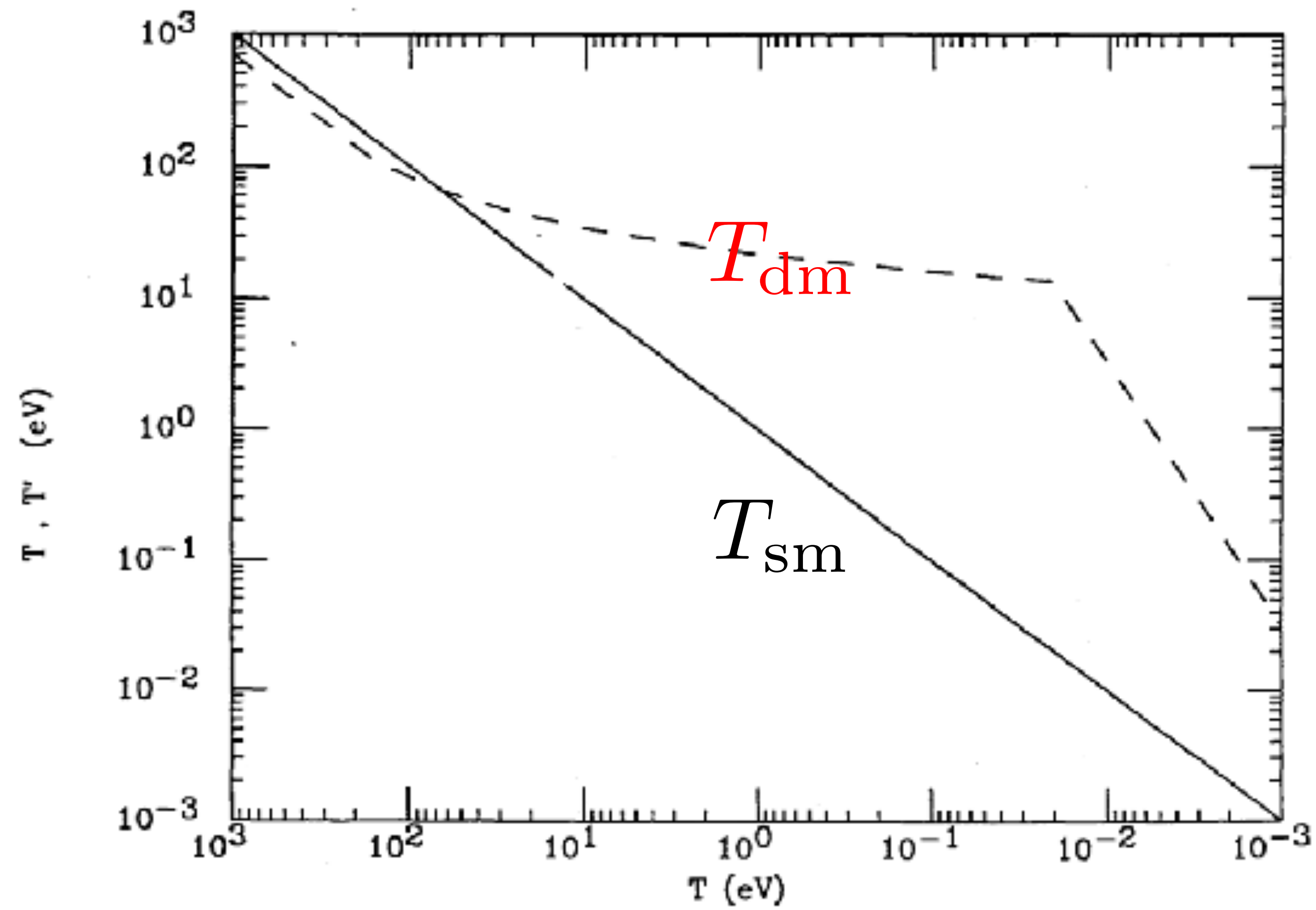
Solid curves: solution to Boltzmann eq.

Dashed curves: along that solution

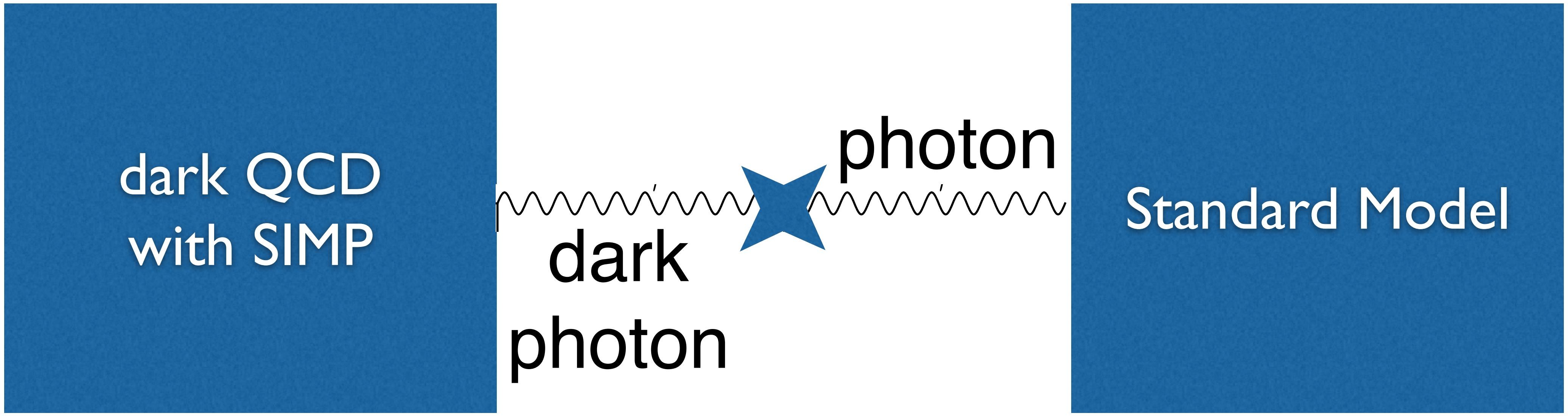
$$\frac{m_\pi}{f_\pi} \propto m_\pi^{3/10}$$

$$\frac{\sigma_{\rm scatter}}{m_\pi} \propto m_\pi^{-9/5}$$

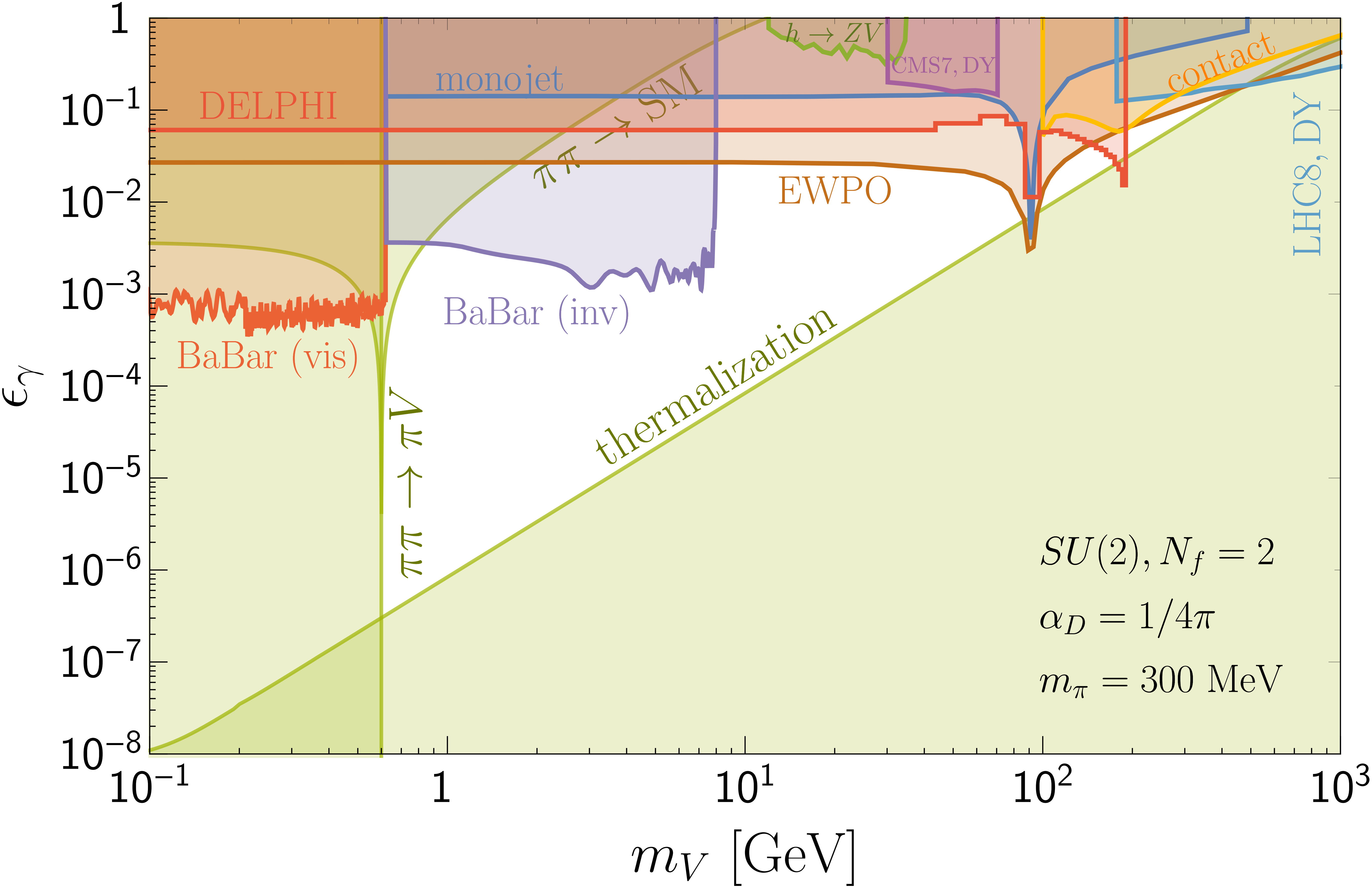
need couplings to SM



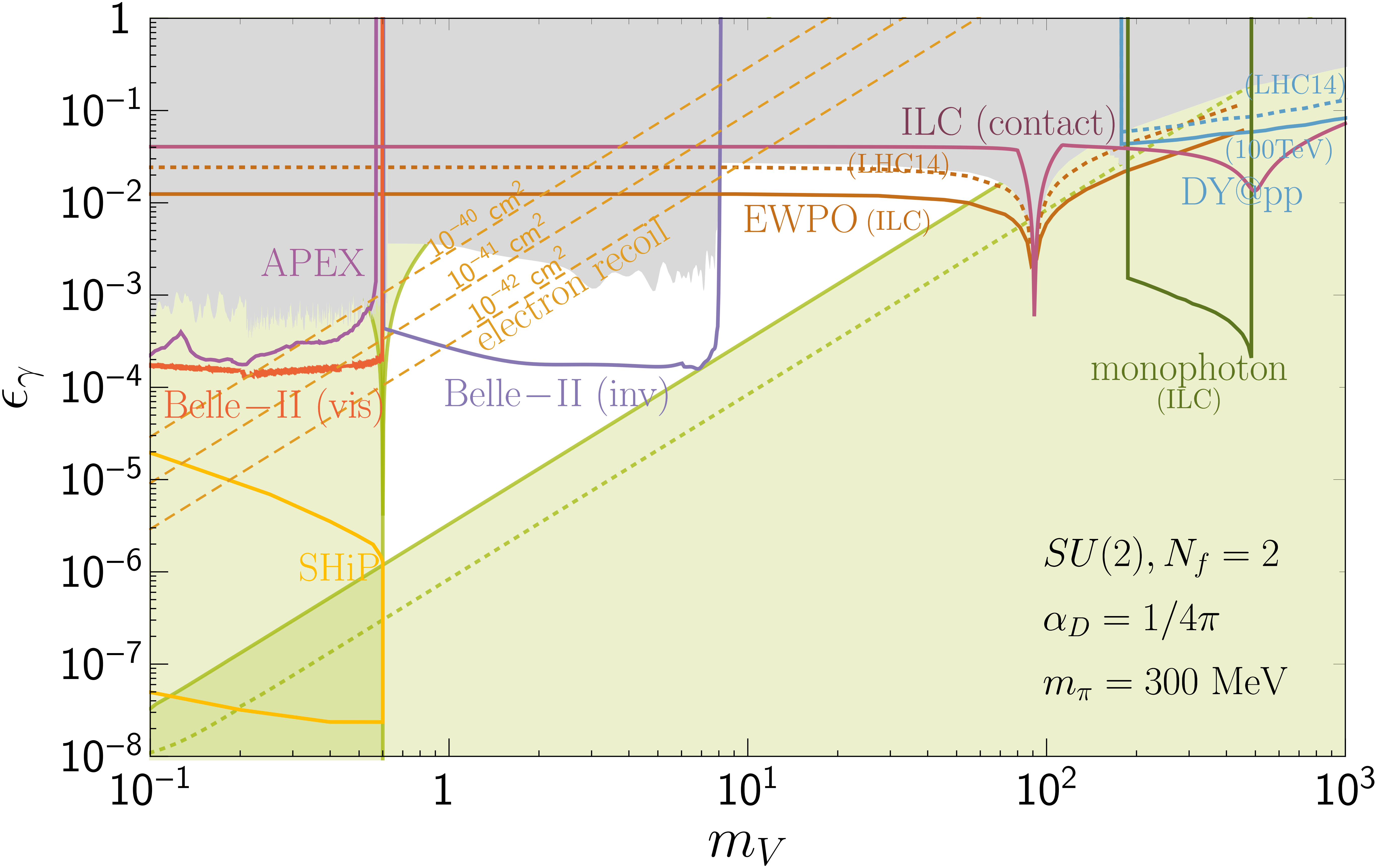
Carlson, Hall and Machacek, Astrophys. J. 398, 43 (1992)



also axion portal: Hochberg, Kuflik, McGehee, HM, Schutz, 1806.10139

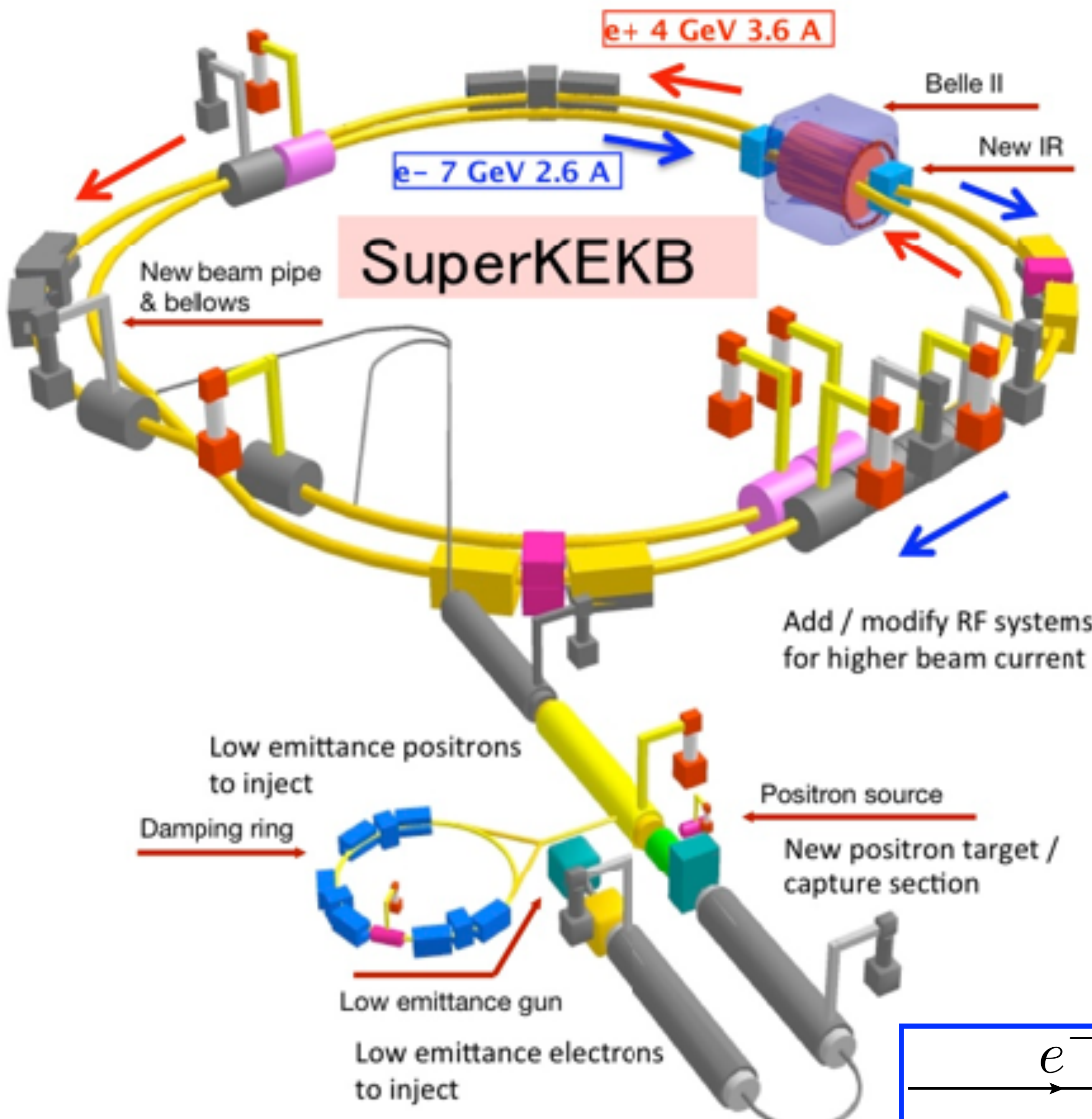


Hochberg, Kuflik, HM, arXiv:1512.07917

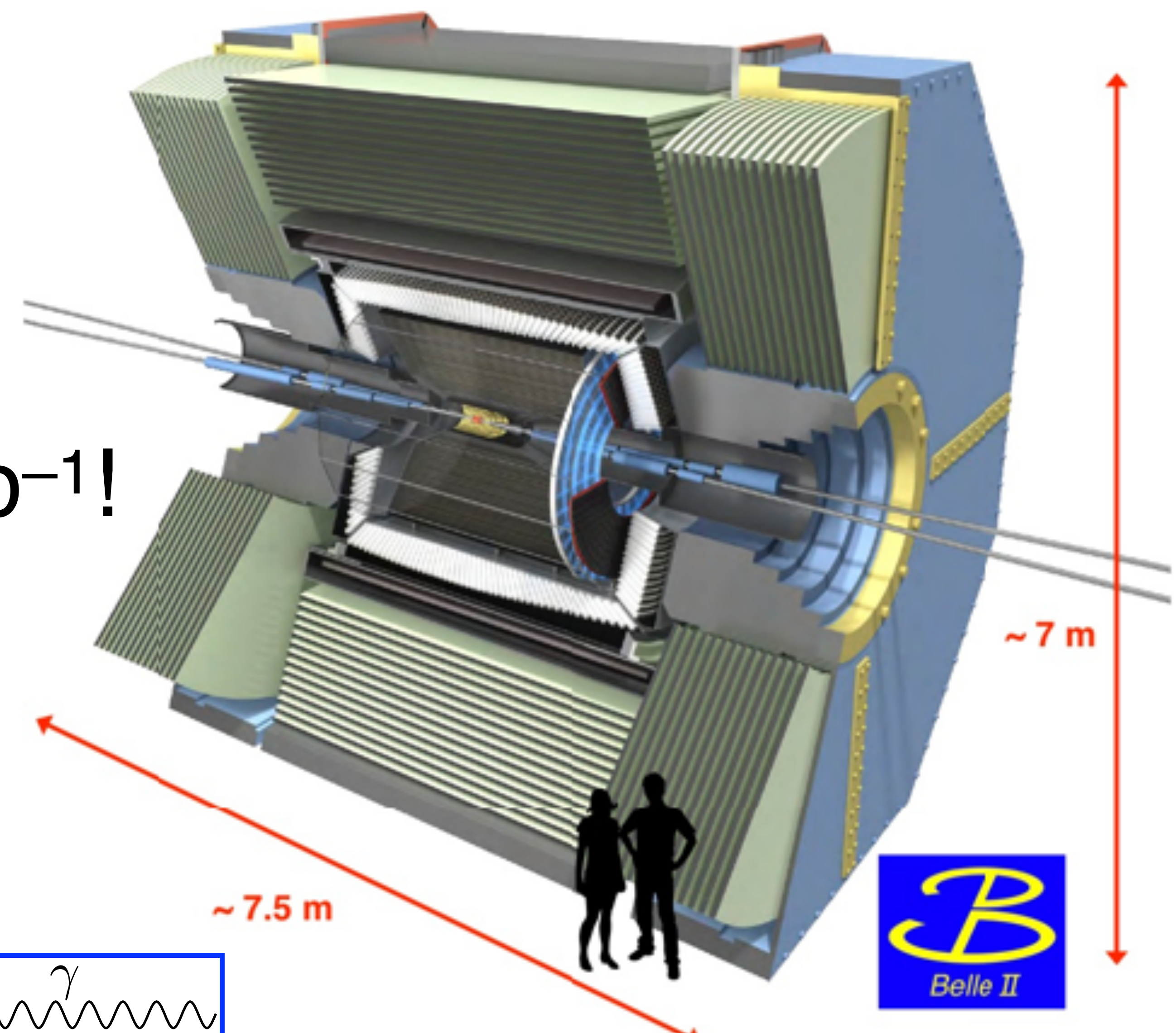


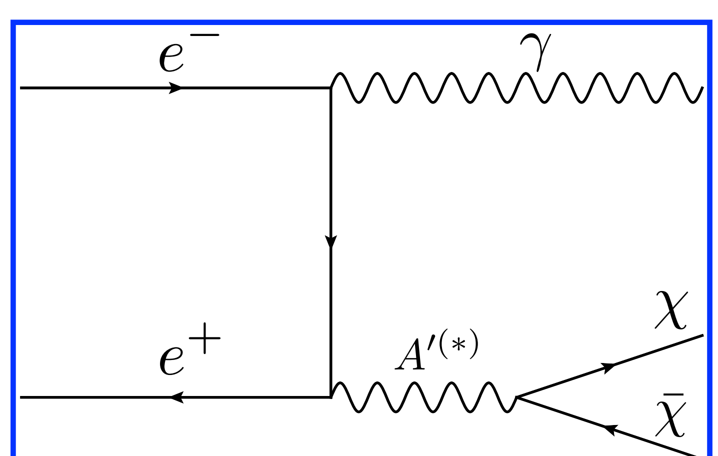
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
ϵ_γ
10^{-1}
1
10^{1}
10^{2}
10^{3}
m_V
APEX
Belle−II (vis)
Belle−II (inv)
SHiP
10^{-40} cm^2
10^{-41} cm^2
10^{-42} cm^2
electron recoil
ILC (contact)
(LHC14)
EWPO (ILC)
(LHC14)
(100TeV)
DY@pp
monophoton
(ILC)
$SU(2), N_f = 2$
$\alpha_D = 1/4\pi$
$m_\pi = 300$ MeV

Super KEK B & Belle II

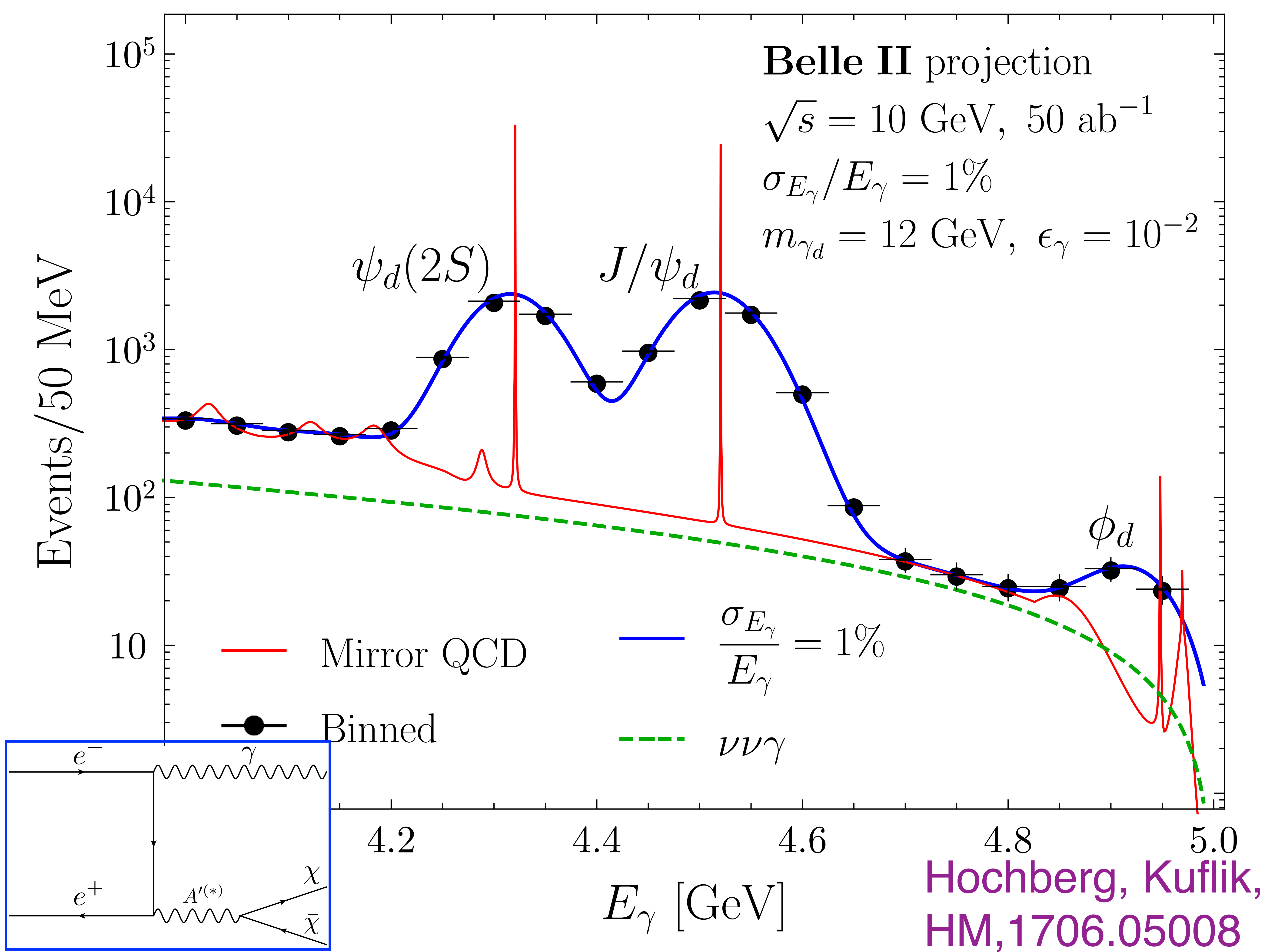


50 ab^{-1}!

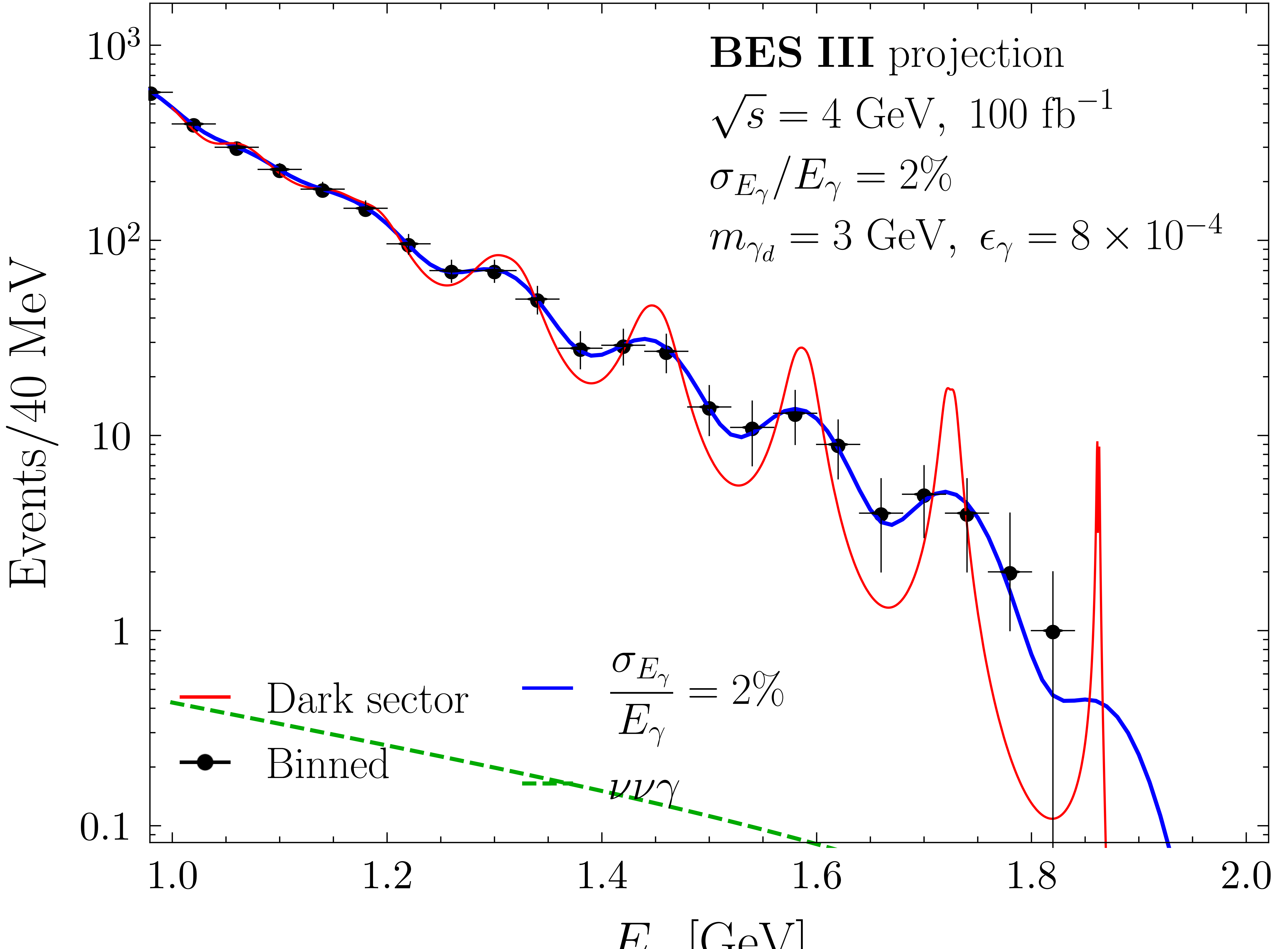




$$E_\gamma = \frac{\sqrt{s}}{2}\left(1 - \frac{M_{\mathrm{inv}}^2}{s}\right)$$

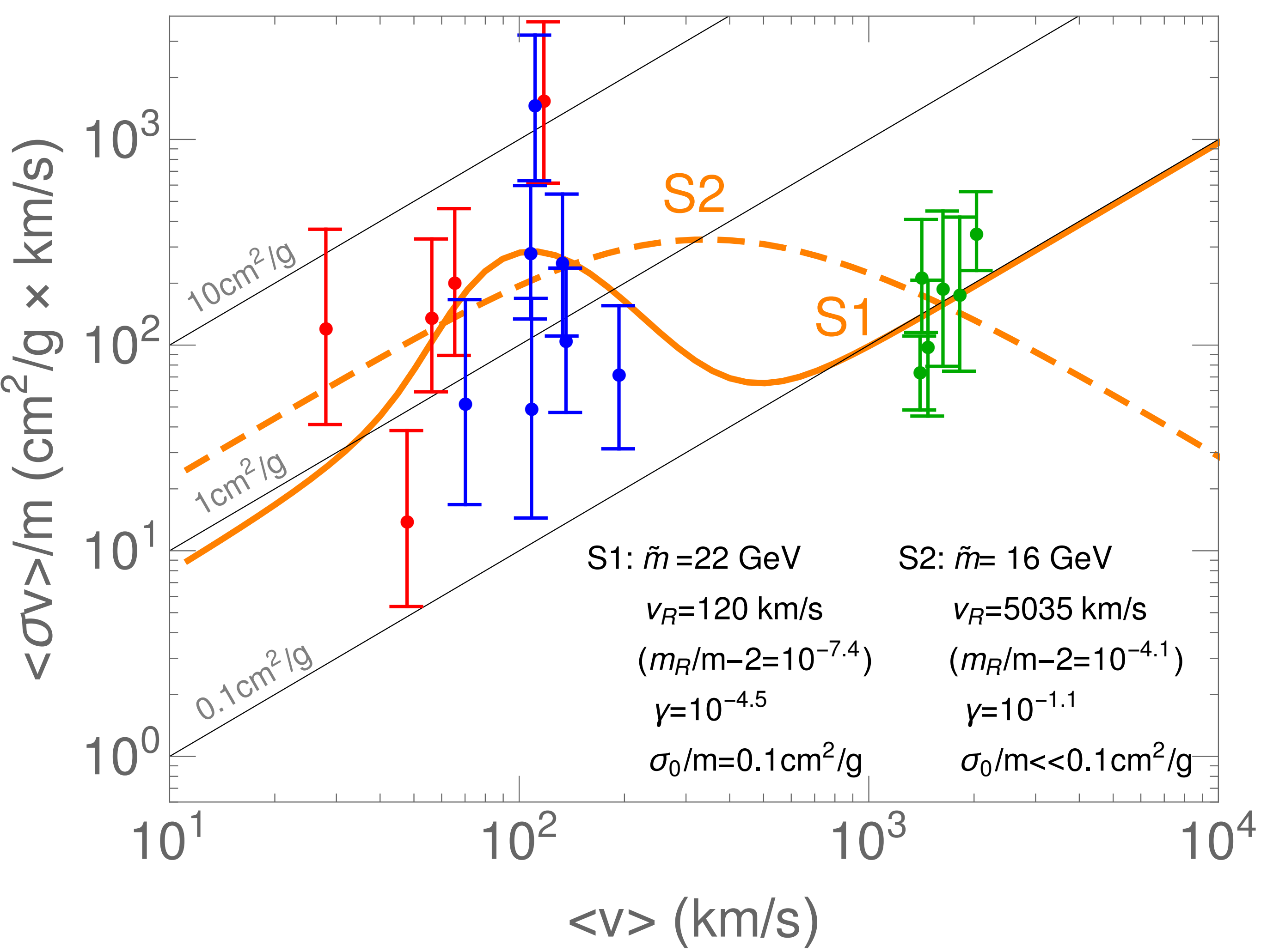


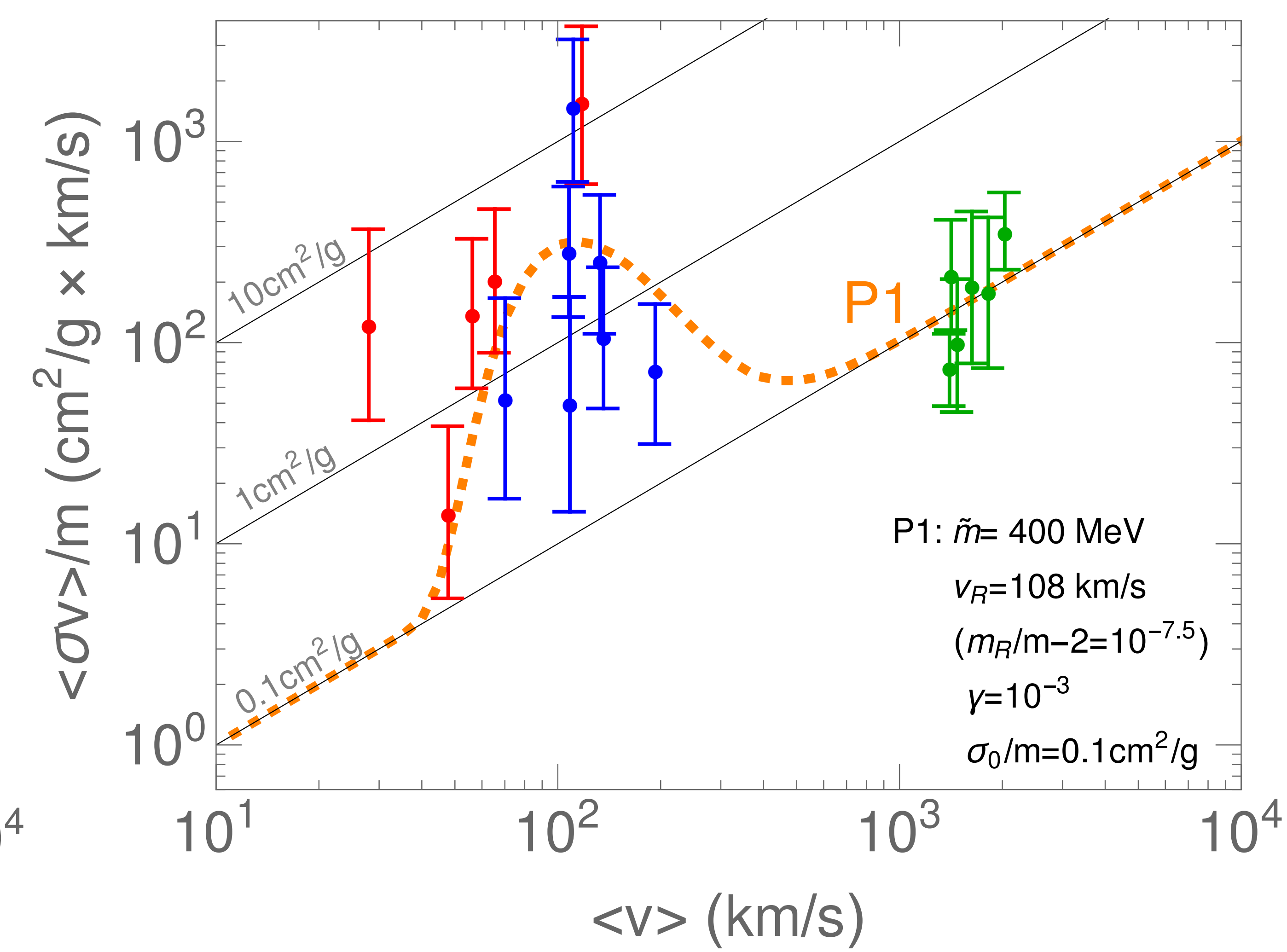
Hochberg, Kuflik, HM,1706.05008



BES III projection
$\sqrt{s} = 4$ GeV, 100 fb^{-1}
$\sigma_{E_\gamma}/E_\gamma = 2\%$
$m_{\gamma_d} = 3$ GeV, $\epsilon_\gamma = 8 \times 10^{-4}$
Dark sector
Binned
$\frac{\sigma_{E_\gamma}}{E_\gamma} = 2\%$
$\nu\nu\gamma$
Events/40 MeV
E_γ [GeV]
10^3
10^2
10
1
0.1
1.0
1.2
1.4
1.6
1.8
2.0

Resonant scattering





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

large low-energy velocity-dependent σ

$n\,p \rightarrow n\,p$

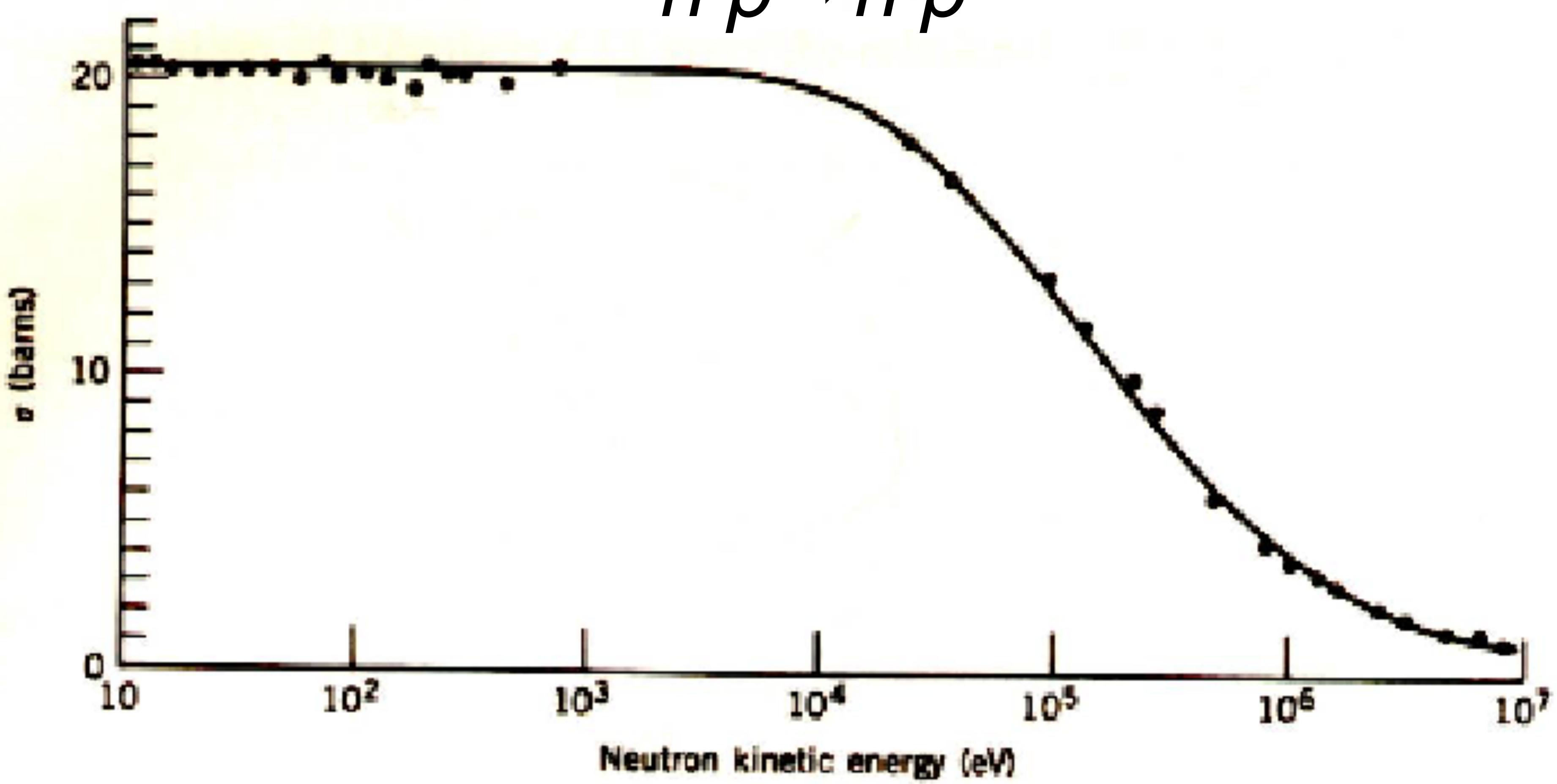


Figure 4.6 The neutron–proton scattering cross section at low energy. Data taken from a review by R. K. Adair, *Rev. Mod. Phys.* **22**, 249 (1950), with additional recent results from T. L. Houk, *Phys. Rev. C* **3**, 1886 (1970).

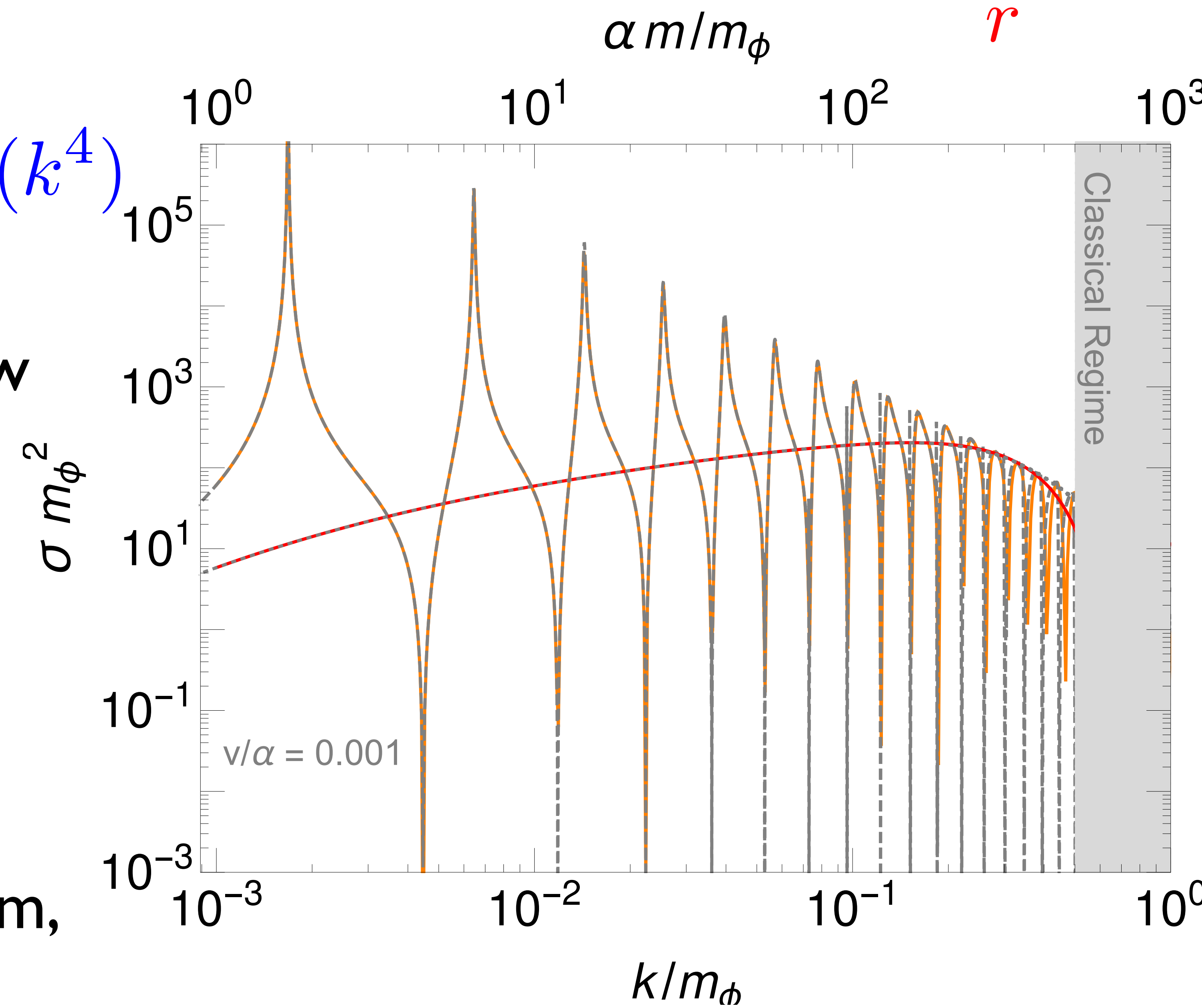
Unified description of SIDM

- Hans Bethe: effective range theory

$$k \cot\delta = -\frac{1}{a} + \frac{1}{2} r_e k^2 + O(k^4)$$

- only two parameters to describe scattering at low velocities
- fully unitary and non-perturbative
- covers bound state, resonance, virtual level
- one more parameter accommodates continuum, anti-resonance
- ideal for simulations!

$$V = -\alpha \frac{e^{-m_\phi r}}{r}$$



Xiaoyong Chu, Camilo Garcia-Cely, HM, appeared *today*

Why do we exist at all?

—Baryogenesis and Inflation–

Hitoshi Murayama (Berkeley & Kavli IPMU)

Summer Institute 2019 Gangneung

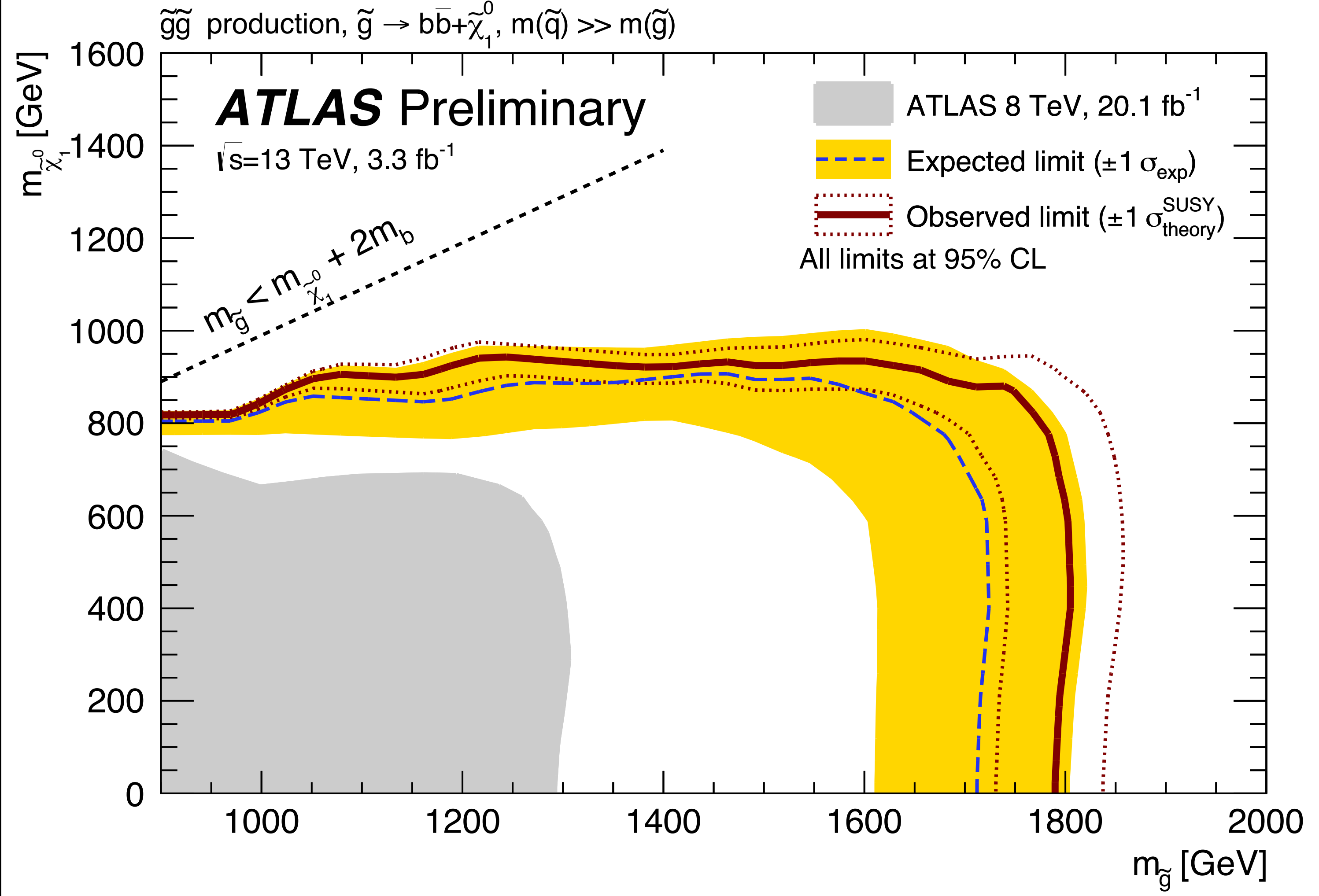
August 19, 2019

東京大学 THE UNIVERSITY OF TOKYO

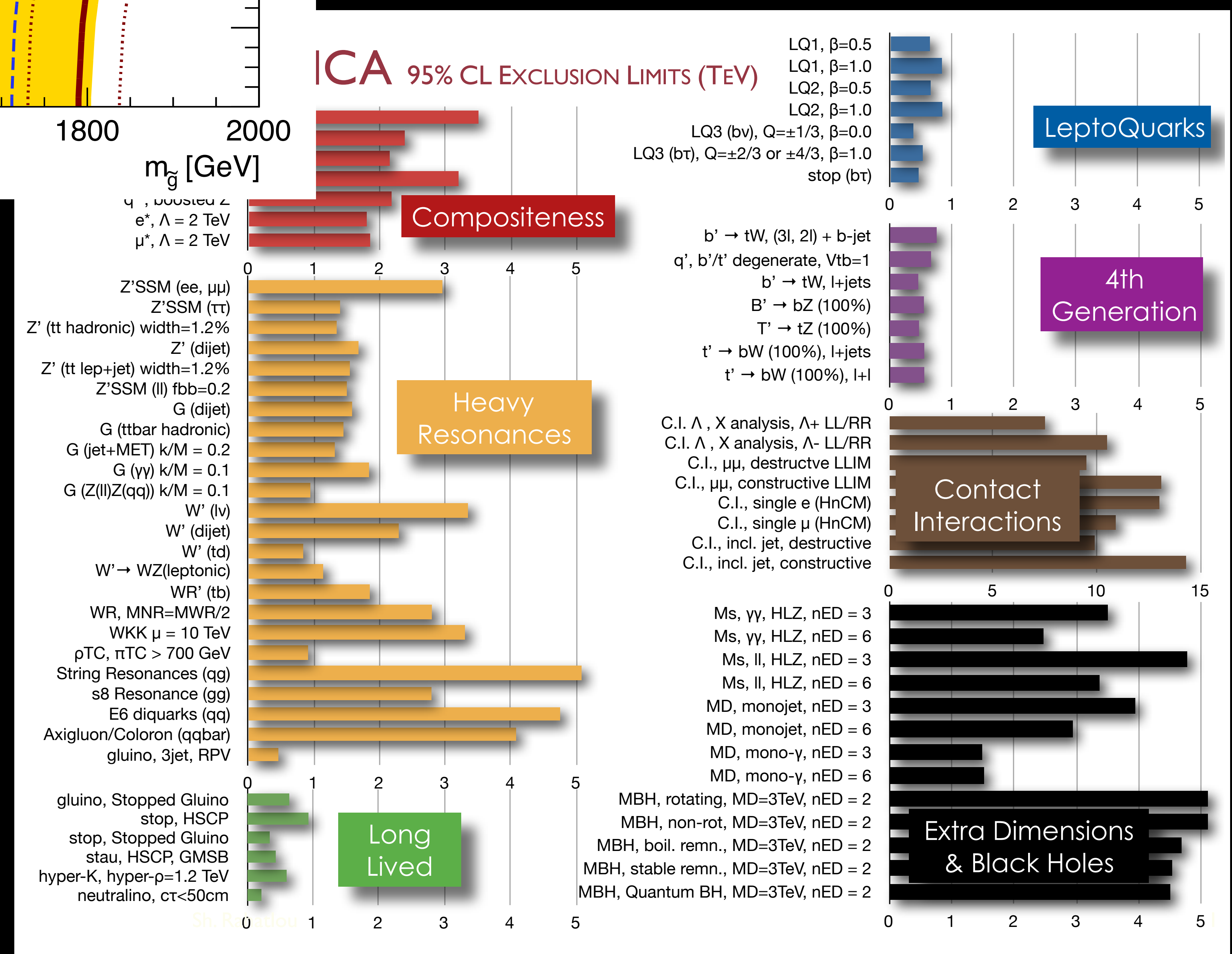
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

KAVLI IPMU

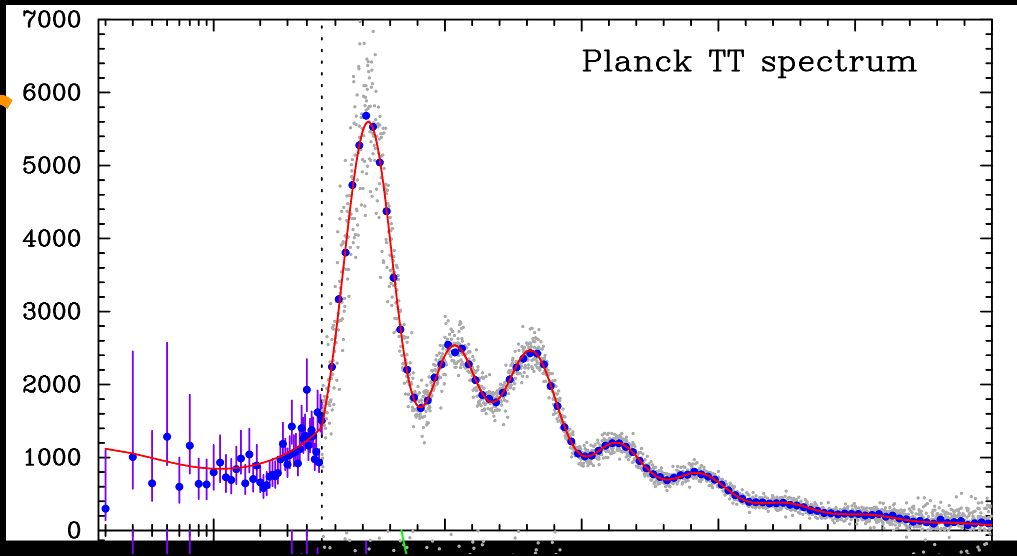


no sign of
new physics
that explains Higgs!



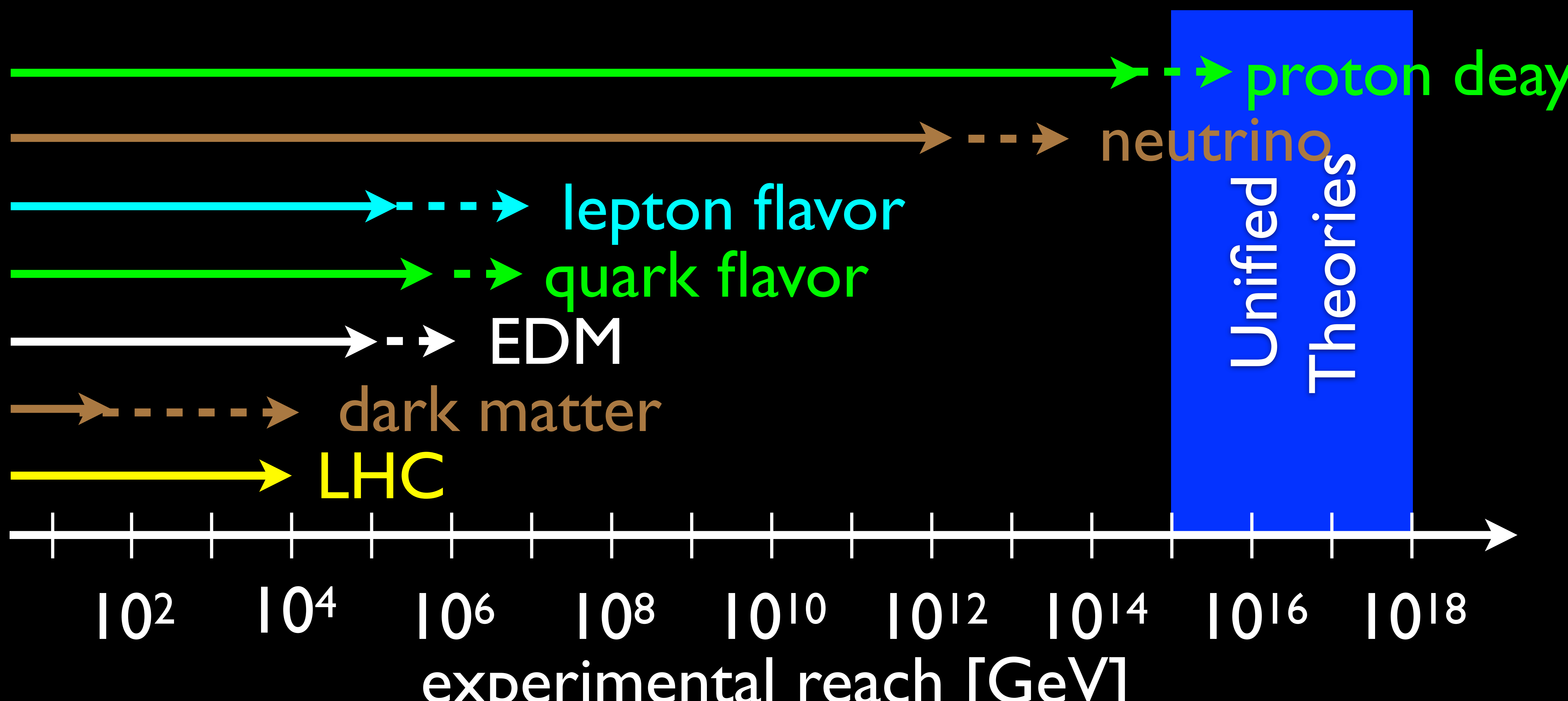
Five evidences for physics beyond SM

- 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...

Power of Expedition



(with significant simplifying assumptions)

with Zoltan Ligeti

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

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

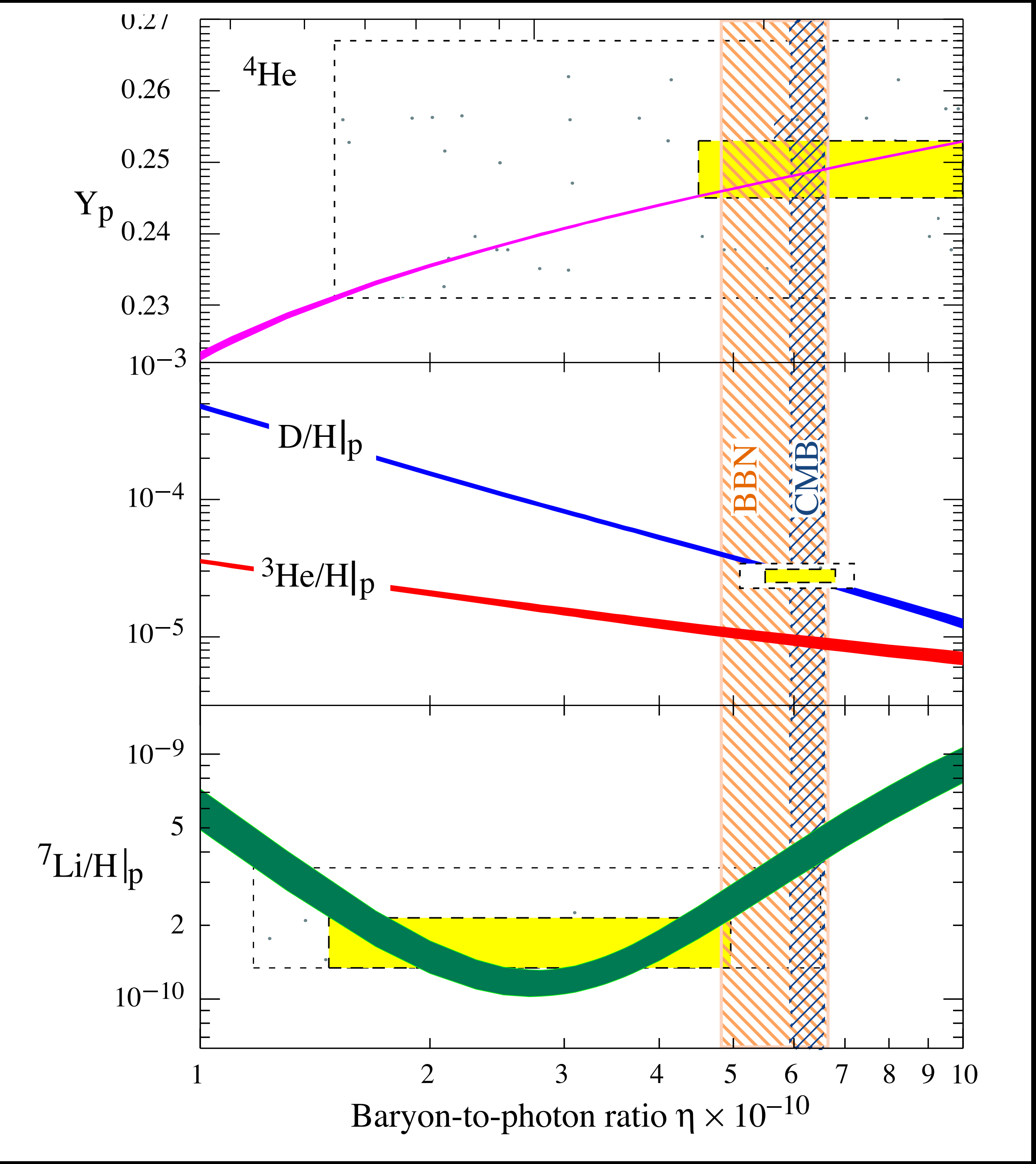
$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda}, (H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \cdots$$

unique role of m_ν

- Lowest order effect of physics at short distances
- tiny effect: $(m_\nu/E_\nu)^2 \approx (0.1\text{eV}/\text{GeV})^2 \approx 10^{-20}$!
- 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

BBN & CMB

- At T>MeV, the soup of e^+, e^-, ν, $\bar{\nu}$
- 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

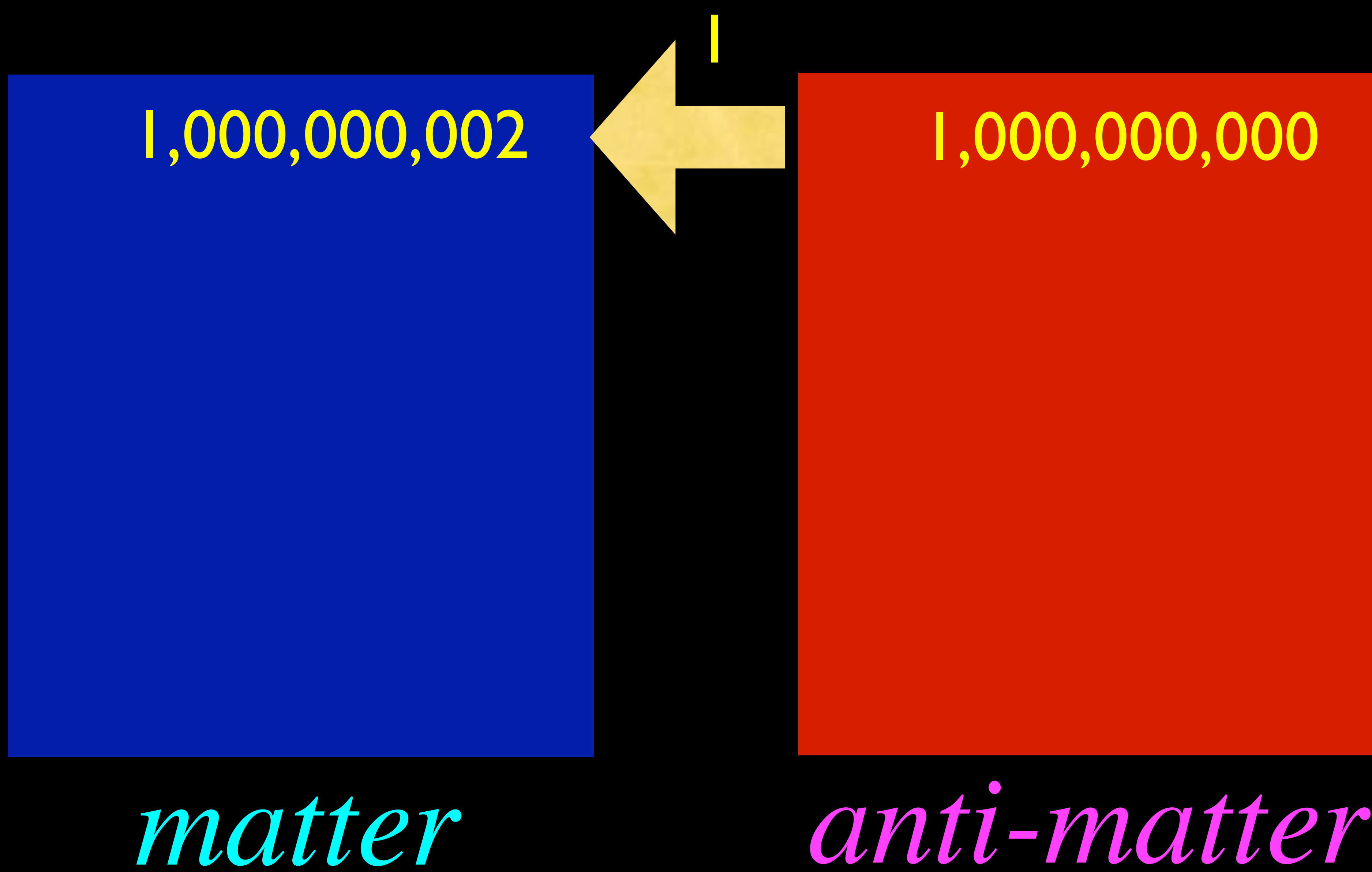


EW baryogenesis?
⇒Chang Sub Shin

Beginning of Universe

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

fraction of second later



turned an anti-matter out of a billion to matter

Universe Now

2

us

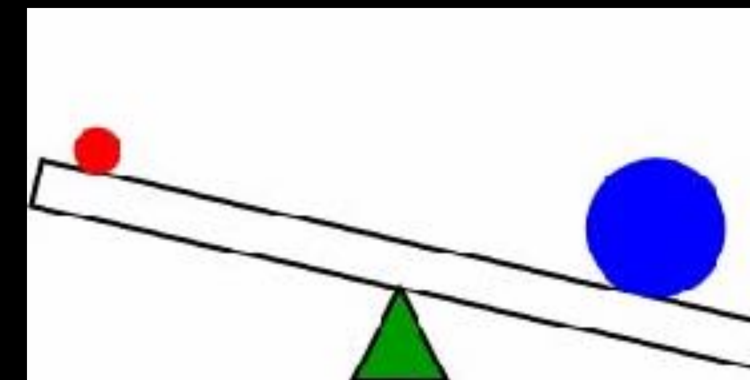
matter *anti-matter*

This must be how we survived the Big Bang!

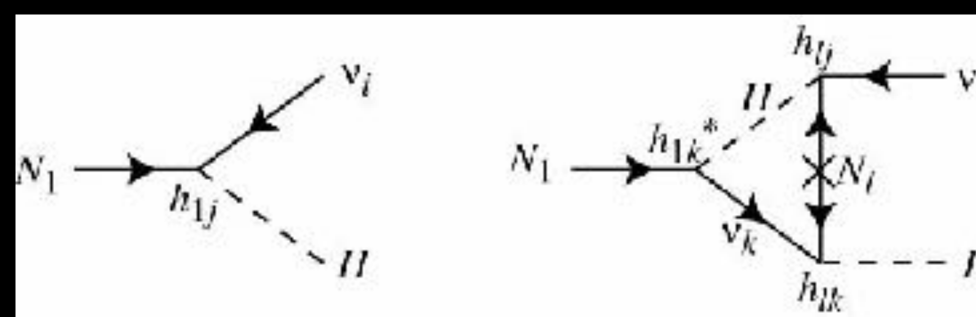
Fukugita

Yanagida

Seesaw



- Seesaw mechanism explains
  - small but finite neutrino masses $m_\nu \sim v^2 / M_R$
  - baryon asymmetry of the Universe through leptogenesis



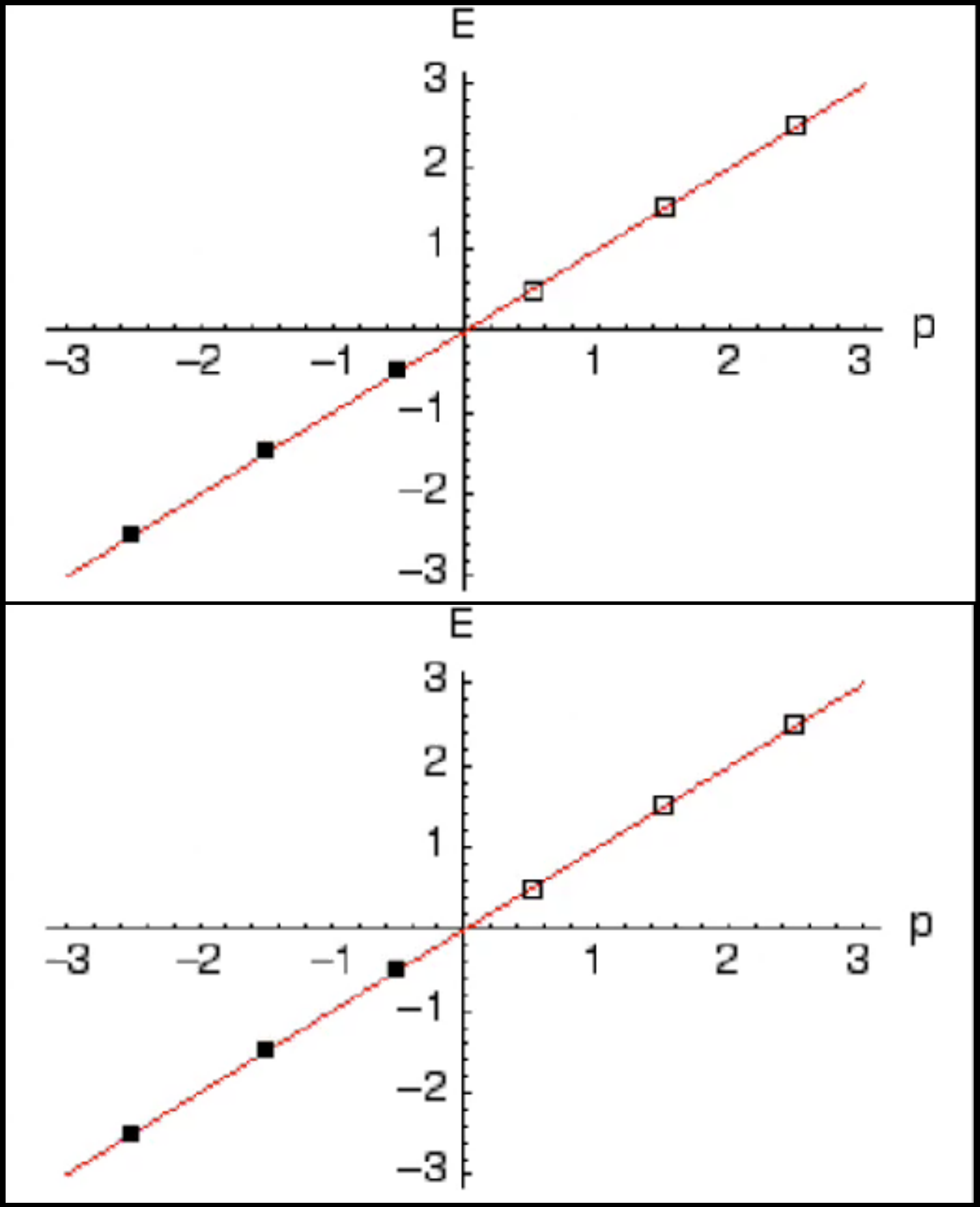
$$\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H^*) \propto \Im m(h_{1j} h_{1k} h^*_{lk} h^*_{lj})$$

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

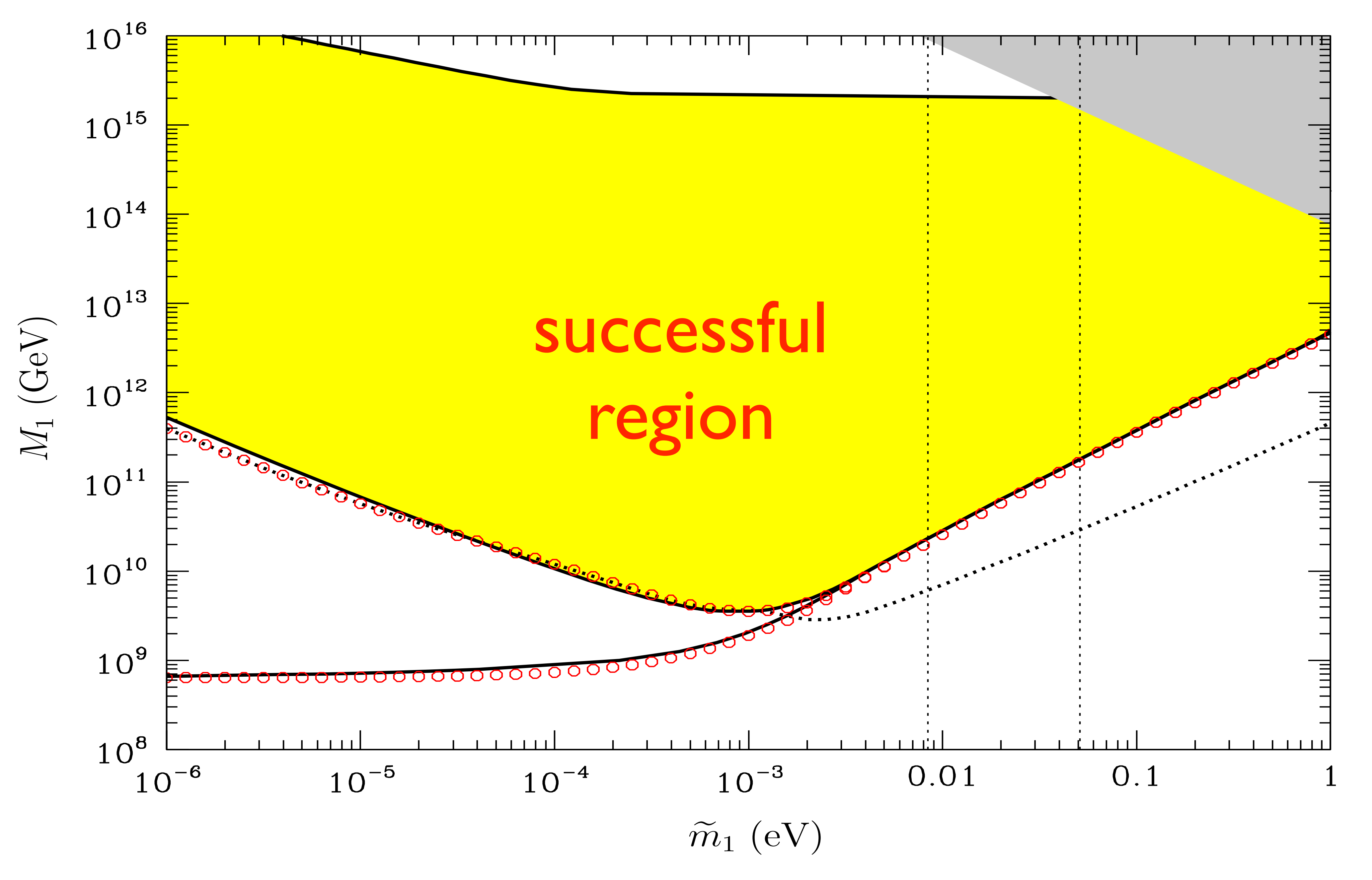
Anomaly!

- *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

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



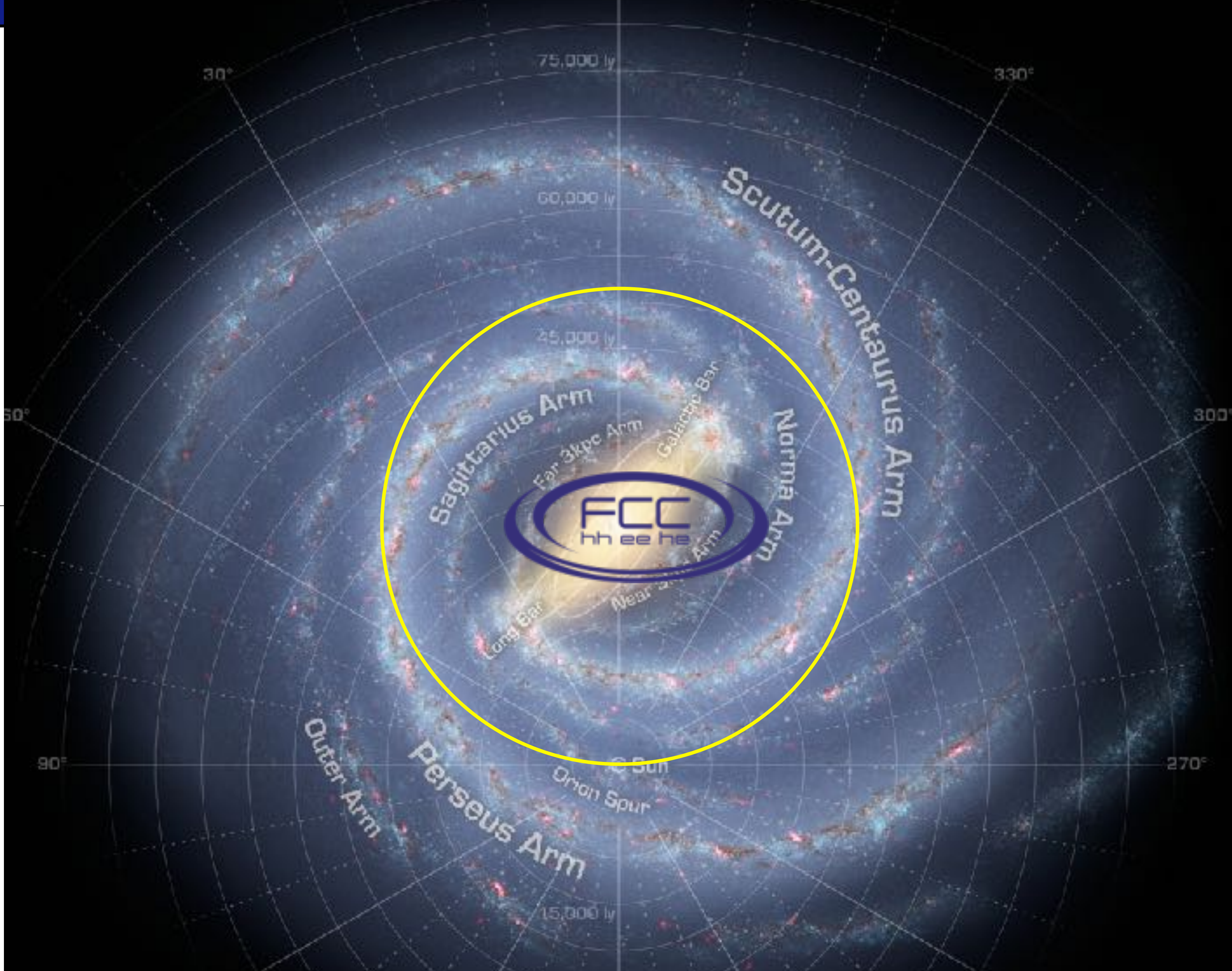
Leptogenesis



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

di Bari, Plümacher, Buchmüller

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?*

Excitement

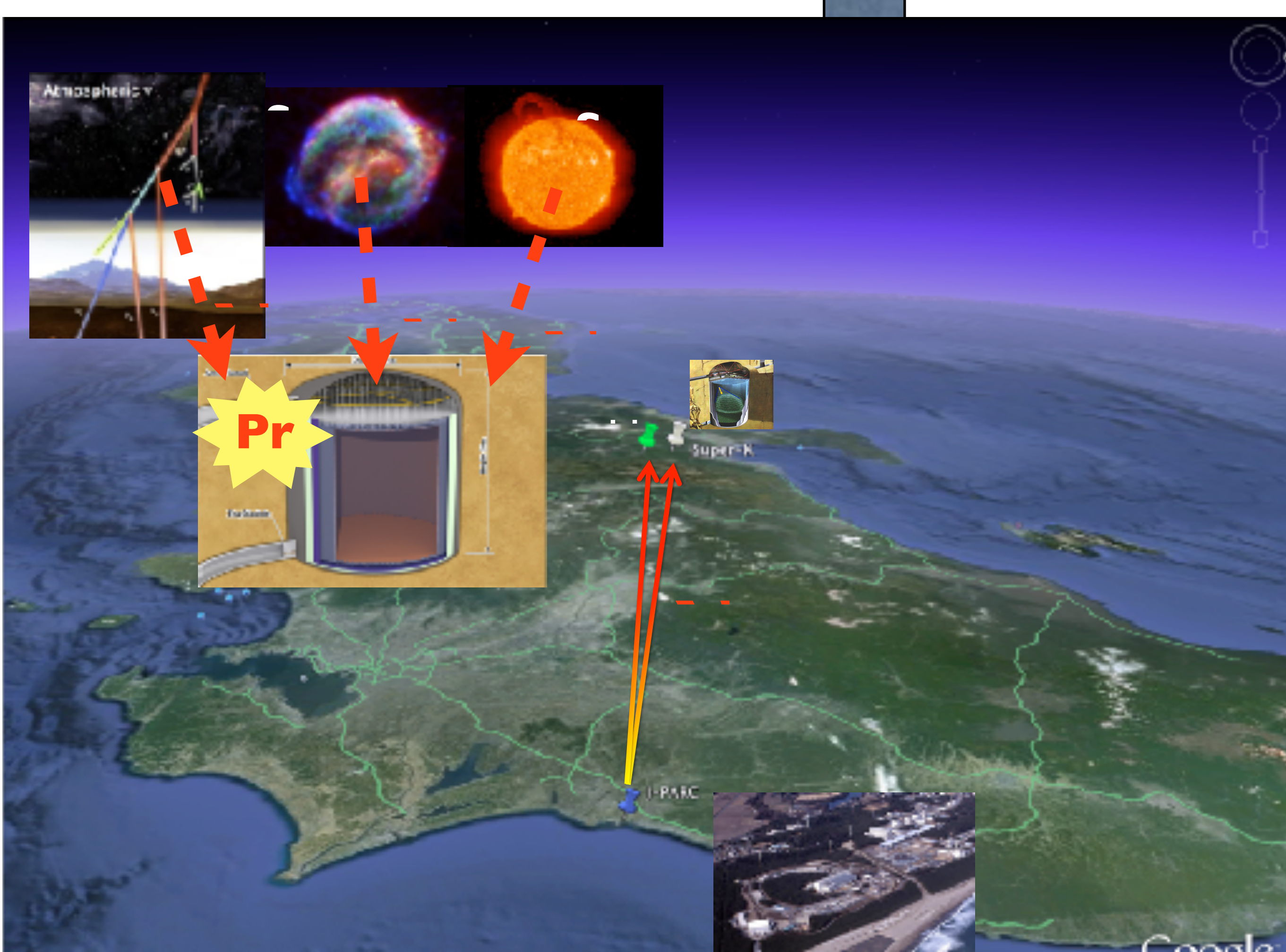
- CP violation in neutrino sector may be observable with conventional technique

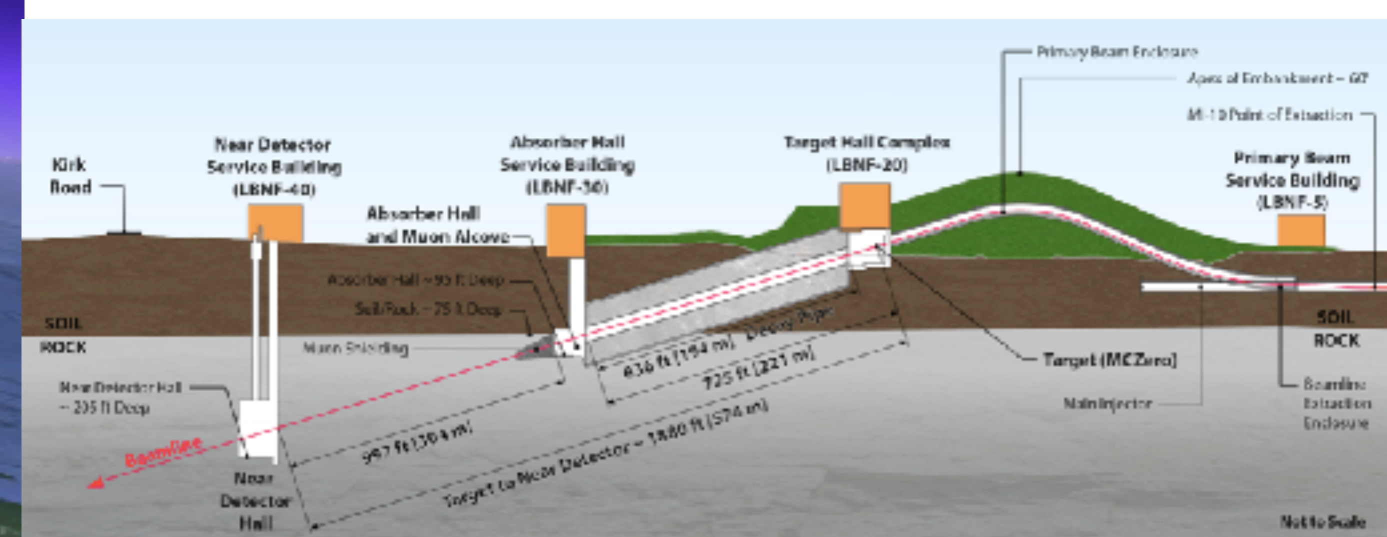
$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 \boxed{s_{12}} c_{12} \boxed{s_{13}} c_{13}^2 \boxed{s_{23}} c_{23} \sin\delta \sin\boxed{\frac{\Delta m^2_{12} L}{4E}} \sin\boxed{\frac{\Delta m^2_{13} L}{4E}} \sin\boxed{\frac{\Delta m^2_{23} L}{4E}}$$

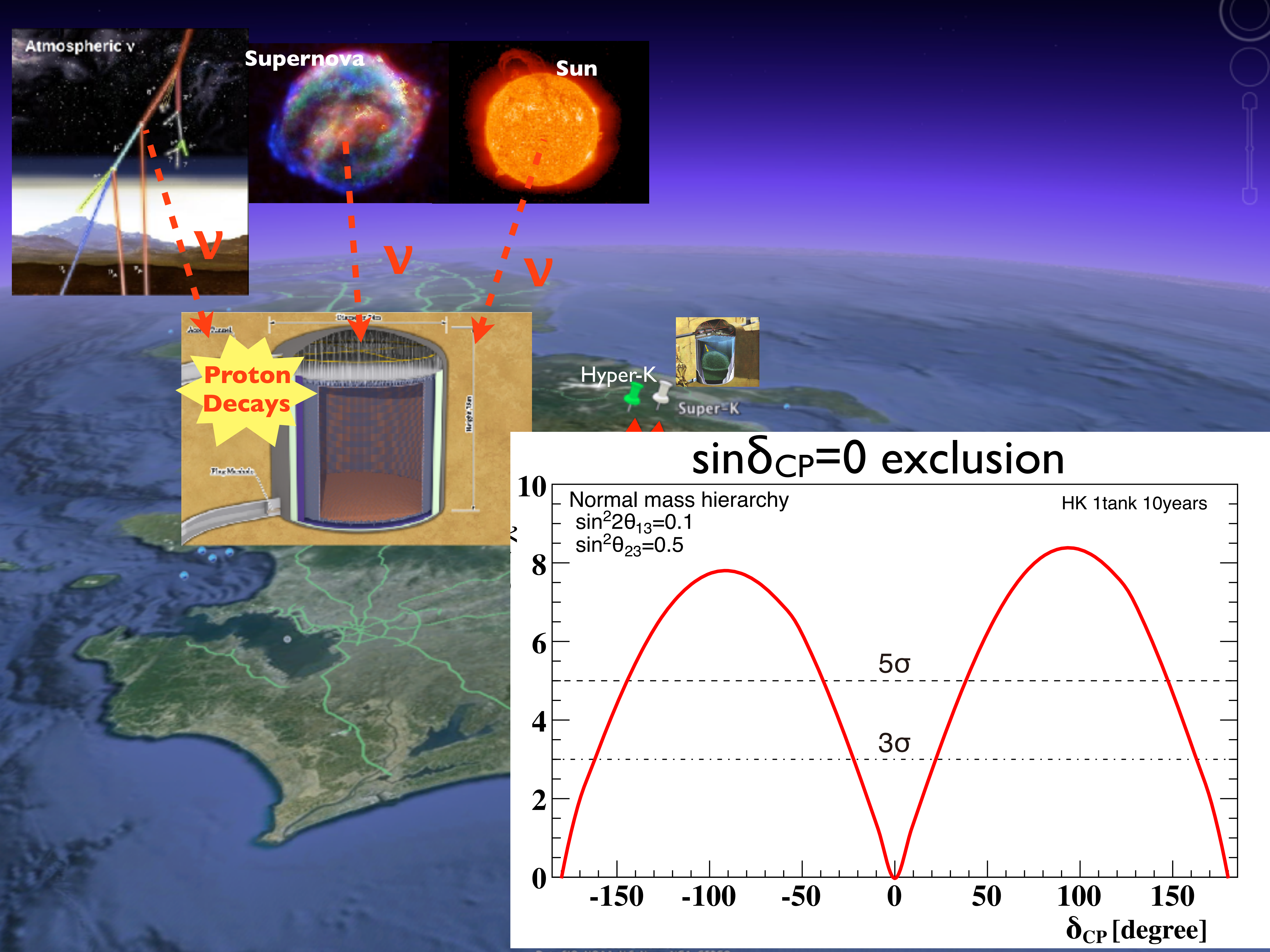
2002
KamLAND
SNO

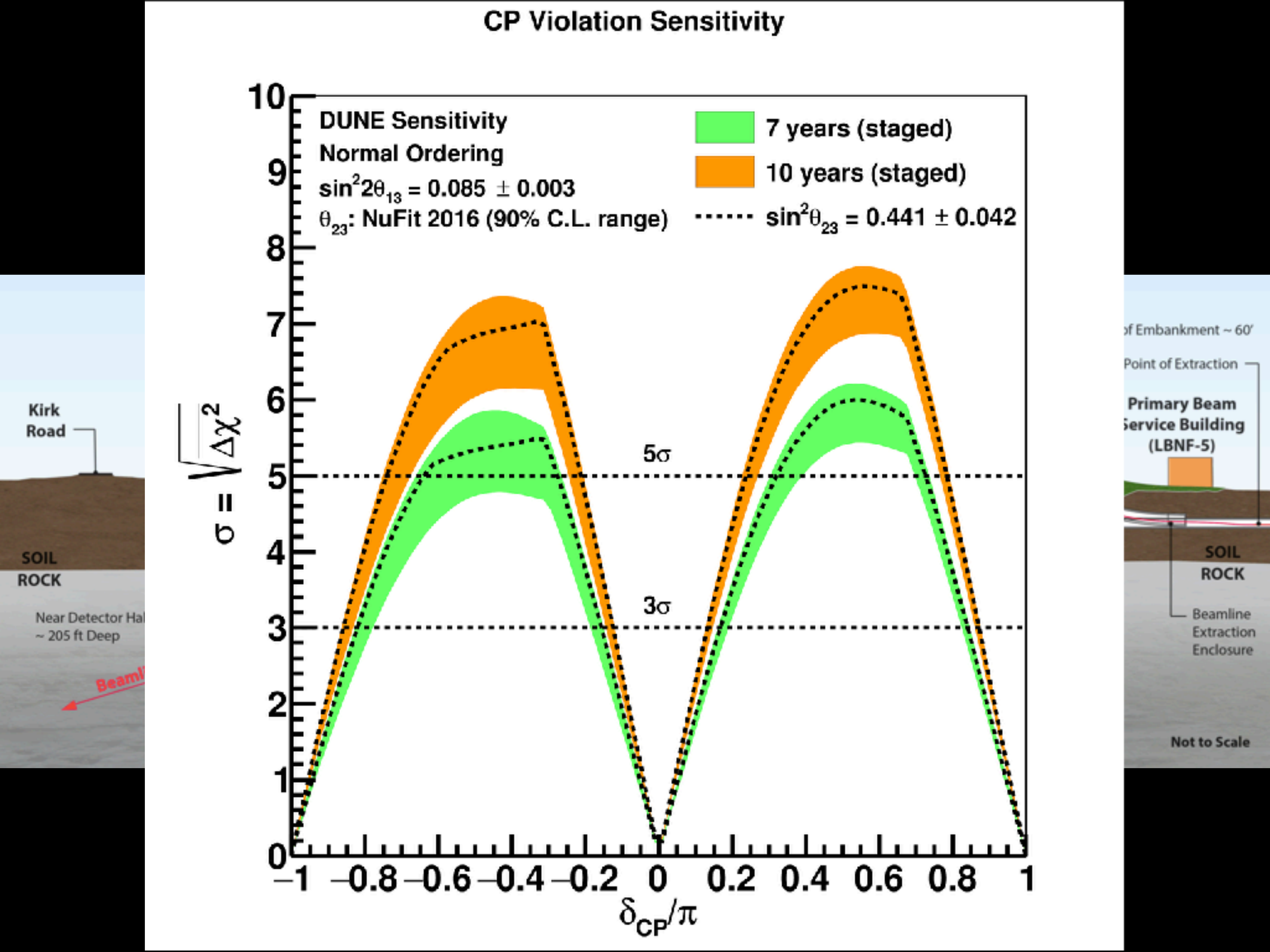
2012
Daya Bay
RENO

1998
Super-K






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

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.

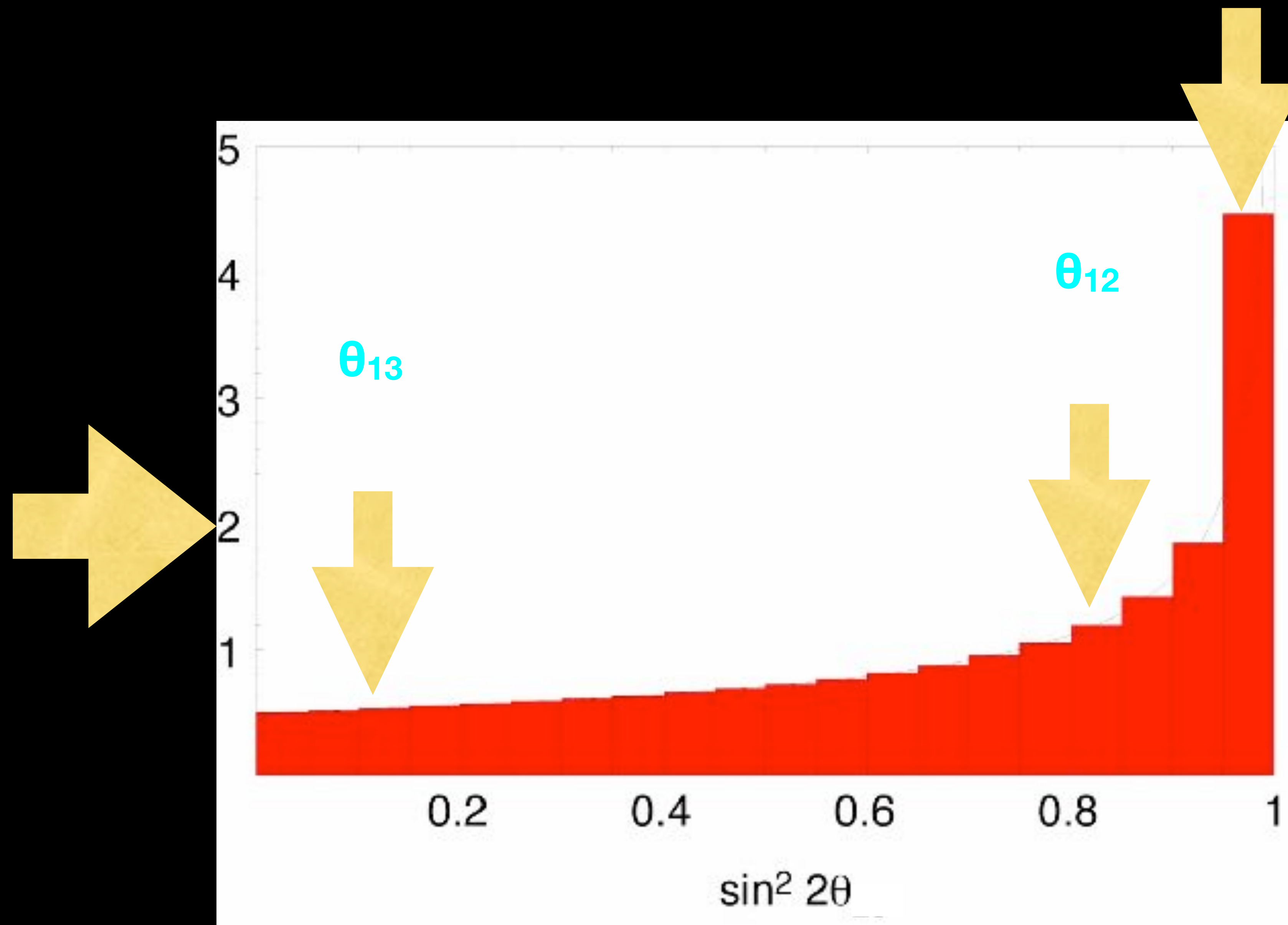
The University of Tokyo pledges to ensure construction of the Hyper-Kamiokande detector commences as scheduled in April 2020. The University of Tokyo has made this decision in recognition of both the project's importance and value both nationally and internationally.

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.

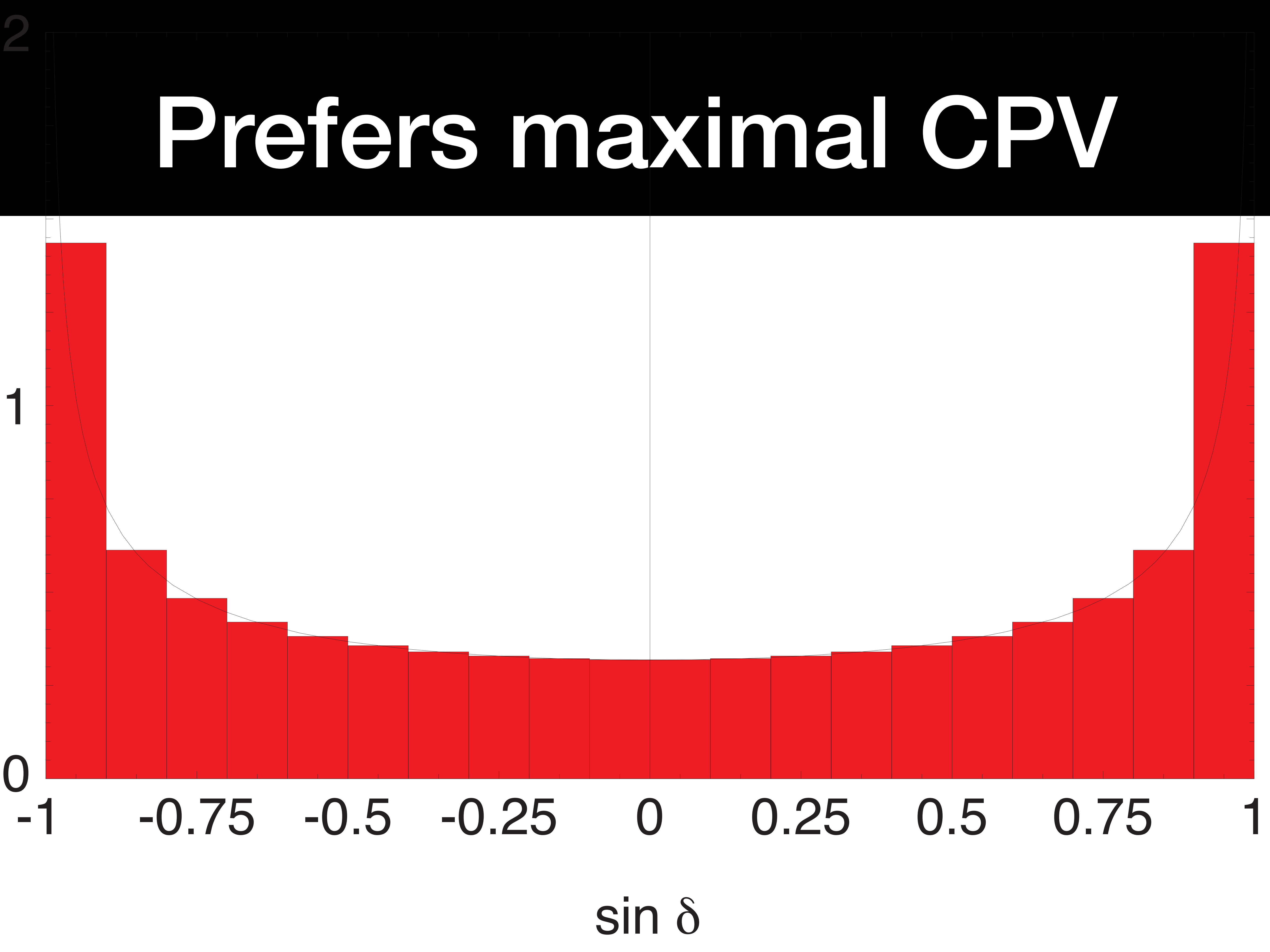
Makoto Gonokami

Makoto Gonokami
President, The University of Tokyo

anarchy



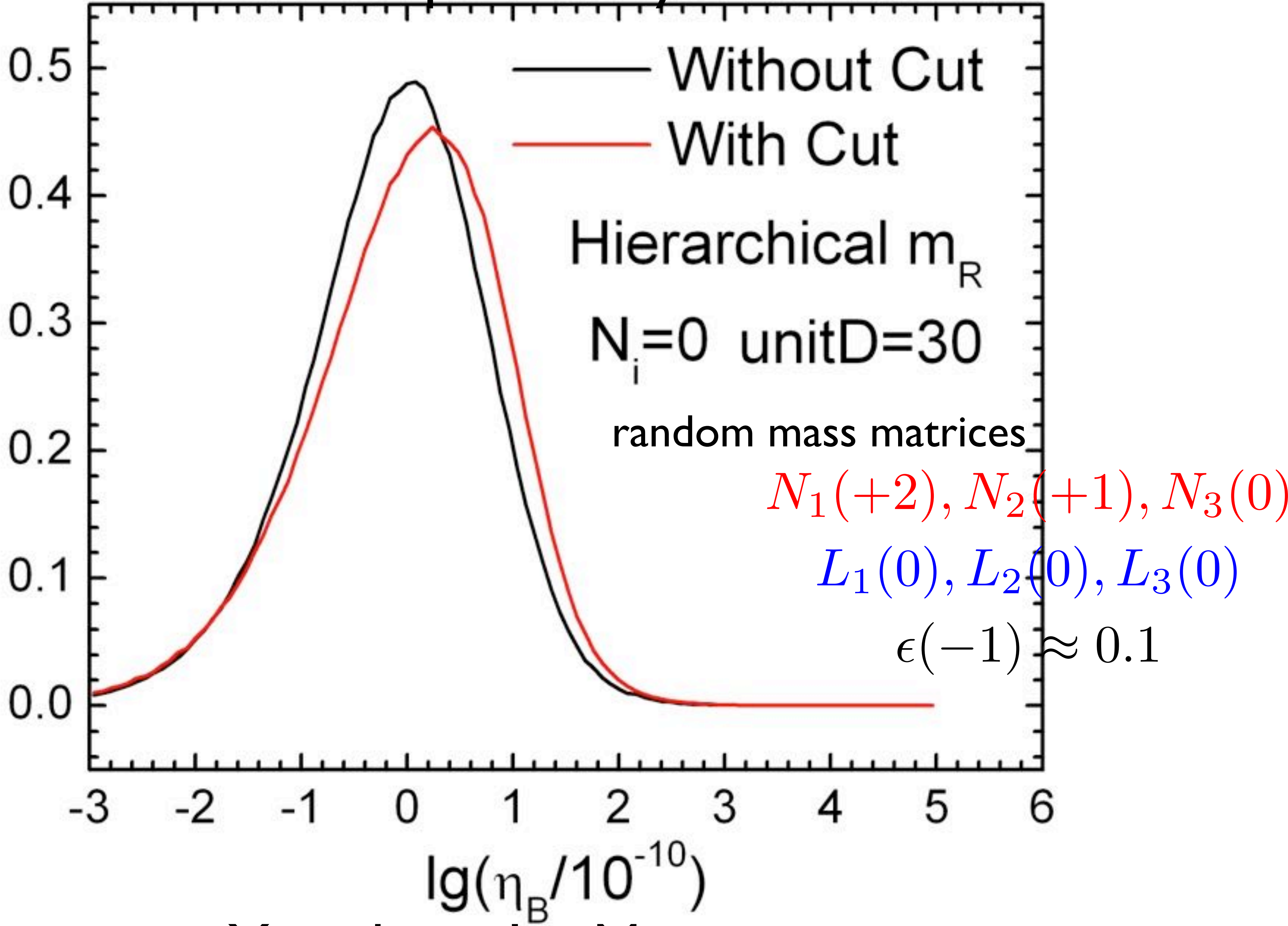
Kolmogorov-Smirnov test (de Gouvêa, HM)
nature has 47% chance to choose this kind of numbers



Prefers maximal CPV
2
1
0
-1
-0.75
-0.5
-0.25
0
0.25
0.5
0.75
1
sin δ

no direct connection to CP violation in oscillation

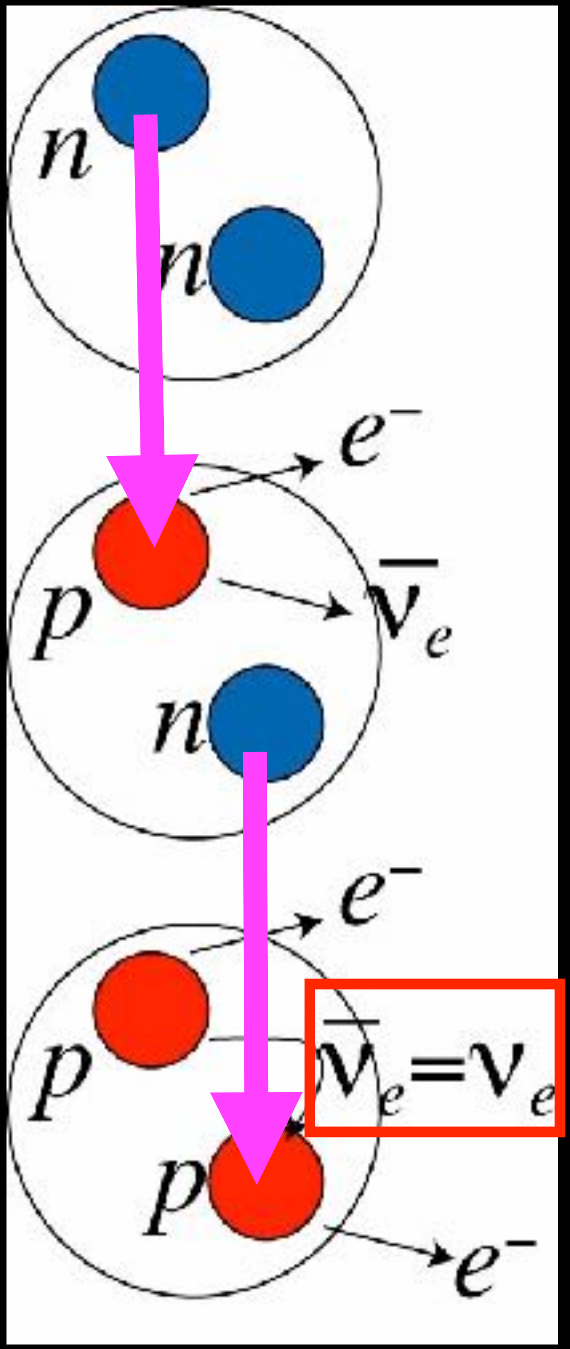
but a plausibility test



Xiaochuan Lu, Murayama

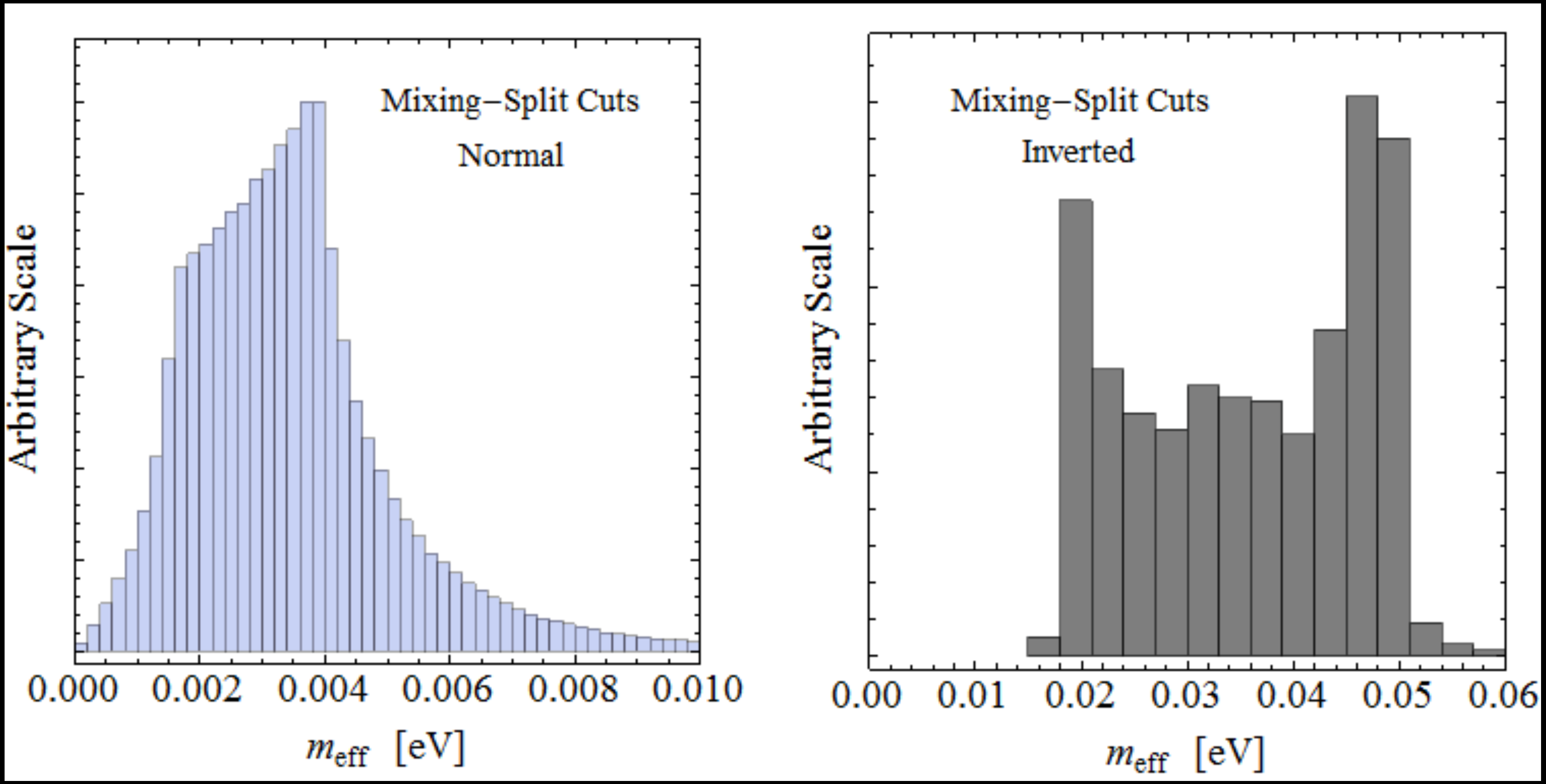
Can anti-matter turn into matter?

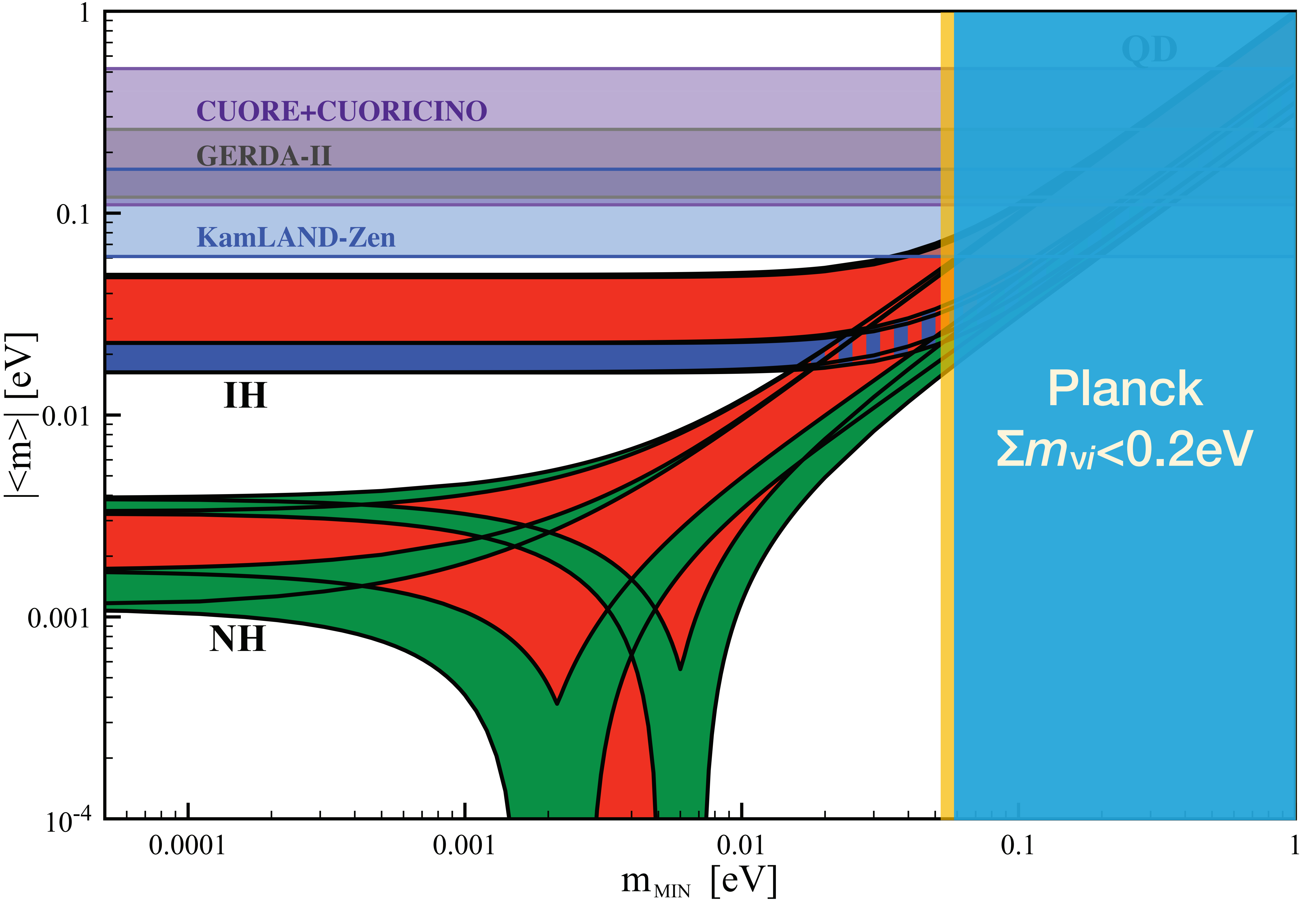
- proton is positively charged, anti-proton negatively
- can never turn into each other
- But neutrinos or anti-neutrinos do not have electric charge
- neutrinoless double beta decay: $nn \to ppe^- e^-$
- can we look for anti-matter turning into matter?



Not easy

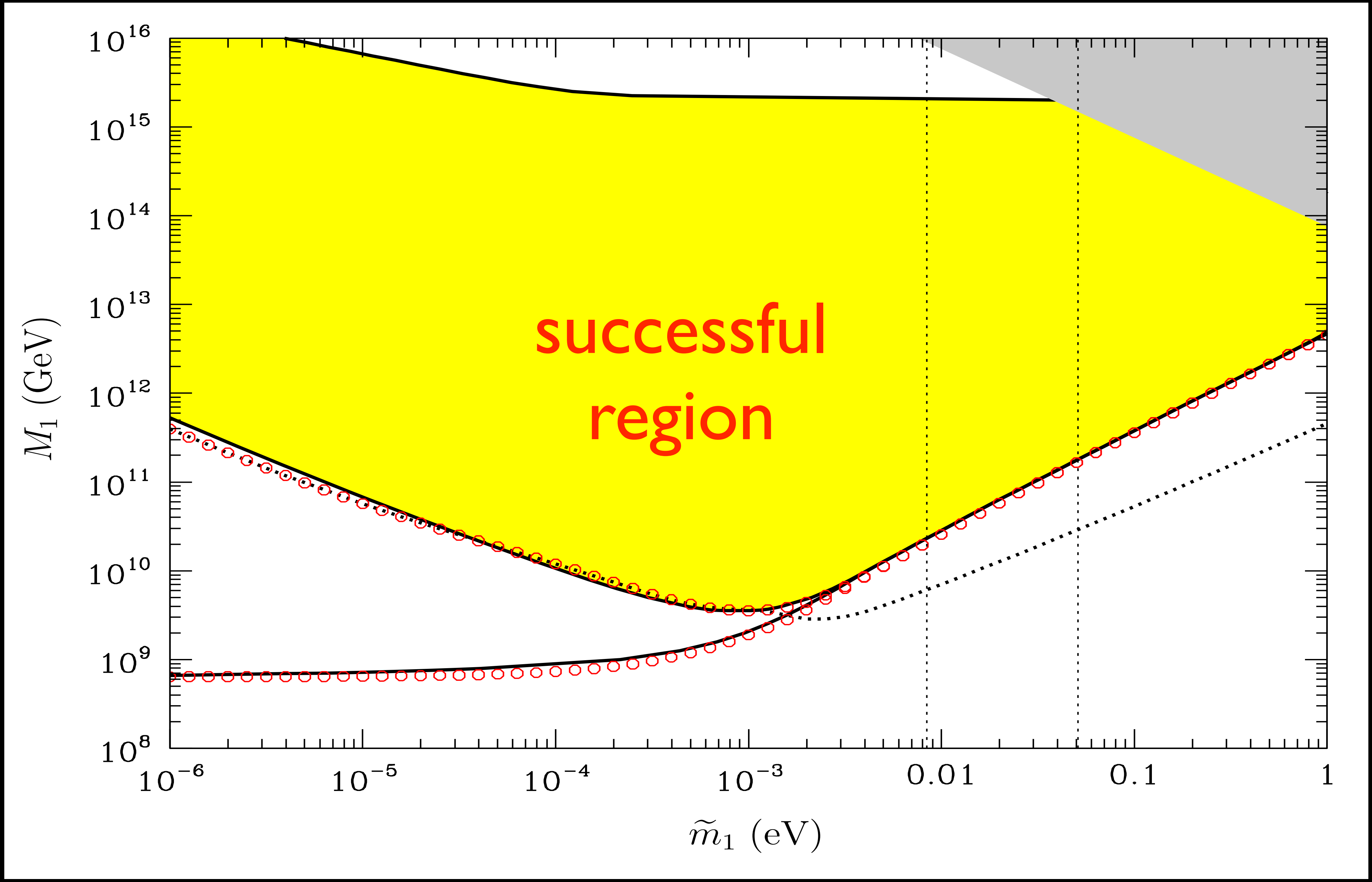
- anarchy prefers normal hierarchy
- quite difficult to reach the sensitivity levels
- but if LBL discovers inverted hierarchy, it is in a much better shape!





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

Leptogenesis



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

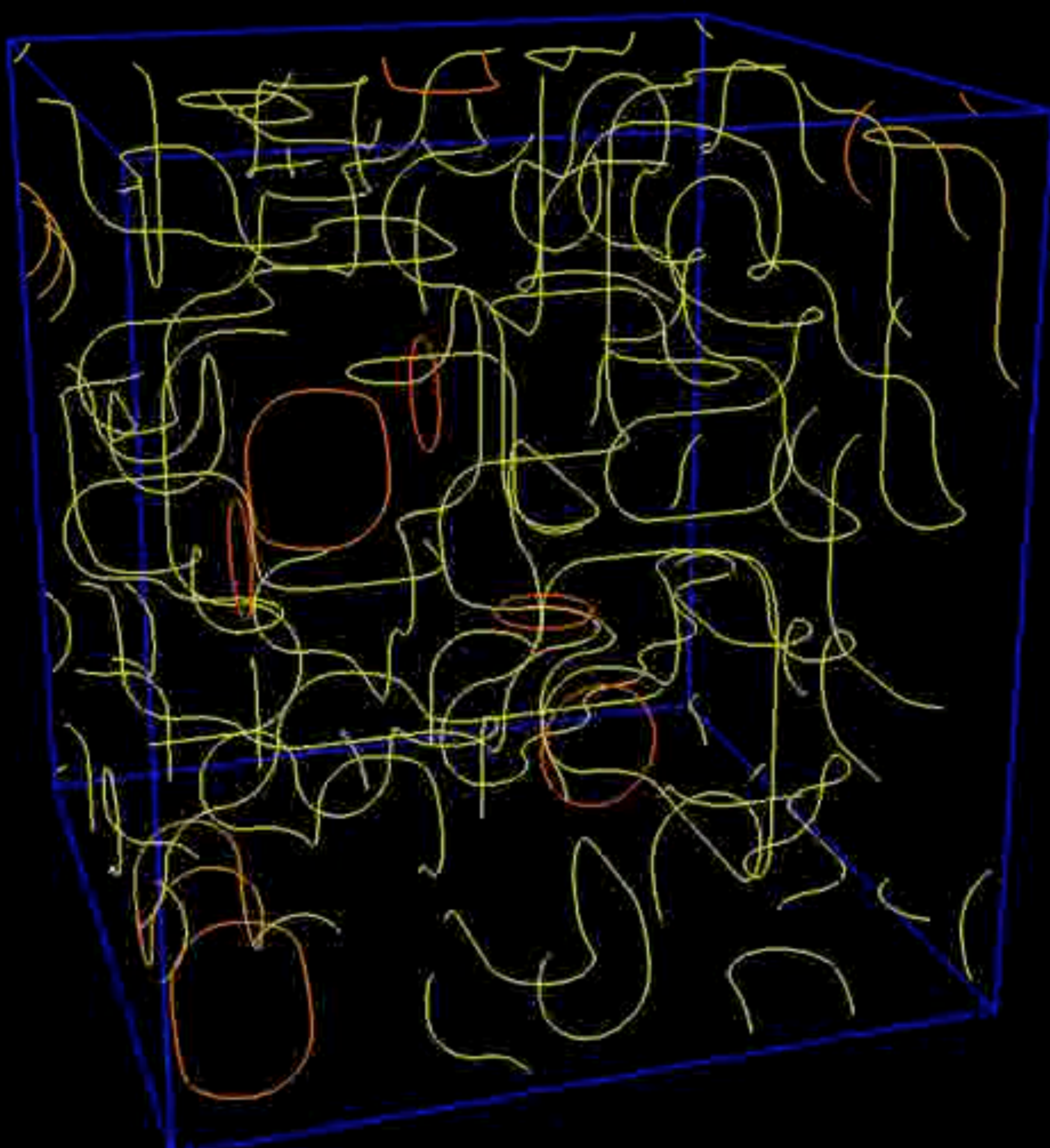
di Bari, Plümacher, Buchmüller

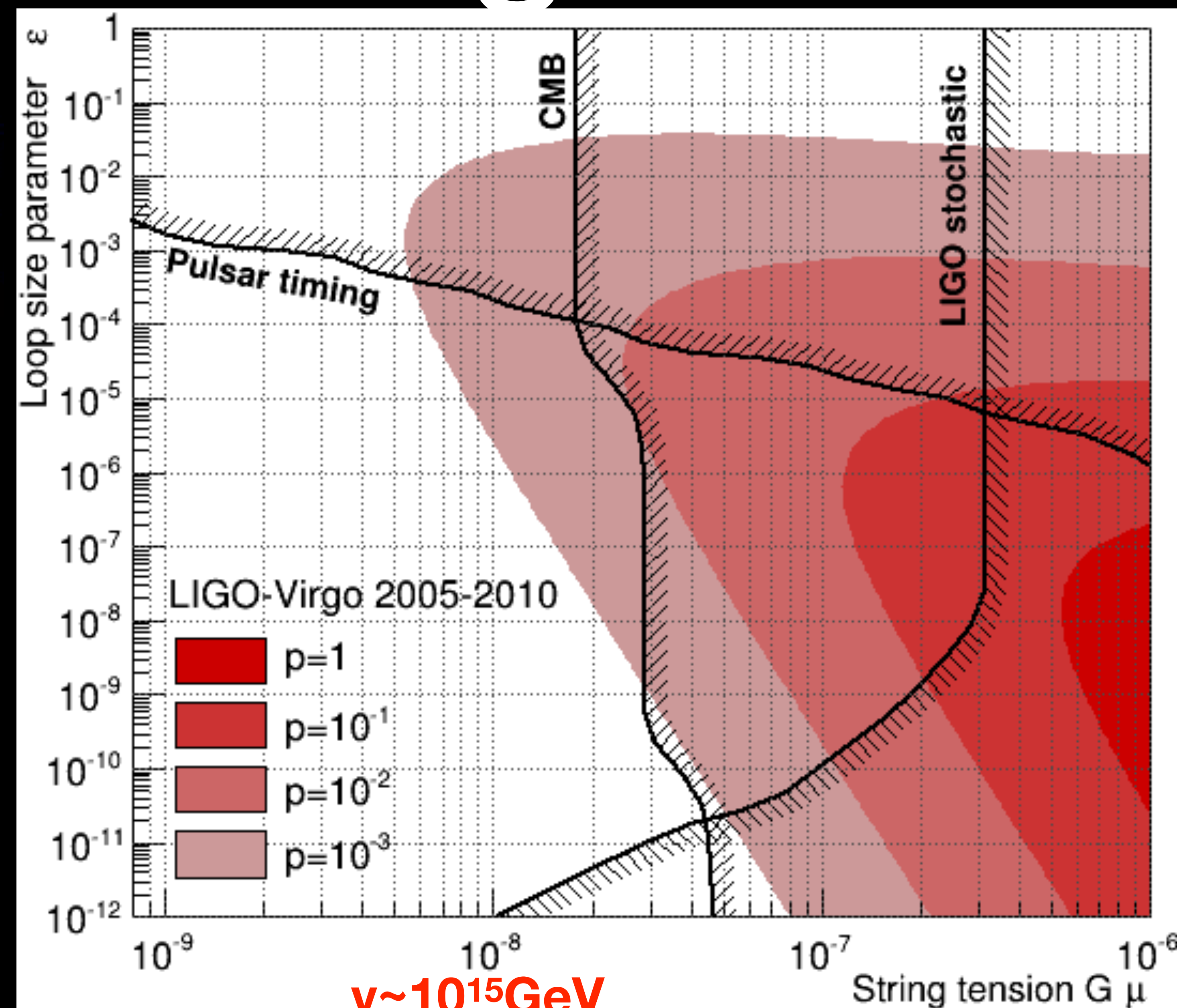
$U(1)_{B-L}$

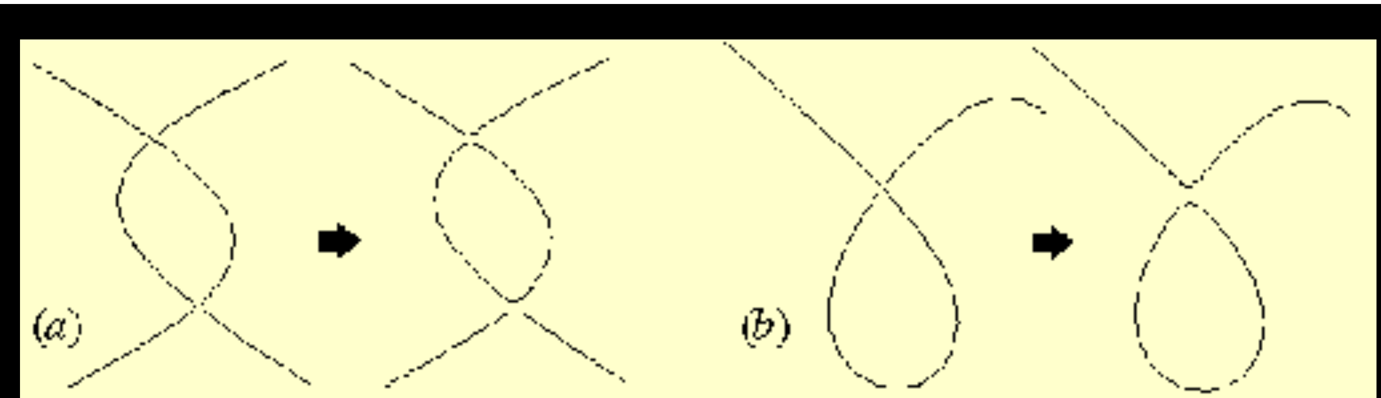
- $v_R < 10^{15}$ GeV for leptogenesis is much below M_{Pl}
- Consider $\langle\phi\rangle \neq 0$
  - M_R from $\langle\phi\rangle v_R v_R$ or $\langle\phi^2\rangle v_R v_R / M_{Pl}$
- U(1) breaking produces cosmic strings because $\pi_1(U(1)) = Z$

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

cosmic strings



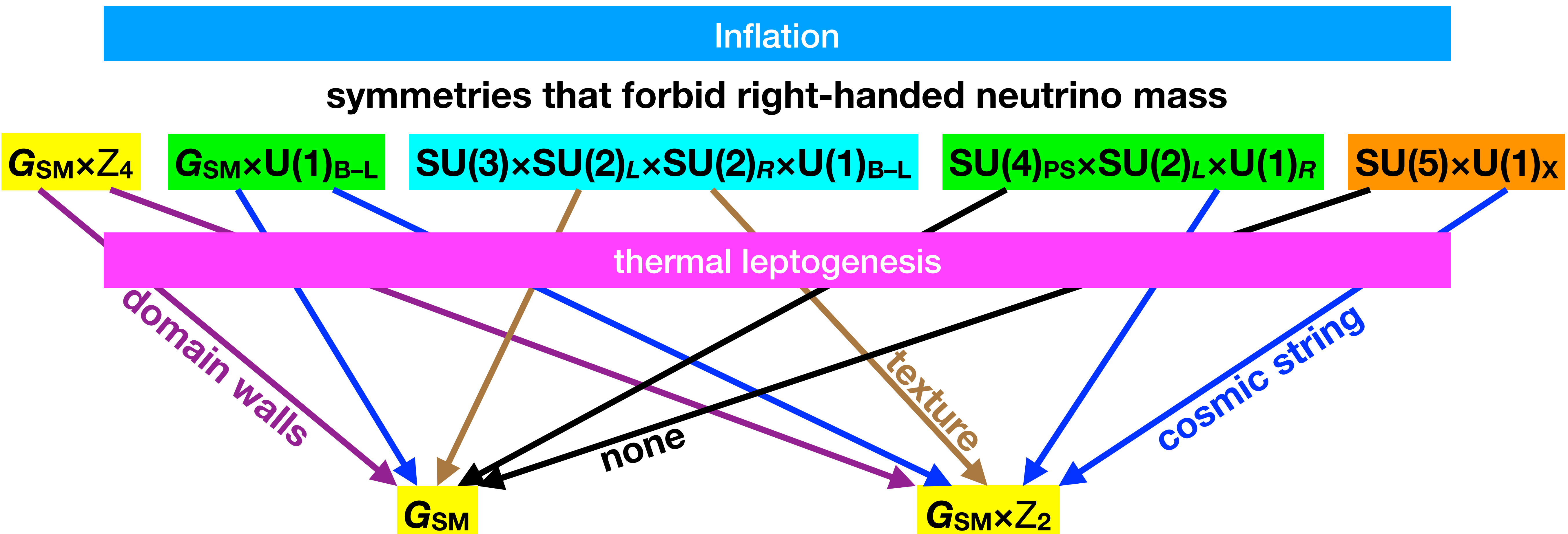




$G\mu \sim v^2/M_{Pl}^2$

probably $M_R \nu_R \nu_R$ forbidden

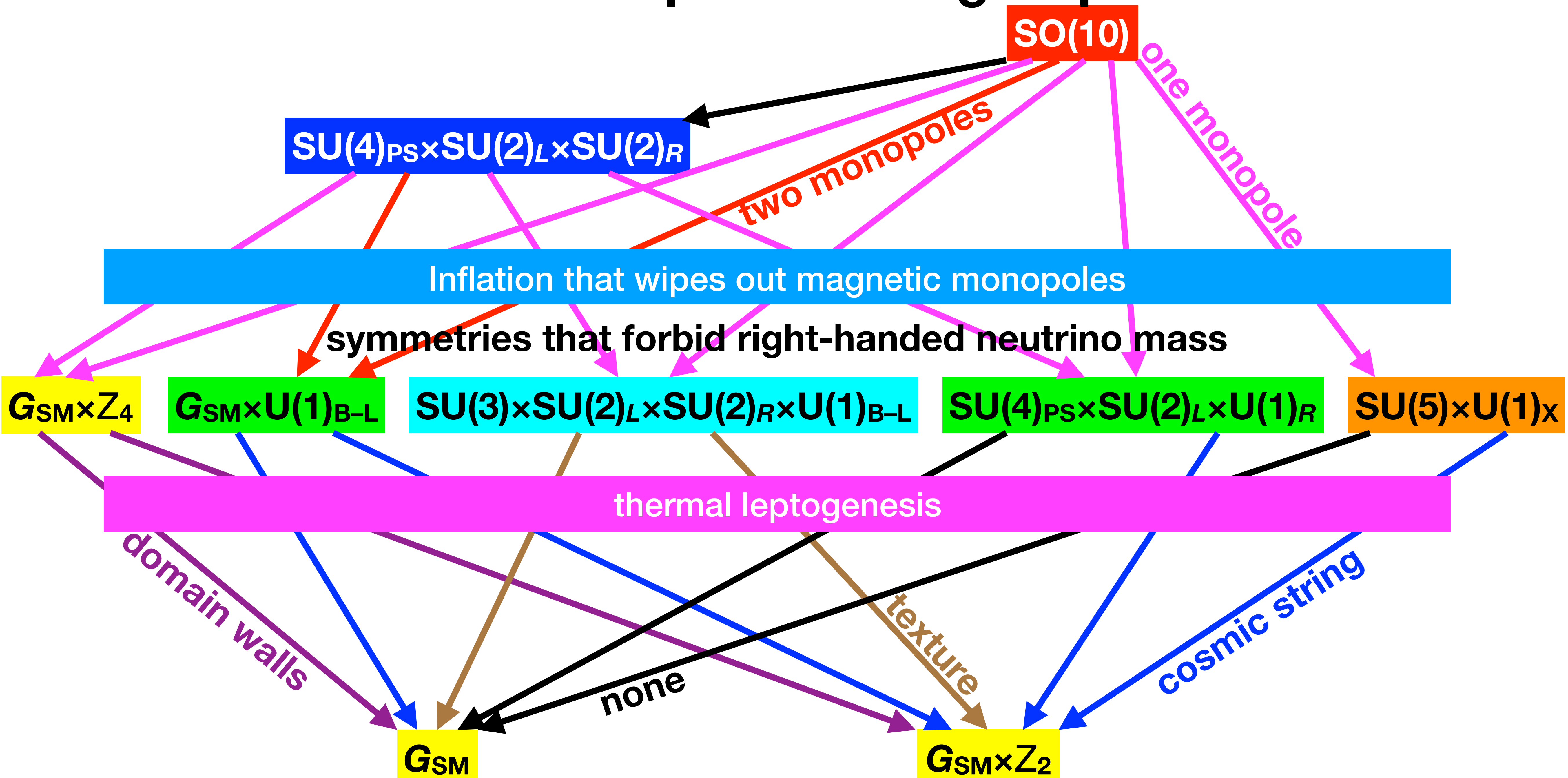
$\langle \phi \rangle \nu_R \nu_R$ or $\langle \phi \rangle^2 \nu_R \nu_R / M_{Pl}$



Jeff Dror, Takashi Hiramatsu, Kazunori Kohri, HM, Graham White

arXiv:1908.03227

Semi-simple unified groups

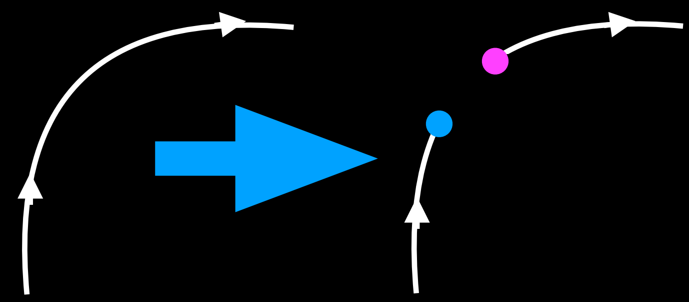


intermediate gauge symmetry

- intermediate gauge symmetry *G* protects ν_R mass
- breaks either with or without matter parity
- matter parity always leads to stable Z_2 string
- $U(1)_{B-L}$ string breaks by monopole creation if embedded in SO(10)

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

	$H = G_{\rm SM}$		$H = G_{\rm SM} \times \mathbb{Z}_2$	
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	$(\mathbf{4},\mathbf{1},1)$	$\mathbb{Z}_2$ string	$(\mathbf{15},\mathbf{1},2)$
$G_{\rm flip}$	none	$(\mathbf{10},1)$	$\mathbb{Z}_2$ string	$(\mathbf{50},2)$

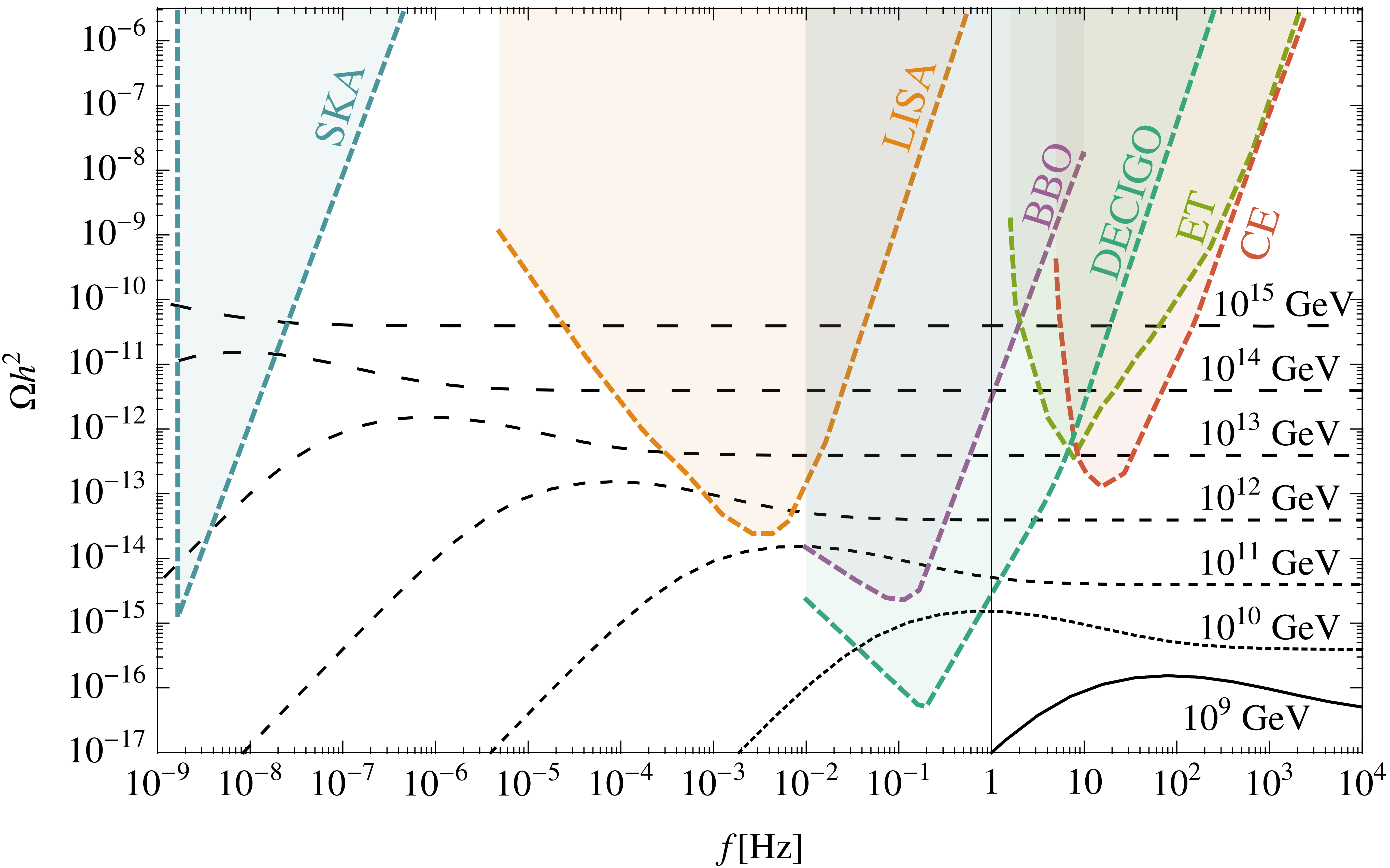


Schwinger

- Schwinger computed the production of e^+e^- pairs in a constant electric field in 3+1 dimension
- adopt it to 1+1 dimension
- dualize it to magnetic field

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

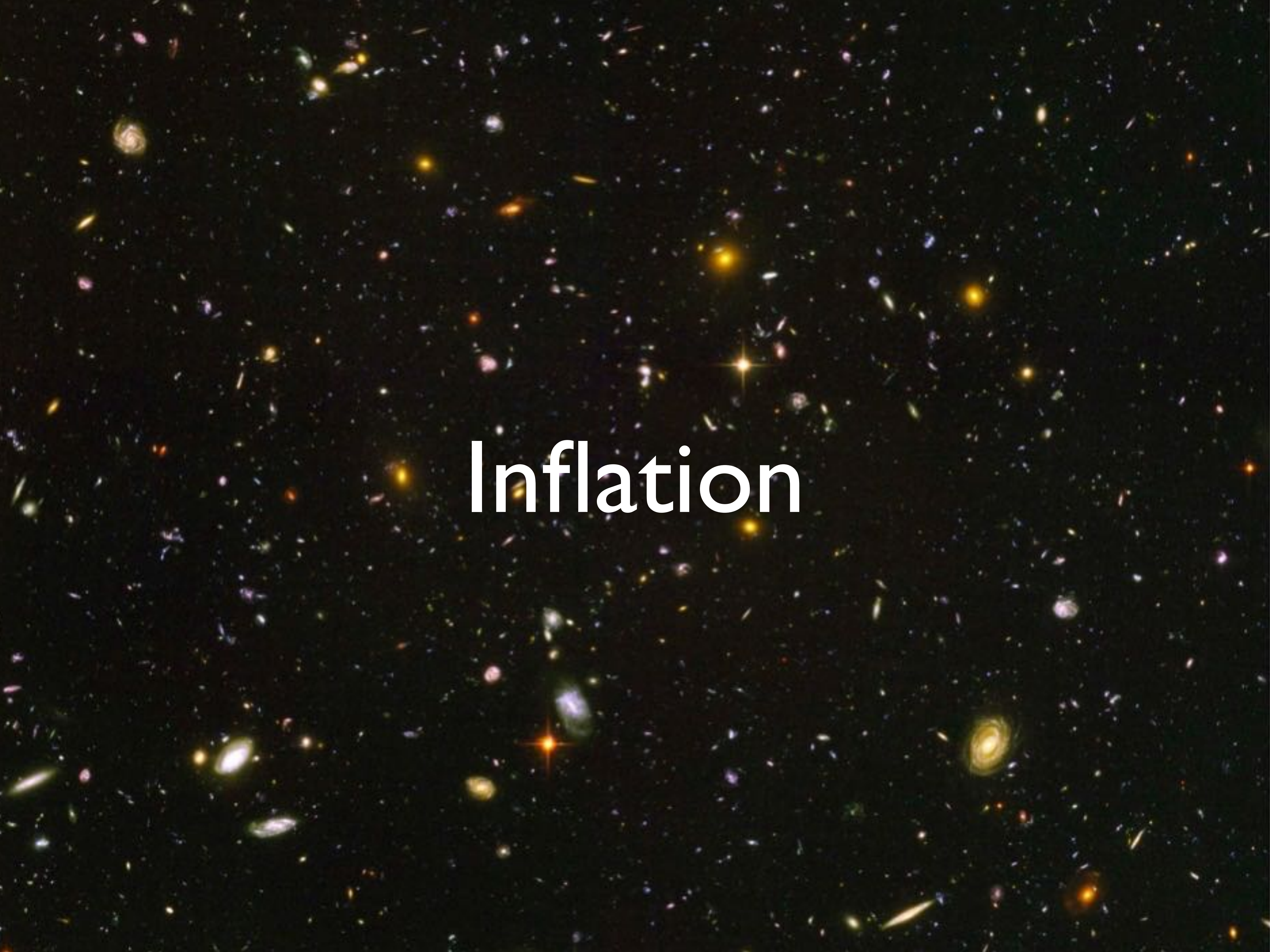
- cross section of the string $A \sim (g\, v)^{-2}$
- $B\, A \sim 2\pi/(g\, Q)$
- length of the string $L \sim H^{-1}$
- strings get cut when $H \sim \Gamma/L \times L \sim \Gamma/L \times H^{-1}$
- string network persists until $H^2 \sim (\Gamma/L) \sim (g\, v)^2 \exp(-\pi m^2/gB)$
- monopole mass $m \sim V/g$
- survives to date if $v < 10^{15}$GeV



covers pretty much the entire range for leptogenesis!

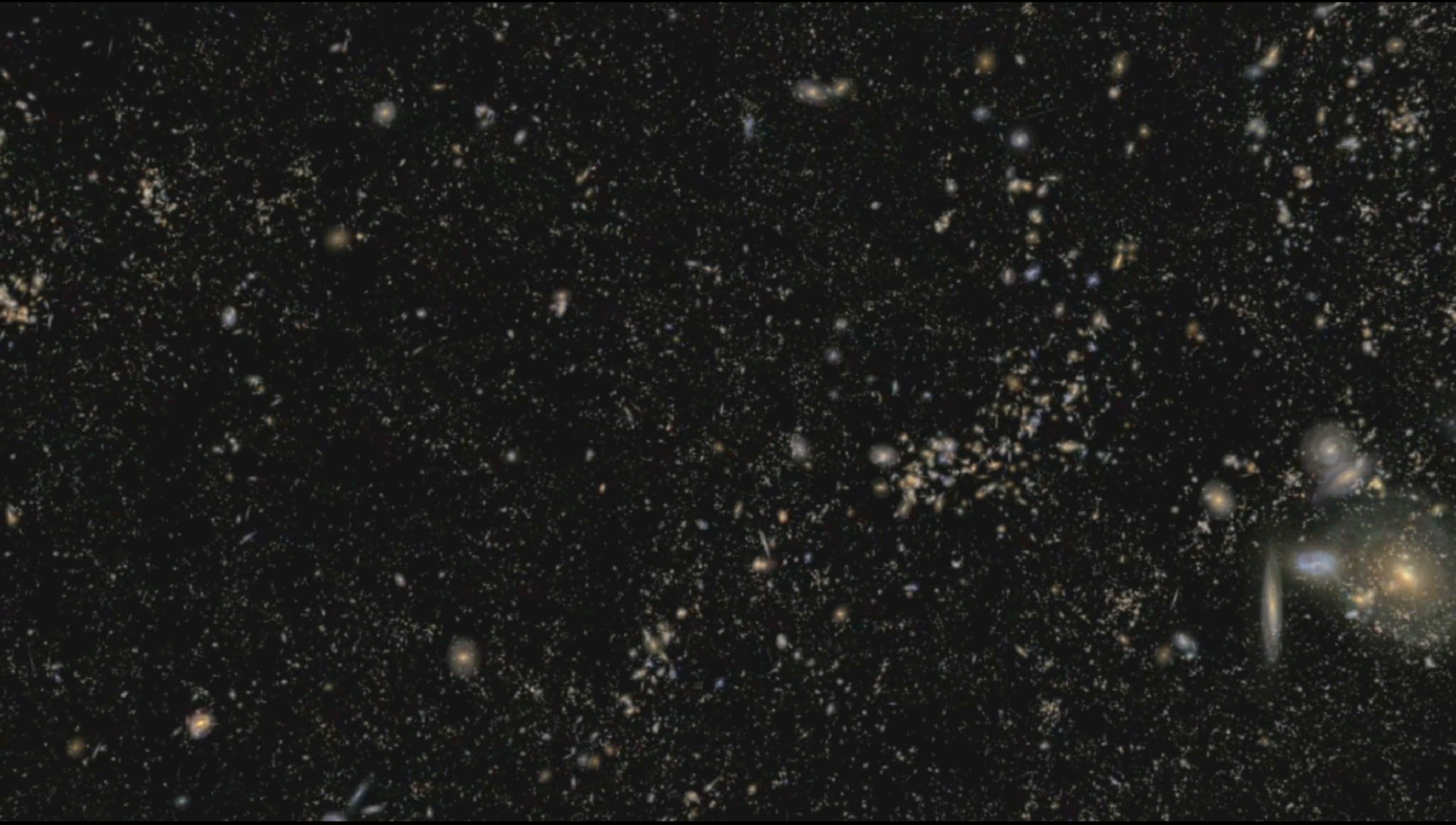
based on Jose J. Blanco-Pillado, Ken D. Olum arXiv:1709.02693

caveat: particle emission from cosmic strings



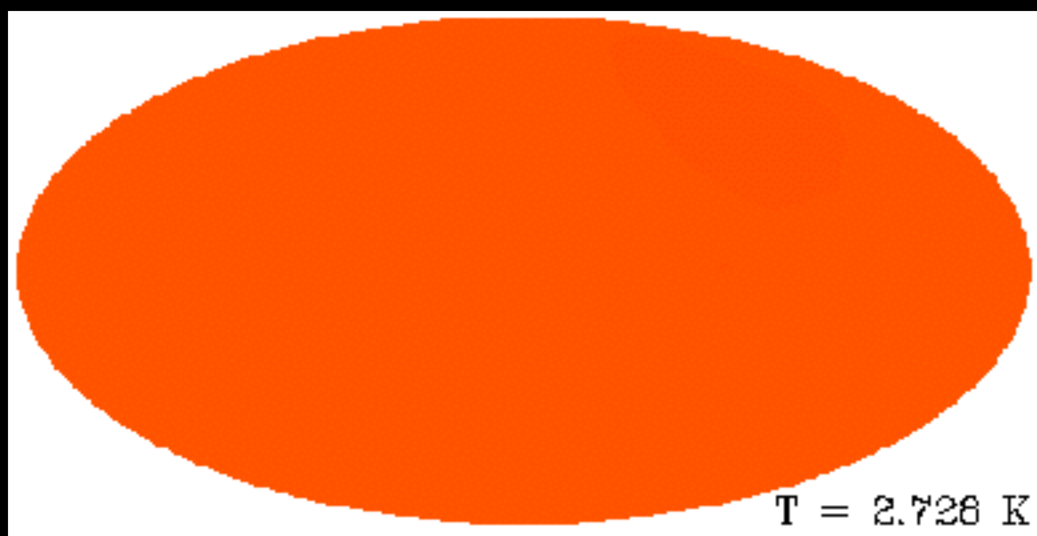
Inflation

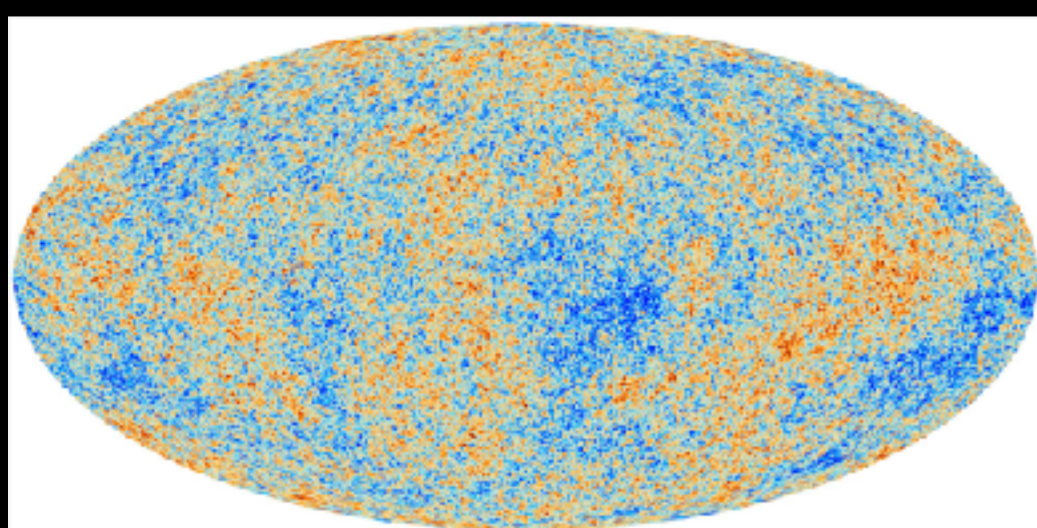
fly-by simulation based on real data



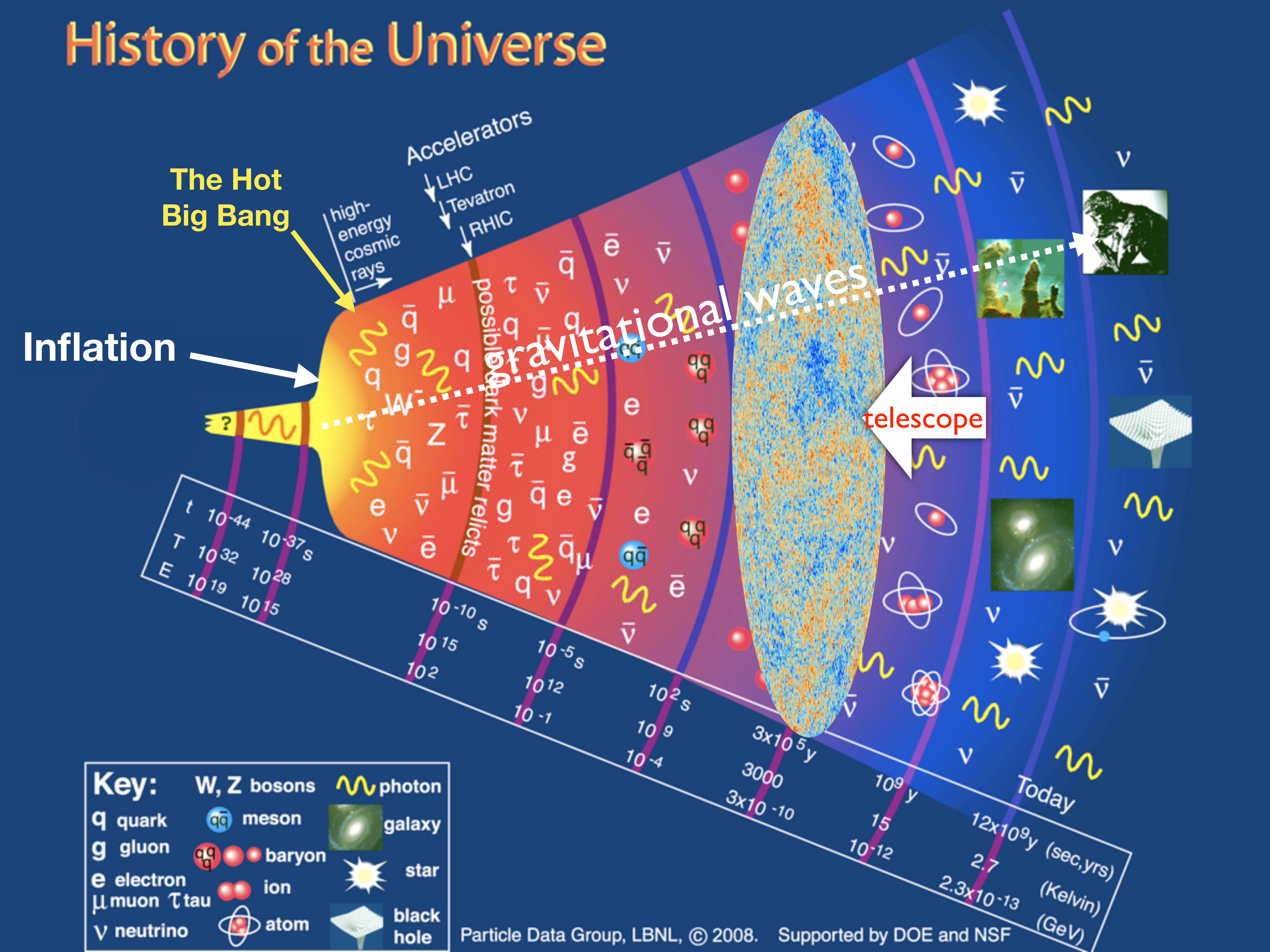
about ten trillion times faster than light
practically the same no matter how far you go

How do they know each other?

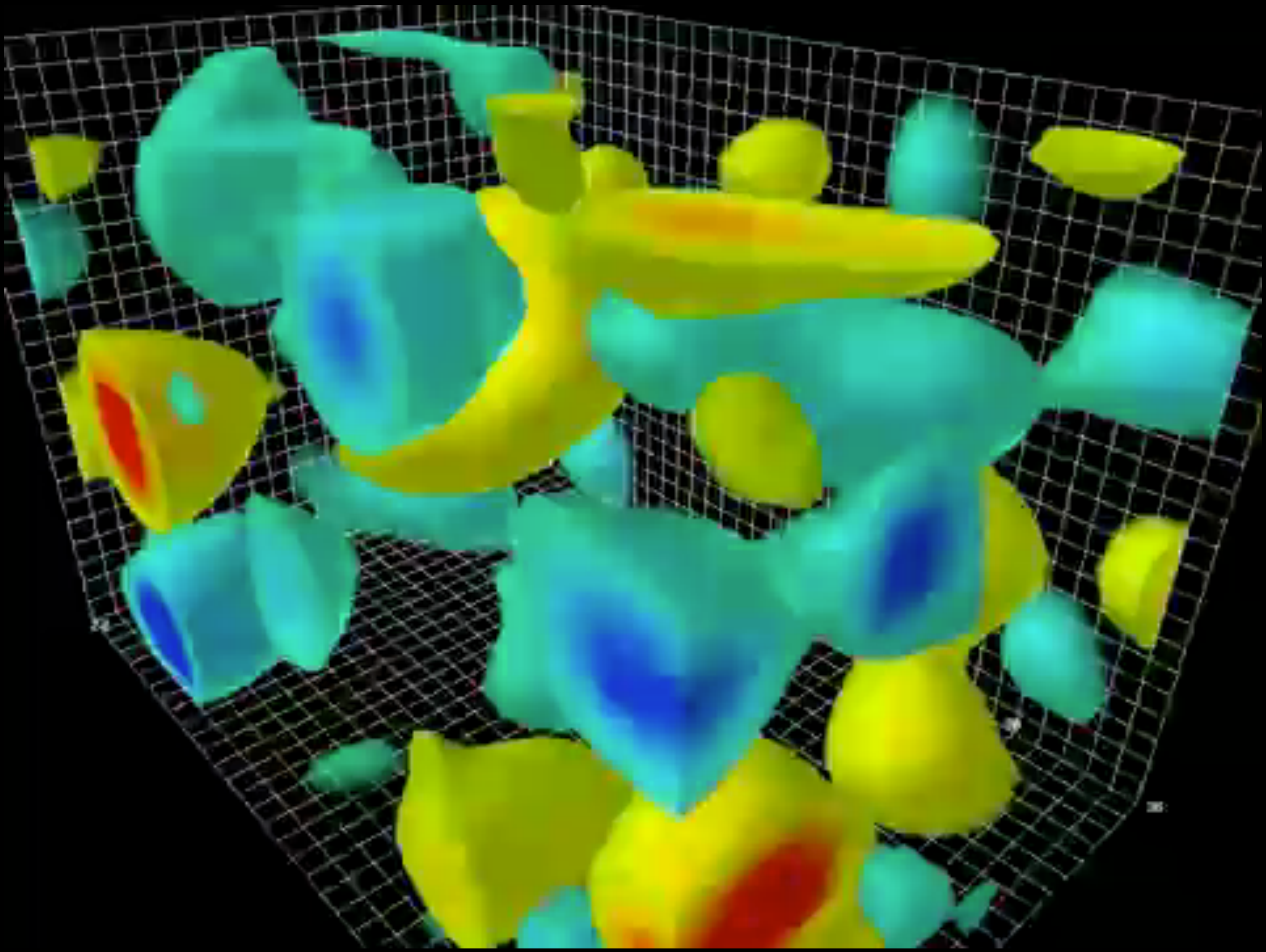




- Like having discovered two remote islands in very different parts of the world, but people speak the same language
- we suspect they were together at some point

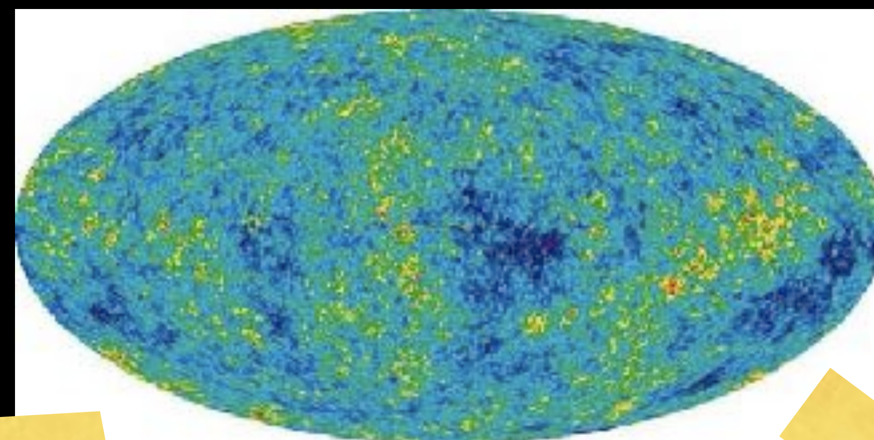

History of the Universe
The Hot Big Bang
Inflation
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
possible dark matter relicts
gravitational waves
telescope
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
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

vacuum is active

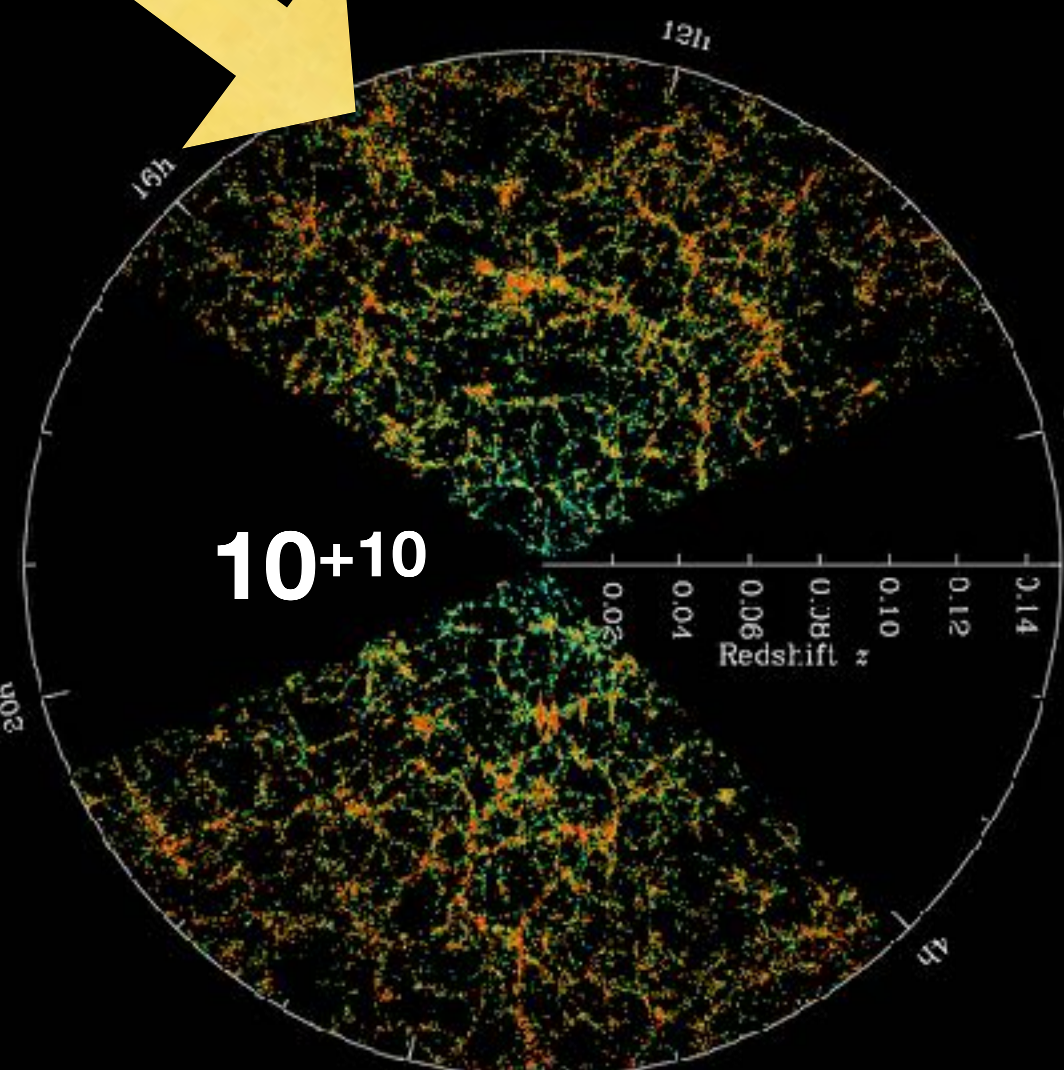


http://www.youtube.com/watch?v=uxIOMa6pdr4

Seeds for structure

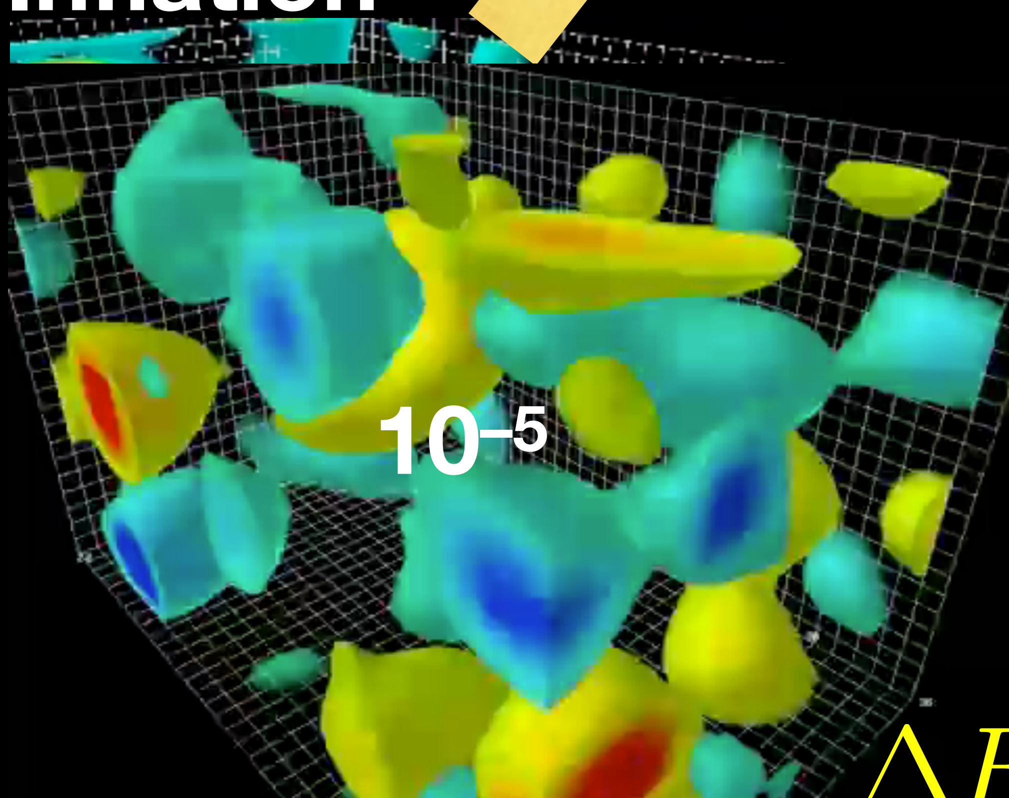


Dark Matter



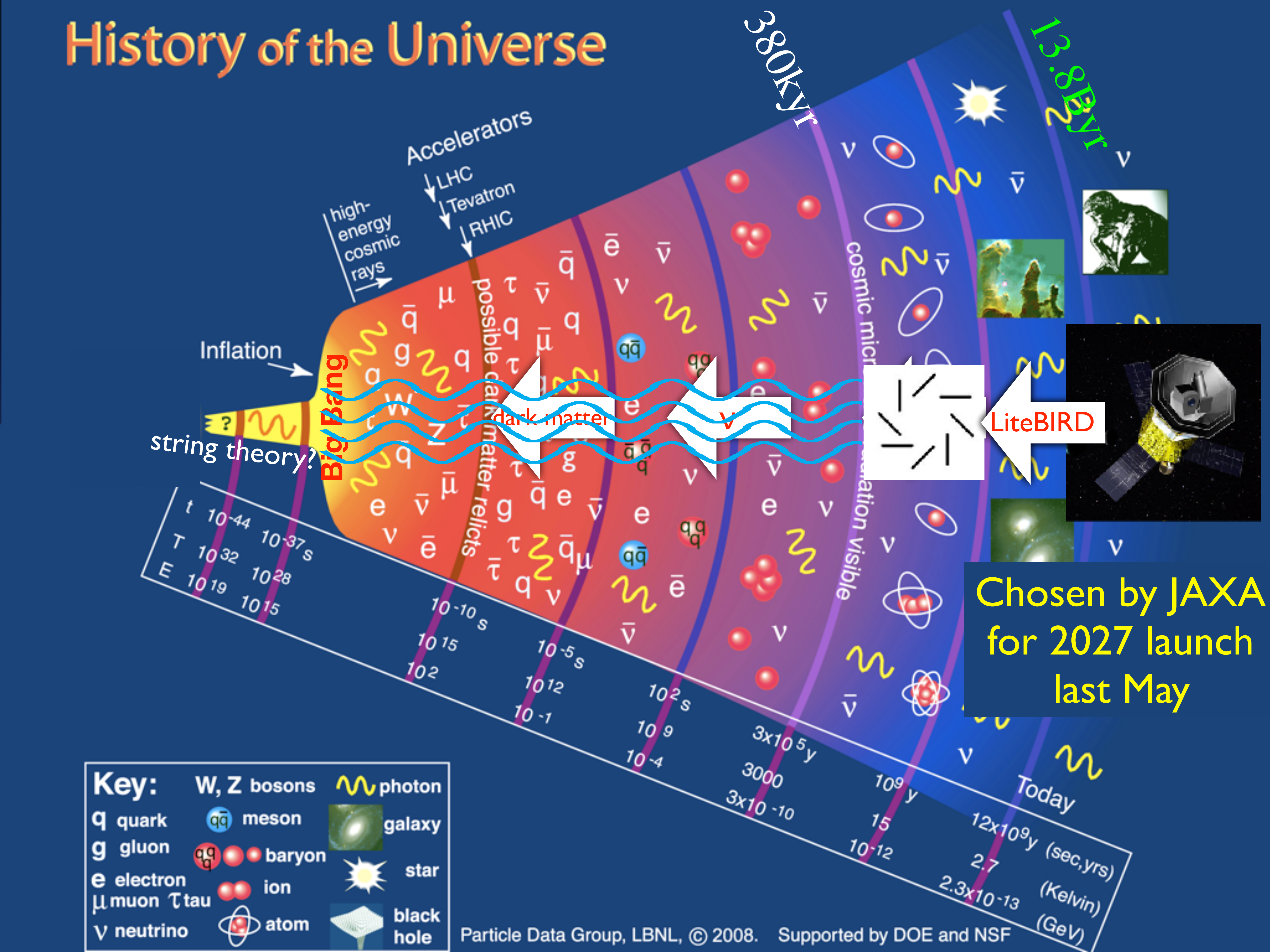
10^{+10}

Inflation



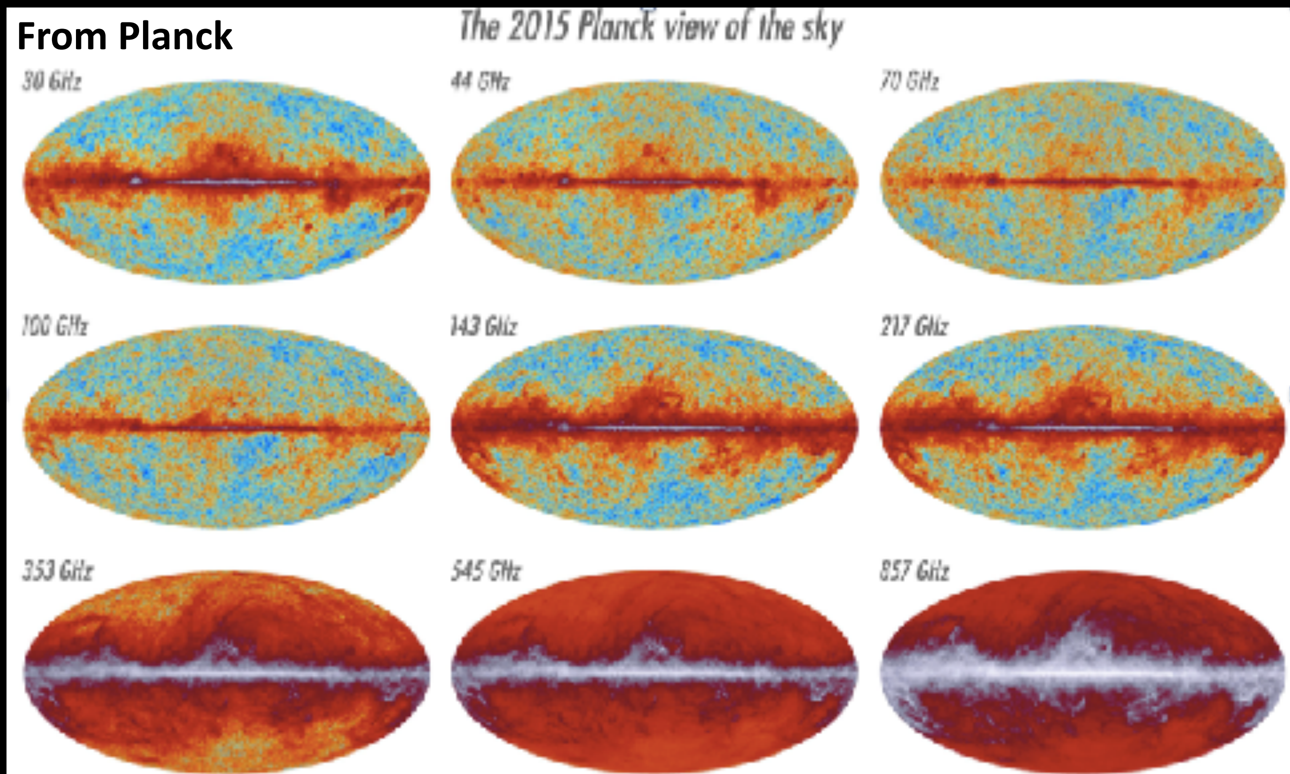
10^{-5}

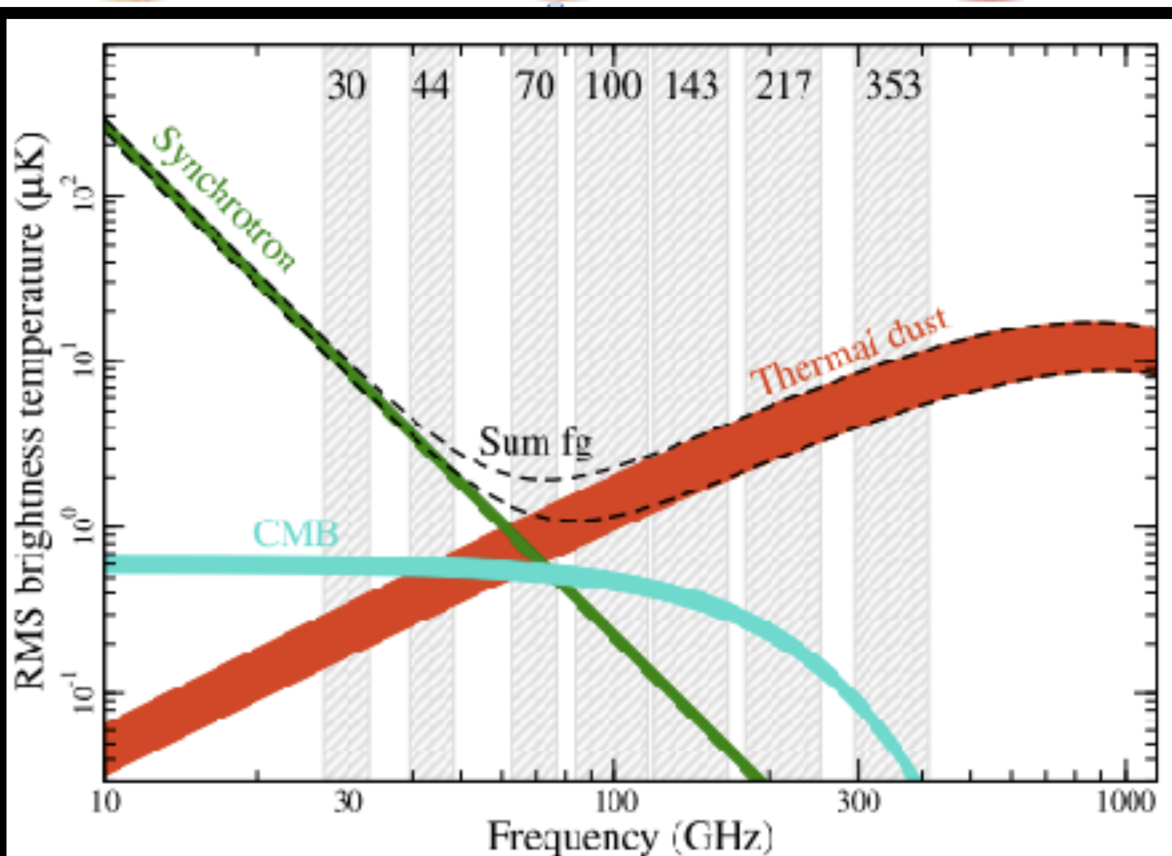
$$\Delta E \Delta x \gtrsim \hbar c$$



History of the Universe
380kyr
13.8Byr
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
Big Bang
string theory?
possible dark matter relicts
dark matter
ν
LiteBIRD
Chosen by JAXA for 2027 launch last May
Today
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)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Foreground emission



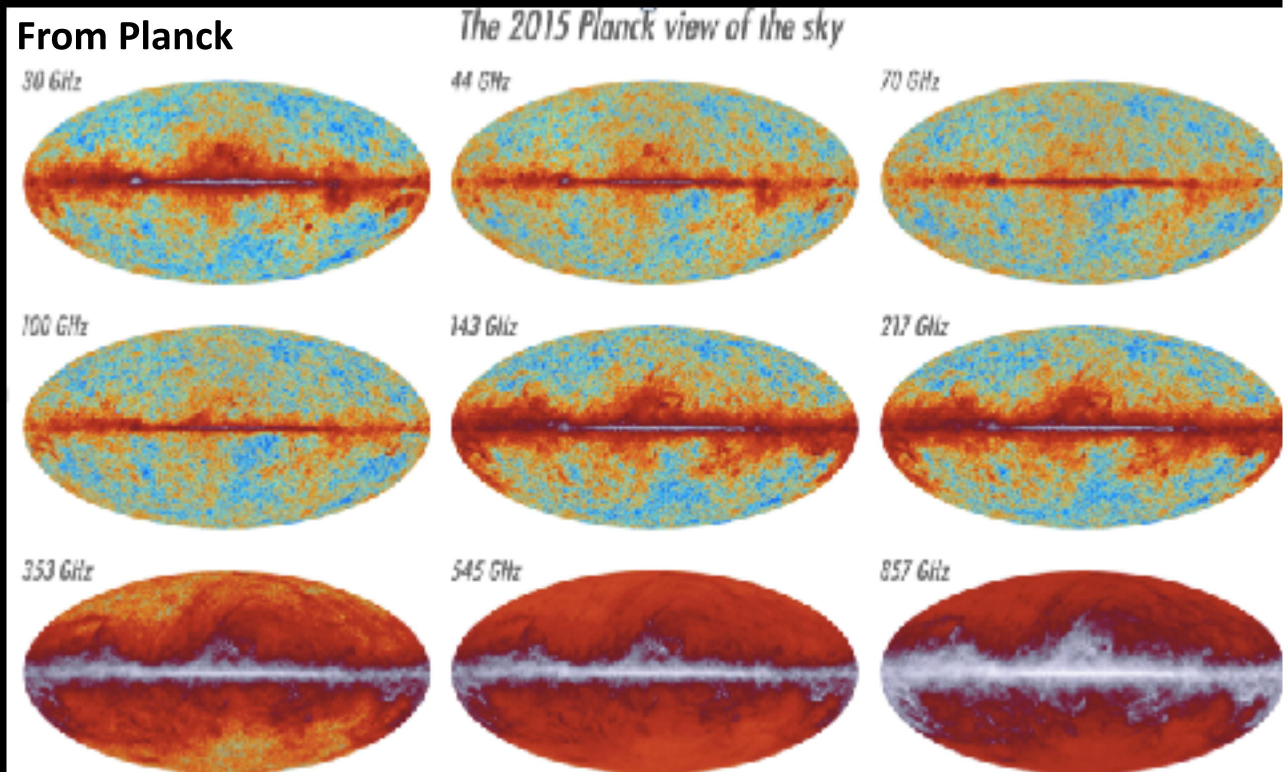


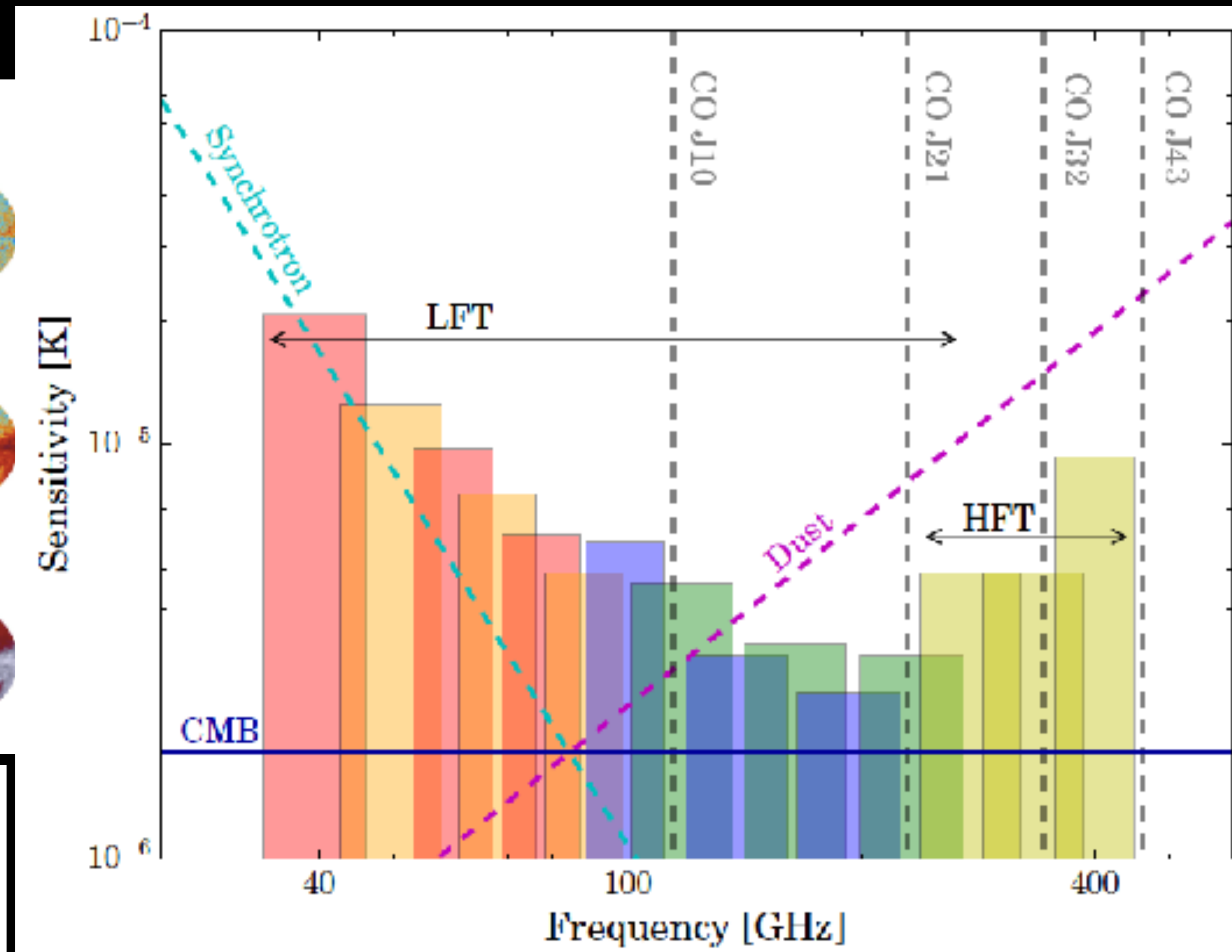
We are living in the Galaxy.

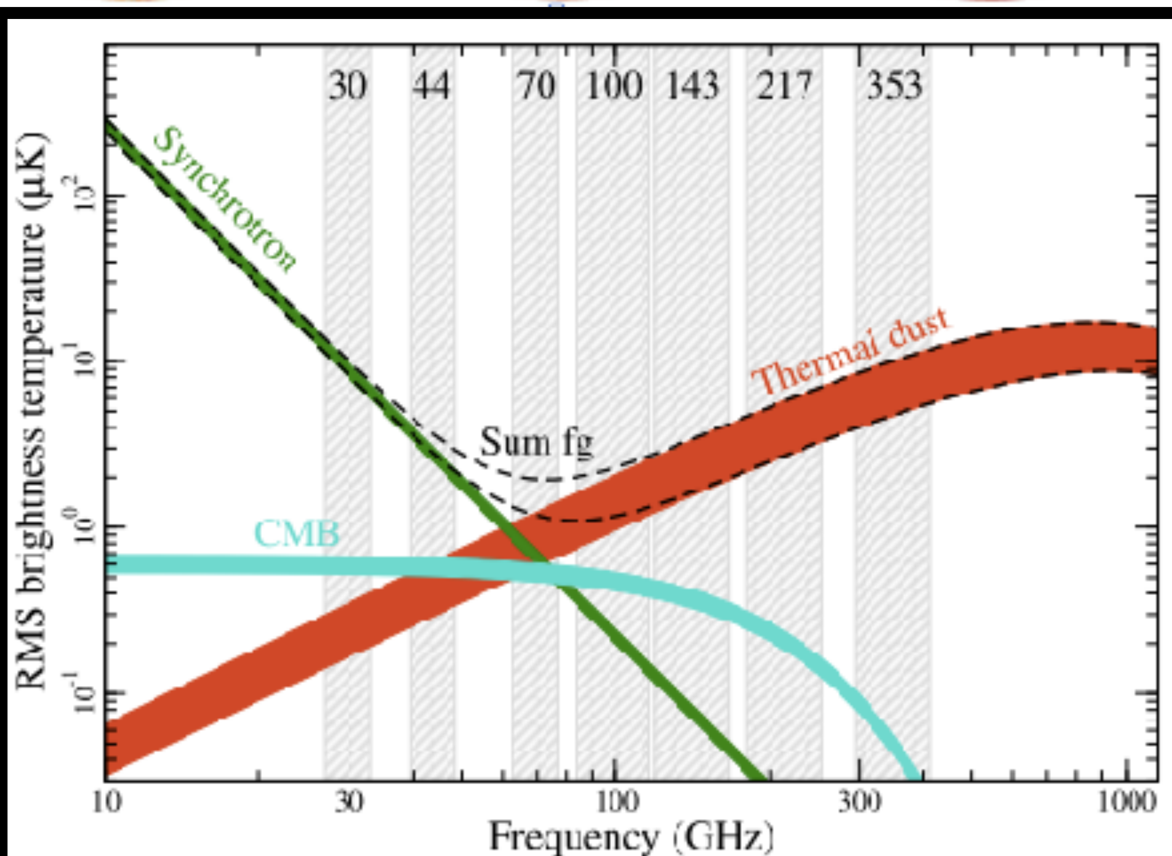
Andromeda@NASA

T. Matsumura, Kavli IPMU

Foreground emission





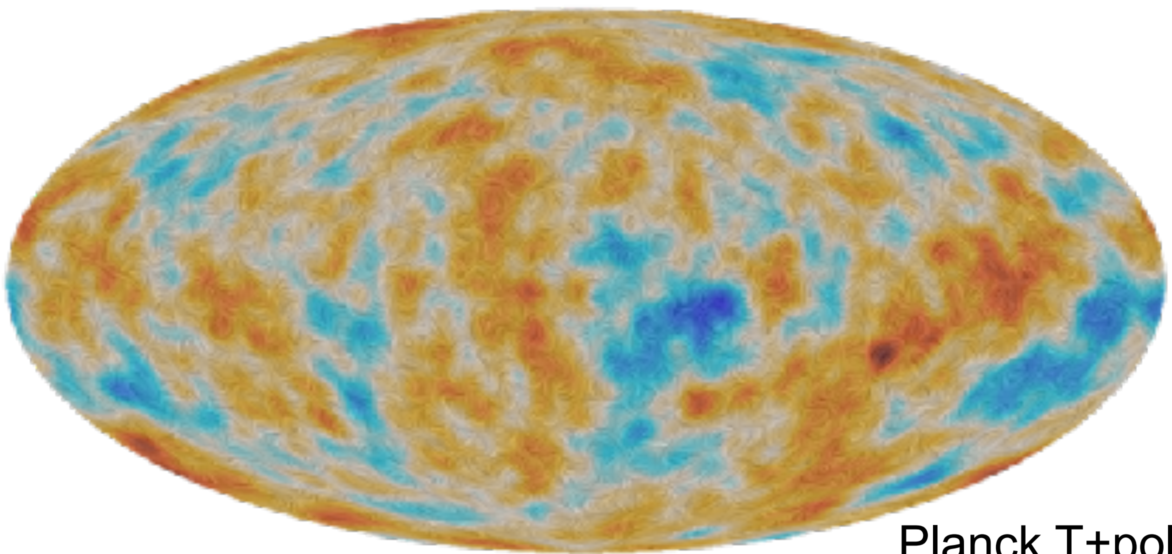


We need to observe in multiple bands to subtract the foreground reliably.

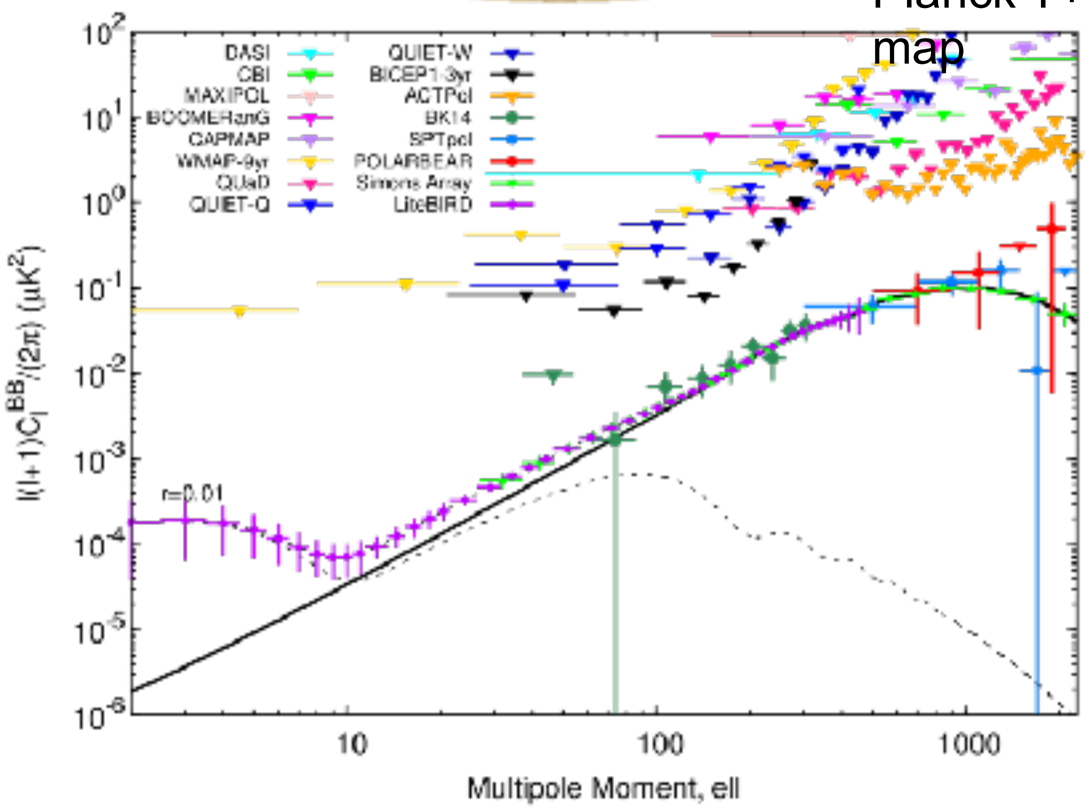
Andromeda@NASA

T. Matsumura, Kavli IPMU

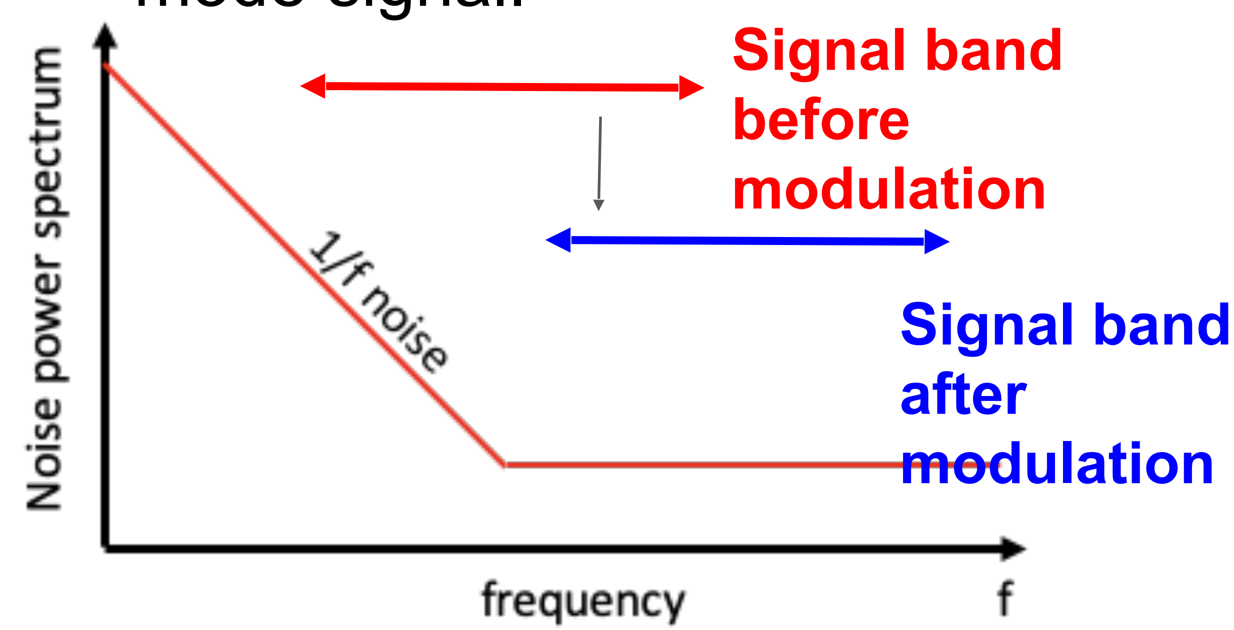
Why modulator for LiteBIRD?



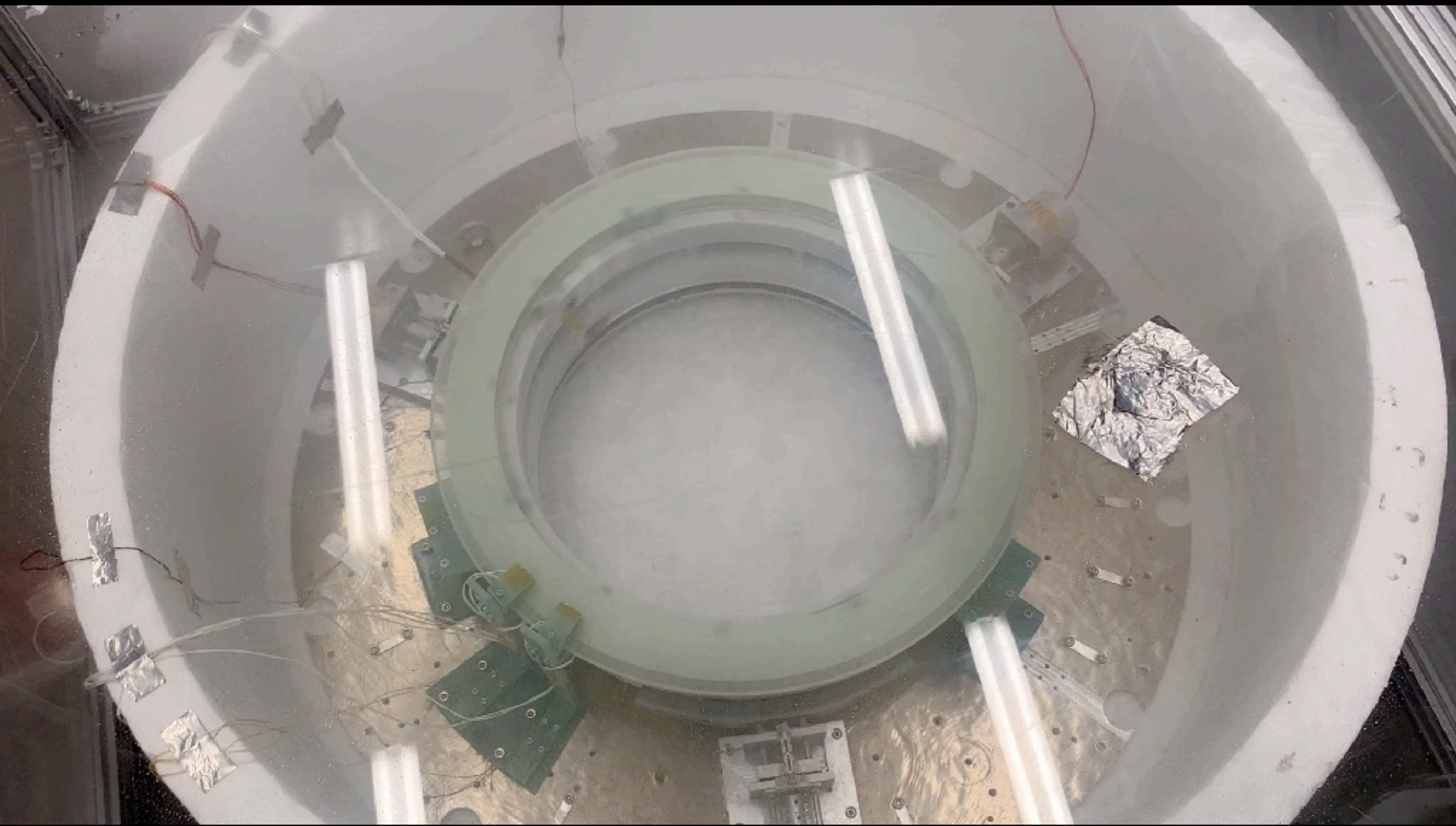
Planck T+pol map



- The goal is to measure the fluctuation of the polarization signal at nano-Kelvin level over the large angular scale.
- The instrument is required to
  - be stable enough to make a distinction between the fluctuation from the sky signal and fluctuation from the instrument.
  - minimize the conversion from the temperature signal leaking into the B-mode signal.

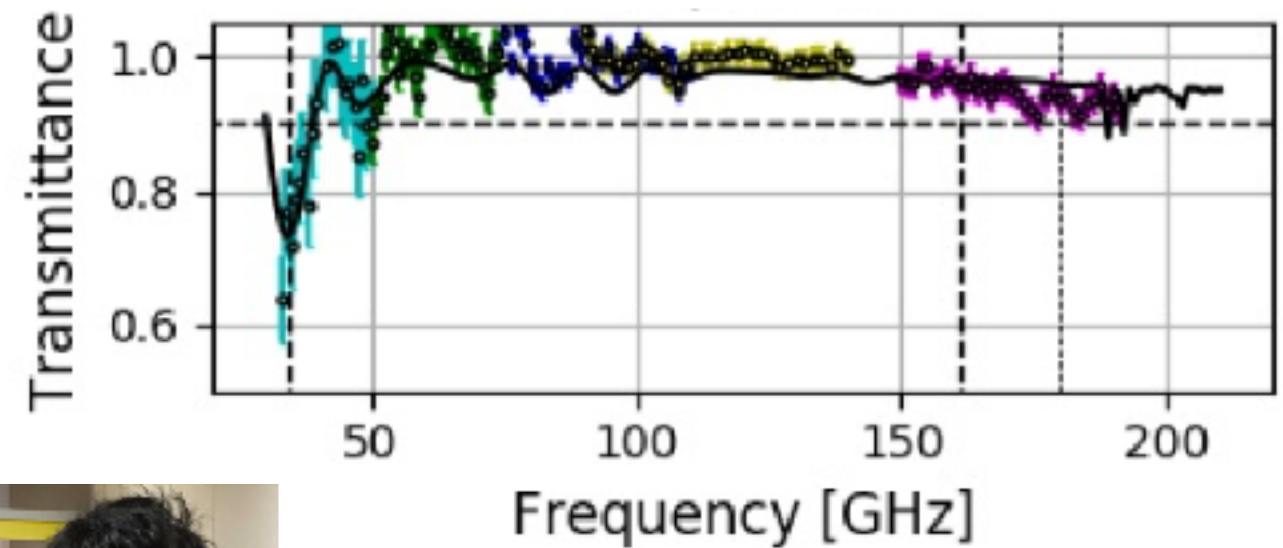


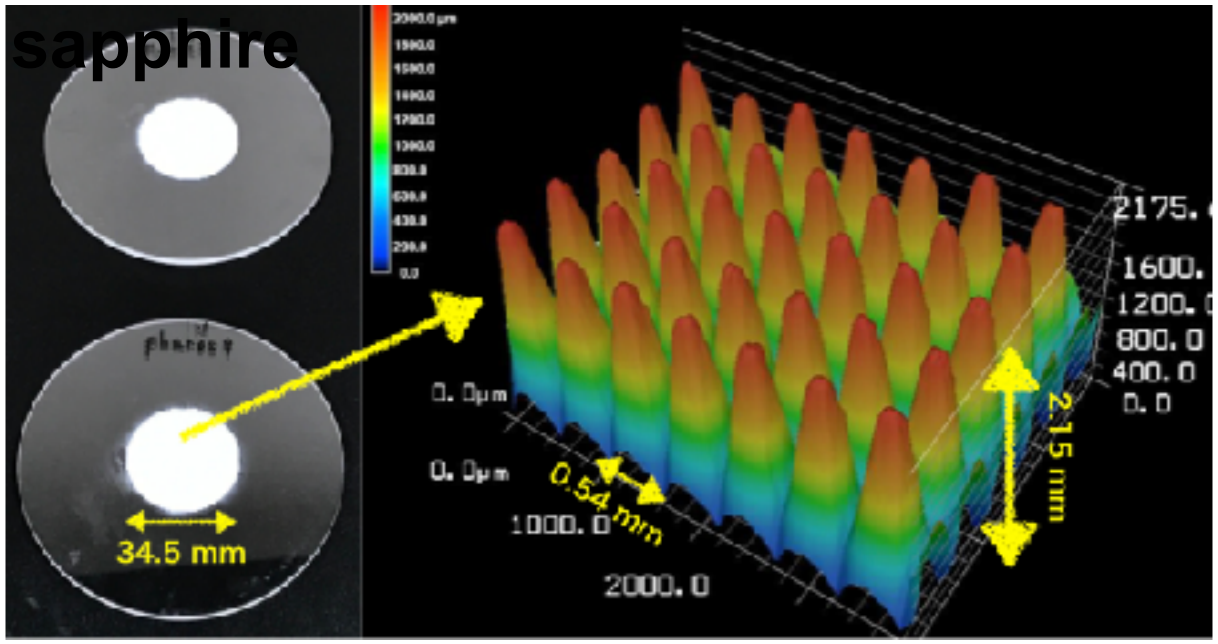
polarization modulator@IPMU
zero-contact mechanism



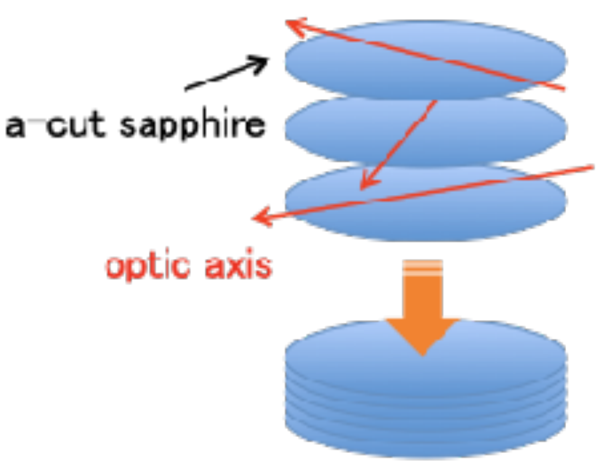
Development results

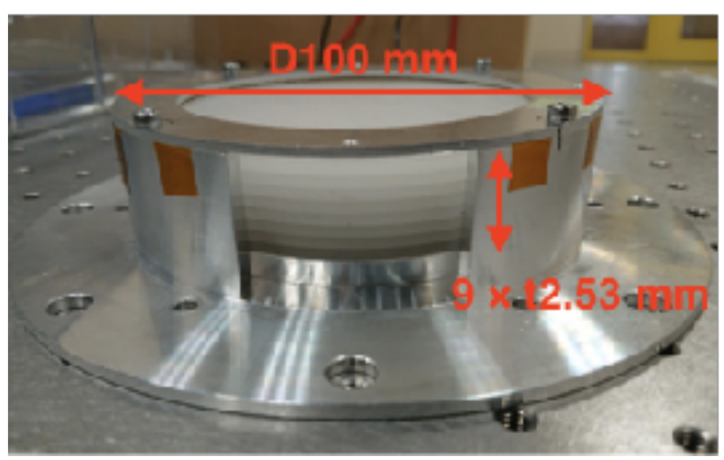
Broadest AR and achromatic HWP using sapphire

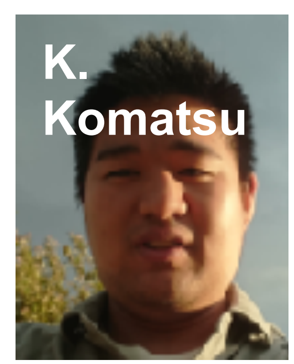




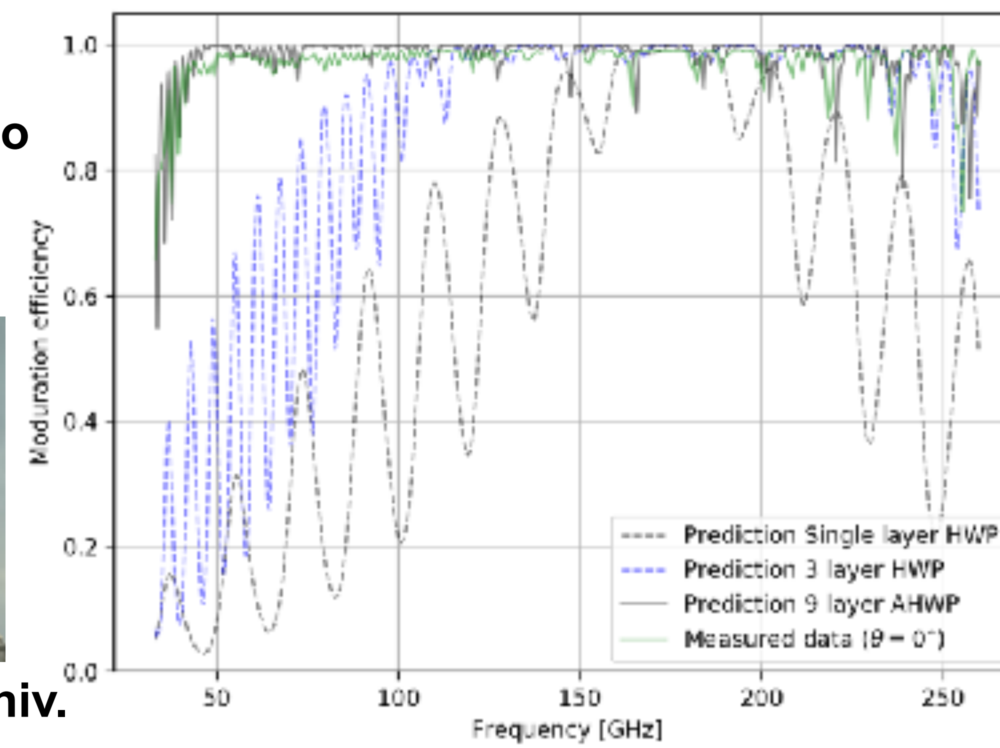
R. Takaku
Univ. of Tokyo





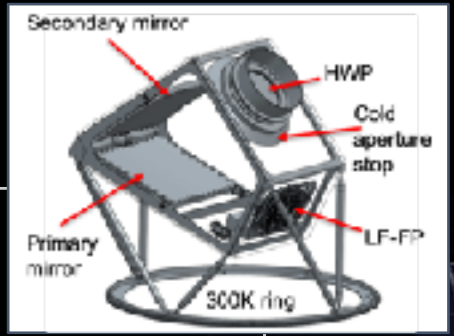


K. Komatsu
Okayama Univ.



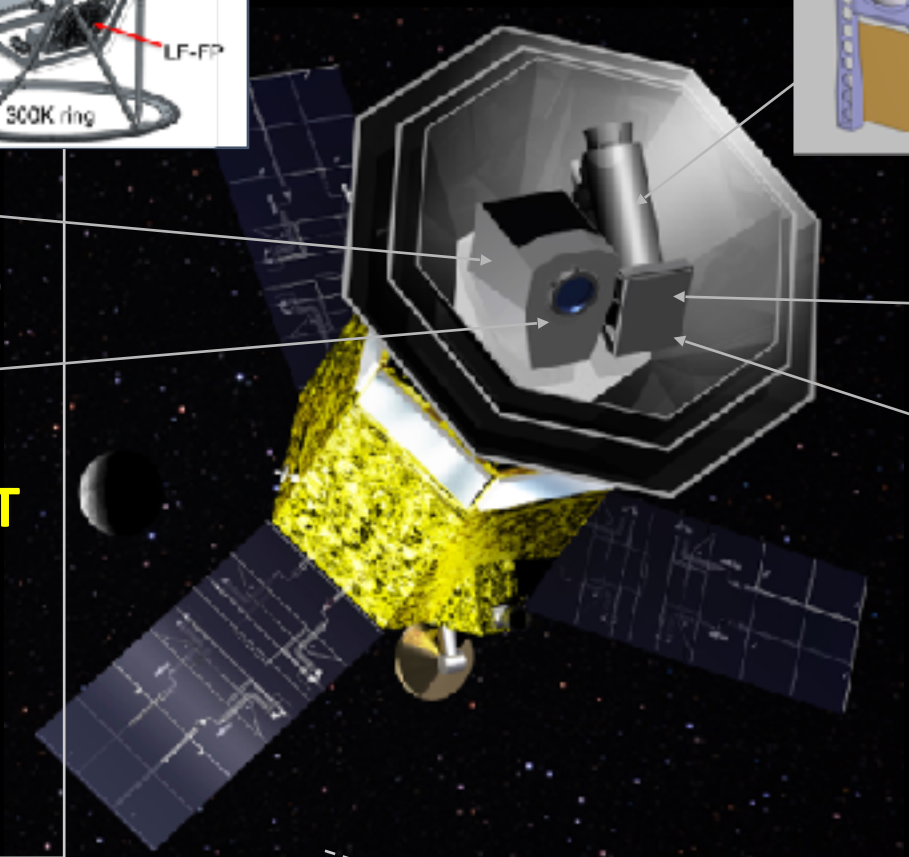
Role of IPMU in LiteBIRD

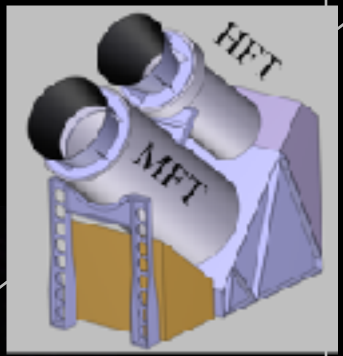
JAXA
- Launch
- Satellite system
- Low frequency telescope (LFT)



Kavli IPMU
- **Polarization modulator for LFT**
- **Data analysis lead in Japan**

KEK
- Ground calibration





Europe
- Middle and high frequency telescope
- Sub-K cooler

US
- Superconducting detector (TES) array
- Sub-K cooler

Canada
- Warm readout electronics

JAXA H3 rocket

Conclusions

- Particle Physics: exciting as ever!
- dark matter: open mind, broad search
  - cosmology, direct, indirect, collider
  - "table top" experiments
  - may learn from astrophysical surveys PFS
- baryogenesis: leptogenesis?
  - need many fossils to get convinced
  - cosmic strings quite generic
- inflation: CMB B-mode
  - LiteBIRD launch in 2027!


Dark Matter is Mom
Inflation is Dad
Neutrino is superhero