Physics of the Universe

Hitoshi Murayama (Berkeley, Kavli IPMU)

50 years of Physics from Particles to the Universe

December 10, 2021

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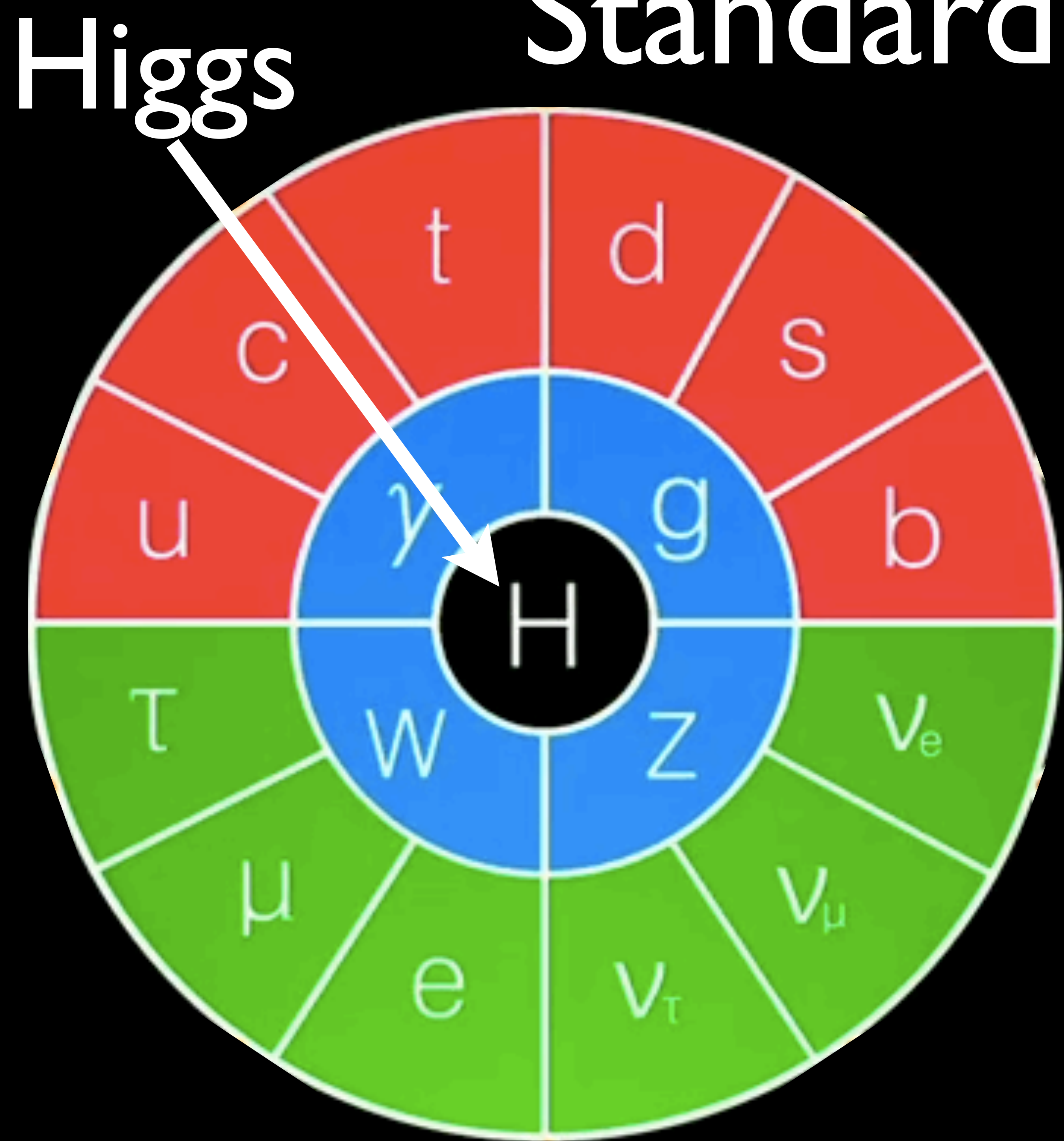
BERKELEY LAB
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Institut National de Physique Nucléaire et de Physique des Particules

Where do we go from here?

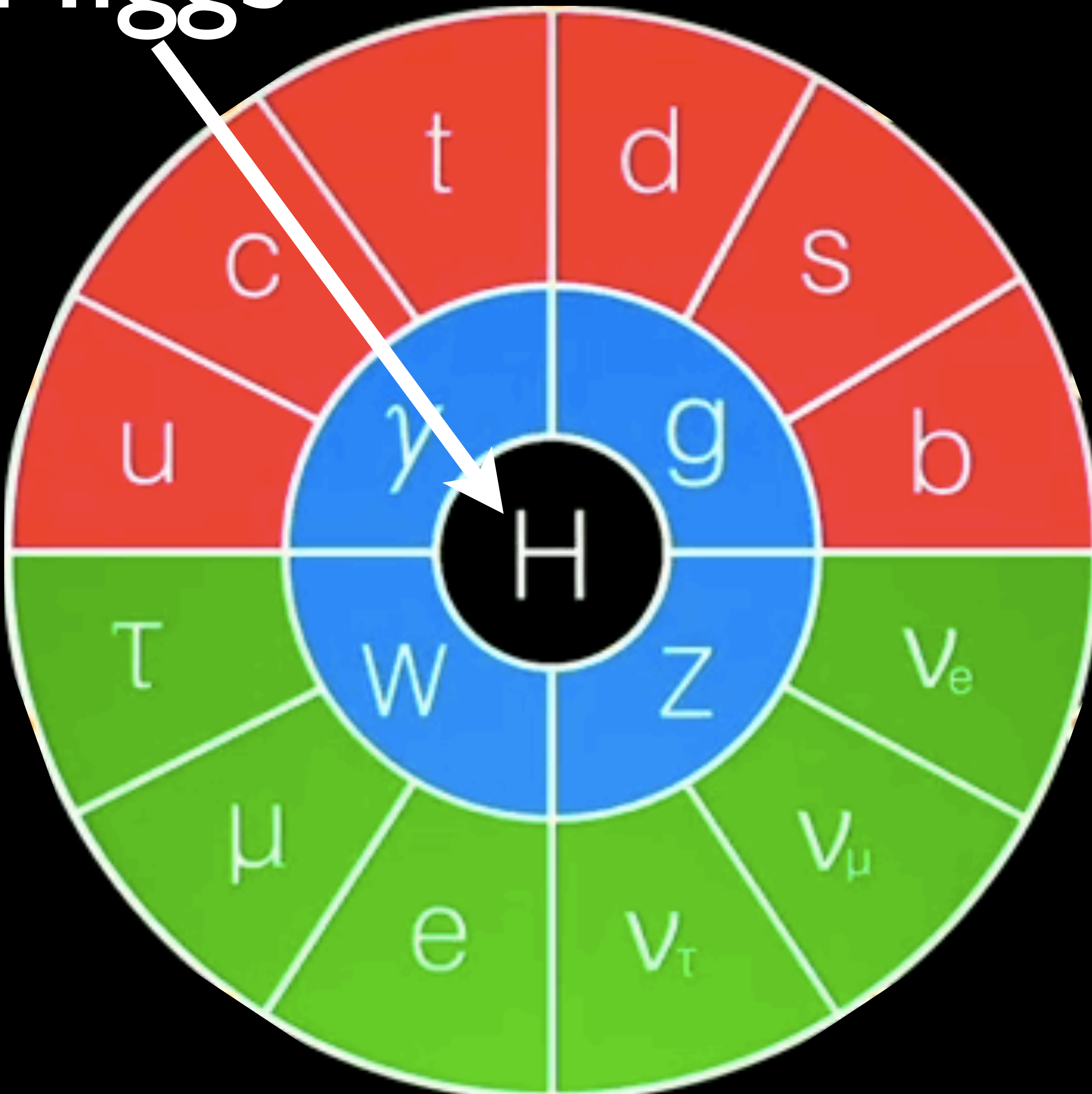
Standard Models



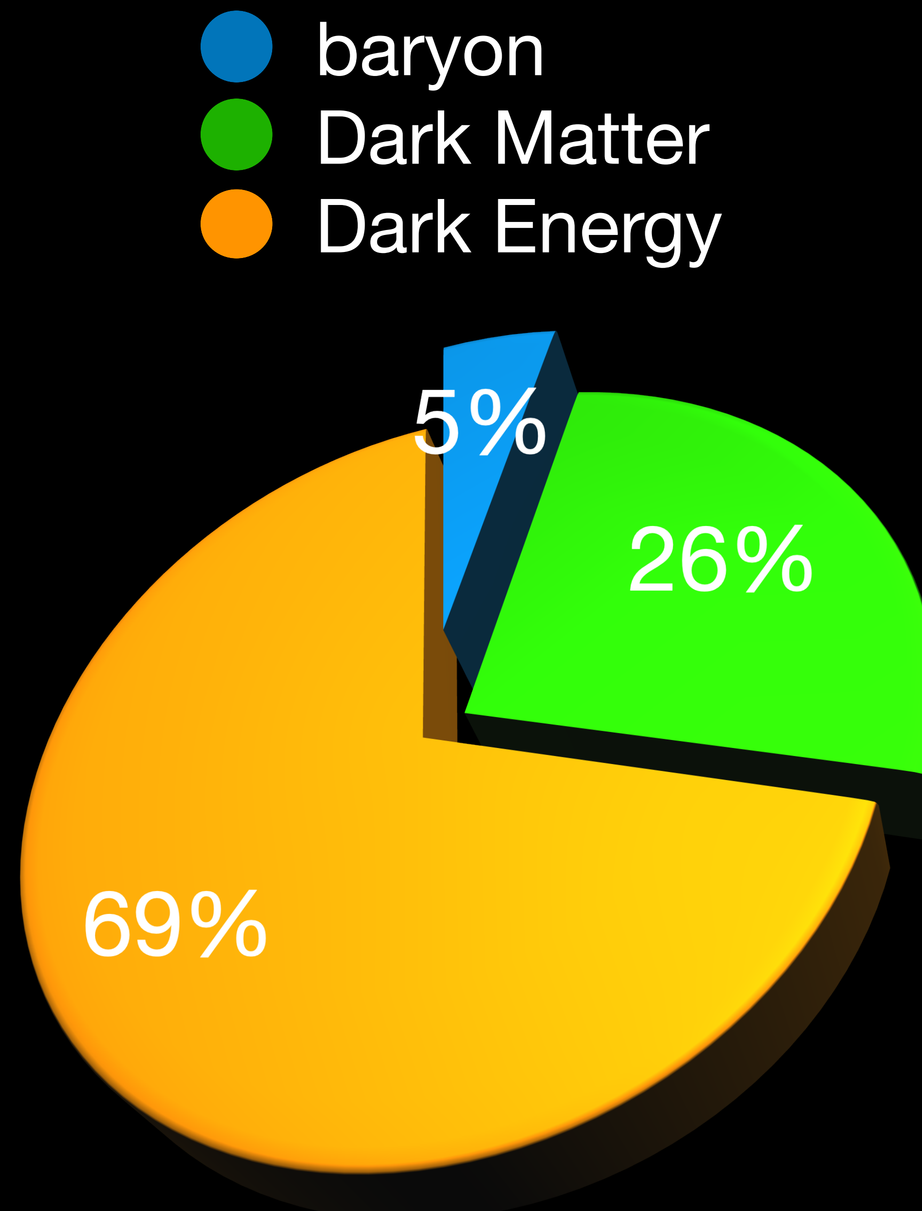
SU(3)xSU(2)xU(1)

Standard Models

Higgs



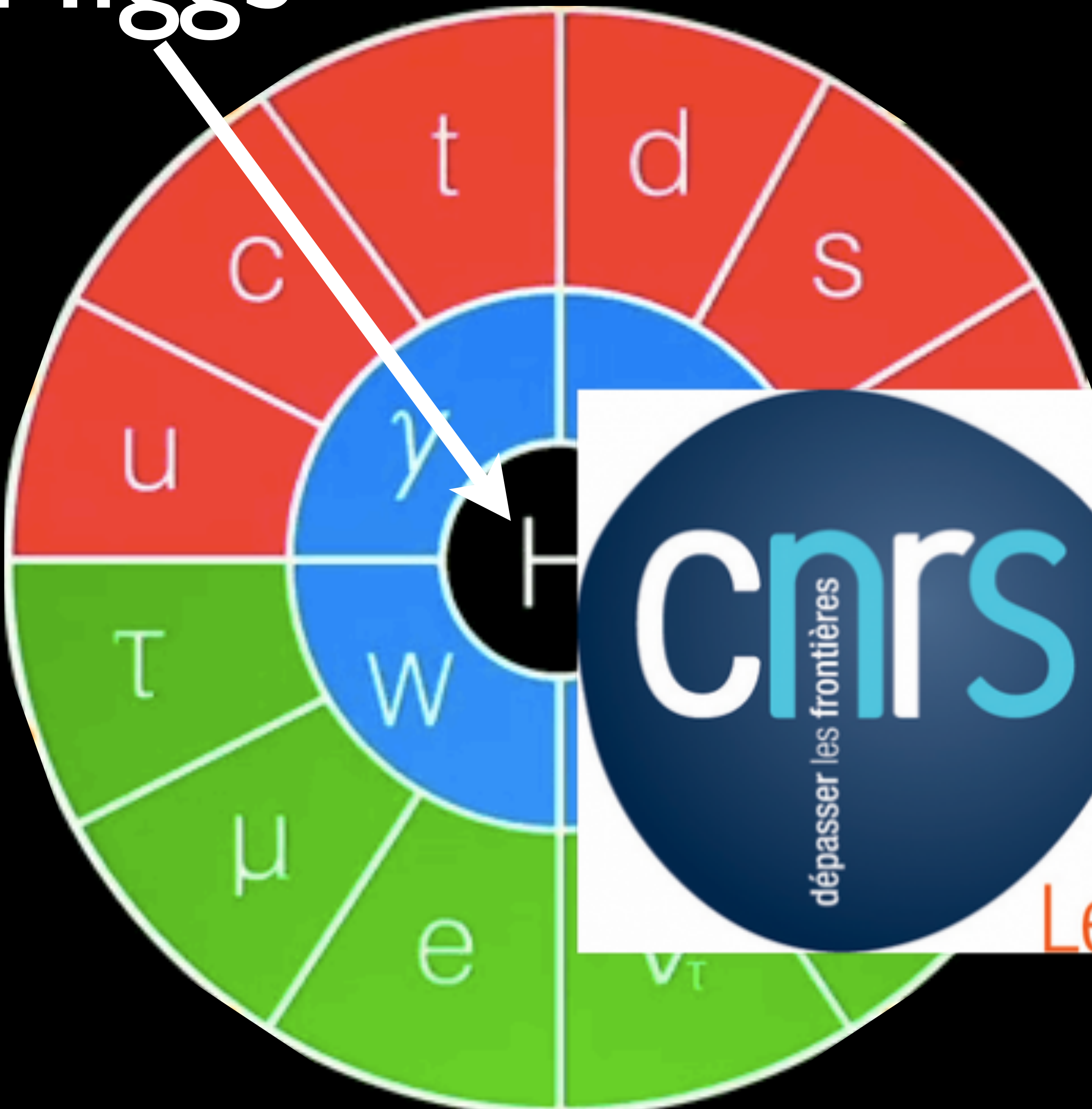
SU(3)xSU(2)xU(1)



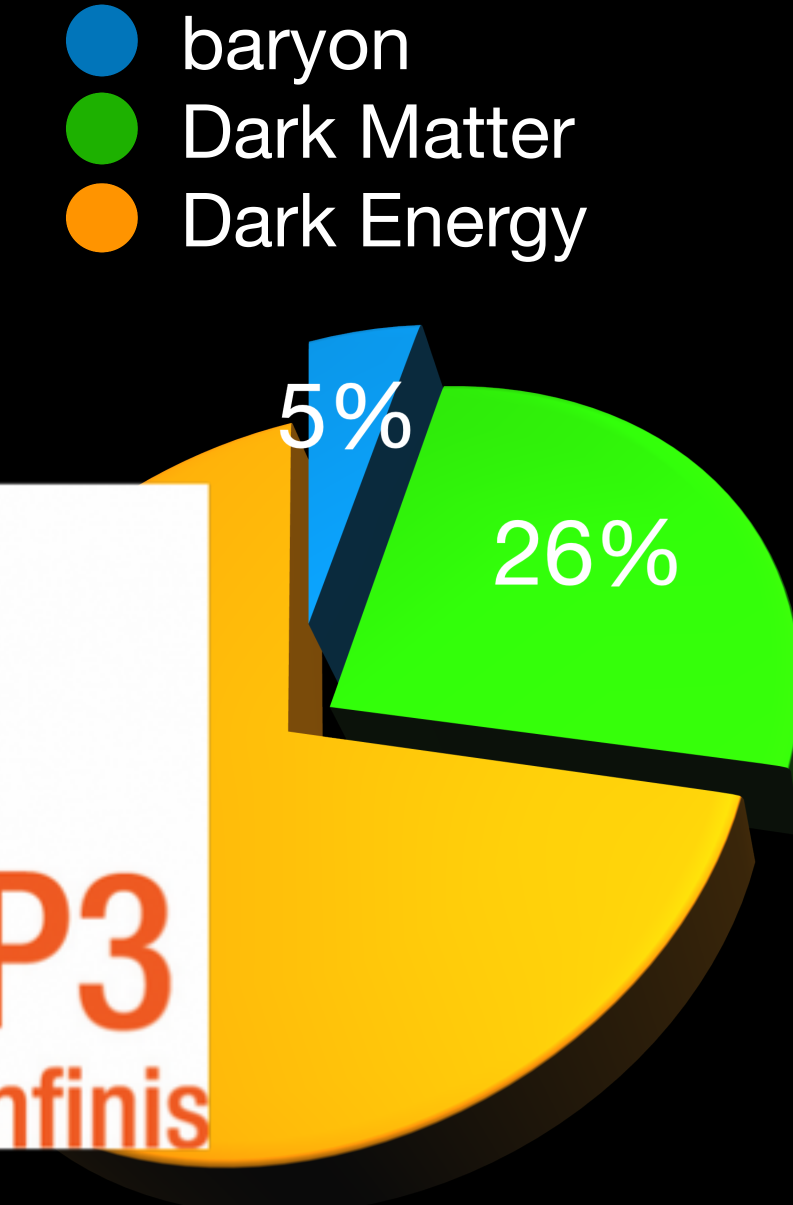
ΛCDM w/ power law density fluctuation

Standard Models

Higgs

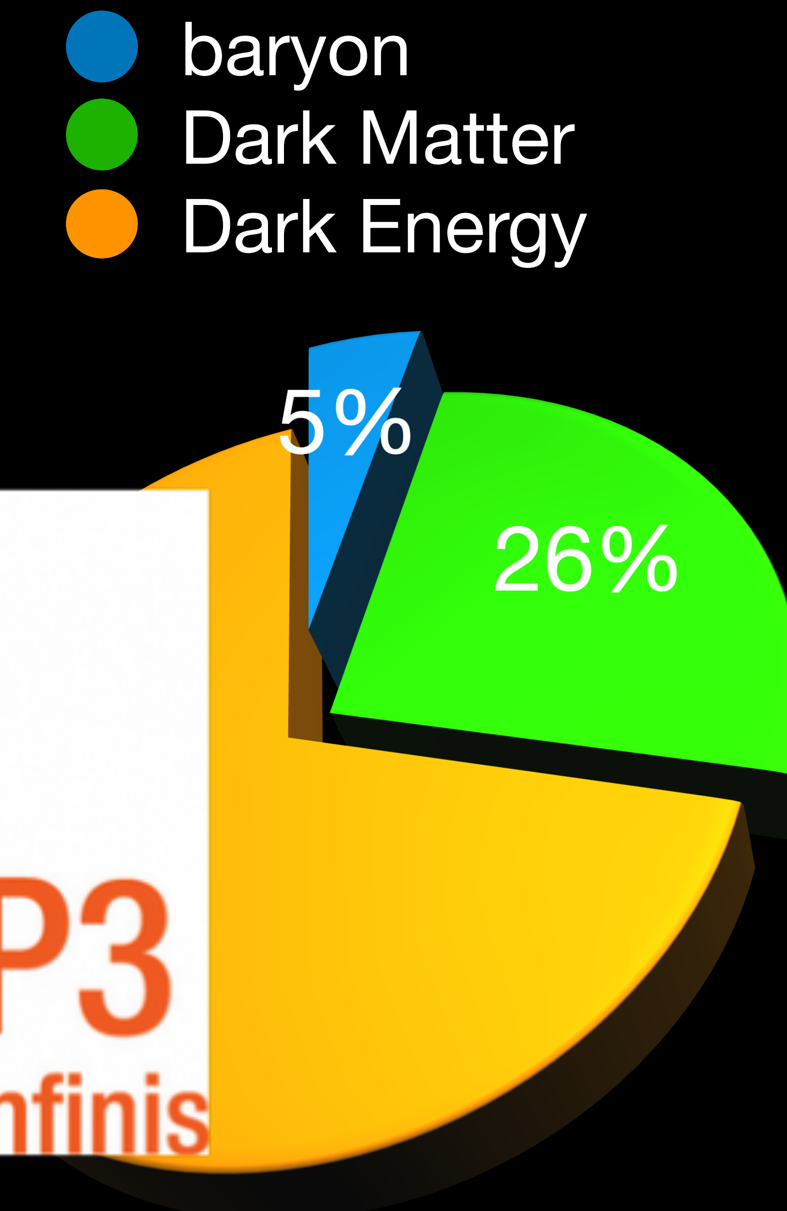


SU(3)xSU(2)xU(1)



ΛCDM w/ power law density fluctuation

Standard Models



SU(3)xSU(2)xU(1)

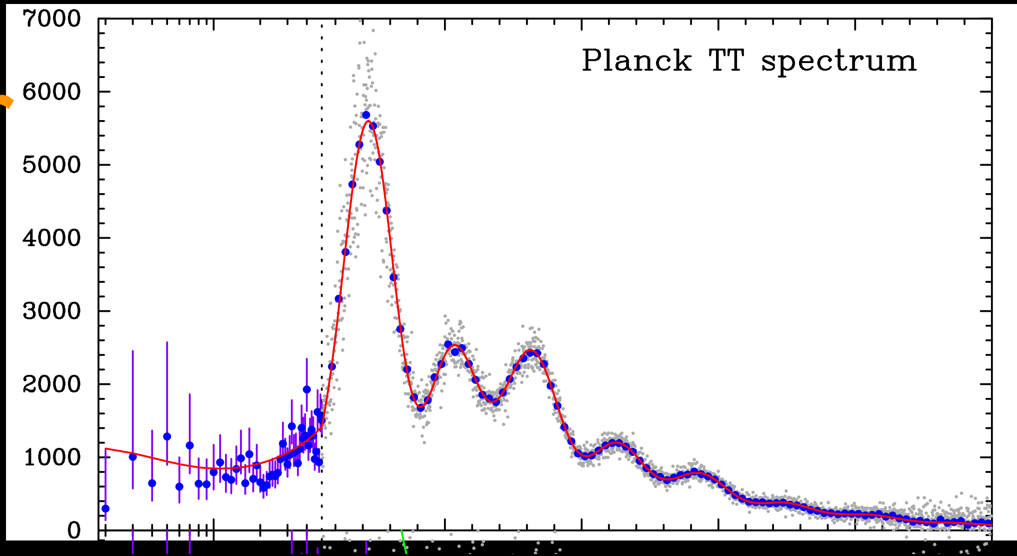
ΛCDM w/
power law density fluctuation

time to go beyond them!

two new tools: Higgs & gravitational wave

Five empirical 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...

Beginning of Universe

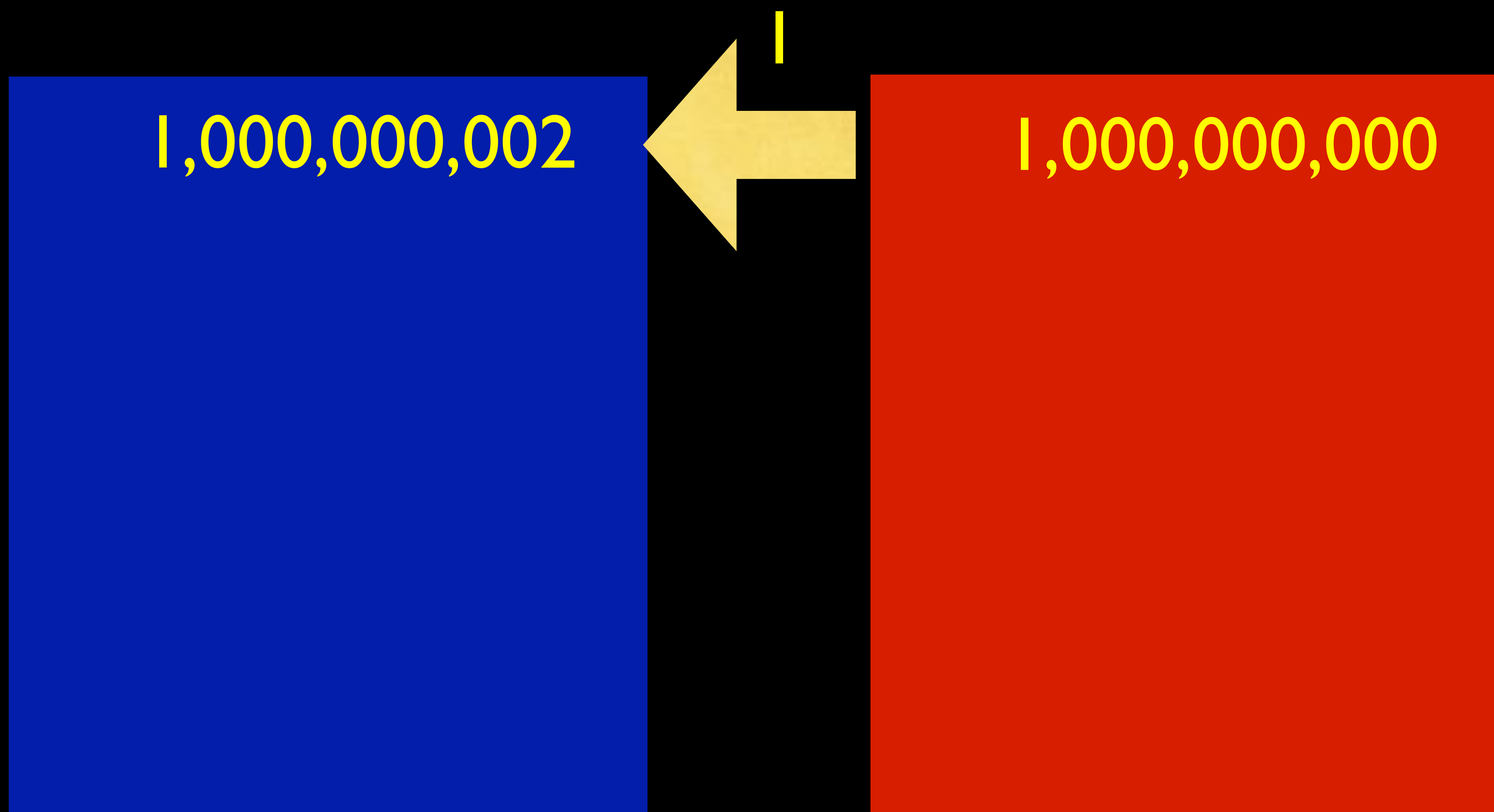
1,000,000,001

1,000,000,001

matter

anti-matter

fraction of second later



matter *anti-matter*

turned a billionth of anti-matter to matter

Universe Now

2

•

us

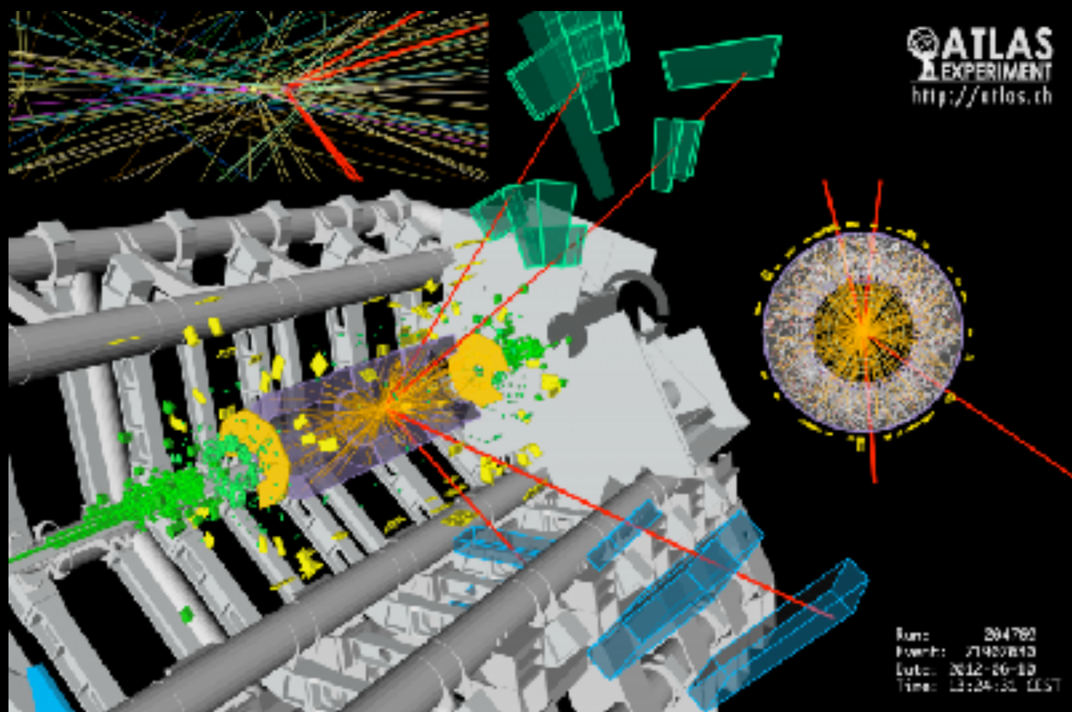
matter

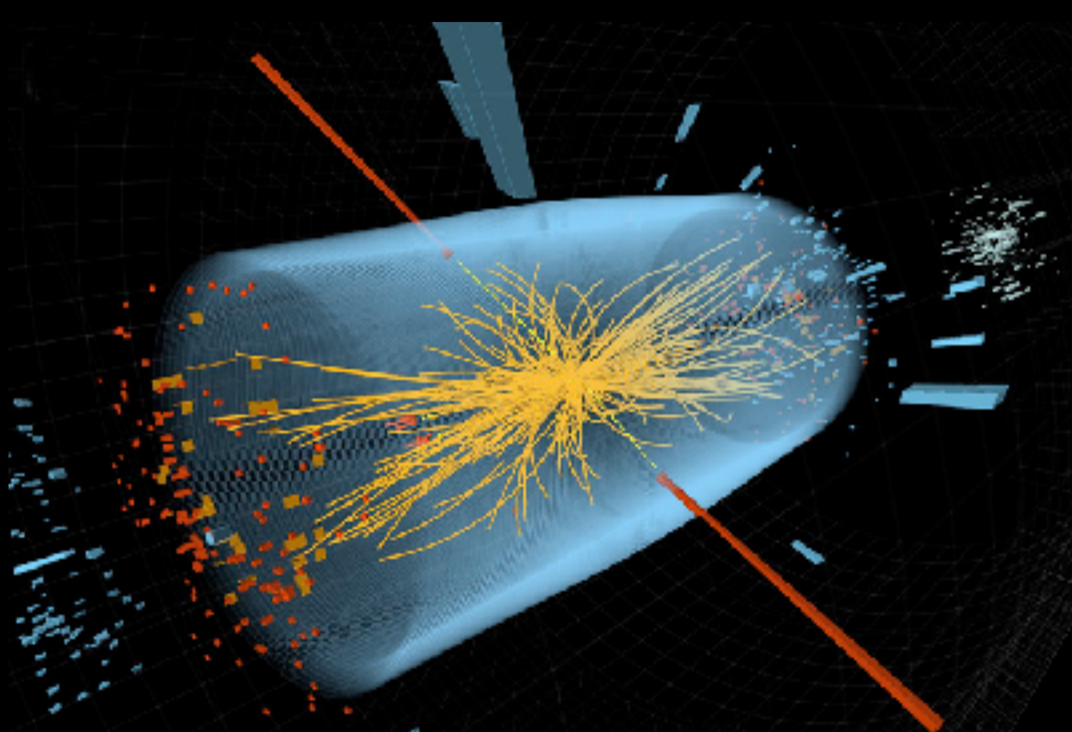
anti-matter

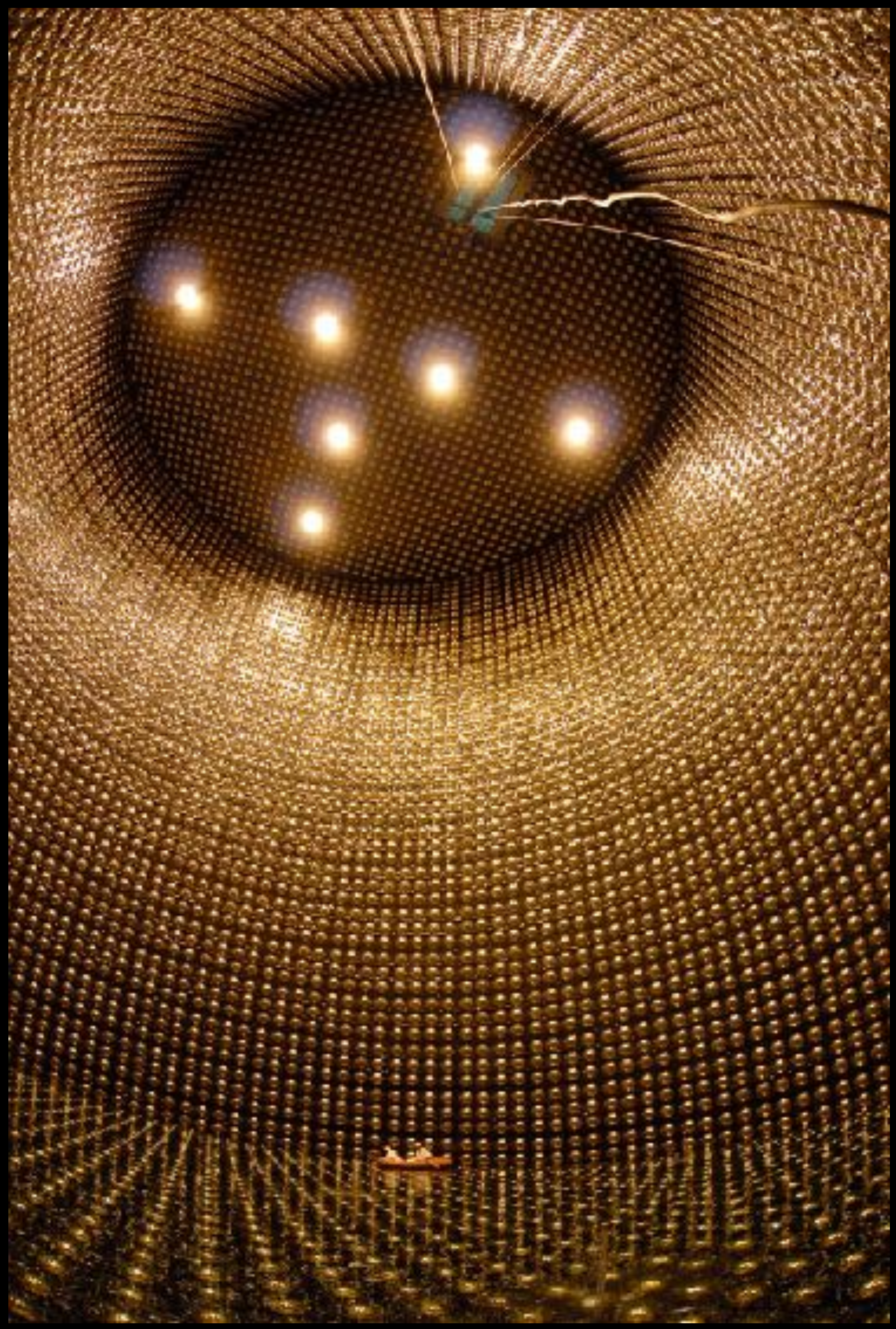
we were saved from the complete annihilation!


Who saved us from
a complete annihilation?

two directions

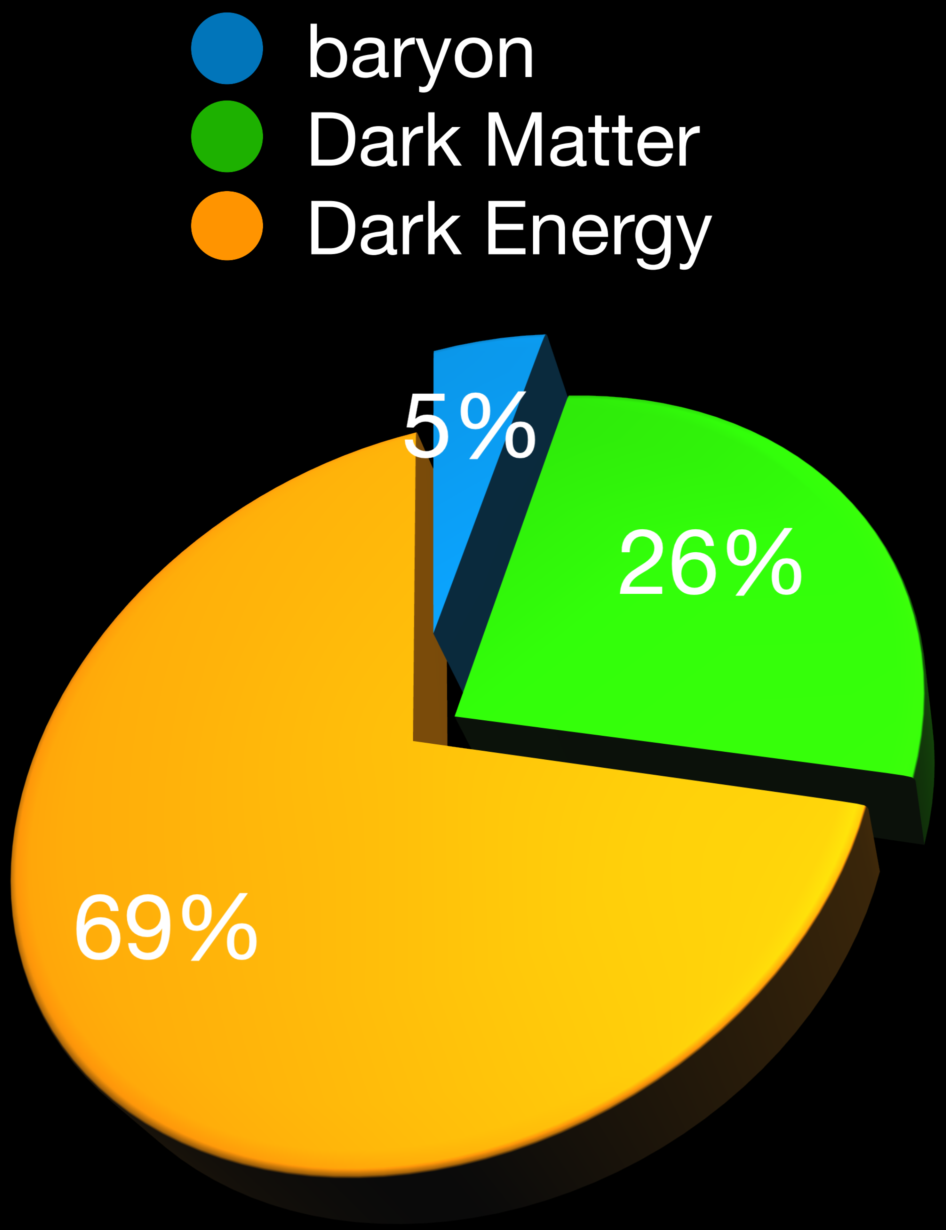






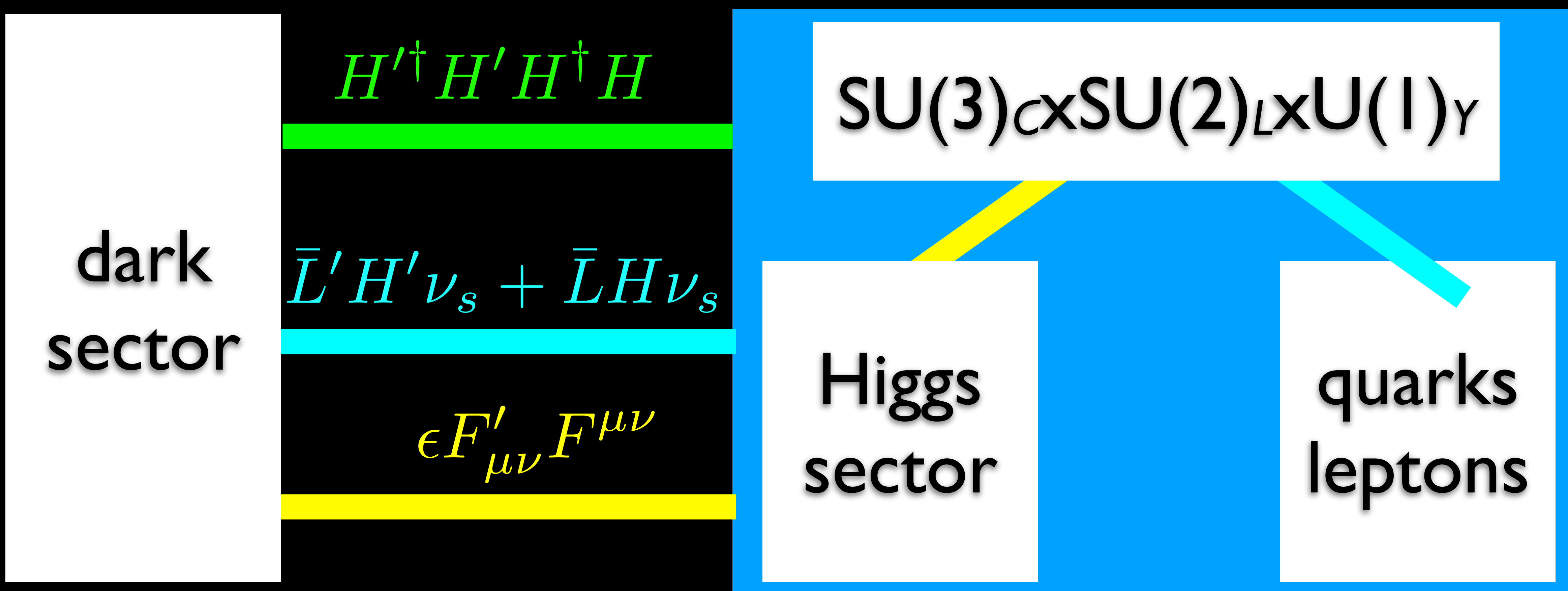
asymmetric dark matter

- we don’t know what dark energy is
- we don’t know what dark matter is
- we don’t know why baryons exist
- why do they happen to be so close to each other?
- perhaps baryon and dark matter have common origin



portals

three possible portals in renormalizable theories



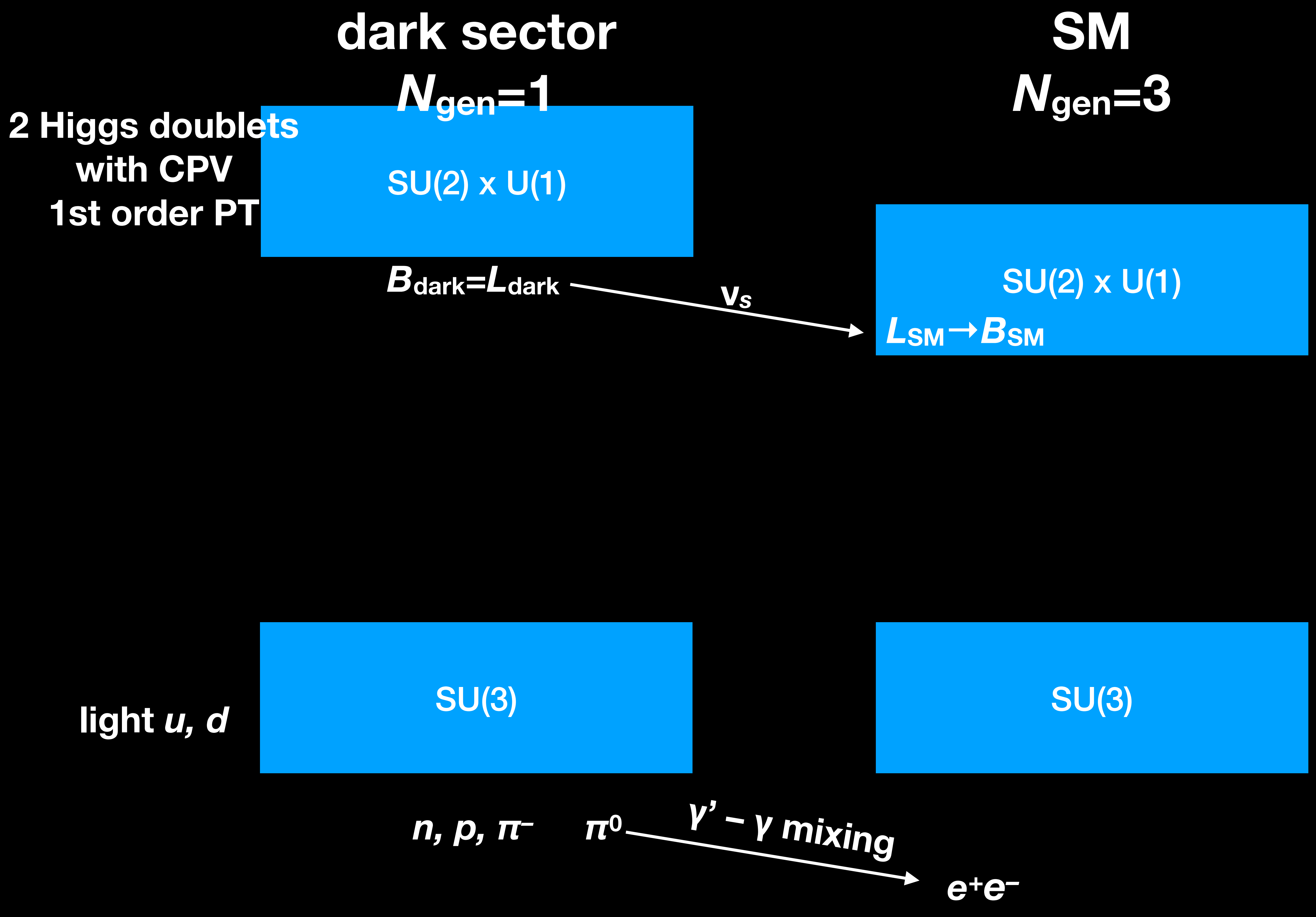
SM

$N_{gen}=3$

SU(2) x U(1)

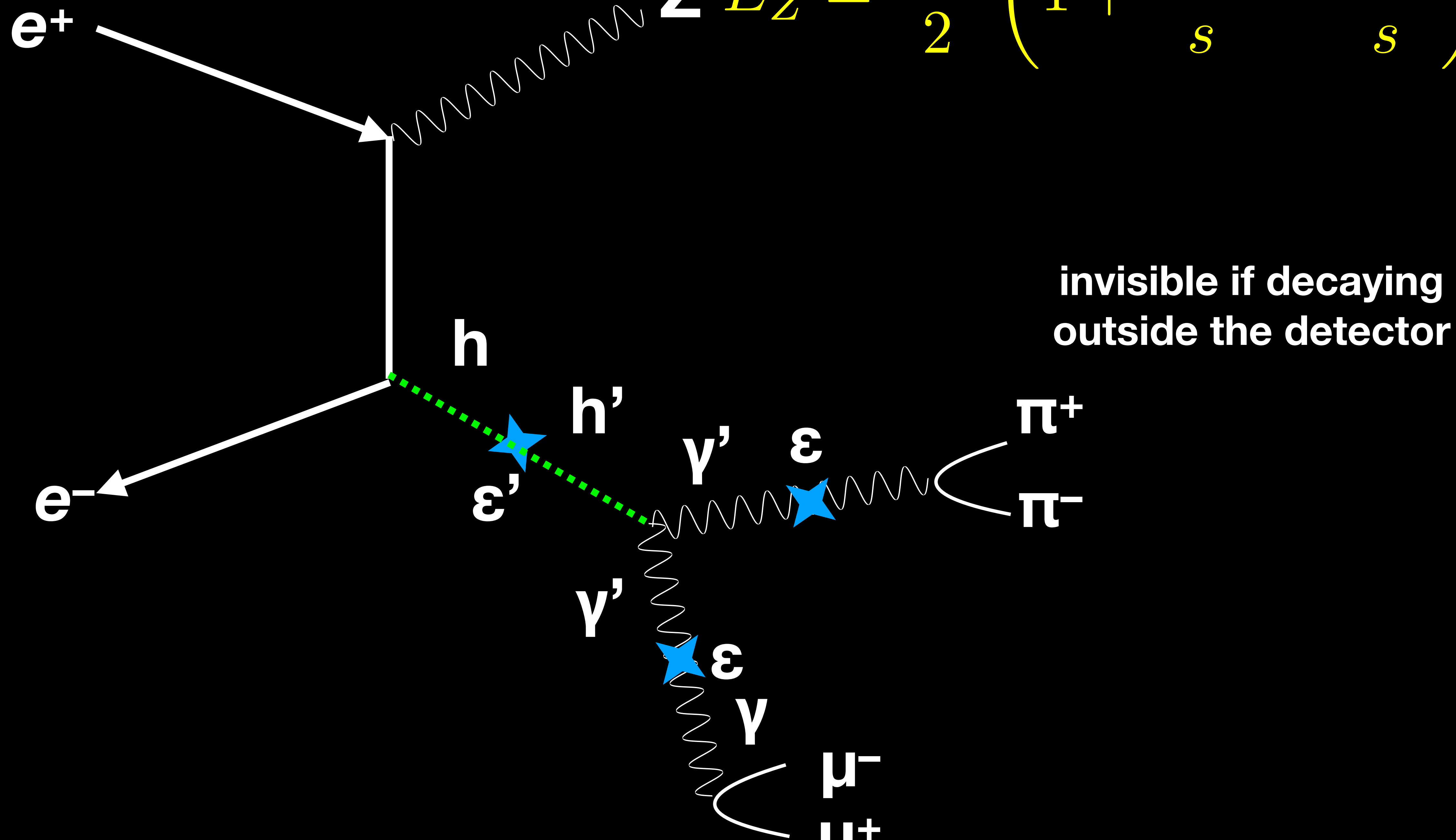
SU(3)

dark sector N_{gen}=1	SM N_{gen}=3
SU(2) x U(1)	SU(2) x U(1)
SU(3)	SU(3)


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

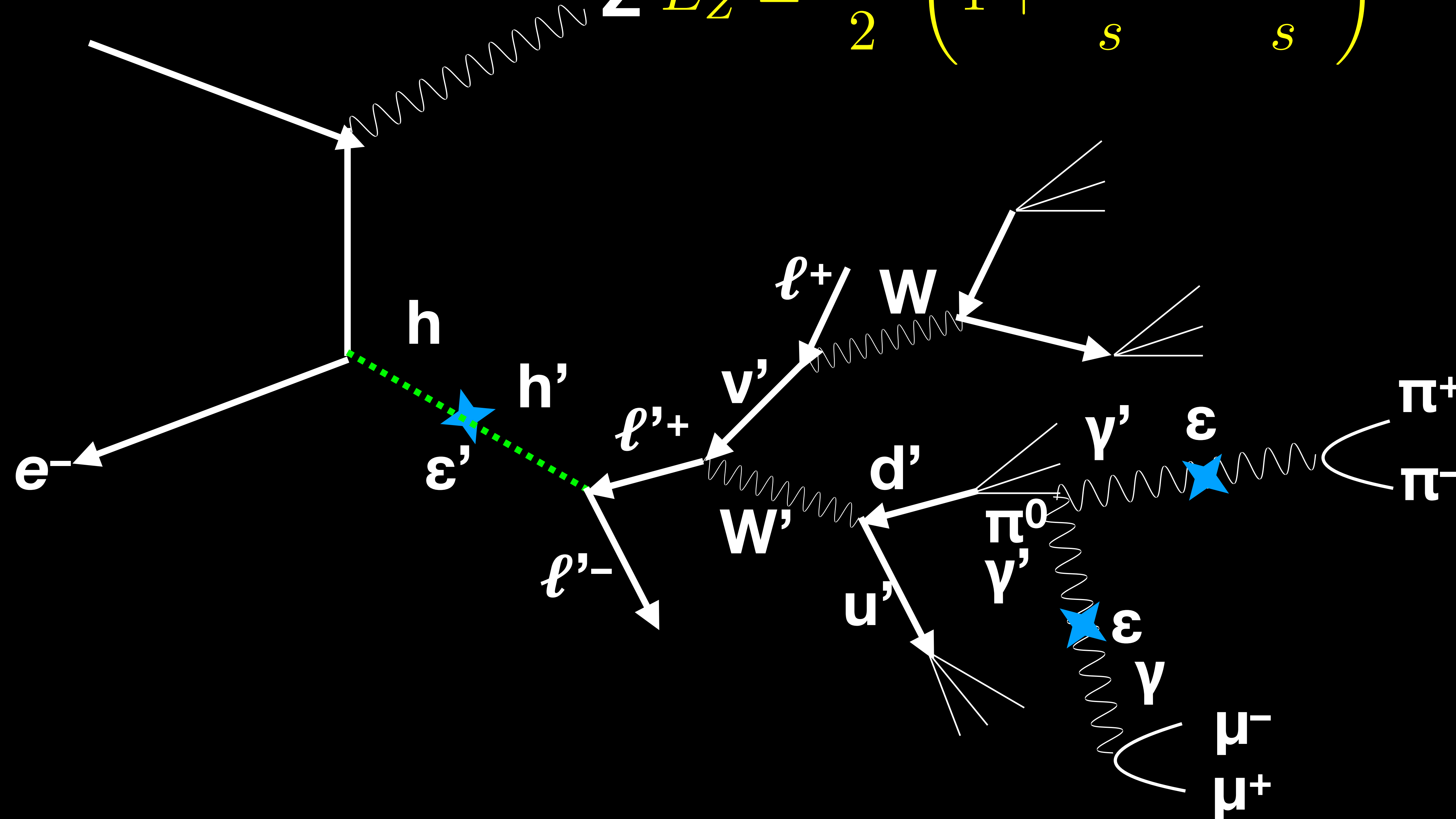
Higgs portal

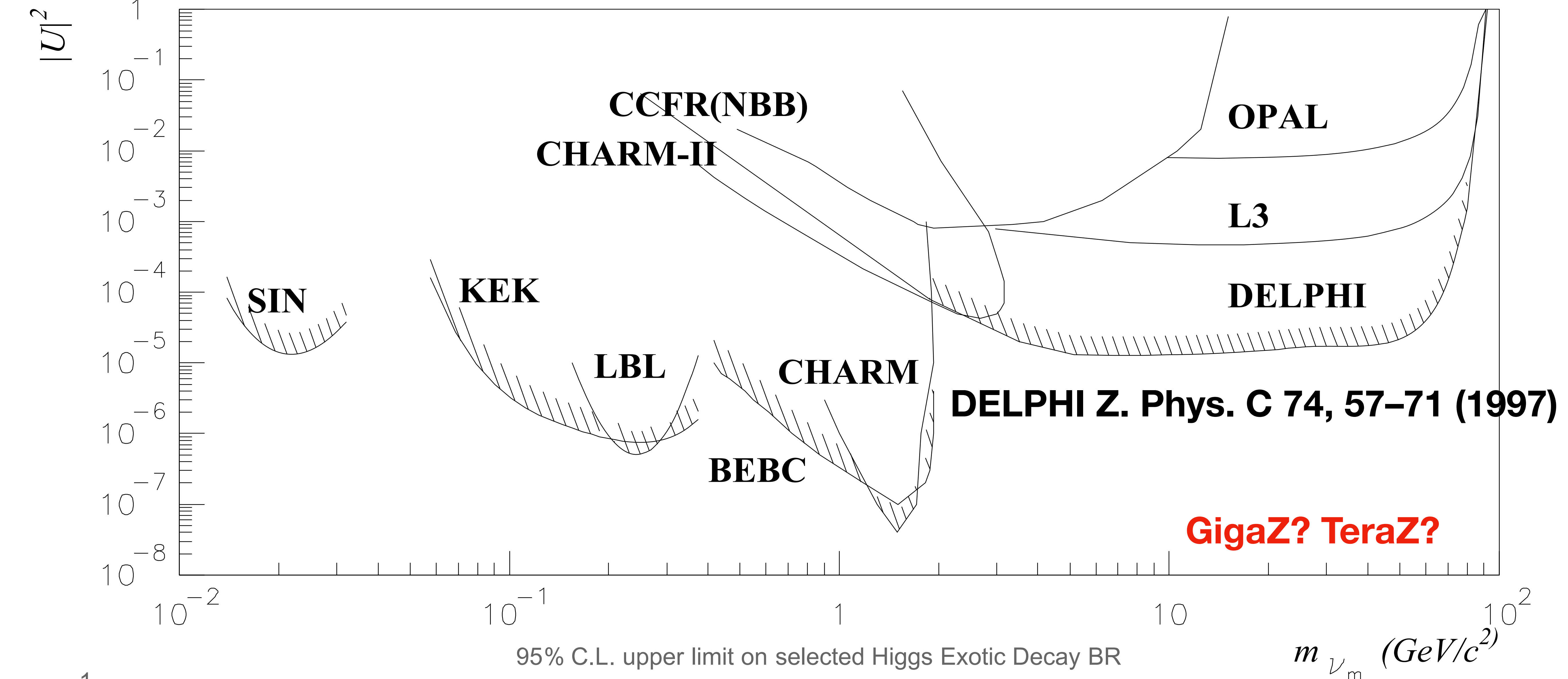
$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$

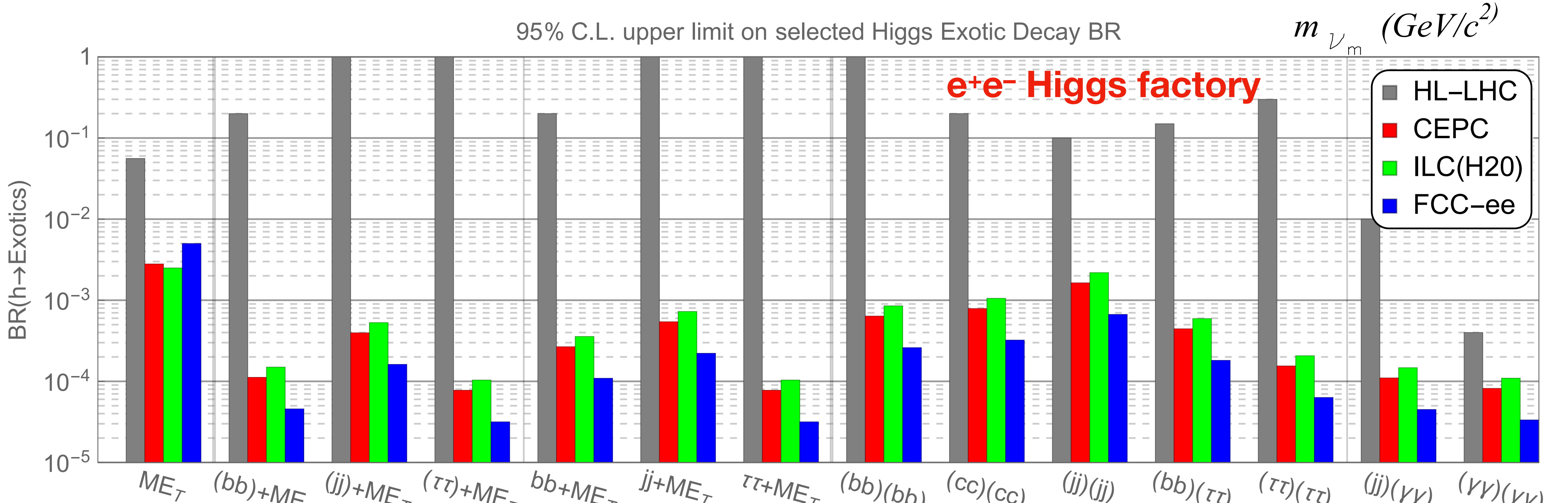


Higgs portal

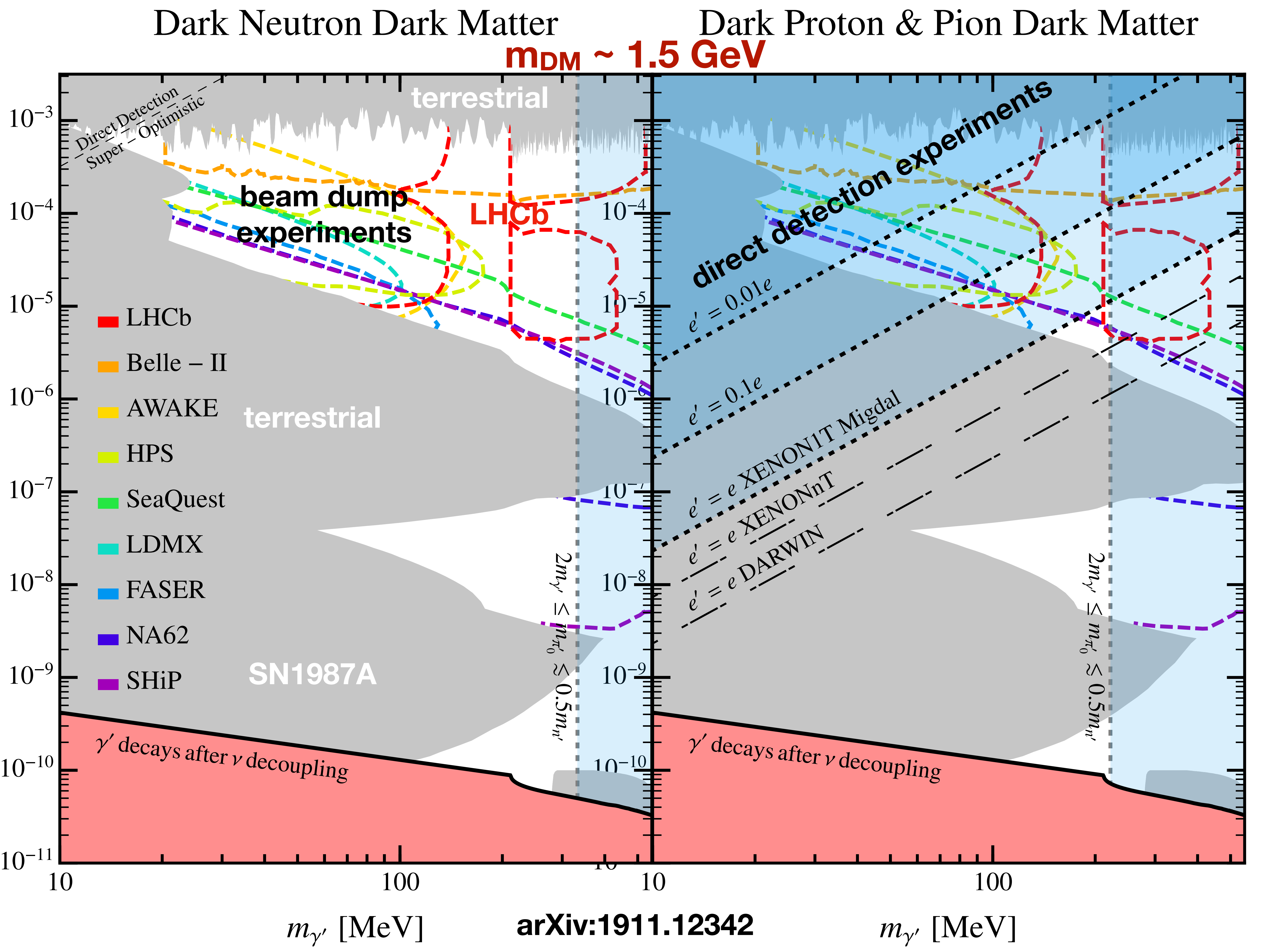
$$E_Z = \frac{\sqrt{s}}{2}\left(1 + \frac{m_Z^2}{s} - \frac{M_h^2}{s}\right)$$







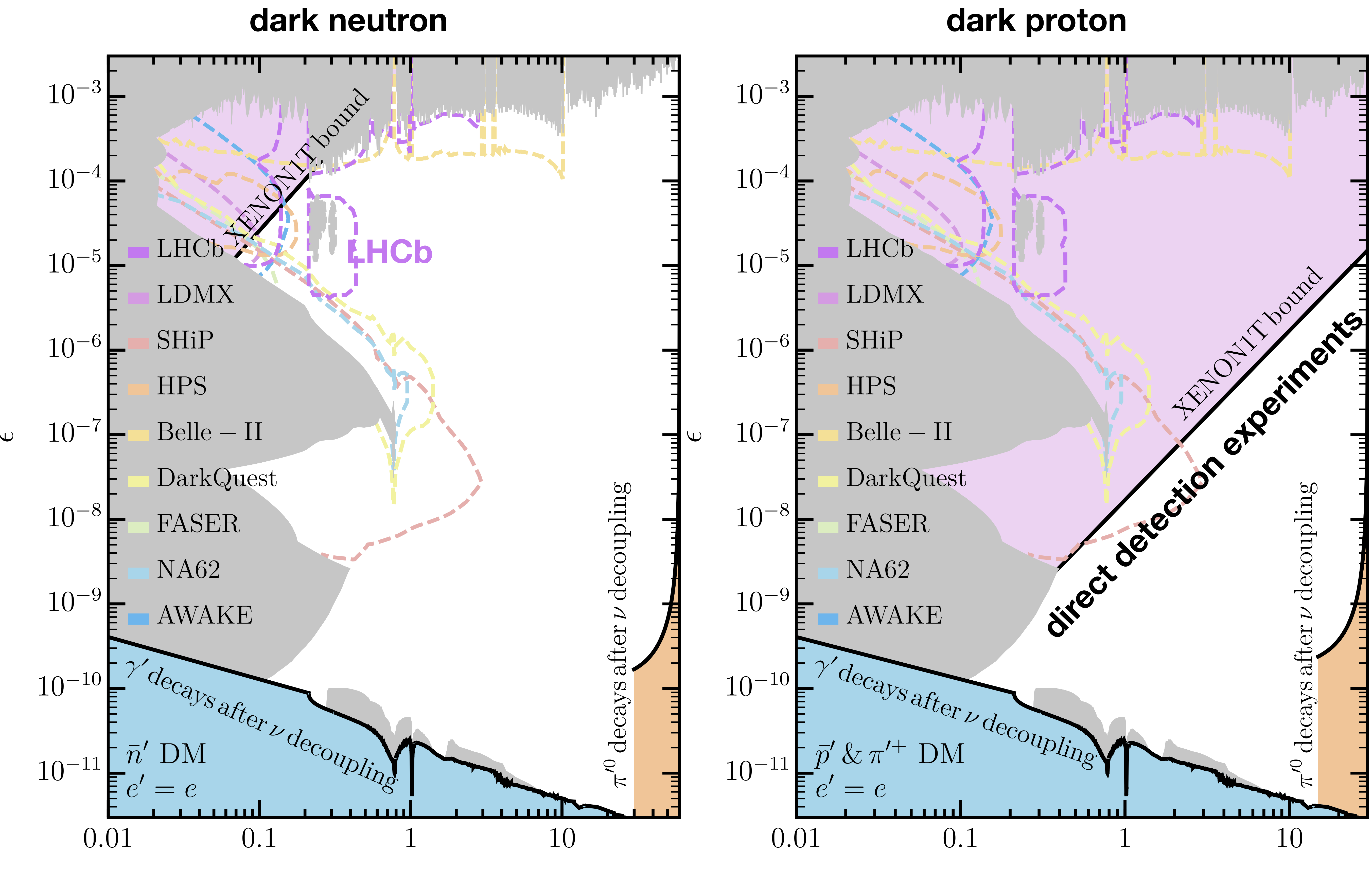
Zhen Liu, Lian-Tao Wang, Hao Zhang, arXiv:1612.09284



Dark Neutron Dark Matter
Dark Proton & Pion Dark Matter
m_DM ~ 1.5 GeV
terrestrial
Direct Detection
Super − Optimistic
beam dump
experiments
LHCb
direct detection experiments
e′ = 0.01e
e′ = 0.1e
e′ = e XENON1T Migdal
e′ = e XENONnT
e′ = e DARWIN
LHCb
Belle − II
AWAKE
HPS
SeaQuest
LDMX
FASER
NA62
SHiP
terrestrial
SN1987A
2m_γ′ ≤ m_π′0 ≲ 0.5m_n′
γ′ decays after ν decoupling
m_γ′ [MeV]
arXiv:1911.12342

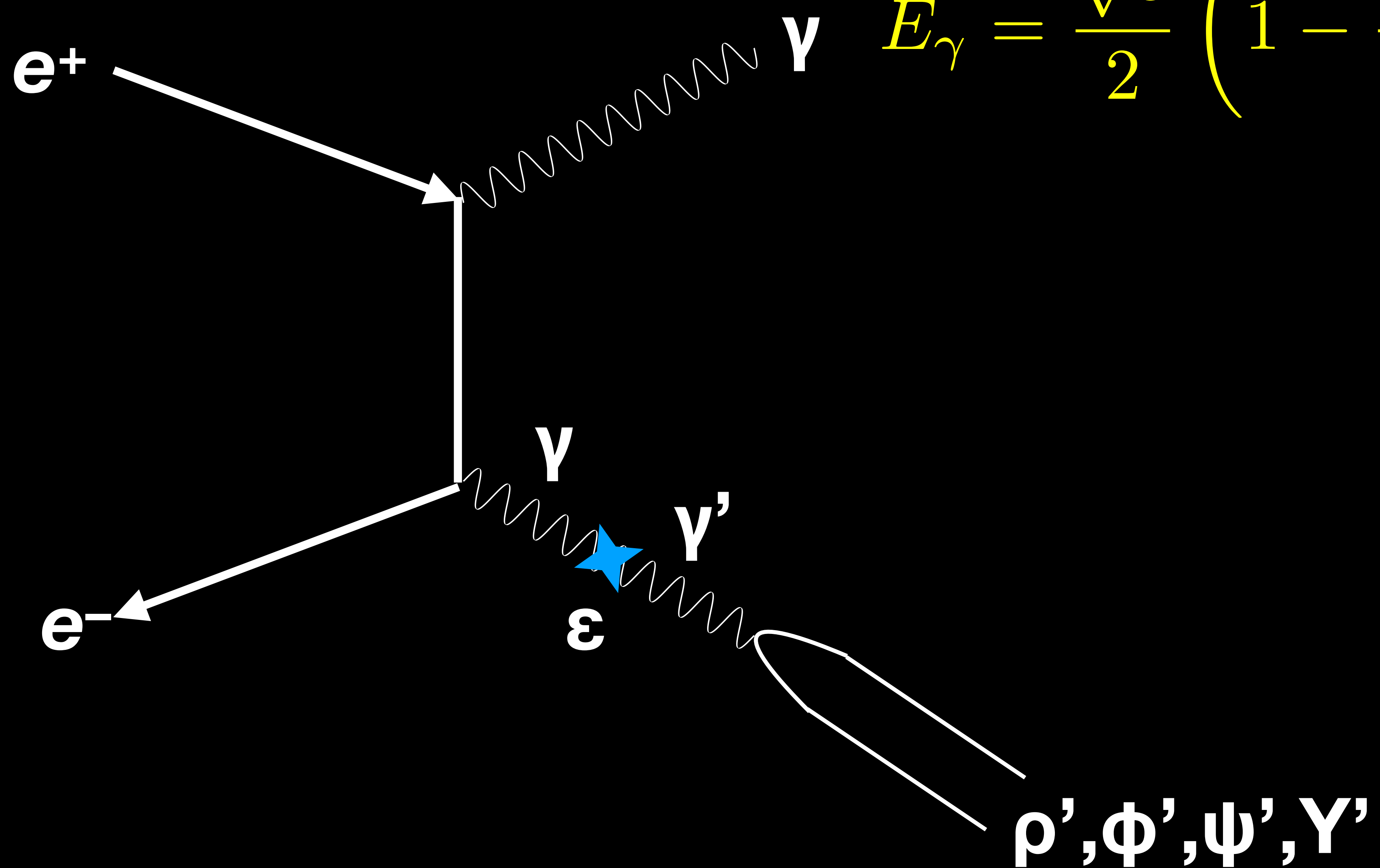
If the asymmetry originates in the SM side transferred to the dark side

m_{DM} ~ 16 GeV



arXiv:2107.03398

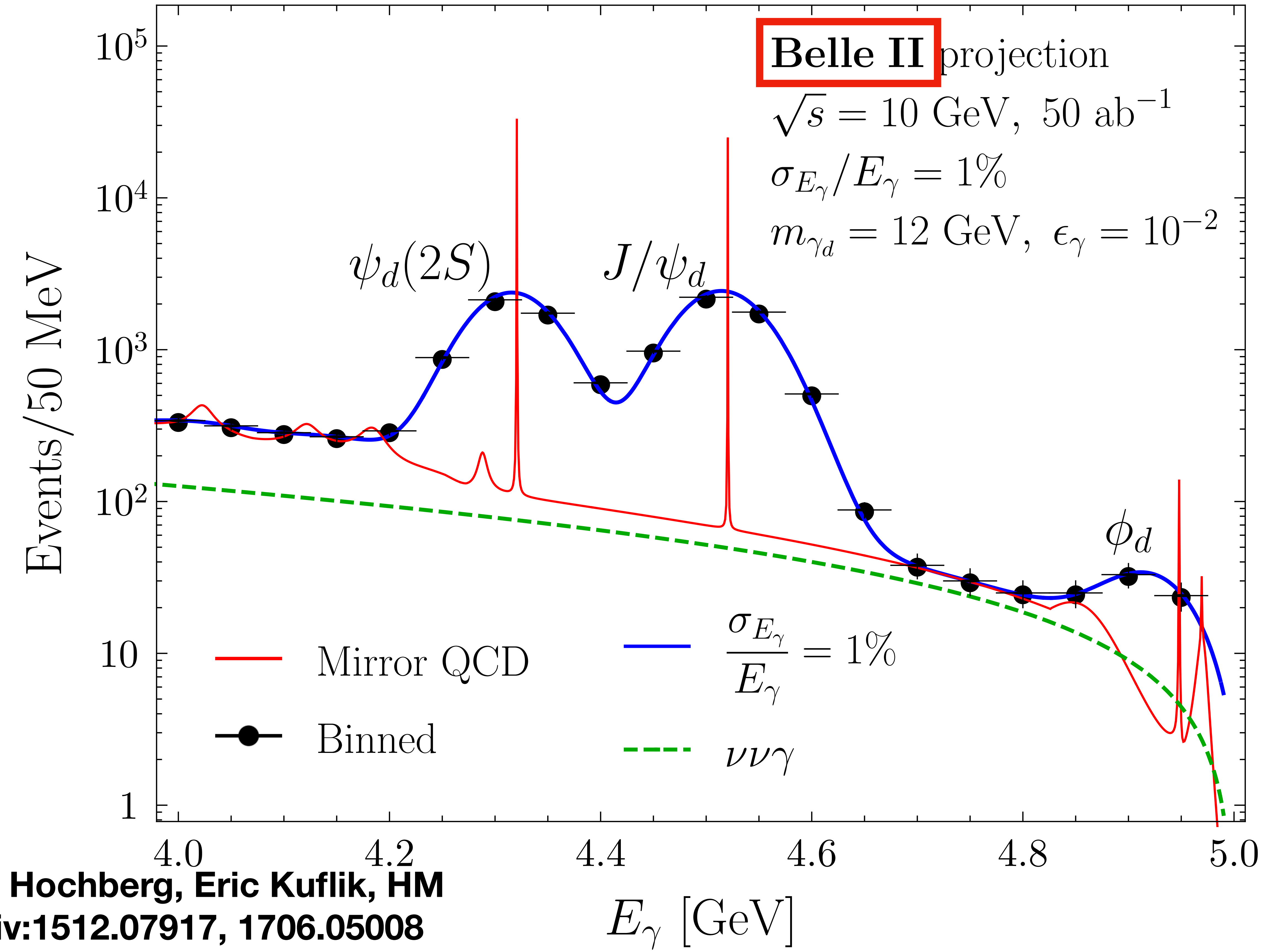
Dark Spectroscopy



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

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

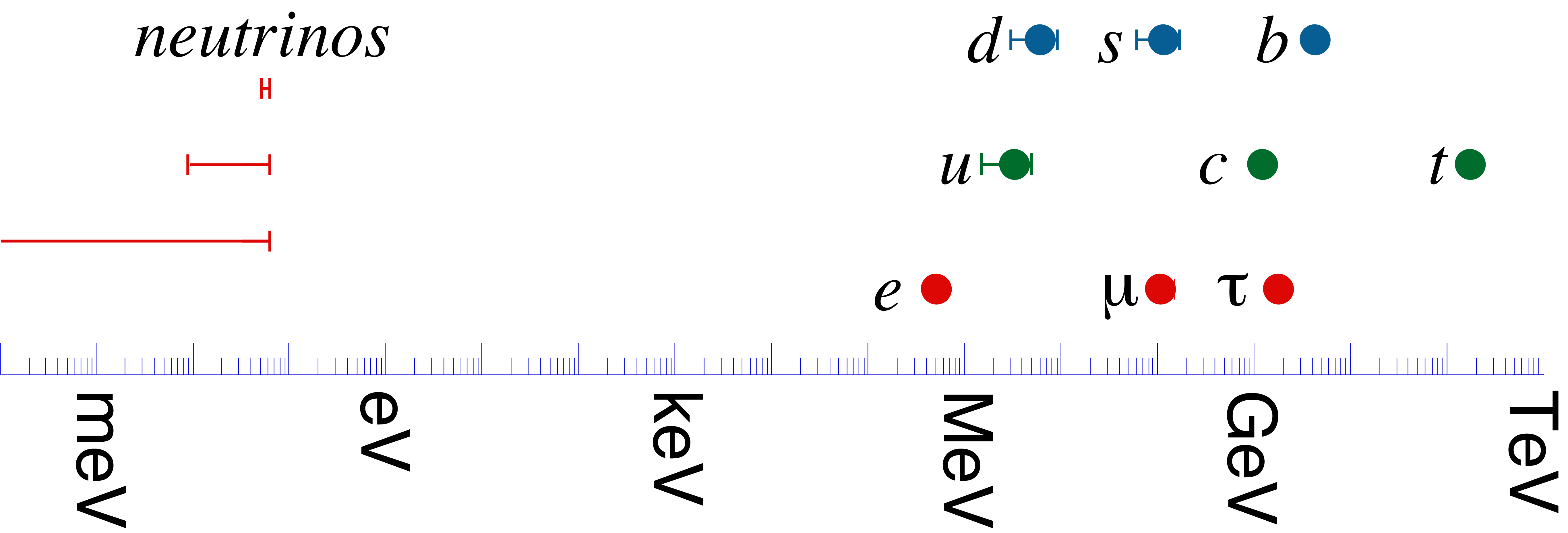
Dark Spectroscopy



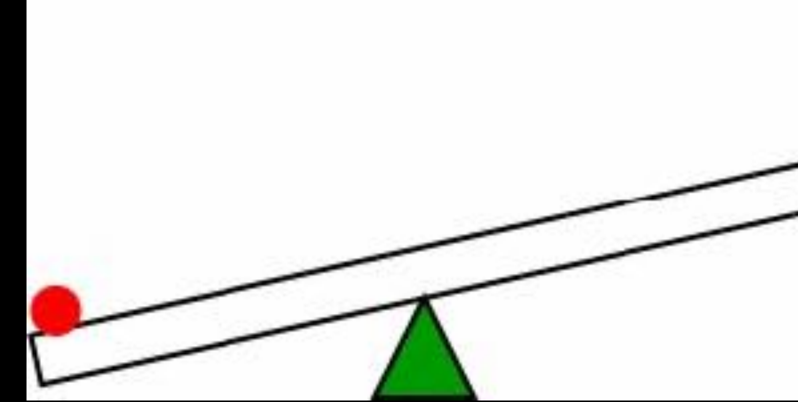
Yonit Hochberg, Eric Kuflik, HM
arXiv:1512.07917, 1706.05008

DISNEY PRESENTS A PIXAR FILM
THE INCREDIBLES
NOW PLAYING

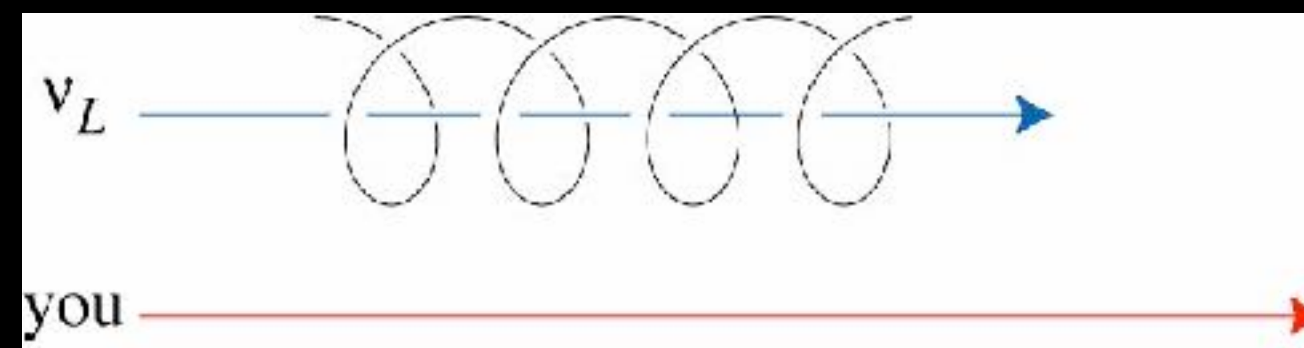
very light

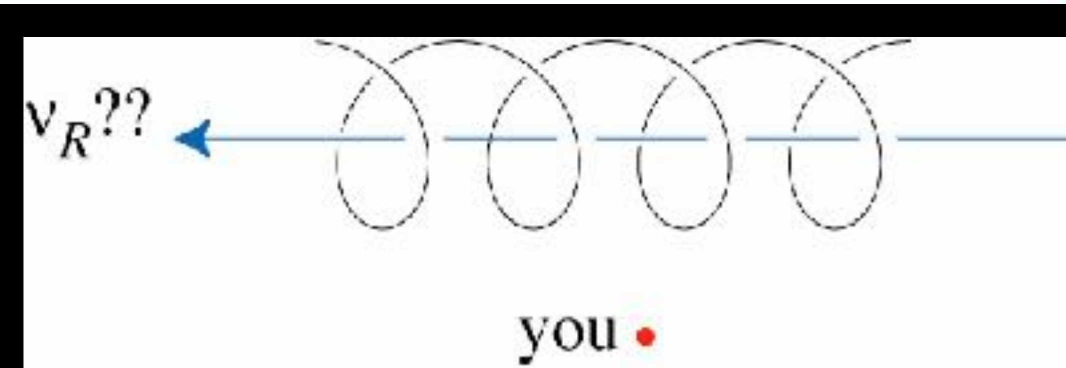


Seesaw



- 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

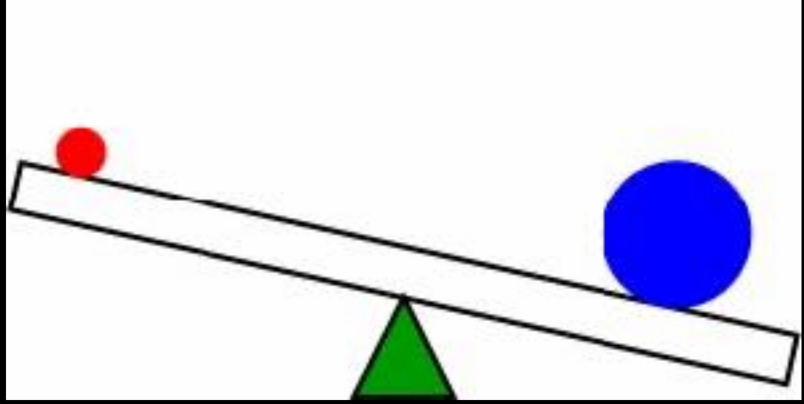




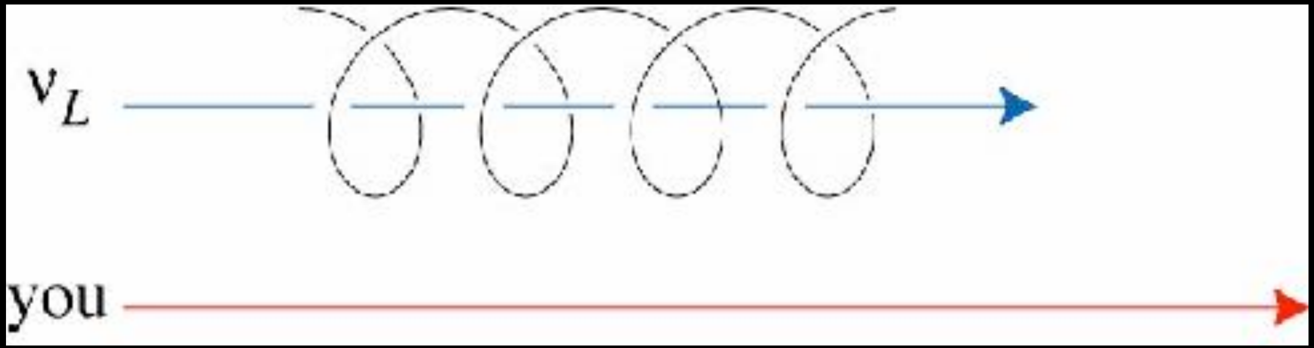
$$\mathcal{L} = -yLNH$$

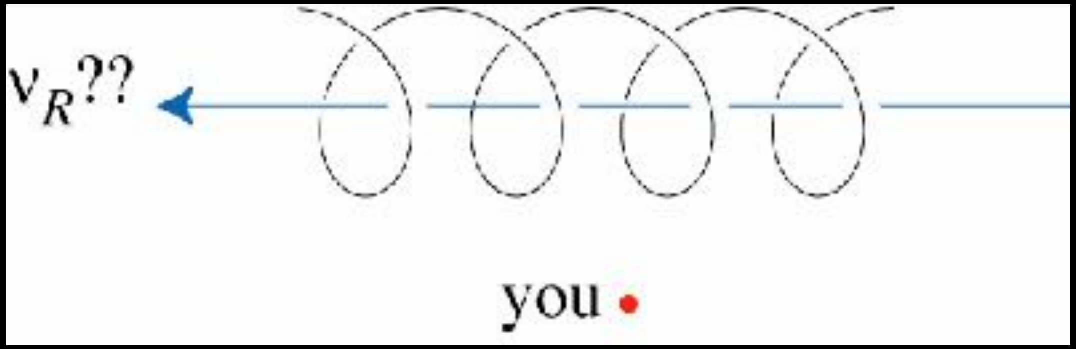
$$\begin{pmatrix} \nu & N \end{pmatrix} \begin{pmatrix} 0 & yv \\ yv & 0 \end{pmatrix} \begin{pmatrix} \nu \\ N \end{pmatrix}$$

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

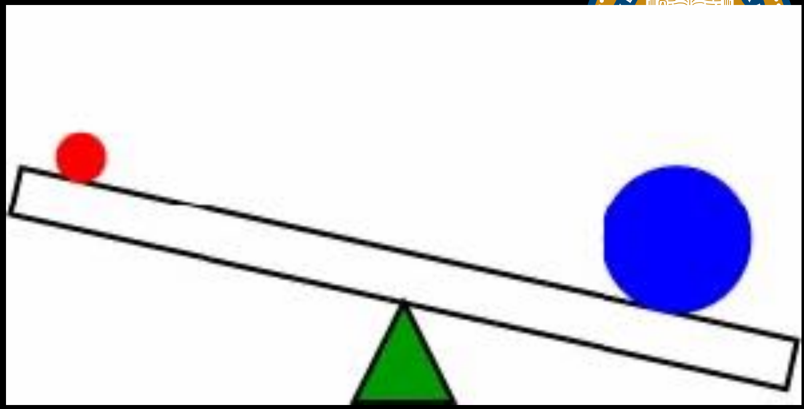




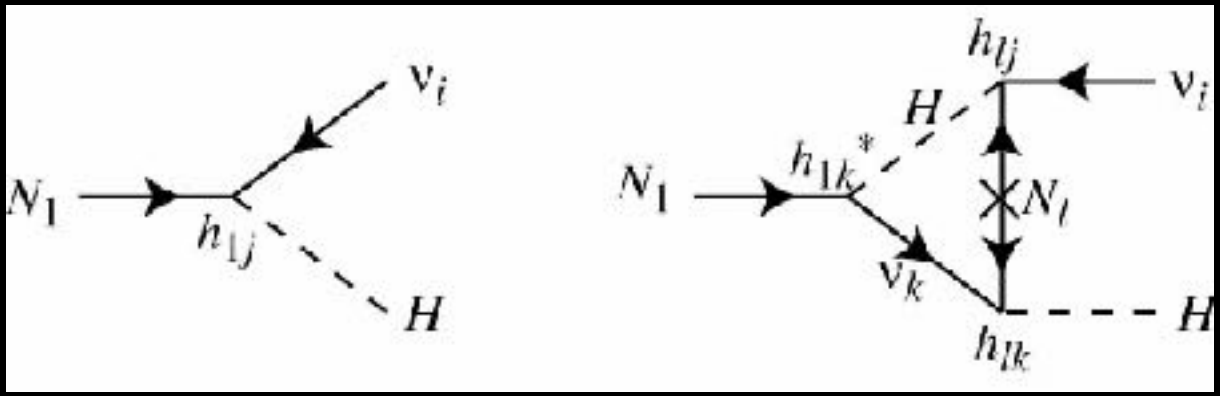
$$\mathcal{L} = -yLNH - \frac{1}{2}MNN$$

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

Leptogenesis



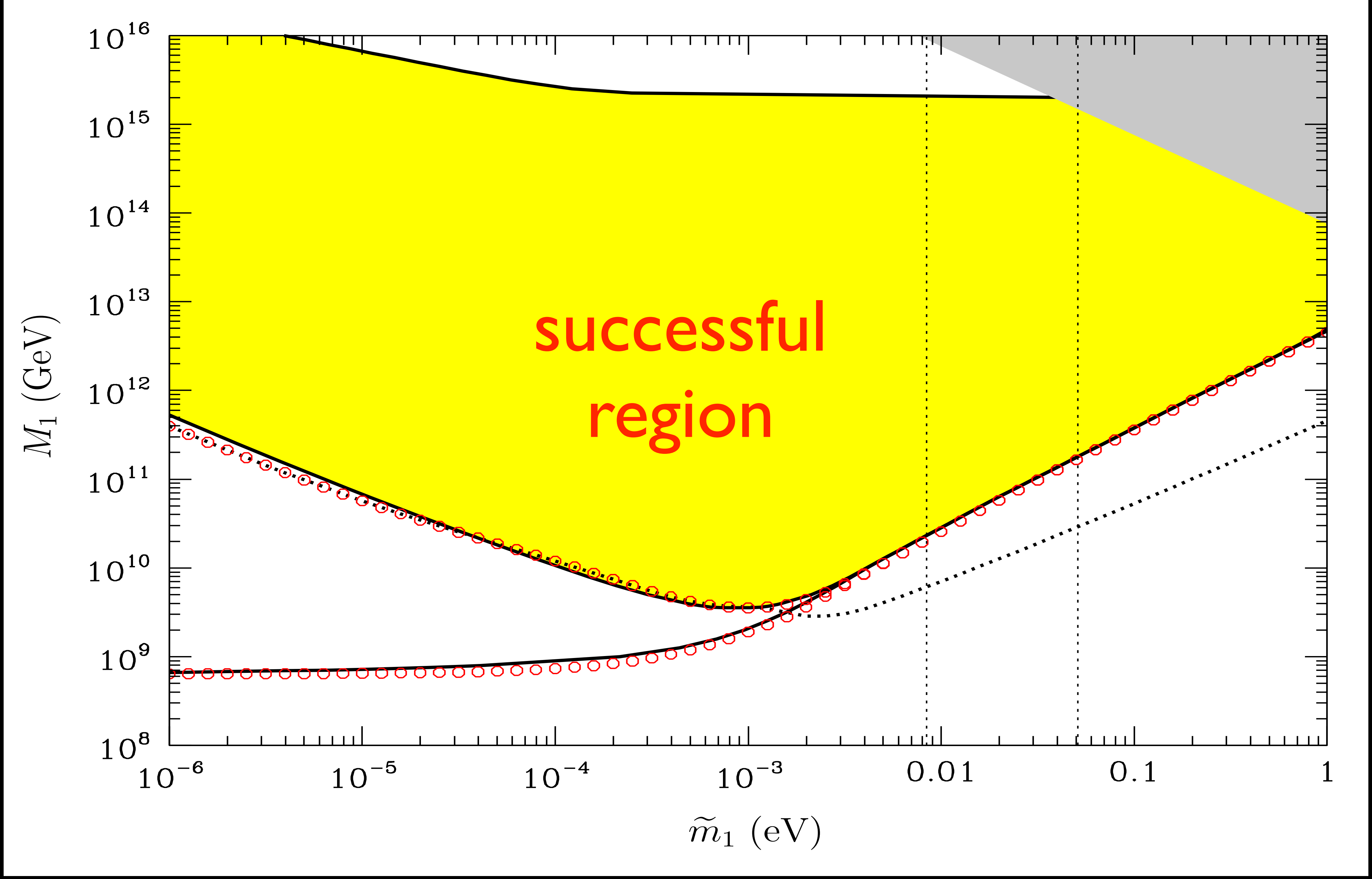
- Right-handed neutrinos in early universe
- when they decay, produce $L \neq 0$



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

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

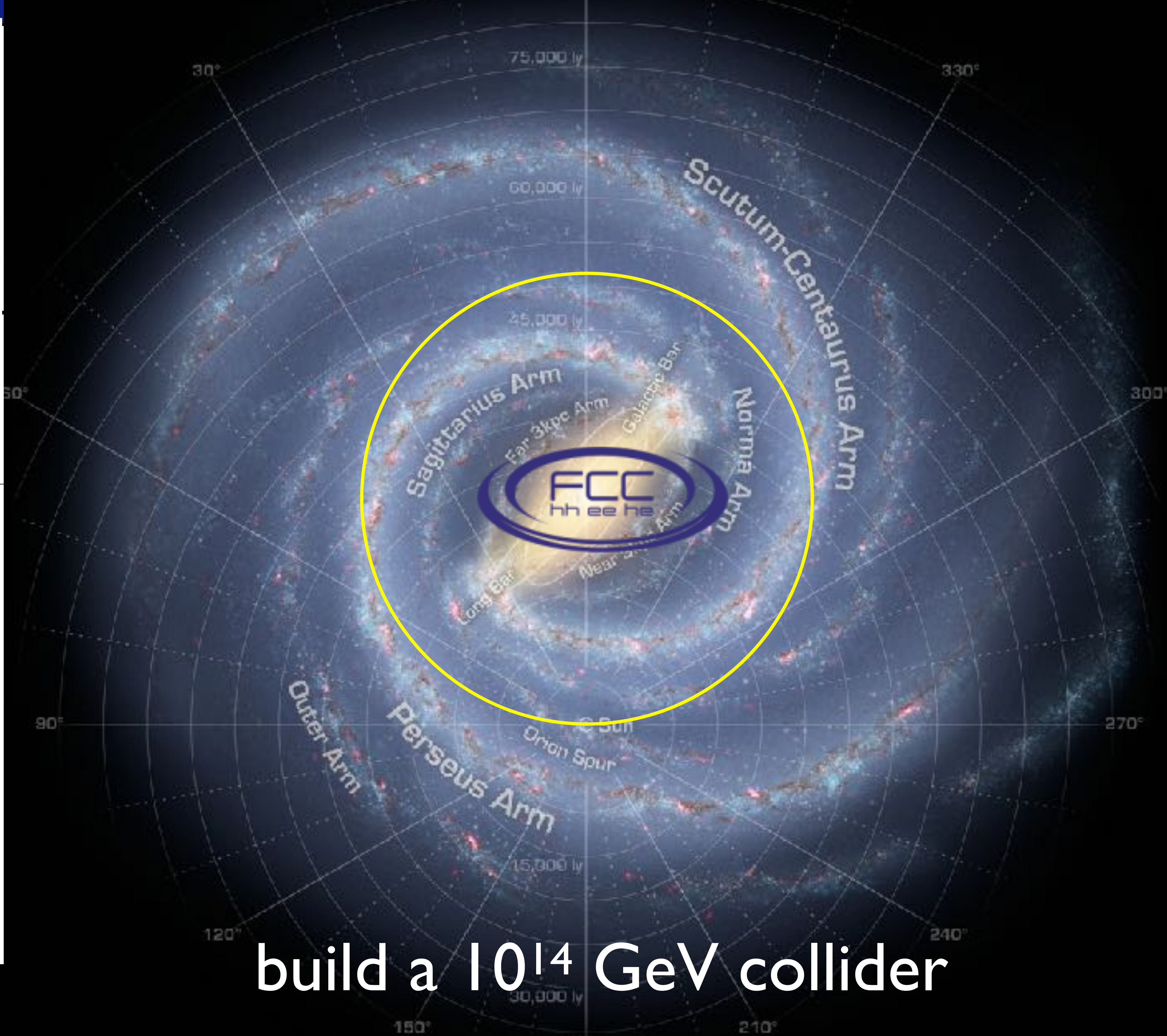
Leptogenesis



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

di Bari, Plümacher, Buchmüller

How do we test it?



build a 10^{14} GeV collider

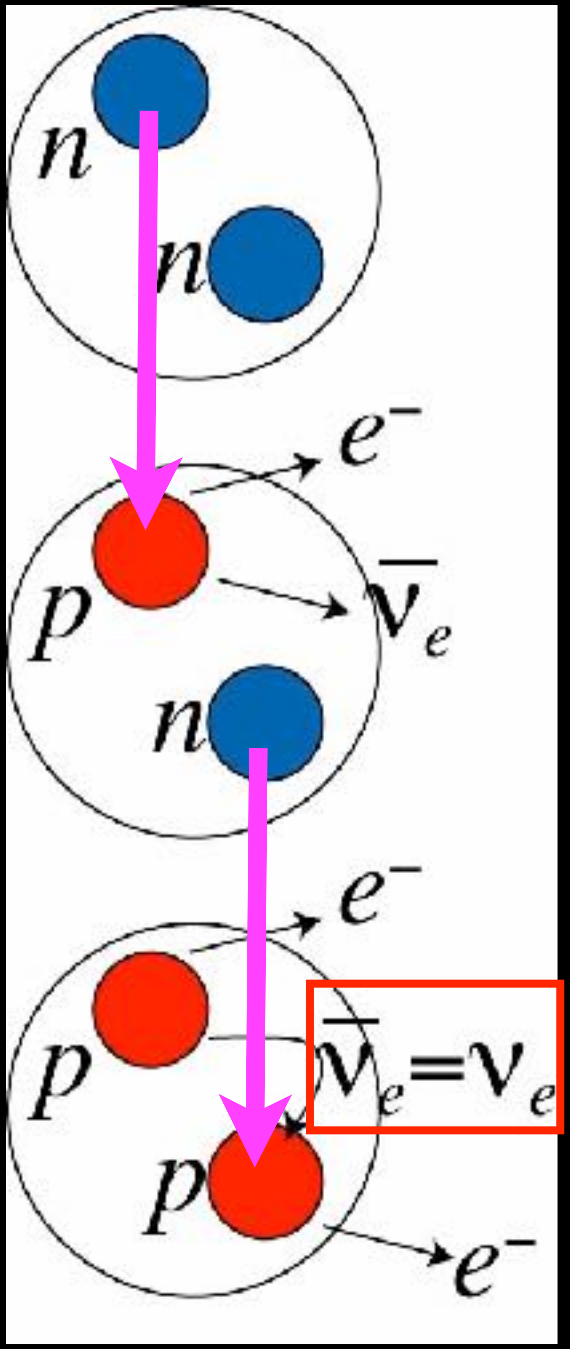
how do we test it?

- 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?*

Turn anti-matter into matter

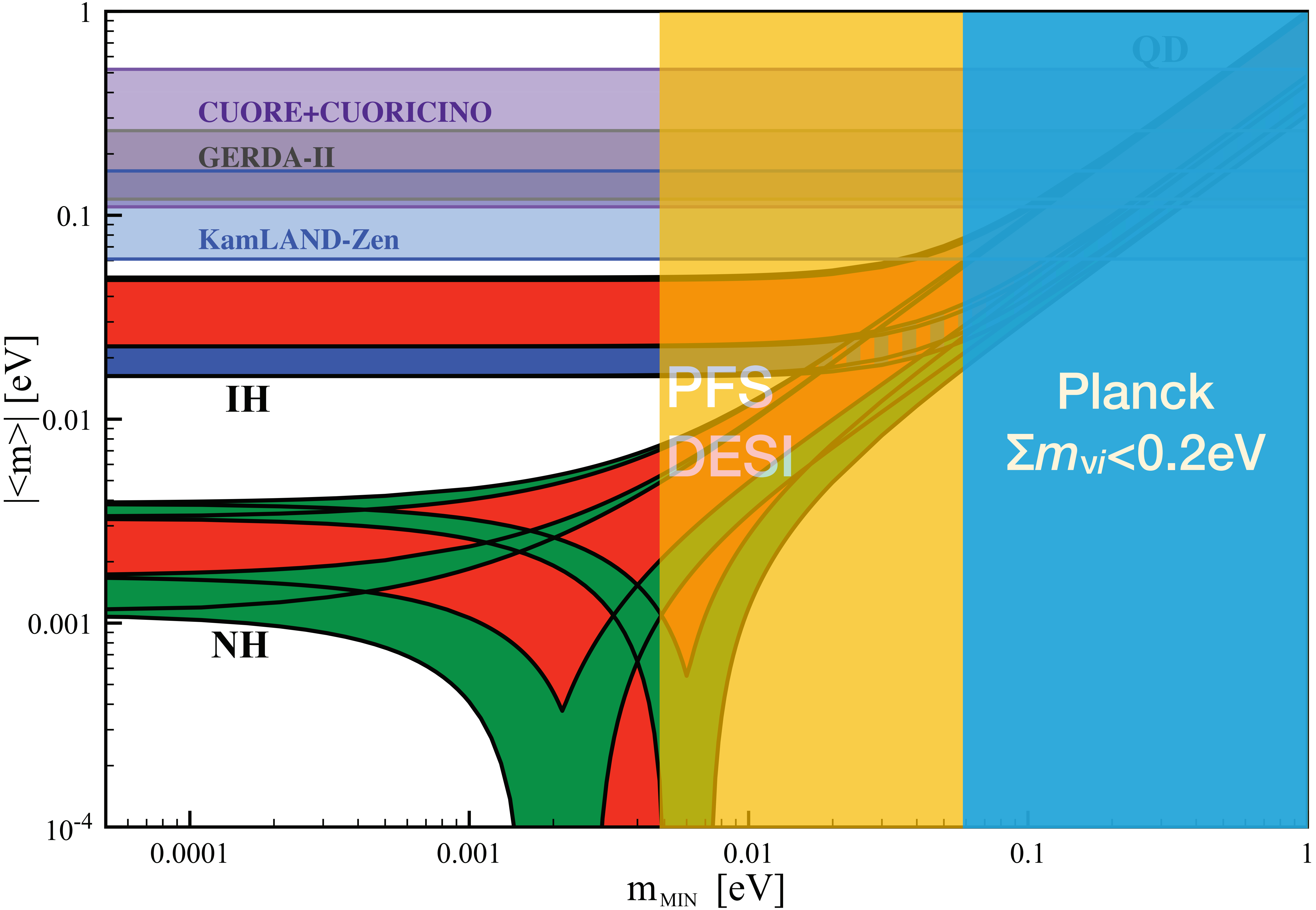
- Can anti-matter turn into matter?
- Maybe anti-neutrino can turn into neutrino because they don't carry electricity
- $0\nu\beta\beta$: $nn \to ppe^- e^-$ with no neutrinos
- $>10^{24}$ years

patience!

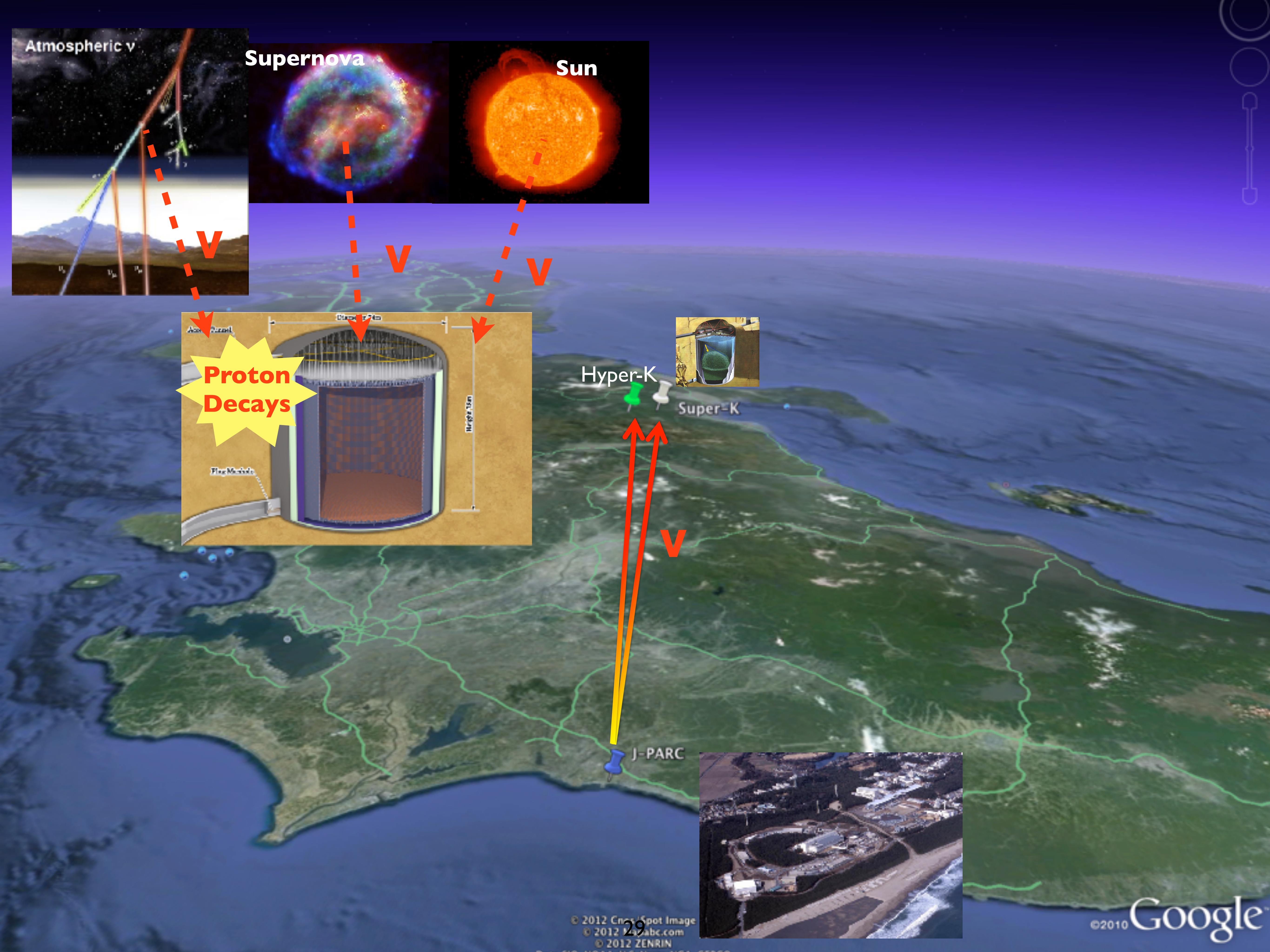


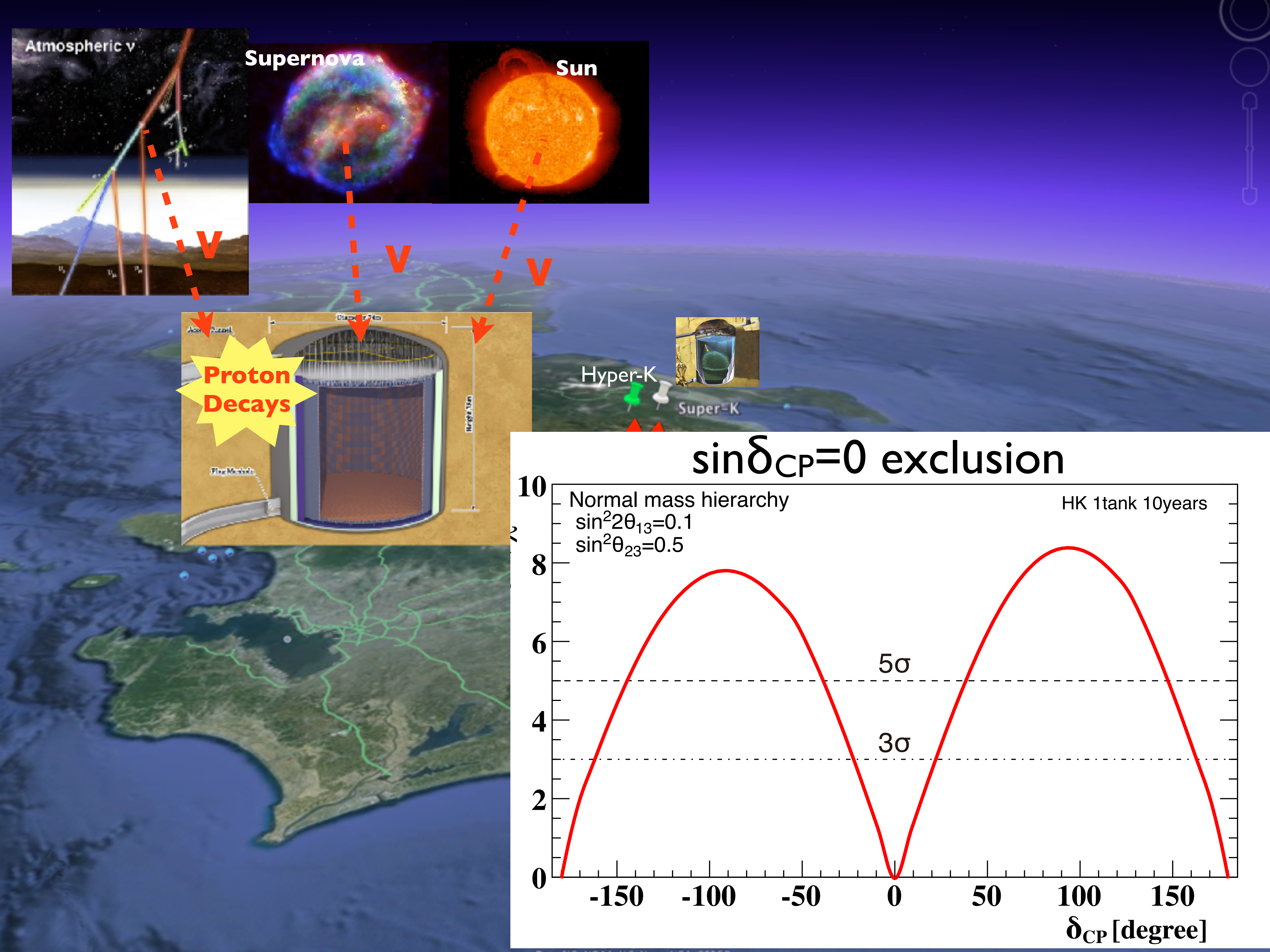
$\bar{\nu}_e$

$\bar{\nu}_e = \nu_e$



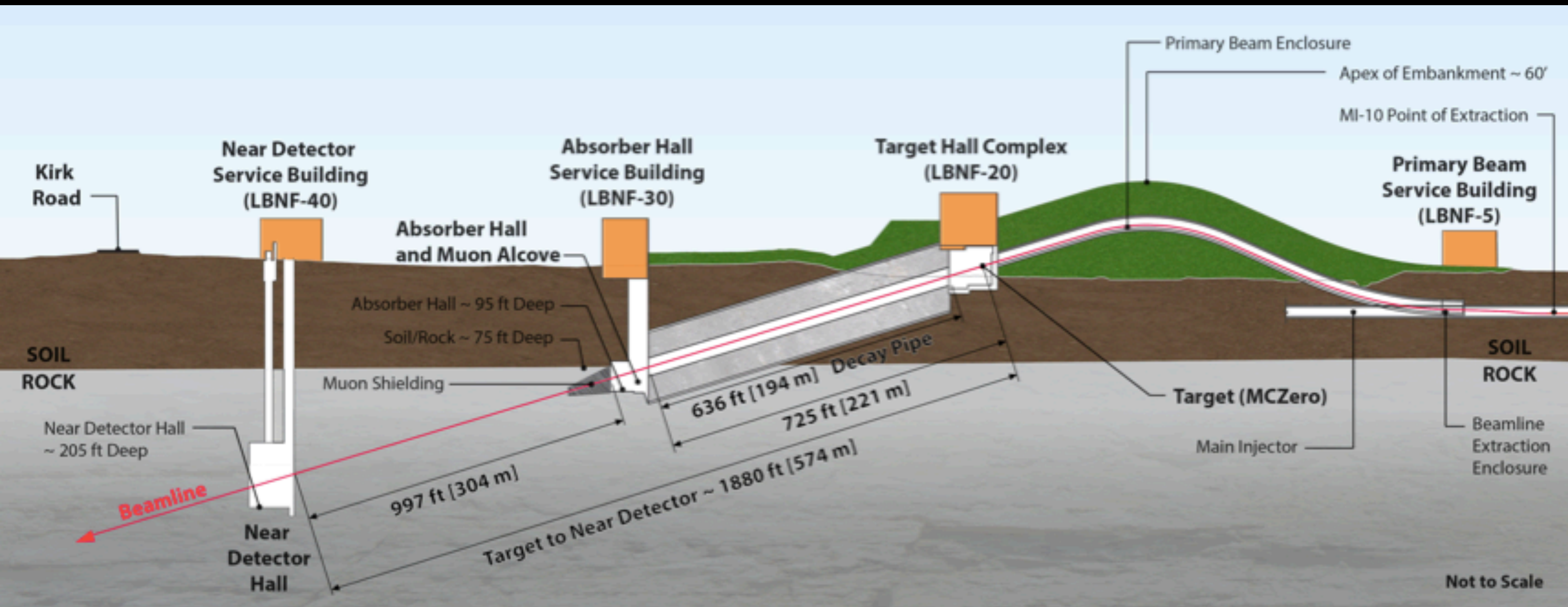
QD
CUORE+CUORICINO
GERDA-II
KamLAND-Zen
IH
NH
PFS
DESI
Planck
$\Sigma m_{\nu i}$<0.2eV
1
0.1
0.01
0.001
10^{-4}
0.0001
0.001
0.01
0.1
1
|<m>| [eV]
m_{MIN} [eV]


Atmospheric ν
Supernova
Sun
ν
ν
ν
Proton Decays
Hyper-K
Super-K
ν
J-PARC
© 2012 ZENRIN
©2010 Google

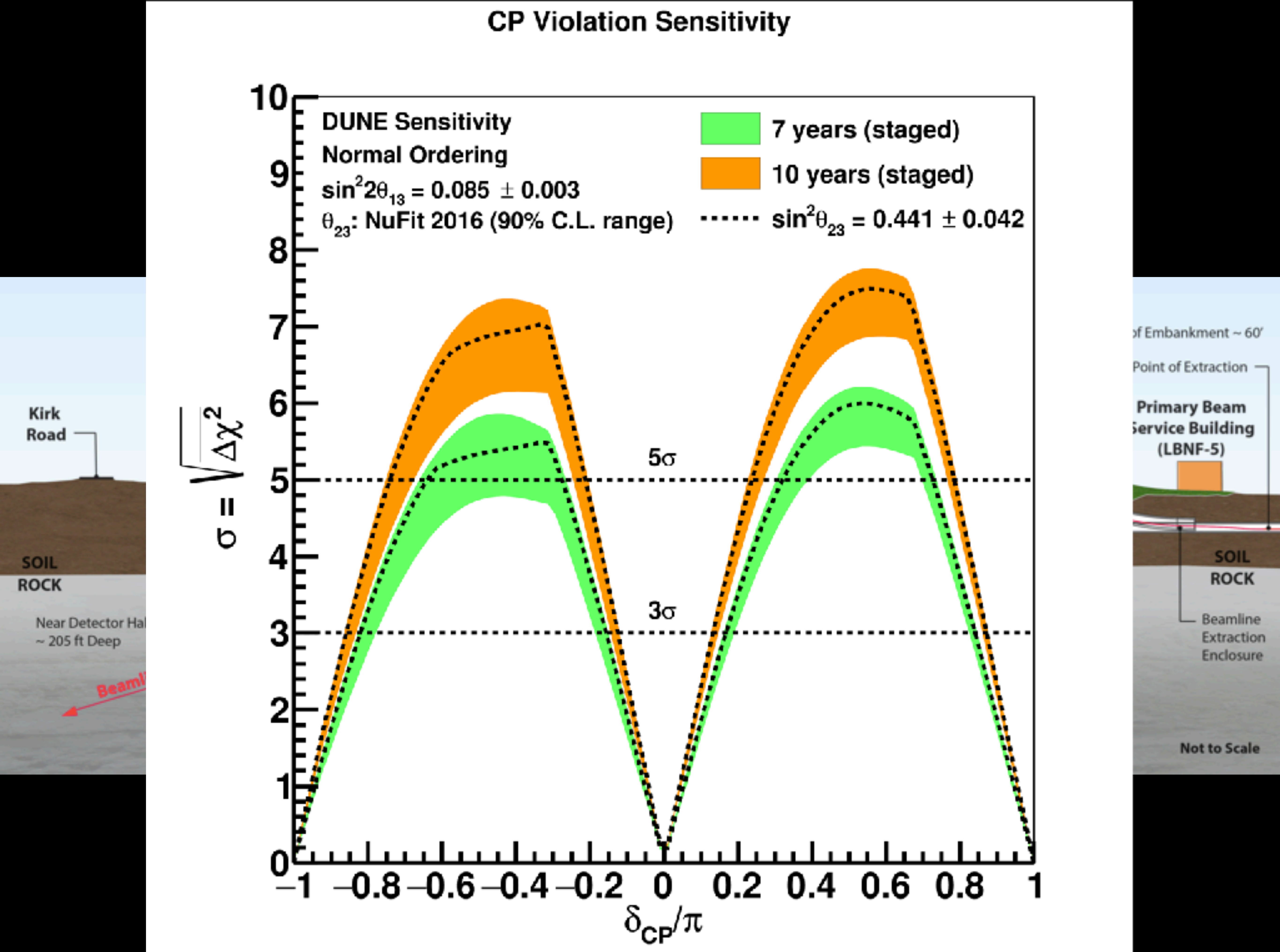


Atmospheric ν
Supernova
Sun
ν
ν
ν
Proton Decays
Hyper-K
Super-K
sinδ$_{CP}$=0 exclusion
Normal mass hierarchy
sin^{2}2θ$_{13}$=0.1
sin^{2}θ$_{23}$=0.5
HK 1tank 10years
5σ
3σ
10
8
6
4
2
0
-150
-100
-50
0
50
100
150
δ$_{CP}$ [degree]

DUNE/LBNF



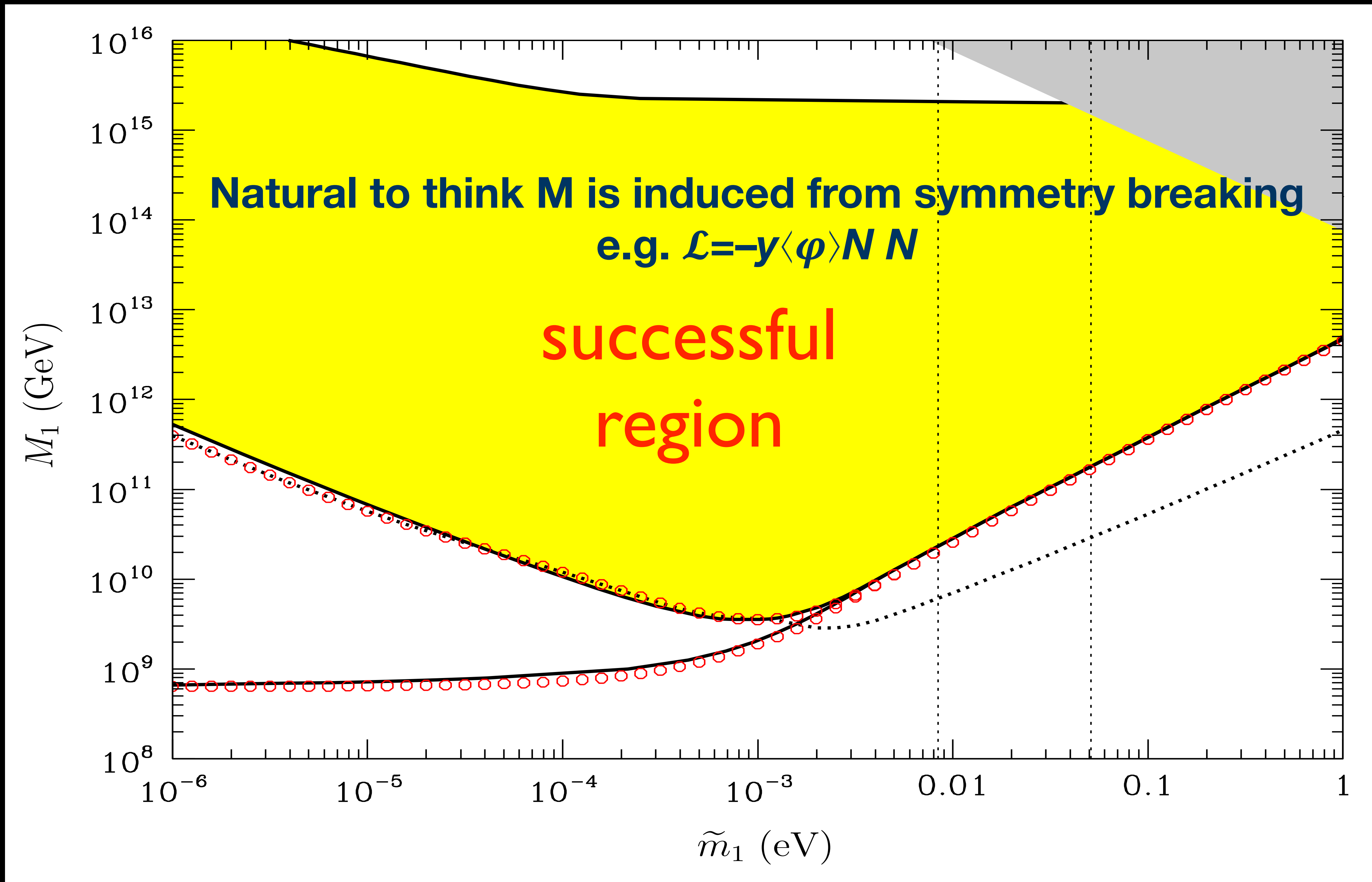
Primary Beam Enclosure
Apex of Embankment ~ 60'
MI-10 Point of Extraction
Kirk Road
Near Detector Service Building (LBNF-40)
Absorber Hall Service Building (LBNF-30)
Target Hall Complex (LBNF-20)
Primary Beam Service Building (LBNF-5)
Absorber Hall and Muon Alcove
Absorber Hall ~ 95 ft Deep
Soil/Rock ~ 75 ft Deep
Muon Shielding
SOIL
ROCK
Decay Pipe
636 ft [194 m]
725 ft [221 m]
Target (MCZero)
Main Injector
Beamline Extraction Enclosure
Near Detector Hall ~ 205 ft Deep
Beamline
997 ft [304 m]
Target to Near Detector ~ 1880 ft [574 m]
Near Detector Hall
Not to Scale



CP Violation Sensitivity
DUNE Sensitivity
Normal Ordering
sin²2θ13 = 0.085 ± 0.003
θ23: NuFit 2016 (90% C.L. range)
7 years (staged)
10 years (staged)
sin²θ23 = 0.441 ± 0.042
5σ
3σ
σ = √Δχ²
δCP/π
0
1
2
3
4
5
6
7
8
9
10
−1
−0.8
−0.6
−0.4
−0.2
0.2
0.4
0.6
0.8
Kirk
Road
SOIL
ROCK
Near Detector Hal
~ 205 ft Deep
f Embankment ~ 60'
Point of Extraction
Primary Beam
Service Building
(LBNF-5)
SOIL
ROCK
Beamline
Extraction
Enclosure
Not to Scale

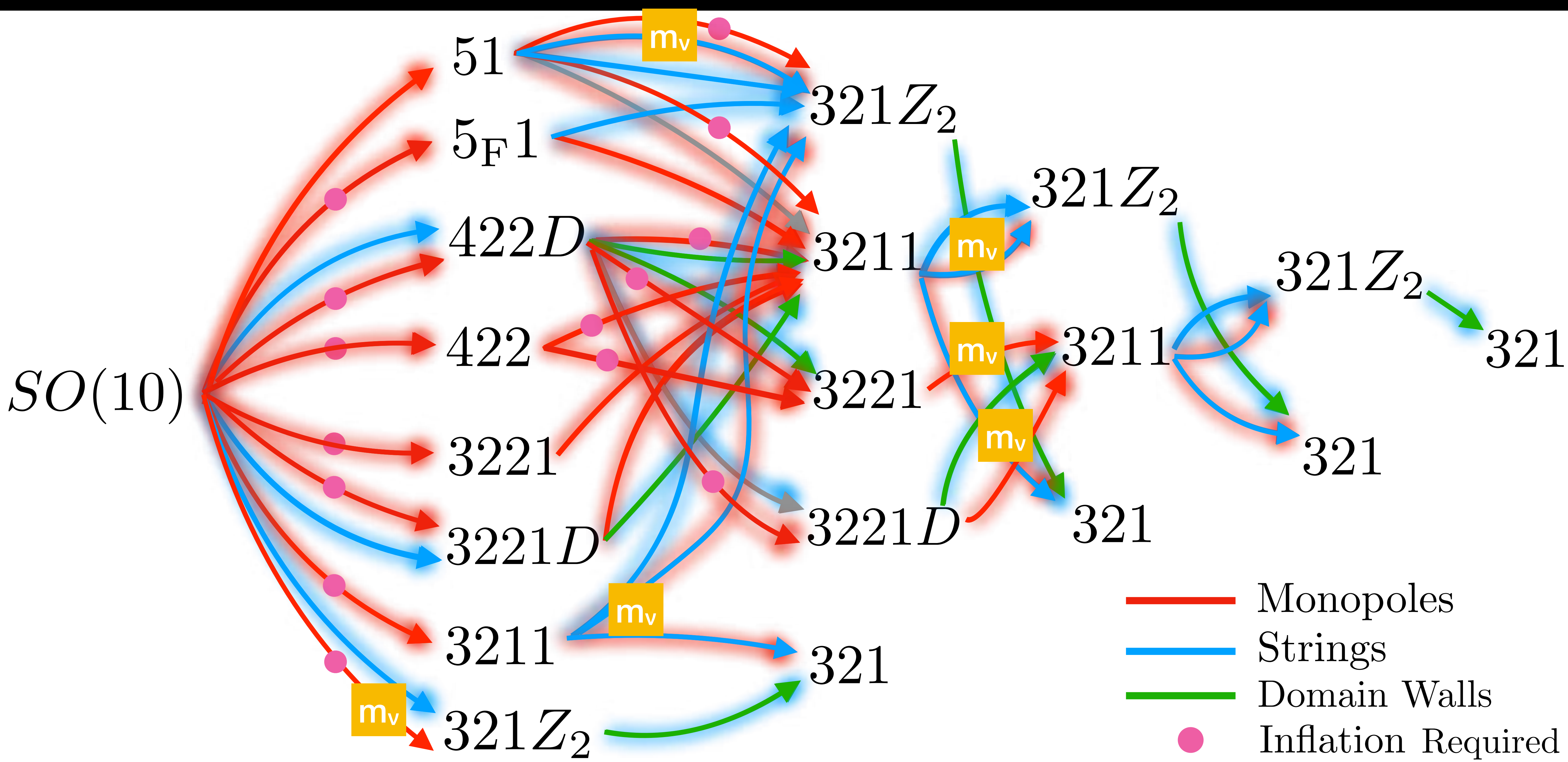
M_{Pl}

inflation



Phase Transition → **Gravitational Waves?**

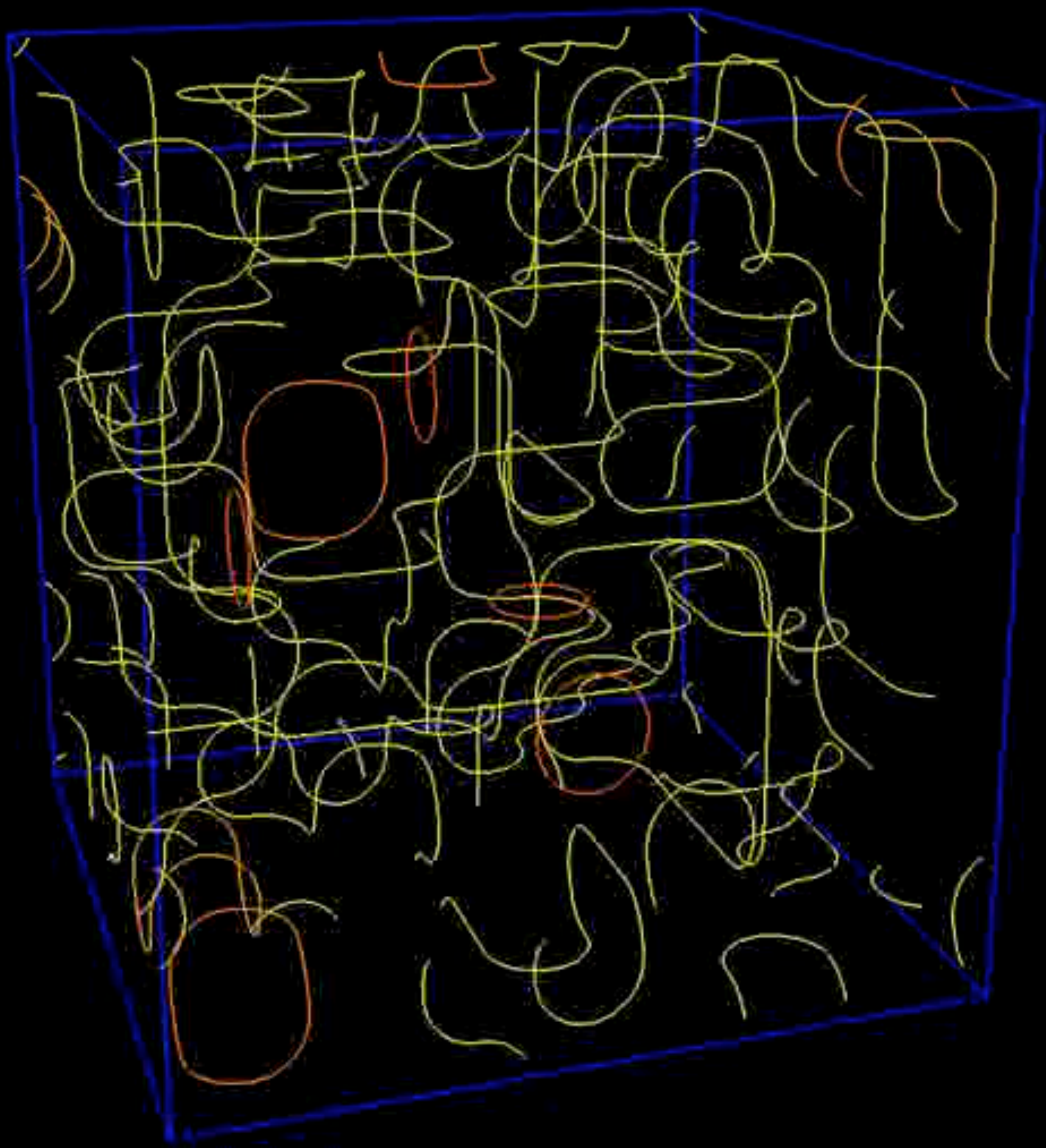
symmetry breaking

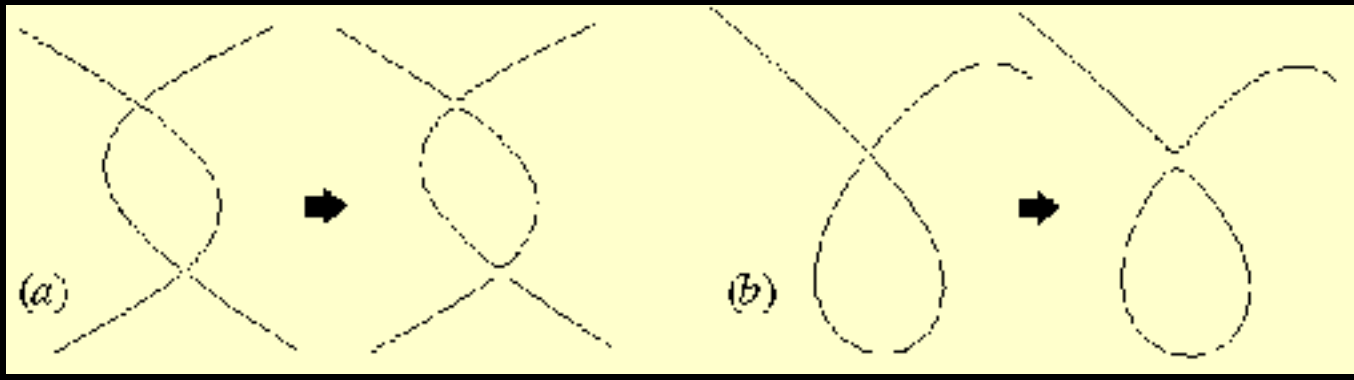


many possible topological defects!

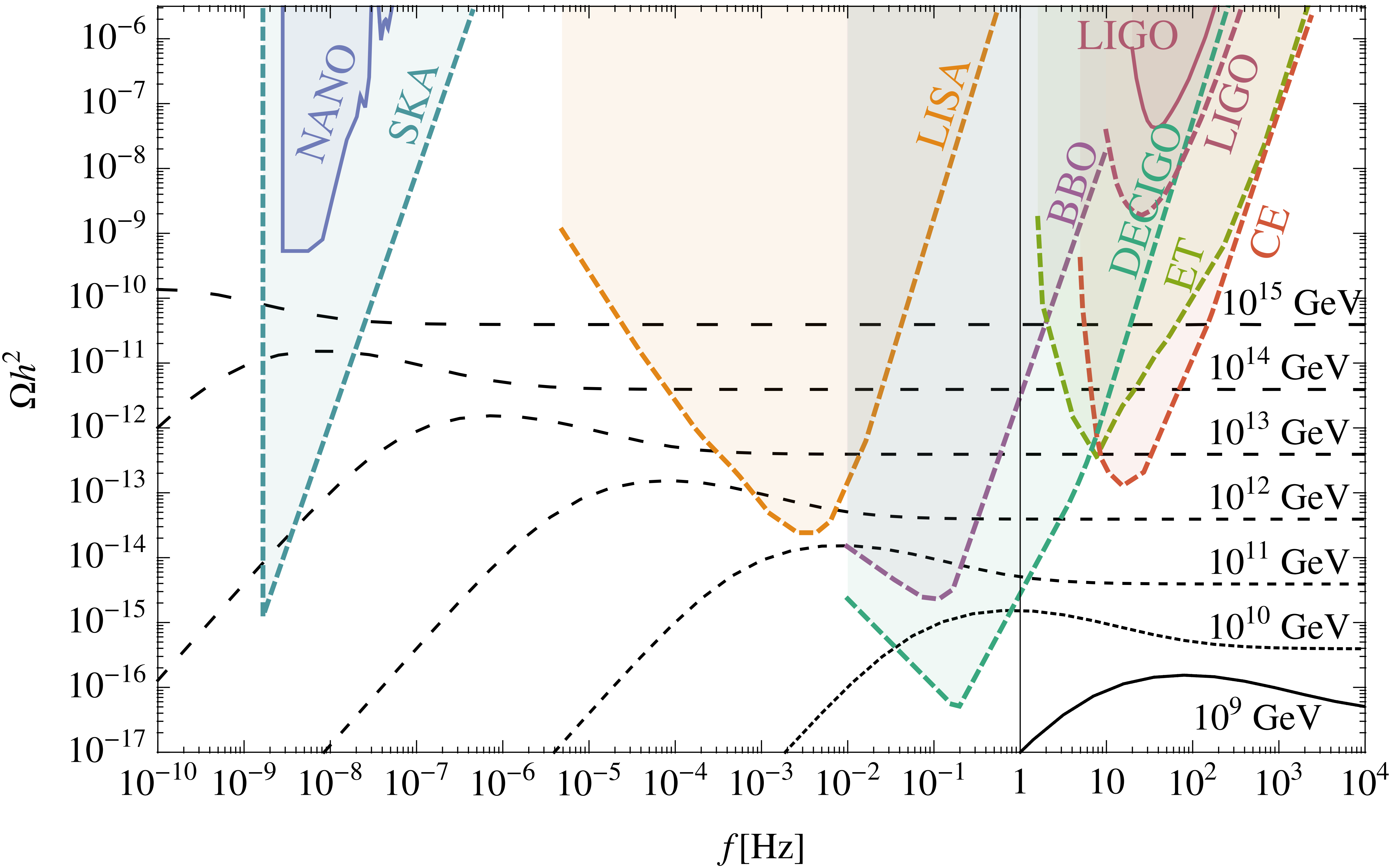
https://www.ligo.org/science/Publication-S5S6CosmicStrings/index.php

cosmic strings





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



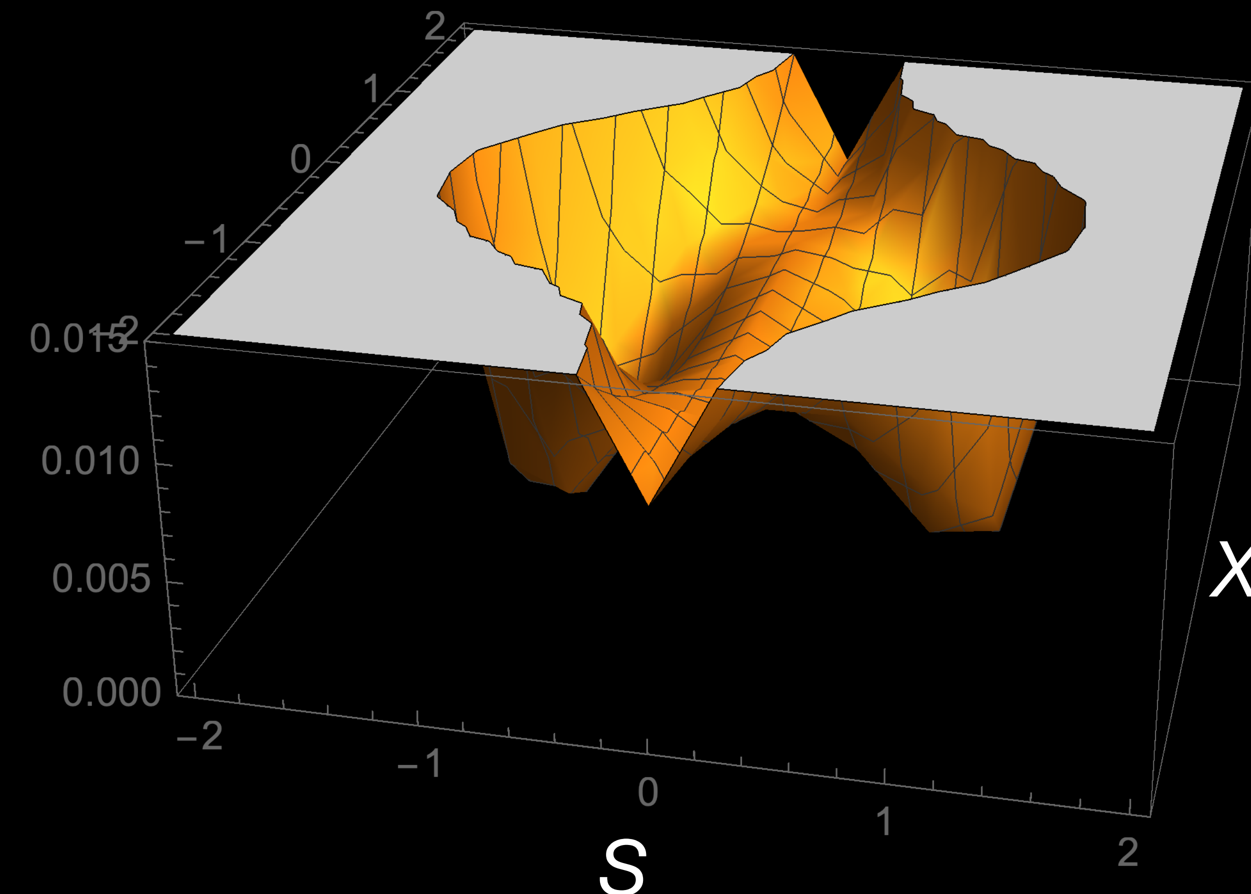
J. Dror, T. Hiramatsu, K. Kohri, HM, G. White, arXiv:1908.03227

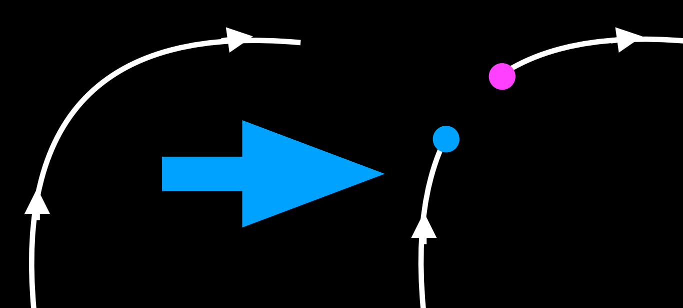
covers pretty much the entire range for leptogenesis!

caveat: particle emission from cosmic strings

Hybrid inflation

- supersymmetric inflation
- U(1)$_{B\text{-}L}$ broken after inflation
  - generates M_R
- forms cosmic strings
- requires high $v \geq$ a few 10^{15} GeV
- *excluded* by Pulsar Timing Array?
- strings may be cut by magnetic monopoles

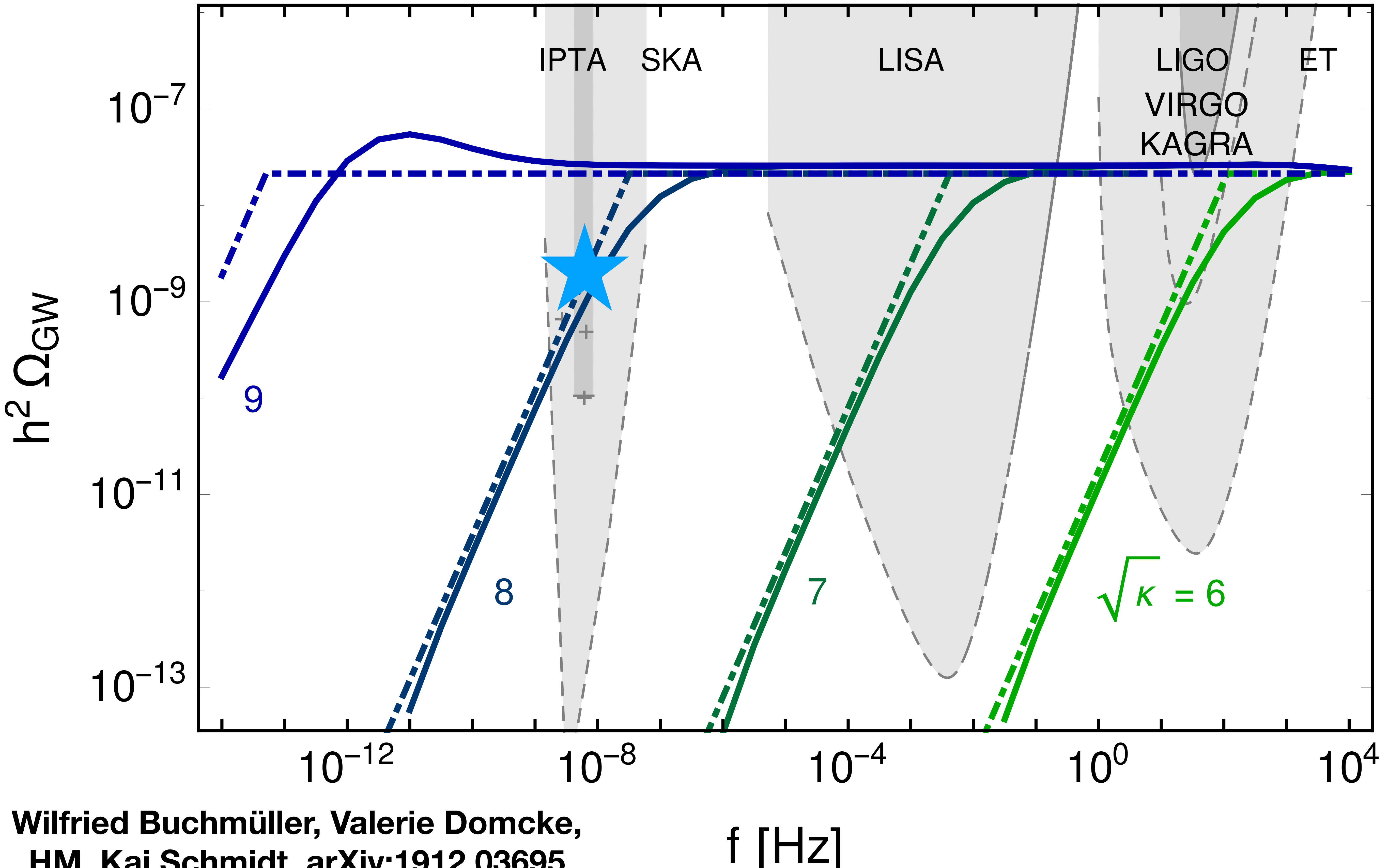




Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695

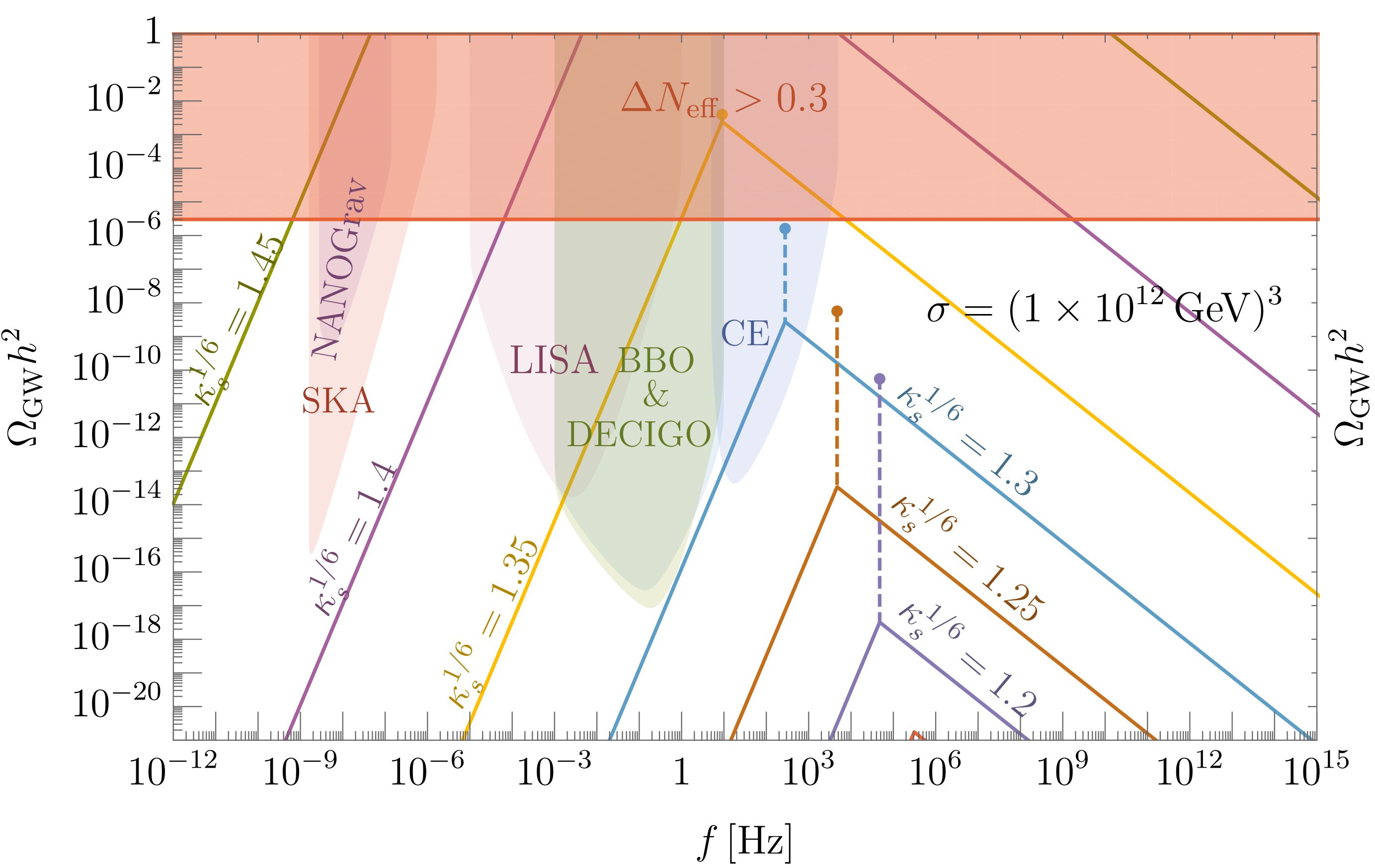
monopoles can cut strings

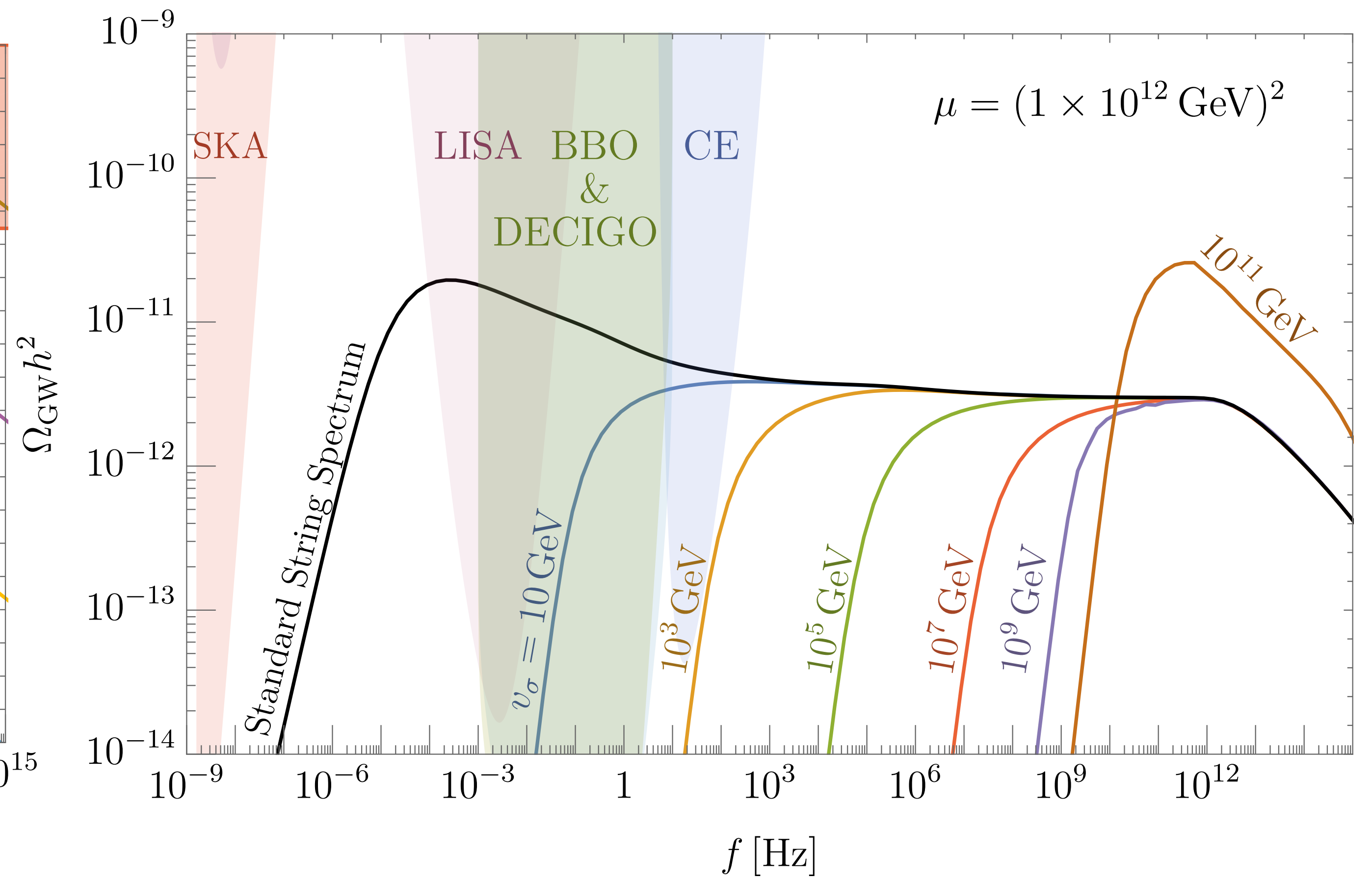
$\kappa = m^2_{\text{monopole}}/\mu$

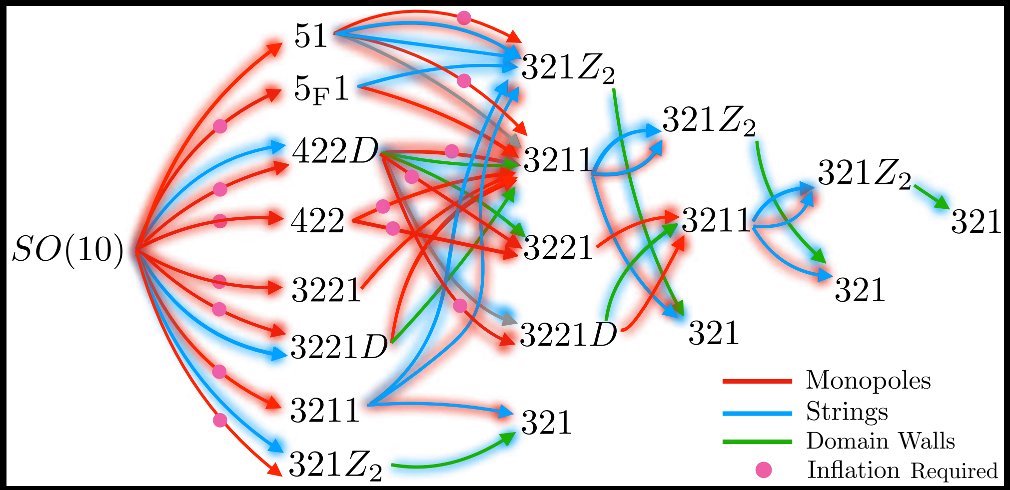


Wilfried Buchmüller, Valerie Domcke, HM, Kai Schmidt, arXiv:1912.03695

topological defects







strings can connect monopoles and **devour** them
monopoles can cut strings and **eat** them
walls can fill strings and **devour** them
strings can punch holes in walls and **eat** them
all with characteristics cutoffs
prove GUT?

Gravitational Wave Gastronomy

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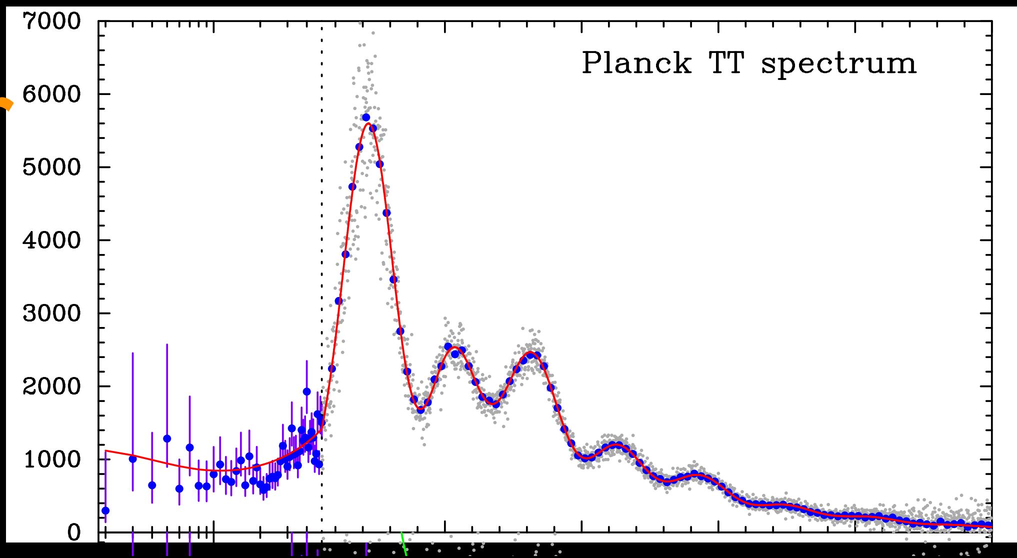
(Dated: November 18, 2021)

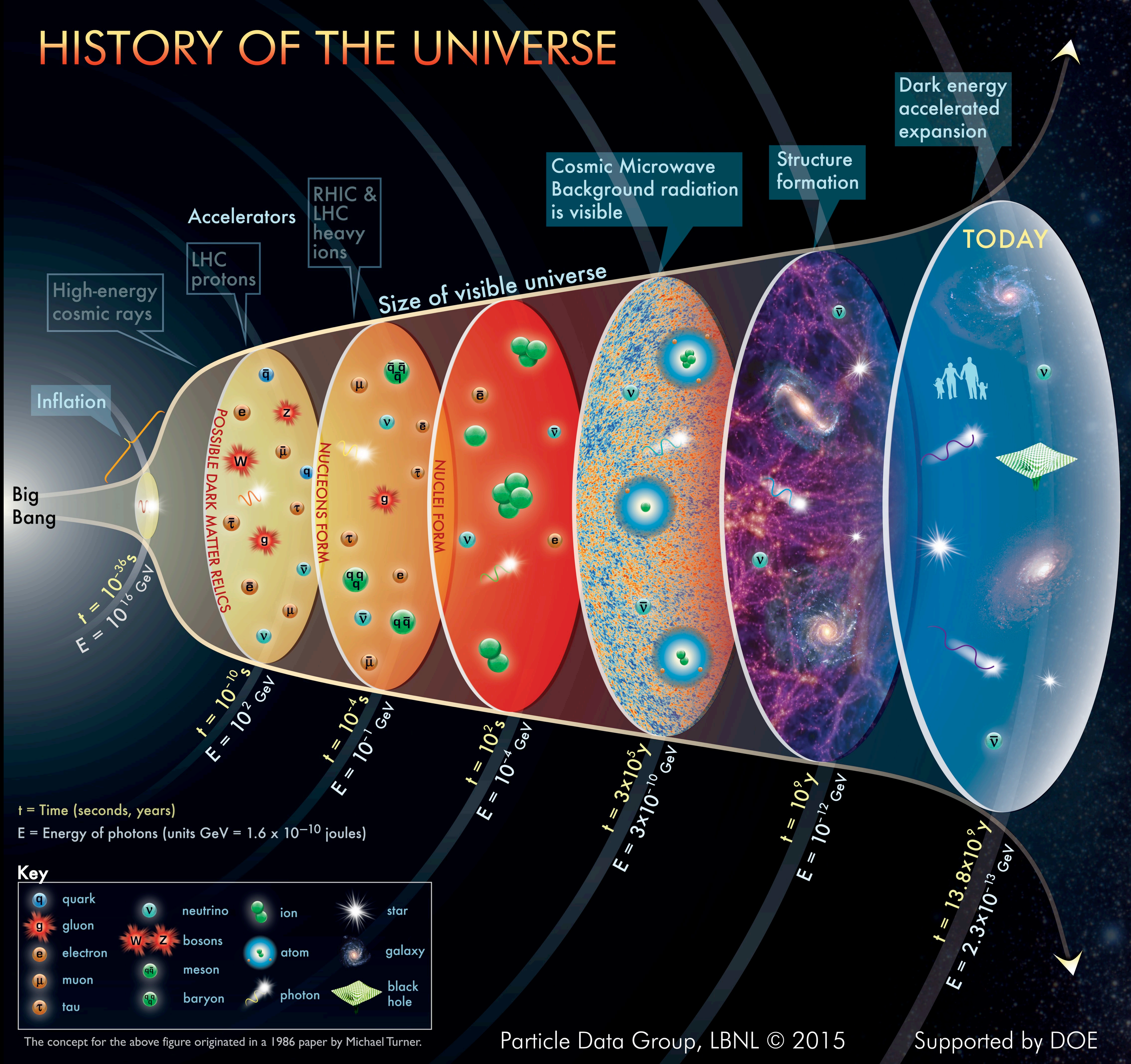
The symmetry breaking of grand unified gauge groups in the early Universe often leaves behind relic topological defects such as cosmic strings, domain walls, or monopoles. For some symmetry breaking chains, hybrid defects can form where cosmic strings attach to domain walls or monopoles attach to strings. In general, such hybrid defects are unstable, with one defect 'eating' the other via the conversion of its rest mass into the other's kinetic energy and subsequently decaying via gravitational waves. In this work, we determine the gravitational wave spectrum from 1) the destruction of a cosmic string network by the nucleation of monopoles which cut up and 'eat' the strings, 2) the collapse and decay of a monopole-string network by strings that 'eat' the monopoles, 3) the destruction of a domain wall network by the nucleation of string-bounded holes on the wall that expand and 'eat' the wall, and 4) the collapse and decay of a string-bounded wall network by walls that 'eat' the strings. We call the gravitational wave signals produced from the 'eating' of one topological defect by another *gravitational wave gastronomy*. We find that the four gravitational wave gastronomy signals considered yield unique spectra that can be used to narrow down the SO(10) symmetry breaking chain to the Standard Model and the scales of symmetry breaking associated with the consumed topological defects. Moreover, the systems we consider are unlikely to have a residual monopole or domain wall problem.

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



New tools: Higgs & gravitational wave



HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Cosmic Microwave Background radiation is visible
Structure formation
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
E = 2.3x10^-13 GeV
t = Time (seconds, years)
E = Energy of photons (units GeV = 1.6 x 10^-10 joules)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
The concept for the above figure originated in a 1986 paper by Michael Turner.
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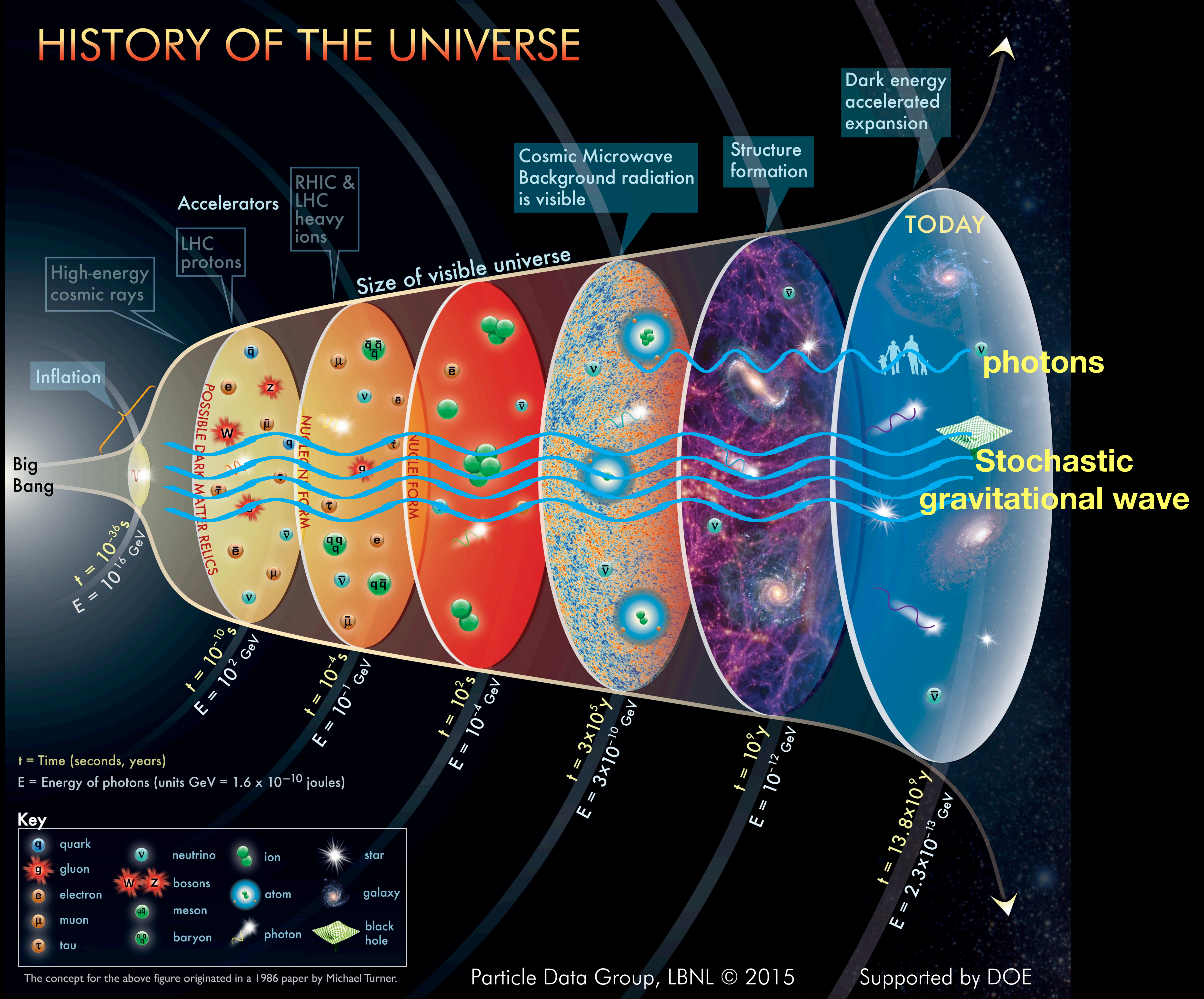
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NUCLEONS FORM
NUCLEI FORM
Stochastic gravitational wave
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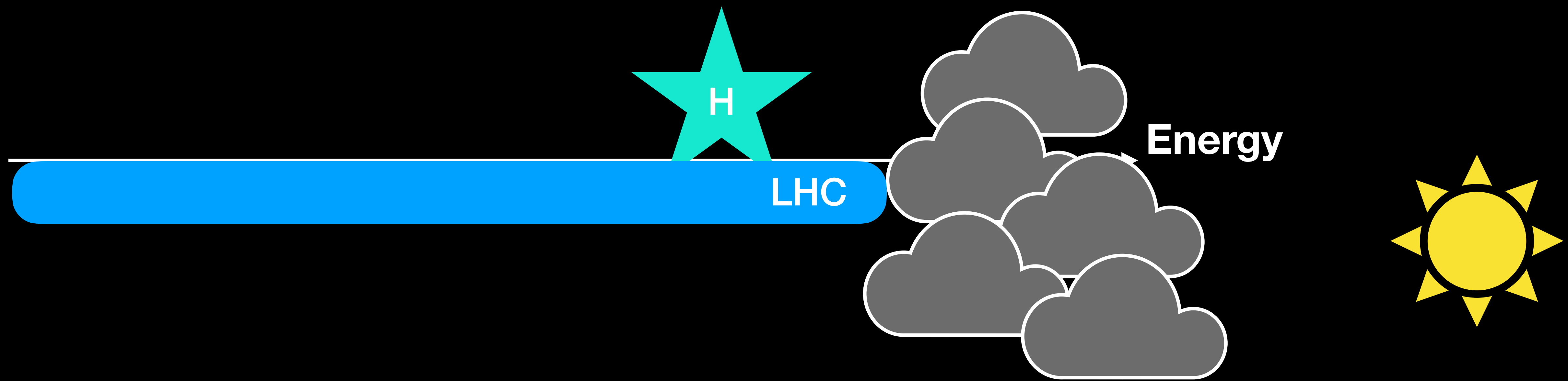
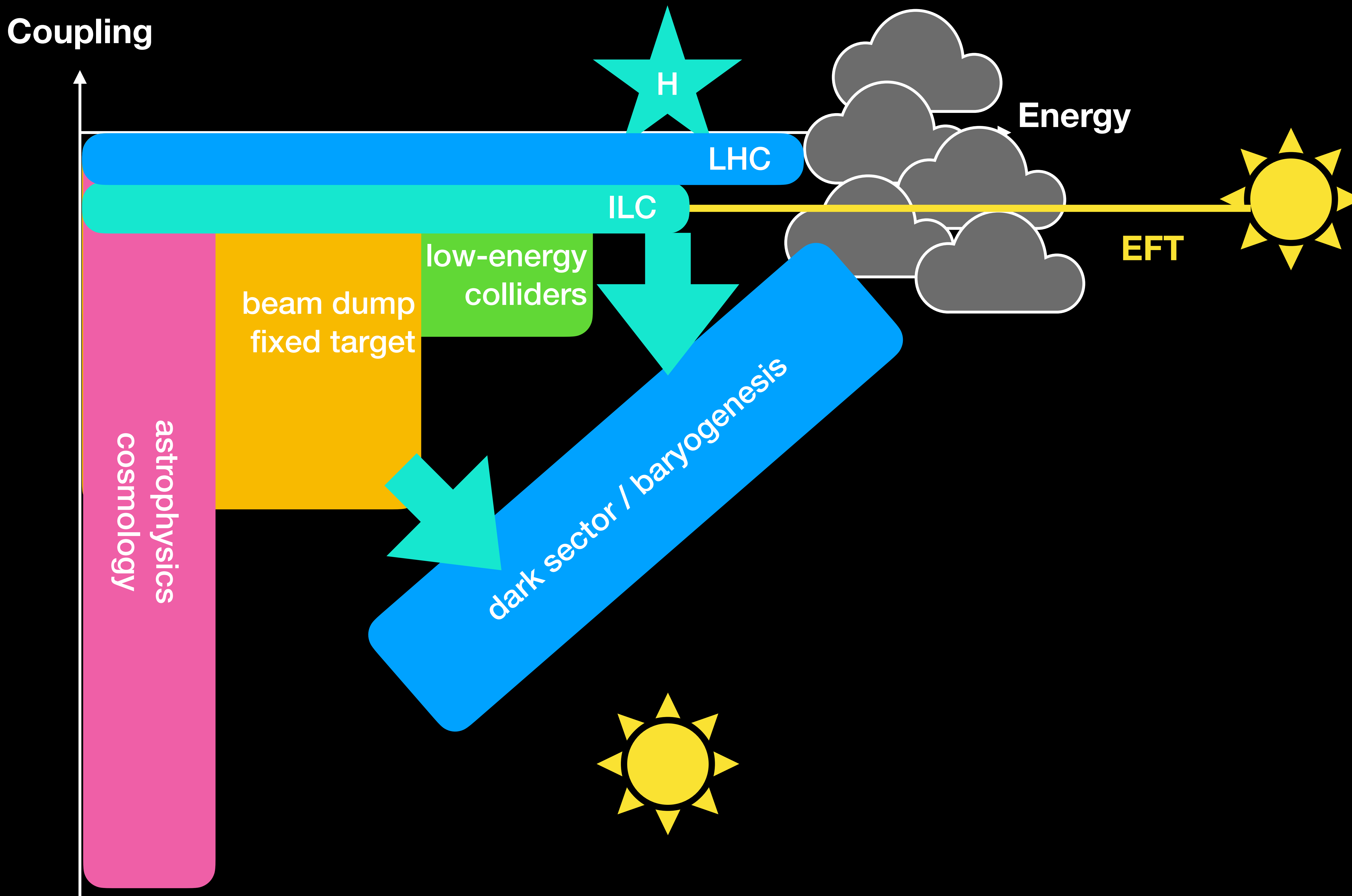
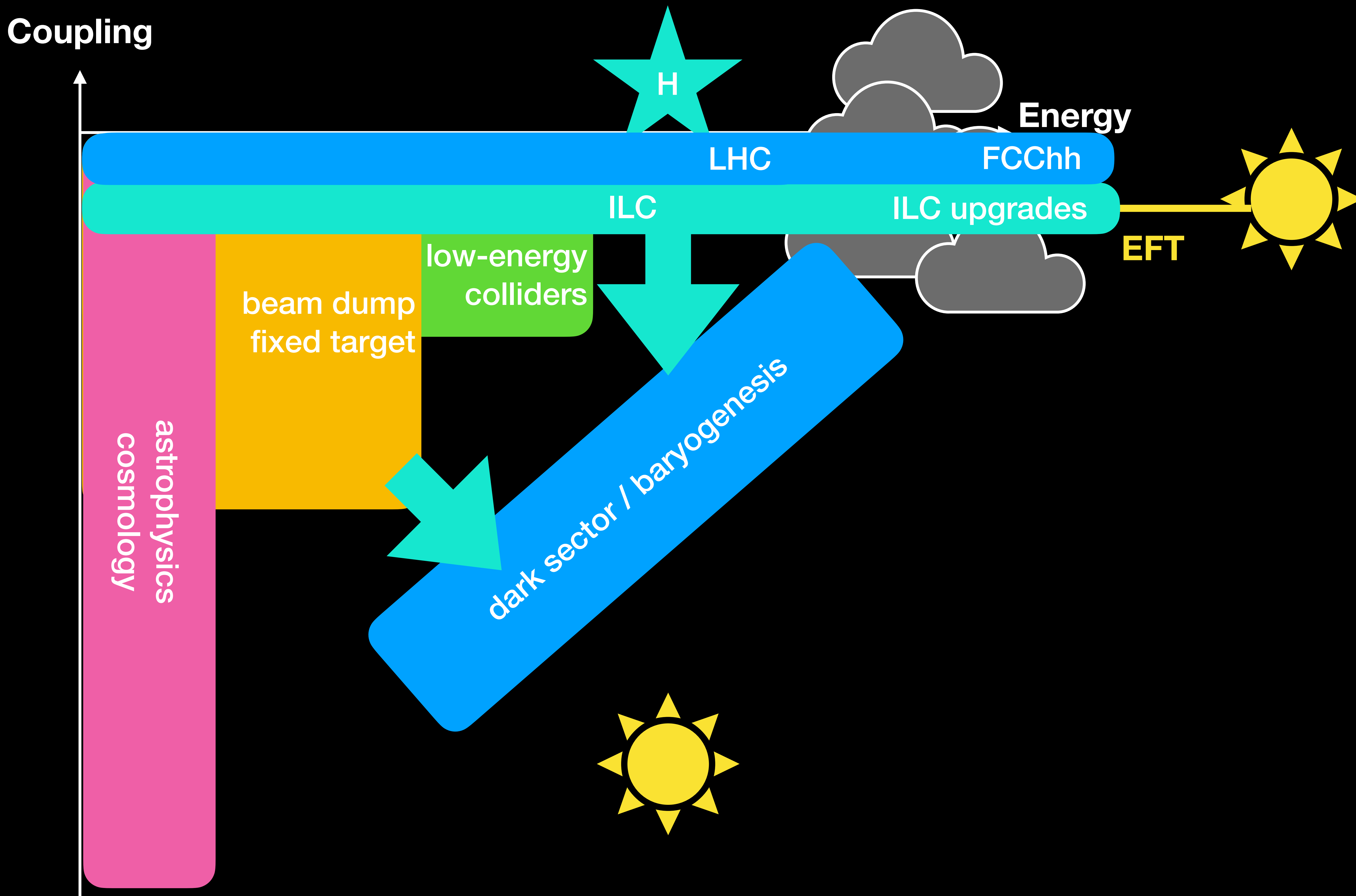

H
Energy
LHC


Coupling
H
Energy
LHC
ILC
EFT
low-energy
colliders
beam dump
fixed target
astrophysics
cosmology
dark sector / baryogenesis


Coupling
H
Energy
LHC
FCChh
ILC
ILC upgrades
EFT
low-energy colliders
beam dump fixed target
astrophysics cosmology
dark sector / baryogenesis


many things
to look forward to!