Marco Drewes, Université catholique de Louvain

LONG LIVED PARTICLES BEYOND THE SM

03/06/2019

31st Rencontres de Blois

Blois, France

Further reading and sources of unaccredited figures:

Theory/models:	**arXiv:1806.07396 [hep-ph]**
LHC Search strategies:	**arXiv:1903.04497 [hep-ex]**
Beyond Colliders:	**arXiv:1901.09966 [hep-ex]**

Overview

Why bother about long lived particles?

- Dark Matter
- Neutrino Masses
- Baryon Asymmetry
- Hierarchy Problem

How long lived can a particle be?

- Big Bang Nucleosynthesis
- Cosmic Microwave Background

How to find long lived particles?

- A holistic approach to the LHC
- New detectors
- Beyond the LHC

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Why search for LLPs?

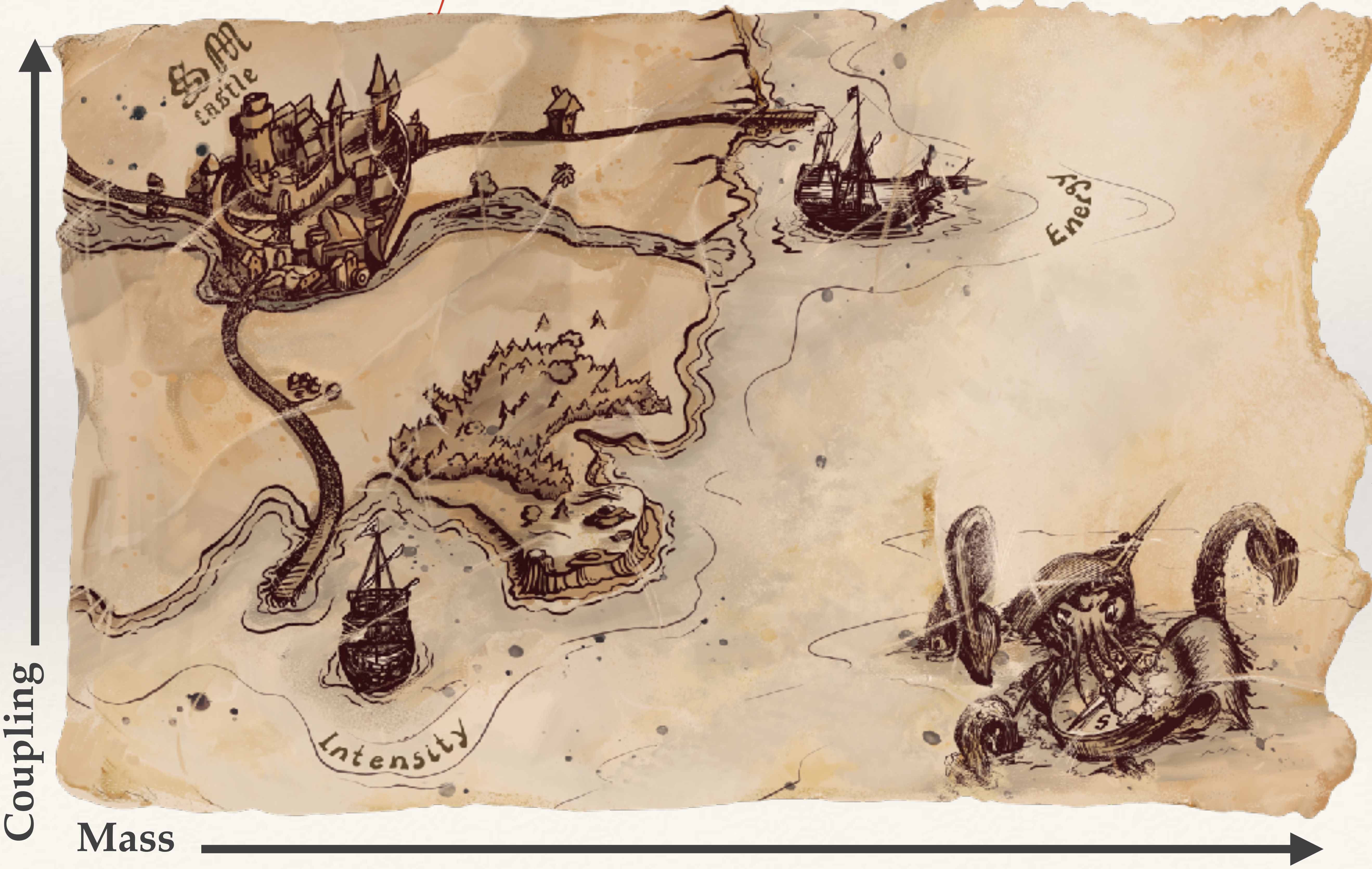
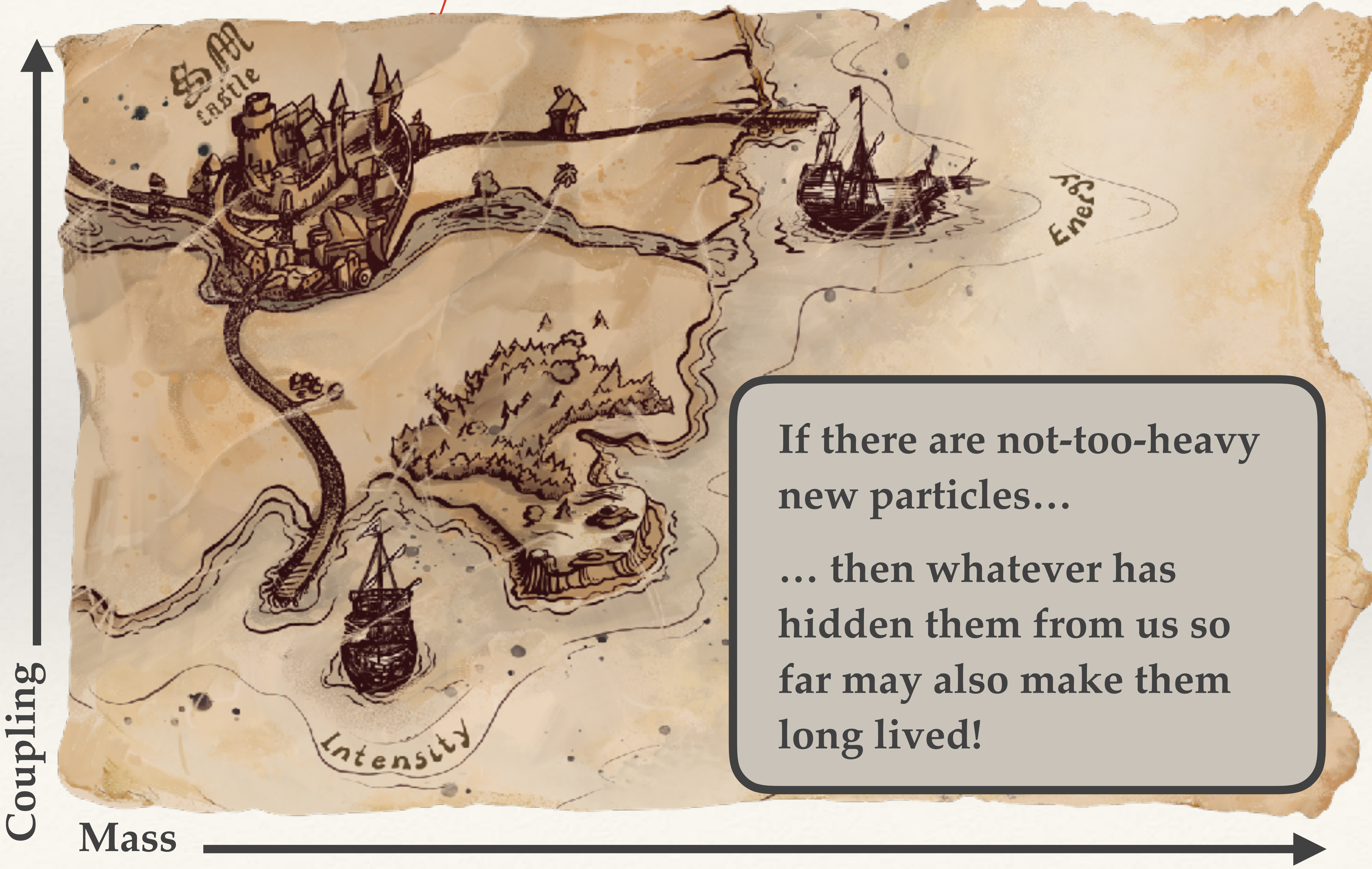


Figure: C. Hambrock for Physik Journal 18, Februar 2019, S. 28

Why search for LLPs?



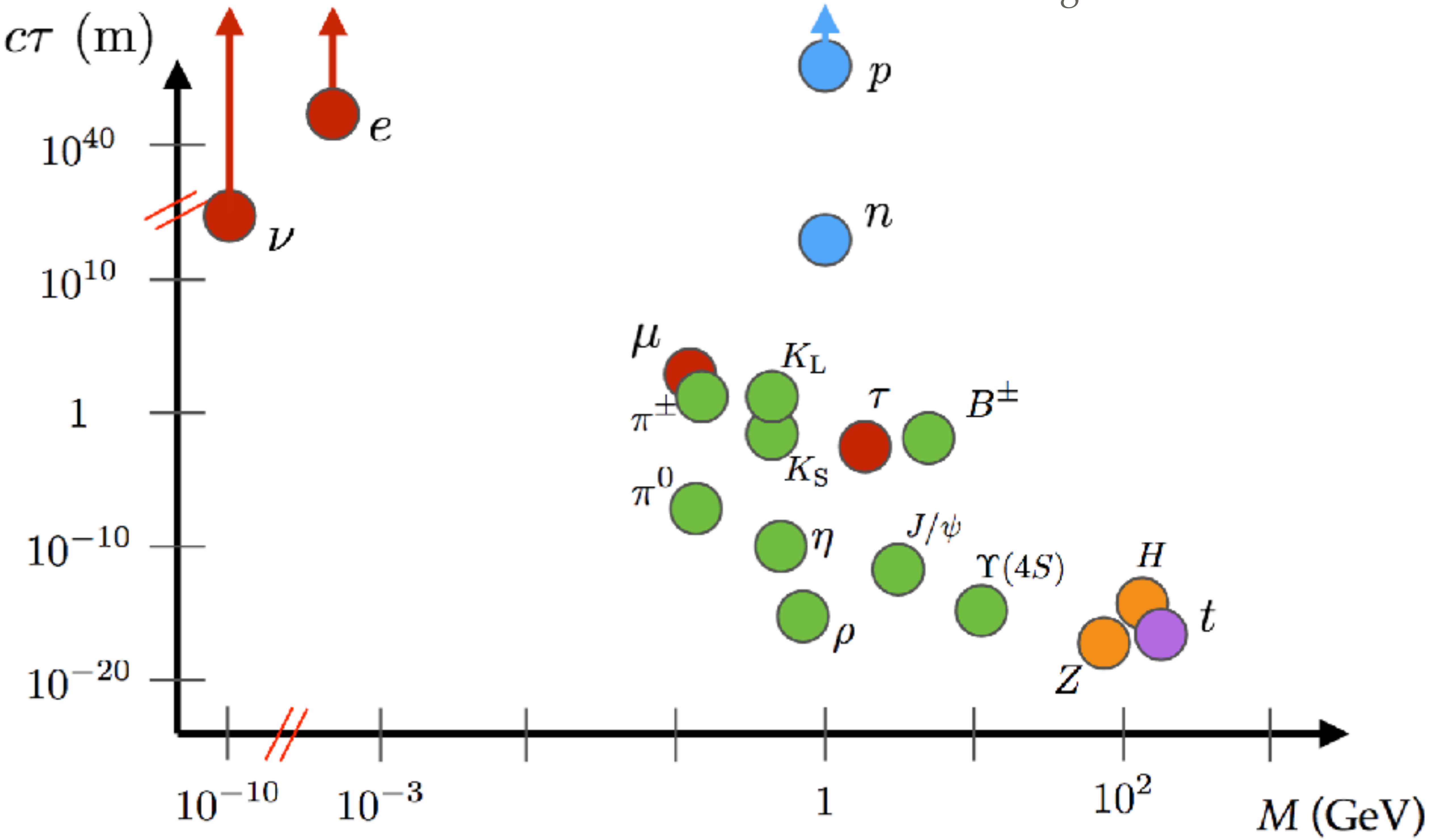
If there are not-too-heavy new particles…

… then whatever has hidden them from us so far may also make them long lived!

Figure: C. Hambrock for Physik Journal 18, Februar 2019, S. 28

Longevity in the Standard Model

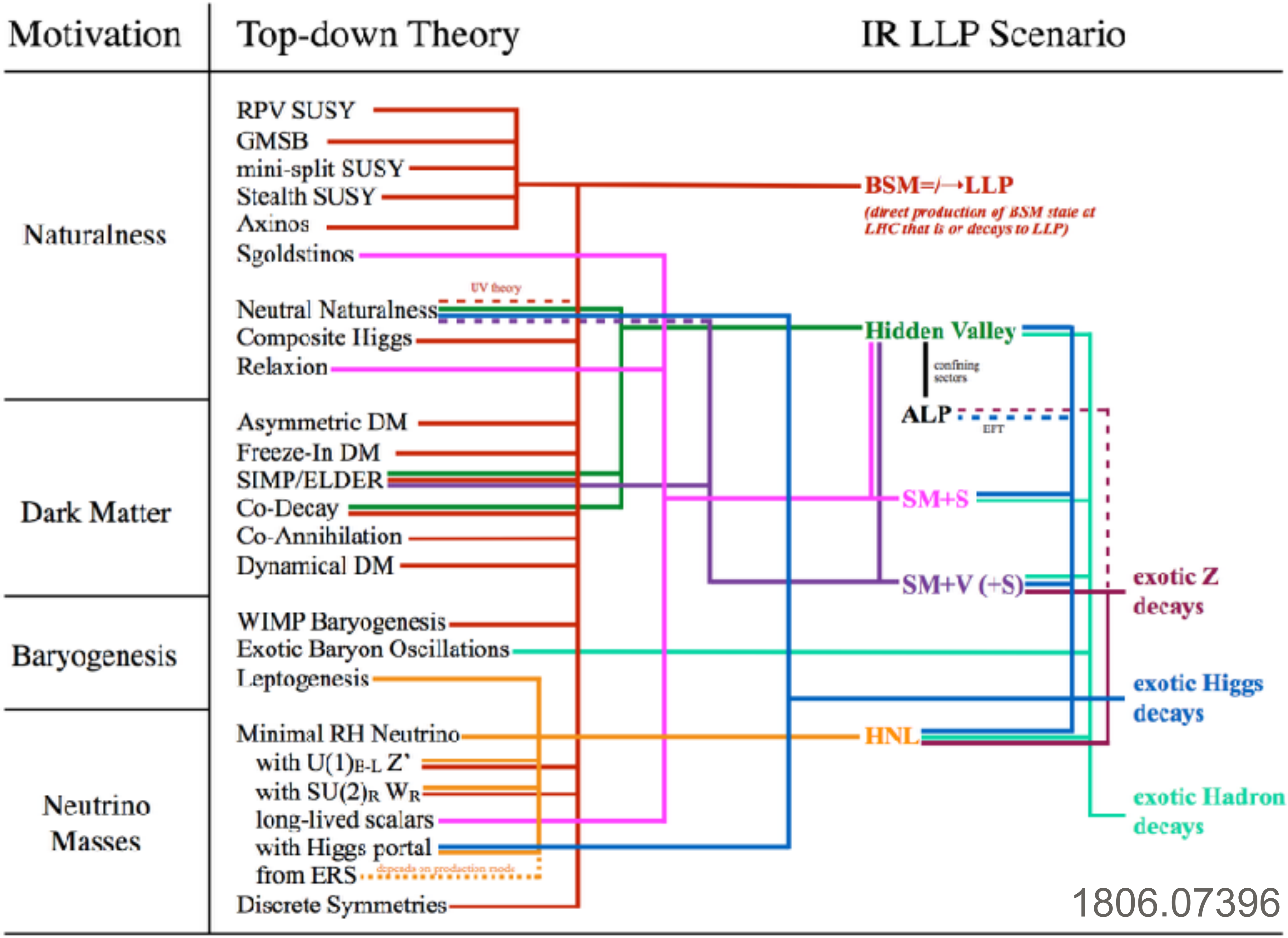
figure from Brian Shuve



Keys to Longevity

	SM example	reason	BSM examples
heavy mediator	muon	W mass	hidden valley
mass spectrum	neutron	isospin	FIMP DM
small mixing	B hadrons	CKM suppression	dark photon
small coupling constant			heavy neutrino

Theory Motivations



Motivation

Top-down Theory

IR LLP Scenario

Naturalness

RPV SUSY
GMSB
mini-split SUSY
Stealth SUSY
Axinos
Sgoldstinos
Neutral Naturalness
Composite Higgs
Relaxion

Dark Matter

Asymmetric DM
Freeze-In DM
SIMP/ELDER
Co-Decay
Co-Annihilation
Dynamical DM

Baryogenesis

WIMP Baryogenesis
Exotic Baryon Oscillations
Leptogenesis

Neutrino Masses

Minimal RH Neutrino
with $U(1)_{B-L}$ Z'
with $SU(2)_R$ W_R
long-lived scalars
with Higgs portal
from ERS
Discrete Symmetries

UV theory

depends on production mode

BSM=/→LLP

(direct production of BSM state at LHC that is or decays to LLP)

Hidden Valley

confining sectors

ALP

EFT

SM+S

SM+V (+S)

HNL

exotic Z decays

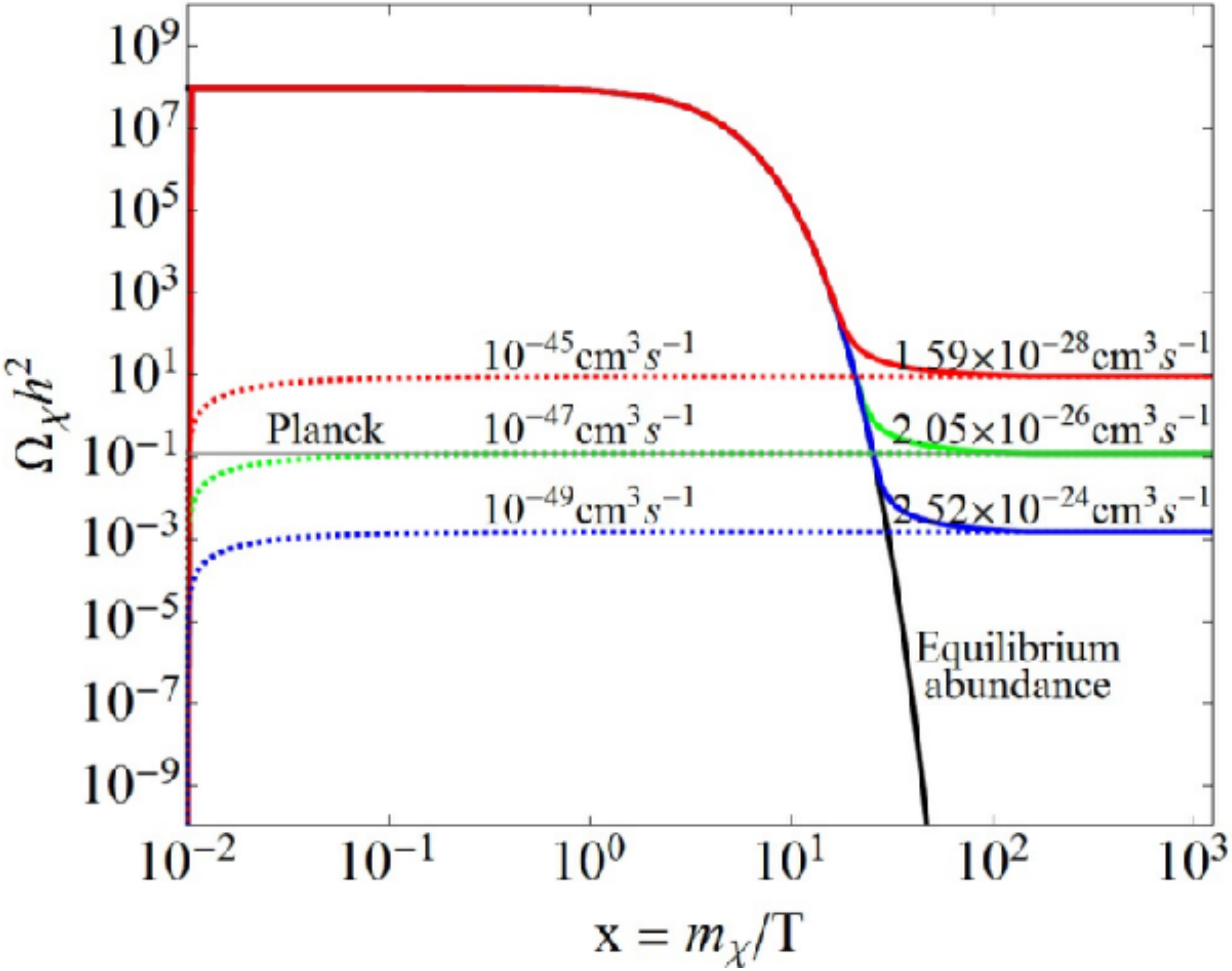
exotic Higgs decays

exotic Hadron decays

1806.07396

Dark Matter Connection

Example: FIMP Dark Matter recent review: arXiv:1706.07442

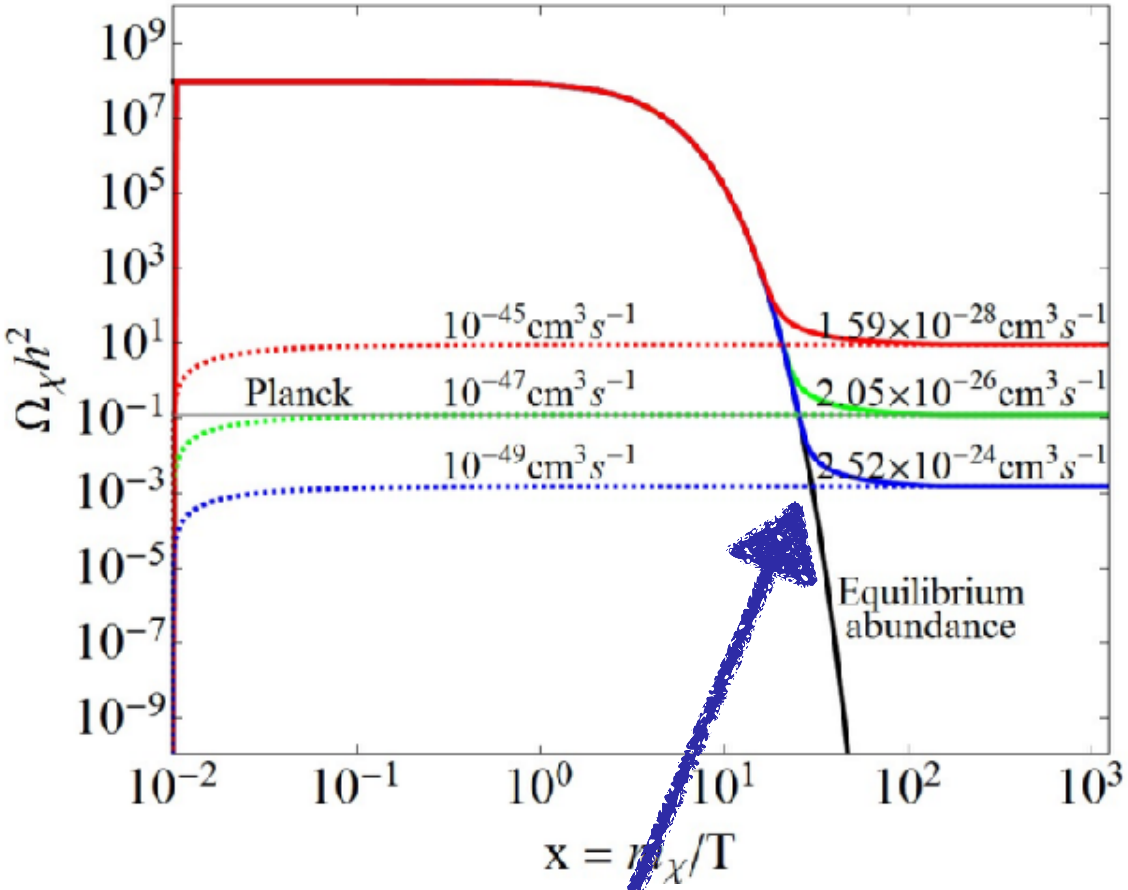


"Freeze in" vs "freeze out" figure from Dev et al 1311.5297

Dark Matter Connection

“Freeze in” scenario

- example: sterile neutrinos,
  recent review arXiv:1602.04816
- if produced in heavy particle decay, parent can be searched for



“Freeze out” with compressed spectrum

- DM and mediator “freeze out” around the same time in the early universe
  $\Rightarrow$ abundance determined by co-annihilation / co-scattering
- small mass splitting can make the mediator long lived in colliders

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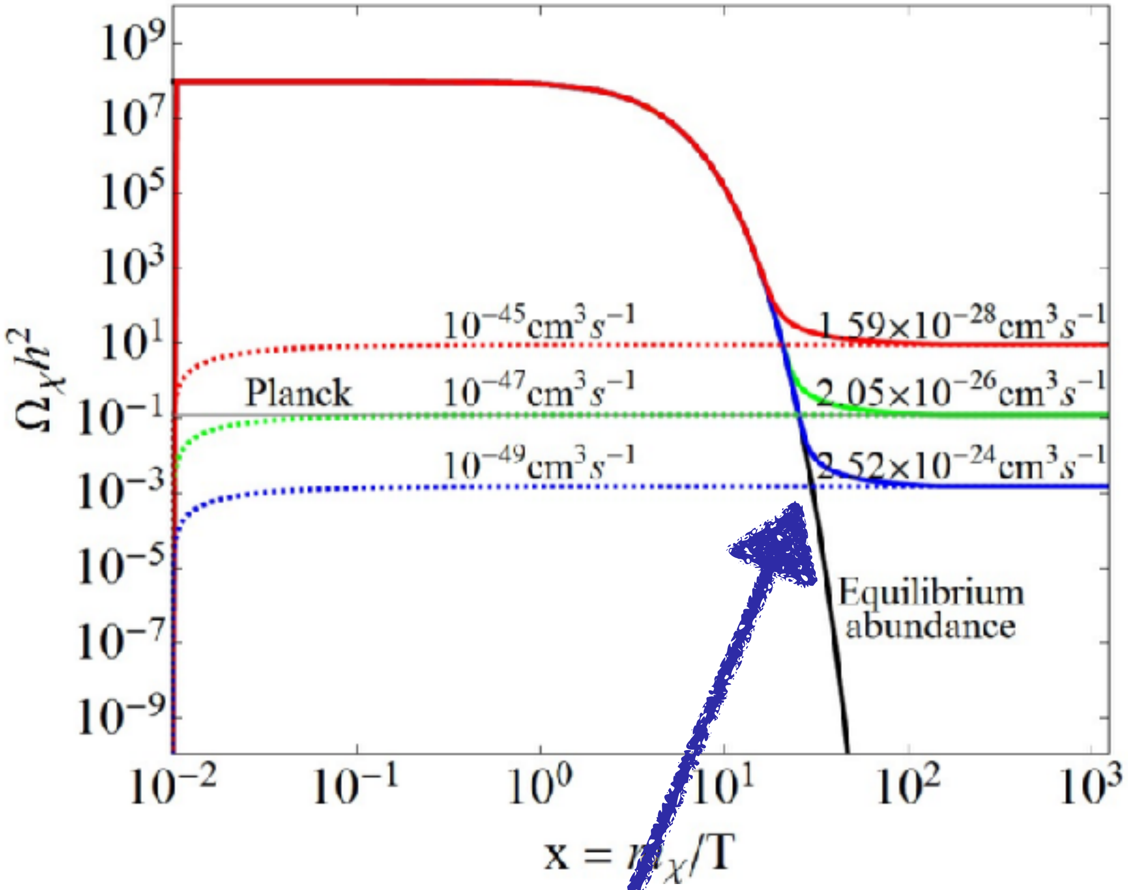

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Example: Higgs Portal Dark Matter

$$\mathcal{L}_{\text{eff}} = -\frac{m_S}{2}\overline{\chi}_S\chi_S - \frac{m_T}{2}\overline{\chi}_T\chi_T + \frac{\kappa}{\Lambda}\left[(H^\dagger\overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger\chi_T H)\right]$$

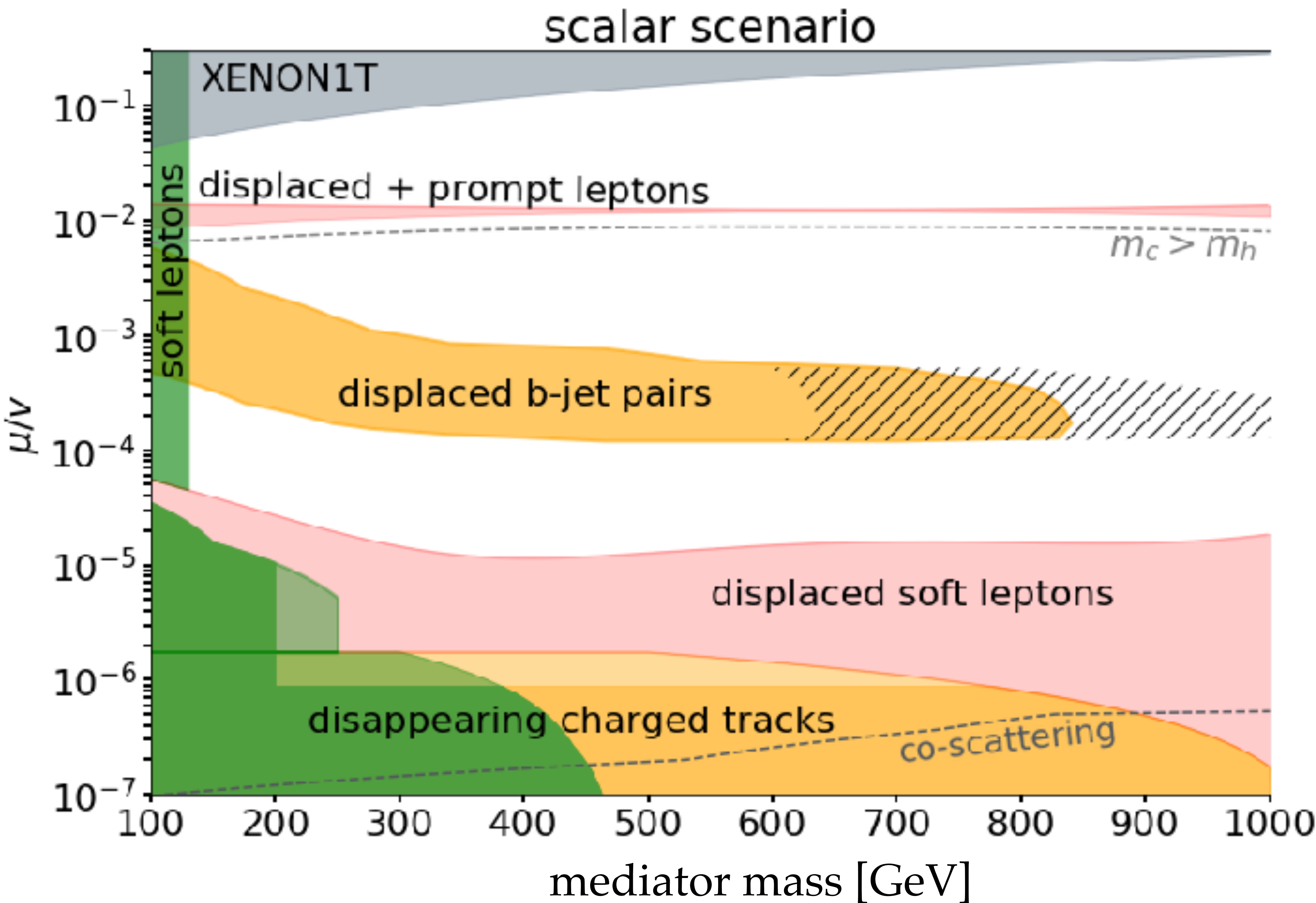
Filimonova / Westhoff 1812.04628

portal coupling

$$\mu = \frac{\kappa v^2}{\sqrt{2}\Lambda}$$

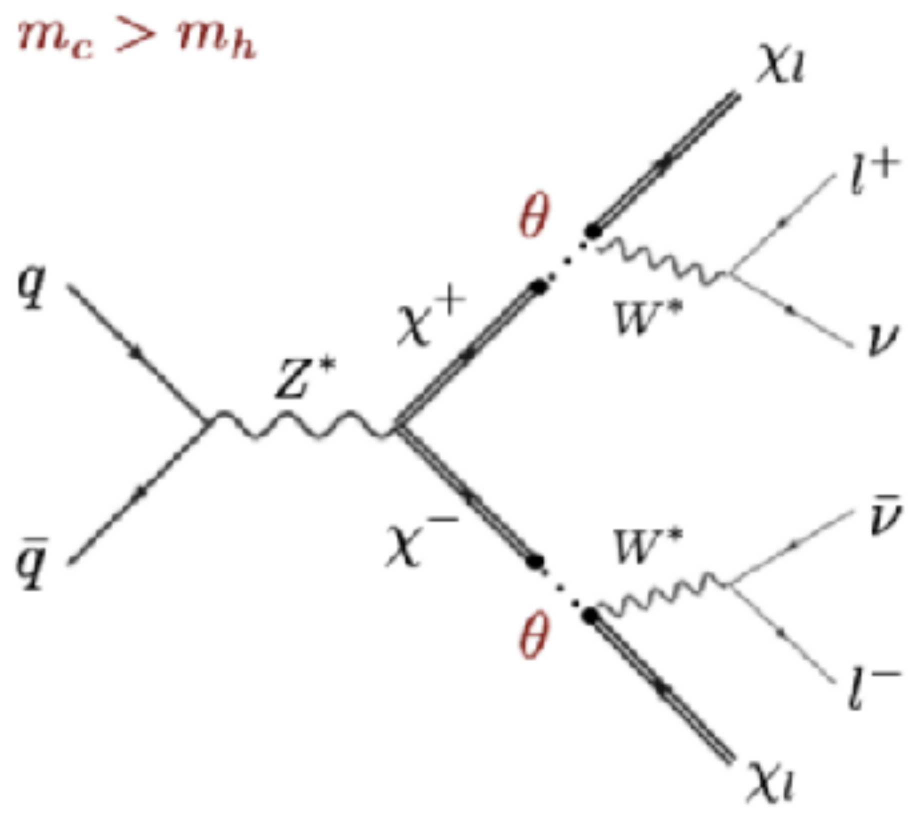
mediator width

$$\Gamma_\chi \sim \left(\frac{\mu}{v}\right)^x (\Delta m)^y$$



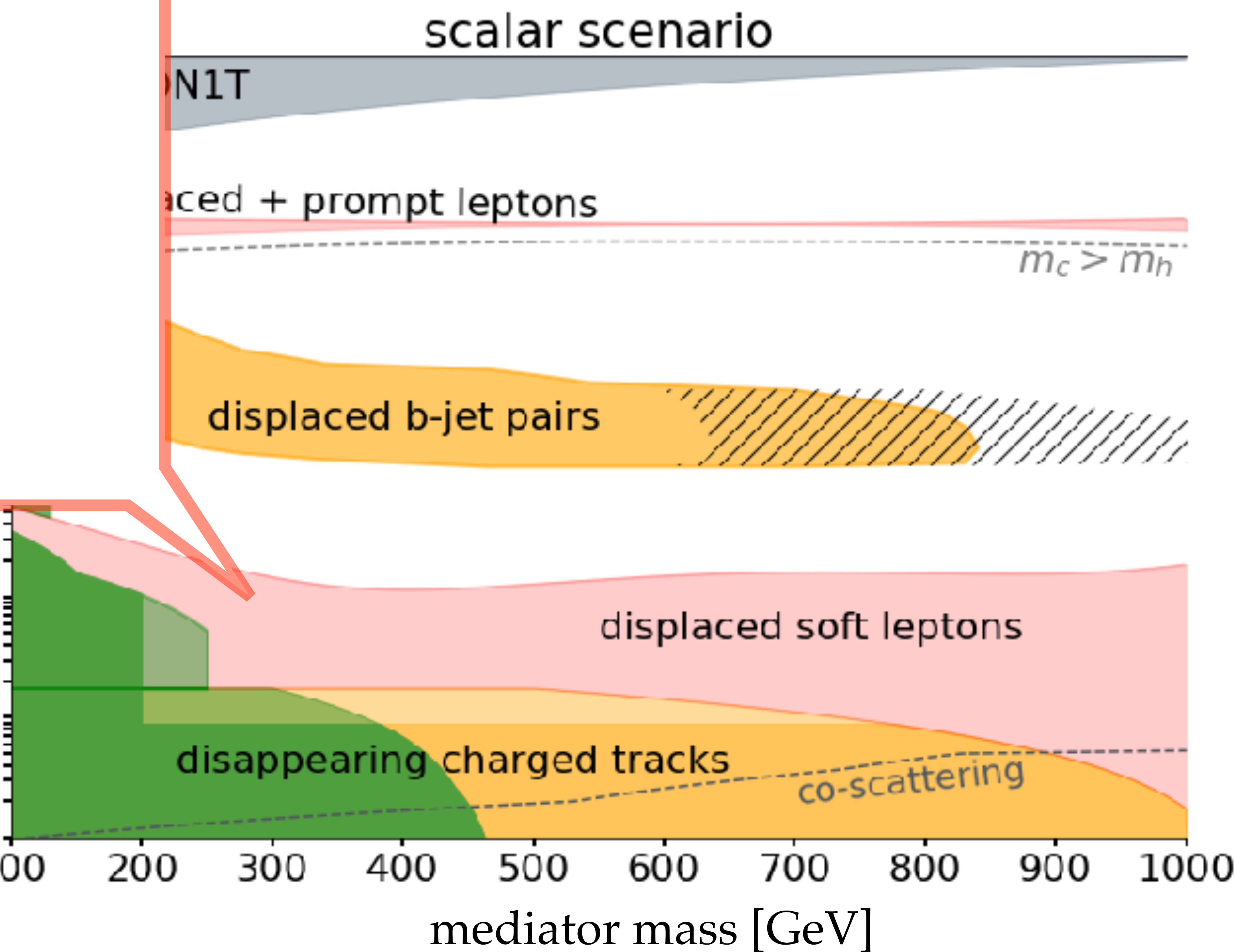
Example: Higgs Portal Dark Matter

displaced soft lepton signatures



$$_T + \frac{\kappa}{\Lambda}\left[(H^\dagger \overline{\chi}_T H)\chi_S + \overline{\chi}_S(H^\dagger \chi_T H)\right]$$

Filimonova / Westhoff 1812.04628



mediator width

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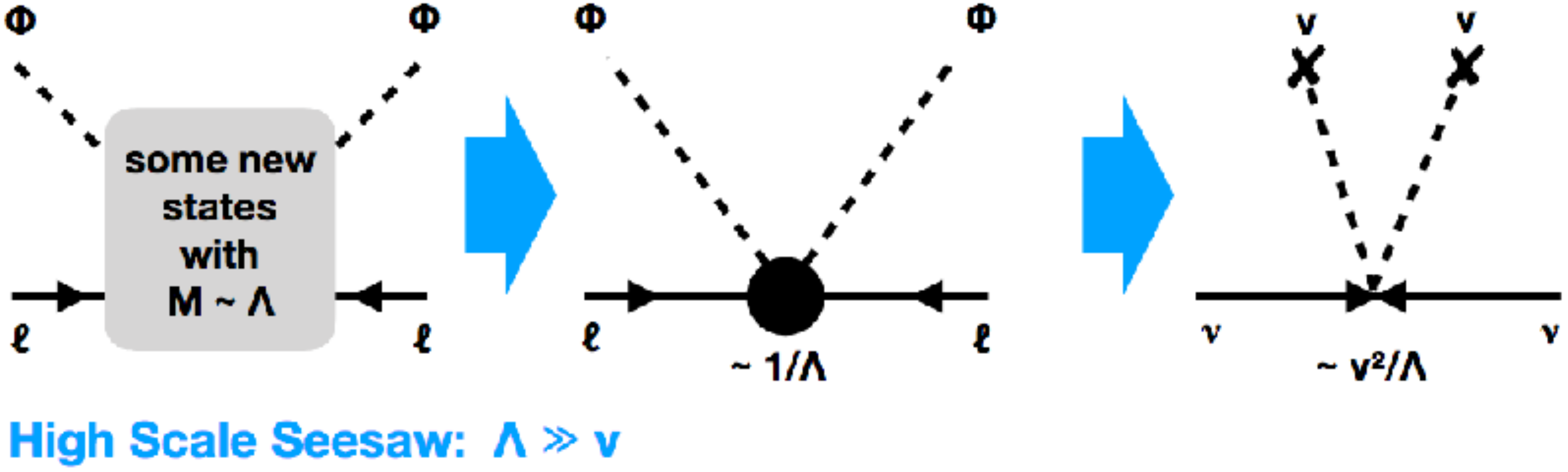
Neutrino Masses

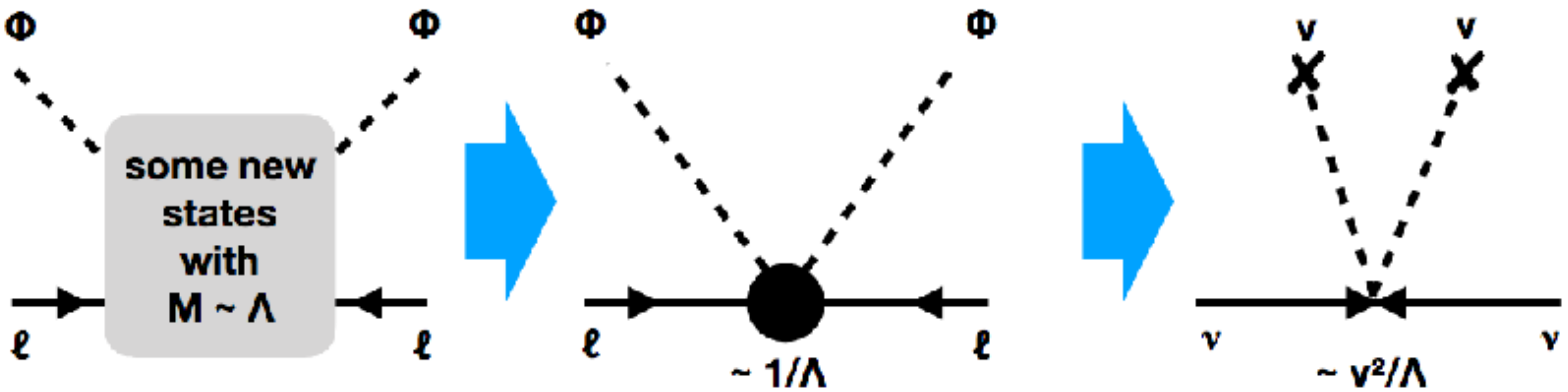


$$\frac{1}{2}\overline{l_L}\tilde{H}c^{[5]}\Lambda^{-1}\tilde{H}^T l_L^c + h.c. \quad \rightarrow \quad \overline{\nu_L} m_M \nu_L^c + h.c.$$

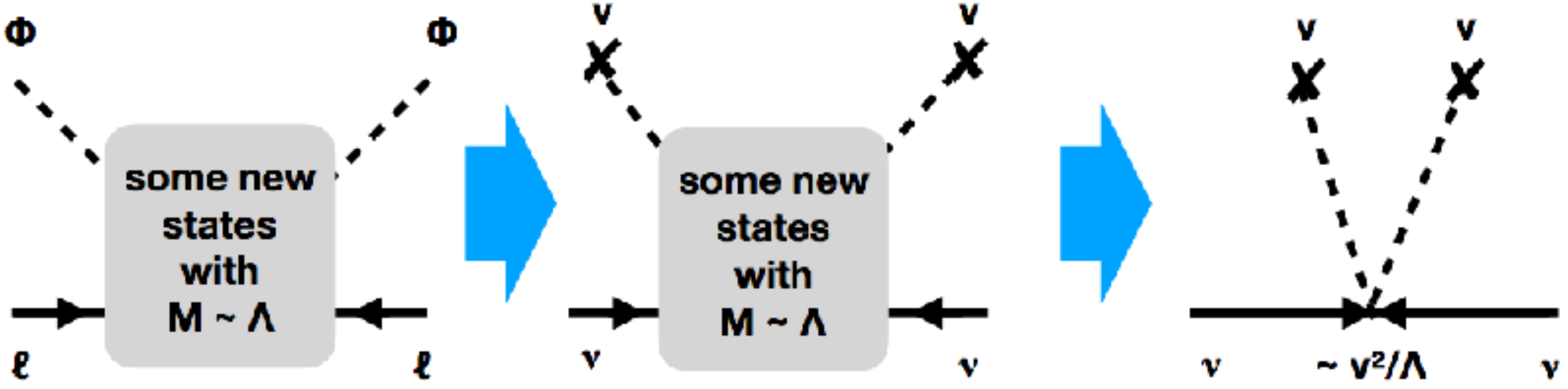
"integrating out" heavier states with masses ~*Λ* >> *E*$_\nu$
gives the Weinberg operator

figure from 1807.07938

Neutrino Masses



High Scale Seesaw: $\Lambda \gg v$

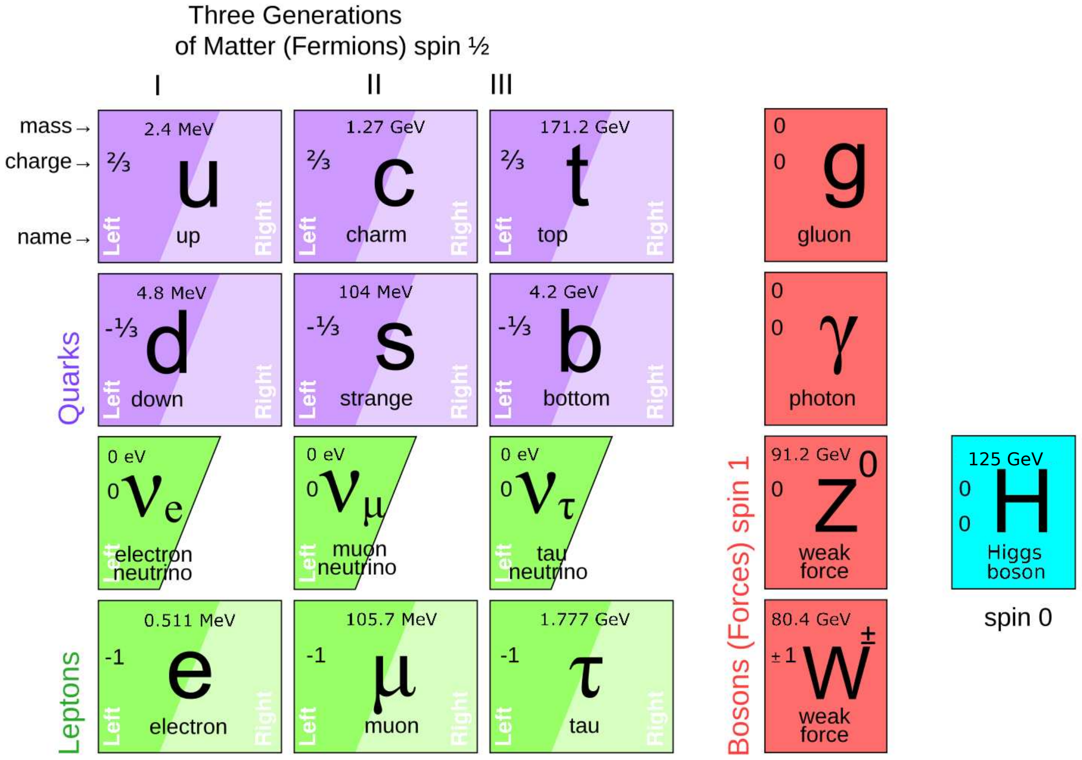


Low Scale Seesaw: $\Lambda \lesssim v$

figure from 1807.07938

Example: Right Handed Neutrino

$$\mathcal{L} = \mathcal{L}_{SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \bar{L}_L F \nu_R \tilde{H} - \tilde{H}^\dagger \bar{\nu}_R F^\dagger L$$



$$\frac{1}{2}(\bar{\nu}^c{}_R M_M \nu_R + \bar{\nu}_R M_M^\dagger \nu_R^c)$$

May explain Asaka/Shaposhnikov 2005

- **Neutrio masses**
- **Leptogenesis**
- **Dark Matter**

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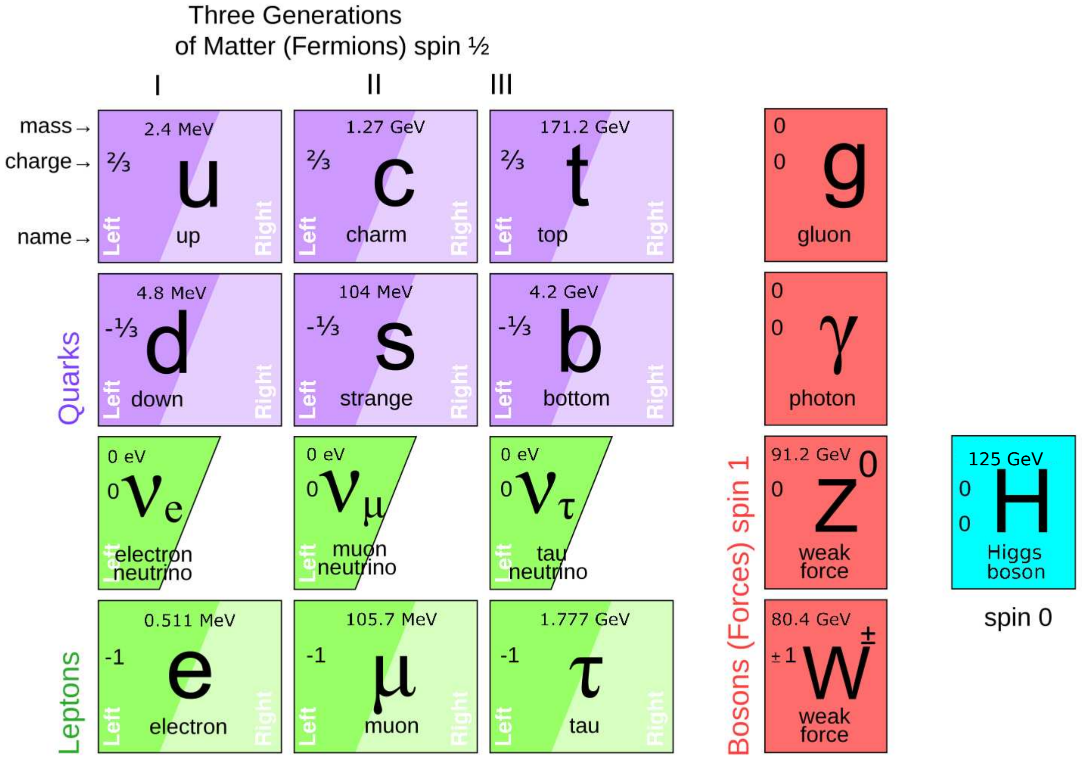


May explain Asaka/Shaposhnikov 2005

- **Neutrino masses**
- **Leptogenesis**
- **Dark Matter**

three light neutrinos mostly "active" SU(2) doublet
$\nu \simeq U_\nu(\nu_L + \theta\nu_R^c)$
with masses $\boldsymbol{m_\nu \simeq \theta M_M \theta^T = v^2 F M_M^{-1} F^T}$

three heavy mostly singlet neutrinos
$N \simeq \nu_R + \theta^T \nu_L^c$
with masses $\boldsymbol{M_N \simeq M_M}$

for M below the electroweak scale these are long lived!

Thermal Leptogenesis

Basic idea Fukugita/Yanagida 86

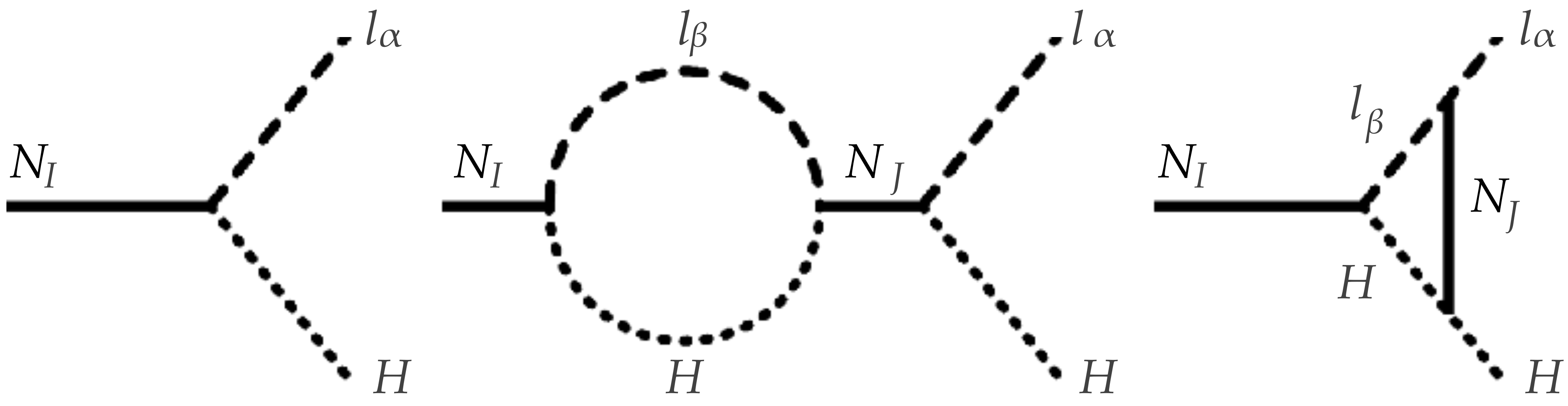
- *N* are around in the early universe
- Yukawas *F* are CP violating
- *N* may preferably decay into matter

CP violating parameter ϵ

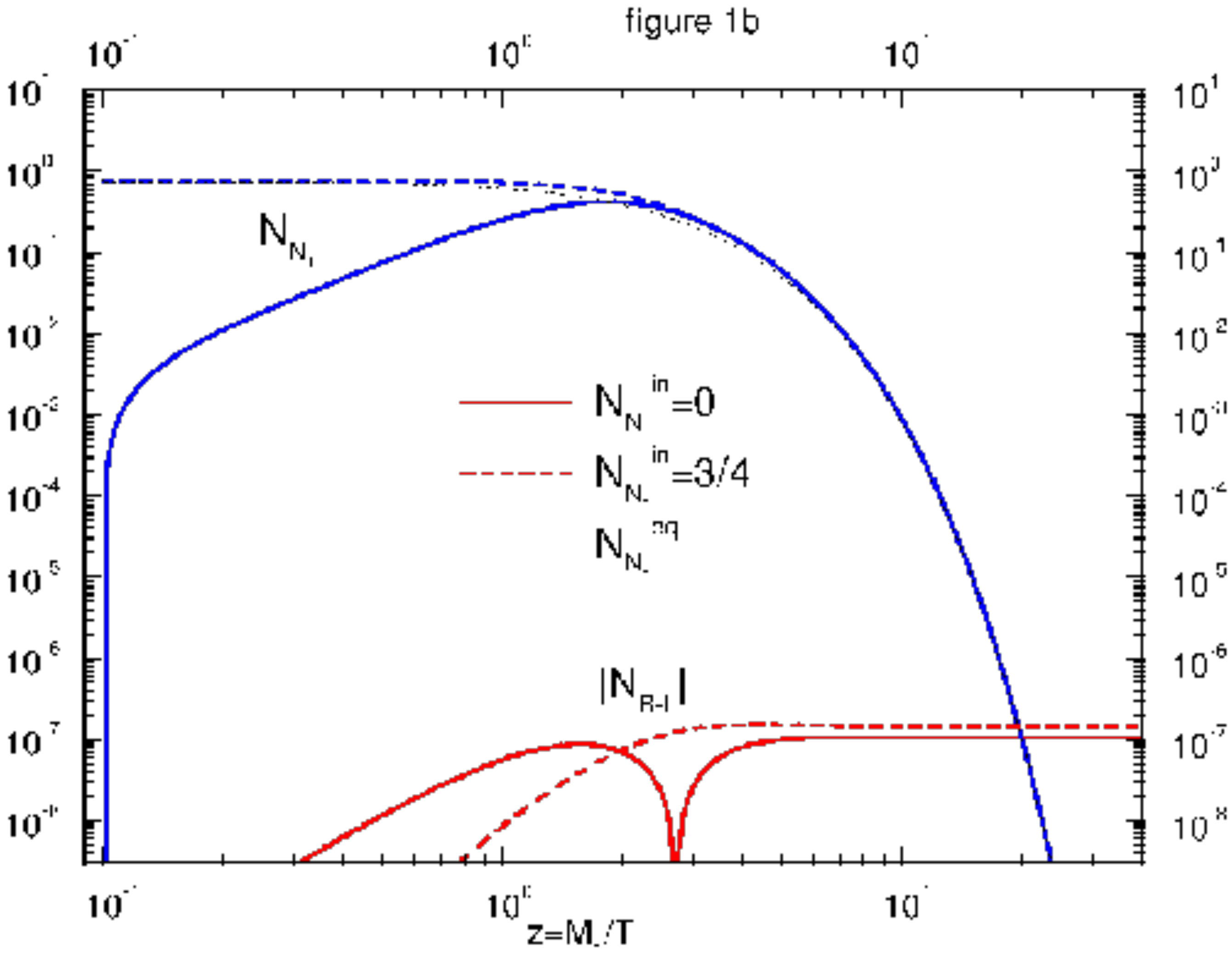
$$\epsilon = \frac{\Gamma_{N\to\ell H} - \Gamma_{N\to\bar{\ell}H^*}}{\Gamma_{N\to\ell H} + \Gamma_{N\to\bar{\ell}H^*}}$$

final asymmetry

$$Y_{B-L} \;\propto\; \epsilon/g_*$$



Leptogenesis with small *M*?



Buchmuller / Di Bari / Plumacher 0205349

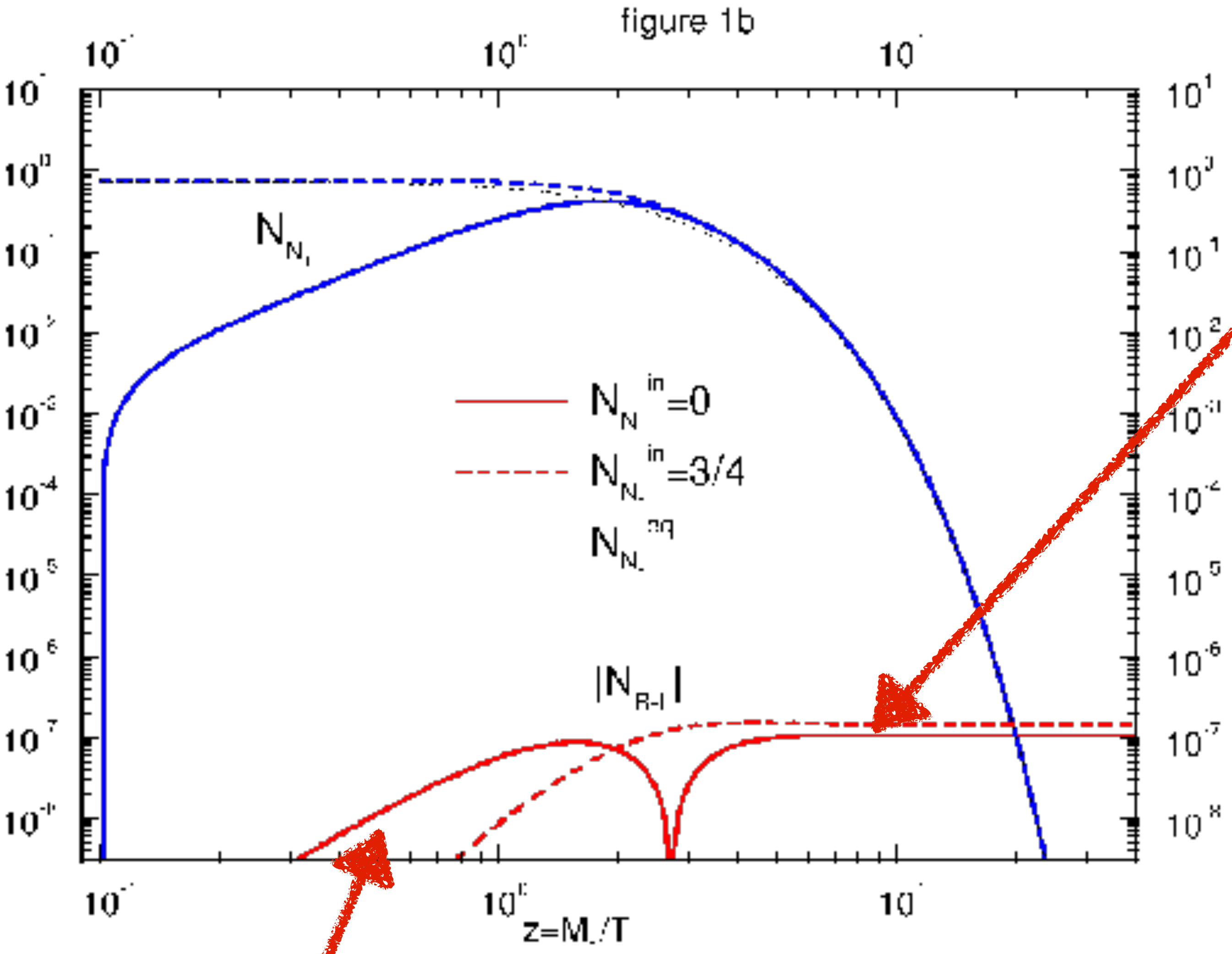
What about the famous Davidson-Ibarra bound M > 10 ^{9} GeV? 0202239

$$xH\frac{dY_N}{dx} = -\Gamma_N(Y_N - Y_N^{\rm eq}) \qquad x = M/T$$

$$xH\frac{dY_{\rm B-L}}{dx} = \epsilon\Gamma_N(Y_N - Y_N^{\rm eq}) - c_W\Gamma_N Y_{\rm B-L}$$

“source” “washout”

Leptogenesis with small *M*?



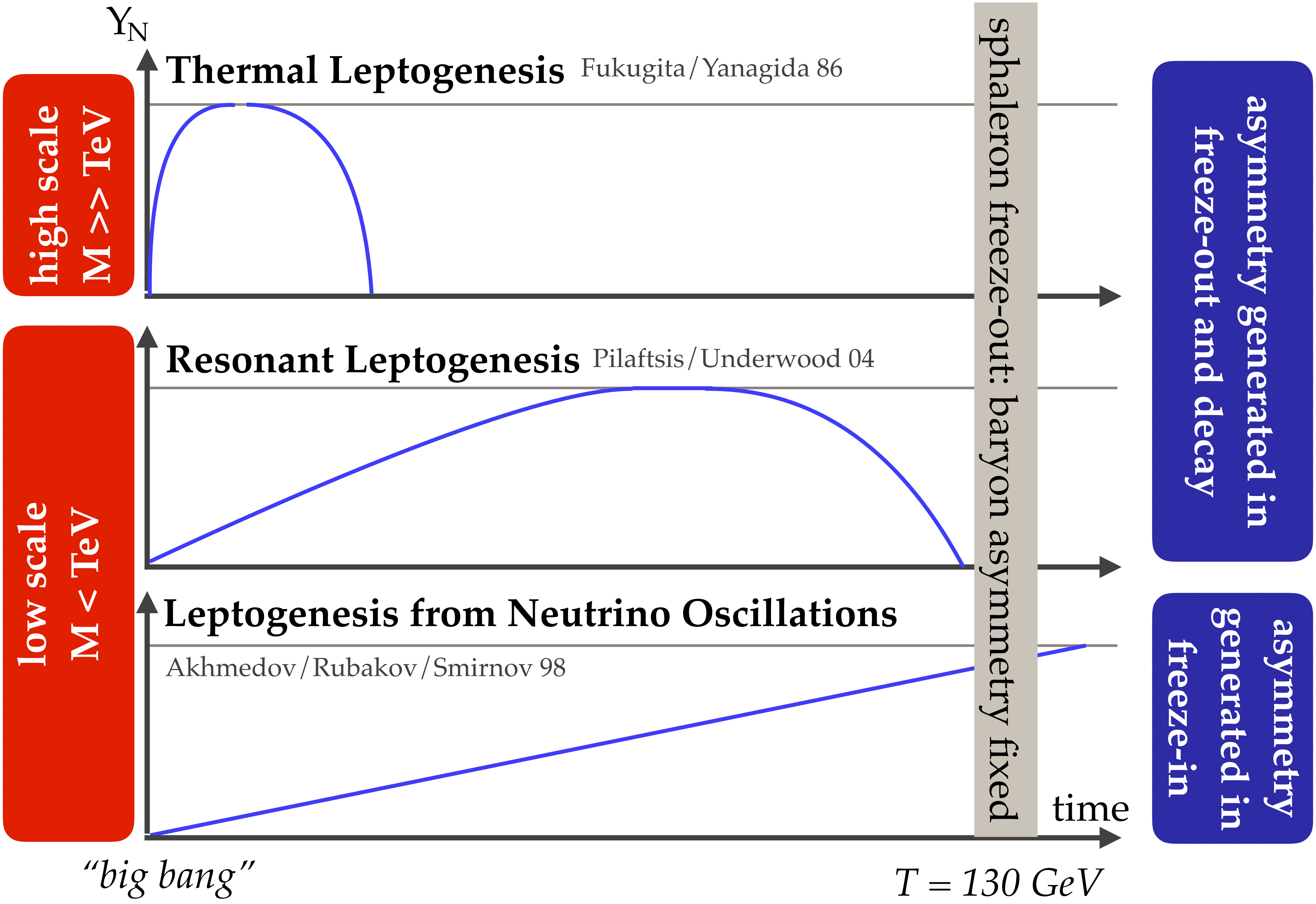
asymmetry generated during *N* decay ("freeze-out scenario")

asymmetry generated during *N* production ("freeze-in scenario")

Sakharov's nonequilibrium condition can be fulfilled in two ways.

$$xH\frac{d\mathrm{Y}_N}{dx} = -\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}}) \qquad x = M/T$$

$$xH\frac{d\mathrm{Y}_{\mathrm{B-L}}}{dx} = \underbrace{\epsilon\Gamma_N(\mathrm{Y}_N - \mathrm{Y}_N^{\mathrm{eq}})}_{\text{"source"}} - \underbrace{c_W\Gamma_N\mathrm{Y}_{\mathrm{B-L}}}_{\text{"washout"}}$$



high scale
M >> TeV

Y_N

Thermal Leptogenesis Fukugita/Yanagida 86

Resonant Leptogenesis Pilaftsis/Underwood 04

low scale
M < TeV

Leptogenesis from Neutrino Oscillations

Akhmedov/Rubakov/Smirnov 98

sphaleron freeze-out: baryon asymmetry fixed

asymmetry generated in freeze-out and decay

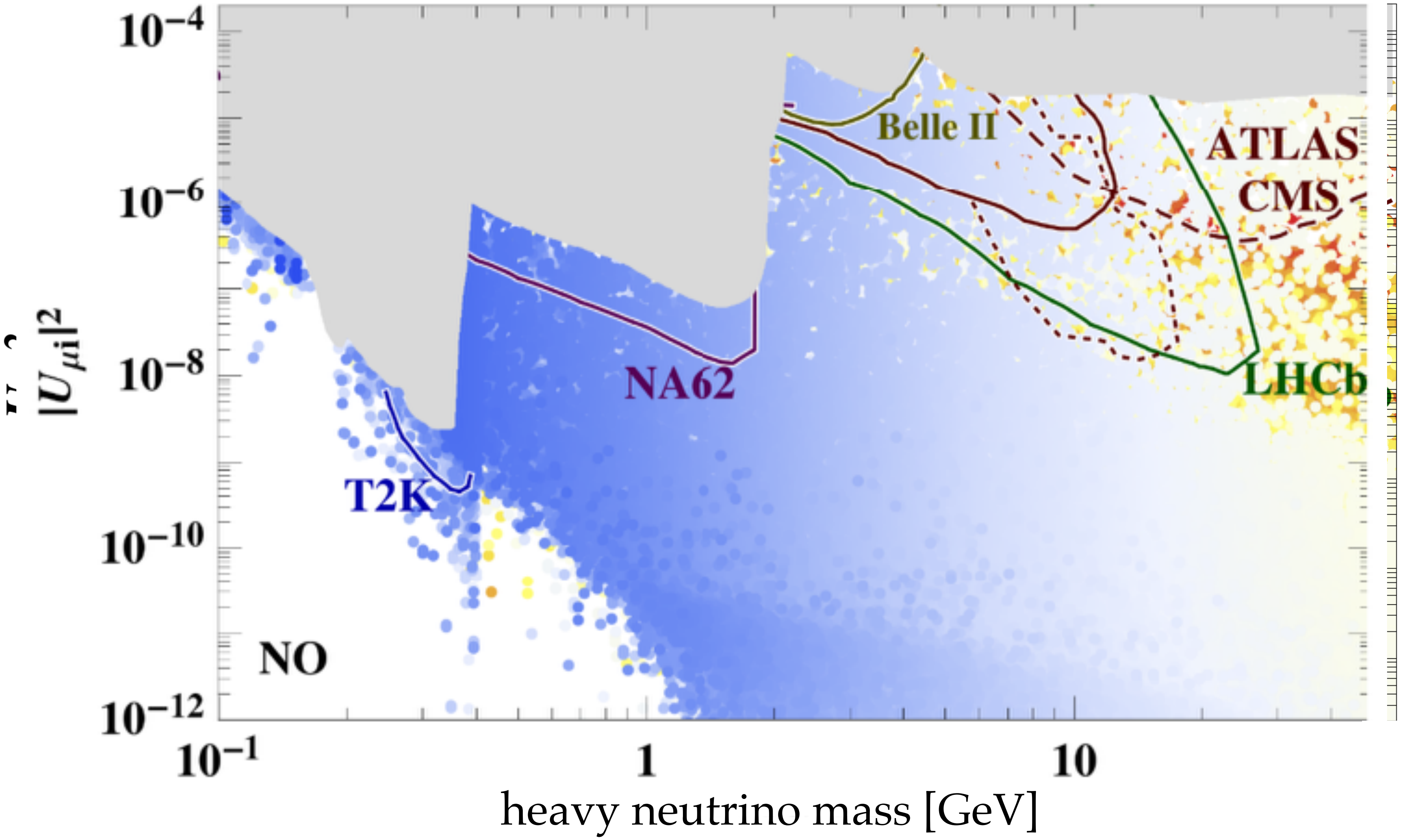
asymmetry generated in freeze-in

time

“big bang”

$T = 130$ GeV

Low Scale Leptogenesis at the LHC



plot from
Abada et al 1810.12463

For experimental searches: Talk by Jan Hajer

- colourful points:
  leptogenesis + neutrino masses with three heavy neutrinos
- colour code measures the degree of fine tuning

The Hierarchy Problem

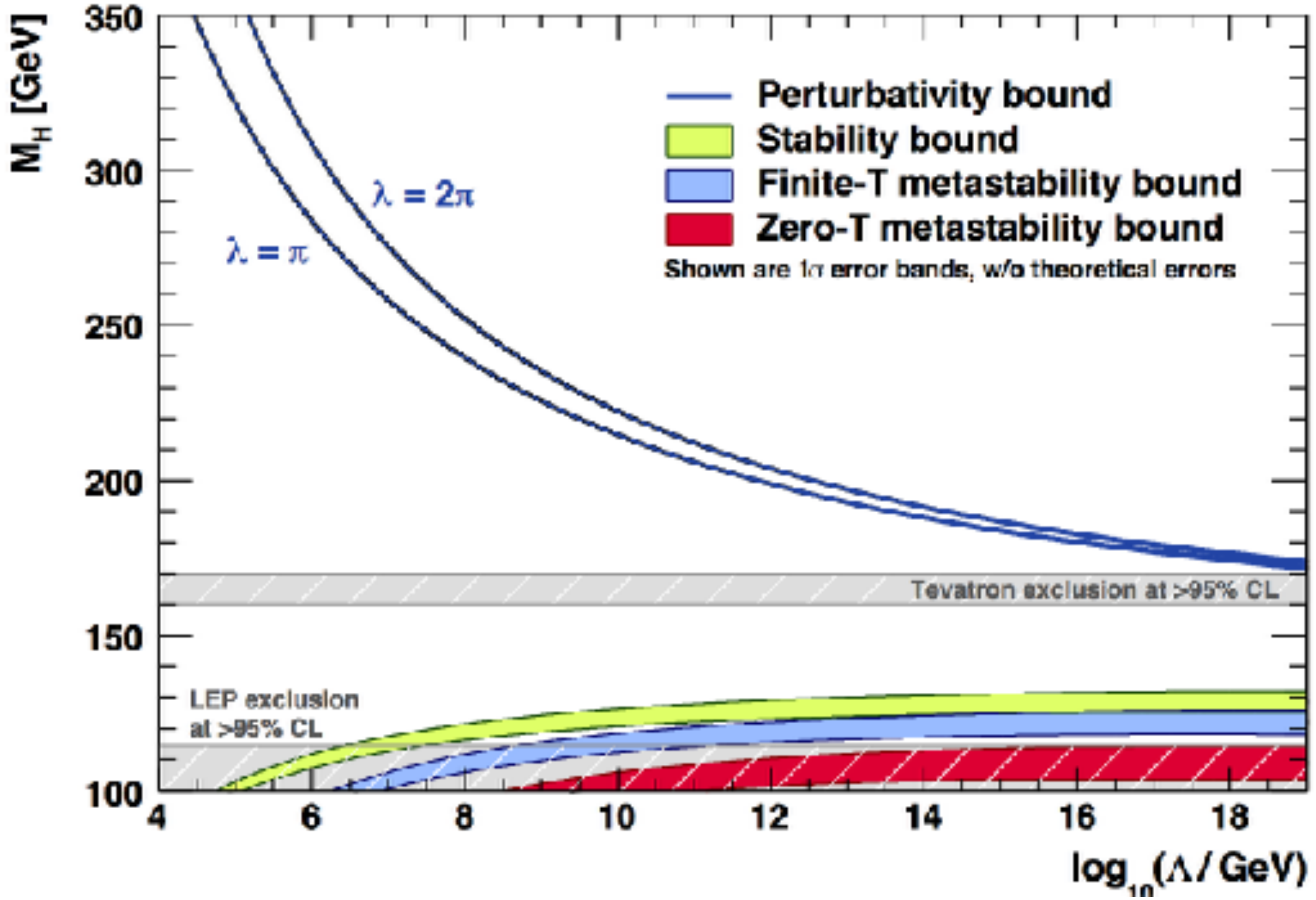
Hierarchy Problem

- Adding heavy states leads to electroweak hierarchy problem
- No problem if all masses below electroweak scale

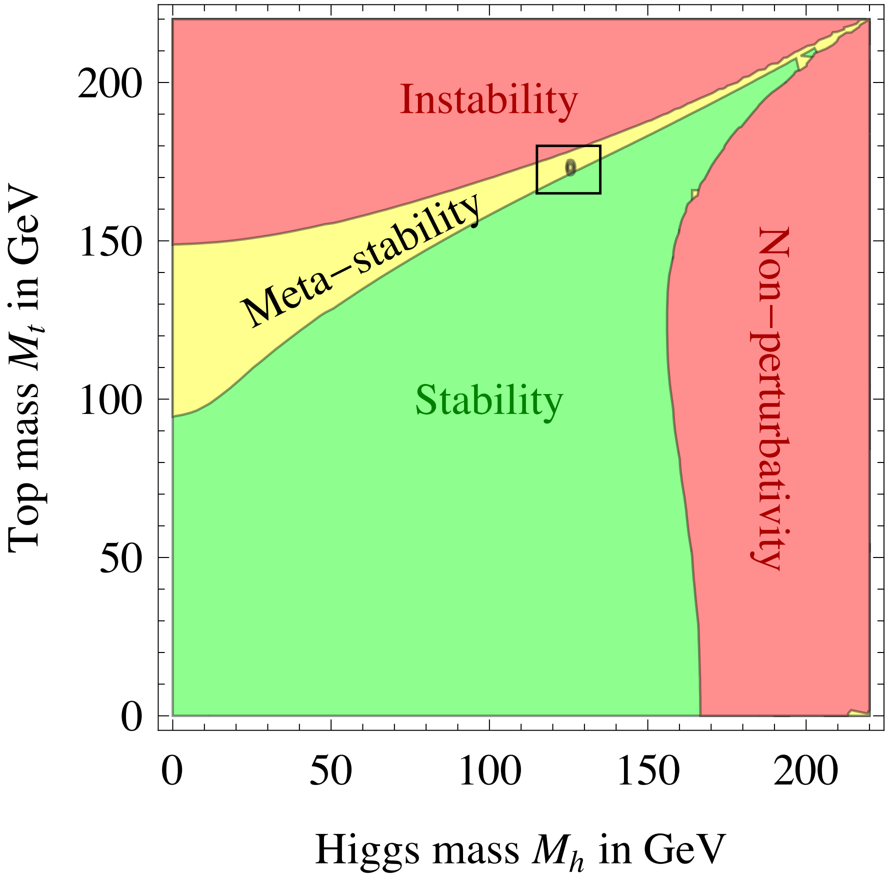
Bardeen 95,
Shaposhnikov 07

Higgs properties / vacuum stability

- SM could e valid EFT to Planck scale!



Ellis et et al 09



Degrassi et al 1205.6497

Overview

Why bother about long lived particles?

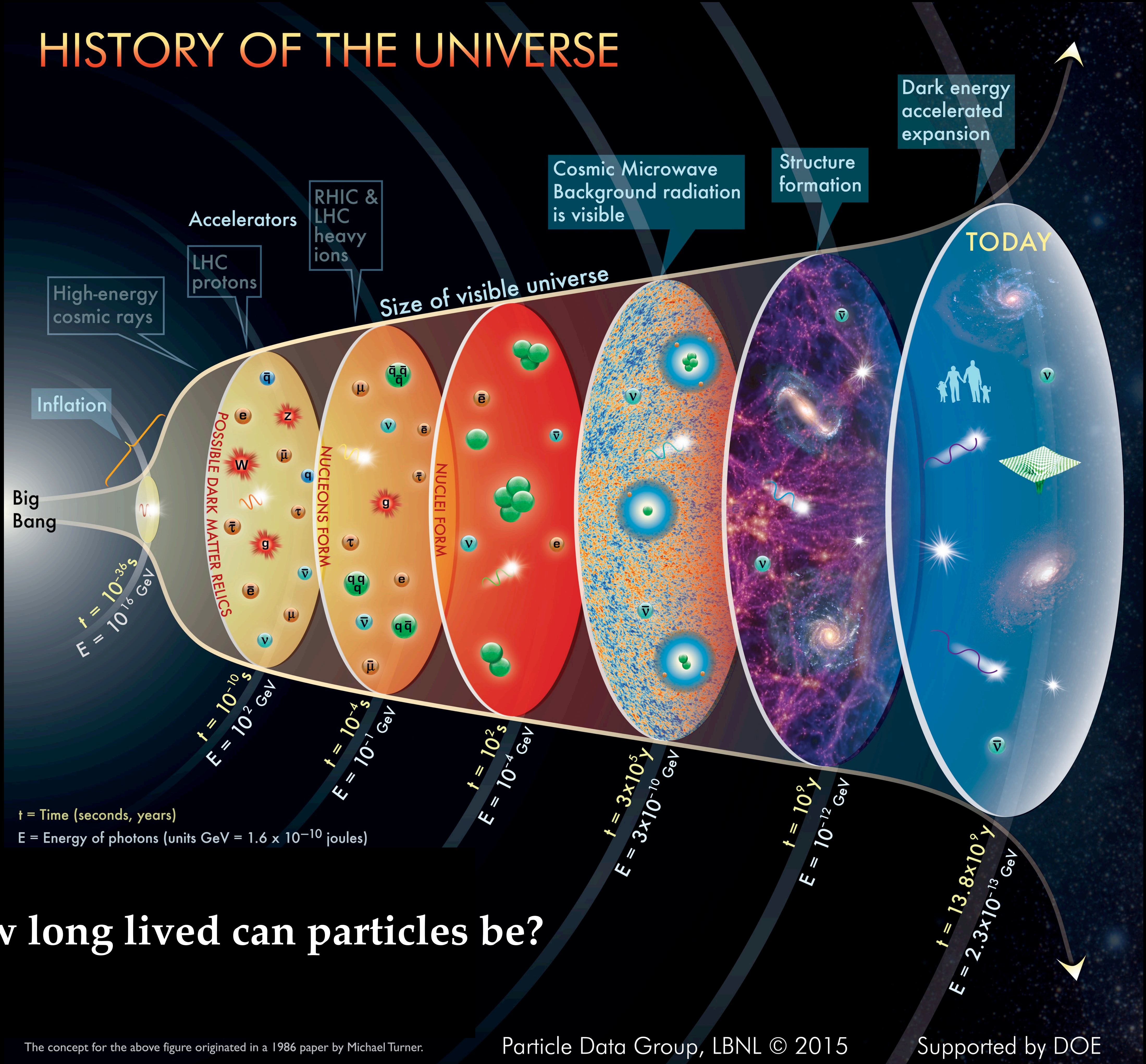
- Dark Matter
- Neutrino Masses
- Baryon Asymmetry
- Hierarchy Problem

How long lived can a particle be?

- Big Bang Nucleosynthesis
- Cosmic Microwave Background

How to find long lived particles?

- A holistic approach to the LHC
- New detectors
- Beyond the LHC



t = Time (seconds, years)

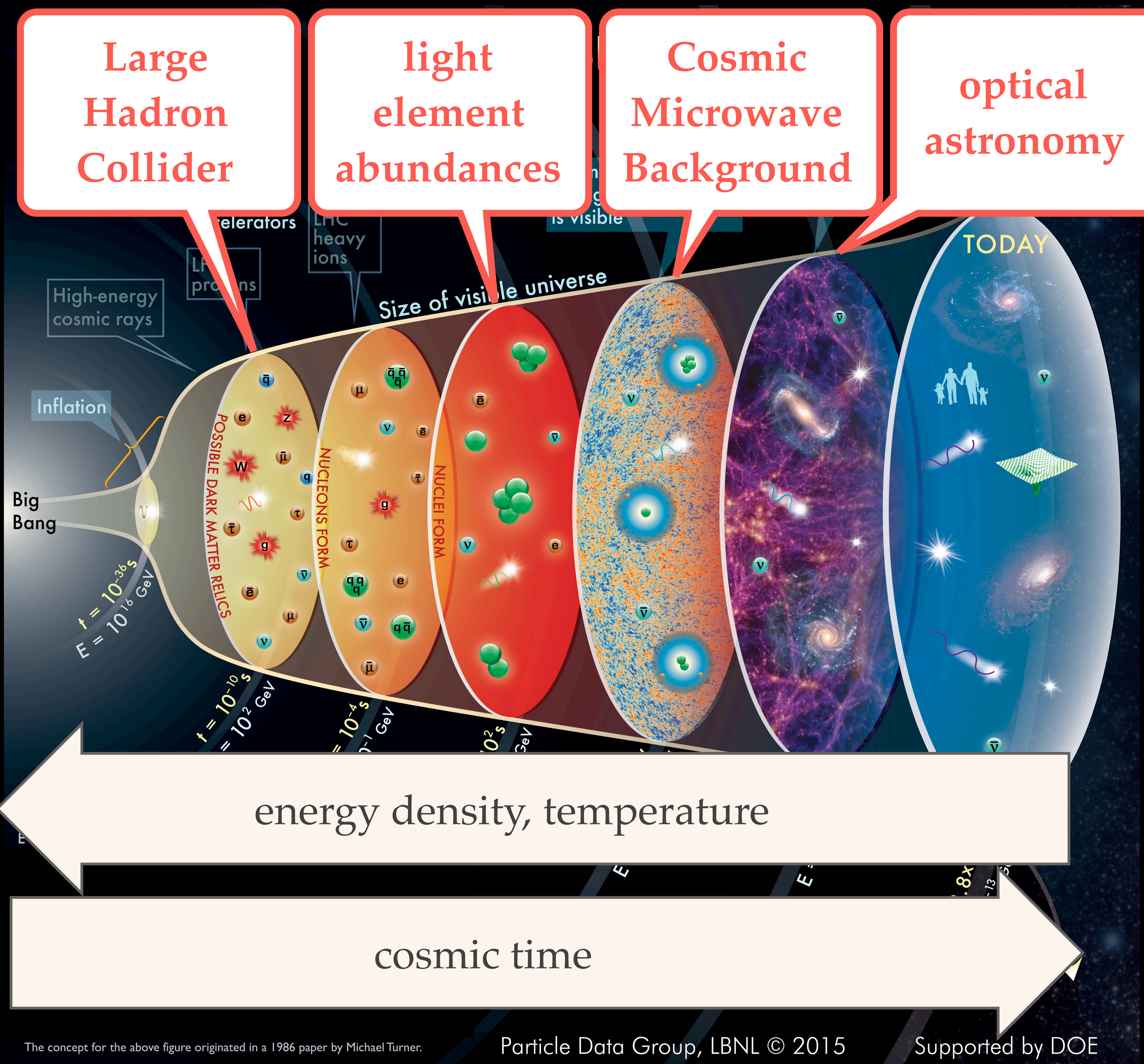
E = Energy of photons (units GeV = 1.6 x 10^{-10} joules)

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE

How long lived can particles be?



Large Hadron Collider

light element abundances

Cosmic Microwave Background

optical astronomy

energy density, temperature

cosmic time

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

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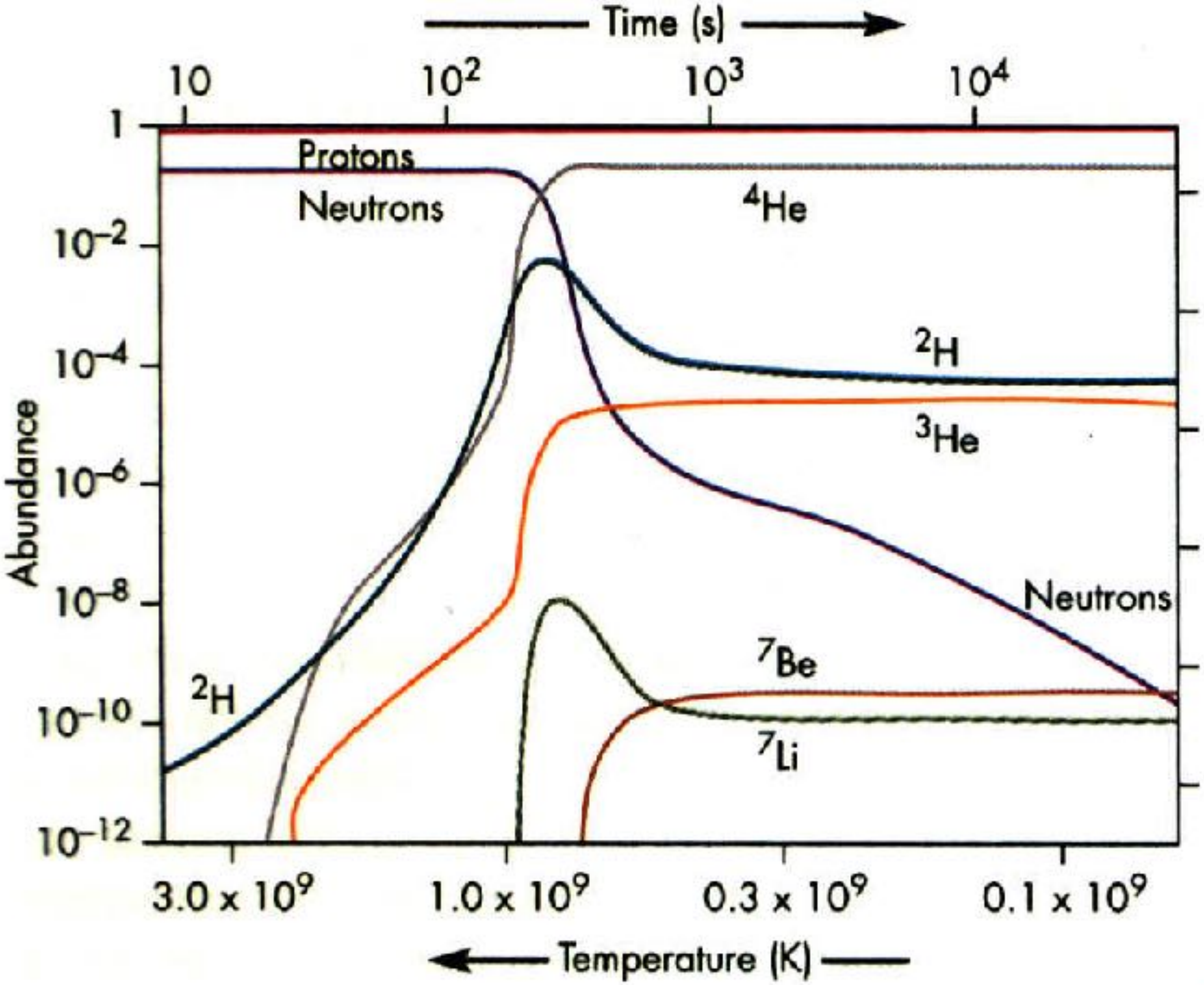
Big Bang Nucleosynthesis



Light elements are produced in a chain of nuclear reactions.

Theory is in good agreement with observed abundances in IGM

Decay of LLPs would disturb BBN

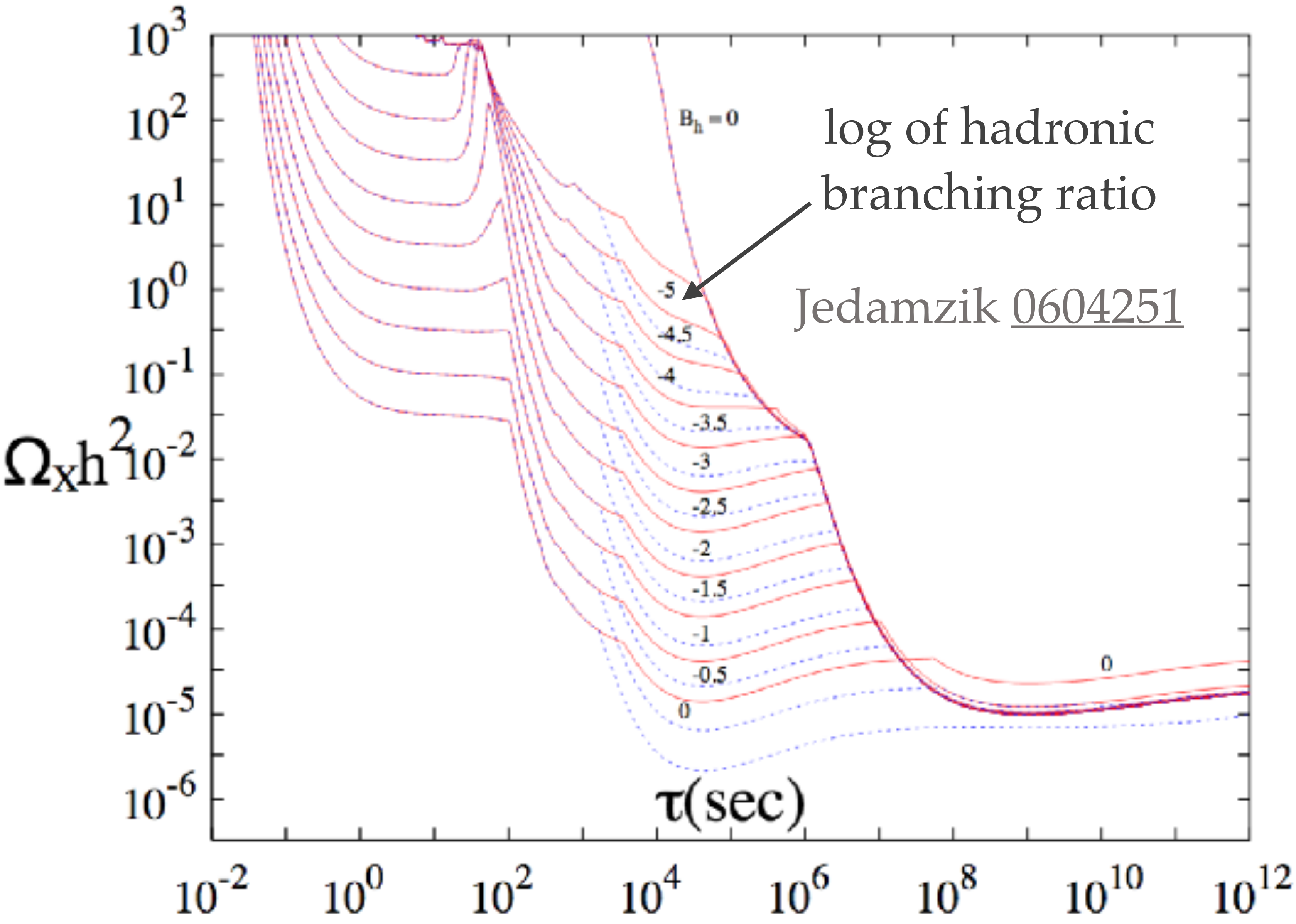
⇒ LLP must not decay during BBN!

Big Bang Nucleosynthesis

What exactly goes wrong?

recent update: Hufnagel et al 1808.09324

- **Decay products can dissociate nuclei**



log of hadronic branching ratio

Jedamzik 0604251

Big Bang Nucleosynthesis

What exactly goes wrong?

recent update: Hufnagel et al 1808.09324

- Decay products can dissociate nuclei

- Decay modifies relation between temperature and energy density…

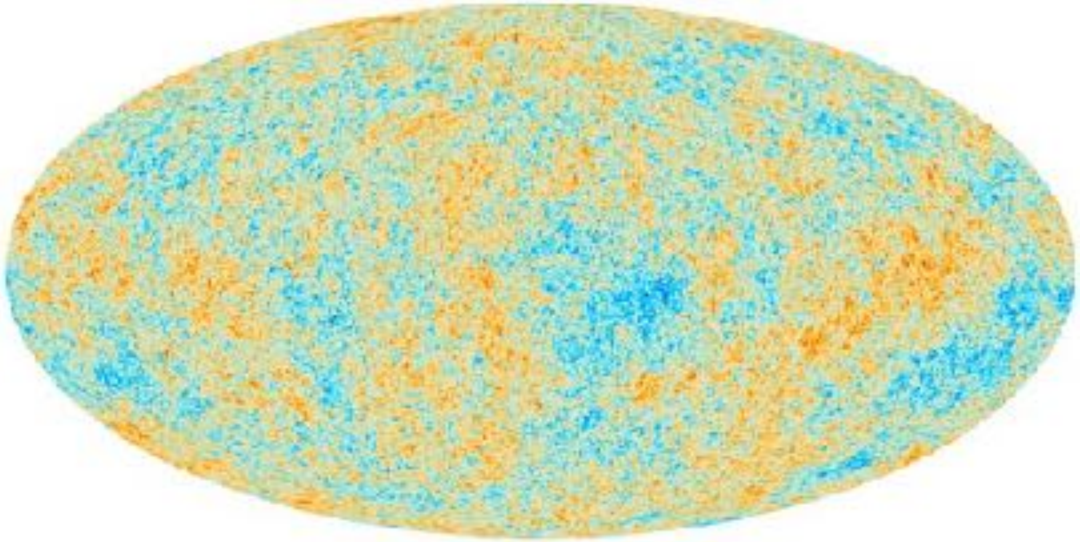
$$\rho_\gamma + \rho_{\text{neutrinos}} + [\text{new physics effects}] \equiv \rho_\gamma + \boxed{N_{\text{eff}}}\rho_\nu = \frac{\pi^2}{15}T_\gamma^4\left[1 + N_{\text{eff}}\frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]$$

…and thereby the Hubble rate

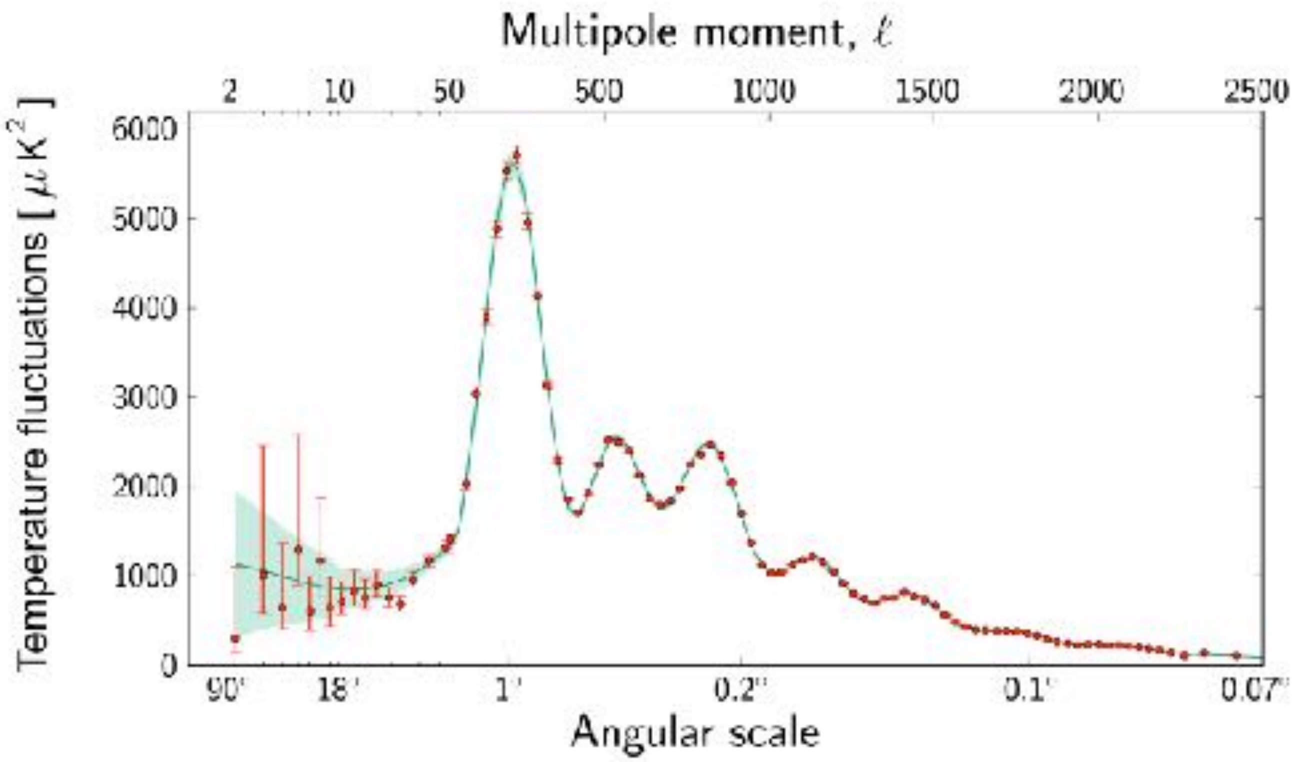
$$H^2 = \frac{8\pi}{3}G\rho$$

- Entropy injection modifies baryon to photon ratio

Cosmic Microwave Background



CMB is sensitive to the number of relativistic particle species in the primordial plasma



SM predicts 3 neutrinos (in addition to photons). This prediction **assumes thermal distributions with single T**.

Observed value:

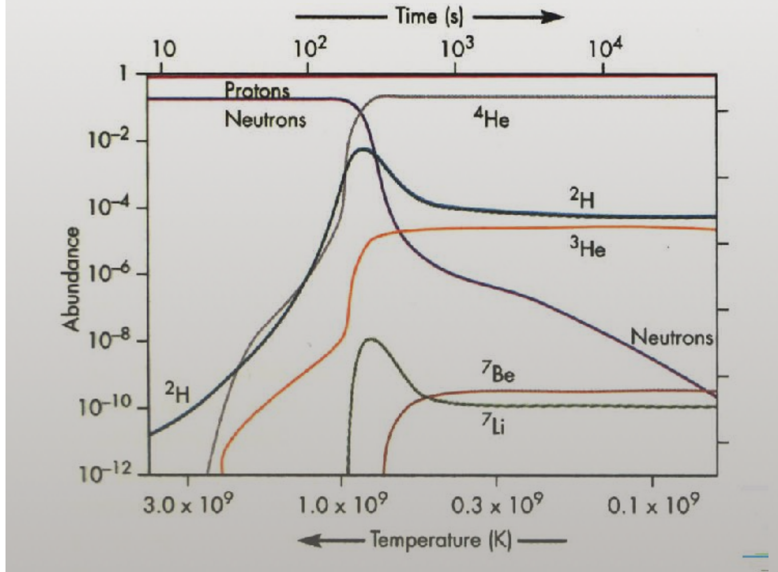
$N_{eff} = 2.99 \pm 0.17$ Planck 1807.06209

LLP decay would create entropy, disturb spectra and ruin this agreement

How long lived can new particles be?

0.1s

300.000 yrs



hot plasma

galaxy formation

⇐ must decay before 0.1s …

…or after more than 300.000 yrs ⇒

(e.g. Dark Matter)

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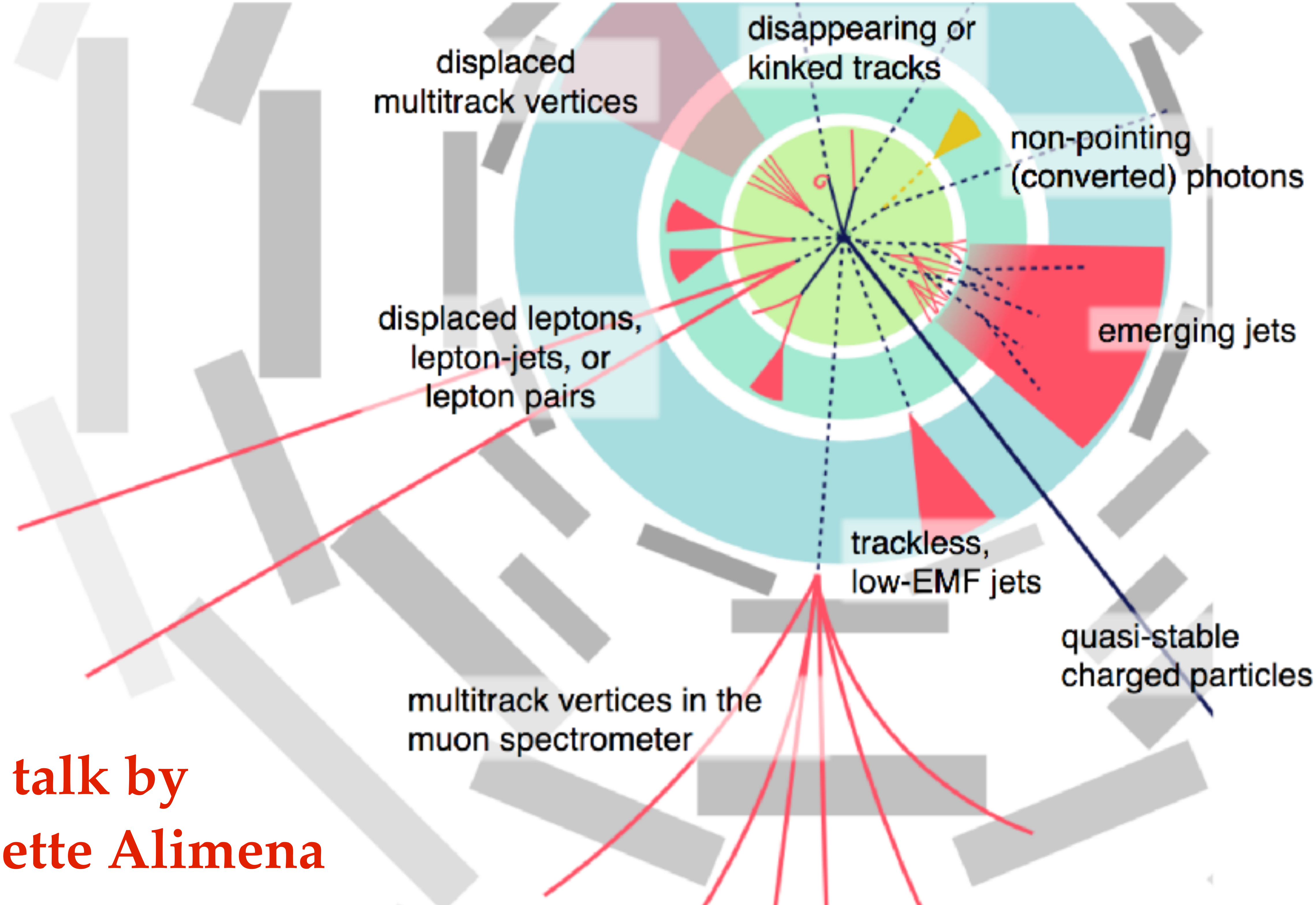
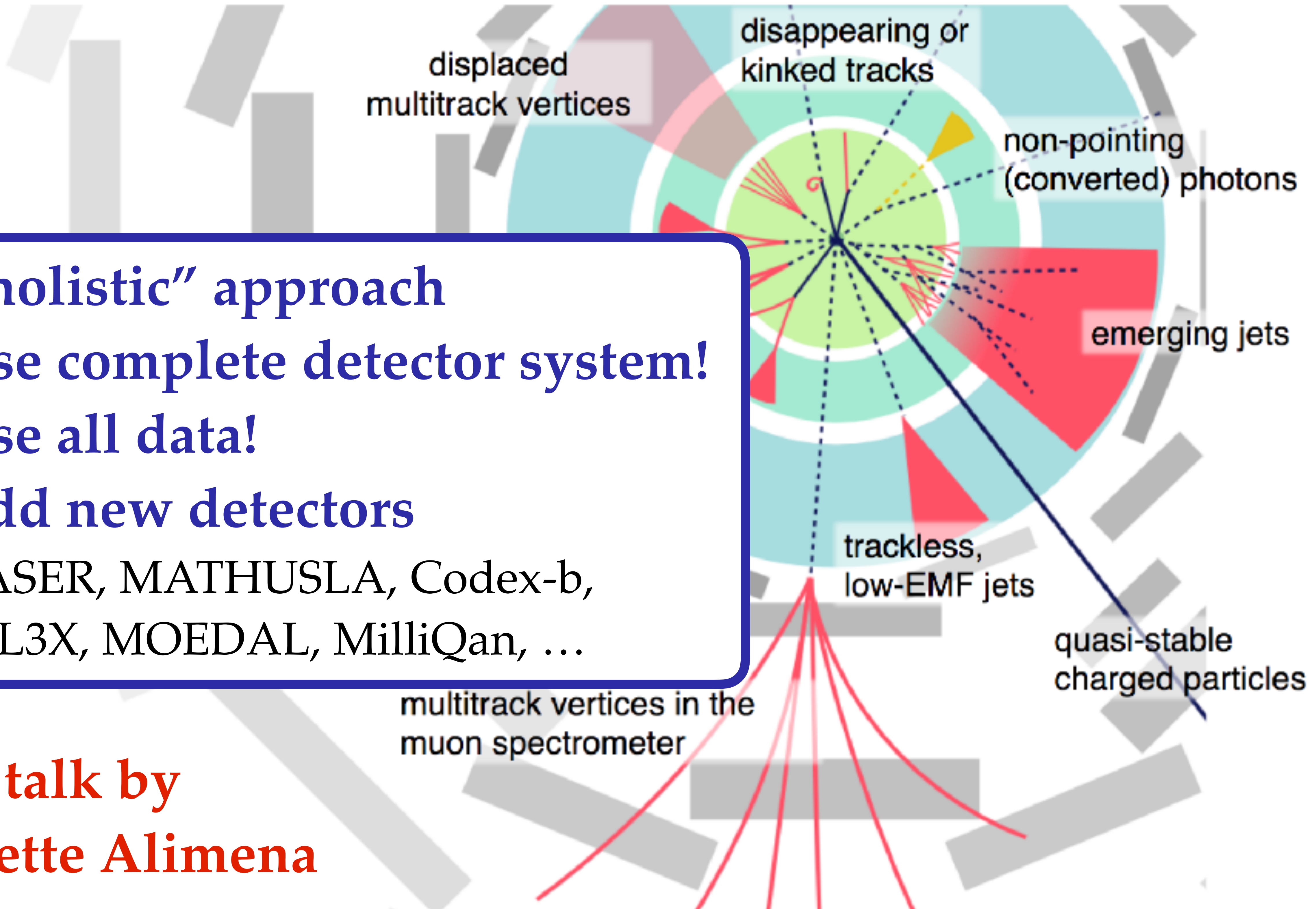
Searches at the LHC



See talk by Juliette Alimena

Searches at the LHC



A "holistic" approach

- **use complete detector system!**
- **use all data!**
- **add new detectors**

FASER, MATHUSLA, Codex-b,
AL3X, MOEDAL, MilliQan, …

See talk by
Juliette Alimena

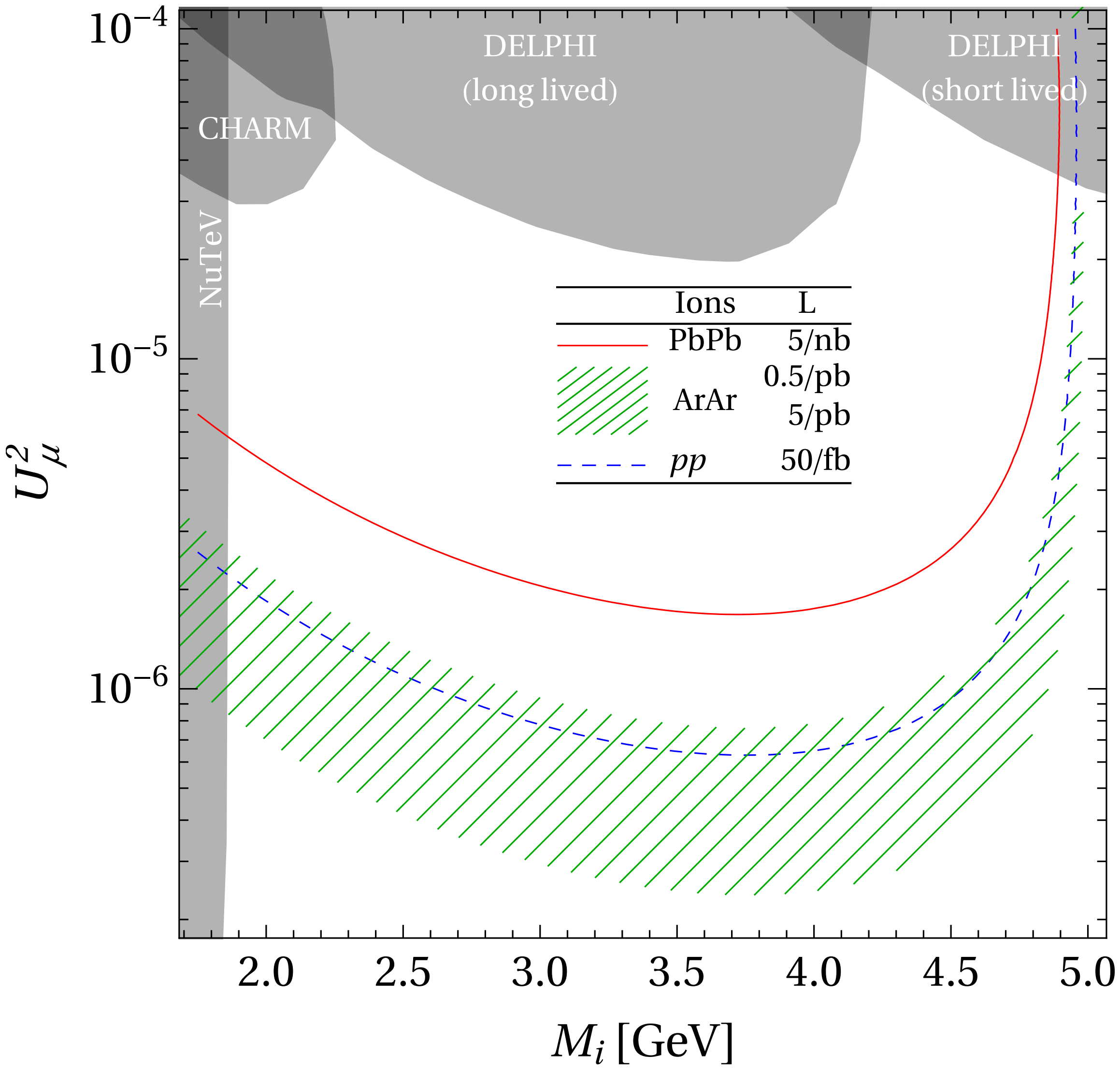
Use all Data!

Example: Heavy ion data can help to fully explore the parameter space

- strongly enhanced production cross section for ALPs, monopoles etc.
- no pile up = no primary vertex misidentification
- different backgrounds
- triggers can be lowered to see soft particles

see Jan Hajer's talk

and Bruce et al 1812.07688

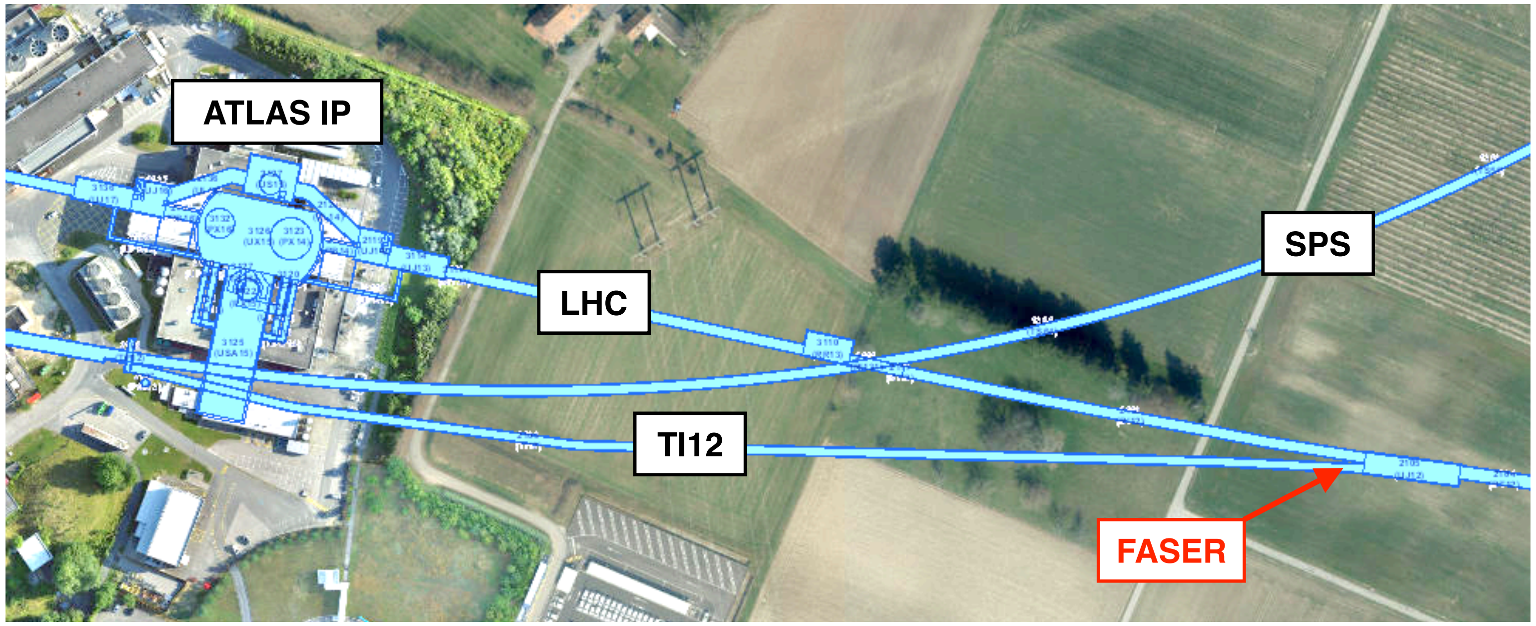


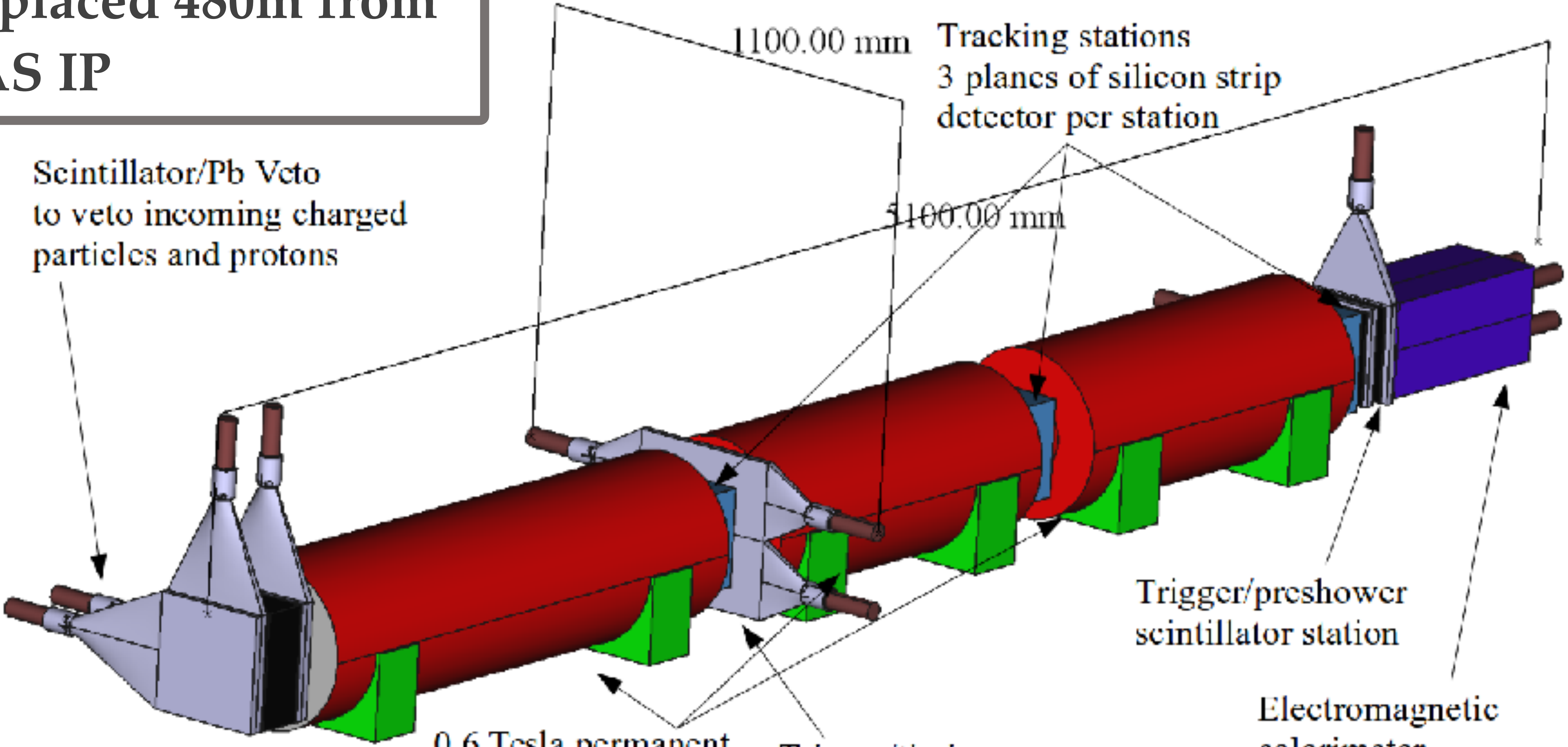
Example displaced vertex from heavy neutrinos in heavy ion collisions

MaD et al 1905.09828

FASER

- dedicated LLP detector
- size: 20cm x 5m
- to be placed 480m from ATLAS IP





Tracking stations
3 planes of silicon strip detector per station

Scintillator/Pb Veto
to veto incoming charged particles and protons

Trigger/preshower scintillator station

Electromagnetic calorimeter (Lead/scintillator)

0.6 Tesla permanent dipole magnets with 20 cm aperture

Trigger/timing scintillator station

FASER 1812.09139

FASER

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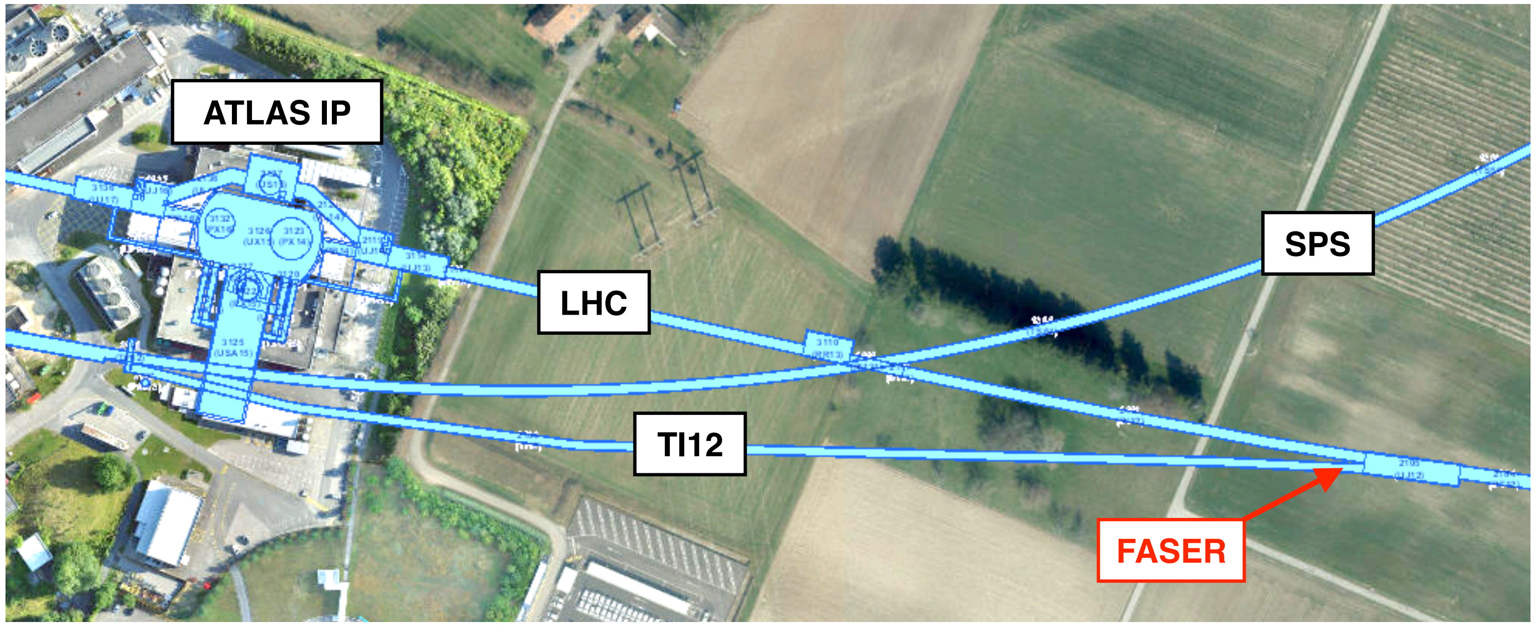
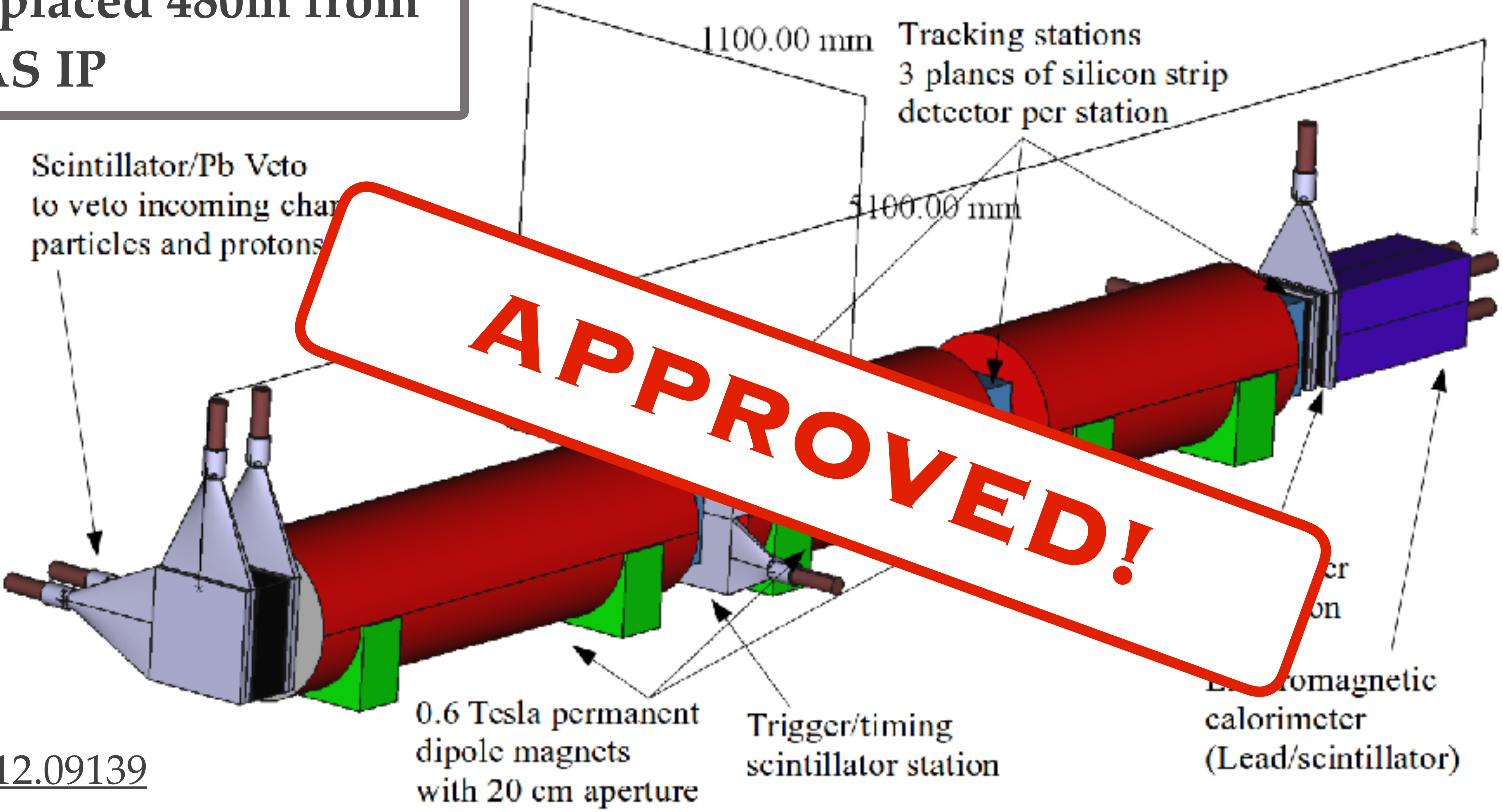




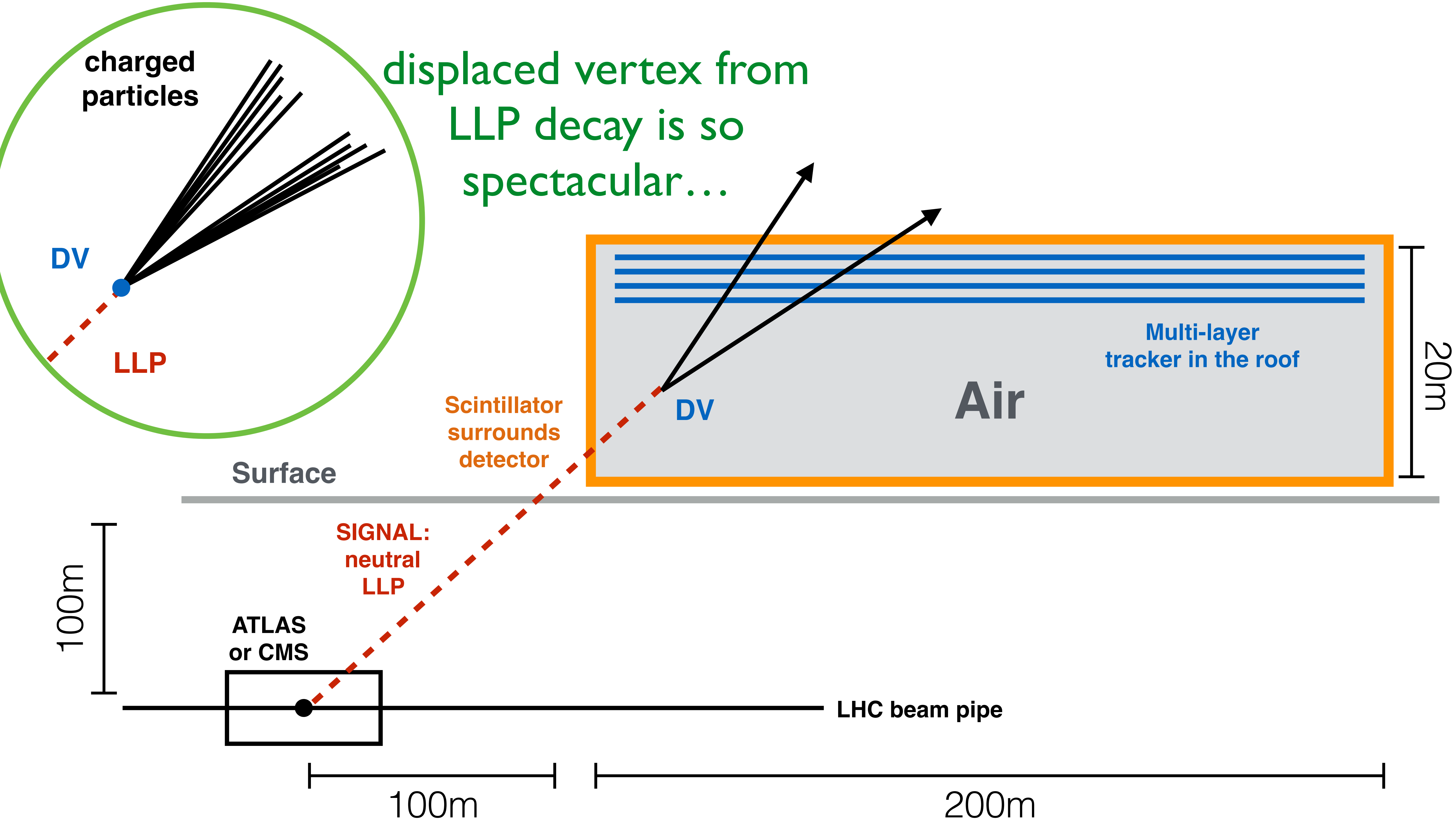
APPROVED!

FASER 1812.09139

MATHUSLA

MAssive Timing Hodoscope for Ultra-Stable NeutraL PArticles

displaced vertex from LLP decay is so spectacular…

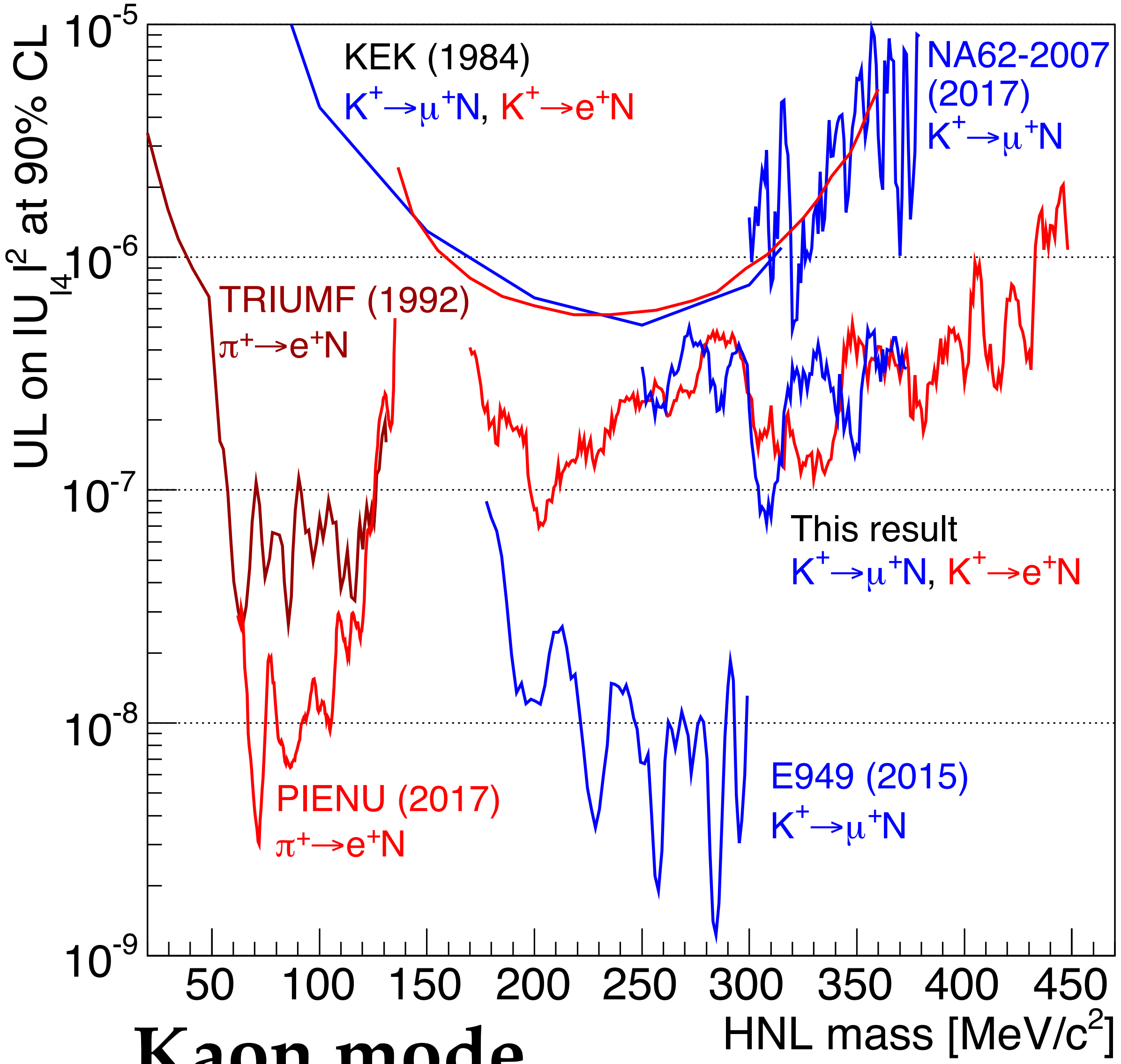


MATHUSLA 1811.00927

slide by David Curtin

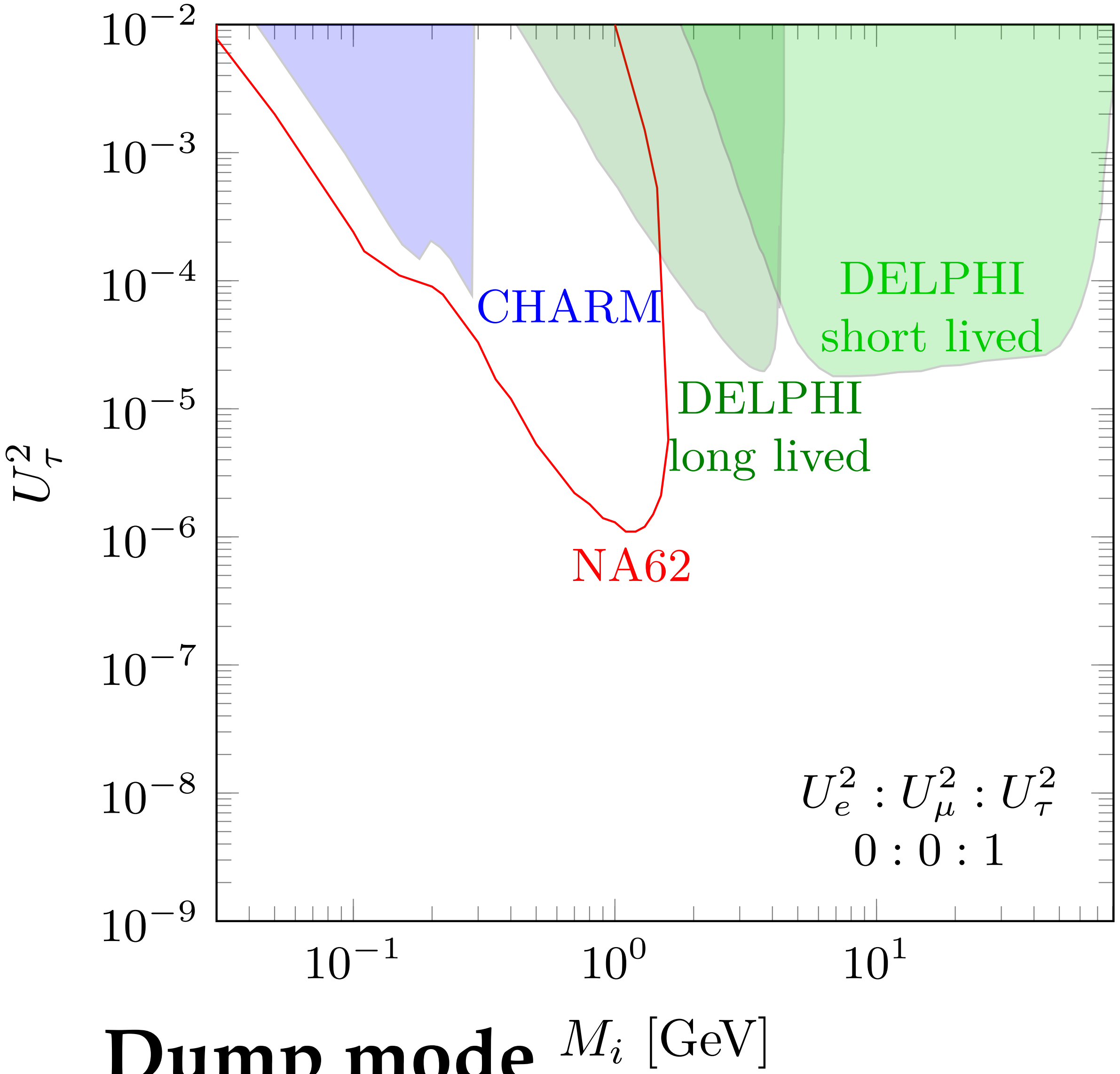
Beyond Colliders: Fixed Target

Example: Heavy neutrino searches with NA62



Kaon mode

Cortina-Gil et al 1712.00297

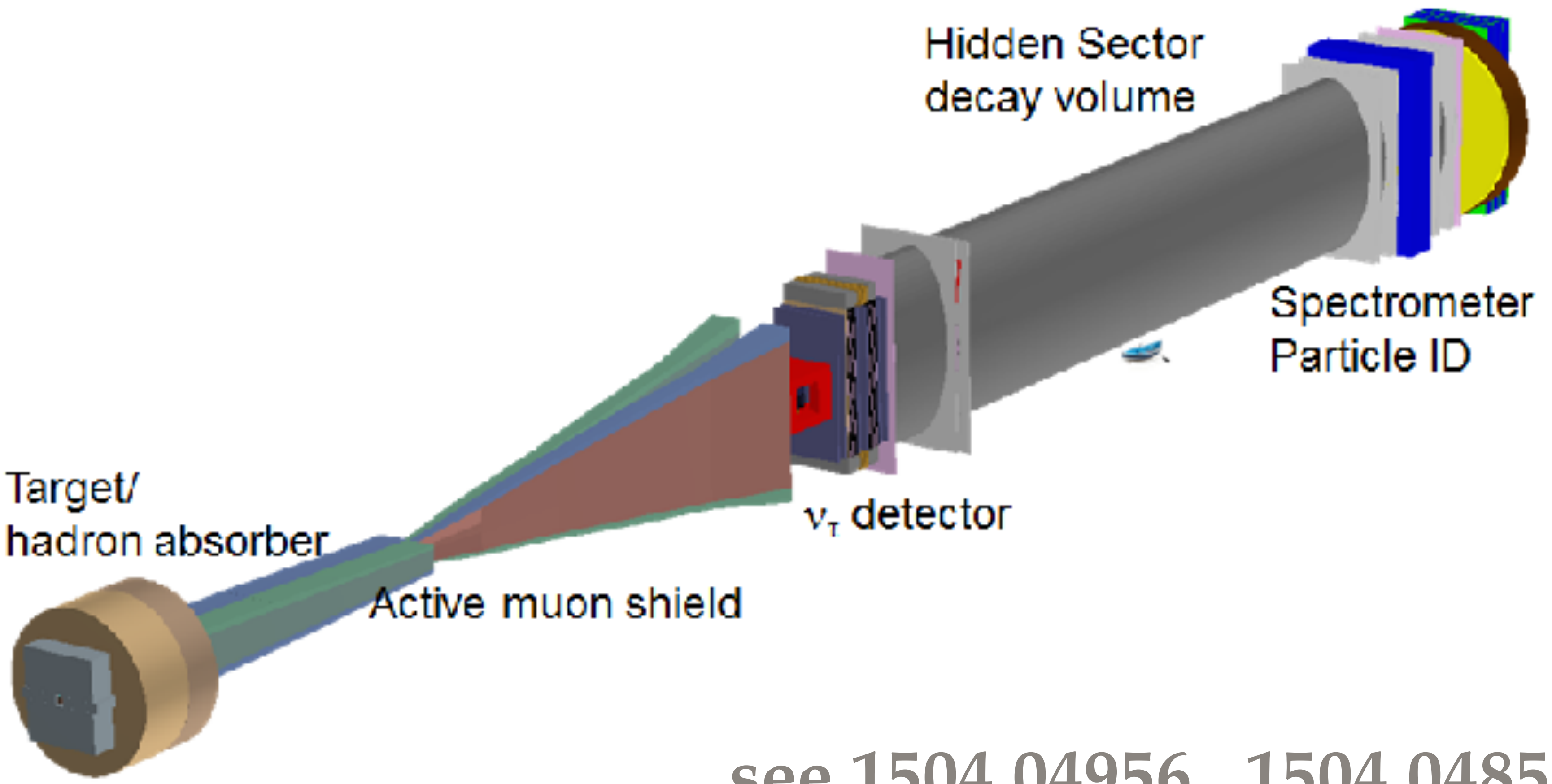


Dump mode

MaD/Hajer/Klaric/Lafranchi 1801.04207

see Jan Hajer's talk

The SHiP Proposal



SHiP
Search for Hidden Particles

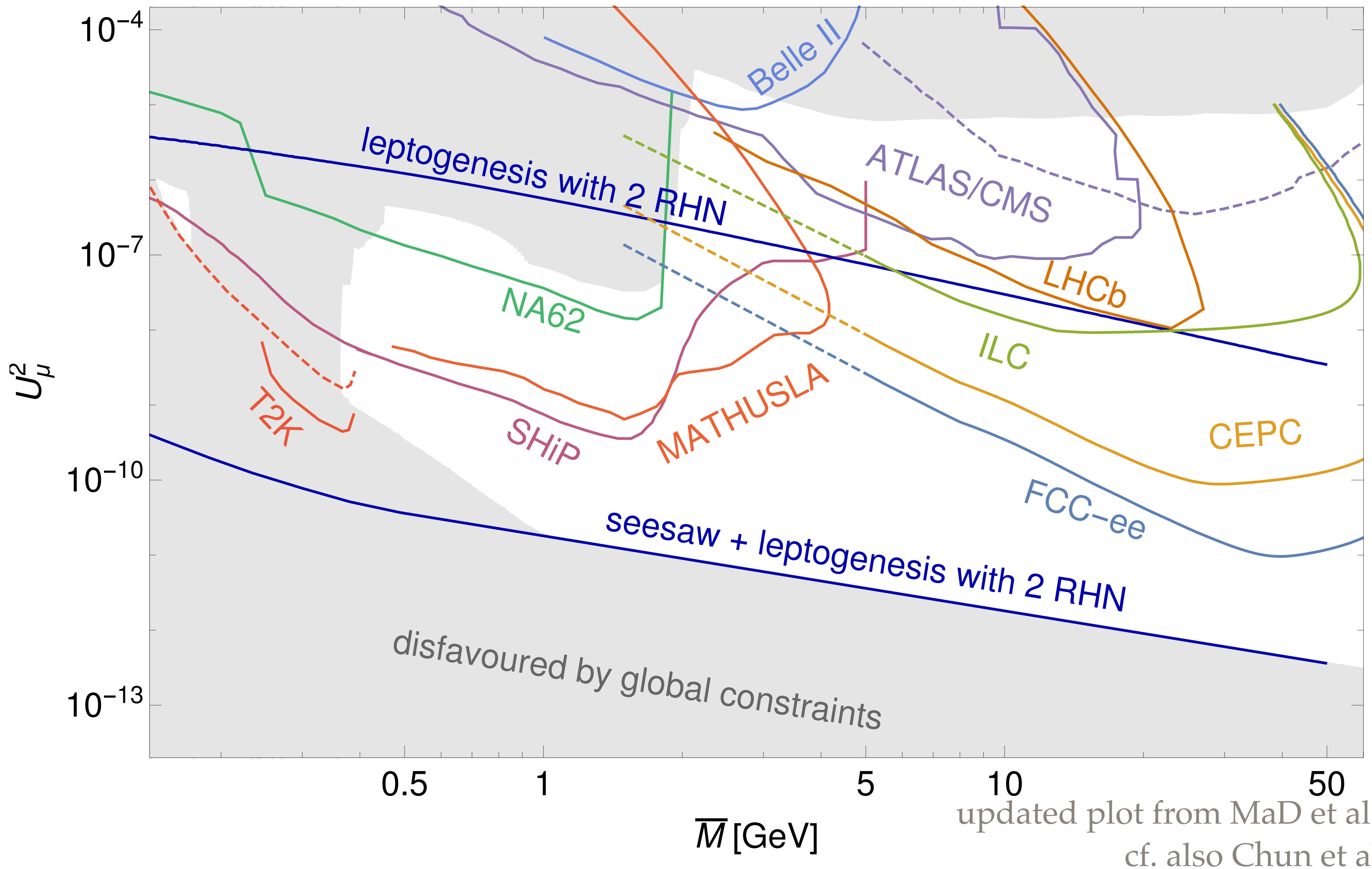
see 1504.04956 , 1504.04855

Search for Hidden Particles

- new fixed target experiment using SPS beam with 10^{20} protons on target
- would be world’s most sensitive fixed target experiment
- see https://indico.cern.ch/event/792346/contributions/3442749/attachments/1852329/3041310/Mermod_LHCLLP_May19.pdf

Complementarity

Example: Heavy neutrino searches in the νMSM



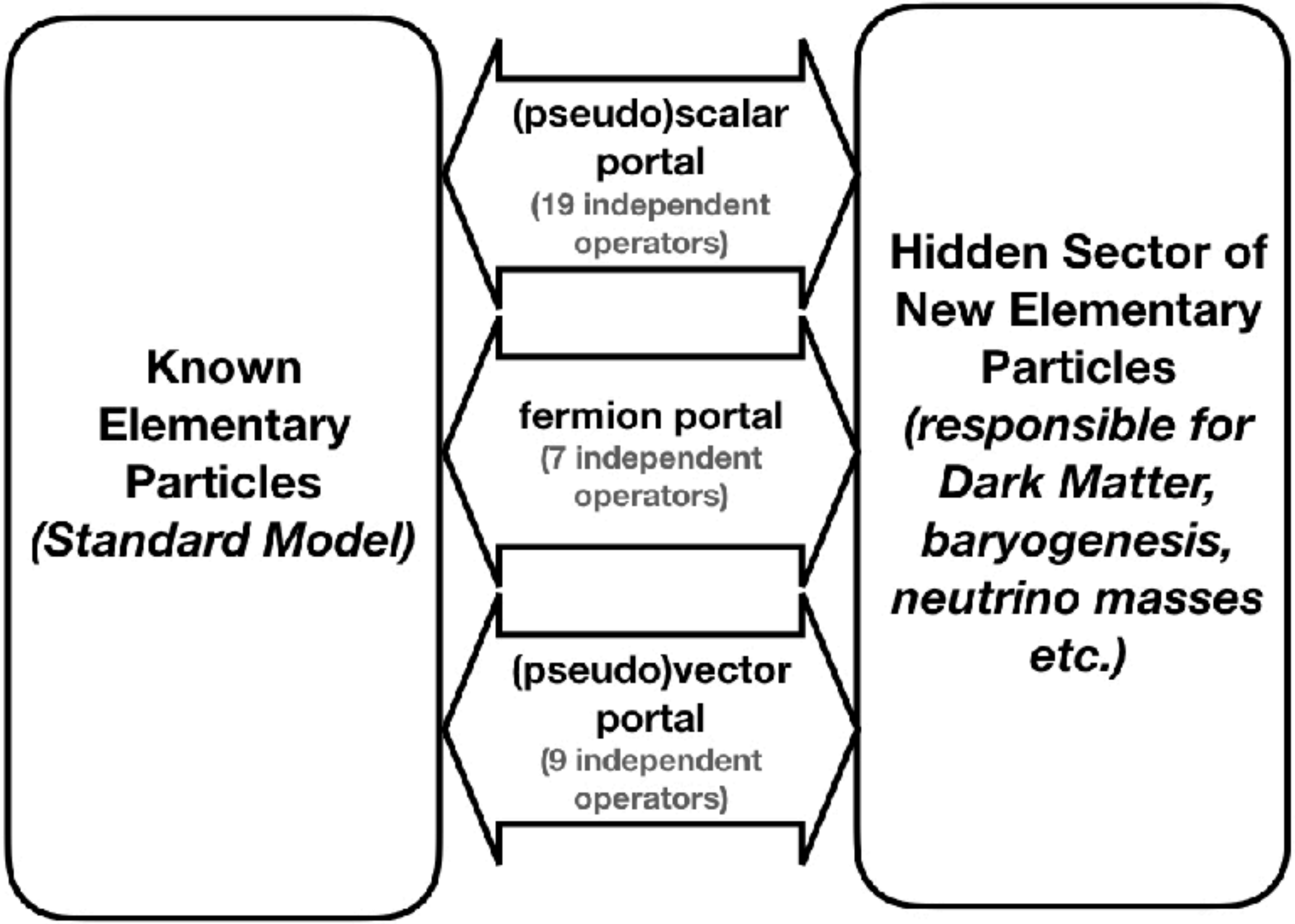
updated plot from MaD et al 1609.09069,
cf. also Chun et al 1711.02865

Summary

- LHC still has great potential to discover new particles!
- Cosmology provides valuable input
  (DM clustering, BBN, neutrino masses, baryogenesis, phase transitions, gravitational waves, light inflaton, …)
- Non-collider experiments are complementary to LHC
- There is room for crazy ideas!

Backup Slides

Portals to Hidden Sectors



Known Elementary Particles ***(Standard Model)***

(pseudo)scalar portal
(19 independent operators)

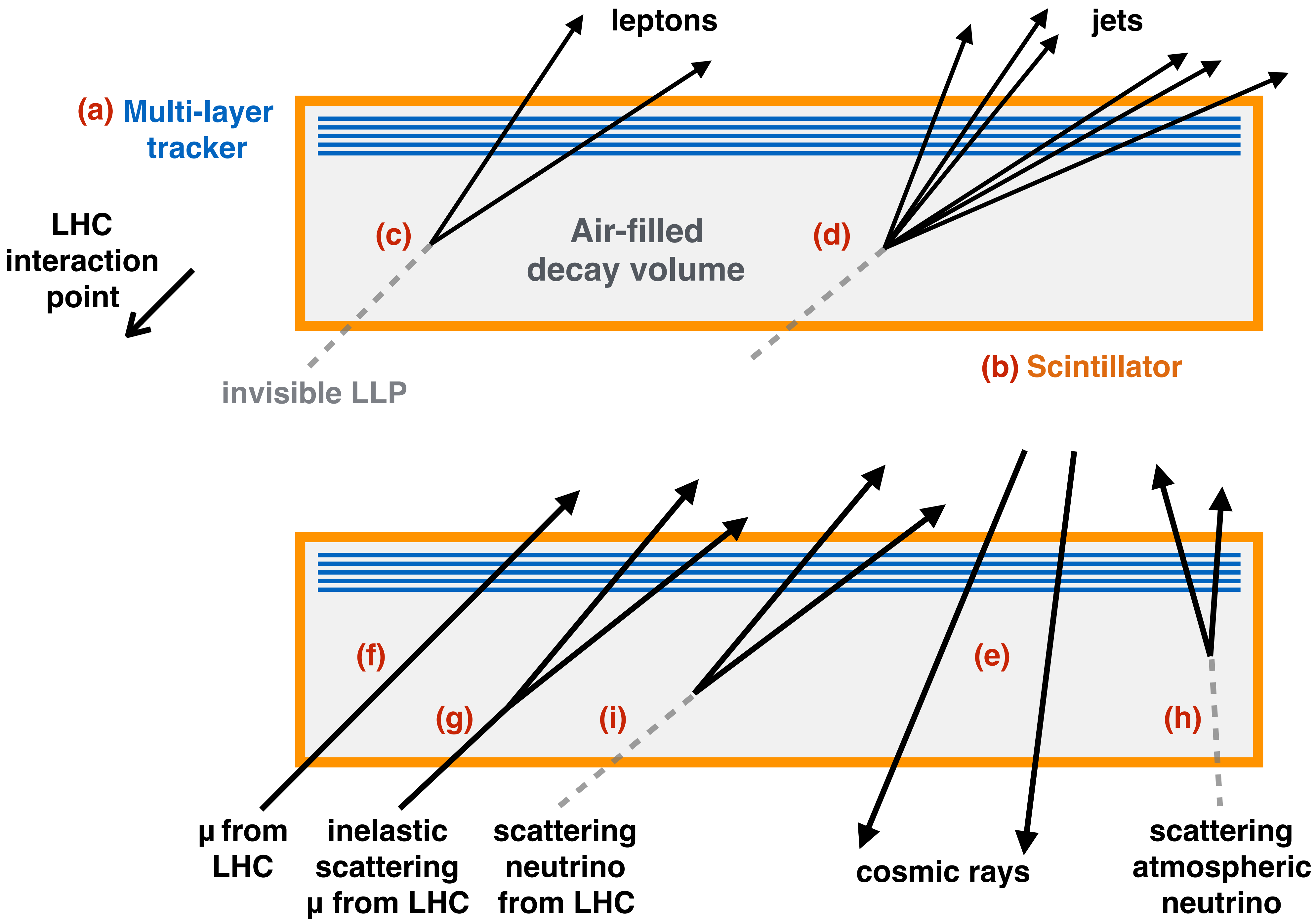
fermion portal
(7 independent operators)

(pseudo)vector portal
(9 independent operators)

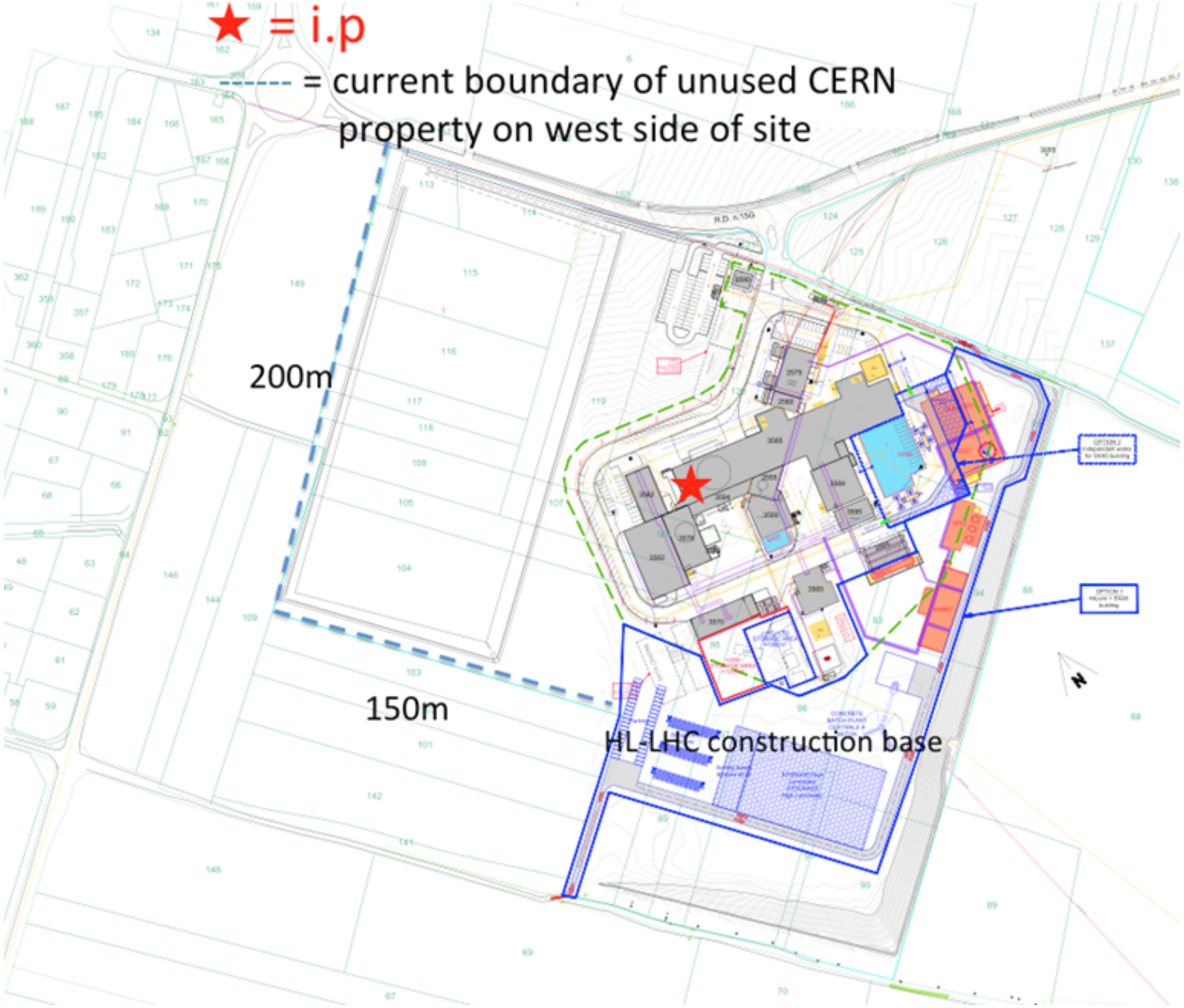
Hidden Sector of New Elementary Particles ***(responsible for Dark Matter, baryogenesis, neutrino masses etc.)***

MATHUSLA

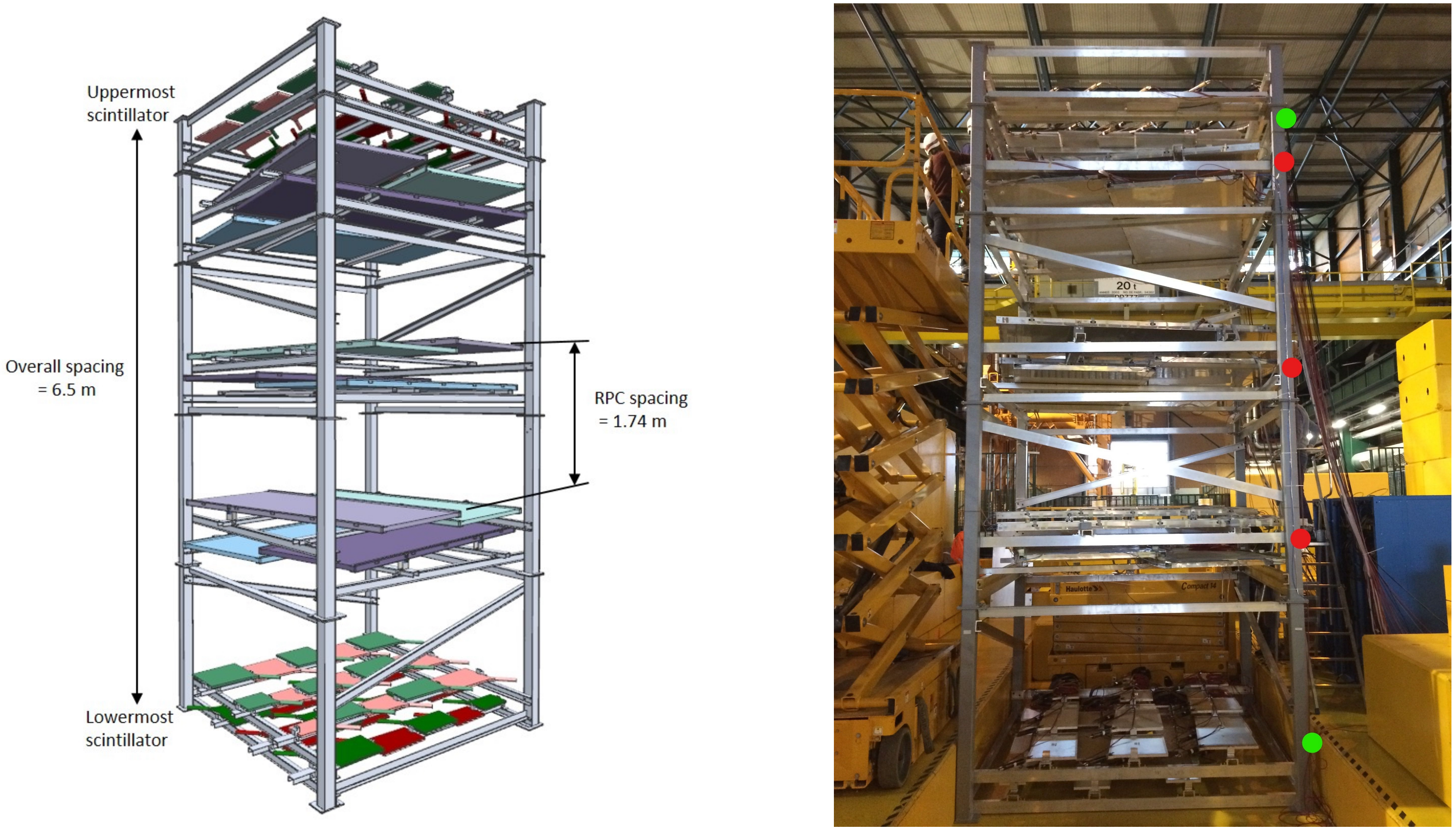
Schematic Design



Where to put this?



MATHUSLA Test Stand

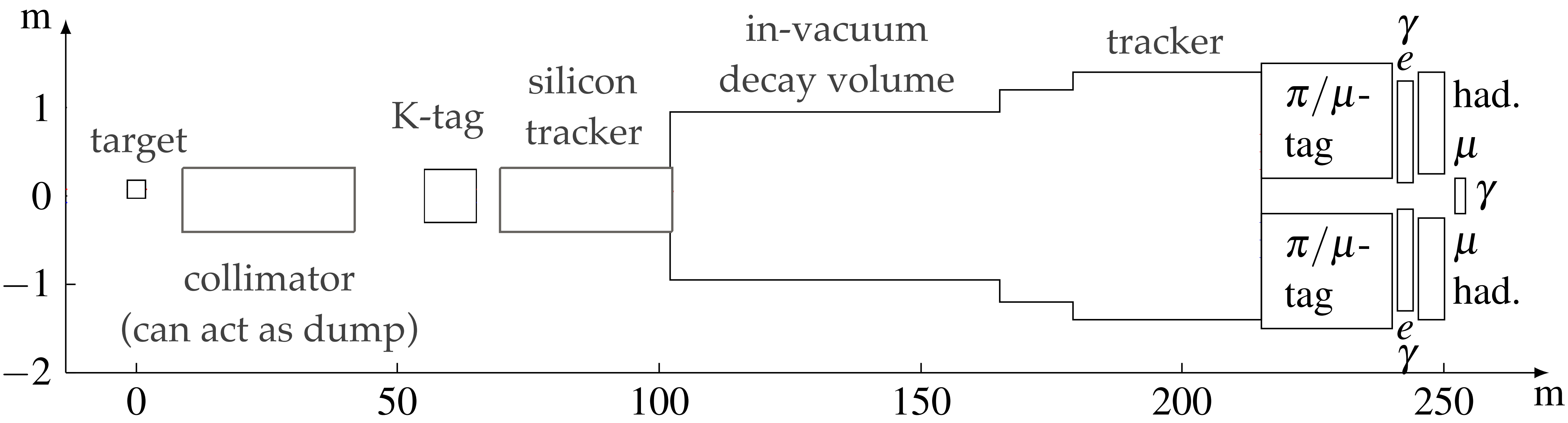


(a) (b)

Figure 20. (a): schematic view of the MATHUSLA test stand. (b): picture of the final assembled structure in his test area in the ATLAS SX1 building at CERN. The green dots identify the two scintillator layers used for triggering, while the red dots the three RPC layers used for tracking.

NA62

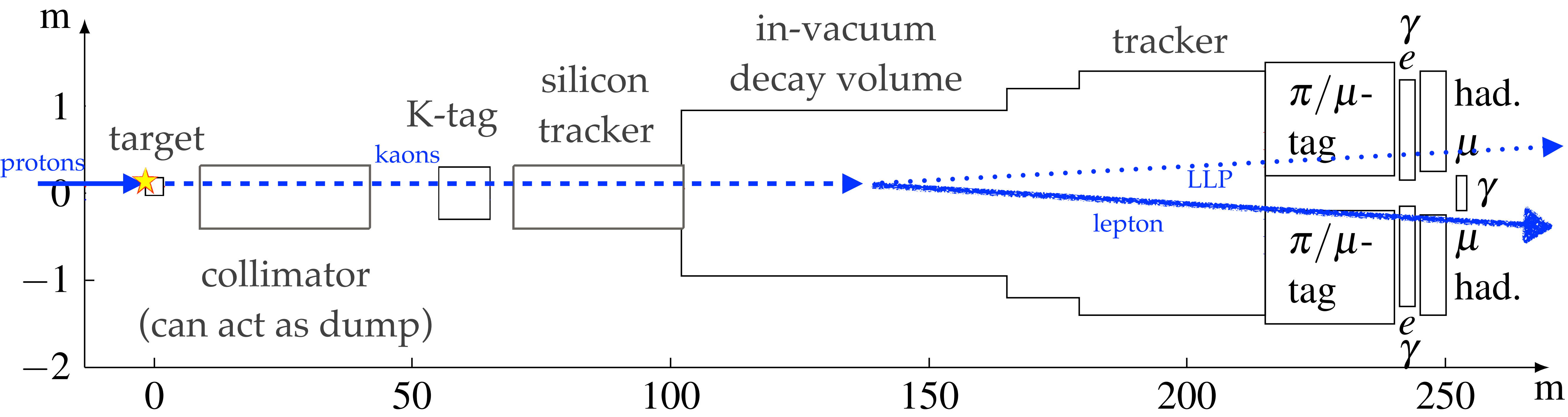
The NA62 Experiment



- fixed target experiment in CERN's North Area
- primary purpose: measure kaon decay into pion + neutrino + antineutrino

pictureFigure/picture from the NA62 collaboration

NA62 Kaon Mode

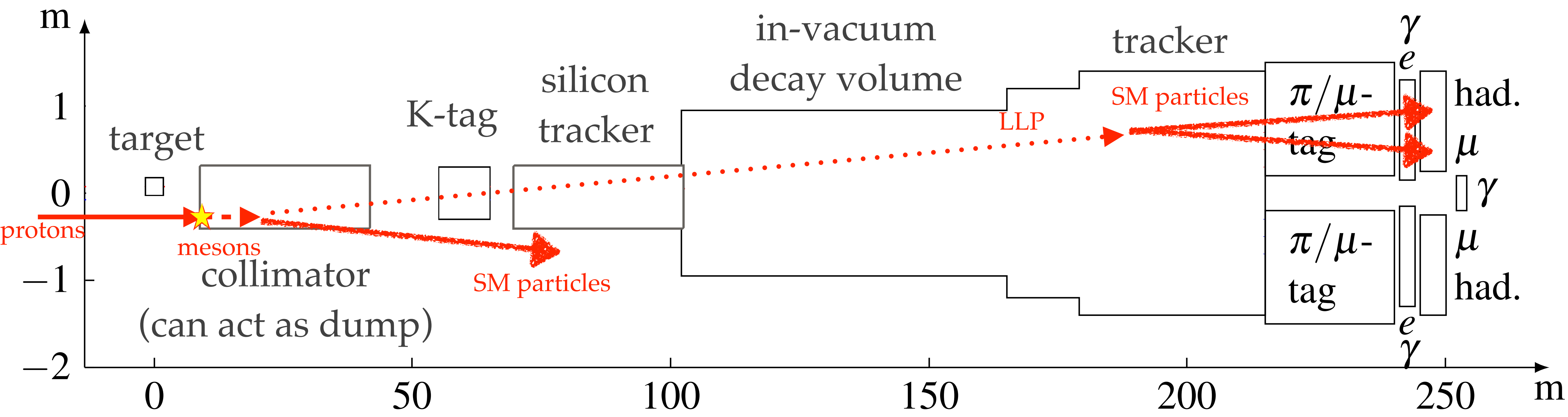


Target Mode: cf. 1712.00297 for recent results

- protons hit target ⇒ produce 75 GeV beam hadrons, leptons
- tag kaons
- kaons decay into HNL + lepton in the in-vacuum decay volume

  ⇒ **search for peak in lepton spectrum**

NA62 Dump Mode



Dump mode

- target removed, protons hit collimator ⇒ produce mesons, leptons
- mesons / tauons decay into HNL + SM particles
- HNL pass all components and decay in the in-vacuum decay volume

⇒ search for decay nothing → leptons/hadrons in vacuum chamber

Baryogenesis

Baryon Asymmetry of the Universe

The observable universe contains almost no antimatter and a lot more photons than baryons. e.g. Canetti/MaD/Shaposhnikov arXiv:1204.4186

CMB constraint on baryon-to-photon ratio η:

$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:

$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

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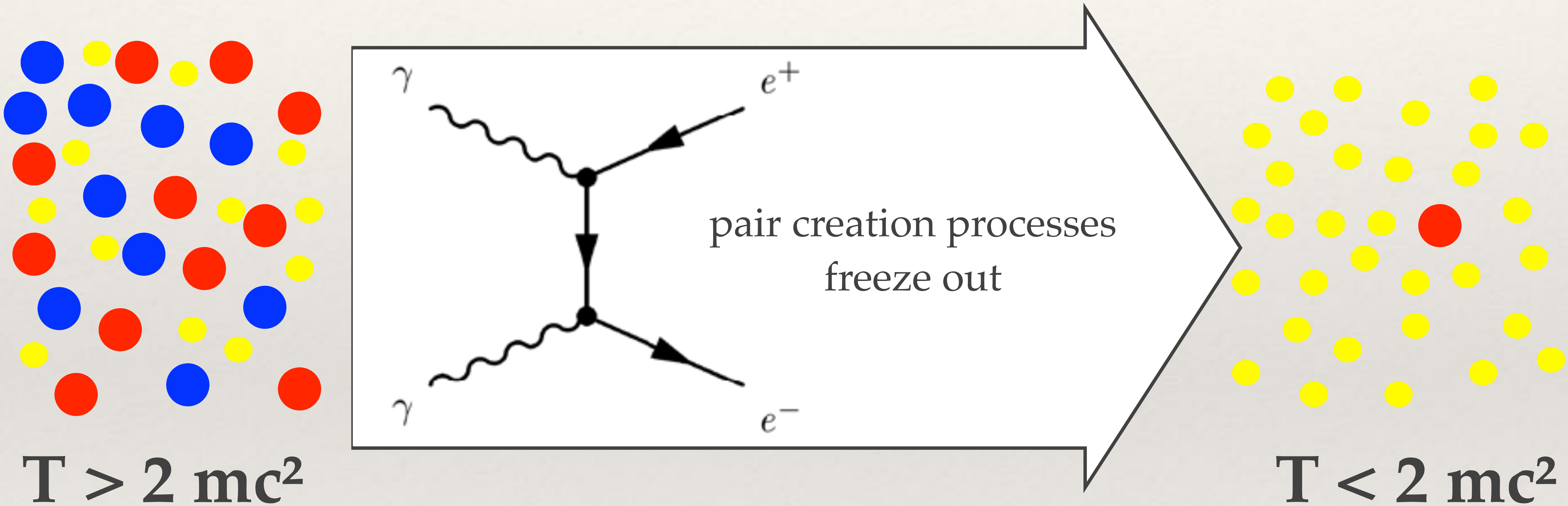


pair creation processes freeze out

$T > 2\,mc^2$

$T < 2\,mc^2$

CMB constraint on baryon-to-photon ratio η:

$6.03 \times 10^{-10} < \eta < 6.15 \times 10^{-10}$

(Planck Collaboration)

BBN constraint on baryon-to-photon ratio η:

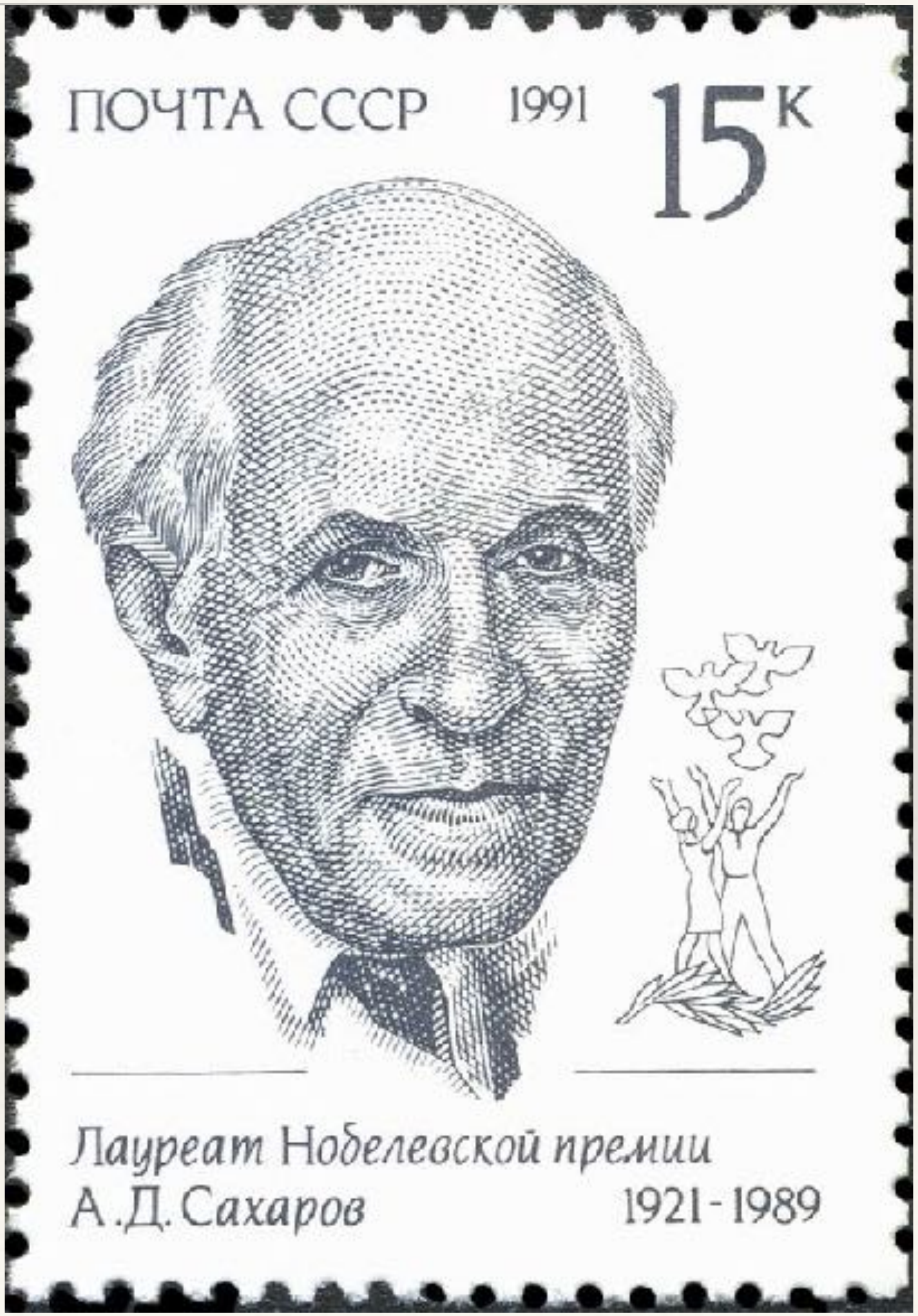
$5.8 \times 10^{-10} < \eta < 6.6 \times 10^{-10}$

(PDG)

Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation
- C and CP violation
- Deviation from thermal equilibrium



Where does the asymmetry come from?

Sakharov Conditions (1967)

- Baryon number violation

Exists in Standard Model
at T > 130 GeV
(sphaleron)

- C and CP violation

Exists in Standard Model
(weak interaction, CKM phase)

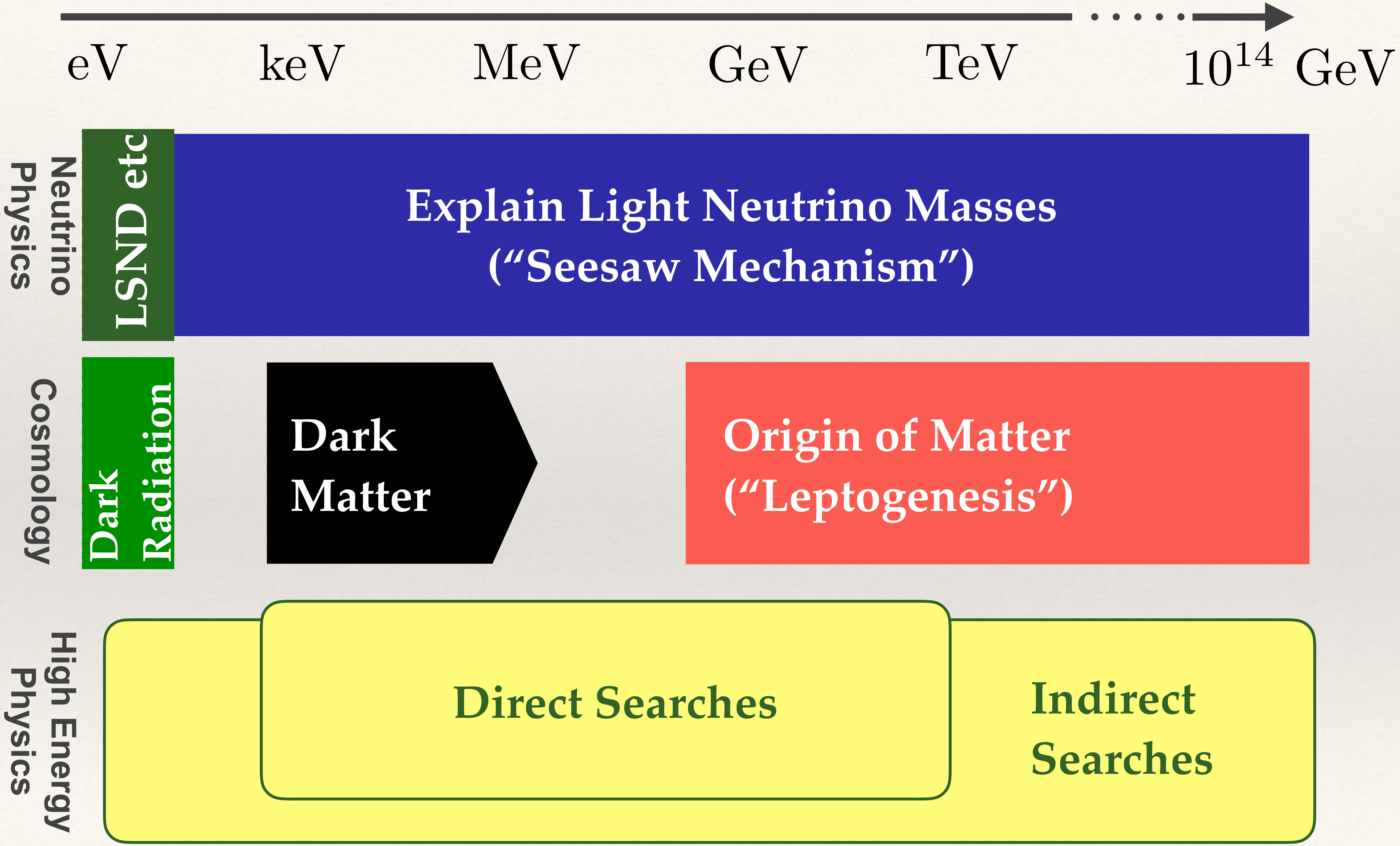
…but Jarlskogg invariant too small!

- Deviation from thermal equilibrium

Exists in Standard Model
(Hubble expansion of the universe)
…but deviation too small!

Heavy Neutrinos

Right Handed Neutrino Mass Scale



eV

keV

MeV

GeV

TeV

10^{14} GeV

Neutrino Physics

LSND etc

Explain Light Neutrino Masses (“Seesaw Mechanism”)

Cosmology

Dark Radiation

Dark Matter

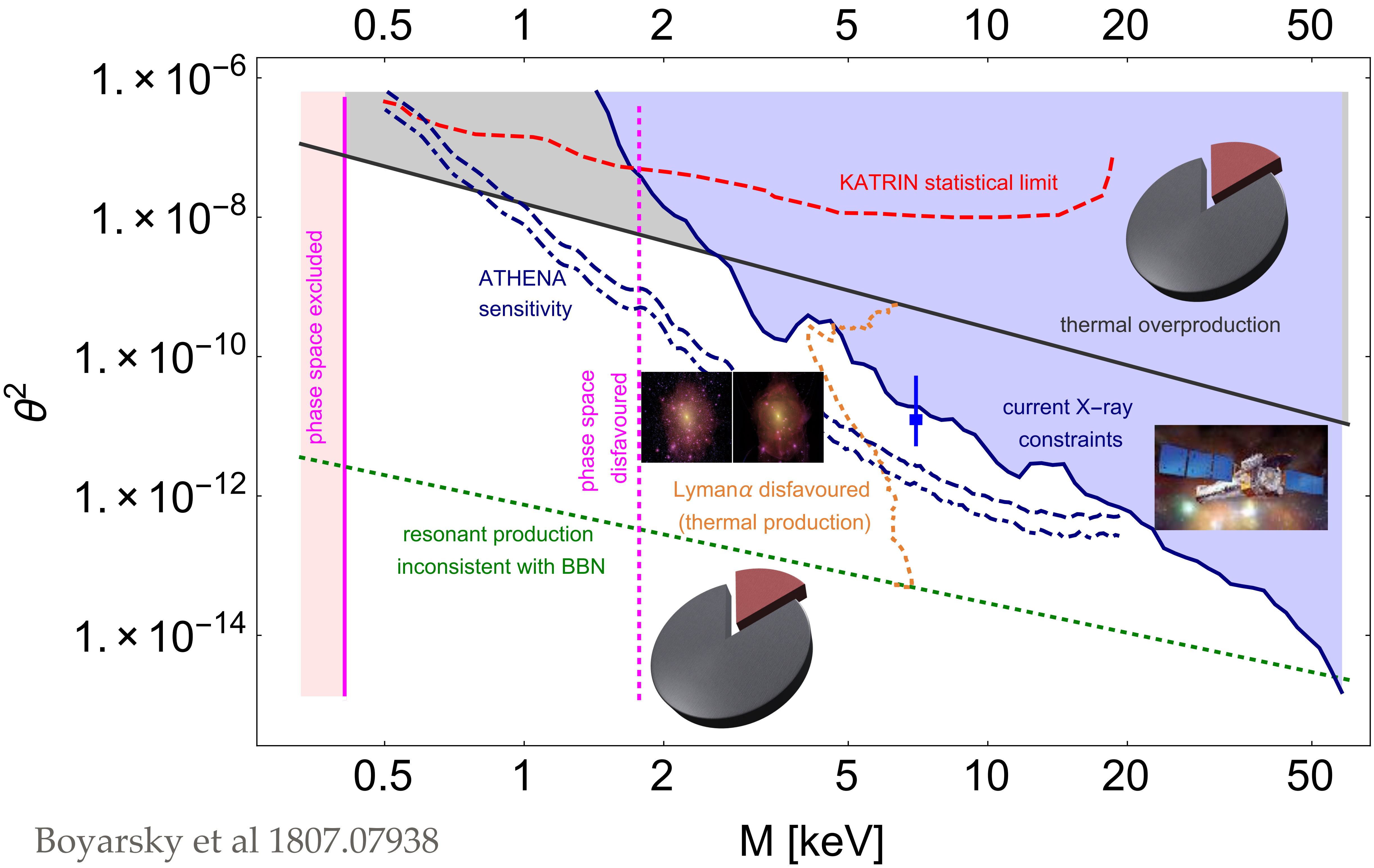
Origin of Matter (“Leptogenesis”)

High Energy Physics

Direct Searches

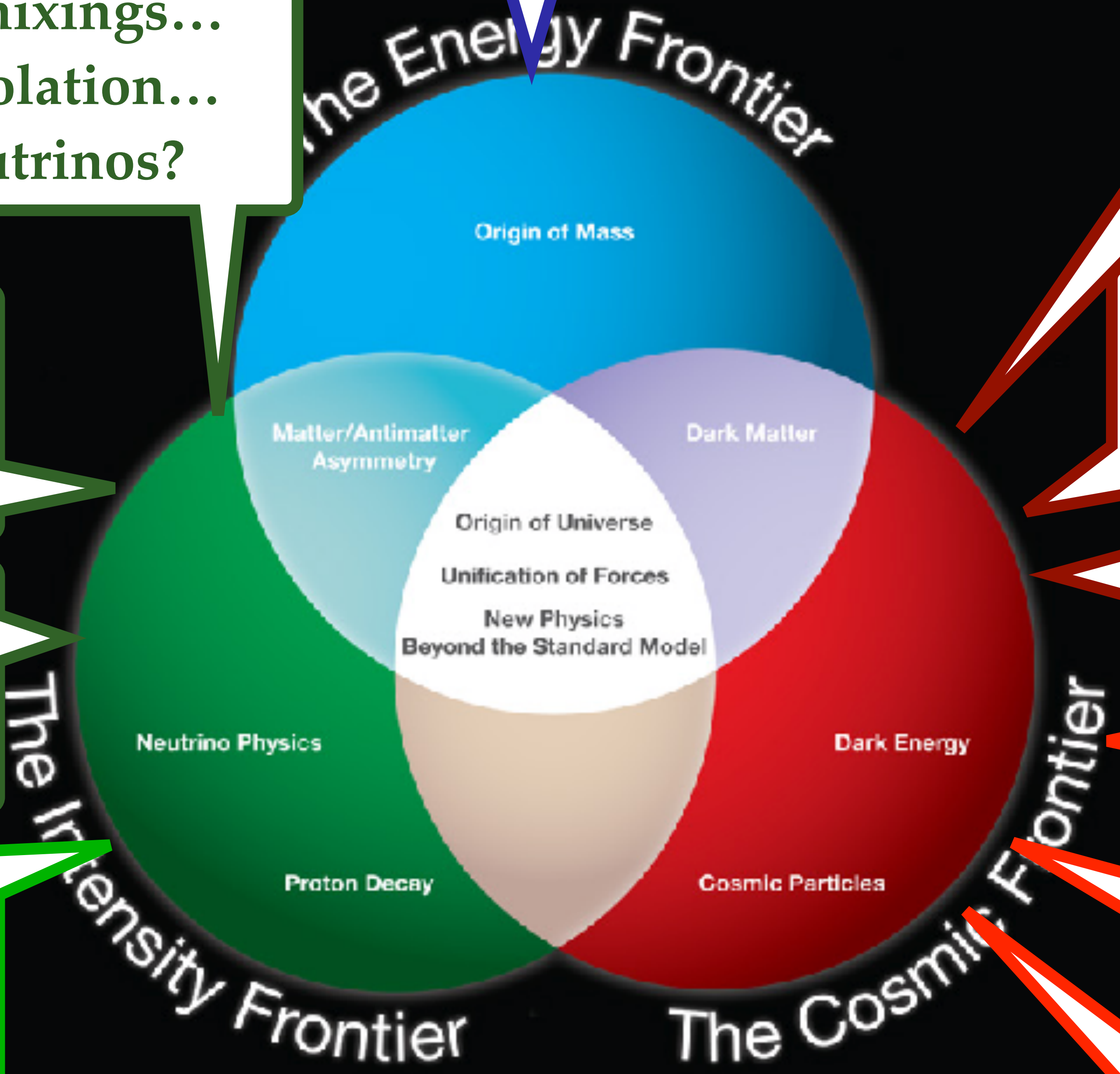
Indirect Searches

Sterile Neutrino Dark Matter



Boyarsky et al 1807.07938

A Multi-Frontier Problem



Collider Probes of the origin of neutrino mass

neutrino oscillation experiments
mass differences, mixings…
… hierarchy, CP violation…
…light sterile neutrinos?

absolute neutrino
mass searches
(KATRIN ect.)

neutrinoless
double β decay:
Dirac or Majorana?

fixed target
experiments
(SHiP, NA62, …)

CMB and LSS :
absolute neutrino mass

CMB and BBN :
light sterile neutrinos?

IceCube
“neutrino astronomy”

Cosmic Neutrino
Background

Leptogenesis?

Sterile Neutrino
Dark Matter?