What will we find at 100 TeV and Beyond?

...on how to give
a “nearly impossible”
as a “urgently necessary”
talk…

Andrea Addazi, Sichuan University
and INFN Rome 2

“Contemporary Mantra”:

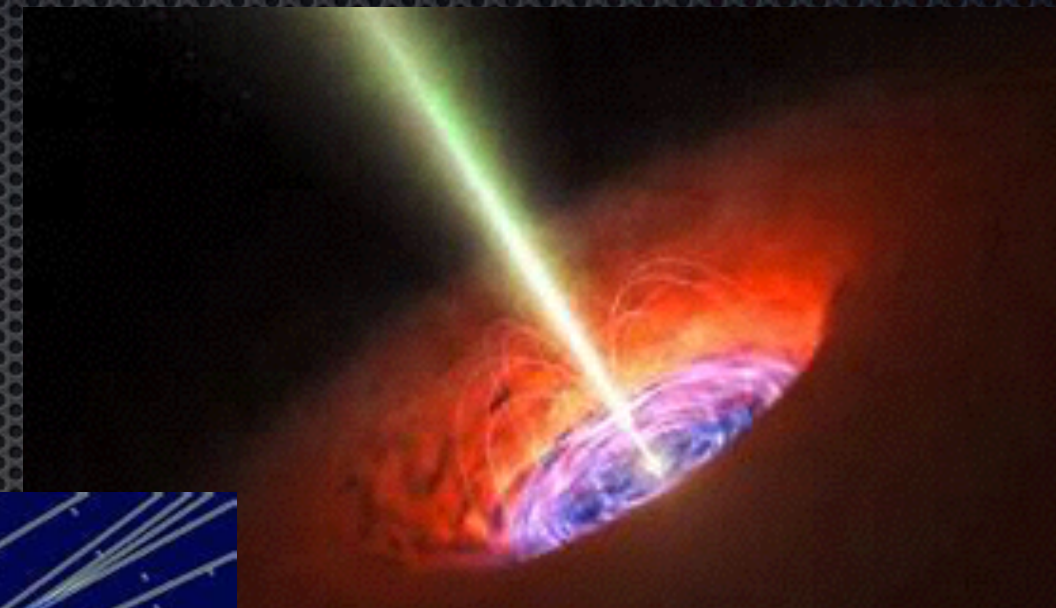
We desperately need to go beyond the Standard Model or particle physics and Cosmology

For many reasons!

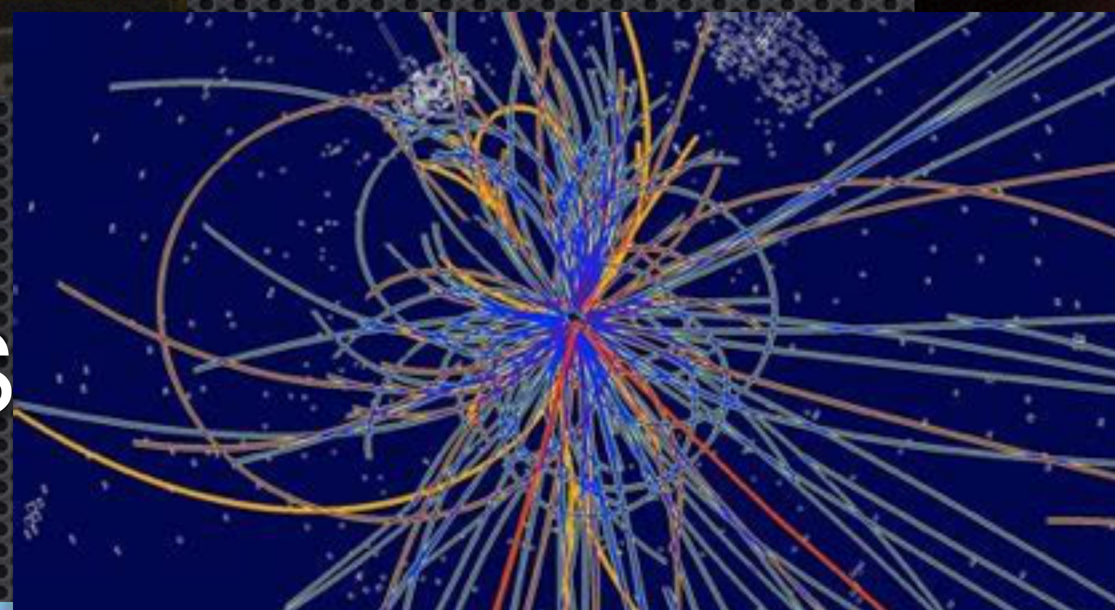
Dark side of the Universe, Neutrino mass, electroweak stabilization,
Early and Late Universe acceleration…and why we live in a so fine-tuned Universe

HOW (Do we solve it)?

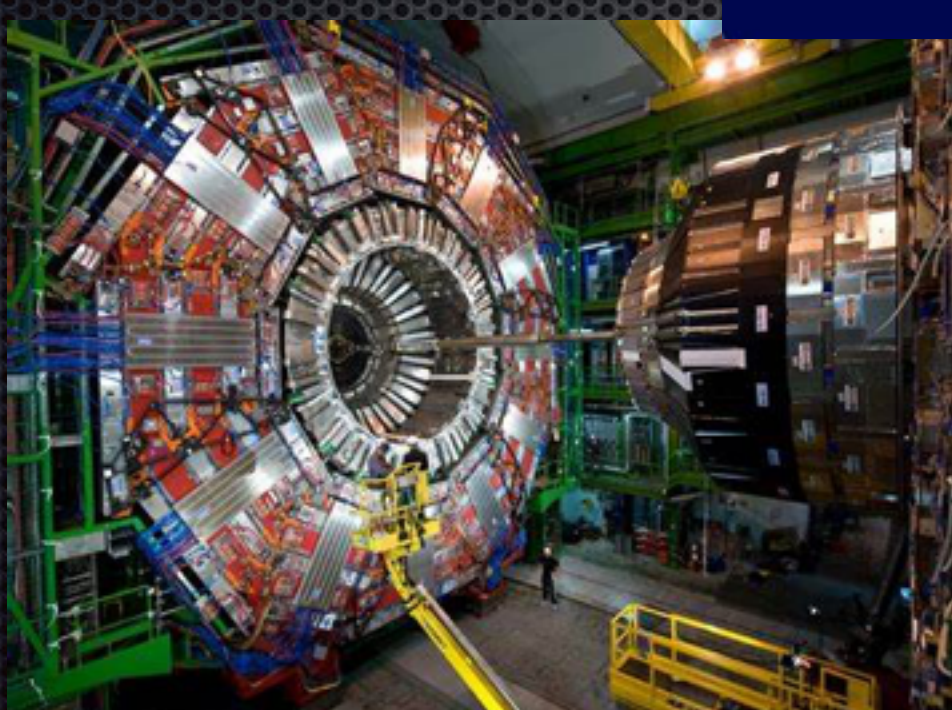
Extreme High energy Physics

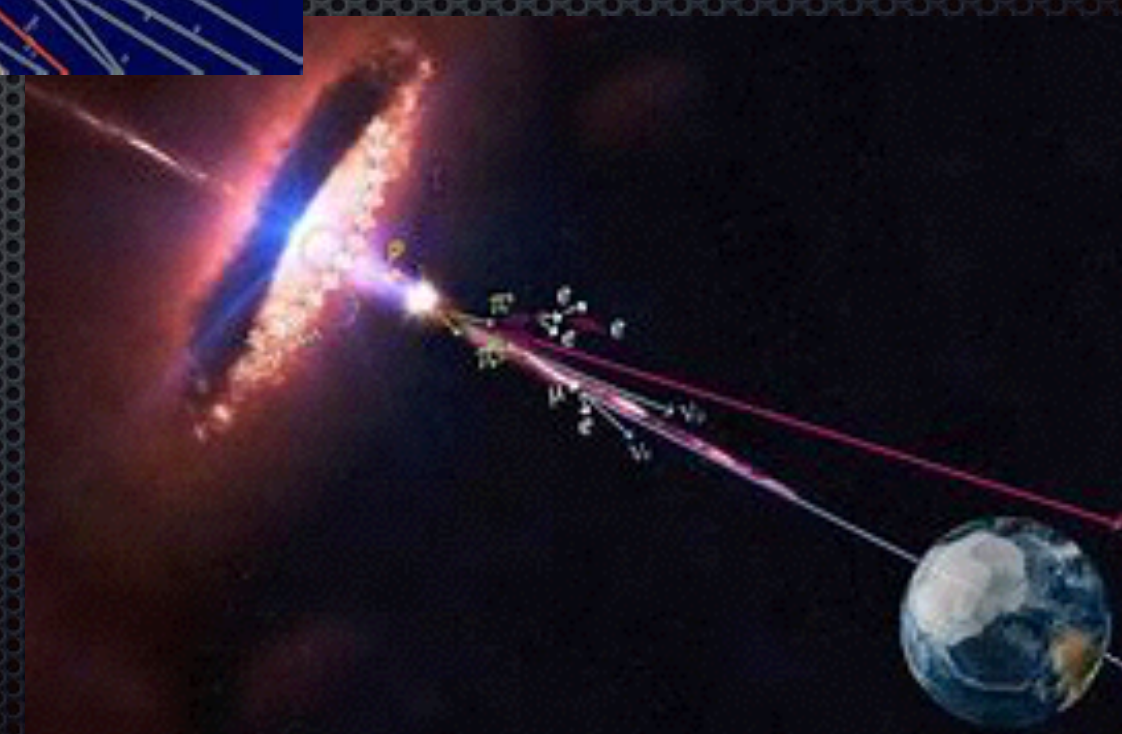


Colliders



CR





Time scales

Next colliders?

in 40-50 years…

Astroparticle CR experiments?

Next Physics in

Next 10/20 years

Gravitational waves?

Powerful in the

“Multi-messenger arena”

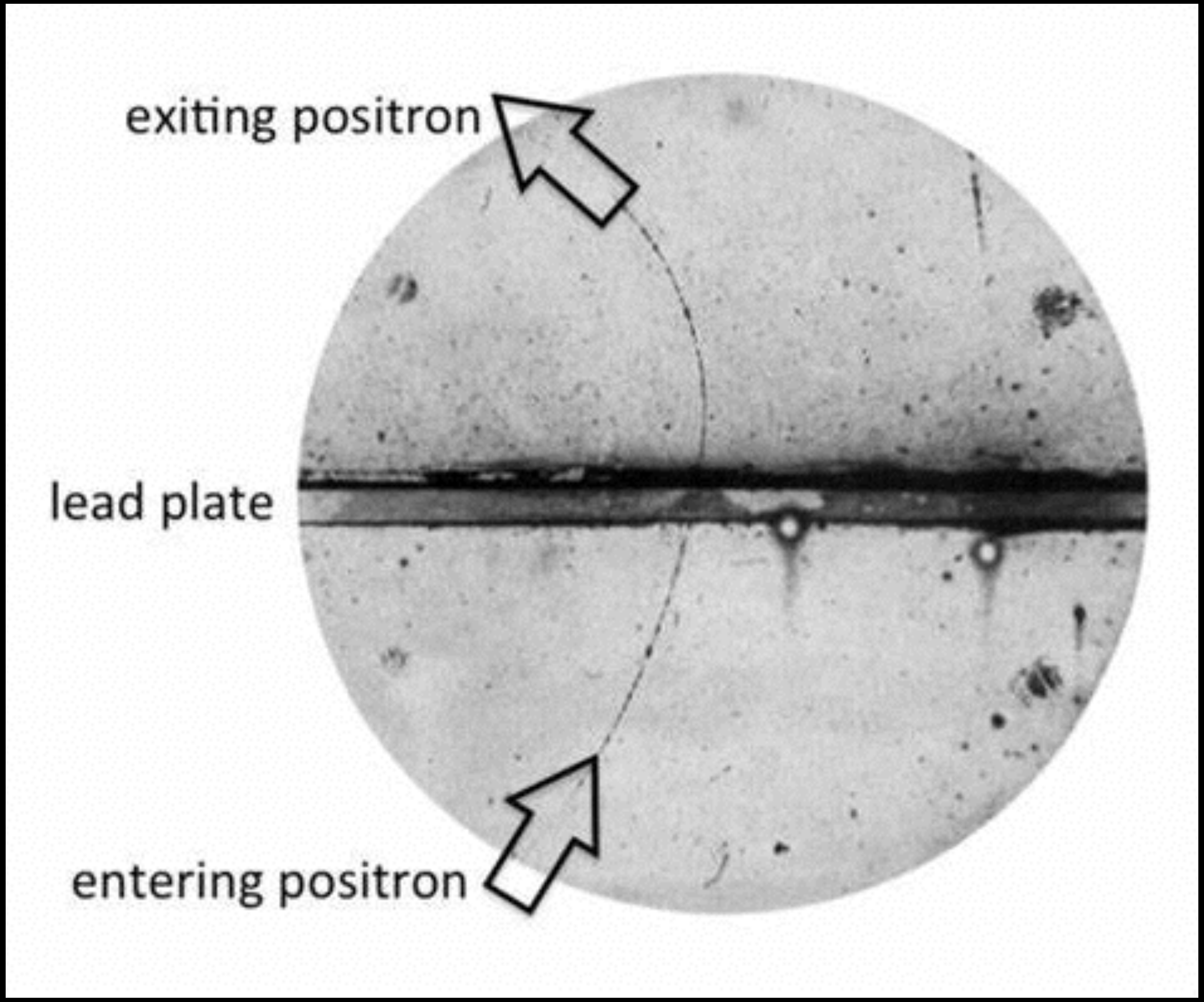
Opportunities from CR

A “plethora” of new data is coming

We need to be ready
or we miss potentially
mastodontic opportunities

Searching for new physics

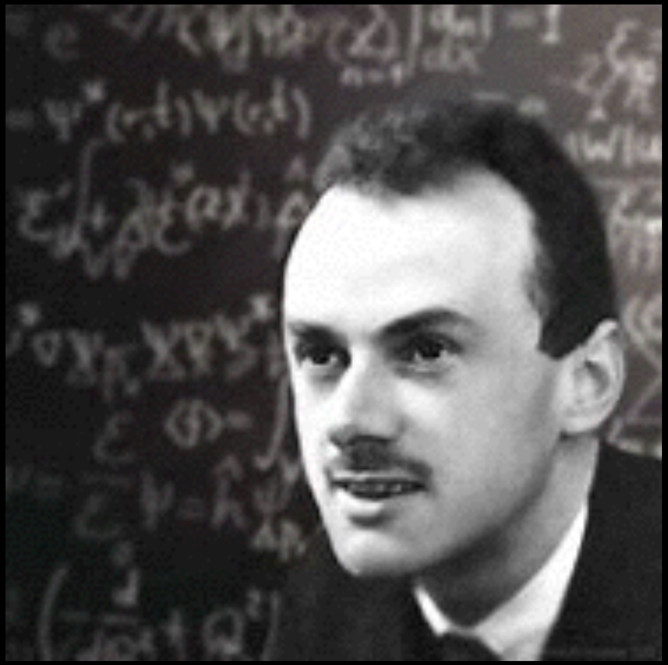
History: antimatter discovery in cosmic rays



Cloud Chambers, *Anderson 1932; Blackett & Occhialini*

The "power" of theoretical predictions

$$\left(i\gamma^{\mu}\partial_{\mu} - m\right)\psi = 0$$



Very High Energy Gamma rays beyond FERMI/LAT energies

Today: HAWC the High-Altitude Water Cherenkov Observatory

Coming: CTA Cherenkov Telescope Array

Coming soon: LHAASO
The Large High Altitude Air Shower Observatory

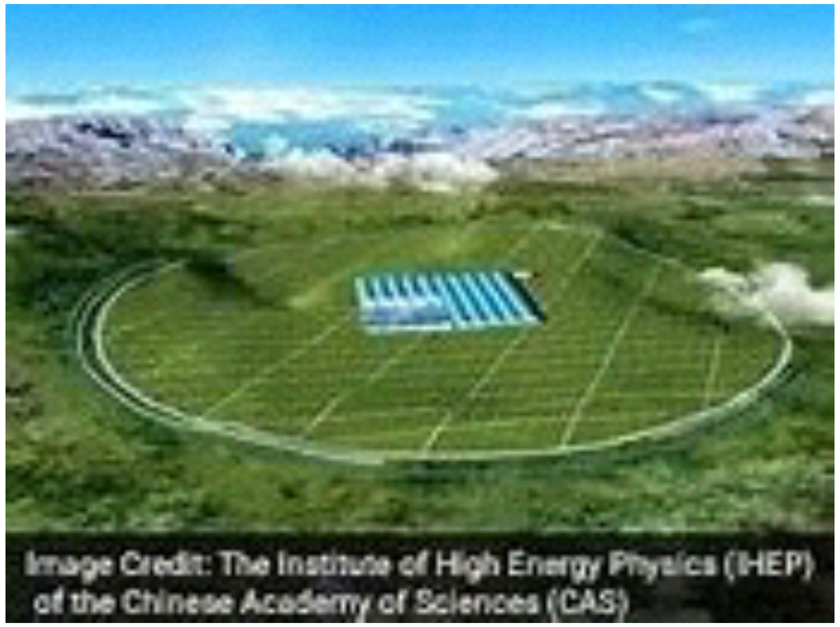
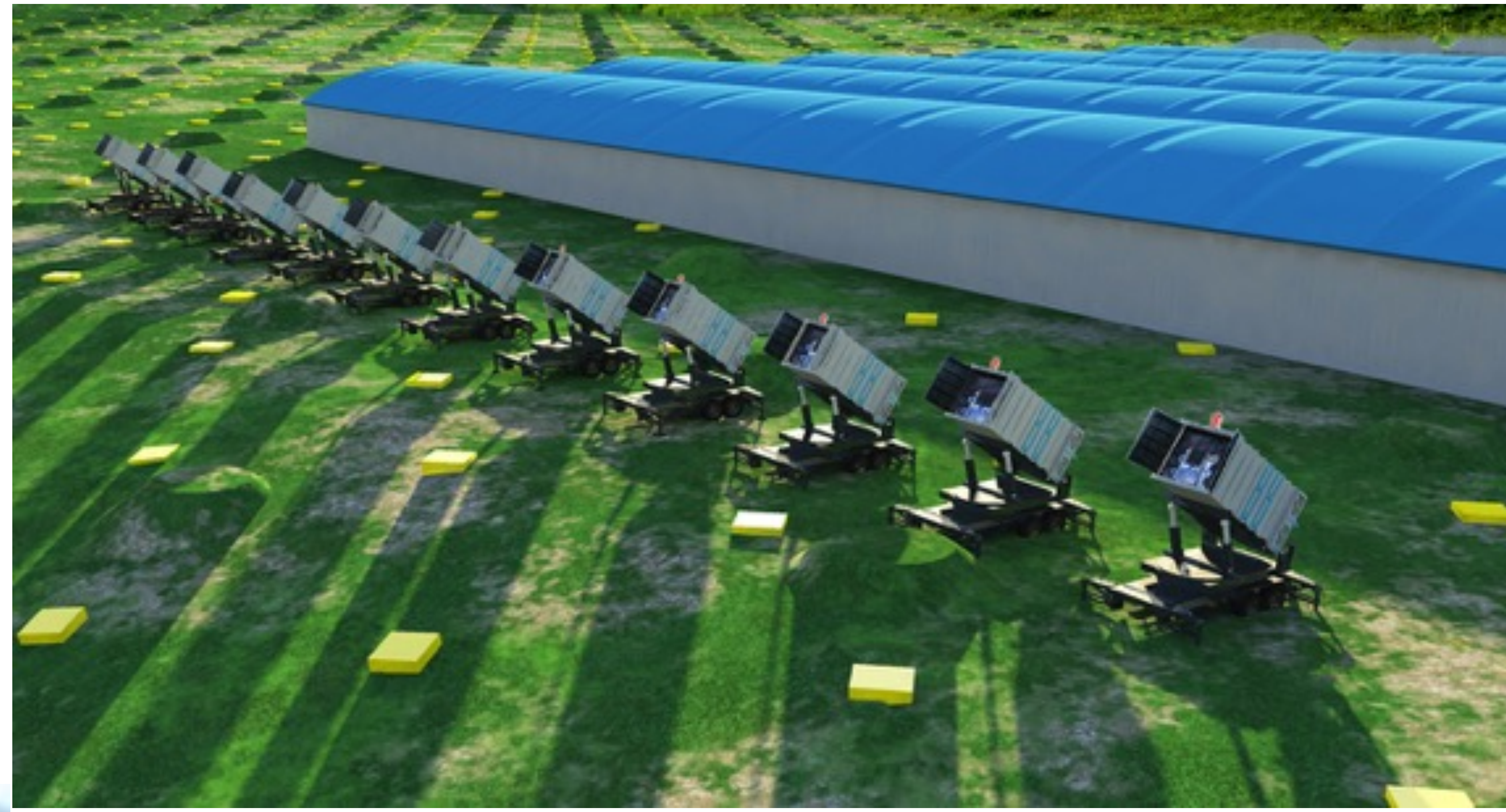
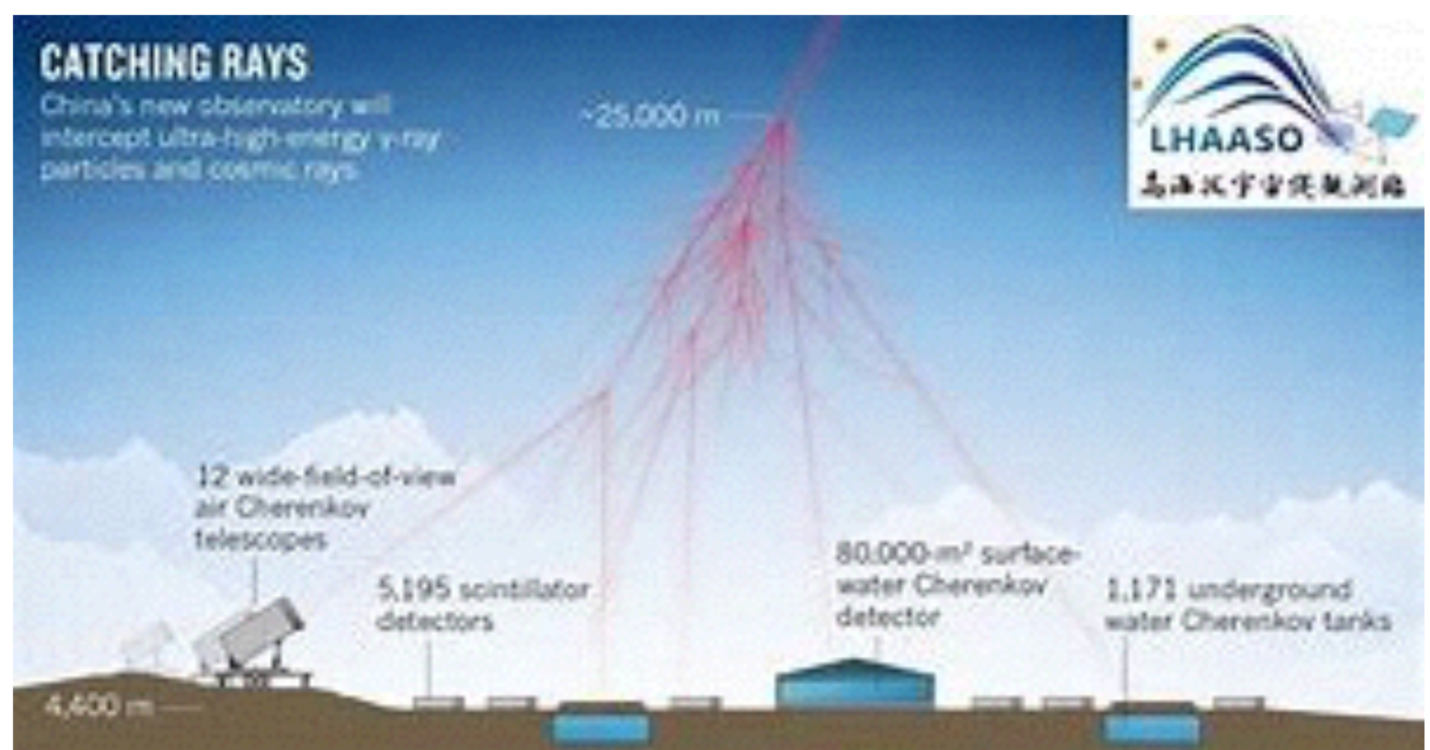


Image Credit: The Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences (CAS)





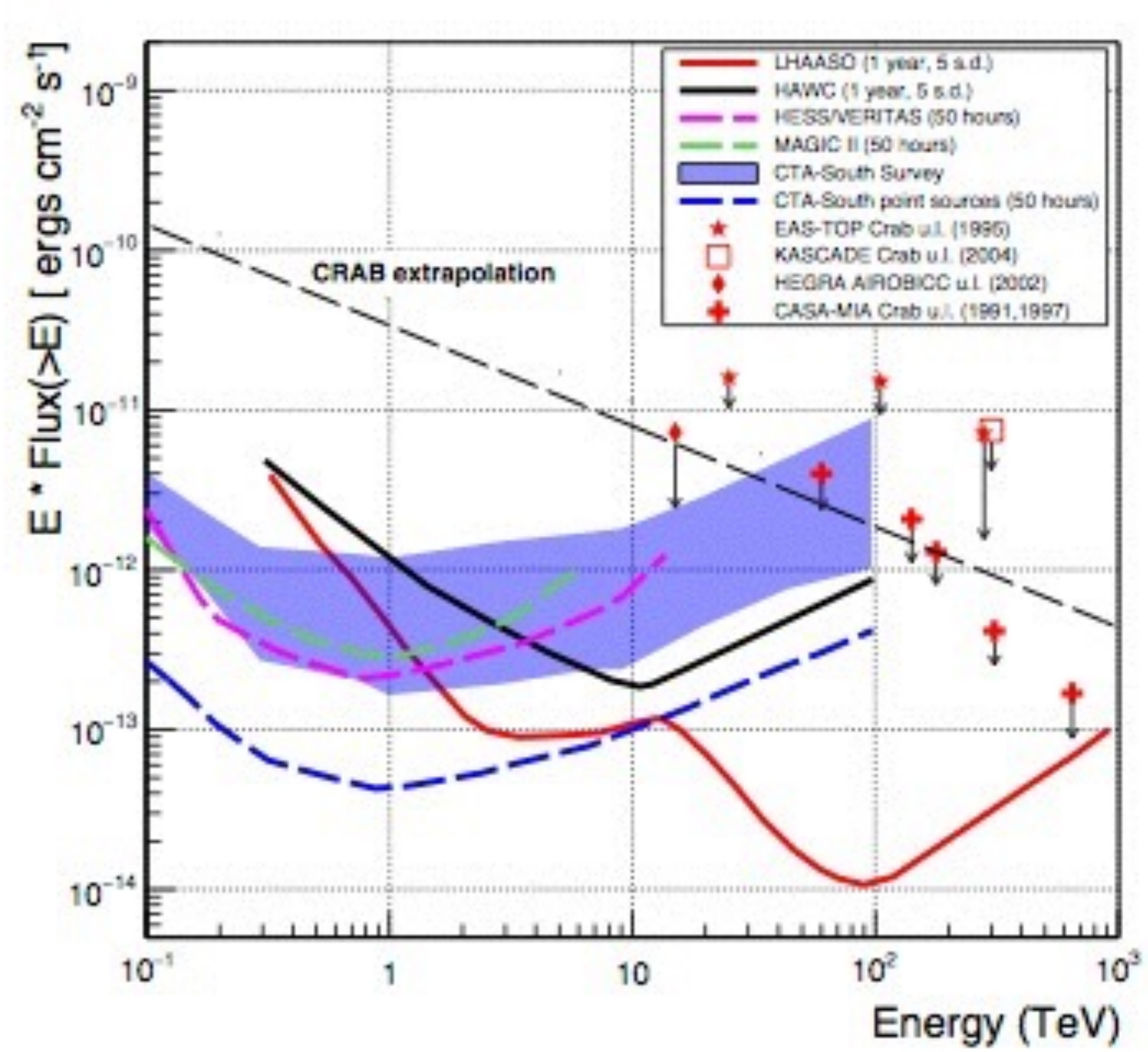
LHAASO

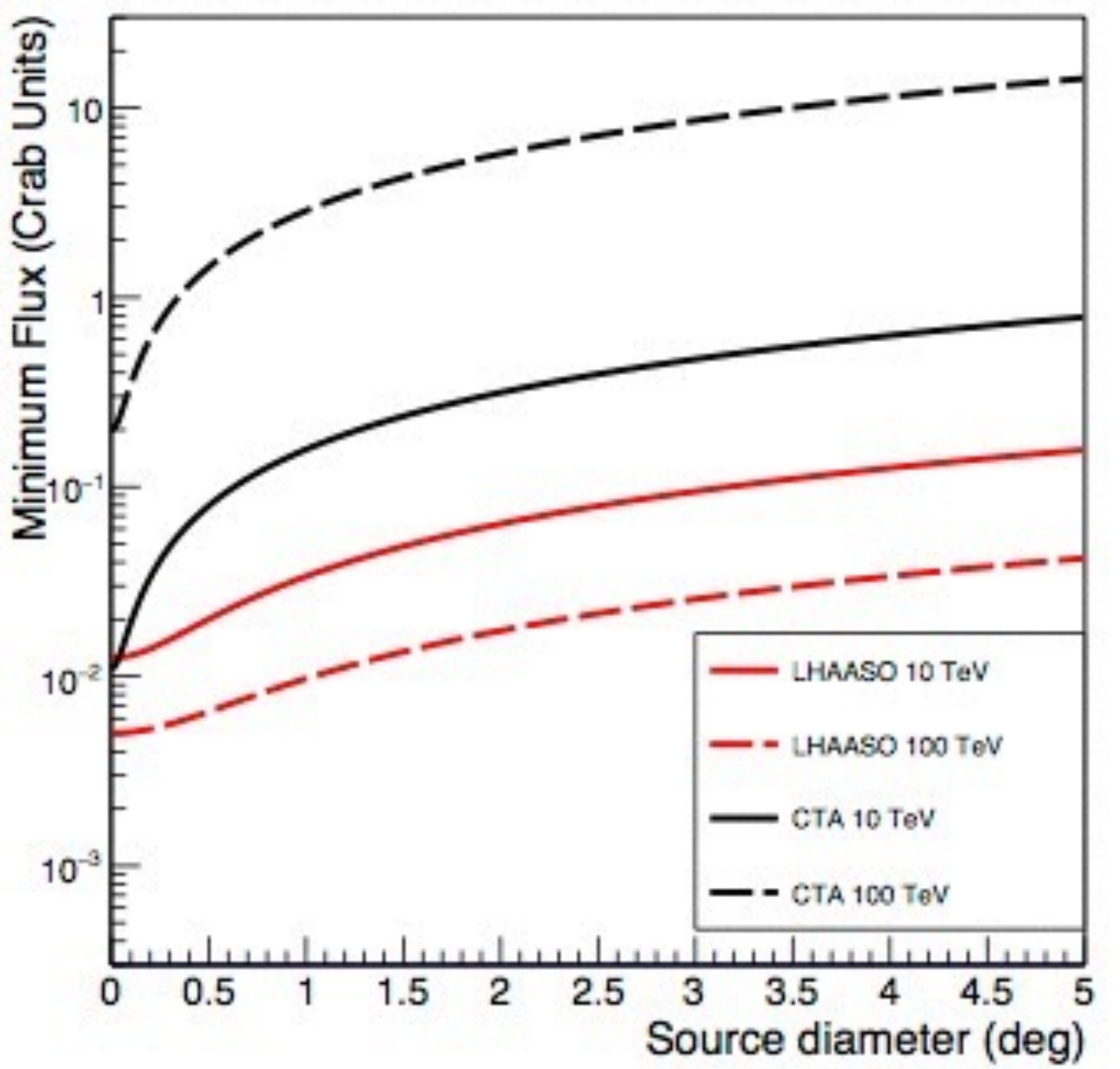
11-17th digits (eV) of charged particle spectrum (mainly hadrons)

50GeV-1PeV for gamma rays

A powerful double channel

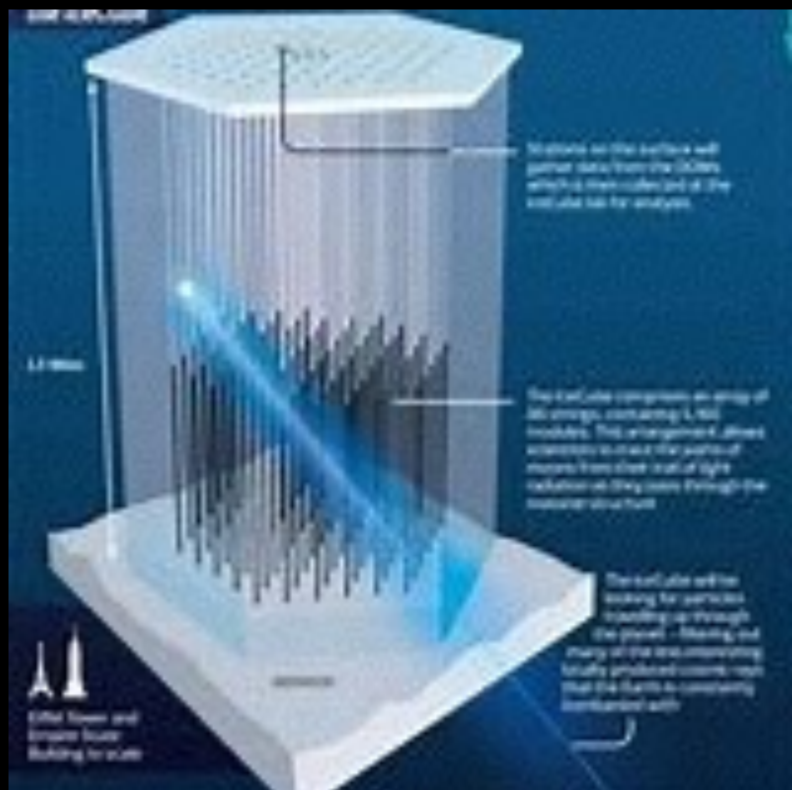
Gamma ray sensitivity

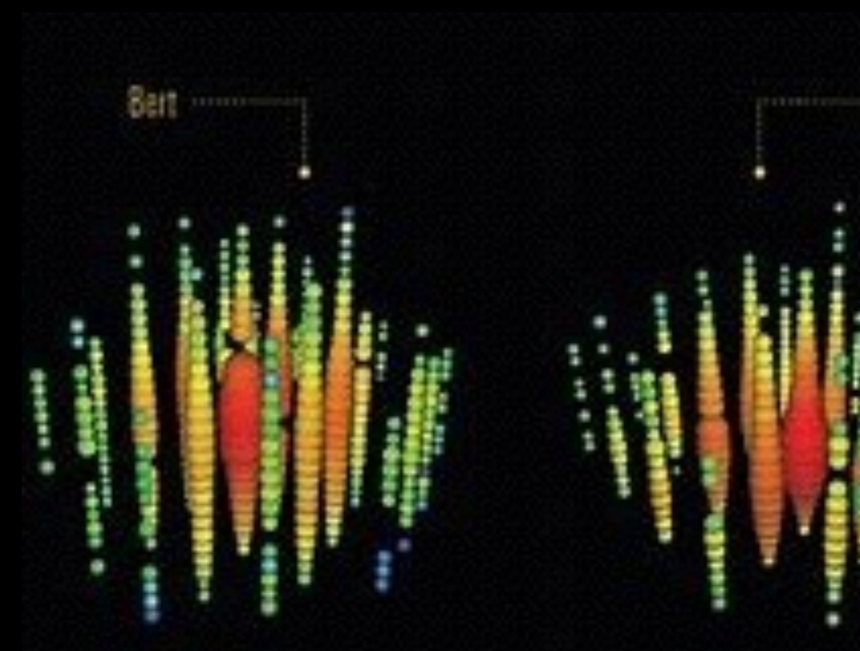




Di Sciascio behold on LHAASO collaboration, arXiv.1602.07600

An interesting overlap with Very High Energy Neutrinos





ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

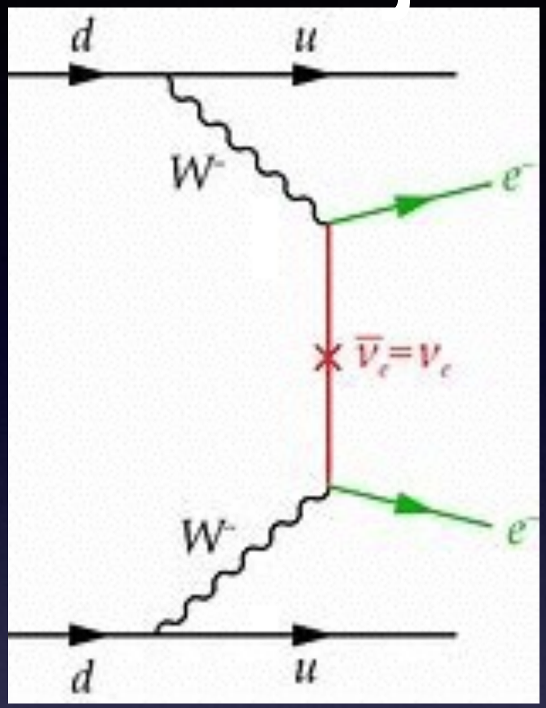
Multi-messenger very high energy astroparticle physics!
Just in next future!
Very exciting

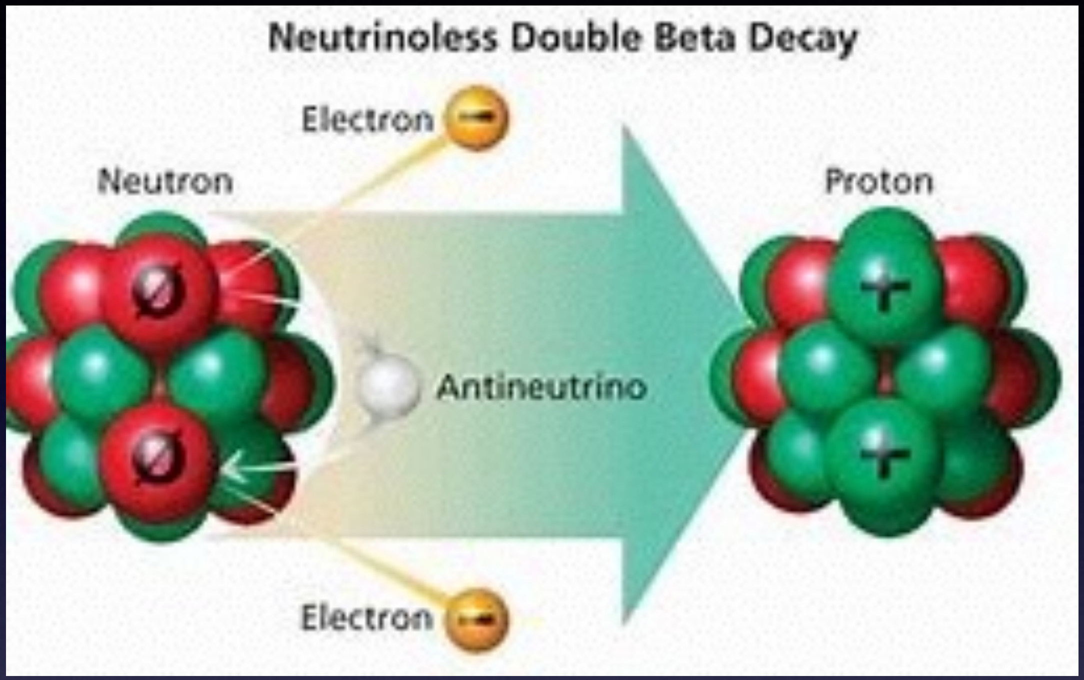
On the other hand
Let's not forget
rare transition physics

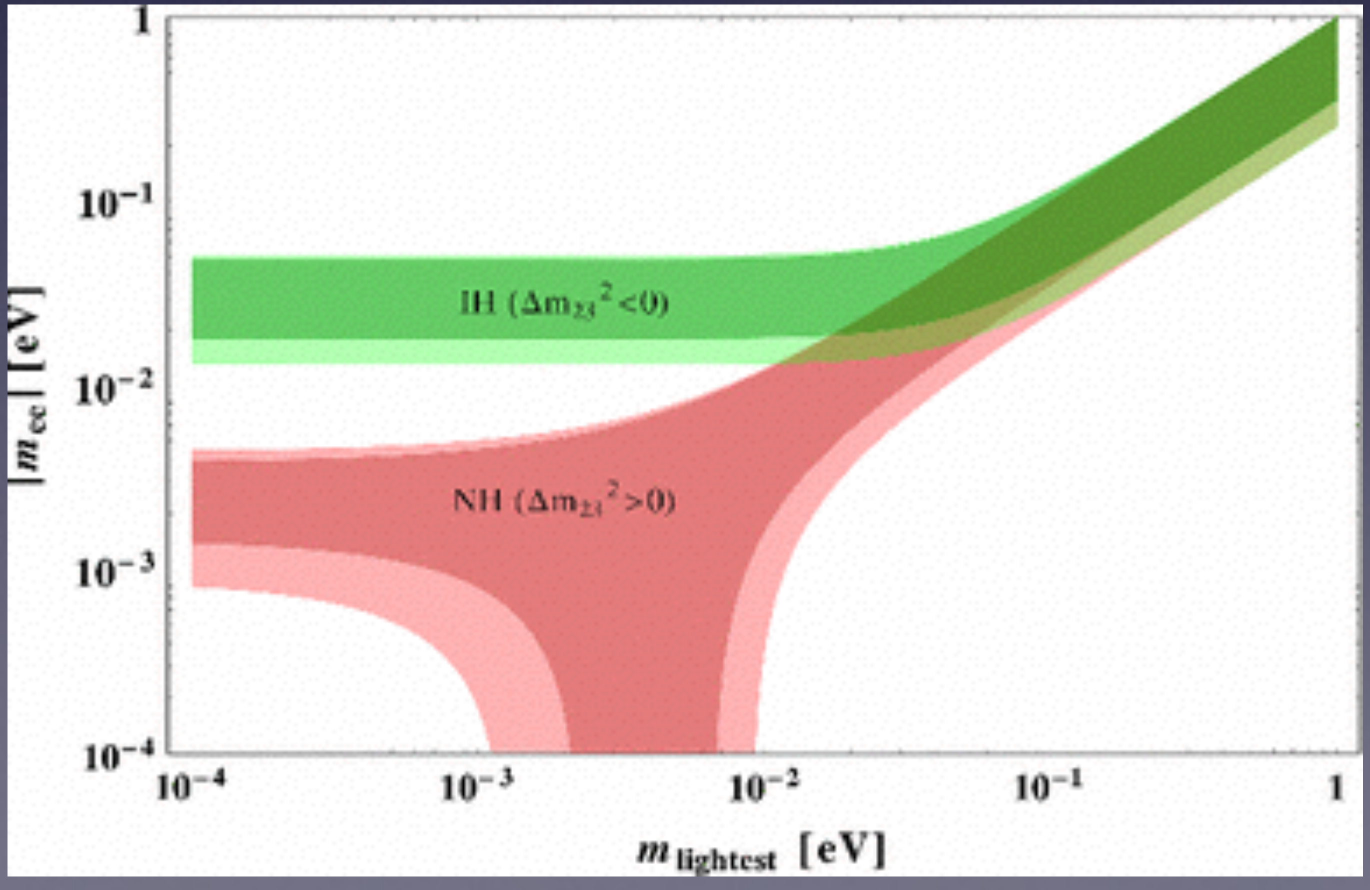
Rare processes beyond the SM are related to effective operators (*Weinberg*). Tests of new physics

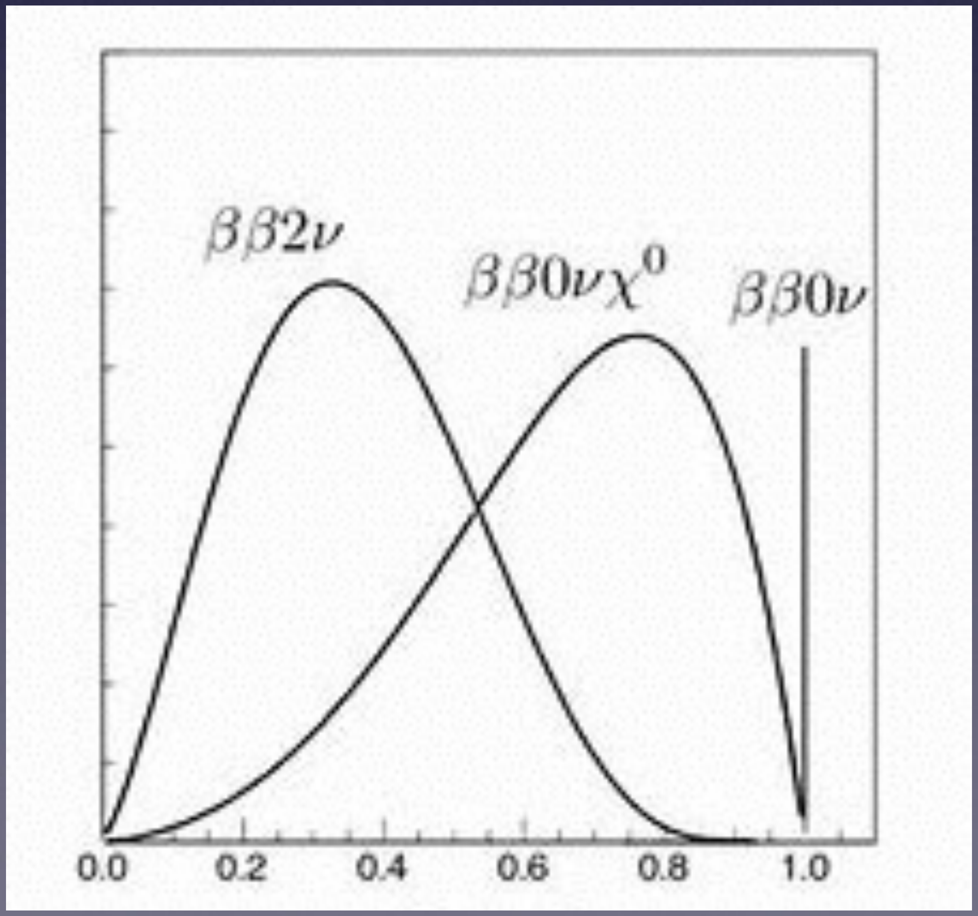
Highly motivated by Lepton/Baryon violations

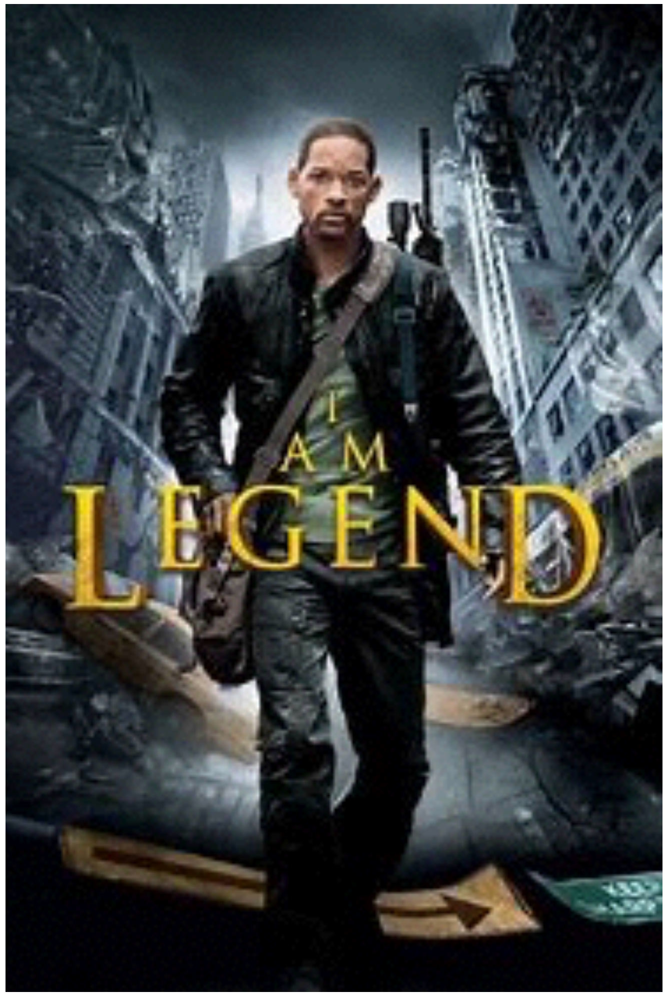
Lepton violations and Majorana neutrinos










I AM LEGEND

LEGEND promises to improve the current bound of 25th digits to two orders

The see-saw mechanisms

All based on integrating out heavy states!

Type I-II-III etc

...

Left-Right symmetry

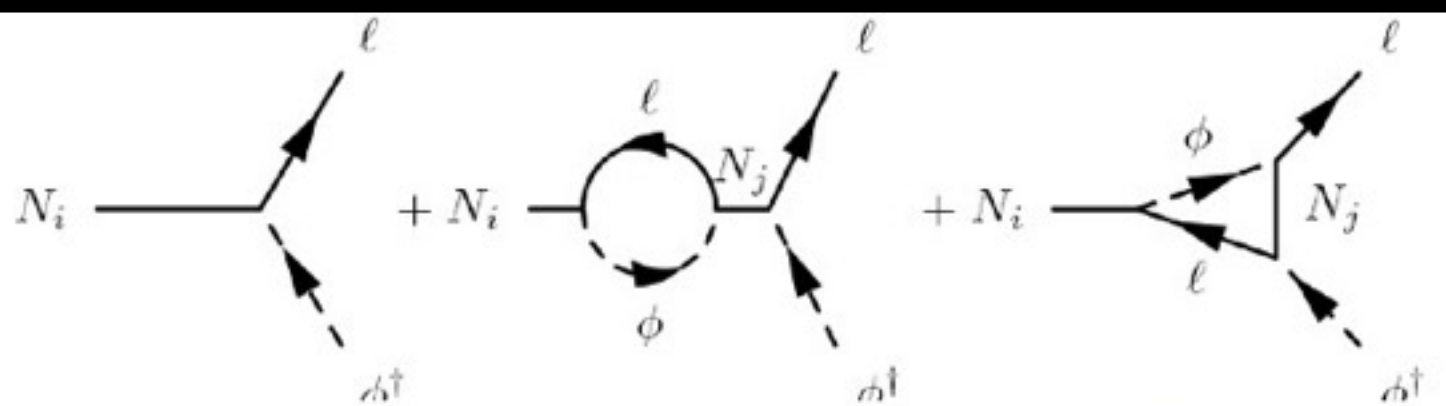
(Mohapatra, Senjanovic)

3-3-1 Model

Frampton; Valle et al

Matter genesis and Majorana neutrinos

notorious example
for the see-saw type I



(Flanz,Paschos,Sark
Covi,Roulet,Vissani'
Buchmüller,Plümach

$$\varepsilon_i \simeq \frac{1}{8\pi v^2 (m_D^\dagger m_D)_{ii}} \sum_{j \neq i} \mathrm{Im}\left[(m_D^\dagger m_D)^2_{ij}\right] \times \left[f_V\left(\frac{M_j^2}{M_i^2}\right) + f_S\left(\frac{M_j^2}{M_i^2}\right)\right]$$

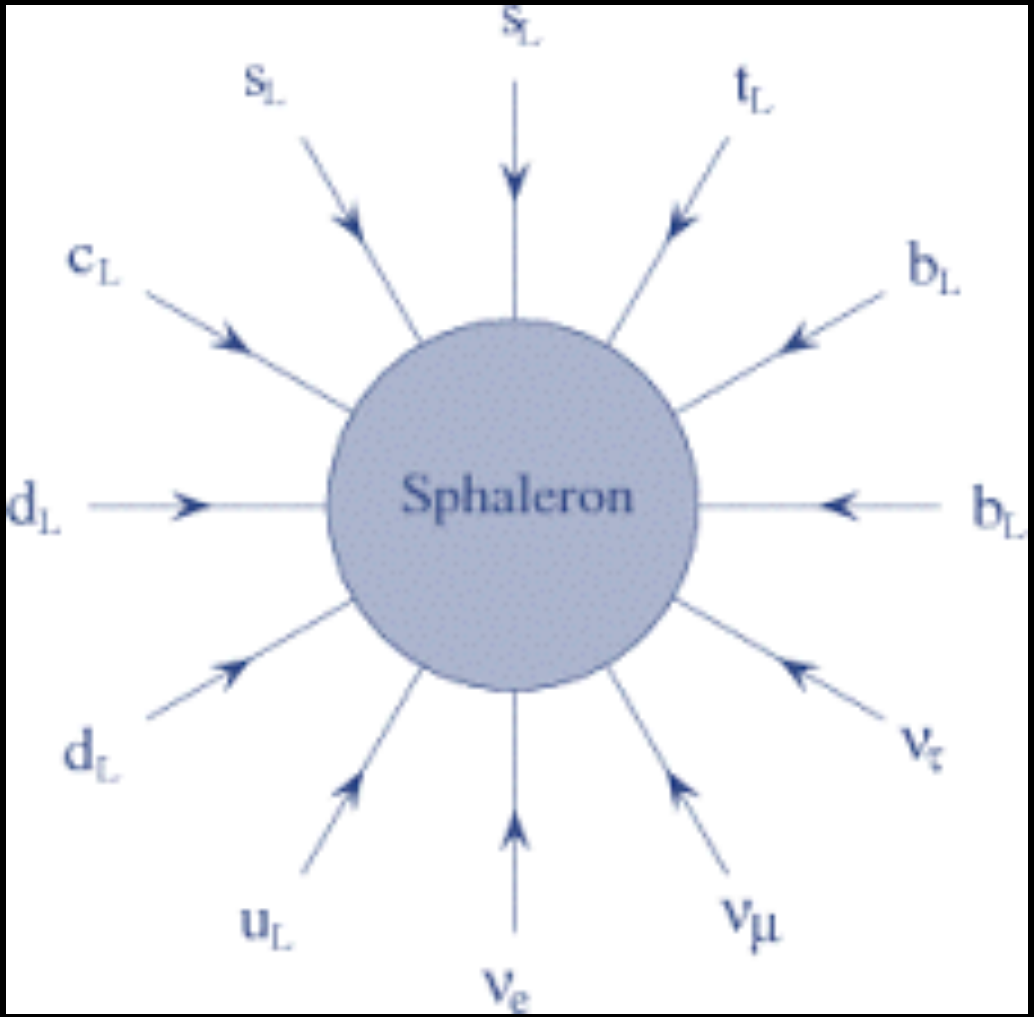
Satisfying all
Sakharov's condition

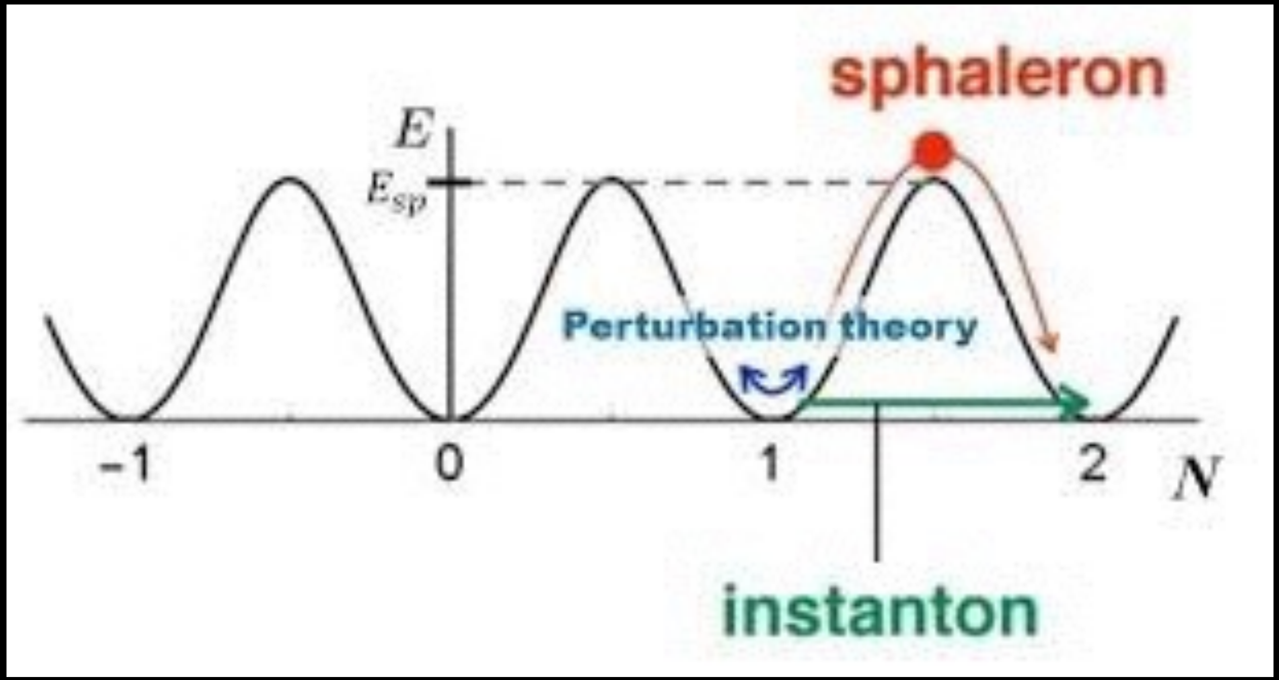
1) out of equilibrium

2) B-L violations

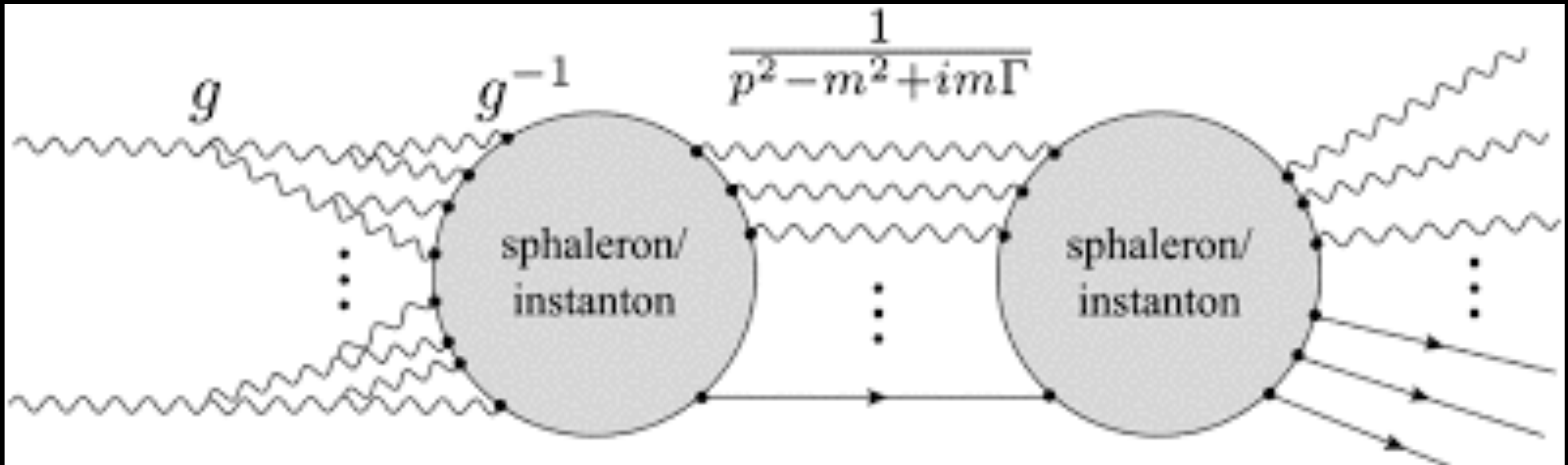
3) CP violations

Sphalerons as a L to B converter

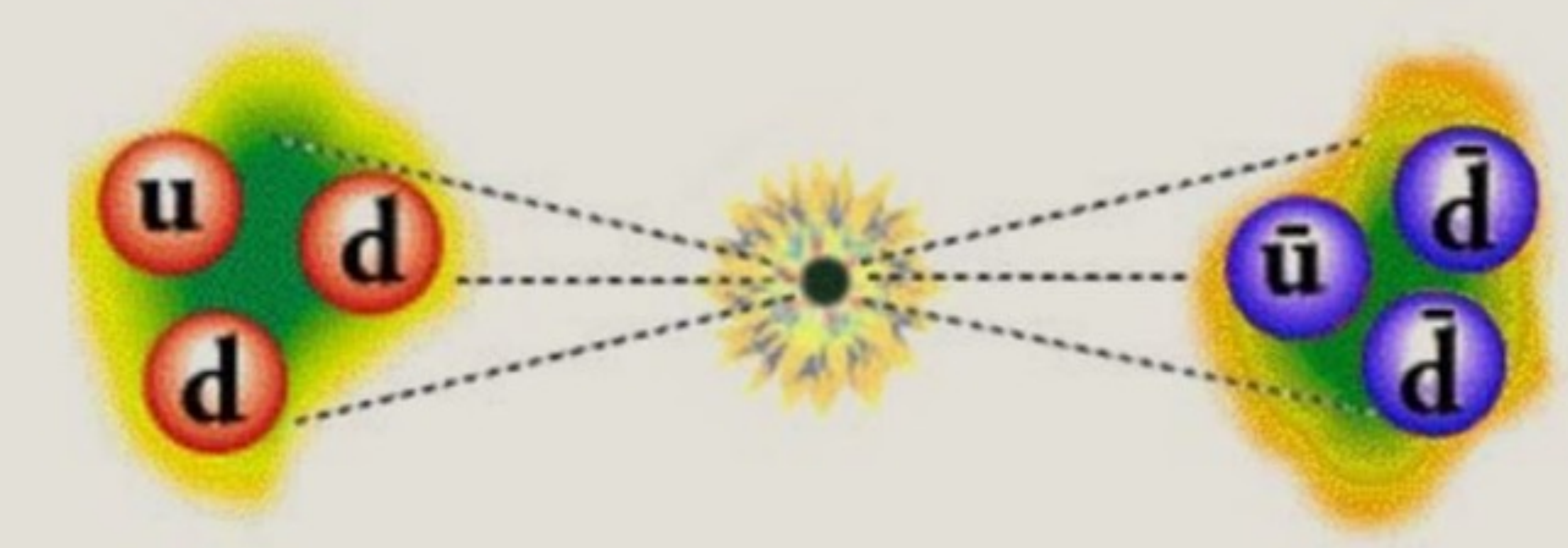




Detectable in future colliders?



However also Majorana’s neutron!



$$n \longrightarrow \bar{n}$$

37’ Nuovo Cimento

Majoran mass for the neutron

$$\mathscr{O}_{\Delta\mathscr{B}=2} = \frac{1}{\mathscr{M}^5}(udd)^2 + \text{h.c.}$$

$$\frac{\varepsilon_{n\bar{n}}}{2}(n^T C n + \bar{n} C \bar{n}^T) = \frac{\varepsilon_{n\bar{n}}}{2}(\overline{n_c} n + \bar{n} n_c)$$

$$\varepsilon_{n\bar{n}} = \frac{C\Lambda_{\text{QCD}}^6}{\mathscr{M}^5} = C\left(\frac{500\ \text{TeV}}{\mathscr{M}}\right)^5 \times 7.7 \cdot 10^{-24}\ \text{eV},$$

$$\varepsilon_{n\bar{n}}^{-1} = \tau_{n\bar{n}} > 0.86 \times 10^8\ \text{s}$$

$$\varepsilon_{n\bar{n}} < 7.7 \times 10^{-24}\ \text{e}$$

Baldo-Coelin 97'

$$\mathscr{M} > 500\ \text{TeV}$$

New high-sensitivity searches for neutrons converting into antineutrons and/or sterile neutrons at the European Spallation Source

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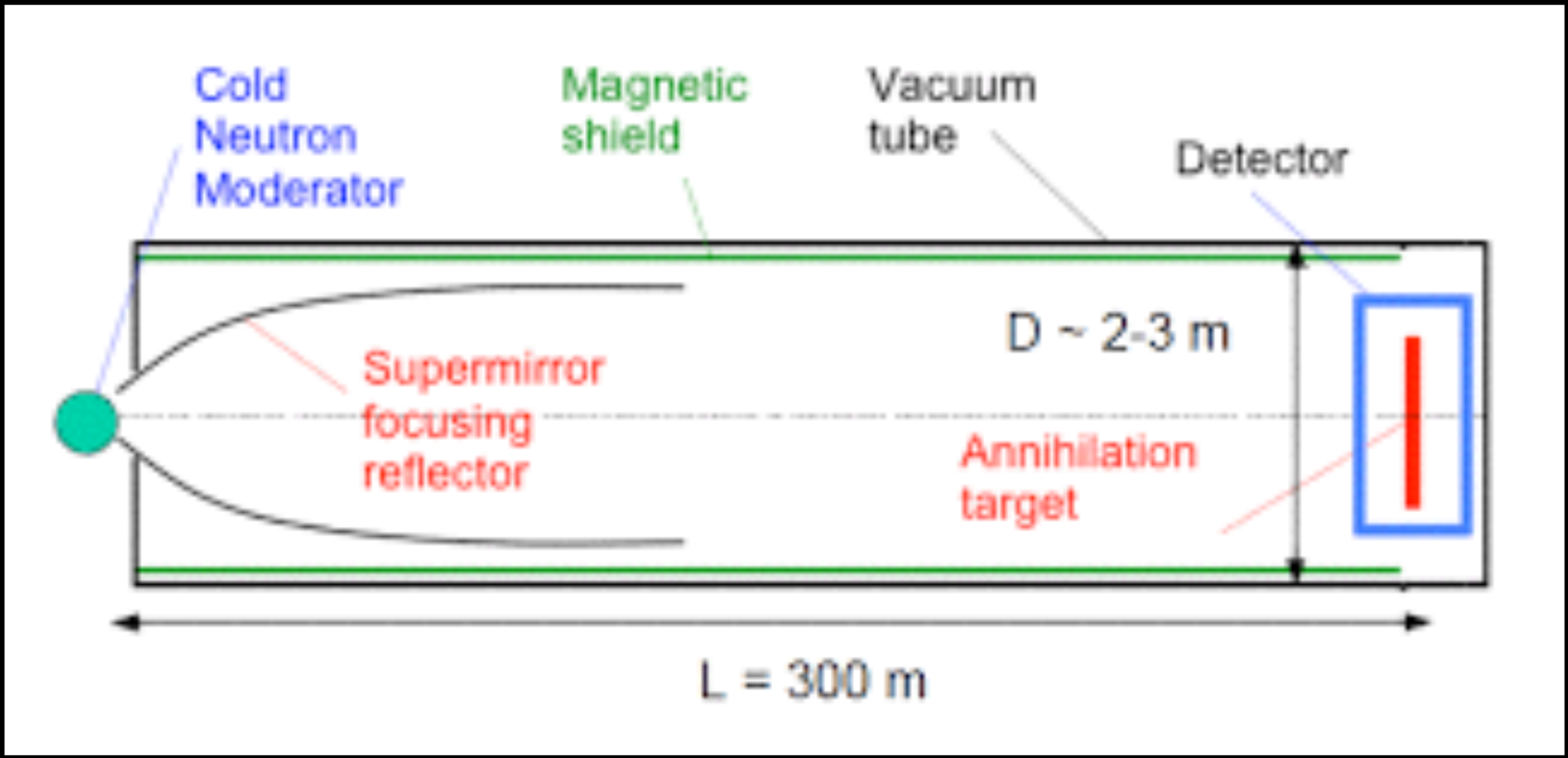

Cold
Neutron
Moderator
Magnetic
shield
Vacuum
tube
Detector
D ~ 2-3 m
Supermirror
focusing
reflector
Annihilation
target
L = 300 m

Post-sphaleron baryogenesis

Addazi JHEP 15'

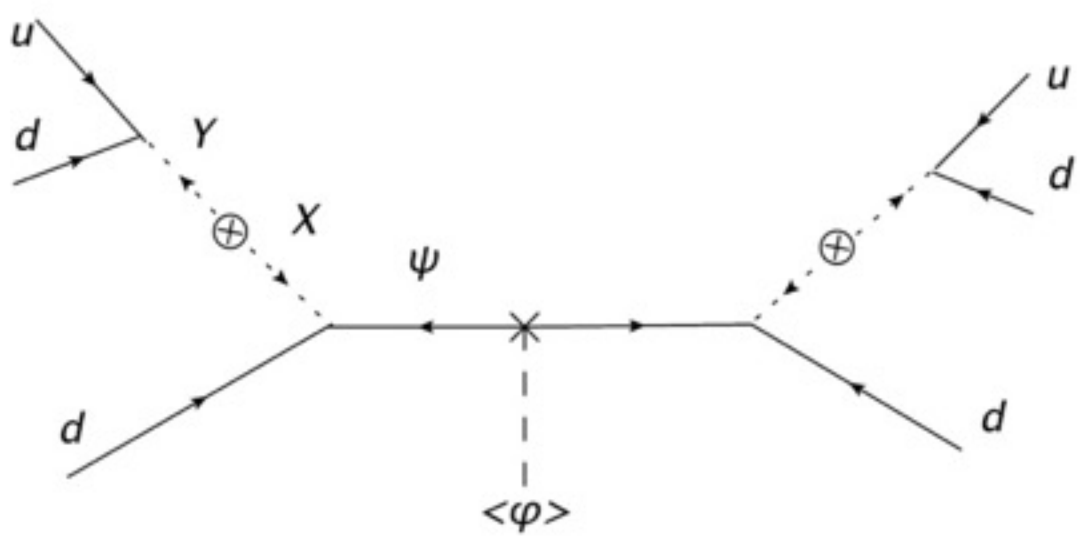
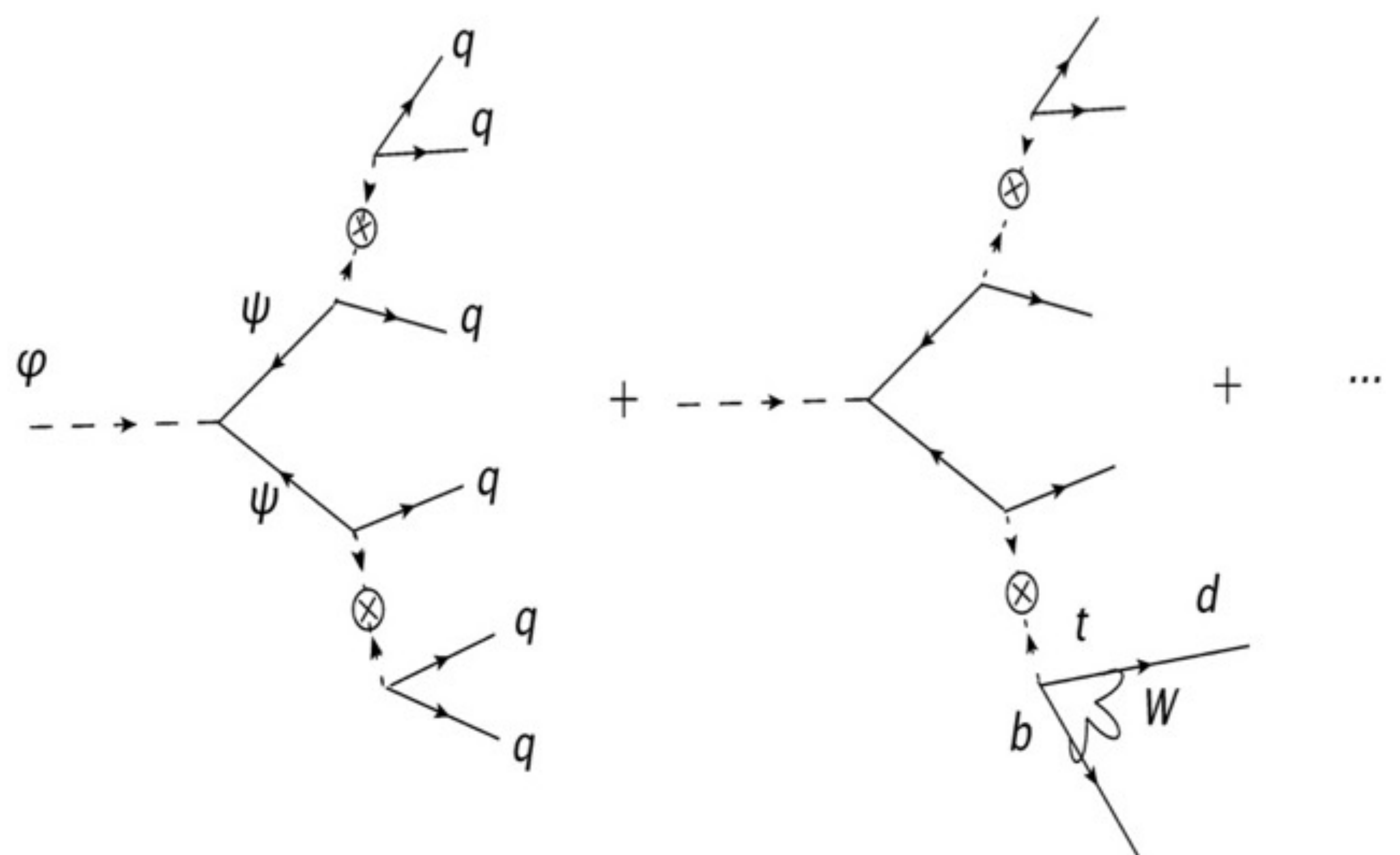
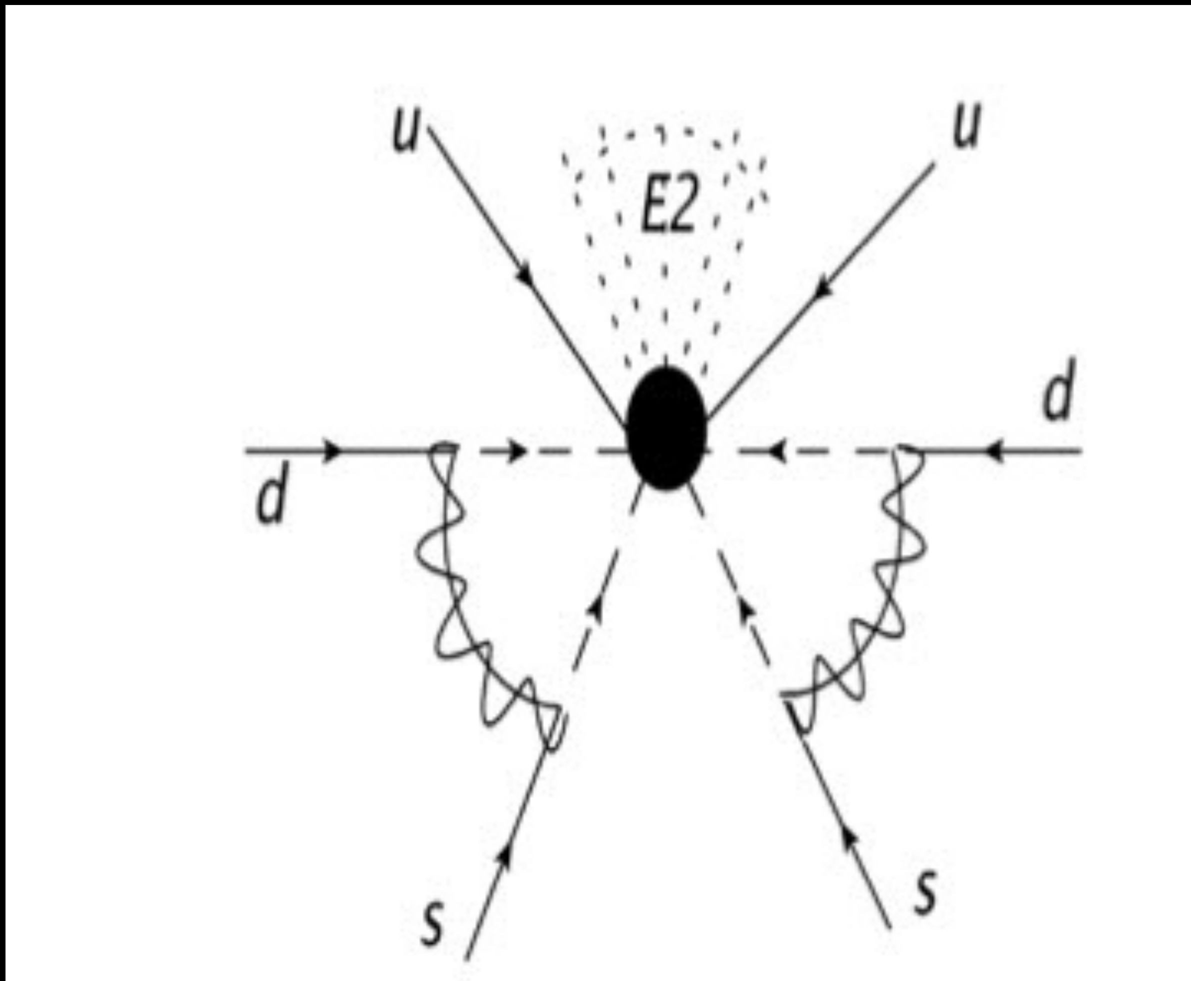
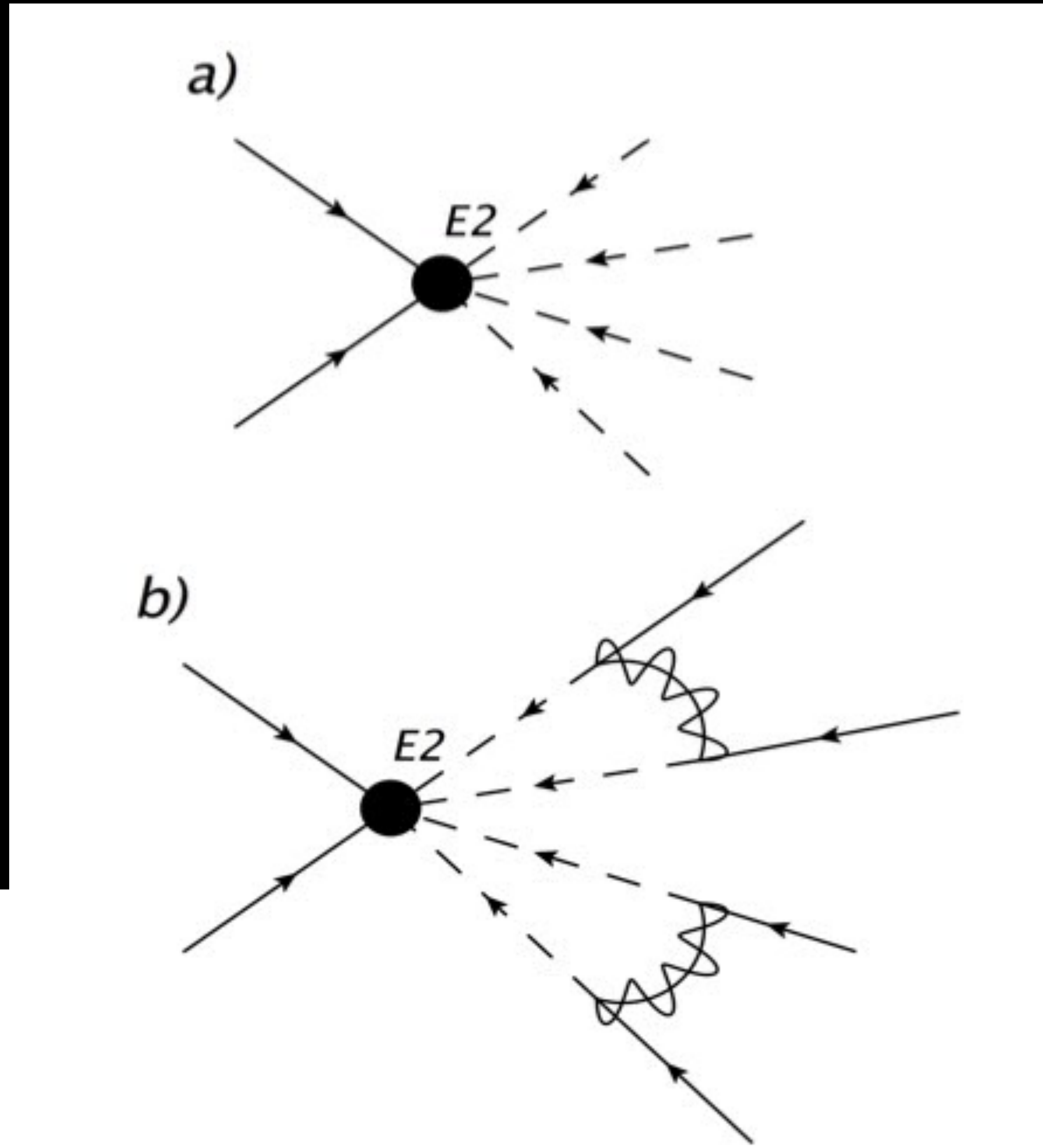


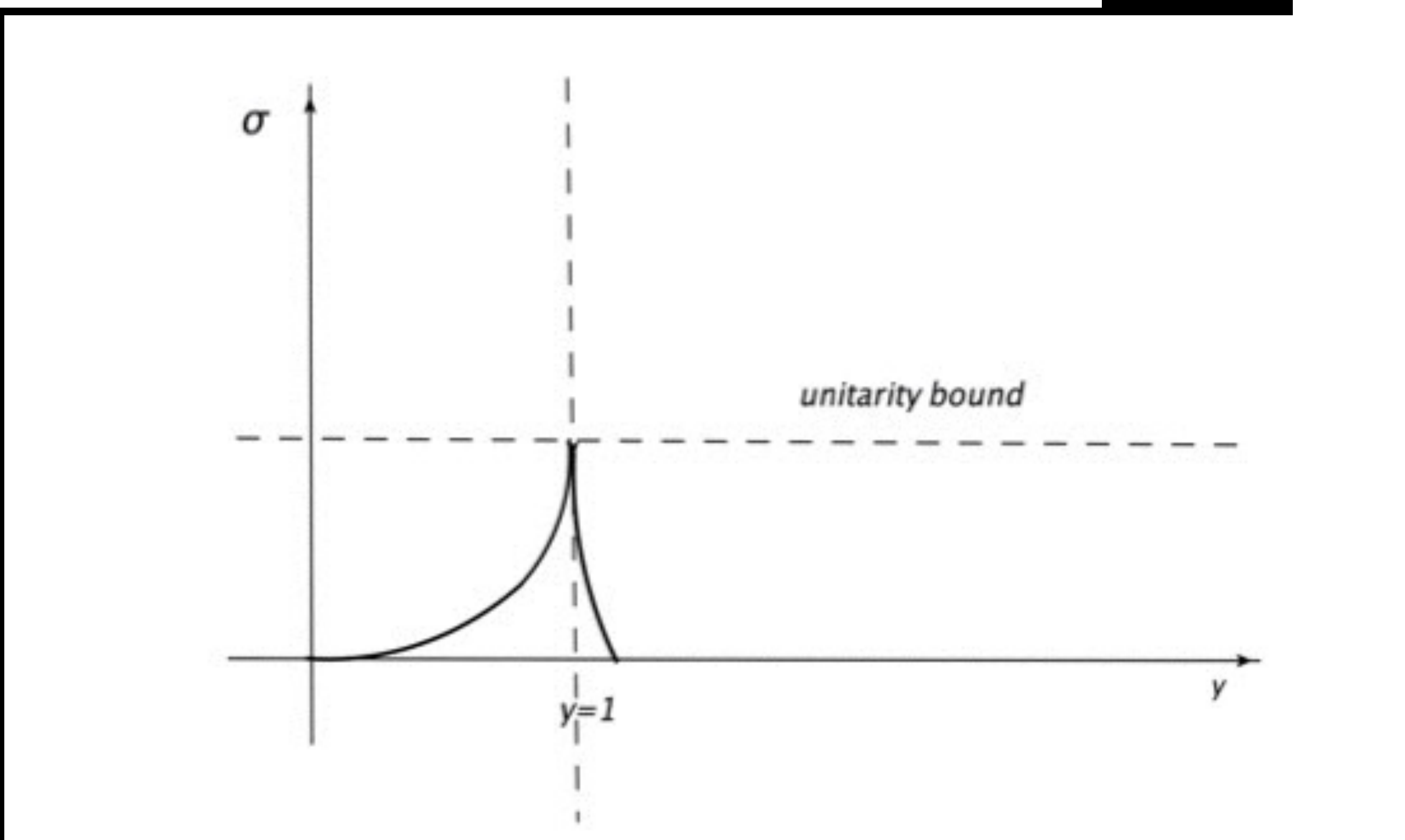
Figure 1: Diagram inducing a Neutron-Antineutron transition. The white blobs indicate the mixing mass term between the vector-like pair of color scalar triplets $\mathcal{X}, \mathcal{Y}$. The central propagator is the Majorana fermion ψ.



B-violations in future100-TeV colliders







Addazi
Kang,
Khlopov 17’ CPC

Here we were considering new non-perturbative instantons violating B-L (no sphalerons) beyond the standard model
The so dubbed Exotic Instantons

See Addazi, Bianchi (2014,2015 JHEP);
Addazi, Kang, Khlopov (2017 CPC)

Vexata Questio:

Colliders

Multi-messenger physics

Rare processes???

Possibly all in!

For theoreticians
CR and rare processes
are more urgent since data
are coming soon!

LHC demonstrated that sometimes we can be absolutely convinced about wrong arguments

t’Hooft Naturalness?

I don’t think

it’s the road to new physics.

Why I think we do not need for

TeV Supersymmetry

or Composite Higgs

A new paradigm: Holographic Naturalness

$$S_{in\ vacuo} \sim A/L_{Pl}^2\,,$$

$$S_{de\ Sitter} \sim r_\Lambda^2/L_{Pl}^2\,,$$

dS/CFT (Strominger et al)

$$T \sim \sqrt{\Lambda}\,.$$

our Universe has a enormous hidden entropy

A series of recent works

arXiv:2004.08372

arXiv:2004.07988

arXiv:2005.02040

$$\Omega_U = e^{S_U} \sim 10^{10^{123}} >>> \Omega_B = 10^{10^{88}},$$

Configuration space of our Universe with a CC

Configuration space of the CMB

Where the missing information?
NO CLASSICAL HAIR THEOREM
by Hawking

QUANTUM HAIRS
Veneziano (1986); Coleman, Preskill,
Wilczek (1992)

Hidden quantum hairs stored and accounting for the quibits and the temperature,
i.e. to Cosmological Constant

$$\Omega(h_1, ..., h_n) \sim 10^{10^{123}} .$$

$$S \sim N \sim M_{Pl}^2/\Lambda$$

$$T \sim \sqrt{\Lambda} \sim M_{Pl}/\sqrt{N} .$$

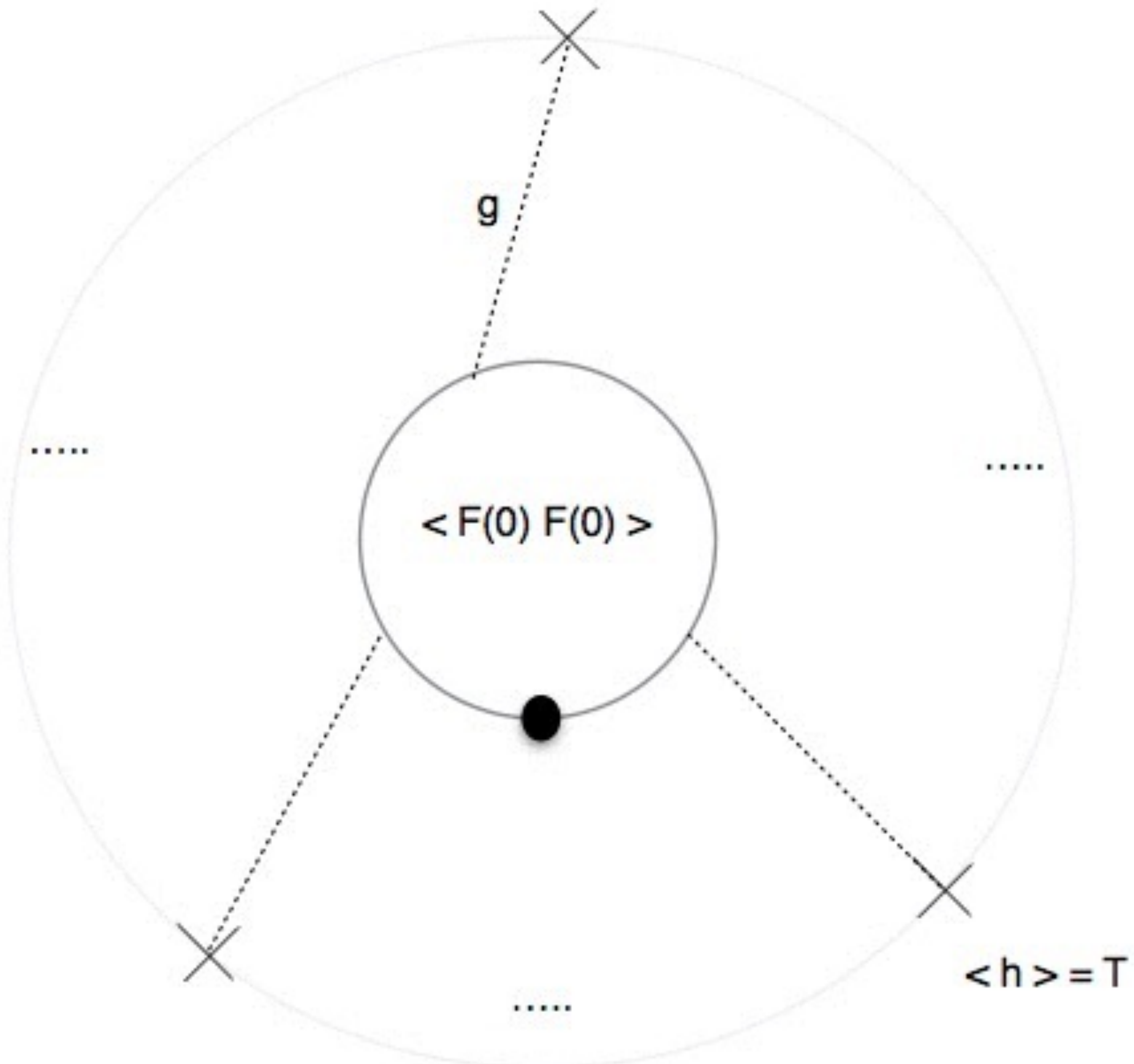


FIG. 1. The standard model vacuum bubble diagrams for any fields F, corresponding to $\langle F(0)F(0)\rangle$, have N-graviton insertions from hairon background fields, with a thermal expectation value of $\langle h\rangle = T$.

$$\langle T|F^2(x)|T\rangle = \langle T|0\rangle\langle 0|F^2(x)|0\rangle\langle 0|T\rangle\,,$$

$$\langle T|0\rangle = \langle 0|T\rangle^*$$

$$\sim e^{-S} M_{Pl}^4 \sim e^{-10^{123}} 10^{123}\Lambda$$

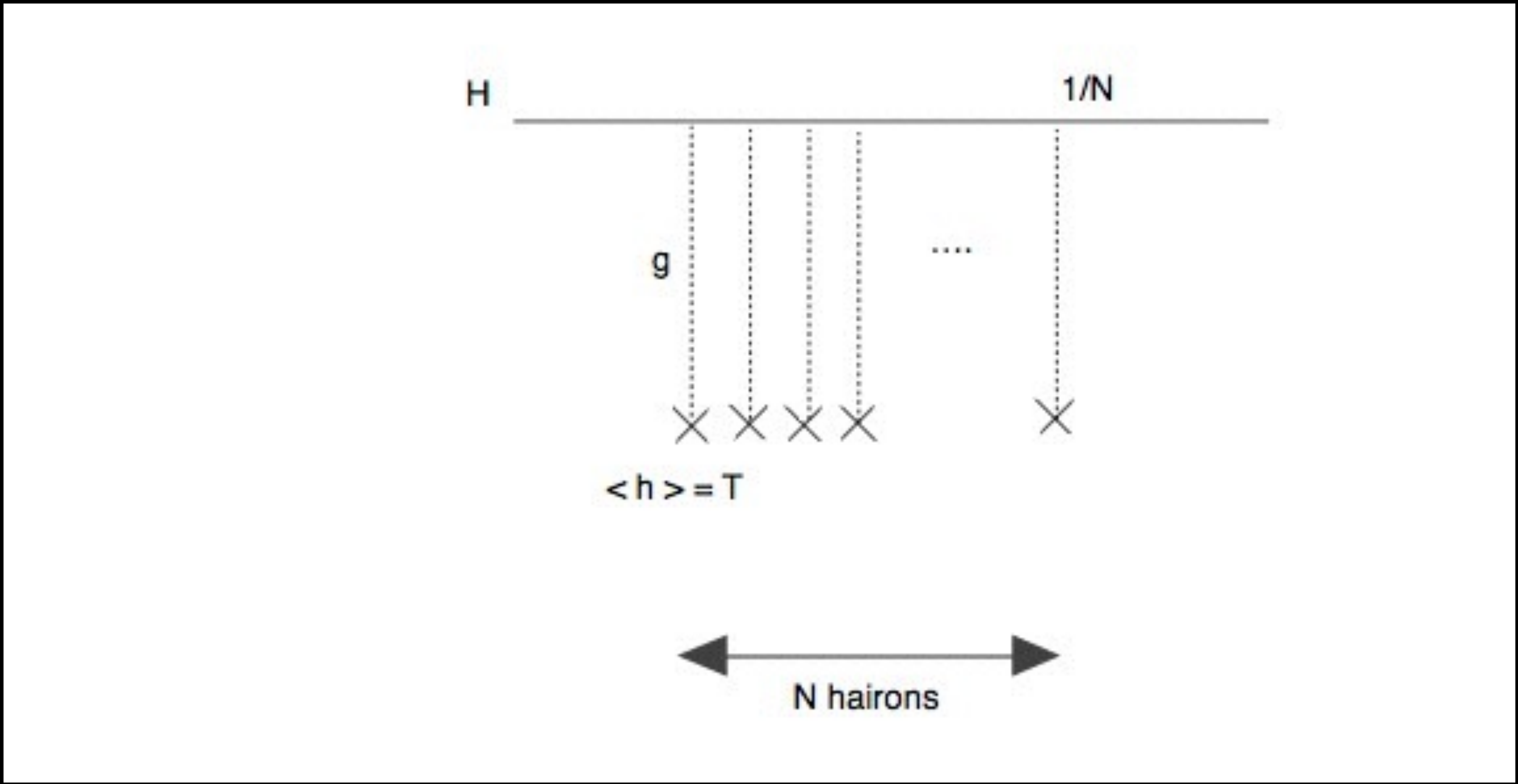
$$|T\rangle \simeq |N\rangle.$$

Leading contribution are others:
Thermal Field Theory

$$\Delta\rho_\Lambda \sim (n_B - n_F) T^4\,.$$

$$T \simeq \sqrt{\Lambda}$$

Higgs



The Higgs is assumed with an electroweak bare mass. Then, it feels hadrons in an electroweak volume. 34th qubits dividing the electroweak scale and the Planck scale

$$S \sim N = M_{Pl}^2/m_H^2 \sim 10^{34} \, .$$

Every gravitational Higgs-hairon coupling is

$$\alpha_G(E) = E^2/M_{Pl}^2 \sim N^{-1} \, ,$$

$$\langle N|F^2(x)|N\rangle = e^{-2N}\langle 0|F^2(x)|0\rangle$$

and

$$\langle N|F^\dagger(x)F(y)|N\rangle = e^{-2N}\langle 0|F^\dagger(x)F(y)|0\rangle\,.$$

$$T = M_{Pl}/\sqrt{N} \sim m_H$$

$$(c_B n_B - c_F n_F)T^2 \sim \frac{1}{N}(c_B n_B - c_F n_F)M_{Pl}^2$$

HN does not predict any new heavy UV completing field around the TeV-scale!

The vacuum state is stabilized because corresponding to a maximal entropic state in the Universe: the holographic dS-like entropy

What can eventually motivate (next) new physics beyond the TeV scale?

Neutrino mass

Dark Matter

Matter/Antimatter asymmetry in the Universe

Inflation (but in Cosmology)

Where NP in CR?

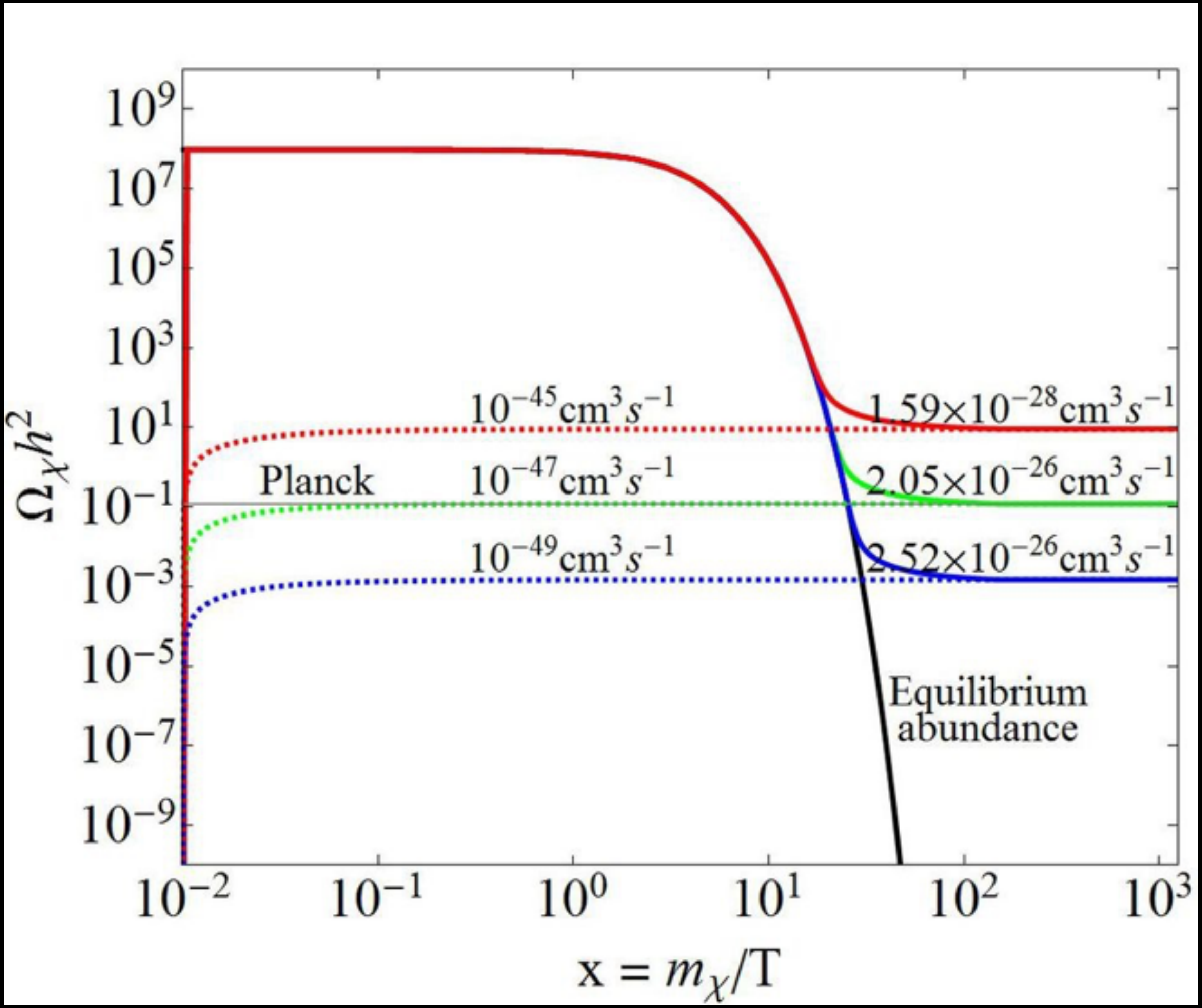
New Sources?

Propagation?

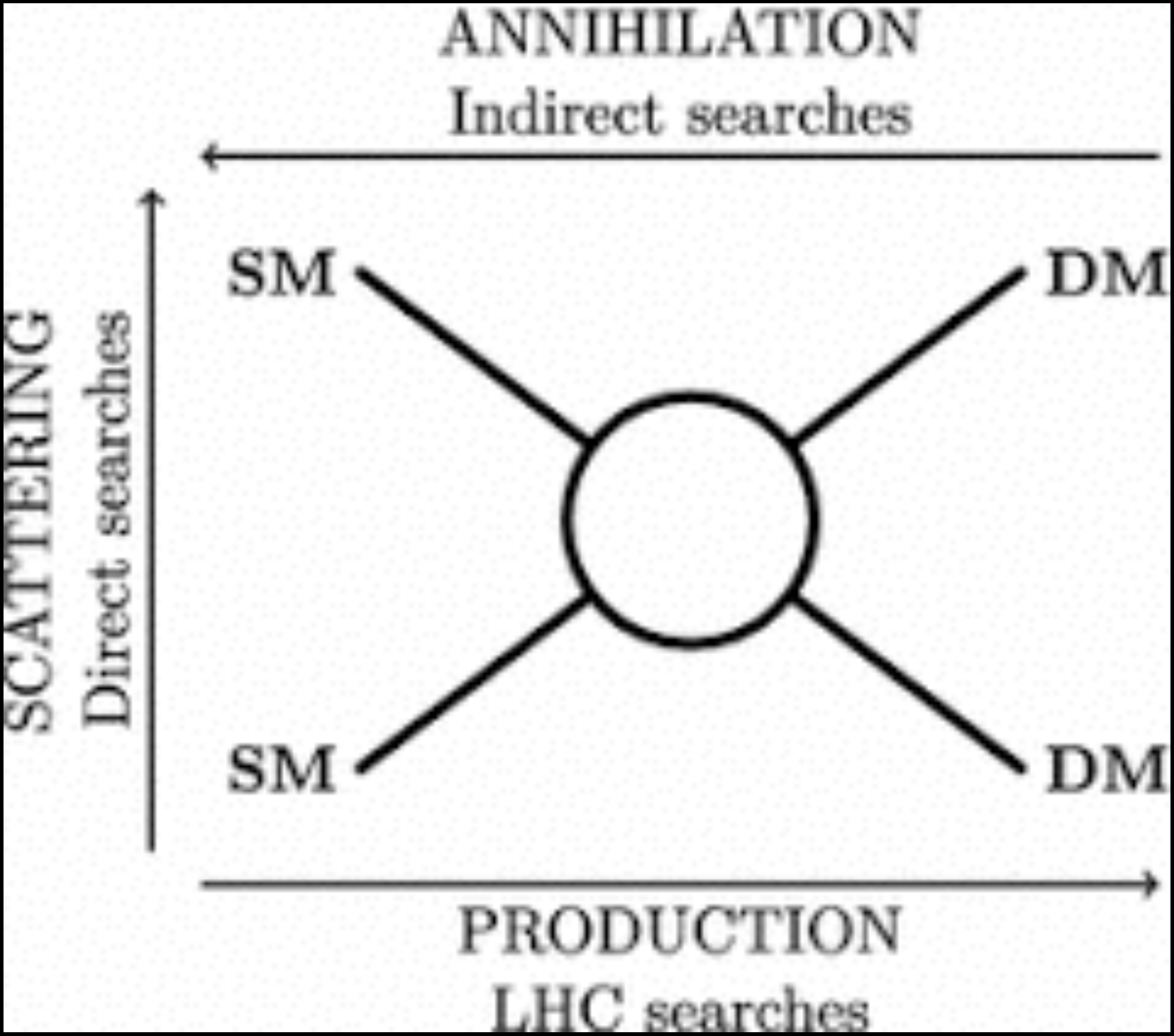
New Particle species?

Dark Matter candidates beyond traditional WIMPs

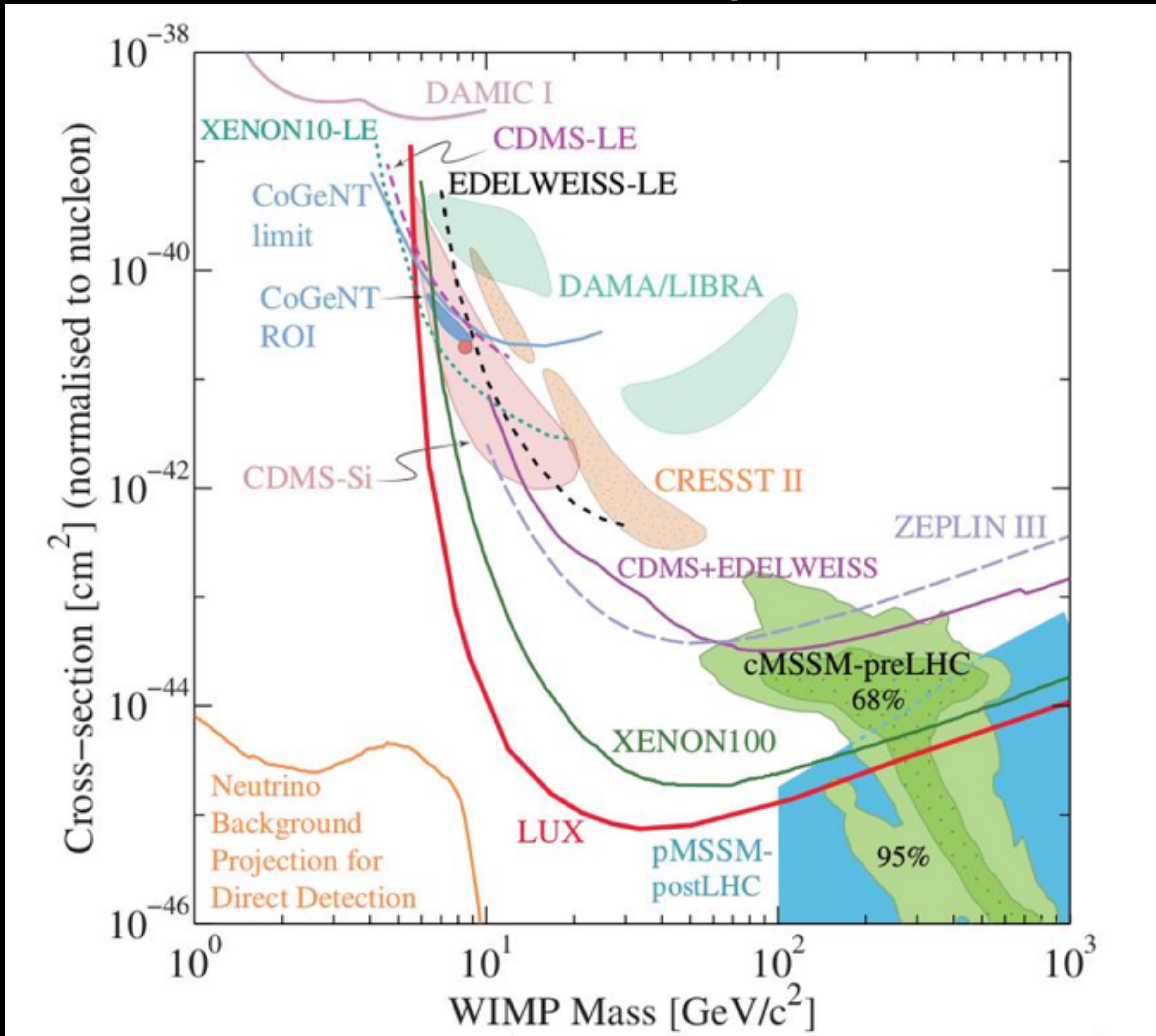
The old boy:
Thermally produce WIMPs
Freeze out
WIMP miracle



The WIMP Miracle is predictive

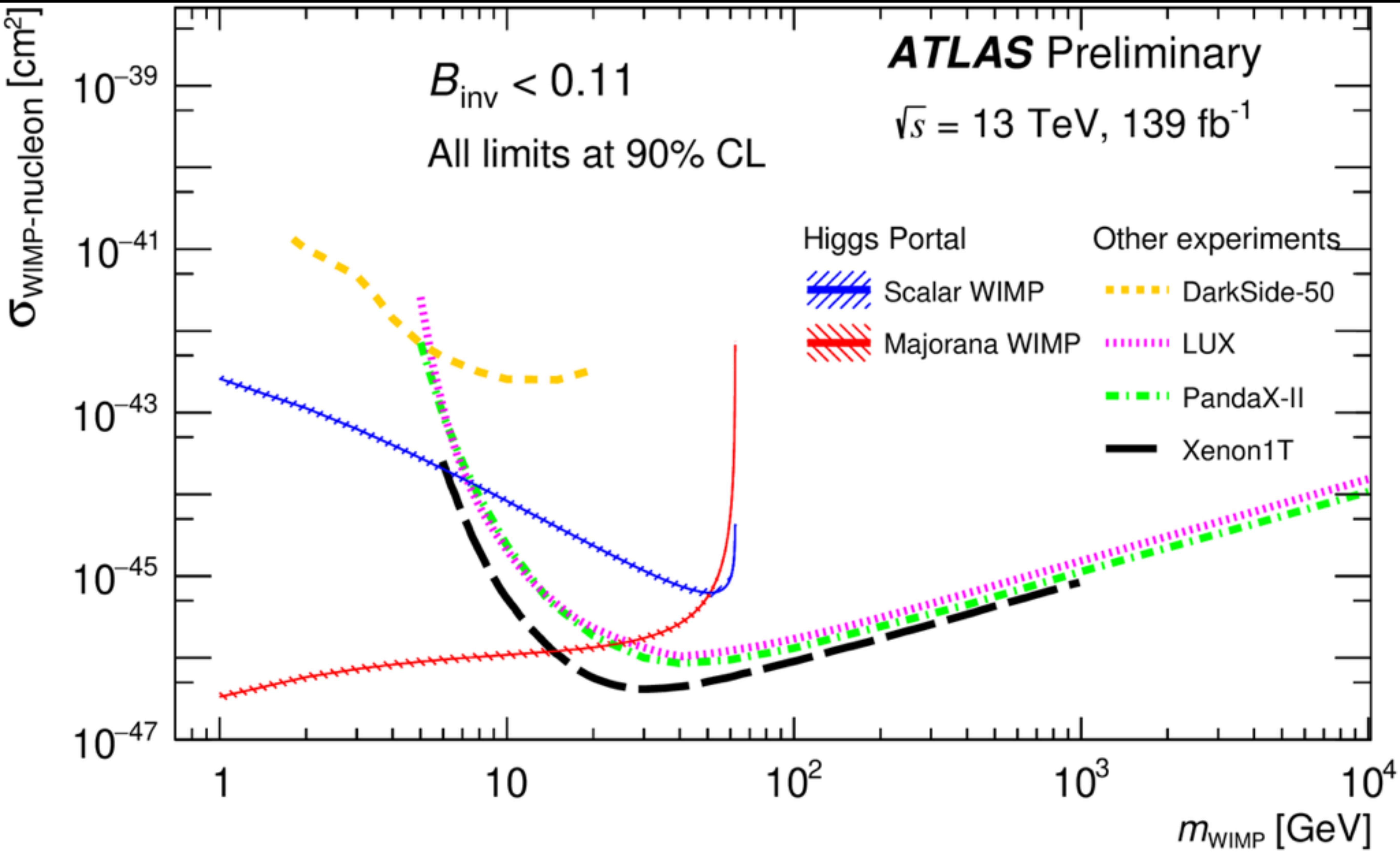


10-100 GeV WIMPs: a disappointing situation

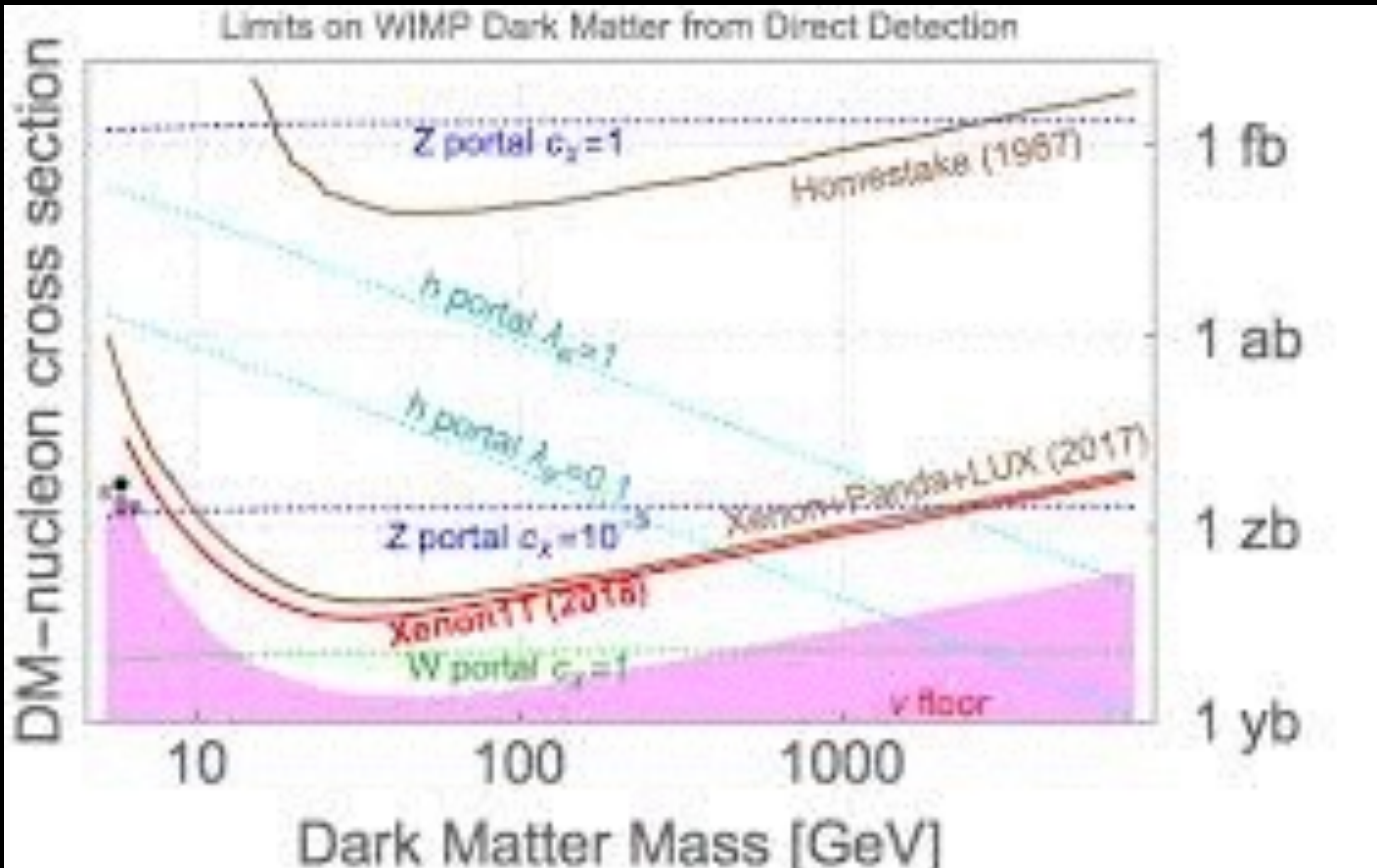


With a remark:
too strong assumptions on the DAMA quenching factors!!!
It can displace the DAMA region with several orders!!!
See DAMA collaboration papers

LHC Vs Direct Detection



After XENON 1T



We conclude that the perturbative WIMP miracle is ruled out!

We were convinced MSSM was there.
The TeV-scale!
DM as Neutralinos
Higgs hierarchy problem solved
GUT matching was perfect

Damn!
It wasn't

Assuming here everybody
is doing “their good job”.
Any possible explanations?

We should not forget that
DAMA is a detector based on
a different technology than
XENON/LUX/PANDA-X
Is there any possible way out?

Next step

Changing DM candidate

Changing Symmetry
principles and motivations

Changing DM genesis

Changing DM interactions

Dark Atoms?

Dark Matter can emerge as a composite bound state rather than a single fundamental particle.

Hidden gauge sectors. SU(N), U(1), SO(N), Sp(N)

Naturally emerging in many GUT, Heterotic string theory intersecting D-branes models

Mirror Dark Matter

$SU(3)\times SU(2)\times U(1)$ gauge (g, W, Z, γ) & Higgs (ϕ) fields	$\times$	$SU(3)'\times SU(2)'\times U(1)'$ gauge (g', W', Z', γ') & Higgs (ϕ') fields

quarks (B=1/3)	leptons (L=1)	quarks (B′=1/3)	leptons (L′=1)
$q_L = (u,d)^t_L$	$l_L = (\nu, e)^t_L$	$q'_L = (u',d')^t_L$	$l'_L = (\nu', e')^t_L$
$u_R \ \ d_R$	e_R	$u'_R \ \ d'_R$	e'_R
$\widetilde{\text{quarks}}$ (B=-1/3)	$\widetilde{\text{leptons}}$ (L=-1)	$\widetilde{\text{quarks}}$ (B′=-1/3)	$\widetilde{\text{leptons}}$ (L′=-1)
$\tilde{q}_R = (\tilde{u},\tilde{d})^t_R$	$\tilde{l}_R = (\tilde{\nu}, \tilde{e})^t_R$	$\tilde{q}'_R = (\tilde{u}',\tilde{d}')^t_R$	$\tilde{l}'_R = (\tilde{\nu}', \tilde{e}')^t_R$
$\tilde{u}_L \ \ \tilde{d}_L$	$\tilde{e}_L$	$\tilde{u}'_L \ \ \tilde{d}'_L$	$\tilde{e}'_L$

$$- \quad \mathcal{L}_{\rm Yuk} = f_L Y \tilde{f}_L \phi + \tilde{f}_R Y^* f_R \tilde{\phi} \qquad | \qquad \mathcal{L}'_{\rm Yuk} = f'_L Y' \tilde{f}'_L \phi' + \tilde{f}'_R Y'^* f'_R \tilde{\phi}'$$

- D-parity: $L \leftrightarrow L', \ R \leftrightarrow R', \ \ \phi \leftrightarrow \phi' :$ $\quad Y' = Y$ • *identical xero copy*
- M-parity: $L \leftrightarrow R', \ R \leftrightarrow L', \ \ \phi \leftrightarrow \tilde{\phi}' :$ $\quad Y' = Y^\dagger$ • *mirror (chiral) copy*

Lee & Yang 56'; Kobzarev, Okun, Pomeranchuk 66';
Blinnikov, Khlopov 86', Foot et al *and Berezhiani* et al *following*

From Berezhiani's talks

Spontaneously Broken Mirror Symmetry

two electroweak scales $\langle\phi'\rangle = v'$ and $\langle\phi\rangle = v$

$$v' \gg v.$$

$$M_{W',Z',\phi'} = \zeta M_{W,Z,\phi}$$

$v'/v \sim 100$, and $\Lambda'/\Lambda \sim 5$.

THE HADRON MASSES SCALE ONLY AS THE QUARK DIFFERENCE AND A SLOW CHANGE IN LAMBDA
ON THE OTHER HAND
THE ELECTRON MASS SCALE LINEARLY

A HYDROGEN-LIKE COMPACT ATOM CAN BE ENVISAGED sterile neutrino bound from BBN

$$\Delta g_* = 1.75\,\Delta N_\nu = (2 + 5.25x^4)\left(\frac{T'}{T}\right)^4, \qquad x = T'_\nu/T'$$

CMB distorsion
and CDM abundance

$$\frac{T'}{T} < \frac{1.6}{x\zeta^{2/3}} \approx 0.4\left(\frac{30}{\zeta}\right)^{\frac{2}{3}}$$

$$x = T'_\nu/T'$$

$$\frac{T'_R}{T_R} = \left(\frac{2 + 5.25x^3}{10.75}\right)^{\frac{1}{3}}\frac{T'}{T} \approx 0.6\,\frac{T'}{T}$$

$$\eta \to -\eta.$$

$$\propto \eta(\phi^\dagger \phi - \phi'^\dagger \phi').$$

We also assume that initially $g_* = g'_*$ despite different T_R and T'_R, which is natural if $T_R, T'_R \gg v'$

$$\mathcal{V}(\phi, \phi') = (m^2\phi^2 + h\phi^4) + (m'^2\phi'^2 + h'\phi'^4) + a\phi^2\phi'^2$$

$$\mathcal{V}(\check{\eta}; \phi, \phi') = (f\phi^2 + f'\phi'^2)\mu\check{\eta} + (g\phi^2 + g'\phi'^2)\check{\eta}^2 + (k\phi^4 + k'\phi'^4)\frac{\check{\eta}}{M_{Pl}} + \dots$$

$$m^2(m'^2) = m_0^2 + \mu^2(F \pm \tilde{F}), \quad h(h') = h_0 + (K \pm \tilde{K}), \quad a = a_0 + A$$

$$f(f') = \frac{\mu}{M_{Pl}}(F_z \pm \tilde{F}_z), \quad g(g') = \frac{\mu^2}{M_{Pl}^2}(F_{zz} \pm \tilde{F}_{zz}), \quad k(k') = K_z \pm \tilde{K}_z$$

$$\check{\eta} = \eta - \eta_0$$

INFLATON

PARITY EVEN FIELD

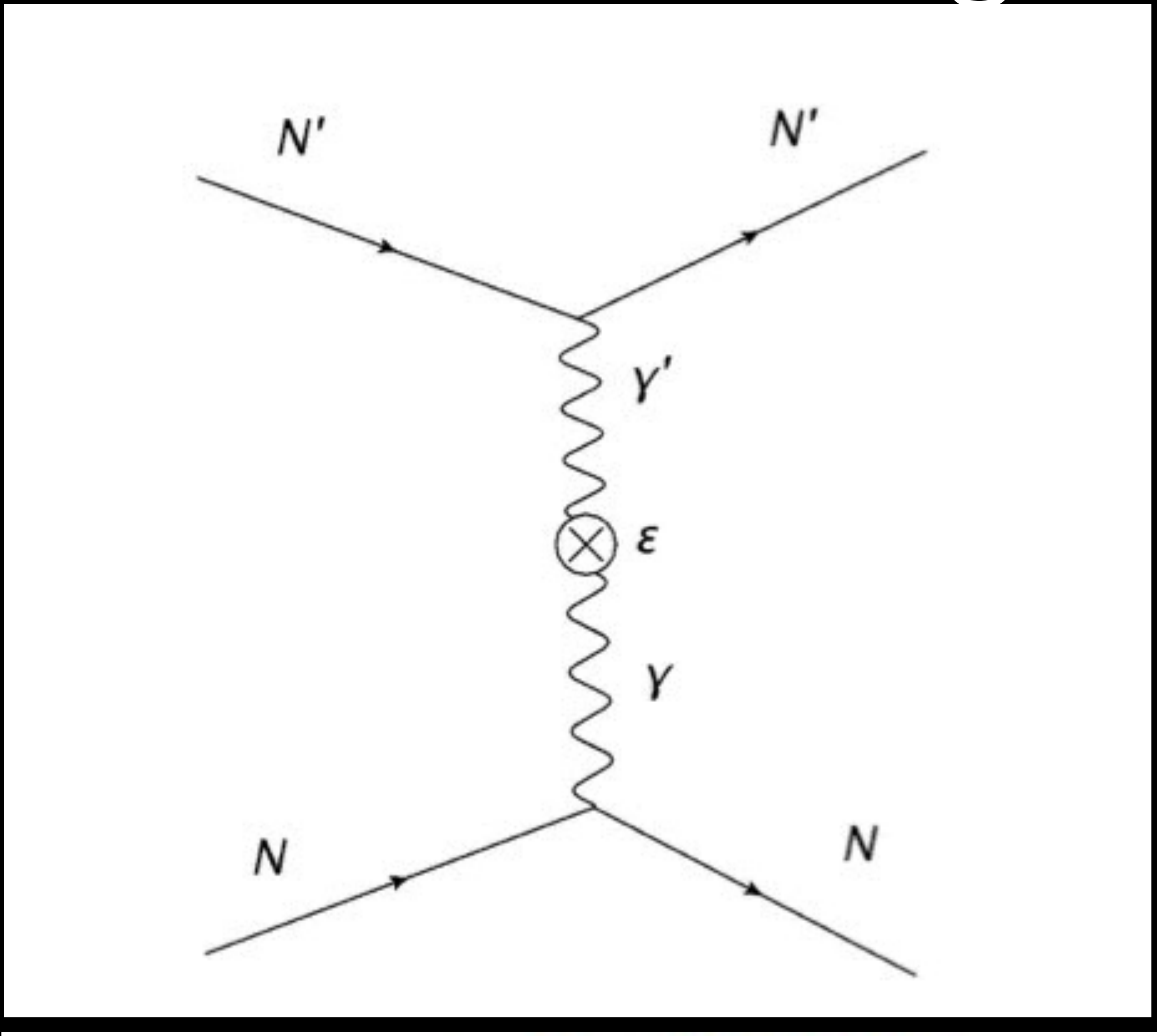
Astrophysical complexity sequestered and Asymmetric DM production

other nuclei are unstable if v'>>v.
Only the Mirror Hydrogen is stable in a large region of parameters

Berezhiani, Dolgov, Mohapatra 90';
Addazi et al 05'

Dark photons and kinetic mixing

$$\mathcal{L} = -\varepsilon F^{\mu\nu} F'_{\mu\nu}$$

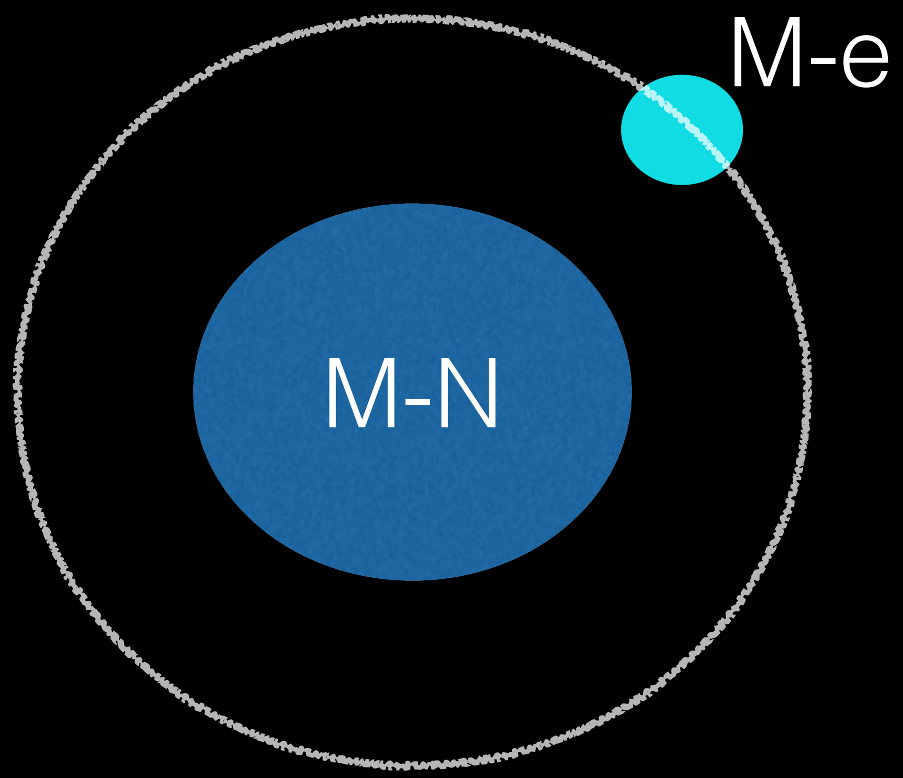


$$\frac{d\sigma_{A,A'}}{dE_R} = \frac{\mathcal{C}_{A,A'}}{E_R^2 v^2}$$

$$\mathcal{C}_{A,A'} = \frac{2\pi\epsilon^2\alpha^2 Z^2 Z'^2}{M_A}\mathcal{F}_A^2\mathcal{F}_{A'}^2$$

ORTHOPOSITRONIUM DESAPPARENCES ARE SEQUESTERED SINCE v'>>v

$$e^+e^- \rightarrow e'^+e'^-$$


M-e
M-N

Proton-electron: too large self-interactions

$$\sigma/M \geq 3\times 10^{-23}\ \mathrm{cm}^2/\mathrm{GeV}$$

Way-out: two Higgs up-down model

$\zeta_u = \langle H'_u\rangle/\langle H_u\rangle$ and $\zeta_d = \langle H'_d\rangle/\langle H_d\rangle$

$\tan\beta' \neq \tan\beta$

$v'/v \sim 100$, and $\Lambda'/\Lambda \sim 5$.

Mirror up much lighter than mirror down now

$\Delta'^{++} = u'u'u'$ bound state with spin 3/2

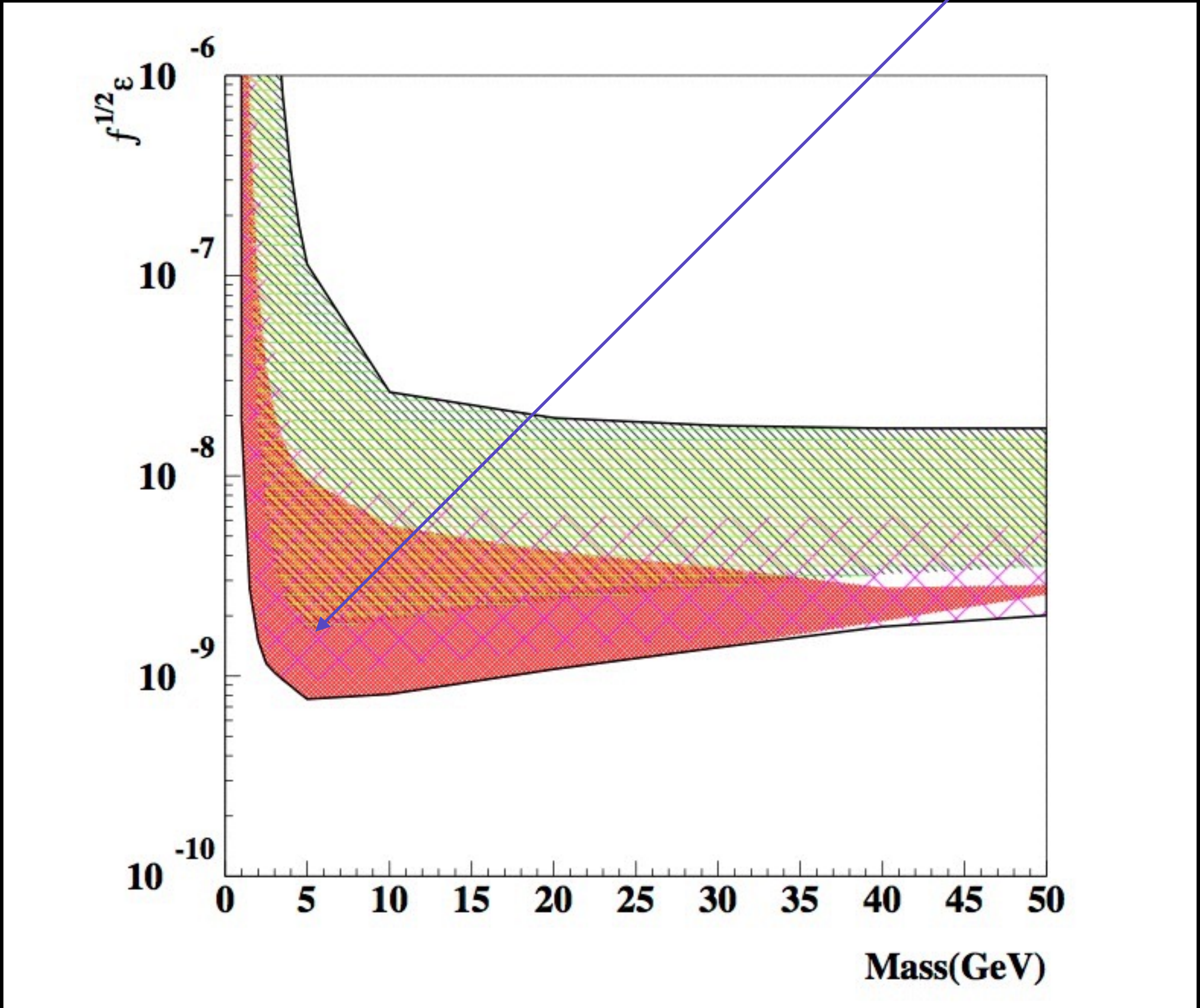
$M_\Delta \simeq 1.2$ GeV

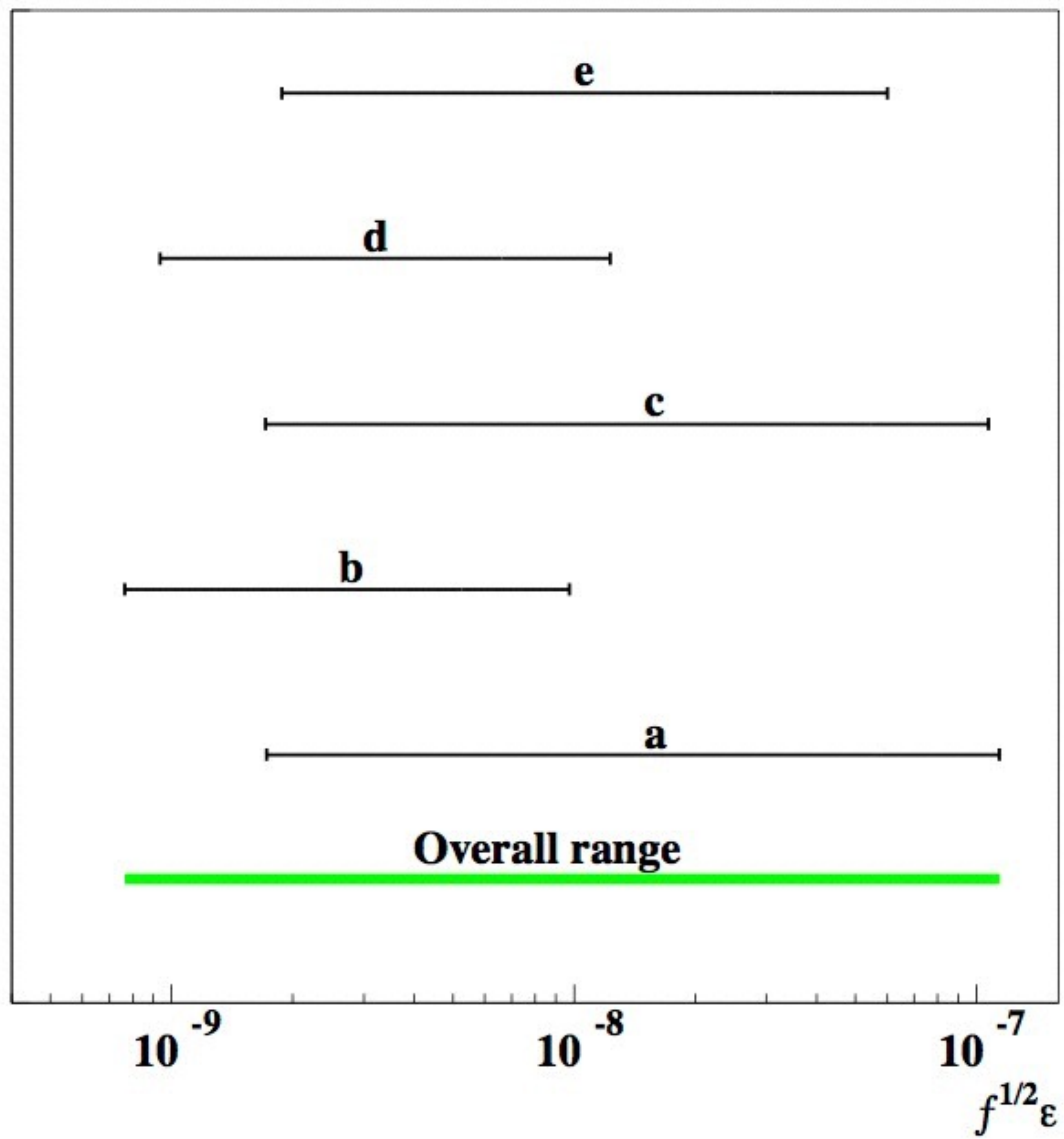
$\Lambda'/\Lambda \simeq 4$

$M'_A \sim 6$ GeV

the Bohr radius $a' = a/\zeta_d$, we obtain $\sigma_{A'A'}/M'_A \simeq 2\times 10^{-24}\ \mathrm{cm}^2/\mathrm{GeV}$

XENON is not sensitive there





e
d
c
b
a
Overall range
10 -9
10 -8
10 -7
f 1/2 ε

How we did it

Table 2: Results on the $\sqrt{f}\epsilon$ parameter in the considered scenarios obtained by analysing the DAMA data in a mirror DM framework as discussed in the text. For each scenario the best fit value of the $\sqrt{f}\epsilon$ parameter and the relative allowed interval (corresponding to model providing the deeper $\Delta\chi^2$) are reported as well as the cumulative allowed interval for $\sqrt{f}\epsilon$ obtained when considering all the above mentioned models. The allowed intervals identify the $\sqrt{f}\epsilon$ values corresponding to C.L. larger than 5σ from the *null hypothesis*, that is $\sqrt{f}\epsilon = 0$. See text.

Scenario	Quenching Factor	Channeling	Migdal	$\sqrt{f}\epsilon$ best	$\sqrt{f}\epsilon$ interval ($\times 10^{-9}$)
a	Q_I [4]	no	no	4.45×10^{-9} (9.2σ C.L.)	1.86–4.52 (all) 1.73–114.
b	Q_I [4]	yes	no	2.89×10^{-9} (9.3σ C.L.)	1.16–2.93 (all) 0.77–9.72
c	Q_I [4]	no	yes	4.40×10^{-9} (9.2σ C.L.)	1.85–4.47 (all) 1.72–107.
d	Q_{II} [87]	no	no	2.44×10^{-9} (9.5σ C.L.)	1.03–2.48 (all) 0.94–12.3
e	Q_{III} [87]-normalized	no	no	5.18×10^{-9} (9.0σ C.L.)	2.24–5.26 (all) 1.89–60.1

Long-range interactions:
No any collider bound

However, if other future experiments in preparation more similar to DAMA/LIBRA will not see any signal, then Dark Atoms cannot reconcile it with XENON/LUX/PANDA-X anymore from Mirror Dark atoms

Then we'd explore the heavier DM candidates.
DM may be heavier than thought before…
No any probes from colliders

Or Just around the 10 TeV corner?
In this case the only probe may be from Cosmic Rays,
i.e. Dark Matter Indirect Detection

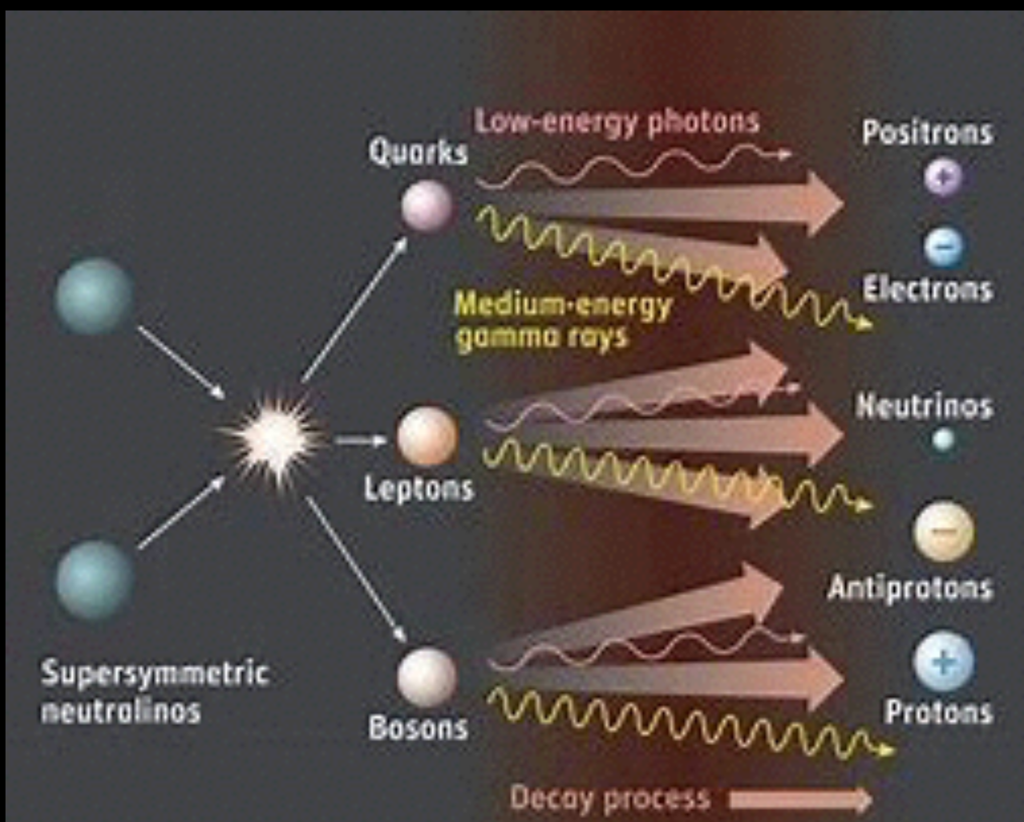
Possible DM genesis mechanisms

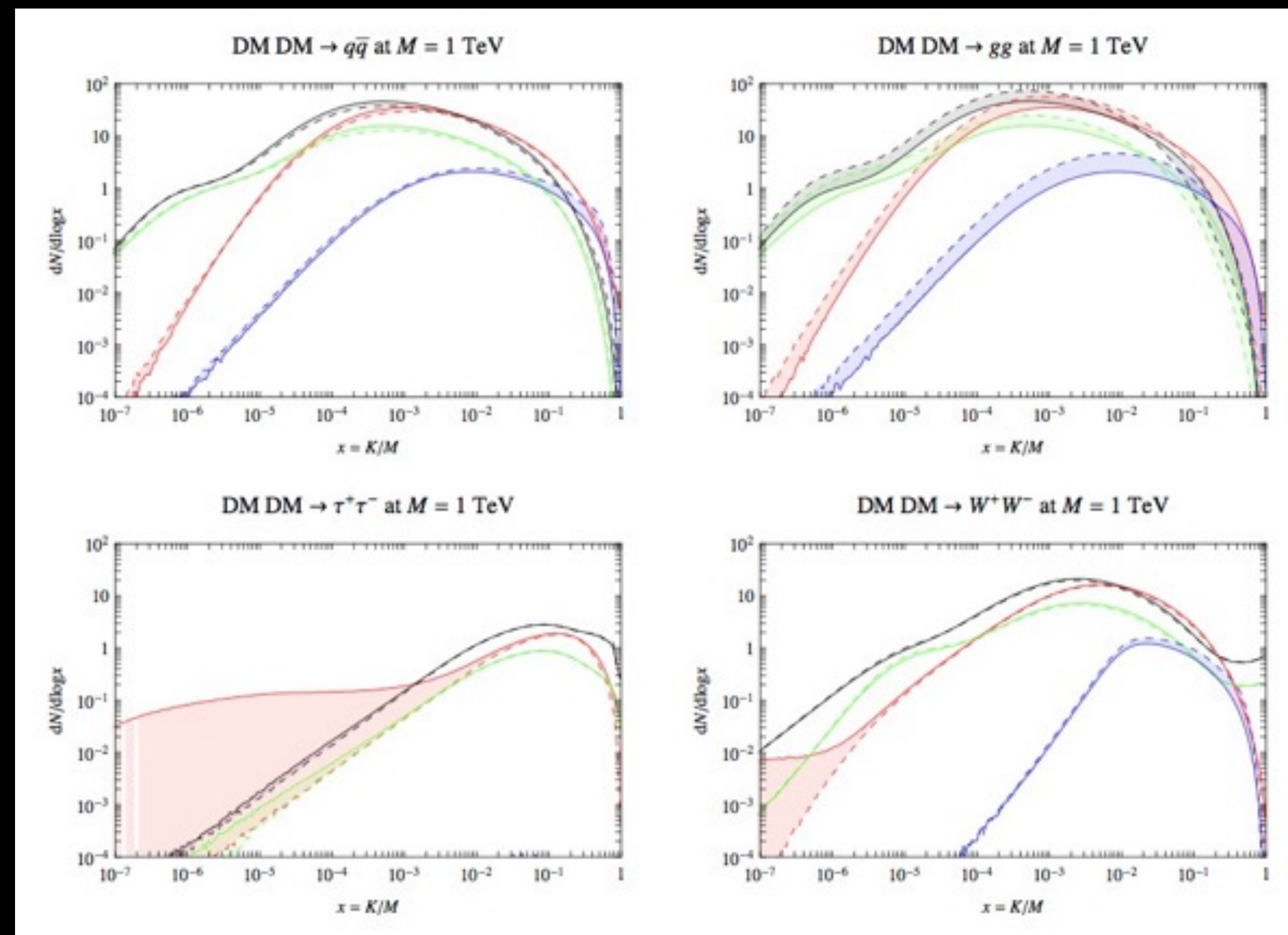
Thermal production: still allowed for around 100 TeV but it is beyond the perturbative unitarity bound; non-perturbative numerical effects.
If true we'd see annihilation signals in next experiments

non-thermal production: DM is produced after the reheating from processes out of the thermal equilibrium
such as inflaton decay, Schwinger effect during inflation, first order phase transitions, topological defect decays…

Heavy Dark Matter

Annihilation and decays





Photons (red), $e^{\pm}$ (green), $\bar{p}$ (blue), $\nu = \nu_e + \nu_\mu + \nu_\tau$ (black)

beyond TeV, beyond perturbativity bound!

An old standing idea:
Indirect searches for Dark Matter

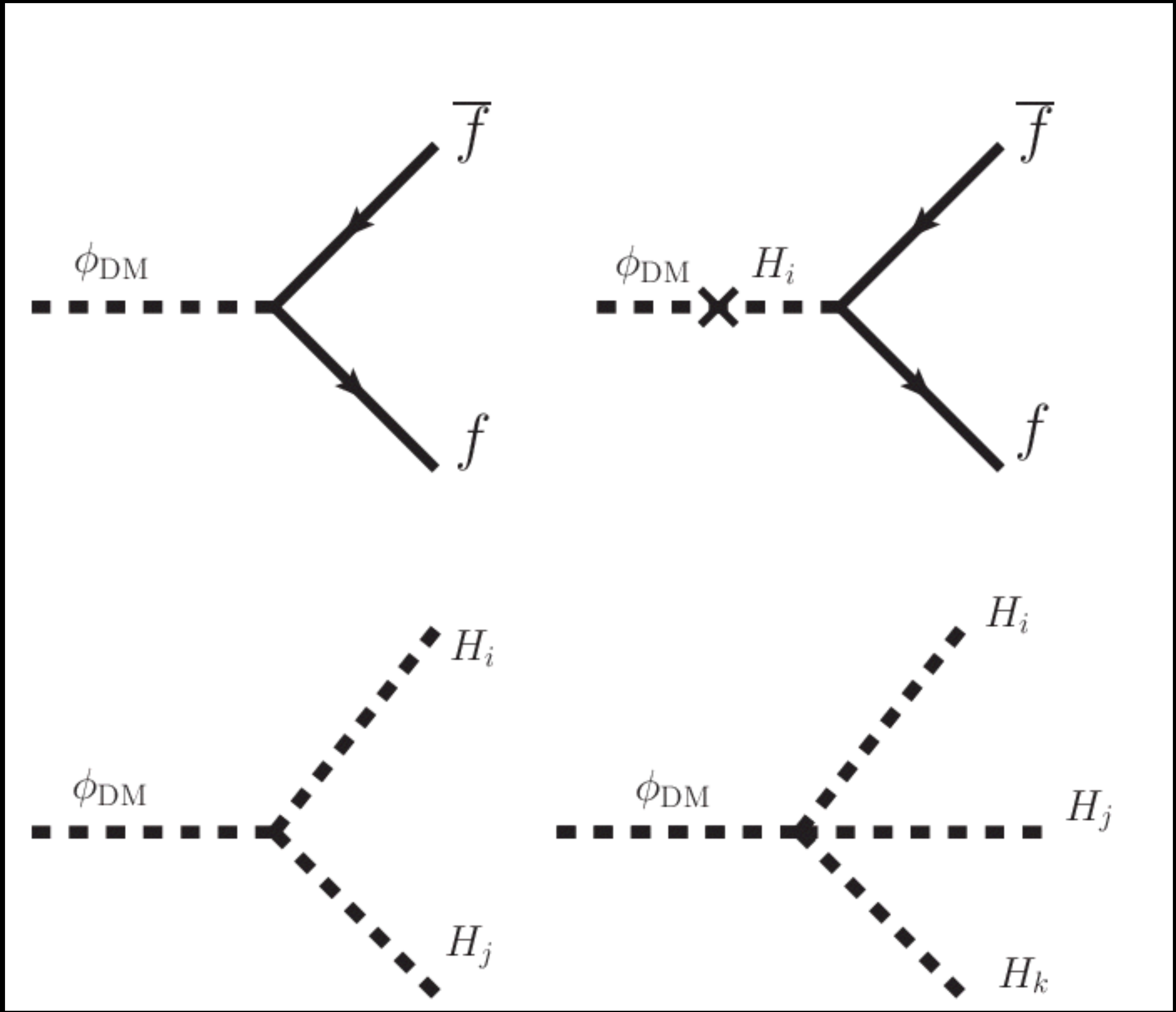
Astrophysical bounds on the mass of heavy stable neutral leptons

Ya. B. Zel'dovich, A. A. Klypin, M. Yu. Khlopov, and V. M. Chechetkin

Institute of Applied Mathematics, USSR Academy of Sciences
(Submitted 29 November 1979)
Yad. Fiz. **31**, 1286–1294 (May 1980)

Analytical and numerical calculations show that heavy neutral stable leptons are carried along by the collapsing matter during the formation of galaxies and possibly stars as well. The condensation in galaxies and stars results in appreciable annihilation of leptons and antileptons. Modern observations of cosmic-ray and γ-ray fluxes establish a limit $m_\nu \gtrsim 100$ GeV for the mass of neutral leptons, since annihilation of neutral leptons produces γ rays and cosmic rays. The obtained bound, in conjunction with ones established earlier, precludes the existence of stable neutral leptons (neutrinos) with $m_\nu > 30$ eV.

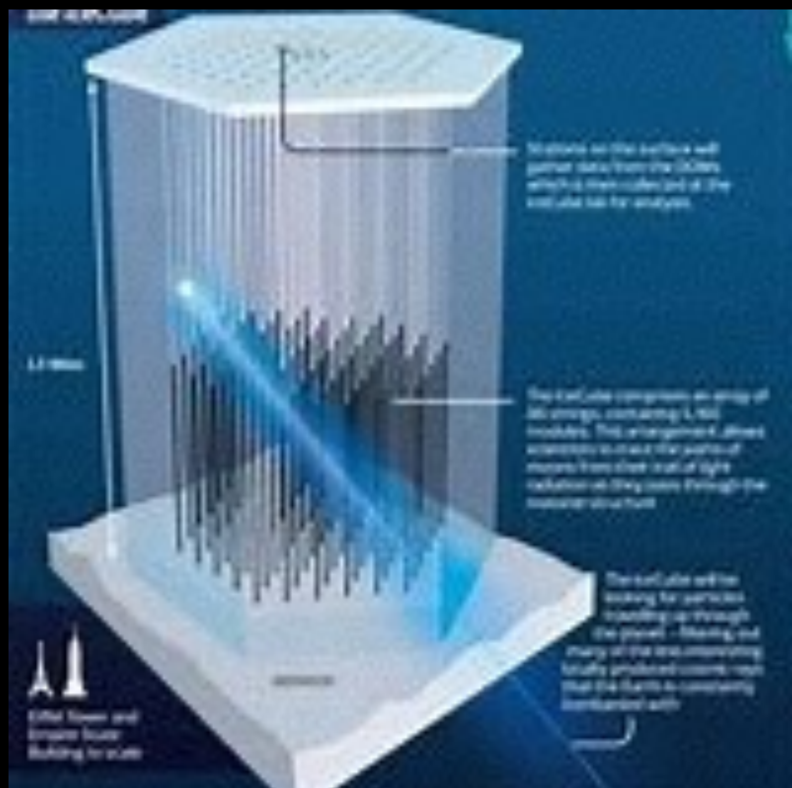
DM decays

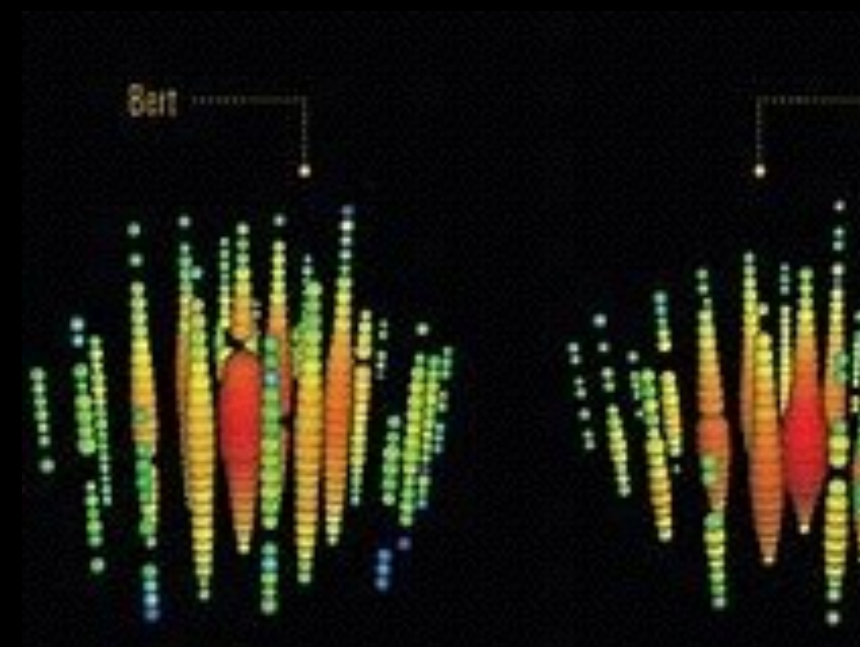

$\overline{f}$
$\phi_{\rm DM}$
f
$\overline{f}$
$\phi_{\rm DM}$
H_i
f
H_i
$\phi_{\rm DM}$
H_j
H_i
$\phi_{\rm DM}$
H_j
H_k

"Hit when it hurts!"

(Ninjitsu master)

Dark Matter or Violent Astrophysics in IceCube?





ICECUBE
SOUTH POLE NEUTRINO OBSERVATORY

The IceCube puzzle

PeV Dark matter decays or astrophysical sources?

Multi-messengers will suggest us it in the next years

Theoretical side: motivations and possible candidates for PeV DM

supersymmetry can be broken at higher scales. In this case it has nothing to do with the hierarchy problem of the Higgs mass

If Supersymmetry is broken around the inflation scale, then inflation and DM can be unified in Starobinsky's supergravity

In this case the inflaton behaves as Starobinsky's inflation while DM is provided by gravitons, in turn naturally much heavier than the TeV-scale

Addazi, Khlopov, Ketov et al 2016-2020

Heavy Gravitino decays

$\tilde{G} \to \gamma\nu$

$y_{hL} H_\alpha L^\alpha \longrightarrow \frac{S^n}{\Lambda^n} h_\alpha L^\alpha$

$$L_{int} = -\frac{i}{8M_{Pl}} \bar{\psi}_\mu [\gamma^\nu, \gamma^\rho] \gamma^\mu \lambda F_{\nu\rho}$$

$$\Gamma(\tilde{G} \to \gamma\nu) = \frac{\cos^2\theta_W}{32\pi} \frac{m_\nu}{m_\chi} \frac{m_{\tilde{G}}^3}{M_{Pl}^2} \left(1 - \frac{m_\nu^2}{m_{\tilde{G}}^2}\right)^3 \left(1 + \frac{m_\nu^2}{3m_{\tilde{G}}^2}\right)$$

Gamma rays and DM decays

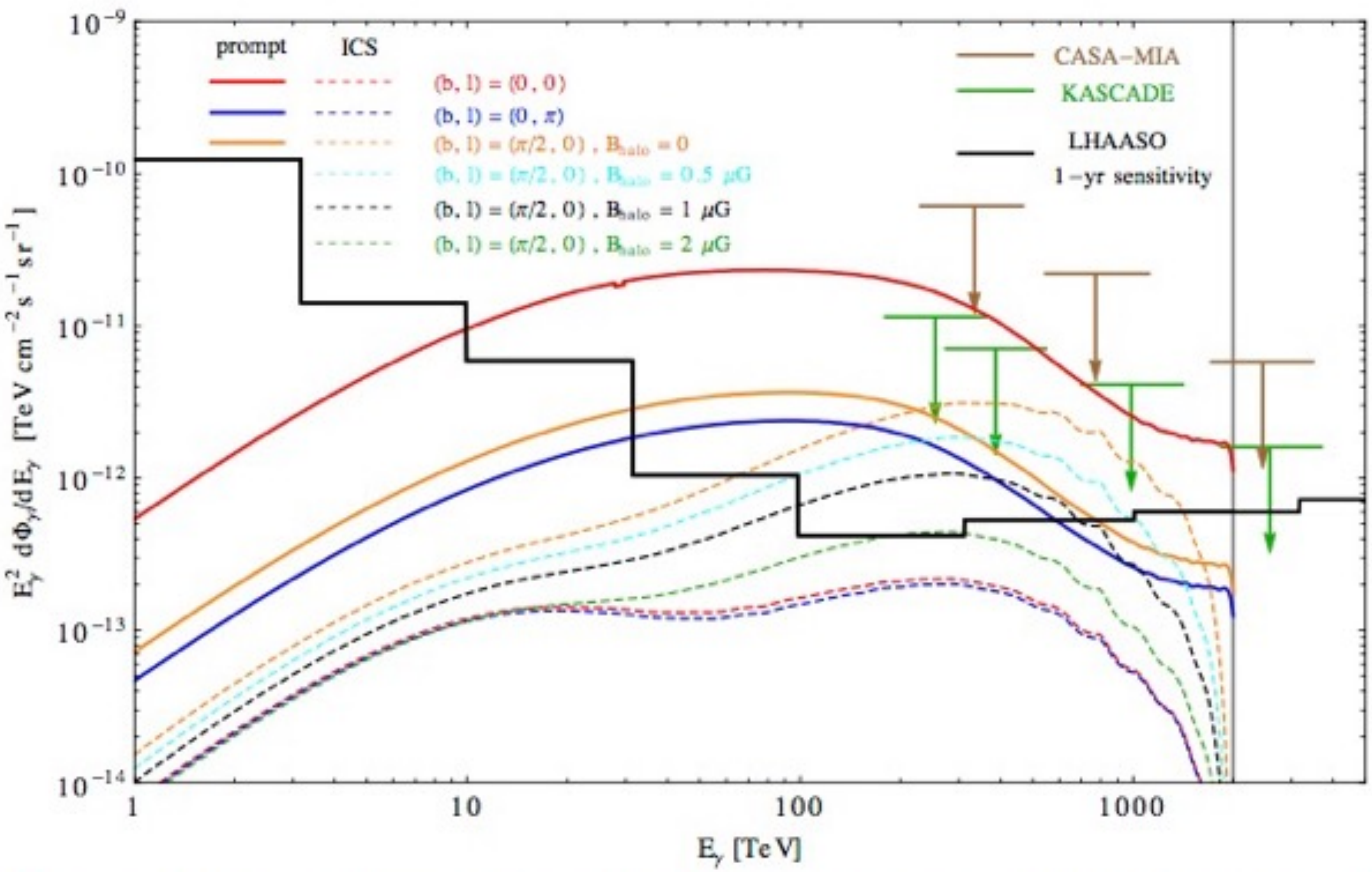


Fig. 1. The γ-ray flux from DM decay from various directions, with $m_{\rm DM}$=4 PeV and $\tau_{\rm DM}=10^{28}$ s, and branching ratios reported in the text. The solid colored curves show the prompt flux, including the absorption of γ-rays; different colors represent different directions in the sky. The dashed curves show the IC flux, for various assumptions for the constant halo magnetic field, $B_{\rm halo}$, possibly pervading the thick diffusive halo of the Galaxy up to large distances. The green and brown bar lines show the upper bound on γ-ray flux from CASA-MIA [71] and KASCADE [72], respectively. The black line is an indicative 1 yr LHAASO sensitivity.

Addazi, Cirelli, Panci, Sala, Semikoz, Serpico et al

For the LHAASO book in preparation

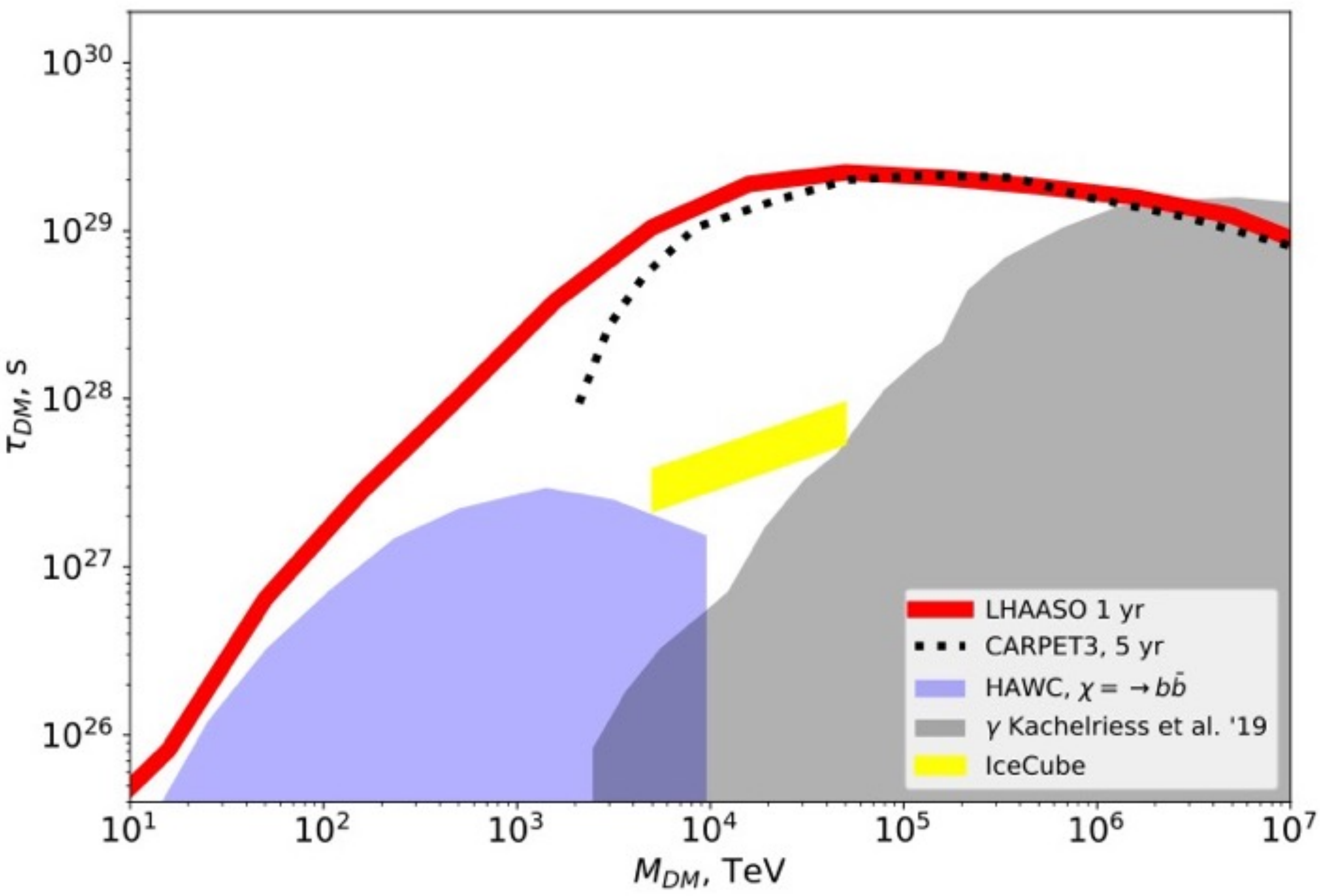


Fig. 2. Sensitivity of LHAASO for the measurement of dark matter decay time (for DM decaying into quarks). Yellow band shows the range of decay times for which DM decays give sizeable contribution to the IceCube neutrino signal [74]. Blue and grey shaded regions show the existing bounds imposed by HAWC [69] and ultra-high-energy cosmic ray experiments [75]. and dashed cureves are from the HAWC search of the DM decay signal in the Fermi Bubble regions [69]. From [53].

Addazi, Cirelli, Panci, Sala, Semikoz, Serpico et al

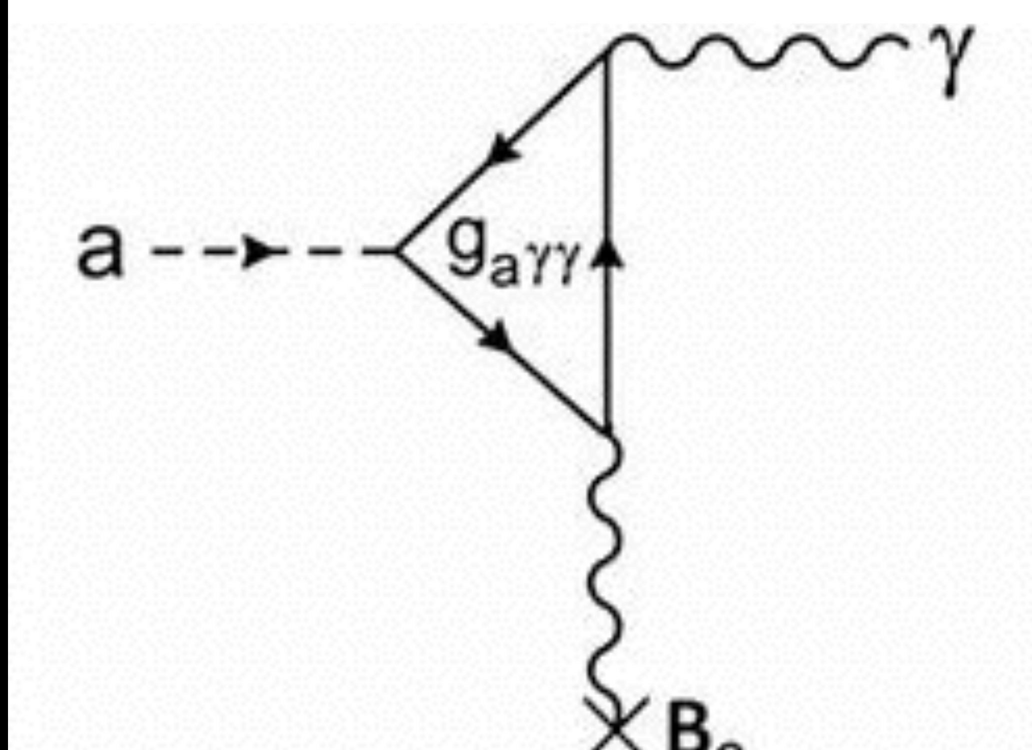
On the other hand

The high energy frontier does not necessary mean only a test for heavy new states!

Test of ALPs?

Axion-like-particles in CR propagation

$$\mathcal{L}_{\phi\gamma} = -\frac{1}{4M} F^{\mu\nu} \tilde{F}_{\mu\nu} \phi = \frac{1}{M} \mathbf{E} \cdot \mathbf{B} \phi$$



$$(E - i\partial_z - M)\vec{A} = 0$$

$$\vec{A} = \begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix}$$

$$M = \begin{bmatrix} \Delta_{11} & \Delta_{12} & \Delta_{a\gamma} c_\phi \\ \Delta_{12} & \Delta_{22} & \Delta_{a\gamma} s_\phi \\ \Delta_{a\gamma} c_\phi & \Delta_{a\gamma} s_\phi & \Delta_a \end{bmatrix}$$

QCD axion: CP problem solved

Peccei-Quinn, Wilczek, Weinberg

$$m \simeq 0.7 \cdot k \left(\frac{10^{10}\,\mathrm{GeV}}{M} \right) \mathrm{eV}$$

Neutrino and composite axions

Dvali & Funcke; Addazi, Capozziello, Odintsov (2016)

no-QCD ALPs from string compactifications? (Witten et al)

Gamma rays transparency

$$P^{(0)}_{\gamma\to\phi}(x) = \sin^2 2\theta \, \sin^2\left(\frac{\Delta_{\rm osc}\, x}{2}\right) \quad \theta = \frac{1}{2}\arcsin\left(\frac{B_{\rm T}}{M\,\Delta_{\rm osc}}\right) \quad \Delta_{\rm osc} = \left[\left(\frac{m^2-\omega_{\rm pl}^2}{2E}\right)^2 + \left(\frac{B_{\rm T}}{M}\right)^2\right]^{1/2}$$

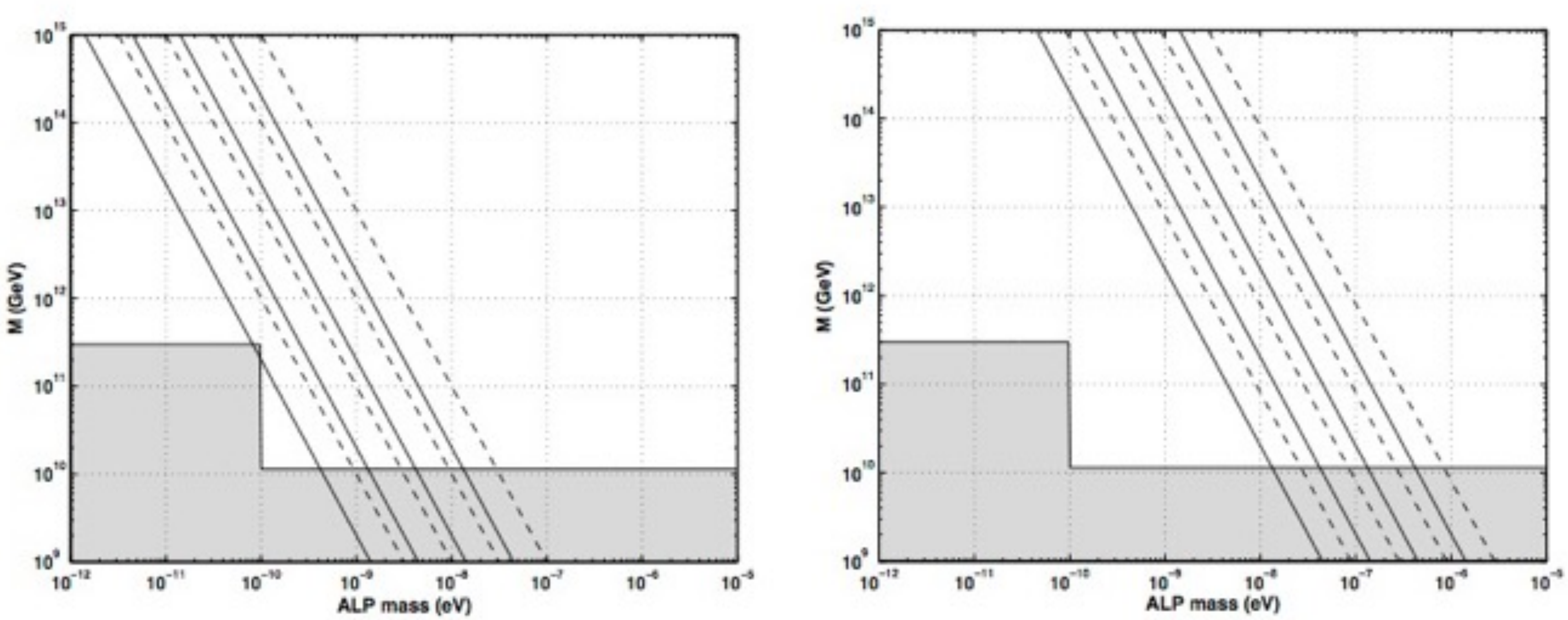


Fig. 2. Left panel: values of the pair (m, M) which determine the critical energy $E_* = 1$ GeV, 10 GeV, 100 GeV and 1 TeV (from left to right) for a magnetic field strength of $B = 1 \cdot 10^{-9}$ G (solid line) and $B = 5 \cdot 10^{-9}$ G (dotted line) and a plasma frequency $\omega_{\rm pl} \sim 10^{-14}$ eV. The gray region represents the values excluded by astrophysical arguments and by the CAST experiment.
Right panel: same as left panel, but with $B = 1{\cdot}10^{-6}$ G (solid line) and $B = 4{\cdot}10^{-6}$ G (dotted line) and a plasma frequency $\omega_{\rm pl} \sim 10^{-12}$ eV.

Roccardelli, De Angelis et al in many papers for Blazars

Pheno in Perseus D. Malyshev[1], A. Neronov[2], D. Semikoz[3,4], A. Santangelo[1], J. Jochum[5]

On the other hand

Dark Matter does not necessary mean Weak interacting Massive particles

SIMPs?

SIMP (Strongly Interacting Massive Particles) and Multiple Charged "Exotic" Leptons

Nuclear-interacting composite dark matter: O-helium «atoms»

If we have a stable double charged particle X^{--} *in excess over its partner* X^{++} *it may create Helium like neutral atom (O-helium) at temperature* $T < I_o$

$$R_o = 1/(ZZ_{He}\alpha m_{He}) = 2\cdot 10^{-13}\,cm$$

$$I_o = Z_{He}^2 Z_\Delta^2 \alpha^2 m_{He} = 1.6\,MeV$$

$$X^{--} + {}^4He \Rightarrow (X\,He) + \gamma$$

^4He is formed at T ~100 keV (t~100 s)
This means that it would rapidly create a neutral atom, in which all X^{--} are bound

The Bohr orbit of O-helium « atom » is of the order of radius of helium nucleus.

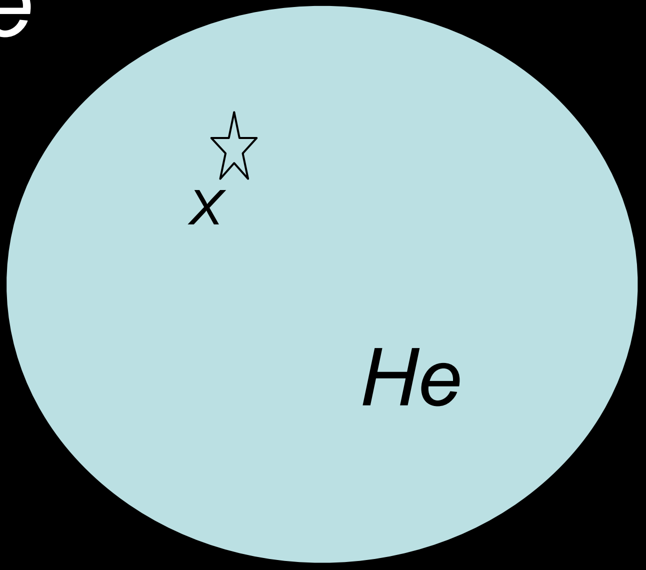
Khlopov et al 06',

Stable multiple charged particles

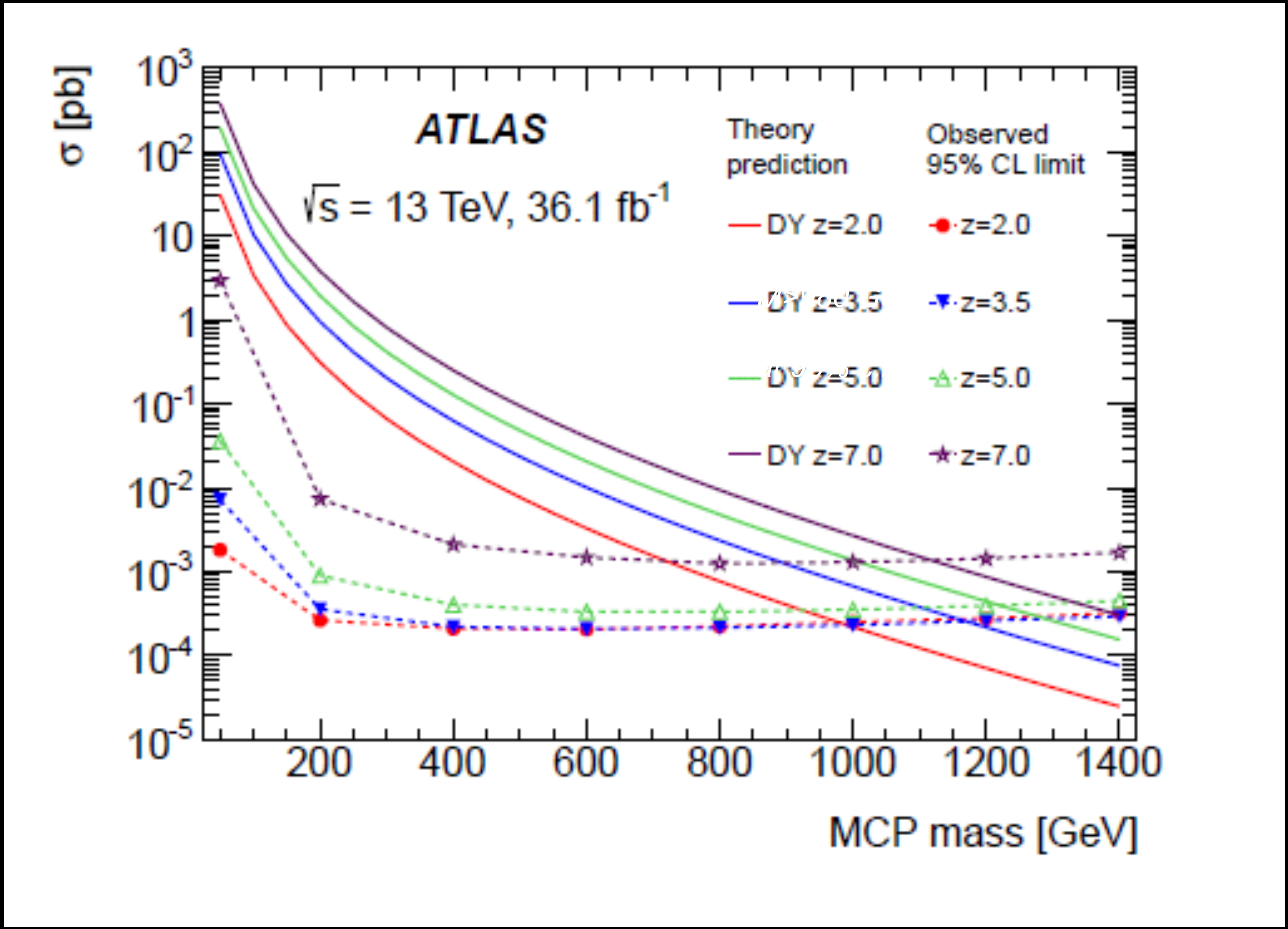
Walking Technicolor

q	$UU(q+1)$	$UD(q)$	$DD(q-1)$	$\nu'(\frac{1-3q}{2})$	$\zeta(\frac{-1-3q}{2})$
1	**2**	1	0	−1	**−2**
3	**4**	3	**2**	**−4**	−5
5	**6**	5	**4**	−7	**−8**
7	**8**	7	**6**	**−10**	−11

-2n charged particles in WTC bound with n nuclei of primoridal He form Thomson atoms of XHe



ATLAS



[ATLAS Collaboration, Search for heavy long-lived multi-charged particles in proton-proton collisions at √ s= 13 TeV using the ATLAS detector. Phys. Rev. D 99, 052003 (2019)

M>980 GeV for |q|=2e at 95% c.l.

Exotic multi-charged Leptons:

In principle they may be distinguished by nuclear CR

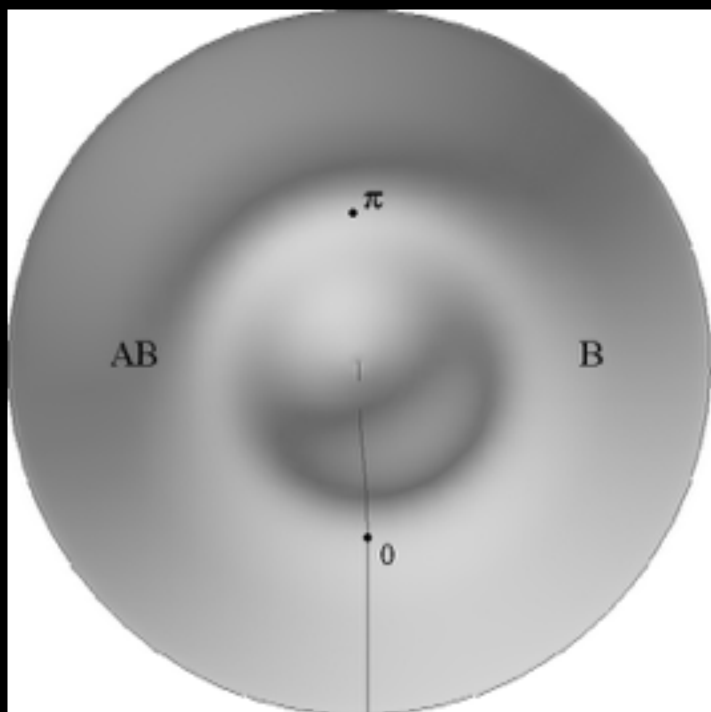
They may form a completely electromagnetic shower in atmosphere

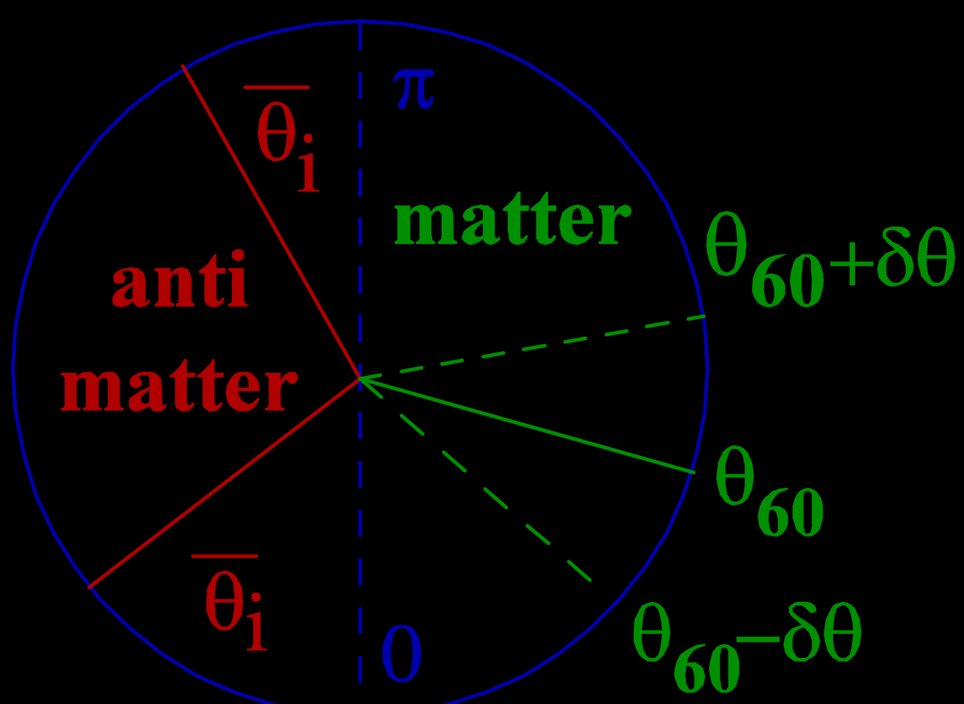
— testable in LHAASO???

(Addazi and Khlopov in private conversations)

Exotic Remnants from the Early Universe

Antimatter "island"





- *Spontaneous baryosynthesis* provides quantitative description of combined effects of inflation and not homogeneous baryosynthesis, leading to formation of **antimatter domains**, surviving to the present time.

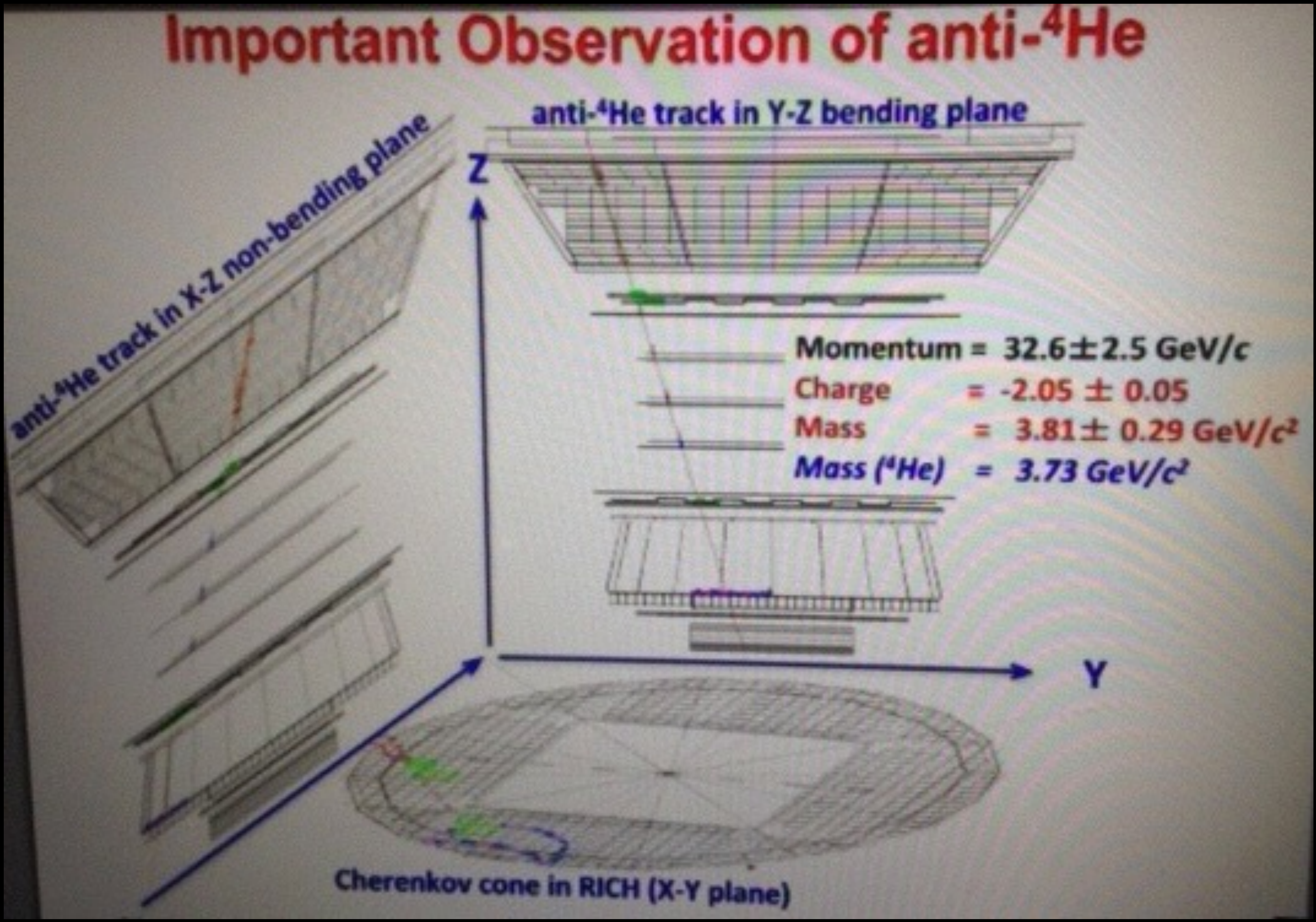
Searches for Antimatter nuclei and radiation from dark matter annihilation

Number of e-fold	Number of domains	Size of domain
59	0	$1103Mpc$
55	$5.005 \cdot 10^{-14}$	$37.7Mpc$
54	$7.91 \cdot 10^{-10}$	$13.9Mpc$
52	$1.291 \cdot 10^{-3}$	$1.9Mpc$
51	0.499	$630kpc$
50	74.099	$255kpc$
49	$8.966 \cdot 10^{3}$	$94kpc$
48	$8.012 \cdot 10^{5}$	$35kpc$
47	$5.672 \cdot 10^{7}$	$12kpc$
46	$3.345 \cdot 10^{9}$	$4.7kpc$
45	$1.705 \cdot 10^{11}$	$1.7kpc$

Anti globular clusters in our Galaxy, from around 1000 to 100000

M. Khlopov (1998)

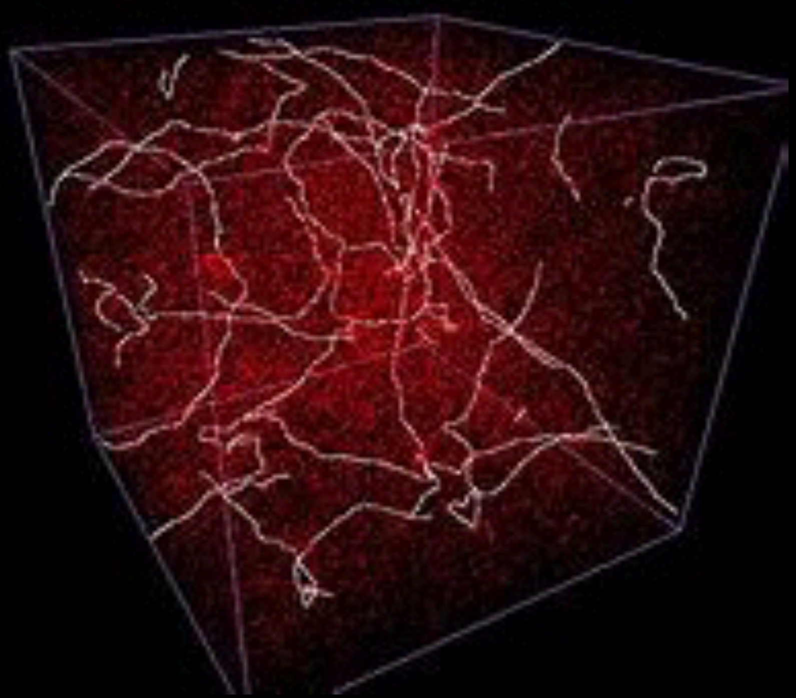
First signal from antimatter stars in AMS02?



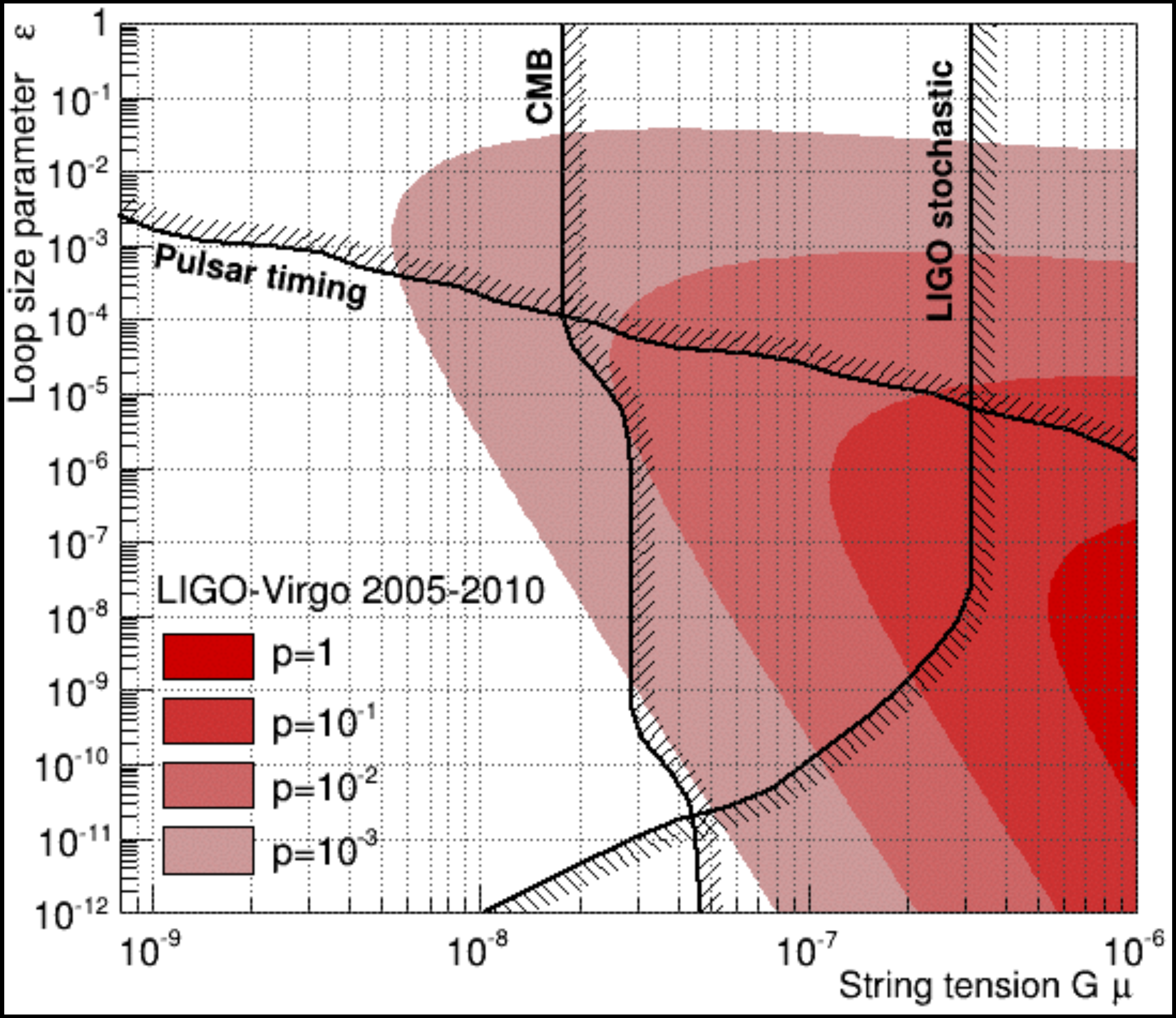
Samuel Ting, CERN, 24 May 2018

Topological Defects

Cosmic Strings



Berezinsky, Vilenkin et al



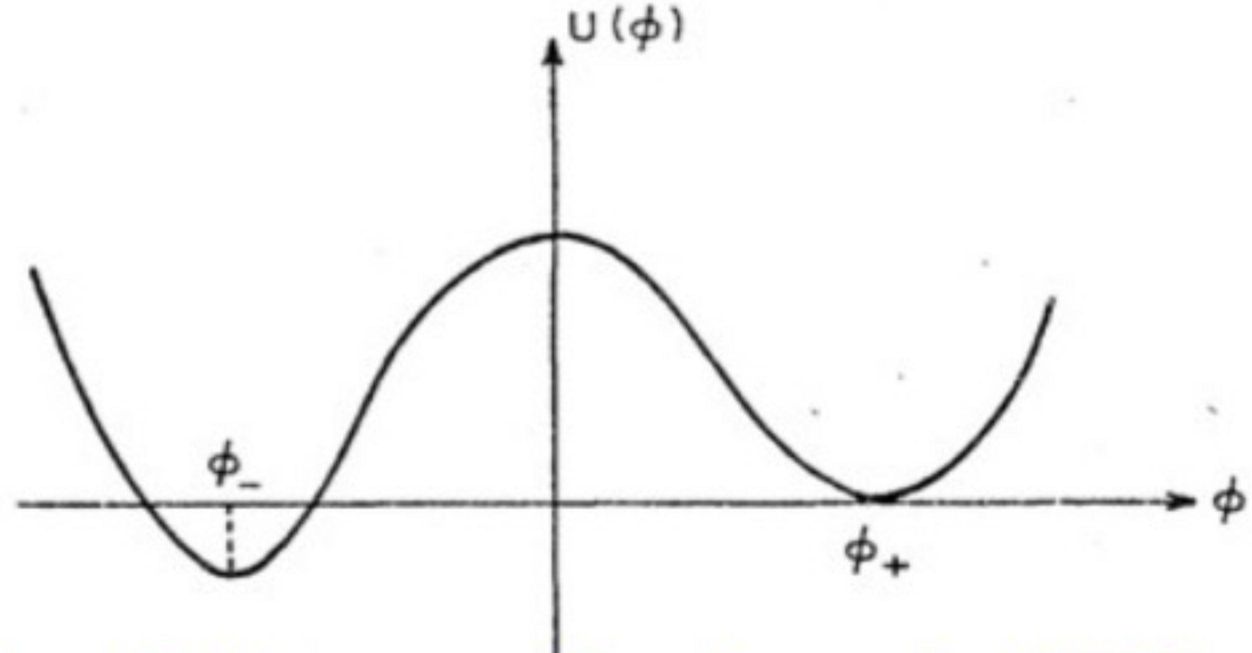
This is really genuine
Multi-Messenger New Physics:
GW, Gamma rays, UHECR comparions

What about Gravitational Waves

Test of the first order phase transitions beyond the standard model!

Gravitational Waves Radiation (GWR) as the NEW CMB?

Coleman's idea '77



Tunneling mediated by Coleman-De Luccia ('80) instanons. First order phase transitions and

Materialization of Bubbles

Bubbles!

Latent energy $$\mathcal{E}(\bar{T}) = \left[T\frac{dV_{eff}}{dT} - V_{eff}(T)\right]_{T=\bar{T}},$$

$$\alpha = \frac{\mathcal{E}(\bar{T})}{\rho_{rad}(\bar{T})}, \ \ \rho_{rad} = \frac{\pi^2}{30}g_*(T)T^4.$$

Bubble nucl.par $$\beta = -\left[\frac{dS_E}{dt}\right]_{t=\bar{t}} \simeq \left[\frac{1}{\Gamma}\frac{d\Gamma}{dt}\right]_{t=\bar{t}},$$

$$S_E(T) \simeq \frac{S_3(T)}{T}, \ \ \Gamma = \Gamma_0(T)\exp[-S_E(T)],$$

$$\Gamma_0(T) \sim T^4, \ \ S_3 \equiv \int d^3r\left(\partial_i s^\dagger \partial_i s + V_{eff}(s,T)\right).$$

Test of the electroweak phase transition:
a first order electroweak scale corresponds to a GW signal around the mHZ.
LISA pathfinder

The first order electroweak phase transitions are necessary beyond the minimal SM.

If we see it, the Higgs will be coupled with a new scalar partner.

Double channels in future Higgs factories like CEPC and GW experiments like LISA!

The case of Majoron

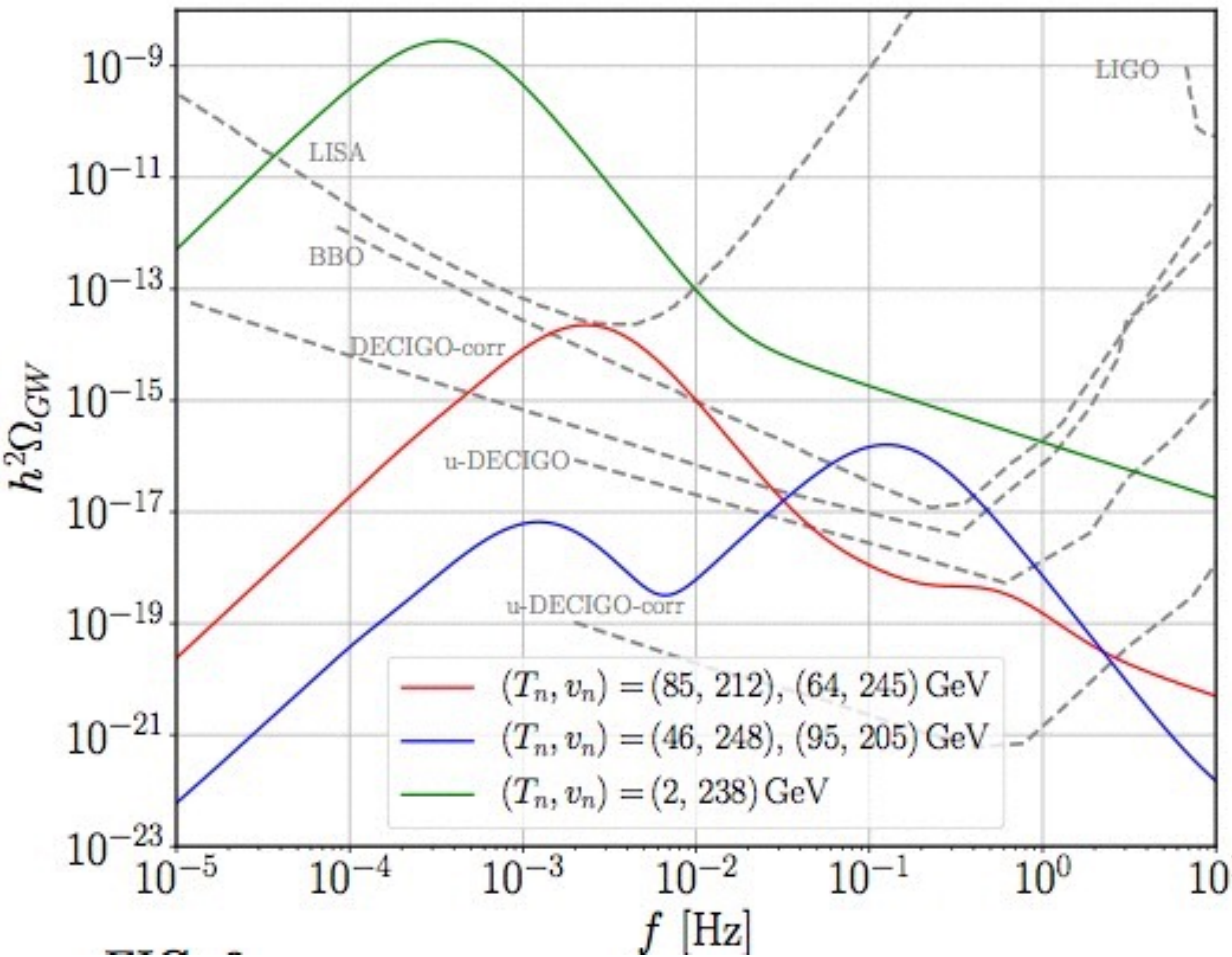
A simple model for ***Dark Matter*** and ***neutrino mass***

A. Addazi, M. Marciano, Y. Cai, J. Valle, R. Pasechnick, A. Morais (PLB 2020)

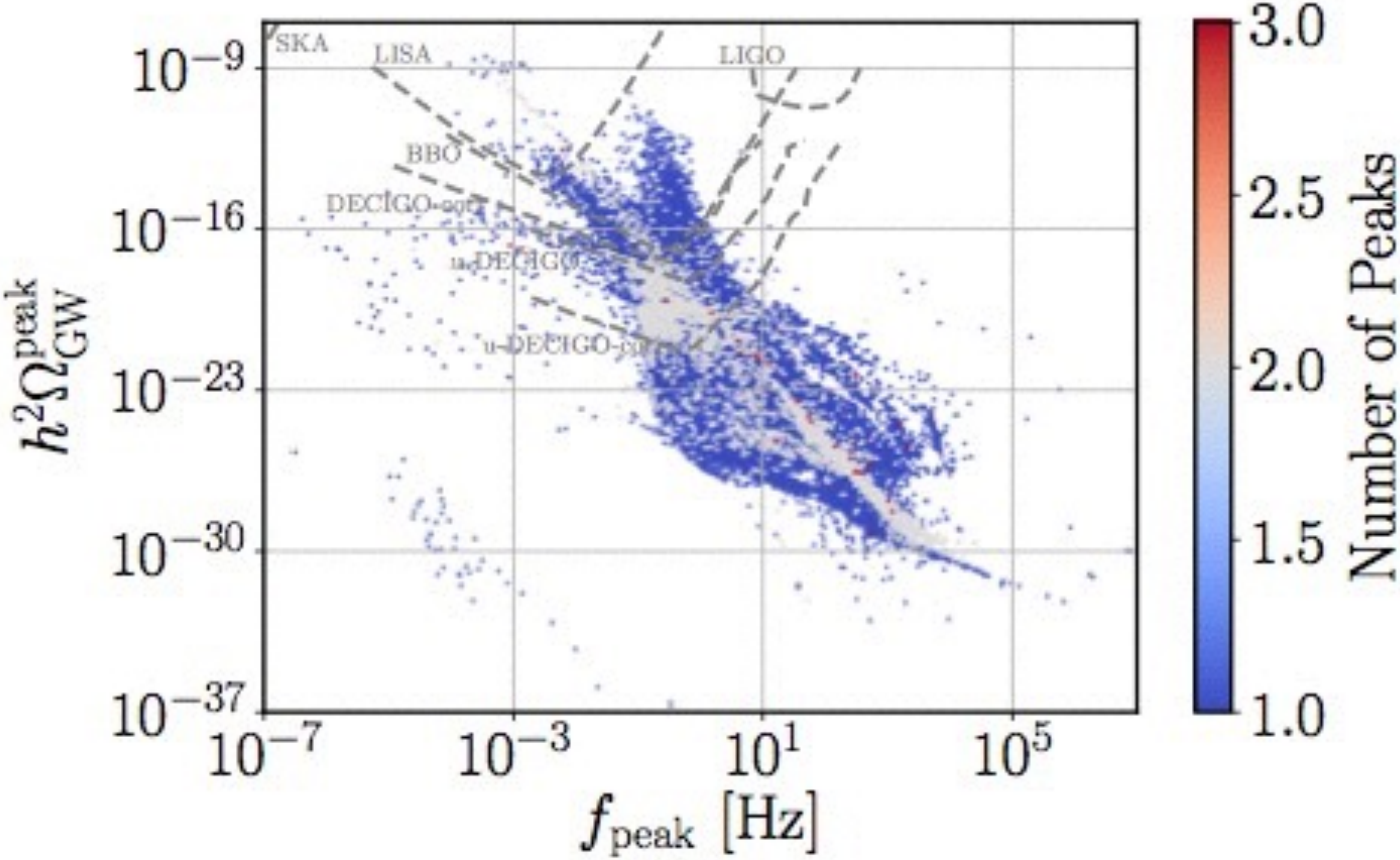
Majoron & Inverse see-saw type-I

$$\mathcal{L}_{\text{Yuk}}^{\text{lept}} = \mathcal{L}_{\text{Yuk}}^{\text{SM}} + Y_\nu \bar{L}^c \Phi \nu^c + M \nu^c S + \mu S S + \text{h.c.}$$

$$\mathcal{M}_\nu = \begin{bmatrix} 0 & Y_\nu^T \langle \Phi \rangle & 0 \\ Y_\nu \langle \Phi \rangle & 0 & M^T \\ 0 & M & \mu \end{bmatrix}$$



LIGO
LISA
BBO
DECIGO-corr
u-DECIGO
u-DECIGO-corr
$(T_n, v_n) = (85, 212), (64, 245)$ GeV
$(T_n, v_n) = (46, 248), (95, 205)$ GeV
$(T_n, v_n) = (2, 238)$ GeV
$h^2\Omega_{GW}$
f [Hz]
10^{-9}
10^{-11}
10^{-13}
10^{-15}
10^{-17}
10^{-19}
10^{-21}
10^{-23}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}



SKA
LISA
LIGO
BBO
DECIGO
u-DECIGO
10^{-9}
10^{-16}
10^{-23}
10^{-30}
10^{-37}
$h^2\Omega_{\rm GW}^{\rm peak}$
10^{-7}
10^{-3}
10^{1}
10^{5}
$f_{\rm peak}$ [Hz]
3.0
2.5
2.0
1.5
1.0
Number of Peaks

… Beyond the Electroweak scale!

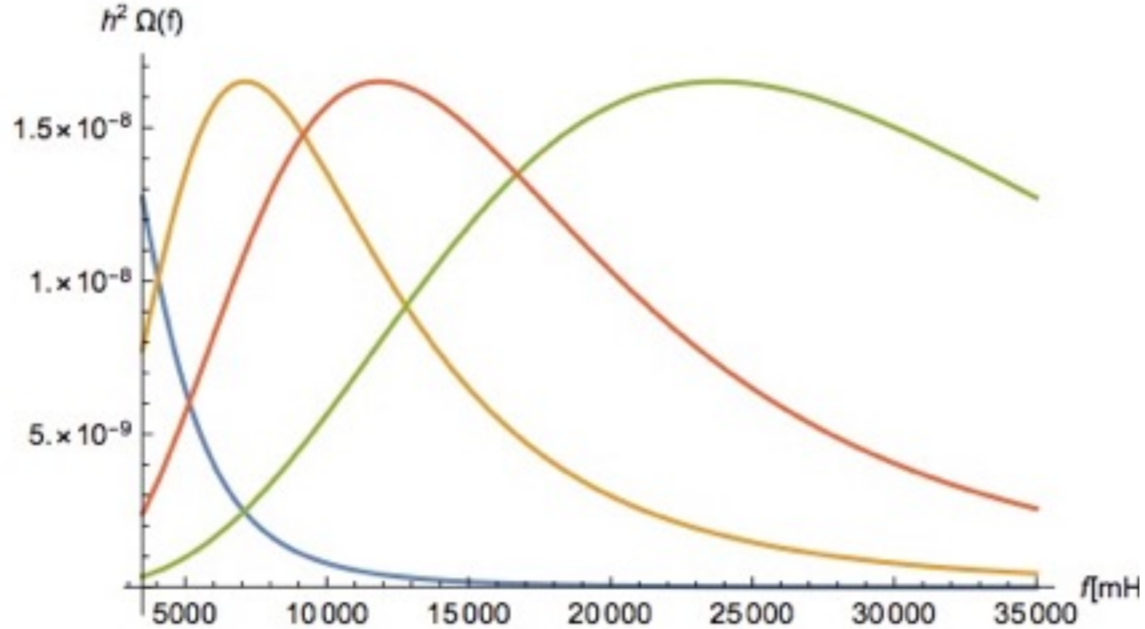


FIG. 1. Examples of non-runaway cases are displayed, wi the same value of the parameters $v_w = 0.8$, $\alpha = 0.9$, $g_* \simeq g_S$ and $\beta/H_* = 10$, but with varying FOPT temperature, name $T_*/(10^8\,\mathrm{GeV}) = \{0.1, 0.3, 0.5, 5\}$, corresponding to the blu orange, red and green lines, respectively.

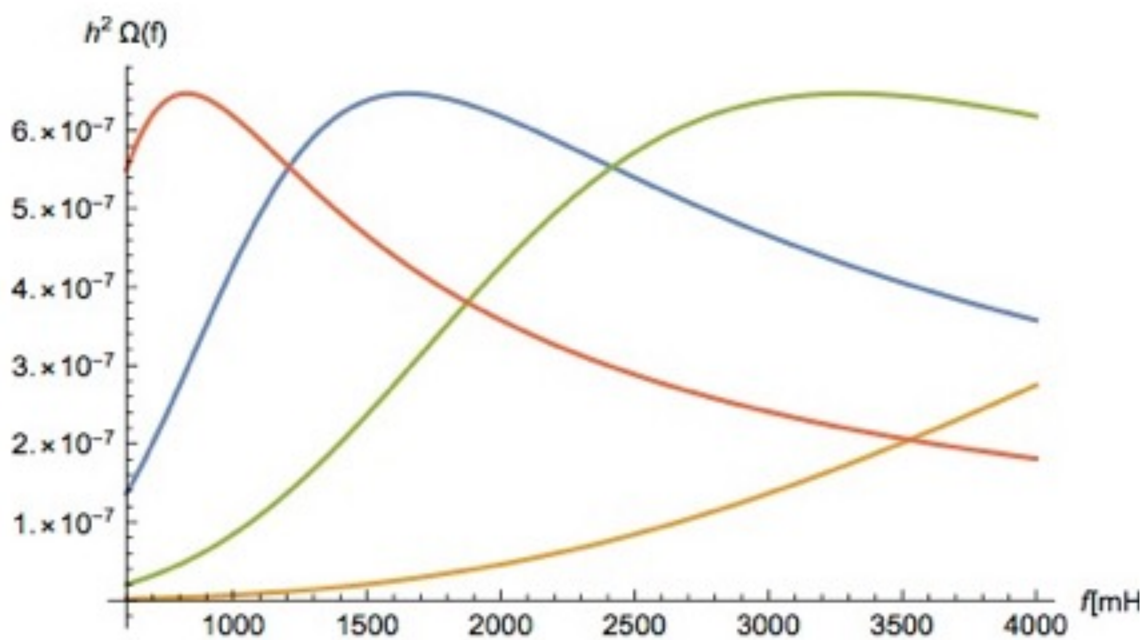


FIG. 2. Examples of runaway cases are displayed, with sar $v_w = 1$, $\alpha = 1$, $g_* \simeq g_{\mathrm{SM}}$, $\beta/H_* = 10$ and $T_*/(10^8\,\mathrm{GeV})$ $\{0.5, 1, 2, 5\}$ in red, blue, green, orange lines, respectively.

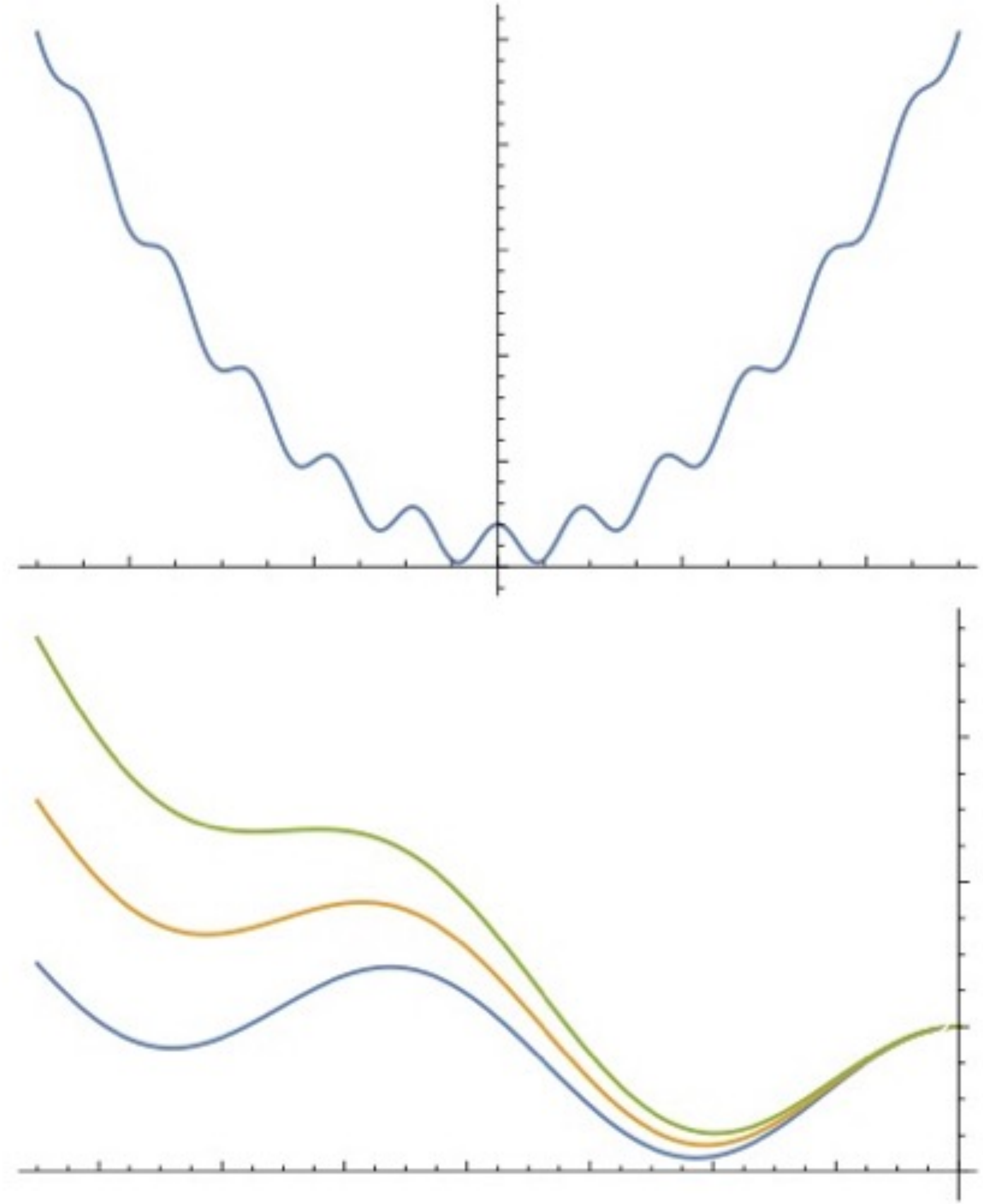


FIG. 3. A typical axion monodromy potential as a function of the inflaton field, $V(a)$. In the first figure, we consider the non-thermally corrected potential while in the second figure we show the relevant corrections from thermal field theory to the last false minima, close to the reheating epoch, triggering an efficient phase transition when the thermal corrections are comparable with the local potential curvature. In this plot, we compared thermal corrections in the range $T/(10^8\,\mathrm{GeV}) = (0, 0.5, 1\,\mathrm{GeV})$,within the illustrative simplified case that the inflaton coupling with fermion species is equal to one.

Other scenarios:

GW from Dark SM
Addazi 2015

GW from Dark U(1)
Addazi, Marciano 2017

GW from
Majoron itself decoupled by the
Higgs
Addazi, Marciano 2017

Conclusions (as a starting point)

To predict where New Physics beyond the TeV frontier will appear out is a "nearly impossible mission";

However new physics is "urgently necessary", i.e. it is Not just a *"why? why not?" sophism*

Now Multi-messenger astroparticle physics appear pretty urgent: a lot data coming soon

Colliders? We can wait

Let's not forget rare process physics and neutrinos

Therefore, I suggest to try…

Defeatist attitudes will lose by definition.

A non-zero lottery chance for "Contemporary antimatter" discovery…

it may be just around the corner…

Thank You for the attention