Fundamental physics with LHAASO

…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…”Home is burning!”

HOW (Do we solve it)?

LA SAPIENZA ROME

TOR VERGATA ROME

APC PARIS

LUND UNIVERSITY

MEPHI MOSCOW

TMP TOMSK

SFedU ROSTOV

L’Aquila University

New York University (NYU)

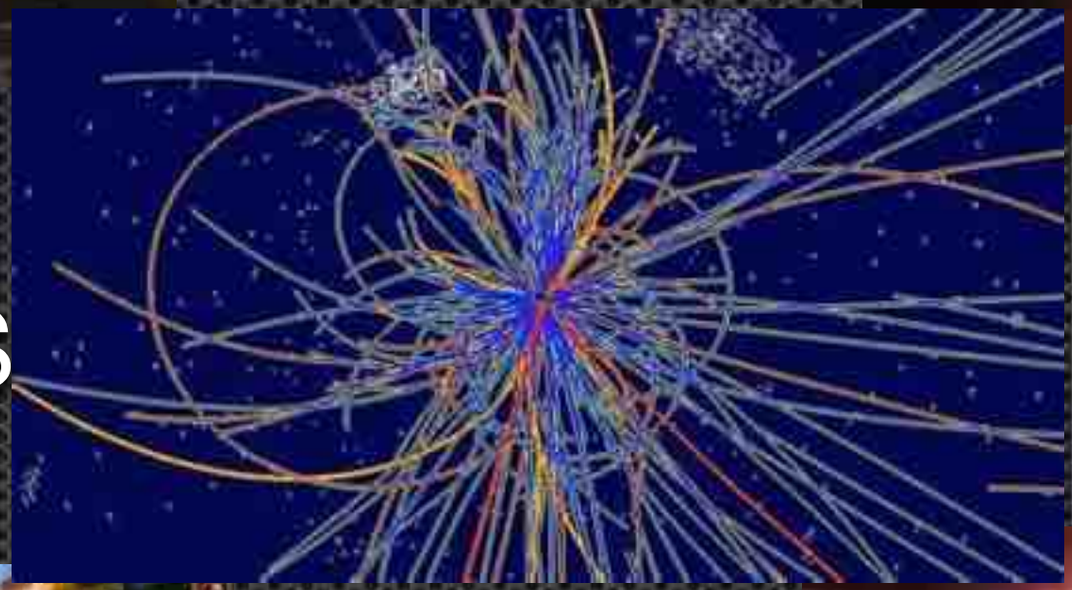
Gran Sasso Laboratory (LNGS)

CERN Geneve

COST Action

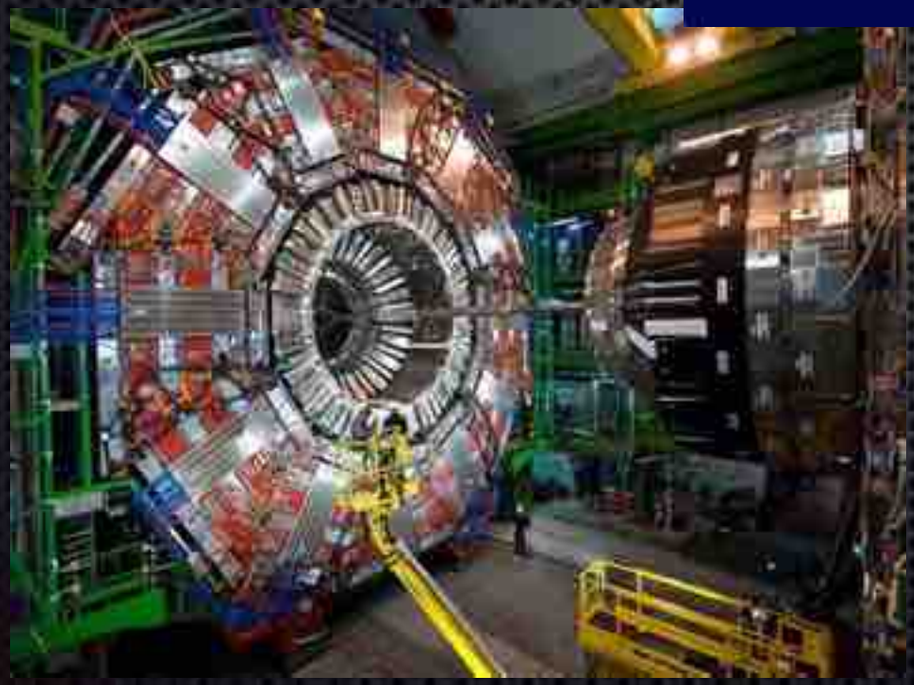
An interesting duality

Extreme High energy Physics



Colliders

CR



Time scales

Next colliders?

in 40-50 years…

But next lower energy data, eventually, soon

Astroparticle CR experiments?

Next Physics in

Next 10/20 years

Gravitational waves?

Powerful in the

“Multi-messenger arena”

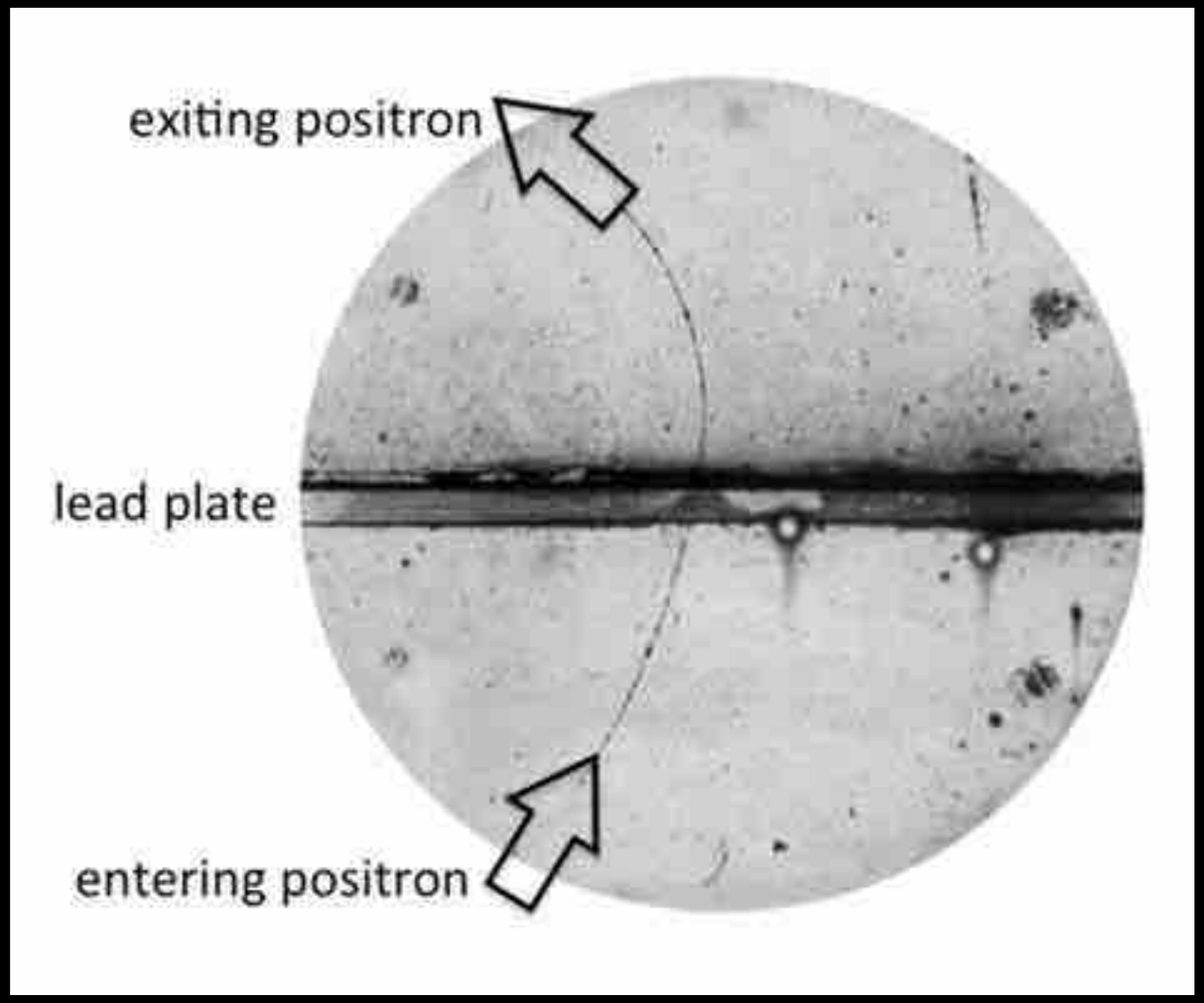
Opportunities from CR

A “plethora” of new data is coming

We need to be ready *or* we miss potentially mastodontic opportunities

Searching for new physics

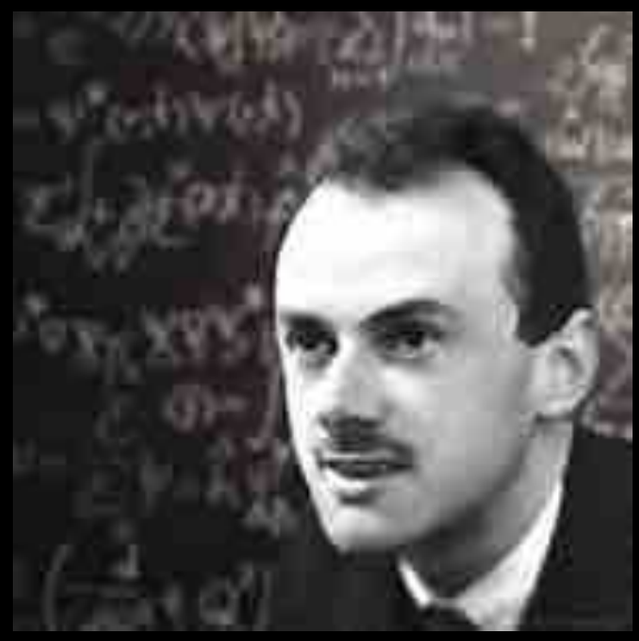
History: antimatter discovery in cosmic rays



Cloud Chambers, *Anderson 1932; Blackett & Occhialini*

The “power” of theoretical predictions

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



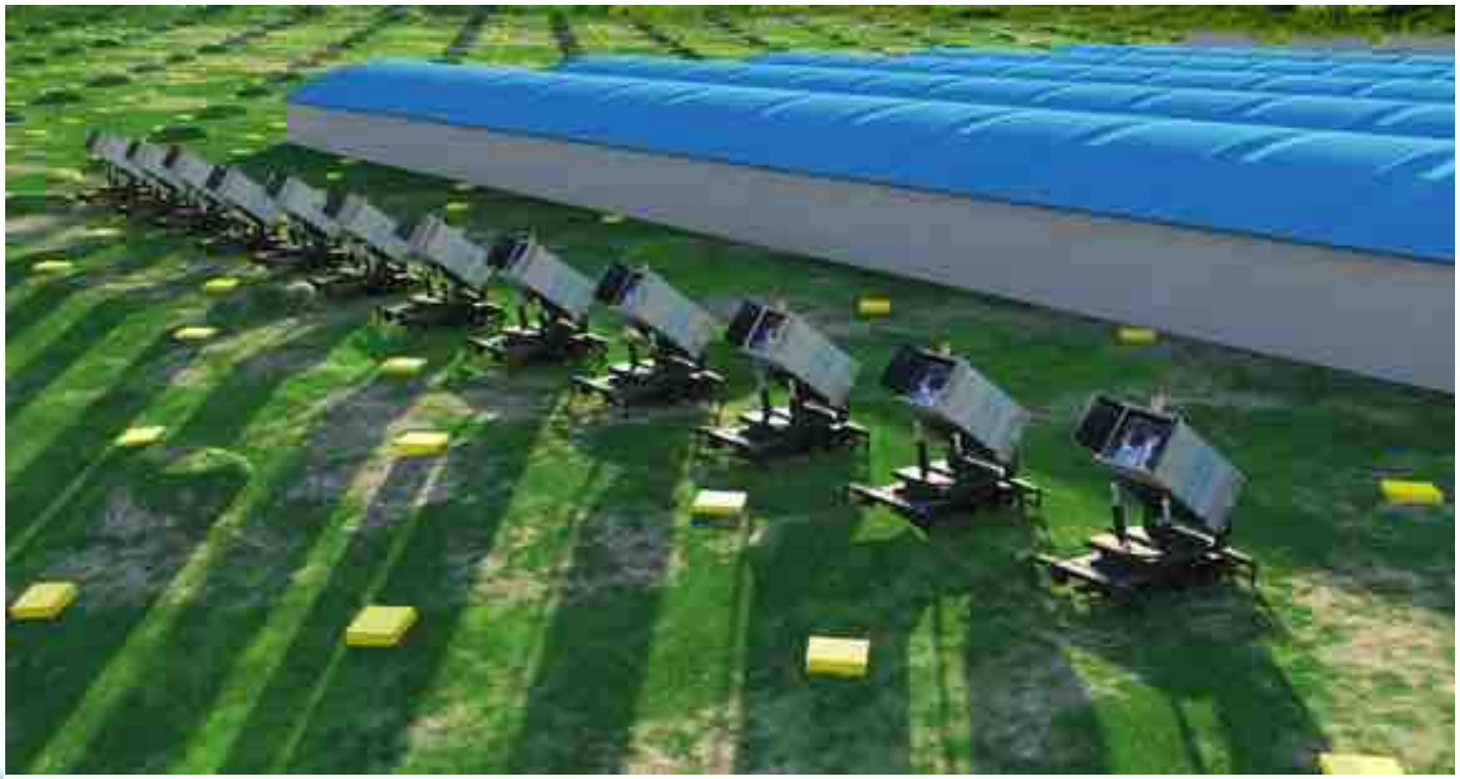
Very High Energy Gamma rays beyond FERMI/LAT and MAGIC energies

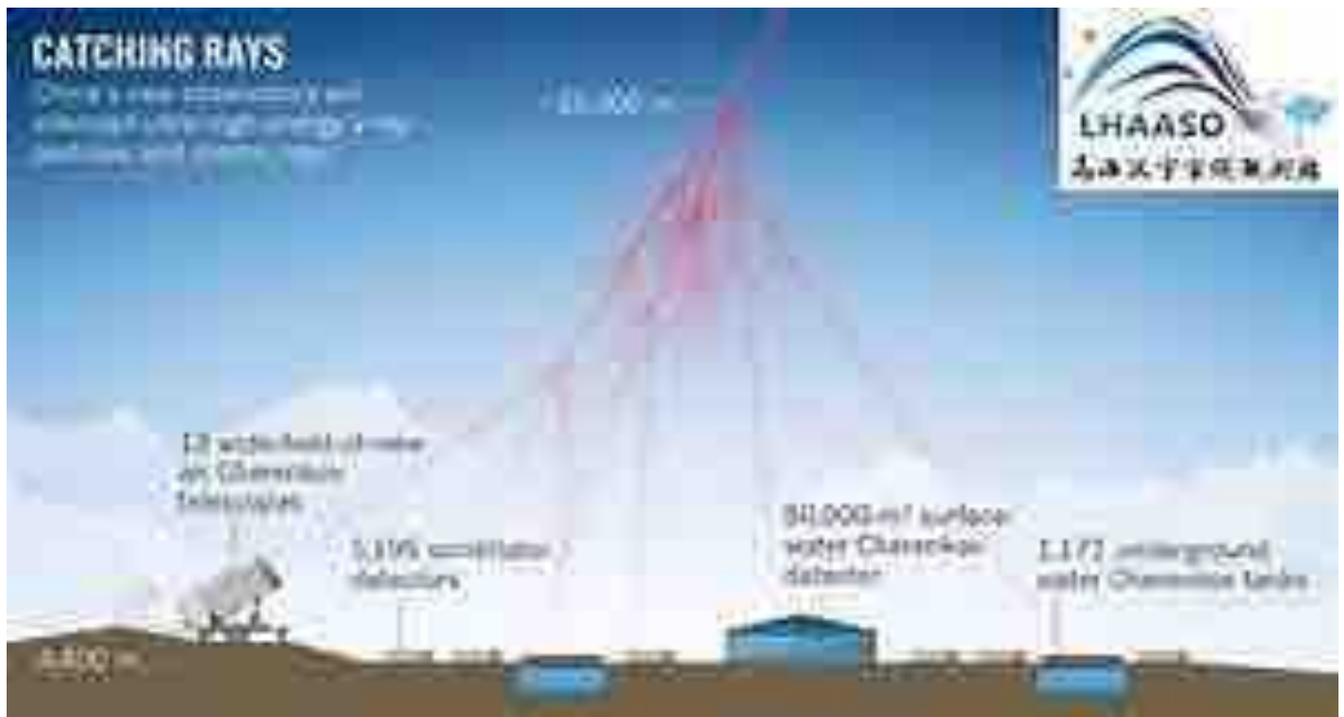
Today: HAWC the High-Altitude Water Cherenkov Observatory

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)




CATCHING RAYS
LHAASO

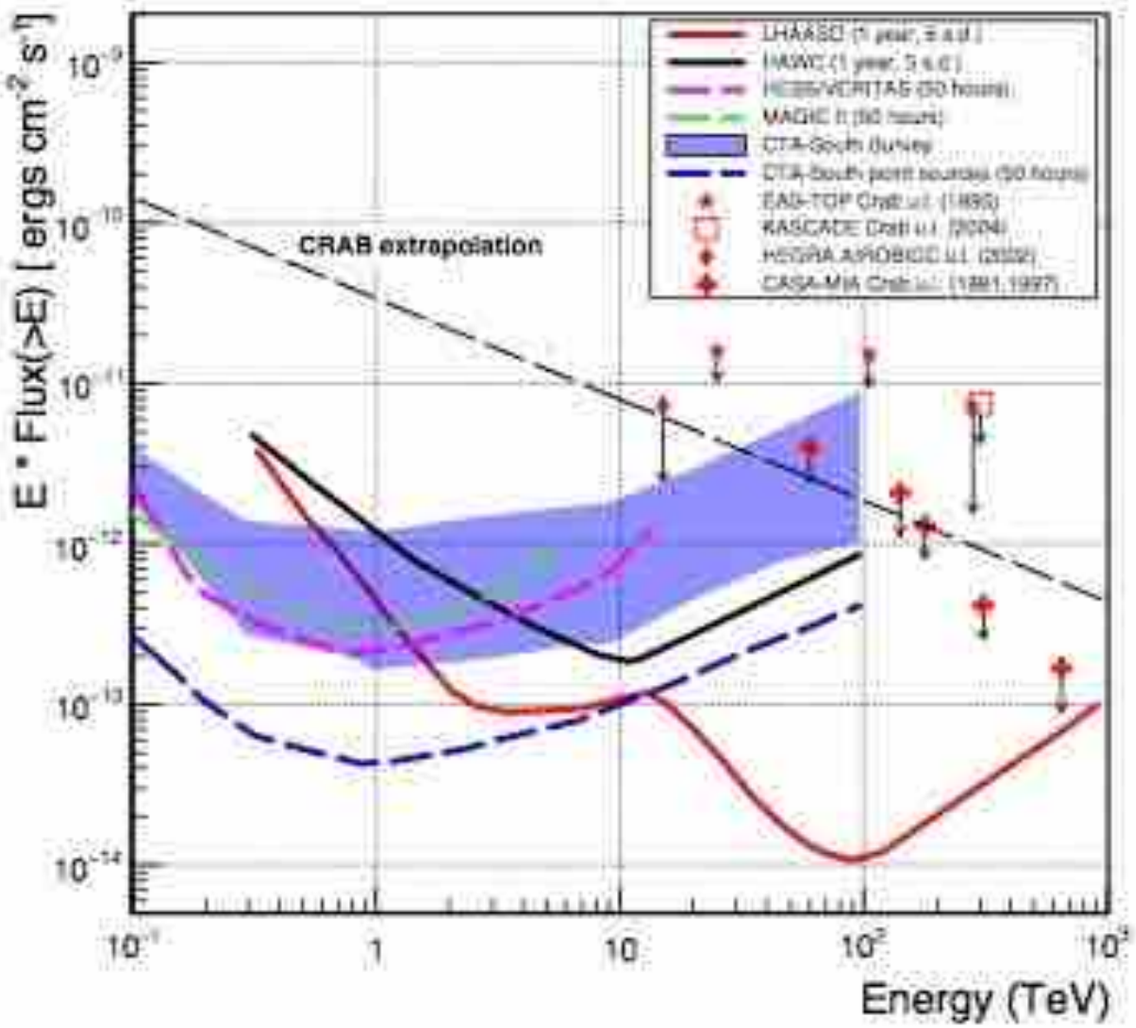
LHAASO

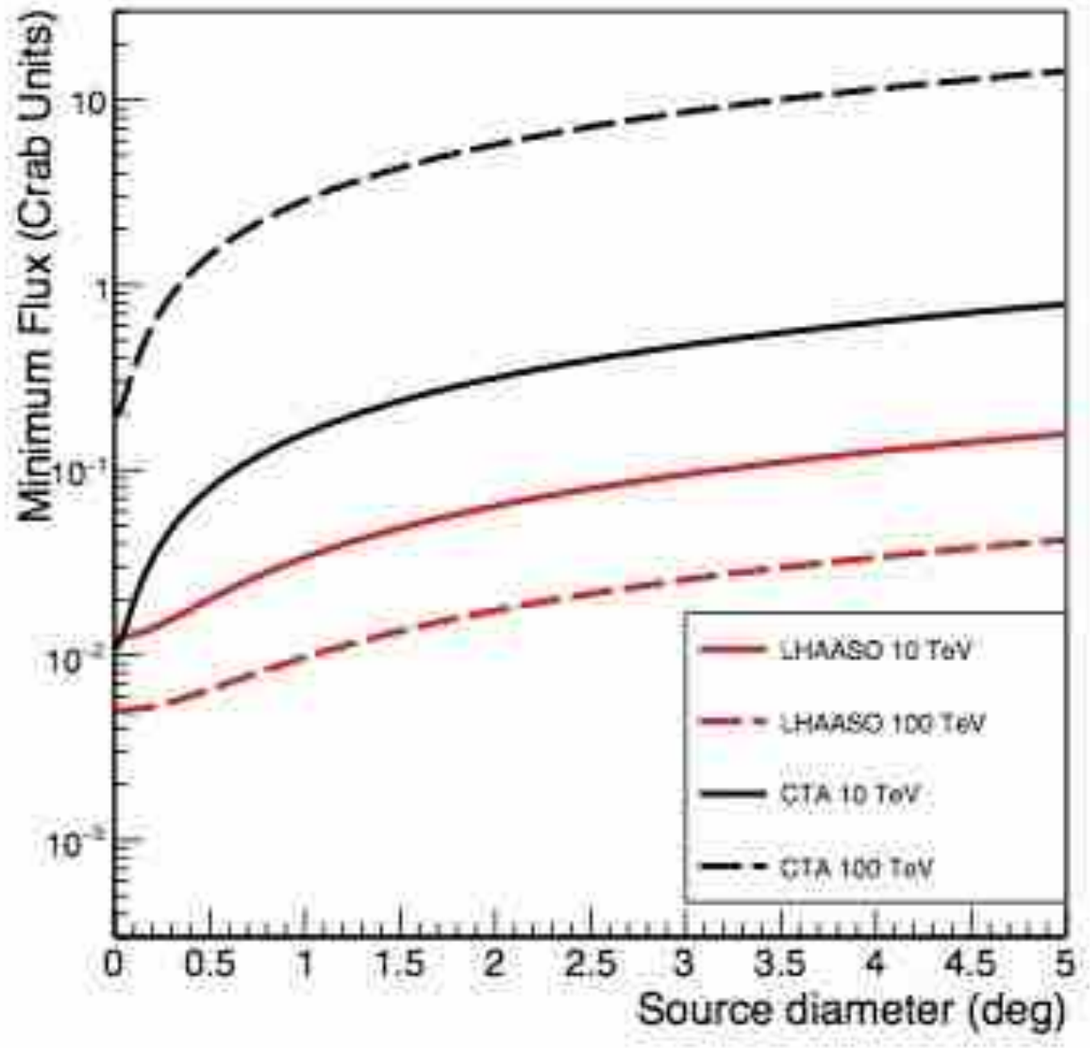
11-17th digits (eV) of charged particle spectrum (mainly hadrons)

50GeV-PeV for gamma rays

A powerful double channel

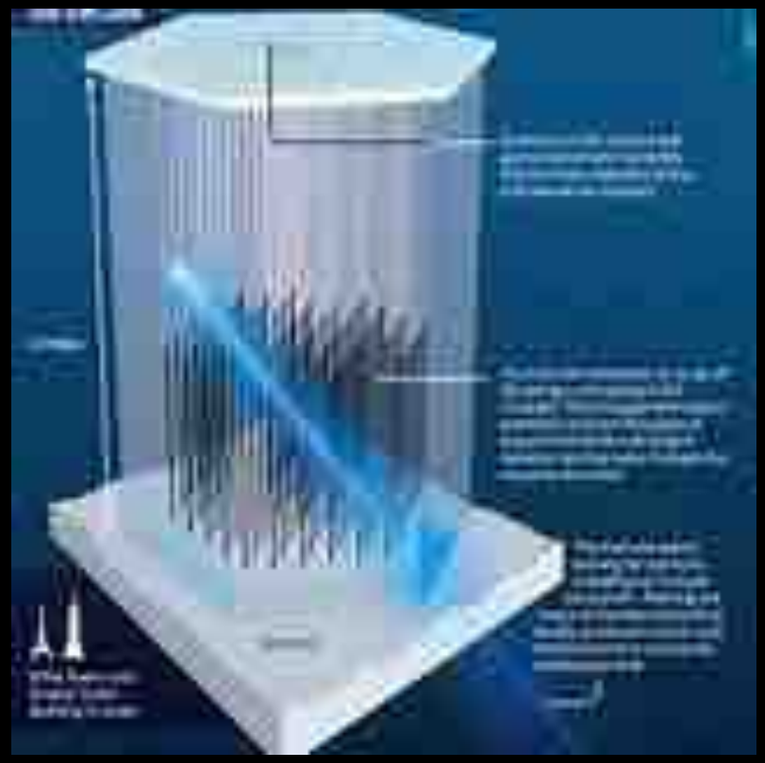
Gamma ray sensitivity

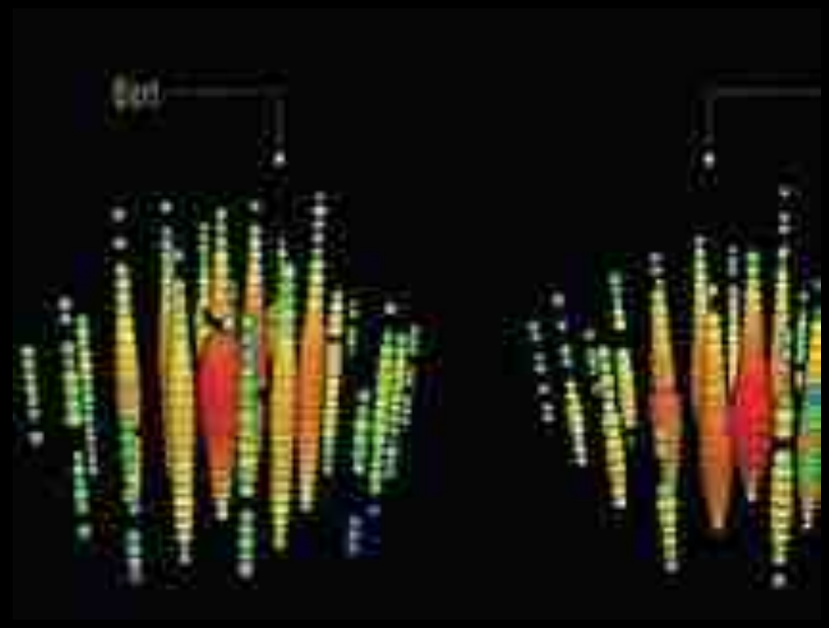




arXiv.1602.07600

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

Where NP in CR?

New Sources?

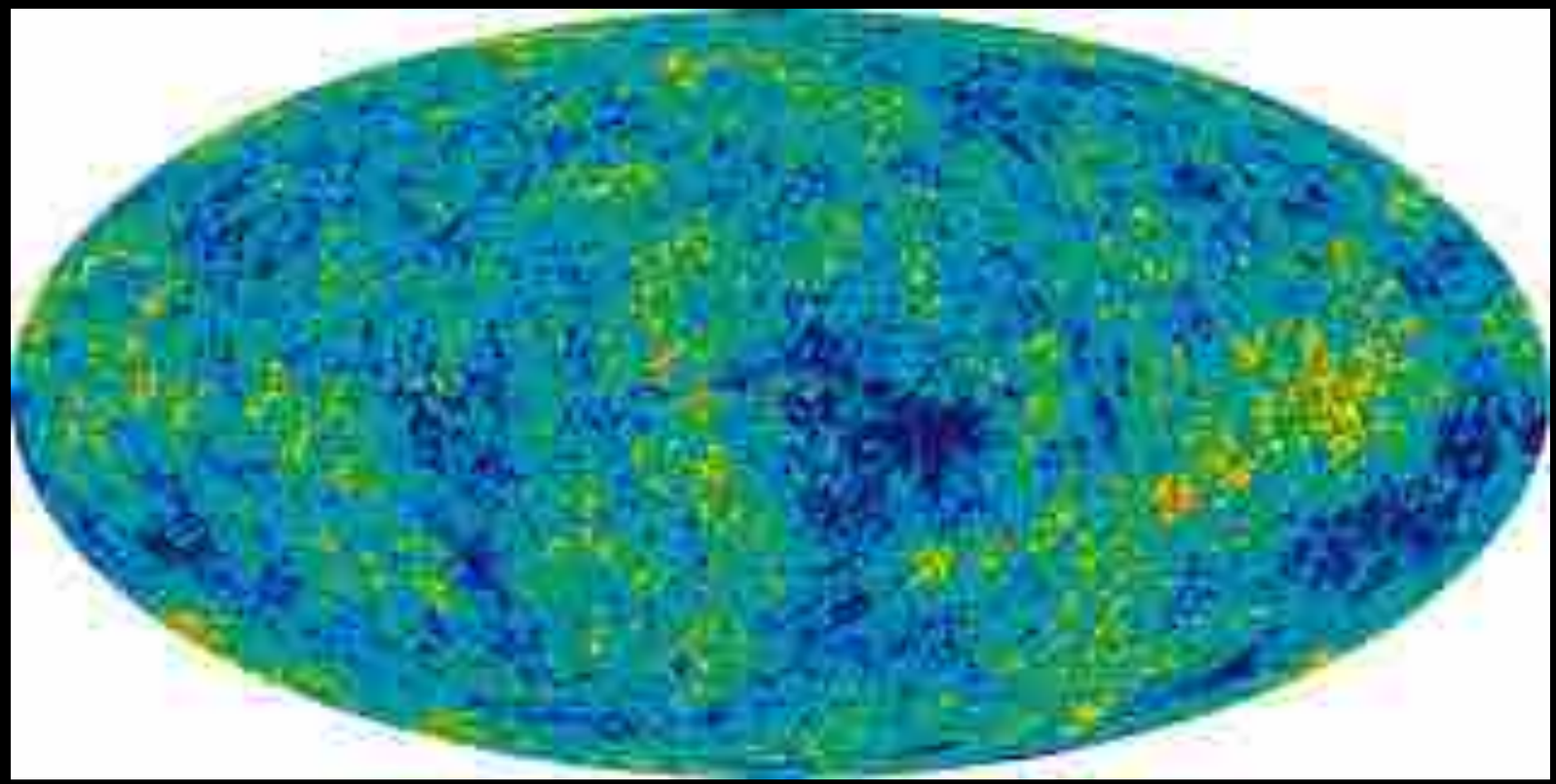
Propagation?

New Particle species?

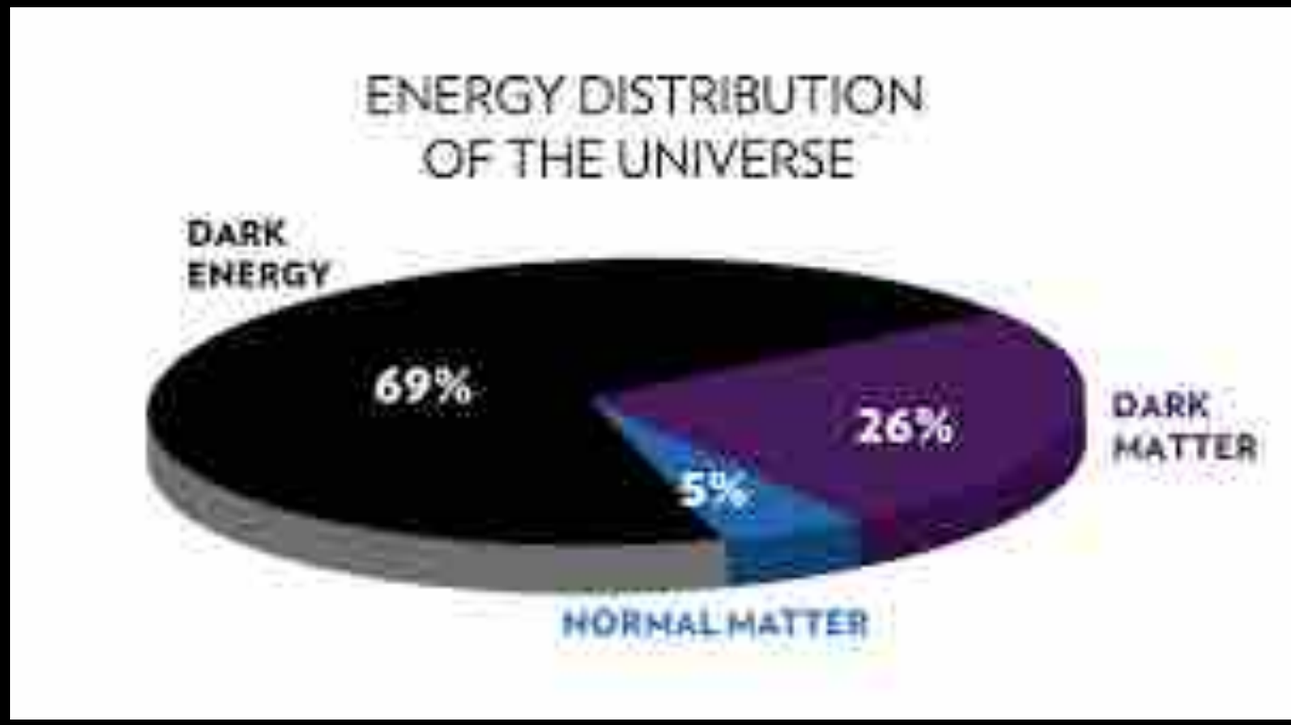
Dark Matter candidates beyond traditional WIMPs

Evidences of Cold Dark Matter

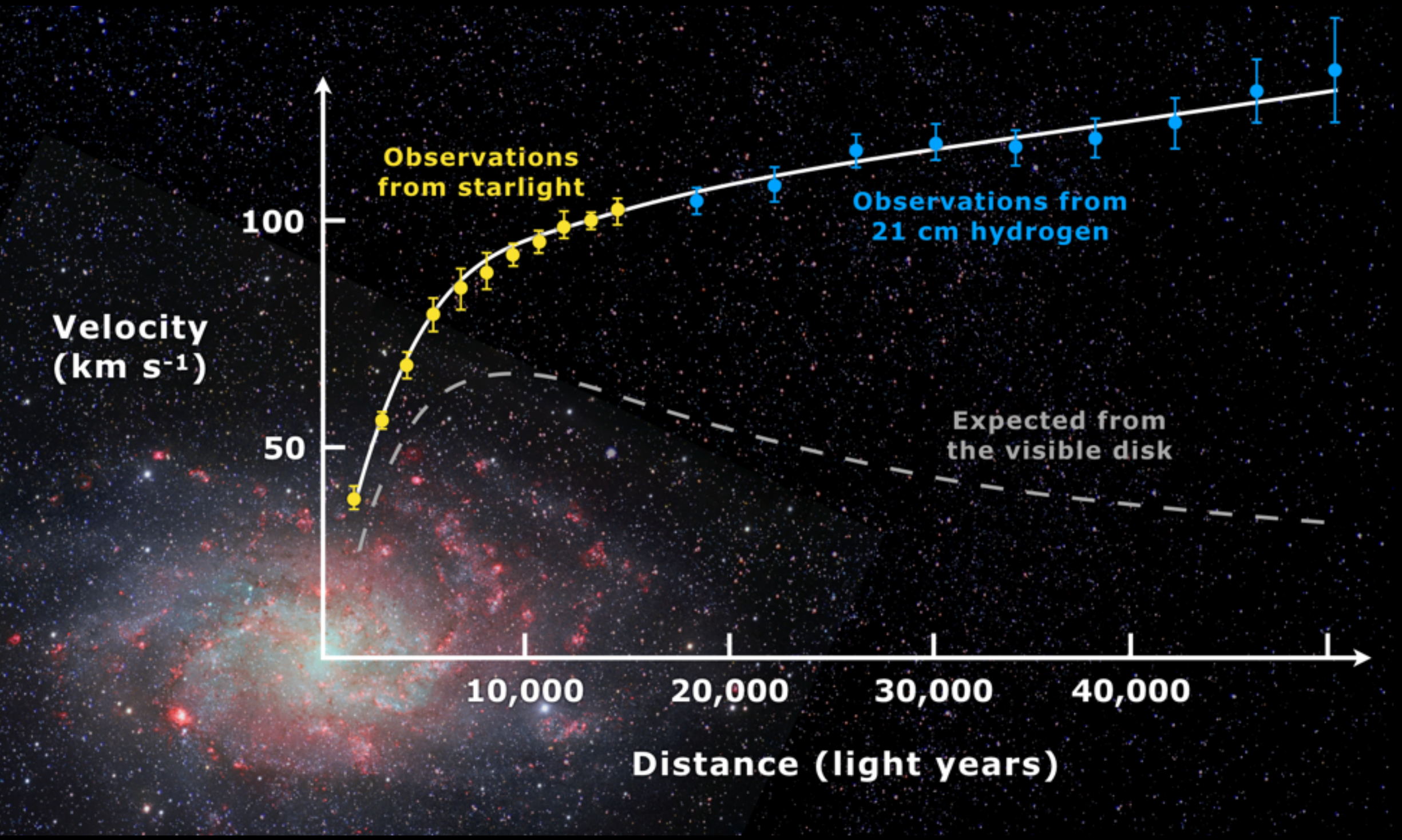
Cosmic Microwave Background (CMB)



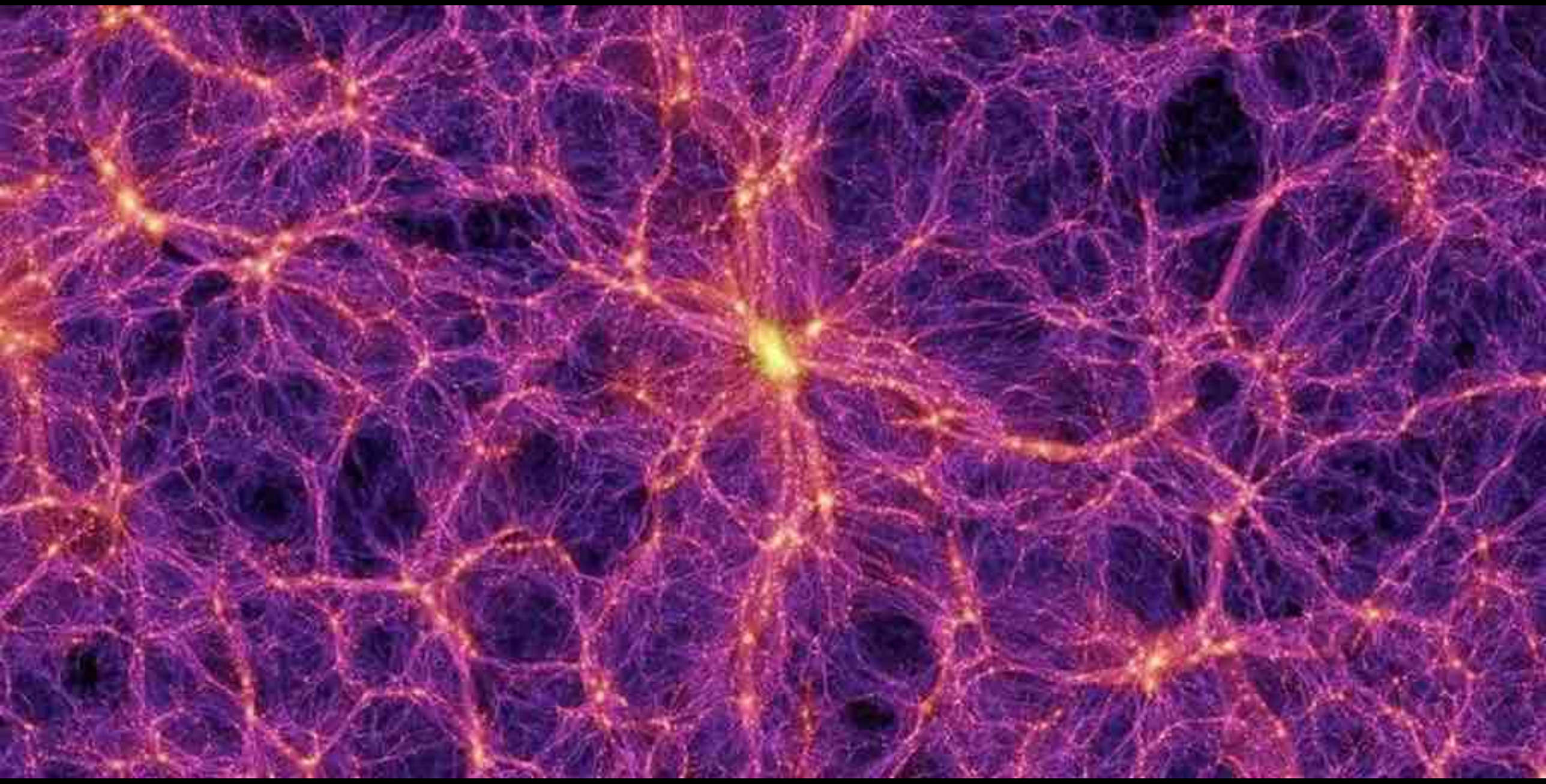
Planck collaboration



Galactic rotational curves



Structure formation and Cosmic Web: Dark Matter cannot be too “hot”



Theories of Dark Matter

?

MSSM

R-parity violating

NMSSM

Supersymmetry

WIMPless DM

Hidden Sector DM

Self-Interacting DM

Technicolor

mSUGRA

pMSSM

Gravitino DM

Q-balls

Dark Photon

R-parity Conserving

Decay DM

Asymmetric DM

Light Force Carriers

Extra Dimensions

Universal ED

Warm DM

Sterile Neutrinos

Solitonic DM

Quirk Higgs

UED DM

KK

3d

Warped Extra Dimensions

RS DM

Axion DM

T-odd DM

Little Higgs

QCD Axions

Axion-like Particles

Littlest Higgs

T Tait

And btw this is a very incomplete list of particle DM candidates…
And sorry if I write down all the references
…
no way in a 25 mins talk…

Trying to figure out how, when, where “to fish” these DM guys!

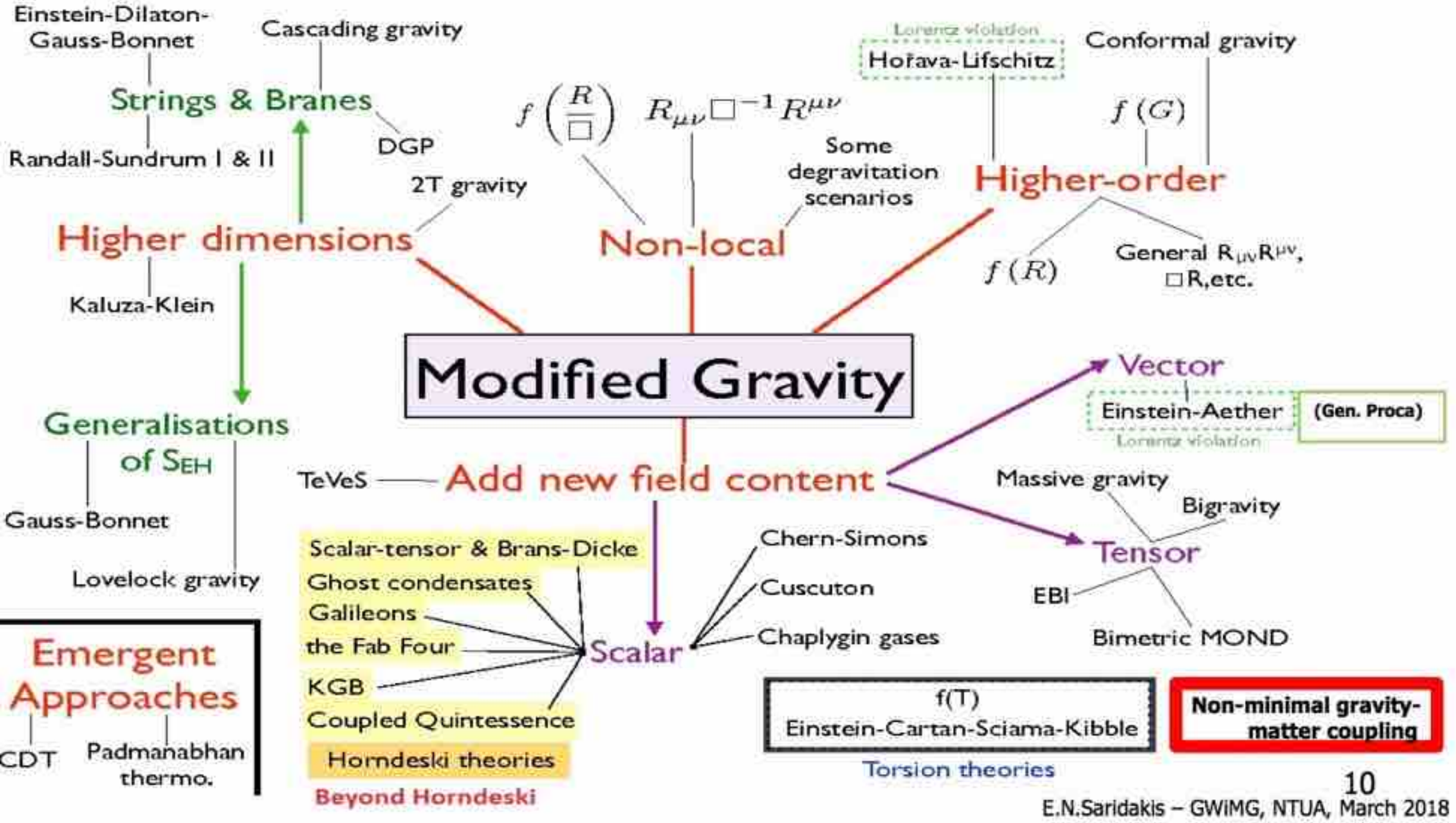
…Btw in Ocean pits, still 90% of species may be unknown…
Interesting analogy with DM/DE

Indeed any DM candidates have
different interaction portals with ordinary SM
particles as well as different mass spectra

If we try to “fish” them with
“the wrong techniques”
we will fail.
So far, we failed
(but we don’t have time to cry…)

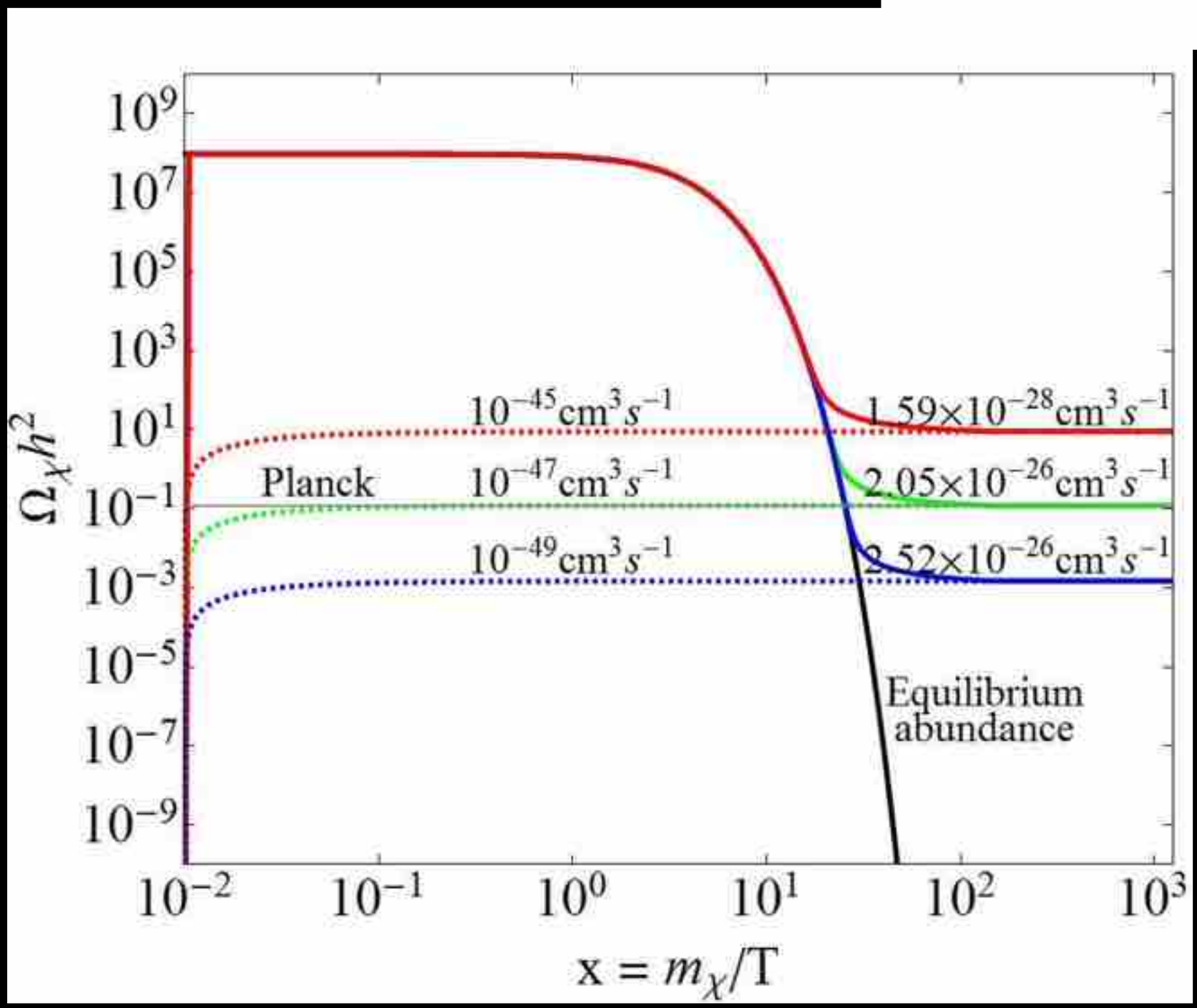
Chinese fisherman fishing with a cormorant

Modified gravity? Not excluded yet but less easy…



The “old boy”:
Thermally produce WIMPs
Freeze out
WIMP miracle

$$\Omega h^2 \simeq \frac{0.3 \times 10^{26}\,\mathrm{cm}^3/\mathrm{s}}{\langle \sigma_{\mathrm{eff}} v \rangle}.$$



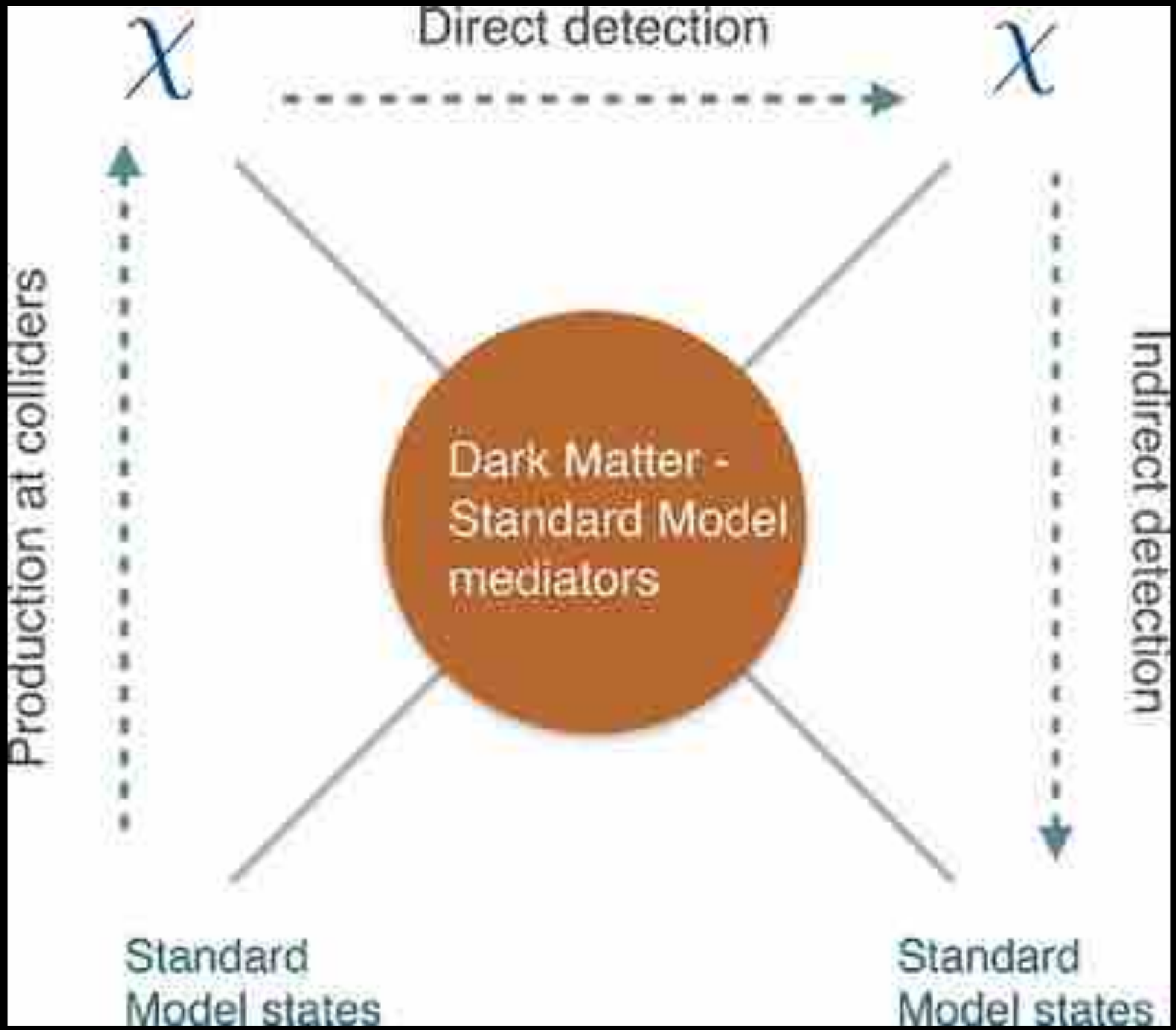
$$\dot{n} + 3Hn = -\langle \sigma_{\rm eff} v \rangle \left(n^2 - n_{\rm eq}^2 \right), \qquad \text{where } \langle \sigma_{\rm eff} v \rangle = \sum_{i\,\mathcal{X}\to\mathcal{Y}} \langle \sigma_{i\mathcal{X}} v_{i\mathcal{X}} \rangle \frac{n_i^{\rm eq}}{n^{\rm eq}} \frac{n_{\mathcal{X}}^{\rm eq}}{n^{\rm eq}}.$$

$$x = m/T \qquad Y \equiv n/s$$

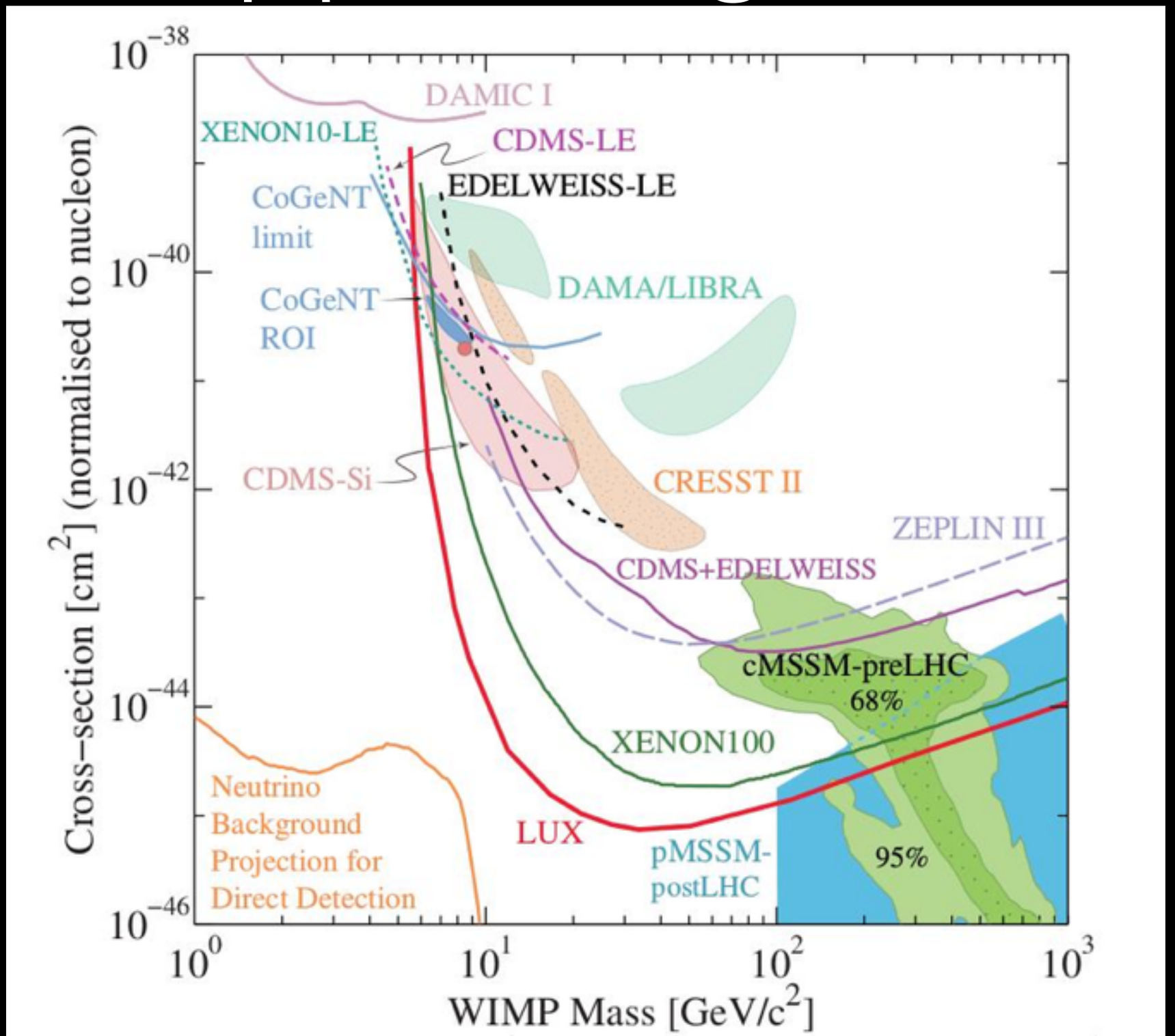
$$\frac{dY}{dx} = -\frac{x \langle \sigma_{\rm eff} v \rangle s}{H(m)} \left(Y^2 - Y_{\rm eq}^2 \right), \qquad \text{with } H(m) = \sqrt{\frac{4\pi^3\, g_*}{45}} \frac{m^2}{m_{\rm pl}}.$$

$$\begin{aligned} Y_{\rm eq}(x) &= \frac{45}{2\pi^4} \sqrt{\frac{\pi}{8}} \frac{g}{g_{*s}} x^{\frac{3}{2}} e^{-x} \qquad \text{for } x \gg 3, \\ Y_{\rm eq}(x) &= \frac{45}{2\pi^4} k_1 \zeta(3) \frac{g}{g_{*s}} \qquad \text{for } x \ll 3. \end{aligned}$$

The WIMP Miracle is predictive

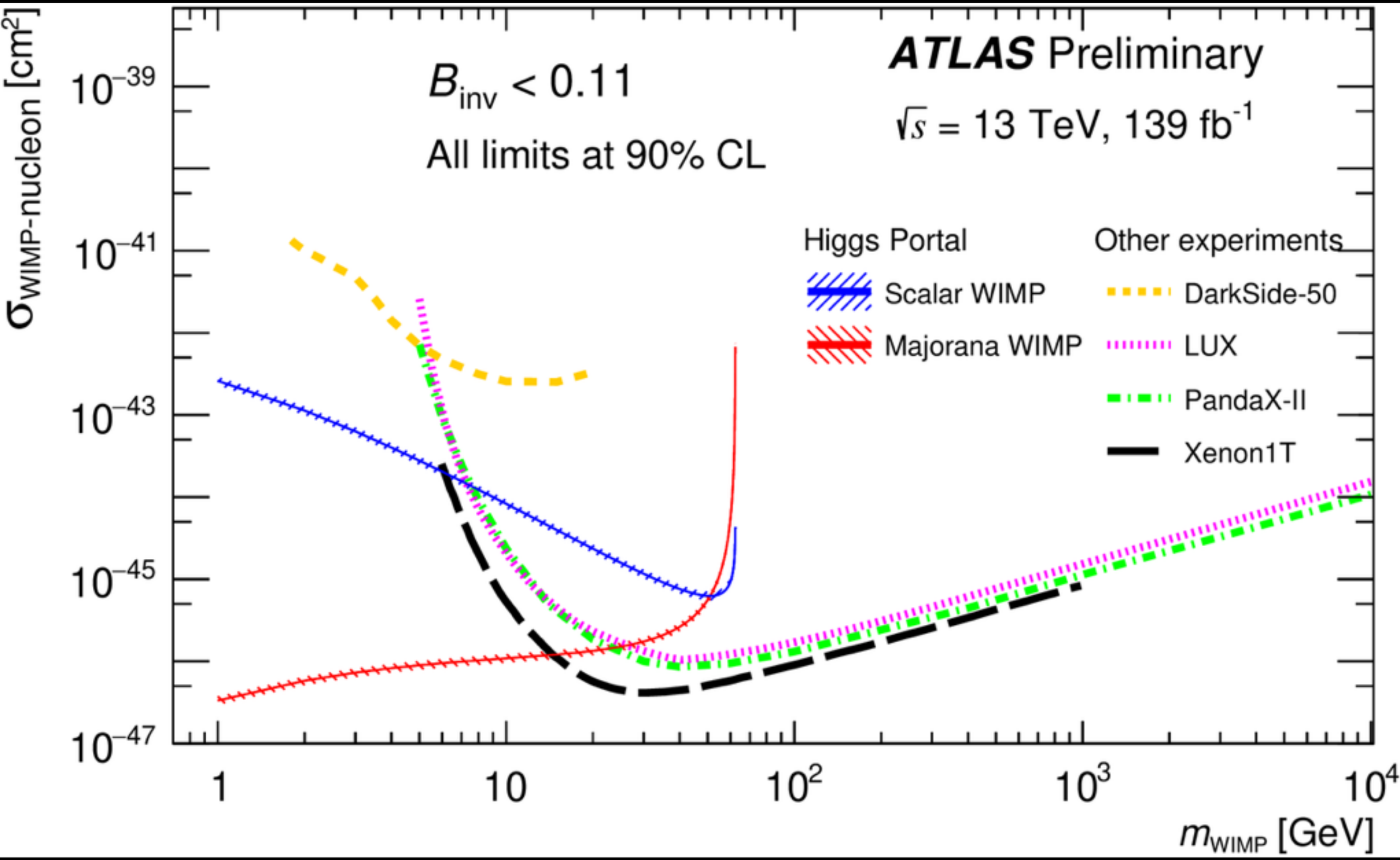


10-100 GeV WIMPs: a disappointing situation



With a remark:
too strong assumptions on the DAMA quenching factors!!!
It can displace the DAMA region with several orders!!!
See R. Bernabei et al,
DAMA collaboration papers

LHC Vs Direct Detection



The electroweak WIMP miracle seems to be ruled out!

Many people was convinced

MSSM (SUSY) there,

The TeV-scale (LHC frontier)!

DM as Neutralinos

Higgs hierarchy problem solved

GUT matching was perfect

Damn!

It wasn't there

Next steps

Changing DM candidate

Changing Symmetry principles and motivations

Changing DM genesis

Changing DM interactions

Possible DM genesis mechanisms

Thermal production: still allowed for around 100 TeV but it is saturating the perturbative unitarity bound; more sophisticated numerical simulations .

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…

Both the DM genesis categories allow for heavy DM, beyond the TeV frontier

Heavy DM candidates.

DM may be heavier than thought before, beyond the TeV scale…

No any direct probes from TeV-colliders.

Low hit probability in Direct Detection.

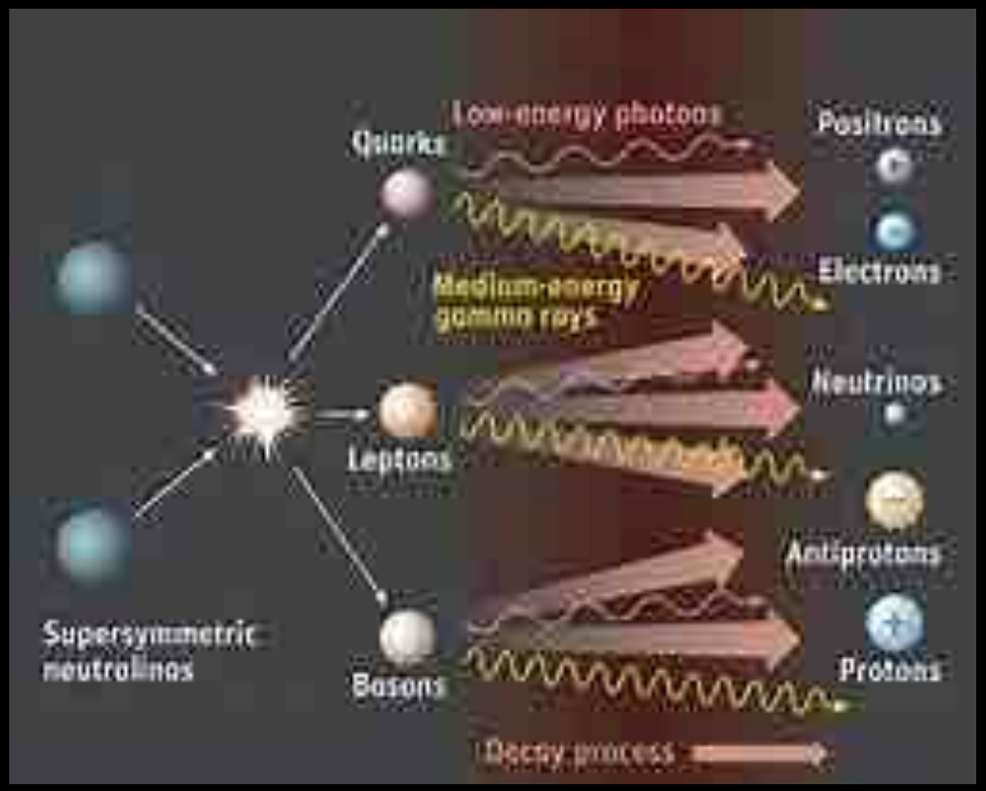
Annihilation and decays into Very High energy Cosmic Rays

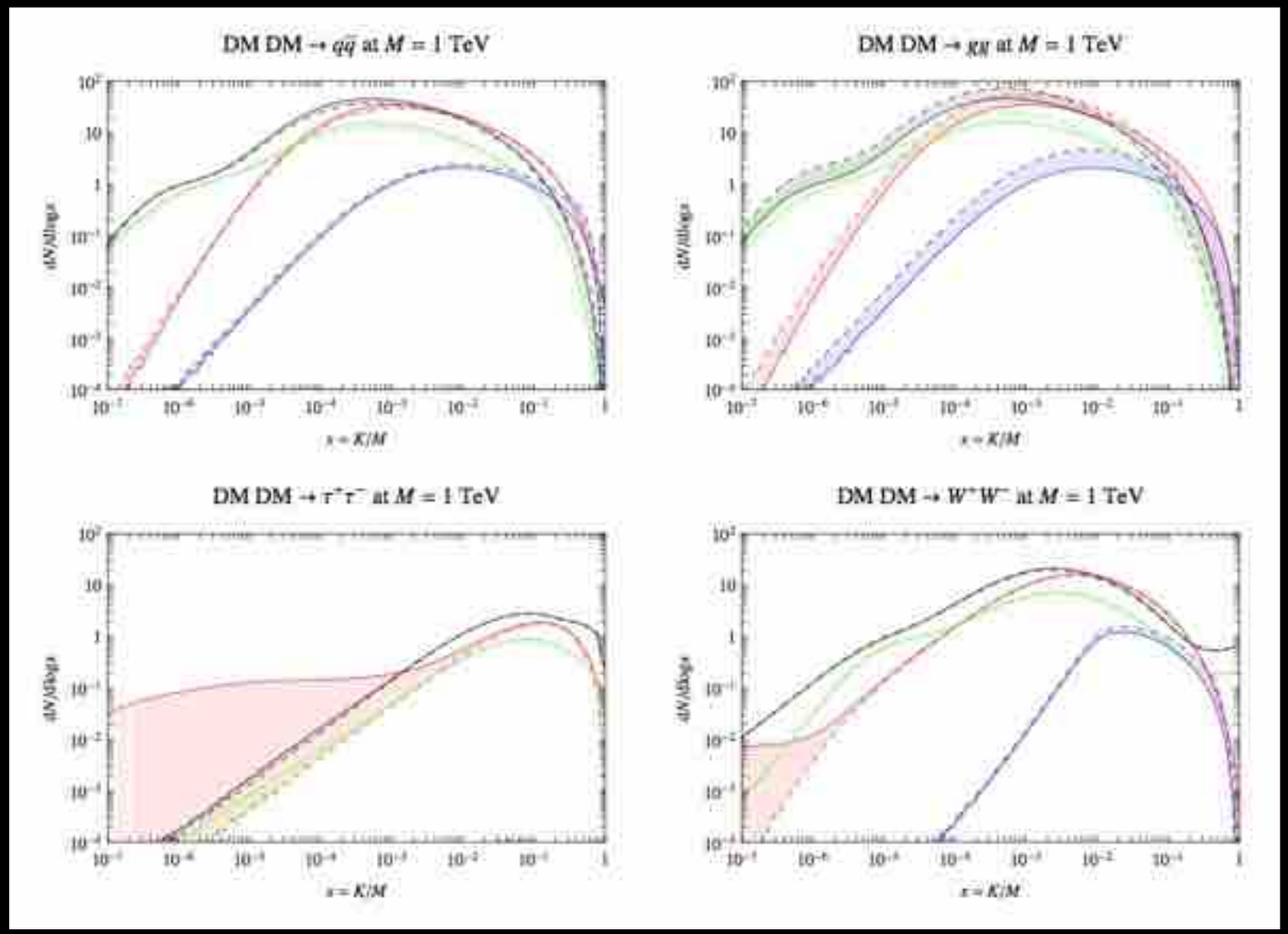
10 TeV - 100 PeV range?

Annihilation
or
Decay

Heavy Dark Matter

Annihilation and decays





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

An old standing idea:
Indirect searches for heavy neutral particle annihilation

Astrophysical bounds on the mass of heavy stable neutral leptons

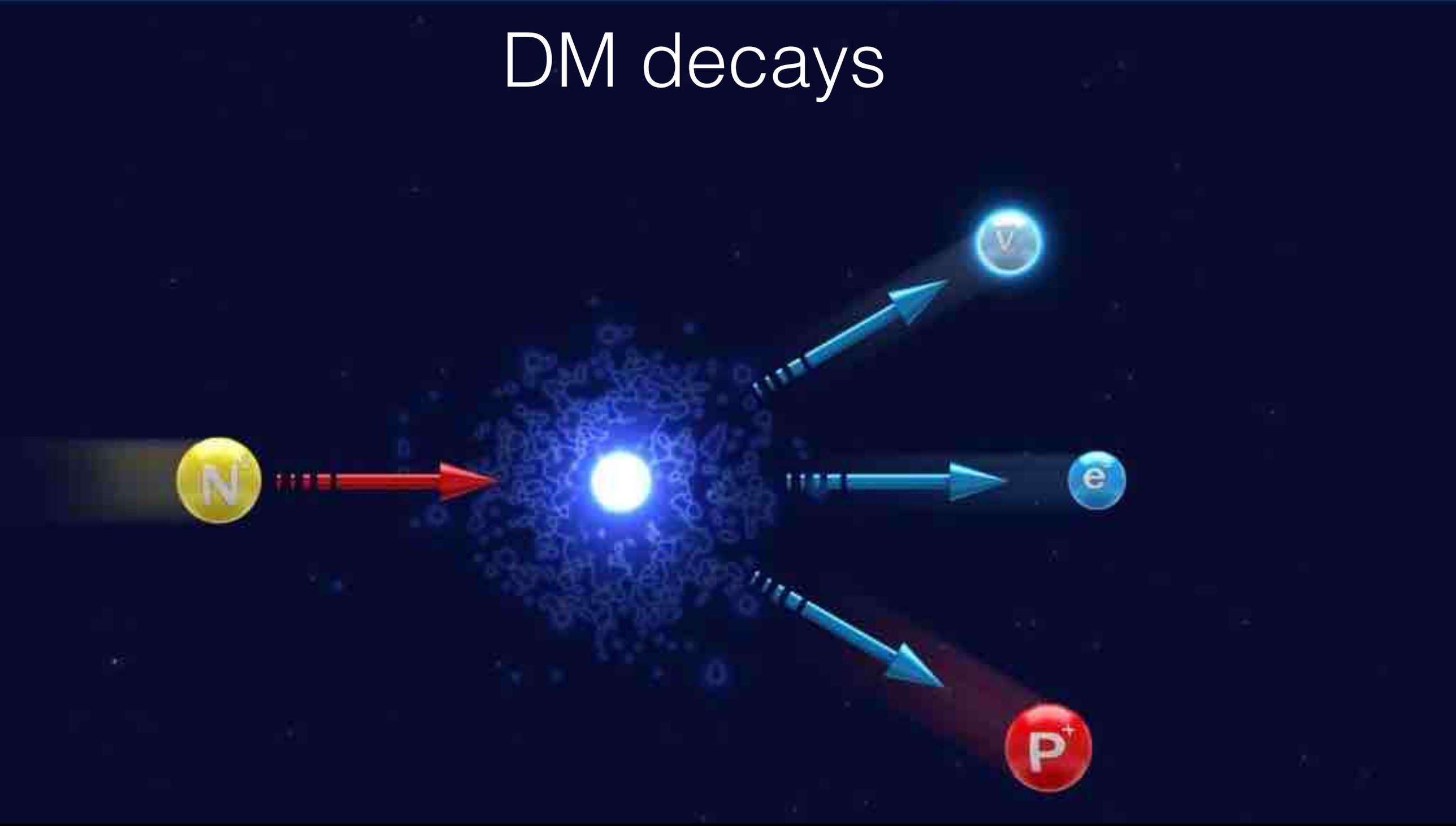
Ya. B. Zel'dovich, A. A. Klypin, M. Yu. Khlopov, and V. M. Chechetkin

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

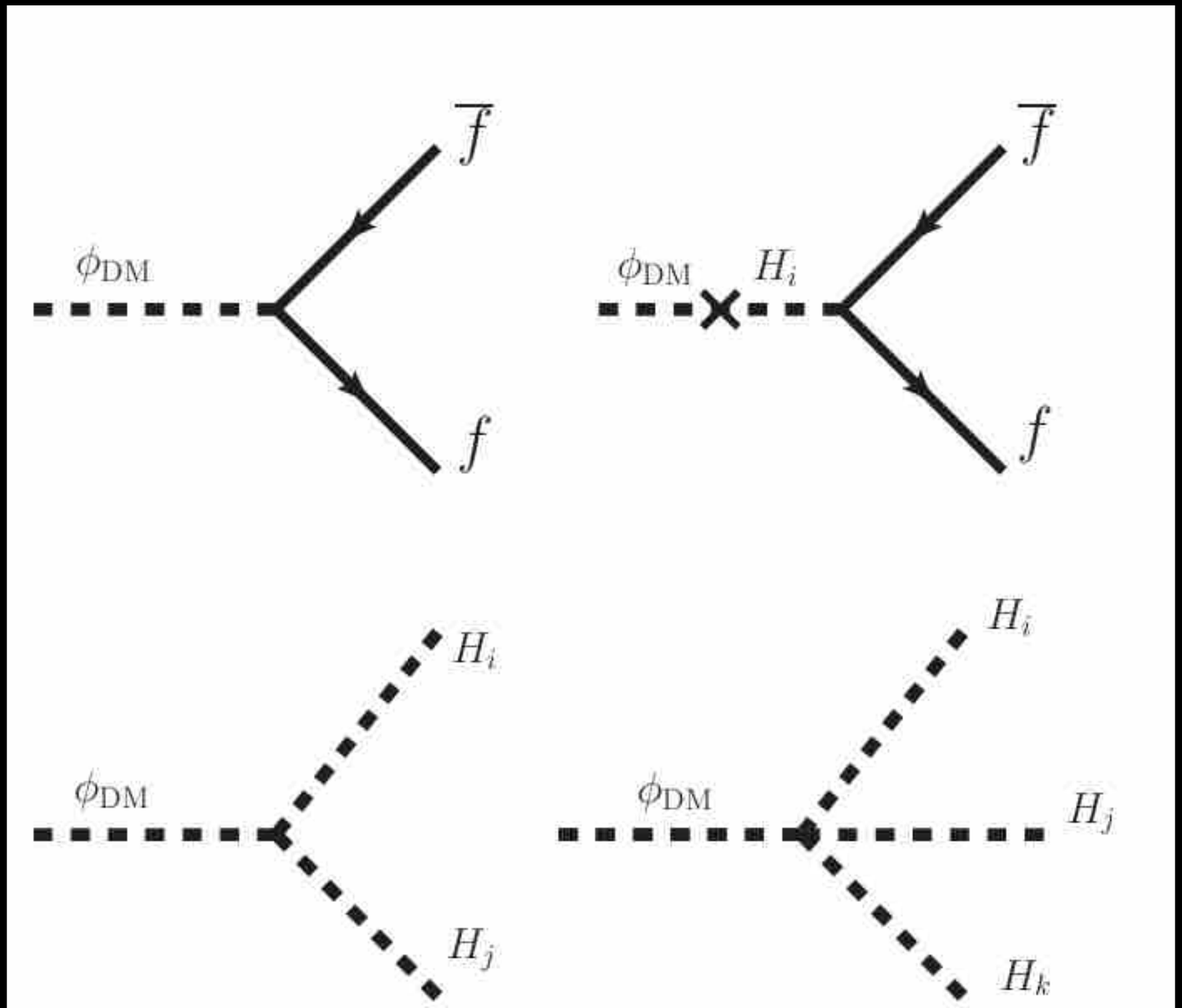
Analytical and numerical calculations show that heavy neutral stable leptons are carried along by the collapsing matter during the formation of galaxies and possibly stars as well. The condensation in galaxies and stars results in appreciable annihilation of leptons and antileptons. Modern observations 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.

Remark:
100 TeV is the maximum mass value for thermal production as a unitarity bound.

DM decays



DM decays


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

For LHAASO, Very Heavy DM decay
is the most exciting frontier of explorations beyond
the SM physics!

This is my claim here.

1. We do not need for DM over densities in the galactic bulge, tests of diffuse gamma
2. DM decay into pions: VHE neutrinos and photons

Gamma rays and DM decays

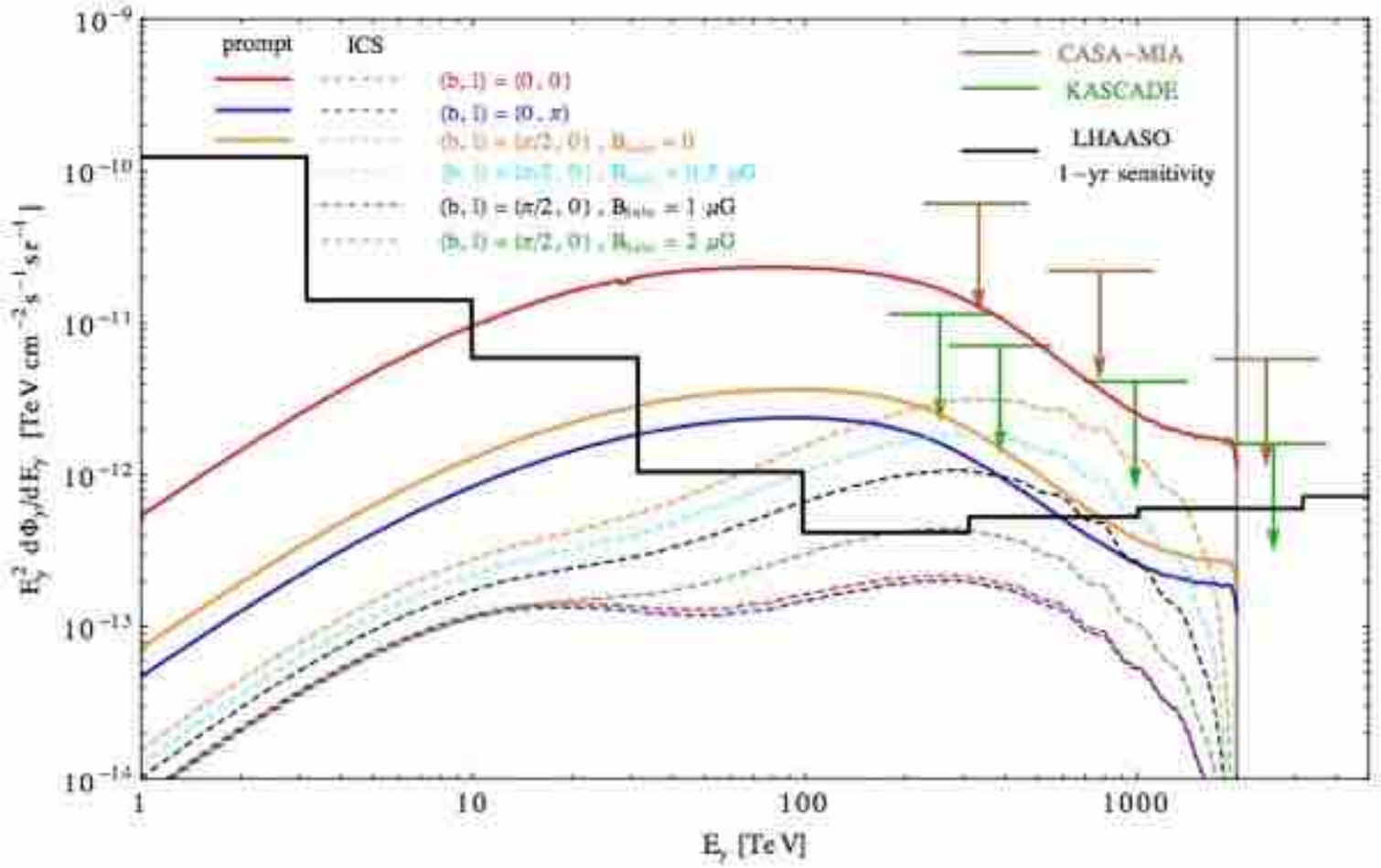


Fig. 1. The γ-ray flux from DM decay from various directions, with $m_{\rm DM}$=4 PeV and $\tau_{\rm DM}$=10^{28} s, and branching ratios reported in the text. The solid colored curves show the prompt flux, including the absorption of γ-rays; different colors represent different directions in the sky. 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.

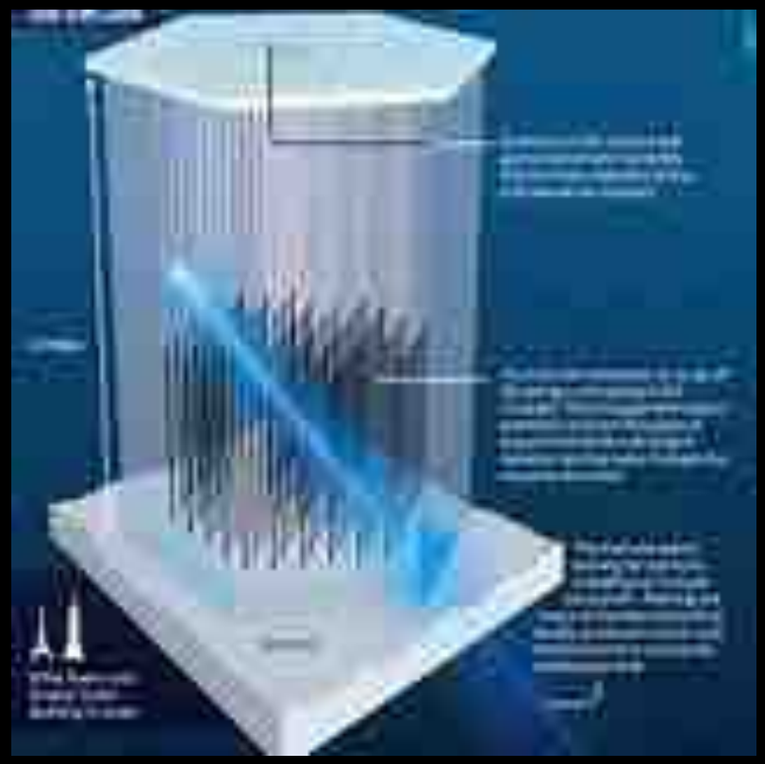
Addazi, Cirelli, Fornengo, Panci, Sala, Semikoz, Serpico et al
For the LHAASO book in preparation

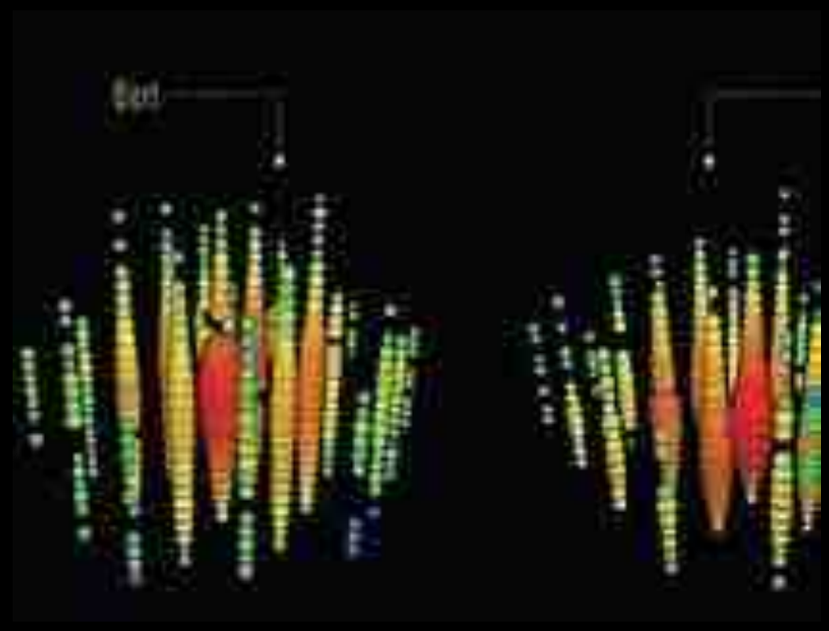
"Hit when it hurts!"

(Ninjitsu master)

Dark Matter decays 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

For the LHAASO book in preparation

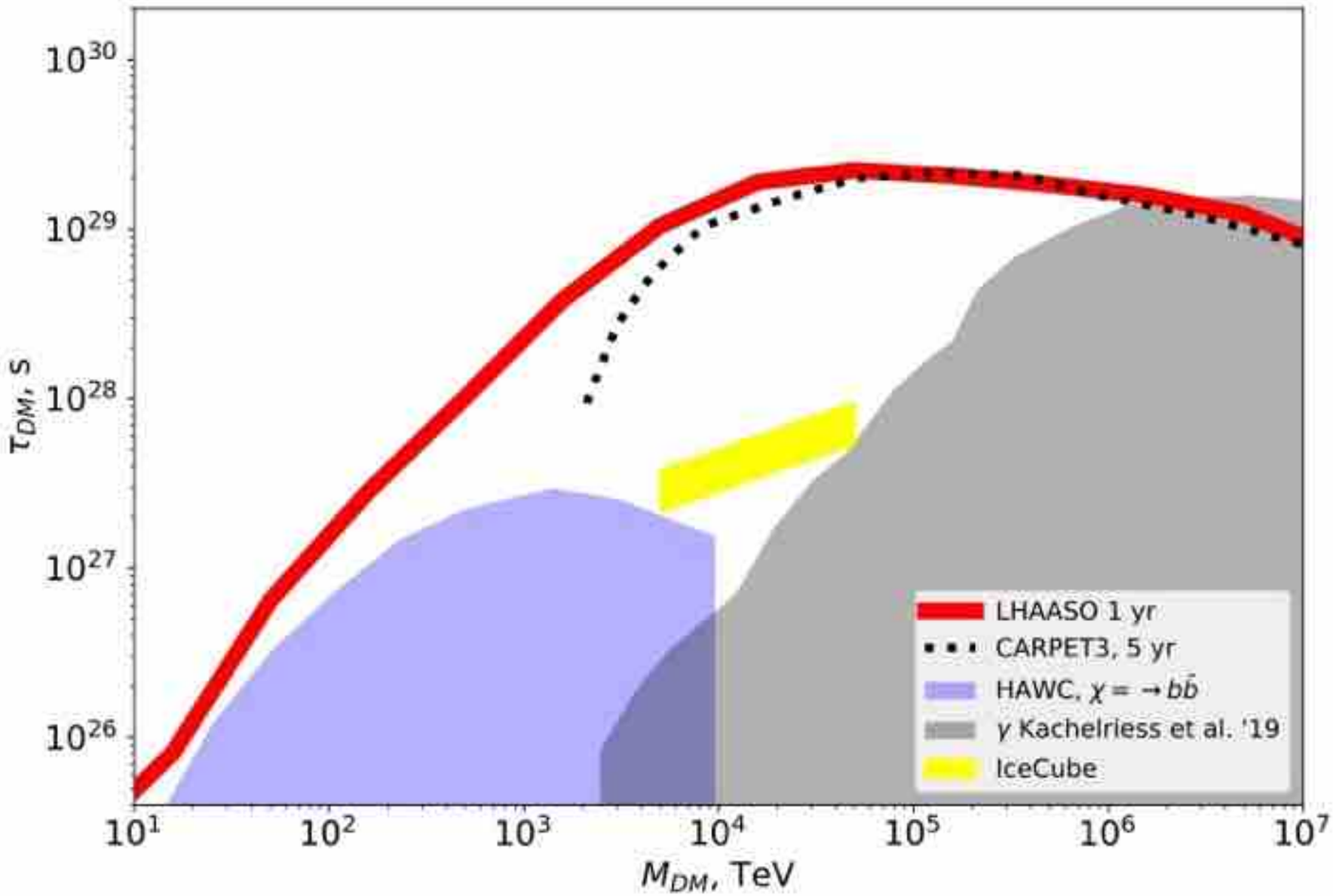


Fig. 2. Sensitivity of LHAASO for the measurement of dark matter decay time (for DM decaying into quarks). Yellow band shows the range of decay times for which DM decays give sizeable contribution to the IceCube neutrino signal [74]. Blue and grey shaded regions show the existing bounds imposed by HAWC [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, Fornengo, Panci, Sala, Semikoz, Serpico et al

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

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

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

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

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

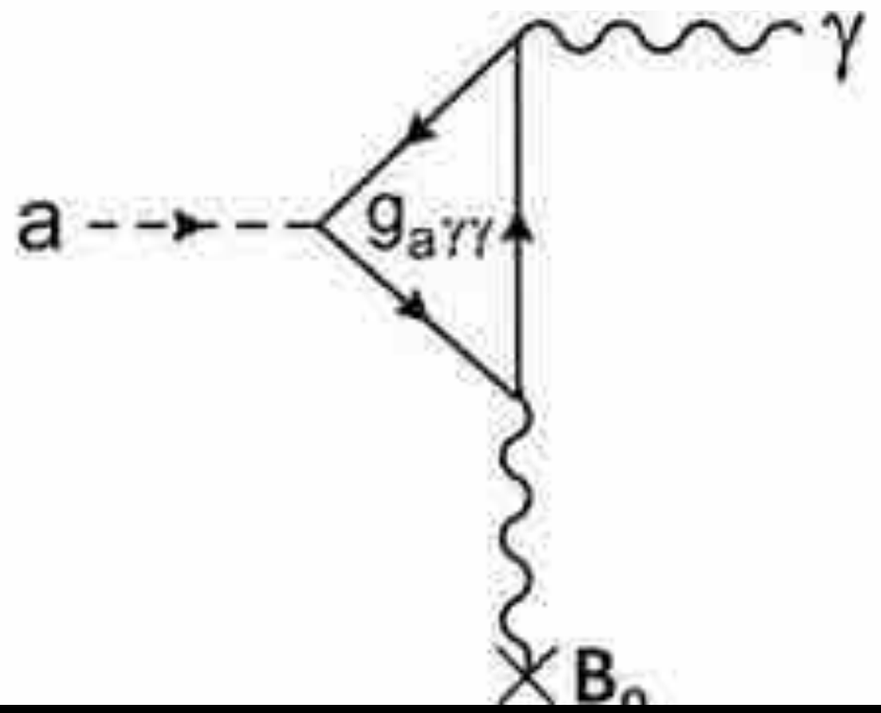
On the other hand

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

Test of ALPs?

Axion-like-particles in CR propagation

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



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

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

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

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

QCD axion: CP problem solved
Peccei-Quinn, Wilczek, Weinberg

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

Gamma rays transparency

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

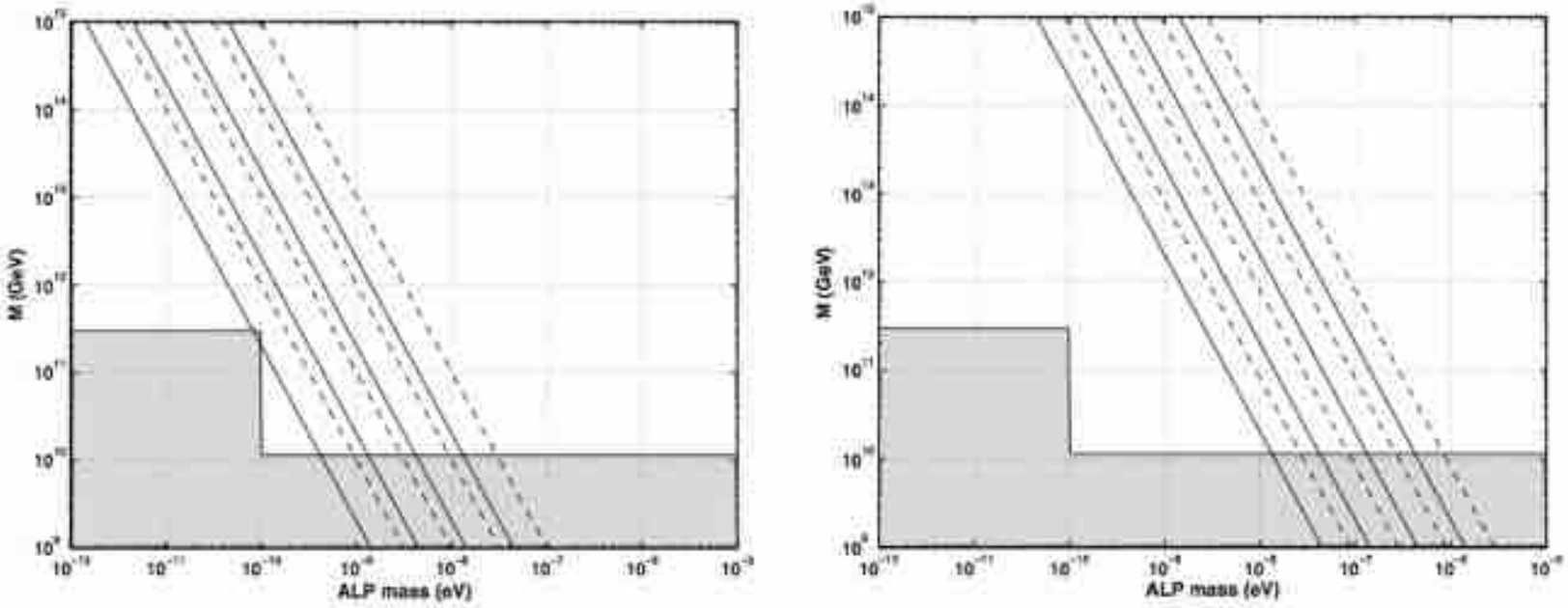


Fig. 2. Left panel: values of the pair (m, M) which determine the critical energy $E_\star = 1$ GeV, 10 GeV, 100 GeV and 1 TeV (from left to right) for a magnetic field strength of $B = 1 \cdot 10^{-9}$ G (solid line) and $B = 5 \cdot 10^{-9}$ G (dotted line) and a plasma frequency $\omega_{\rm pl} \sim 10^{-14}$ 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[5], J. Jochum[5]

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

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…

LHAASO may write important pages in the history of fundamental physics

Thank You for the attention