Probing fundamental laws of physics from multi-messenger astronomy

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

Andrea Addazi, Sichuan University

Acknowledgements

A. Di Matteo (INFN Torino)

A. Gazizov (INFN LNGS)

M. Khlopov (APC Paris, MEPHI, SFedU)

in memory of Dima Polyakov

Disclaim: this talk will not provide any new results

Objectives:

Motivations,

Broad Panorama,

Stimulating Debats and Discussions

Research Strategy

The great ‘era’ of multi-messanger

“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)?

Opportunities from CR

Next colliders?

in 40-50 years…

Astroparticle CR experiments?

Next Physics in
Next 10/20 years

Gravitational waves?

Powerful in the
“Multi-messanger arena”

A “plethora” of new data is coming

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

Multi-tasking expertise

Hadronic physics

Showers

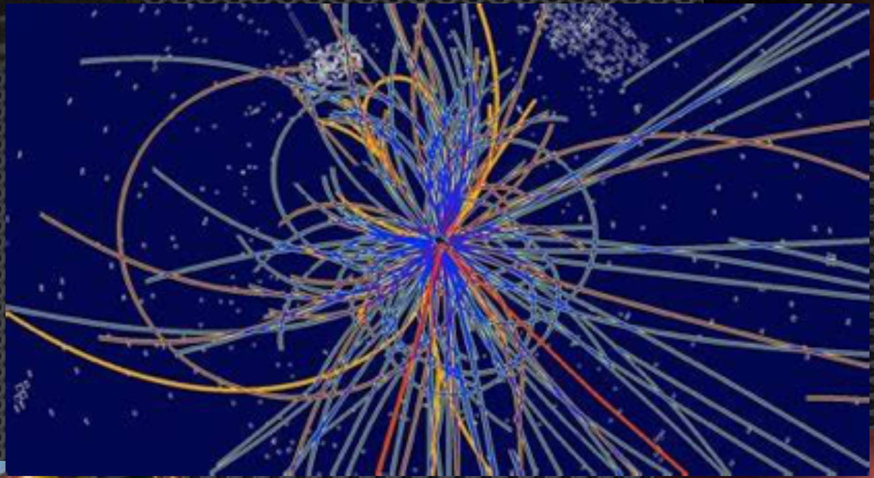
Propagations

Multi-messengers

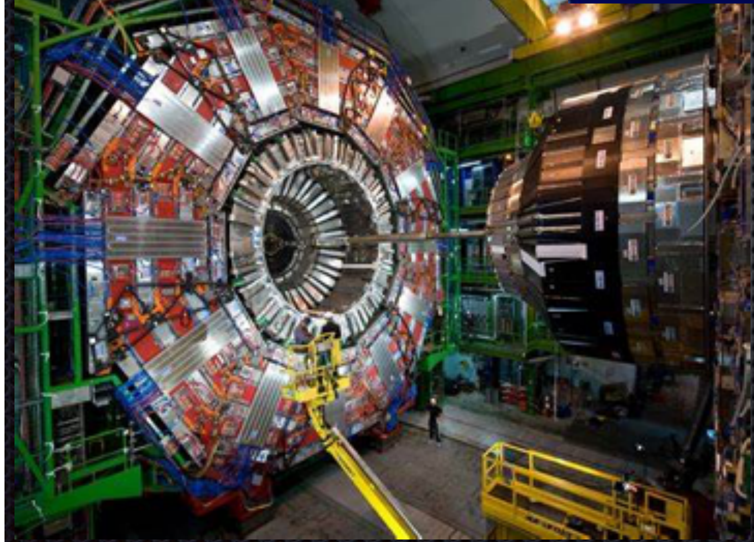
Astrophysical Sources

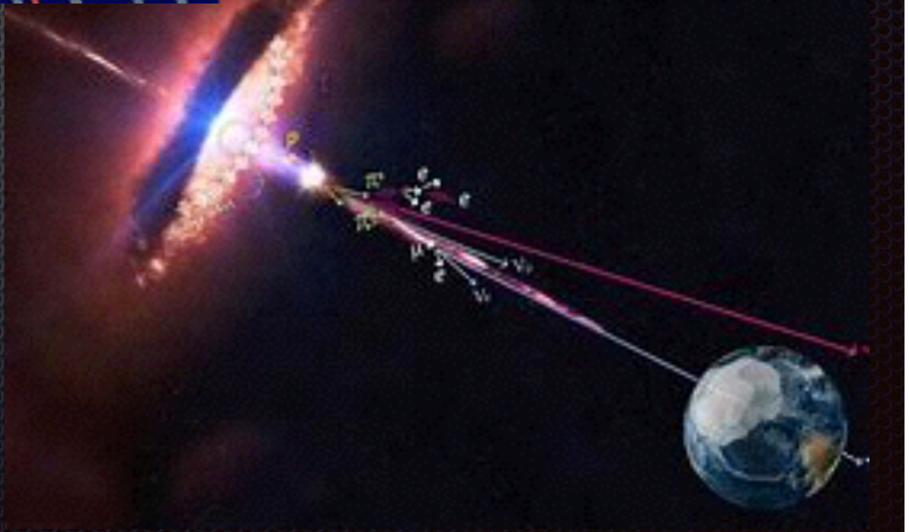
Extreme High energy Physics

LHC



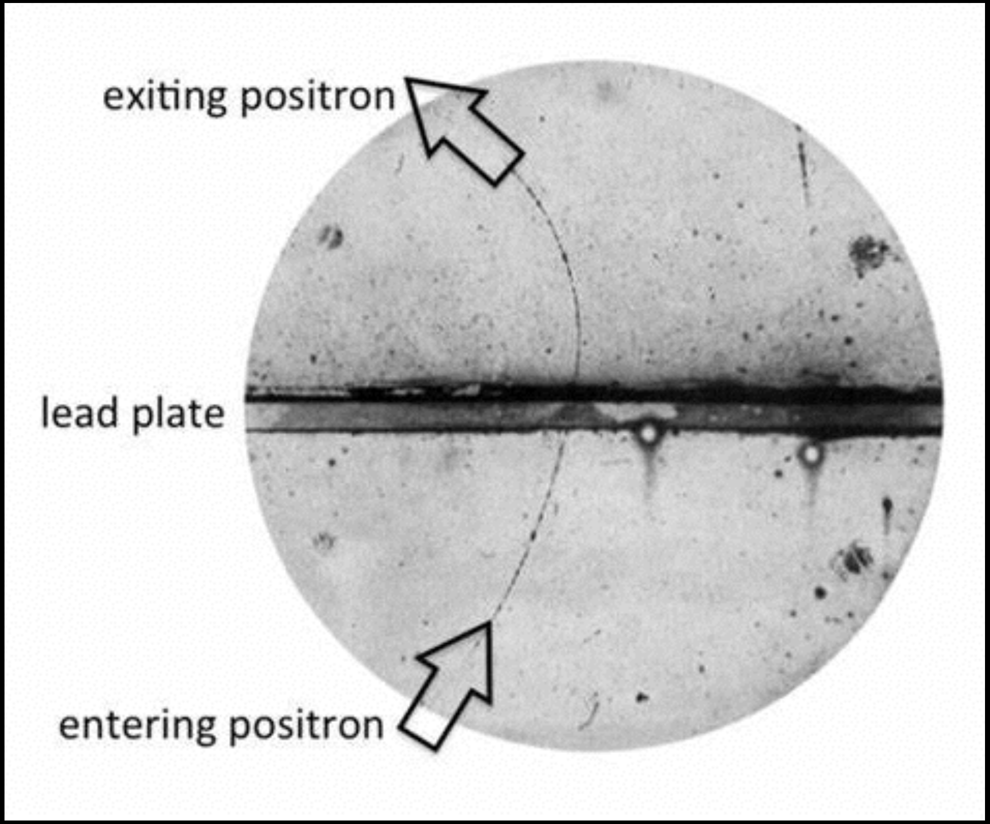
LHAASO





Searching for new physics

History: antimatter discovery in cosmic rays

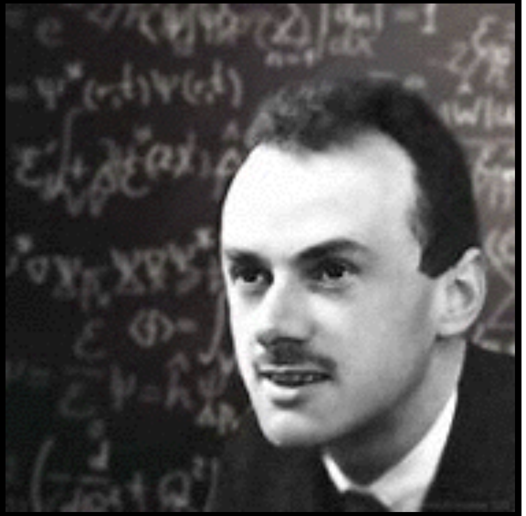


Cloud Chambers, *Anderson 1932; Blackett & Occhialini*

The "power" of theoretical predictions

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

… sometimes wrongly right…



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APC PARIS

MEPHI MOSCOW

TMP TOMSK

SFedU ROSTOV

New York University (NYU)

L’Aquila University

Gran Sasso Laboratory (LNGS)

CERN Geneve

COST Action

Where NP?

New Sources?

Propagation?

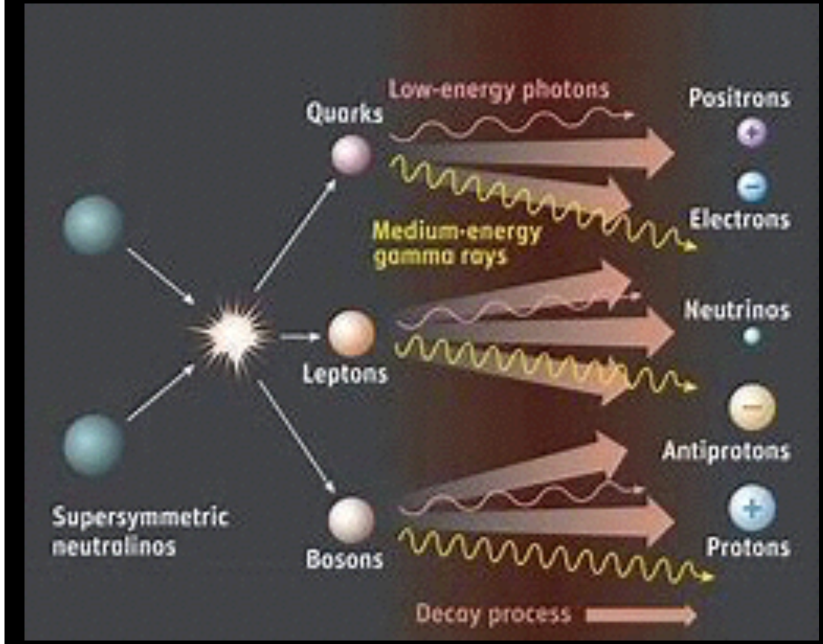
New Particle species?

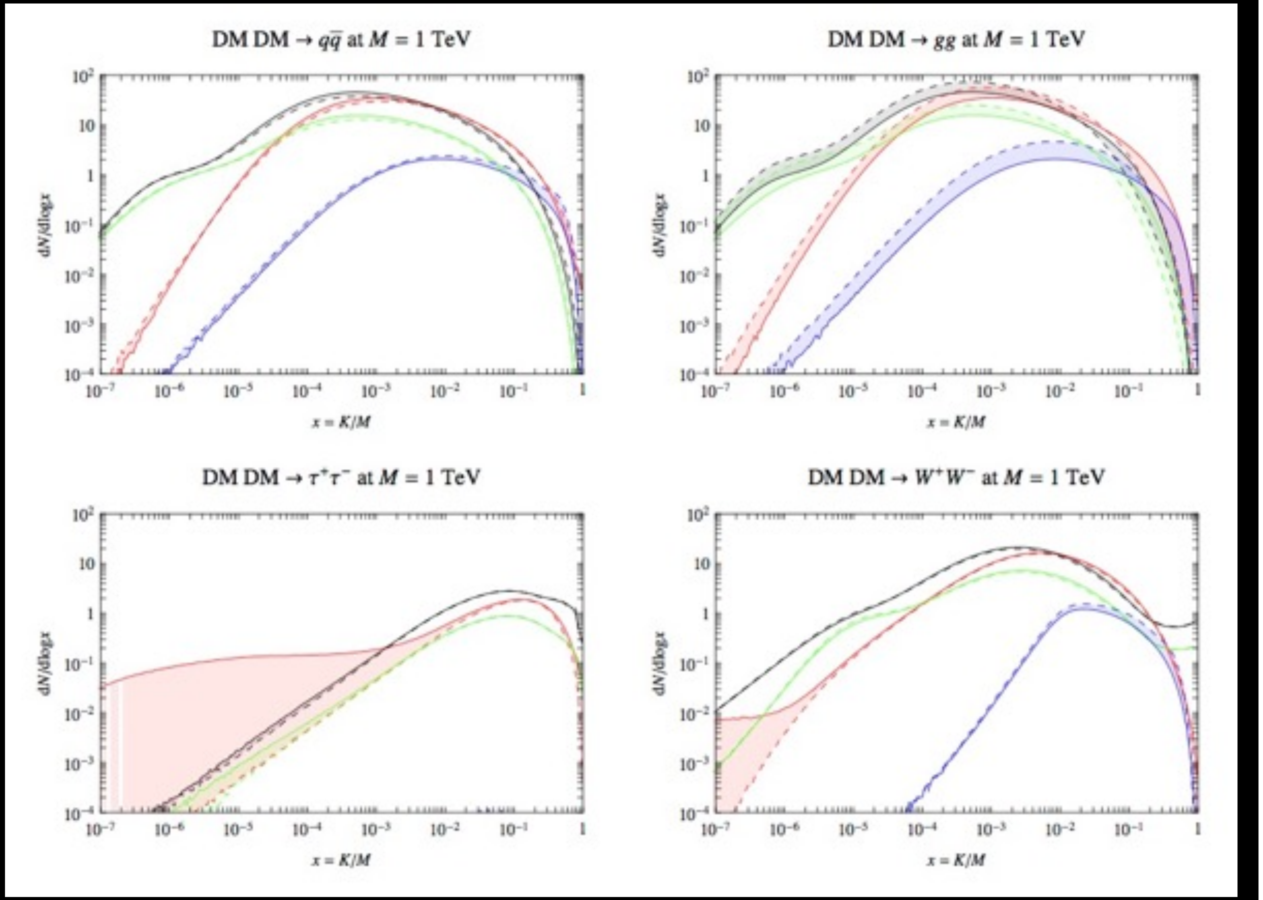
The Early Universe and Cosmology *Program*

(1) Dark Matter candidates beyond traditional WIMPs

(1.1) Heavy Dark Matter

Annihilation and decays

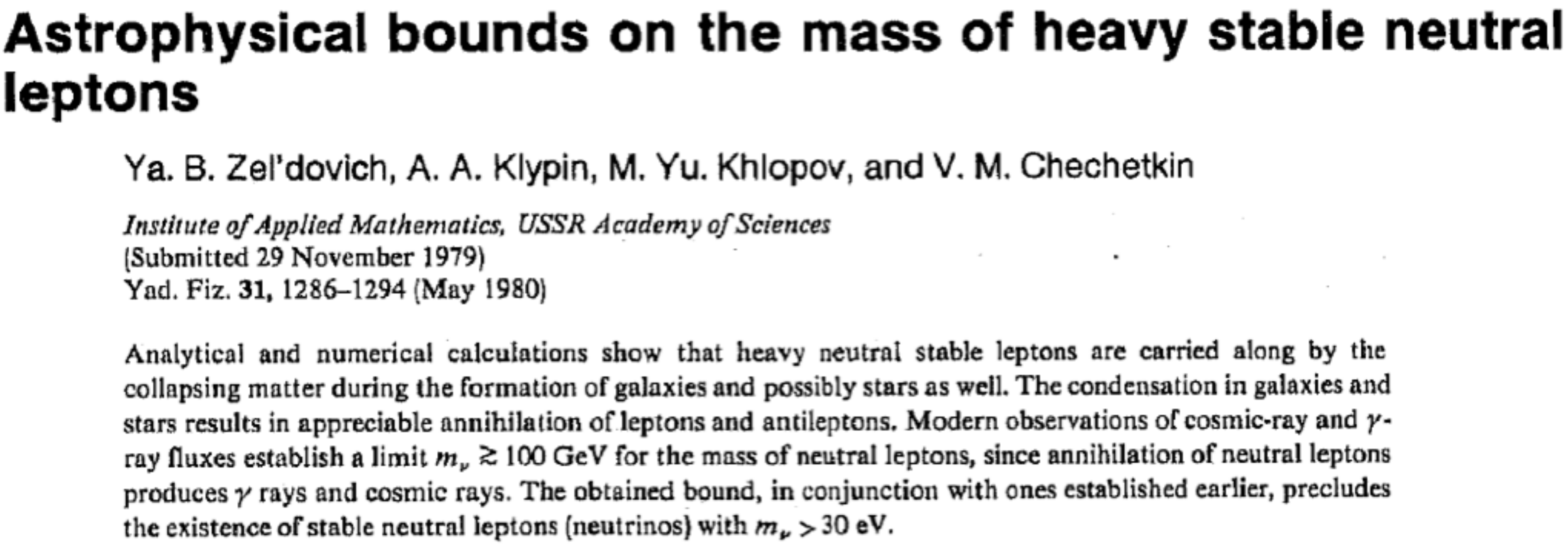




Photons (red), $e^\pm$ (green), $\bar{p}$ (blue), $\nu = \nu_e + \nu_\mu + \nu_\tau$ (black)

beyond TeV, beyond perturbativity bound!

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.

Crucial issues

From private discussions with *Cirelli, Panci, Serpico,*
Di Sciascio, Sala, Fornengo

Developing of Numerical tools capturing non-perturbative effects (such as Sommerfeld effect as well as electroweak corrections)

Effective area Vs Energy

Hadronic Background rejection Vs Energy (saved gammas over rejection)

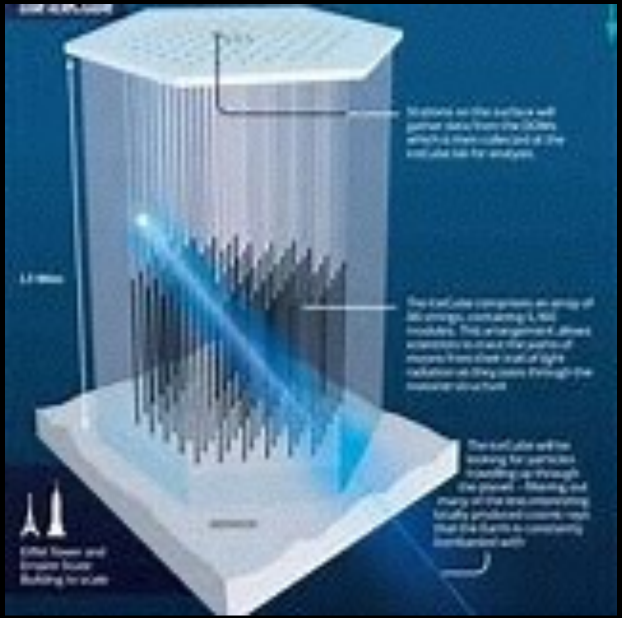
angular resolution and systematics;
ex. dipole/uniforme rel. intensity?

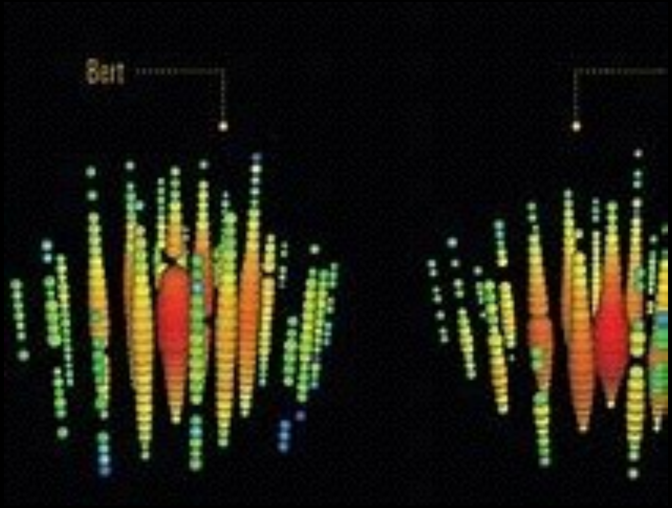
Field of view at “any time”

“Hit when it hurts!”

(Ninjitsu master)

Dark Matter or Violent Astrophysics in IceCube?





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

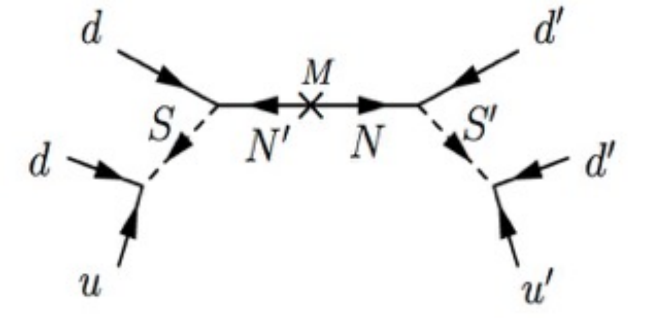
(1.2) Dark Mirror Sectors

Neutron mixing with Mirror twin

$(A, Z) \to (A-1, Z) + n'$ *not allowed by phase space !*

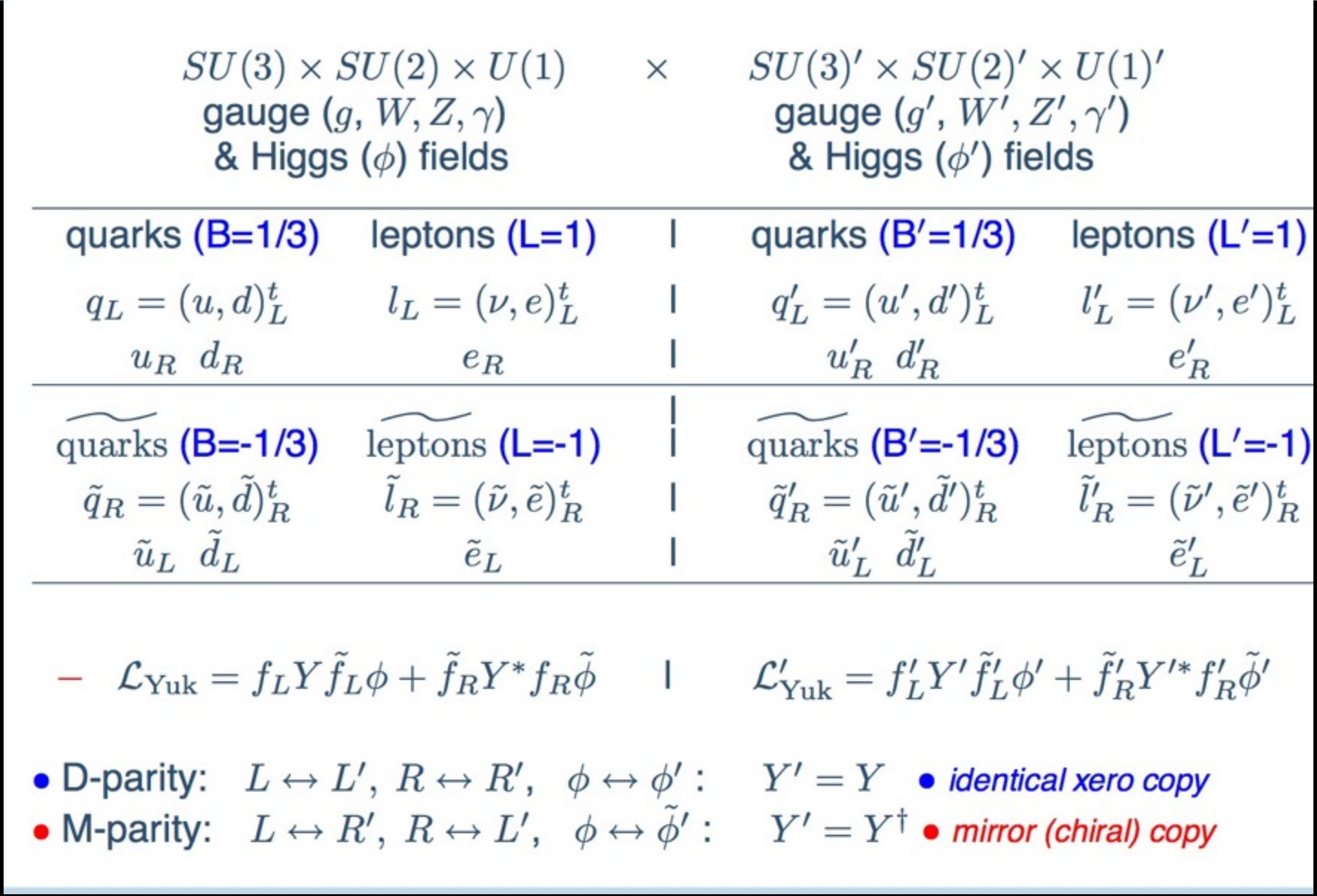
$$\tau_{nn'} < 10\,\mathrm{min}$$

$$\frac{1}{\mathcal{M}^5}(udd)(u'd'd')\ (\Delta B = 1)$$



$$H = \begin{pmatrix} m - i\,\Gamma/2 + V + \mu(\vec{B}\cdot\vec{\sigma}) & \delta m \\ \delta m & m' - i\,\Gamma'/2 + V' + \mu'(\vec{B}'\cdot\vec{\sigma}) \end{pmatrix}$$

Berezhiani, Bento, Mohapatra, Nussinov, Nesti, Gazizov, Addazi, Kamyshkov, Biondi,…



$SU(3)\times SU(2)\times U(1)$ × $SU(3)'\times SU(2)'\times U(1)'$

gauge (g, W, Z, γ) & Higgs (ϕ) fields	×	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)
$\tilde q_R = (\tilde u, \tilde d)^t_R$	$\tilde l_R = (\tilde\nu, \tilde e)^t_R$	|	$\tilde q'_R = (\tilde u', \tilde d')^t_R$	$\tilde l'_R = (\tilde\nu', \tilde e')^t_R$
$\tilde u_L \;\; \tilde d_L$	$\tilde e_L$	|	$\tilde u'_L \;\; \tilde d'_L$	$\tilde e'_L$

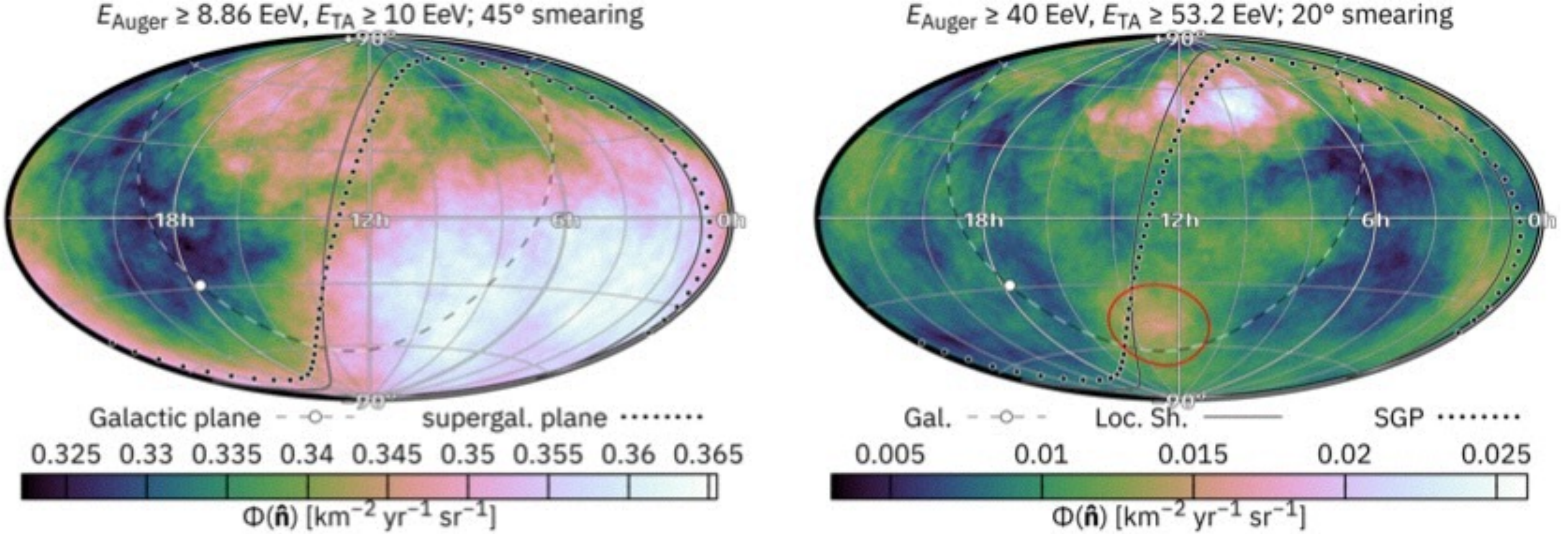
− $\mathcal{L}_{\rm Yuk} = f_L Y \tilde f_L \phi + \tilde f_R Y^* f_R \tilde\phi$ | $\mathcal{L}'_{\rm Yuk} = f'_L Y' \tilde f'_L \phi' + \tilde f'_R Y'^* f'_R \tilde\phi'$

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

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

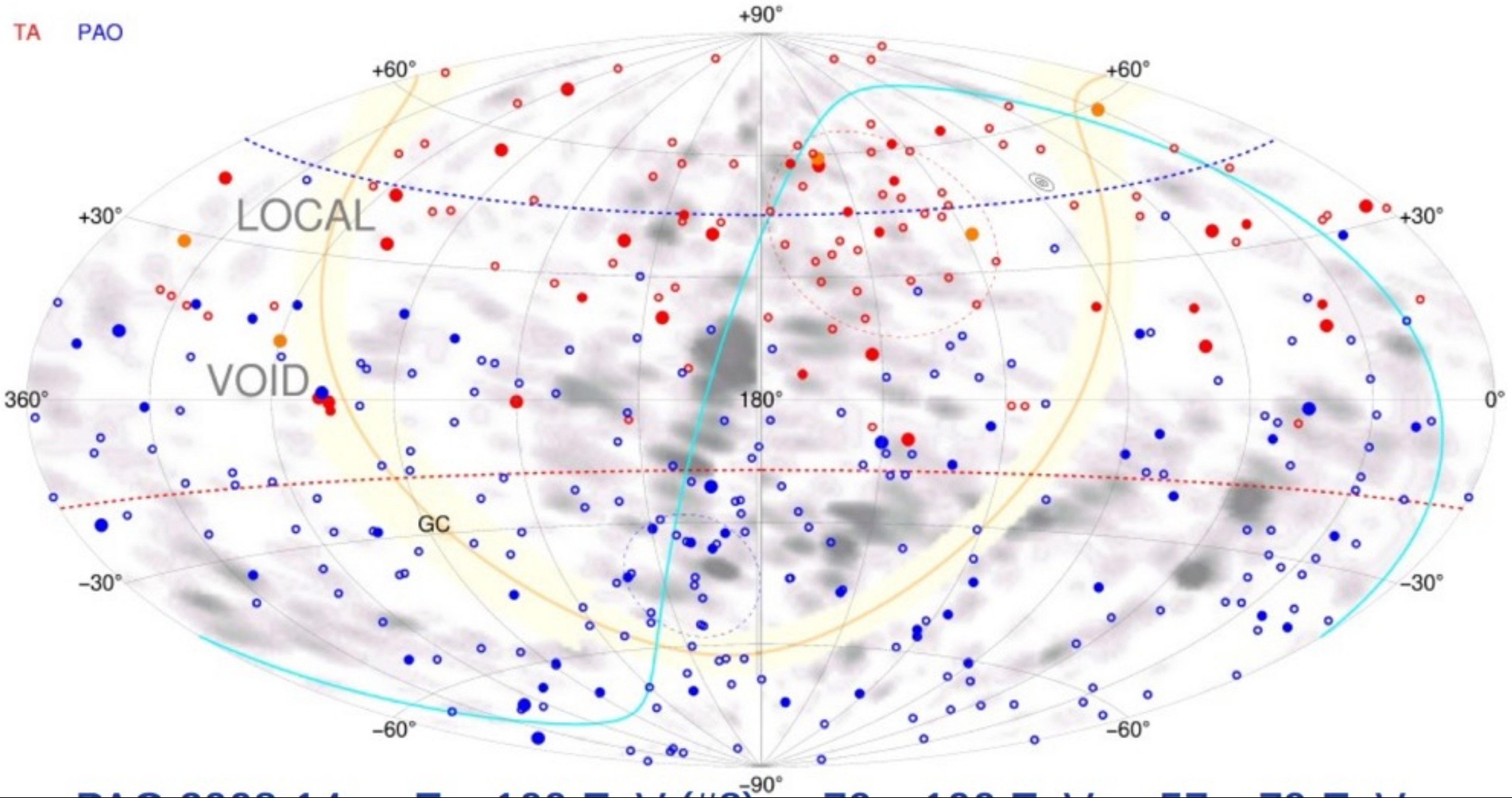
From Berezhiani's talks

UHECR “Panorama” Anisotropy and Voids



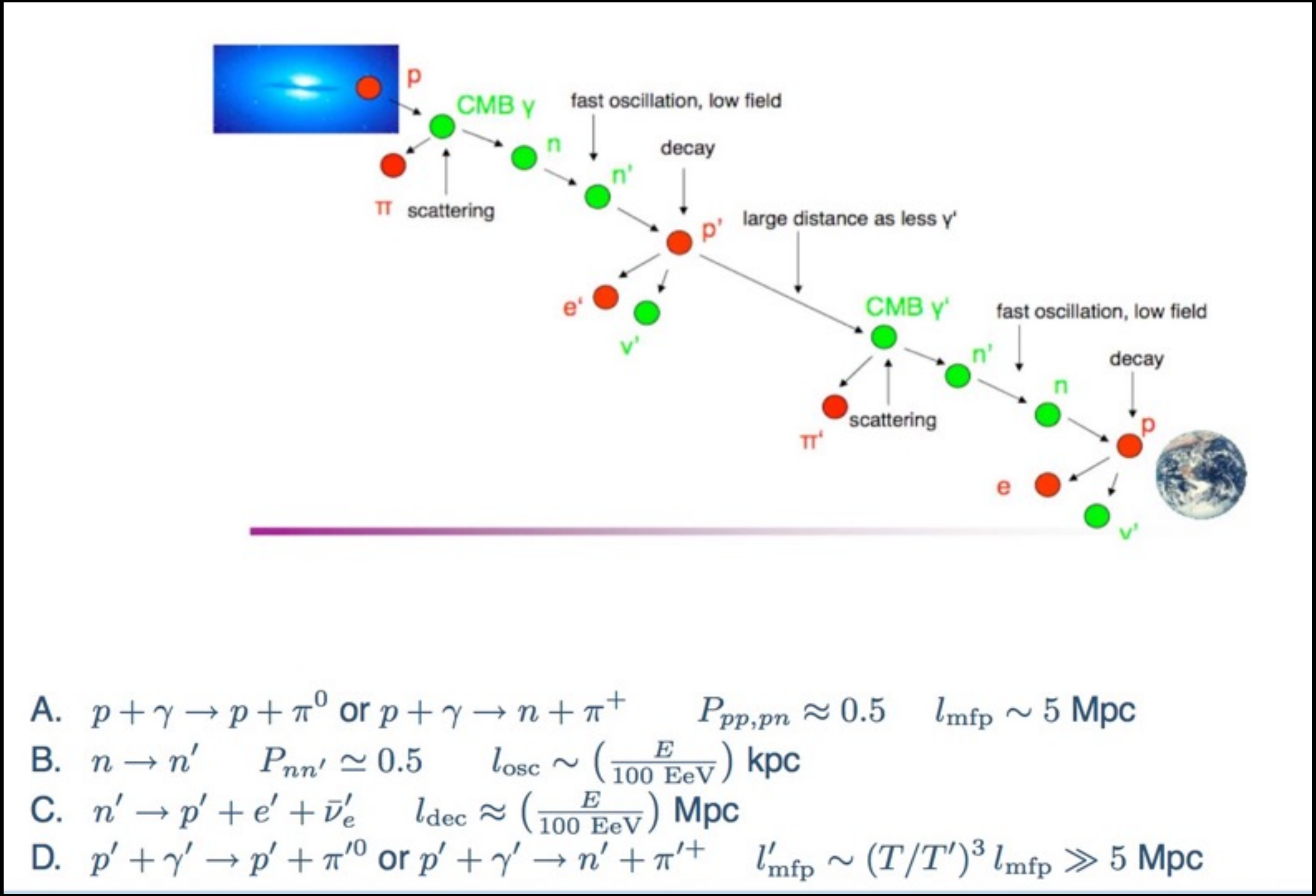
Auger+T.E.

Courtesy of A. Di Matteo



Berezhiani, Biondi, Gazizov, work in progress

Courtesy of A. Gazizov



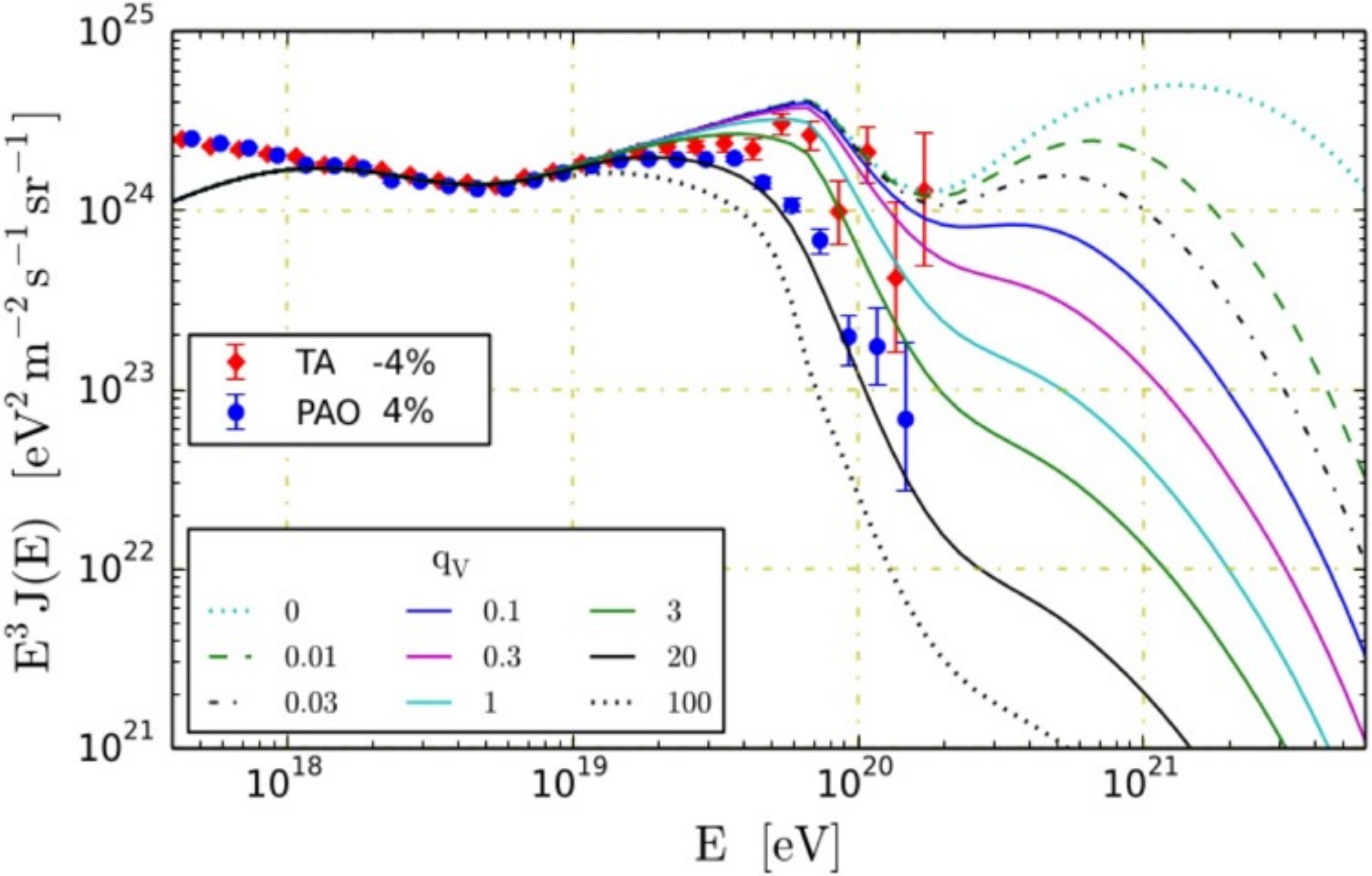
A. $p + \gamma \to p + \pi^0$ or $p + \gamma \to n + \pi^+$ $\quad P_{pp,pn} \approx 0.5 \quad l_{\rm mfp} \sim 5$ Mpc

B. $n \to n' \quad P_{nn'} \simeq 0.5 \quad l_{\rm osc} \sim \left(\frac{E}{100\ {\rm EeV}}\right)$ kpc

C. $n' \to p' + e' + \bar{\nu}'_e \quad l_{\rm dec} \approx \left(\frac{E}{100\ {\rm EeV}}\right)$ Mpc

D. $p' + \gamma' \to p' + \pi'^0$ or $p' + \gamma' \to n' + \pi'^+ \quad l'_{\rm mfp} \sim (T/T')^3\, l_{\rm mfp} \gg 5$ Mpc

Berezhiani's talks



Most energetic ***CRs*** should arrive from voids.

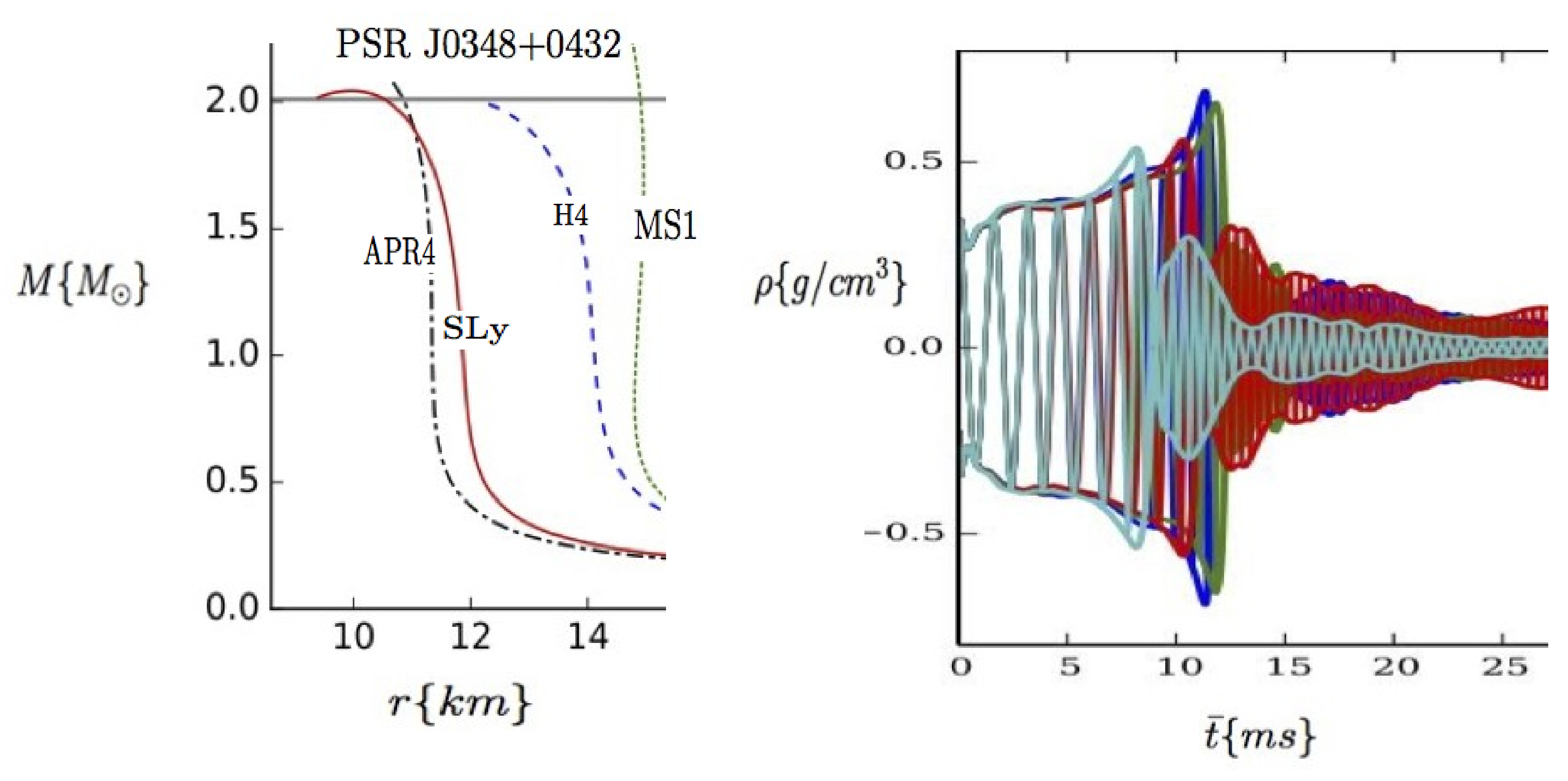
They must be **protons**.

The number of voids and their properties are more favorable in the *northern* sky.

Berezhiani, Biondi, Gazizov, work in progress

Courtesy of A. Gazizov

Mirror Dark Neutron stars mergings



Addazi, Marciano, IJMPA 2017

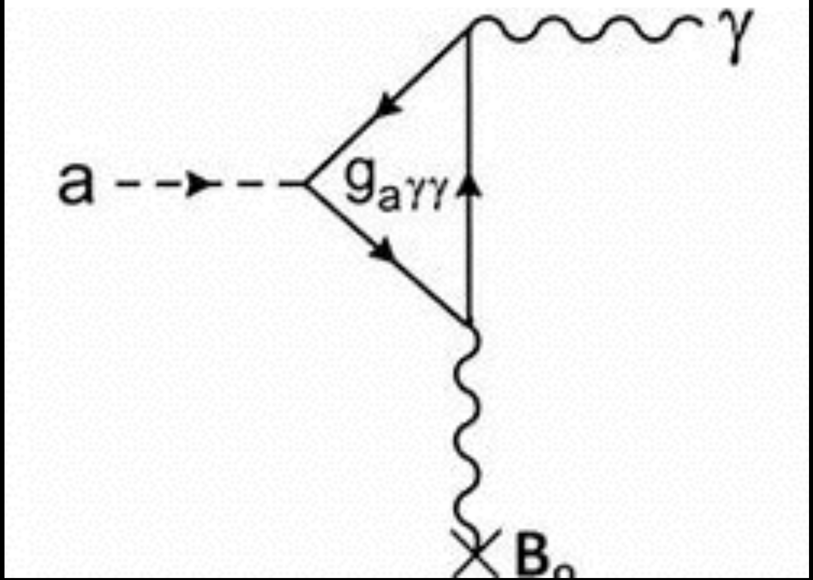
LHAASO for Mirror

100TeV-PeV-Gamma-rays cross-measures
for UHECR from Voids
(Extragalactic physics)
470 TeV hint?

For Lower energies protons from Mirror nuclei
photo-disintegration,
neutron—Mirror-neutron
transitions and following beta-decays
(negligible or not?)

(1.3) Axion-like-particles

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



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

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

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

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

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

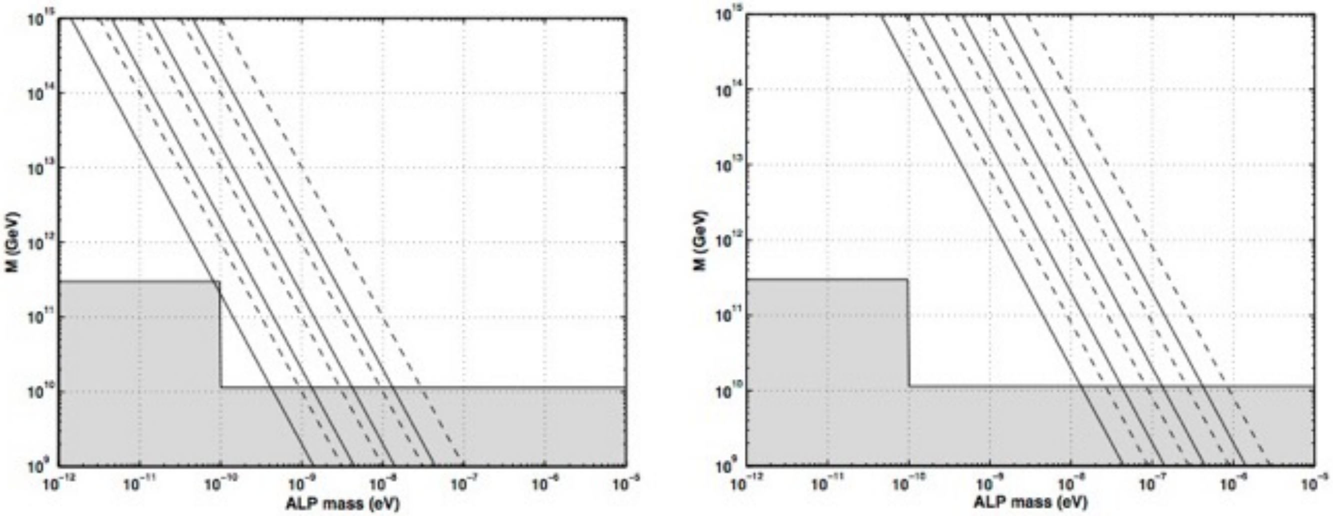


Fig. 2. Left panel: values of the pair (m, M) which determine the critical energy $E_* = 1$ GeV, 10 GeV, 100 GeV and 1 TeV (from left to right) for a magnetic field strength of $B = 1 \cdot 10^{-9}$ G (solid line) and $B = 5 \cdot 10^{-9}$ G (dotted line) and a plasma frequency $\omega_{\rm pl} \sim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

(1.4) 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* $T < I_o$

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

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

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

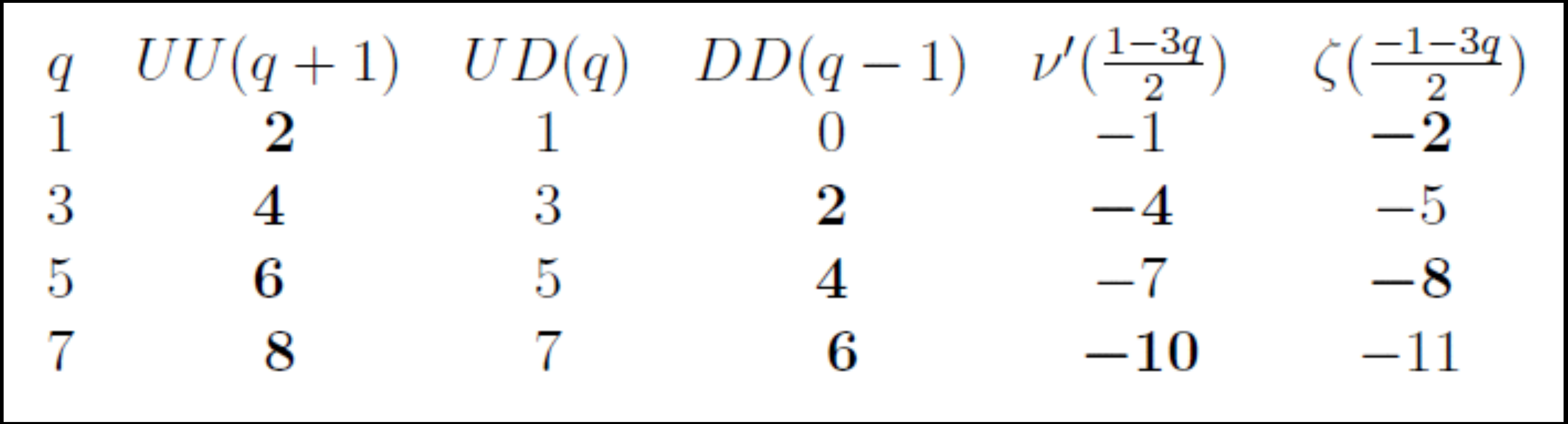
^{4}He is formed at T ~100 keV (t~100 s)
This means that it would rapidly create a neutral atom, in which all X^{--} are bound

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

References
1. M.Yu. Khlopov, *JETP Lett.* 83 (2006) 1;
2. D. Fargion, M.Khlopov, C.Stephan, *Class. Quantum Grav.* 23 (2006) 7305;
2. M. Y. Khlopov and C. Kouvaris, *Phys. Rev.* D 77 (2008) 065002]

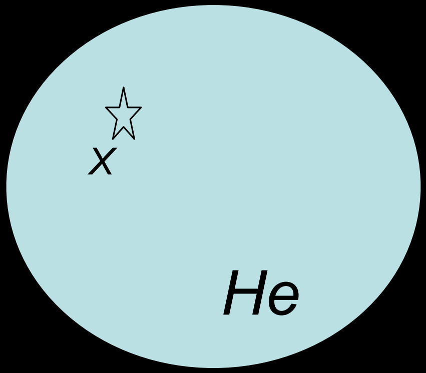
Stable multiple charged particles

Walking Technicolor

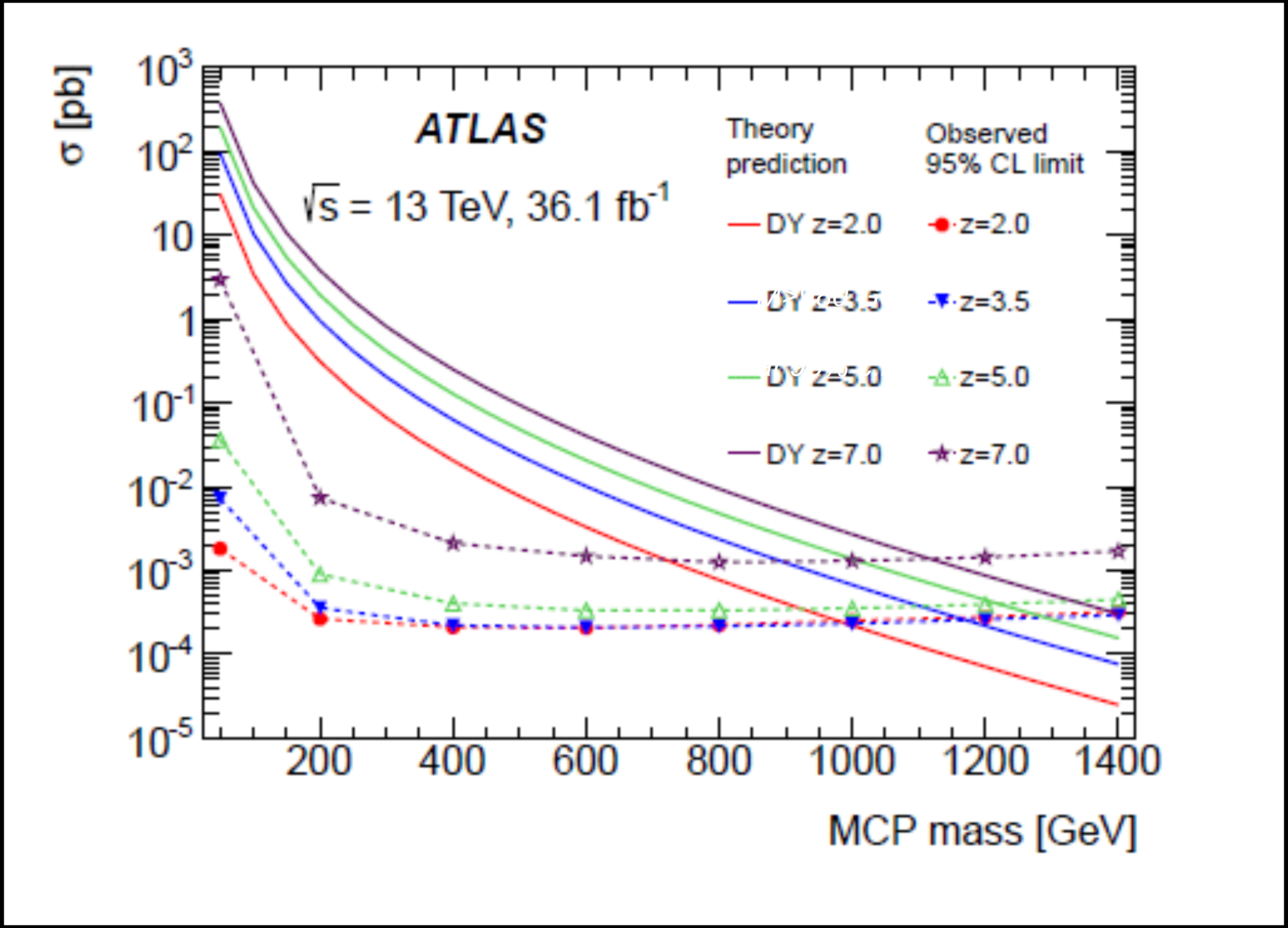


q	$UU(q+1)$	$UD(q)$	$DD(q-1)$	$\nu'(\frac{1-3q}{2})$	$\zeta(\frac{-1-3q}{2})$
1	**2**	1	0	−1	**−2**
3	**4**	3	**2**	**−4**	−5
5	**6**	5	**4**	−7	**−8**
7	**8**	7	**6**	**−10**	−11

-2n charged particles in WTC bound with n nuclei of primordial 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.

(1.5) Primordial Black Holes

$$r \le r_g = \frac{2GM}{c^2}$$

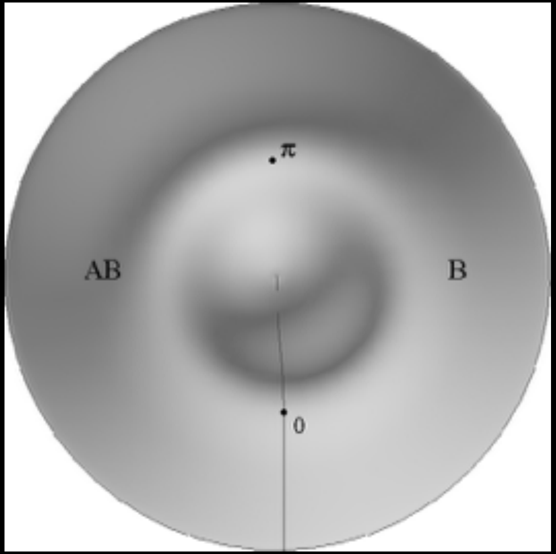
It corresponds to strong inhomogeneity developed in the early Universe

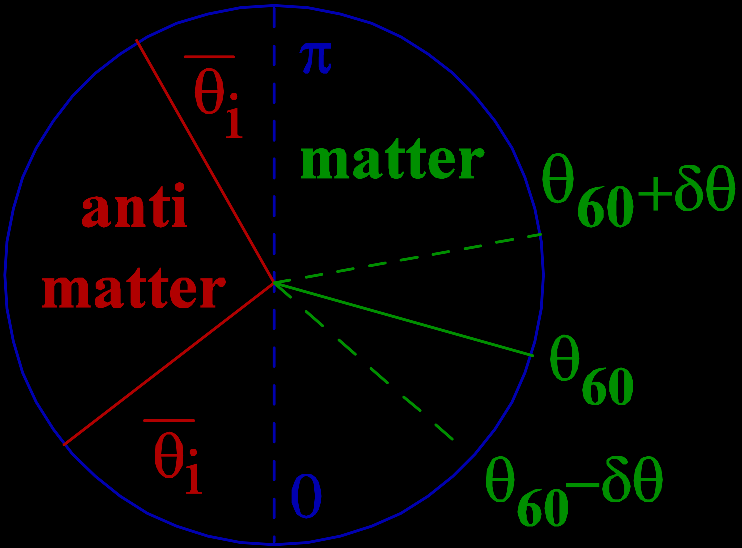
$$\delta \equiv \frac{\delta\rho}{\rho} \sim 1$$

BH can be formed in the early Universe if expansion stops within the cosmological horizon *Zeldovich, Novikov 1966*

(2) Exotic Remnants from the Early Universe

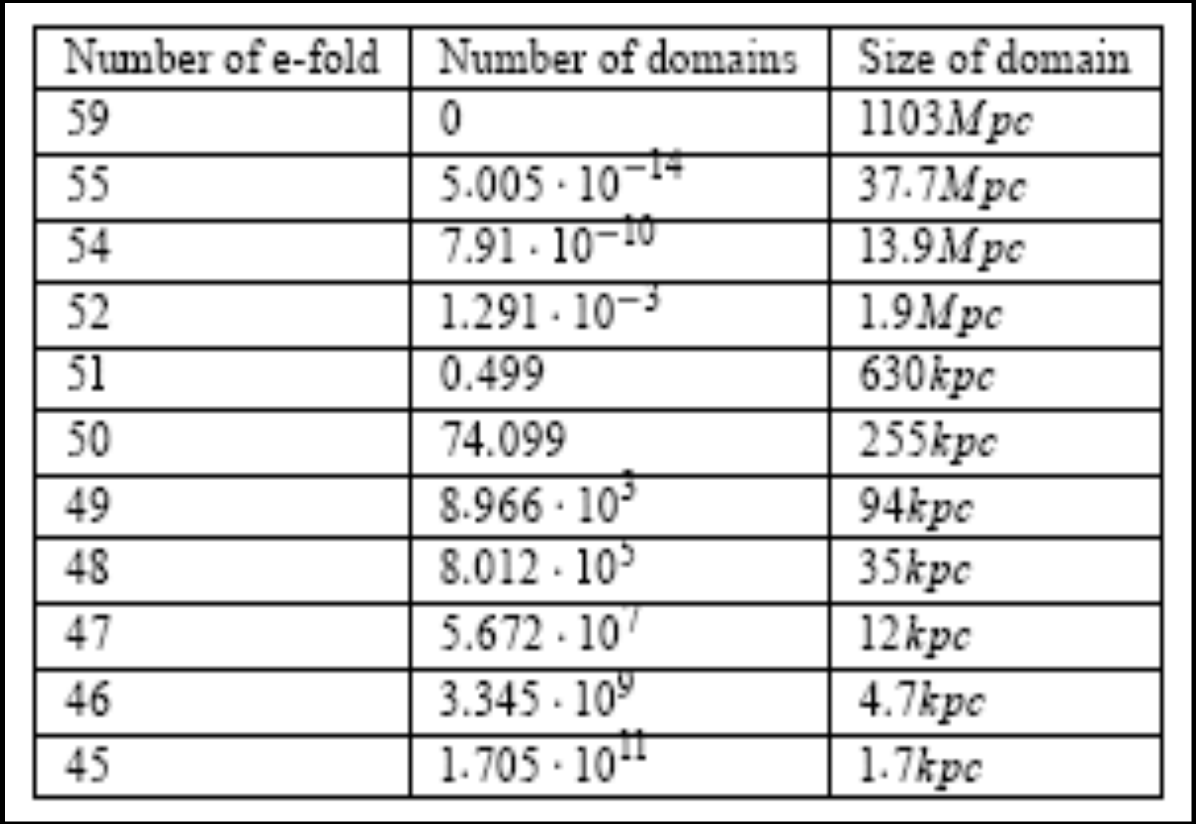
(2.1) Antimatter “island”





- *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

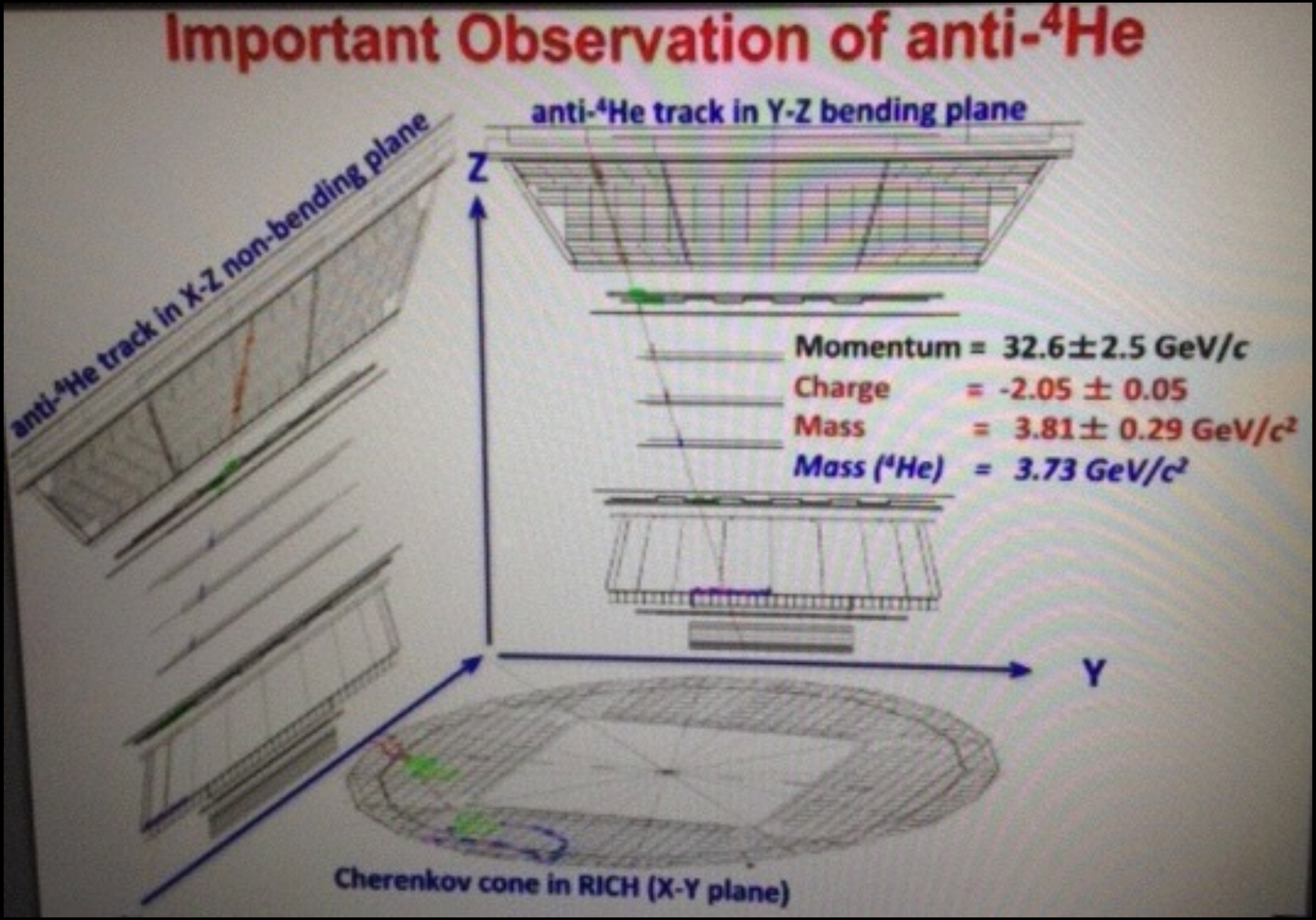


Number of e-fold	Number of domains	Size of domain
59	0	1103 Mpc
55	$5.005 \cdot 10^{-14}$	37.7 Mpc
54	$7.91 \cdot 10^{-10}$	13.9 Mpc
52	$1.291 \cdot 10^{-3}$	1.9 Mpc
51	0.499	630 kpc
50	74.099	255 kpc
49	$8.966 \cdot 10^{3}$	94 kpc
48	$8.012 \cdot 10^{5}$	35 kpc
47	$5.672 \cdot 10^{7}$	12 kpc
46	$3.345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

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

M. Khlopov (1998)

First signal from antimatter stars in AMS02?



Important Observation of anti-^{4}He

anti-^{4}He track in Y-Z bending plane

anti-^{4}He track in X-Z non-bending plane

Momentum = 32.6 ± 2.5 GeV/c

Charge = -2.05 ± 0.05

Mass = 3.81 ± 0.29 GeV/c^2

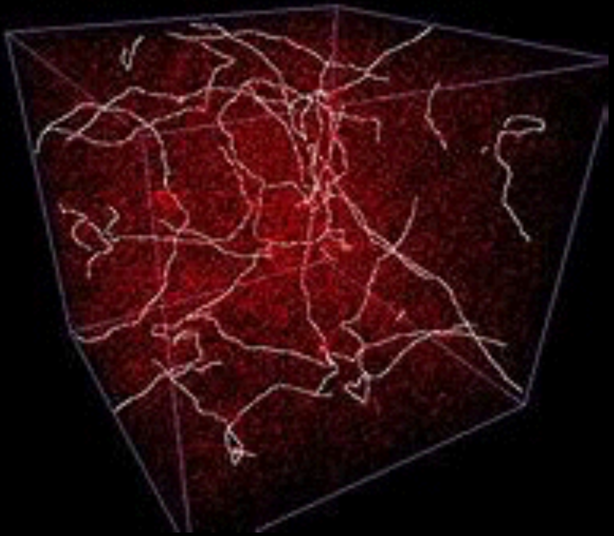
Mass (^{4}He) = 3.73 GeV/c^2

Cherenkov cone in RICH (X-Y plane)

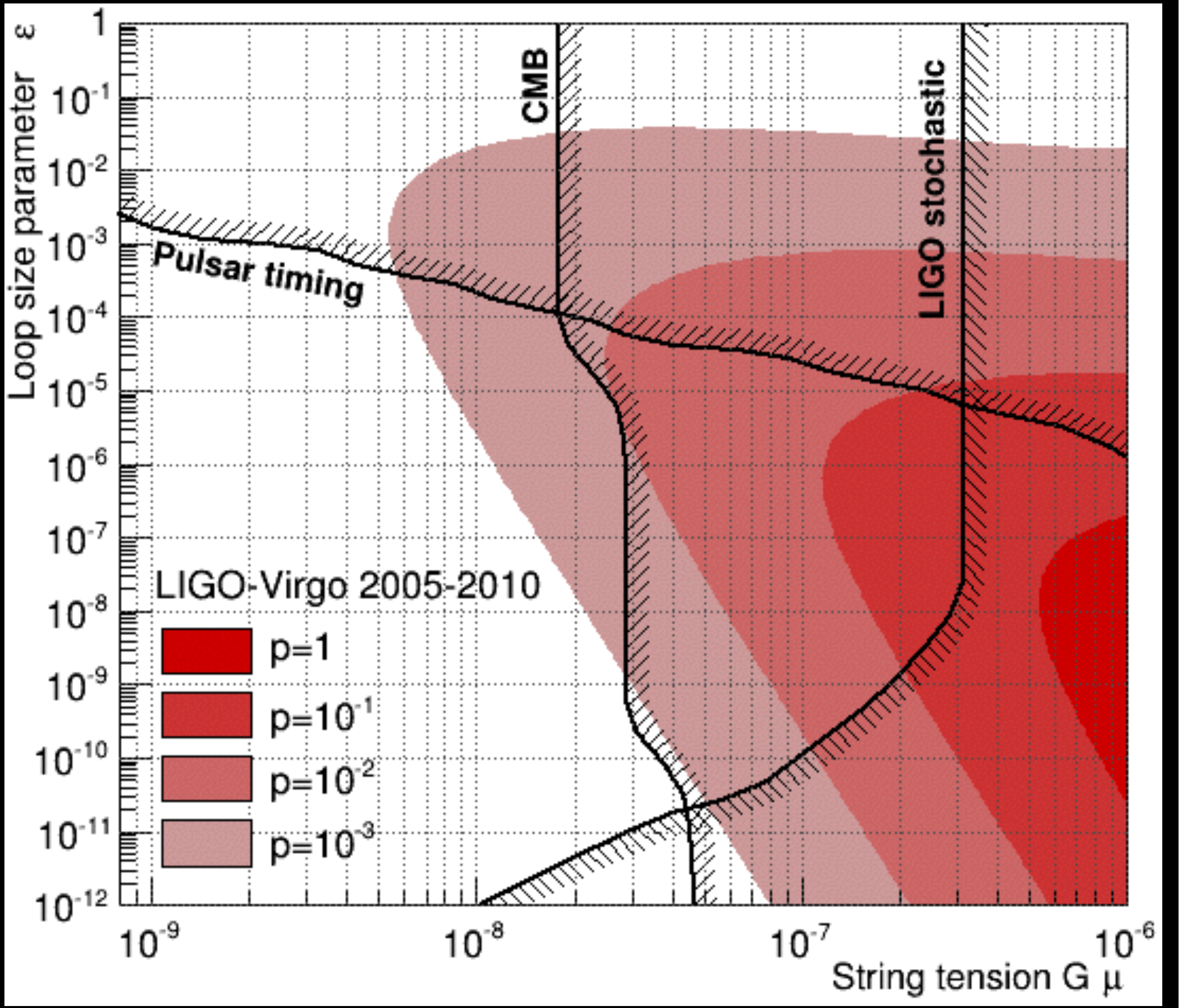
Samuel Ting, CERN, 24 May 2018

(2.2) Topological Defects

Cosmic Strings



Berezinsky, Vilenkin et al



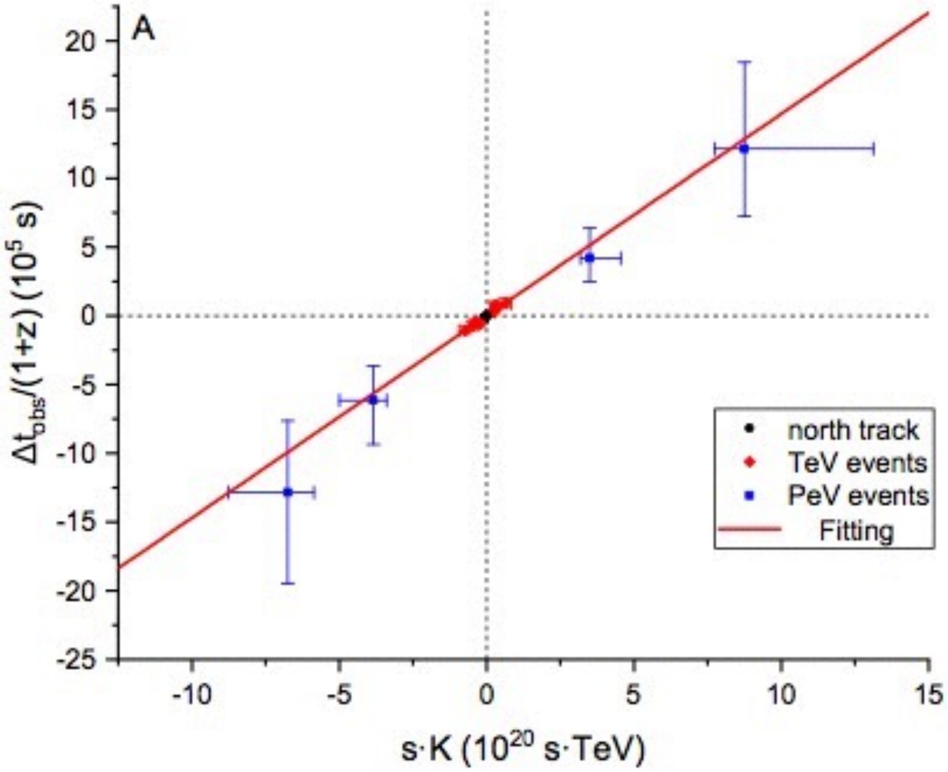
This is really genuine
Multi-Messenger New Physics:
GW, Gamma rays, UHECR comparions

(3) Fundamental space-time symmetries: Lorentz and CPT “deformations”

Quantum gravity may deform CPT, Locality, Causality, Lorentz

$$M_k: \quad \delta^2(E) = c_k \frac{E^k}{\Lambda^k} + O(E^{k+1})$$

$$v(E) = c\left[1 - s_n \frac{n+1}{2}\left(\frac{E}{E_{\mathrm{LV},n}}\right)^n\right],$$



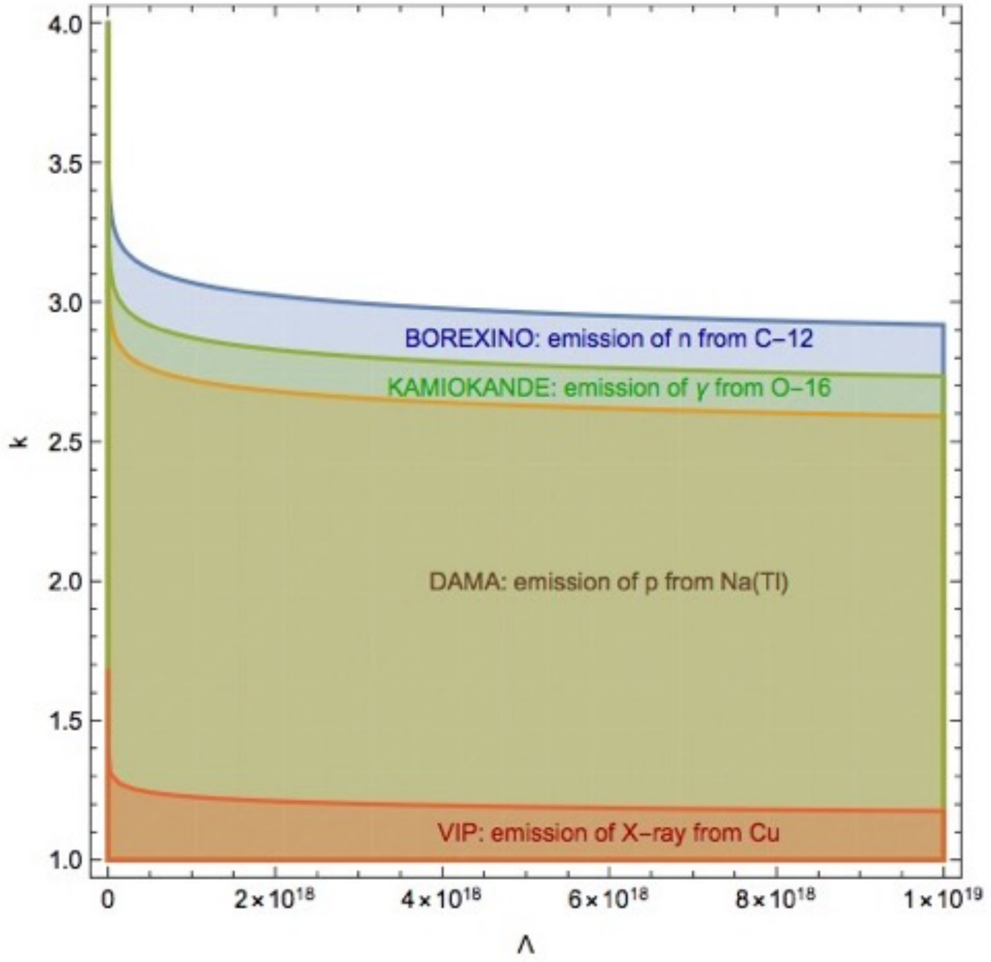


FIG. 2: Exclusion limits at 90% C.L. on the k–Λ parameters'

B.Q. Ma et al in many recent papers

Addazi, Marciano et al 2017

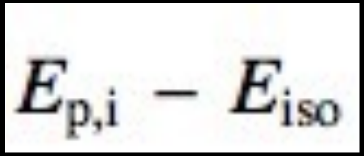
(4) DARK ENERGY

Cosmological constants
of *time-varying dynamical field*?

Gamma-Ray-Bursts
as *Standard Candles*

comparison with CMB,
Supernovae IA, 21 cm radioastronomy

“Amati’s law”



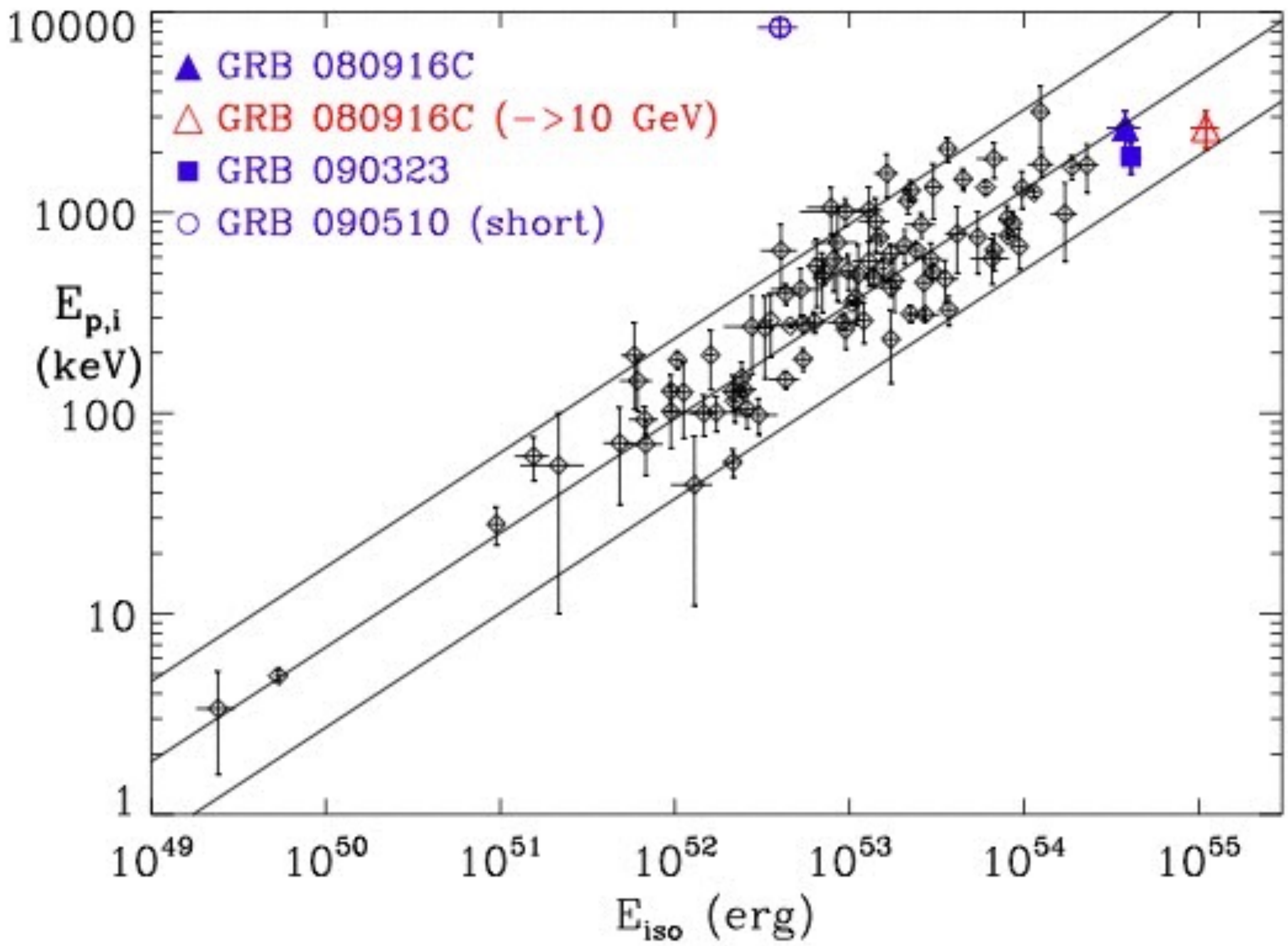
$E_{\mathrm{p,i}} - E_{\mathrm{iso}}$

correlation between the cosmological rest-frame peak energy and the isotropic equivalent radiative energy

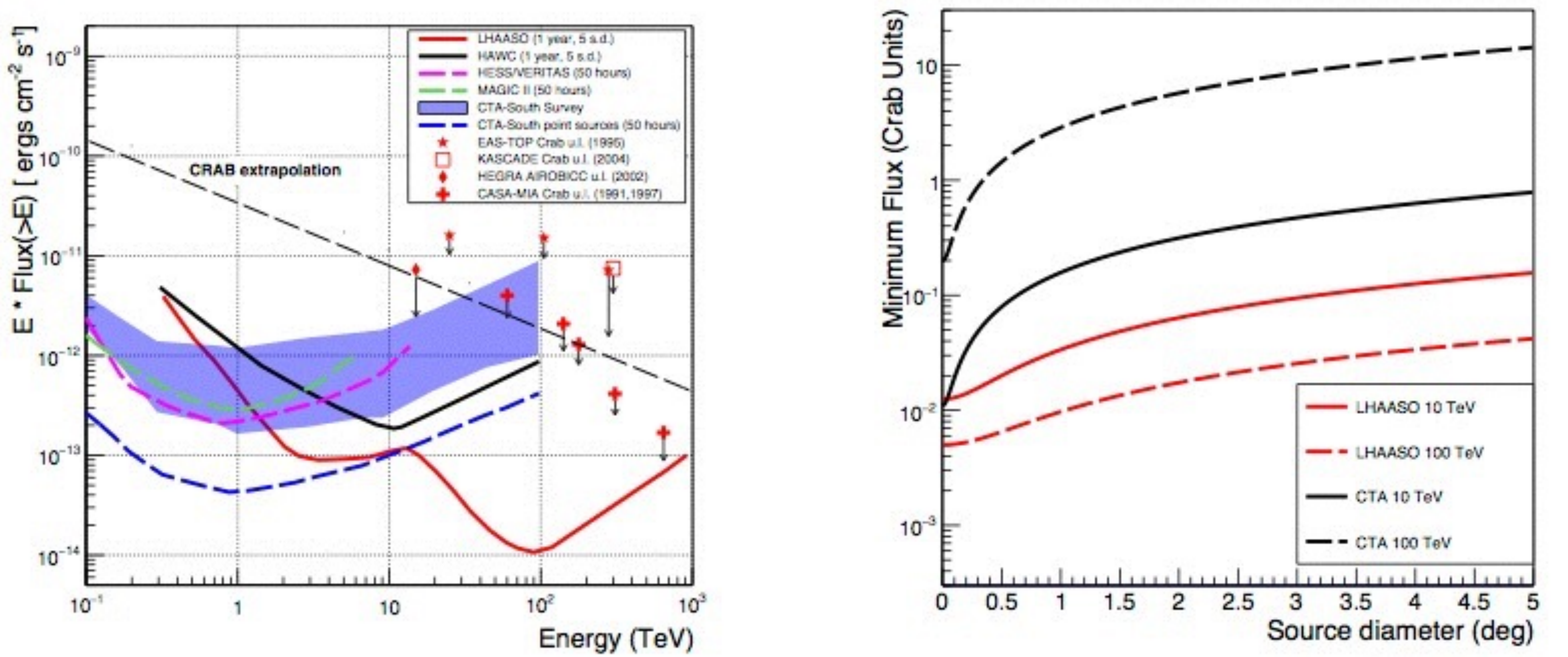
Amati (2006), Ghirlanda et al (2008)

Fermi-LAT and GRBs:
GRB080916C in 1 keV-10 GeV;
no-violations for Amati’s rule
(for instance, no flat plateau)

Redshift estimators,
GRB metrometers



Amati et al (2009), analyzing FERMI-LAT and SWIFT



Di Sciascio behold on LHAASO collaboration, arXiv.1602.07600

LHAASO
Test of Amati’s law at higher energies

Cosmology group

Y. Cai (USTC, Hefei)

A. Marciano (Fudan, Shanghai)

Yanzhou university group (Prof. Santos, Dr. Andre Costa)

M. Khlopov (APC Paris, MEPHI, SFedU)

S. Capozziello (Federico II, Napoli)

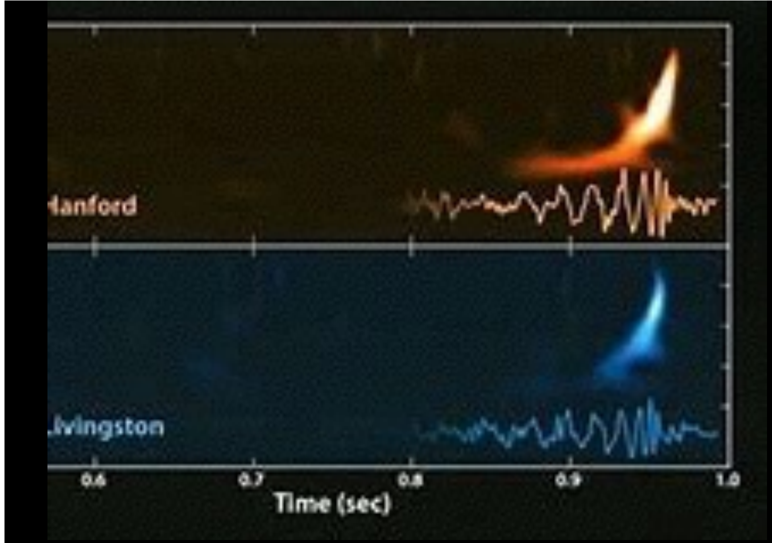
S. Odintsov (ifaee, Barcellona)

M. Bucher (APC Paris)

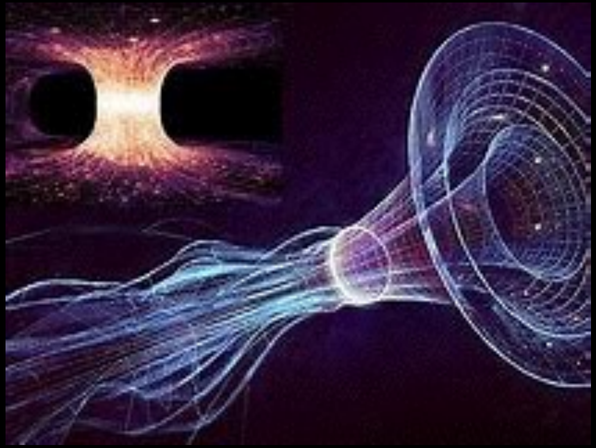
P. Panci (Pisa U, Italy)

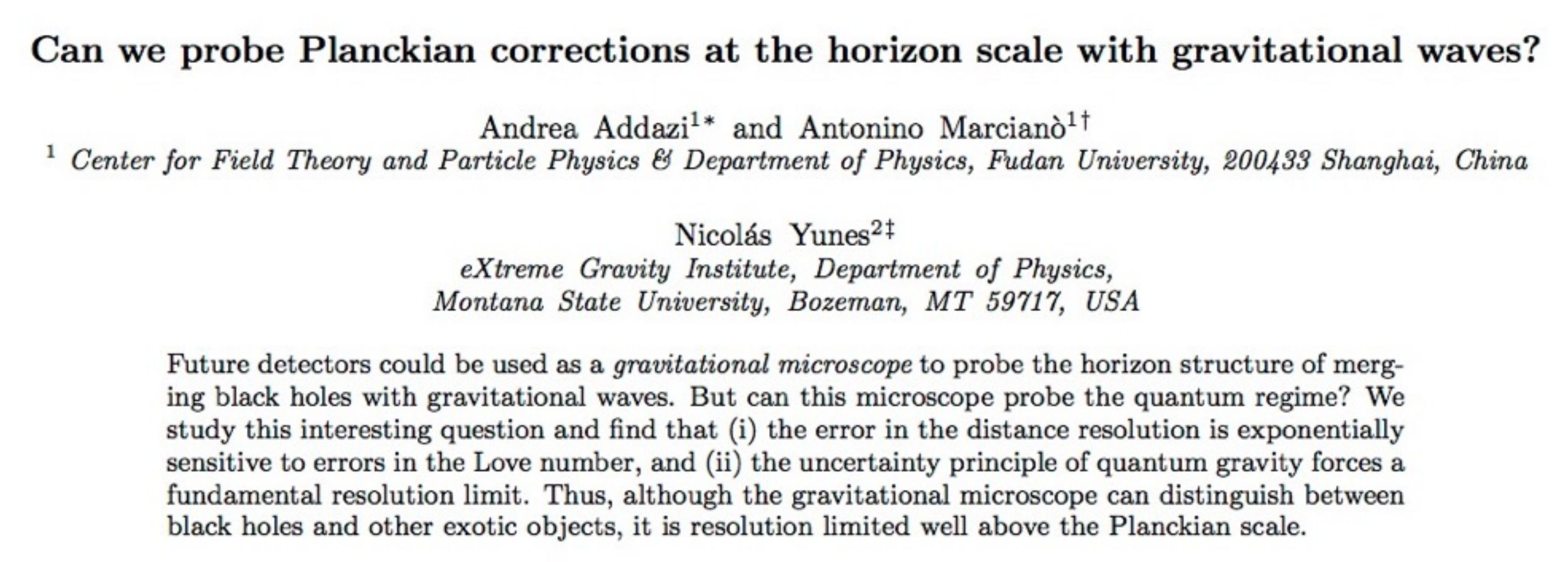
(5) Exotic Compact Objects and Quantum gravity

Black Hole information paradox


anford
ivingston
0.6
0.7
0.8
0.9
1.0
Time (sec)


Gravastars





Can we probe Planckian corrections at the horizon scale with gravitational waves?

Andrea Addazi[1*] and Antonino Marcianò[1†]
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Nicolás Yunes[2‡]
eXtreme Gravity Institute, Department of Physics,
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Future detectors could be used as a *gravitational microscope* to probe the horizon structure of merging black holes with gravitational waves. But can this microscope probe the quantum regime? We study this interesting question and find that (i) the error in the distance resolution is exponentially sensitive to errors in the Love number, and (ii) the uncertainty principle of quantum gravity forces a fundamental resolution limit. Thus, although the gravitational microscope can distinguish between black holes and other exotic objects, it is resolution limited well above the Planckian scale.

Phys.Rev.Lett. 122 (2019) no.8, 081301 (Highlights)

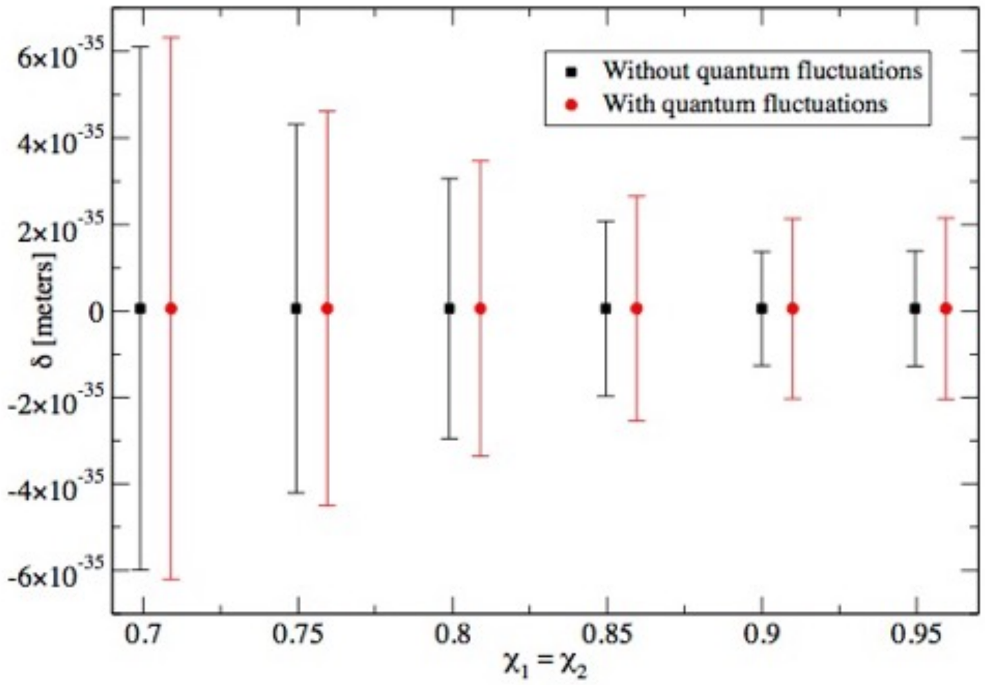
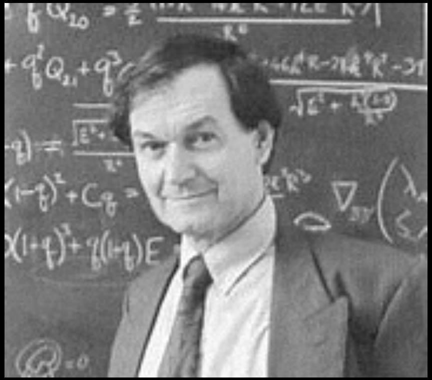
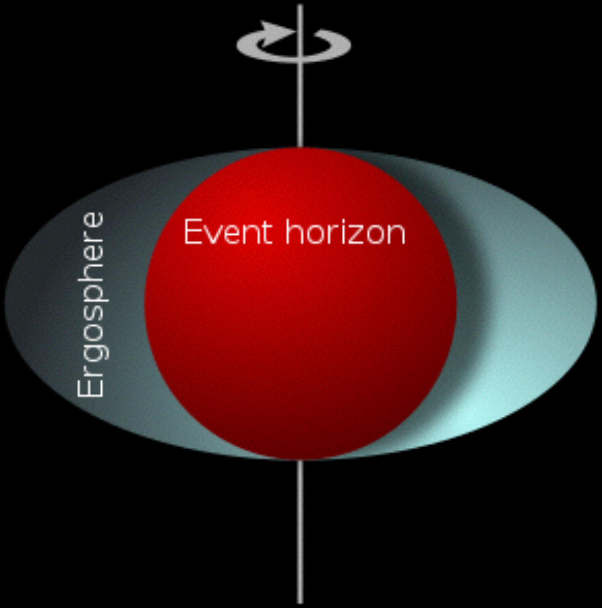
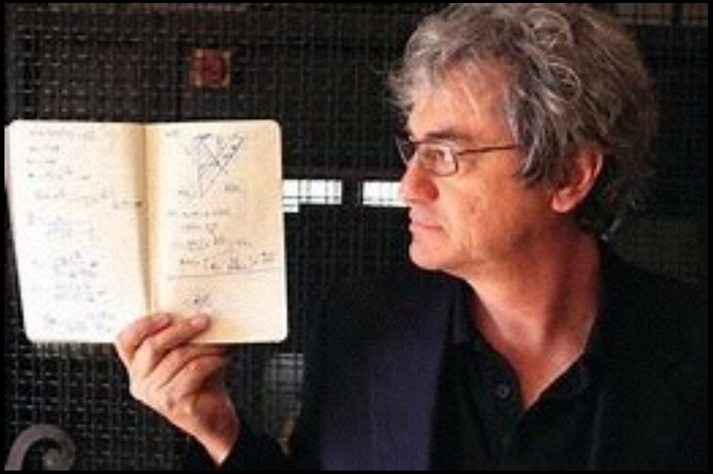


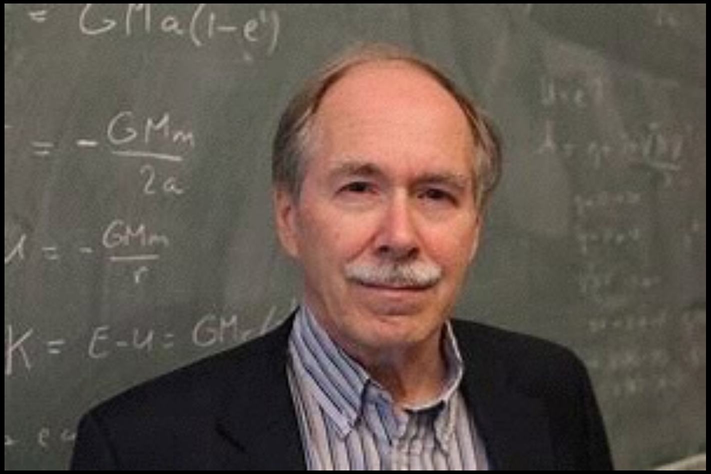
FIG. 1. (Color Online). Inferred value of δ and 1σ errors with (black, Eq. (7)) and without (red, Eq. (10)) quantum fluctuations. We have here assumed a GW observation of a compact ECO inspiral with $m_1 = 1.1 \times 10^6 M_\odot$ and $m_2 = 10^6 M_\odot$, dimensionless spin $\chi_{1,2}$, Love numbers $k_1 = k_2 = 0.02$ at a distance of 2Gpc. For the uncertainties in M and k, we used $\sigma_M^{\rm stat}/\hat{M} = 10^{-5}$ and $\sigma_k^{\rm stat}/\hat{k} \in (0.2, 1)$ (see the appendix), while for the quantum fluctuations we set $a = 1$. Observe that the error bars on the inferred value of δ are much larger than the measurement itself.





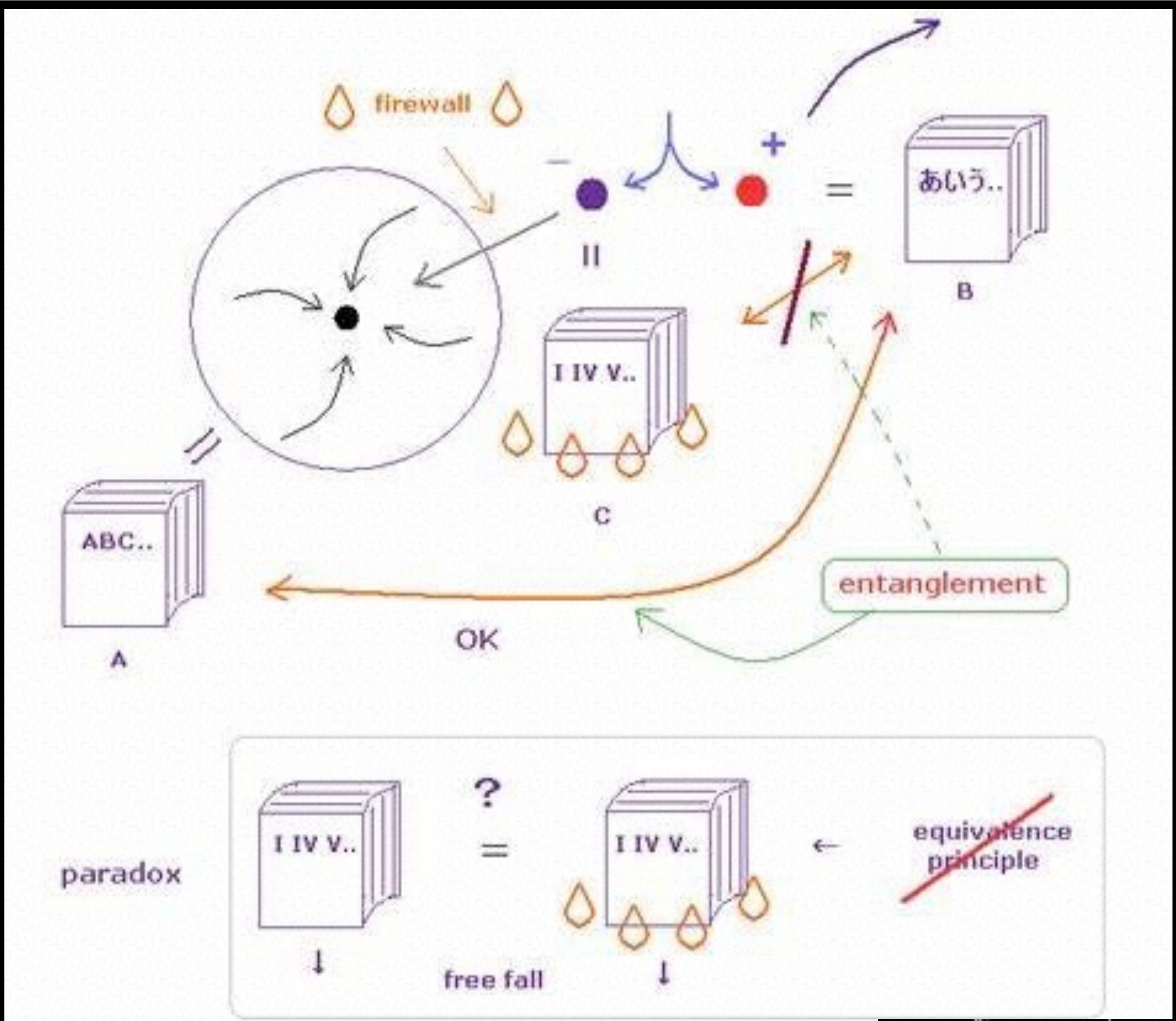
Penrose's mechanism

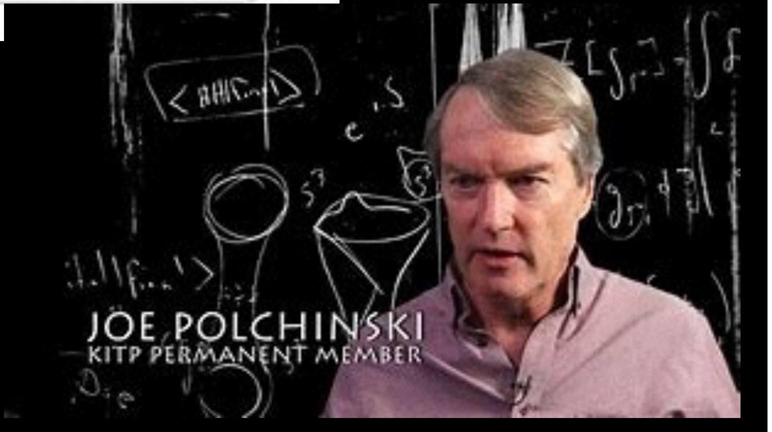




Black Explosions, White holes, Mini-Bangs

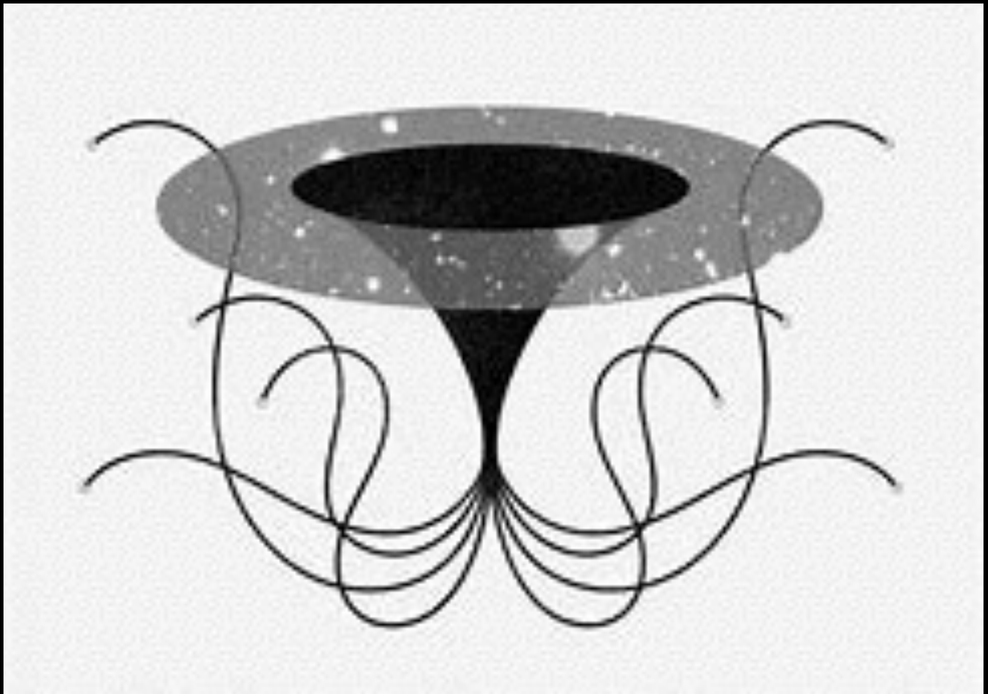
Firewall Paradox!




JOE POLCHINSKI
KITP PERMANENT MEMBER

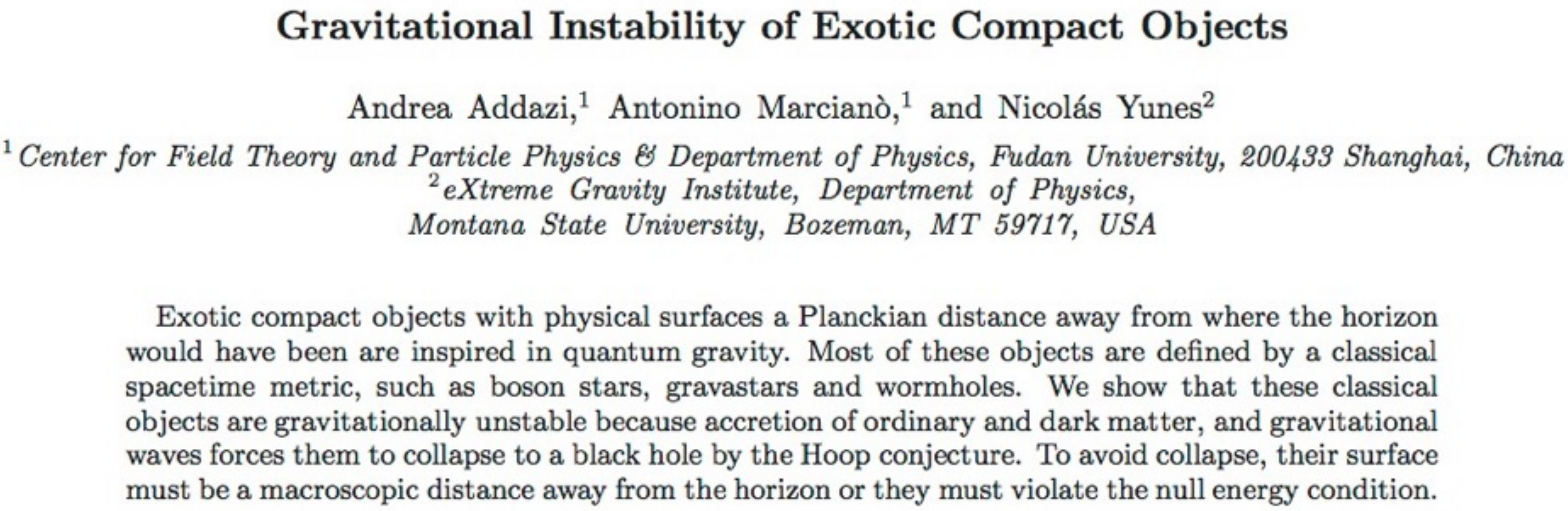
Kac-Moodions quantum hairs

no firewalls



A.Addazi, P. Chen, Yong-Shi Wu, A.Marciano

Gravastar explosion and Bosonovas



Gravitational Instability of Exotic Compact Objects

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Exotic compact objects with physical surfaces a Planckian distance away from where the horizon would have been are inspired in quantum gravity. Most of these objects are defined by a classical spacetime metric, such as boson stars, gravastars and wormholes. We show that these classical objects are gravitationally unstable because accretion of ordinary and dark matter, and gravitational waves forces them to collapse to a black hole by the Hoop conjecture. To avoid collapse, their surface must be a macroscopic distance away from the horizon or they must violate the null energy condition.

accepted in EPJC

Conclusions (as a starting point)

Search for New Physics from cosmic rays is a “nearly impossible mission”;

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

Both positive and negative results would improve our picture of high energy physics and Cosmology

Therefore, I suggest to try…

Non-zero lottery chance for “Contemporary antimatter” discovery may be just around the corner…

Thank You and see you around!