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Non-standard Universe: Cosmology and Axion-like particles

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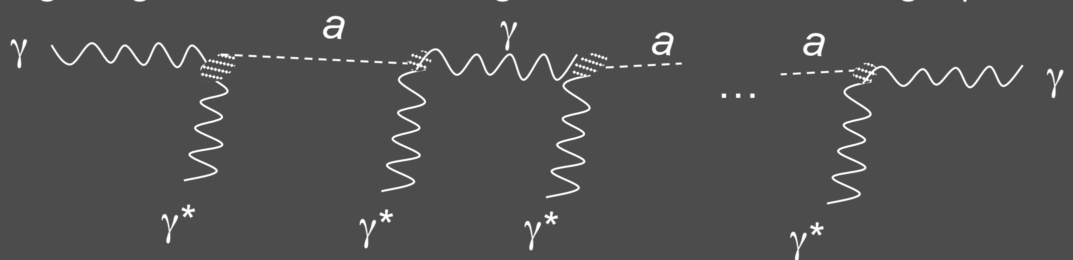
The Dark Universe: Axion Like Particles

Axions and axion-like particles

- Pseudo scalar Axion Like Particles (ALPs) with $a\gamma\gamma$ coupling are predicted in many extensions of the Standard Model

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

- Contrarily to QCD axions, ALPs mass and $a\gamma\gamma$ coupling are generally unrelated
- Photons propagating in an external magnetic field can undergo γ-a oscillations



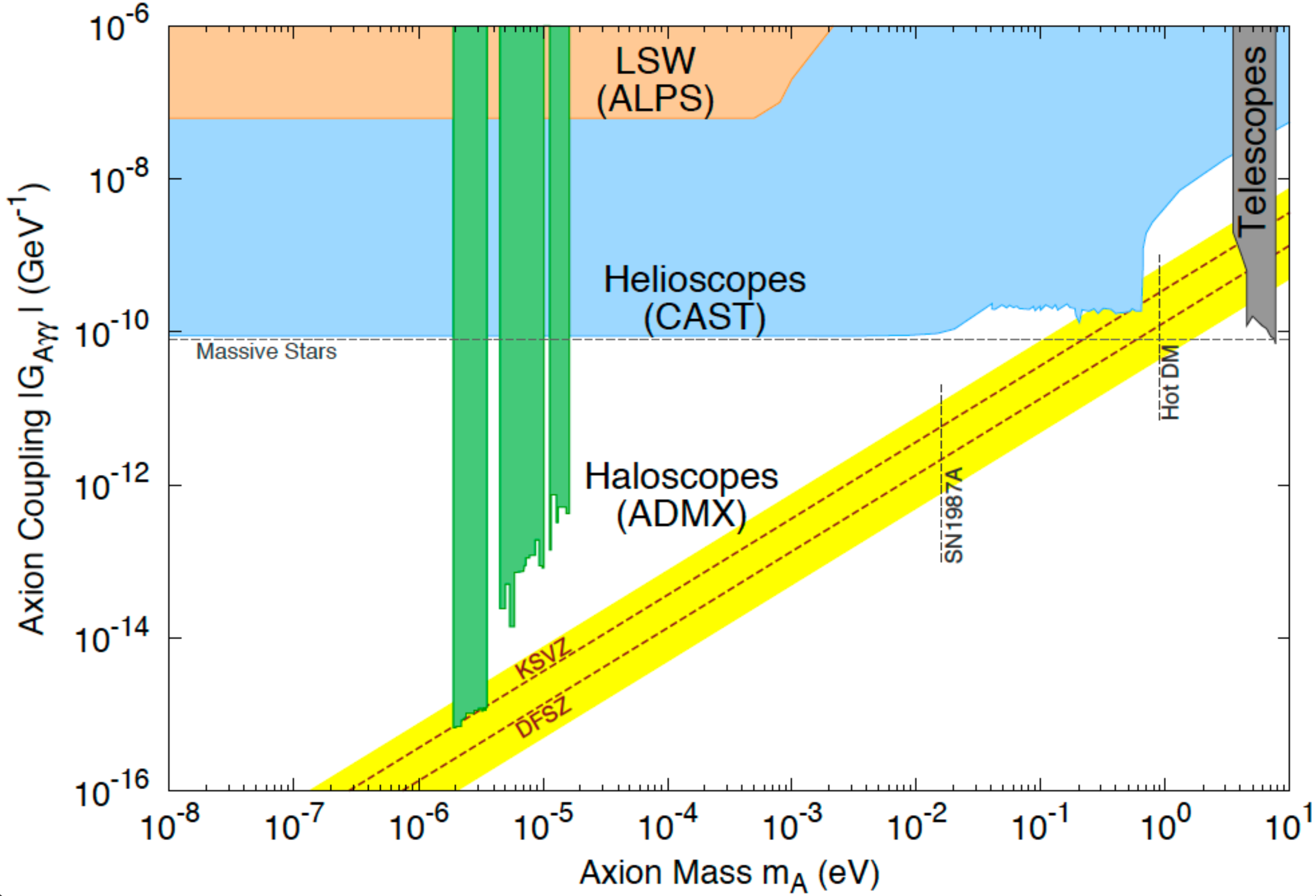
$$i\partial_{x_3} \begin{pmatrix} \hat{A}_1 \\ \hat{A}_2 \\ \hat{a} \end{pmatrix} = \begin{pmatrix} \omega(n-1) & 0 & \frac{1}{2} g_{a\gamma\gamma} B_{e,1} \\ 0 & \omega(n-1) & \frac{1}{2} g_{a\gamma\gamma} B_{e,2} \\ \frac{1}{2} g_{a\gamma\gamma} B_{e,1} & \frac{1}{2} g_{a\gamma\gamma} B_{e,2} & -\frac{m_a^2}{2\omega} \end{pmatrix} \begin{pmatrix} \hat{A}_1 \\ \hat{A}_2 \\ \hat{a} \end{pmatrix} .$$

(neglecting vacuum birefringence effect)

ω=photon energy
m_a=ALP mass
n=(complex) refraction index

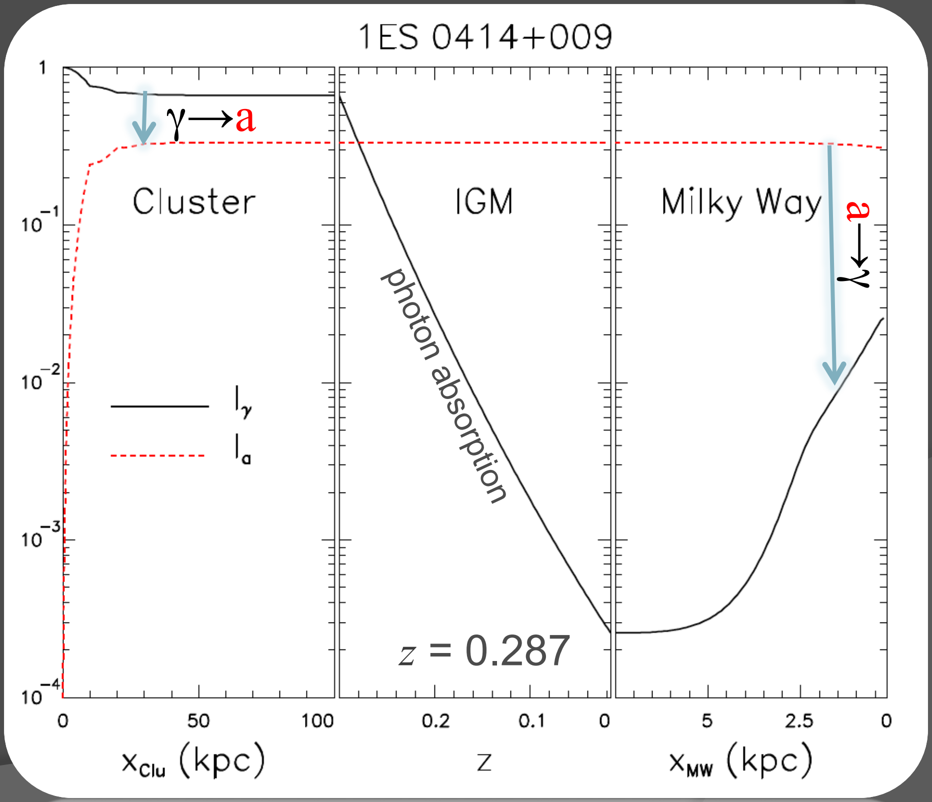
$$\Im[n] = -i \frac{\Gamma_{\text{abs}}}{2\omega}$$

Currents Bounds on ALPs parameters (from PDB)



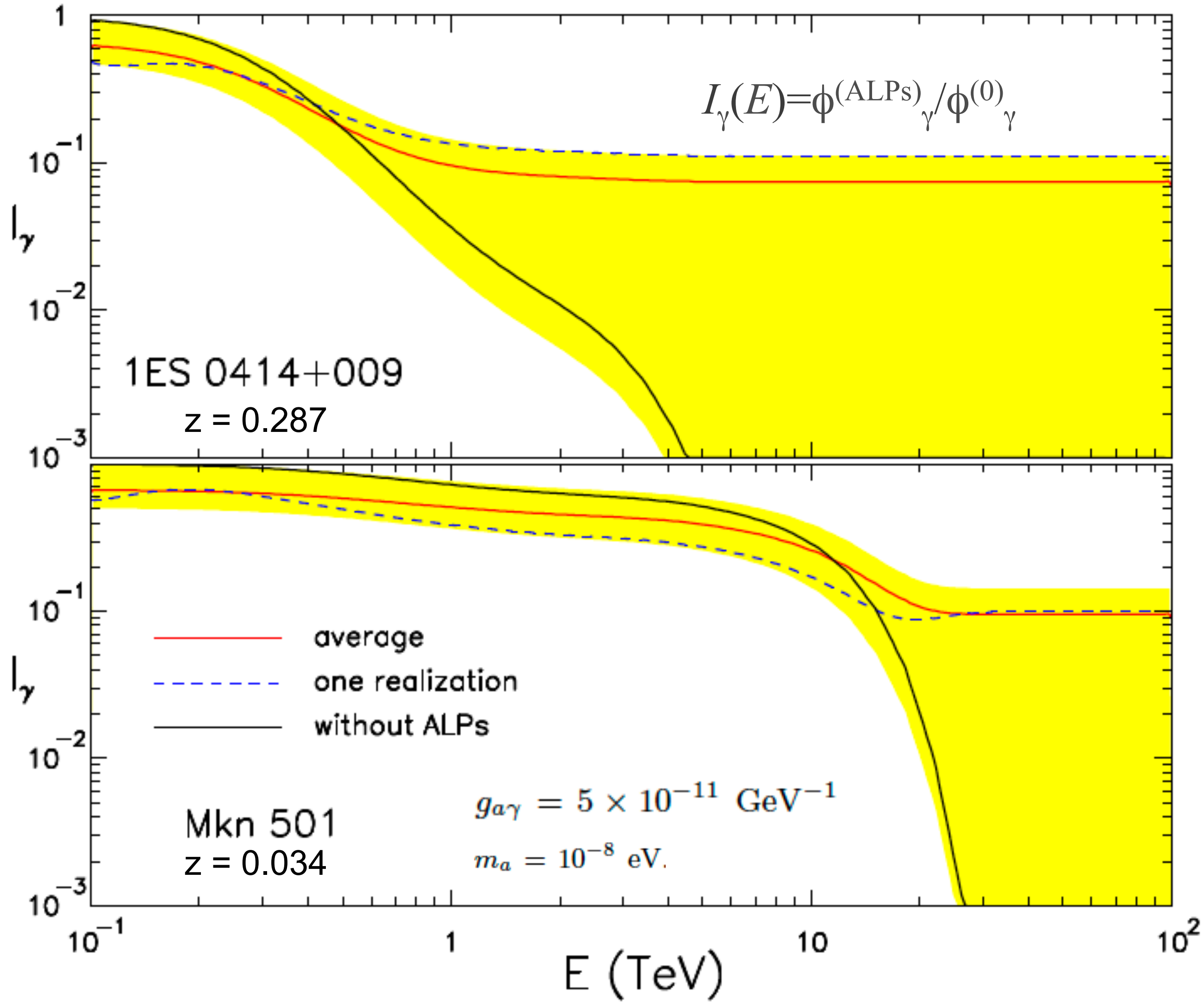
Conversion in Galaxy Clusters [1]

- Galaxy clusters sometimes host Active Galactic Nuclei (AGNs) which are sources of very high energy (≳TeV) gamma rays
- VHE photons undergo in large extent to absorption on Extragalactic Background ambient light due to pair production $\gamma^{(VHE)}\gamma^{(bkg)} \to e^{+} e^{-}$
- If some of photons are converted into ALPs in the (~μG) cluster magnetic field they can evade absorption. Further, ALPs can be reconverted into photons resulting in a cosmic "light shining through wall effect"
- The effect can be observed as a harder spectrum than expected



[1] D. Horns, L. Maccione, M. Meyer, A. Mirizzi, D. M. and M. Roncadelli, **Phys. Rev. D86, 075024 (2012)**

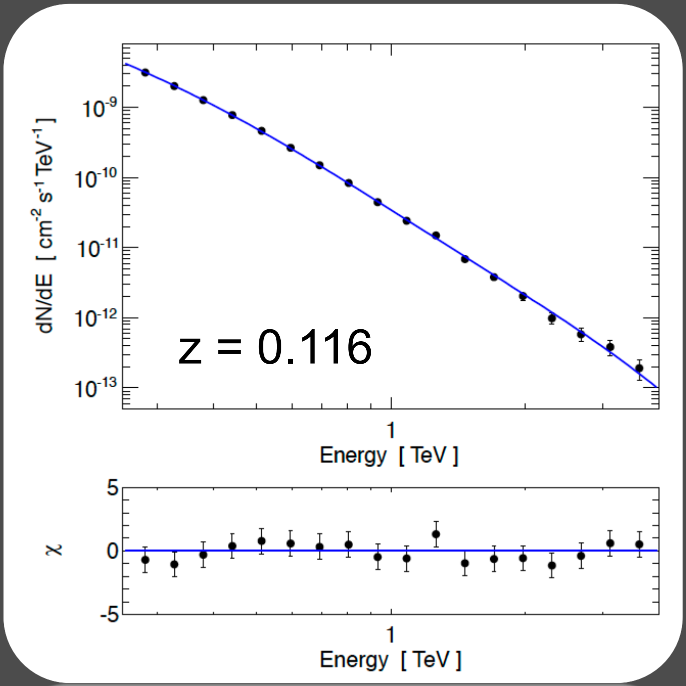
Photon "survival" probability

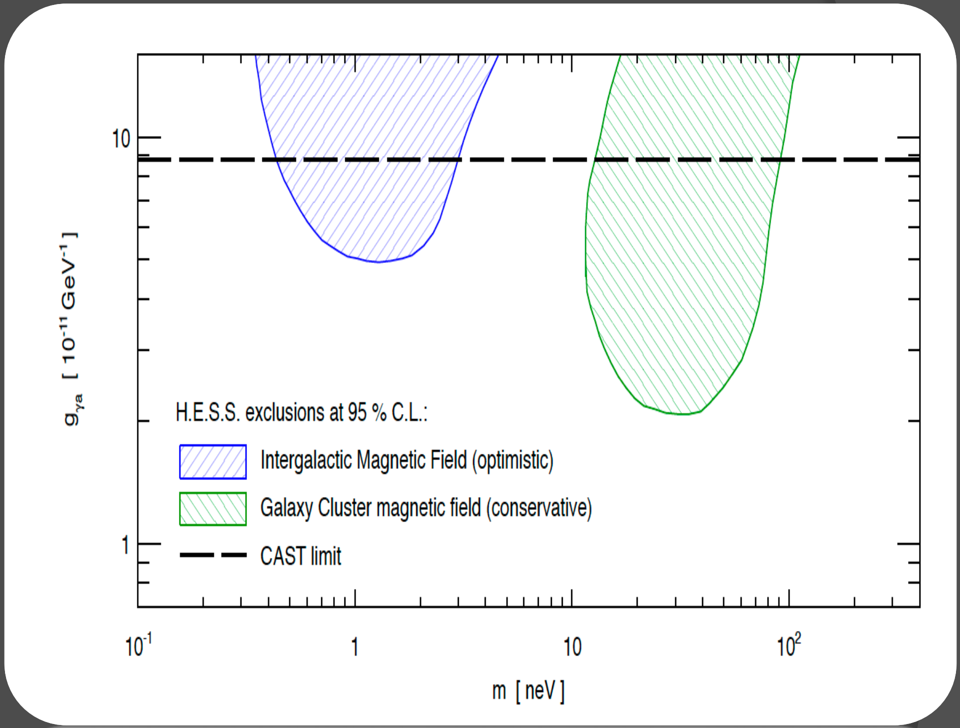


Yellow area: all possible magnetic field realizations

- H.E.S.S. spectral analysis analysis shows no evidence for spectral distortion at photon energy ~1TeV from source PKS 2155-304 at z = 0.116 [HESS Collaboration, Phys. Rev. D88, 102003 (2013)]

Reconstructed spectrum





- However, the limits are only marginally better than existing ones already superseded by limits coming from SN1987A)
- With new detectors there is still room to improve limits observing sources at higher redshift

Forecast for future experiments [2]

- Three scenarios has been analyzed:
  - A galaxy cluster with a cell-like magnetic field morphology (with random orientation in each cell)
  - A galaxy cluster with a turbulent “tangled” magnetic field

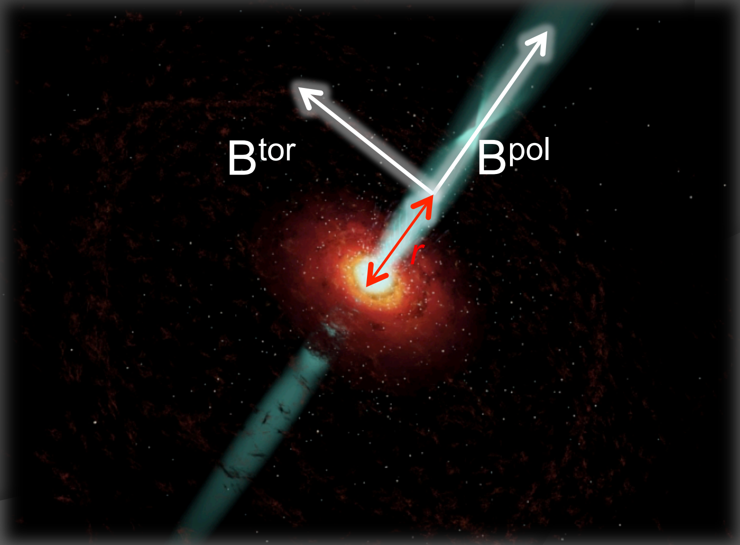
$$\langle \tilde{B}_i(\mathbf{k}) \tilde{B}_j(\mathbf{k}') \rangle = (2\pi)^6 M(k) \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \delta^3(\mathbf{k} - \mathbf{k}')$$

with a power law “Kolmogorov-like” spectrum $M(k)=Ak^q$ for $k_L \leq k \leq k_H$. Many possible realizations of the magnetic field configuration has been simulated by a montecarlo

  - BL Lac jets with coherent magnetic field with a dominant toroidal (perpendicular to jet axis) given by

$$B^{\mathrm{tor}}(r) = B_0 \frac{r_{\mathrm{VHE}}}{r}$$

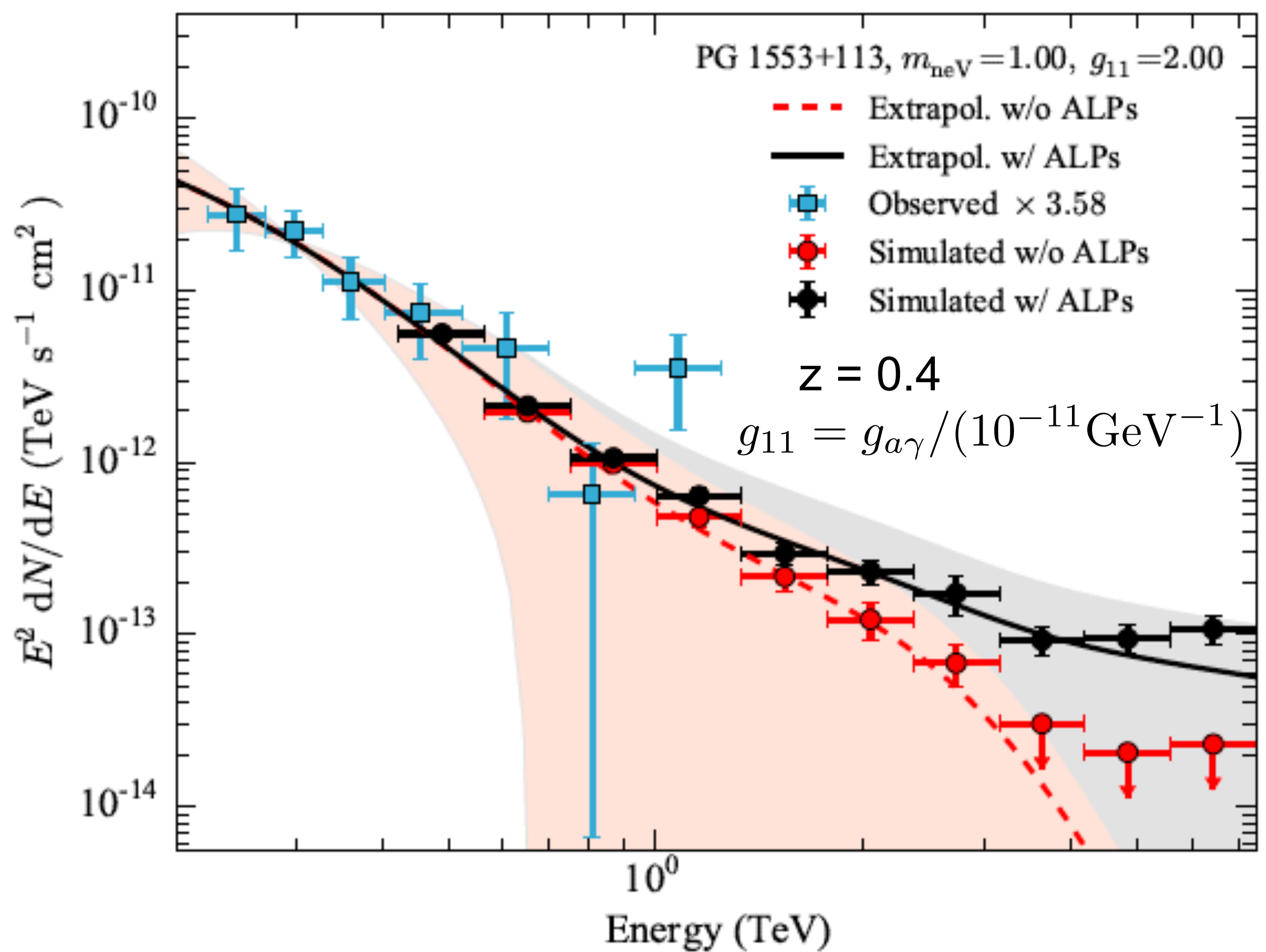
with $r_{\mathrm{VHE}} \sim 0.01\mathrm{pc}$ and $B_0 \sim 0.1\mathrm{G}$



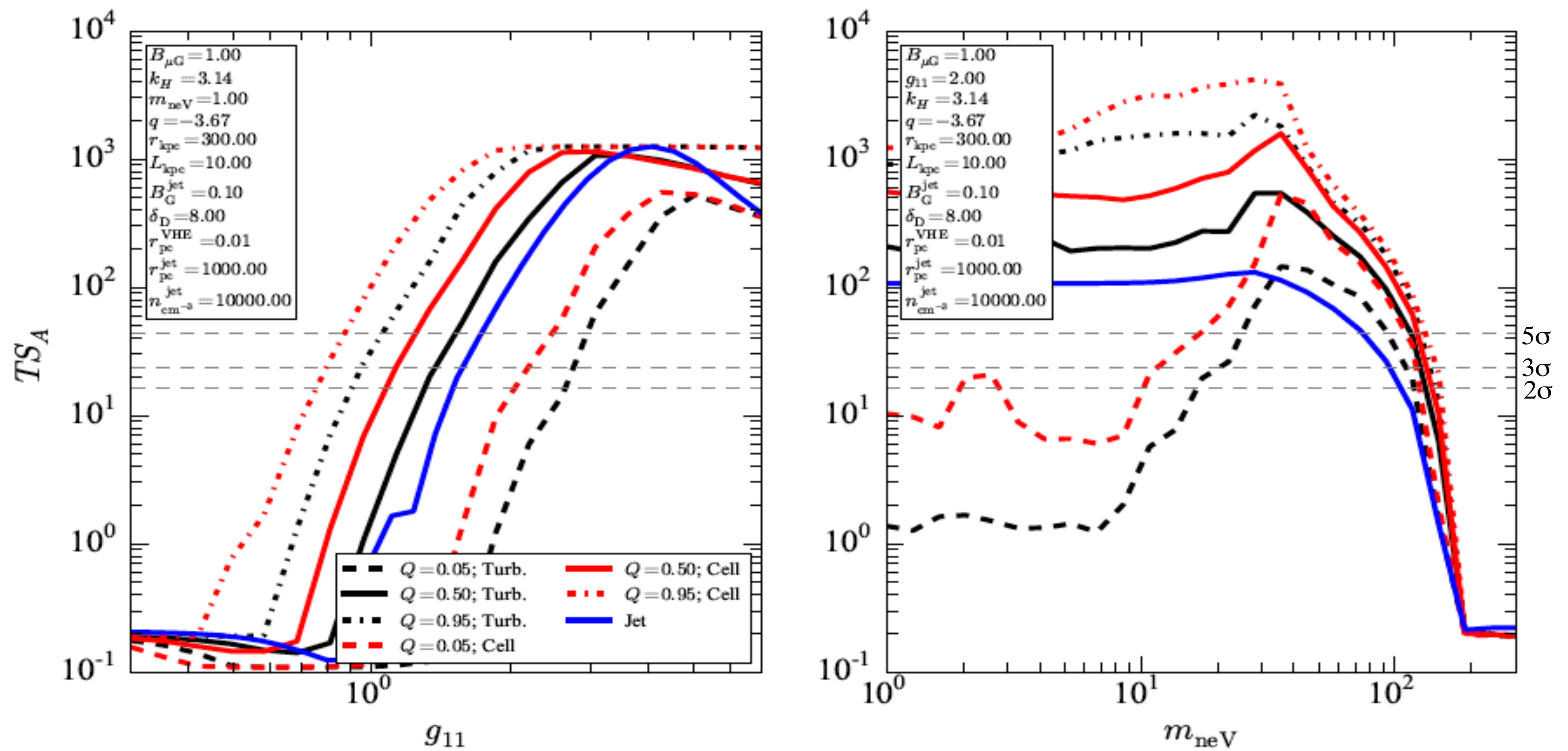
- PG 1553+113 at z = 0.4 has been considered for reference for both scenarios

[2] M. Meyer, D. M. and J. Conrad, **JCAP 1409, 003 (2014)**

An example of simulated results for turbulent magnetic field for a CTA (or HESS II) –like array experiment



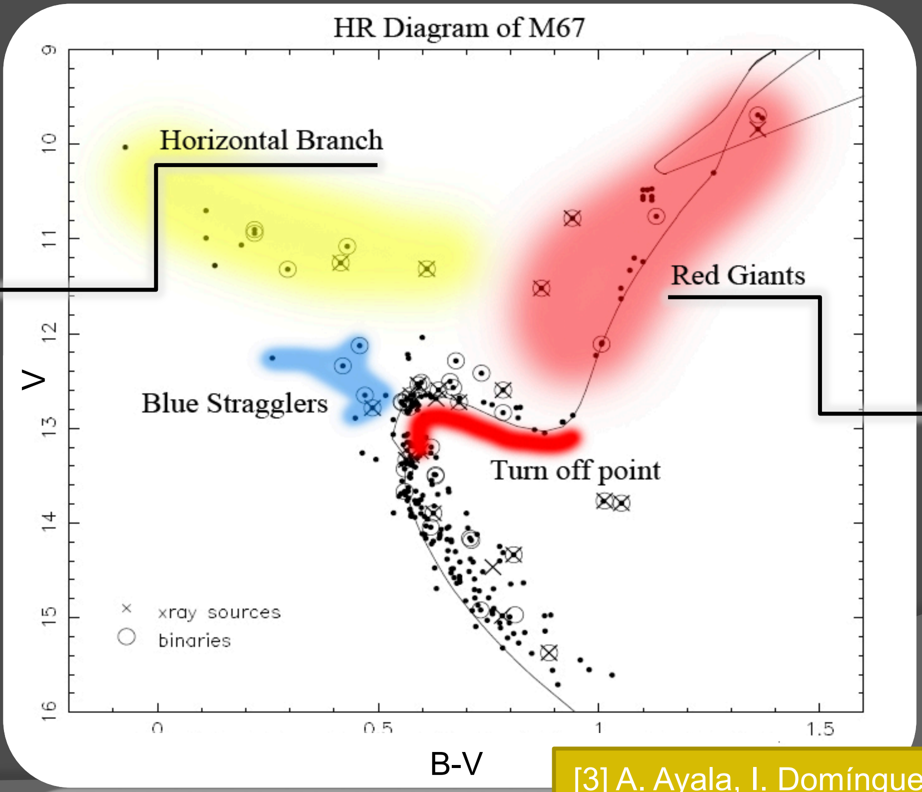
- A complex likelihood ratio test on simulated mock data has been performed in term of a statistical variable TS_A
- 1000 random realizations of the magnetic field are simulated for each parameter
- Q are the quantiles for the cumulative distribution $CDF(TS_A)$. For example the curve corresponding to Q=0.05 means that 95% of all realizations give a higher test statistic and the corresponding B-field can be regarded as pessimistic in terms of photon-ALP mixing
- For example: if $g_{11}=3$ there is 95% probability to make a discovery (>5σ) for a turbulent B field
- More or less a sensitivity up to $g_{11}\sim1$ for CTA-like experiments



Bound on axion-photon coupling from Globular Clusters [3]

- Globular Cluster (CG) stars are gravitationally bound stars with approximately the same age
- A typical CG harbors a few millions stars, so that the various evolutionary phases are well populated and distinguished from each other.

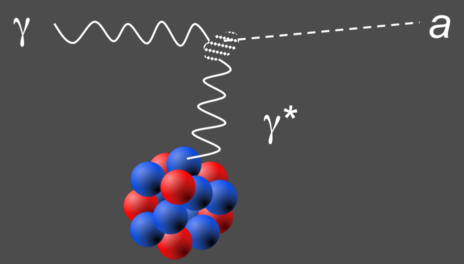
HB stars:
Helium Burning phase



RGB stars
H burning phase

[3] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi and O. Straniero, **Phys. Rev. Lett 113, 191302 (2014)**

- Stars during evolution can radiate energy through Primakoff-effect in electric nuclear field



$$\Gamma = \frac{g_{a\gamma}^2\, \alpha\, n_p^{\text{eff}}}{8}\left[\left(1+\frac{\kappa^2}{4E^2}\right)\ln\left(1+\frac{4E^2}{\kappa^2}\right)-1\right]$$

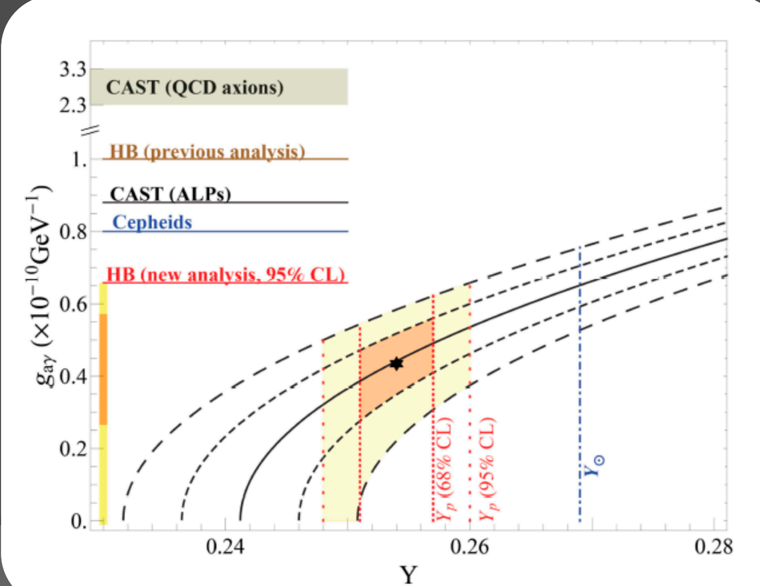
- Energy loss can influence the life the duration of the HB stars while have only little influence on RGB stars
- From stellar model it is possible to infer the ratio $R = N(\mathrm{HB})/N(\mathrm{RGB})$. A degeneracy between $g_{a\gamma}$ and the initial Helium abundance Y is found

$$R_{\text{th}}(g_{a\gamma}, Y) = 6.26\, Y - 0.41\, g_{10}^2 - 0.12\,,$$

- From GCs R is well known: R=1.33±0.06
- From studies of chemical composition of Blue Compact Dwarfs Galaxies Y=0.2535±0.0036
- Limits on $g_{a\gamma}$ can be inferred

$$g_{a\gamma} = 0.45^{+0.12}_{-0.16} \times 10^{-10}\ \text{GeV}^{-1} \quad (68\%\ \text{CL})$$

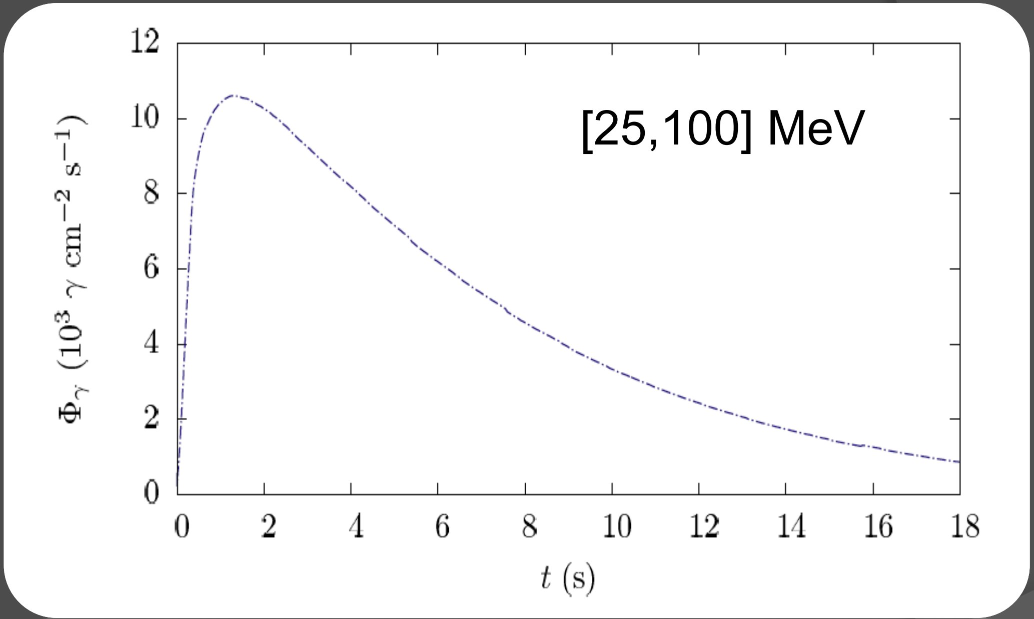
$$g_{a\gamma} < 0.66 \times 10^{-10}\ \text{GeV}^{-1} \quad (95\%\ \text{CL})$$



Bound on axion-photon coupling from SN 1987A [4]

- Primakoff effect can convert photons into axions in superova core during SNII explosion

- Axions eventually reconvert in Galactic magnetic field into photons resulting in a few second burst of ~100 MeV gamma rays

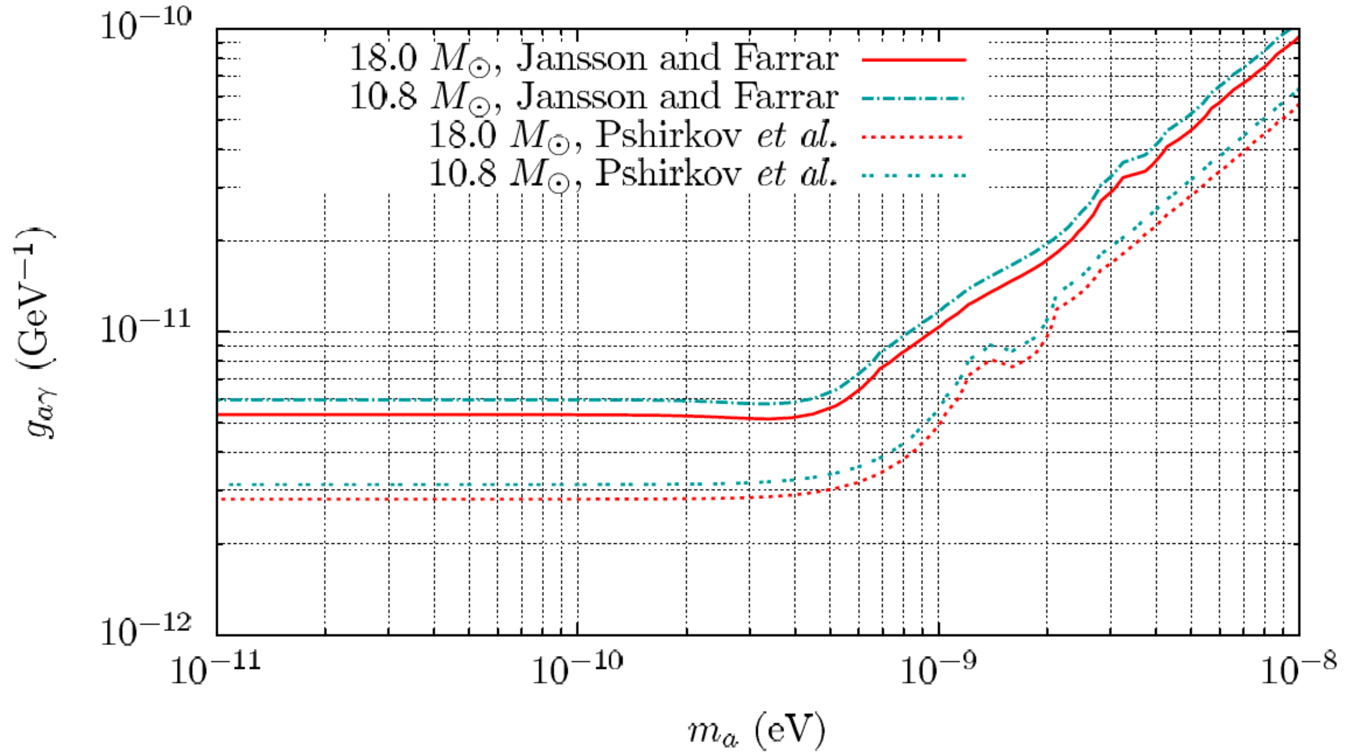


- No evidence for such burst from Gamma-Ray Spectrometer (GRS) of the Solar Maximum Mission (SMM)

- Very strong bounds on $g_{a\gamma}$ are set but they are model dependent

[4] A. Payez, C. Evoli, T. Fischer, M. Giannotti, A. Mirizzi and A. Ringwald, **JCAP 1502, 006 (2015)**

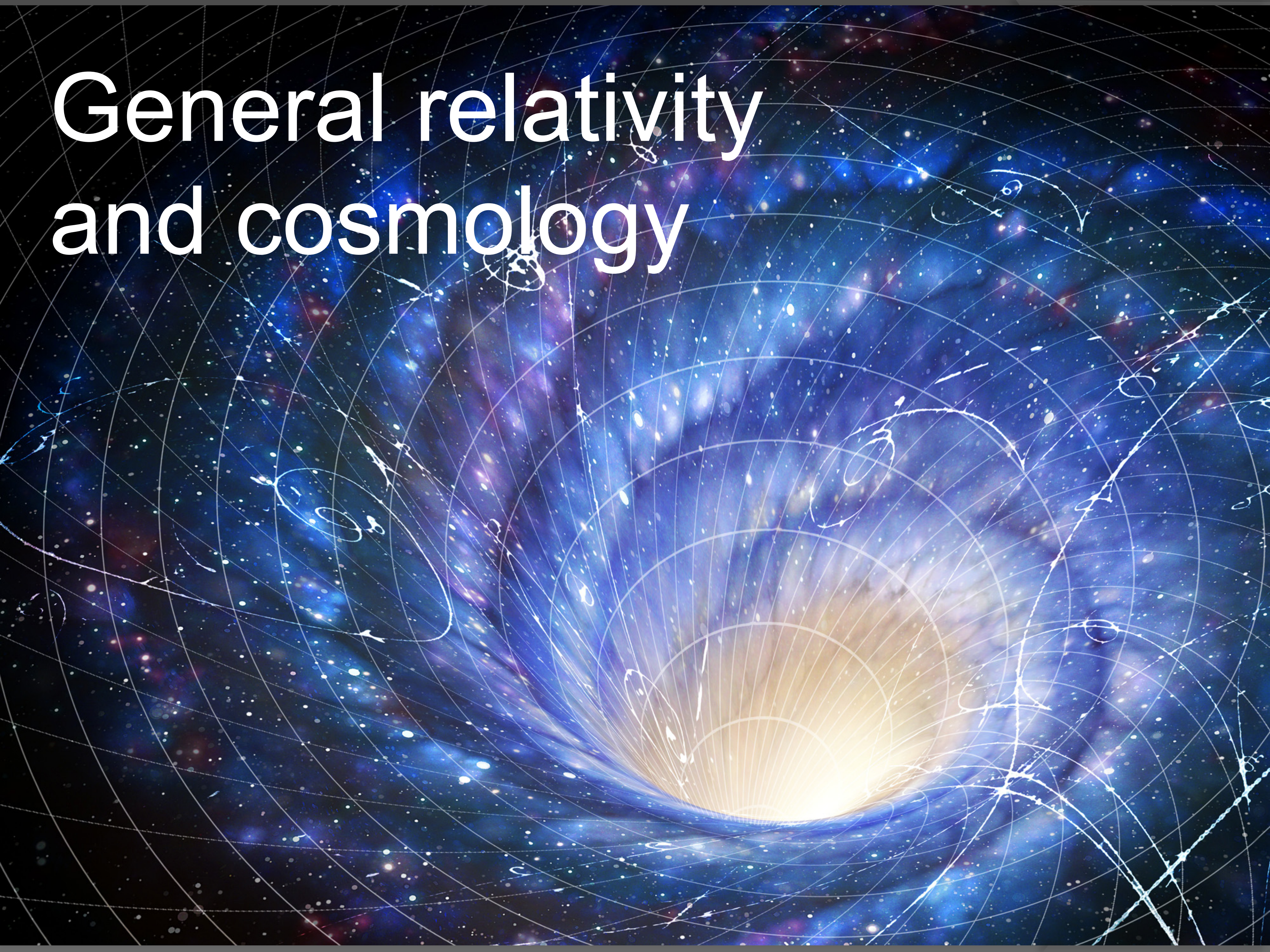
Limits on $g_{a\gamma}$ from SN1987A



Conservative bounds

$$g_{a\gamma} \lesssim 5.3 \times 10^{-12} \ \text{GeV}^{-1}, \quad \text{for} \quad m_a \lesssim 4.4 \times 10^{-10} \ \text{eV}$$

General relativity and cosmology



Lensing in the geometric light cone model and in perturbed cosmological background [5,6]

- Lensing (involving convergence, magnification and shear and vorticity) is calculated using the Geodesic Light-Cone metric which is adapted to describe signals propagating in the past light-cone

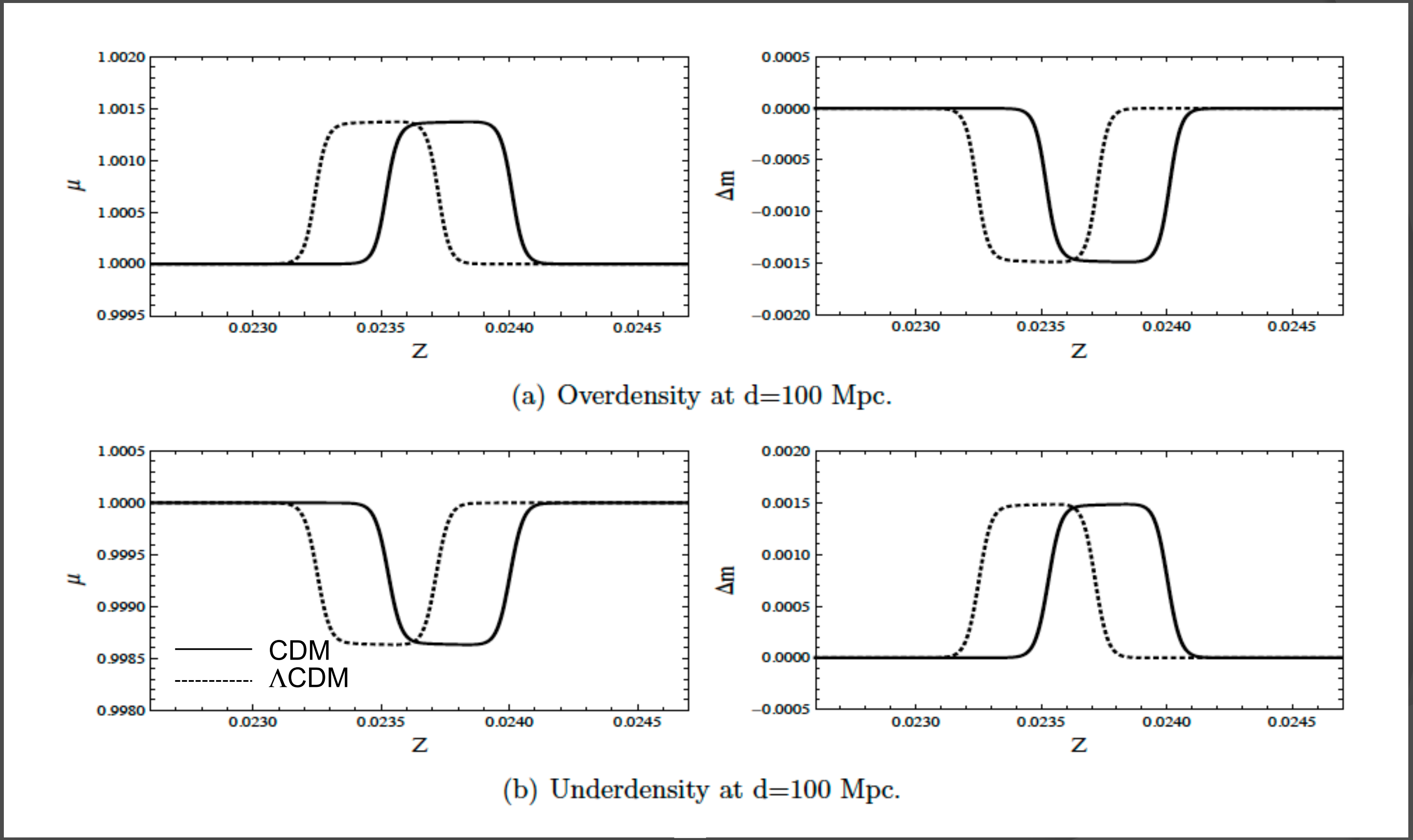
$$ds^2 = \Upsilon^2 dw^2 - 2\Upsilon dw d\tau + \gamma_{ab}(d\tilde{\theta}^a - U^a dw)(d\tilde{\theta}^b - U^b dw) \quad , \qquad a,b = 1,2$$

  where w is a foliation of space time in term of null-hypersurfaces, τ is a time-like coordinate, θ are angular coordinates.
- These expressions are simple and non-perturbative (as long as no caustics are created) on the past light-cone and are free from the thin lens approximation
- General expressions applied on the example of an Lemaître-Tolman-Bondi (LTB) model with an off-center observer and explicit forms for the lensing quantities are obtained
- Evolution in redshift after a numerical integration, for underdense and overdense LTB models is shown
- Deflection of light rays signals in a perturbed cosmological background are calculated up to third order in perturbation expansion with a “chain” expansion of lower orders.

[5] G. Fanizza and F. Nugier, **JCAP 1502, 002 (2015)**
[6] G. Fanizza, M. Gasperini, G. Marozzi and G. Veneziano, **arXiv:1506.02003 [astro-ph.CO]**

$\mu(z)=\bar{\Phi}/\Phi=(\bar{d}_L/d_L)^2$ "magnification"

$\Delta m = 5\log_{10}(d_L/\bar{d}_L)$



Bubbles of radius r_0=1Mpc with a transition shell of Δr=0.1Mpc and a variation of $H_0(r)$=2km/(s Mpc) (corresponding to a $\delta(r)={}_{-0.176}{}^{+0.181}$) are considered for illustrative purposes

Inhomogeneous and anisotropic Universe and apparent acceleration [6,7]

- Non homogeneous **Bianchi I** model is considered with x-y the plane of symmetry

$$ds^2 = dt^2 - a^2(t)(dx^2 + dy^2) - b^2(t)dz^2$$

or in polar coordinates this metrics can be written as

$$\begin{aligned} ds^2 = dt^2 &- (A'^2_{\|}\sin^2\theta + A'^2_{\perp}\cos^2\theta)dr^2 \\ &- (A^2_{\|}\cos^2\theta + A^2_{\perp}\sin^2)d\theta^2 \\ &- (A^{2\prime}_{\|} - A^2_{\perp}{}') \sin\theta\cos\theta dr d\theta + -A^2_{\|}\sin^2\theta d\phi^2. \end{aligned}$$

with $A_{\perp}(r,t) \equiv b(t) \cdot r$, $A_{\|}(r,t) \equiv a(t) \cdot r$

- The generic Lemaître-Tolman-Bondi (LTB) Bianchi I metric is obtained considering $A_{\perp}(r,t)$, $A_{\|}(r,t)$ as generic functions of r and t
- A "degree of anisotropy" $\varepsilon(r,t) = A_{\perp} - A_{\|}$ is introduced as a perturbation

[6] G. Fanizza and L. Tedesco, **Phys. Rev. D91, 023006 (2015)**
[7] G. Fanizza and L. Tedesco**, Eur. Phys. J. C74, 2786 (2014)**

- In a null-curvature and matter dominated universe solutions can be parameterized as

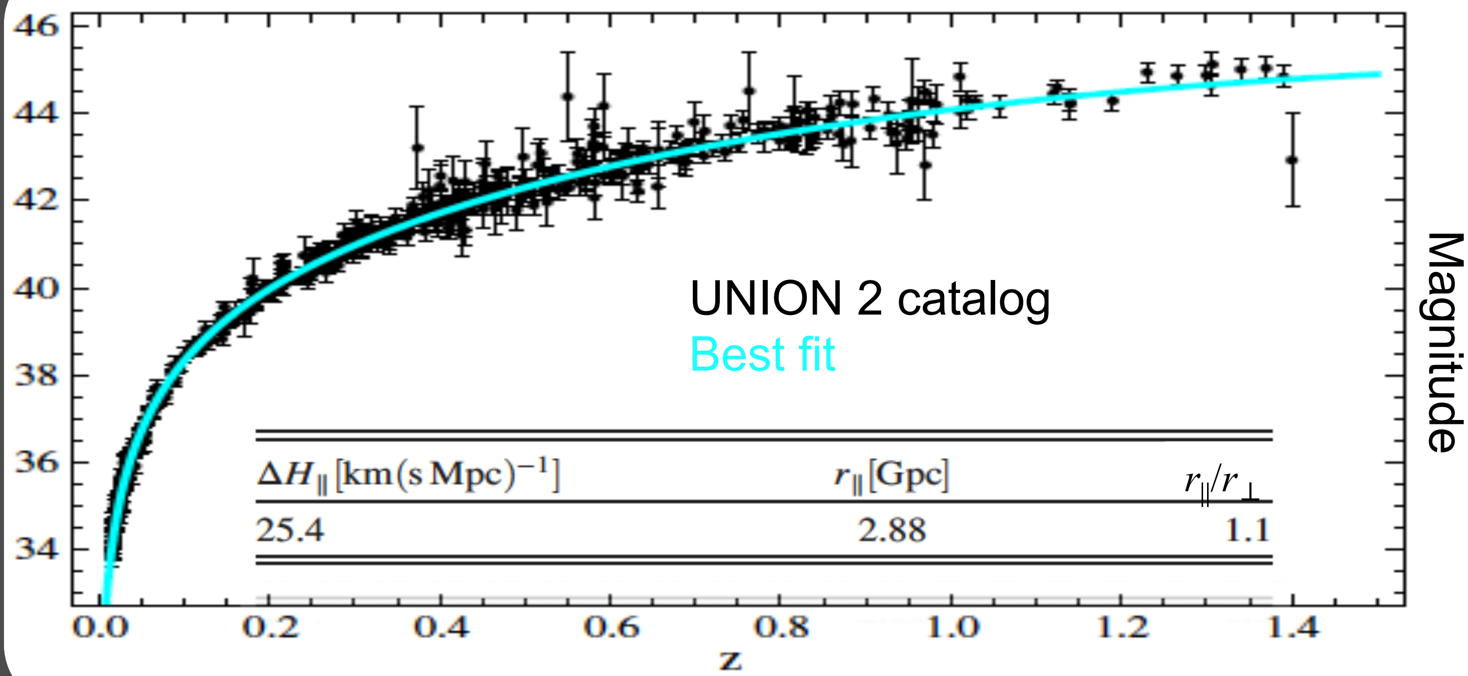
$$A_{\parallel}(r,t) = r\left(1+\frac{3}{2}H_{\parallel}(r)t\right)^{\frac{2}{3}},$$

$$A_{\perp}(r,t) = r\left(1+\frac{3}{2}H_{\perp}(r)t\right)^{\frac{2}{3}},$$

with

$$H_{\parallel/\perp}(r) = H_{\parallel/\perp} + \Delta H_{\parallel/\perp}\exp\left(-\frac{r}{r_{\parallel/\perp}}\right).$$

- Luminosity distance is calculated within this model and UNION 2 catalog of type I supernovae is used to fit the parameters. <u>No need for Dark Energy to fit data</u>



$\Delta H_{\parallel}$ [km(s Mpc)$^{-1}$]	$r_{\parallel}$ [Gpc]	$r_{\parallel}/r_{\perp}$
25.4	2.88	1.1

- Electrodynamics in Lemaître-Tolman-Bondi (LTB) scenario is also studied

Who we are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Luigi TEDESCO (staff, Univ. of Bari)


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Giuseppe FANIZZA (PhD student, Univ. of Bari)


Daniele MONTANINO (Staff, Univ. of Salento)

The areas of competence

WP3:
- General Relativity
- Cosmology

WP4:
Axion-like particles

WP2:
- Neutrino Physics and oscillations
- Supernova neutrinos

See the Capozzi Talk


Thank you
for attention!