High-energy photons from distant sources, particle physics and cosmology

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(INR RAS and MSU)

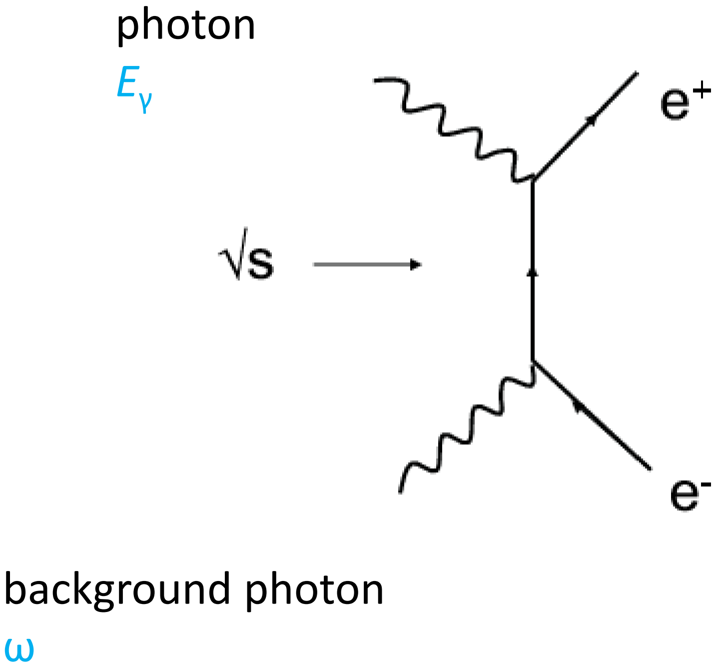
Rubakov Conference, Yerevan, October 2023

Supported by the Russian Science Foundation, project 22-12-00253

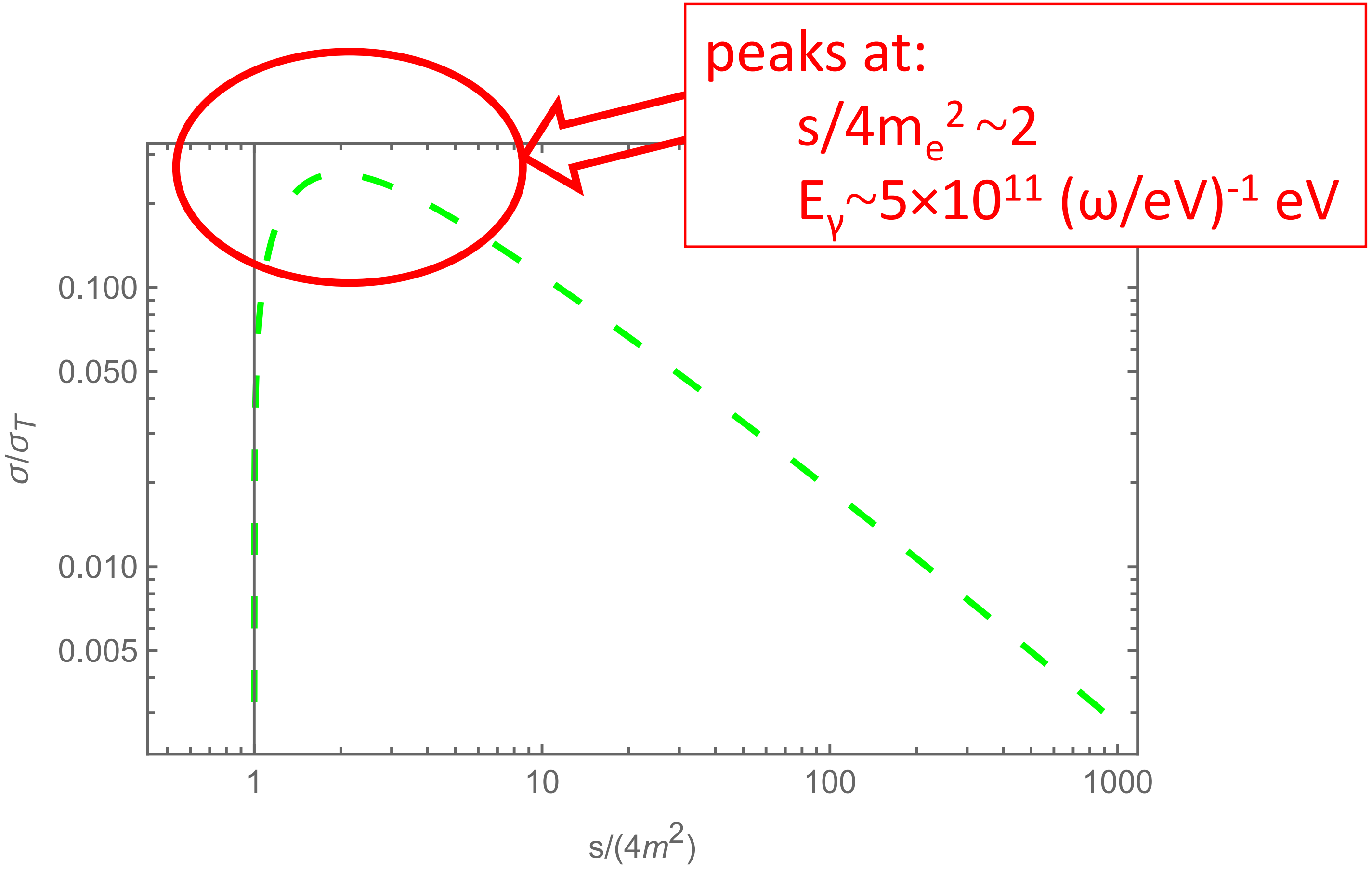
High-energy photons from distant sources, particle physics and cosmology

Pair production

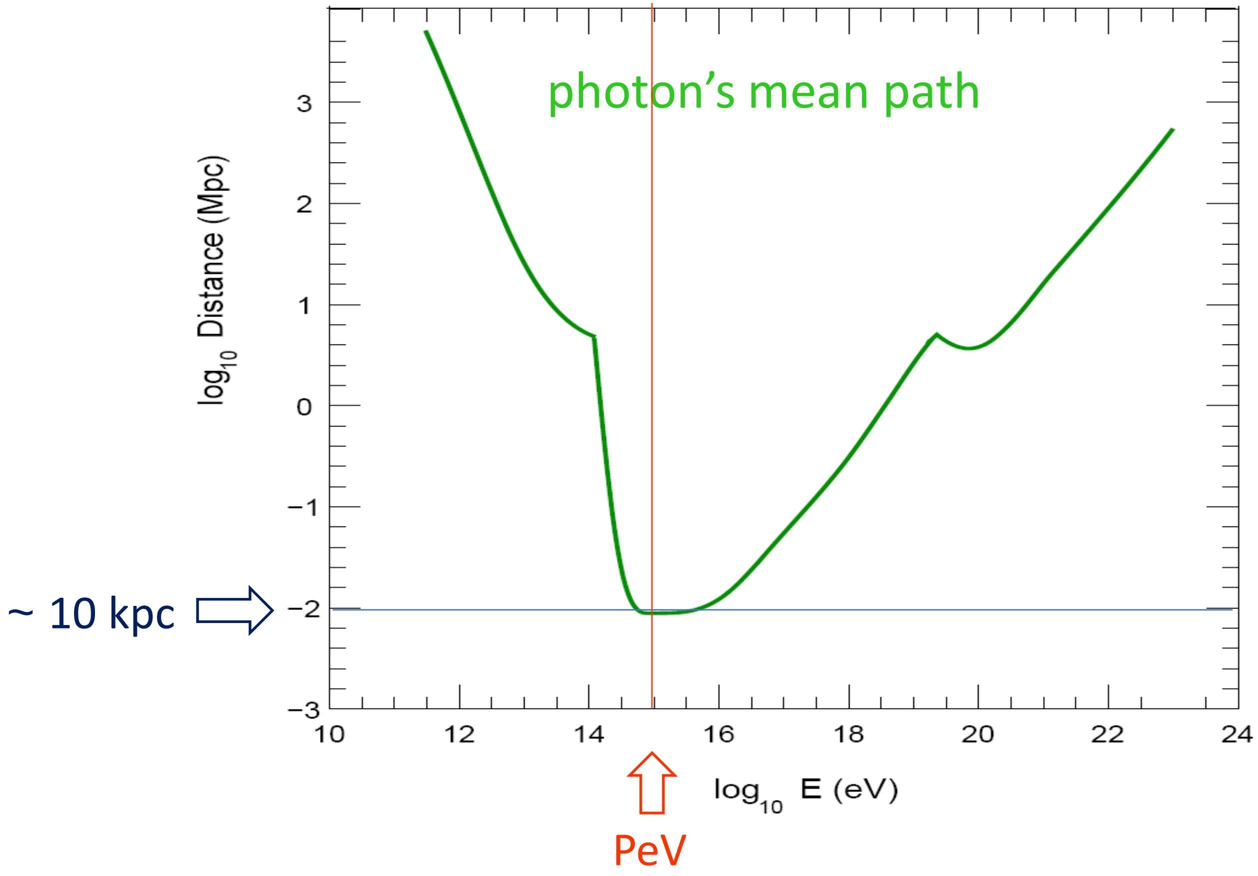
by energetic photons
on the background radiation
Nikishov 1962



PP cross section:



Pair production in the Universe



Gamma-ray burst GRB 221009A

✓ **record-breaking in intensity and photon energy**

- Fermi LAT: 99 GeV, possibly 400 GeV
- LHAASO: photons up to 18 TeV, (230-2000) sec after trigger
- Carpet-2: a photon-like event of 251 ТэВ, 4356 sec after trigger

- distance: redshift z=0.151
- Galactic latitude 4° - close to the Milky Way plane

- short distance and high intensity – expected to be observed at the Earth once in (10-50) thousand years

GRB 221009A, observations at very high energies

TITLE: GCN CIRCULAR
NUMBER: 32677
SUBJECT: LHAASO observed GRB 221009A with more than 5000 VHE photons up to around 18 Te\
DATE: 22/10/11 09:21:54 GMT
FROM: Judith Racusin at GSFC <judith.racusin@nasa.gov>

Yong Huang, Shicong Hu, Songzhan Chen, Min Zha, Cheng Liu, Zhiguo Yao and Zhen Cao report on behalf of the LHAASO experiment

We report the observation of GRB 221009A, which was detected by Swift (Kennea et al. GCN #32635), Fermi-GBM (Veres et al. GCN #32636, Lesage et al. GCN #32642), Fermi-LAT (Bissaldi et al. GCN #32637), IPN (Svinkin et al. GCN #32641) and so on.

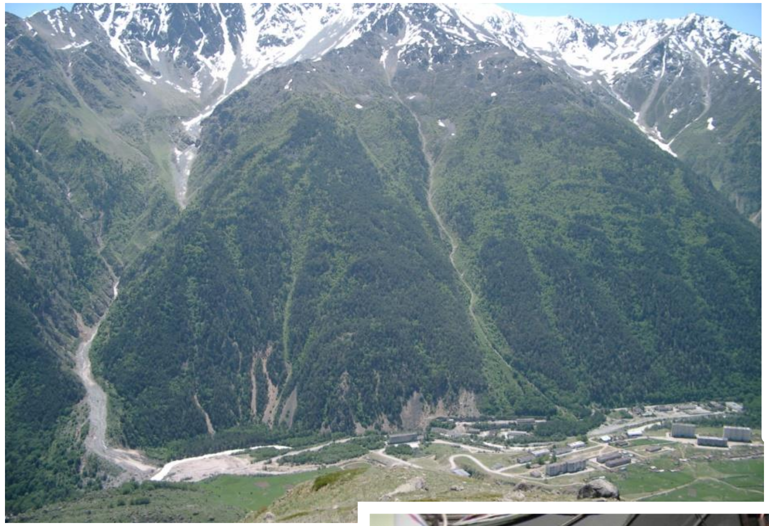
GRB 221009A is detected by LHAASO-WCDA at energy above 500 GeV, centered at RA = 288.3, Dec = 19.7 within 2000 seconds after T0, with the significance above 100 s.d., and is observed as well by LHAASO-KM2A with the significance about 10 s.d., where the energy of the highest photon reaches 18 TeV.

This represents the first detection of photons above 10 TeV from GRBs.

The LHAASO is a multi-purpose experiment for gamma-ray astronomy (in the energy band between 10^11 and 10^15 eV) and cosmic ray measurements.

LHAASO: photons up to 18 TeV, (230-2000) sec after trigger

GRB 221009A, observations at very high energies



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2 Nov 2022; 09:59 UT

This space for free for your conference.

MIAPP workshop on
Interacting Supernovae
6 February - 3 March 2023
Garching, Germany

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e. Thank you.

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Swift J1913.1+1946/GRB 221009A: detection of a 250-TeV photon-like air shower by Carpet-2

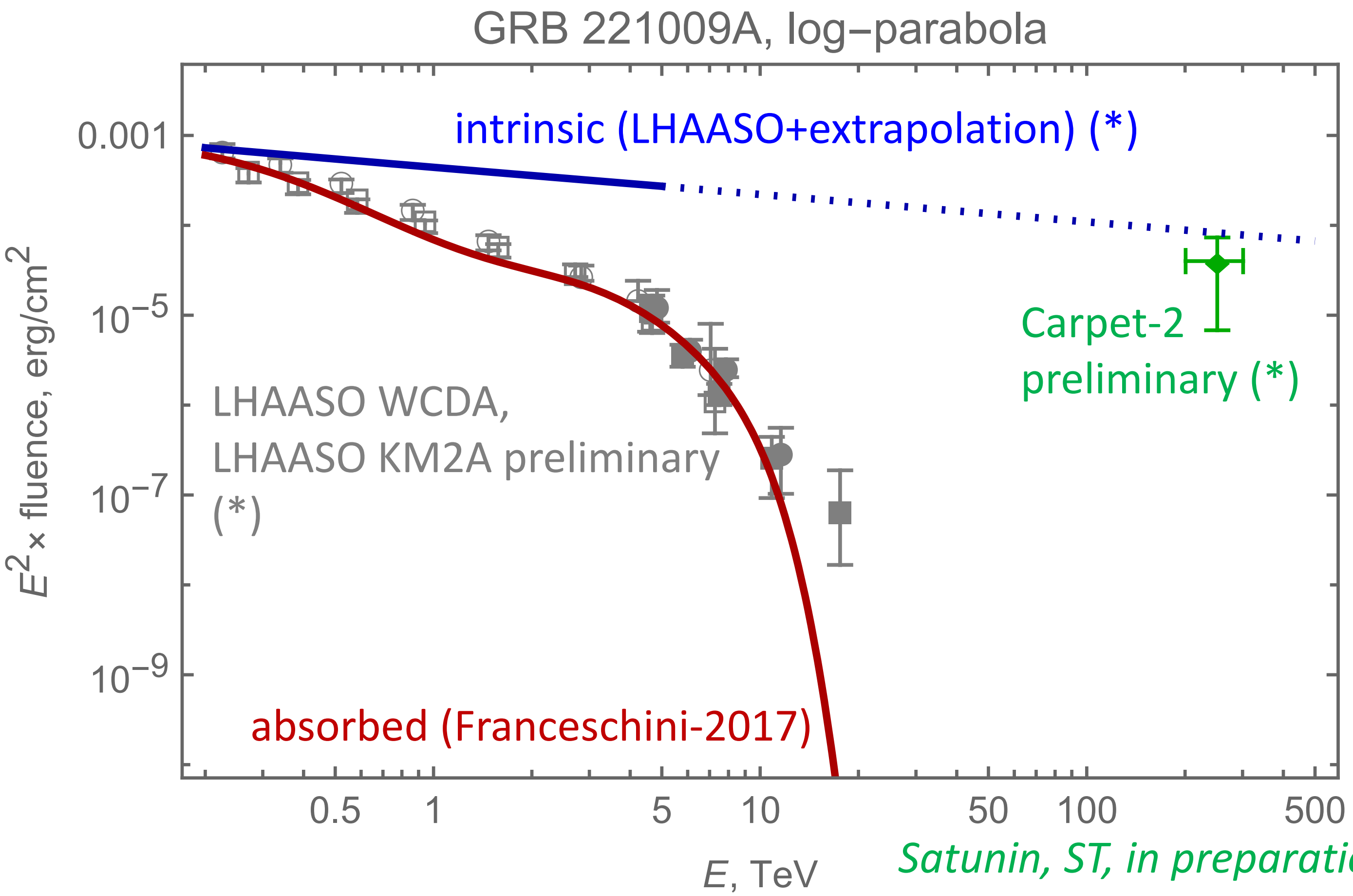
ATel #15669; *D. D. Dzhappuev, Yu. Z. Afashokov, I. M. Dzaparova, T. A. Dzhatdoev, E. A. Gorbacheva, I. S. Karpikov, M. M. Khadzhiev, N. F. Klimenko, A. U. Kudzhaev, A. N. Kurenya, A. S. Lidvansky, O. I. Mikhailova, V. B. Petkov, E. I. Podlesnyi, N. A. Pozdnukhov, V. S. Romanenko, G. I. Rubtsov, S. V. Troitsky, I. B. Unatlokov, I. A. Vaiman, A. F. Yanin, K. V. Zhuravleva (Carpet-2 group, INR RAS)*
on 12 Oct 2022; 13:56 UT
Credential Certification: Sergey Troitsky (st@ms2.inr.ac.ru)

Related

15712 Detection of the emerging supernova spectrum from the afterglow of GRB221009A
15703 Insight-HXMT observation on the prompt emission and afterglow of GRB 221009A
15685 GRB221009A/Swift J1913.1+1946: RT-22 Simeiz observations
15677 MAXI/GSC refined analysis of the bright X-ray afterglow of GRB 221009A/Swift J1913.1+1946
15675 Swift J1913.1+1946/GRB 221009A: Galactic sources of > 100 TeV-photon in spatial coincidence with the 250-TeV photon-like air shower reported by Carpet-2

Carpet-2: a photon-like event of ≈ 251 TэВ, 4356 sec after trigger (background of 1.2×10^{-4})

GRB 221009A, observations at very high energies



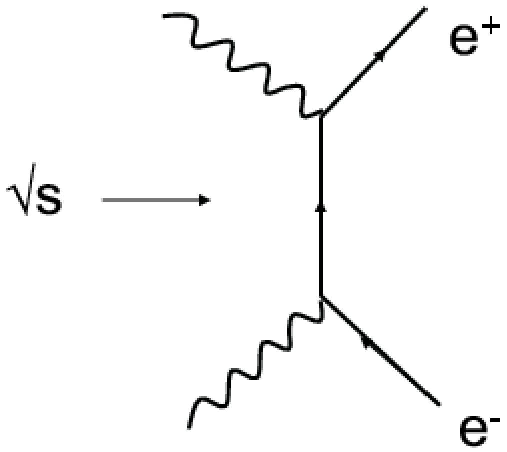
Satunin, ST, in preparation

(*) converted to fluence by ST

High-energy photons from distant sources, particle physics and cosmology

No pair production: Lorentz-invariance violation?

- phenomenological approach
- spontaneous Lorentz-symmentry breaking?
- quantum-gravity models?



change of the dispersion relations:

$$E_a^2 - p_a^2 = m_a^2 \pm |\delta_{a,n}| p_a^{n+2},$$

⇩

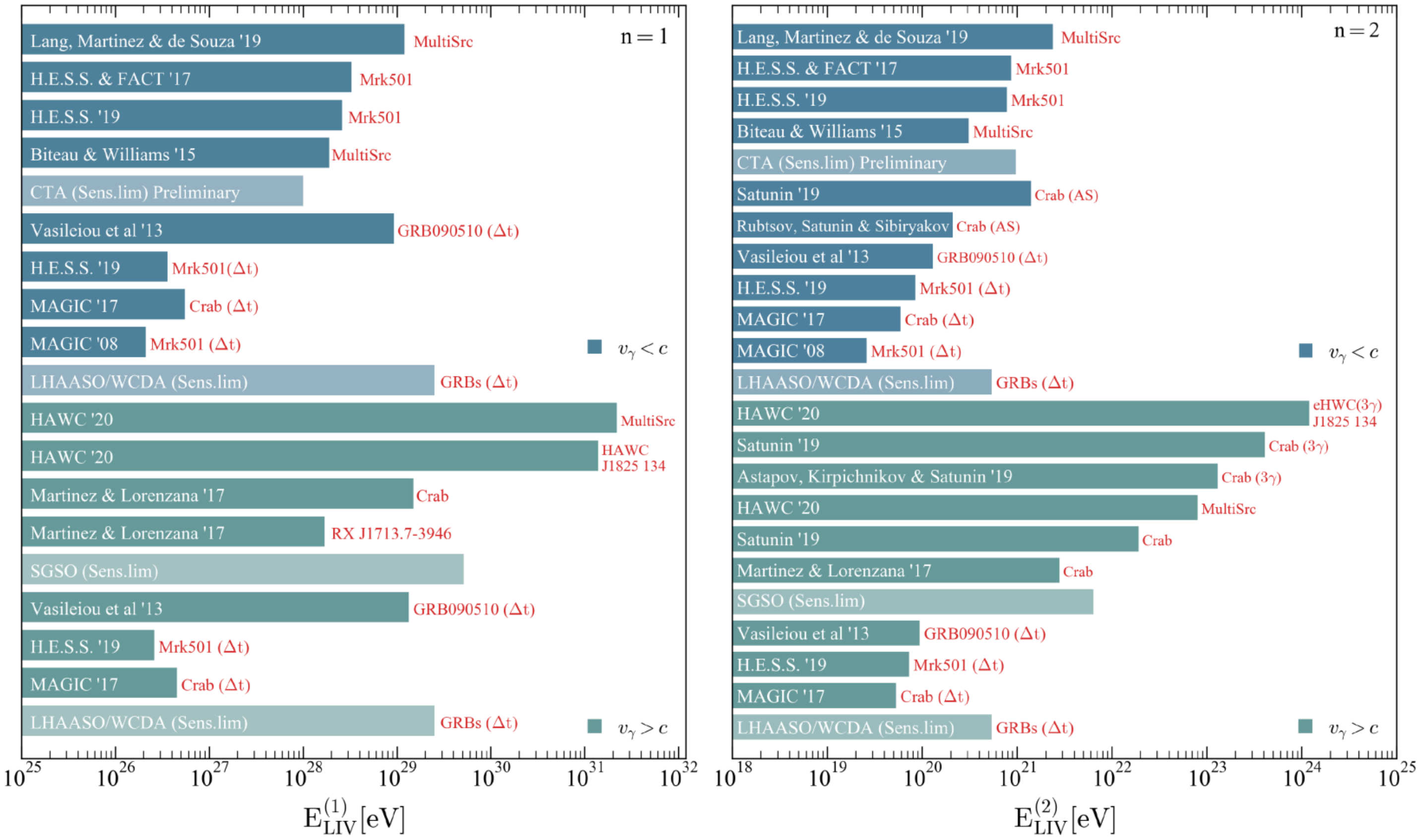
$$E_{\gamma_b}^{th} = \frac{m_e^2}{E_\gamma} - \frac{1}{4}\delta_{\gamma,n}\, E_\gamma^{n+1}$$

shift of the pair-production threshold

No pair production: Lorentz-invariance violation?

- various observational constraints
(strongest come from atmospheric shower development) *Vankov, Stanev 2002*

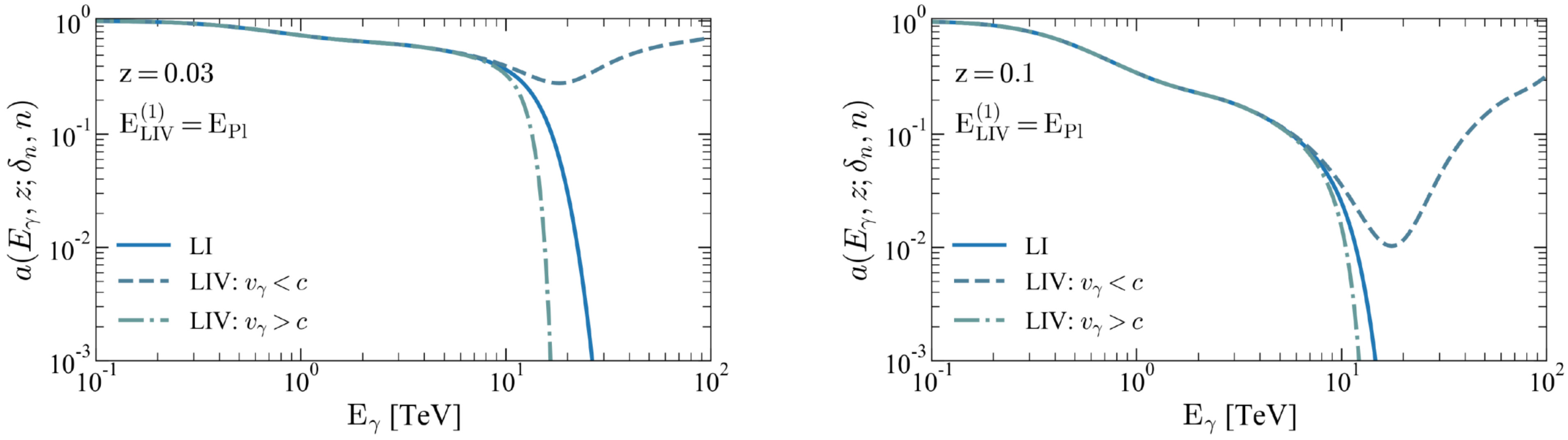
Rubtsov, Satunin, Sibiryakov 2012, 2017



Lang et al. 2020

No pair production: Lorentz-invariance violation?

- shift of the pair-production threshold



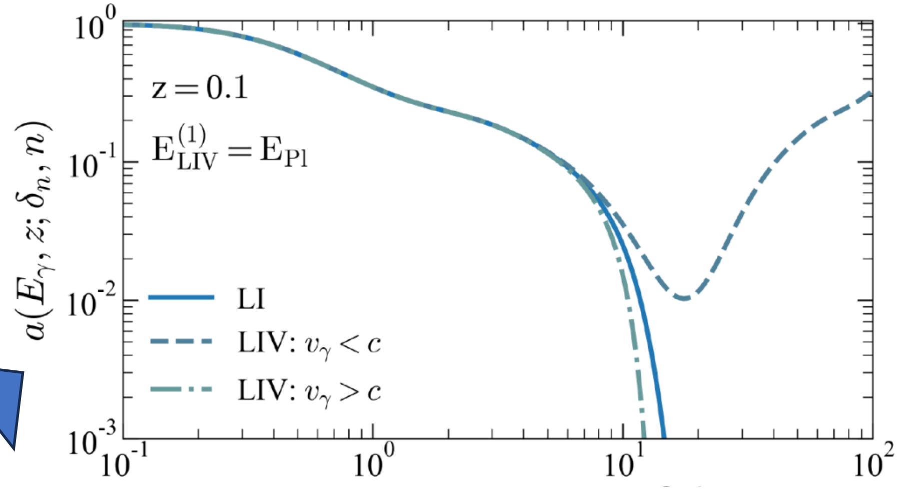
effect depends on energy, redshift< LIV model etc.

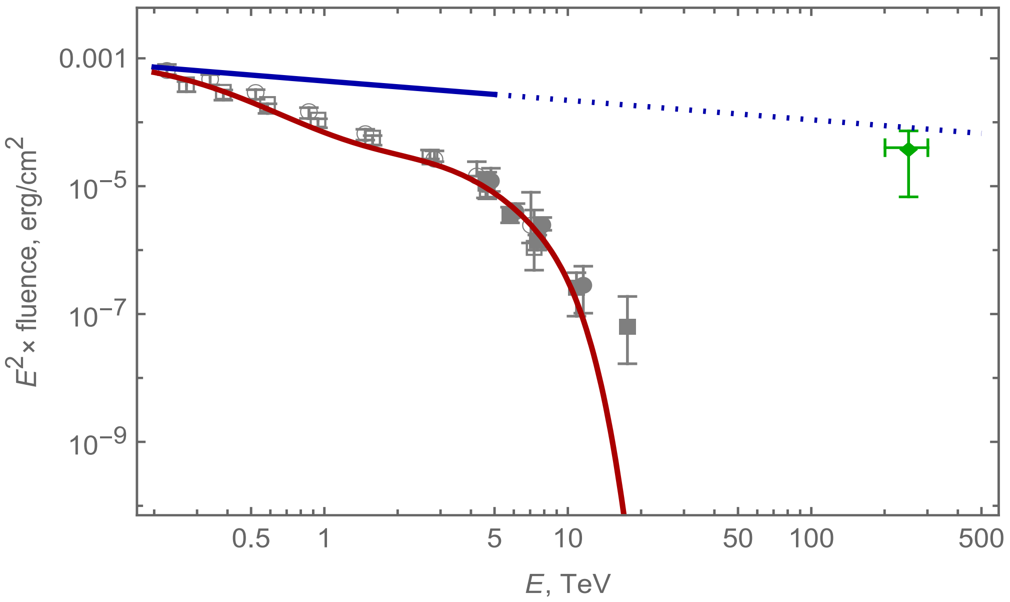
Lang et al. 2019, 2020

No pair production: Lorentz-invariance violation?

waiting for precise data to be published…

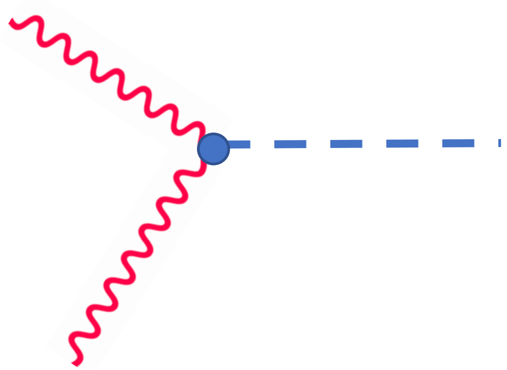
Satunin, ST, in preparation





Axion-like particles (ALPs)

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial a)^2 - \frac{1}{2}m^2a^2 - \frac{1}{4}gaF_{\mu\nu}\tilde{F}^{\mu\nu}$$

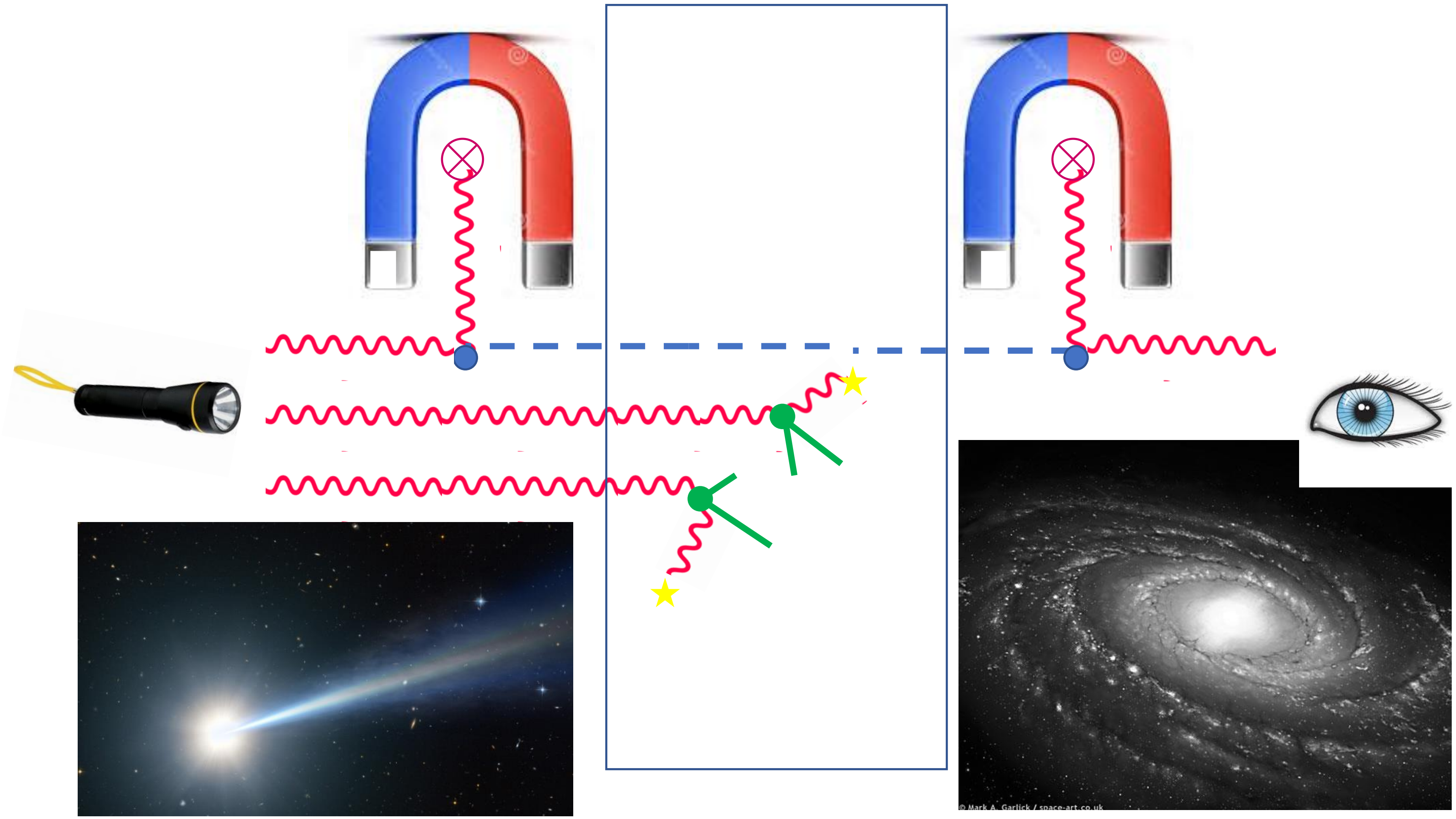


- two-photon coupling

$$\frac{a}{M}F_{\mu\nu}\tilde{F}_{\mu\nu}, \quad M \sim f_A \sim \frac{\Lambda^2_{\mathrm{QCD}}}{m}$$

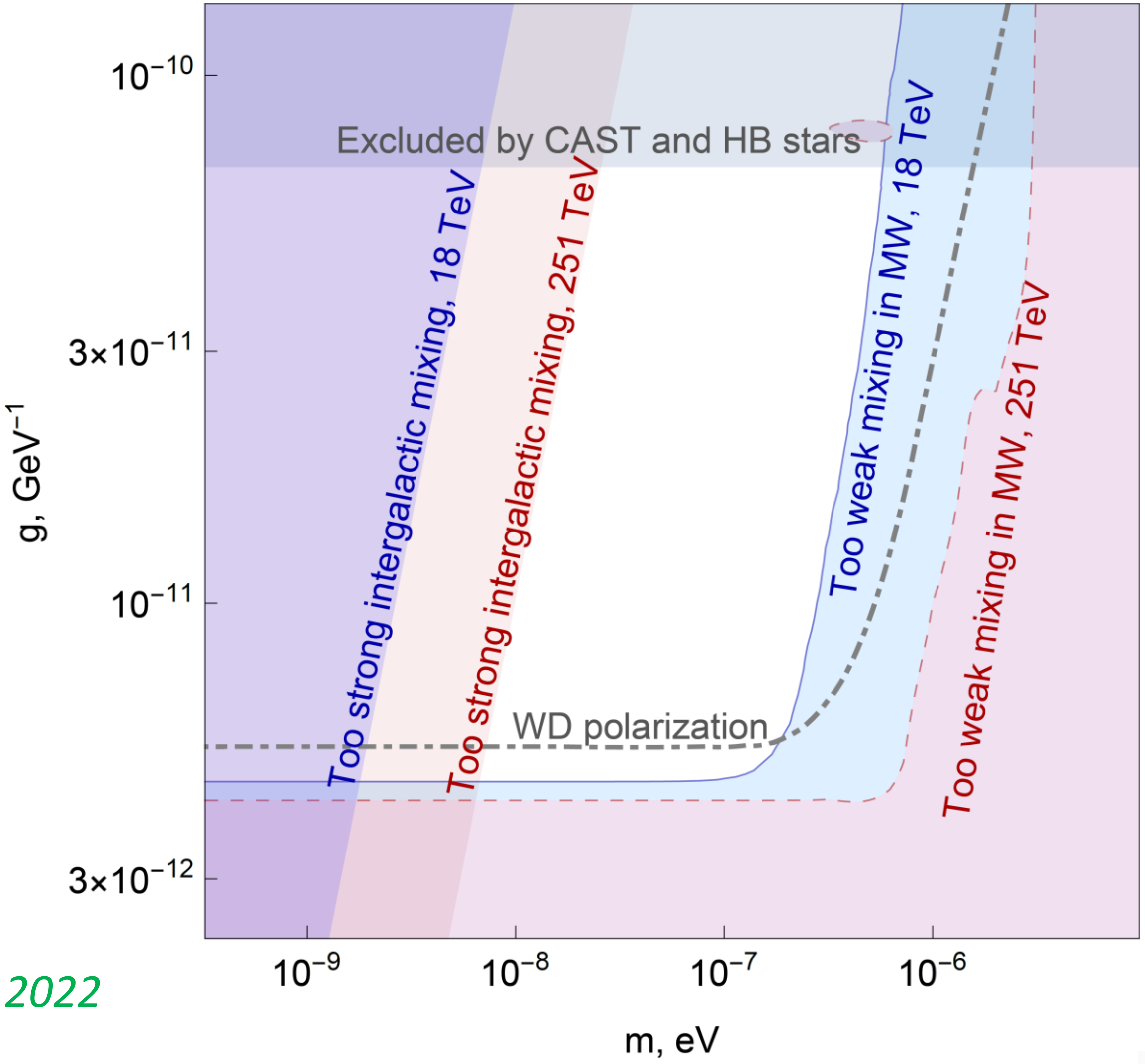
- (dimensionful) g is suppressed by some U(1) breaking scale
  - ✓ g and m could be related for particular models (e.g. QCD axion)
- ALP-photon conversion in the external magnetic field
- the conversion probability depends on ALP parameters (m and g), energy and magnetic field

ALP: shining light through the Universe



ALP parameters for GRB 221009A

- assume the maximal mixing in the source:
  1/3 of photons to ALP
- no mixing in intergalactic space (all gamma rays absorbed)
- calculate mixing in the Milky Way (direction to the GRB, magnetic field by Pshirkov et al.)
- require >1% of the flux survived



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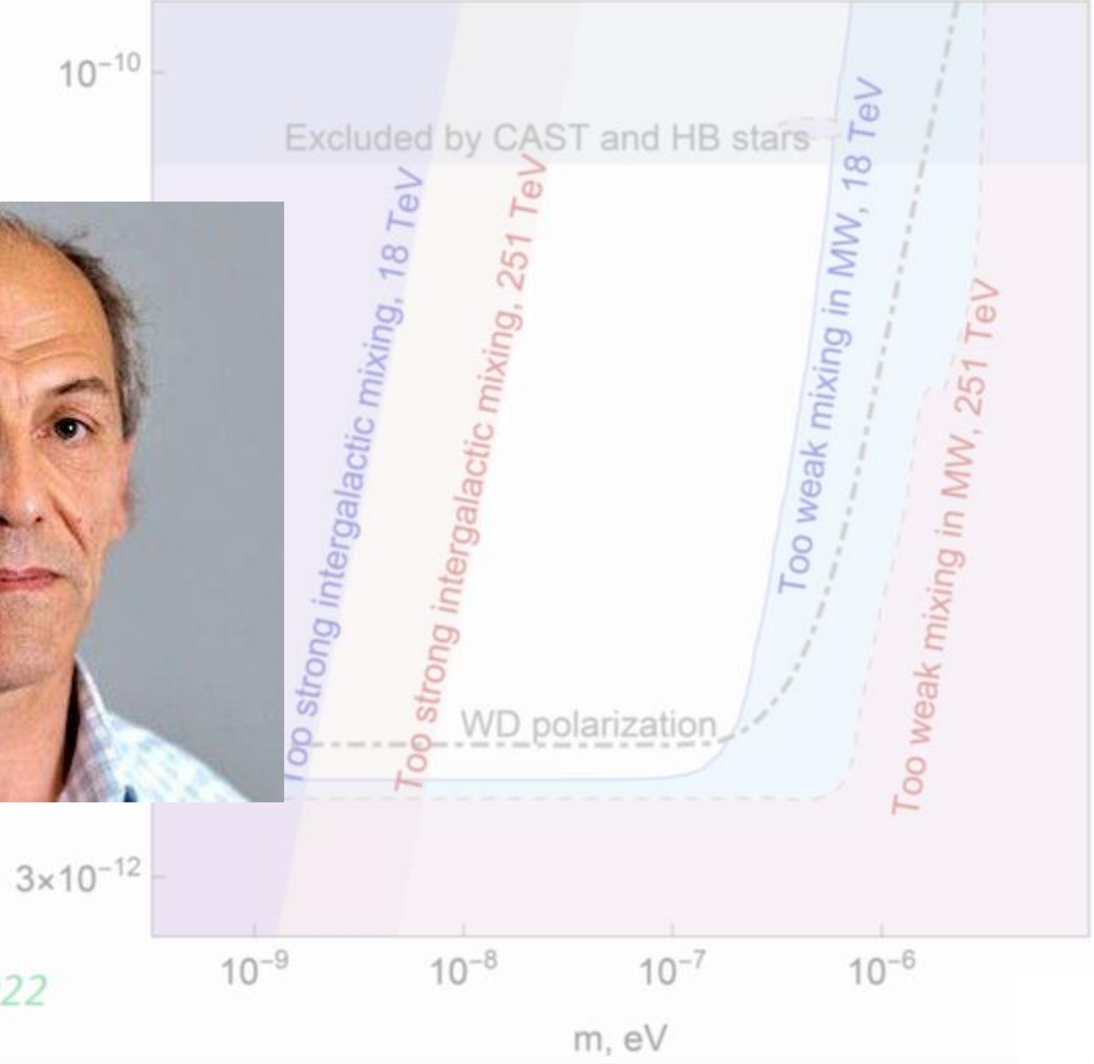

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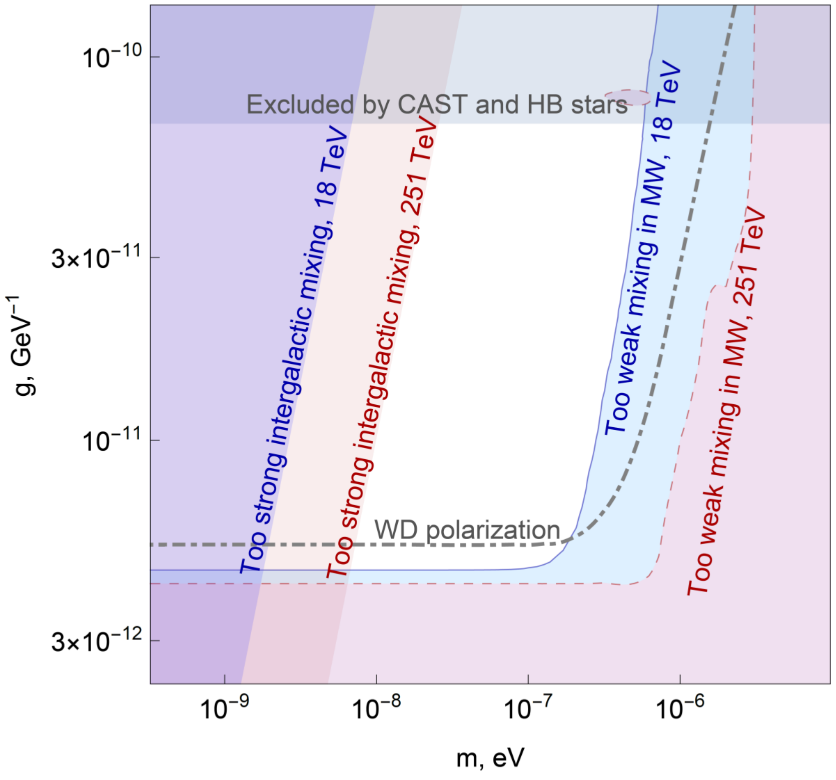
Mixing in the source?

- assume the maximal mixing in the source:
  1/3 of photons to ALP

some enthusiasm,
but this assumption
resulted in reasonable criticism:

Galanti, Roncadelli, Tavecchio – “wishful thinking”

Carenza, Marsh – assumed that the host galaxy field = the Milky Way field, that the GRB sits in the host-galaxy center, the galaxy orientation to the line of sight is random – did not obtain the maximal mixing



The host galaxy of GRB 221009A

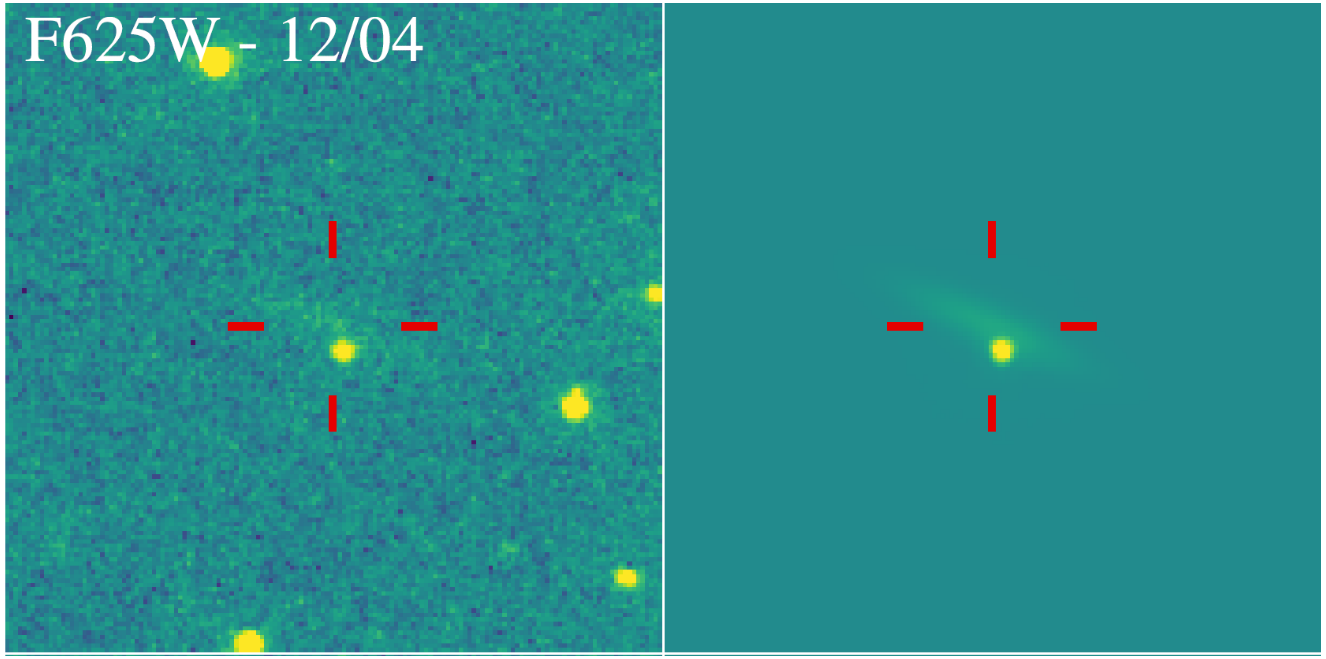
Hubble Space Telescope
Levan et al. 2023

information scarce but interesting!

- geometry
  - a disk galaxy, seen edge-on!
  - GRB position in the galaxy (projected)

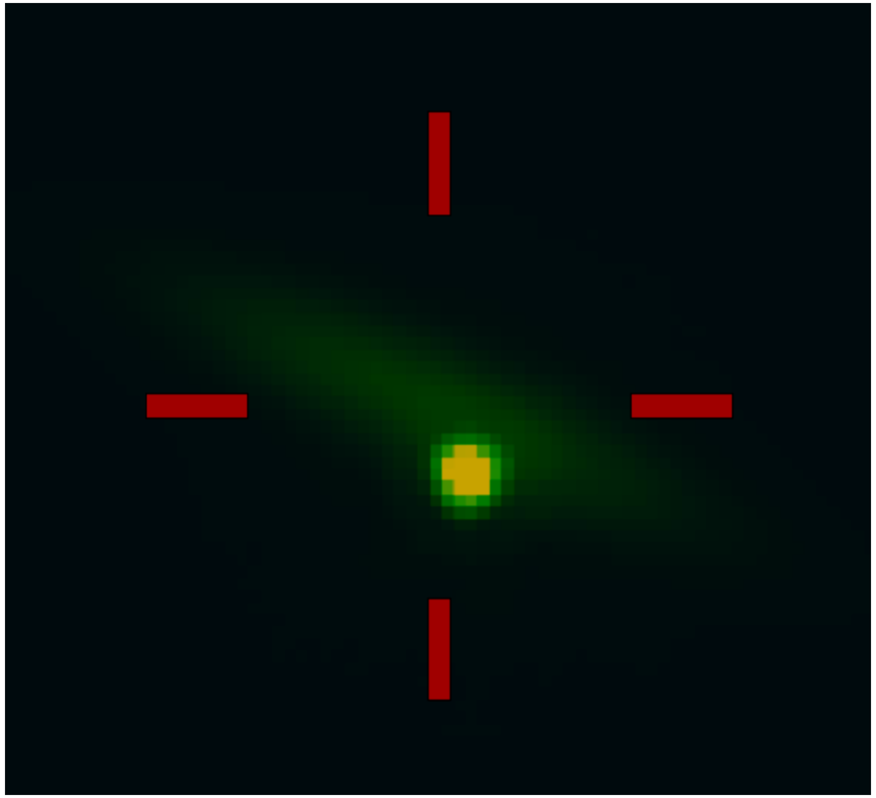
- size, luminosity,
- profile of the stellar distribution...

- the galaxy is typical for long-GRB host galaxies



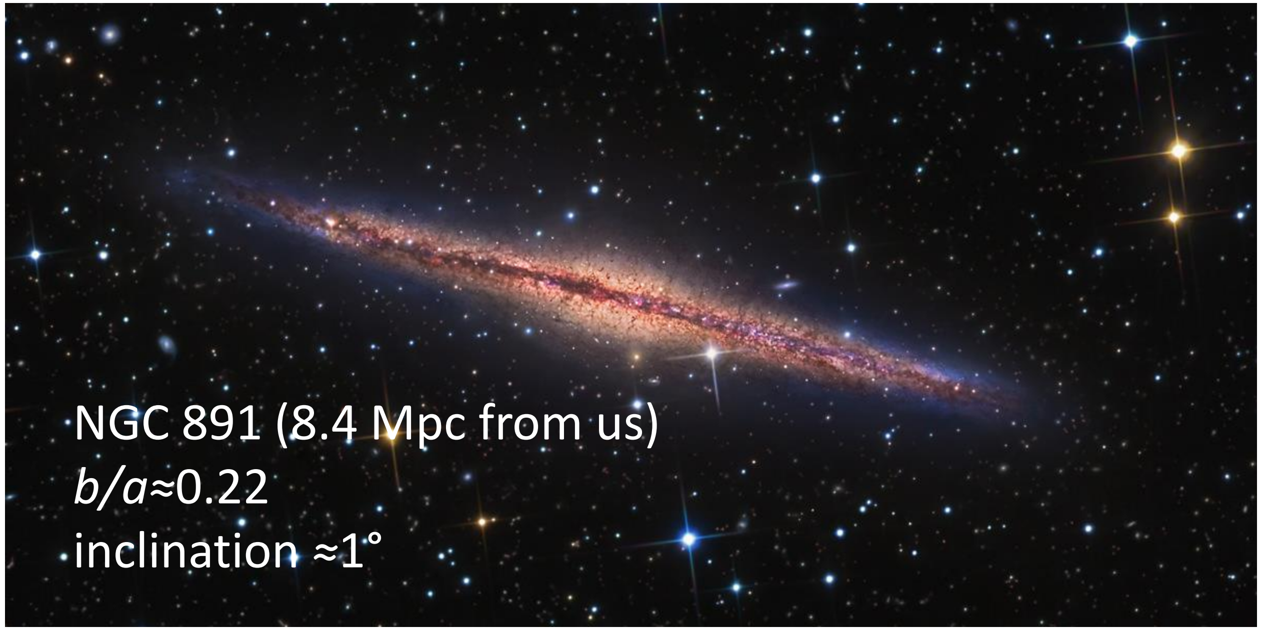
The host galaxy of GRB 221009A – is seen edge-on!

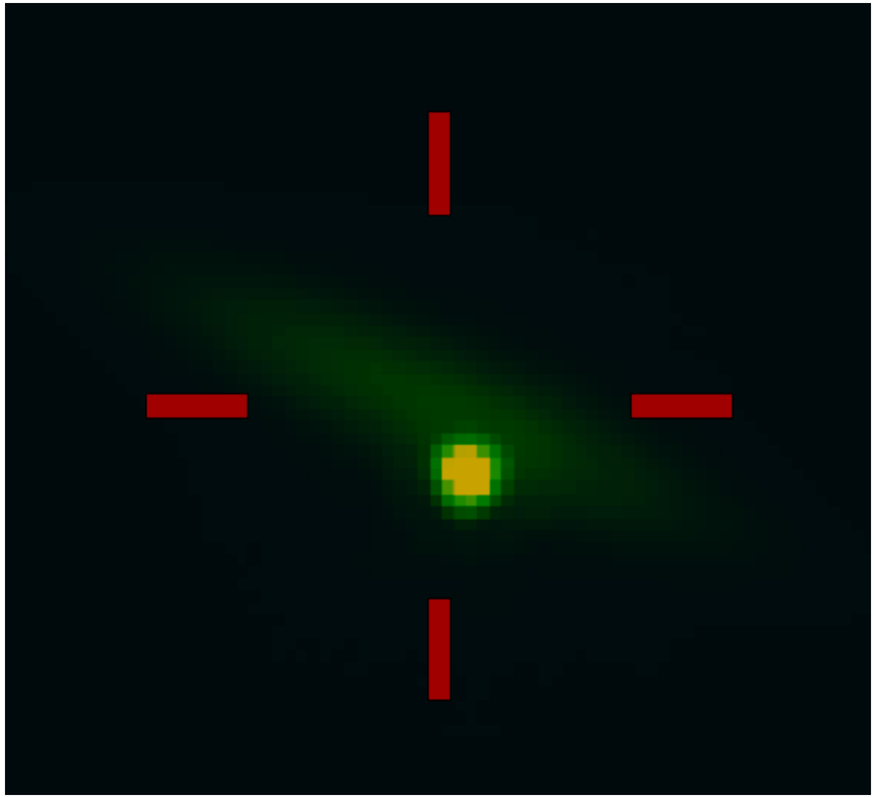
elliptic fit: ratio of half-axes $a/b \approx 0.21$
Levan et al. 2023



The host galaxy of GRB 221009A – is seen edge-on!

half-axes ratio $b/a \approx 0.21$
Levan et al. 2023





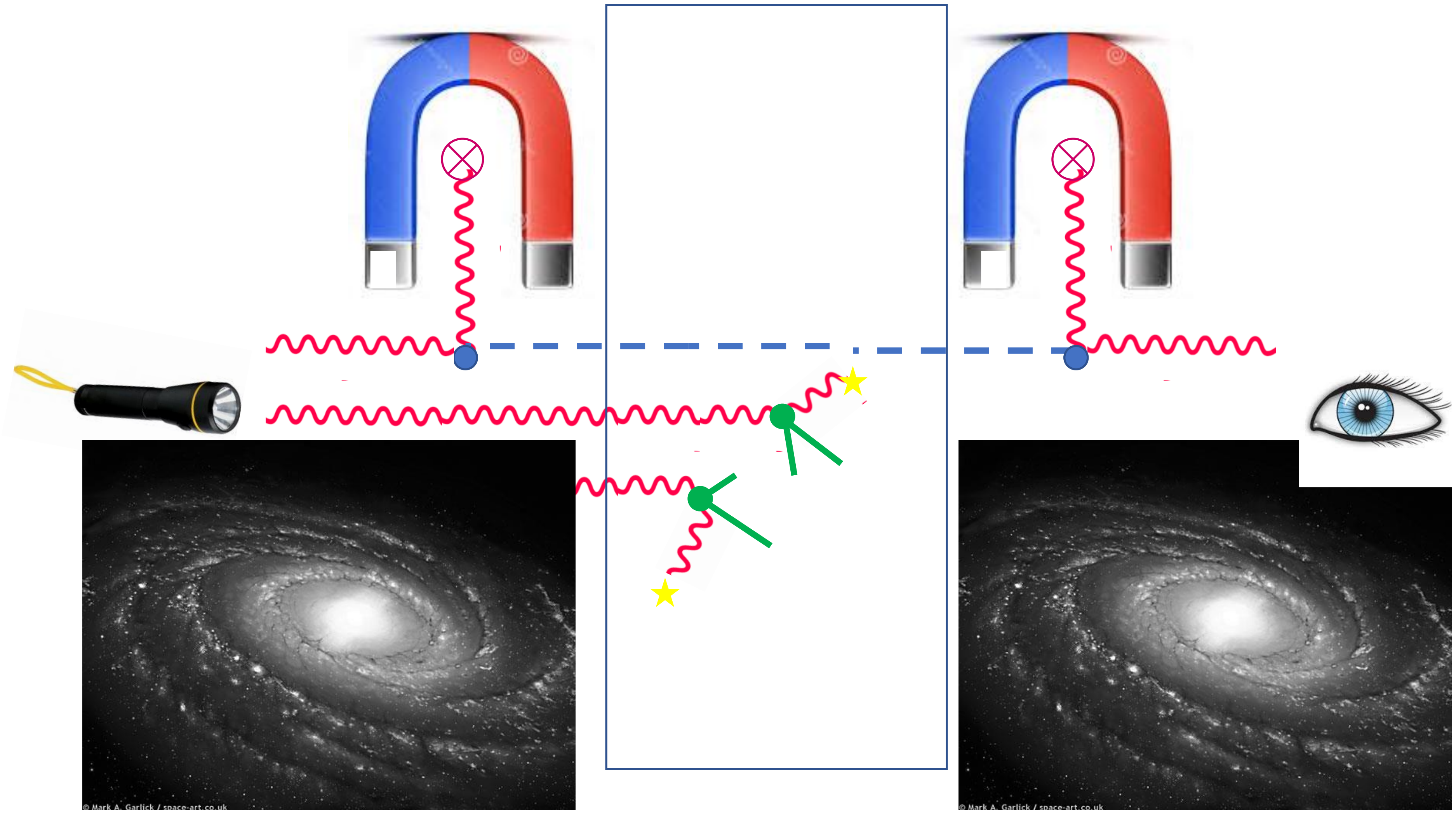
The host galaxy of GRB 221009A – is seen edge-on!

- a rare case: the inclination angle ≈0°
- observed radiation of GRB passed through the host-galaxy disk
- but the line of sight angle to the Milky-Way disk ≈ 4°

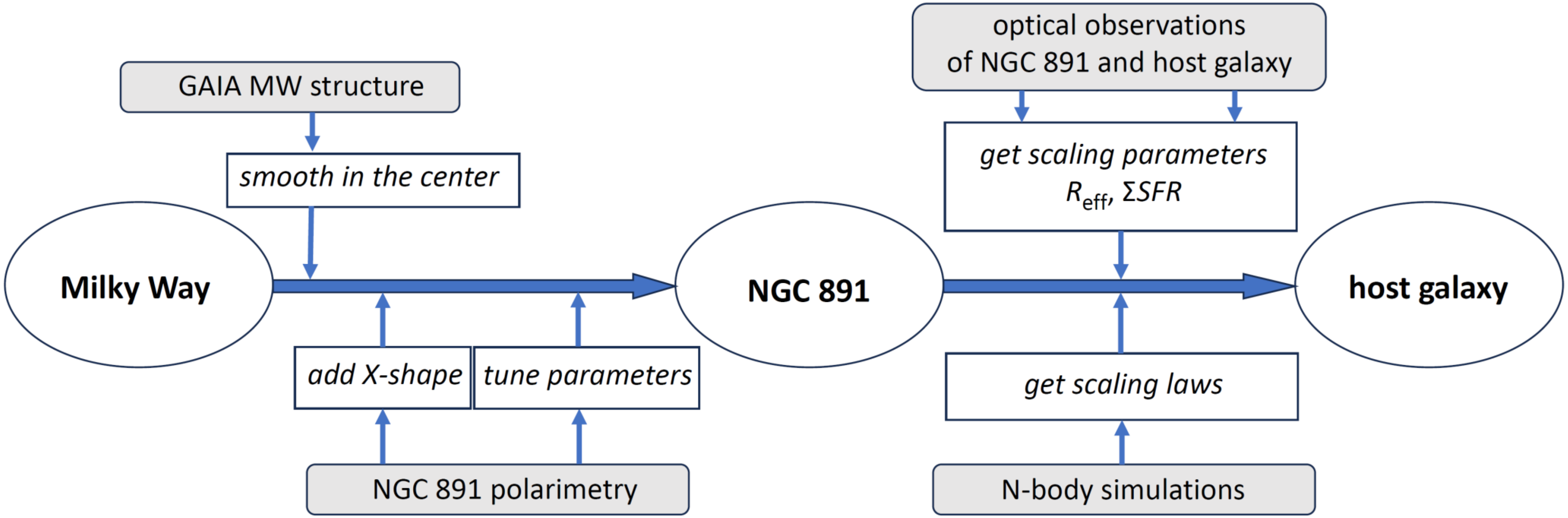
the GRB radiation passes throough the disks of both the host galaxy and the Milky Way!

magnetic fields stronger in the disks – higher probability of photon/ALP conversion

ALP: shining light through the Universe



The host galaxy of GRB 221009A: a toy model of the magnetic field



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Photon/ALP conversion in the host galaxy of GRB 221009A

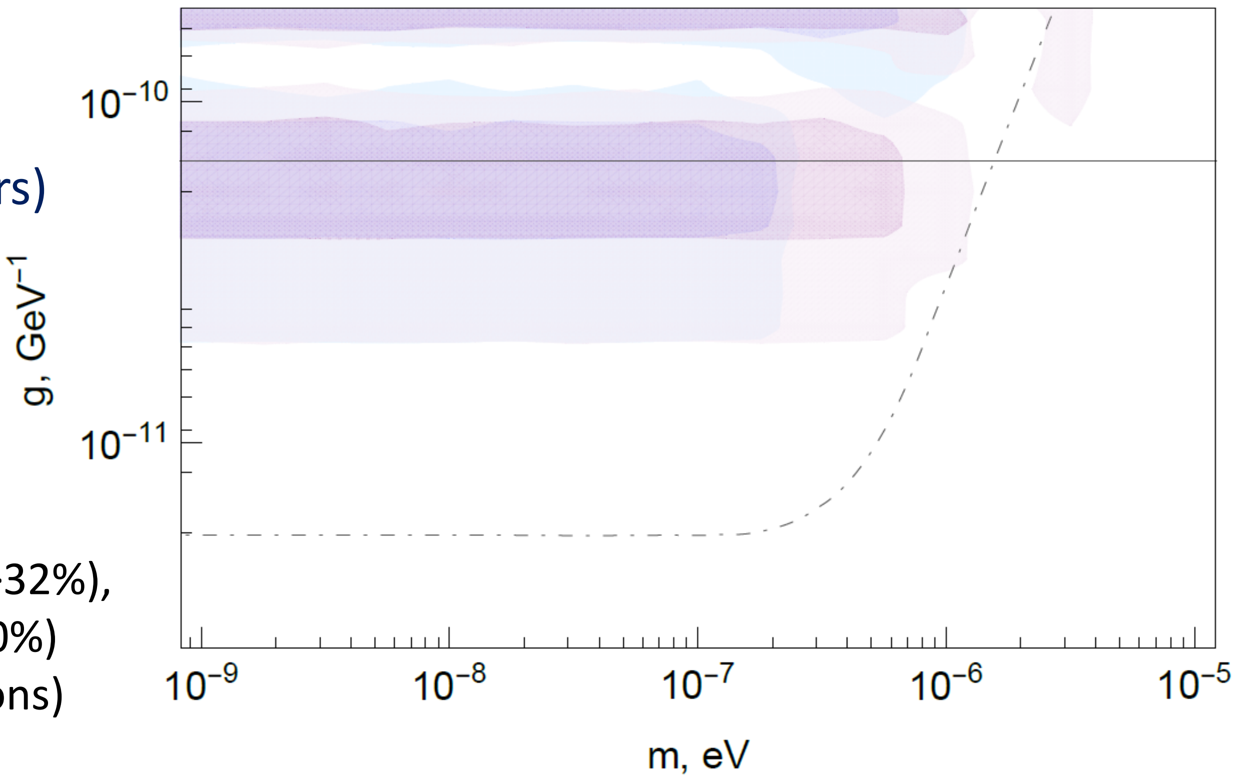
- unknown unknowns:
- GRB position along the line of sight (only projection observed)
  (random positions following the distribution of stars)
- orientation of the spiral arms
  (random rotations for 0 to 2π)

- result:

ALP parameter space

dark color: maximal mixing (>32%),
light color: strong mixing (>10%)
(in 68% of realizations)

pink: for 18 TeV
blue: for 251 TeV



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High-energy photons from distant sources, particle physics and cosmology

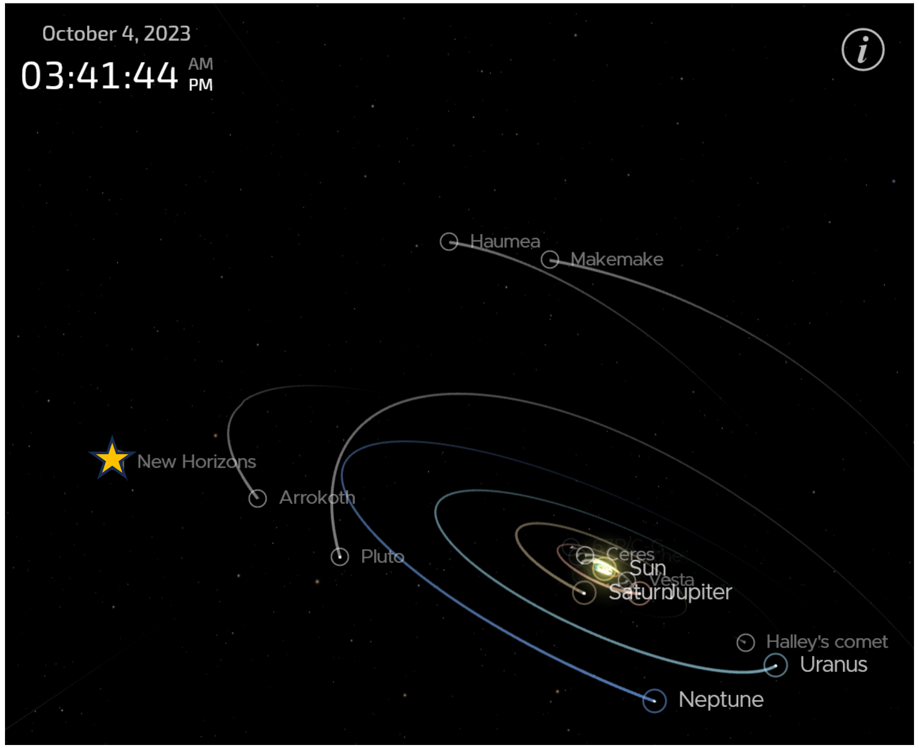
Optical depth of the Universe depends on cosmological parameters

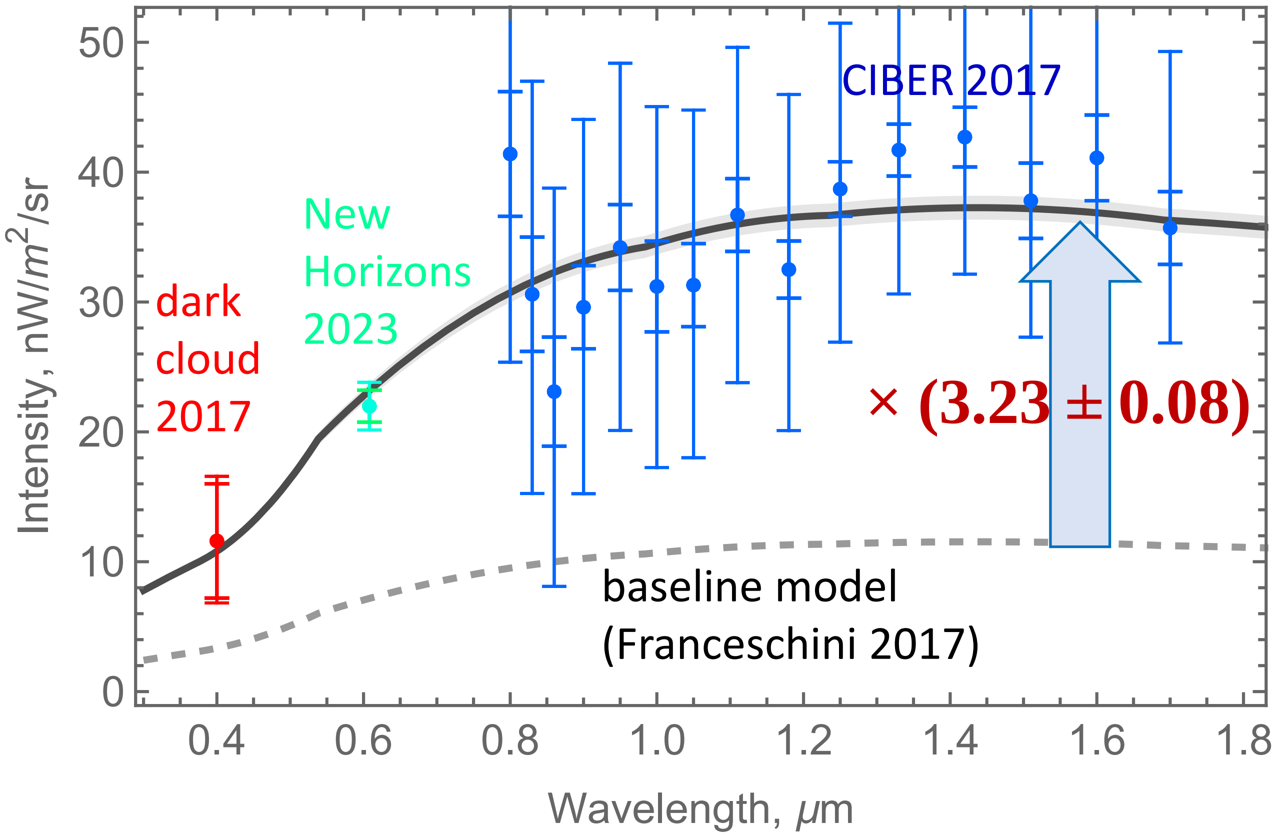
$$\frac{dt_*}{dz} = \frac{-1}{H_0(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}$$

$$\tau_{\gamma\gamma}(\epsilon_1, z) = \frac{c\pi r_e^2}{\epsilon_1^2} \int_0^z dz' \left|\frac{dt^*}{dz'}\right| \frac{1}{(1+z')^2} \times \int_{1/\epsilon_1(1+z')}^{\infty} d\epsilon \frac{n_{\rm ph}(\epsilon; z')}{\epsilon^2} \bar{\varphi}[\epsilon\epsilon_1(1+z')].$$

A [not perfect] study of gamma-ray blazars suggests $\Omega_m = 0.19 \pm 0.07$ *Dominguez et al. 2023*

New Horizons: measurement outside the Solar System





If true:

- **better agreement with Ω_m,**
- **stronger trouble with gamma rays,**
- **more motivation for ALP/LIV/BSM/…**

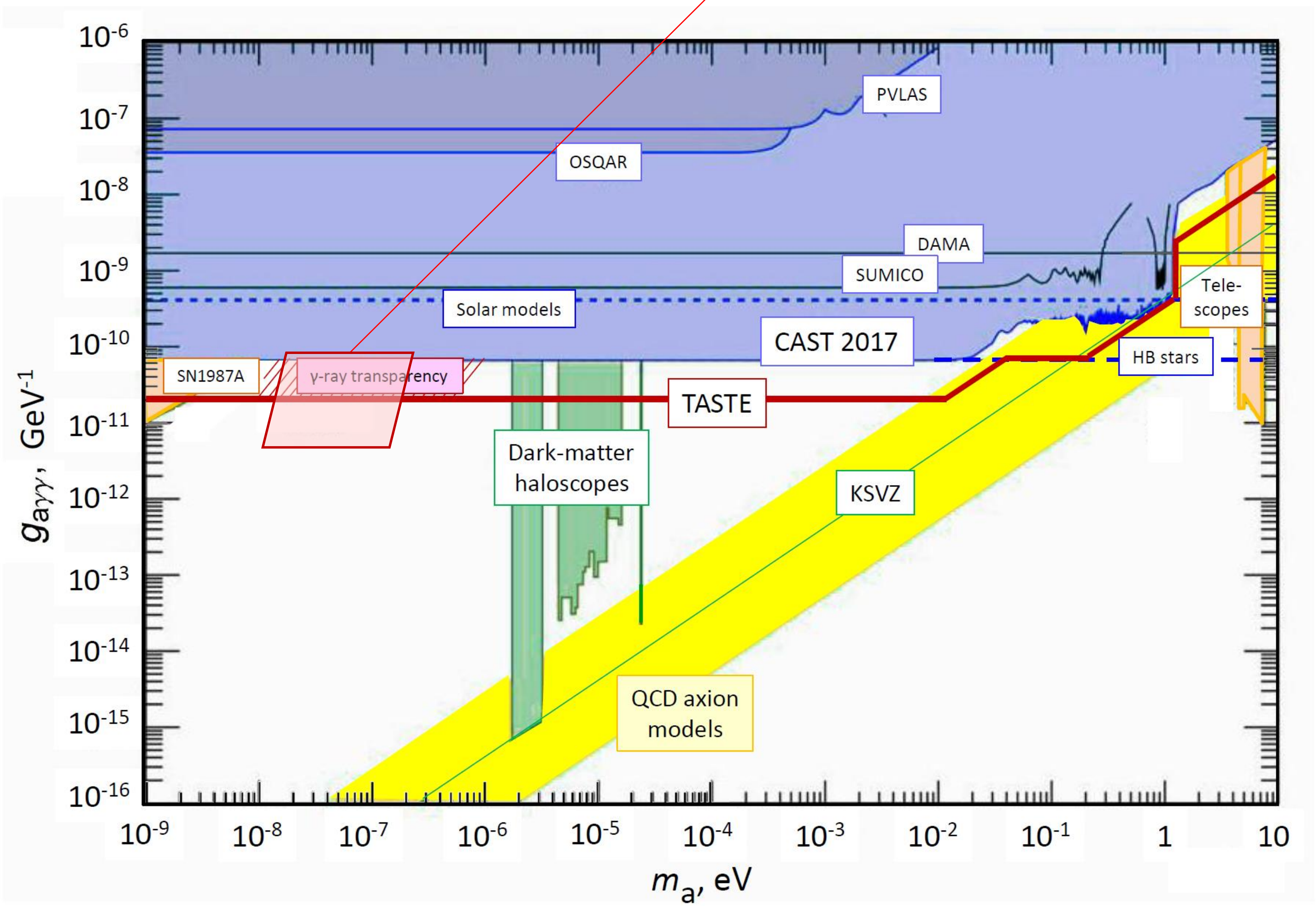
Conclusions

- gamma-ray attenuation is a tool for particle physics and cosmology
- high-energy photons from distant sources remain troublesome
- the brightest-of-all-times GRB 221009A is an example, preliminary suggesting some new physics (ALPs? Lorentz invariance violation?...)
- more puzzles come from the New Horizons measurements
- if true, better agreement with standard cosmology, worse with standard physics

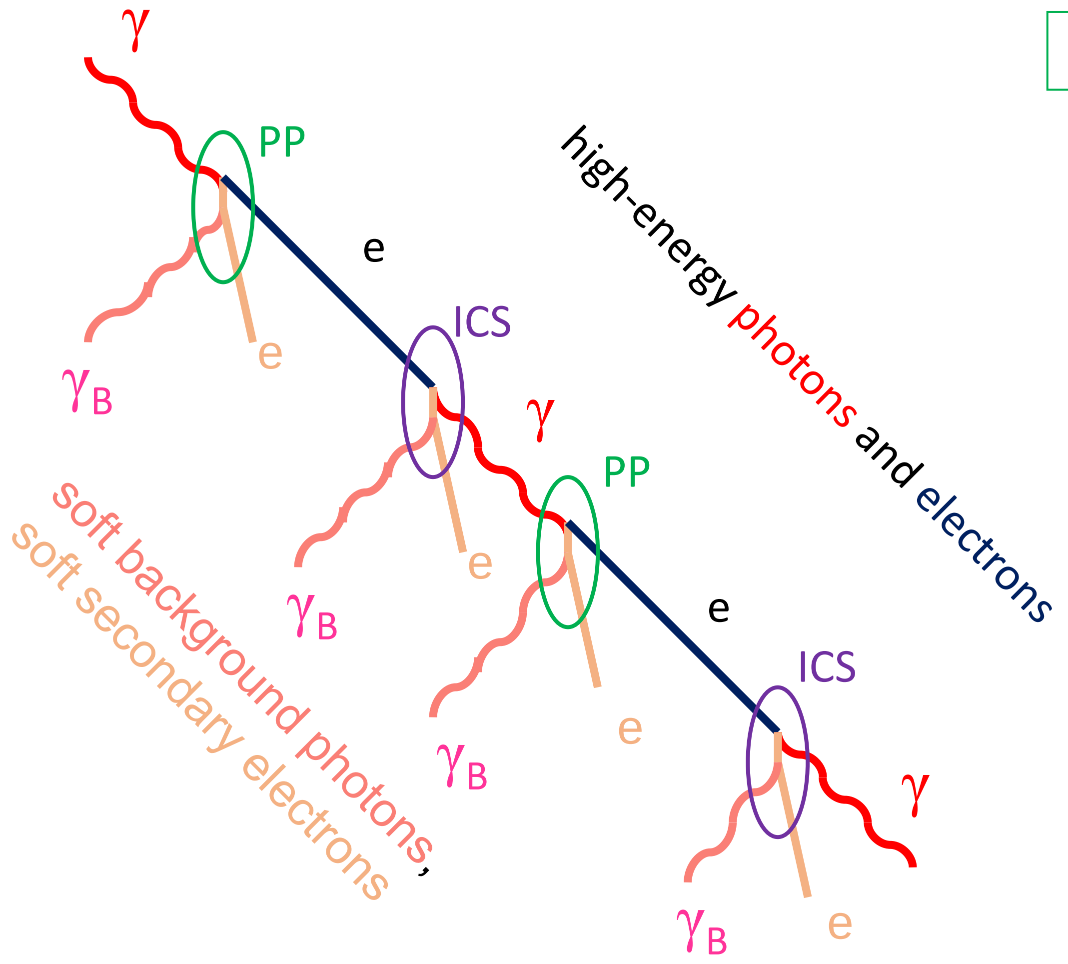
BACKUP SLIDES

ALP parameters

$m \sim$ (a few)10^{-8} eV, $g_{a\gamma} \sim$ (a few)10^{-11} GeV^{-1}



Pair production and electromagnetic cascades



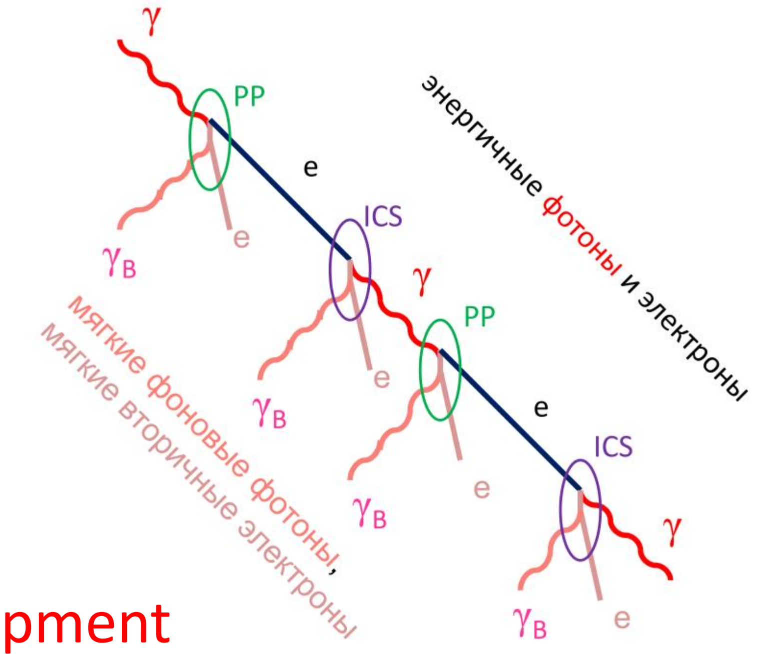
PP = pair production

ICS = inverse Compton scattering

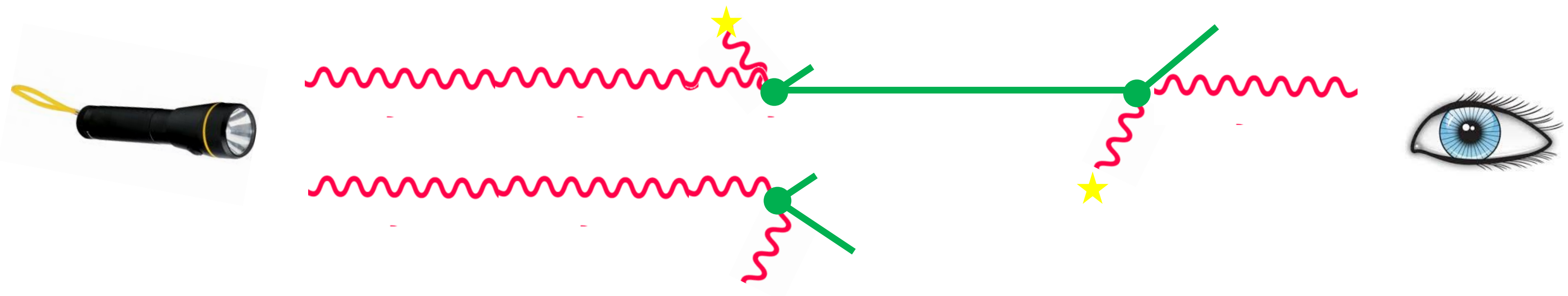
Photons not from the source?

- secondary photons from EM cascades

Dzhatdoev et al.



- ❑ charged particles of different energies follow different trajectories
- ❑ distance to the GRB much larger than the cascade development length

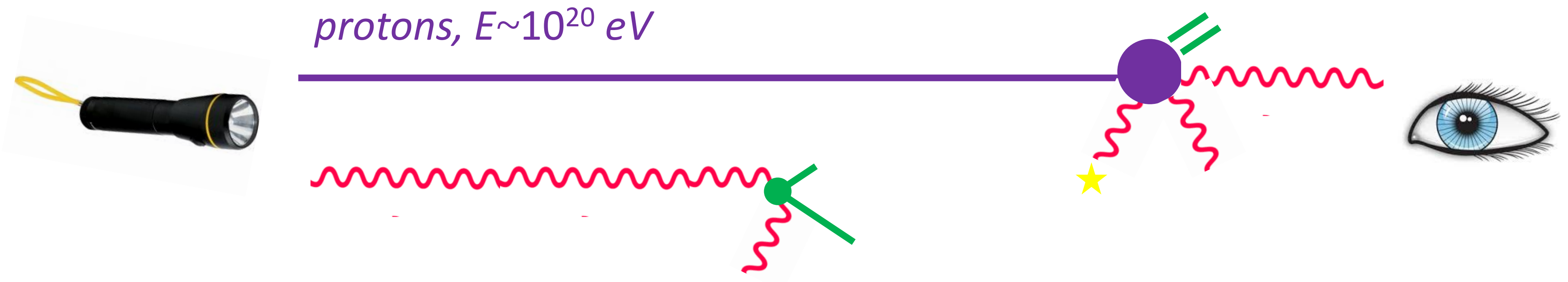


Photons not from the source but related to it?

- the same source produce UHE cosmic protons
- the GZK process gives secondary photons (from π^0 decays)

Essay, Kusenko

- ❑ charged particles of different energies follow different trajectories
- ❑ time delay?
- ❑ distance to the GRB much larger than the GZK length

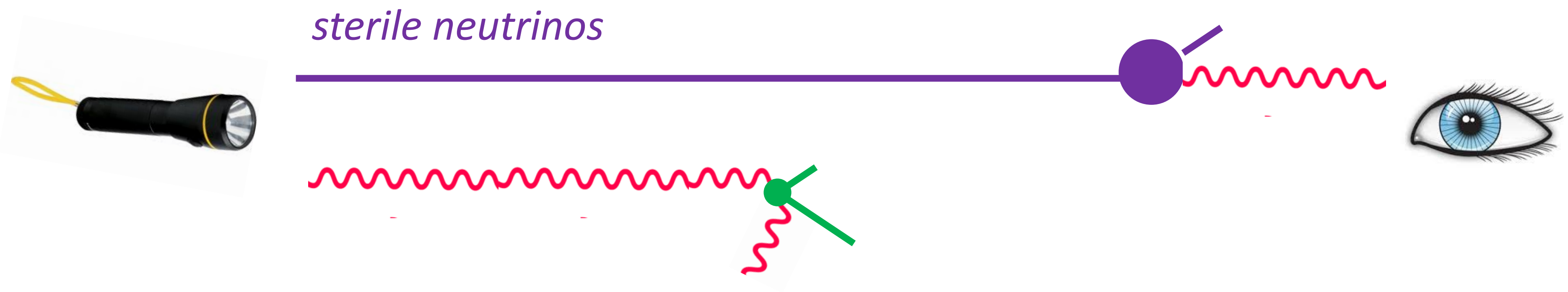


Photons not from the source but related to it?

- the same sources produce high-energy sterile neutrinos
- secondary photons from decays of the sterile neutrinos

Smirnov, Traunter; Huang et al.; ...

- ❑ neutrinos from GRB 221009A not detected
- ❑ neutrinos from the population of GRBs strongly constrained
- ❑ fine tuning: distance to the GRB much larger than the photon m.f.p., one needs to tune the sterile neutrino lifetime



Magnetic field of the GRB 221009A host galaxy: a toy model

- the Milky-Way field model by *Pshirkov et al.*, smoothly corrected in the center
(no spiral arms within 2.5 kpc from the center *Baikova, Bobylev 2022*)

- halo field to explain NGC 891 observations

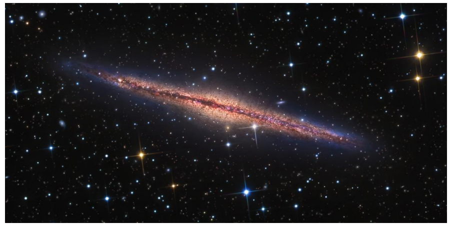
- cosmological simulations of disk-galaxy formation with magnetic fields "Auriga", *Pakmor et al. 2017*

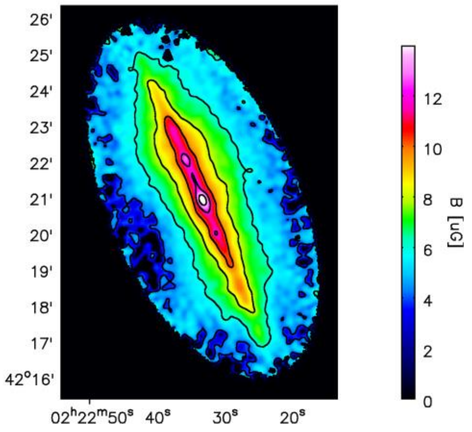
- information about the GRB 221009A host galaxy from HST observations *Levan et al. 2023*

Magnetic field of the GRB 221009A host galaxy:
a toy model
step 1: Milky Way and NGC 891

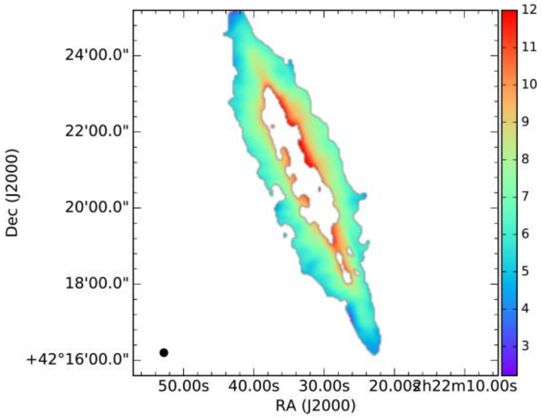
- the Milky-Way field model by *Pshirkov et al.*, smoothly corrected in the center (no spiral arms within 2.5 kpc from the center *Baikova, Bobylev 2022*)

- NGC 891 – a "twin" of the Milky Way, observed edge-on. Close by, which allows to study the field structure. "X-shape" halo field is required.

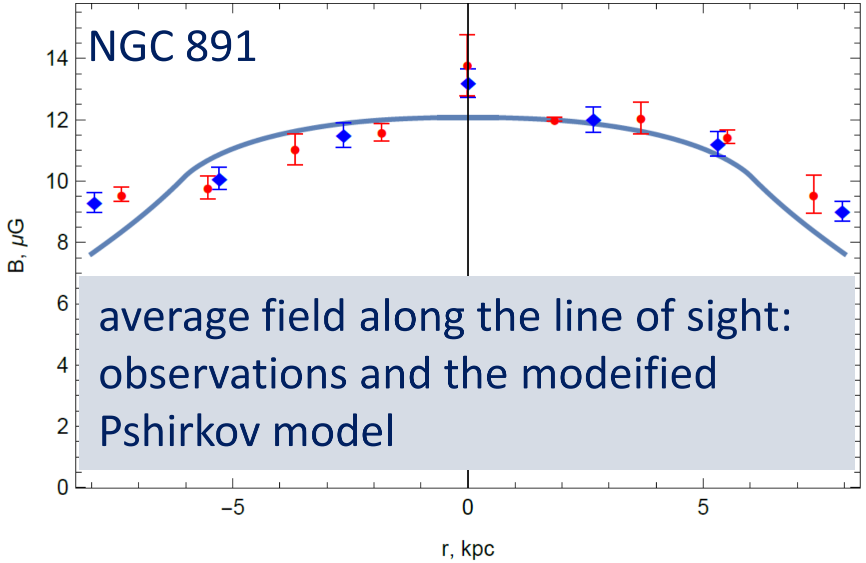




Schmidt et al. 2019

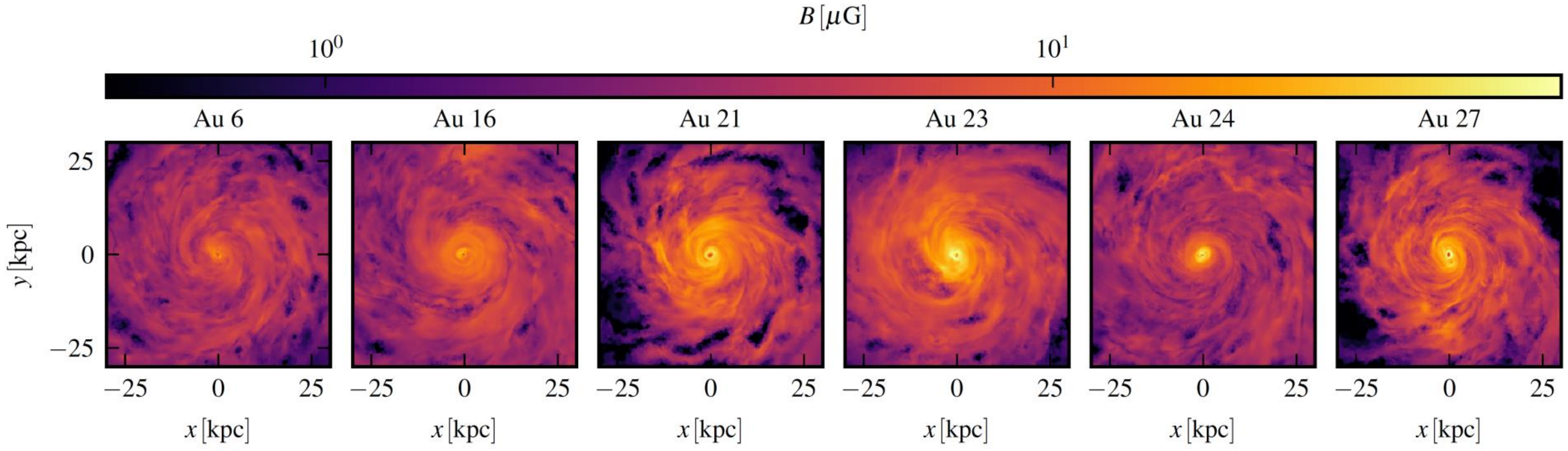


Mulcahy et al. 2018



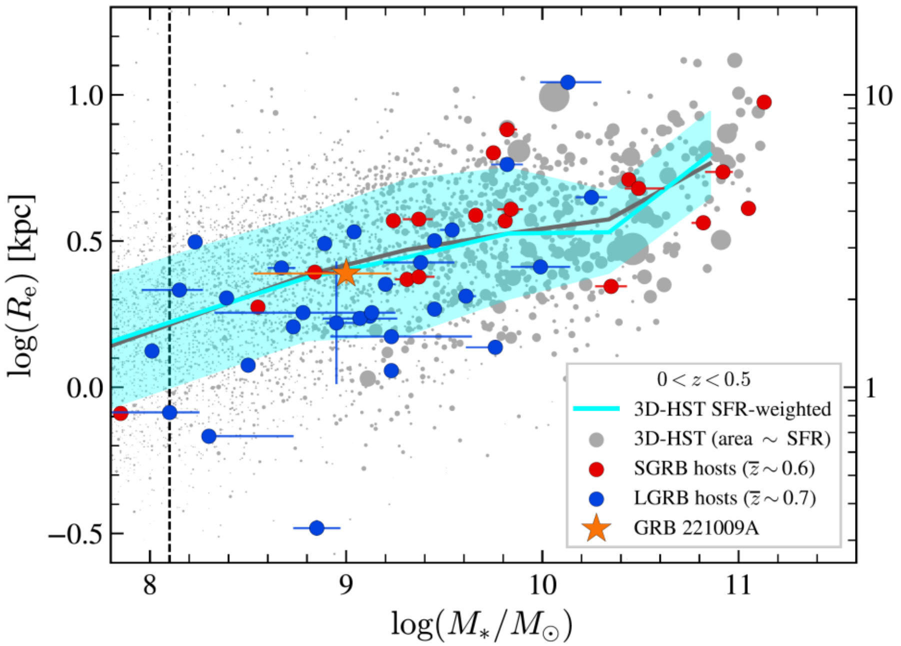
Magnetic field of the GRB 221009A host galaxy: a toy model step 2: scaling with the help of Auriga

- full numerical model of 30 disk galaxies with their magnetic fields, selected from Auriga cosmological simulations *Pakmor et al. 2017*
- scaling:
  - ✓ field values as $(\Sigma\mathrm{SFR})^{0.4}$ ≡ (star formation rate density) $^{0.4}$
  - ✓ radial scales as $(R_{\mathrm{eff}})^{1}$ ≡ (effective radius of the stellar distribution) ^{1}



Magnetic field of the GRB 221009A host galaxy: a toy model step 3: host-galaxy parameters from HST observations

- R_{eff} measured, and the total stellar mass M_* estimated by *Levan et al. 2023*
- the host galaxy is a typical star-forming galaxy *Levan et al. 2023*
- use the relation between M_* and ΣSFR for such galaxies at a given z, *Popesso et al. 2022*
- NGC 891 parameters from literature



ALP-photon oscillations

$$A(\mathbf{x},t) \quad \mapsto \quad A(\mathbf{x})\mathrm{e}^{-i\omega t}, \quad \omega^2+\partial_z^2 \quad \mapsto \quad 2\omega\left(\omega - i\partial_z\right)$$

$$\Downarrow$$

$$(i\partial_z+\omega+\mathcal{M})\begin{pmatrix} A_x \\ A_y \\ a \end{pmatrix} = 0$$

where $\mathcal{M} \equiv \begin{pmatrix} \Delta_p+\Delta_{\mathrm{Q},\|} & 0 & \Delta_{Mx} \\ 0 & \Delta_p+\Delta_{\mathrm{Q},\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$

ALP-photon oscillations

$$\Delta_p = \frac{\omega_p^2}{2\omega}$$

plasma frequency

$$\omega_p^2 = 4\pi\alpha\frac{n_e}{m_e}$$

QED contribution

$$\mathcal{M} \equiv \begin{pmatrix} \Delta_p + \Delta_{Q,\parallel} & 0 & \Delta_{Mx} \\ 0 & \Delta_p + \Delta_{Q,\perp} & \Delta_{My} \\ \Delta_{Mx} & \Delta_{My} & \Delta_m \end{pmatrix}$$

$$\Delta_M = \frac{B}{2M}$$

$$\Delta_m = \frac{m^2}{2\omega}$$

ALP-photon oscillations

$$i\frac{d\rho(y)}{dy} = [\rho(y), \mathcal{M}(E,y)]\,, \qquad \mathcal{M} = \frac{1}{2}\begin{pmatrix} 0 & 0 & -igB_\theta \\ 0 & 0 & -igB_\phi \\ igB_\theta & igB_\phi & \frac{m^2}{E} \end{pmatrix}$$

$$\rho(0) = \mathrm{diag}\,(1/2, 1/2, 0) \Rightarrow \rho_{11}(y) + \rho_{22}(y)$$

conversion probability for constant B, n_e:

$$P = \frac{4\Delta_M^2}{\left(\Delta_p + \Delta_{Q,\perp} - \Delta_m\right)^2 + 4\Delta_M^2} \sin^2\left(\frac{1}{2} L \Delta_{\rm osc}\right)$$

где $\Delta_{\rm osc}^2 = \left(\Delta_p + \Delta_{Q,\perp} - \Delta_m\right)^2 + 4\Delta_M^2$

ALP-photon oscillations

maximal mixing conditions:

$$\Delta_m \ll 2\Delta_M \quad \Rightarrow \quad \omega \gg 700\ \text{eV} \left(\frac{m}{10^{-9}\ \text{eV}}\right)^2 \left(\frac{B}{\text{G}}\right)^{-1} \left(\frac{M}{10^{11}\ \text{GeV}}\right)$$

$$\Delta_p \ll 2\Delta_M \quad \Rightarrow \quad n_e \ll 10^{13}\ \text{cm}^{-3} \left(\frac{\omega}{\text{TeV}}\right) \left(\frac{B}{\text{G}}\right)$$

$$\Delta_{Q,\perp} \ll \Delta_M \quad \Rightarrow \quad \left(\frac{\omega}{\text{TeV}}\right) \left(\frac{B}{\text{G}}\right) \ll 7.52 \times 10^{-2}$$

$$L \gtrsim \frac{\pi}{\Delta_{\text{osc}}} \quad \Rightarrow \quad L \gtrsim 5.8 \times 10^{-2}\ \text{pc} \left(\frac{B}{\text{G}}\right)^{-1} \left(\frac{M}{10^{11}\ \text{GeV}}\right)$$

ALP-photon oscillations

maximal mixing conditions:

$$\Delta_m \ll 2\Delta_M$$
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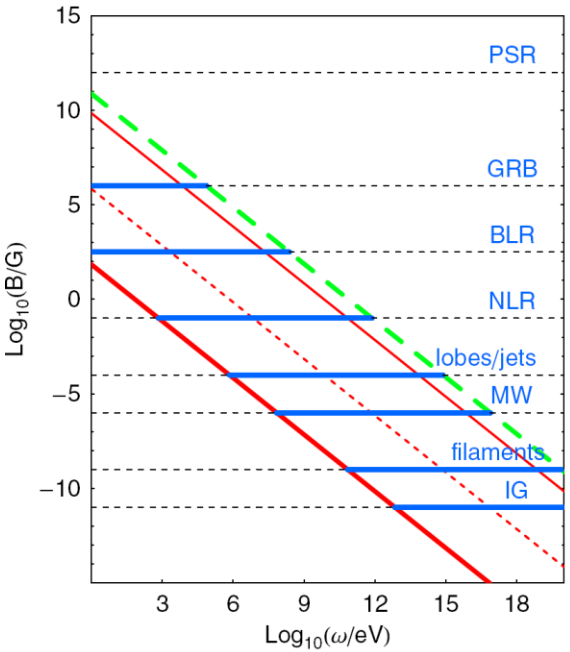
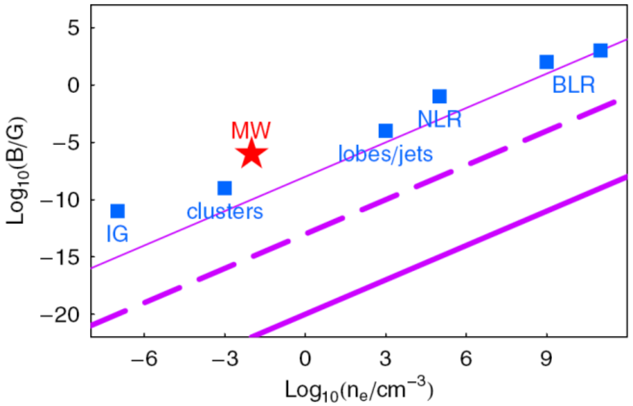
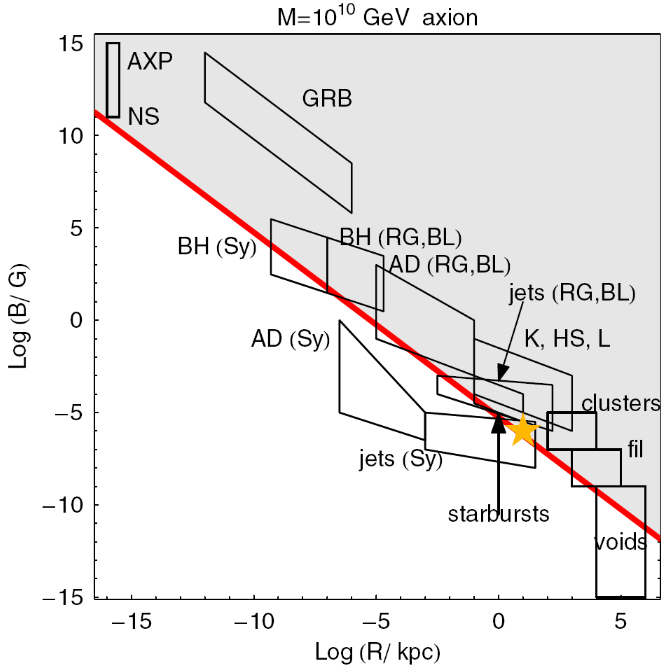
$$\Delta_p \ll 2\Delta_M$$

$$L \gtrsim \frac{\pi}{\Delta_{\mathrm{osc}}}$$







Fairbairn et al. 2009

LHAASO highest-energy photons

Table S2: Detail information of the nine events with the highest energy from GRB 221009A

T_{event}(s)	E_{LP} (TeV)	E_{PLEC} (TeV)	E_{EBL} (TeV)	N_e	N_μ	θ (°)	$\Delta\psi$ (°)	D_{edge} (m)	P (%)
236.6	$12.7^{+6.2}_{-3.8}$	$9.7^{+3.3}_{-2.1}$	$9.8^{+3.1}_{-2.3}$	60.6	0	28.5	0.46	77	7.0
242.5	$10.5^{+5.0}_{-3.2}$	$8.3^{+3.0}_{-2.1}$	$8.4^{+3.2}_{-2.2}$	57.4	0	28.8	0.45	111	10
262.4	$12.6^{+5.5}_{-3.8}$	$9.5^{+3.4}_{-2.3}$	$9.6^{+3.3}_{-2.4}$	57.3	0	28.6	0.53	180	5.7
358.1	$10.0^{+4.8}_{-3.2}$	$7.4^{+3.1}_{-1.8}$	$7.9^{+3.3}_{-2.2}$	46.0	0	28.7	0.54	119	6.0
571.1	$9.4^{+5.1}_{-3.0}$	$7.4^{+2.6}_{-2.5}$	$7.7^{+3.0}_{-2.5}$	45.7	0	29.5	0.52	99	7.8
643.0	$17.8^{+7.4}_{-5.1}$	$12.2^{+3.5}_{-2.4}$	$12.5^{+3.2}_{-2.4}$	81.8	0.3	29.7	0.62	181	4.5
812.4	$11.1^{+5.9}_{-4.3}$	$7.4^{+3.6}_{-2.8}$	$7.6^{+3.9}_{-3.0}$	68.0	0	30.3	0.66	112	11
863.8	$12.9^{+6.1}_{-3.9}$	$9.2^{+3.0}_{-2.8}$	$9.7^{+3.2}_{-3.1}$	100.2	0.8	30.1	1.07	81	17
894.1	$13.6^{+6.1}_{-4.2}$	$9.7^{+3.4}_{-2.5}$	$10.4^{+3.3}_{-3.0}$	60.5	0	31.8	0.83	214	16

LHAASO ICRC2023 preliminary