HIGH ENERGY PHENOMENOLOGY GROUP

YASAMAN FARZAN

SCHOOL OF PHYSICS, IPM

ICTP SIMONS ASSOCIATE

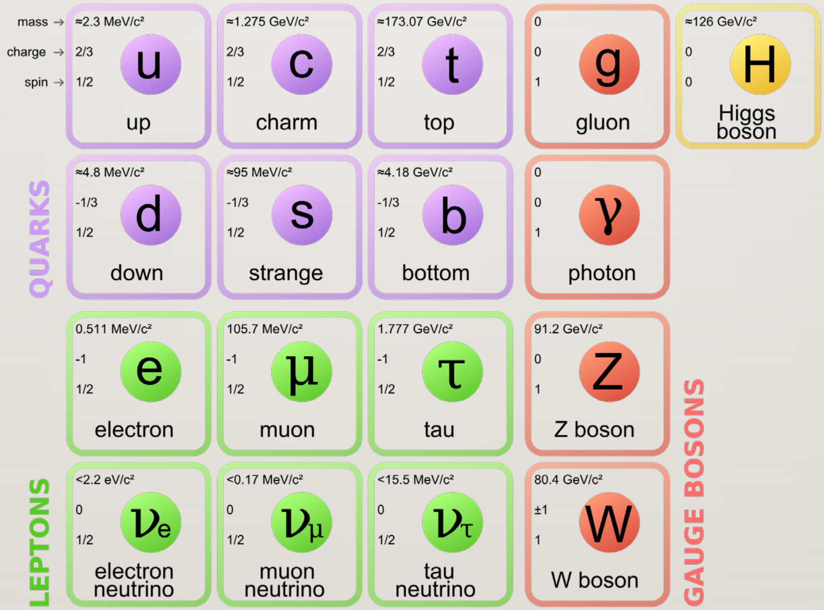
HIDDeν

Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

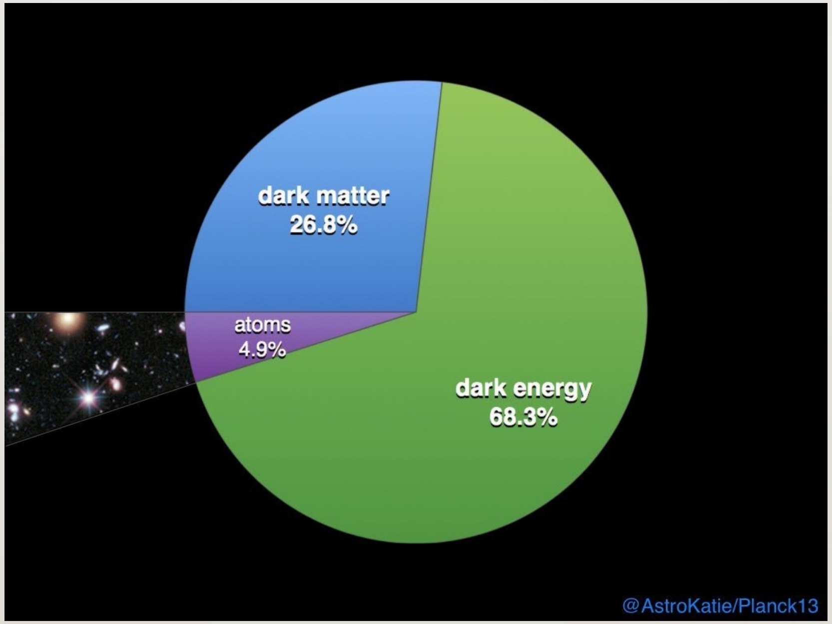
TOPICS

- Neutrino physics
- Dark Matter
- Neutrino interaction with matter (PDFs)
- Forward physics facility

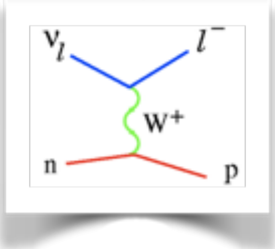
SM PARTICLES



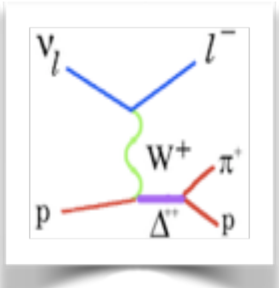
COSMIC PIE


dark matter
26.8%
atoms
4.9%
dark energy
68.3%
@AstroKatie/Planck13

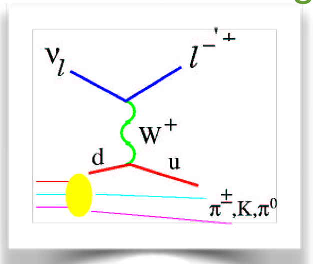
Quasi-elastic scattering (QE)

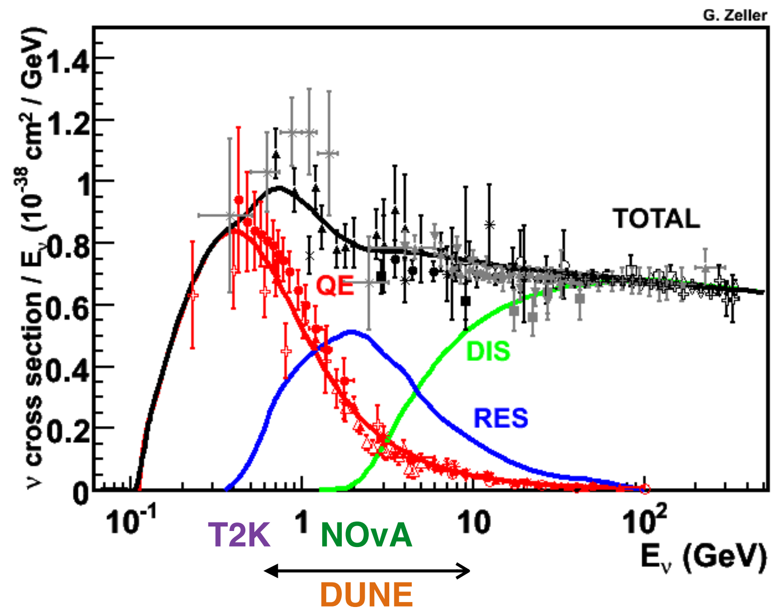


Resonance production (RES)



Deep Inelastic scattering (DIS)





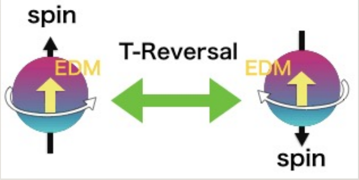
J.A. Formaggio, G. Zeller, Reviews of Modern Physics, 84 (2012)

OLDER TOPICS

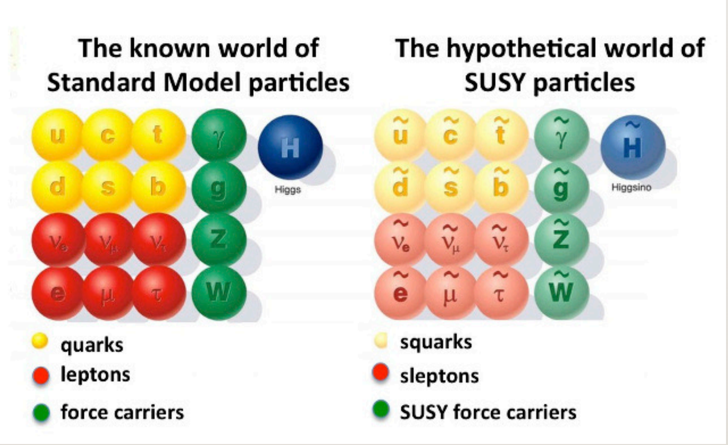
- CP violation (Electric dipole moments of elementary fermions)
- Supersymmetry
- supergravity

OLDER TOPICS

- CP violation (Electric dipole moments of elementary fermions)



- Supersymmetry



- supergravity

OLDER TOPICS

- CP violation (Electric dipole moments of elementary fermions)
- Supersymmetry

- Supergravity
- D.A. Demir and Y.F., "Correlating mu parameter and right-handed neutrino masses in N=1 supergravity," JHEP **03** (2006), 010 doi:10.1088/1126-6708/2006/03/010

GROUP MEMBER

- Yasaman Farzan (founder)

POST-DOCTORAL FELLOWS

- Saeed Abbaslu
- Saeed Ansarifard
- Peyman Zakeri

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Cosmology
Data scientist

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- Peyman Zakeri

Cosmology
Data scientist

Climate change

https://www.aparat.com/schoolofphysics

POST-DOCTORAL FELLOWS

- Saeed Abbaslu
- Saeed Ansarifard
- Peyman Zakeri

LONG TERM VISITOR

- Hamed Abdolmaleki

xFitter Developers' team

MASTER STUDENTS

- Sahar Safari

- Mehran Dehpour

MASTER STUDENTS

- Sahar Safari

- Mehran Dehpour

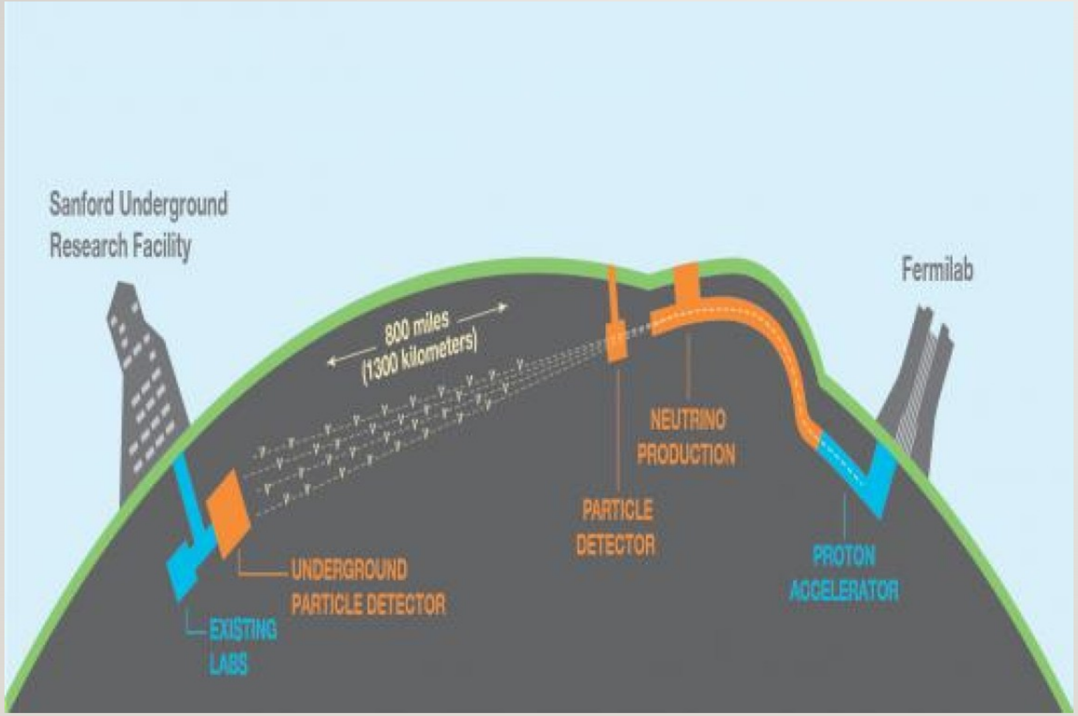
NETWORKS

INVISIBLEs
ELUSIVEs
HiDDeN
ASYMMETRY

Asymmetry
Essential Asymmetries of Nature

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

DUNE COLLABORATION



DEEP UNDERGROUND
NEUTRINO EXPERIMENT

CURRENT AND UPCOMING PROJECTS

- Non-standard interactions of neutrinos
- Solar neutrinos
- Dark matter interaction with matter
- Gears up for serendipitous searches

NON-STANDARD NEUTRINO INTERACTIONS

- Neutral current Non-Standard Interaction (NSI): propagation of neutrinos in matter

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{fX}\, (\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)\, (\bar{f}\gamma_\mu P_X f)$$

$$\text{matter field } f \in \{e, u, d\} \text{ (for NC-NSI)}$$

- Charged current Non-Standard Interaction (NSI): production and detection

$$\mathcal{L}_{\mathrm{CC-NSI}} = -2\sqrt{2}G_F\, \epsilon_{\alpha\beta}^{ff'X}\, (\bar{\nu}_\alpha \gamma^\mu P_L \ell_\beta)\, (\bar{f}'\gamma_\mu P_X f)$$

$$f \neq f' \in \{u, d\} \text{ (for CC-NSI).}$$

NEUTRAL CURRENT NSI

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\,(\bar{f}\gamma_\mu P_X f)$$

$\epsilon_{\alpha\beta}^{fX} \to 0$ ➡ Standard Model

$$P_{R,L} = (1 \pm \gamma_5)/2.$$

matter field $f \in \{e, u, d\}$ (for NC-NSI)

Vector NSI $\boxed{\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}}$

Axial NSI $\boxed{\epsilon_{\alpha\beta}^{fA} = \epsilon_{\alpha\beta}^{fR} - \epsilon_{\alpha\beta}^{fL}}$

PHENOMENOLOGICAL CONSEQUENCES OF VECTOR NSI

$$\boxed{\epsilon_{\alpha\beta}^{fV} = \epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR}}$$

- Neutrino propagation in matter
- Coherent Elastic neutrino Nucleus Scattering $(\mathrm{CE}\nu\mathrm{NS})$: for coupling to u and d quarks

$$\boxed{\epsilon_{\alpha\beta}^{uL} + \epsilon_{\alpha\beta}^{uR}} \qquad \boxed{\epsilon_{\alpha\beta}^{dL} + \epsilon_{\alpha\beta}^{dR}}$$

- Scattering of neutrinos off electron at BOREXINO $\nu + e \to \nu + e$

$$\boxed{\epsilon_{\alpha\beta}^{eL} + \epsilon_{\alpha\beta}^{eR}}$$

- High energy neutrino scattering experiments (CHARM and NuTeV)
- ~~Neutral current scattering off deuterium at SNO~~ $\boxed{\nu + D \to \nu + n + p}$

PHENOMENOLOGICAL CONSEQUENCES OF AXIAL VECTOR NSI

$$\boxed{\epsilon^{fA}_{\alpha\beta} = \epsilon^{fR}_{\alpha\beta} - \epsilon^{fL}_{\alpha\beta}}$$

- ~~Neutrino propagation in matter~~
- ~~Coherent Elastic neutrino Nucleus Scattering $(\text{CE}\nu\text{NS})$: for coupling to u and d~~
- Scattering of neutrinos off electron $\nu + e \rightarrow \nu + e$

$$\boxed{\epsilon^{eA}_{\alpha\beta} = \epsilon^{eR}_{\alpha\beta} - \epsilon^{eL}_{\alpha\beta}}$$

- High energy neutrino scattering experiments (CHARM and NuTeV)
- Neutral current scattering off deuterium at SNO $\boxed{\nu + D \rightarrow \nu + n + p}$

OSCILLATION IN MATTER IN PRESENCE OF NSI

$$i\frac{d}{dx}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = H^\nu \begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

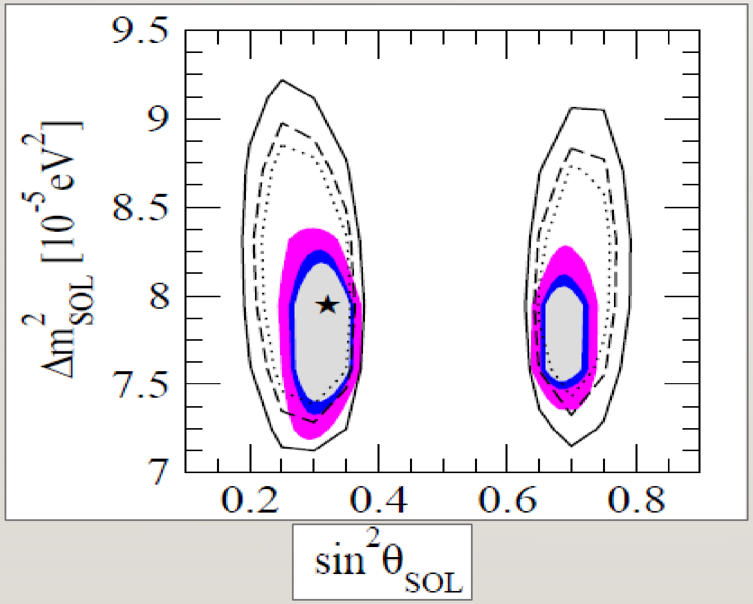
$$H^\nu = H_{\text{vac}} + H_{\text{mat}} \quad \text{and} \quad H^{\bar{\nu}} = (H_{\text{vac}} - H_{\text{mat}})^*$$

$$\epsilon^f_{\alpha\beta} = \epsilon^{fL}_{\alpha\beta} + \epsilon^{fR}_{\alpha\beta}$$

$$H_{\text{mat}} = \sqrt{2}G_F N_e(r)\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix} + \sqrt{2}G_F \sum_{f=e,u,d} N_f(r)\begin{pmatrix}\varepsilon^f_{ee} & \varepsilon^f_{e\mu} & \varepsilon^f_{e\tau}\\ \varepsilon^{f*}_{e\mu} & \varepsilon^f_{\mu\mu} & \varepsilon^f_{\mu\tau}\\ \varepsilon^{f*}_{e\tau} & \varepsilon^{f*}_{\mu\tau} & \varepsilon^f_{\tau\tau}\end{pmatrix}$$

LMA-DARK SOLUTION

- Miranda, Tortola and Valle, JHEP 2006; Escrihuela et al., PRD 2009



$\theta_{12} > \pi/4$

$$-1.40 < \epsilon^u_{ee} - \epsilon^u_{\mu\mu} < -0.68 \quad \text{and} \quad -1.44 < \epsilon^d_{ee} - \epsilon^d_{\mu\mu} < -0.87 \quad \text{at } 3\sigma \text{ C.L.}$$

WHAT IS THE UNDERLYING MODEL FOR THE EFFECTIVE FOUR-FERMION LAGRANGIAN?

- Integrating out Z' with mass $m_{Z'}$ and coupling $g_{Z'}$

$$\boxed{-2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

$$\epsilon = \left(\frac{g_{Z'}^2}{m_{Z'}^2}\right) G_F^{-1}$$

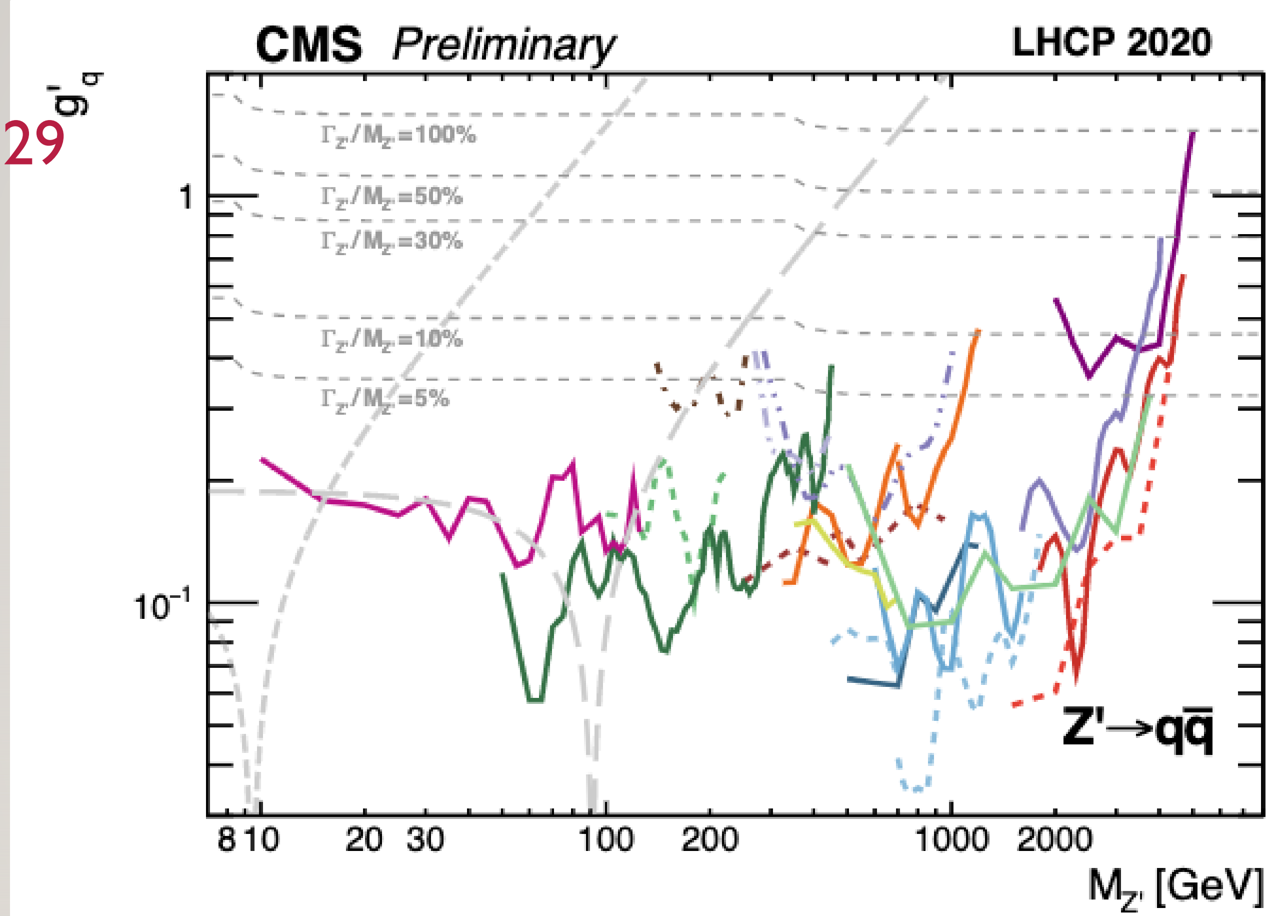
UNDERLYING THEORY FOR NSI

$$\boxed{\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)}$$

Integrating out a heavy intermediate state

Neutral U(1) gauge boson as mediator

$$\boxed{Z'_\mu\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta} \qquad \boxed{Z'_\mu\bar{f}\gamma^\mu P_X f}$$



PDG

ATLAS, CMS, CDF, and UA2 experiments

30 SUGGESTION

- What if $m_{Z'} \sim 10 \text{ MeV}$

YF, "A model for large non-standard interactions leading to LMA-Dark solution," Phys. Lett. B748 (2015) 311-315; YF and J Heeck, "Neutrinophilic nonstandard interactions," PRD 94 (2016) 53010; YF and I Shoemaker, "lepton flavor violating NSI via light mediator," JHEP 1607 (2016) 33.
YF and M Tortola, "neutrino oscillations and non-standard interactions," *Front.in Phys*. 6 (2018) 10; P.B.Denton, Y.F. and I.M.Shoemaker, "Activating the fourth neutrino of the 3+1 scheme," Phys. Rev. D 99 (2019) no.3, 035003; Y.F., "A model for lepton flavor violating non-standard neutrino interactions," Phys. Lett. B **803** (2020), 135349

SUGGESTION

- What if $m_{Z'} \sim 10 \text{ MeV}$

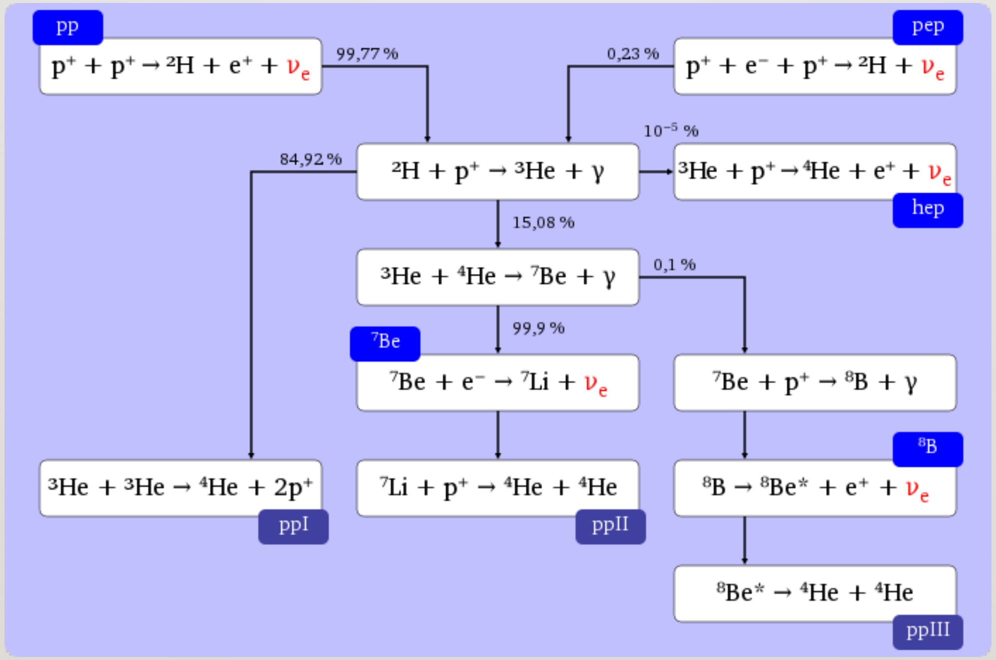
$$\epsilon \sim 1 \Rightarrow g_{Z'} \sim 10^{-5} - 10^{-4}$$

- Bounds can be avoided not because the mass of the intermediate state is high

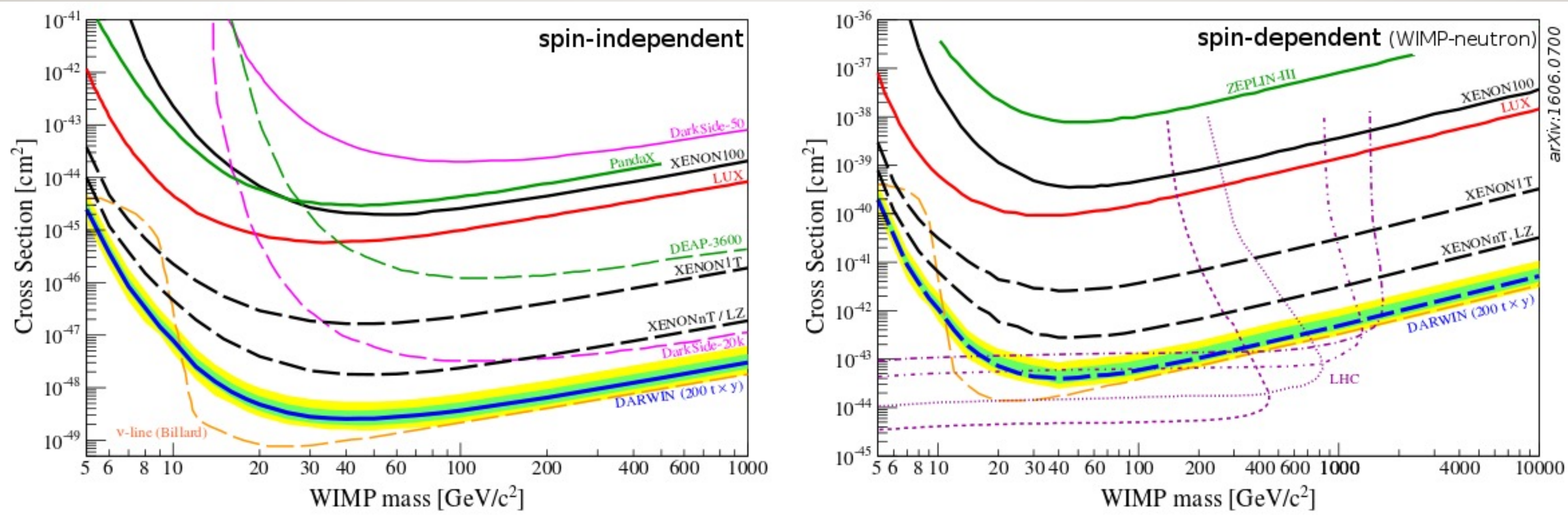
But because coupling is small!

$$\mathcal{L}_{\mathrm{NC-NSI}} = -2\sqrt{2}G_F\,\epsilon_{\alpha\beta}^{fX}\,(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)\left(\bar{f}\gamma_\mu P_X f\right)$$

SOLAR NEUTRINOS

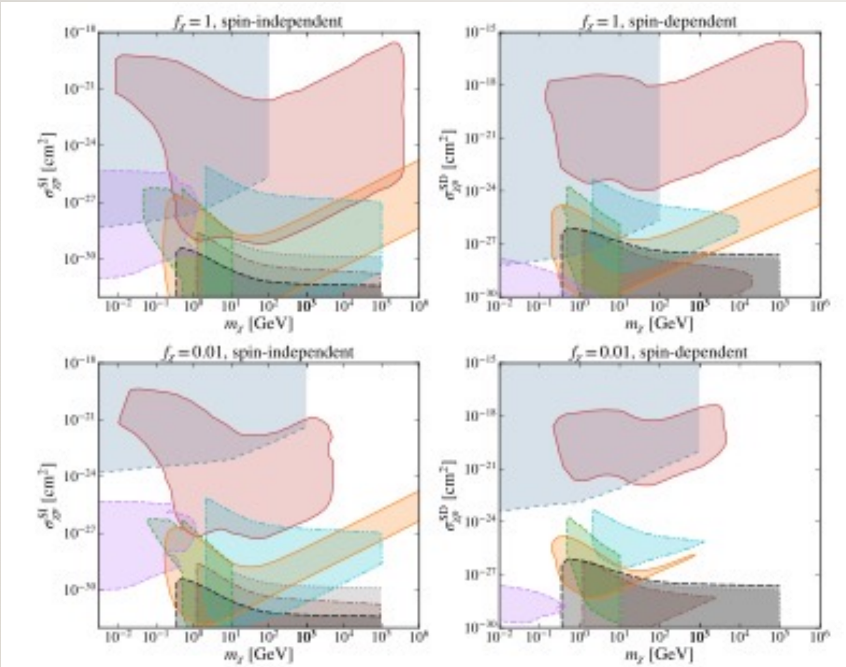


DARK MATTER INTERACTIONS



https://darwin.physik.uzh.ch/darwin.html

DARK MATTER INTERACTION

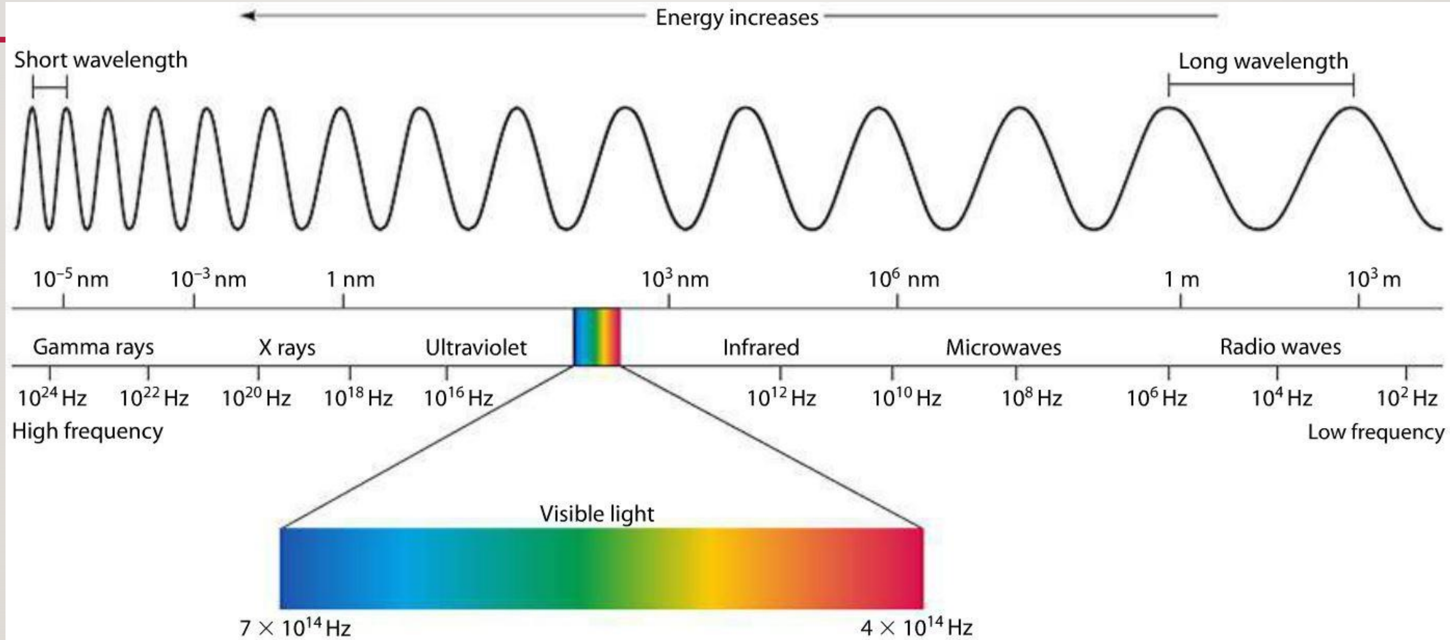


Y. Li, Z. Liu and Y. Xue,
"XQC and CSR constraints on strongly interacting dark matter with spin and velocity dependent cross sections," JCAP **05** (2023), 060

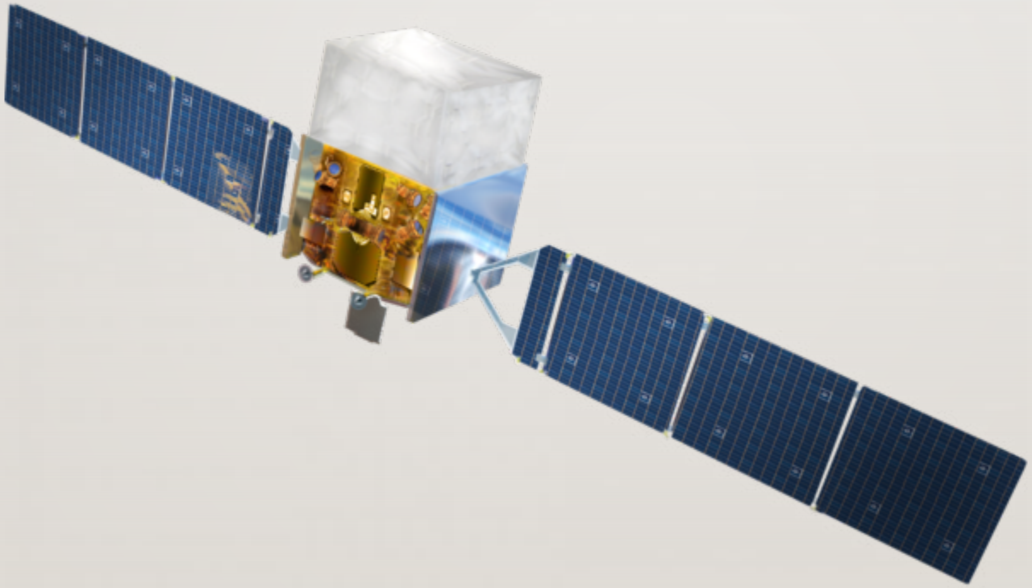
- N. Bernal, Y. Farzan and A. Y. Smirnov, ``Neutrinos from GRB 221009A: producing ALPs and explaining LHAASO anomalous gamma event," JCAP **11** (2023), 098

WORLD AS SEEN UNTILL RECENTLY

MULTIMESSENGER ERA



FERMI GAMMA RAY TELESCOPE



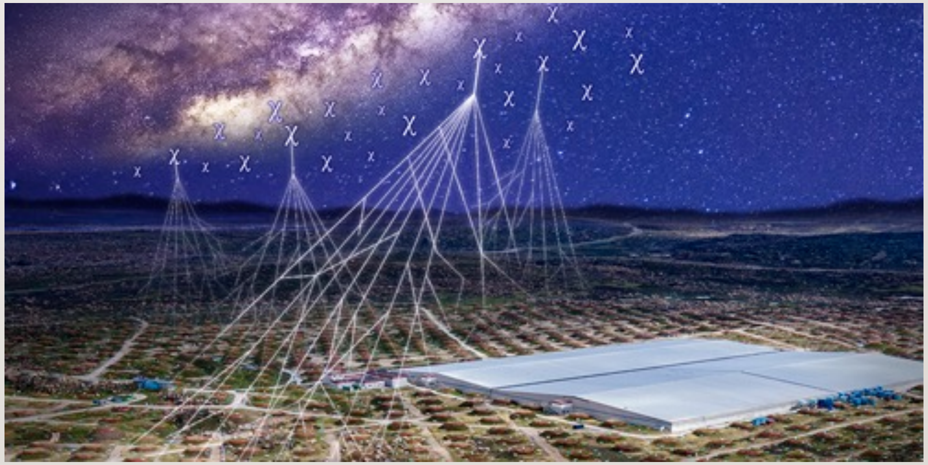
Fermi-LAT

Fermi-GBM

Few GeV

LHAASO

- Large High Altitude Air Shower Observatory



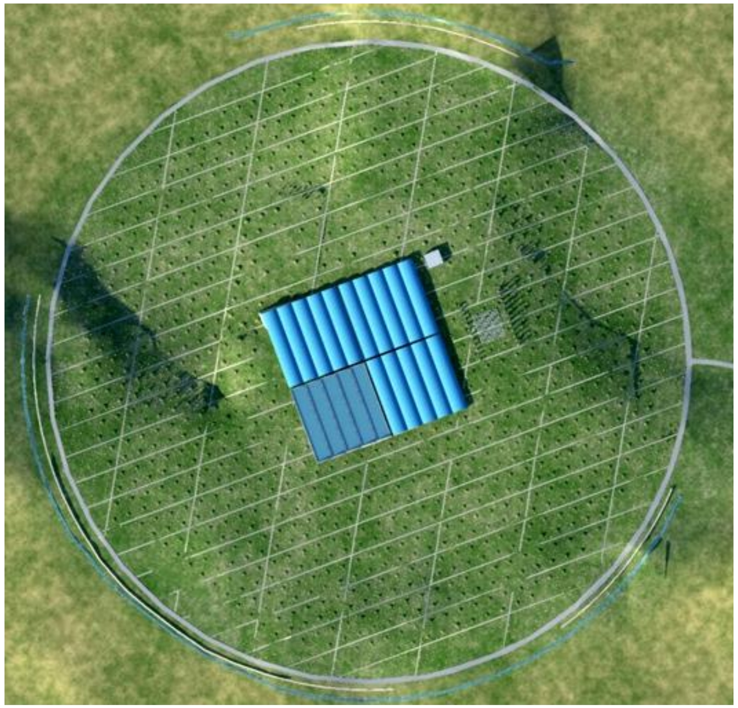
- Sichuan, China (Tibetan plateau)

LHAASO

WCDA

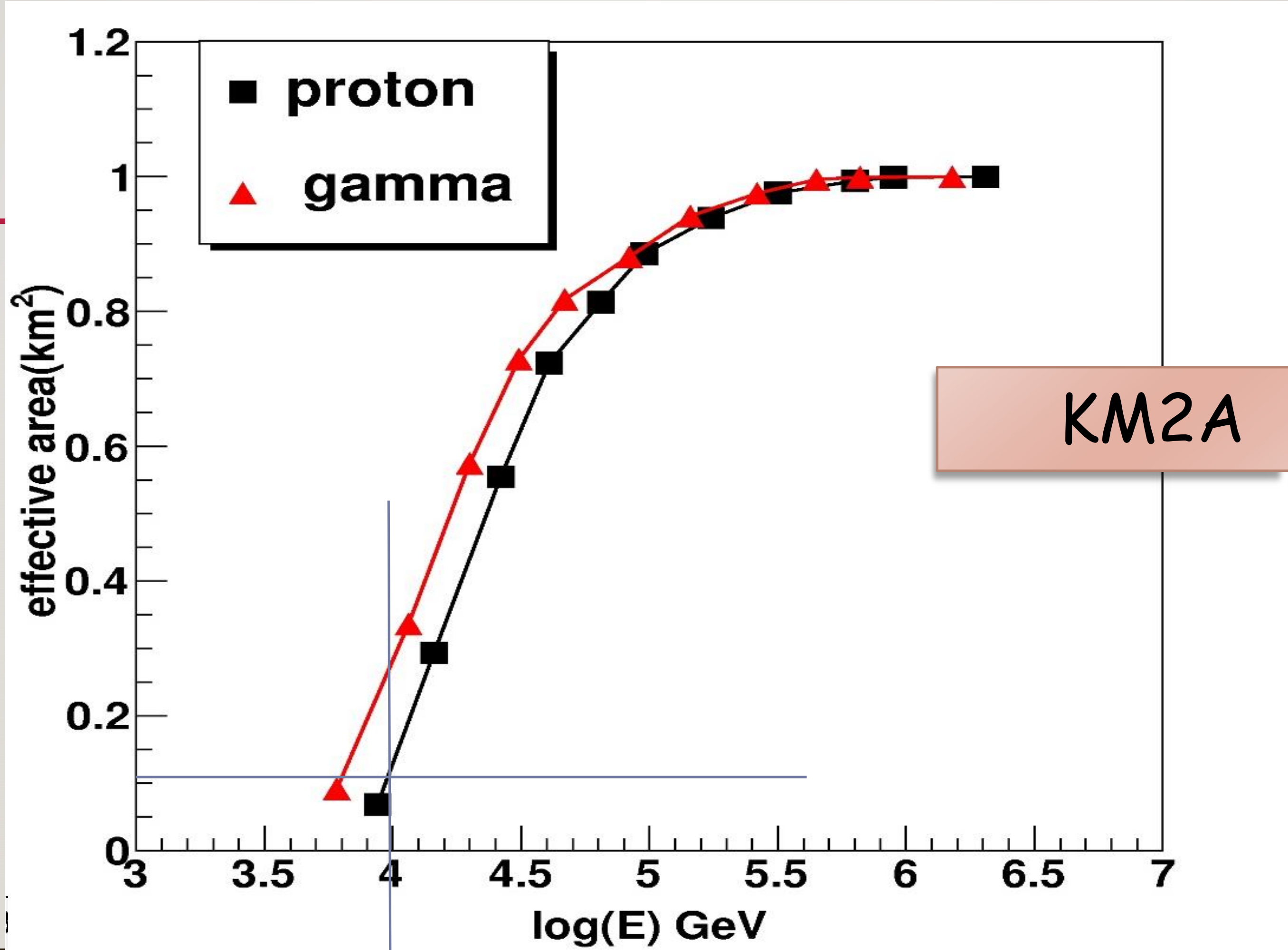
+

KM2A



Z. Cao, International symposium on very high energy particle astromony, 2015

Z. Cao, International symposium on very high energy particle astromony, 2015



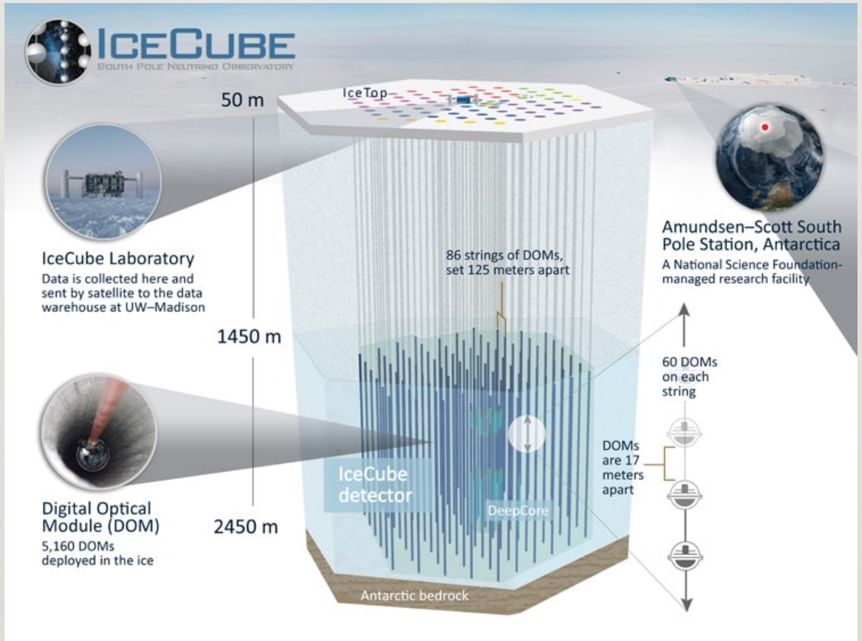
NEW MESSENGERS

- Cosmic ray (Since balloon based experiment since 1912 by Victor Hess)

- High energy Cosmic Neutrinos (by IceCube since 2013---- since 1987 from Supernova– earlier solar neutrinos since 1960s)

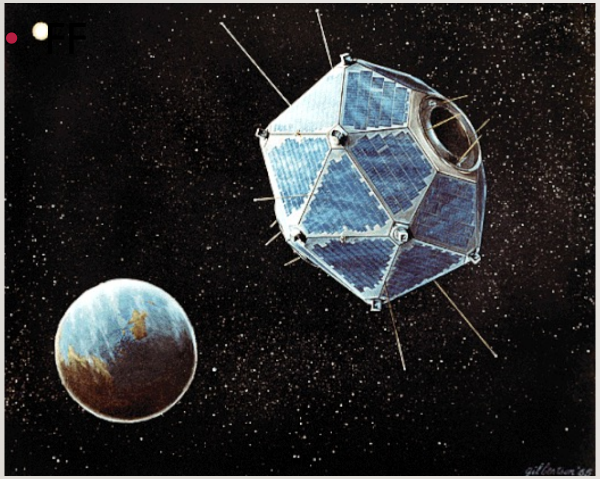
- Gravitational waves (Since 2015)

ICECUB



IceCube
South Pole Neutrino Observatory
IceTop
50 m
IceCube Laboratory
Data is collected here and sent by satellite to the data warehouse at UW–Madison
86 strings of DOMs, set 125 meters apart
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
1450 m
60 DOMs on each string
DOMs are 17 meters apart
IceCube detector
DeepCore
Digital Optical Module (DOM)
5,160 DOMs deployed in the ice
2450 m
Antarctic bedrock

GAMMA RAY BURST (GRB)



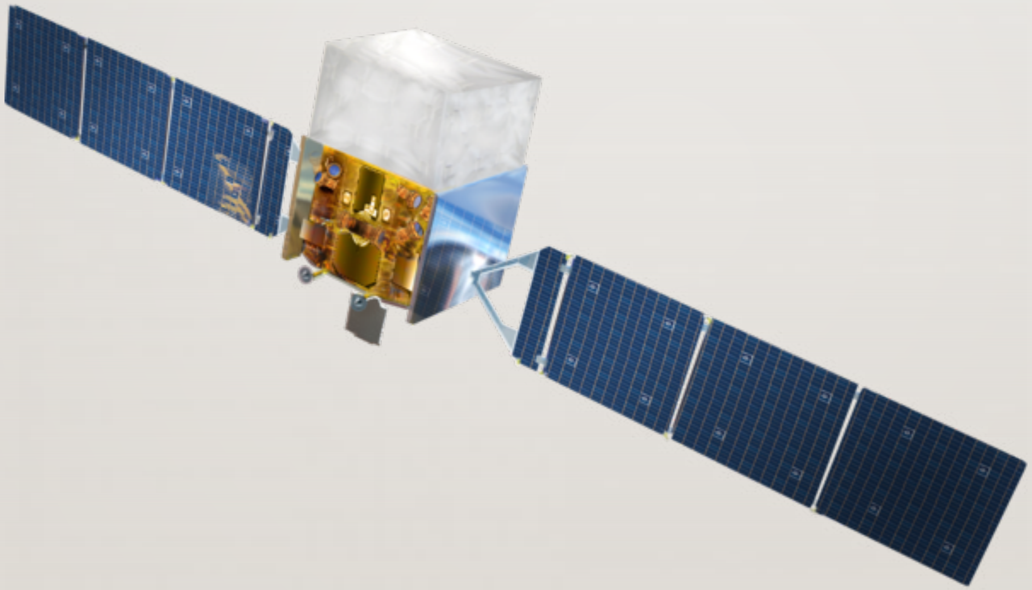
Vela. (US air force)

First GRB discovered in 1967

~1700 GRB since day

One per day these days

FERMI GAMMA RAY TELESCOPE



Fermi-LAT

Fermi-GBM

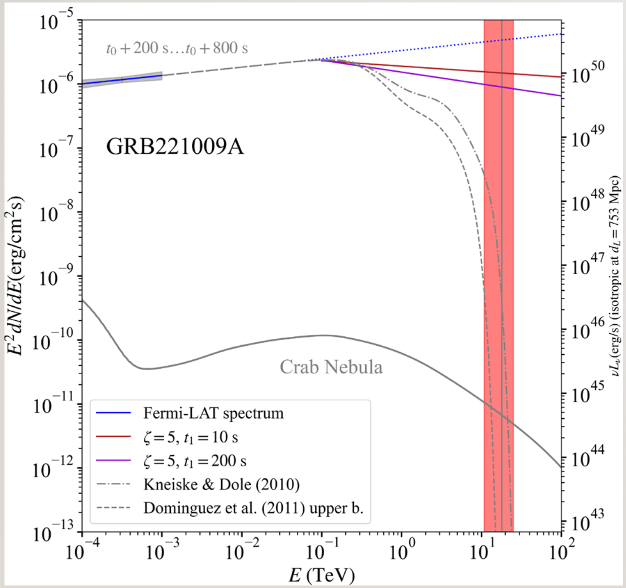
CATEGORIES OF GRB

- Short GRB (duration shorter than 2 sec), 30 % , neutron star merger

- Long GRB (duration longer than 2 sec), 70 %, Core collapse supernova

GRB 221009A

Most luminous GRB discovered ever: GRB 221009A



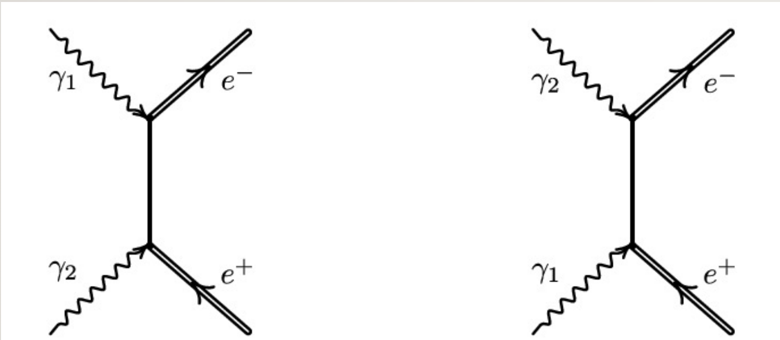
- $\#$ events in LHAASO with $0.5\,\mathrm{TeV} \leq \omega \leq 21\,\mathrm{TeV}$ [observation: $\gtrsim 5000$]
- $\#$ events in LHAASO with $\omega \approx 18\,(\pm 3.6)\mathrm{TeV}$ [observation: 1]

Carenza and Marsh, arXiv:2211.02010

Zhen Cao et al., Science 380 (2023) 6652
And arXiv:2306.06372

Baktash, Horns and Meyer, arXiv:2210.07172

PAIR PRODUCTION



$E_\gamma = 18$ TeV, $\quad \tau_\gamma \simeq 15$

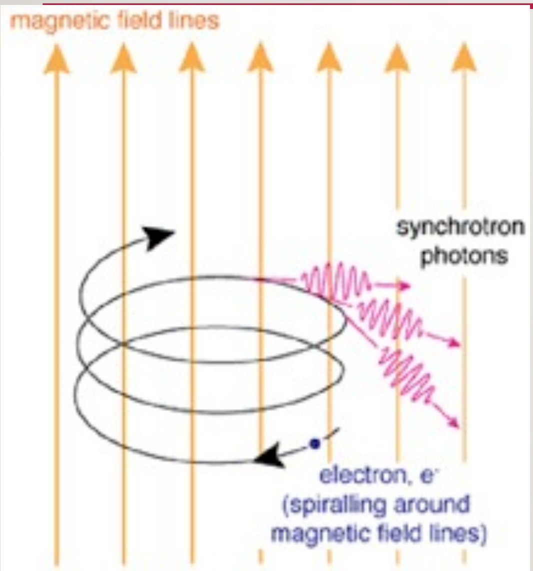
$E_\gamma = 18 \pm 6.5$ TeV,

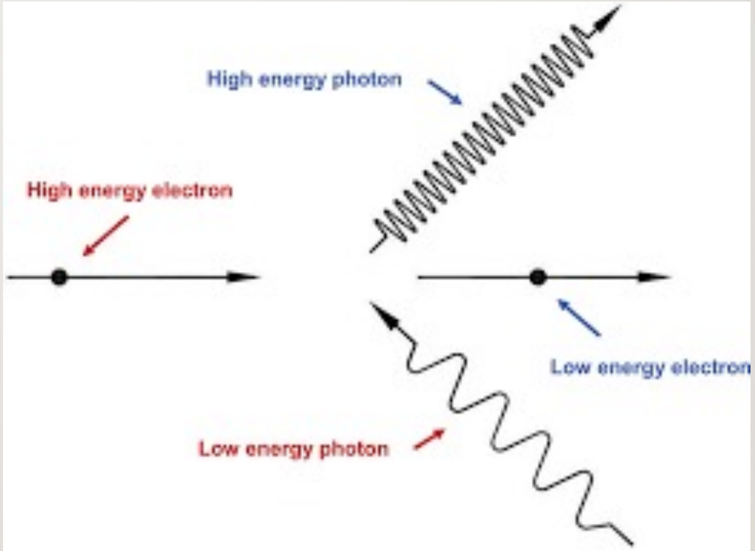
$E_\gamma = 10$ TeV, the optical depth is $\tau_\gamma \simeq 5$

Baktash, Horns and Meyer, arXiv:2210.07172

$\exp(-15) = 3 \times 10^{-7}$ $\quad \exp(-5) = 6.7 \times 10^{-3}$

SYNCHROTRON-SELF COMPTON





NEW PHYSICS?

- Axion or Axion Like Particle (ALP)

Baktash, Horns and Meyer, 2210.07172; Rojas et al., 2305.05145; Galant et al., 2210.05659; Lin and Yanagida, 2210.08841; Tritsky, 2210.09250 ; Nakagawa et al., PLB 839 (2023) 137824; Gonzalez, Astrophys J 944 (2023) 178

- Neutrino based solutions

Cheung, 2210.14178, Smirnov and Traunter, PRL 131 (2023) 021002, Brdar and Li, PLB 839 (2023) 137763; Huang et al, JCAP 04 (2023) 056 ; Guo et al, PRD 108 (2023) L021302

- Lorentz Invariance Violation

Li and Ma, Astropart phys 148 (2023) 10283; 2306.02962; Finke and Razzaque, Astrophys J Lett 942 (2023) L21

NEW PHYSICS?

- Axion or Axion Like Particle (ALP)
- Neutrino based solution
- Lorentz Invariance Violation

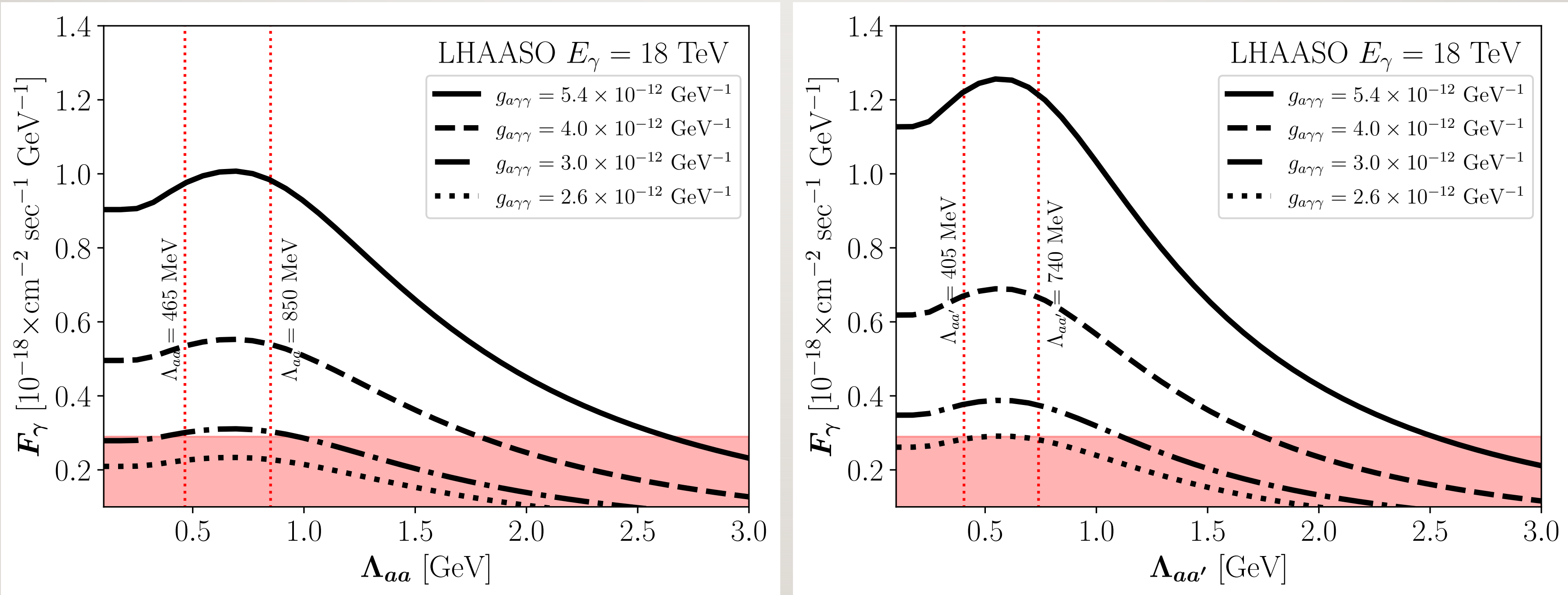
Nicolas Bernal, YF and Alexei Smirnov, JCAP

NEW PHYSICS?

- Axion or Axion Like Particle (ALP)
- Neutrino based solution
- Lorentz Invariance Violation

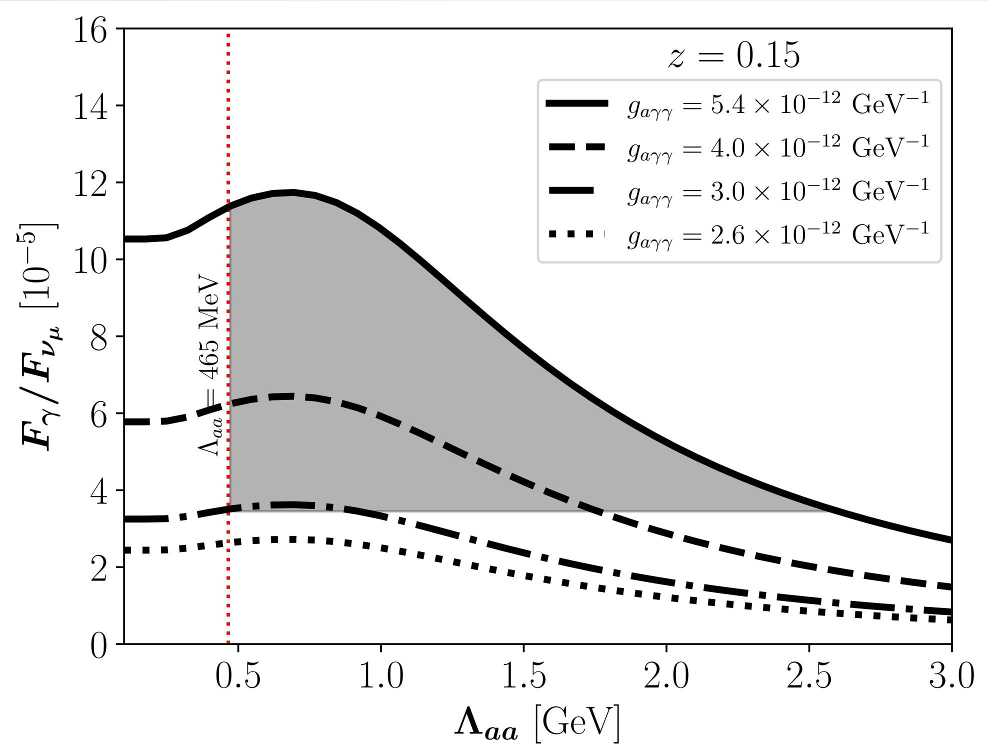
Nicolas Bernal, YF and Alexei Smirnov, JCAP

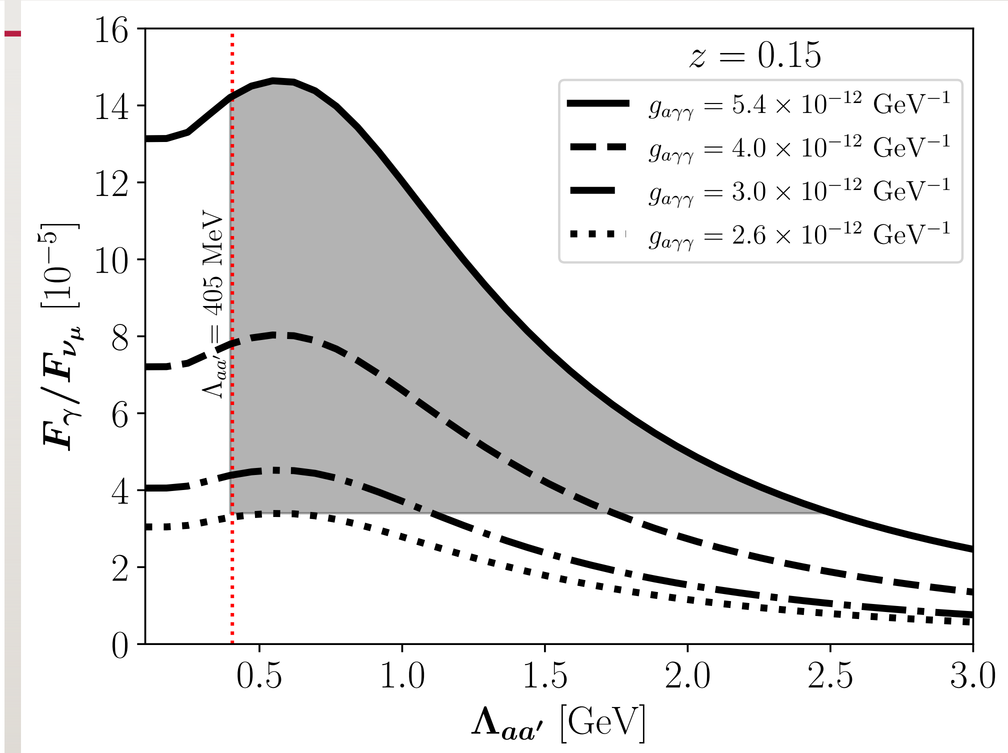
Neutrinos from GRB 221009A:
producing ALPs and
explaining LHAASO anamolous gamma event

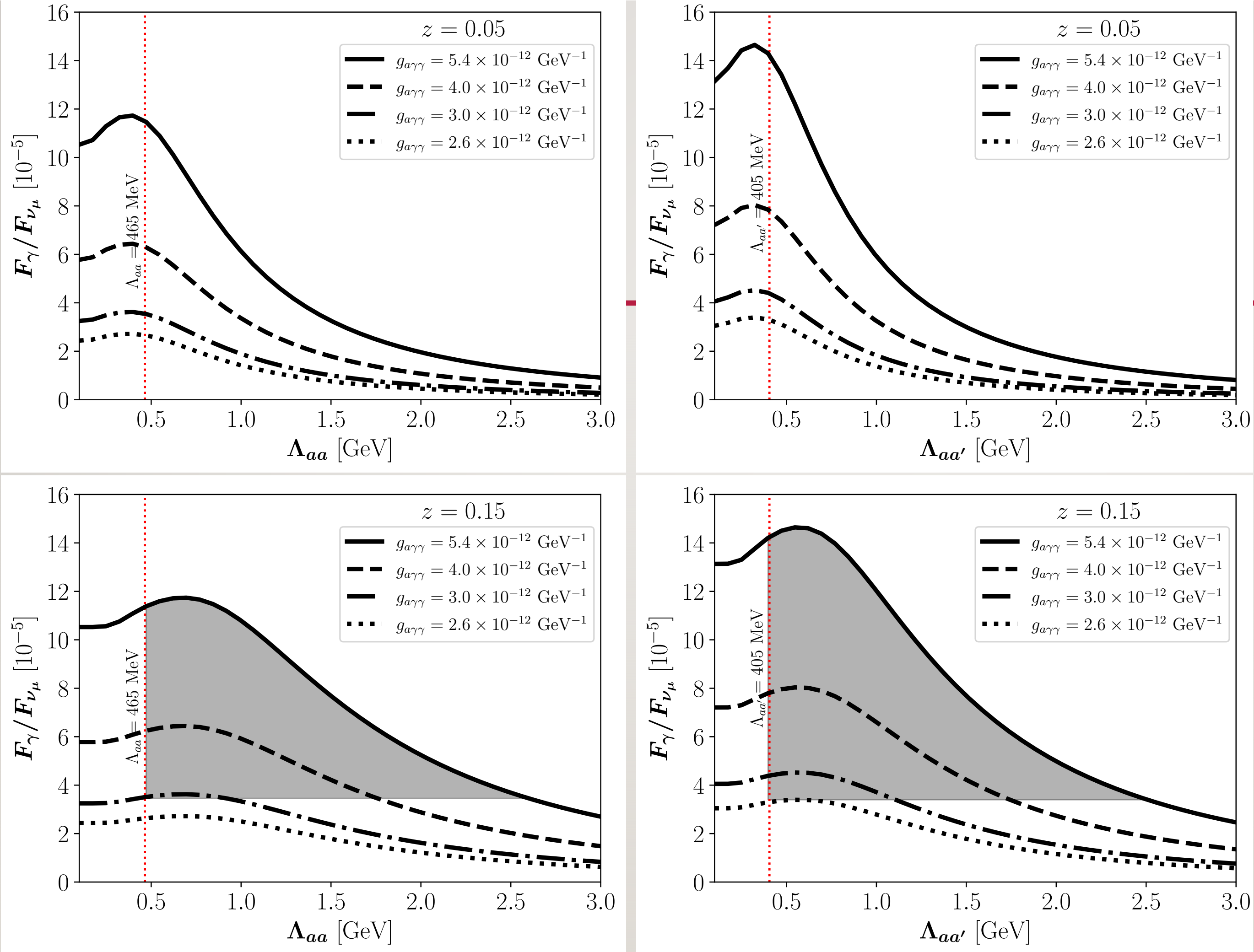


LHAASO $E_\gamma = 18$ TeV
$g_{a\gamma\gamma} = 5.4 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 4.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 3.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 2.6 \times 10^{-12}$ GeV^{-1}
$\Lambda_{aa} = 465$ MeV
$\Lambda_{aa} = 850$ MeV
F_γ [$10^{-18} \times$cm^{-2} sec^{-1} GeV^{-1}]
Λ_{aa} [GeV]
LHAASO $E_\gamma = 18$ TeV
$g_{a\gamma\gamma} = 5.4 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 4.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 3.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 2.6 \times 10^{-12}$ GeV^{-1}
$\Lambda_{aa'} = 405$ MeV
$\Lambda_{aa'} = 740$ MeV
F_γ [$10^{-18} \times$cm^{-2} sec^{-1} GeV^{-1}]
$\Lambda_{aa'}$ [GeV]

DIAGNOSTICS: RATIO OF FLUXES







$z = 0.05$
$g_{a\gamma\gamma} = 5.4 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 4.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 3.0 \times 10^{-12}$ GeV^{-1}
$g_{a\gamma\gamma} = 2.6 \times 10^{-12}$ GeV^{-1}
F_γ / F_{ν_μ} $[10^{-5}]$
$\Lambda_{aa} = 465$ MeV
Λ_{aa} [GeV]
$\Lambda_{aa'} = 405$ MeV
$\Lambda_{aa'}$ [GeV]
$z = 0.15$

- سپاس از توجه شما