NEUTRINO BEACONS

Illuminating New Physics with Cosmic Messengers

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@The future is whispering...

清華大學 (25.06.26)

Outline

- Why Cosmos?
- Neutrinos & Dark matter
- Into the BSM: U(1) extension of SM
- Cosmic sources
  - GRB221009A
  - Blazar: TXS0506 + 056
  - AGN: NGC1068
- Results
- Conclusion

Probing chiral and flavored Z' from cosmic bursts through neutrino interactions

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The origin of tiny neutrino mass is an unsolved puzzle leading to a variety of phenomenological aspects beyond the Standard Model (BSM). Among several interesting attempts, $U(1)$ gauge extension of Standard Model (SM) is a simple and interesting set-up where the so-called seesaw mechanism is incarnated by the addition of three generations of right-handed neutrinos followed by the breaking of $U(1)$ and electroweak symmetries. Such scenarios are anomaly free in nature appearing with a neutral BSM gauge boson (Z'). In addition to that, there comes another open question regarding the existence of a non-luminous, hitherto unidentified object called Dark Matter (DM) originating from the measurement of its relic density. To explore properties of Z', we focus on chiral and flavored scenarios where $Z'-$neutrinos interaction could be probed in the context of cosmic explosions like gamma-ray burst (GRB221009A, so far the highest energy), blazar (TXS 0506+056) and Active galaxy (NGC1068) respectively. The neutrino antineutrino annihilation produces electron-positron pair which could energize GRB through energy deposition. Taking the highest energy GRB under consideration and estimating the energy deposition rates we constrain Z' mass ($M_{Z'}$) and the additional $U(1)$ coupling (g_X) for chiral and flavored scenarios in the Schwarzchild, Hartle-Thorne and modified gravity frameworks. On the other hand, adding viable and alternative DM candidates in these models we study neutrino-DM scattering mediated by Z' in the $t-$ channel and estimate constraints on $g_X - M_{Z'}$ plane using observed data of high energy neutrinos from cosmic blazar and active galaxy at the IceCube experiment. We compare our results with bounds obtained from different scattering, beam-dump and $g-2$ experiments.

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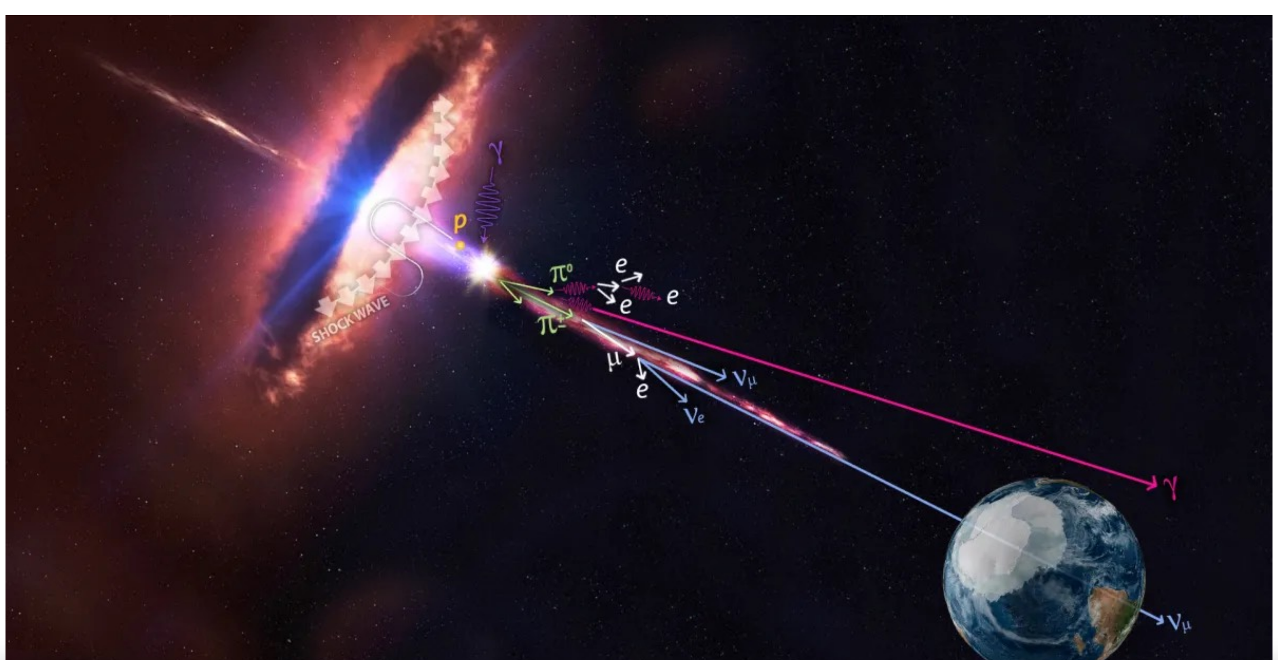
WHY COSMOS?

Natural high energy Accelerators ~PeV

Probes of Complementary phenomenology

ICECUBE, KM3NET, HK, Auger etc let us take a peek



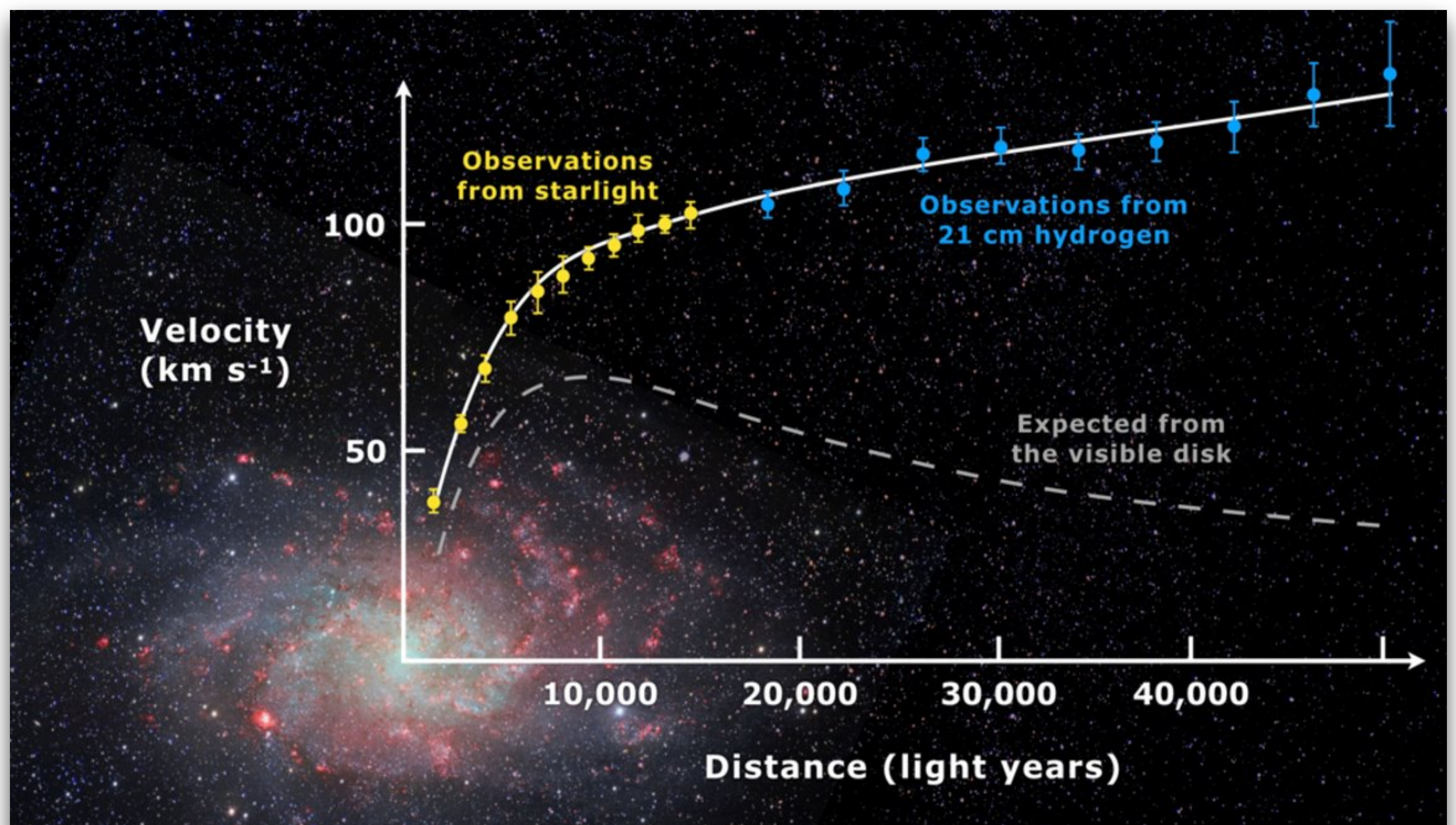
A peek into Neutrinos & Dark matter

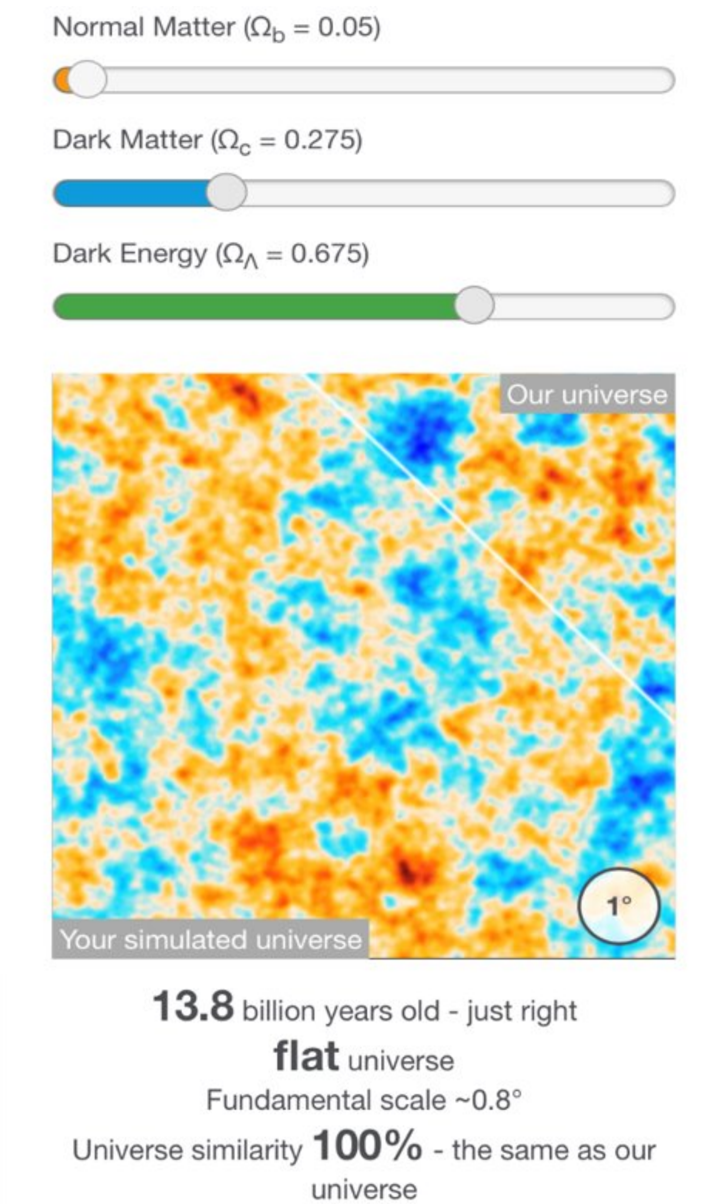
DARK MATTER

Galaxy Rotation Curve

CMB fluctuations

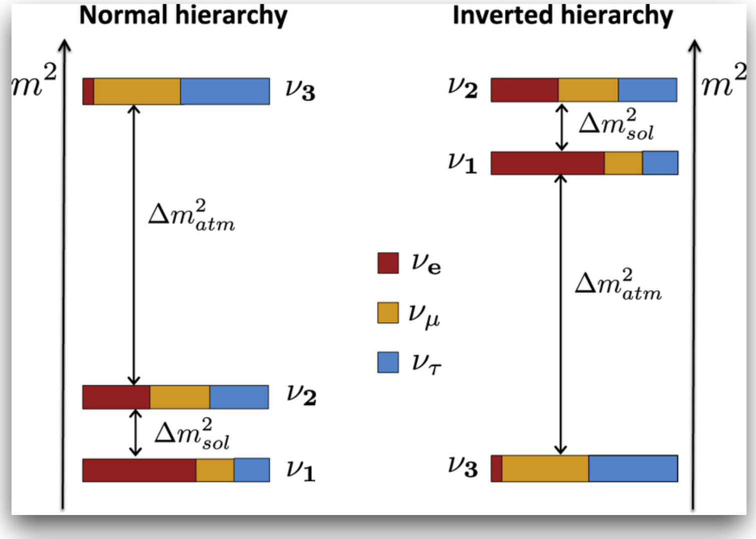
Bullet Cluster Galaxy etc…



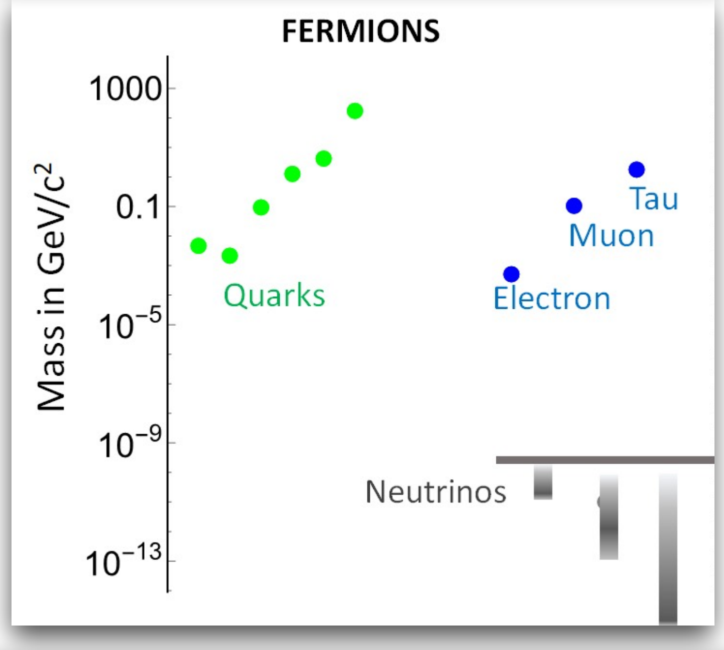


NEUTRINOS

Neutrino oscillations $\longrightarrow$ $m_\nu \neq 0$ $\longrightarrow$



Mass mechanism & hierarchy



$m_\nu < 0.45$ eV

KATRIN

Nature of neutrino:
Dirac or Majorana?

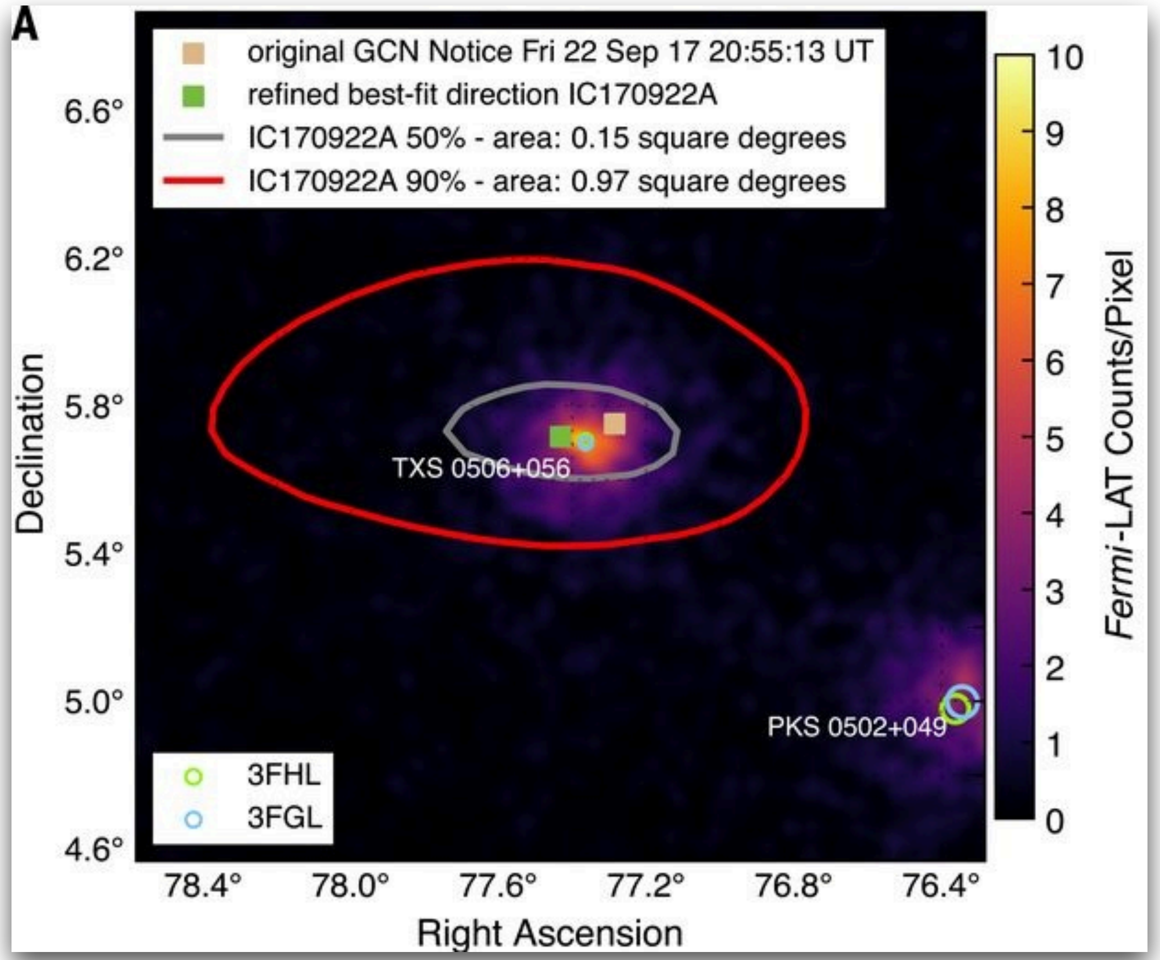
Neutrinoless double beta decay

WHY NEUTRINOS?

Weakly interacting -> Pass right through

Produced in copious amounts everywhere!
Supernovae emit 10^{58} neutrinos!!!

Gamma Ray Burst warning
Super**N**ova **E**arly **W**arning **S**ystem (SNEWS)

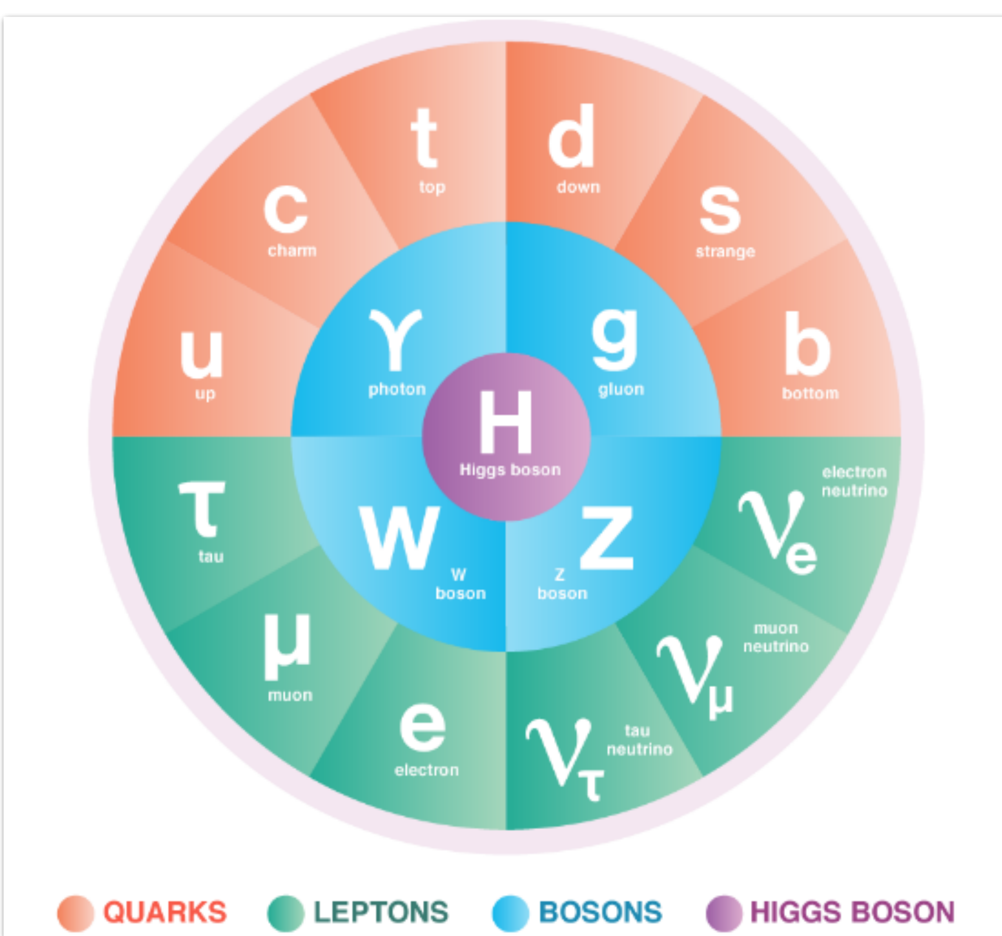


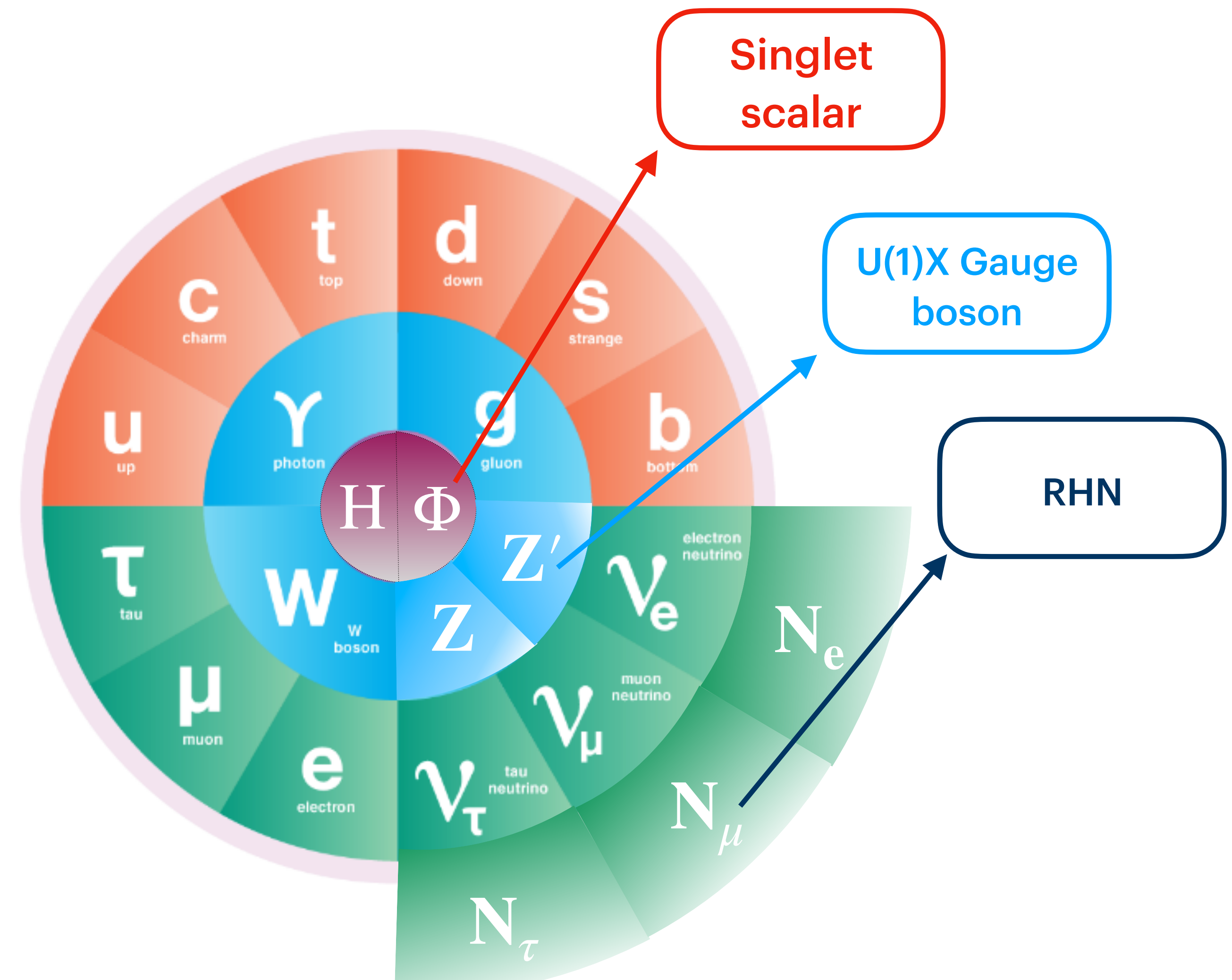
FERMI-LAT Detection of TXS 0506 + 056

EXTENDING SM WITH U(1)

$$\underbrace{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}_{\text{Standard Model - SM}} \quad \otimes \quad \underbrace{U(1)_X}_{\text{BSM}}$$

$$\{M_{Z'}, g_X\}$$





EXTENDING SM WITH U(1)

$$\underbrace{\mathrm{SU(3)_C \otimes SU(2)_L \otimes U(1)_Y}}_{\text{Standard Model - SM}} \otimes \underbrace{\mathrm{U(1)_X}}_{\text{BSM}}$$

$$x_H\, U(1)_Y + x_\Phi\, U(1)_{B-L}$$

Fields	$SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$	$U(1)_X$
q_L^i	$(3, 2, \frac{1}{6})$	$x_q = \frac{1}{6}x_H + \frac{1}{3}x_\Phi$
u_R^i	$(3, 1, \frac{2}{3})$	$x_u = \frac{2}{3}x_H + \frac{1}{3}x_\Phi$
d_R^i	$(3, 1, -\frac{1}{3})$	$x_d = -\frac{1}{3}x_H + \frac{1}{3}x_\Phi$
ℓ_L^i	$(1, 2, -\frac{1}{2})$	$x_\ell = -\frac{1}{2}x_H - x_\Phi$
e_R^i	$(1, 1, -1)$	$x_e = -x_H - x_\Phi$
H	$(1, 2, -\frac{1}{2})$	$-\frac{1}{2}x_H$
N^j	$(1, 1, 0)$	$x_N = -x_\Phi$
Φ	$(1, 1, 0)$	$2\, x_\Phi$

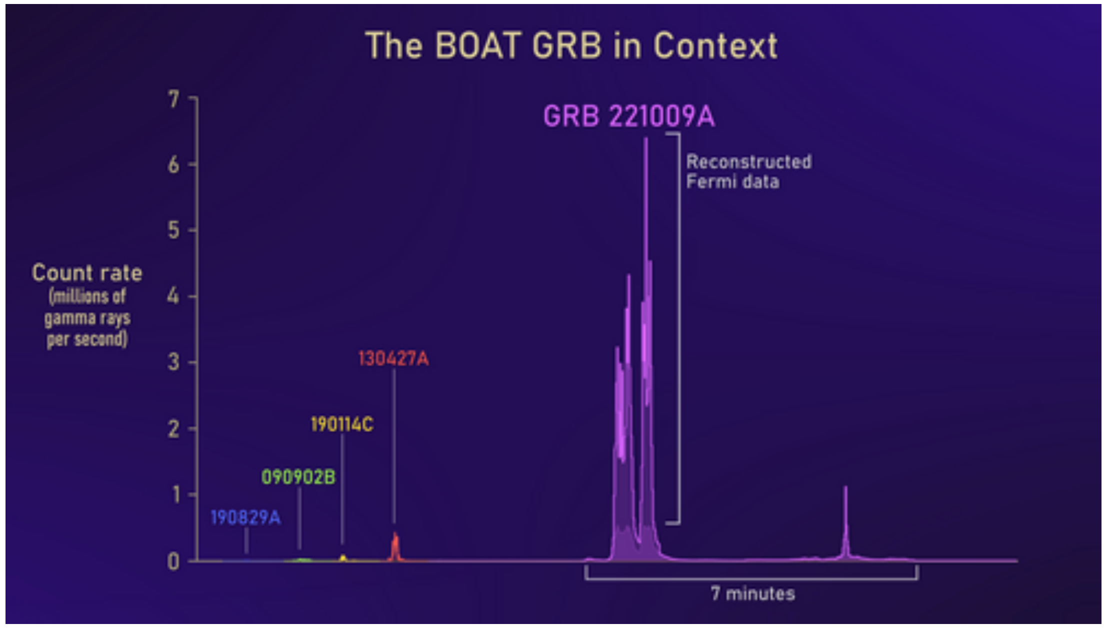

COSMIC
SOURCES

COSMIC SOURCES: GRB 221009A

Highest energy event ever observed

$$E_{iso} = 1.2 \times 10^{55} erg$$

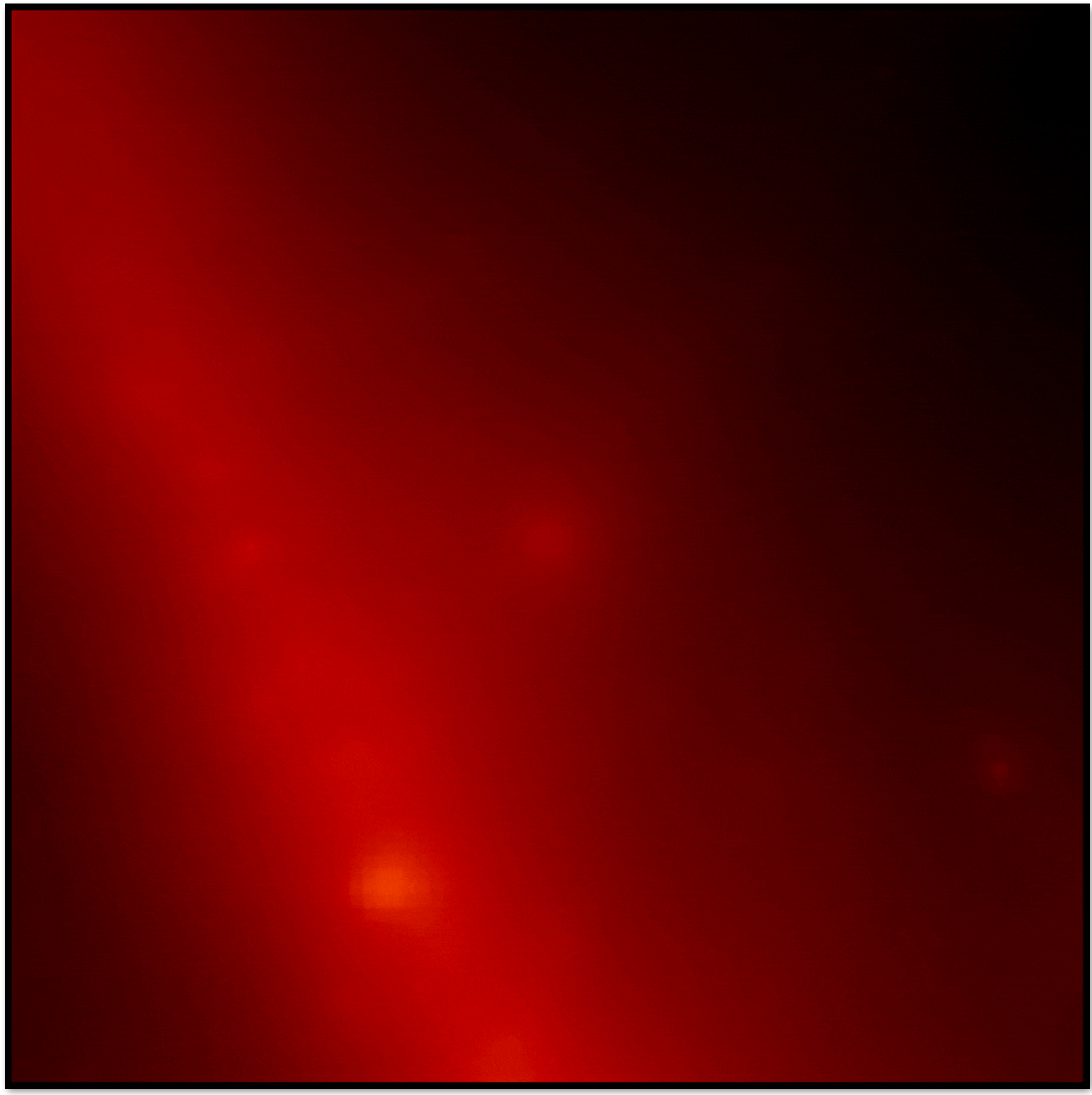
$$\mathrm{E_{true}} = (1 - \cos\theta)\mathrm{E_{iso}} \approx 4 \times 10^{51} erg$$



Confirmed to be from supernova (JWST observations) - Lucky!

Study effects of U(1) extensions and constrain new physics in supernova powered GRB models

10 hours Timelapse of GRB 220911A



Gamma Ray Burst

(2 billion light years away)

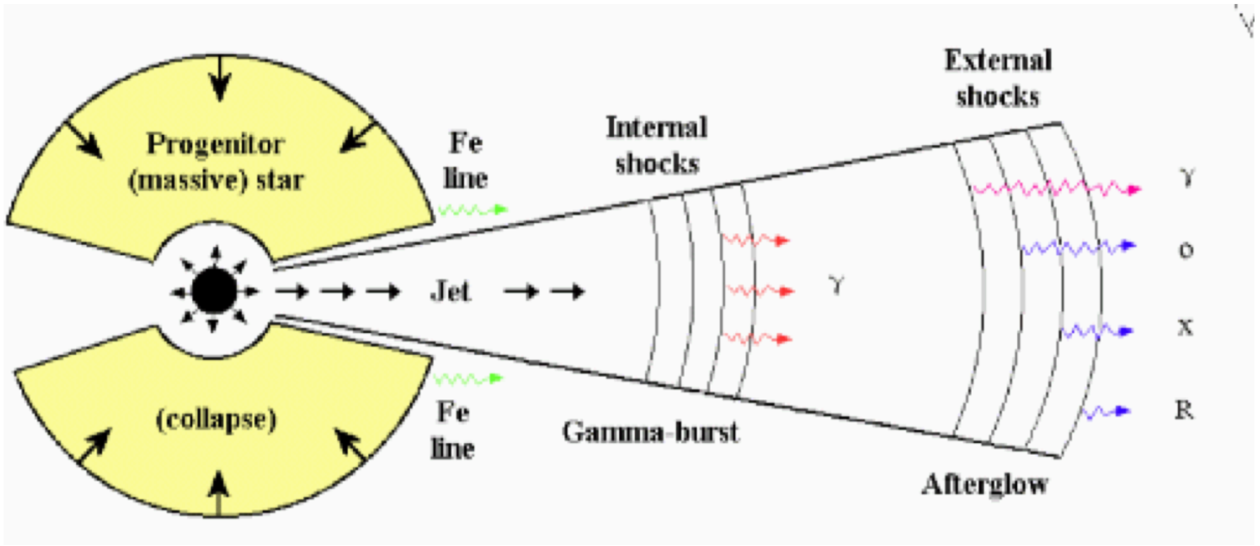
COSMIC SOURCES: GRB 221009A

FIREBALL MODEL

$$\text{Core} \rightarrow \underbrace{\nu\nu \rightarrow e^+e^-}_{\text{process of interest}} \rightarrow \gamma$$

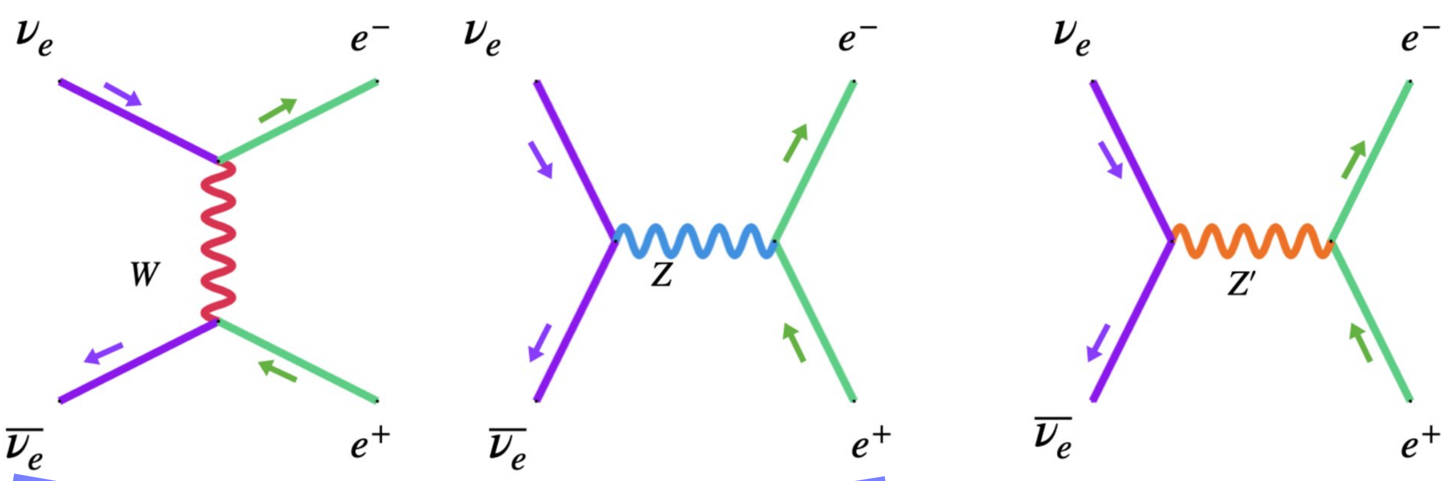
Check out Jakob Ehring's slides

Observed GRB



COSMIC SOURCES: GRB 221009A

$$\text{Core} \rightarrow (\nu\nu \rightarrow \text{e}^+\text{e}^-) \rightarrow \gamma$$



Standard Model

Neutrino heating

$$\boxed{\dot{q}(r) = \int d^3\vec{p}_\nu \; d^3\vec{p}_{\bar{\nu}} \; f_\nu(\vec{p}_\nu, \vec{r}) \; f_{\bar{\nu}}(\vec{p}_{\bar{\nu}}, \vec{r}) \; \{\sigma(\nu\bar{\nu} \rightarrow e^+e^-)\} \; \frac{E_\nu + E_{\bar{\nu}}}{E_\nu E_{\bar{\nu}}}}$$

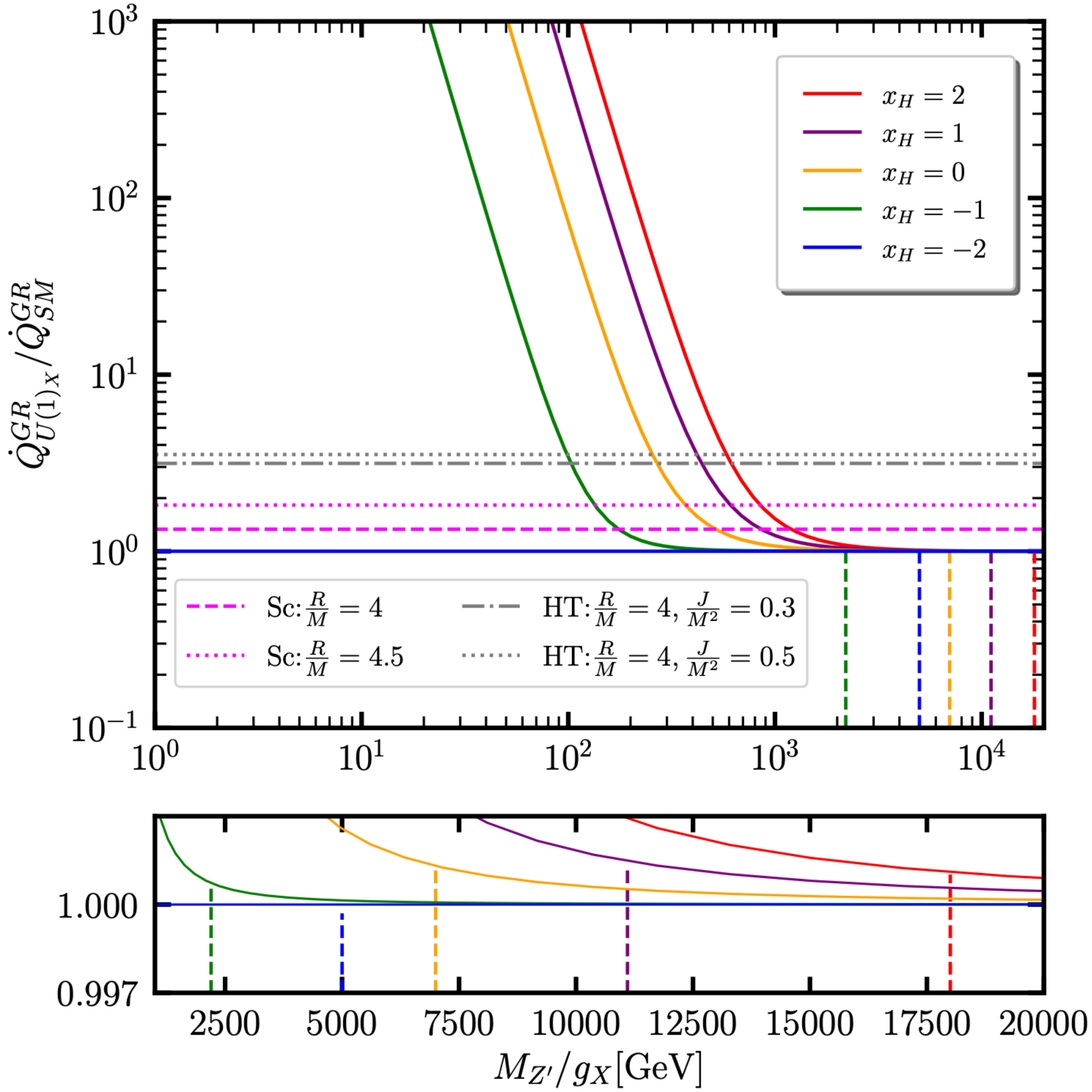
Energy deposition rate per unit volume

$$\boxed{\dot{Q}^{GR}_{\rm BSM} \leq \dot{Q}_{\rm obs} - \dot{Q}^{GR}_{\rm SM}}$$

- Schwarzschild metric
- Hartle - Thorne (solution for rotating neutron stars)

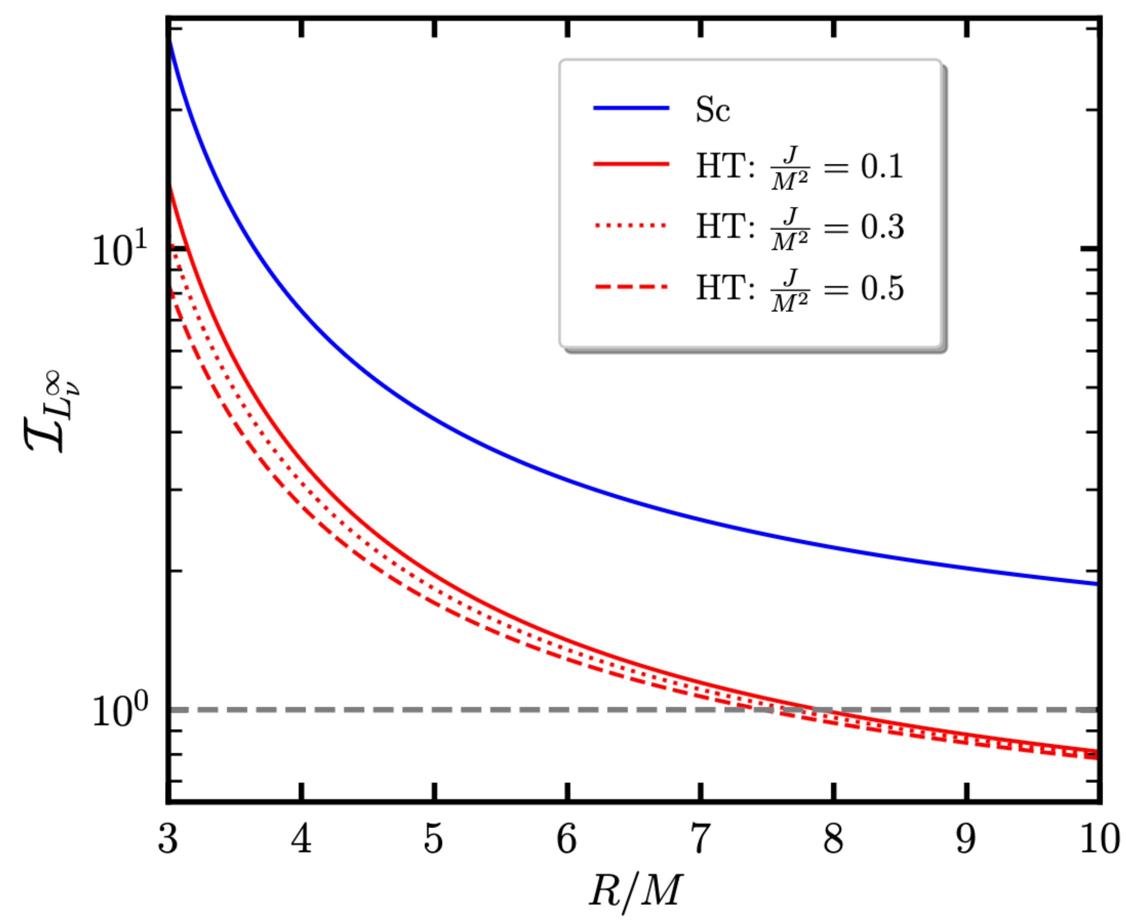
COSMIC SOURCES: GRB 221009A

Q_{BSM}^{GR} has two contributions coming from GR and Z'



Luminosity of neutrinos from simulations

$$\mathcal{I}_{L_\nu^\infty} = \frac{\dot{Q}^{GR}_{L^\infty_{\nu_i}}}{\dot{Q}^{N}_{L^\infty_{\nu_i}}}$$



COSMIC SOURCES: TXS 0506 + 056

IceCube-170922A (IC86A - 898 days)
One high energy muon neutrino
(2017)

$E \approx 290\text{TeV}$

$(p \to \pi \to \nu)$

Observed Gamma ray
emissions in time!

Multi messenger astronomy!

Blazar TXS 0506 + 056
(5.7 billion light years away)

Study effects of U(1) extensions and
constrain new physics through the
high energy neutrino scattering.

COSMIC SOURCES: TXS 0506 + 056

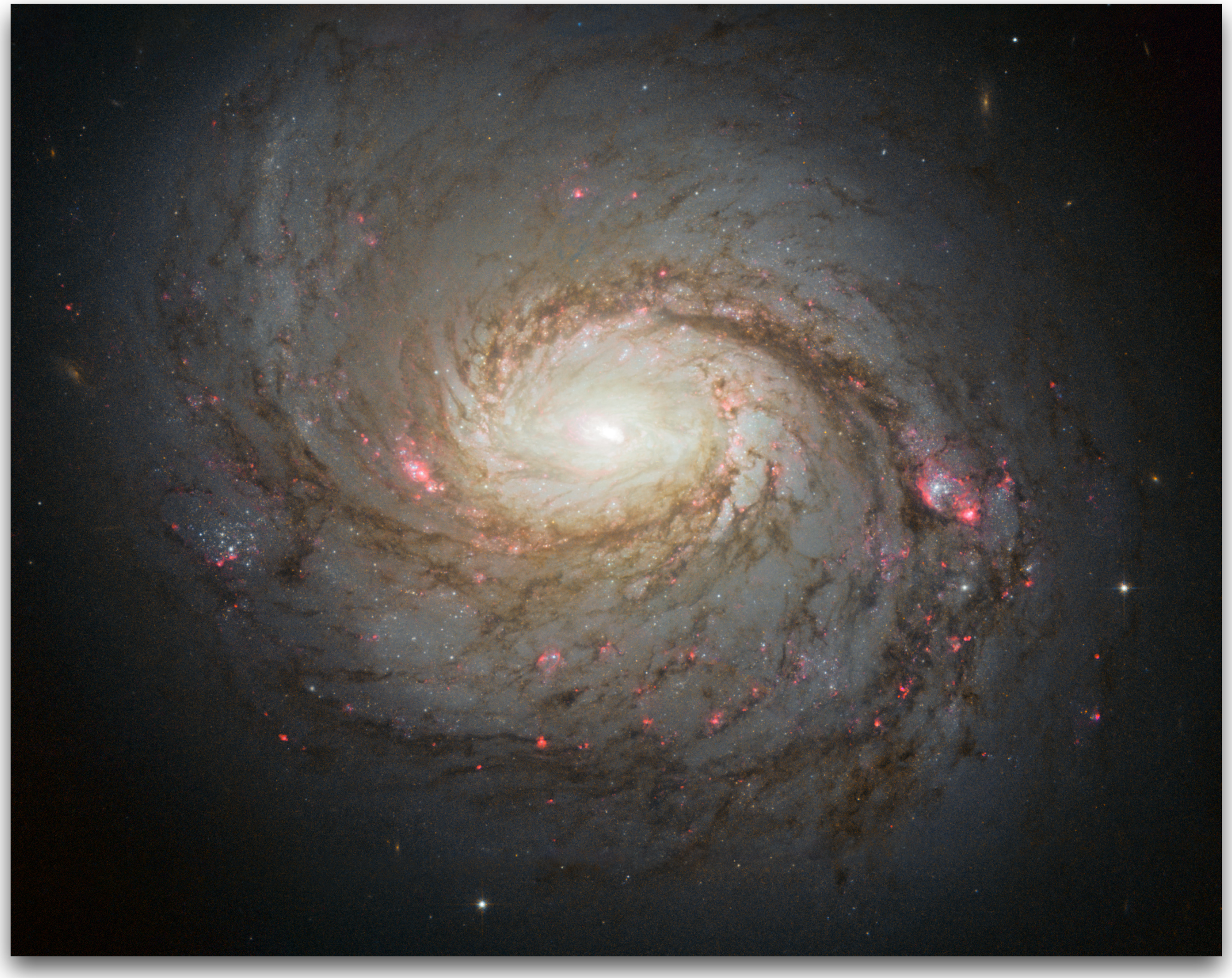
COSMIC SOURCES: NGC1068

ICECUBE reported 79^{+22}_{-20} neutrino events at 4.2σ

3186 days of data taking

ICECUBE reliably measured flux Between 1.5 to 15 TeV

Active Galactic Nuclei
NGC 1068
(47 million light years away)

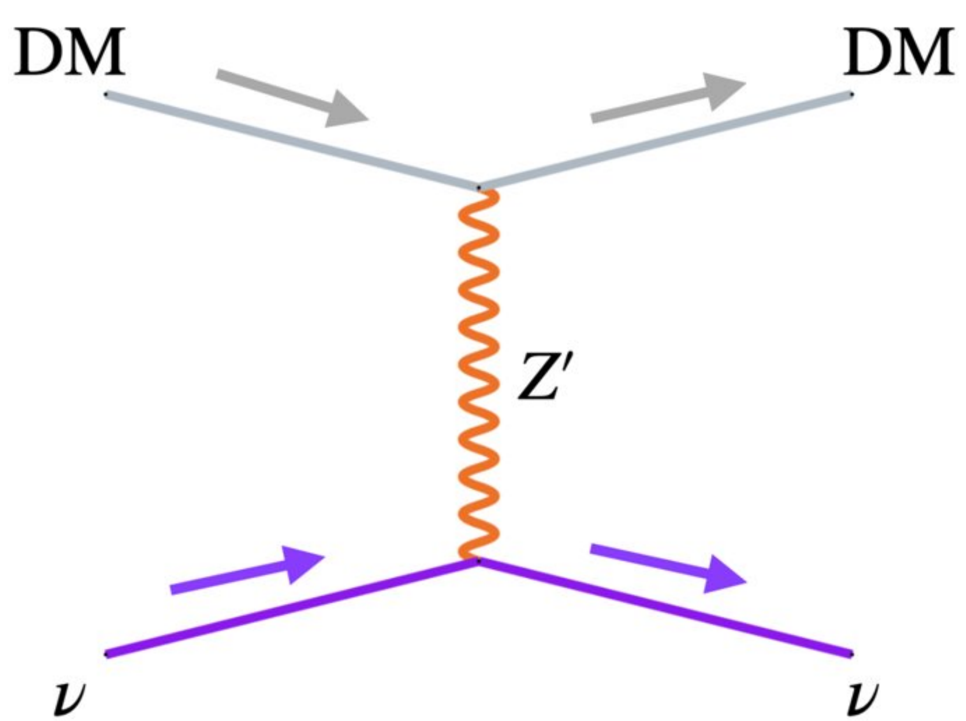


NEUTRINO - DM SCATTERING

Neutrinos are produced at the source and travel towards earth

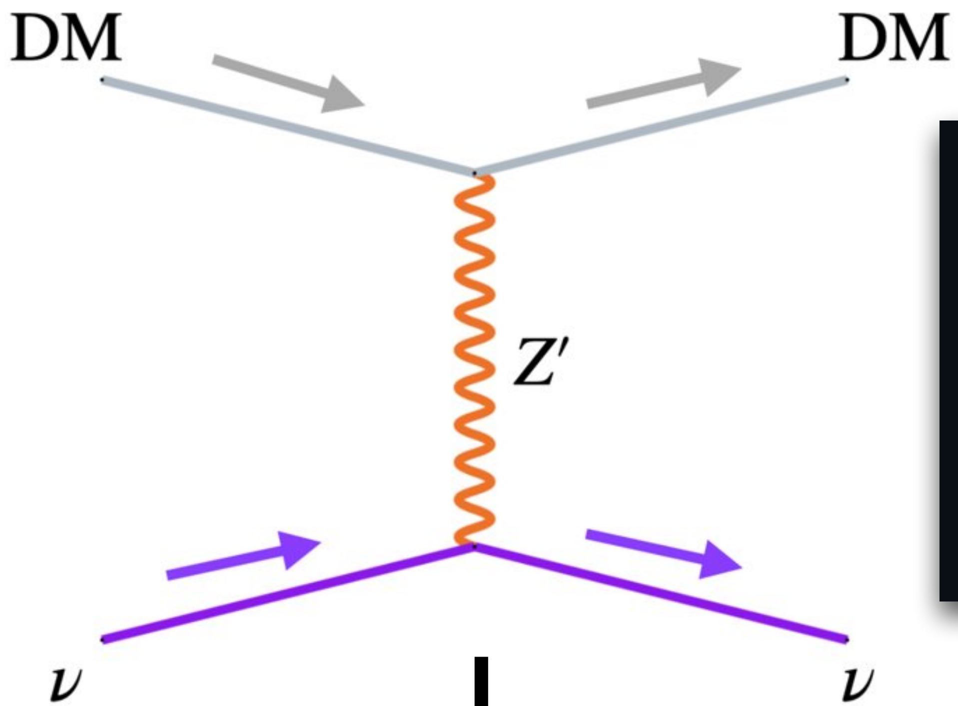
Neutrinos can interact with DM on their way $\nu\,\mathrm{DM} \to \nu\,\mathrm{DM}$

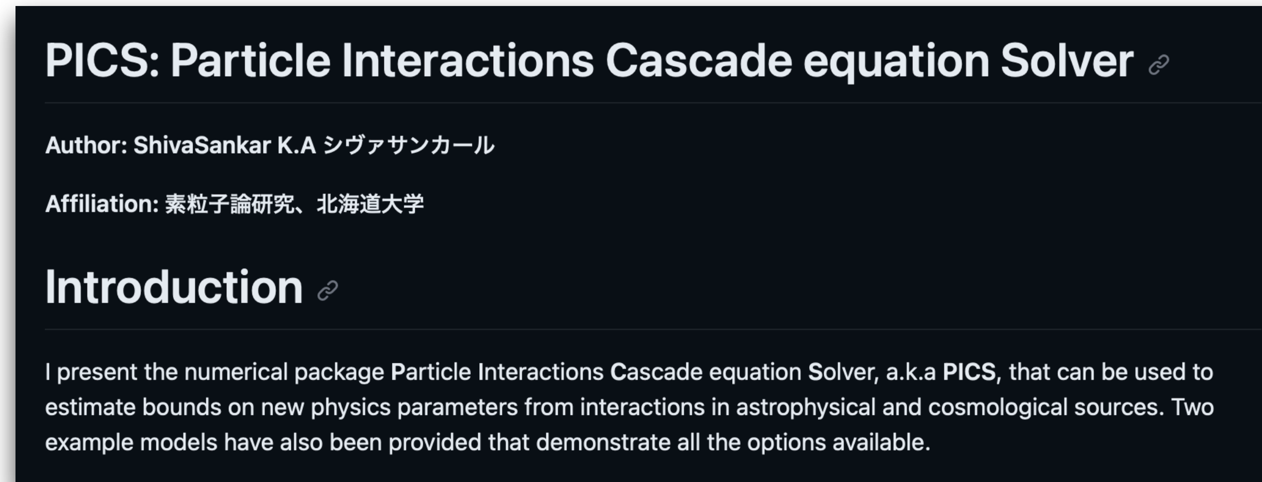
Z' can mediate such decay.
But wait, We don't know what's the nature of DM!



- Dirac fermion
- Majorana fermion
- Complex Scalar

NEUTRINO - DM SCATTERING




PICS: Particle Interactions Cascade equation Solver

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Introduction

I present the numerical package Particle Interactions Cascade equation Solver, a.k.a **PICS**, that can be used to estimate bounds on new physics parameters from interactions in astrophysical and cosmological sources. Two example models have also been provided that demonstrate all the options available.

Attenuated Flux

$$\boxed{\frac{d\Phi}{dx} = -\sigma(g_X, M_{Z'})\frac{\Sigma(r)}{m_{\mathrm{DM}}}\,\Phi + \frac{\Sigma(r)}{m_{\mathrm{DM}}}\int_{E'}^{\infty} dE\,\frac{d\sigma(g_X, M_{Z'})}{dE'}\Phi(E)}$$

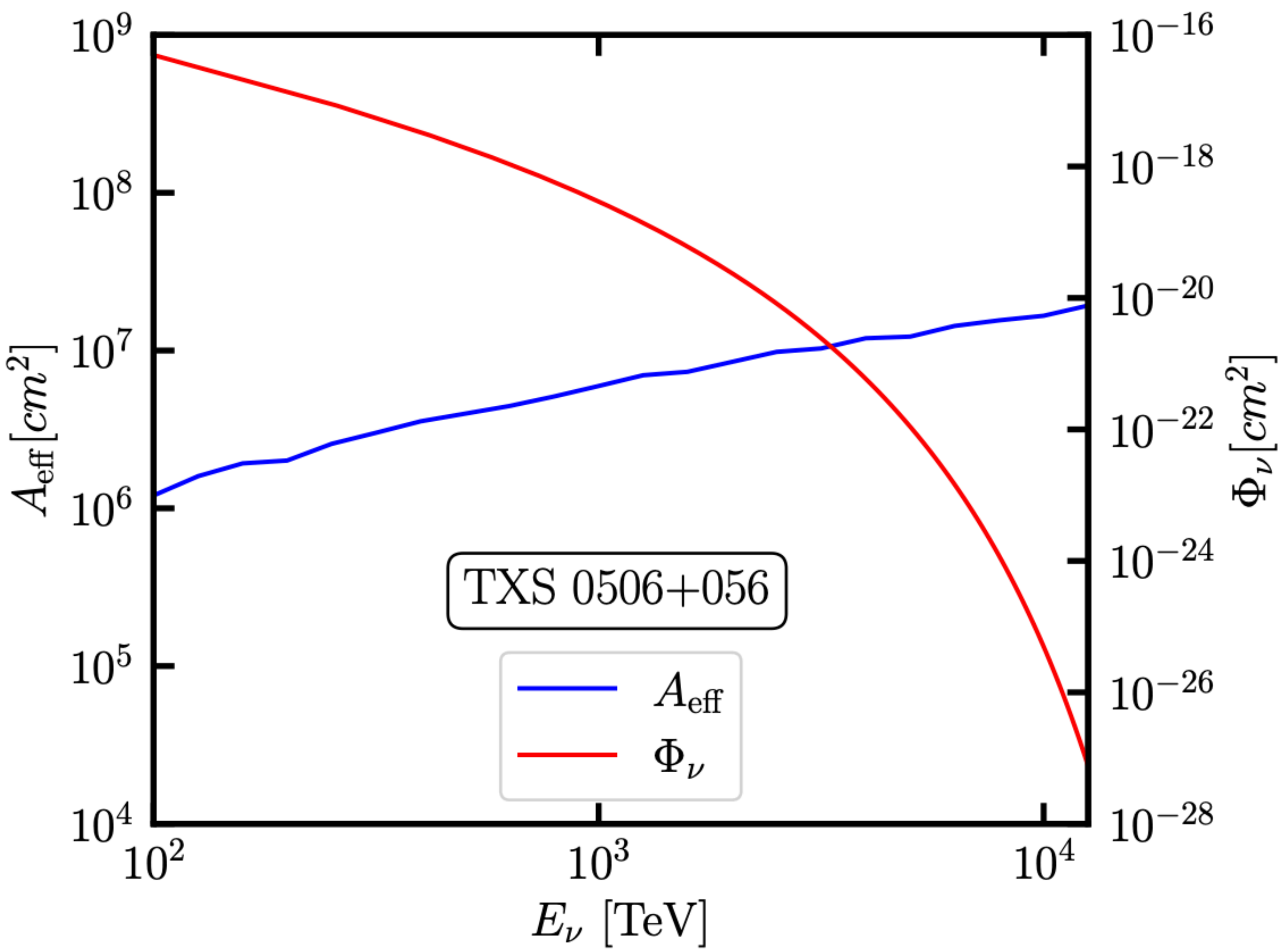
$$\tau = \frac{\Sigma(r)}{m_{DM}} = \int dr\,\frac{\rho_{DM}}{m_{DM}}$$

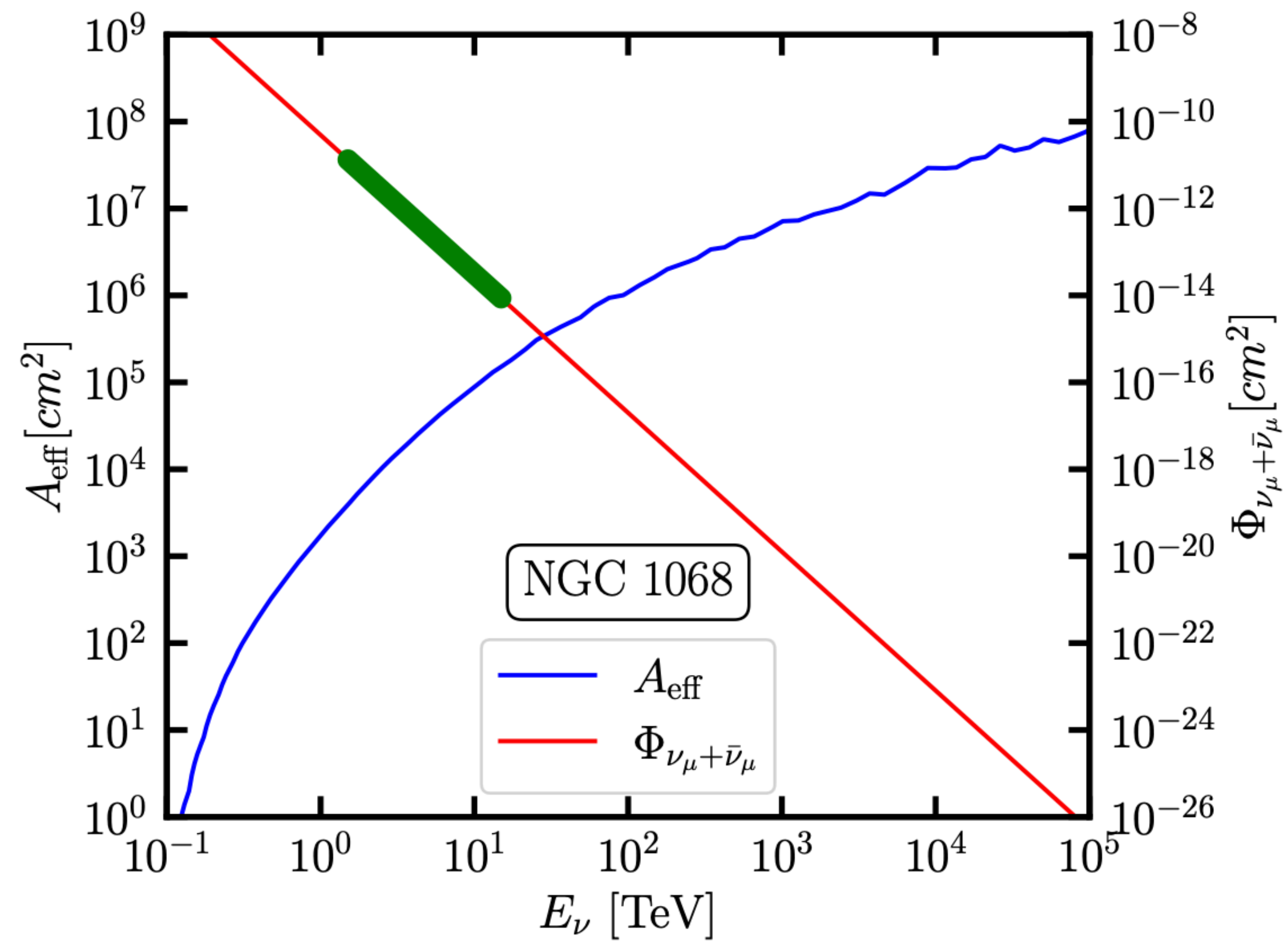
$$x = \tau\frac{m_{DM}}{\Sigma}$$

$x \in [0,1]$

$$\boxed{N_{\mathrm{events}} = t_{\mathrm{obs}}\int dE\; A_{\mathrm{eff}}(E)\;\Phi_\nu(E_\nu)}$$

THE INGREDIENTS: FLUX



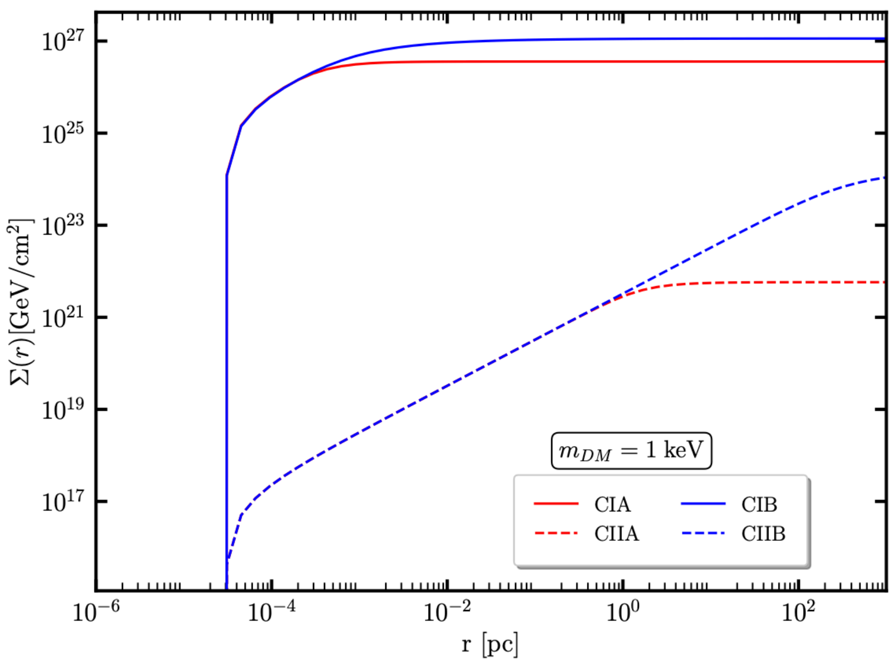


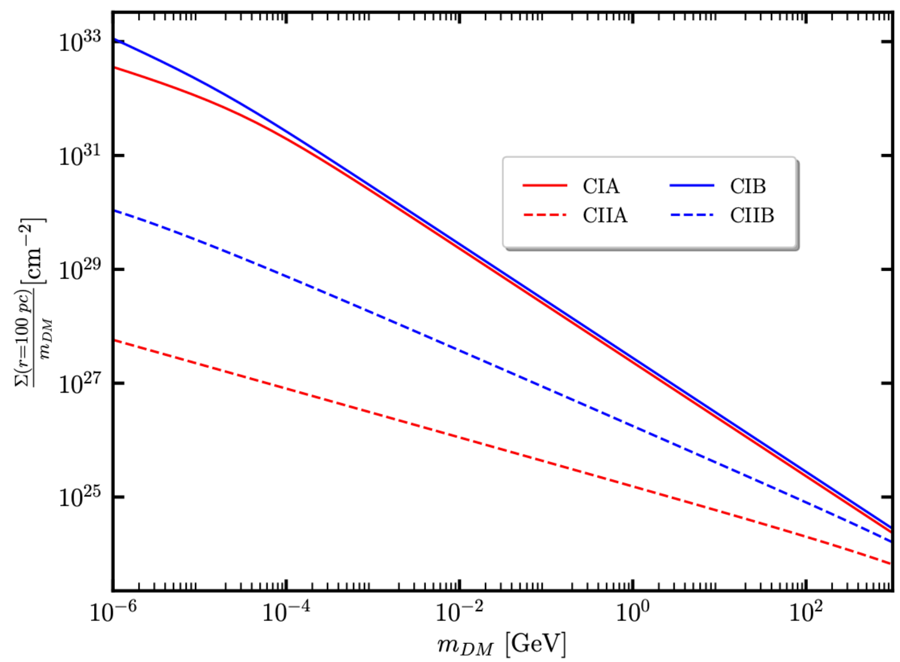
Effective area taken from ICECUBE public data

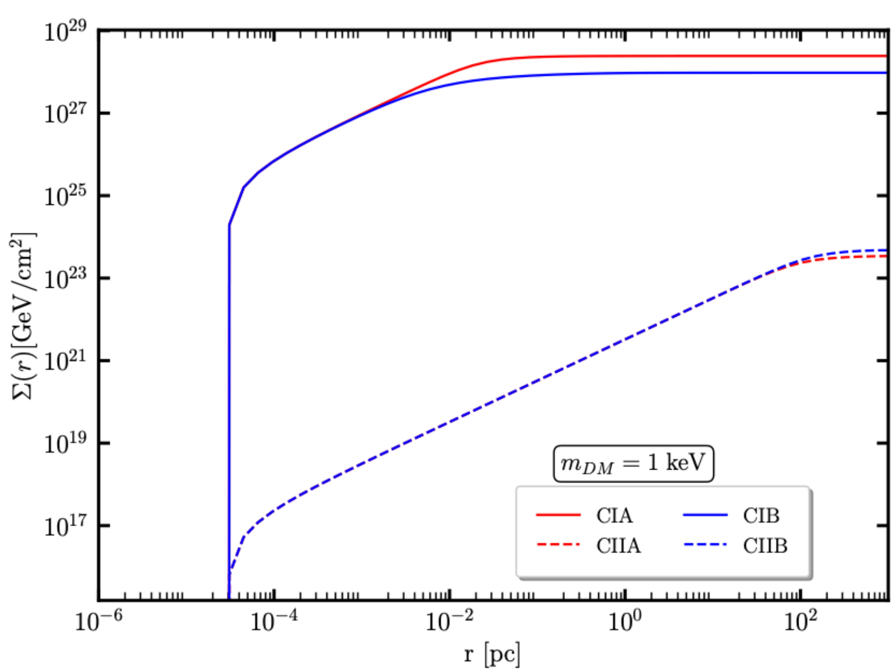
TXS -> Lepto Hadronic model

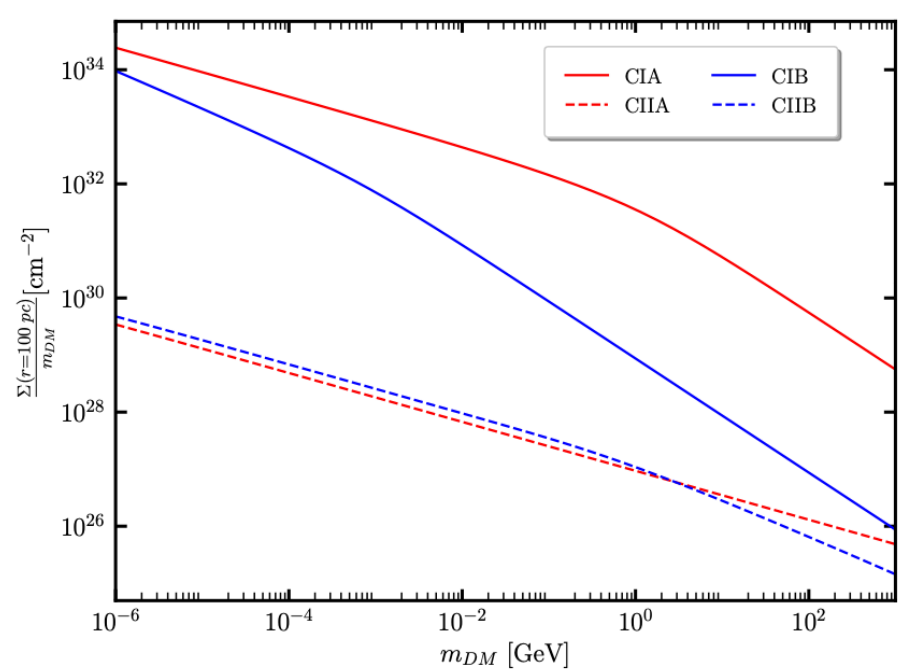
NGC -> ICECUBE flux calculation

THE INGREDIENTS: DM DENSITY









Slope of spike profile

$$\text{CIA}: \langle \sigma \mathrm{v} \rangle_{\mathrm{eff}} = 10^{-34} \mathrm{cm}^3 \mathrm{s}^{-1}, \alpha_{\mathrm{sp}} = 7/3$$

$$\text{CIIA}: \langle \sigma \mathrm{v} \rangle_{\mathrm{eff}} = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}, \alpha_{\mathrm{sp}} = 7/3$$

$$\text{CIB}: \langle \sigma \mathrm{v} \rangle_{\mathrm{eff}} = 10^{-34} \mathrm{cm}^3 \mathrm{s}^{-1}, \alpha_{\mathrm{sp}} = 3/2$$

$$\text{CIA}: \langle \sigma \mathrm{v} \rangle_{\mathrm{eff}} = 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}, \alpha_{\mathrm{sp}} = 3/2$$

Effective thermal avg
DM annihilation
cross section

THE INGREDIENTS: CROSS SECTIONS

Complex Scalar

$$\frac{d\sigma}{dE'_\nu} = \frac{g_X^4 Q_\ell^2 Q_\chi^2}{8\pi}\frac{m_{\rm DM}}{E_\nu^2}\frac{(2E_\nu E'_\nu - m_{\rm DM}(E_\nu - E'_\nu))}{\{M_{Z'}^2 + 2\, m_{\rm DM}(E_\nu - E'_\nu)\}^2}$$

Z_2 ensure DM stability

Dirac

$$\frac{d\sigma}{dE'_\nu} = \frac{g_X^4 Q_\ell^2 Q_\chi^2}{8\pi}\frac{m_{\rm DM}}{E_\nu^2}\frac{(E_\nu^2 + {E'_\nu}^2 - m_{\rm DM}(E_\nu - E'_\nu))}{\{M_{Z'}^2 + 2\, m_{\rm DM}(E_\nu - E'_\nu)\}^2}$$

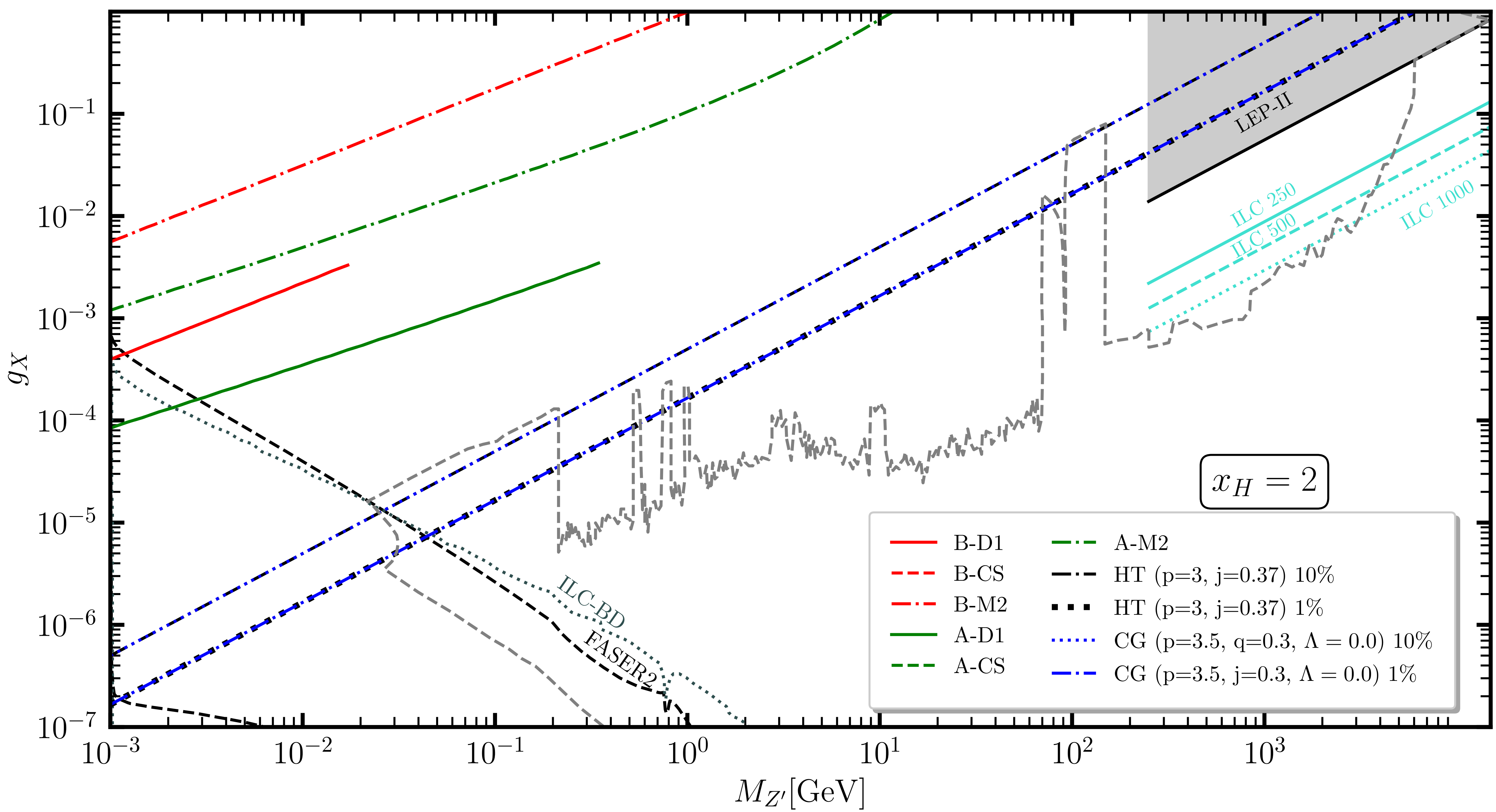
$\pm 3x_\Phi, \pm x_\Phi$ aren't allowed -> Ensure DM Stability

Majorana

$$\frac{d\sigma}{dE'_\nu} = \frac{g_X^4 Q_\ell^2 Q_\chi^2}{8\pi}\frac{m_{\rm DM}}{E_\nu^2}\frac{(E_\nu^2 + {E'_\nu}^2 + m_{\rm DM}(E_\nu - E'_\nu))}{\{M_{Z'}^2 + 2\, m_{\rm DM}(E_\nu - E'_\nu)\}^2}$$

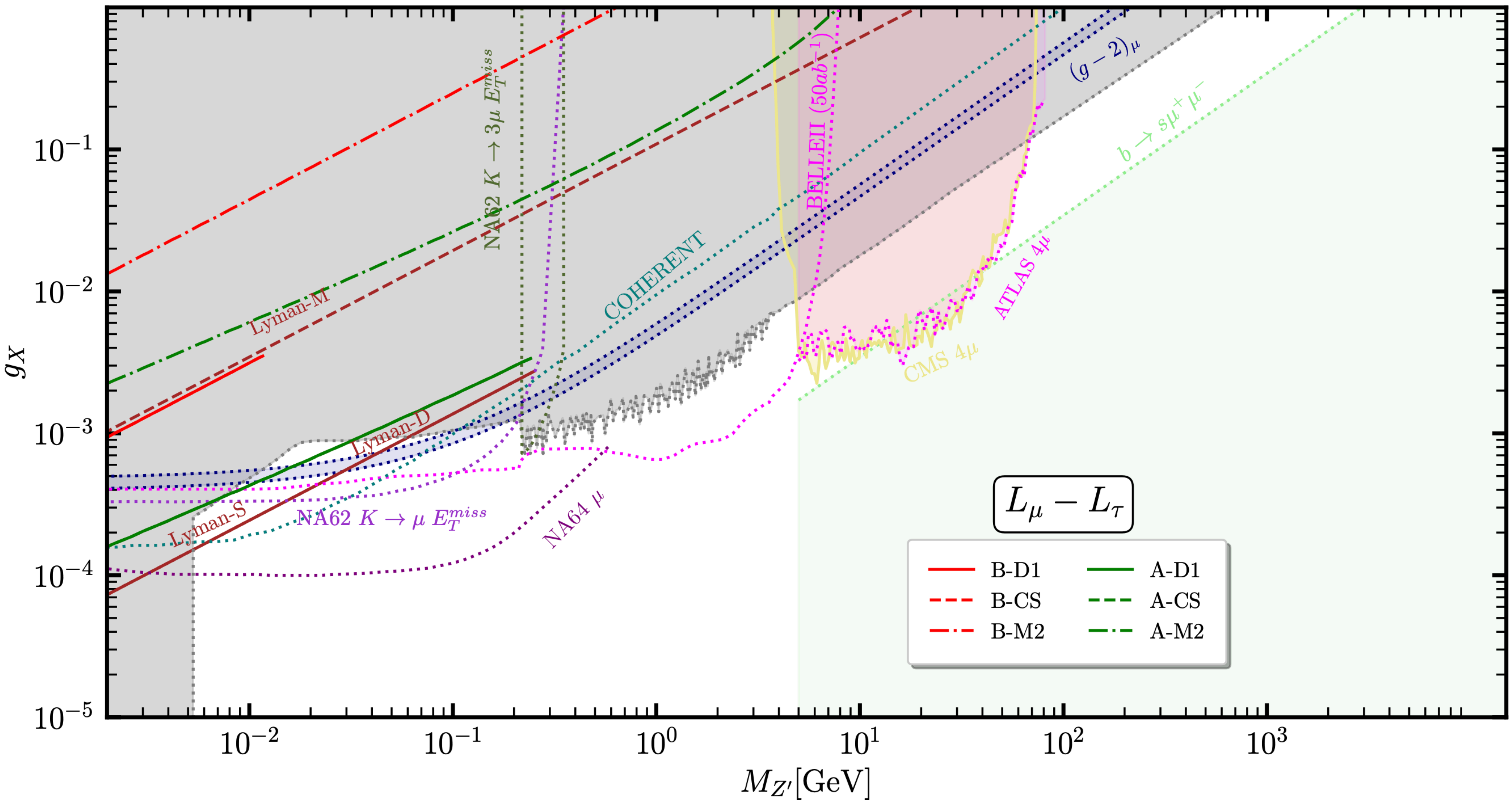
Considering 445 scenario of RHN, Q_χ = 5

Results



LEP-II
ILC 250
ILC 500
ILC 1000
ILC-BD
FASER2
$x_H = 2$
B-D1
B-CS
B-M2
A-D1
A-CS
A-M2
HT (p=3, j=0.37) 10%
HT (p=3, j=0.37) 1%
CG (p=3.5, q=0.3, $\Lambda = 0.0$) 10%
CG (p=3.5, j=0.3, $\Lambda = 0.0$) 1%
g_X
$M_{Z'}$[GeV]

Results



$L_\mu - L_\tau$
B-D1
B-CS
B-M2
A-D1
A-CS
A-M2
Lyman-M
Lyman-D
Lyman-S
NA62 $K \to 3\mu\ E_T^{miss}$
NA62 $K \to \mu\ E_T^{miss}$
NA64 μ
COHERENT
BELLEII $(50ab^{-1})$
$(g-2)_\mu$
$b \to s\mu^+\mu^-$
ATLAS 4μ
CMS 4μ
g_X
$M_{Z'}$[GeV]

SUMMARY

Various cosmic phenomena can be used to study BSM physics!

Multi-messenger physics will help us understand the universe better!

The cosmos is whispering new physics,

All we have to do is listen…

Thank you
for listening to
my whispers!