Neutrino self-interaction effect in signals from Blazar TXS 0506+056

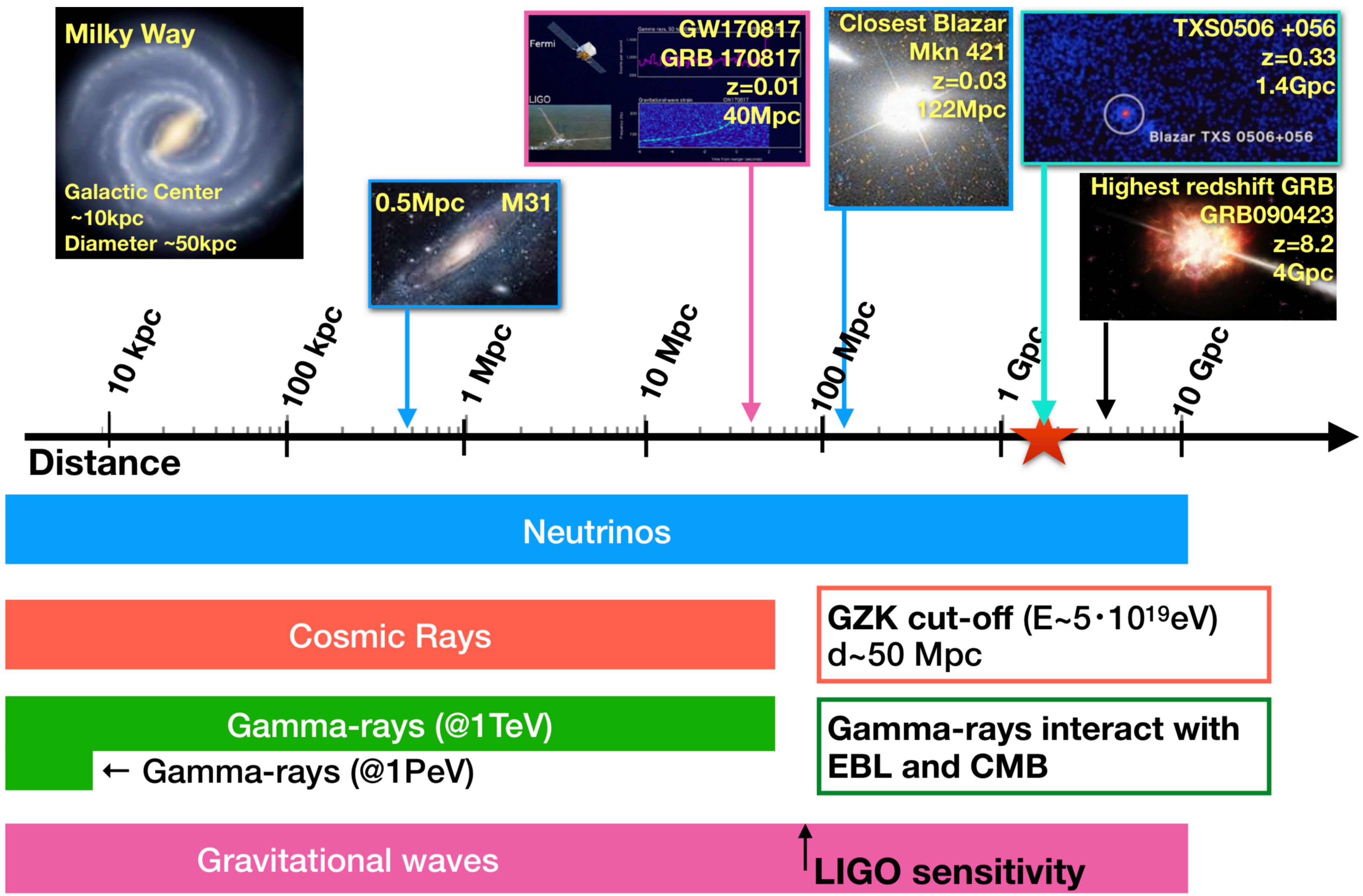
Yongsoo Jho (Yonsei University)

Collaboration with
Jongkuk Kim (KIAS), Dong Woo Kang (KIAS),
Jong-Chul Park (Chungnam Nat. Univ.)
and Seong Chan Park (Yonsei Univ.)

IBS-PNU joint Workshop
5 Dec 2019, Busan
Republic of Korea

How far high E particles can propagate in the universe?

Fig. from C. Rott's talk @NEPLES 2019



How far high E particles can propagate in the universe?

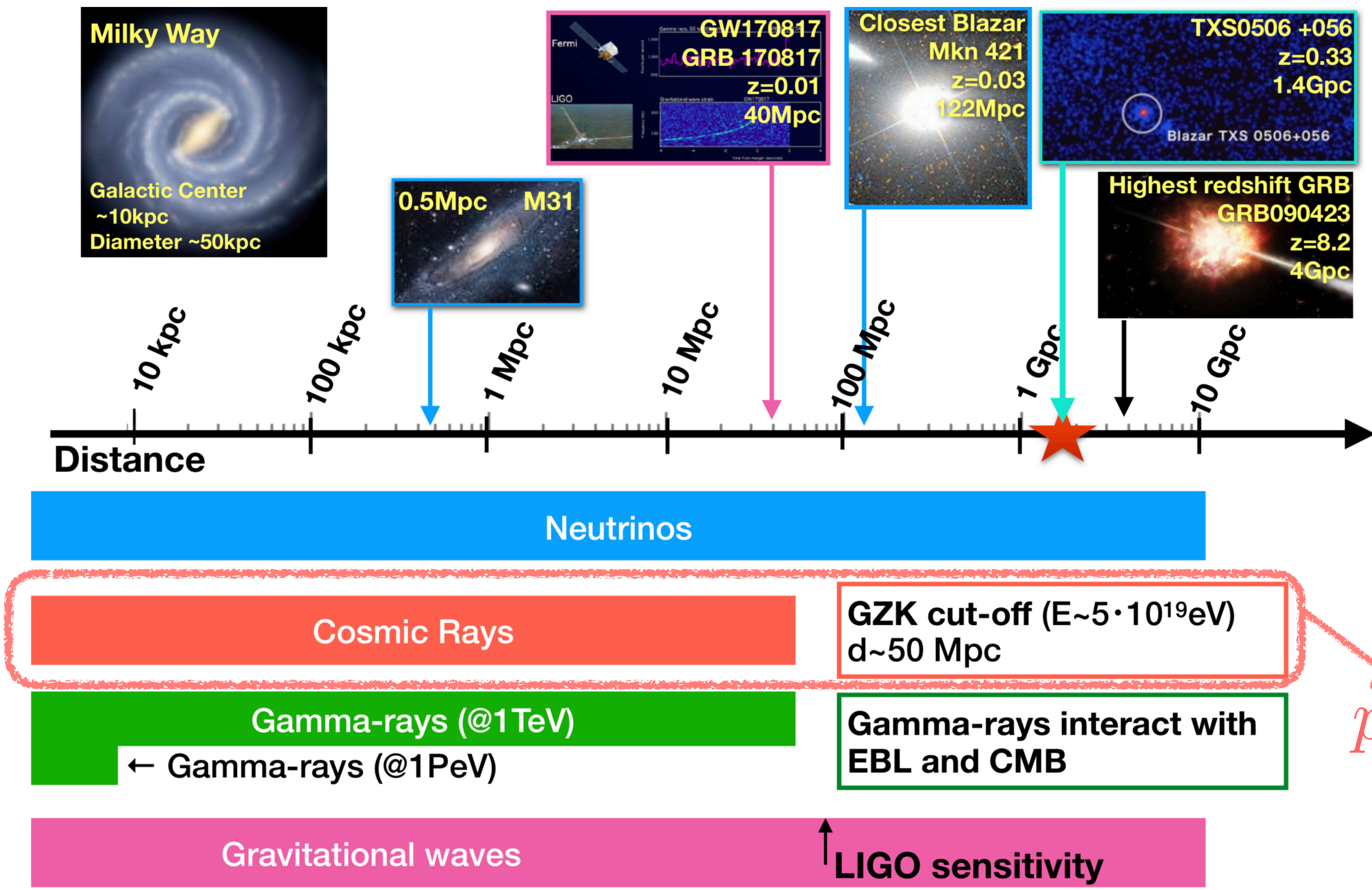


Fig. from C. Rott's talk @NEPLES 2019

$$p\gamma_{\rm bkg} \to p\pi^0, n\pi^+$$

GZK mechanism

How far high E particles can propagate in the universe?

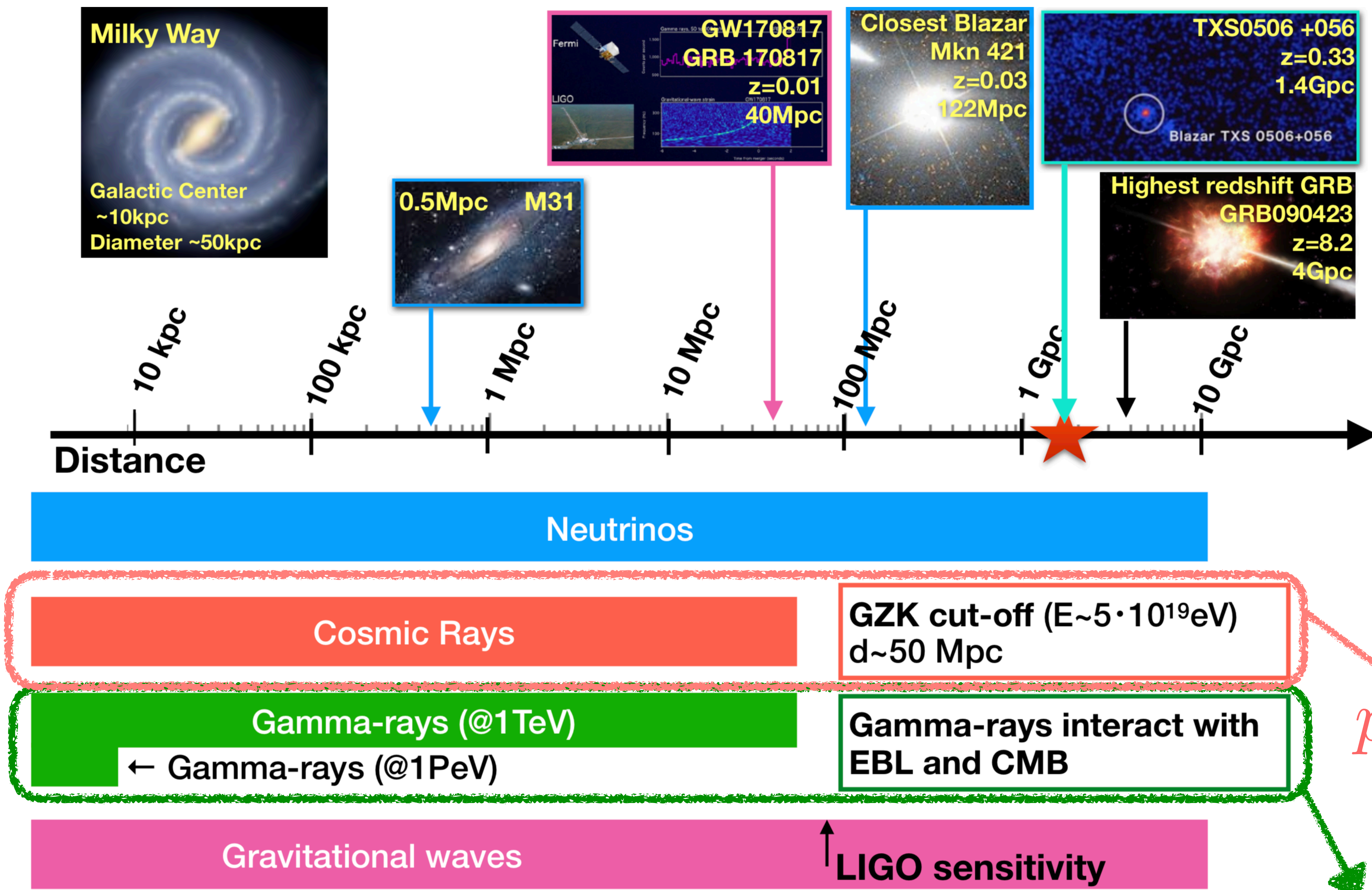


Fig. from C. Rott's talk
@NEPLES 2019

$$p\gamma_{\rm bkg} \to p\pi^0, n\pi^+$$

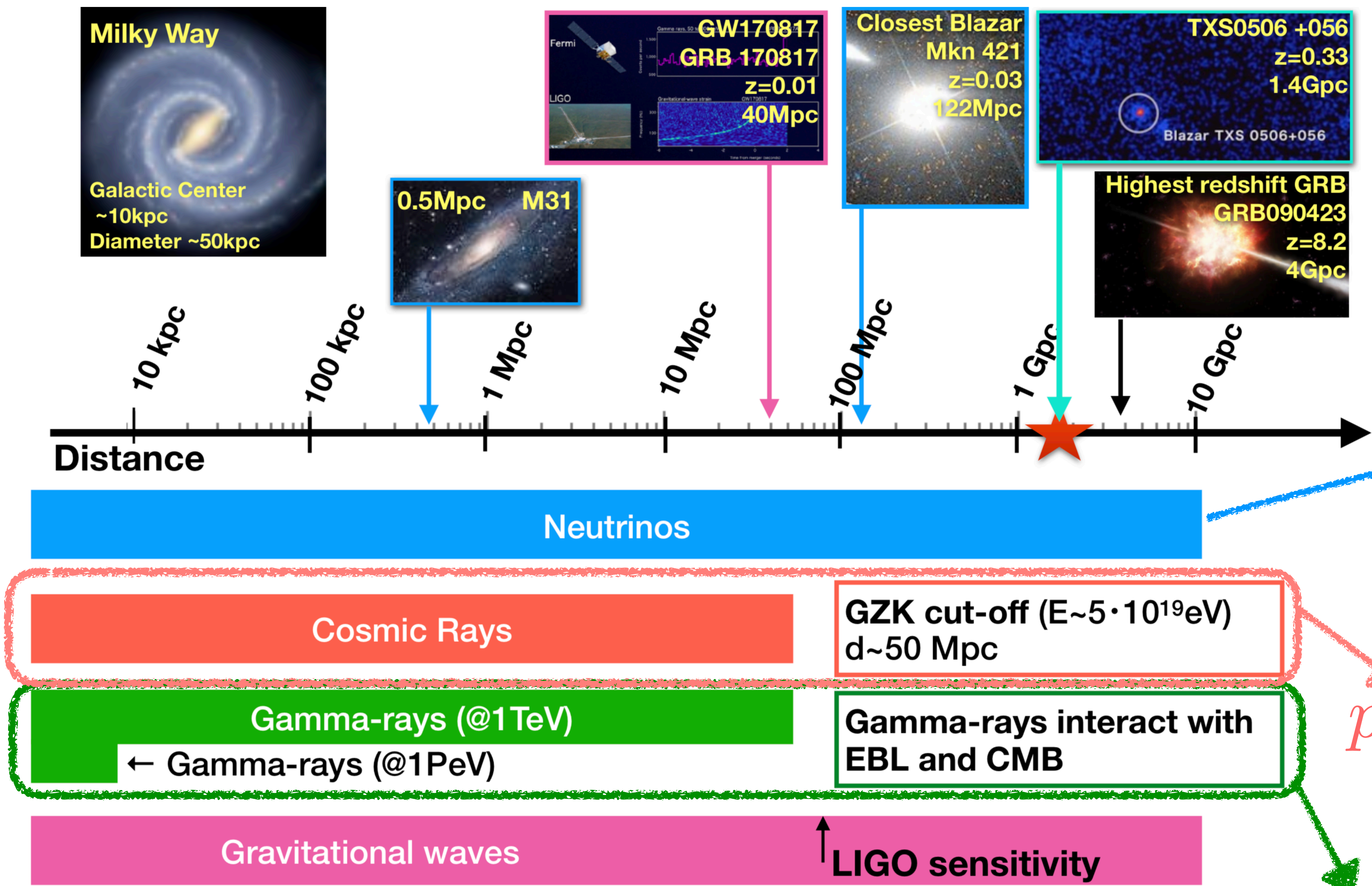
GZK mechanism

$$\gamma\gamma_{\rm bkg} \to e^- e^+$$
$$e\gamma_{\rm bkg} \to e\gamma$$

EM cascade

How far high E particles can propagate in the universe?

Fig. from C. Rott's talk @NEPLES 2019



$$\nu\bar{\nu} \to Z$$

$$2m_\nu E_\nu = m_Z^2$$

For $E_\nu < 10^{22}$ eV

Neutrino freely propagate in the SM.

$$p\gamma_{\rm bkg} \to p\pi^0, n\pi^+$$

GZK mechanism

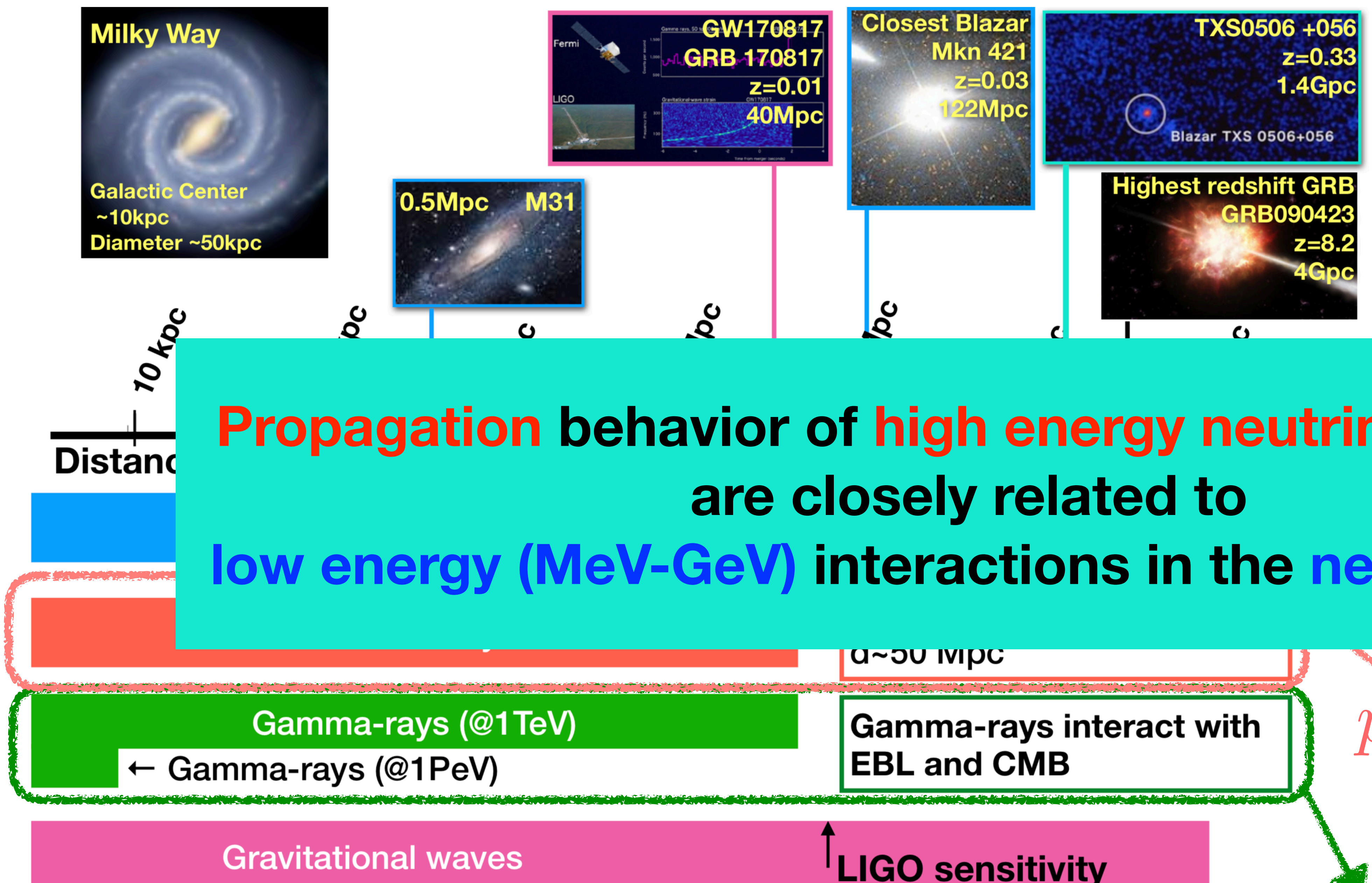
$$\gamma\gamma_{\rm bkg} \to e^- e^+$$

$$e\gamma_{\rm bkg} \to e\gamma$$

EM cascade

How far high E particles can propagate in the universe?

Fig. from C. Rott's talk @NEPLES 2019



Propagation behavior of high energy neutrinos (TeV-PeV) are closely related to low energy (MeV-GeV) interactions in the neutrino sector.

$$\nu\bar{\nu} \to Z$$

$$2m_\nu E_\nu = m_Z^2$$

eV

SM.

$$p\gamma_{\rm bkg} \to p\pi^0, n\pi^+$$

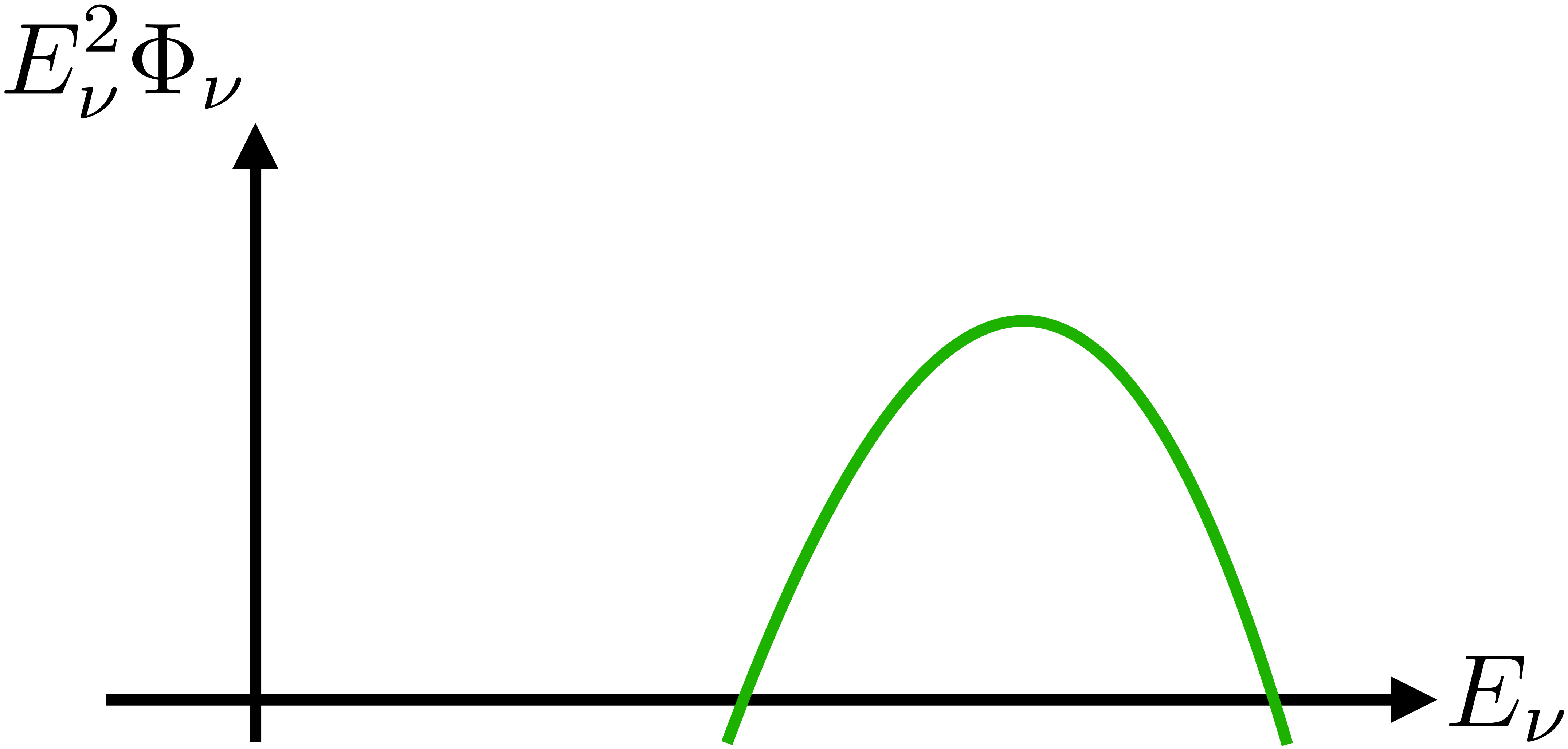
GZK mechanism

$$\gamma\gamma_{\rm bkg} \to e^- e^+$$

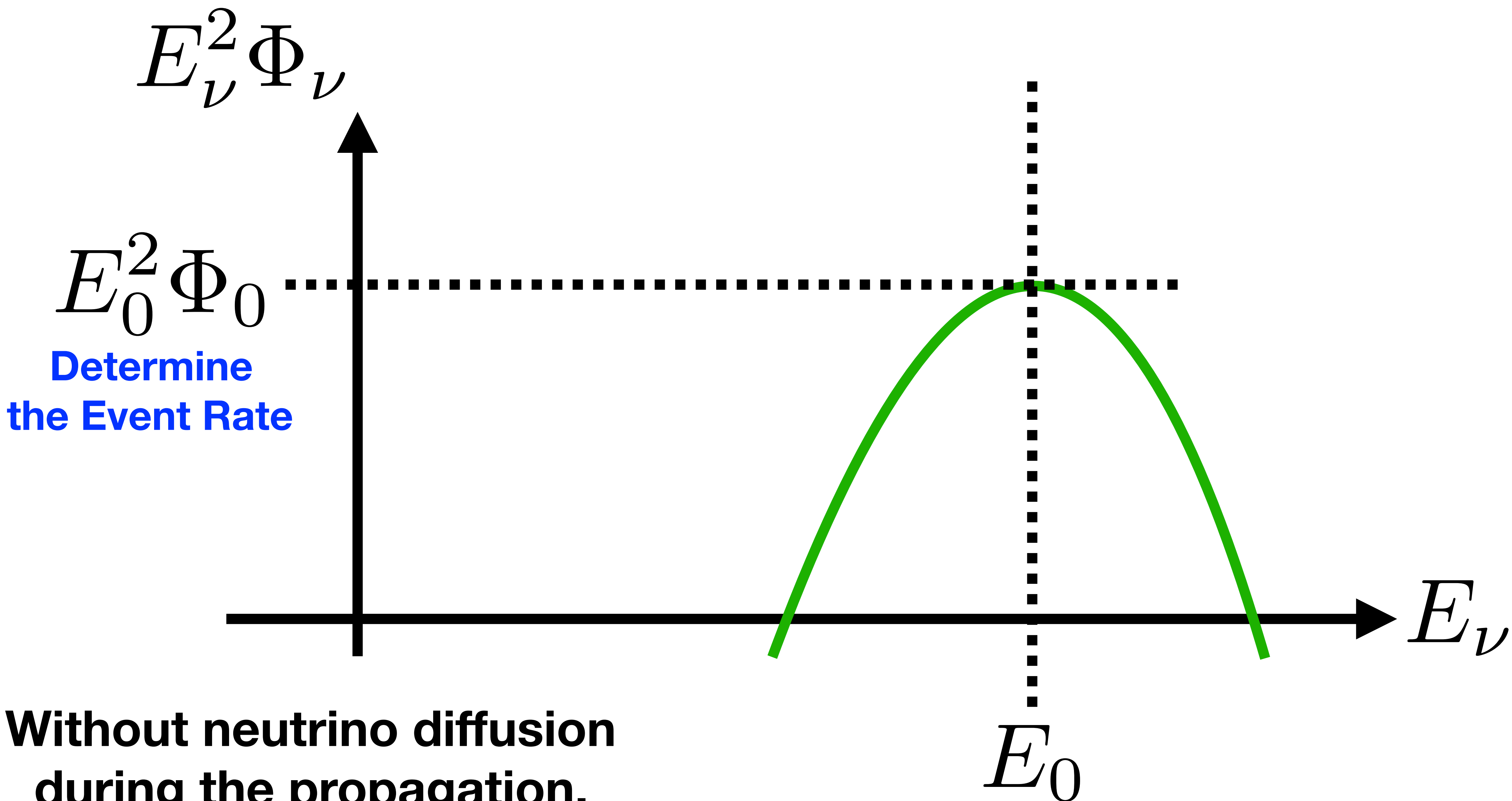
$$e\gamma_{\rm bkg} \to e\gamma$$

EM cascade

How neutrino self-interaction affect High E neutrino event spectrum?



How neutrino self-interaction affect High E neutrino event spectrum?

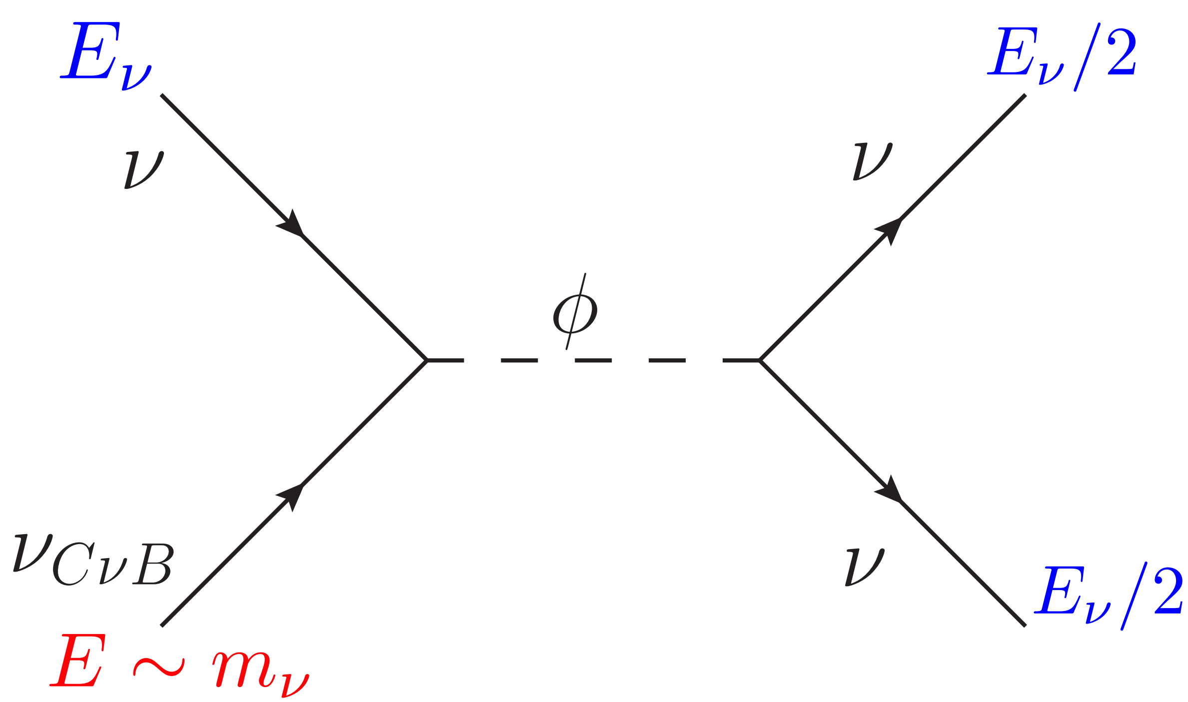


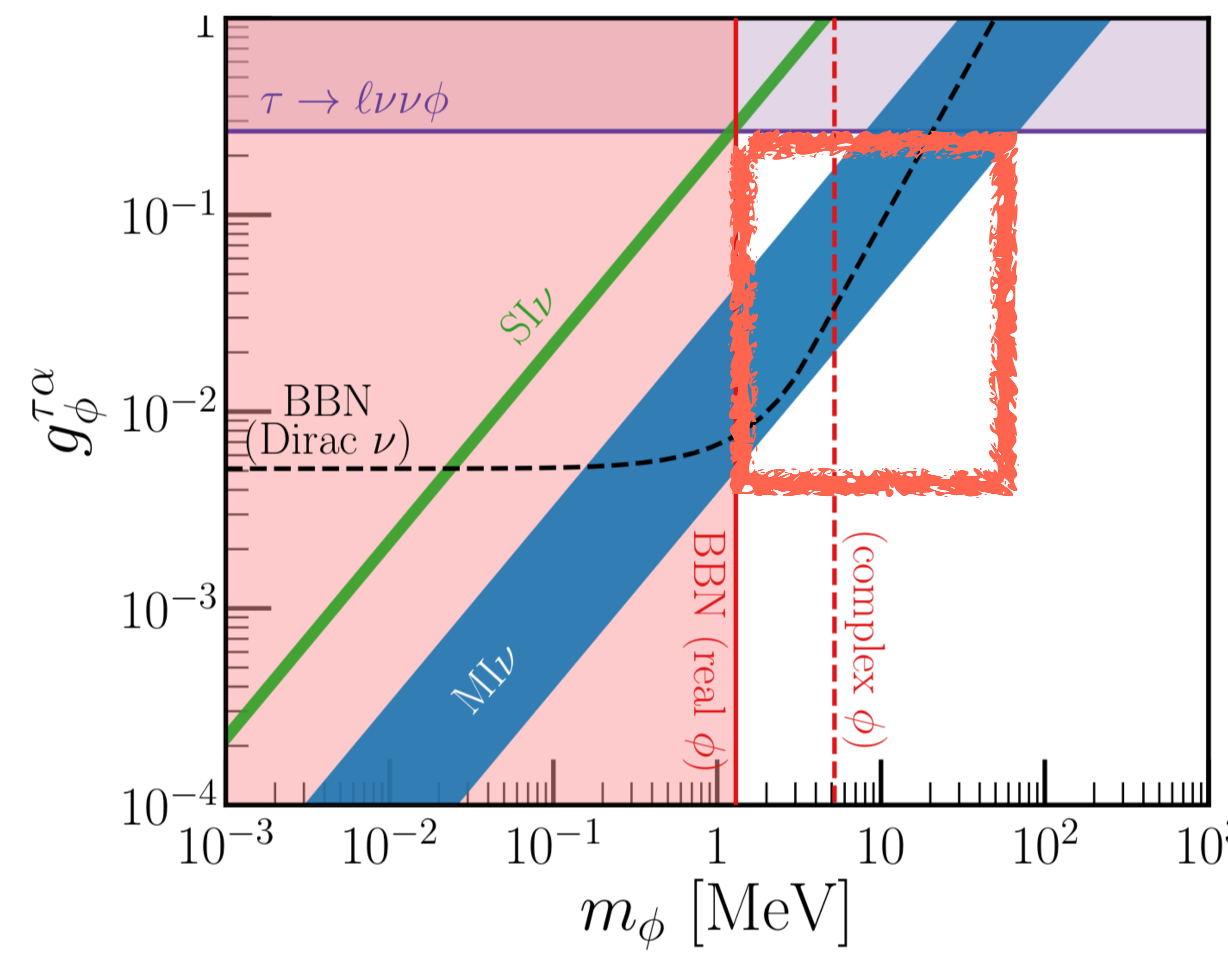
Without neutrino diffusion during the propagation, the observed spectrum is almost same to the spectrum at emission zone.

New self-interaction of neutrinos and neutrino cascade during propagation

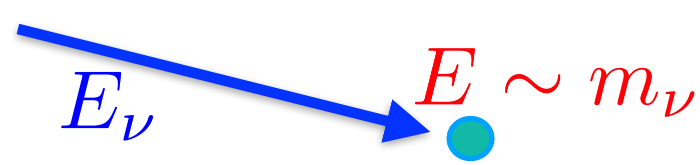
- ν **self-interaction with light mediator**

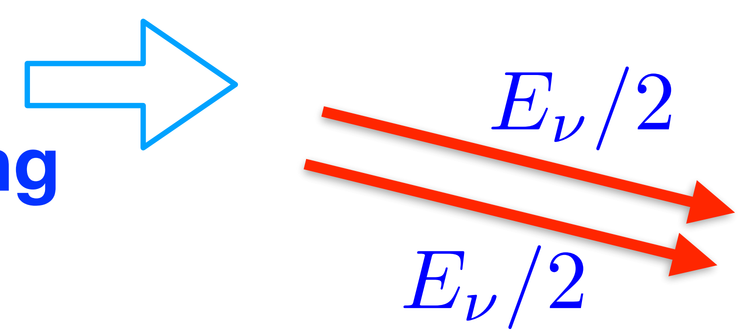
$$\mathcal{L}_{\rm eff} \supset -g_\phi \bar{\nu}_\tau^c \nu_\tau \phi + \text{h.c.}$$





K. J. Kelly et al. PRL 123 (2019) no.19



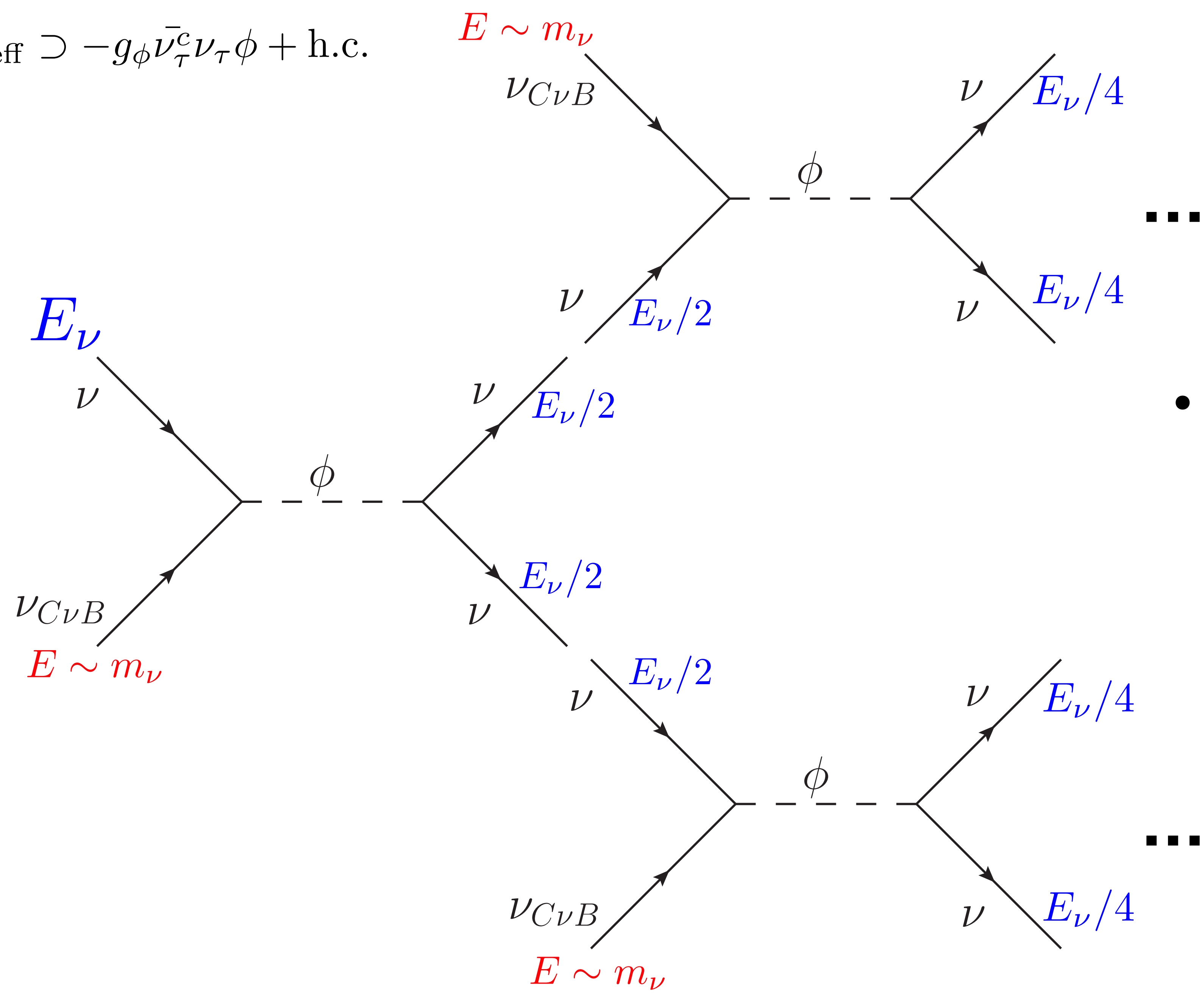


Neutrino cascade occurs during extragalactic propagation with MFP ~ O(200-1000) Mpc

New self-interaction of neutrinos and neutrino cascade during propagation

- ν **self-interaction with light mediator**

$$\mathcal{L}_{\rm eff} \supset -g_\phi \bar{\nu^c_\tau} \nu_\tau \phi + \mathrm{h.c.}$$



- **Successive** ν**-cascades modify event spectrum significantly.**

Similar to EM cascades with bkg photons (EBL&CMB) in High-E gamma-ray propagation.

New self-interaction of neutrinos and neutrino cascade during propagation

- **Obtaining the modified flux with simple neutrino cascades**

$$\frac{\partial f_\nu(\epsilon_\nu^{\rm obs}, z)}{\partial t} = -\frac{c}{\lambda_\nu(\epsilon_\nu, z)} f_\nu(\epsilon_\nu^{\rm obs}, z) + \frac{4c}{\lambda_\nu(2\epsilon_\nu, z)} f_\nu(2\epsilon_\nu^{\rm obs}, z)$$

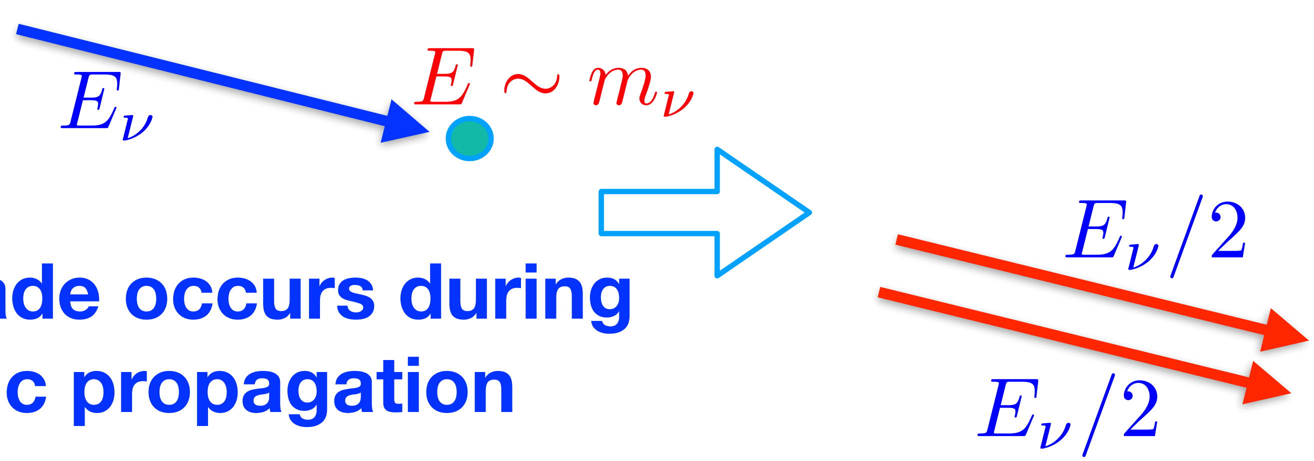
Absorption of energetic neutrino by resonance

Production of down-scattered secondary neutrinos

MFP of neutrino

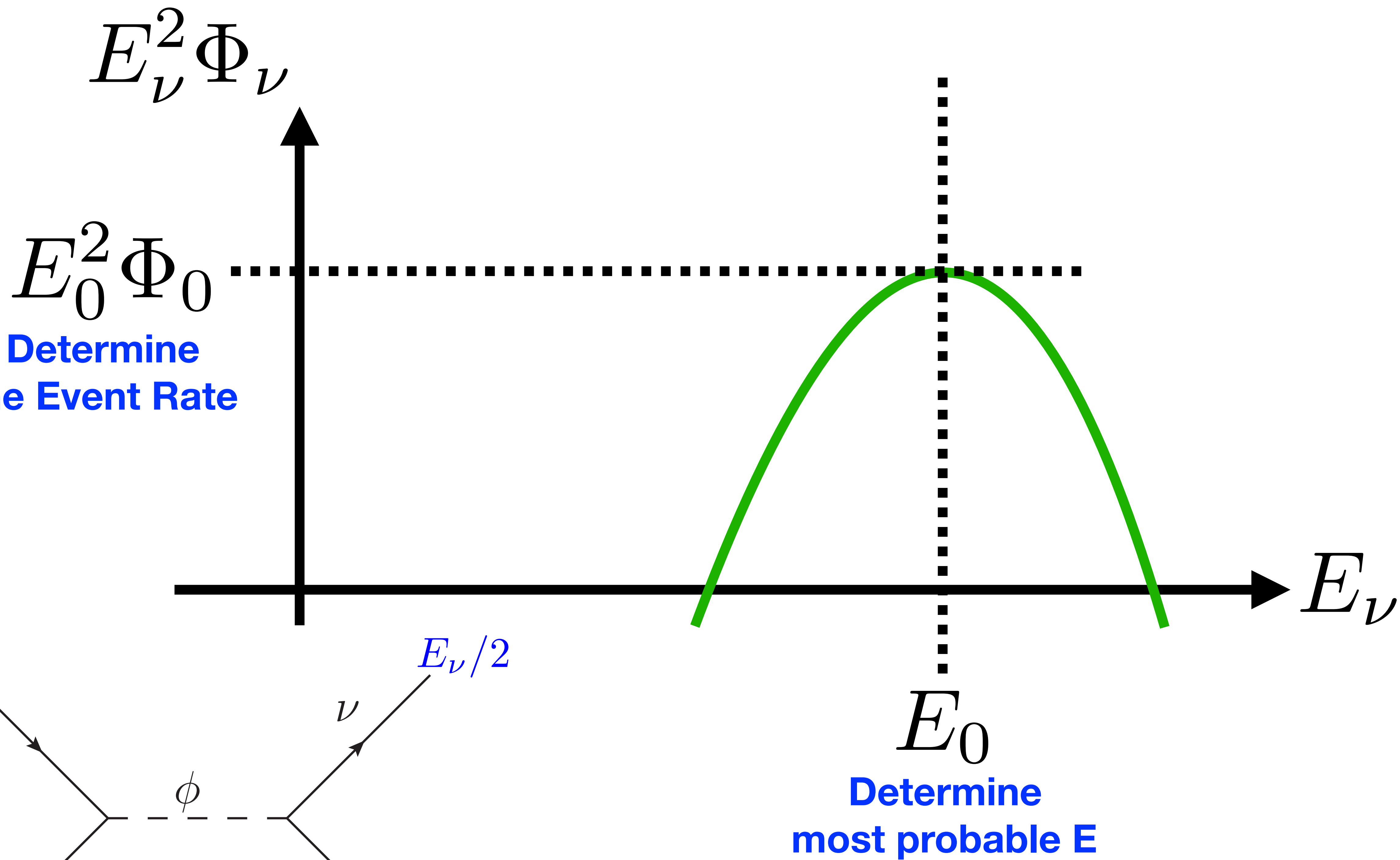
$$\lambda_\nu(\epsilon_\nu, z) = \frac{1}{n_\nu^{\rm C\nu B}(z) \cdot \sigma_\nu^{\nu \rm SI}(\epsilon_\nu)}$$

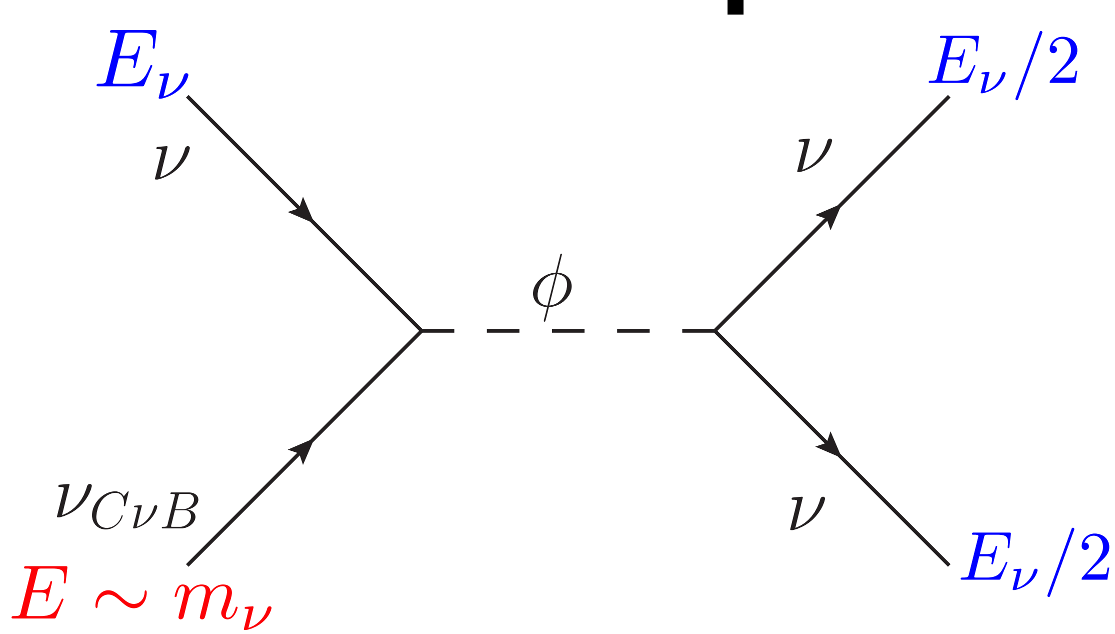
$$\sigma_\nu^{\nu \rm SI}(\epsilon_\nu) \simeq \frac{g_\phi^4}{16\pi} \frac{s}{(s - m_\phi^2)^2 + m_\phi^2 \Gamma_\phi^2}$$



Neutrino cascade occurs during extragalactic propagation

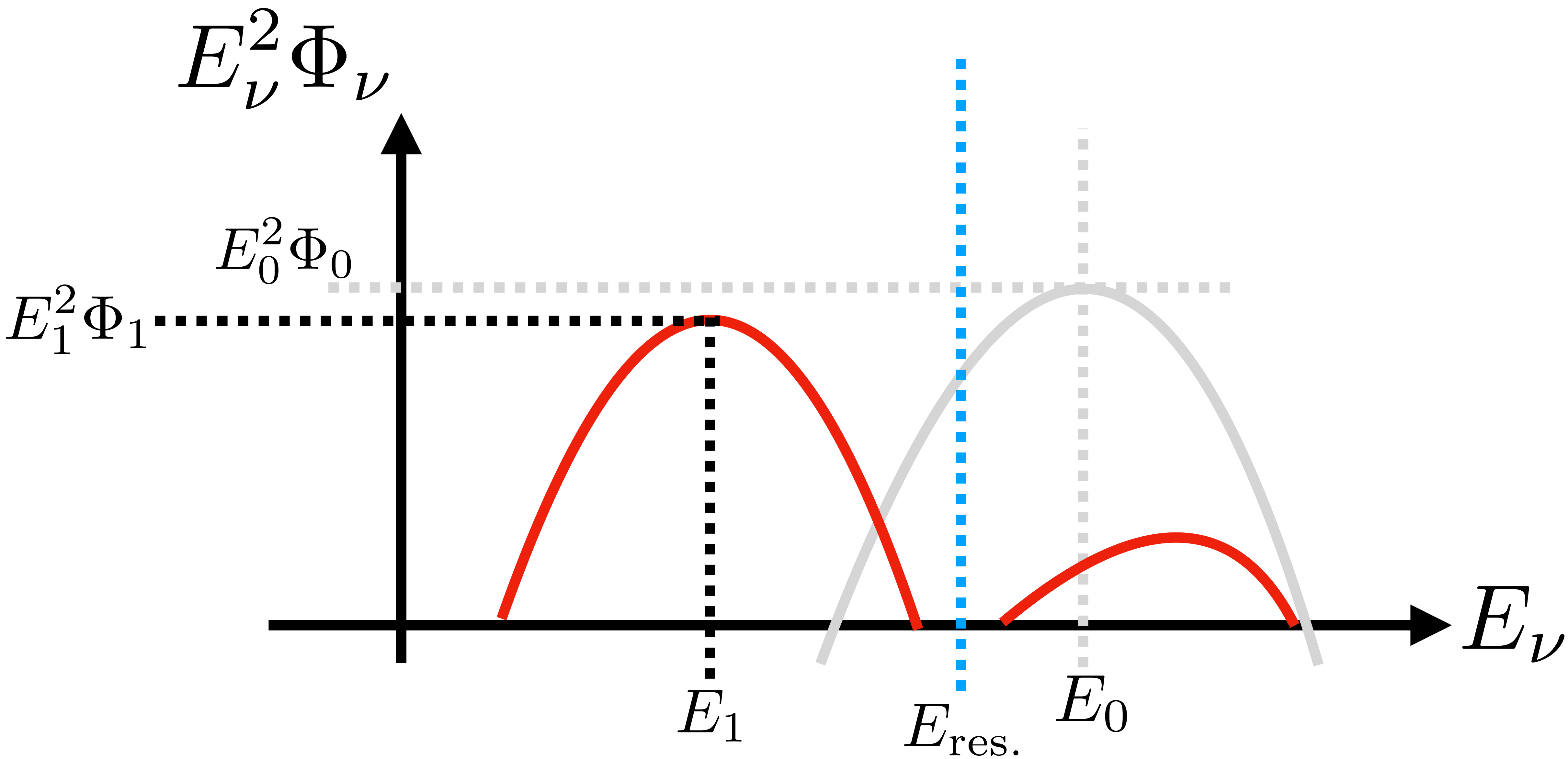
How neutrino self-interaction affect High E neutrino event spectrum?



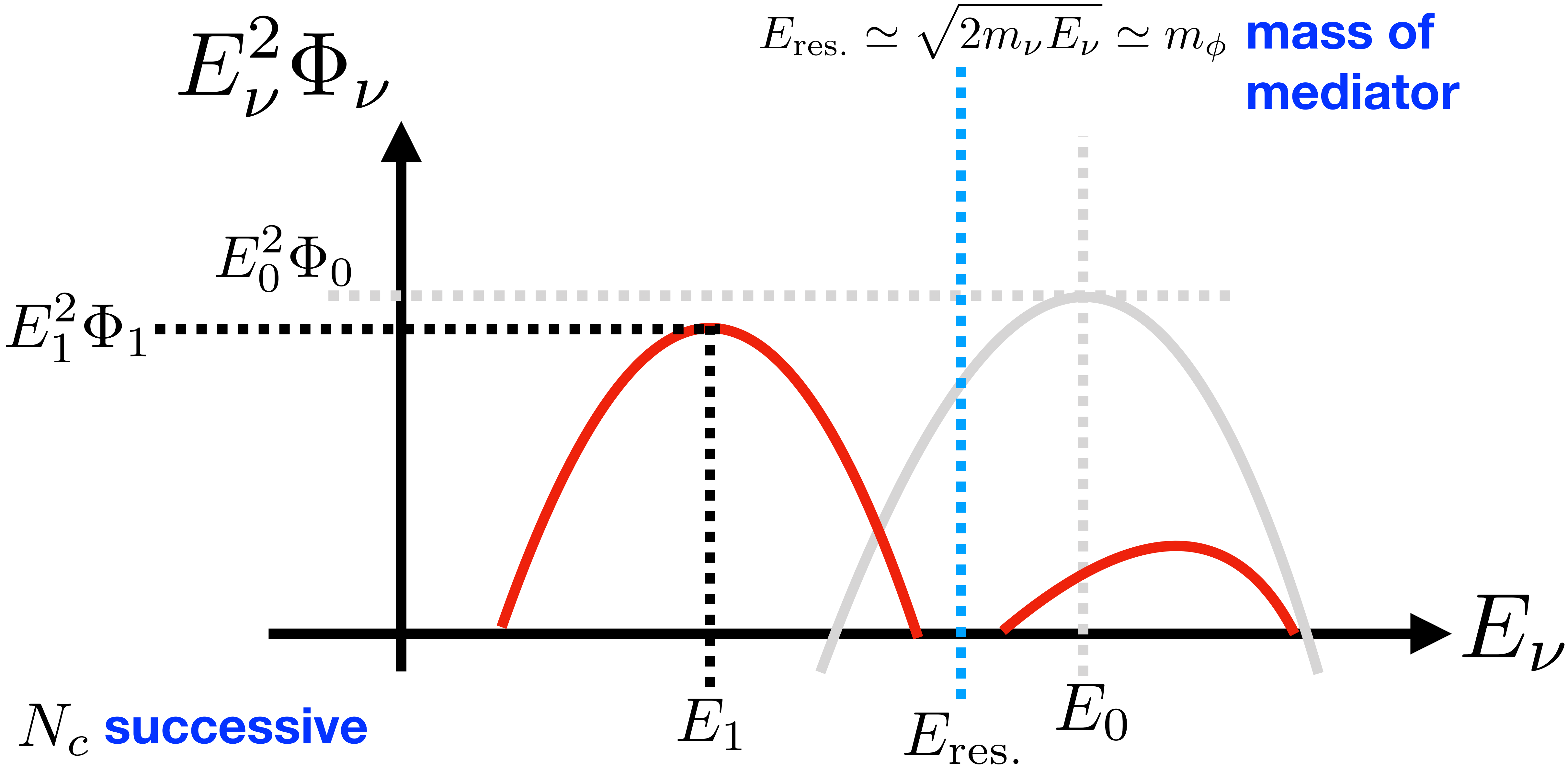


$$\mathcal{L}_{\rm eff} \supset -g_\phi \bar{\nu_\tau^c}\nu_\tau\phi + \text{h.c.}$$

How neutrino self-interaction affect High E neutrino event spectrum?



How neutrino self-interaction affect High E neutrino event spectrum?

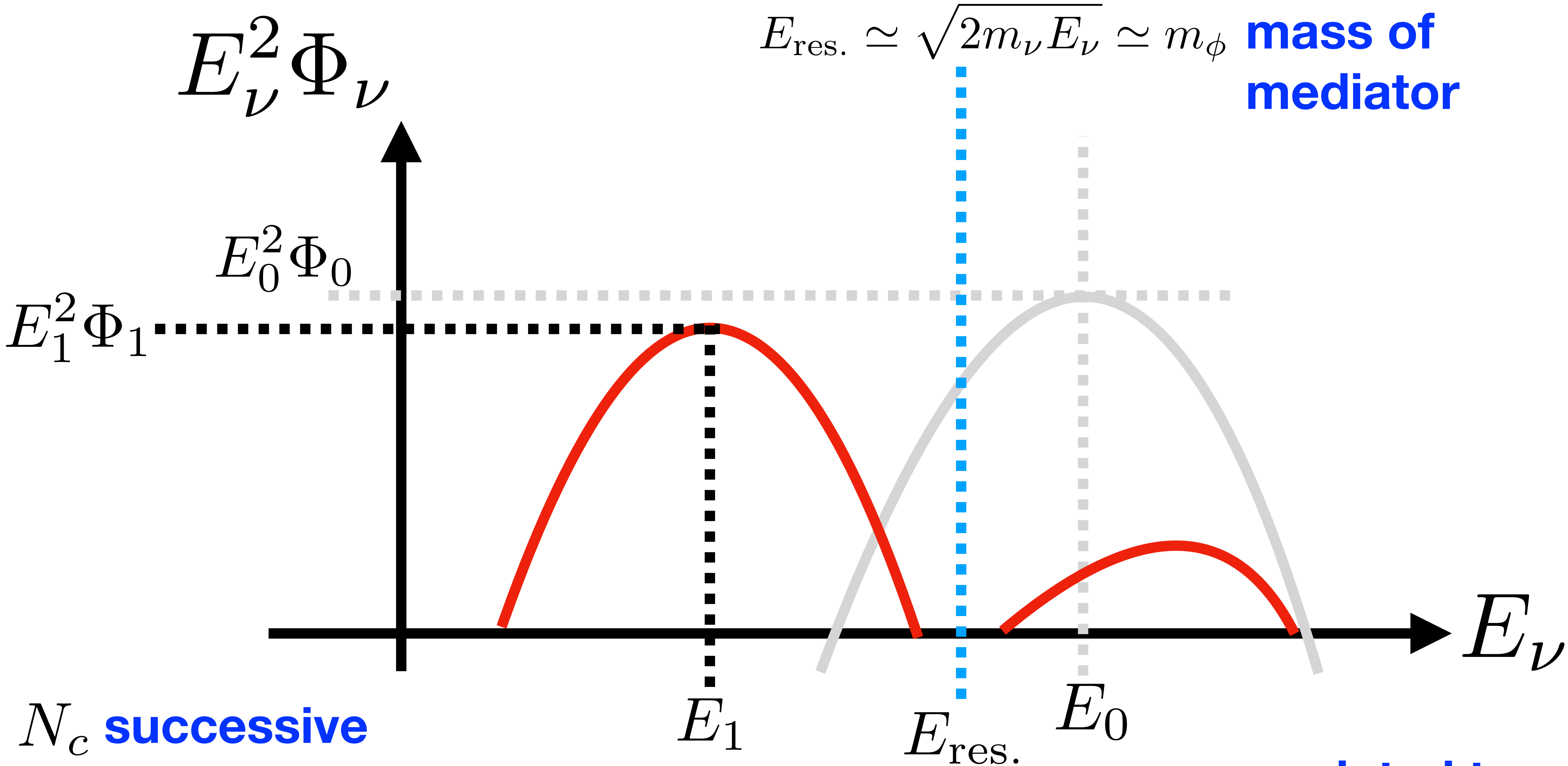


After N_c successive scattering processes during the propagation,

$$E_1 \sim E_0 / 2^{N_c}$$

$$\Phi_1 \sim 2^{N_c} \; \Phi_0$$

How neutrino self-interaction affect High E neutrino event spectrum?



After N_c successive scattering processes during the propagation,

$$E_1 \sim E_0 / 2^{N_c}$$

$$\Phi_1 \sim 2^{N_c} \ \Phi_0$$

➡

N_c determined by Mean Free Path

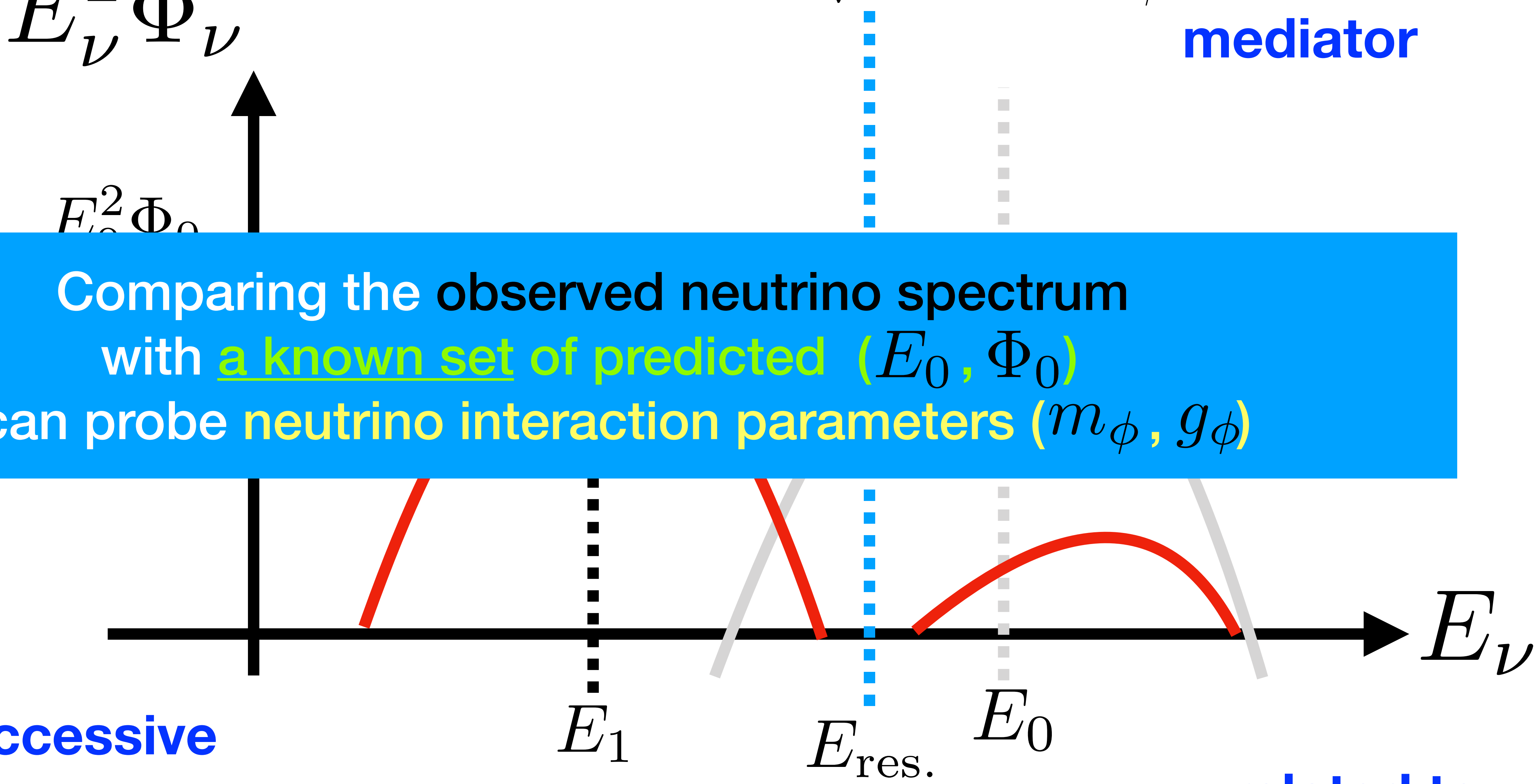
$$N_c = L_{\rm prop} / \lambda_\nu$$

related to coupling of interaction

$$\lambda_\nu = \frac{1}{n_\nu \sigma_{\nu\nu}}$$

How neutrino self-interaction affect High E neutrino event spectrum?

$E_{\rm res.} \simeq \sqrt{2 m_\nu E_\nu} \simeq m_\phi$ **mass of mediator**



Comparing the **observed neutrino spectrum**
with <u>a known set</u> of predicted (E_0, Φ_0)
One can probe neutrino interaction parameters (m_ϕ, g_ϕ)

After N_c successive scattering processes during the propagation,

$$E_1 \sim E_0 / 2^{N_c}$$

$$\Phi_1 \sim 2^{N_c} \; \Phi_0$$

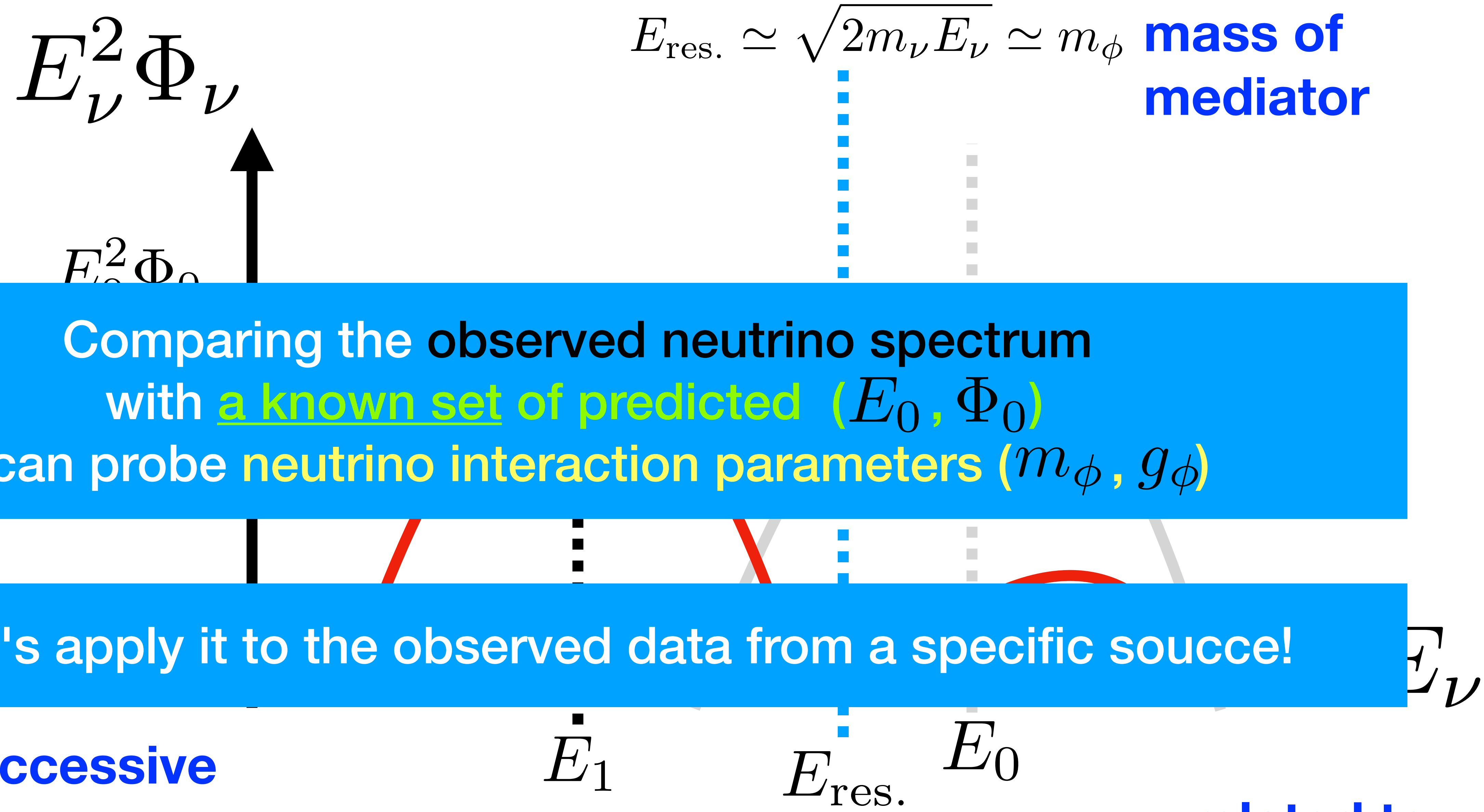
N_c **determined by Mean Free Path**

$$N_c = L_{\rm prop} / \lambda_\nu$$

related to coupling of interaction

$$\lambda_\nu = \frac{1}{n_\nu \sigma_{\nu\nu}}$$

How neutrino self-interaction affect High E neutrino event spectrum?



Comparing the **observed neutrino spectrum**
with a known set of predicted (E_0, Φ_0)
One can probe neutrino interaction parameters (m_ϕ, g_ϕ)

Let's apply it to the observed data from a specific soucce!

After N_c successive scattering processes during the propagation,

$$E_1 \sim E_0 / 2^{N_c}$$

$$\Phi_1 \sim 2^{N_c} \ \Phi_0$$

N_c **determined by Mean Free Path**

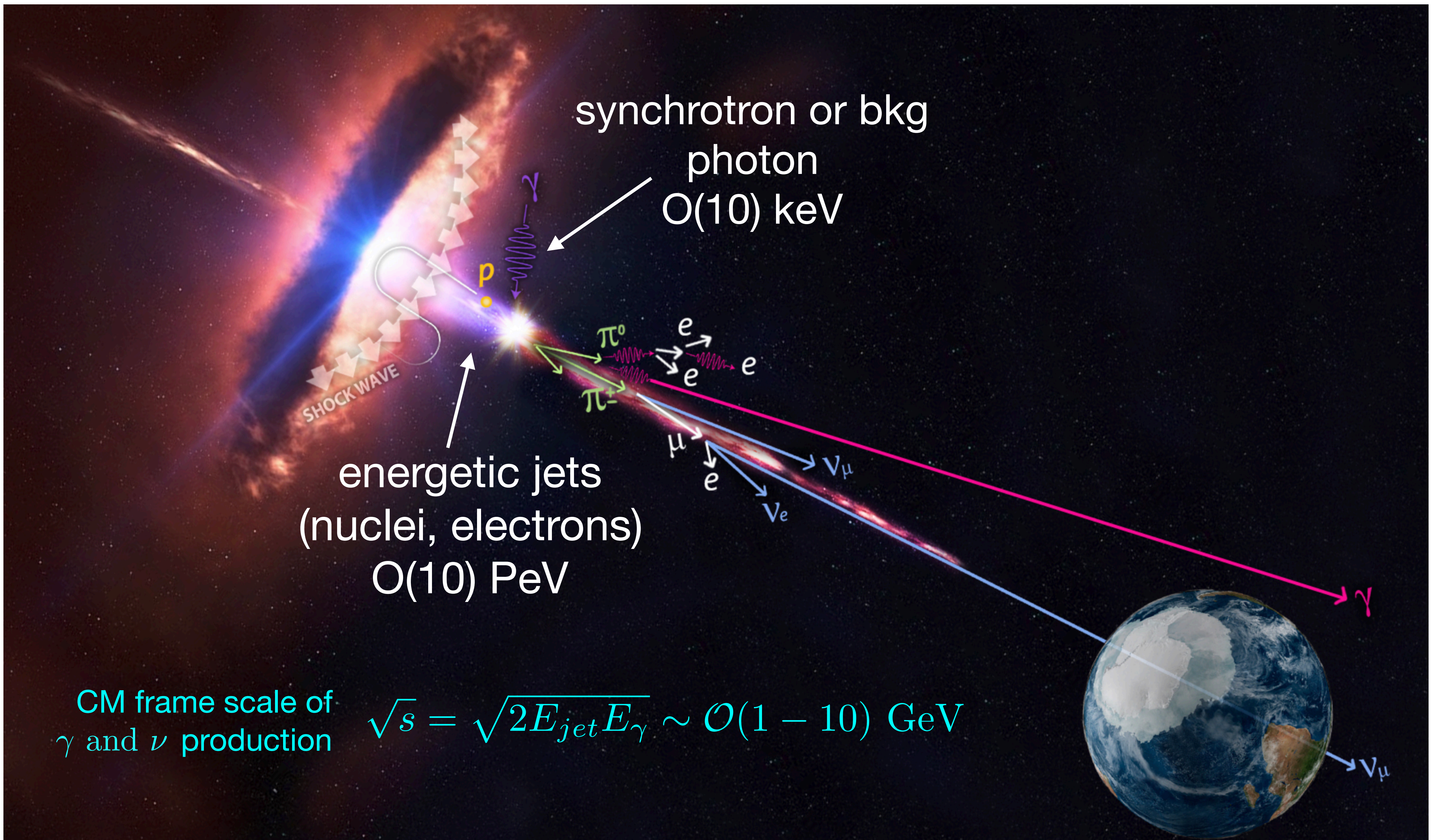
$$N_c = L_{\rm prop} / \lambda_\nu$$

related to coupling of interaction

$$\lambda_\nu = \frac{1}{n_\nu \sigma_{\nu\nu}}$$

Multi-messenger observation from Blazar TXS 0506+056

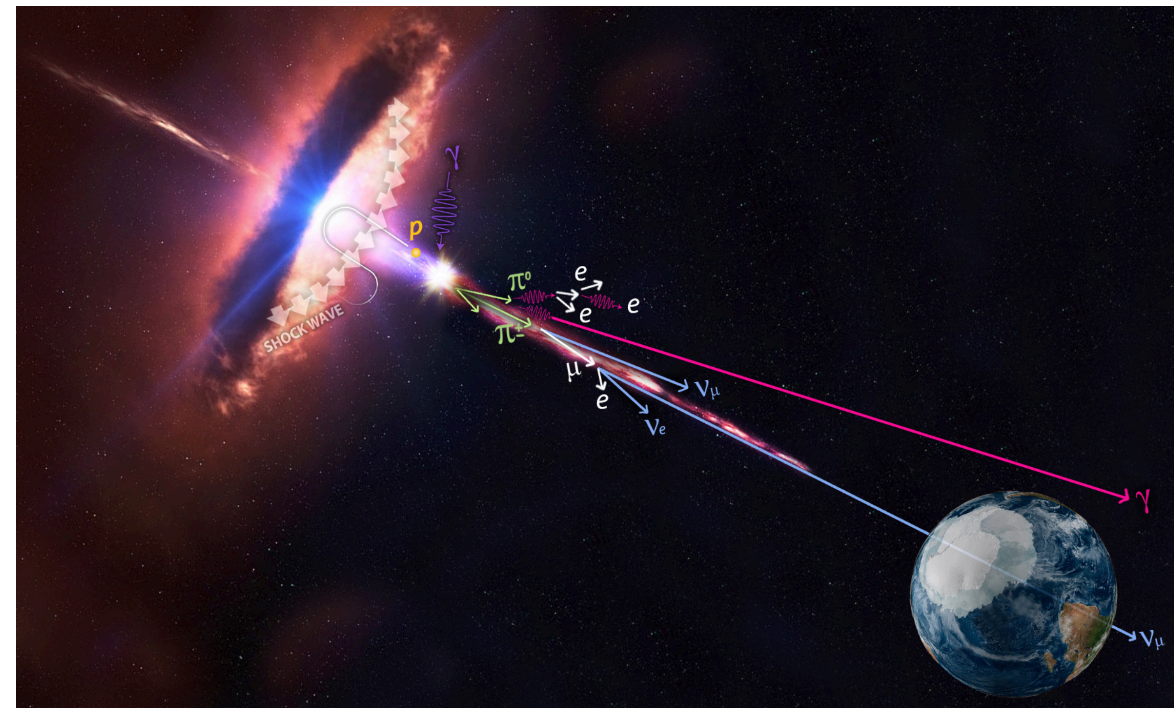
- Blazar : Active Galactic Nuclei (AGN) with **relativistic jets** (mostly energetic p^+, e^- **above PeV energies**)



Multi-messenger observation from Blazar TXS 0506+056

- Blazar : AGN w/ **relativistic jets** (mostly energetic p^+, e^- **above PeV energies**)

- By the **scatterings** with bkg γ and **synchrotron** radiations,



- **Photo-Pion prod.** $p\gamma_{\rm bkg} \to p\pi^0, n\pi^+$ $\qquad n \to pe\nu_e$

$$\pi^0 \to \gamma\gamma \qquad \pi^+ \to \mu^+\nu_\mu$$

$$\mu \to e\nu\bar{\nu}$$

- **Inverse Compton** $e\gamma_{\rm bkg} \to e\gamma$

- Usually both energetic **neutrino** around **O(100) TeV - O(100) PeV** and **multi-wavelength** (from optical to gamma-rays) **photon** fluxes are expected.

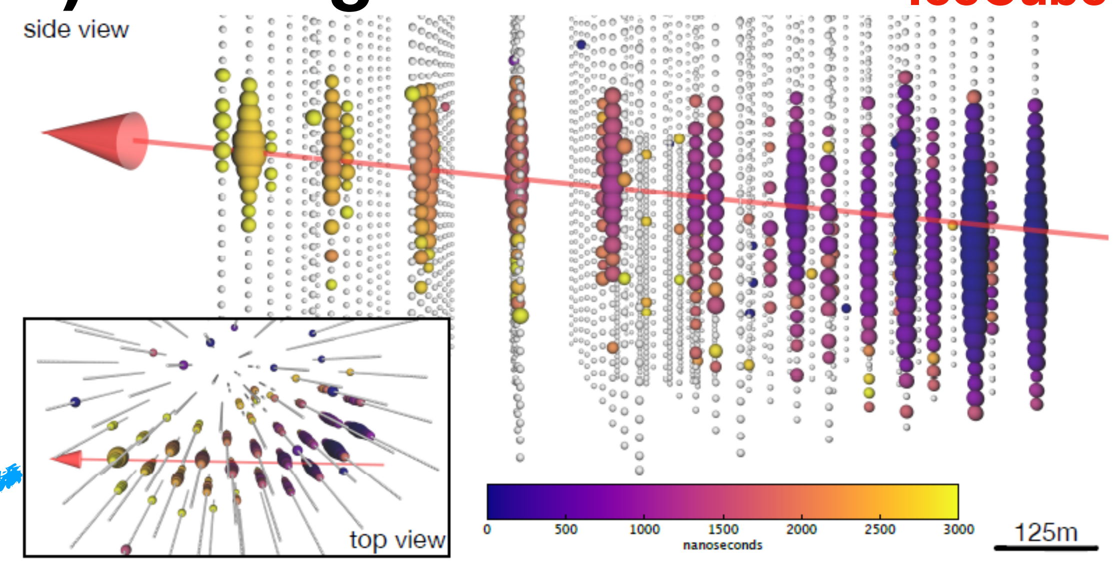
Multi-messenger observation from Blazar TXS 0506+056

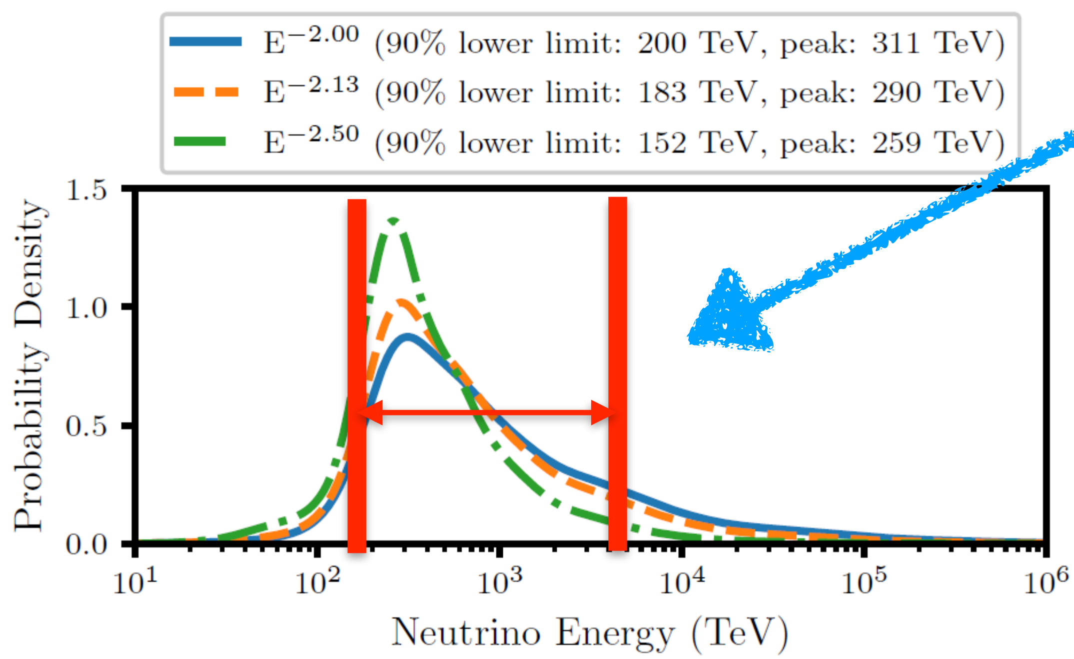
Science 361 (2018) eaat1378 [1807.08816]

- ν flare in TXS 0506+056 (2017) : the first complete set of multi-messenger observation including **both photon and neutrinos** from the **same astrophysical source.**

O(100) TeV high E neutrino

IceCube

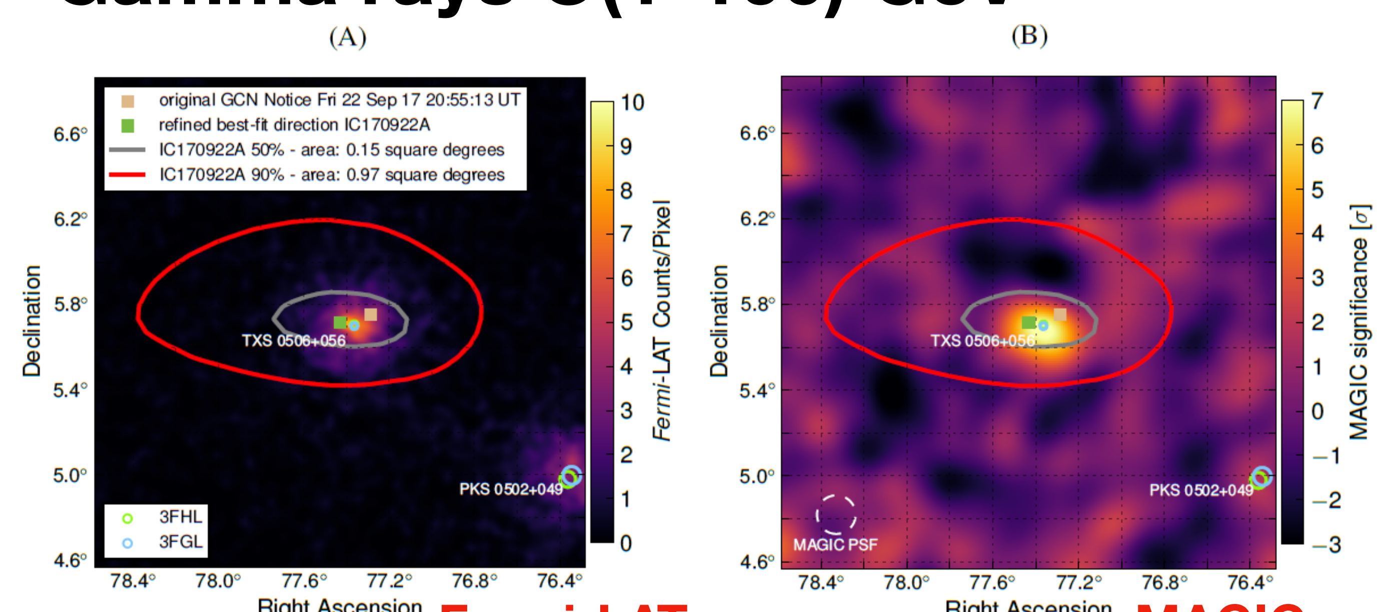




$E_\nu = 290$ TeV **high E muon neutrino**

$$183 \text{ TeV} \leq E_\nu \leq 4.3 \text{ PeV at } 90\% \text{ C.L.}$$

Gamma rays O(1-100) GeV

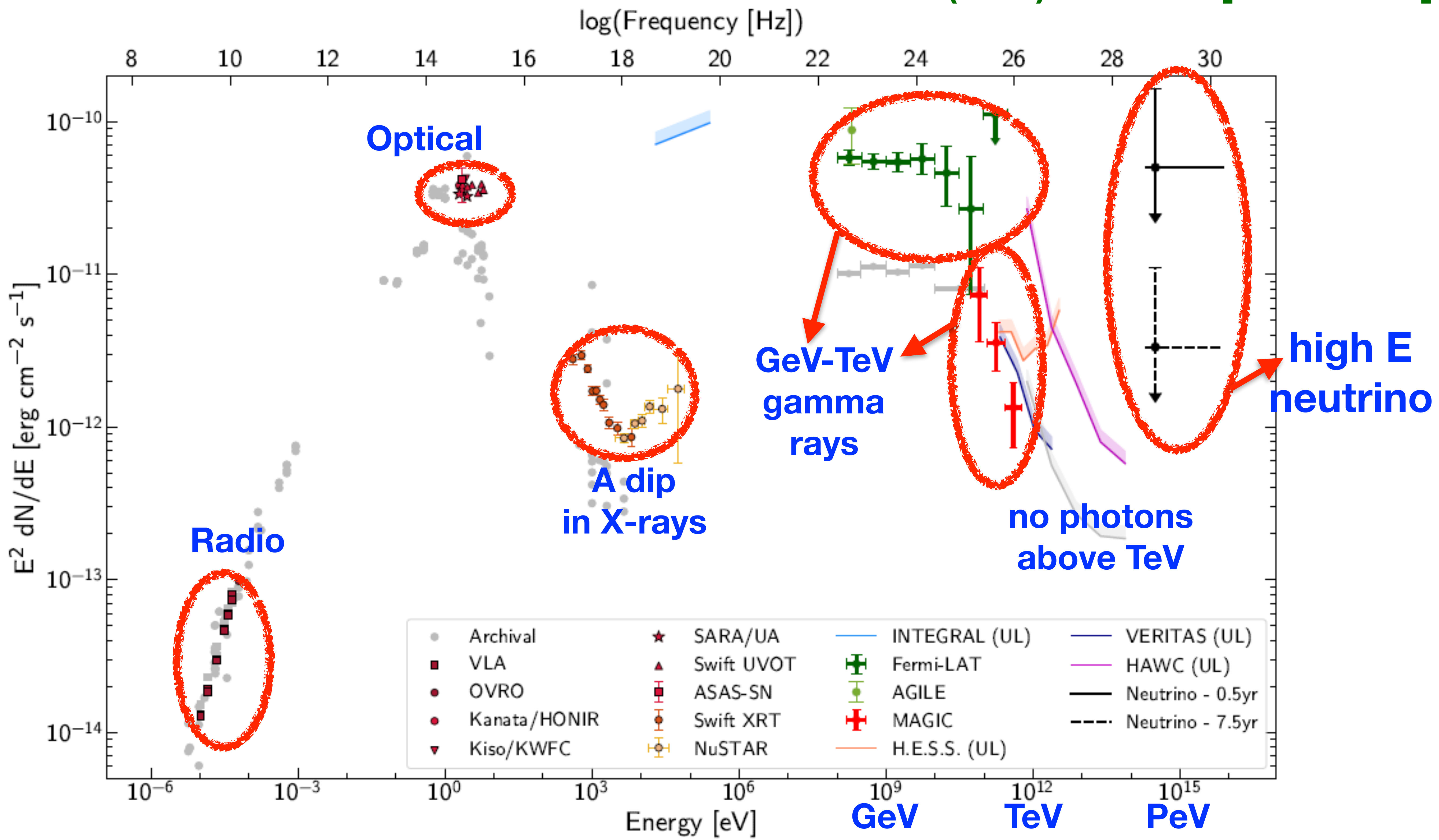


Fermi-LAT

MAGIC

Multi-messenger observation from Blazar TXS 0506+056

Science 361 (2018) eaat1378 [1807.08816]



Astrophysical models for Blazar

- Leptonic vs. Hadronic model

	Leptonic model	Hadronic model
Low energy photon (< O(1) GeV)	electron synchrotron	proton synchrotron
High energy photon (1 GeV ~ 100 TeV)	inverse compton + EM cascade	photopion production + neutral pion decay + EM cascade
high energy neutrino (100 TeV ~ 10 PeV)	**no neutrino in pure leptonic model** -	photopion production + charged pion decay + muon, neutron decay (no cascade during propag.)

Astrophysical models for Blazar

- Leptonic vs. Hadronic model

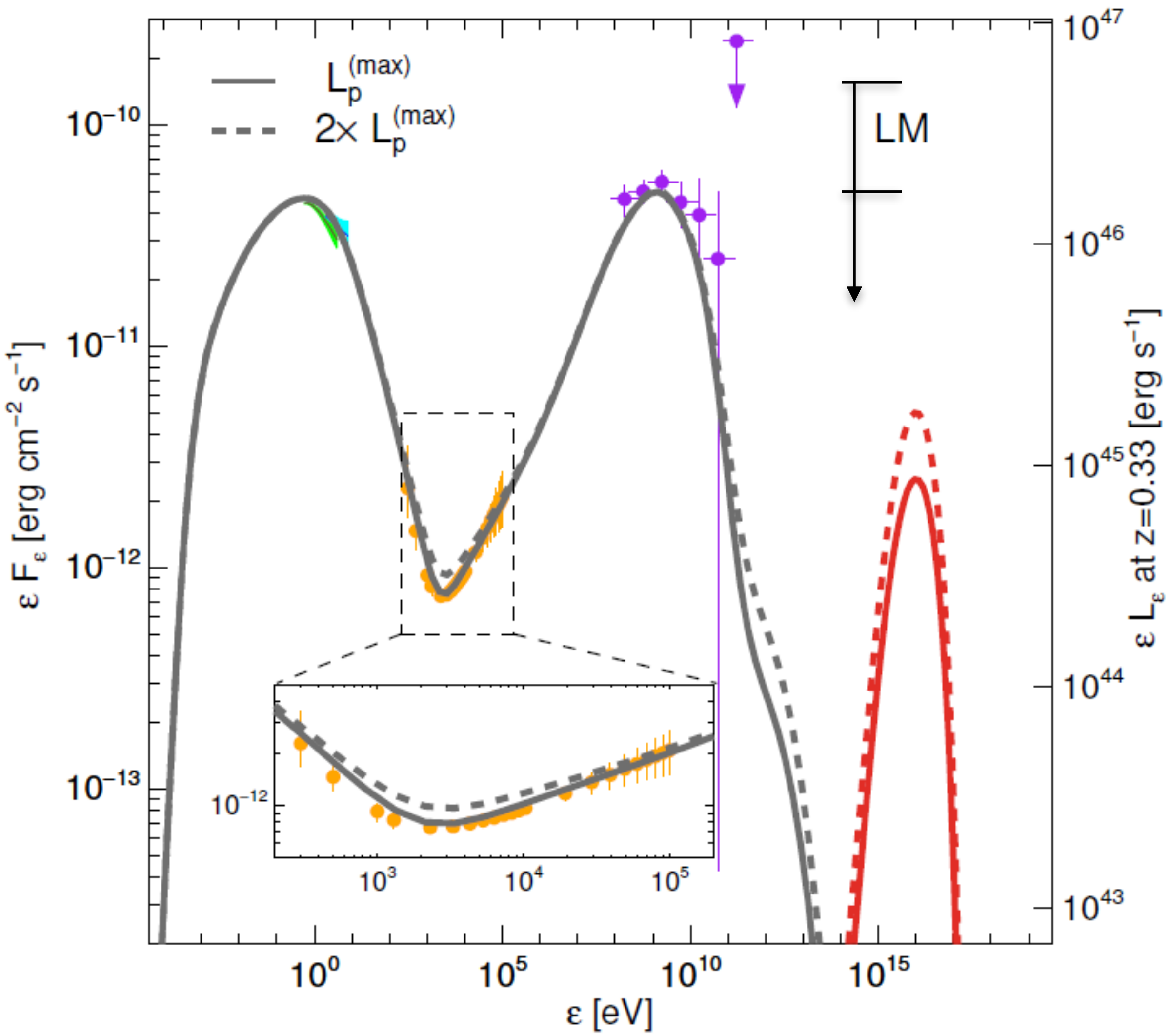
	Leptonic model	Hadronic model
Low energy photon (< O(1) GeV)	electron synchrotron	proton synchrotron
High energy photon (1 GeV ~ 100 TeV)	inverse compton + EM cascade	photopion production + neutral pion decay + EM cascade
high energy neutrino (100 TeV ~ 10 PeV)	- **no neutrino in pure leptonic model**	photopion production + charged pion decay + muon, neutron decay (no cascade during propag.)

Additional small amount of protons

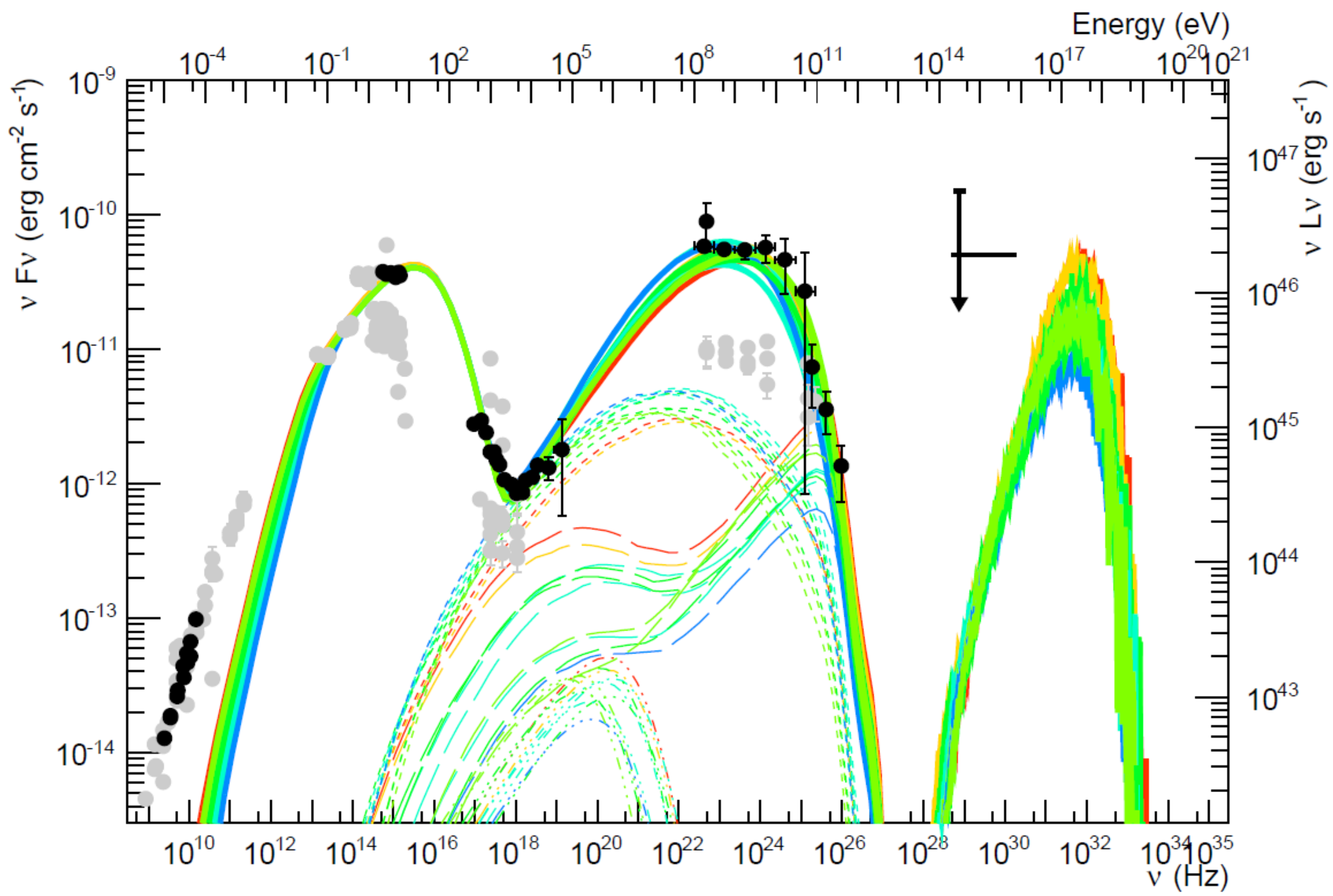
(Lepto-hadronic model)

Favored (but not enough) to explain TXS 0506+056 photon/neutrino spectrum

Astrophysical models for Blazar

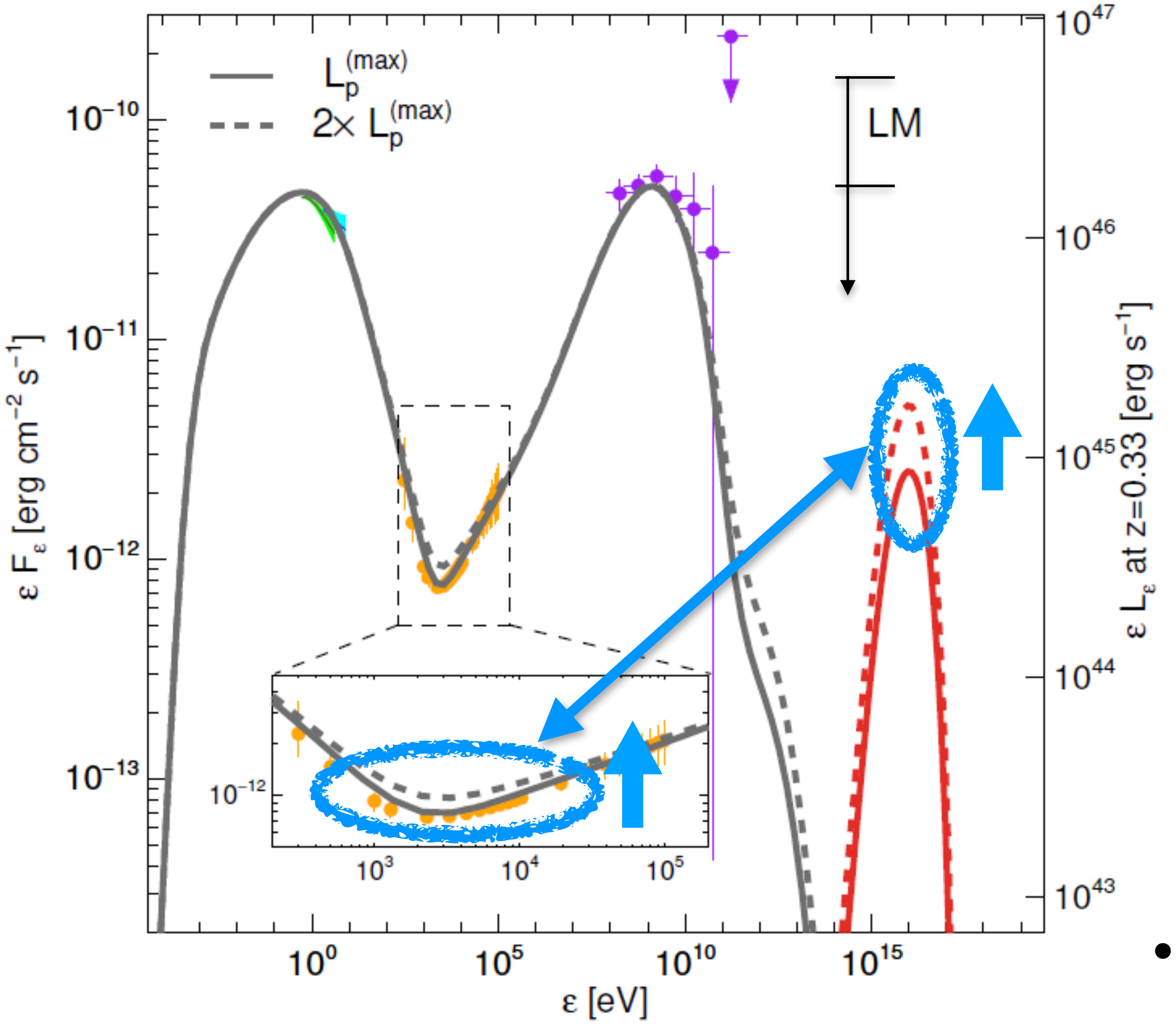


A. Keivani et al. [1807.04537]

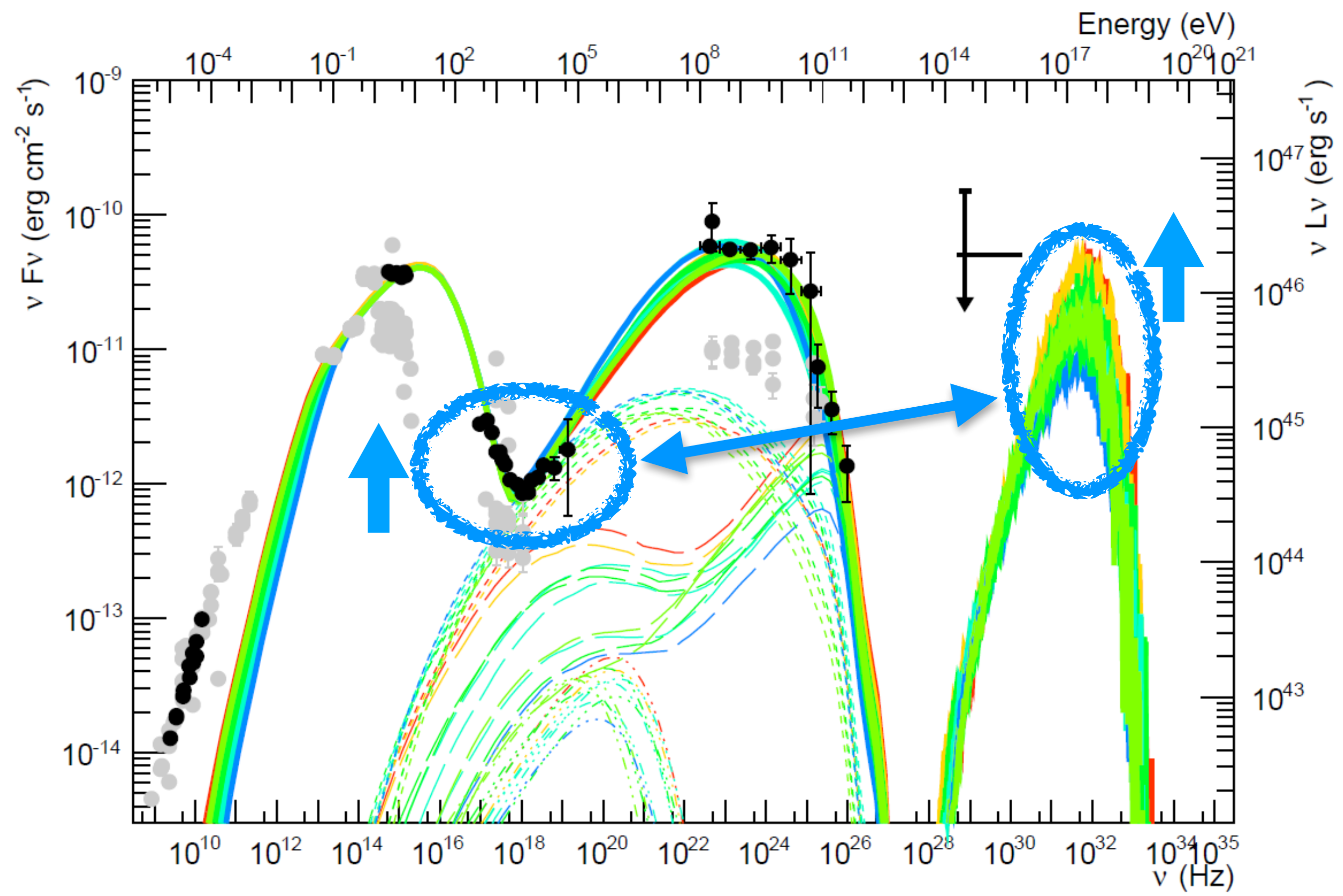


M. Cerruti et al. [1807.04335]

Astrophysical models for Blazar



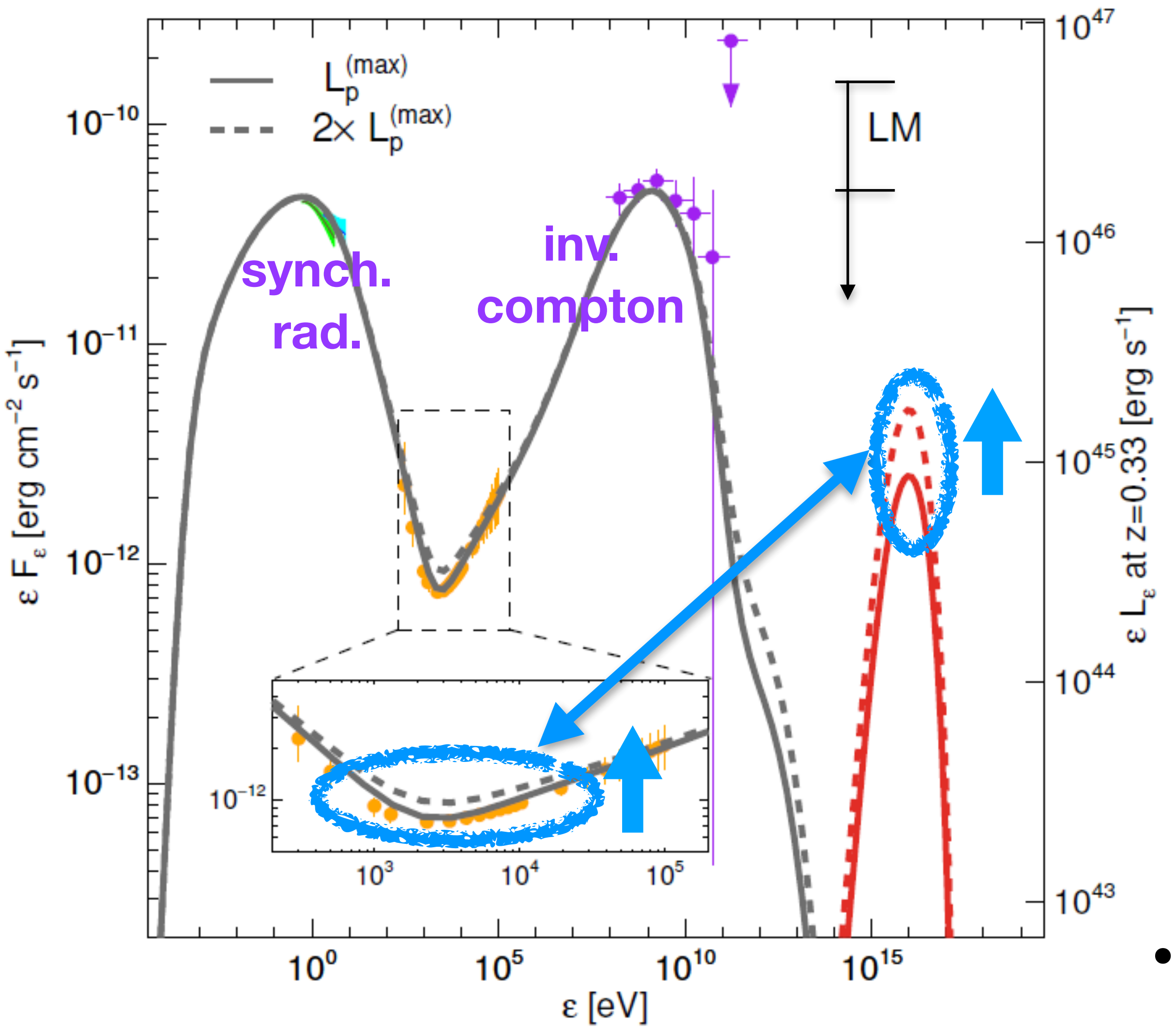
A. Keivani et al. [1807.04537]



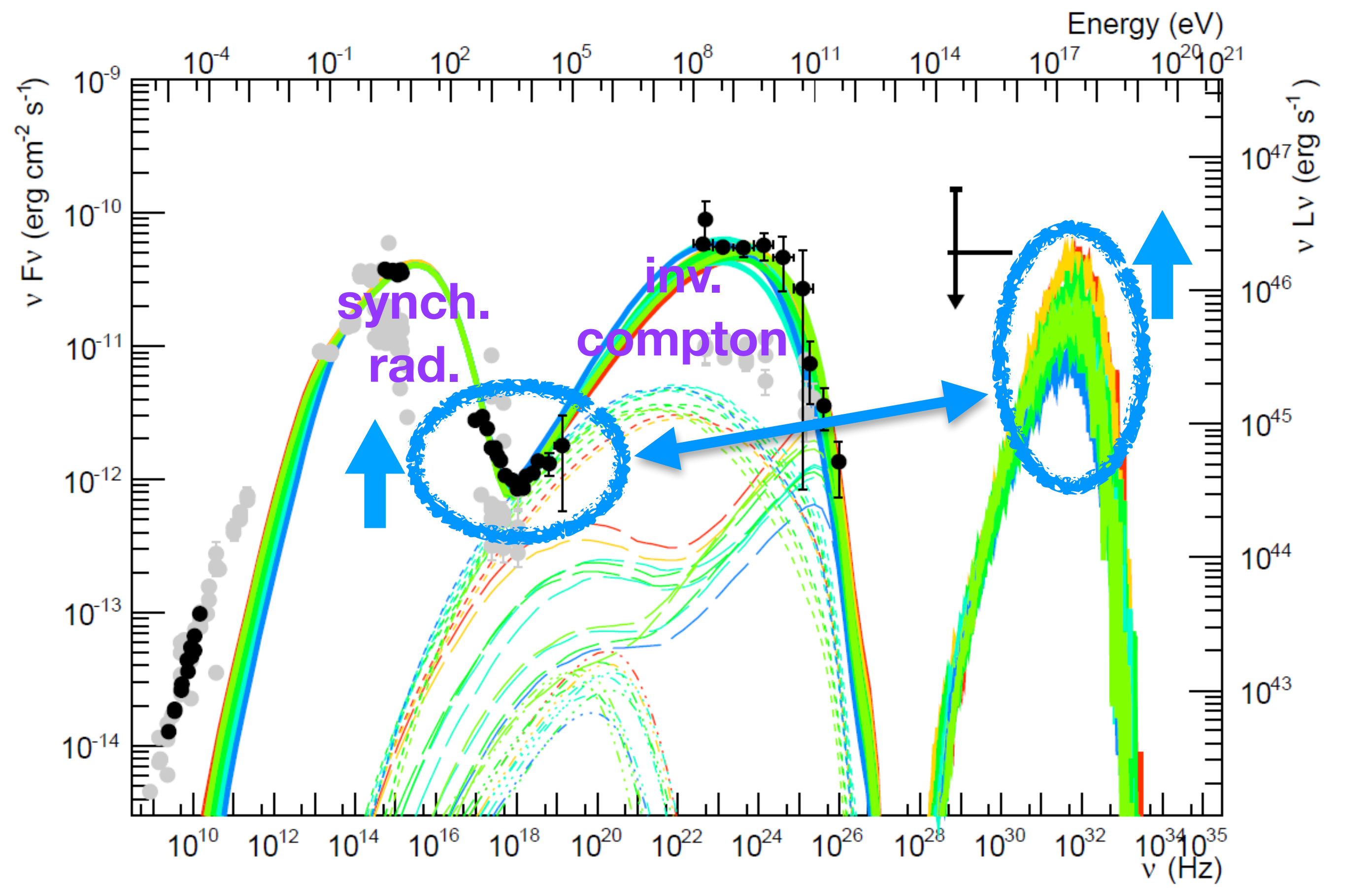
M. Cerruti et al. [1807.04335]

- **Pure hadronic models has been ruled out due to the overshoot in X-ray.**

Astrophysical models for Blazar



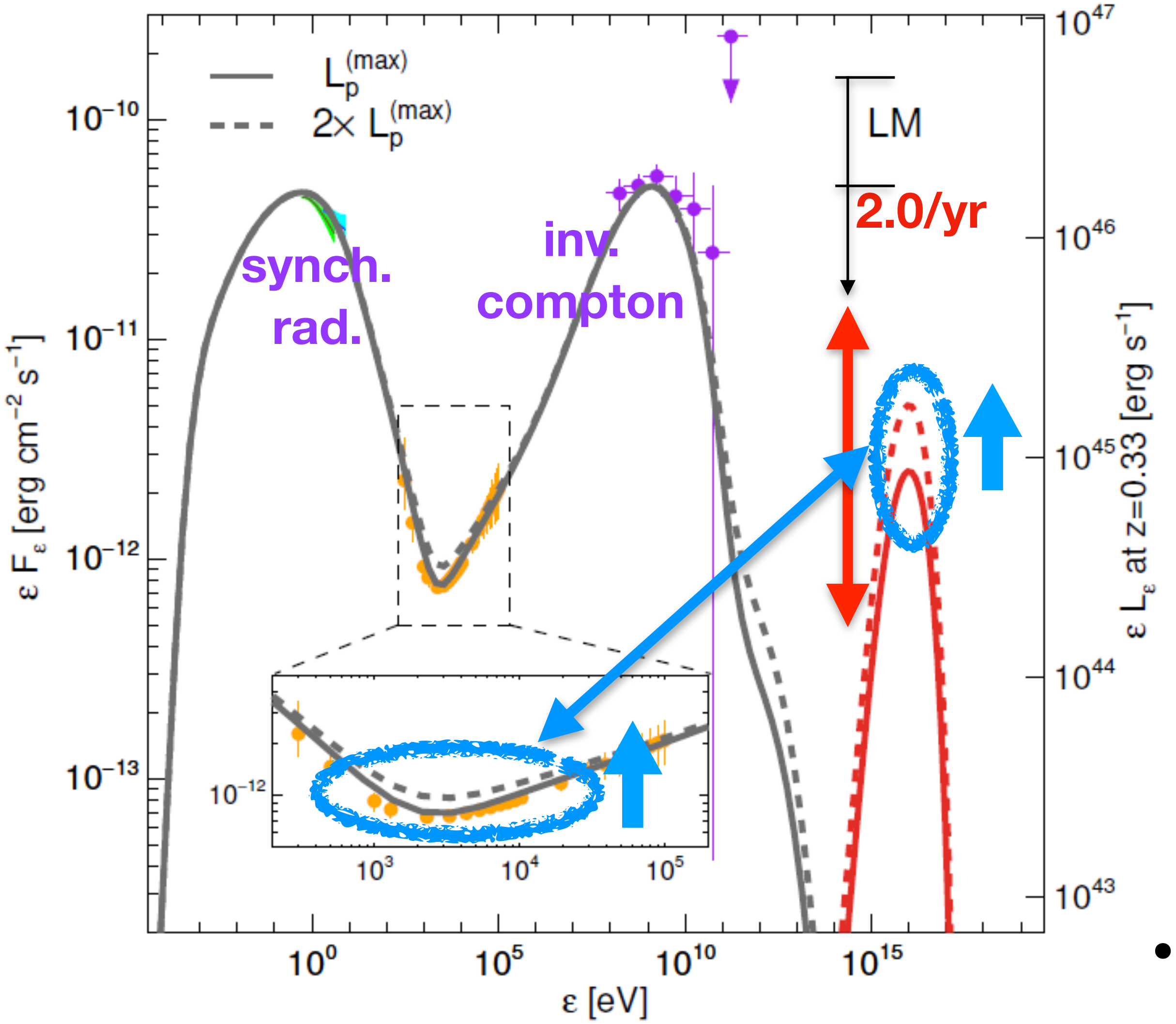
A. Keivani et al. [1807.04537]



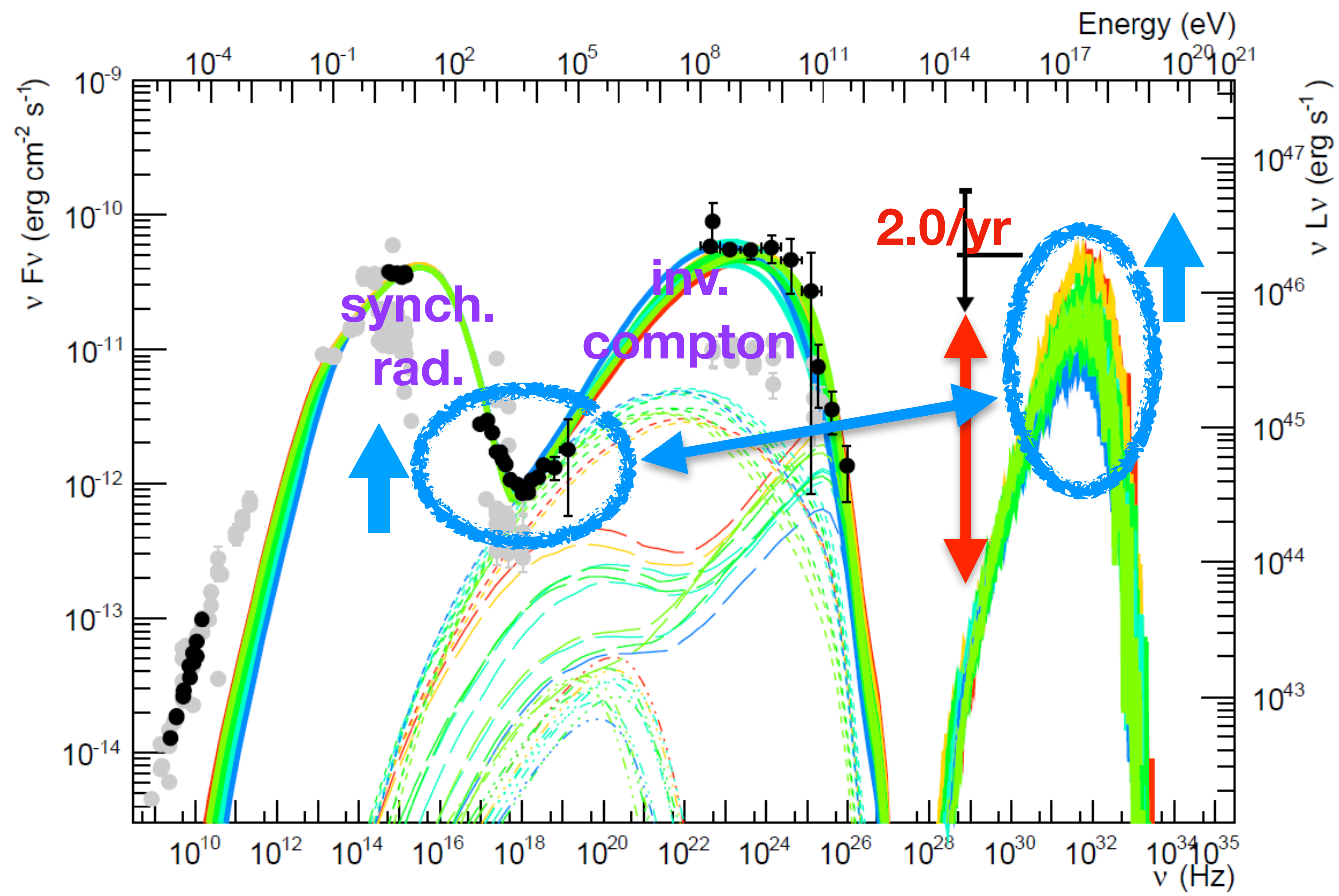
M. Cerruti et al. [1807.04335]

- Pure hadronic models has been ruled out due to the overshoot in X-ray.
- The leptonic model scenarios are favored to explain EM multi-wavelength obs.

Astrophysical models for Blazar



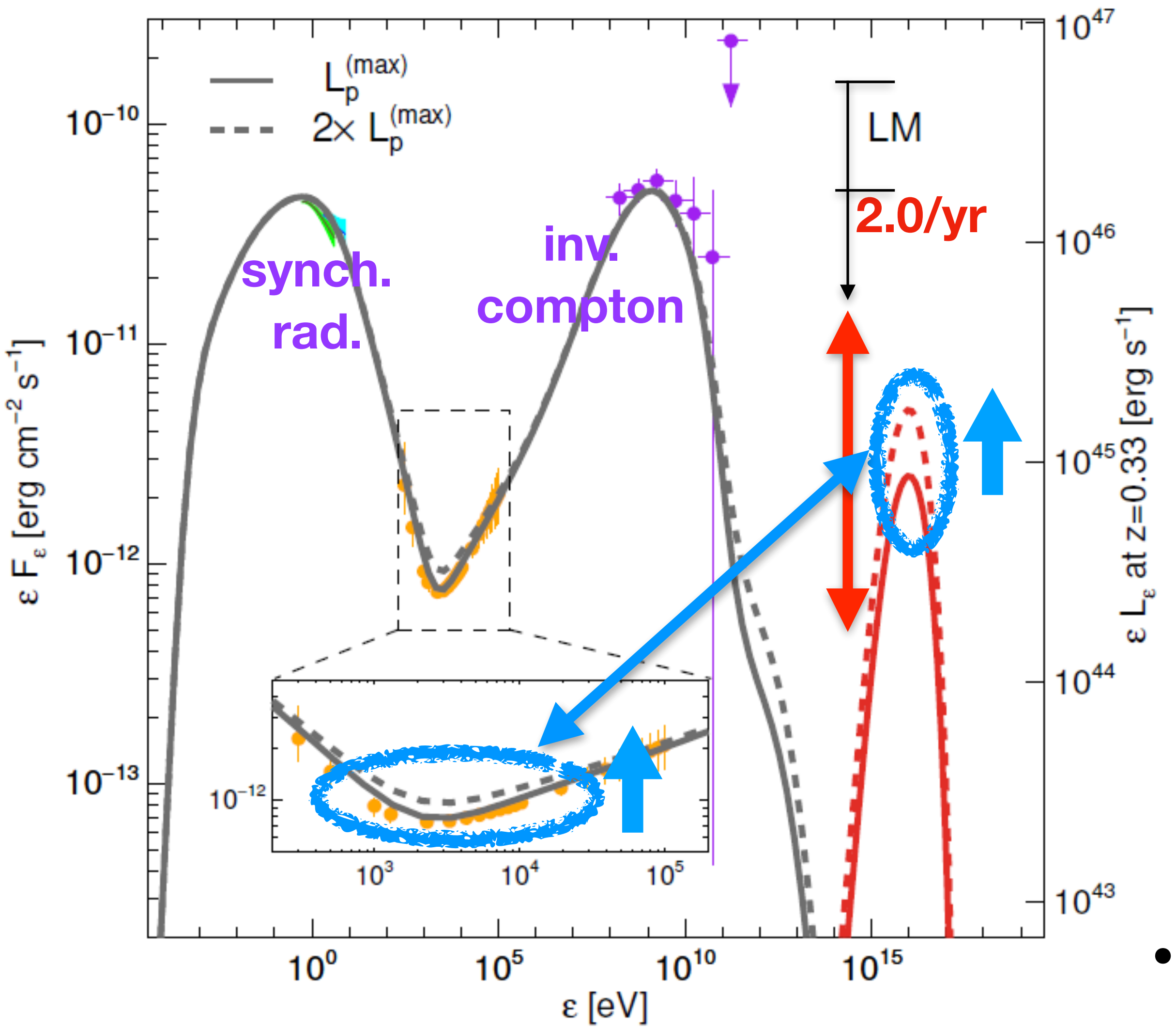
A. Keivani et al. [1807.04537]



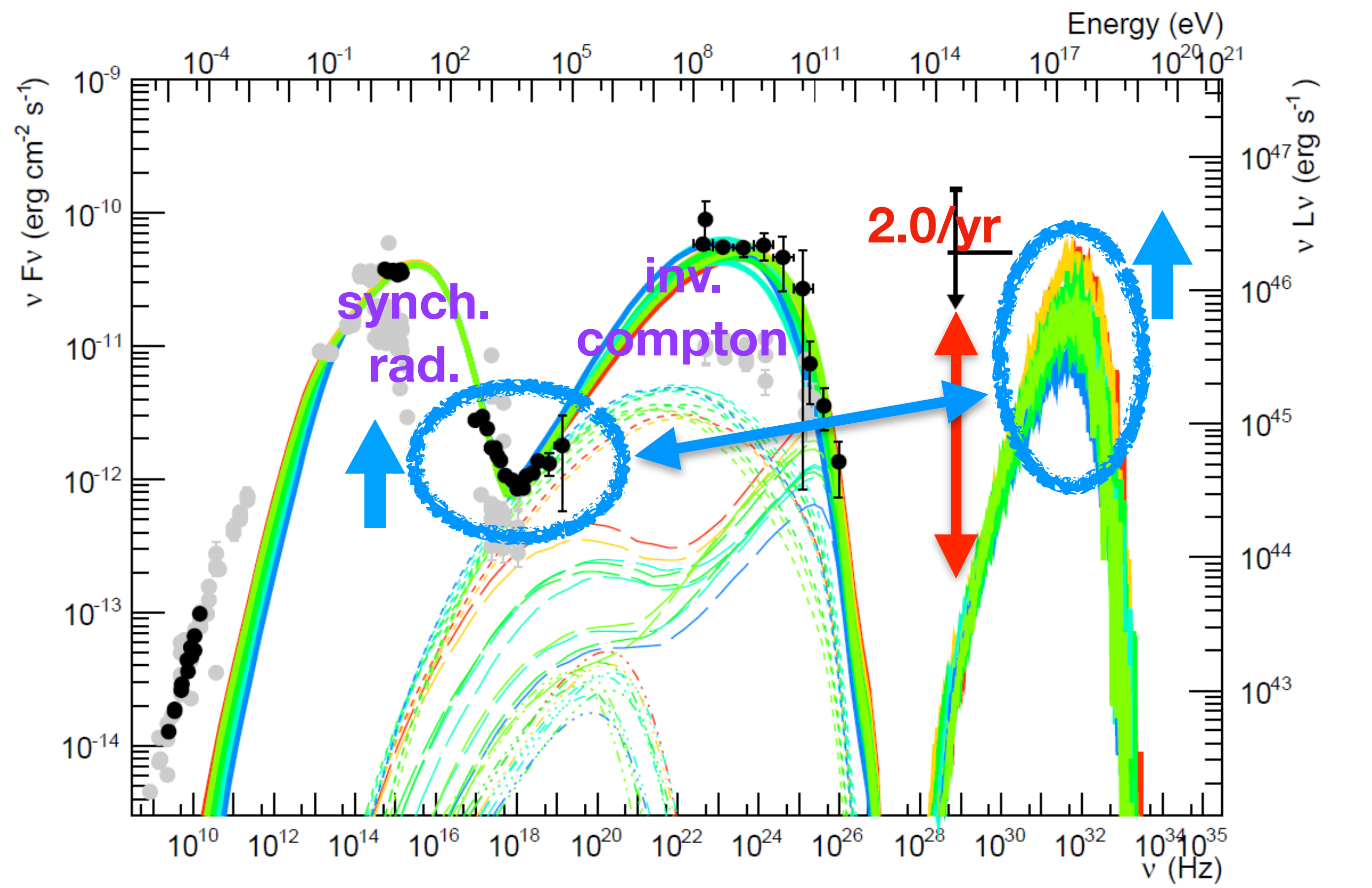
M. Cerruti et al. [1807.04335]

- Pure hadronic models has been ruled out due to the overshoot in X-ray.
- The leptonic model scenarios are favored to explain EM multi-wavelength obs.
- Most events are expected at O(100) PeV energies and Event rate at 100 TeV - 1 PeV energy is suppressed as ~ $10^{-3} - 10^{-2}/\mathrm{yr}$

Astrophysical models for Blazar



A. Keivani et al. [1807.04537]

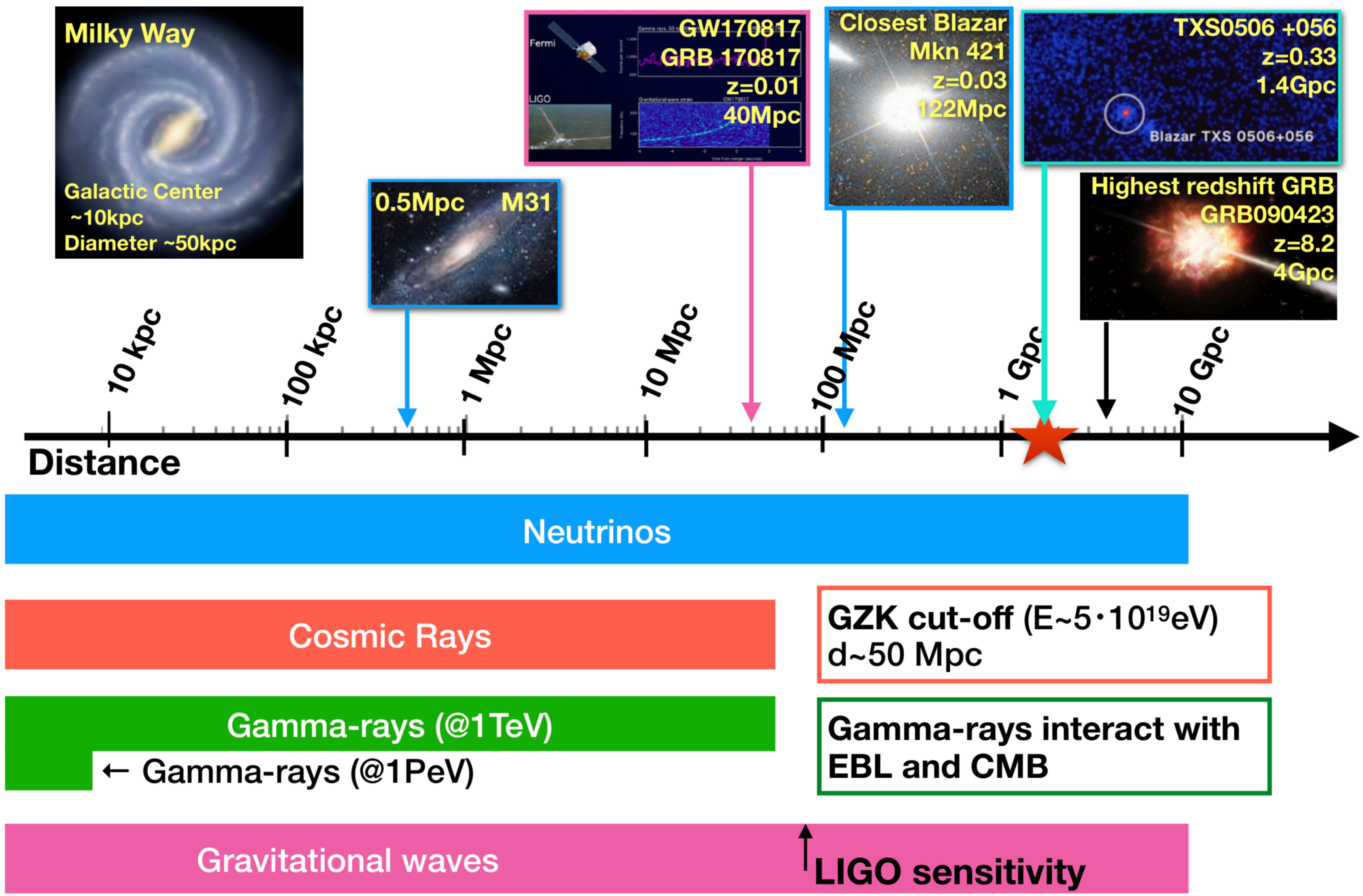


M. Cerruti et al. [1807.04335]

- Pure hadronic models has been ruled out due to the overshoot in X-ray.
- The leptonic model scenarios are favored to explain EM multi-wavelength obs.
- Most events are expected at O(100) PeV energies and Event rate at 100 TeV - 1 PeV energy is suppressed as ~ $10^{-3} - 10^{-2}/\mathrm{yr}$
  - Obtaining O(1)/yr event rate at IceCube is very tough within simplest astrophysical models.

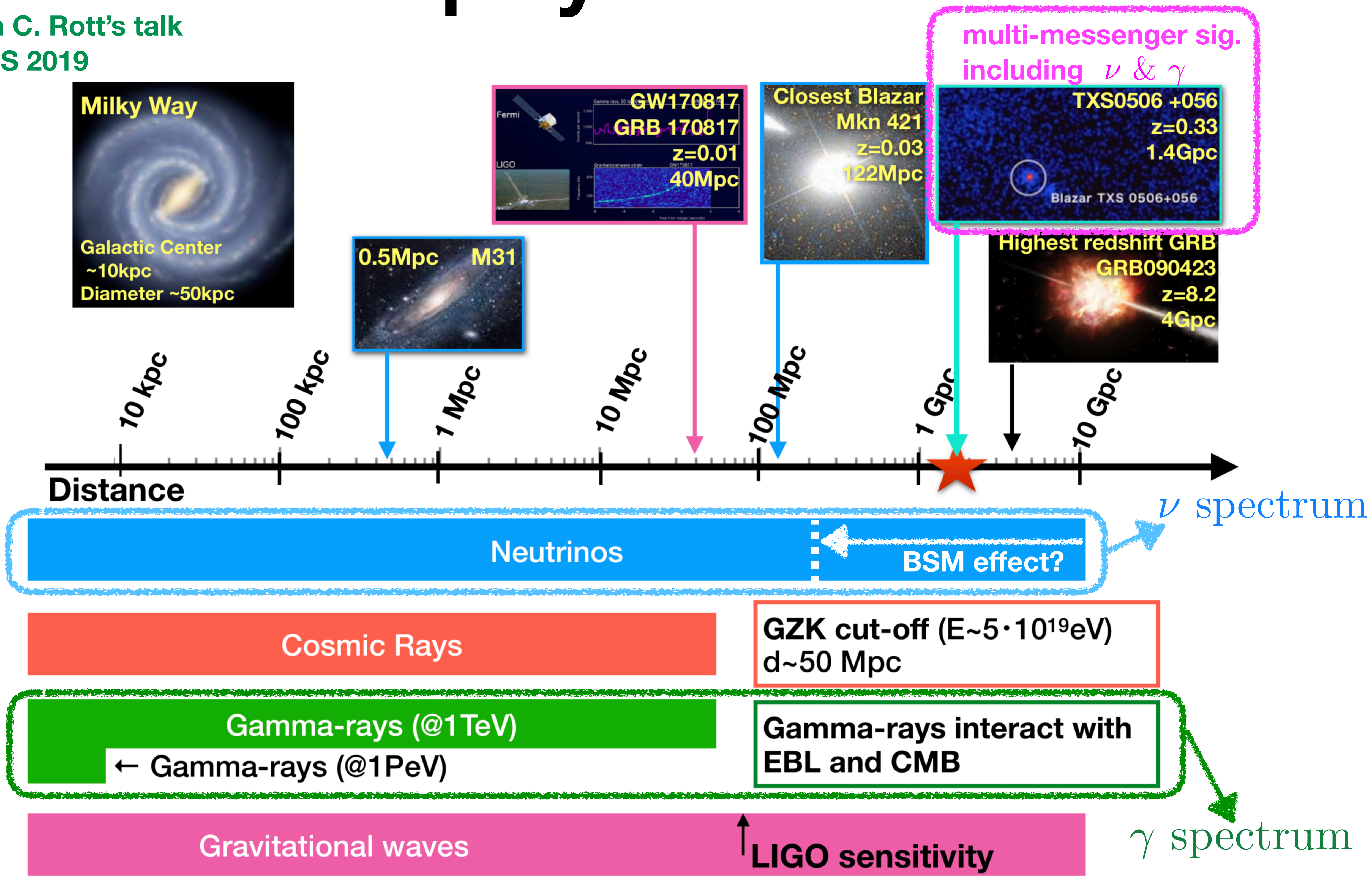
Propagation of messengers in astrophysical events

Fig. from C. Rott's talk @NEPLES 2019



Propagation of messengers in astrophysical events

Fig. from C. Rott's talk @NEPLES 2019



New self-interaction of neutrinos and neutrino cascade during propagation

- **Obtaining the modified flux with simple neutrino cascades**

$$\frac{\partial f_\nu(\epsilon_\nu^{\rm obs}, z)}{\partial t} = -\frac{c}{\lambda_\nu(\epsilon_\nu, z)} f_\nu(\epsilon_\nu^{\rm obs}, z) + \frac{4c}{\lambda_\nu(2\epsilon_\nu, z)} f_\nu(2\epsilon_\nu^{\rm obs}, z)$$

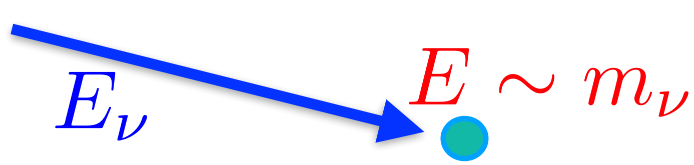
Absorption of energetic neutrino by resonance

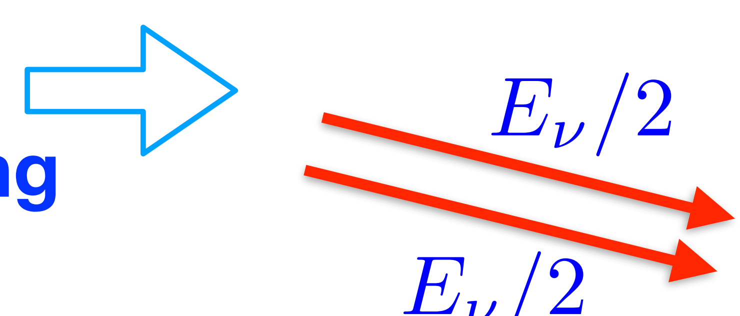
Production of down-scattered secondary neutrinos

MFP of neutrino

$$\lambda_\nu(\epsilon_\nu, z) = \frac{1}{n_\nu^{\rm C\nu B}(z) \cdot \sigma_\nu^{\nu \rm SI}(\epsilon_\nu)}$$

$$\sigma_\nu^{\nu \rm SI}(\epsilon_\nu) \simeq \frac{g_\phi^4}{16\pi} \frac{s}{(s - m_\phi^2)^2 + m_\phi^2 \Gamma_\phi^2}$$

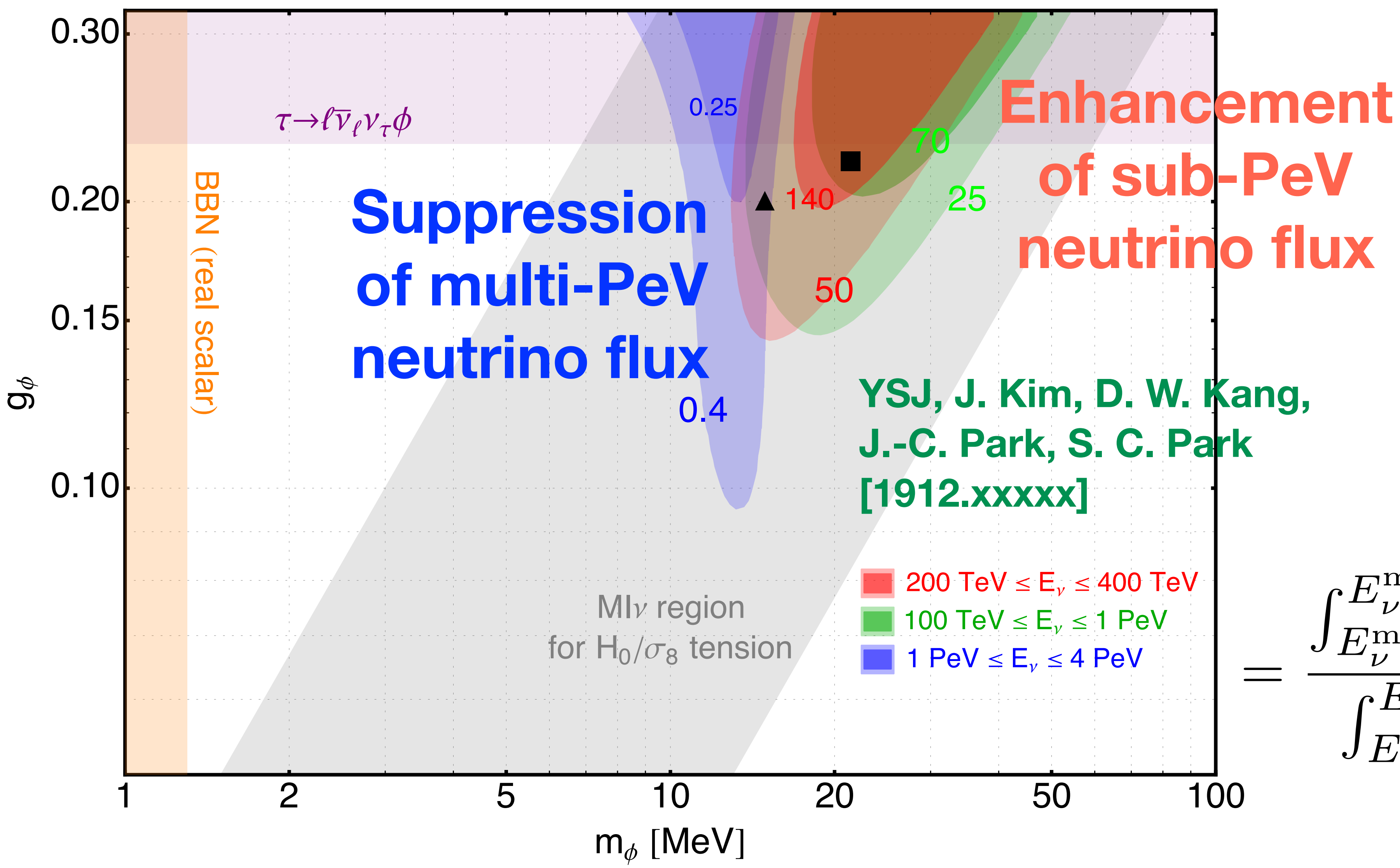




Neutrino cascade occurs during extragalactic propagation with MFP ~ O(200-1000) Mpc

Event spectrum at IceCube

- **Enhancement of neutrino flux at 100 TeV - 1 PeV** $\simeq \mathcal{O}(10-100)$ **without changing any EM component spectrum**
- **Suppression of neutrino flux at ~ 3-10 PeV by resonance**
  ➡ **The absence (or suppression) of multi-PeV neutrino events**

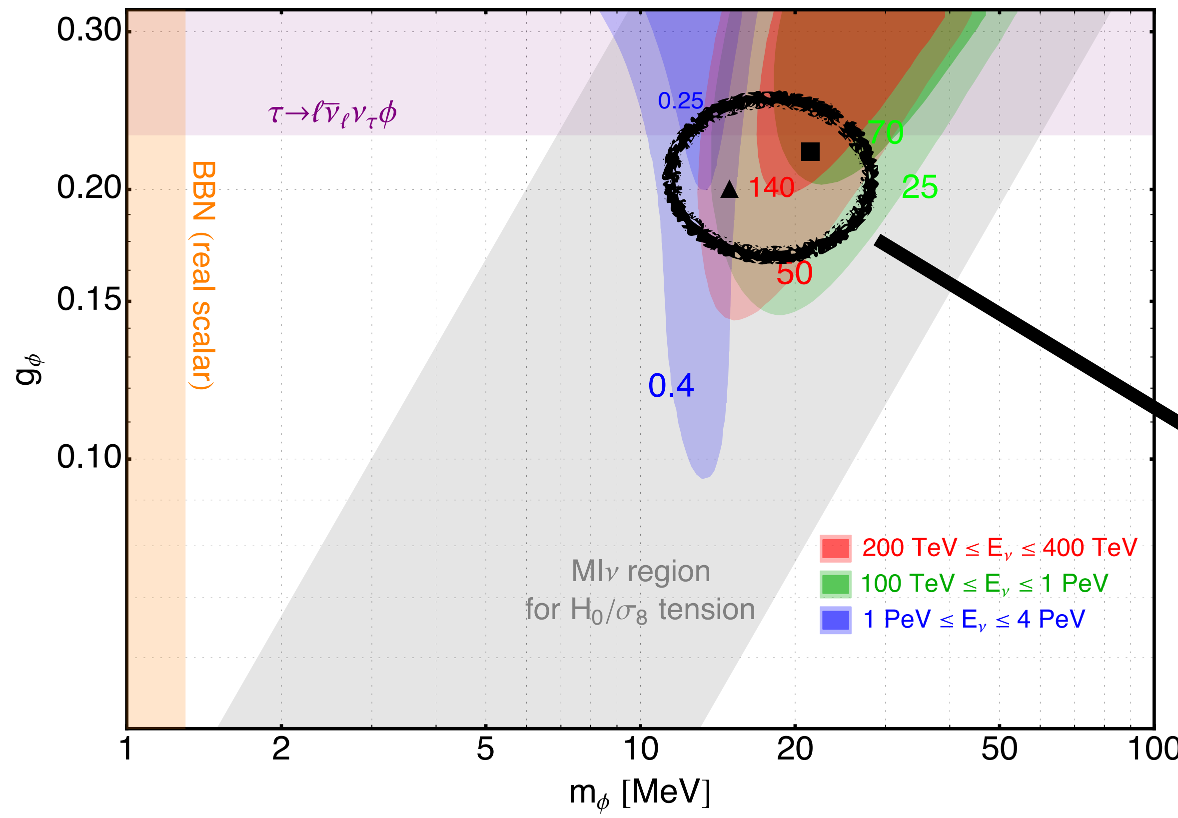


Enhanced # of events

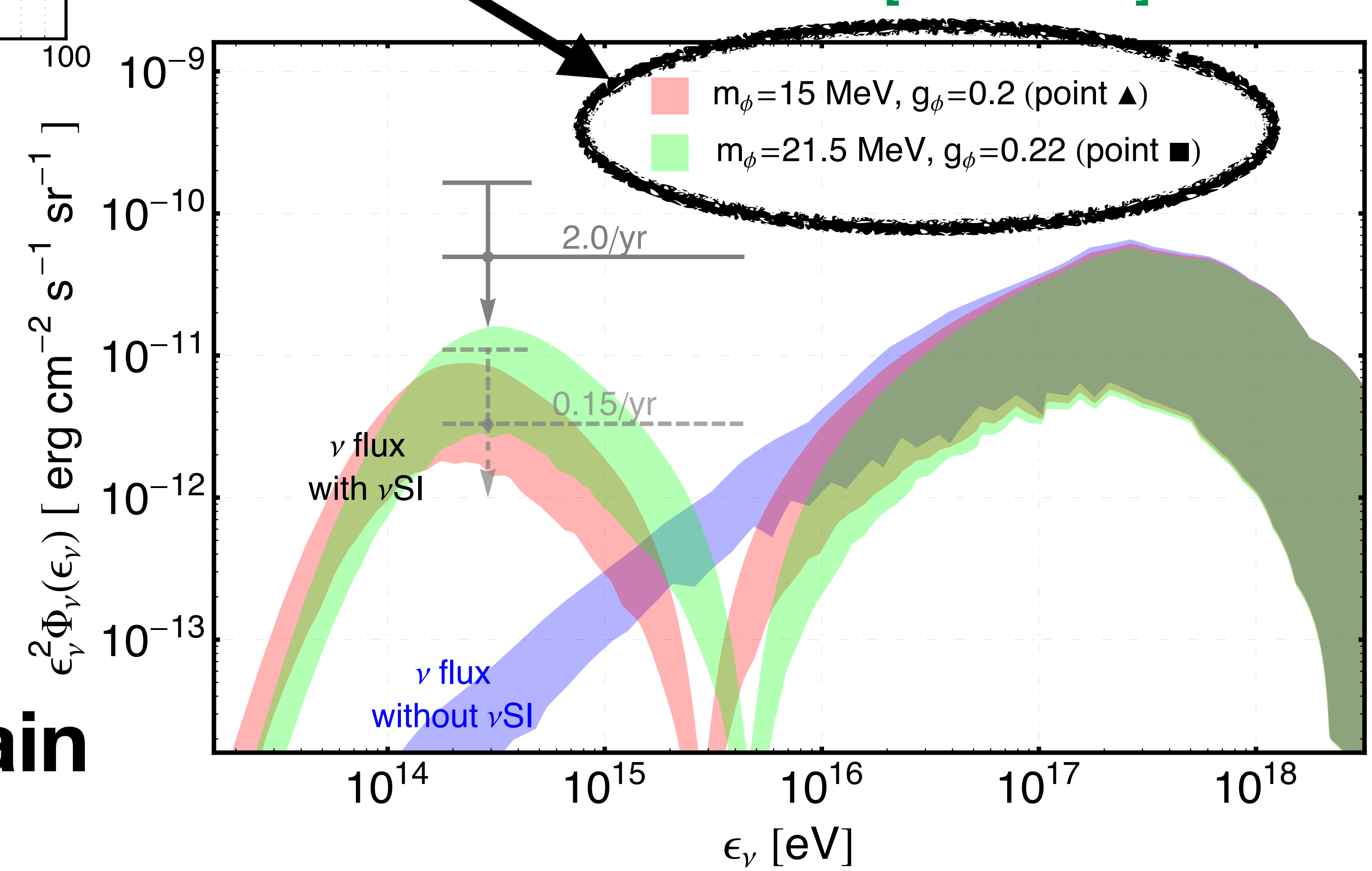
$$R_\nu(E_\nu^{\min}, E_\nu^{\max}, m_\phi, g_\phi) \equiv \left.\frac{N_\nu^{\mathrm{SM}+\phi}}{N_\nu^{\mathrm{SM}}}\right|_{E_\nu^{\min} \le E_\nu \le E_\nu^{\max}}$$

$$= \frac{\int_{E_\nu^{\min}}^{E_\nu^{\max}} A_{\mathrm{eff}}(E_\nu) \Phi_\nu^{\mathrm{SM}+\phi}(E_\nu) dE_\nu}{\int_{E_\nu^{\min}}^{E_\nu^{\max}} A_{\mathrm{eff}}(E_\nu) \Phi_\nu^{\mathrm{SM}}(E_\nu) dE_\nu}$$

Event spectrum at IceCube



YSJ, J. Kim, D. W. Kang, J.-C. Park, S. C. Park [1912.xxxxx]



- **Observation of multi-PeV neutrinos from distant sources (> O(1) Gpc) can constrain this scenario in future.**

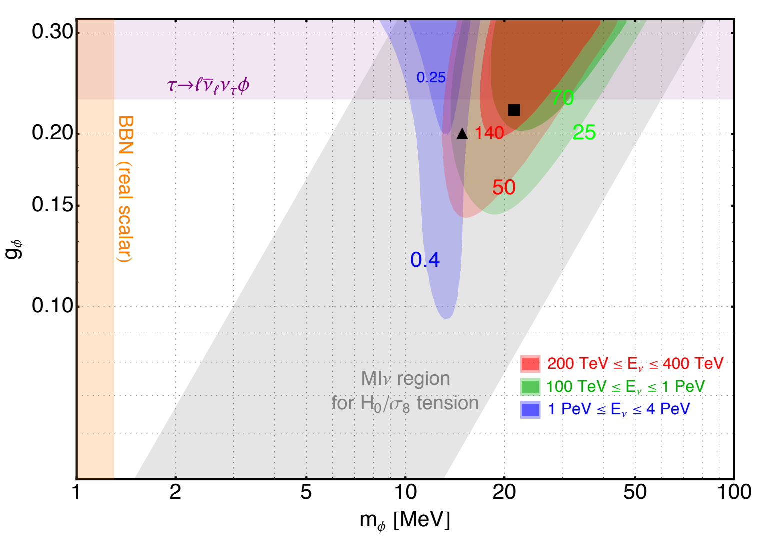
Conclusion

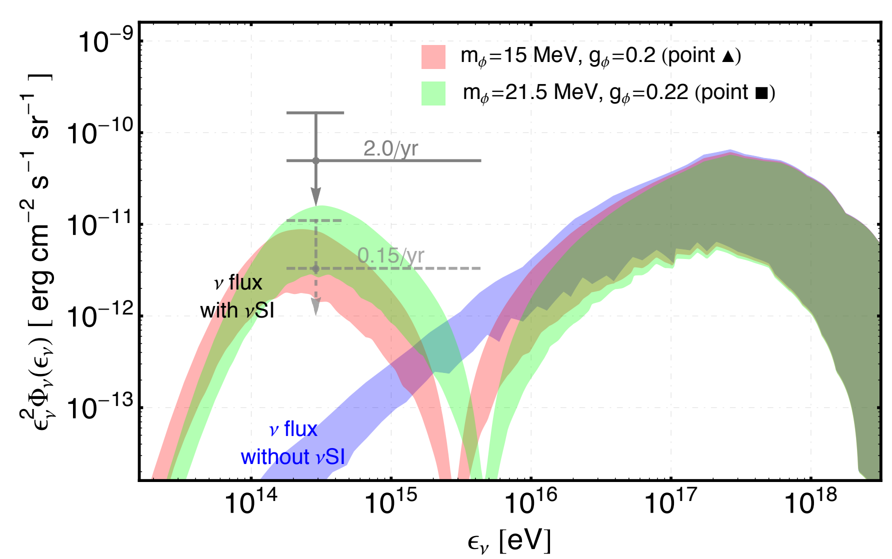
- The neutrino flare at TXS 0506+056 is **a first complete set of multi-messenger observation** including **photons** and **neutrinos**.

- Pure hadronic models are disfavored and
 Leptonic models are suffered from the explanation of IceCube neutrino obs.

- **Neutrino self-interaction** with a light hidden mediator (m ~ 10-50 MeV) **enhances in O(100) TeV neutrinos** and **suppresses O(1-10) PeV neutrinos** due to the neutrino cascade during propagation that can explain the observed anomaly.

- Future multi-messenger observation will increase the statistics for the test of this scenarios, providing the detailed features of low energy neutrino sector.





backup slides