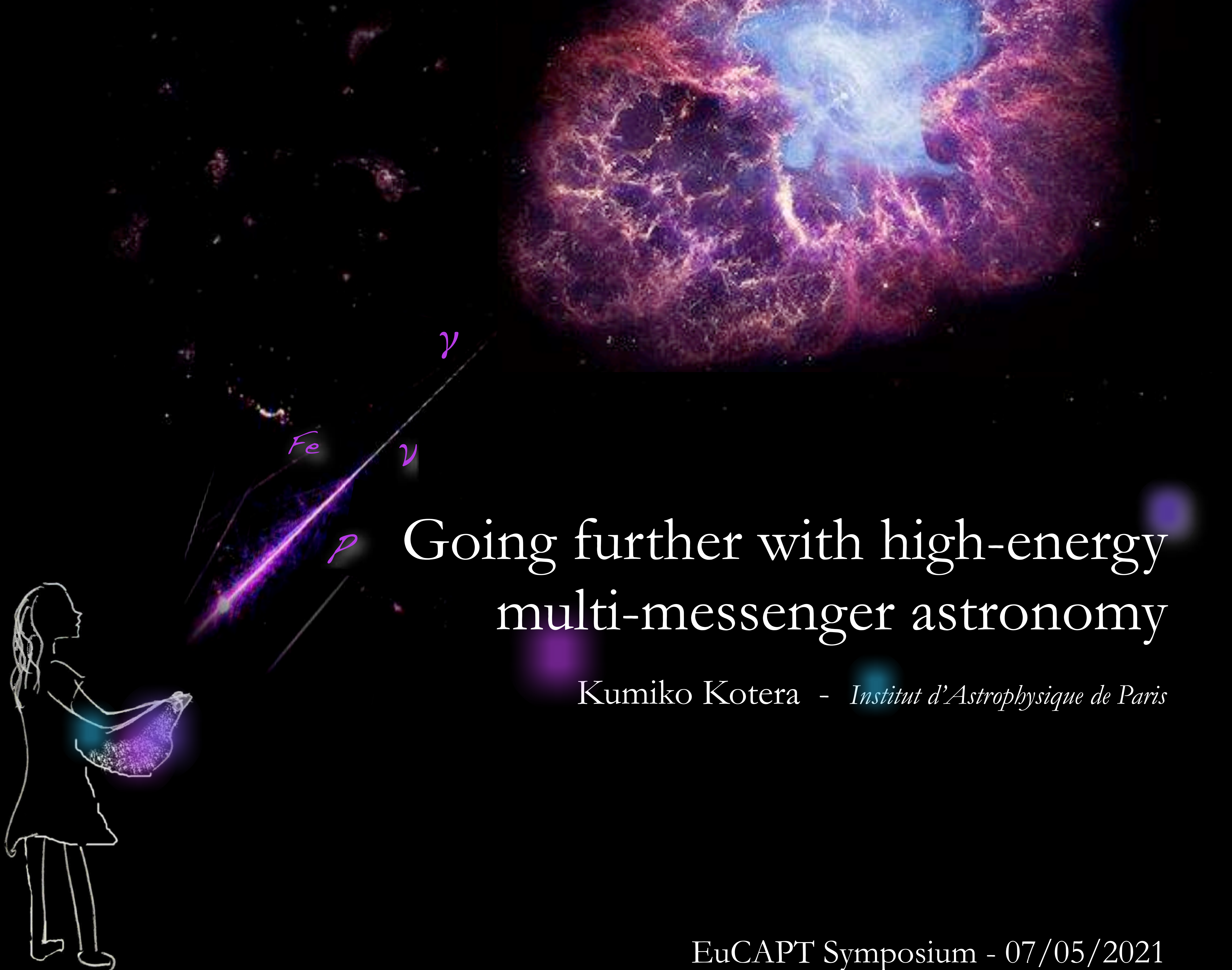
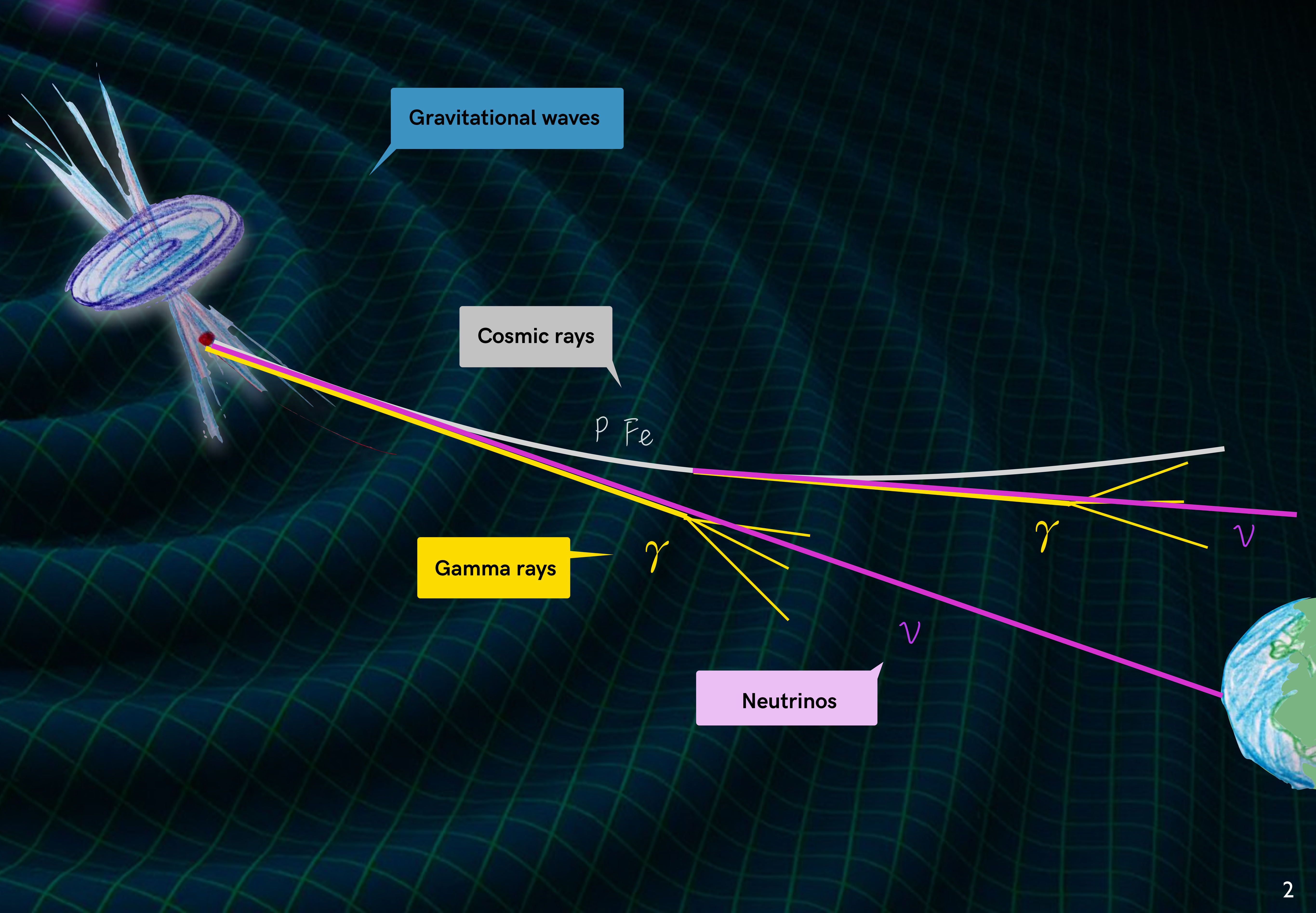


Going further with high-energy multi-messenger astronomy

Kumiko Kotera - *Institut d'Astrophysique de Paris*

EuCAPT Symposium - 07/05/2021

Multi-messengers!

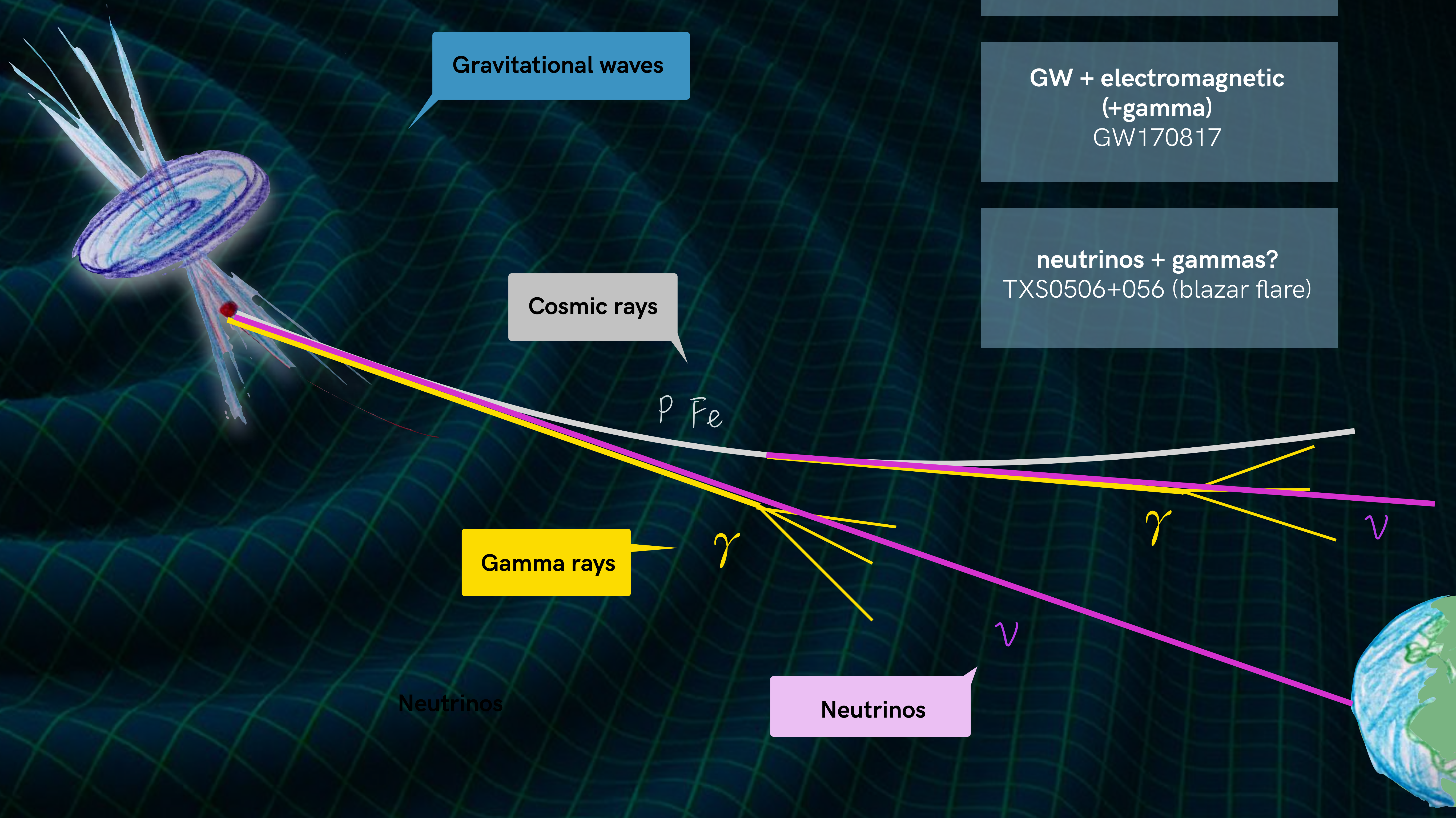


Multi-messengers!

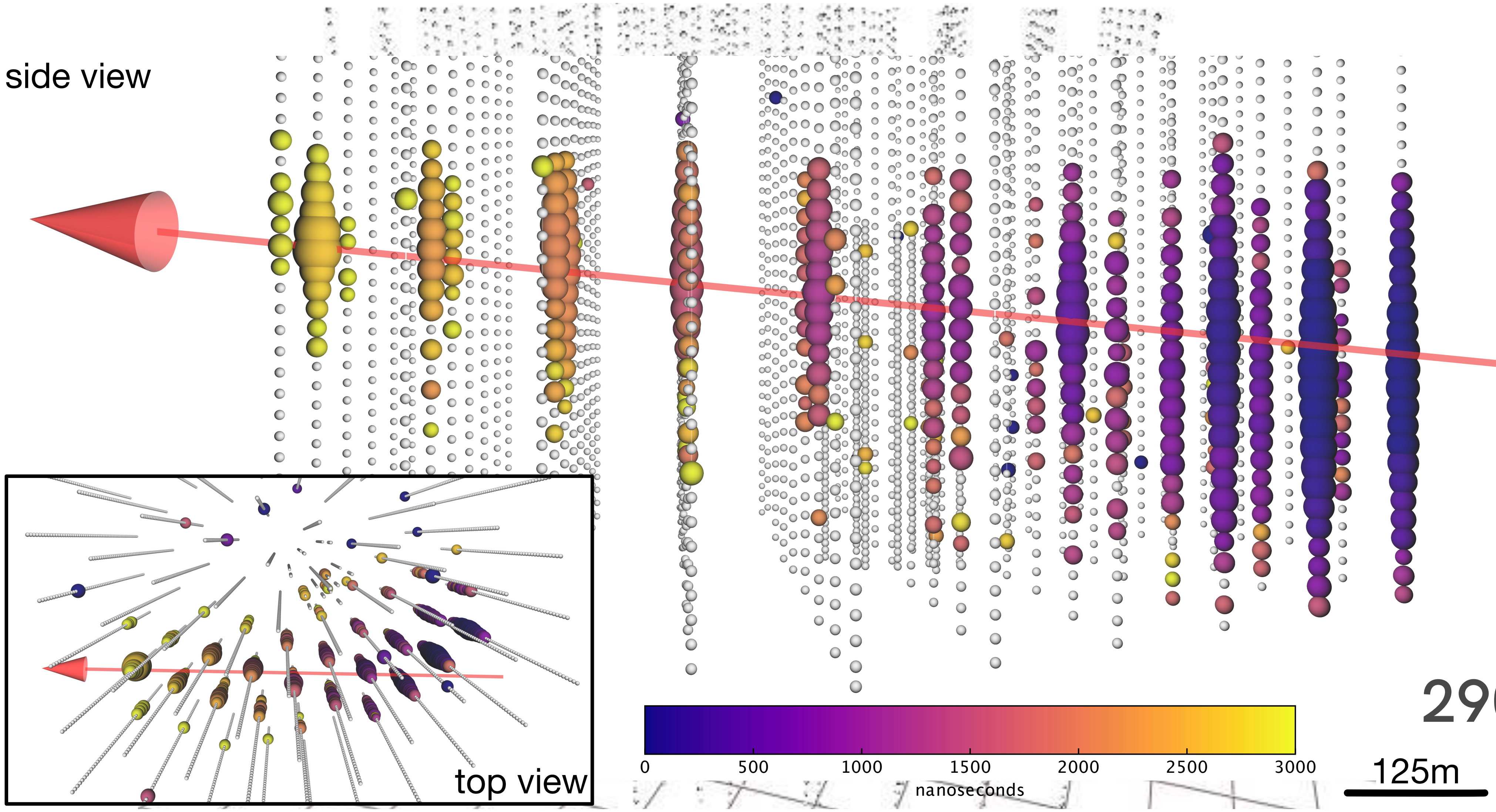
cosmic rays + others
—> temporal coincidence
impossible (deflections)
but studies of diffuse fluxes

GW + electromagnetic (+gamma)
GW170817

neutrinos + gammas?
TXS0506+056 (blazar flare)



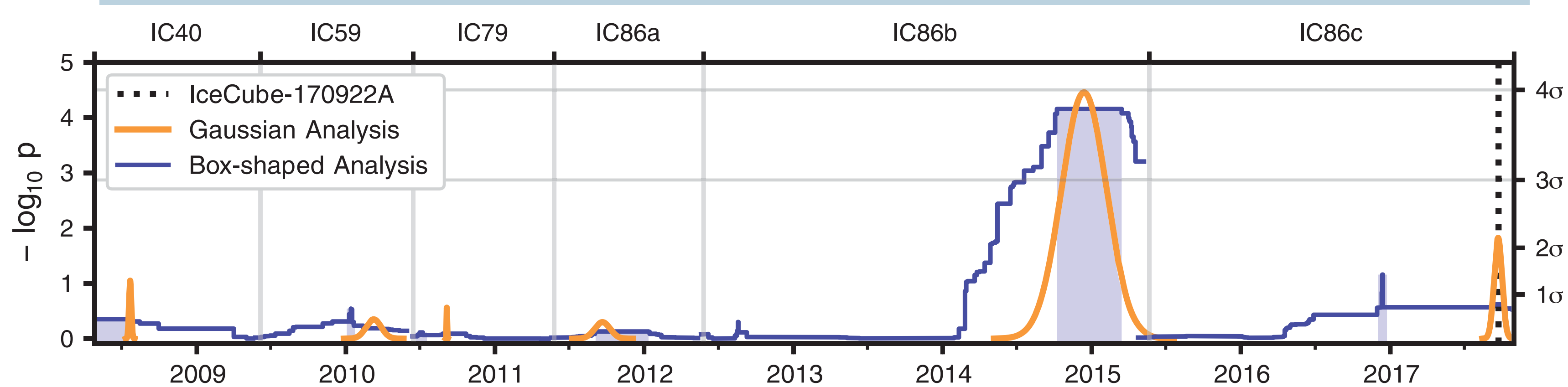
Neutrino flares and TXS 0506+56



IC170922A:
290 TeV neutrino

IceCube Coll. Science (2018)

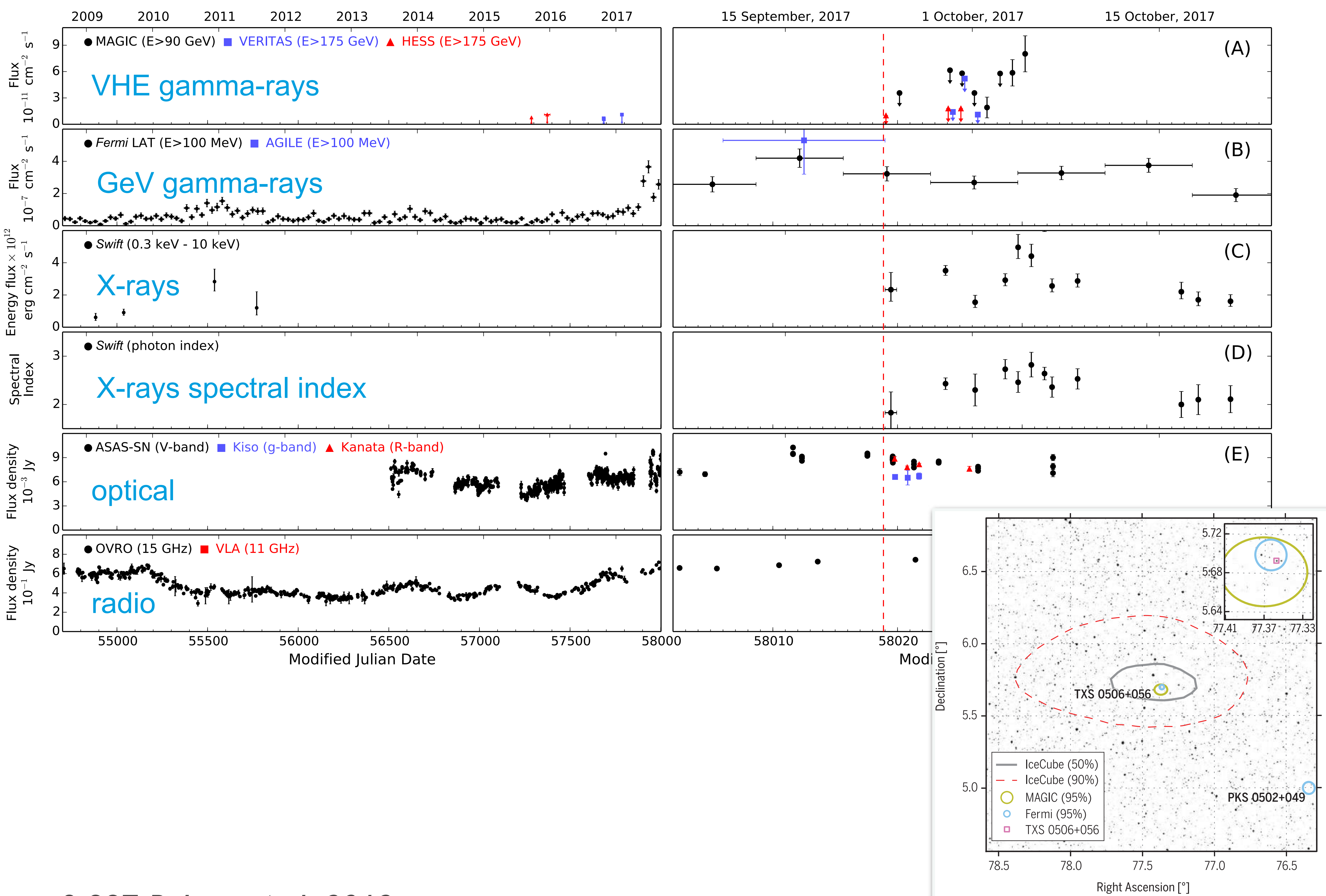
13±5 above the background of atmospheric neutrinos, 3.5σ



Neutrino flares and TXS 0506+56

Post-trials p-value for association: 3.0σ

IceCube Collaboration, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, et al., Science (2018)

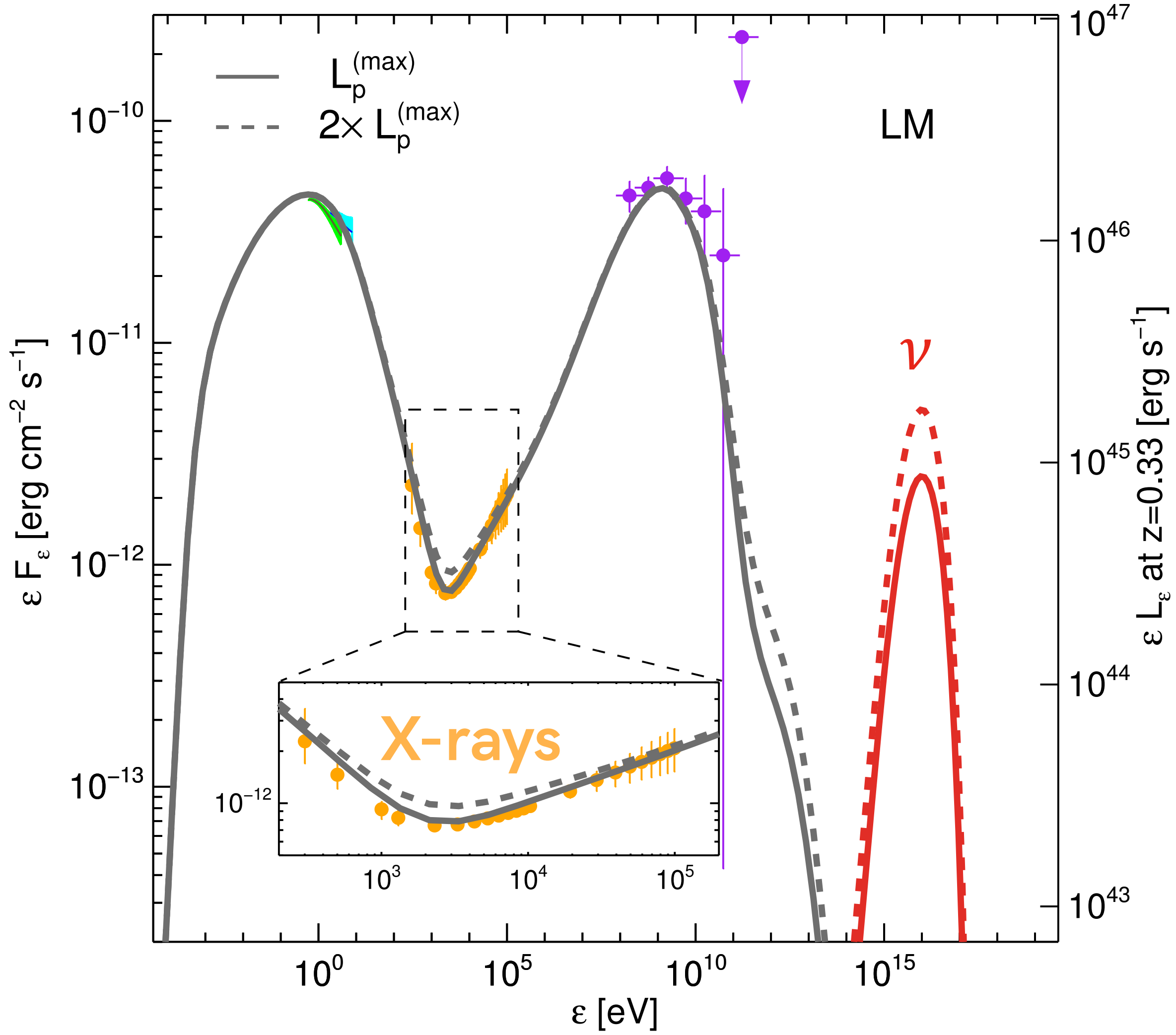


z~0.337 *Paiano et al. 2018*

Candidate Neutrino Source: TXS 0506+056

Keivani et al. 2018

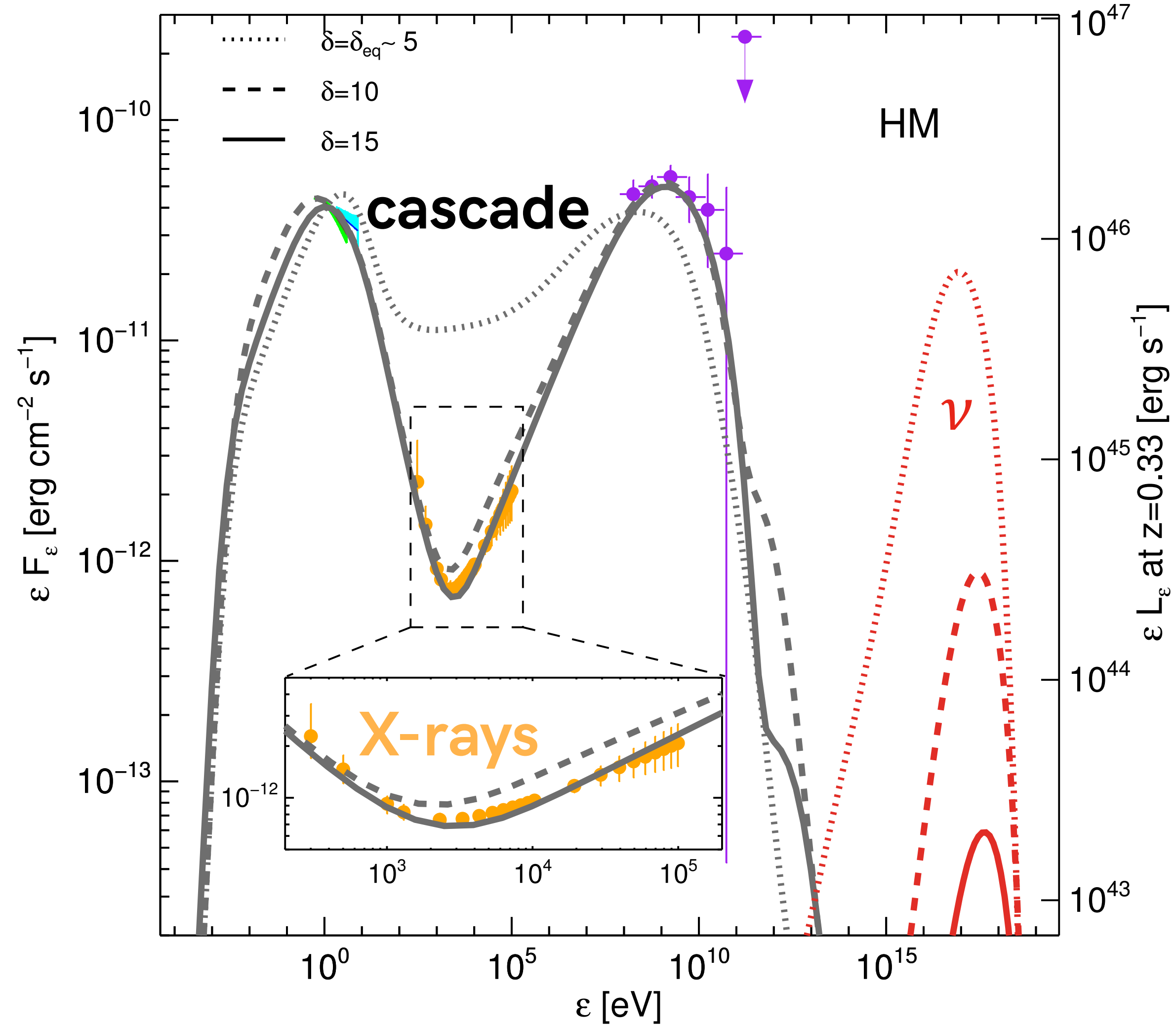
leptonic model



leptonic with radiatively subdominant hadronic component

detection proba. with IC in real time during 6-month flare = 1-2%

hadronic model



cascade implies high X-ray level to match observed neutrino flux

lucky?

but the 2014-2015 neutrino flares require higher rates
(L~ 10^{47} erg/s over 158 days ~ 4 x average gamma-ray luminosity)

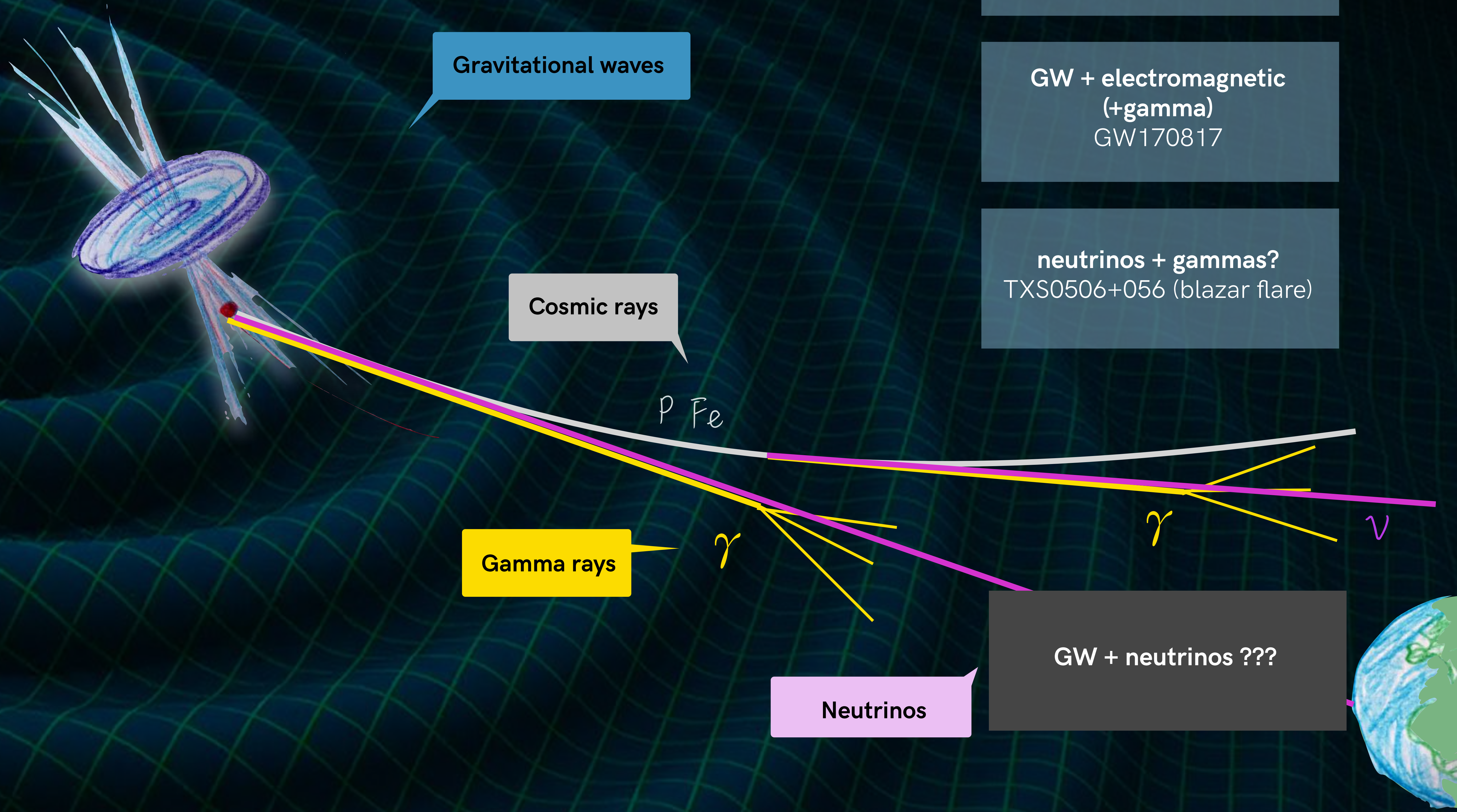
Gao et al. 2018
Cerruti et al. 2018
Zhang, Fang & Li 2018
Gokus et al. 2018
Sahakyan 2018

Multi-zone or more complicated models?
- Additional photomeson production by external radiation fields
- hadronuclear production (e.g., jet-cloud interaction)

More parameters introduced, the setup is ad-hoc

Murase, Oikonomou, Petropoulou 2018

Multi-messengers!



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GW170817

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TXS0506+056 (blazar flare)

GW + neutrinos ???

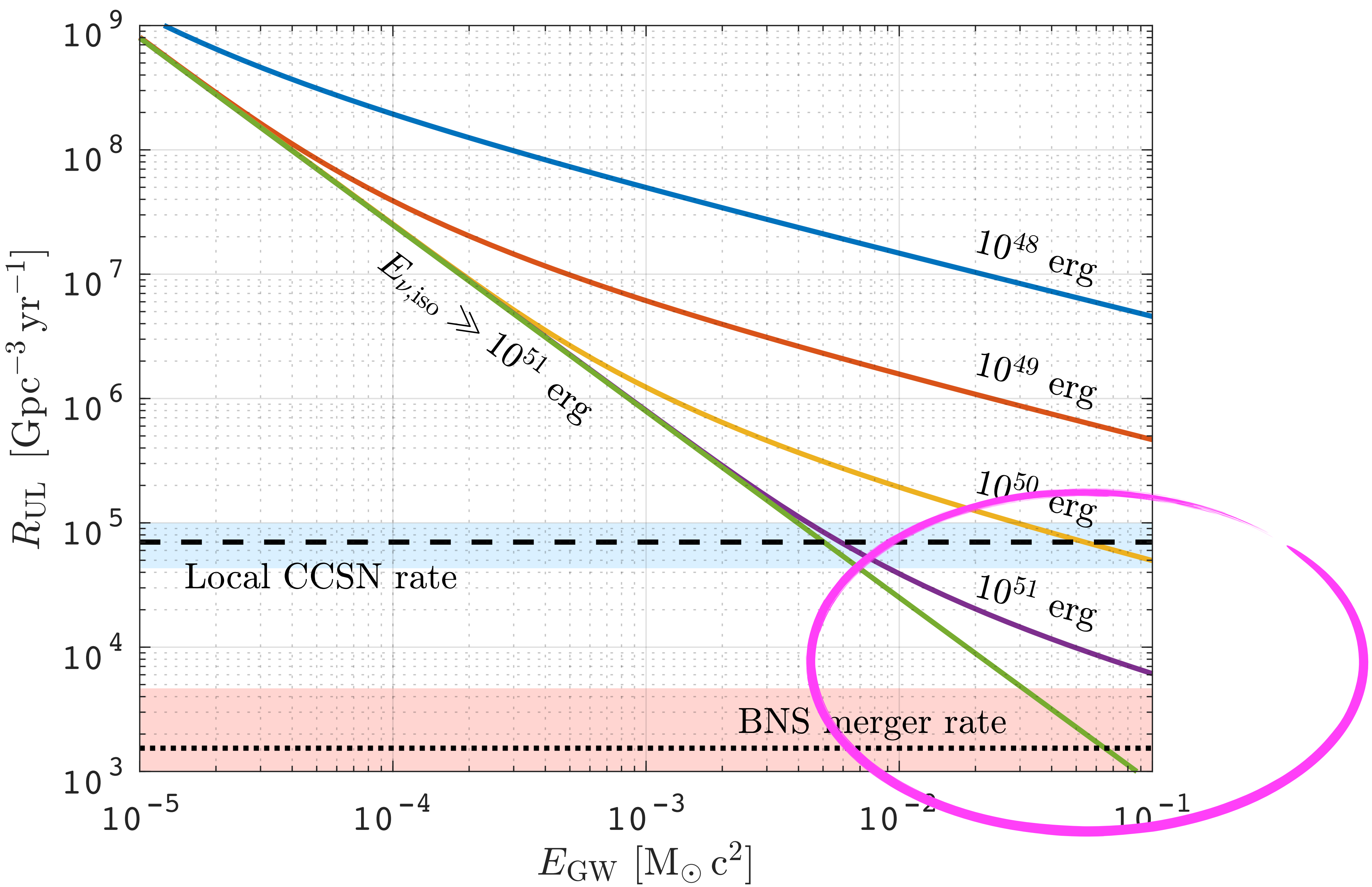
Population constraints from GW+neutrino non-detection

Albert et al. 2019 ApJ 870 134

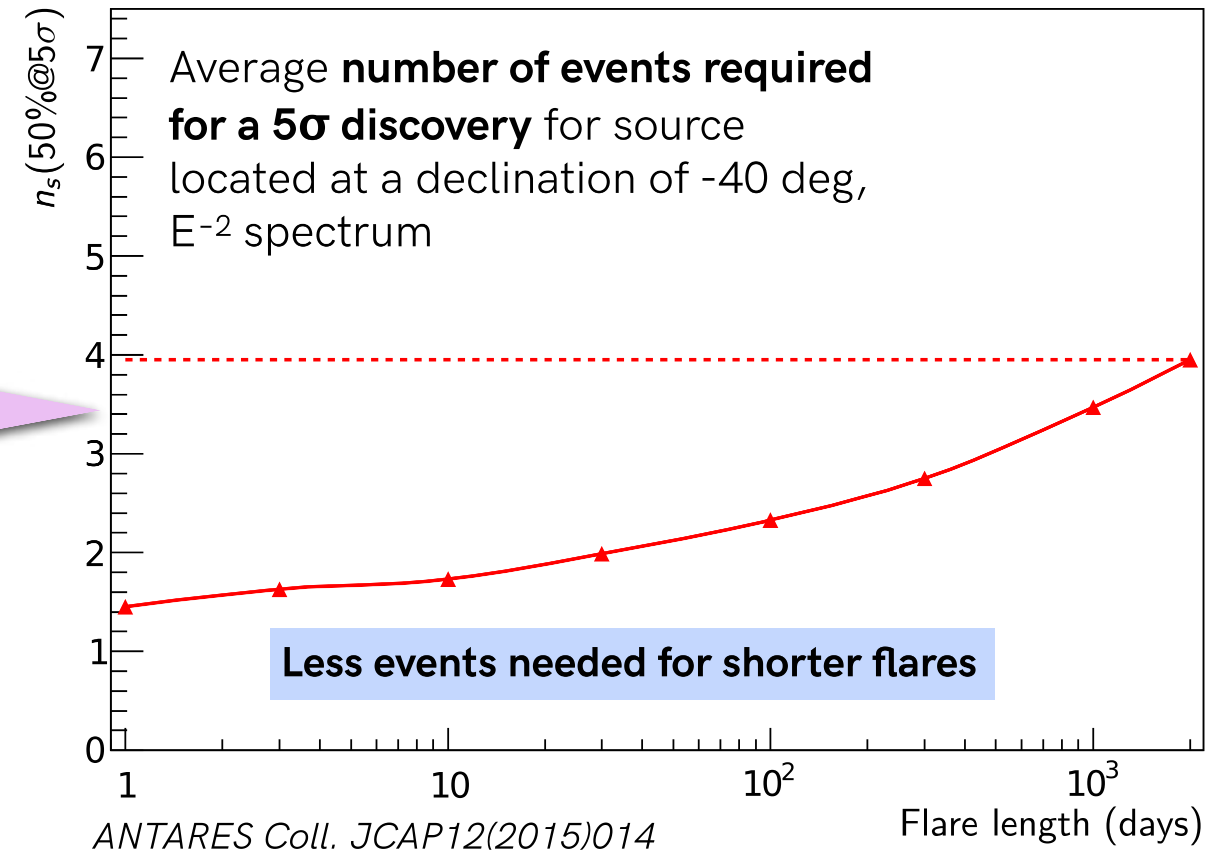
Advanced LIGO

IceCube+ANTARES

Upper limits on rate density of GW+neutrino sources

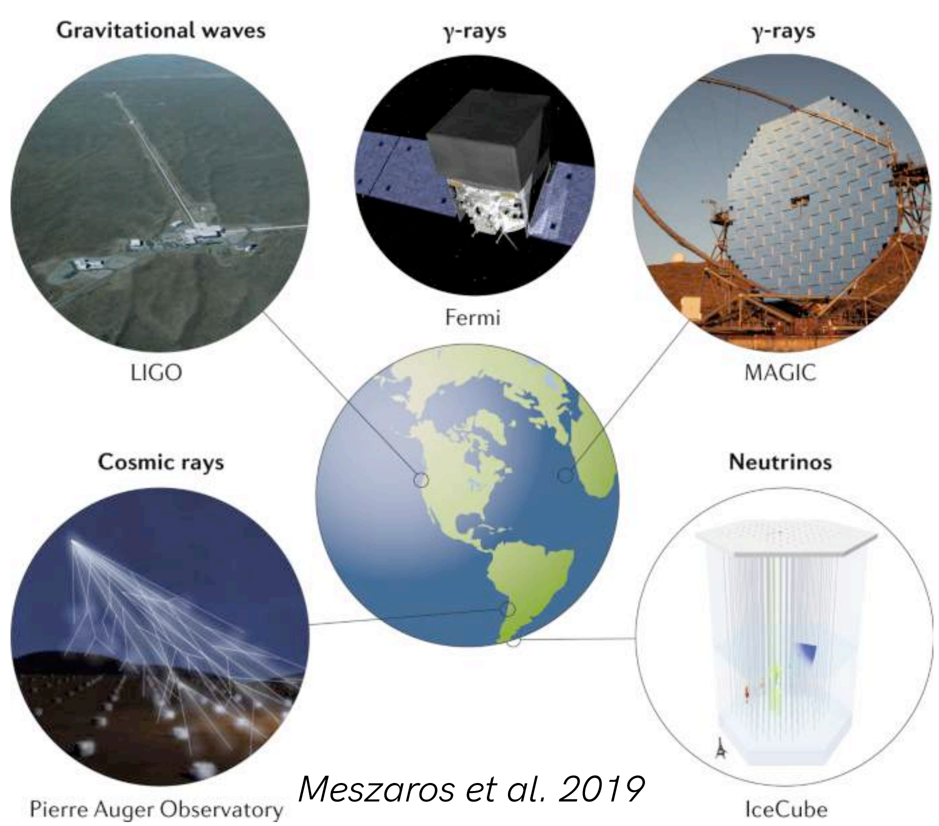


Why focus on transient sources?



ANTARES Coll. JCAP12(2015)014

time-dependent neutrino searches **reduce the background** for sub-PeV energies (atmospheric neutrinos+muons)



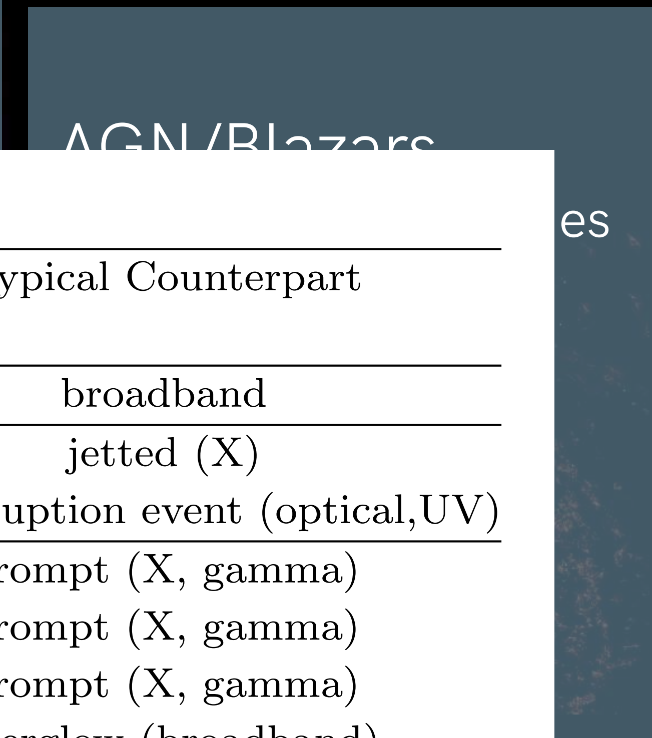
Meszaros et al. 2019

Real-time analysis + multi-messenger follow-up on alerts increase statistical significance of signals

The new high-energy transient zoo

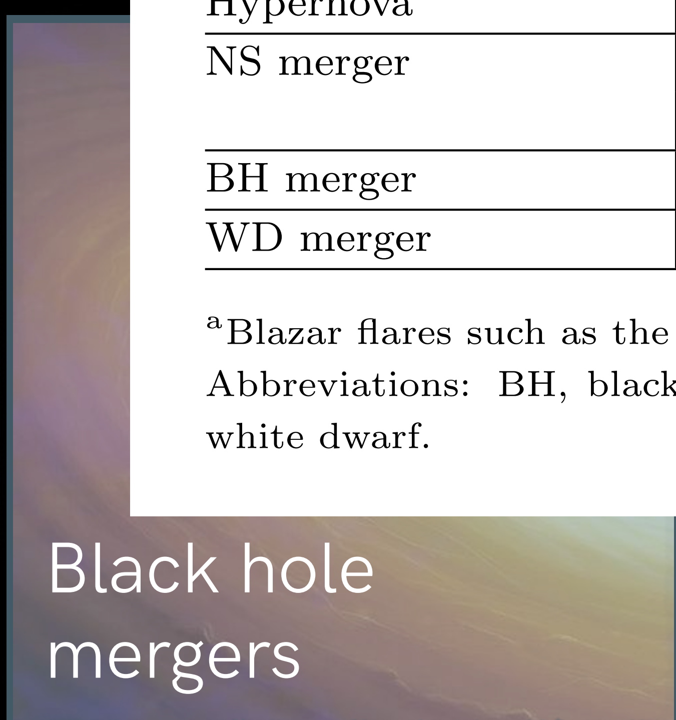
The new high-energy transient zoo

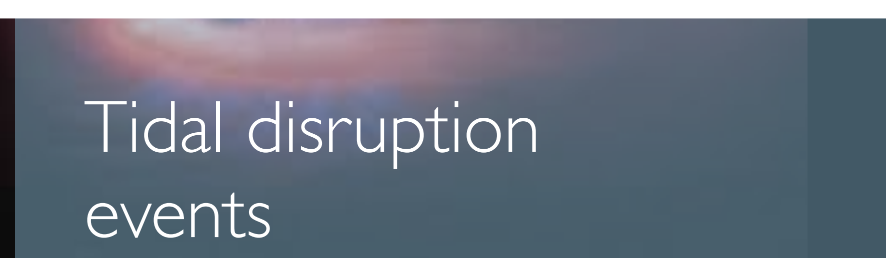
Murase & Bartos 2019

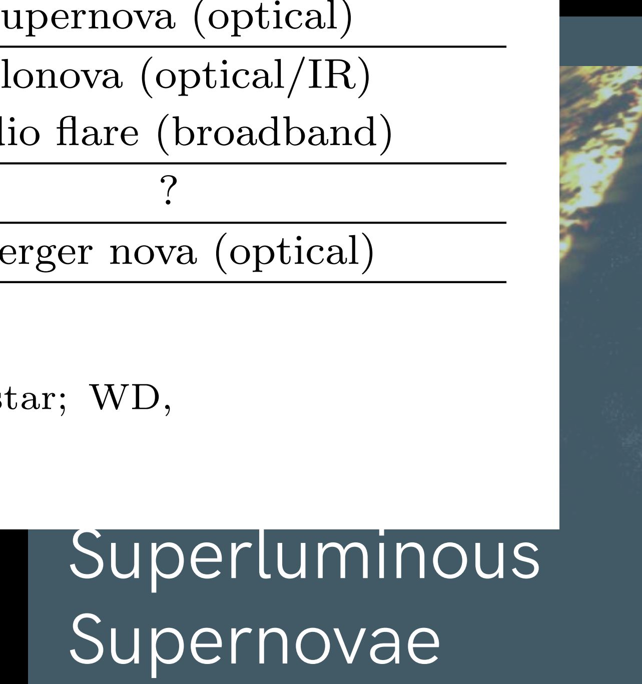


Source	Rate density [Gpc^{-3} yr^{-1}]	EM Luminosity [erg s^{-1}]	Duration [s]	Typical Counterpart
Blazar flare[a]	$10 - 100$	$10^{46} - 10^{48}$	$10^{6} - 10^{7}$	broadband
Tidal disruption event	$0.01 - 0.1$	$10^{47} - 10^{48}$	$10^{6} - 10^{7}$	jetted (X)
	$100 - 1000$	$10^{43.5} - 10^{44.5}$	$> 10^{6} - 10^{7}$	tidal disruption event (optical,UV)
Long GRB	$0.1 - 1$	$10^{51} - 10^{52}$	$10 - 100$	prompt (X, gamma)
Short GRB	$10 - 100$	$10^{51} - 10^{52}$	$0.1 - 1$	prompt (X, gamma)
Low-luminosity GRB	$100 - 1000$	$10^{46} - 10^{47}$	$1000 - 10000$	prompt (X, gamma)
GRB afterglow		$< 10^{46} - 10^{51}$,	$> 1 - 10000$	afterglow (broadband)
Supernova (II)	10^{5}	$10^{41} - 10^{42}$	$> 10^{5}$	supernova (optical)
Supernova (Ibc)	3×10^{4}	$10^{41} - 10^{42}$	$> 10^{5}$	supernova (optical)
Hypernova	3000	$10^{42} - 10^{43}$	$> 10^{6}$	supernova (optical)
NS merger	$300 - 3000$	$10^{41} - 10^{42}$	$> 10^{5}$	kilonova (optical/IR)
		10^{43}	$> 10^{7} - 10^{8}$	radio flare (broadband)
BH merger	$10 - 100$	?	?	?
WD merger	$10^{4} - 10^{5}$	$10^{41} - 10^{42}$	$> 10^{5}$	merger nova (optical)

[a]Blazar flares such as the 2017 flare of TXS 0506+056 are assumed for the demonstration.
Abbreviations: BH, black hole; EM, electromagnetic; GRB, gamma-ray burst; NS, neutron star; WD, white dwarf.

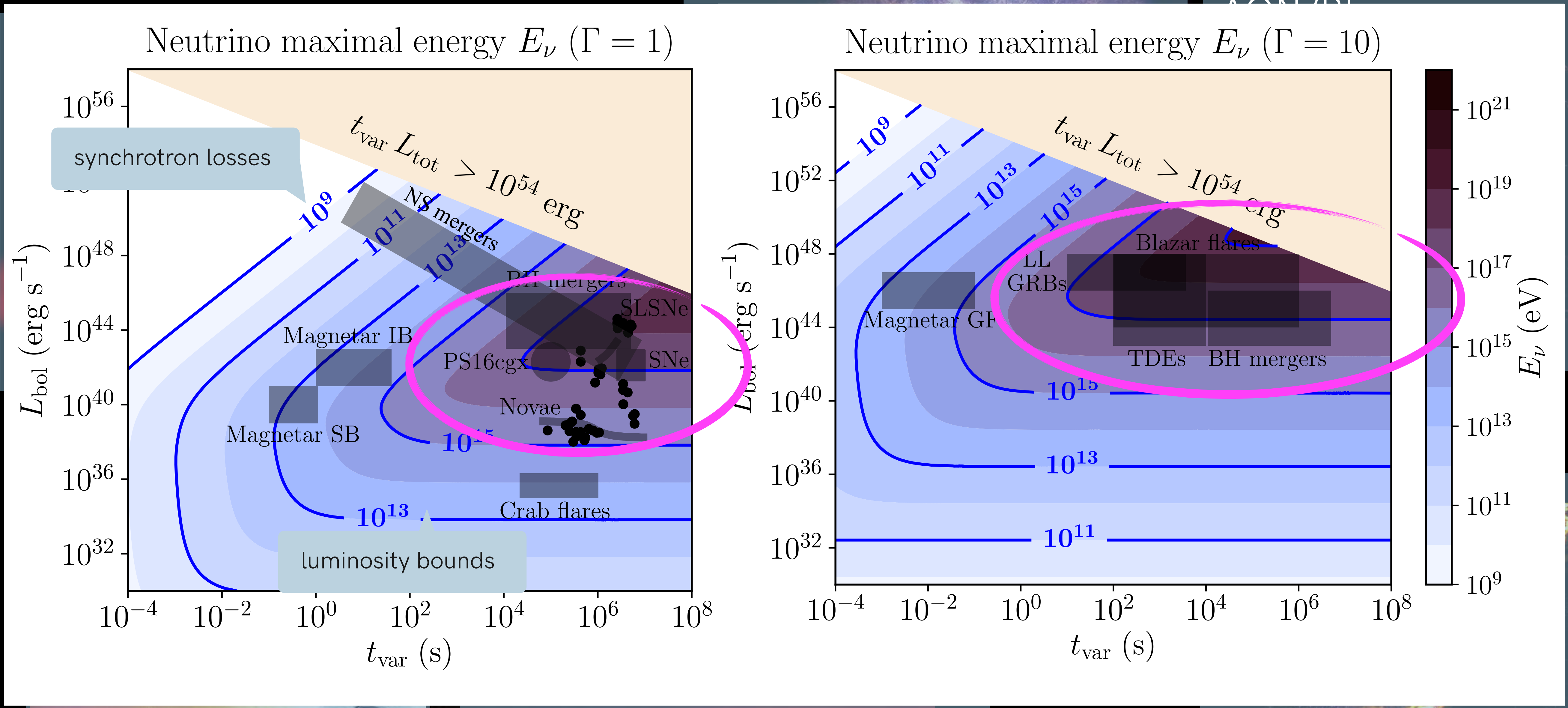


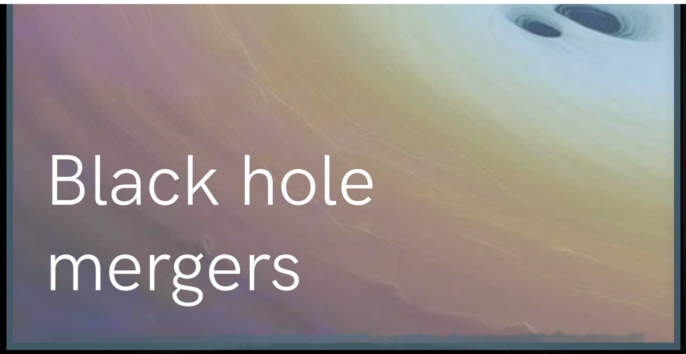


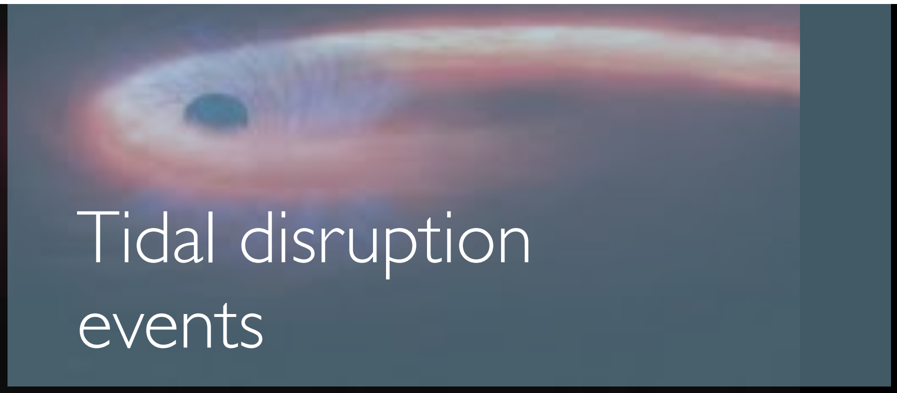


A "Hillas diagram" for high-energy neutrino transients

Guépin & KK 2017





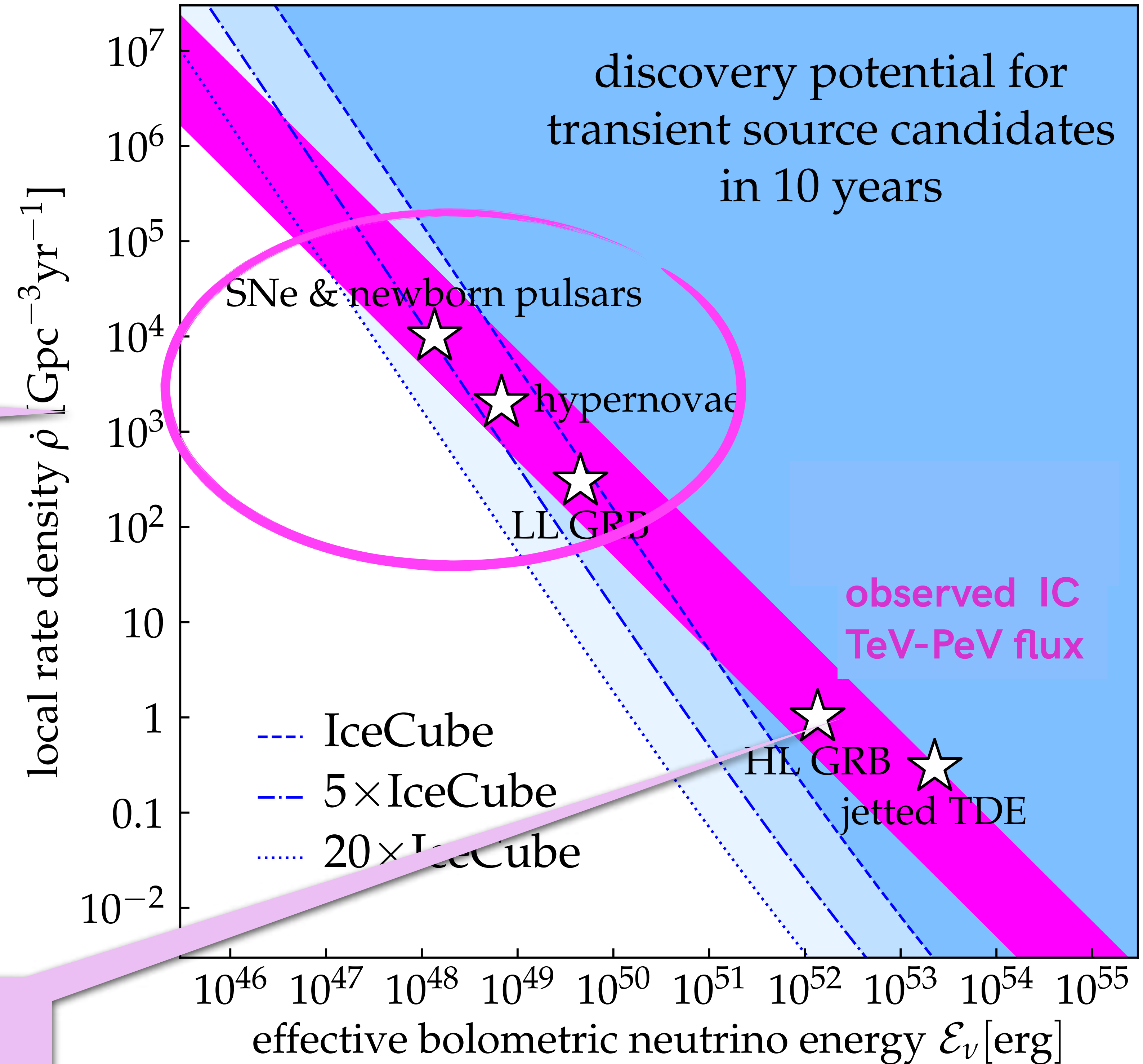


IceCube neutrinos: soon to be probed transients

Detection of **multiplets** depends on number density of sources

Could be probed in the next decade

Rare powerful sources are excluded



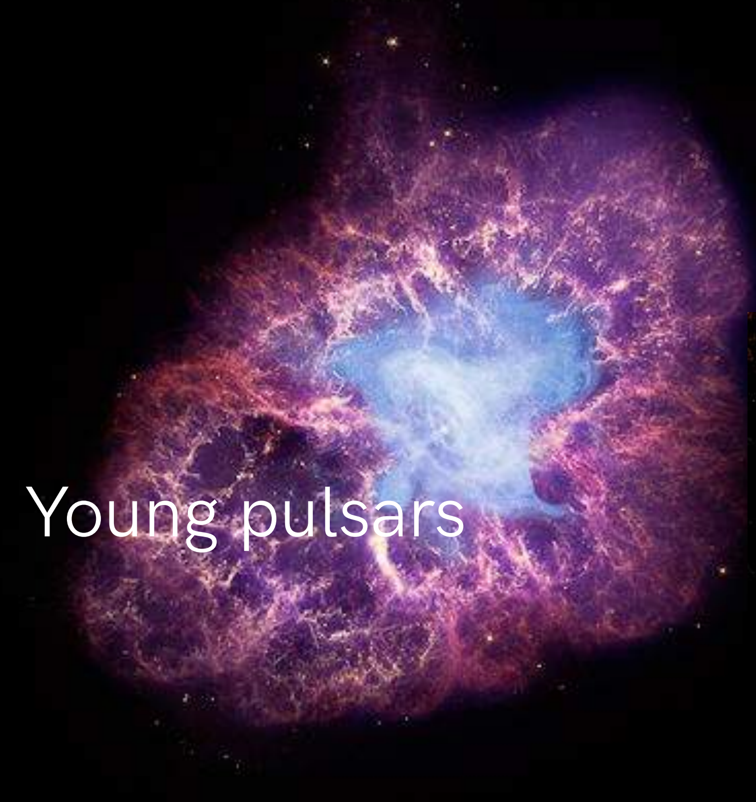
Murase & Waxman 2016, M. Ahlers talk NBI Copenhagen Dec. 2010

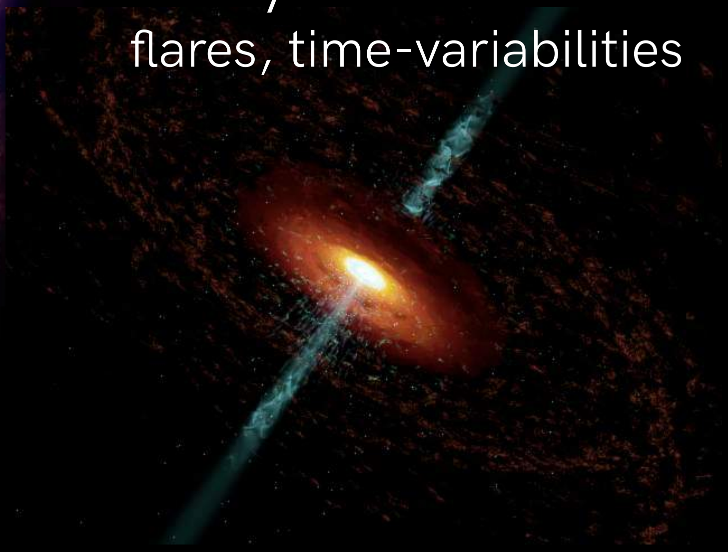
Observed high-energy multi-messenger transients

Murase & Bartos 2019
Guépin & KK 2017

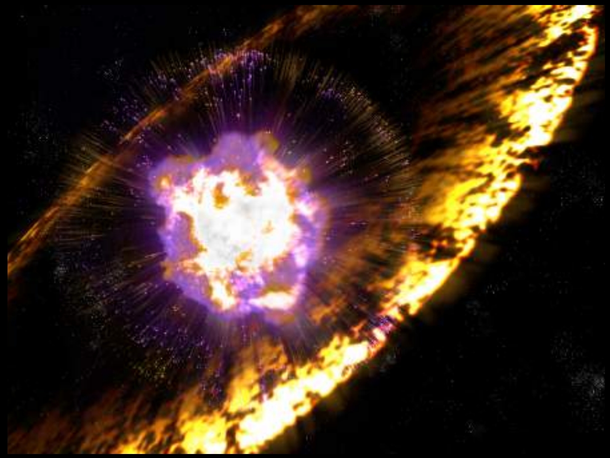
e.g., Kimura et al. 2017, 2018
Biehl et al. 2018
Decoene, Guépin, Fang, KK, Metzger, 2020
Ahlers & Halser 2020

Fang & Metzger 2018





KK & Silk 2016
De Wasseige et al. 2019



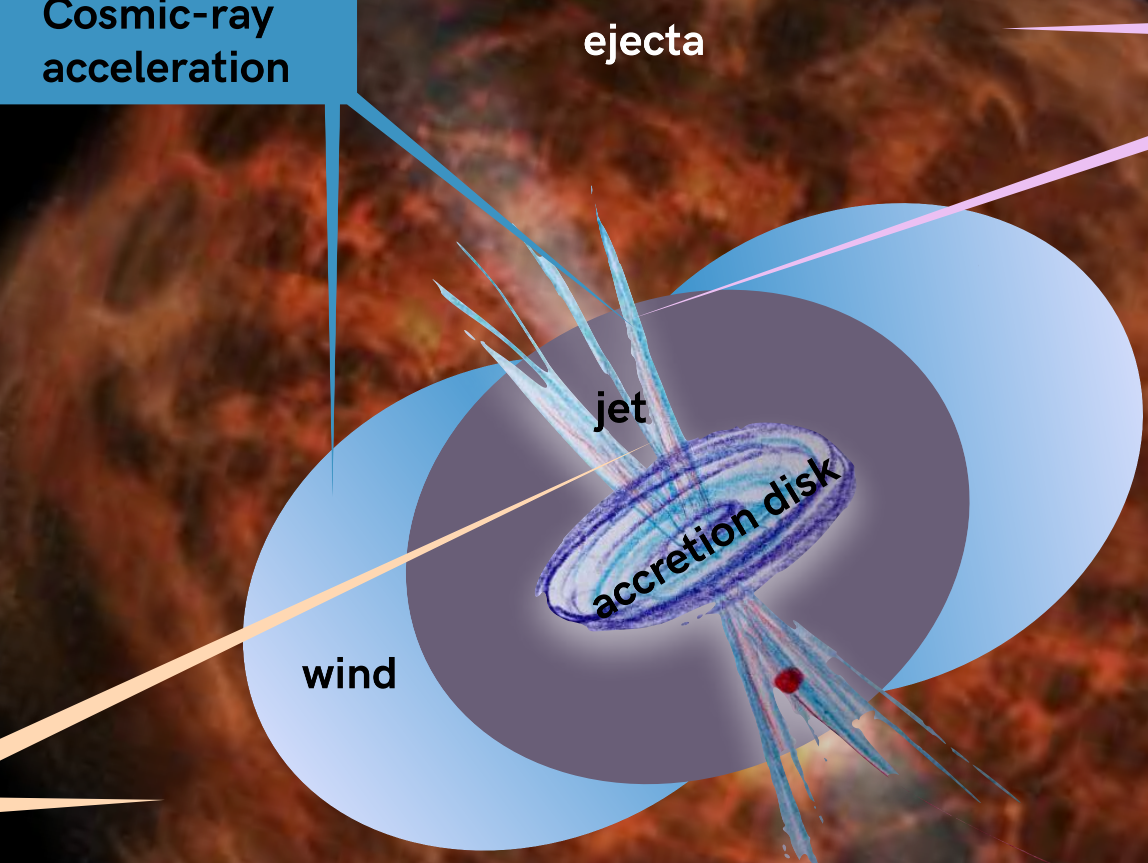
Computing high-energy neutrino fluxes

mechanisms:
shock acceleration
magnetic reconnection…

at various locations:
inner/external/side jet
wind
accretion disk…

—> max. acceleration energy spectrum

Cosmic-ray acceleration



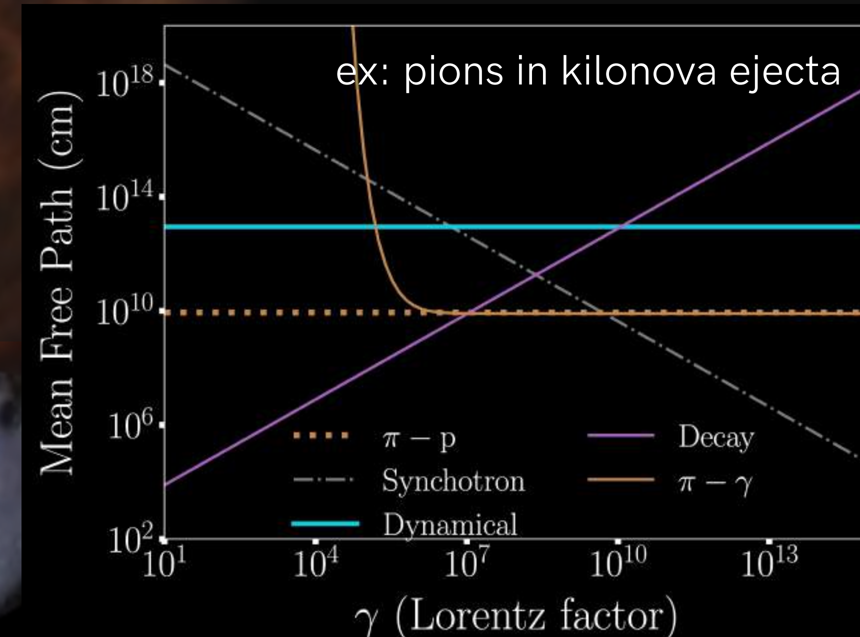
Cosmic-ray interactions + cooling
Neutrino production

$p + \gamma \rightarrow n + \pi^+ + \ldots$

$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu$

cascades
no HE ν

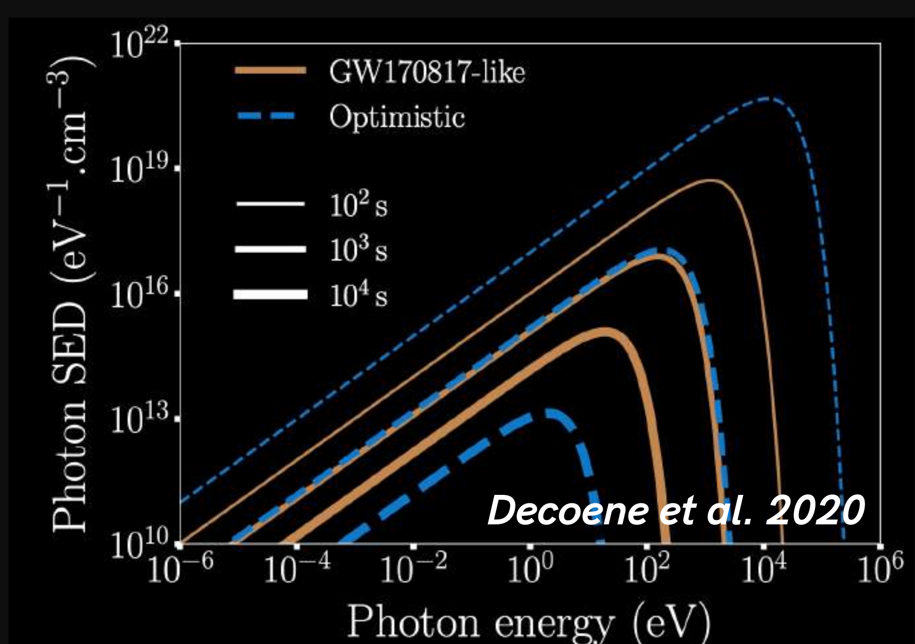
synchrotron cooling
no HE ν



Decoene et al. 2020

Radiative + hadronic backgrounds

density, spectra, time evolution
in acceleration region and beyond



Ex: red kilonova ejecta

- **Thermodynamical equilibrium** Metzger et al. 2011

$$\frac{d\mathcal{E}}{dt} = -\frac{\mathcal{E}}{R}\frac{dR}{dt} - \frac{\mathcal{E}}{t_{esc}} + \dot{Q}_r + \dot{Q}_{fb}$$

energy evolution — mechanical losses — radiative losses

opacity (lanthanides)

$$t_{esc} \approx \left(\frac{3M\kappa}{4\pi R^2} + 1\right)\frac{R}{c}$$

- **Fall-back**

$$\dot{Q}_{fb} = \epsilon_{fb}\dot{M}_{fb}c^2$$

mass accretion rate

- **Nuclear reaction** Barnes et al. 2016, M. R. Drout et al, 2017

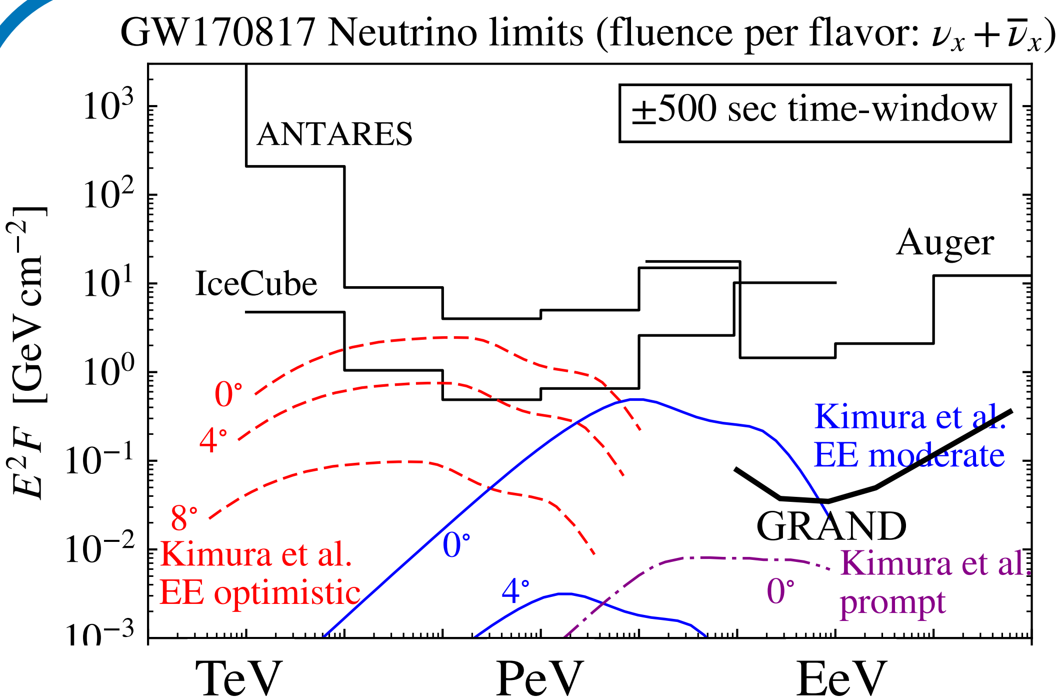
$$\dot{Q}_r = M\, X_r\, \dot{e}_r(t)$$

nuclear mass energy

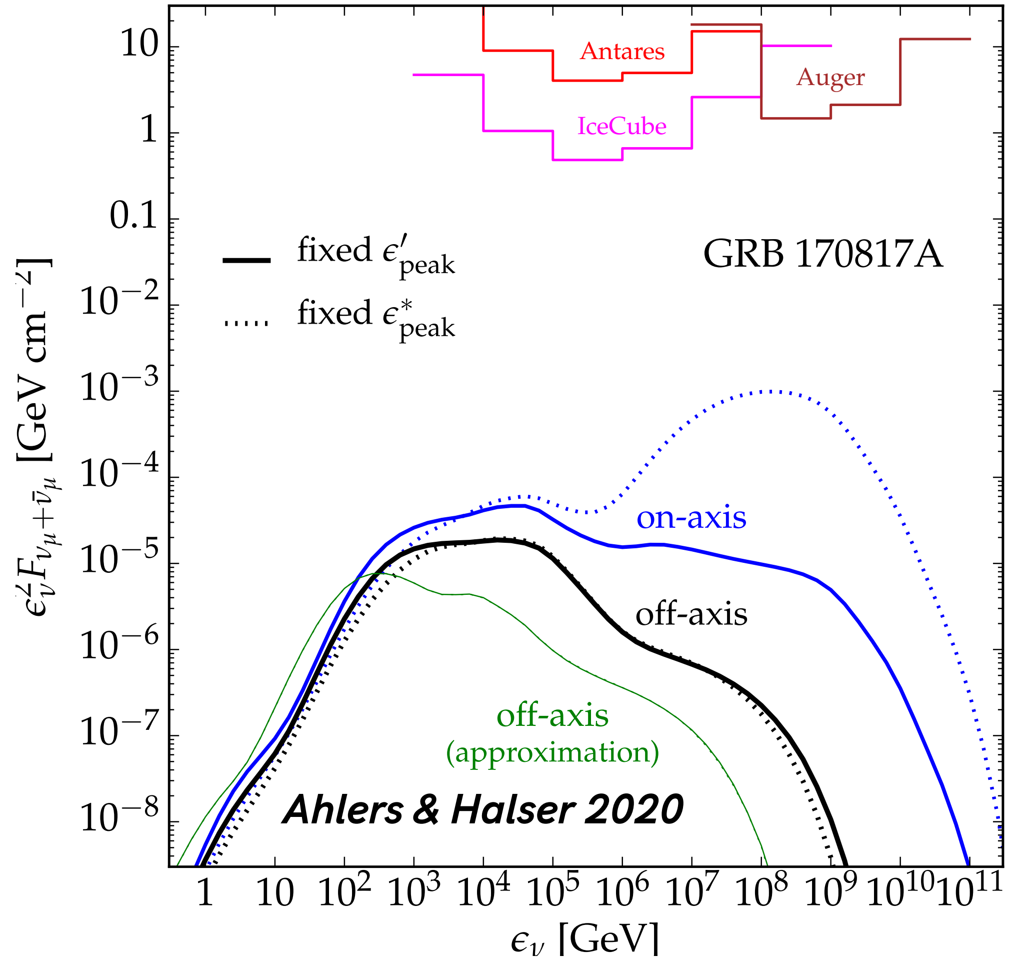
lanthanides mass fraction

V. Decoene PhD

High-energy neutrinos from binary neutron-star mergers



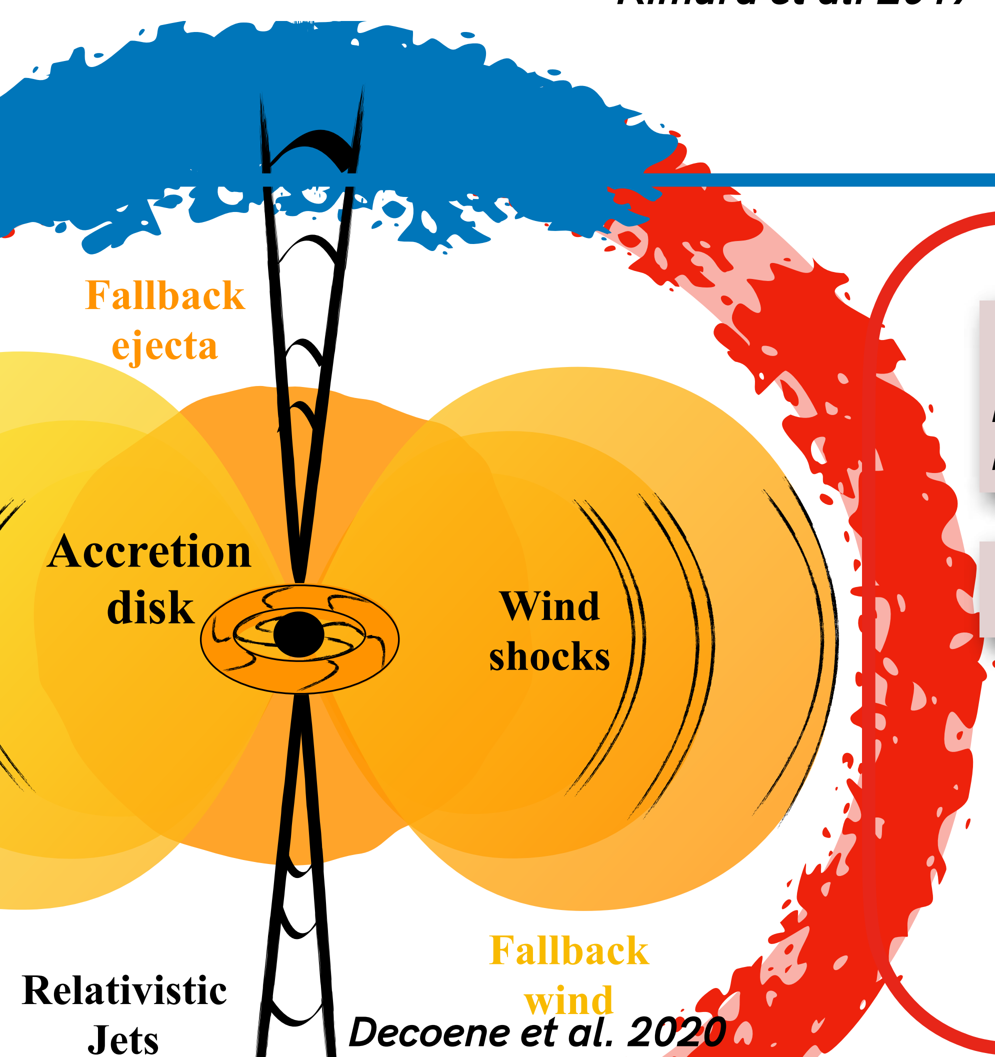
LIGO, VIRGO, IceCube, Auger, ANTARES 2017
Kimura et al. 2017



Successful jet
Kimura et al. 2017
Biehl et al. 2018
Ahlers & Halser 2020

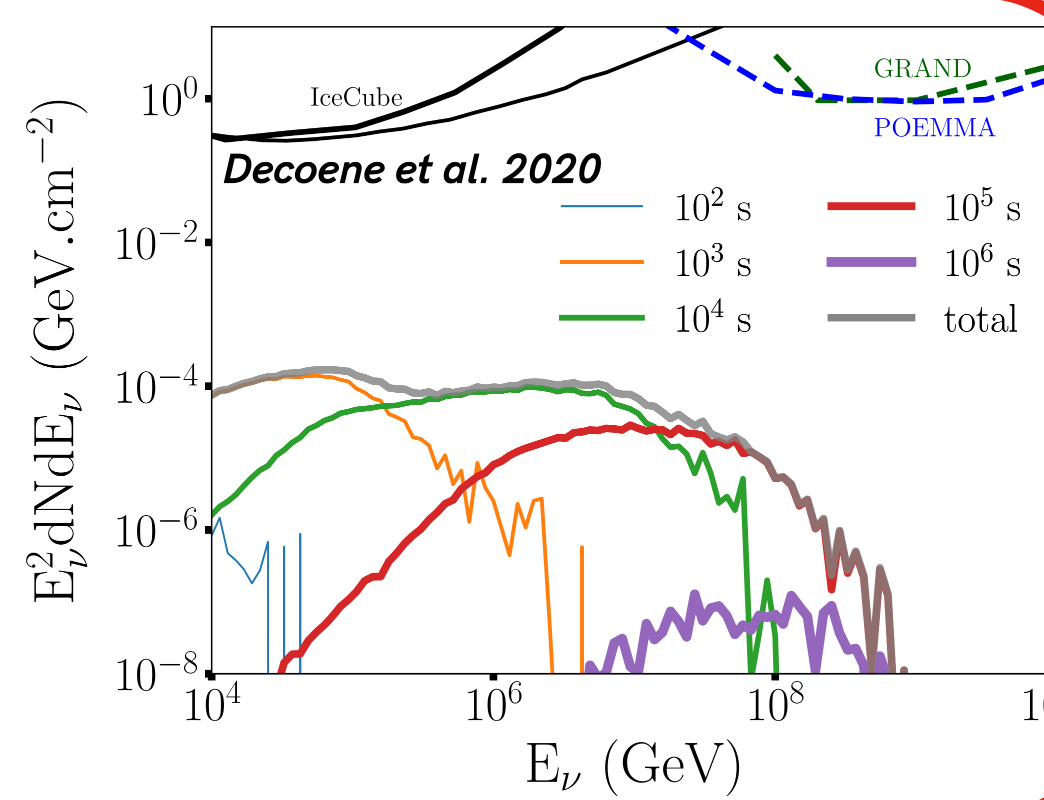
Choked jet
Kimura et al. 2018

Beamed and intense emission



Equatorial emission
Decoene, Guépin, Fang, KK, Metzger, 2020

Isotropic emission



Coincident detection with gravitational waves

GW+neutrino detection rate [yr^{-1}]		
model	IceCube (up+hor+down)	Gen2 (up+hor)
A optimistic	0.38	1.2
B moderate	0.024	0.091

Choked jet

Kimura et al. 2018

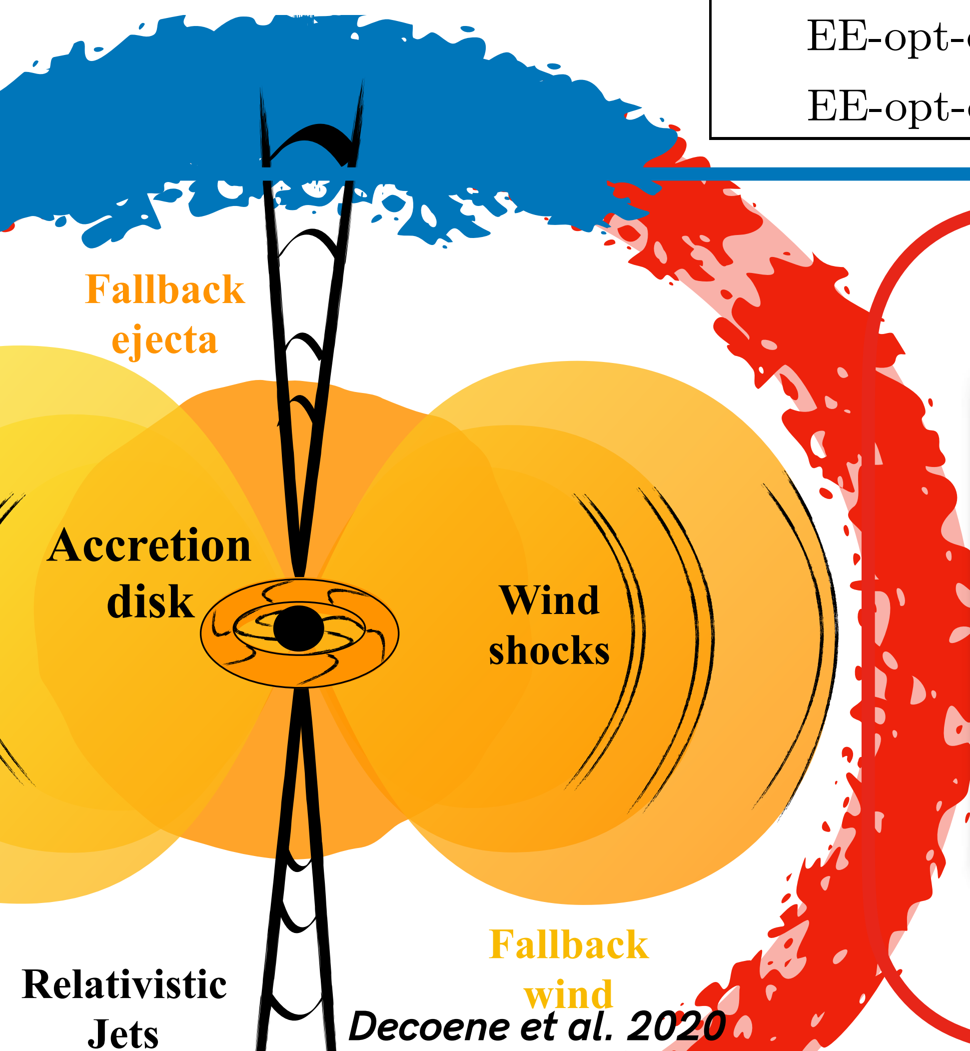
Optimistic model:
Coincident detection possible already with IceCube

NS-NS ($\Delta T = 10$ yr)	IC (all)	Gen2 (all)
EE-mod-dist-A	0.11 – 0.25	0.37 – 0.69
EE-mod-dist-B	0.16 – 0.35	0.44 – 0.77
EE-opt-dist-A	0.76 – 0.97	0.98 – 1.00
EE-opt-dist-B	0.65 – 0.93	0.93 – 1.00

Successful jet

Kimura et al. 2017

Optimistic model:
Coincident detection highly probable already with IceCube

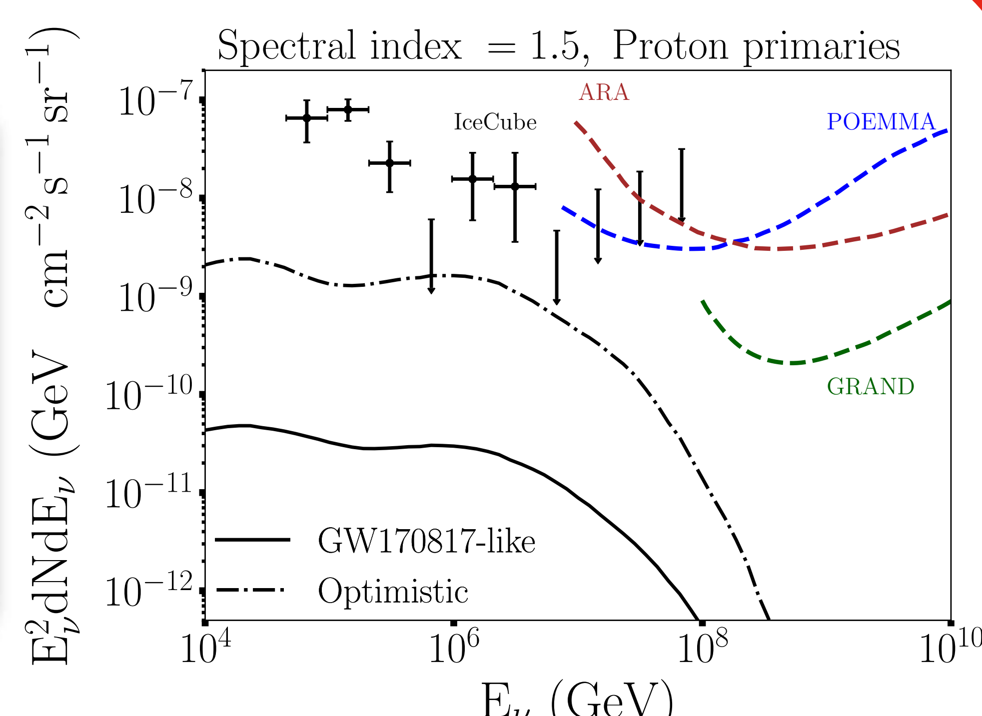


Decoene et al. 2020

Equatorial emission

Decoene, Guépin, Fang, KK, Metzger, 2020

Optimistic model:
10% of IceCube diffuse flux
Interesting for stacking and cross-correlation searches



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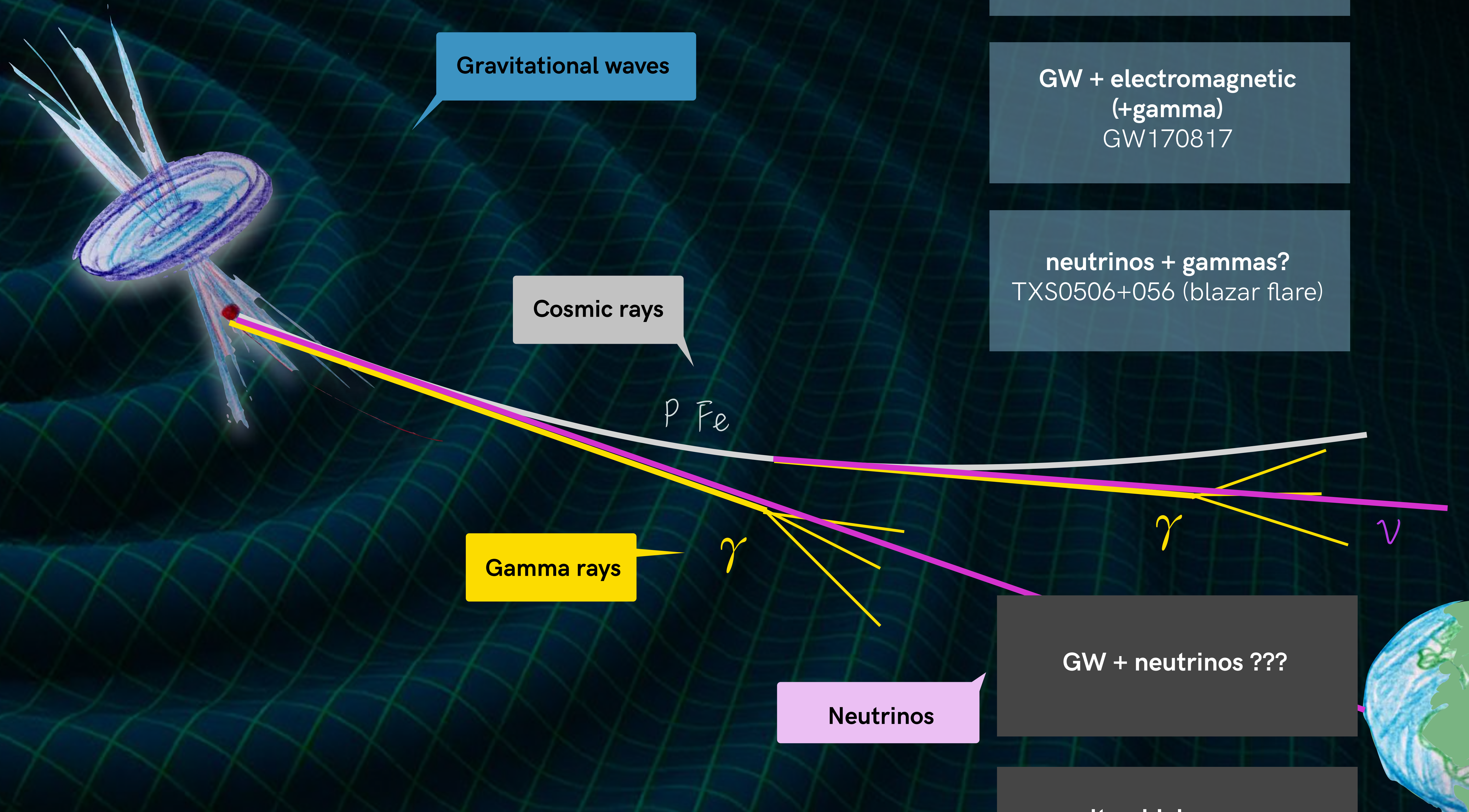


GW + neutrinos ???

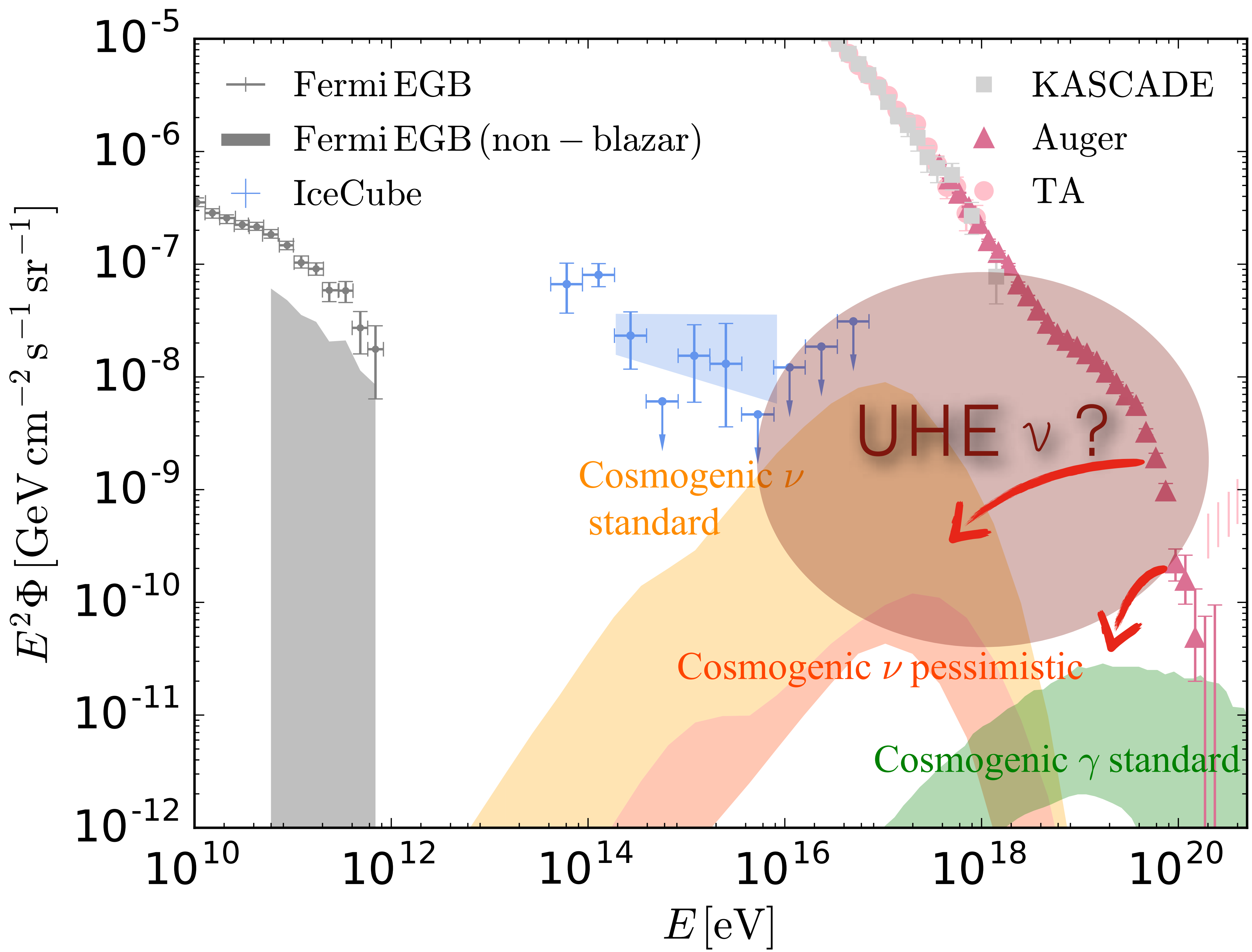
ultra-high energy neutrinos ???

Mauricio's Talk

UHE neutrinos: an unchartered territory!

Mauricio's Talk

Alves Batista, de Almeida, Lago, KK, 2018
GRAND Science & Design, 2018
KK, Allard, Olinto 2010



GRAND
POEMMA
RNO
PUEO