GW-triggered searches with GRAND: the case of BNS mergers

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Pennsylvania State University

GRAND Meeting 2025
University of Warsaw, Poland
June 2 - 6, 2025

Outline

Hunting for high-energy and ultrahigh energy neutrinos from BNS mergers at next-generation GW and neutrino detectors

Based on: **Gravitational wave triggered high energy neutrino searches from BNS mergers: prospects for next generation detectors**
MM, S. S. Kimura, K. Murase
Phys. Rev. D 109, 4, 043053 (2024) ***(arXiv: 2310.16875)***

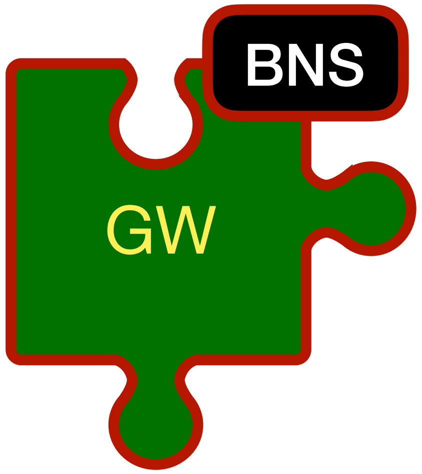
Ultrahigh energy neutrino searches using next-generation gravitational wave detectors at radio neutrino detectors: GRAND, IceCube-Gen2 Radio, and RNO-G
MM, K. Kotera, S. Wissel, K. Murase, S.S. Kimura
Phys. Rev. D 110, 6, 063004 ***(arXiv: 2406.19440)***

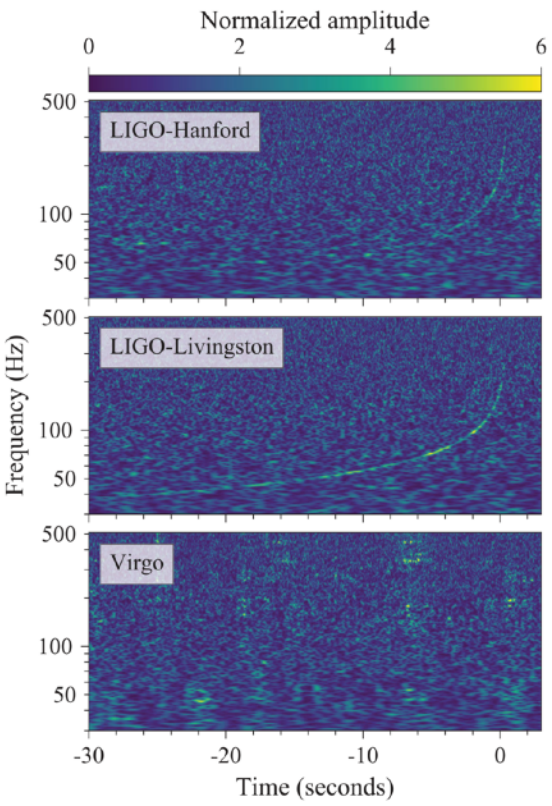
BNS mergers: particle accelerators and multi-messenger zoo

BNS

S. Gezari, Annu. Rev. Astron. Astrophys. 2021. 59:21–58
Kimura+, PRD (2018), Fang & Metzger (2017)
Mukhopadhyay & Kimura (2024)
LIGO Collab (2017)

BNS mergers: particle accelerators and multi-messenger zoo





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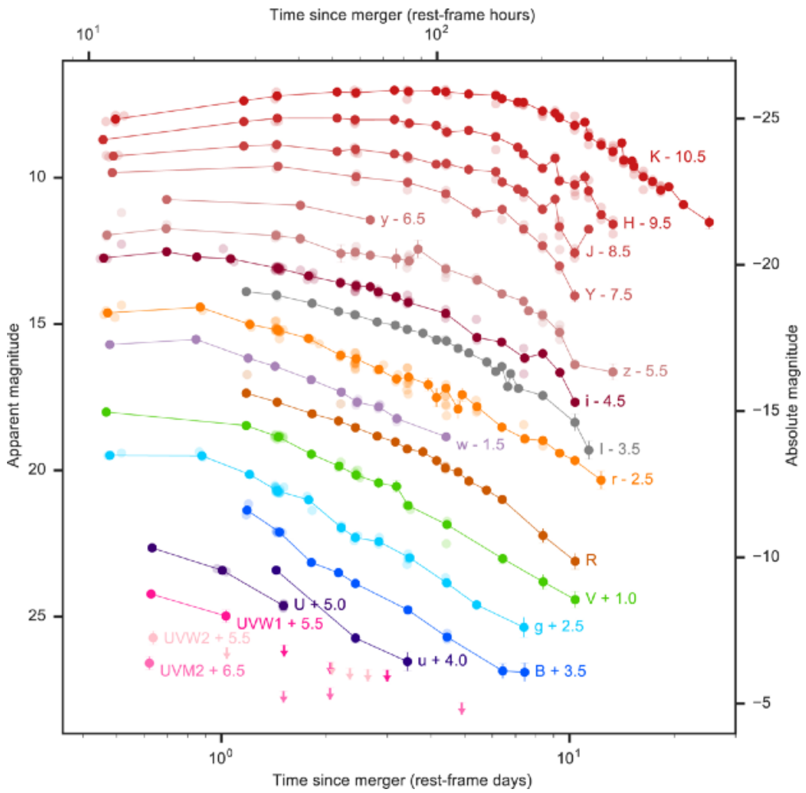
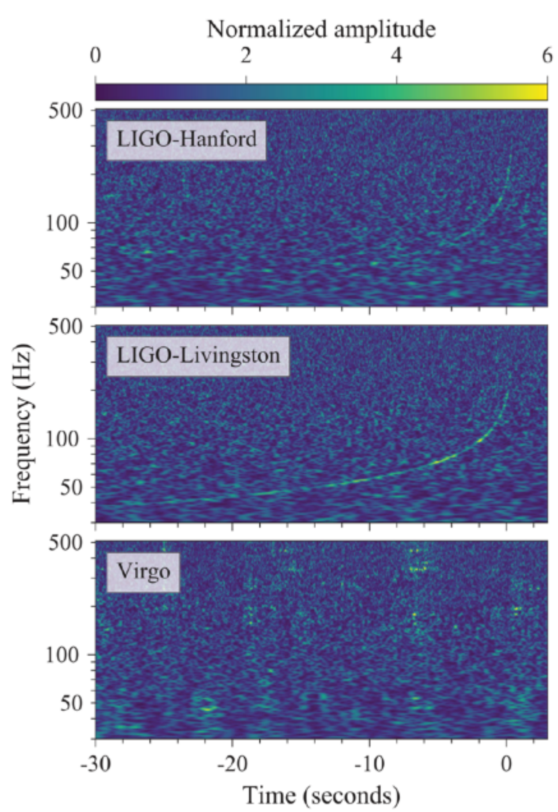
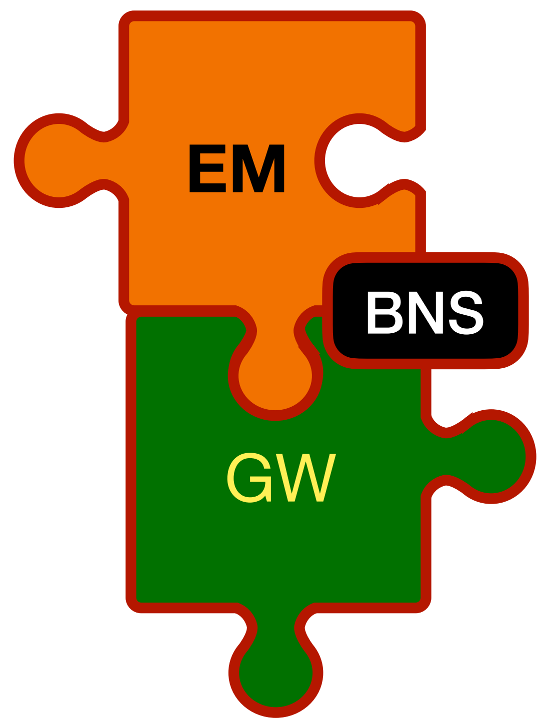




Observed

Kilonova emission
Afterglow emission
Short GRB



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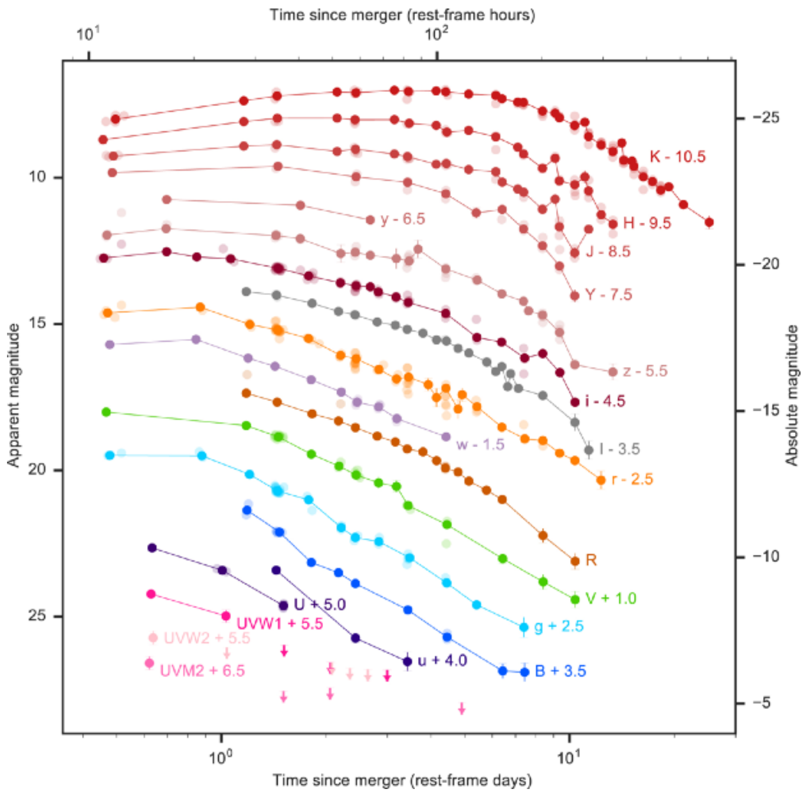

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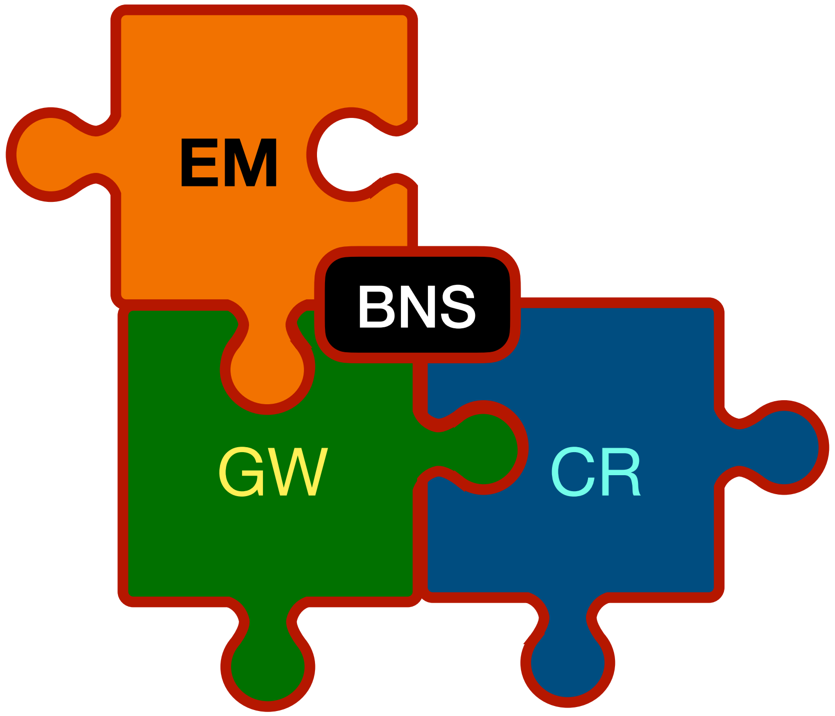

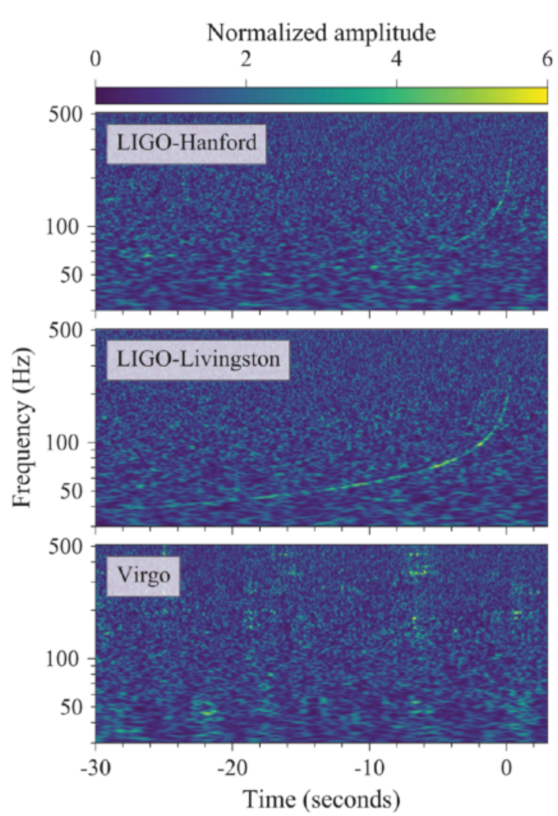

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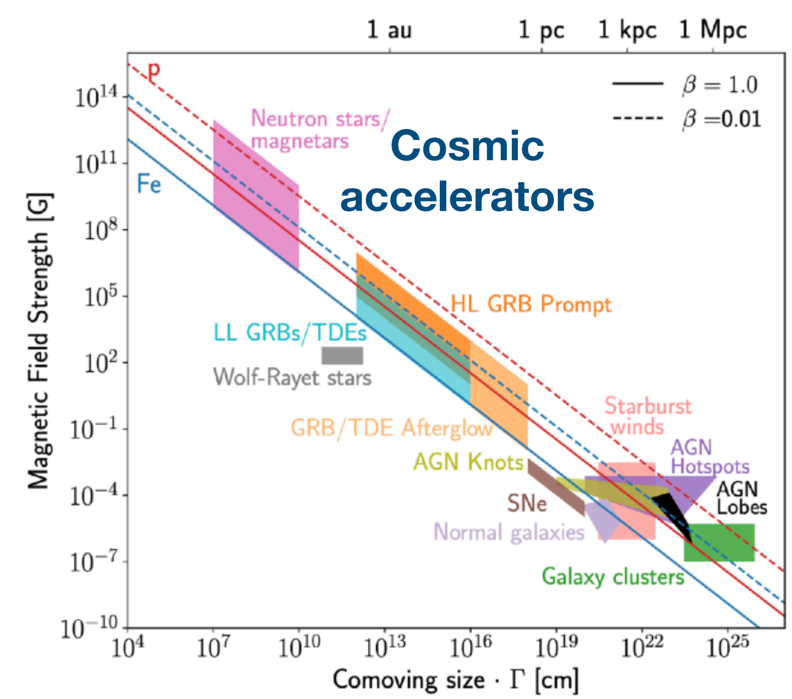

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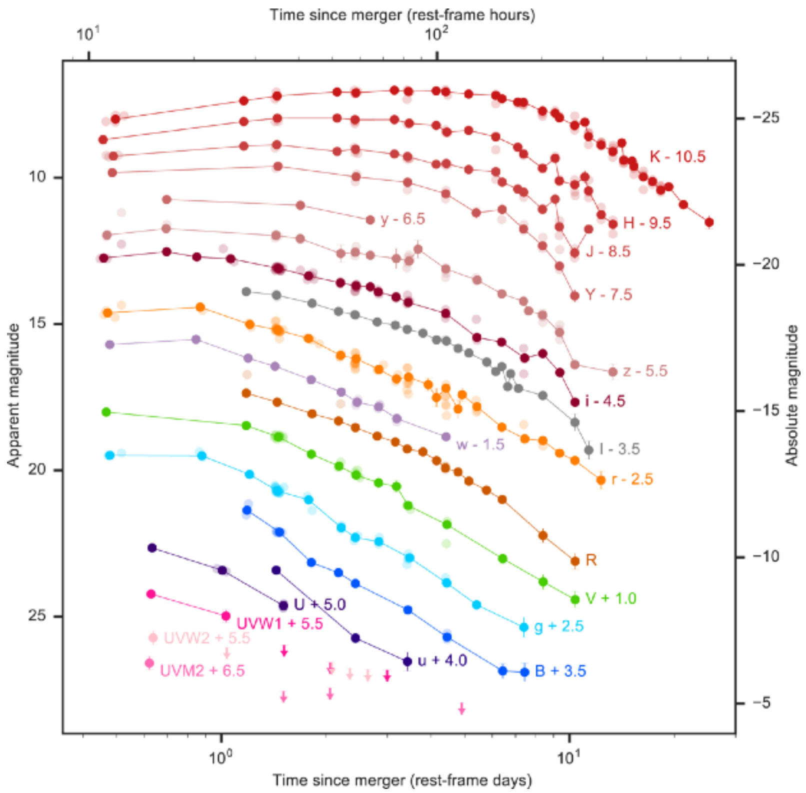

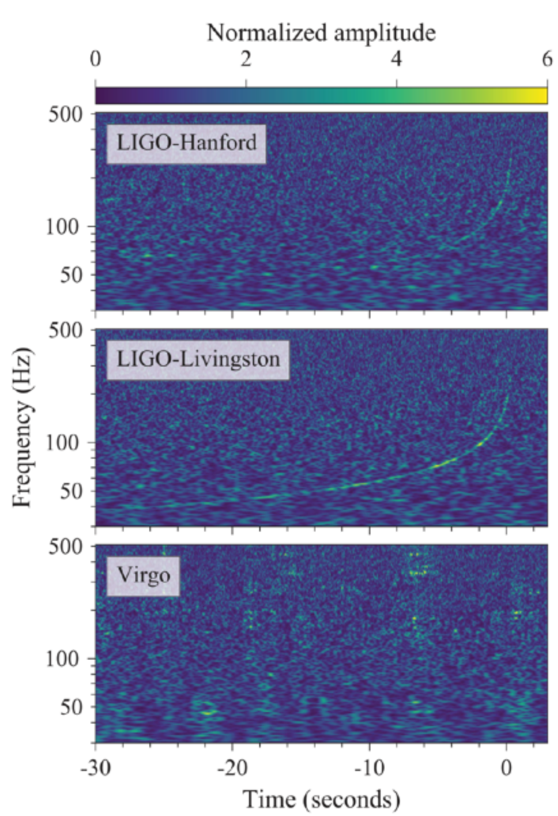

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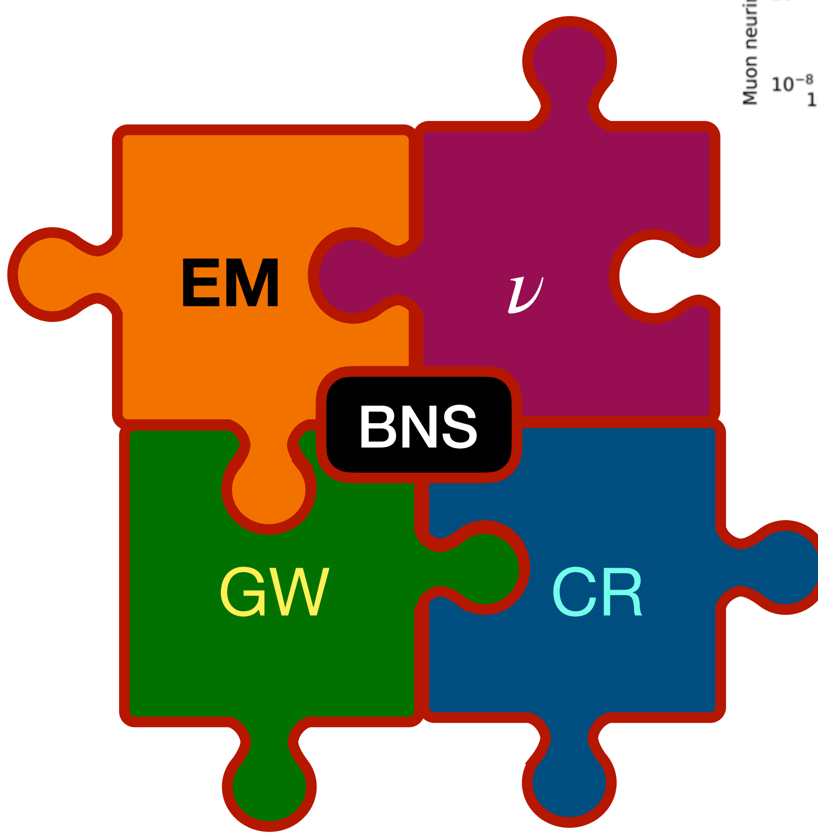
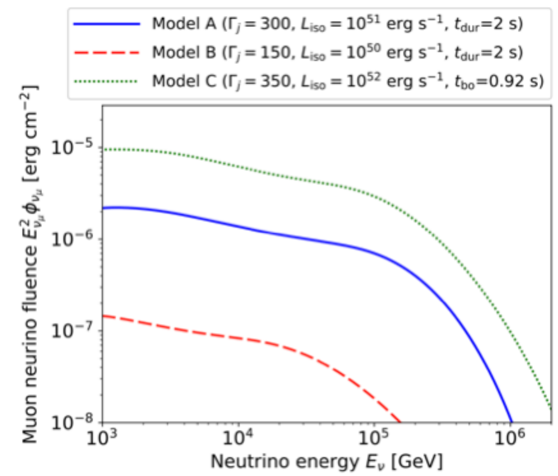
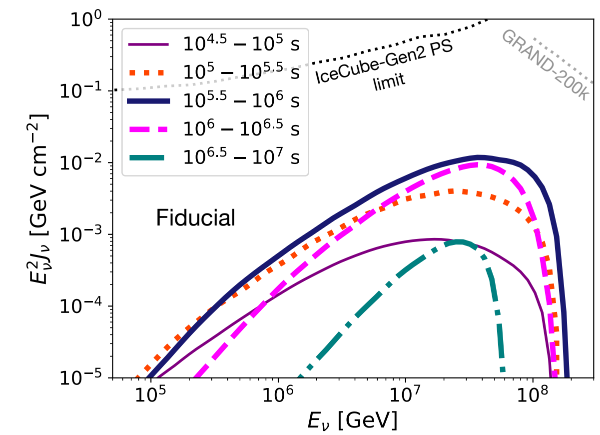
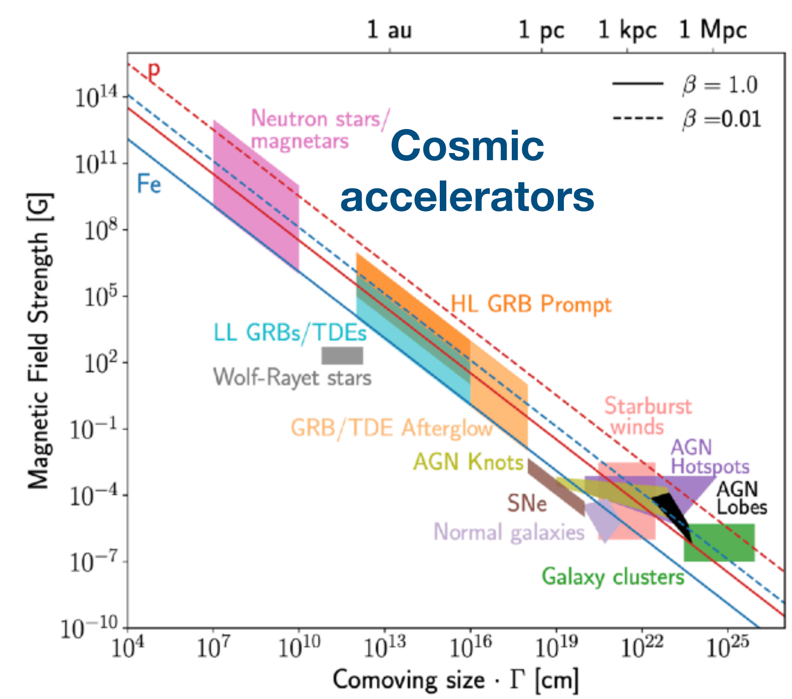




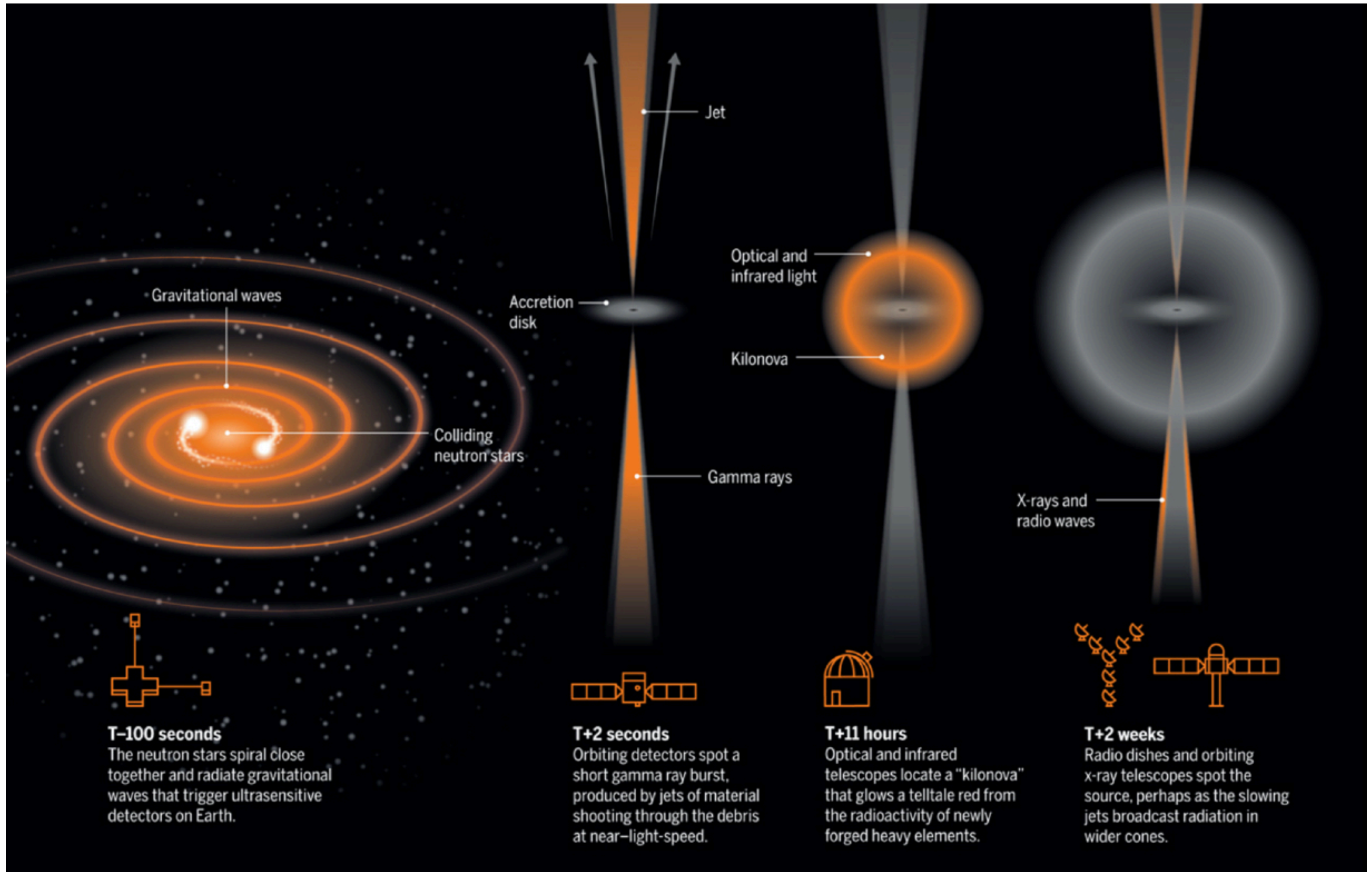




Batista et al., Front. Astron. Space Sci. 6 (2019), 23
Kimura+, PRD (2018), Fang & Metzger (2017)
Mukhopadhyay et al. (2024)
LIGO Collab (2017)

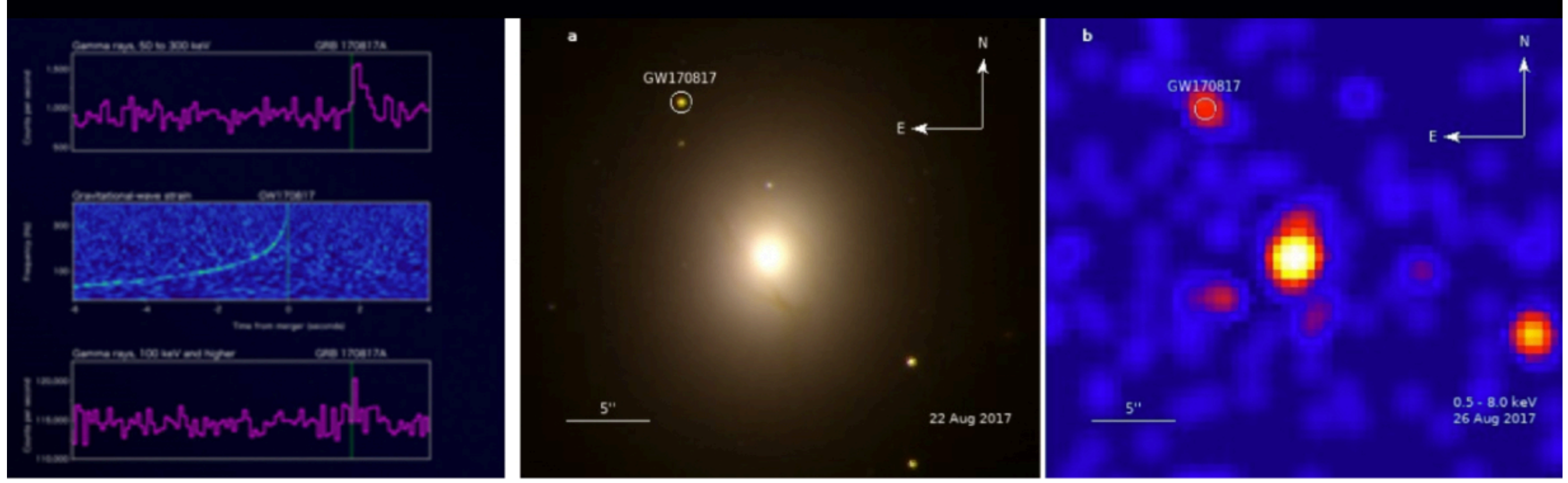
GW170817

~ 40 Mpc (NGC 4993)



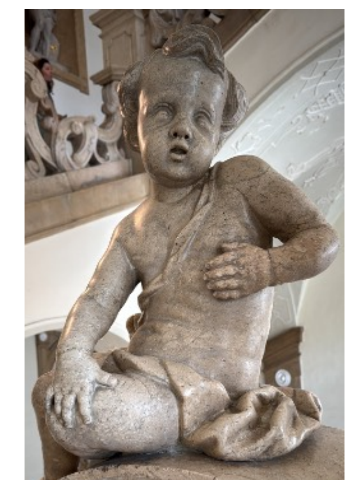
Gamma rays (Fermi+Integral)

GW (Adv. LIGO+Virgo)



Optical (HST)

No neutrinos :(

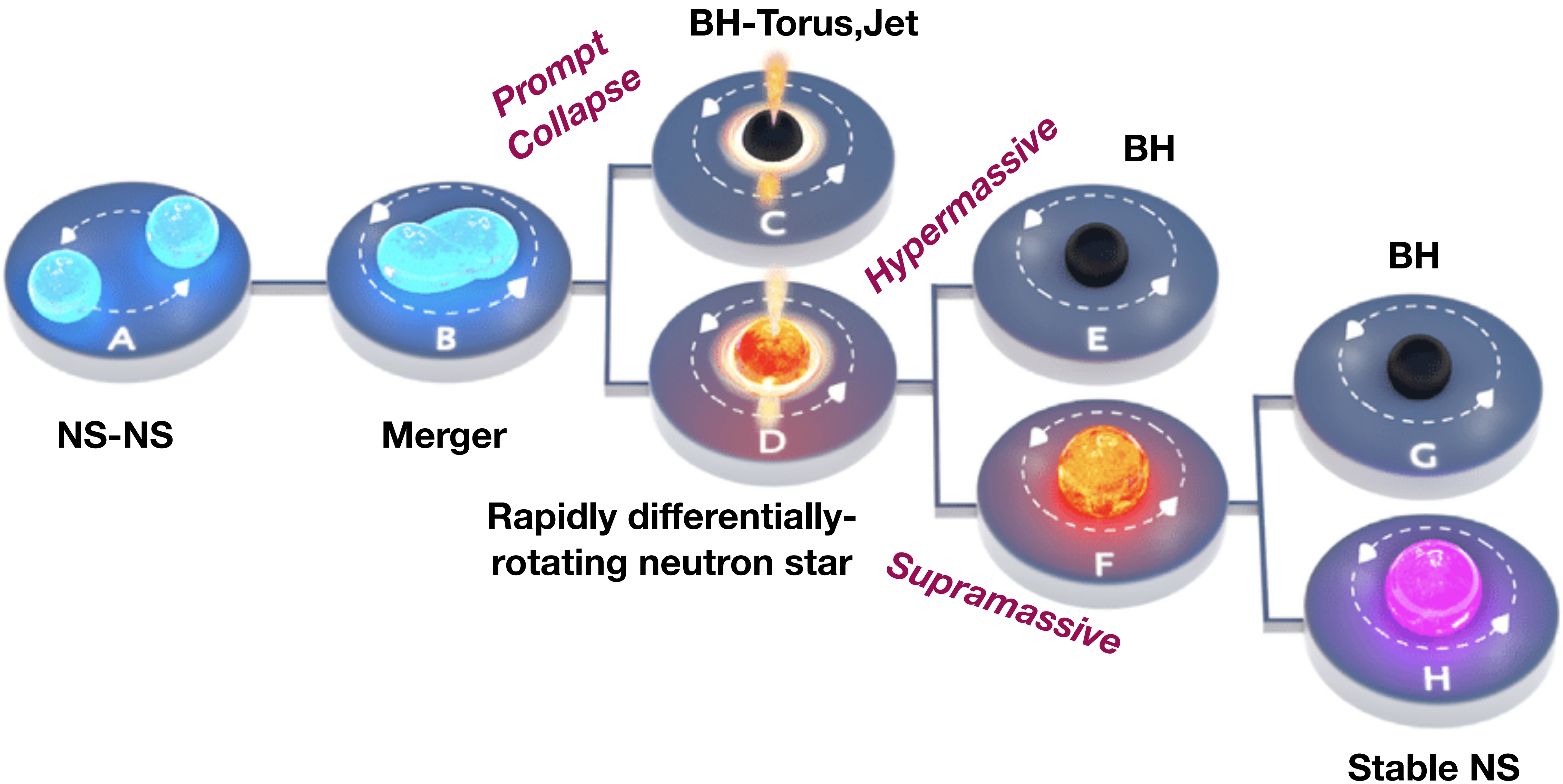


X-rays (Chandra)

Image credits: https://ahead.iaps.inaf.it
Abbott et al. 2017, ApJ 848, L13
Troja, Piro, van Earthen et al., 2017, Nature, 551, 71

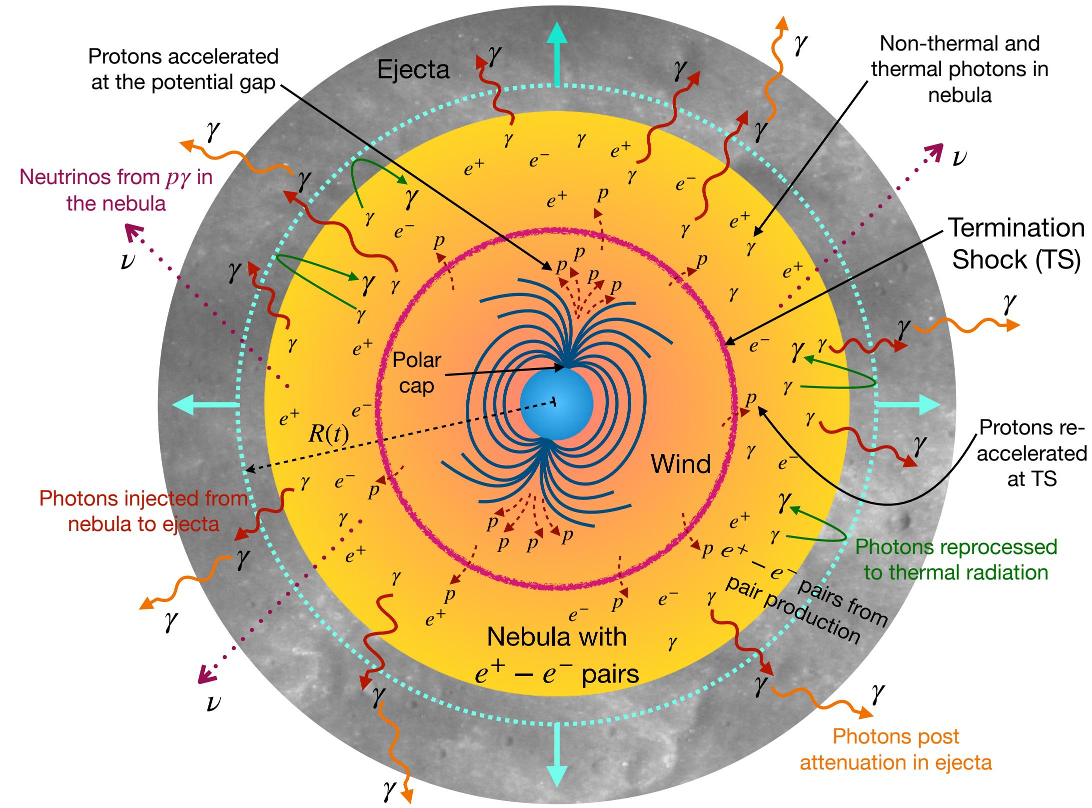
Fate of NS-NS mergers

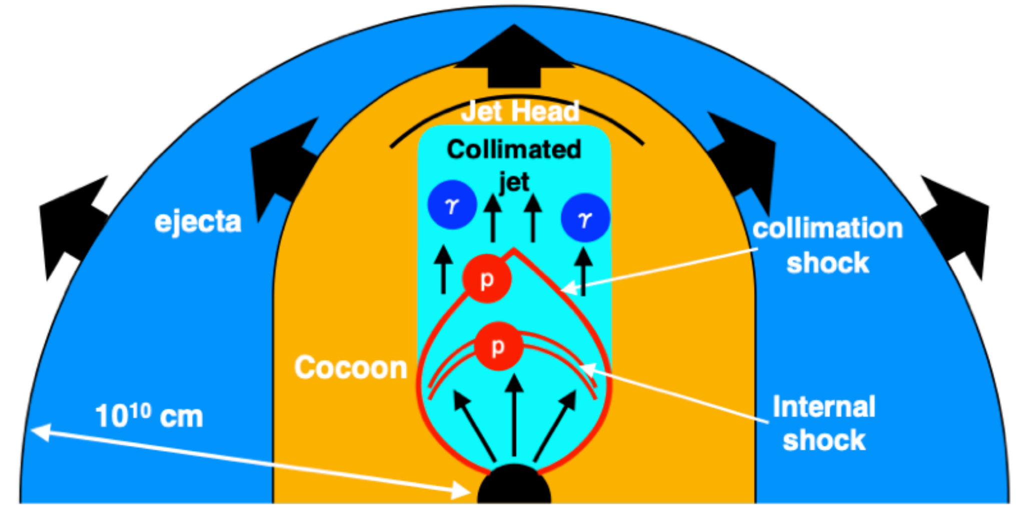
Fate decided by EOS, Mass, Spin, ….

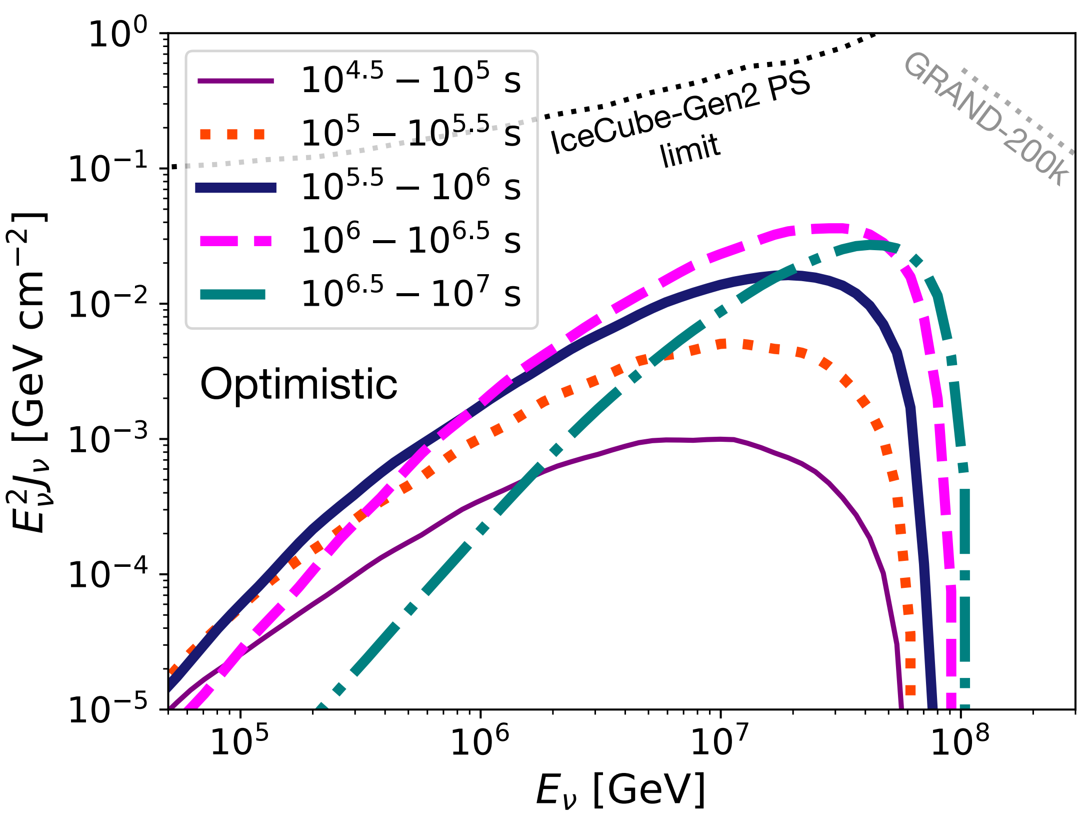


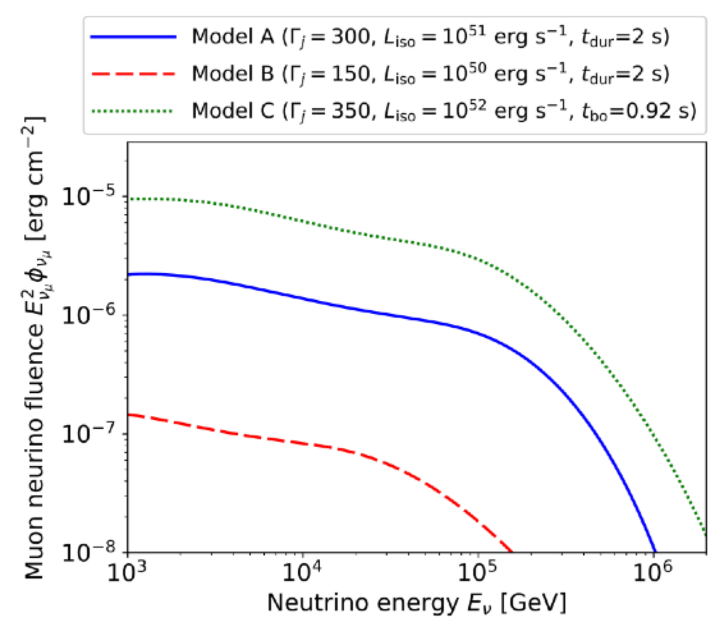
Piro, Giacomazzo, Perna arXiv:1704.08697

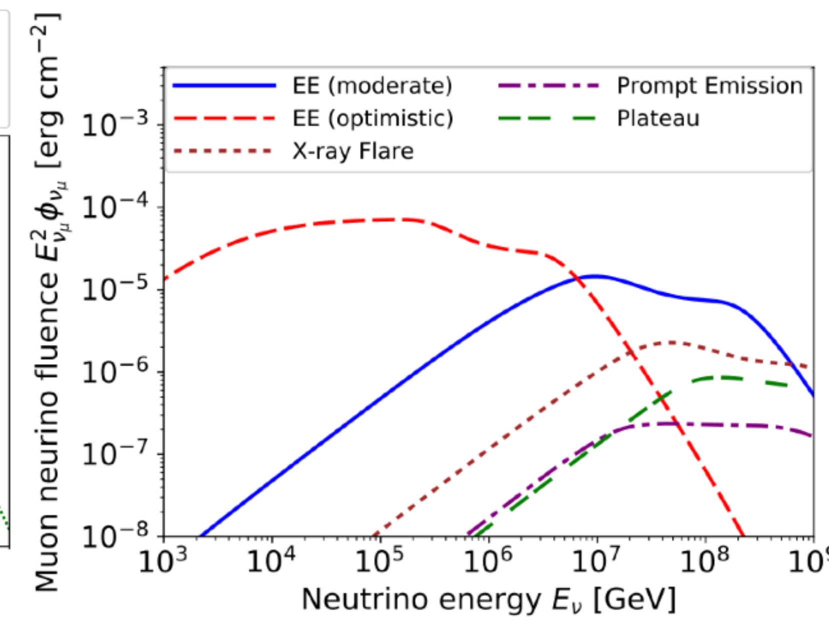
Fate of NS-NS mergers

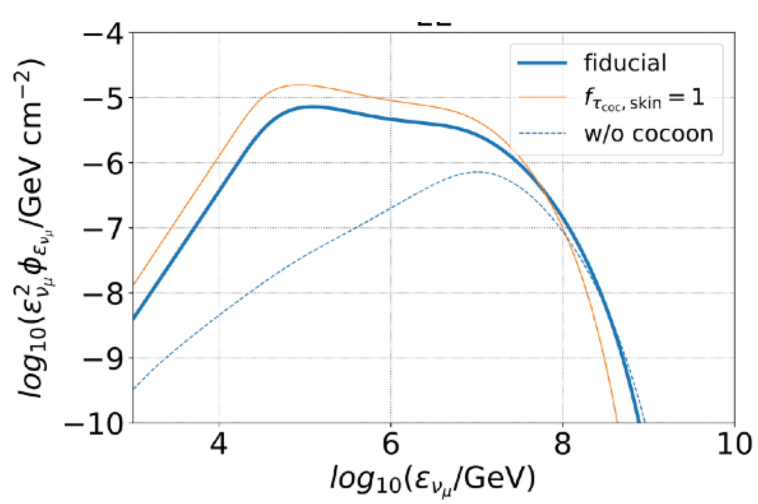








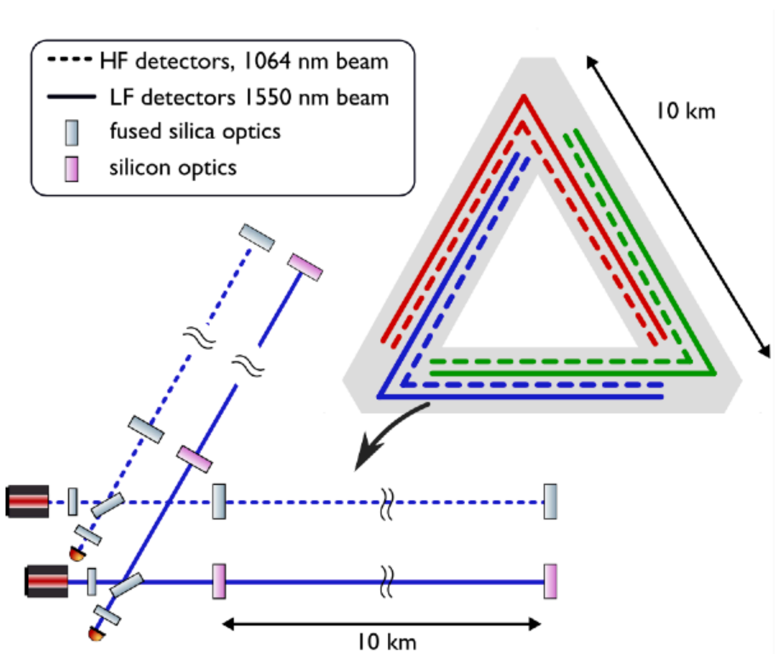




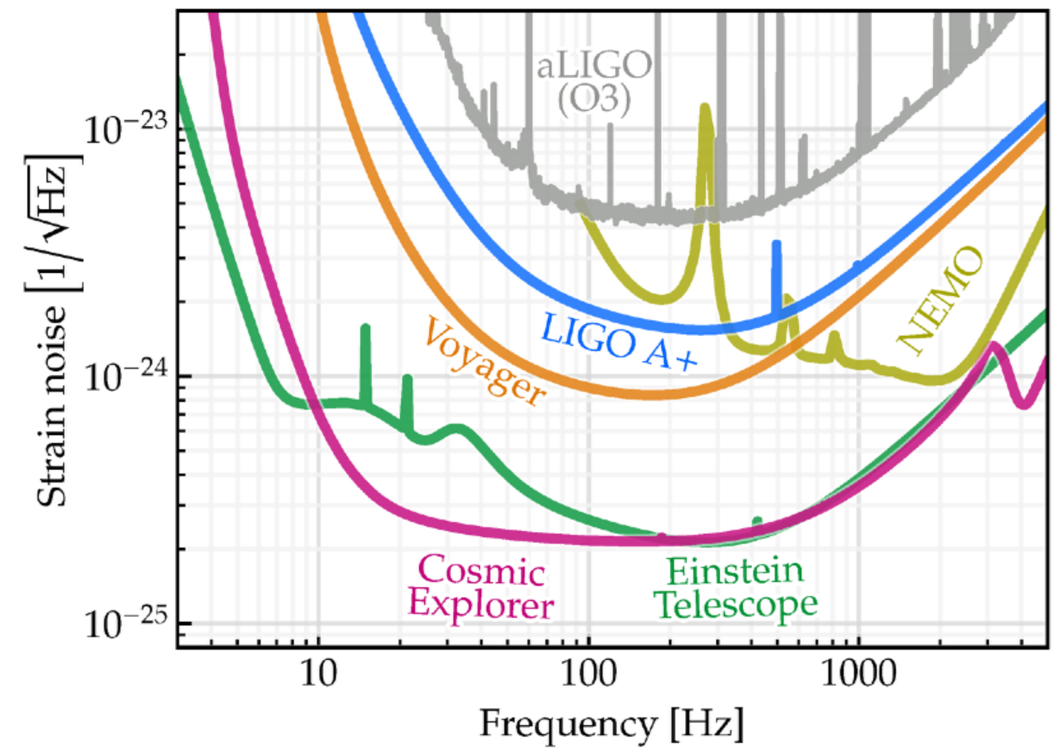
Mukhopadhyay et al. arXiv:1704.08697

Kimura et al. arXiv:1708.07075
Kimura et al. arXiv: 1805.11613
Matsui et al. arXiv: 2405.07695

Next-generation GW and UHE neutrino detectors



Einstein Telescope (ET)



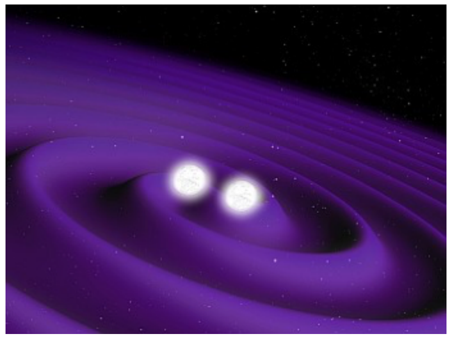
Cosmic Explorer (CE)

GRAND

Giant Radio Array for Neutrino Detection

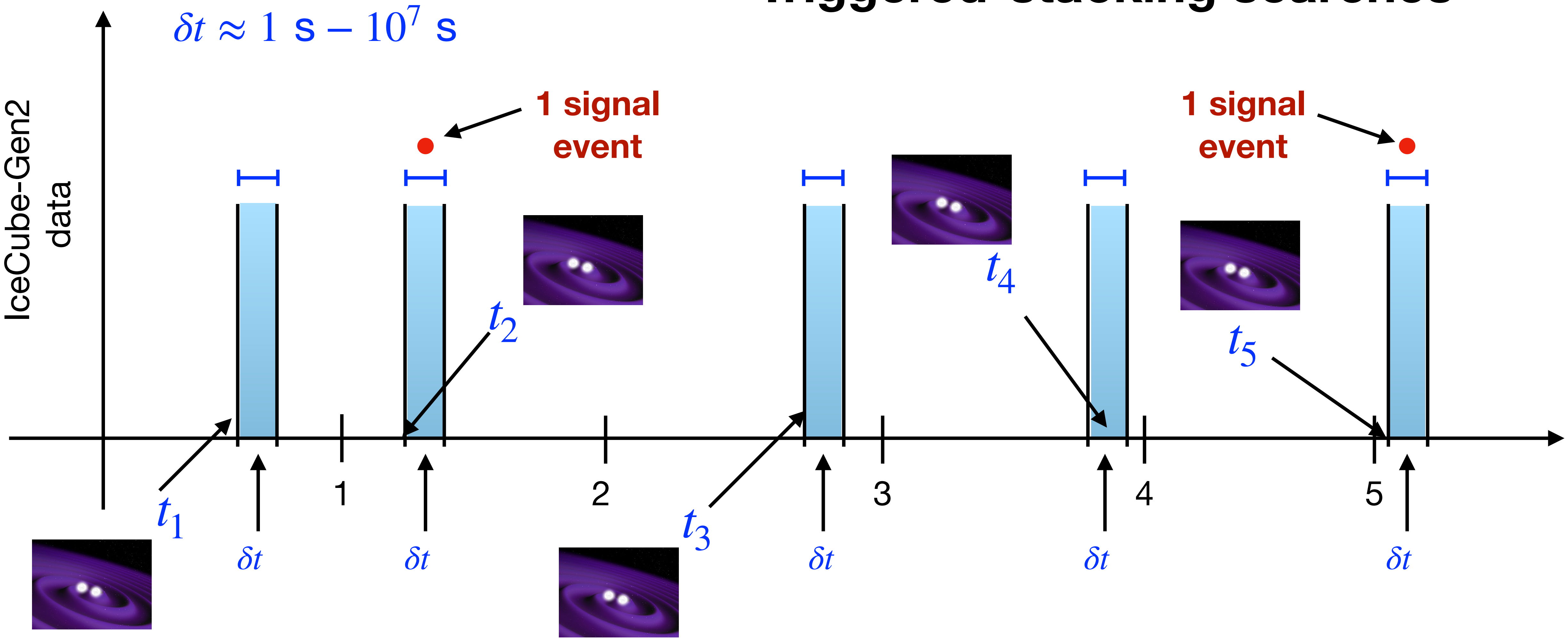
GRAND

Detection strategy: triggered stacking search

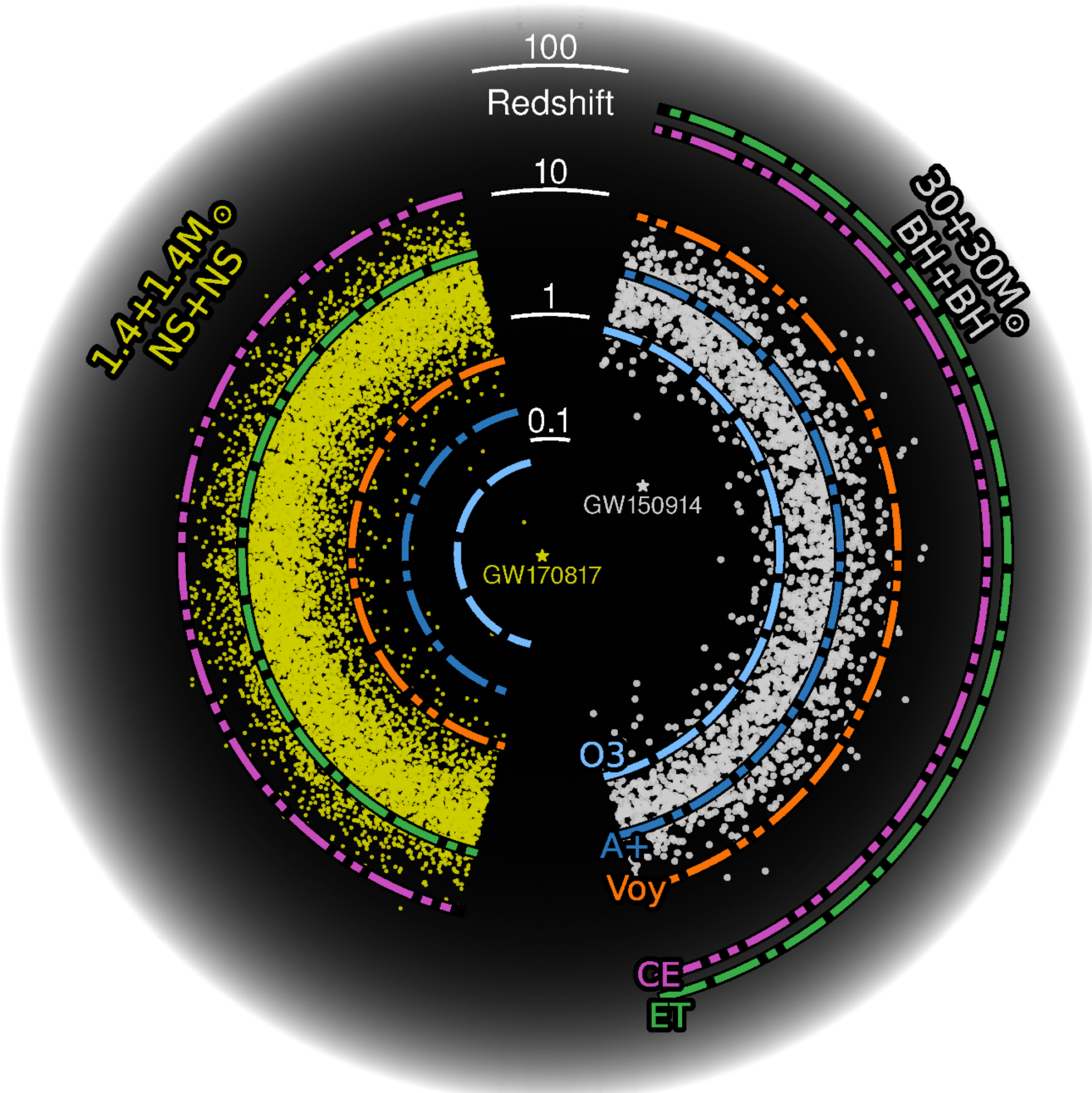


→ **Trigger from next-gen GW detectors** → **Neutrinos in IceCube-Gen 2**

Triggered-stacking searches



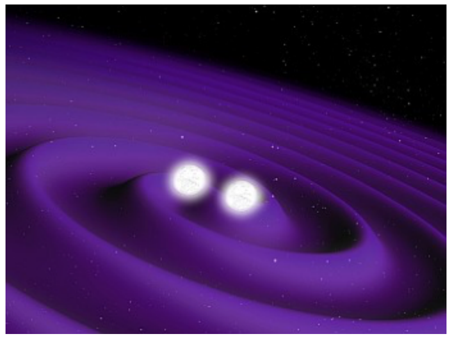
Next-generation GW detectors



Sensitive to NS-NS mergers from very high redshifts

Evans et al., (2021)

Impacts on triggered stacking searches



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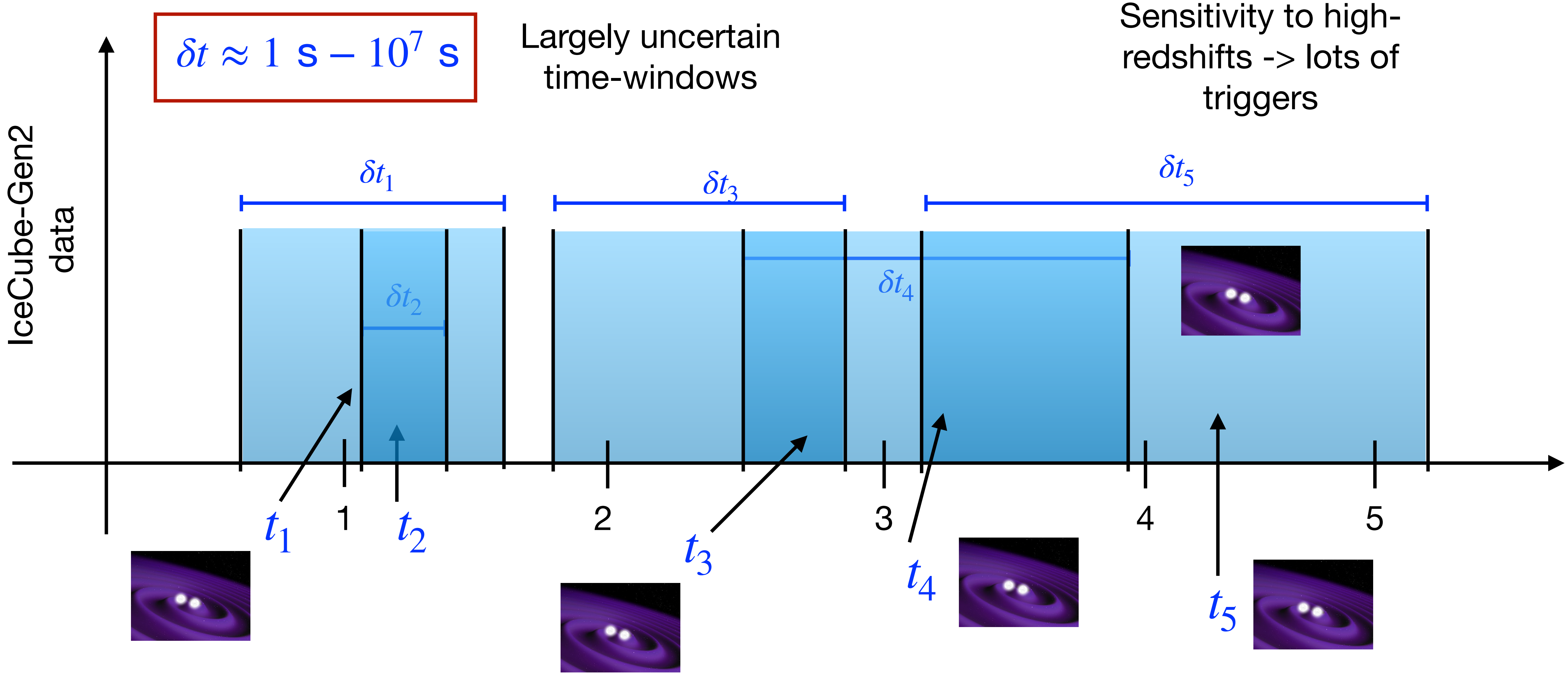
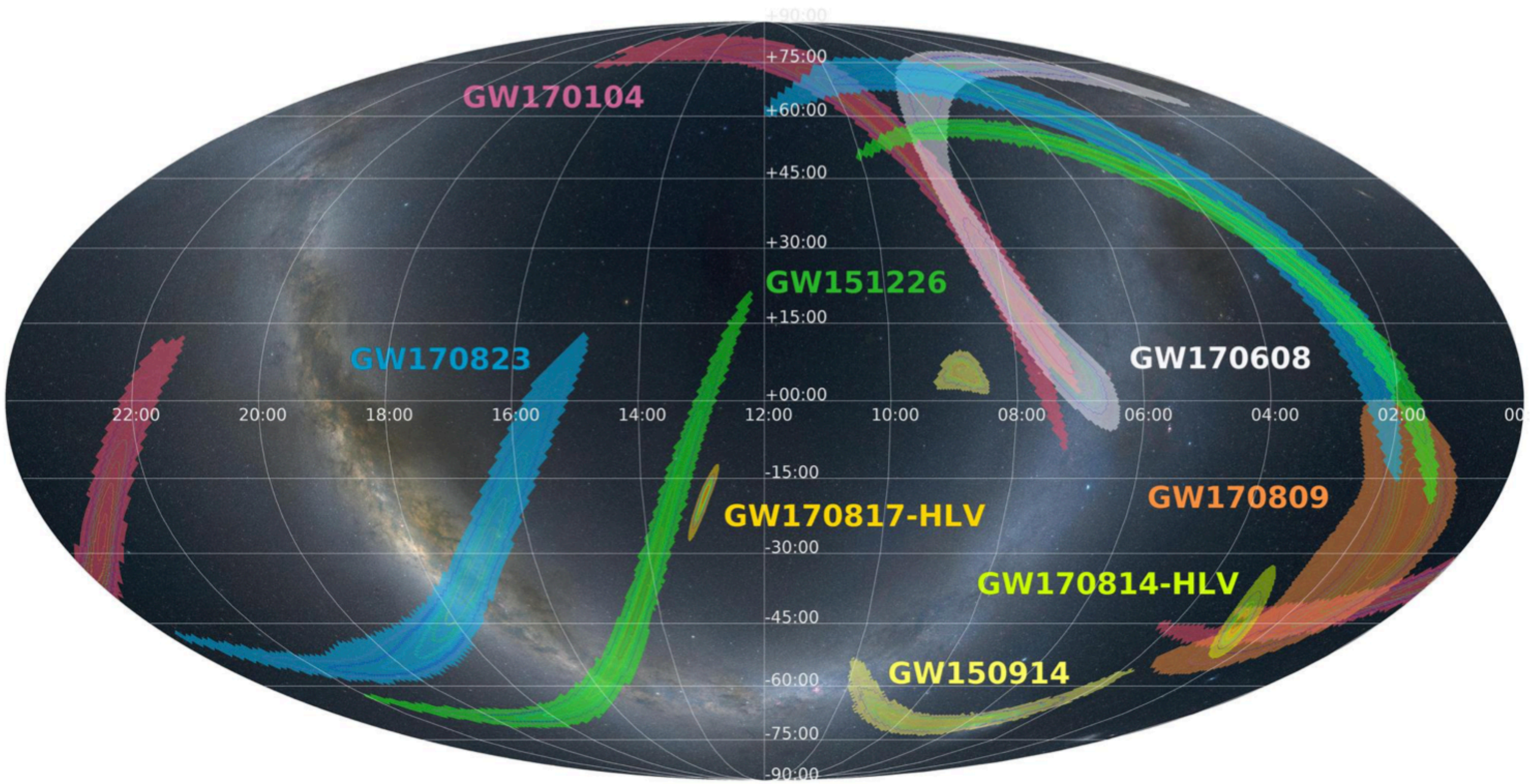


Spoils triggered stacking searches → **How do we find meaningful triggers?**

Motivations: How to obtain meaningful triggers?

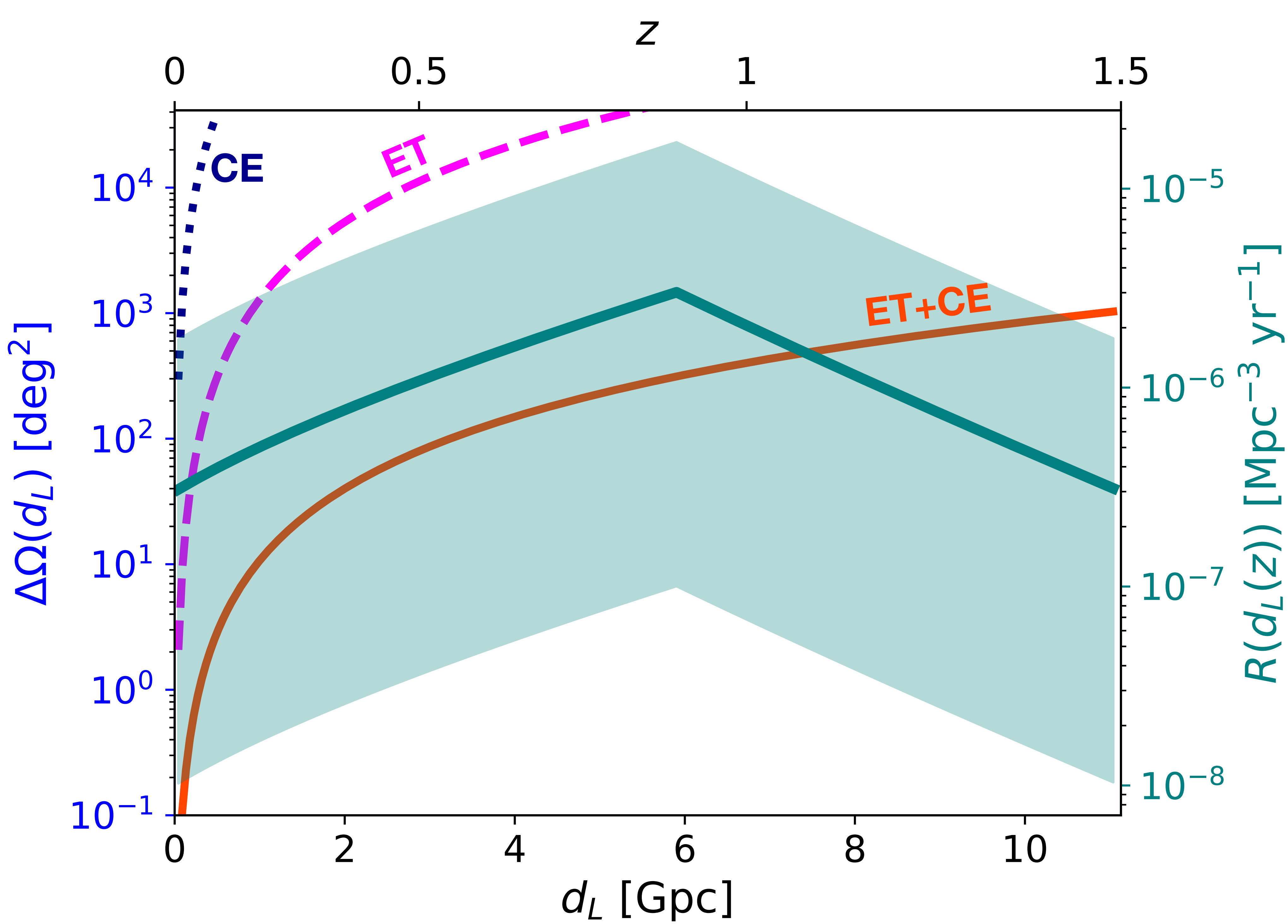
Use the sky localization capabilities of the GW detectors….



Fraction of total sky area covered → Set threshold: $f_{\rm th}$ → Obtain distance limits for GW detectors to collect meaningful triggers

Abbott et al., Liv. Rev. Rel. (2020)

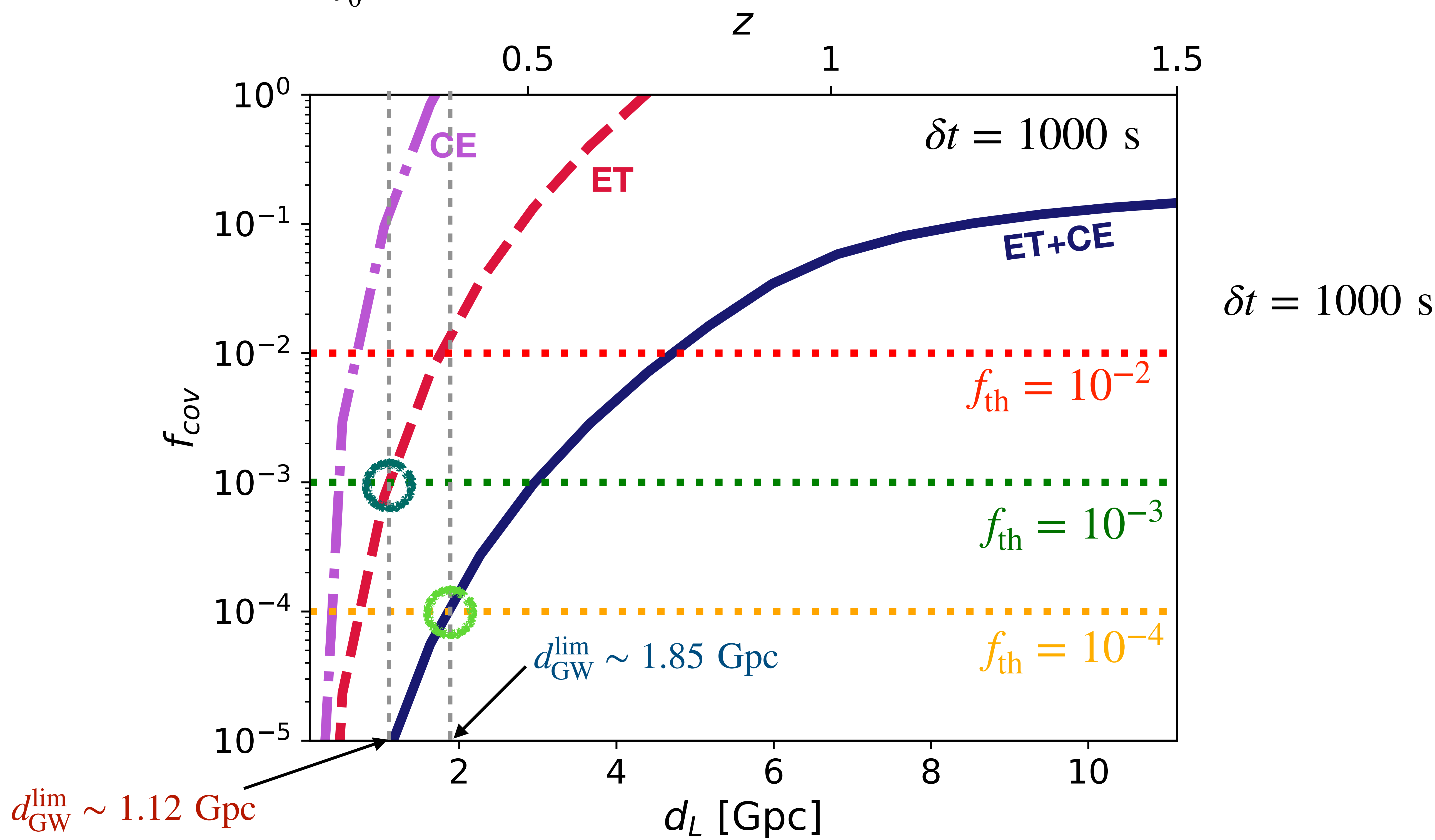
Sky localization and BNS merger rate



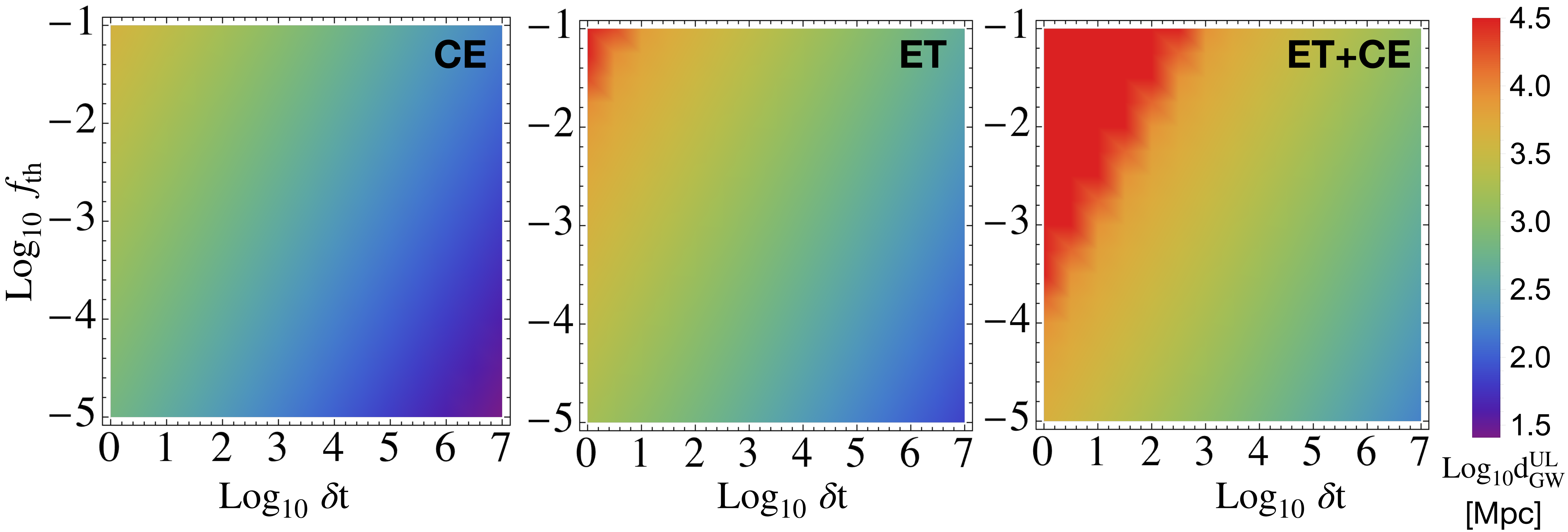
Chan et al., PRD (2018)
Wanderman & Piran, MNRAS (2015)

Distance limits for GW detectors

$$\int_0^{d_{\rm GW}^{\rm lim}} d(d_{\rm com}) \frac{\Delta\Omega(d_L)}{4\pi} R(z) 4\pi d_{\rm com}^2 \delta t = f_{\rm cov}(d_{\rm GW}^{\rm lim})$$



Distance limits for GW detectors - $\delta t - f_{\rm th}$ plane



High energy neutrinos from BNS mergers

Probability to detect more than one neutrino associated with GW signal in T_{op}

$$q\left(d_{\rm GW}^{\rm UL}, T_{\rm op}\right) = 1 - \exp\left(-T_{\rm op} I\left(d_{\rm GW}^{\rm UL}\right)\right)$$

$$I\left(d_{\rm GW}^{\rm UL}\right) = 4\pi \int_0^{d_{\rm GW}^{\rm UL}} d(d_{\rm com}) \frac{T_{\rm op}}{(1+z)} R(z) d_{\rm com}^2 P_{n\geq 1}\left(d_L\right)$$

Probability to detect more than one neutrino

$$d_{\rm GW}^{\rm UL} = \min\left(d_{\rm GW}^{\rm lim}, d_{\rm GW}^{\rm hor}\right)$$

Depends on f_ν

Depends on δt

Assume a Poissonian probability

$$\phi_\nu(\mathscr{E}_\nu^{\rm HE,iso}, E_\nu, d_L) = \frac{(1+z)}{4\pi d_L^2} \frac{\mathscr{E}_\nu^{\rm HE,iso}}{\ln\left(\varepsilon_\nu^{\rm max}/\varepsilon_\nu^{\rm min}\right)} E_\nu^{-2}$$

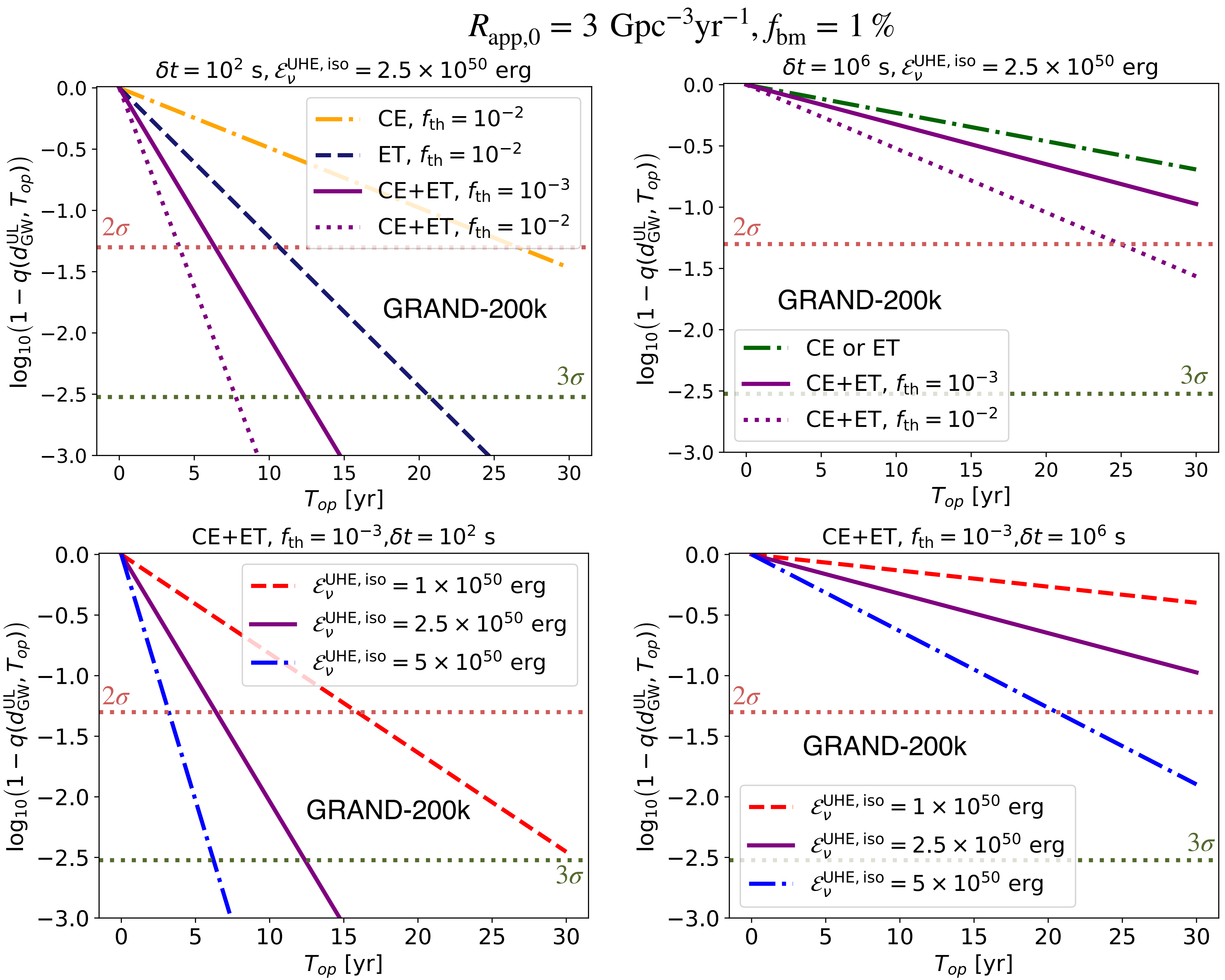
The event rate is calculated is convoluting the GRAND effective area with the muon neutrino flux

$$\mathscr{E}_\nu^{\rm HE,iso} = \frac{\mathscr{E}_\nu^{\rm HE,true}}{f_{\rm bm}} = \left(\frac{f_\nu}{f_{\rm bm}}\right) \mathscr{E}_{\rm GW}$$

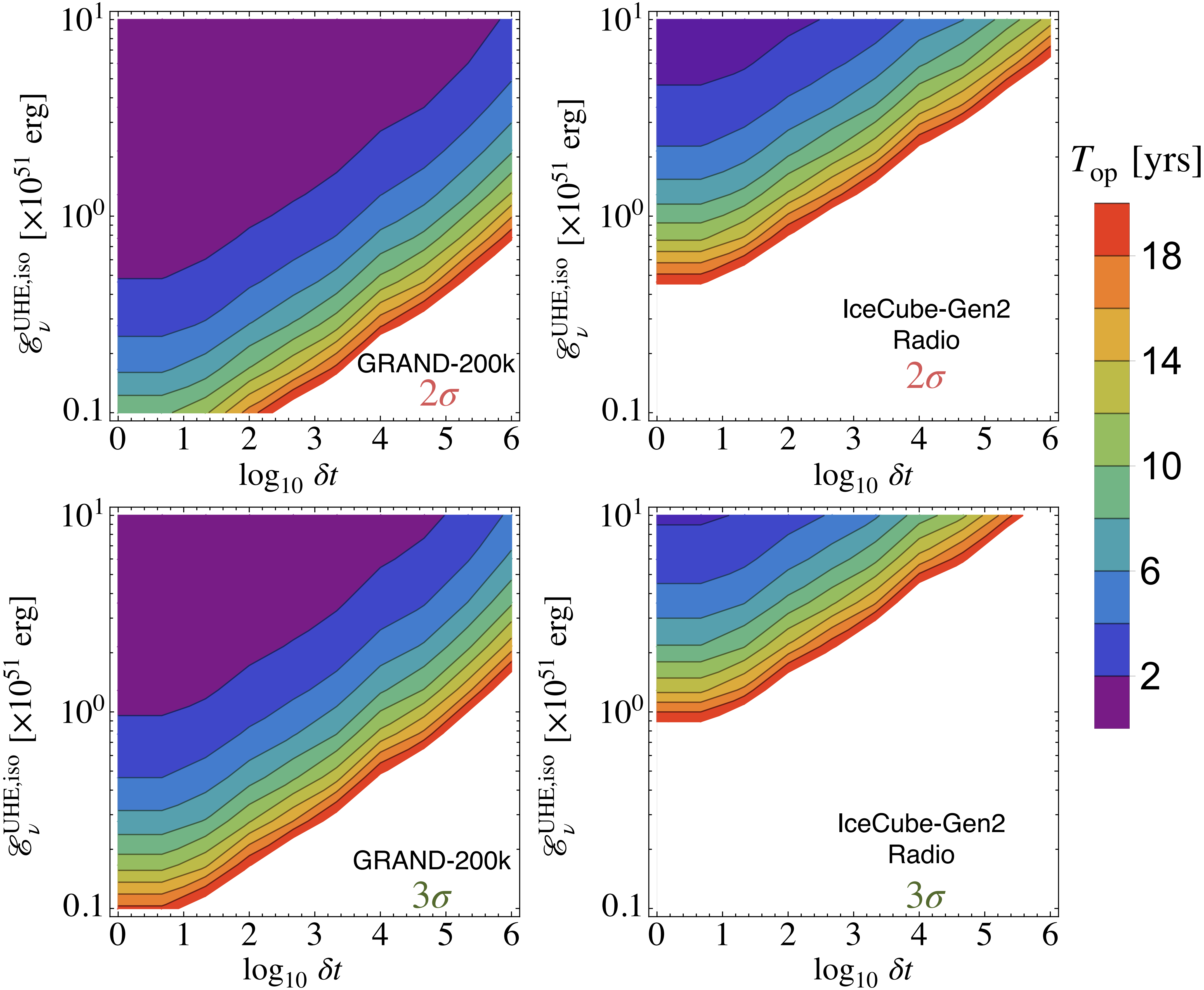
The flux is calculated assuming a $dN_\nu/dE_\nu \propto E_\nu^{-2}$ spectrum.

$$\mathscr{E}_\nu^{\rm HE,true} = f_\nu \mathscr{E}_{\rm GW} \qquad \mathscr{E}_{\rm GW} \sim \alpha \mathscr{E}^{\rm tot} \qquad \alpha \sim 1\,\%$$

GW-triggered UHE neutrino searches at GRAND-200k



Prospects for GRAND and IceCube-Gen2 Radio



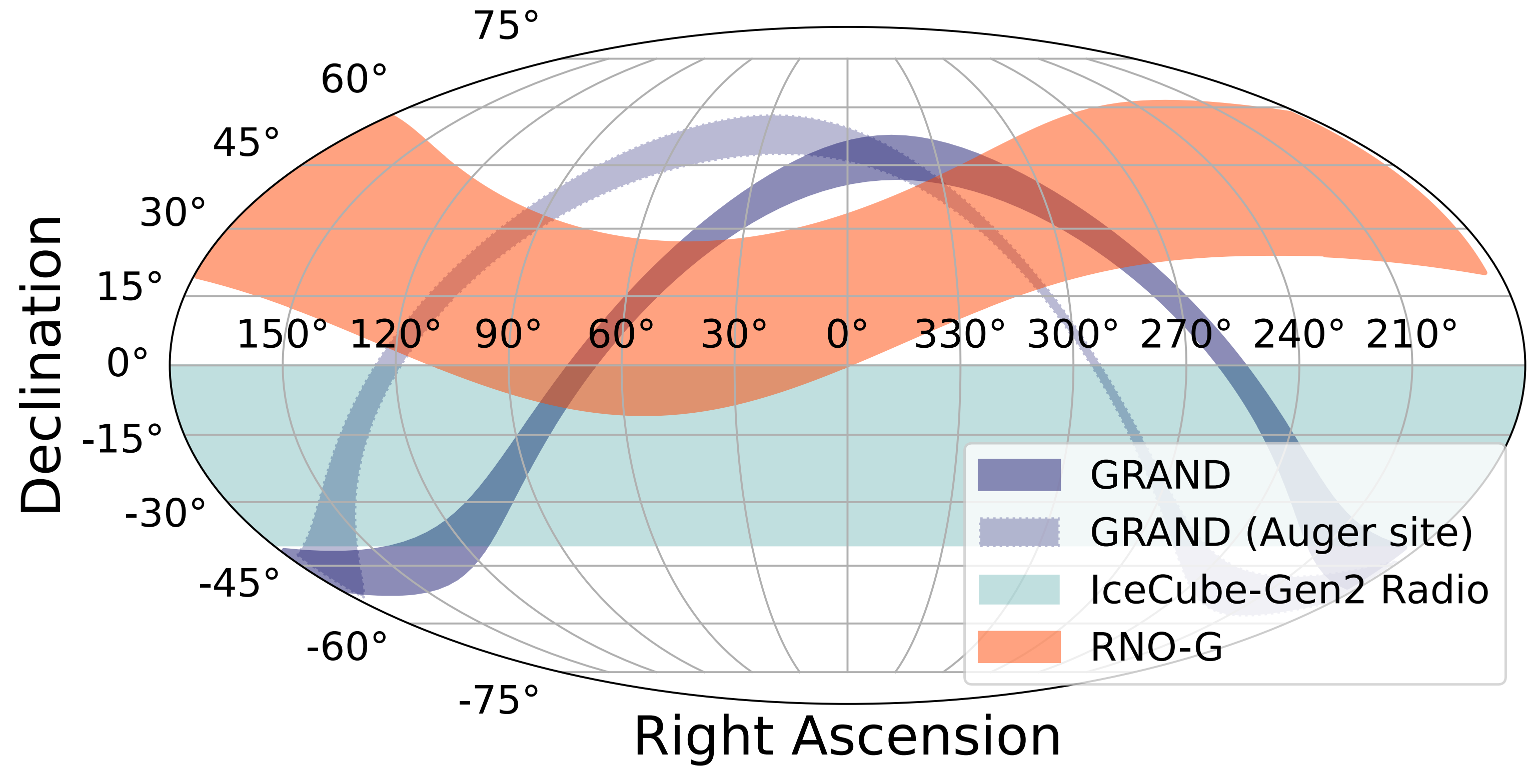
Future prospects: the big picture

Fate of BNS merger remnants - key insights for BNS mergers as particle accelerators [also 1 > 0 :)]

Associating triggers with merger events: EM-triggers - also helps in reducing the localization area

Extending to other transients - TDEs, SLSNe, ….

Probing physics beyond the Standard Model



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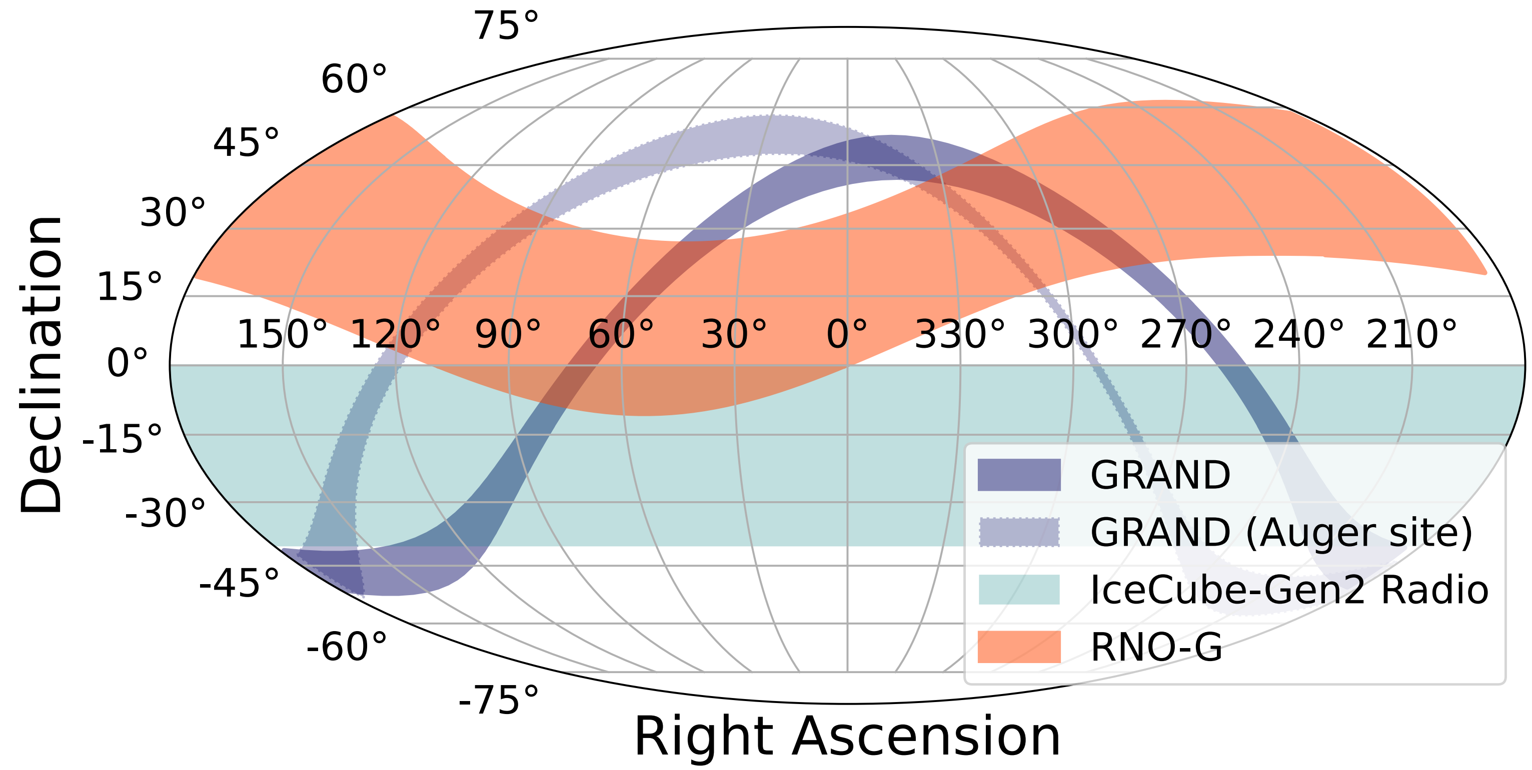


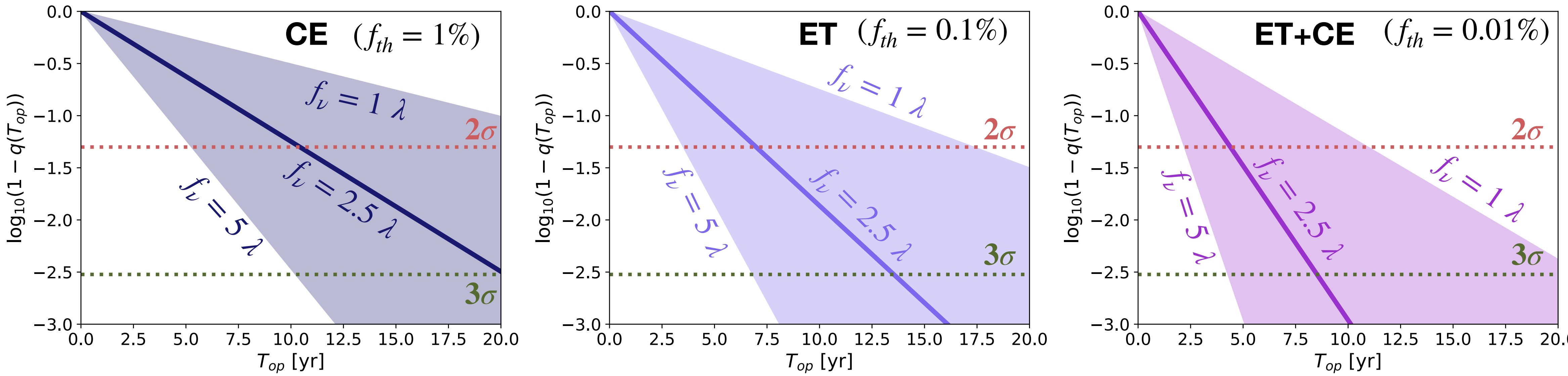
Thank You!

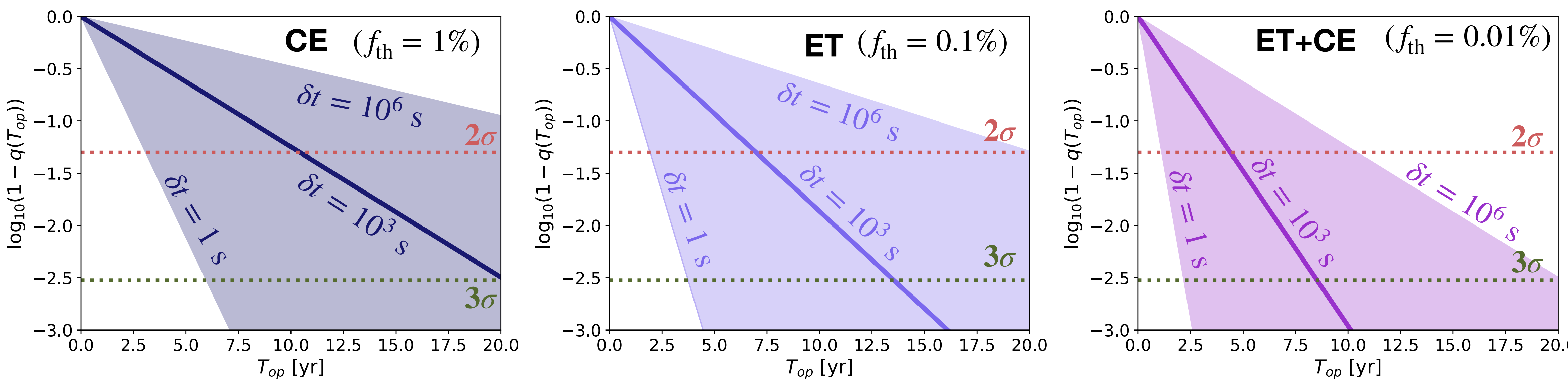
Backup

Results - varying f_ν and δt

f_ν

$\delta t = 1000$ s



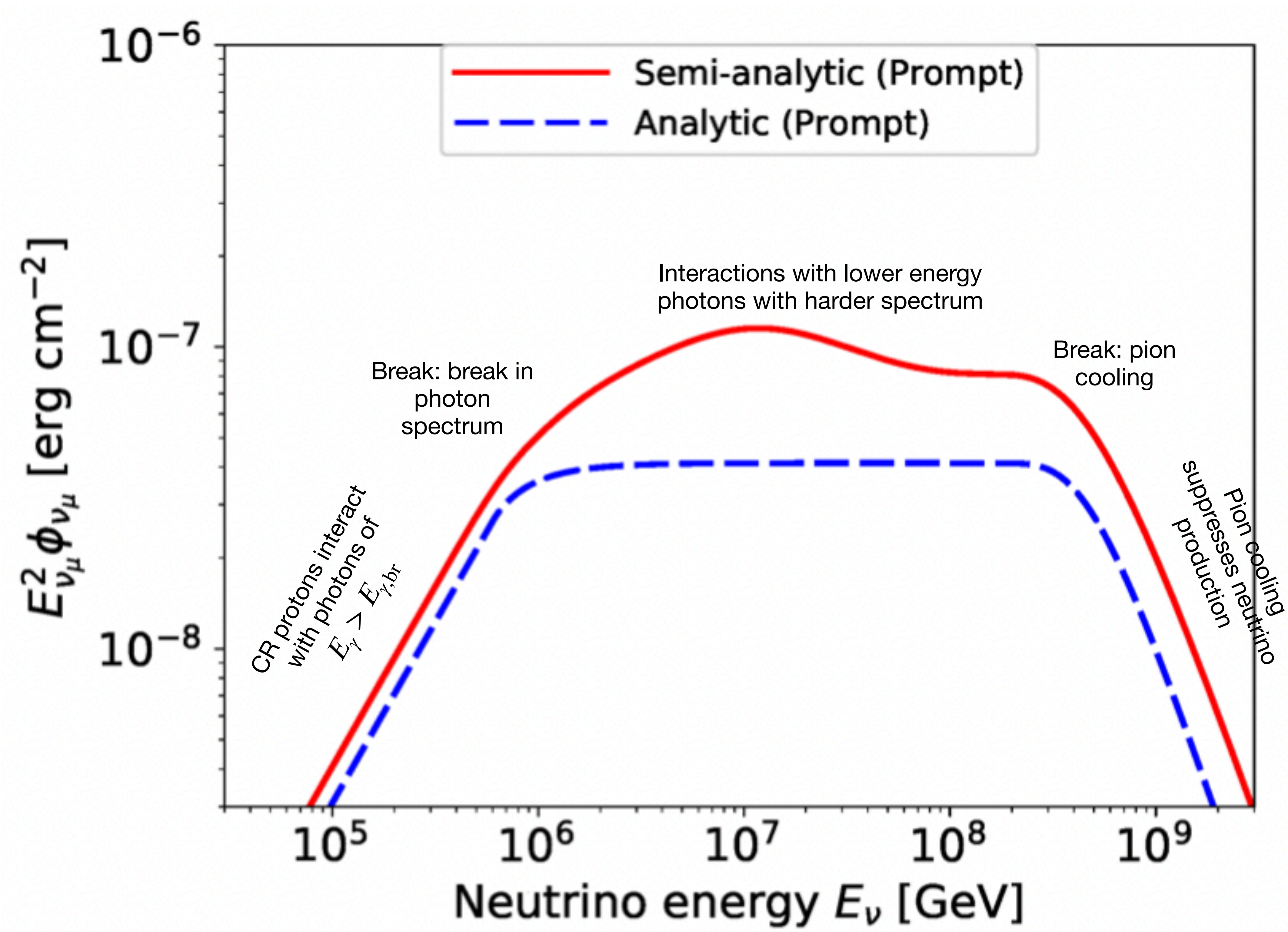


$f_\nu = 2.5\ \lambda$

δt

$\lambda = 10^{-5}$

Effective $p\gamma$ optical depth



Kimura 2022, arXiv: 2202:06480
Kimura, Murase, Mészáros, and Kiuchi. ApJ, 848:L4, 2017