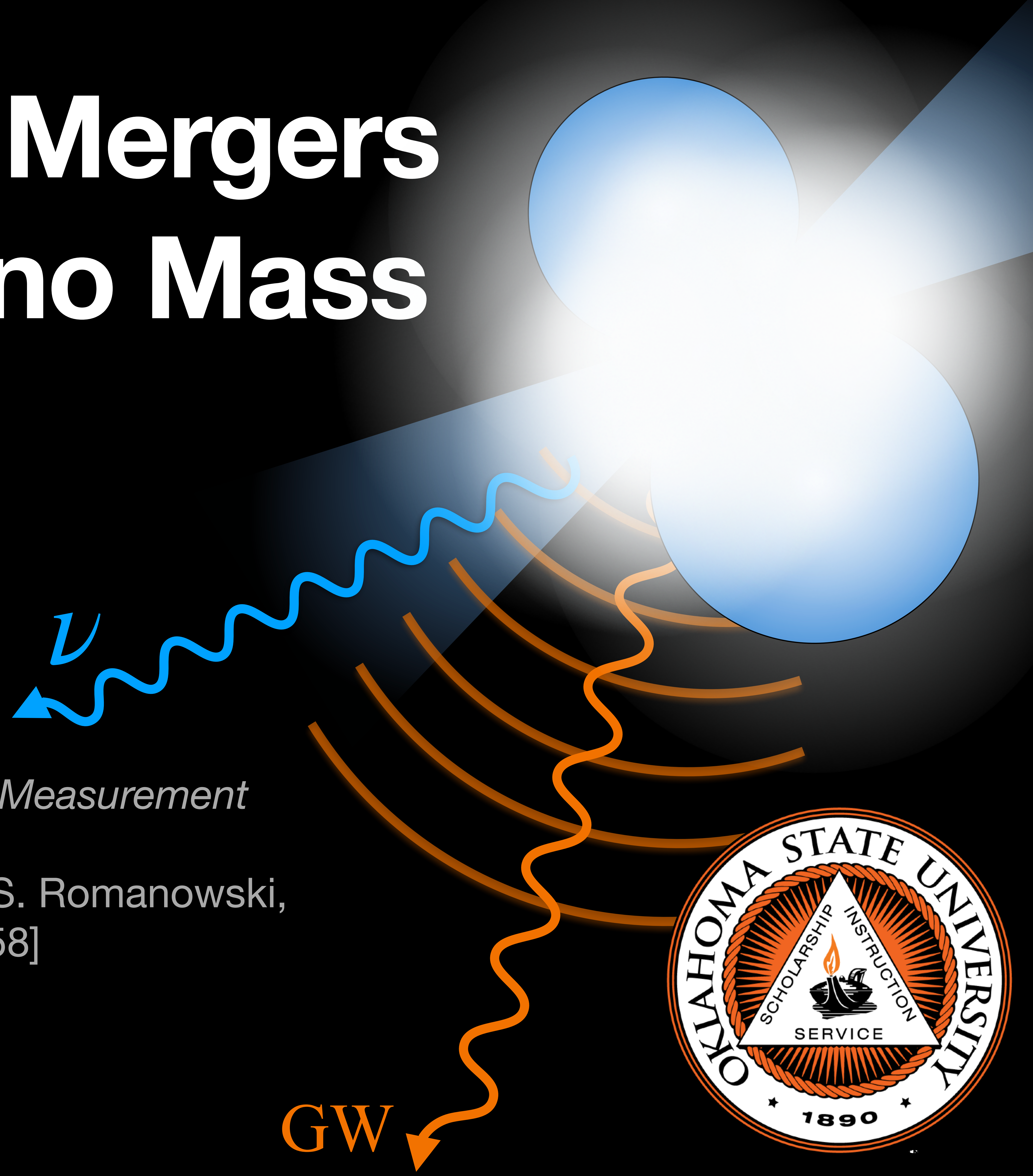
Binary Neutron Star Mergers as a Probe of Neutrino Mass

Dibya S. Chattopadhyay



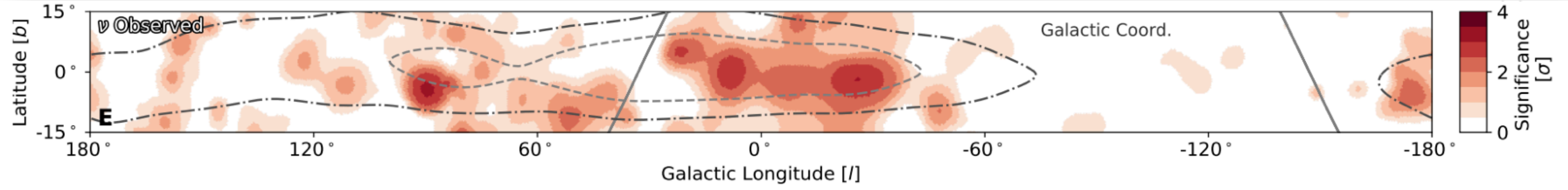
Based on *"Prospects for Neutrino Observation and Mass Measurement from Binary Neutron Star Mergers"*,
V. Brdar, D. S. Chattopadhyay, S. R. Mir, T. Raza, and M. S. Romanowski,
Accepted for publication in Phys. Rev. D [arXiv:2511.16658]

PHENO 2026, 11 May 2026, U. Pittsburgh

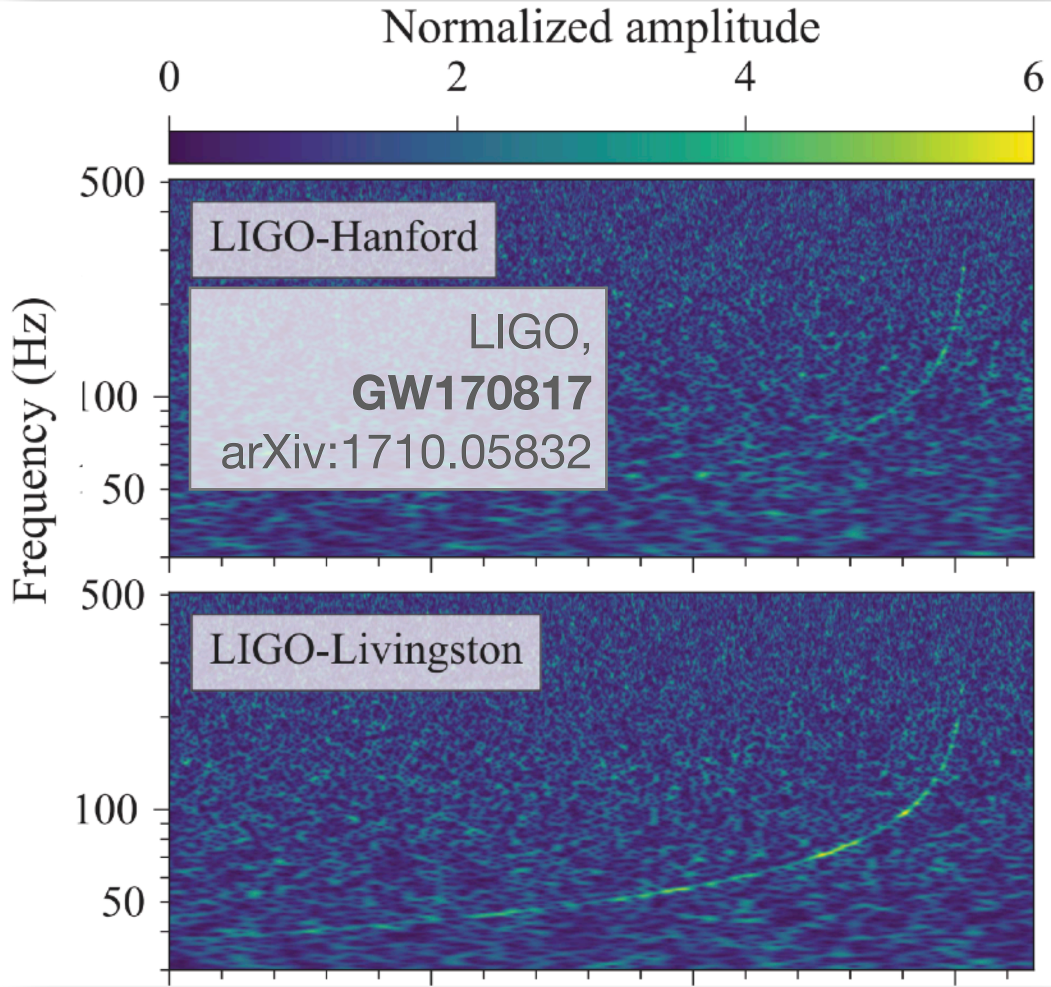
OKLAHOMA STATE UNIVERSITY
1890

Why binary neutron star (BNS) mergers?

- Some of the most violent events in universe, extremely luminous in neutrinos…
- Powerful source of gravitational wave (GW) signatures!
- Long distance + GW timing = great probe for ν mass…

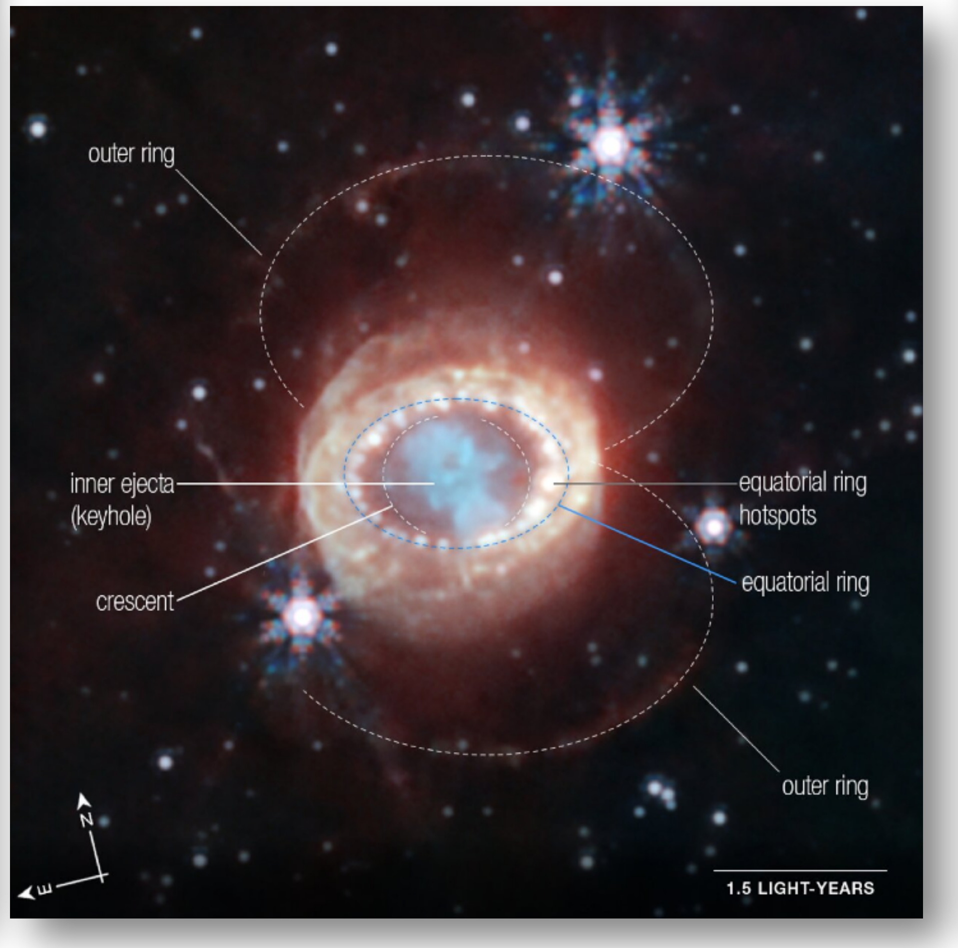


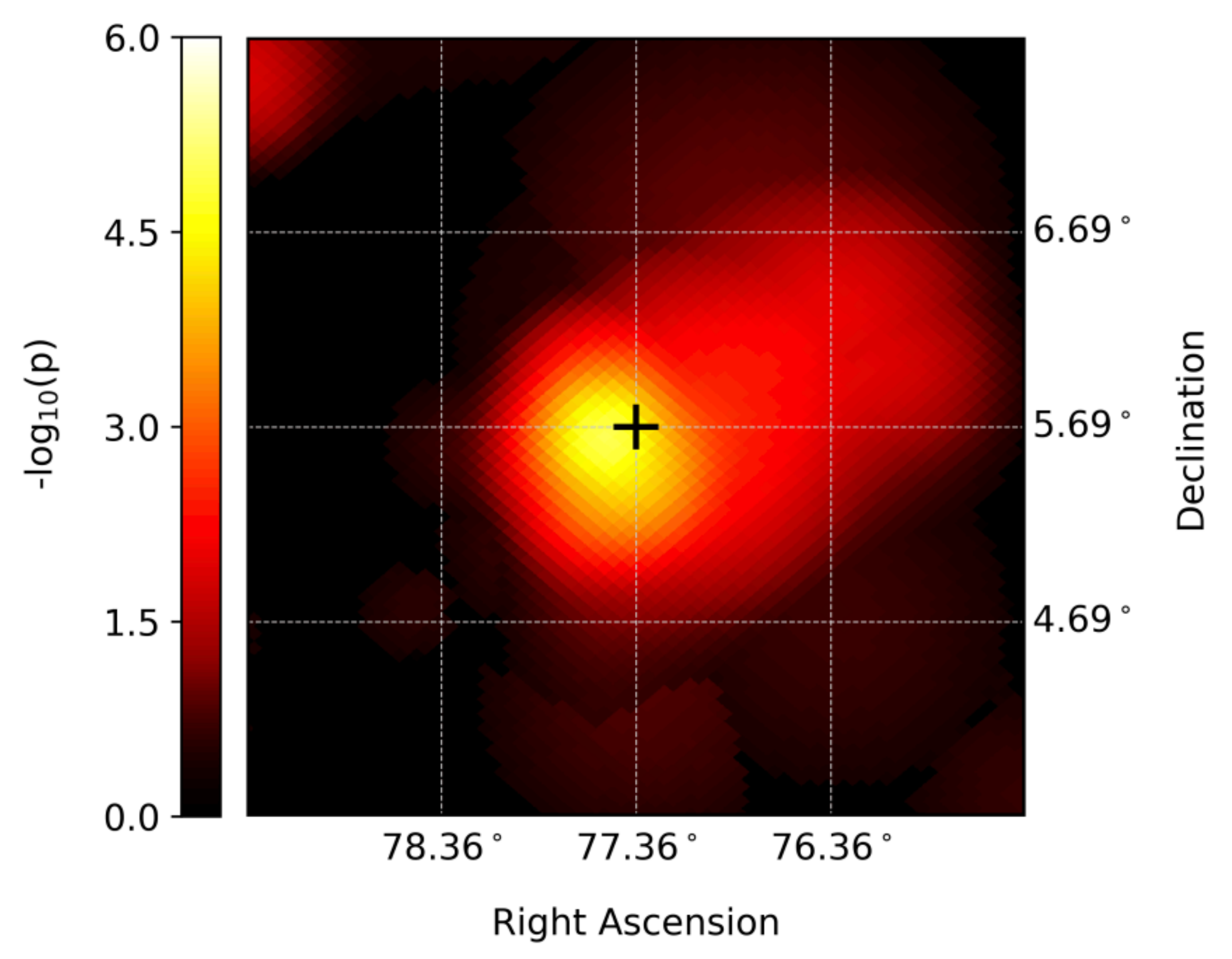
MW observed **in neutrinos**, arXiv:2307.04427



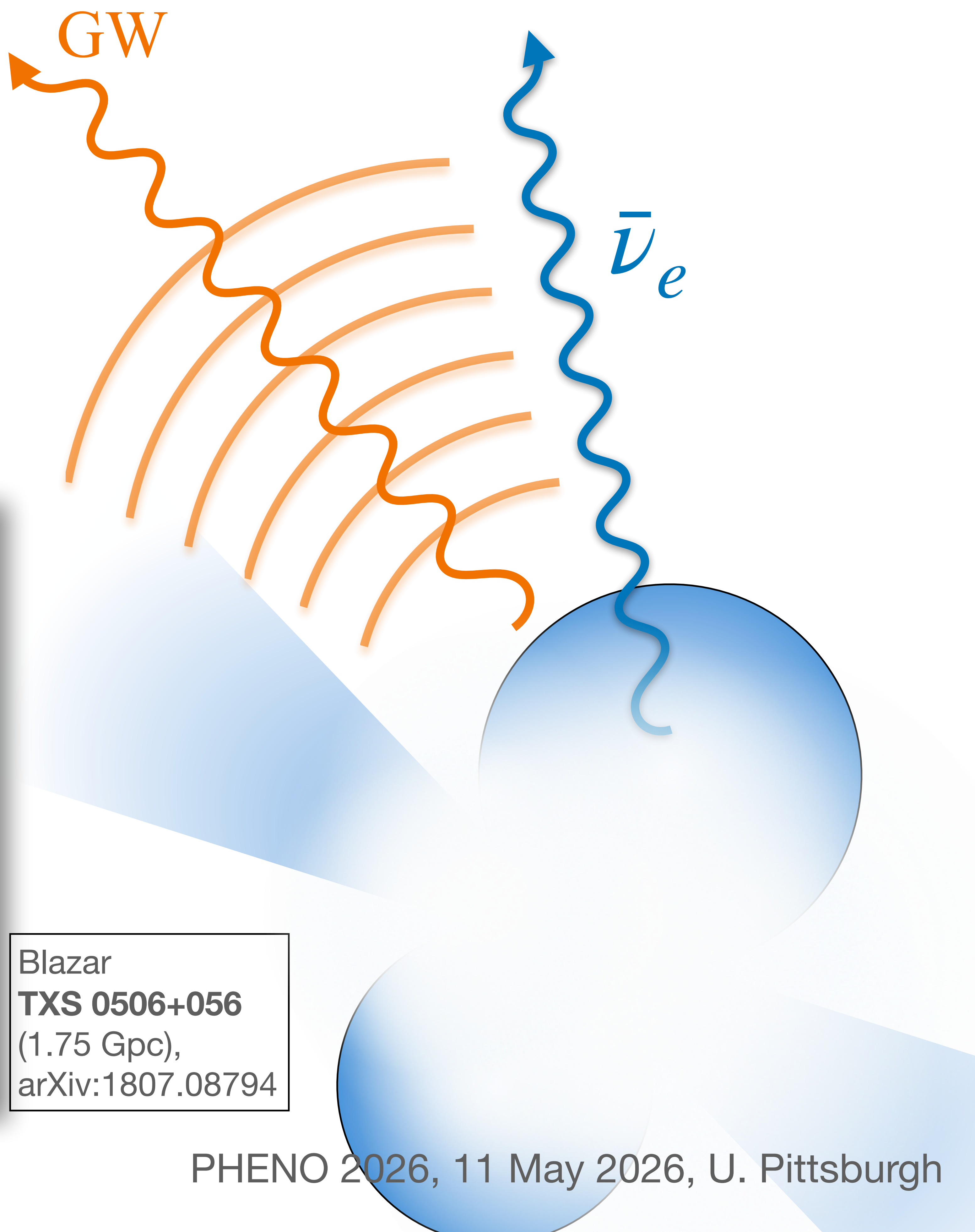
LIGO, **GW170817** arXiv:1710.05832

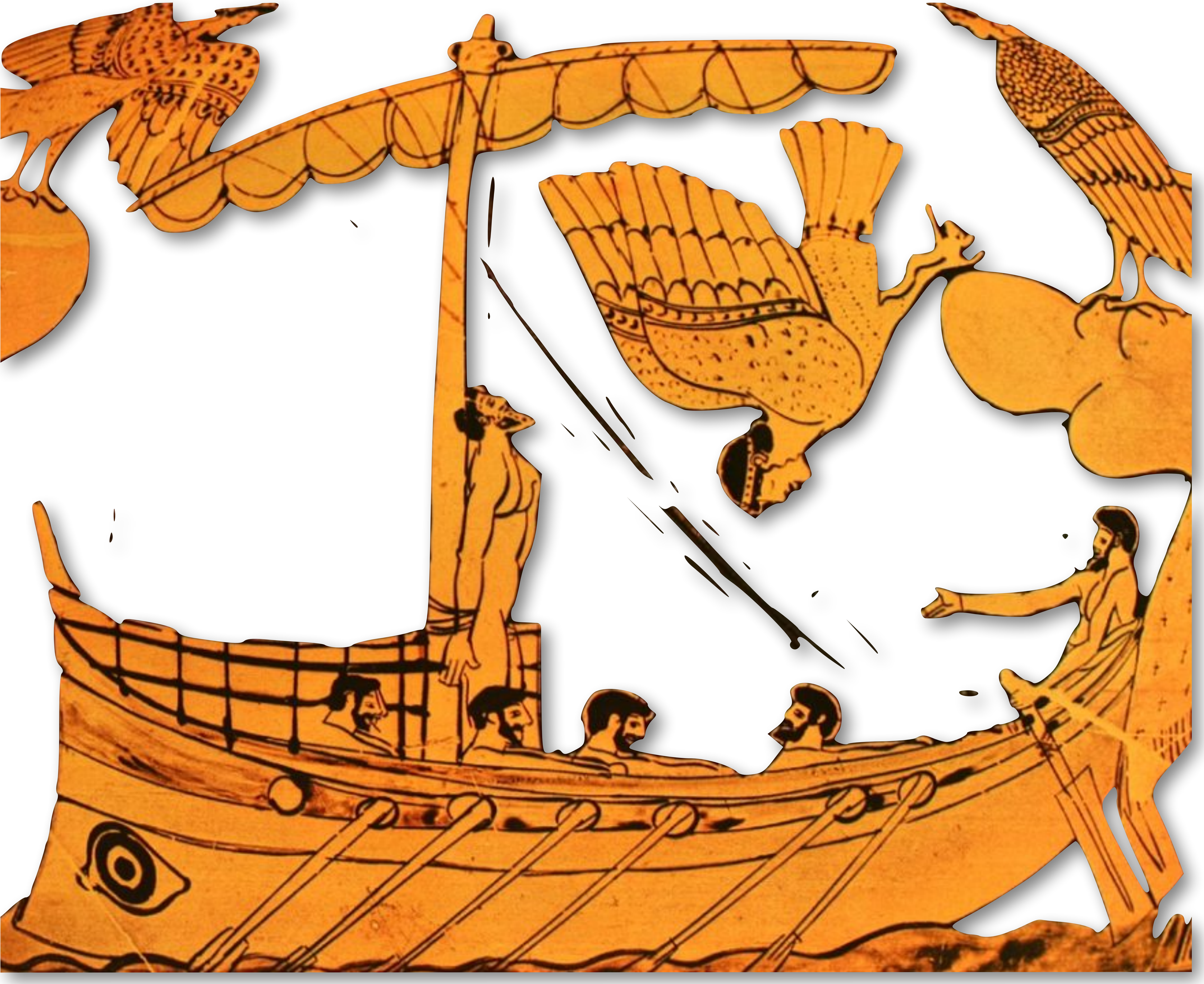
JWST, **SN1987A**





Blazar
TXS 0506+056
(1.75 Gpc),
arXiv:1807.08794





Odysseus and the Sirens, eponymous vase of the Siren Painter, c.480–470 BC (British Museum)

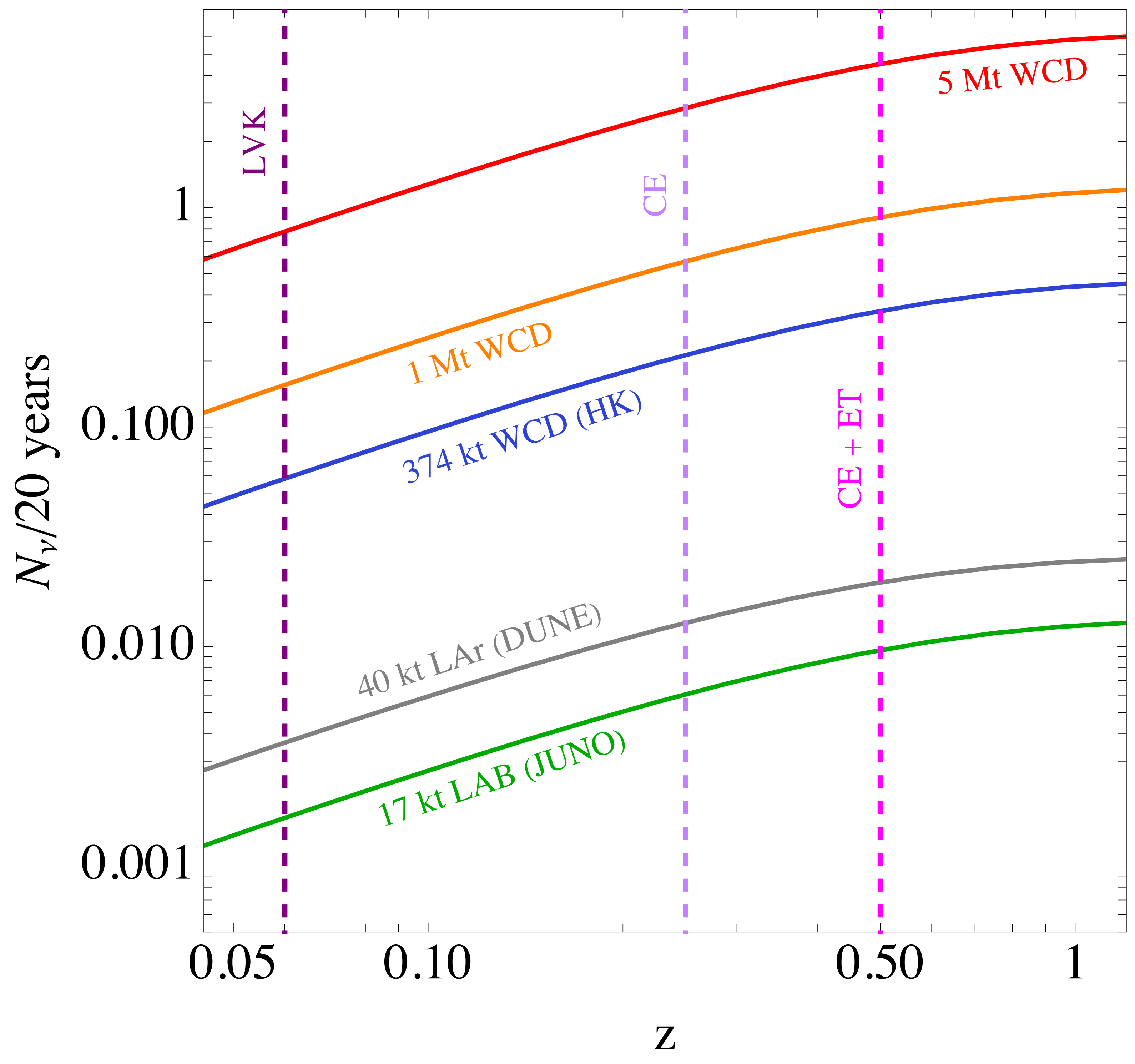
Detecting the very **first neutrino** from a BNS merger

BNS neutrinos are rare, but not that rare…

- Integrated upto a large redshift, BNS mergers are pretty frequent…

Kyutoku, Kashiyama
[arXiv:1710.05922]

- Merger rate of $250\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$



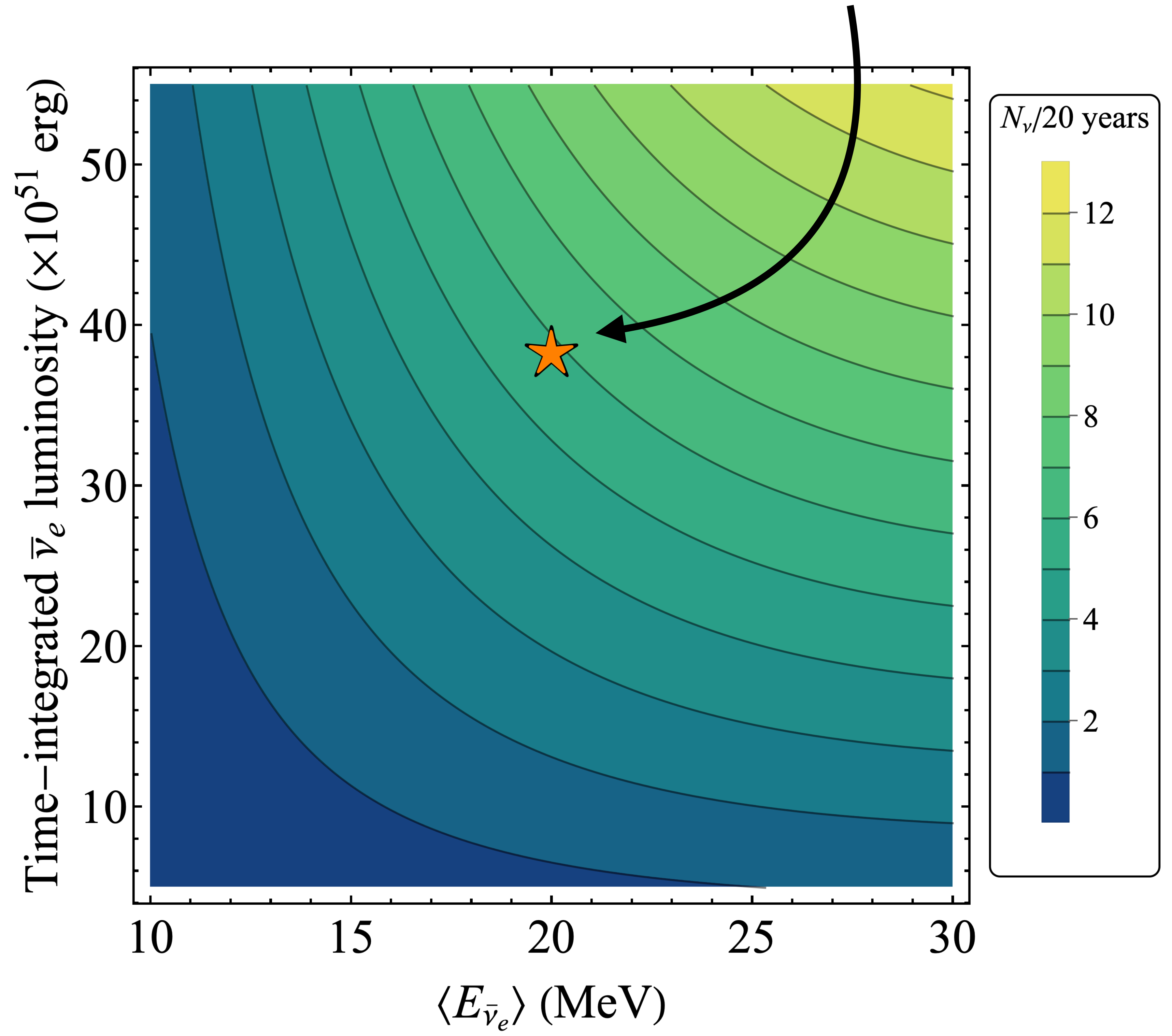
$$\left(\frac{d\phi_\nu}{dE_\nu}\right)_{\text{single BNS}} = \frac{L_\nu}{4\pi d^2}\frac{(1+\alpha)^{1+\alpha}}{\Gamma(1+\alpha)}\frac{E_\nu^\alpha}{\langle E_\nu\rangle^{2+\alpha}} \times \exp\left[-(1+\alpha)\frac{E_\nu}{\langle E_\nu\rangle}\right].$$

Fermi-Dirac: $\alpha = 2.3$

Resulting flux at Earth

$$\frac{d\phi_\nu}{dE_\nu} = \int_0^z (1+z')\,\Phi[E_\nu(1+z')]\,R_{\text{BNS}}(z')\left|\frac{dt}{dz'}\right| dz'$$

$$\left|\frac{dt}{dz}\right| = \left[H_0(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}\right]^{-1}$$



Fujibayashi et al.
[arXiv:2007.00474]

BNS neutrinos are rare…

- Associating a particular neutrino to BNS merger is difficult
- GW triggered neutrino search
- **What's new:** neutrino time-of-flight delay due to nonzero mass…

Kyutoku, Kashiyama
[arXiv:1710.05922]

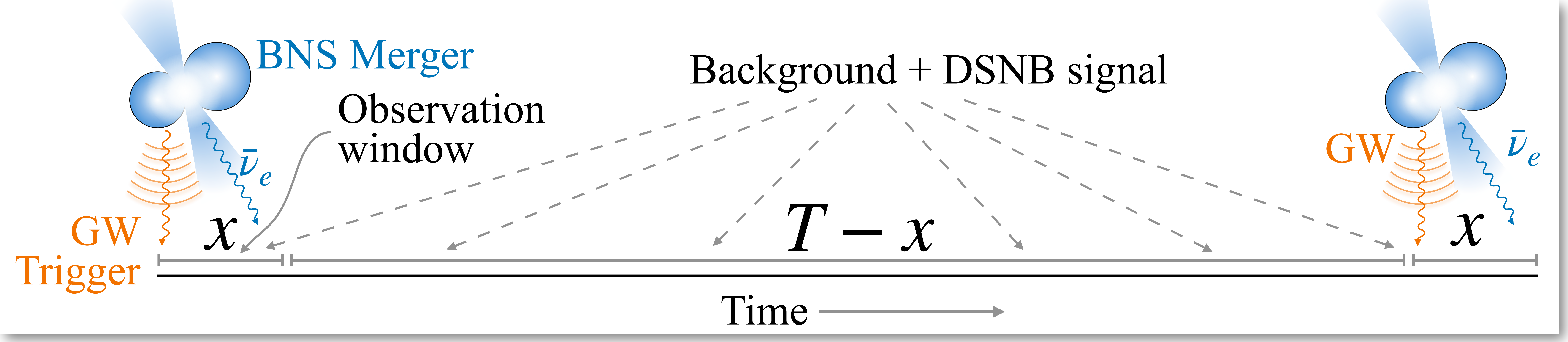
Lin, Lunardini
[arXiv:1907.00034]

Deguire, Caballero, Lehner
[Phys. Rev. D 112, 043002; 1 Aug 2025]

$\mathcal{O}(10^4)\ \mathrm{yr}^{-1}$
5MT Water Cherenkov
Background

$\mathcal{O}(10^2)\ \mathrm{yr}^{-1}$
5MT Water Cherenkov
DSNB

$\sim 0.3\ \mathrm{yr}^{-1}$
5MT Water Cherenkov (z=1)
$\sim 3\times 10^4$ BNS mergers per year
BNS neutrino



GW triggered neutrino search

$$\Delta t(z) = \int_0^z \frac{dz'}{H_0\sqrt{\Omega_m\,(1+z')^3+\Omega_\Lambda}}\,\frac{m_\nu^2}{2E_\nu(z')^2}$$

$$\Delta t \approx L\, m_\nu^2/(2E_\nu^2)$$

- After every GW trigger, we have to wait for $\Delta t_{\rm tot} \equiv \Delta t_{\rm emission} + \Delta t_{\rm delay}$
- We define a proxy for the signal vs. background probability:

$$P_{\rm safe} = \left(1 - \frac{\Delta t_{\rm tot}(z_{\rm cut})}{T(z_{\rm cut})}\right)^{n_{\rm bkg}(z_{\rm cut})}$$

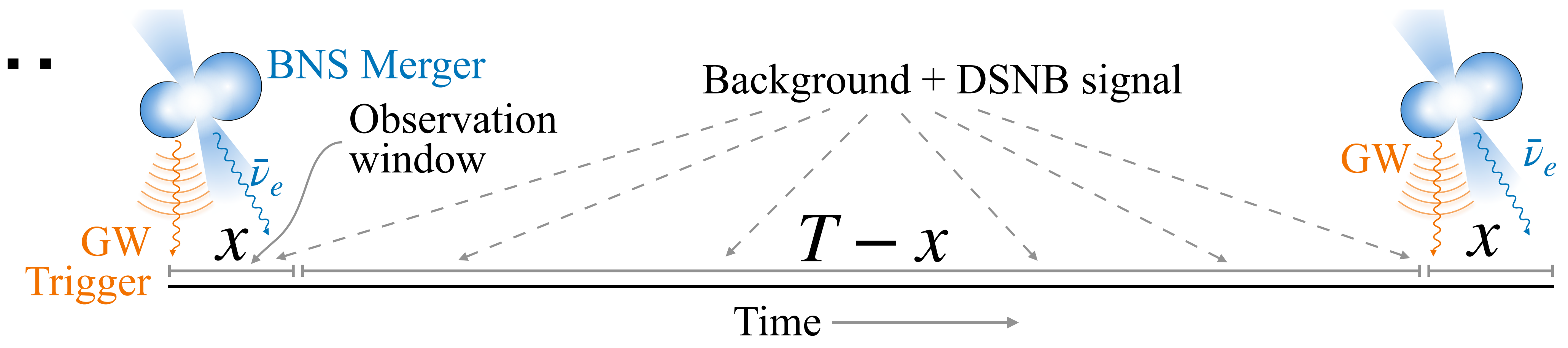
Window of observation after each GW trigger

Total number of background events in the time a single BNS neutrino would be detected

Time between 2 BNS merger triggers

- Overall strategy:
  - be really selective on when to look for a BNS neutrino, **energy dependent redshift cut**
  - Include the **time-of-flight delay,** as a function of the **lightest neutrino mass**
- $P_{\rm safe}$ is a $z_{\rm cut}$ and energy dependent quantity…
- We set $P_{\rm safe} = 0.9$

For every single BNS ν, there would be ~0.1 background ν

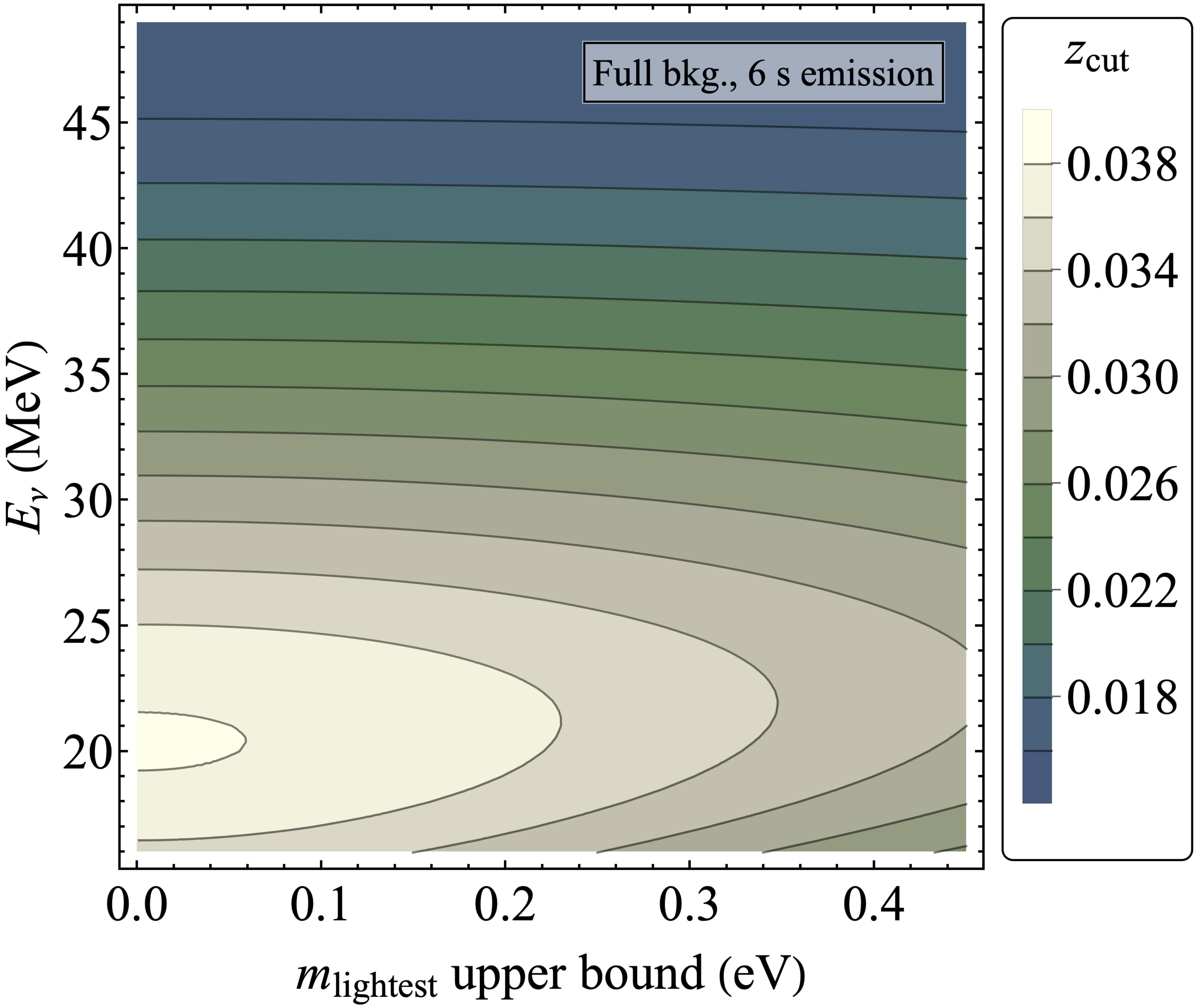


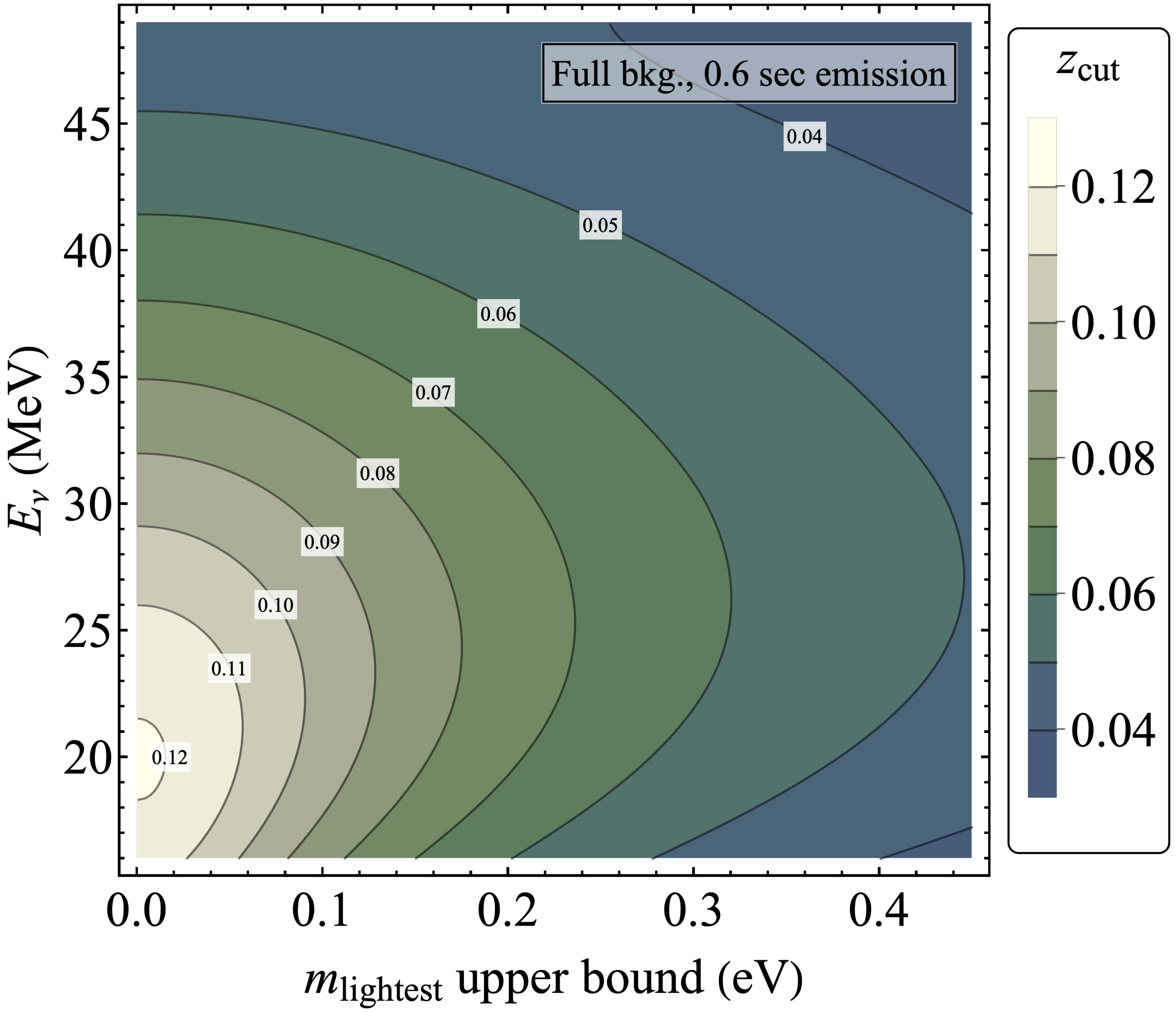
Emission duration matters

Lippuner et al. [arXiv:1703.06216]

- We consider 2 models: 6 and 0.6 second total emission times

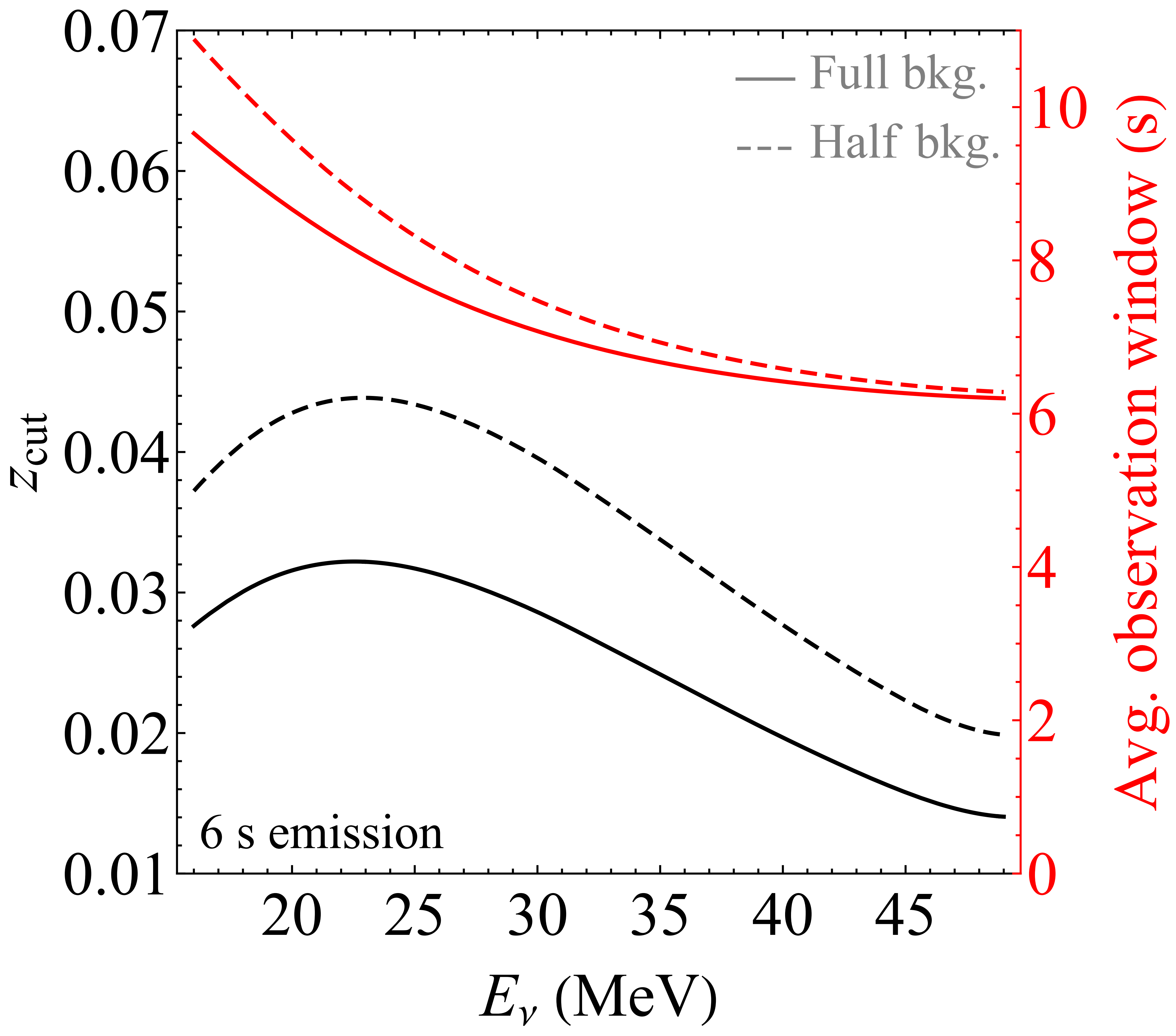
Fujibayashi et al. [arXiv:2007.00474]

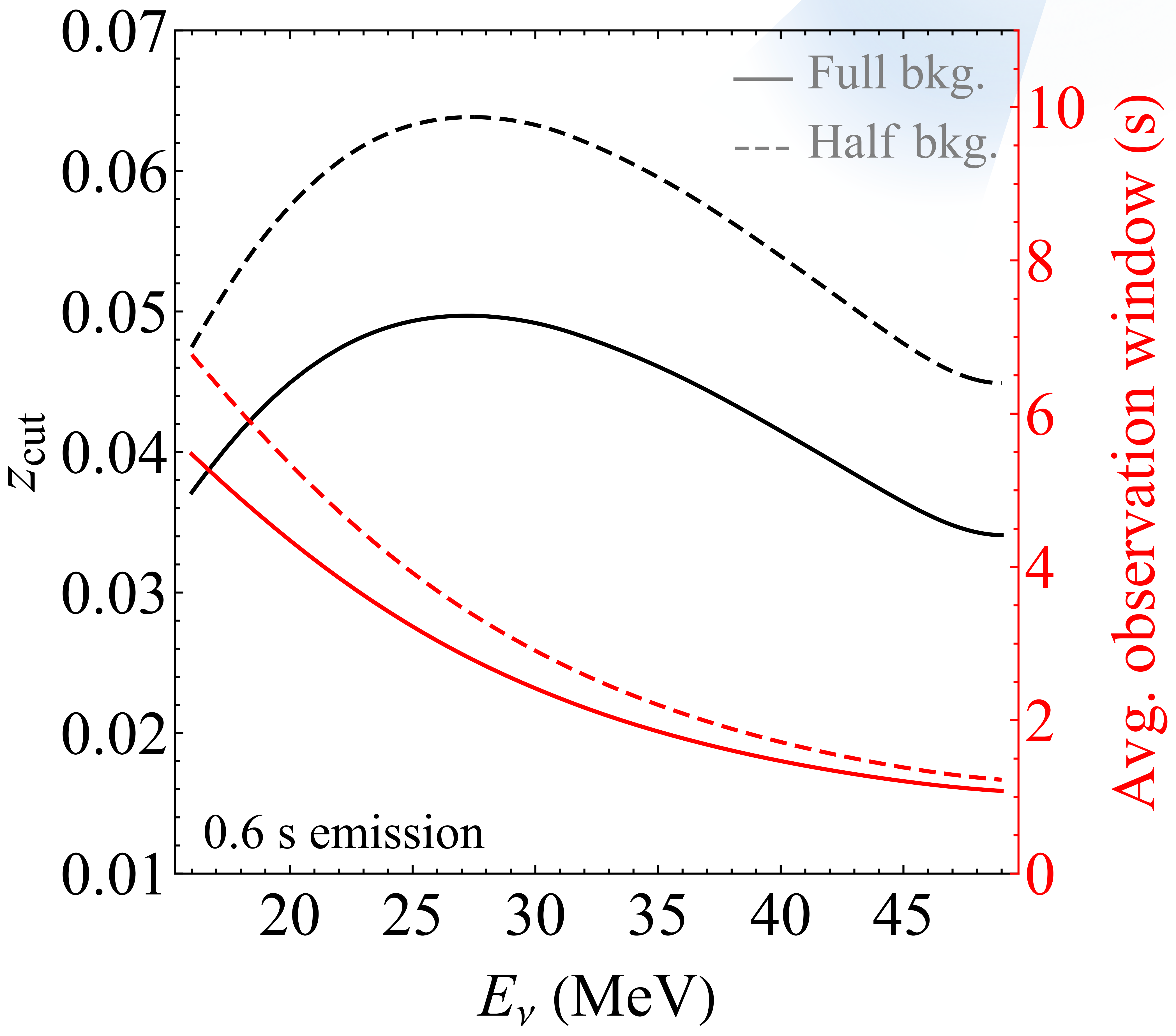




Energy dependent observational range

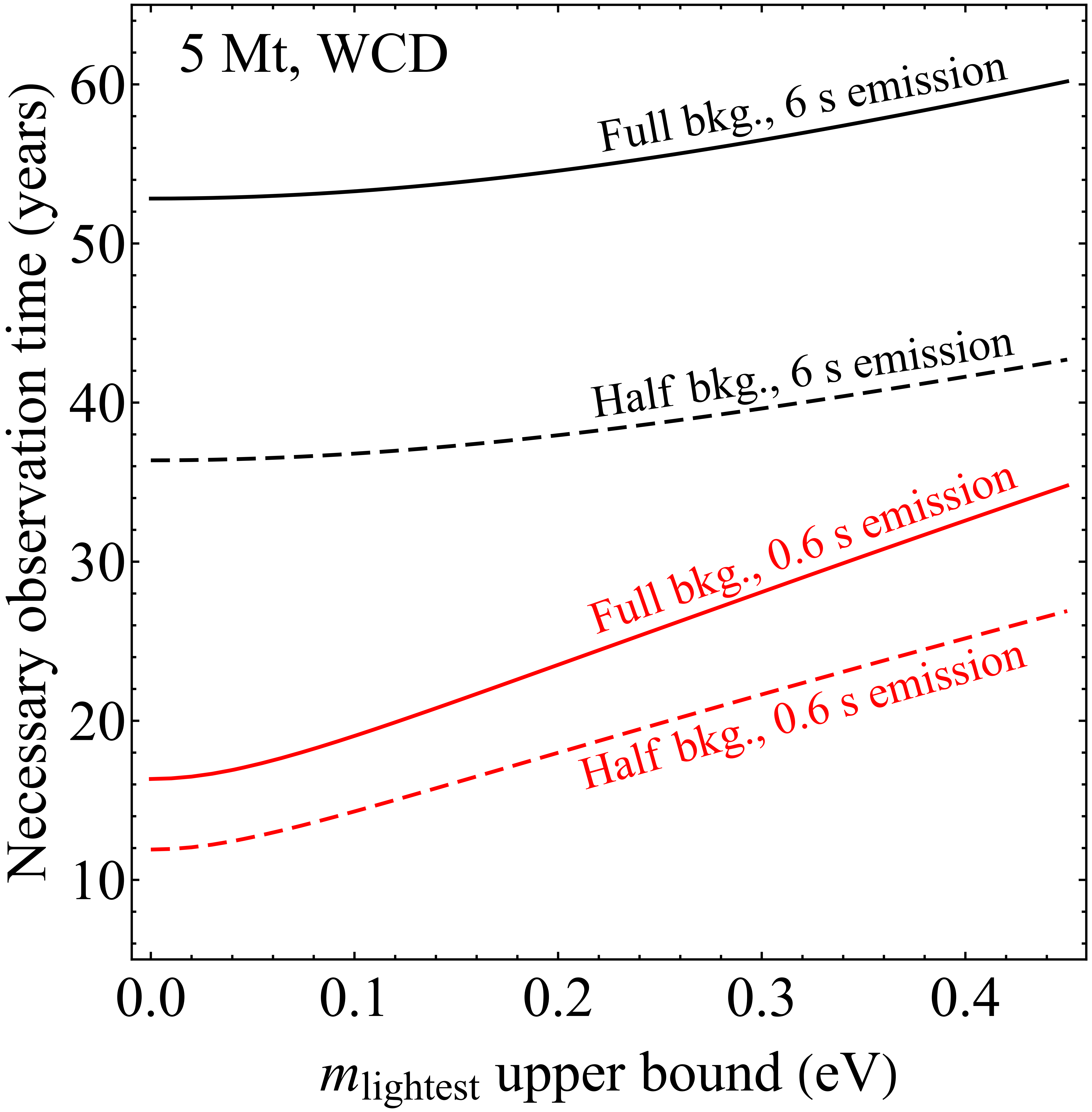
- Only look at specific energy ranges for BNS mergers at specific distances…





Observation time

- We need a very large detector, and a few decades
- 5MT WCD, ~13 times HK-II
- Deep-TITAND, MEMPHYS, MICA
- Depends on the lightest neutrino mass upper bound
- Shorter emission times: ~(12-16) yrs. of observation may be enough…
- **Nonzero neutrino mass can lead to a few extra decades**

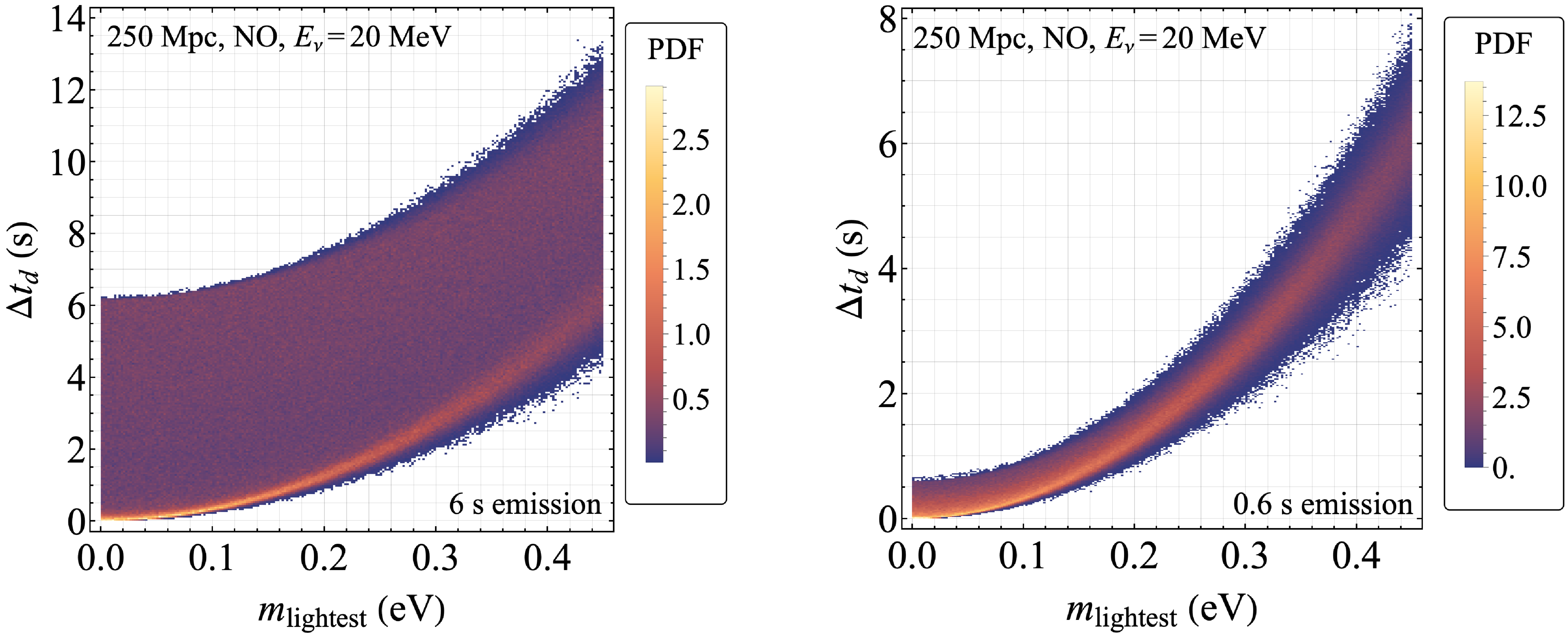


Oldest preserved manuscript of the Odyssey. Institute of Papyrology of the Sorbonne.

What does the **first neutrino** from a BNS merger tell us?

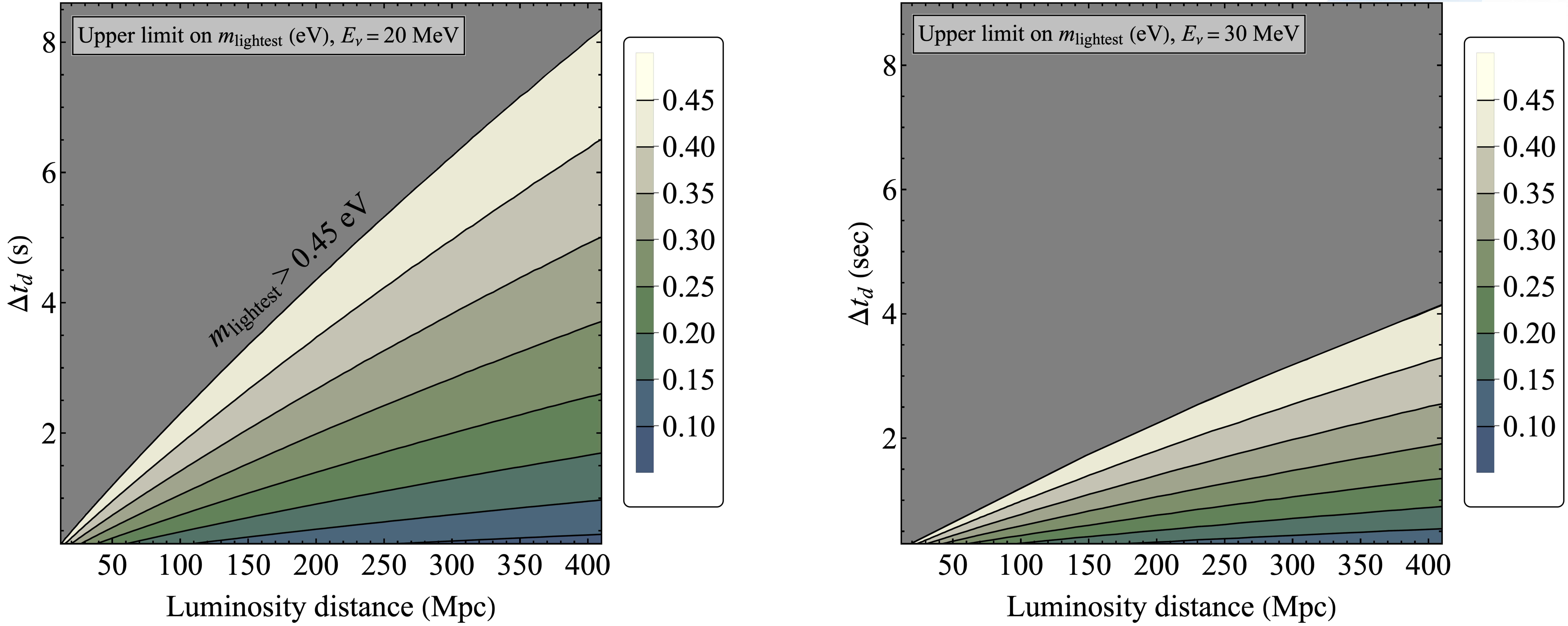
Neutrino mass and arrival time

- The arrival PDF depends on the emission PDF and the time-of-flight delay



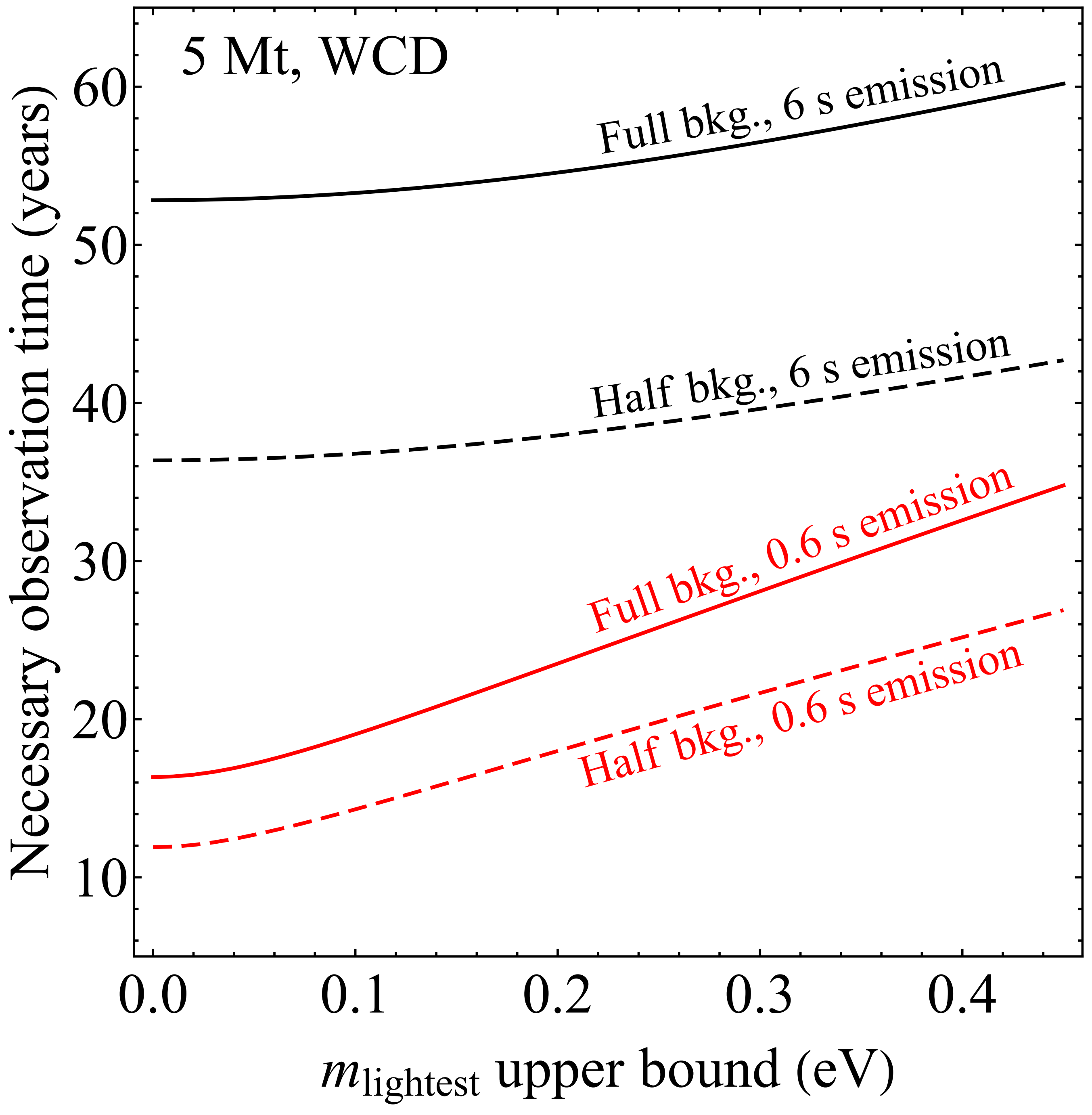
Constraints on neutrino mass…

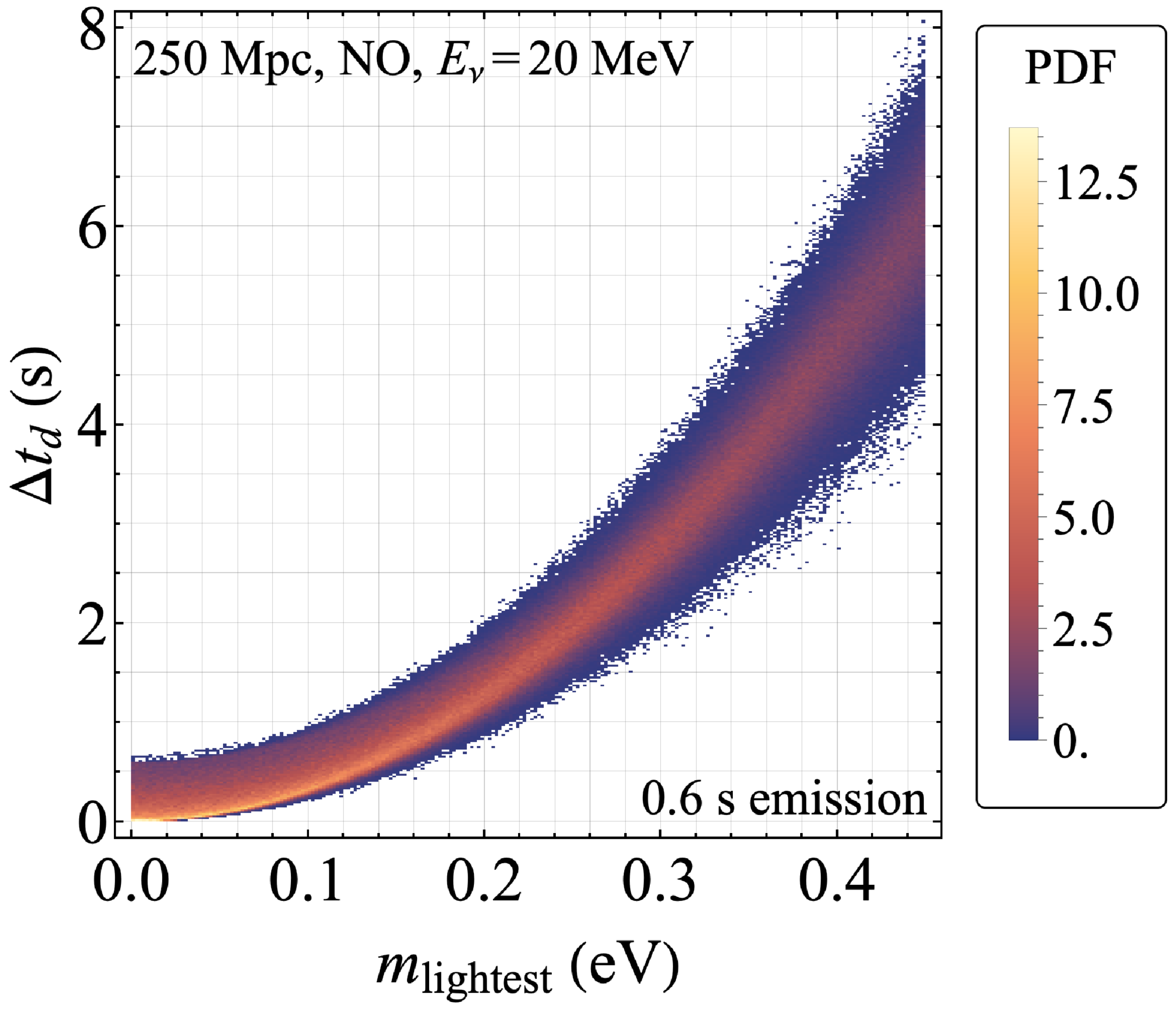
- Observation of a single neutrino can give bounds on the neutrino mass

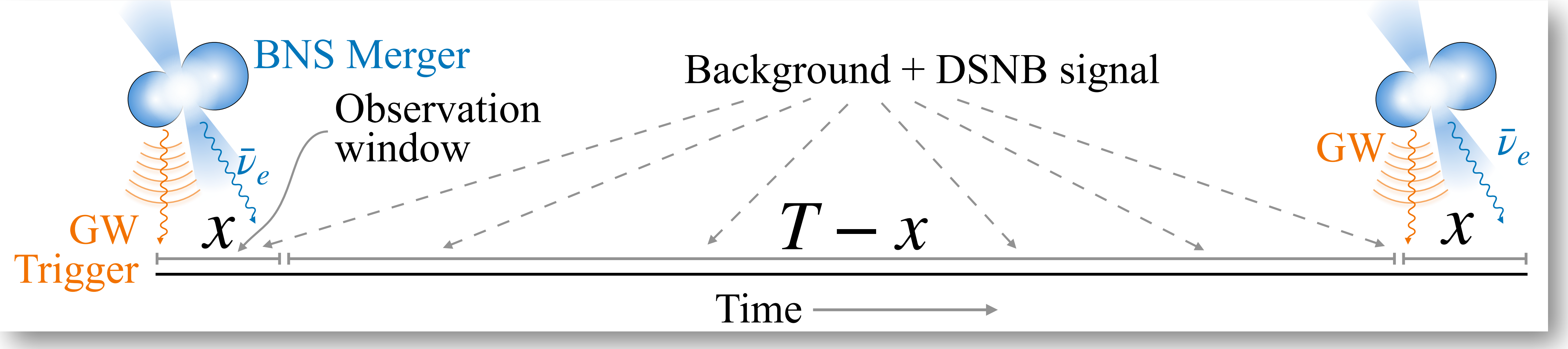


Summary

- BNS neutrinos are rare, confirmed BNS neutrinos rarer…
- Updated merger rate + non-zero neutrino mass time-of-flight delay considered for the first time = uphill battle
- Energy dependent redshift cut + GW trigger to fight the background…
- We would need a large detector + few decades.
- Even a single neutrino can constrain the neutrino mass.







Backup slides

Why electron antineutrinos

- For water Cherenkov detectors, the dominant channel at $\mathcal{O}(10)$ MeV is IBD capture:

$$\bar{\nu}_e + p^+ \rightarrow e^+ + n$$

- The electron antineutrino capture cross-section is:

$$\sigma_{\mathrm{IBD}}(E_\nu) \approx 10^{-43} \left(\frac{E_e p_e}{\mathrm{MeV}^2} \right)$$

$$E_e = E_\Delta - 1.293 \text{ MeV}$$

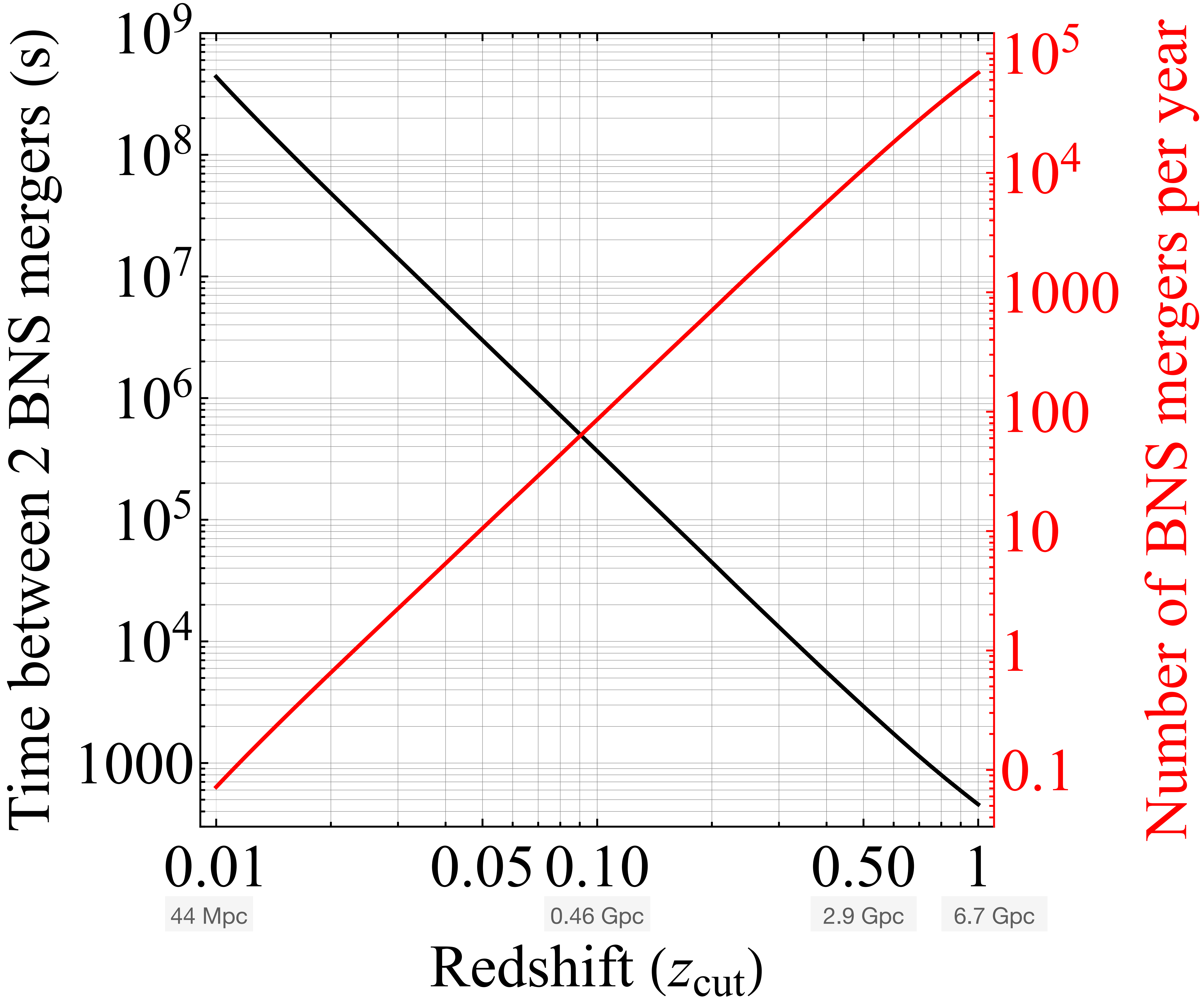
$$p_e = \sqrt{E_e^2 - m_e^2}$$

- Other detectable channels are $\mathcal{O}(100)$ or more weaker at $\mathcal{O}(10)$ MeV…

- We use a conservative estimate, where we assume that the electron antineutrino flux from BNS mergers is 1/6th of the total flux.

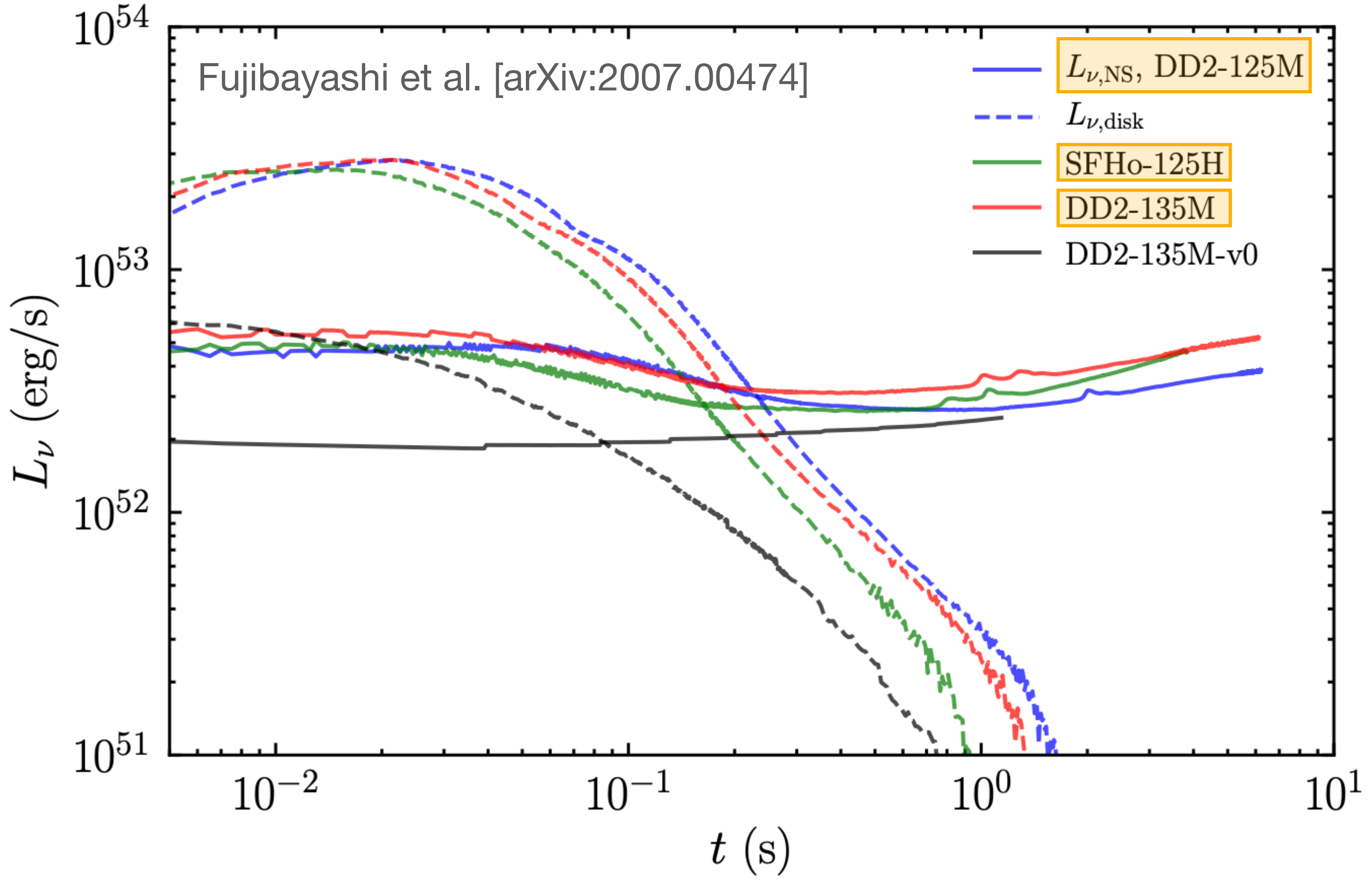
Merger rate & the time between 2 mergers

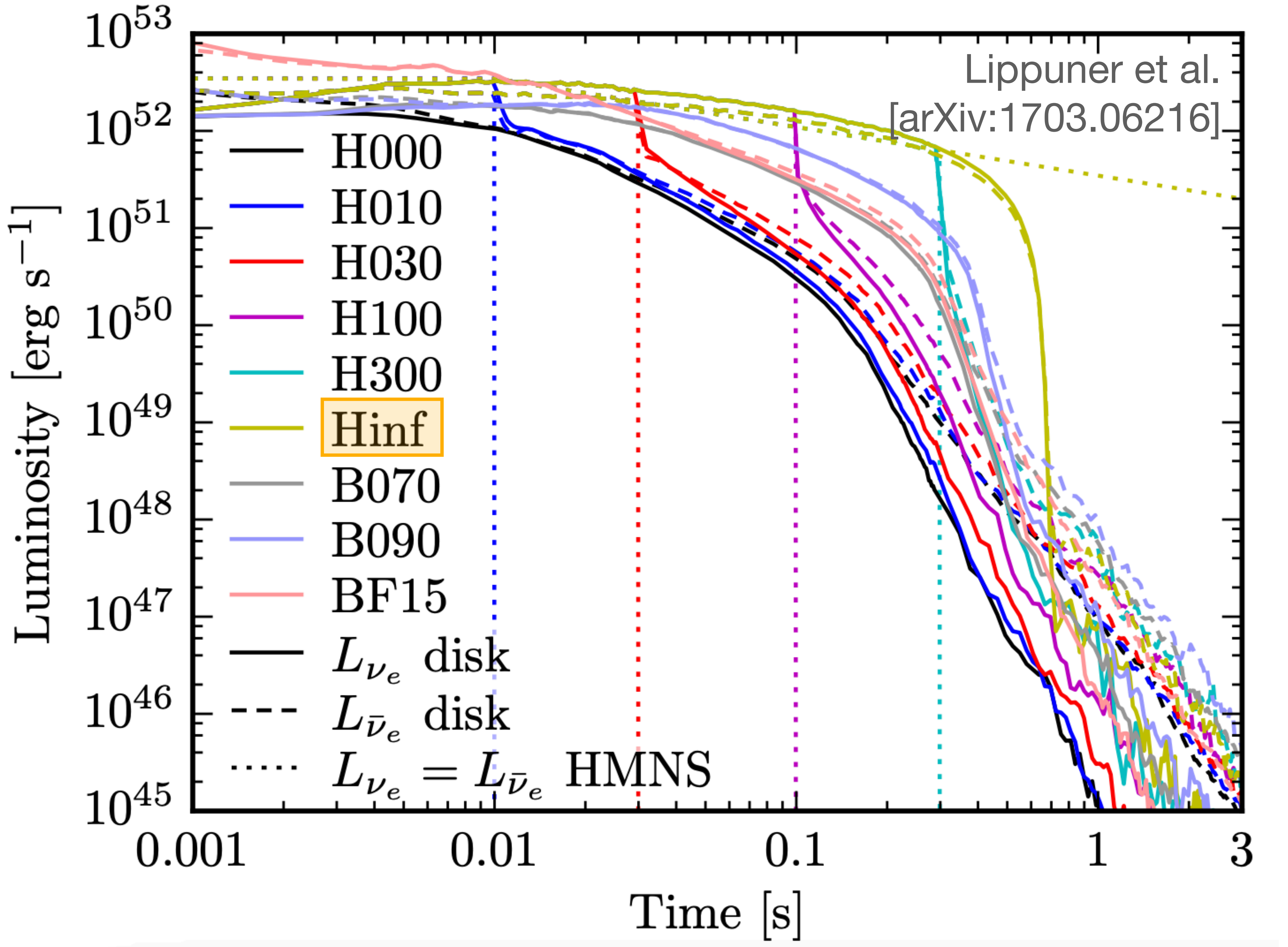
- Our search strategy boils down to looking at $\mathcal{O}(10^2 - 10^3)$ most neutrino luminous BNS mergers.
- How often to trigger the detector, the calculation involves:
  - Neutrino time-of-flight delay (due to nonzero neutrino mass),
  - Emission time,
  - Energy dependent redshift cut, etc.



Neutrino emission from BNS mergers

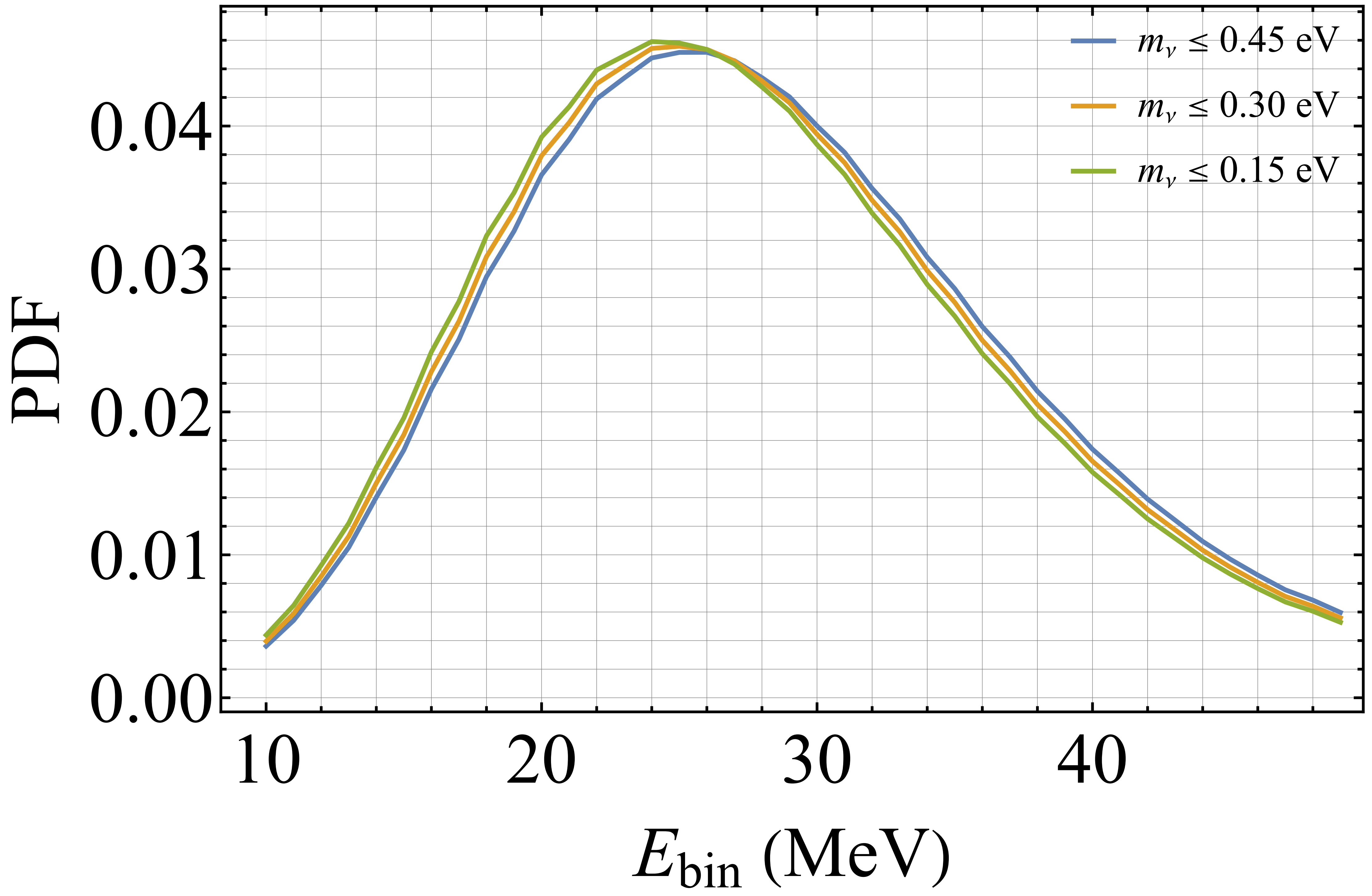
- Emission PDF taken from 2 BNS merger models, with 0.6 s & 6 s emissions
- The mean emission time is ~0.19 s and ~2.7 s, respectively

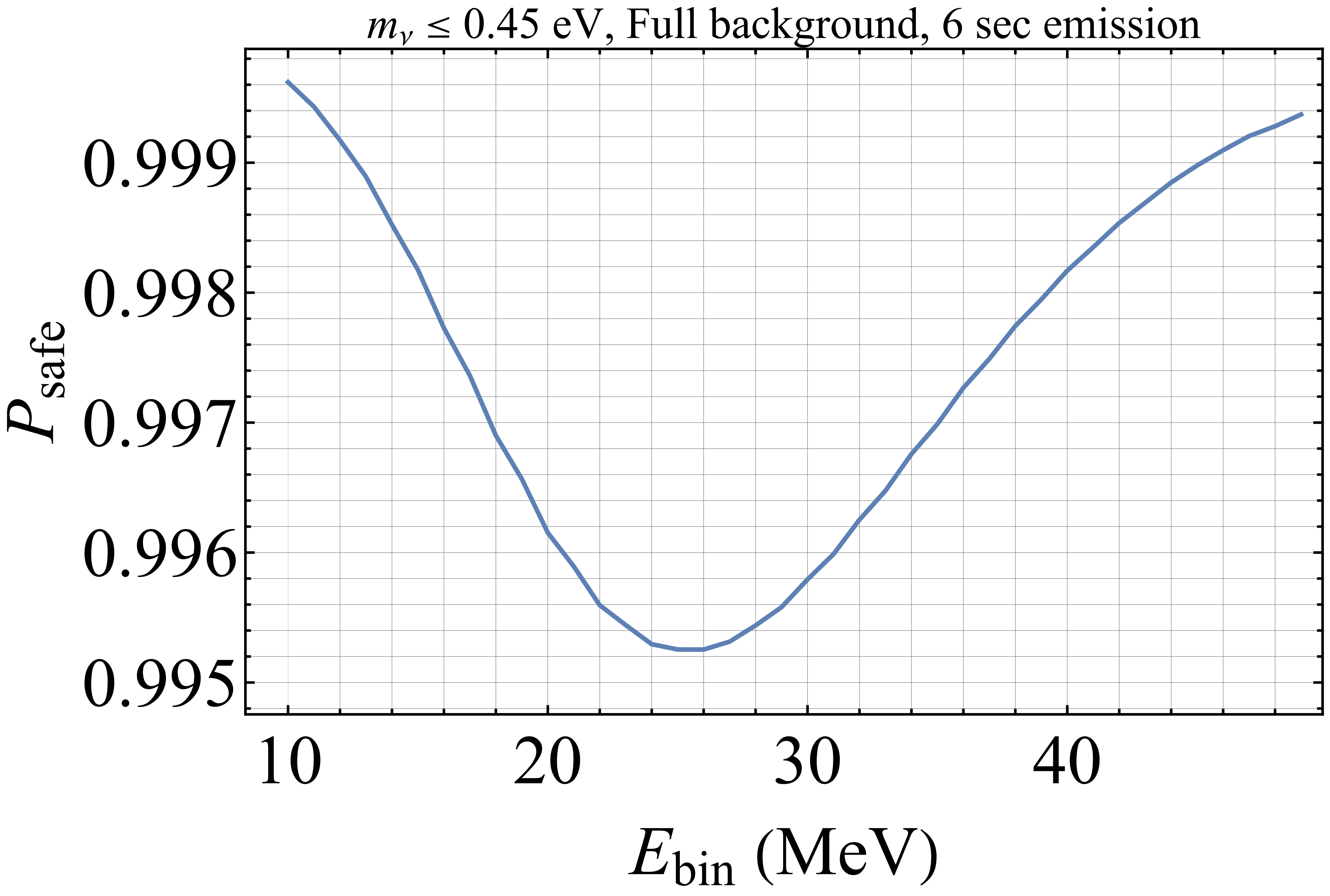




Neutrino arrival and background mitigation

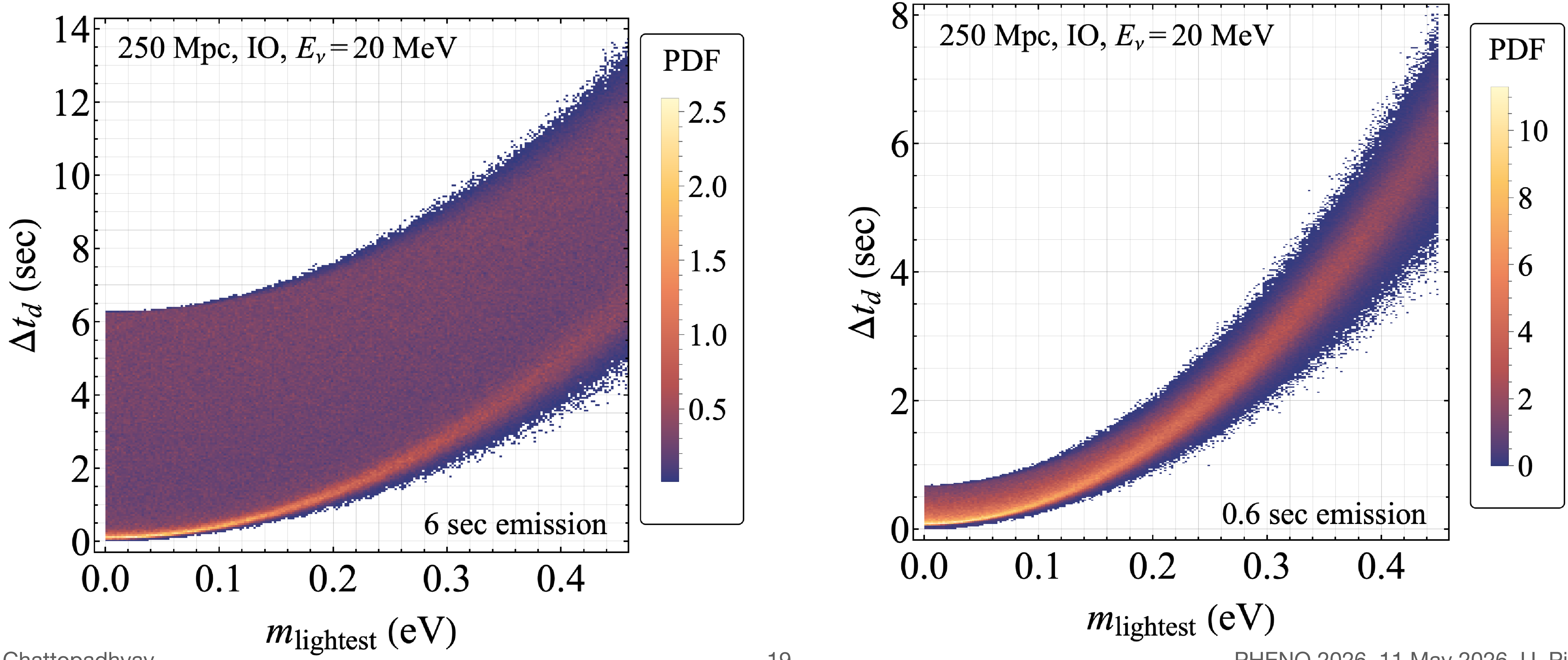
- The finally detected neutrino would have slightly different energy spectrum.
- Some neutrino are easier to detect than other neutrinos due to the large background and the resulting redshift cuts imposed…





Inverted mass ordering & arrival PDF

- A small chance that ν_3 arrives first. Overall behaviour remains the same.



Fixed value of the lightest neutrino mass

- We fix the distance uncertainty to a conservative 10% at 1σ
- For a fixed neutrino mass, this can translate into a large uncertainty in the predicted arrival time.
- Optimize over when to cut off the obs. window
- Cut it off too soon, we don't get enough ν
- Cut it off too late, and the background becomes too large…