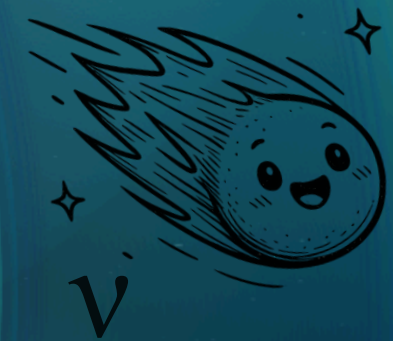


Probing binary black hole mergers in AGN accretion disks with gravitational waves and neutrinos

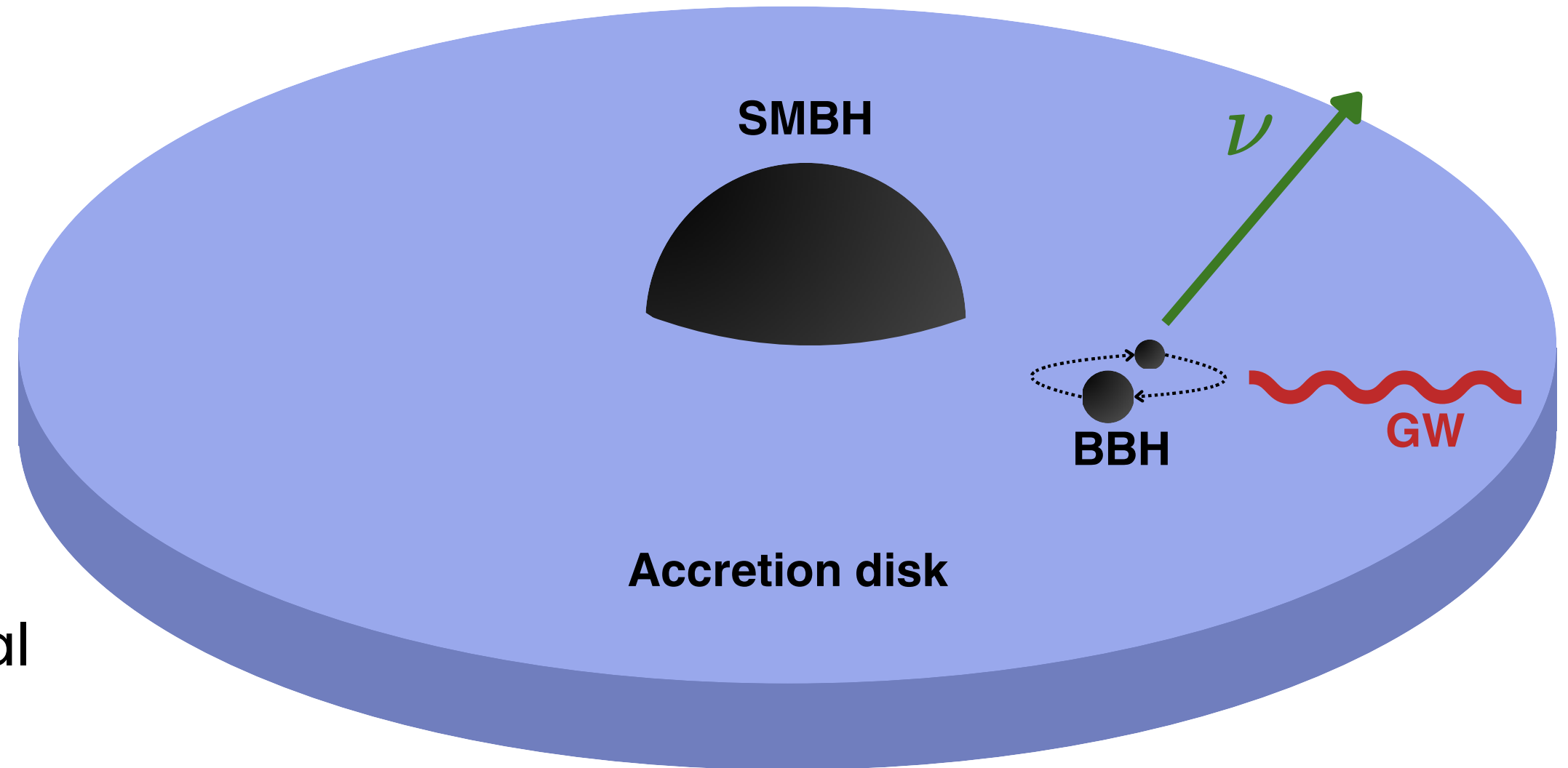
Leonardo Ricca, Matthias Vereecken,
Giacomo Bruno, Gwenhaël de Wasseige
07/10/2026



Probing binary black hole mergers in AGN accretion disks

Why?

- **Supermassive Black Hole (SMBH)** surrounded by a dense disk of **accreting matter**.
- Gas torques drive BHs orbital evolution
- BHs accumulate in **migration traps** [1], efficiently forming BBH systems
- Many BHs can undergo **hierarchical mergers** [2]



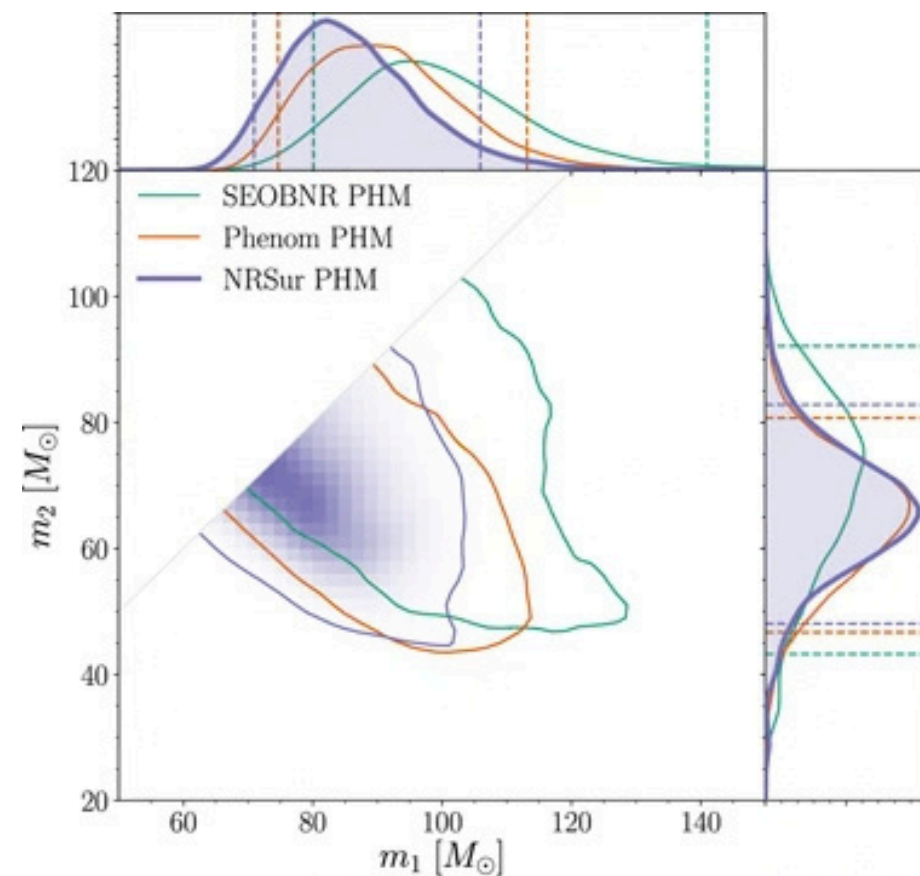
[1] [Bellovary J. M., Mac Low M.-M., McKernan B. and Ford K. E. S. 2016 ApJL 819 L17](#)

[2] [Yang, Y., Bartos, I., Gayathri, V., et al. 2019, Phys. Rev. Lett., 123, 181101](#)

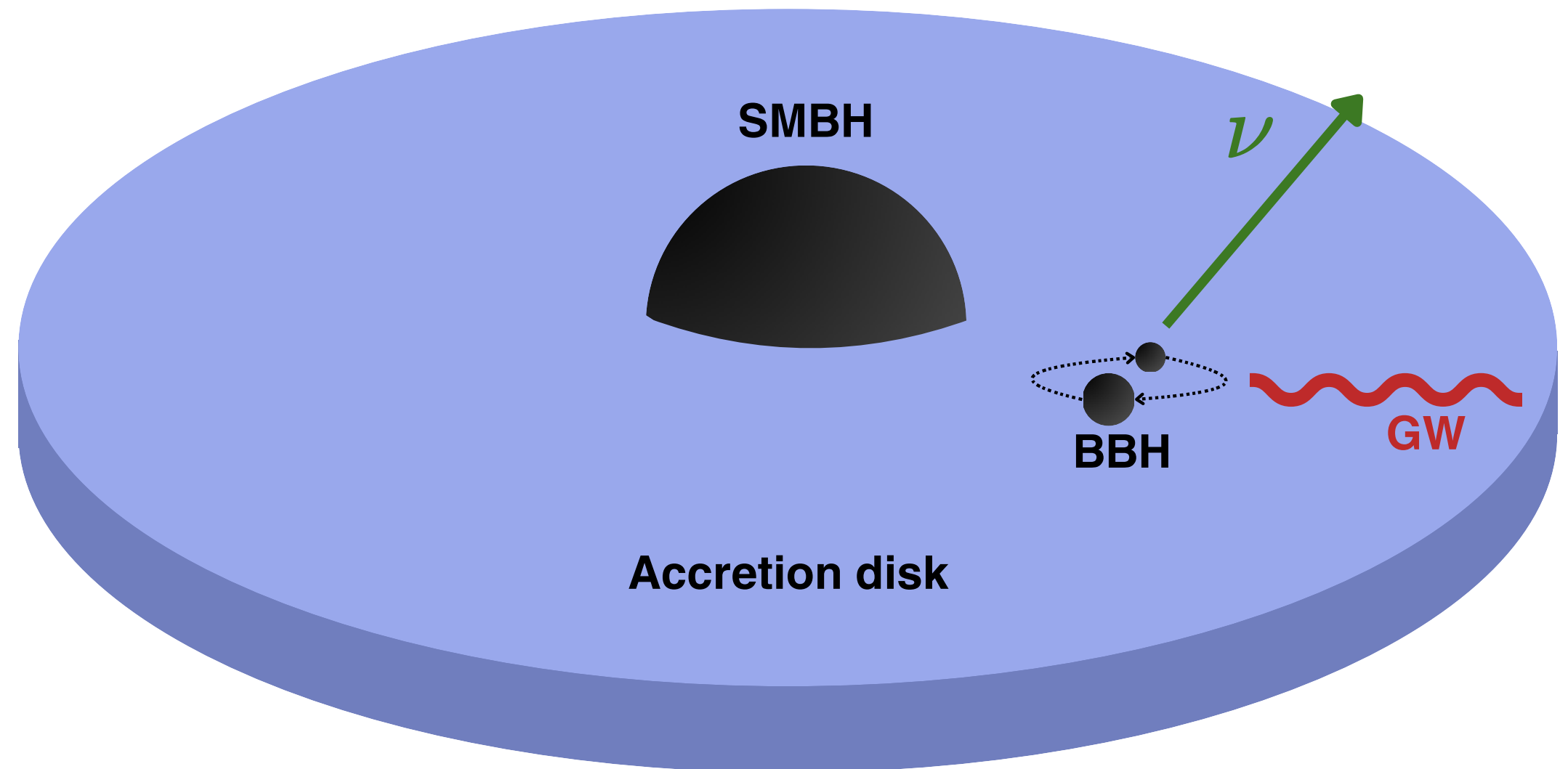
Probing binary black hole mergers in AGN accretion disks

Why?

- Many BHs can undergo **hierarchical mergers**



[1] [R. Abbott et al 2020 ApJL 900 L13](#)



- Possible formation channel for **high-mass** GW events, like **GW190521** [1]
- Component masses fall in the predicted pair-instability mass gap

Multi-messenger signature?

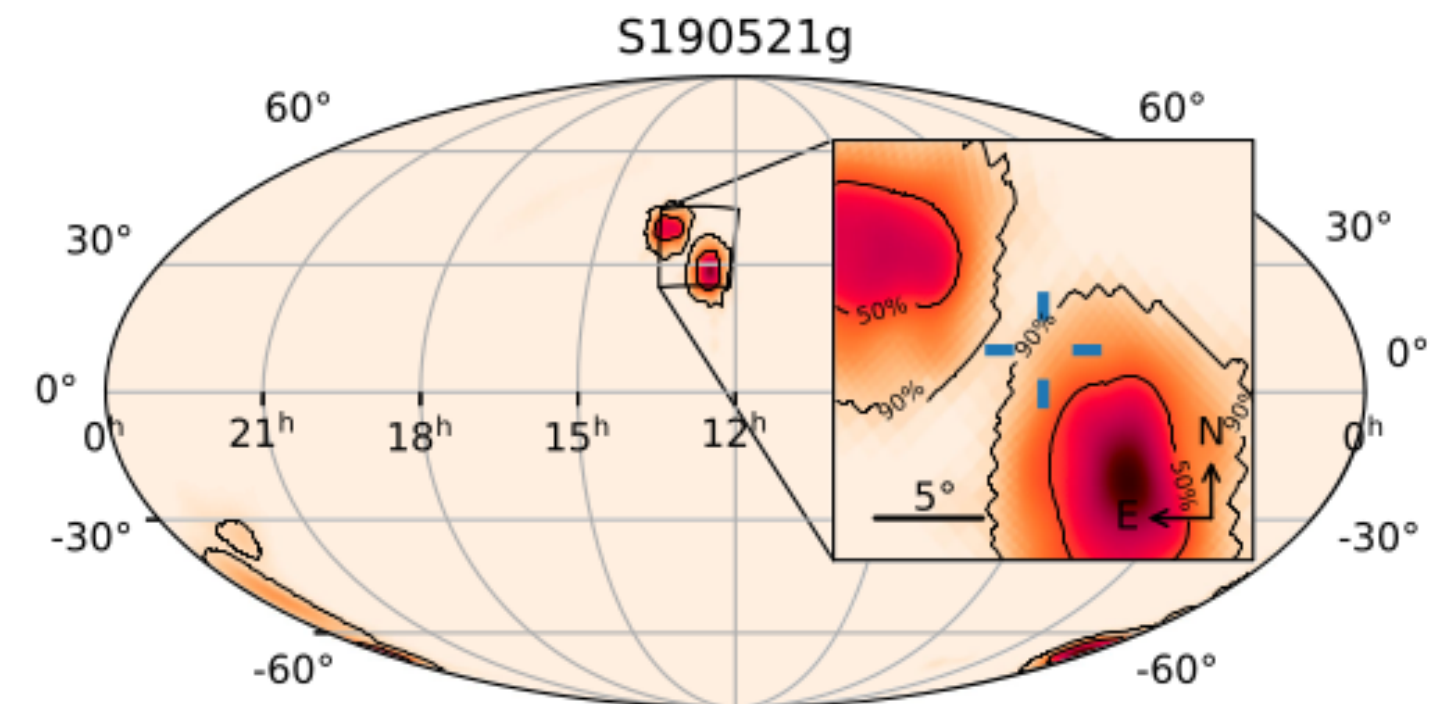
Tentative detections of multi-messenger emission from a **binary black hole** (BBH) merger:

Is there a way to get multi-messenger emission from BBH mergers?

GW190521, highest masses O3 BBH event

+

Zwicky Transient Facility
optical alert, 34 days after [2]

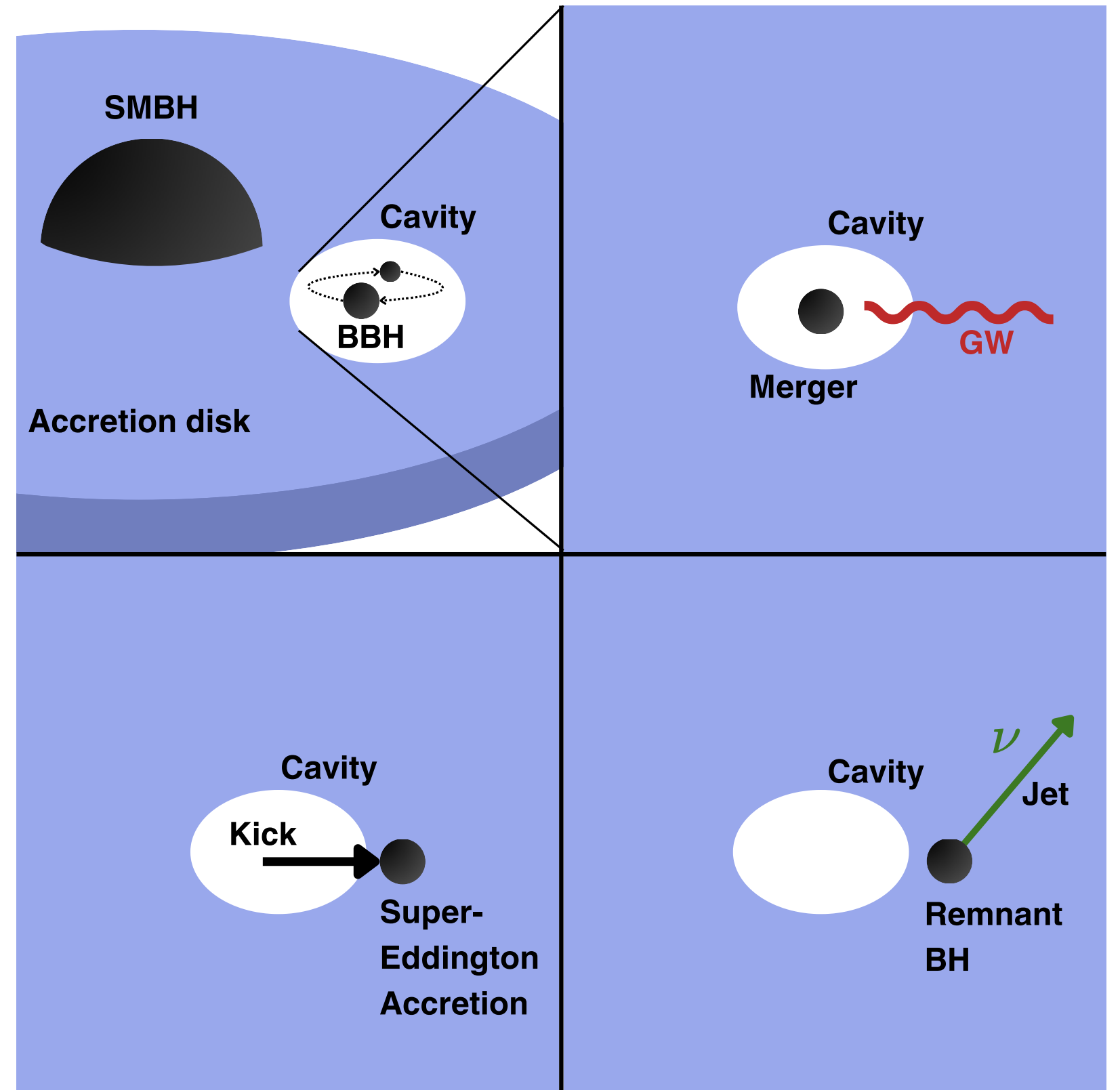


[1] [R. Perna, D. Lazzati and B. Giacomazzo, Astrophys. J. Lett. 821 \(2016\) L18](#)

[2] [M.J. Graham et al, Phys.Rev.Lett. 124 \(2020\) 25, 251102](#)

The model

1. BBH system absorbs matter in its surroundings **before** the merger
2. **GW** emission from the merger
3. The **remnant BH** gets a **kick** → **accretion** at a super-Eddington rate
4. **BZ jet** is launched → possible **neutrino** emission

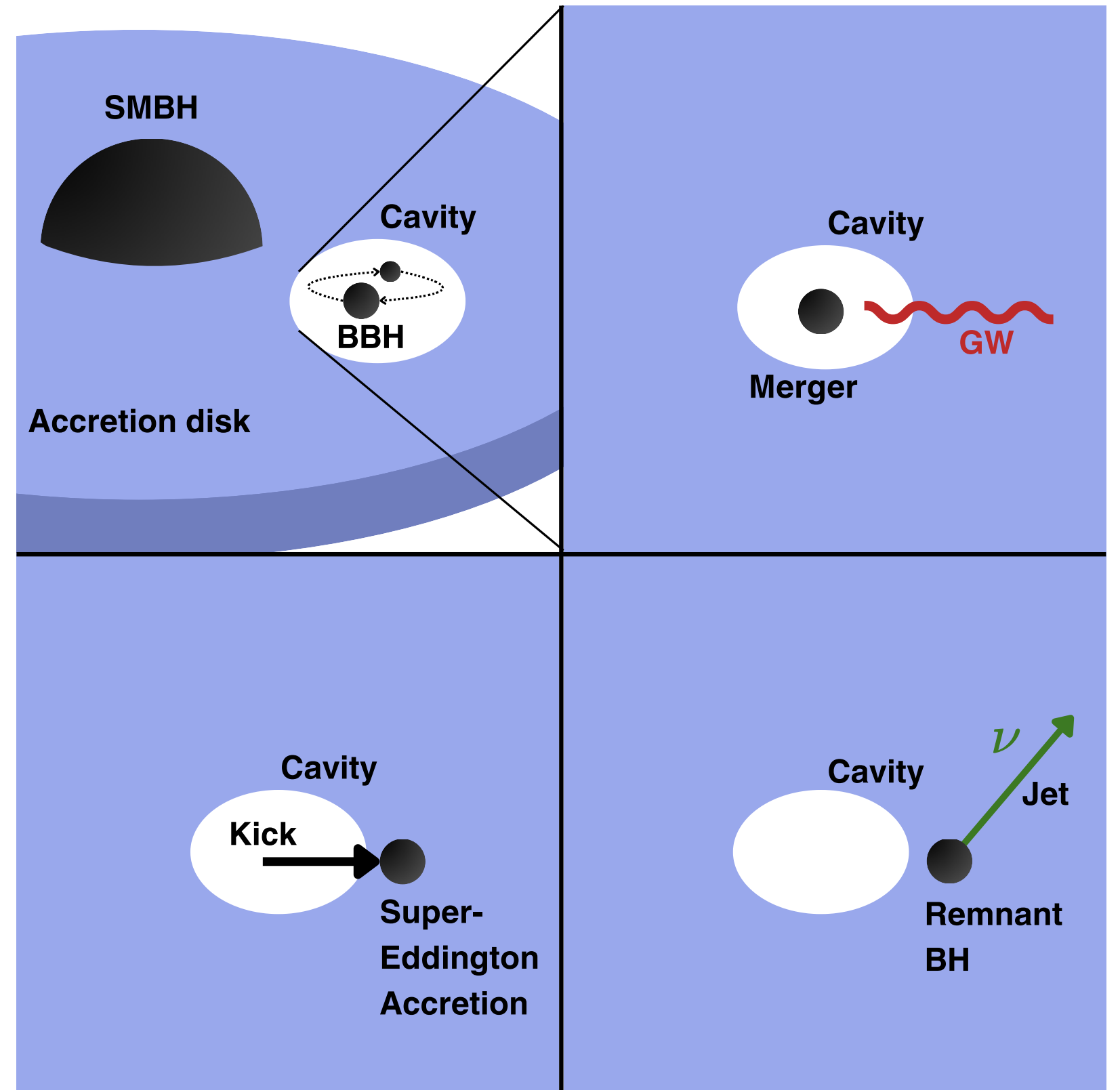


[1] [Kimura, S. S., Murase, K., & Bartos, I. 2021, *Astrophys. J.*, 916, 111](#)

[2] [Zhou, Z.-H., & Wang, K. 2023, *Astrophys. J. Lett.*, 958, L12](#)

The model

- Time delay between **GW** and **neutrino** emission **$\sim 0(10 \text{ days})$**
- Theoretical prediction have many uncertainties
- Model-agnostic: **asymmetric time window of $\sim 100 \text{ days}$**

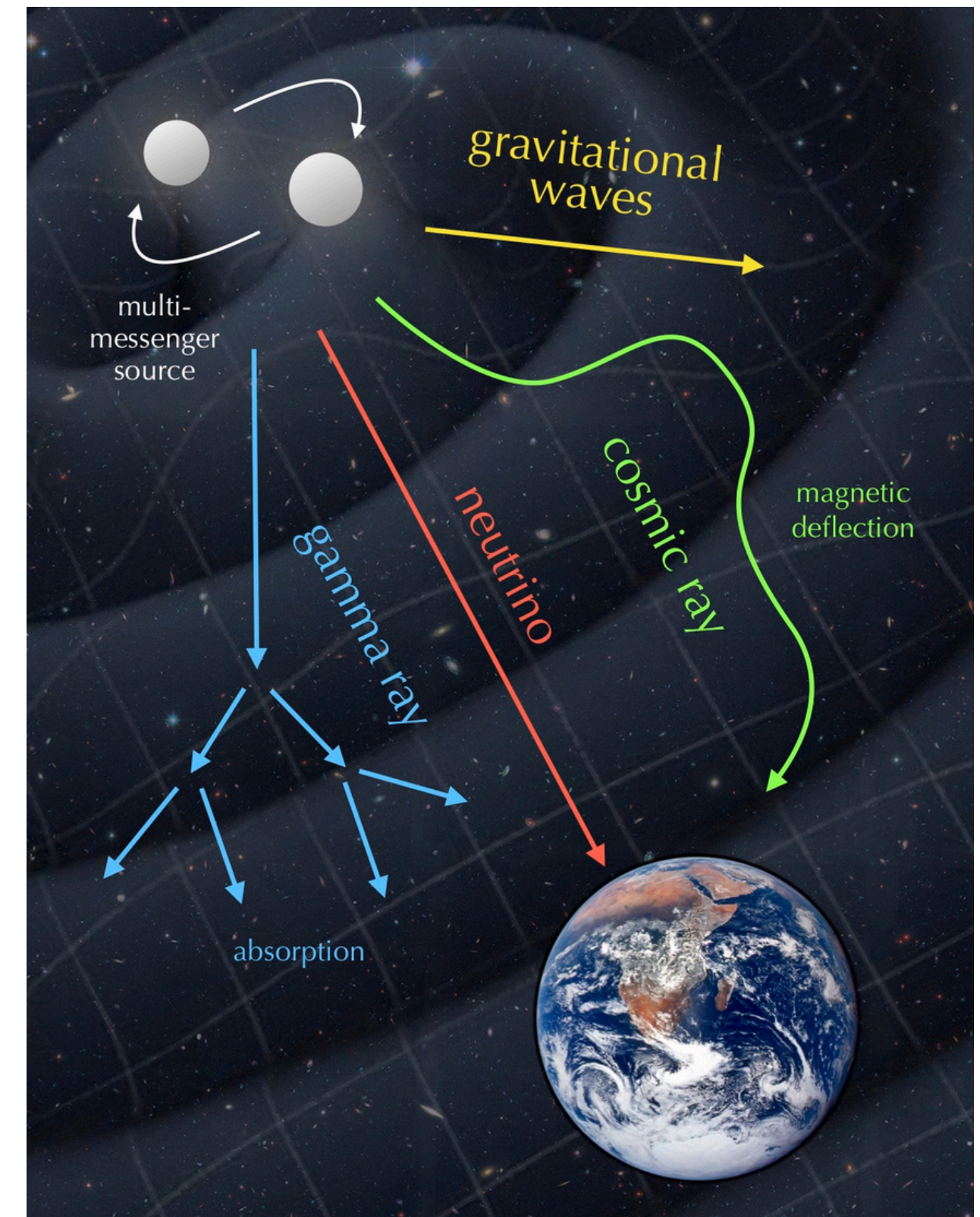


[1] [Kimura, S. S., Murase, K., & Bartos, I. 2021, Astrophys. J., 916, 111](#)

[2] [Zhou, Z.-H., & Wang, K. 2023, Astrophys. J.Lett., 958, L12](#)

Why neutrinos?

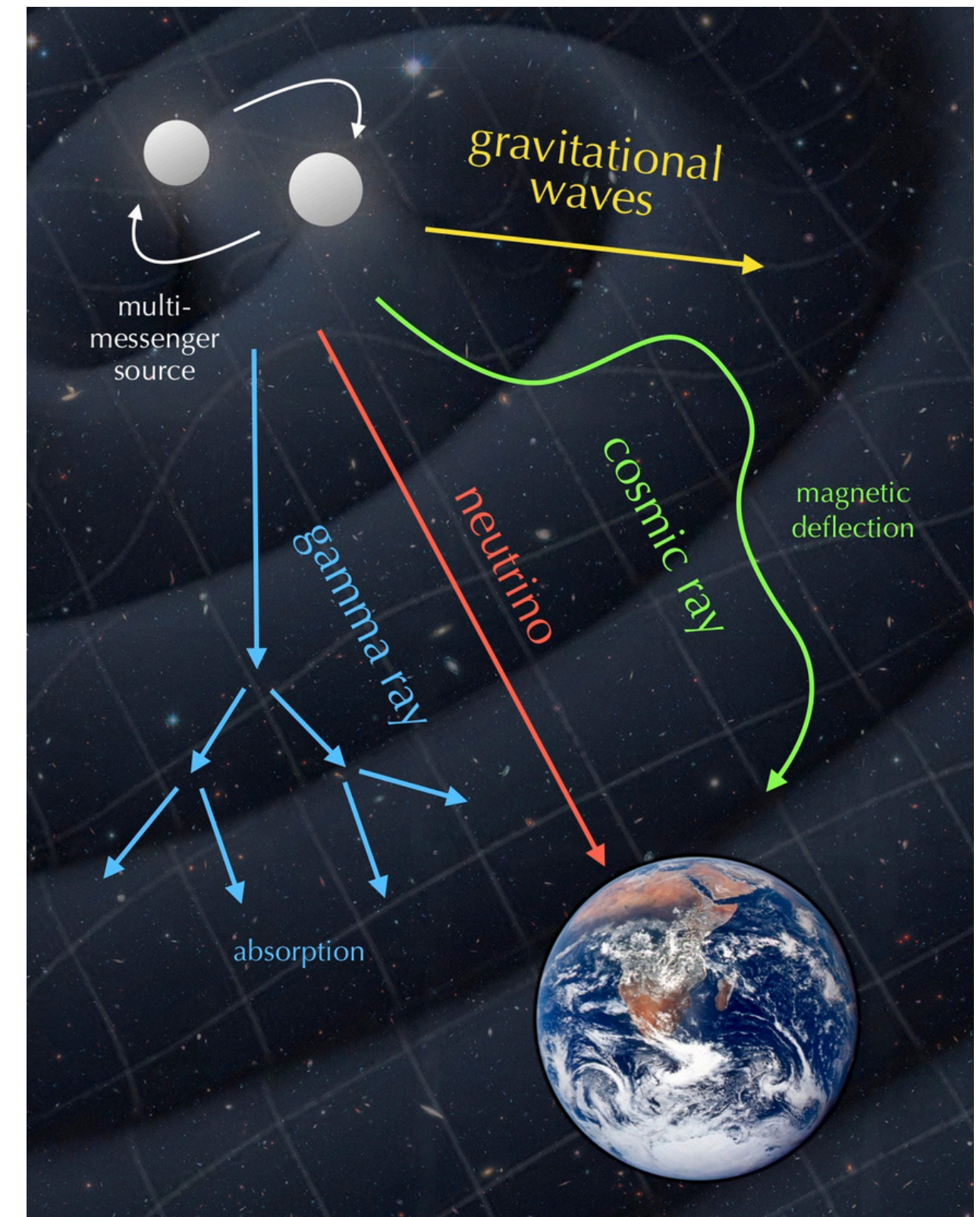
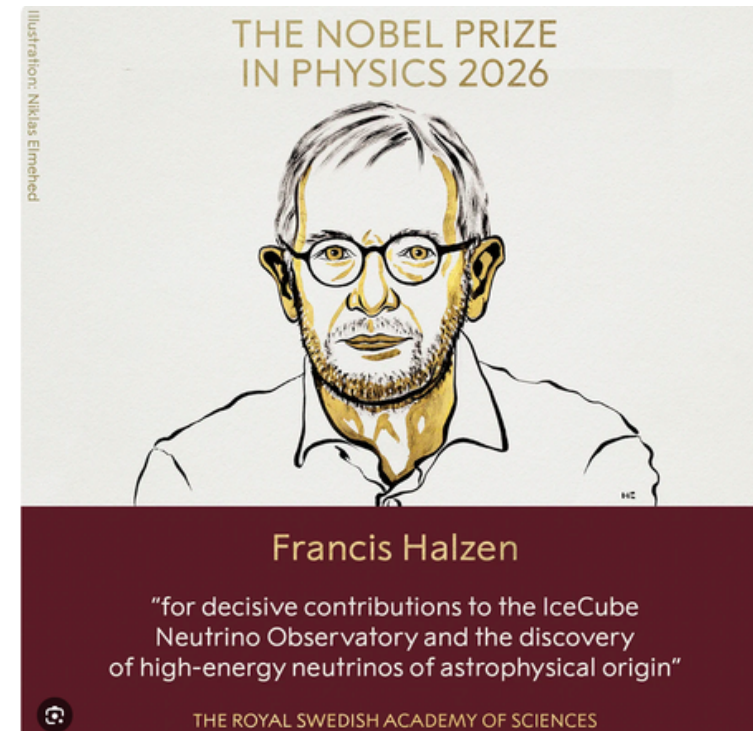
- **Good pointing** ($<1^\circ$ at TeV energies)
- **No deflection**
- **No absorption** → can escape dense environments
- EM flare could be too dim against AGN
- Don't provide **distance** information



Why neutrinos?

- **Good pointing** ($<1^\circ$ at TeV energies)
- **No deflection**
- **No absorption** → can escape dense environments
- EM flare could be too dim against AGN
- Don't provide **distance** information

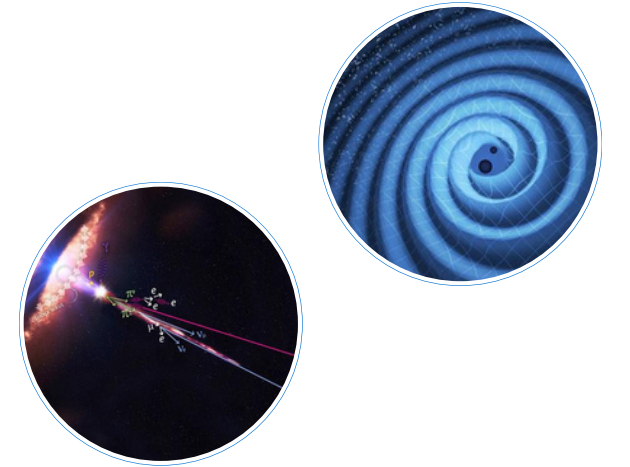
Congrats Francis!



Demonstrate the method:

Ingredients:

1. **Gravitational waves** candidates from O3 with FAR down to 2/day
2. High-energy **neutrinos** from IceCube 10-years Point-Source sample
3. **AGN** from Quia catalog



Key point:

- We use also **subthreshold** GW triggers. Having a **coincidence** with two other messengers can increase the significance of the event.

Test statistic

Designed for subthreshold searches:

$$\Lambda = \frac{I_x}{1 + Q_\nu + Q_{GW} + Q_\nu Q_{GW}}$$

I_x $\longrightarrow$ Overlap integral of the **posteriors distributions** of the three datasets.
Integral computed over sky localization and **distance**.

Q_ν, Q_{GW} $\longrightarrow$ Inverse **Bayes factor** of the **neutrino**, **GW** triggers.

So what do we need?

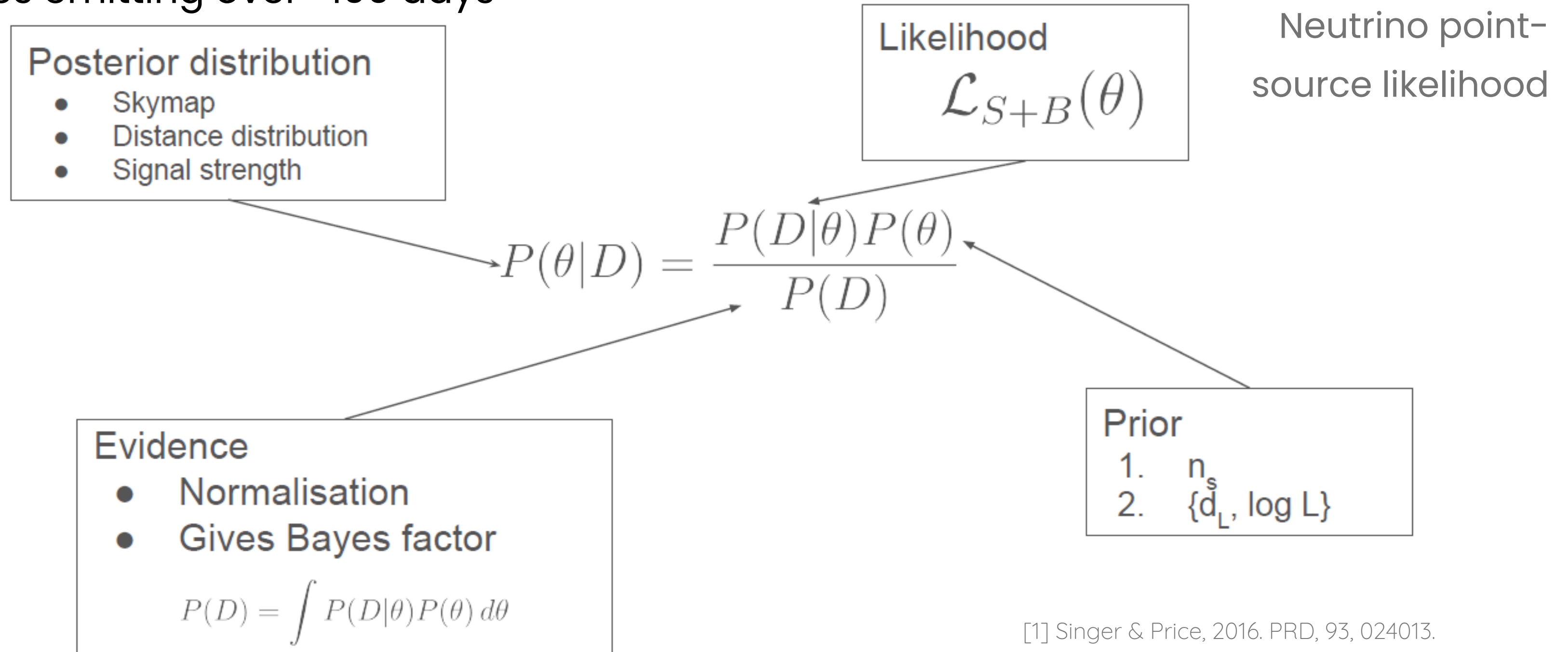
- **Posterior distributions** of each messenger,
- **Evidence** of each messenger.

$$Q_{\text{Data}} = \frac{P(\text{Data}|\text{Noise})}{P(\text{Data}|\text{Signal}+\text{Noise})}$$

Bayesian inference for neutrino skymap

Posterior and evidence are easily available for **GW triggers** → BAYESTAR [1].

Neutrino data: we implement a fast method Bayesian method to search for neutrino sources emitting over ~100 days



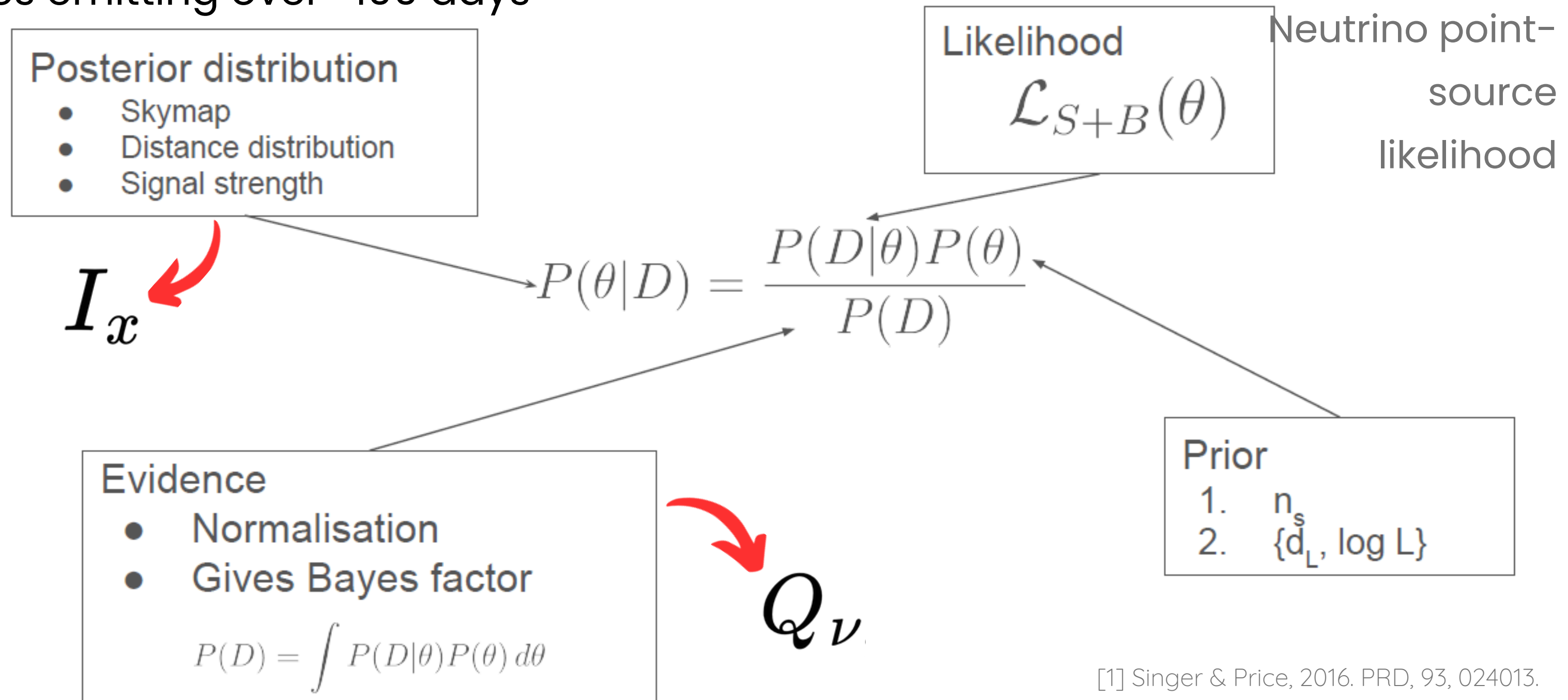
[1] Singer & Price, 2016. PRD, 93, 024013.

[doi:10.1103/PhysRevD.93.024013](https://doi.org/10.1103/PhysRevD.93.024013)

Bayesian inference for neutrino skymap

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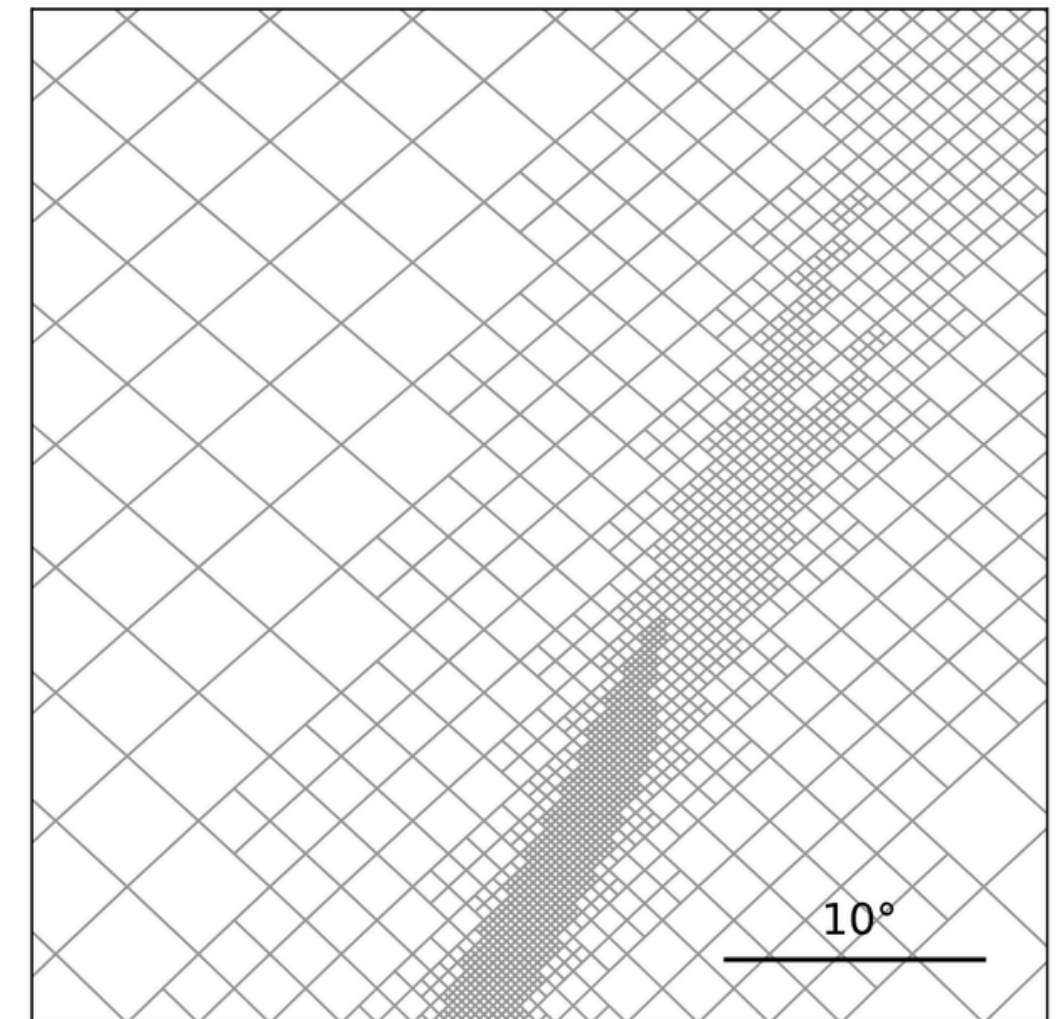
[doi:10.1103/PhysRevD.93.024013](https://doi.org/10.1103/PhysRevD.93.024013)

Bayesian inference for neutrino skymap

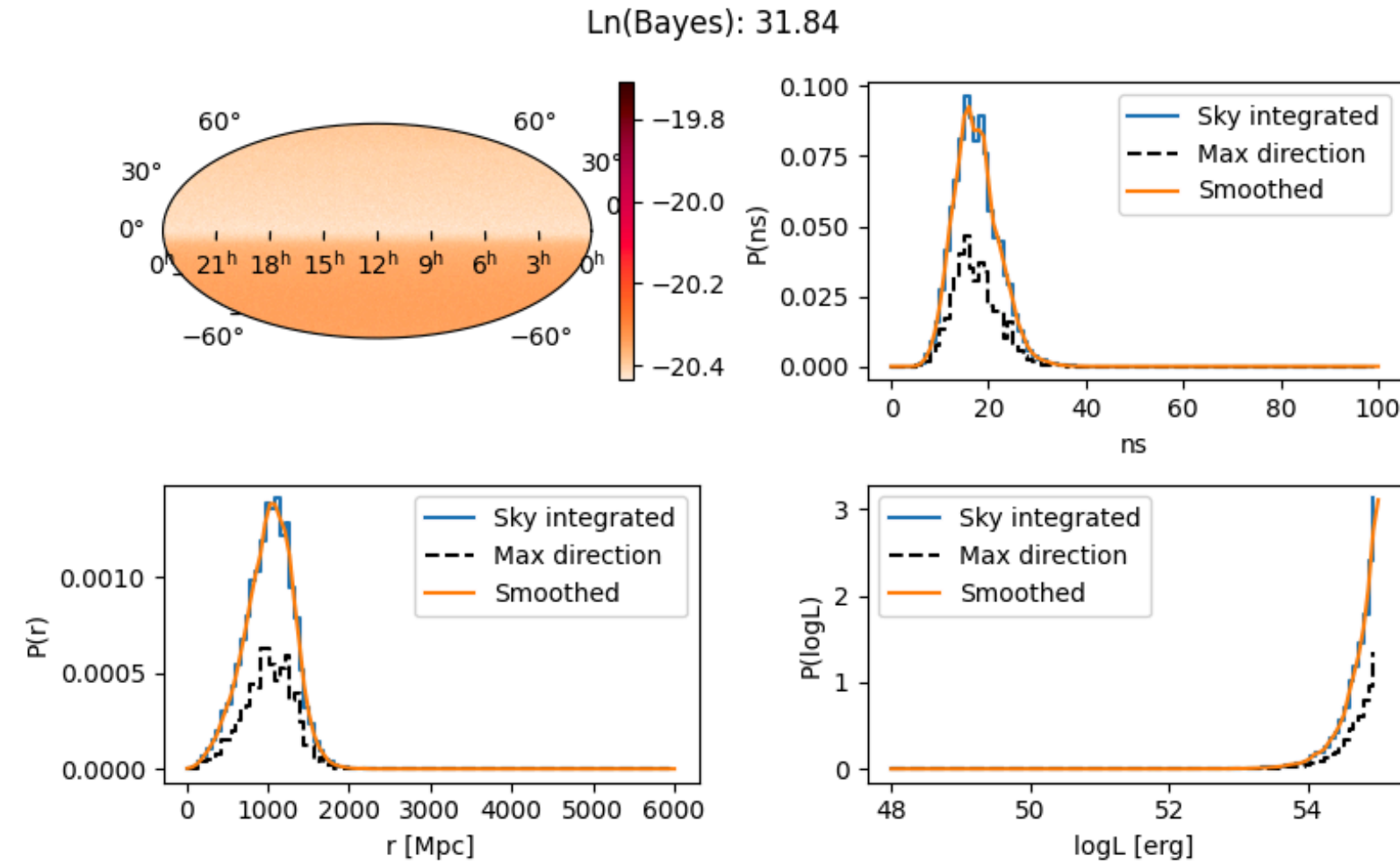
- Formulate **prior** in luminosity distance and luminosity of the source
 - $d_L \sim d_L^2$ in $[10, 6000]$ Mpc
 - $\log L$: uniform in $[48, 55]$ erg
- Convert $\{d_L, \log L\}$ to n_s using IceCube sensitivity and assuming E^{-2} astrophysical neutrino spectrum.

Key ideas to **speed up** the inference:

- Divide the sky in a **healpix grid** and do Bayesian inference for each pixel
- **Don't need high resolution everywhere.** First scan a coarse grid and then refine where probability is high (~BAYESTAR)



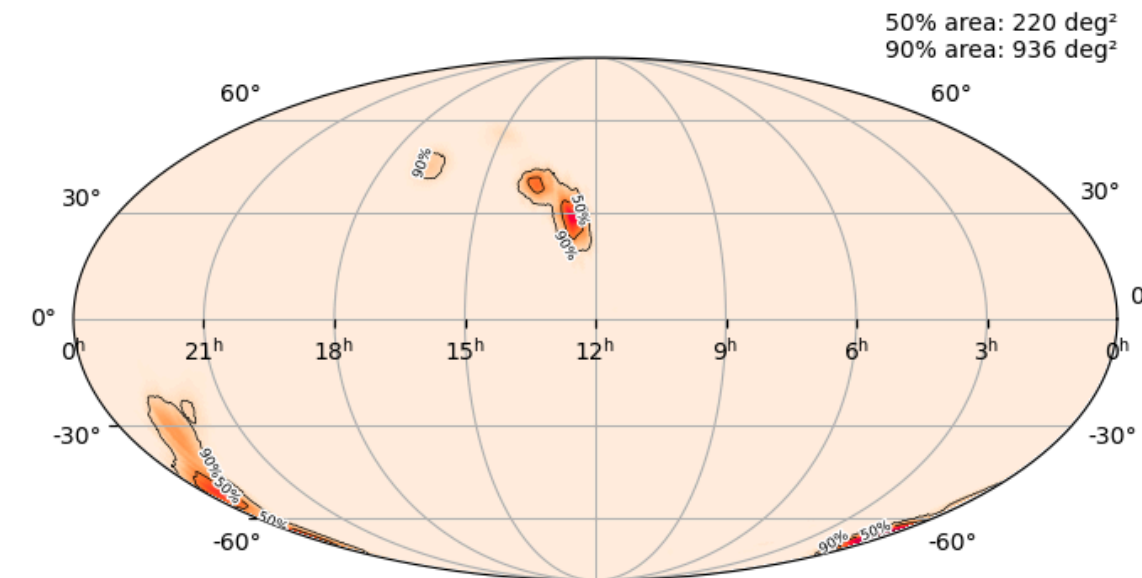
Neutrino posterior



Neutrino injection:

- $n_s = 20$
- $\text{ra} = 126^\circ, \text{dec} = -17^\circ$

We combine neutrino posterior with GW posterior and AGNs position to compute the overlap integral

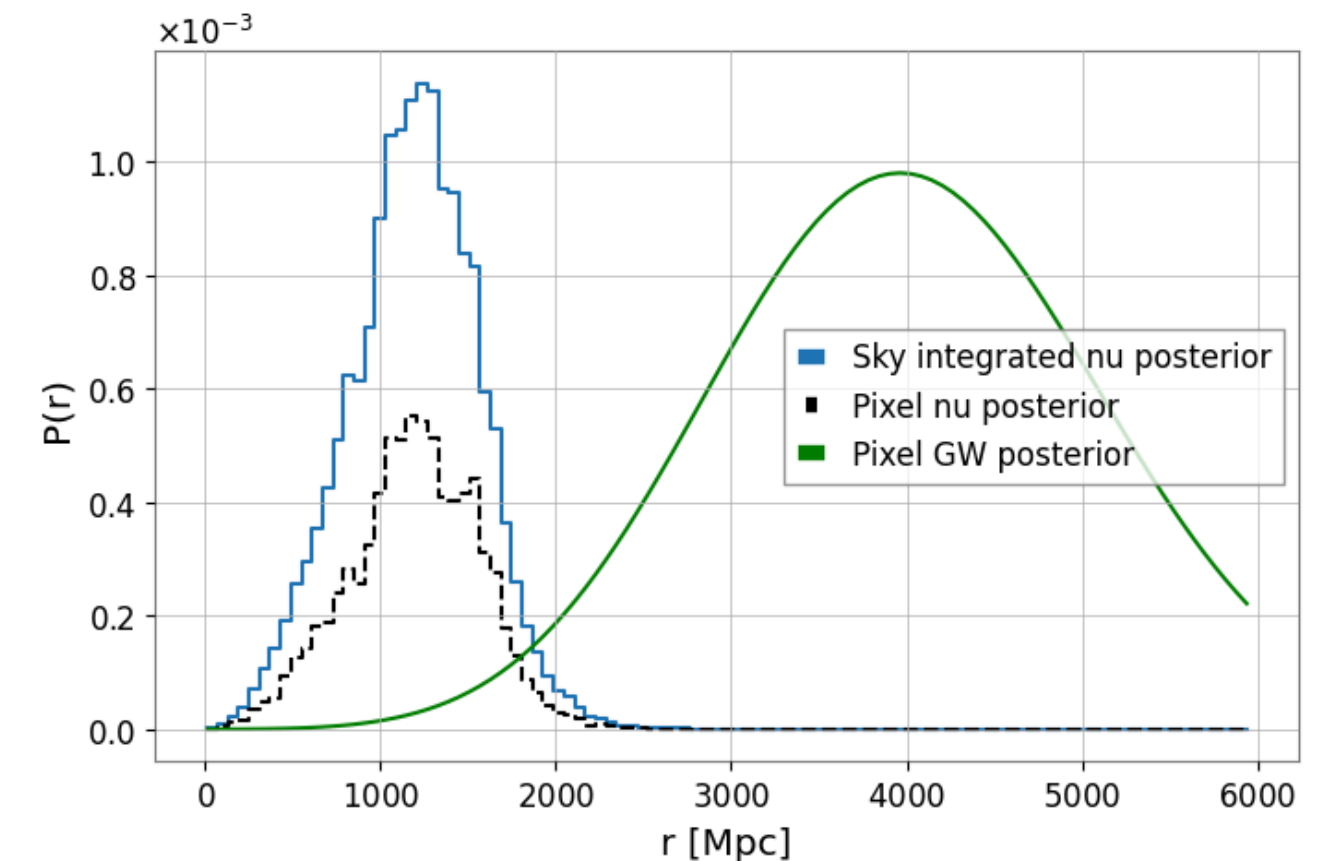


Overlap integral

$$I_{\vec{r}} = \iint dr d\Omega \frac{P(r, \Omega | D_{GW}, \text{signal}) P(r, \Omega | D_{\nu}, \text{signal})}{P(r, \Omega | \text{signal})}$$

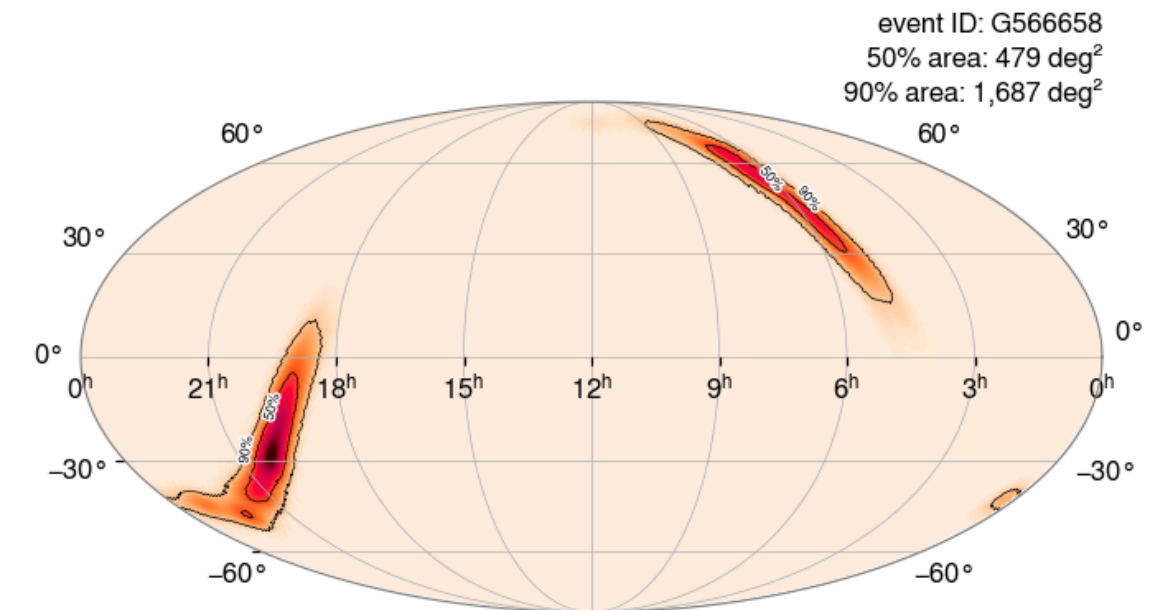
- The integral is computed over position where $P(r, \Omega) > 0$, i.e. AGN positions
- AGN positions can be considered as delta functions.

$$I_{\vec{r}} \propto \sum_{\text{AGN}} P(\vec{r}_{\text{AGN}} | D_{GW}) P(\vec{r}_{\text{AGN}} | D_{\nu})$$

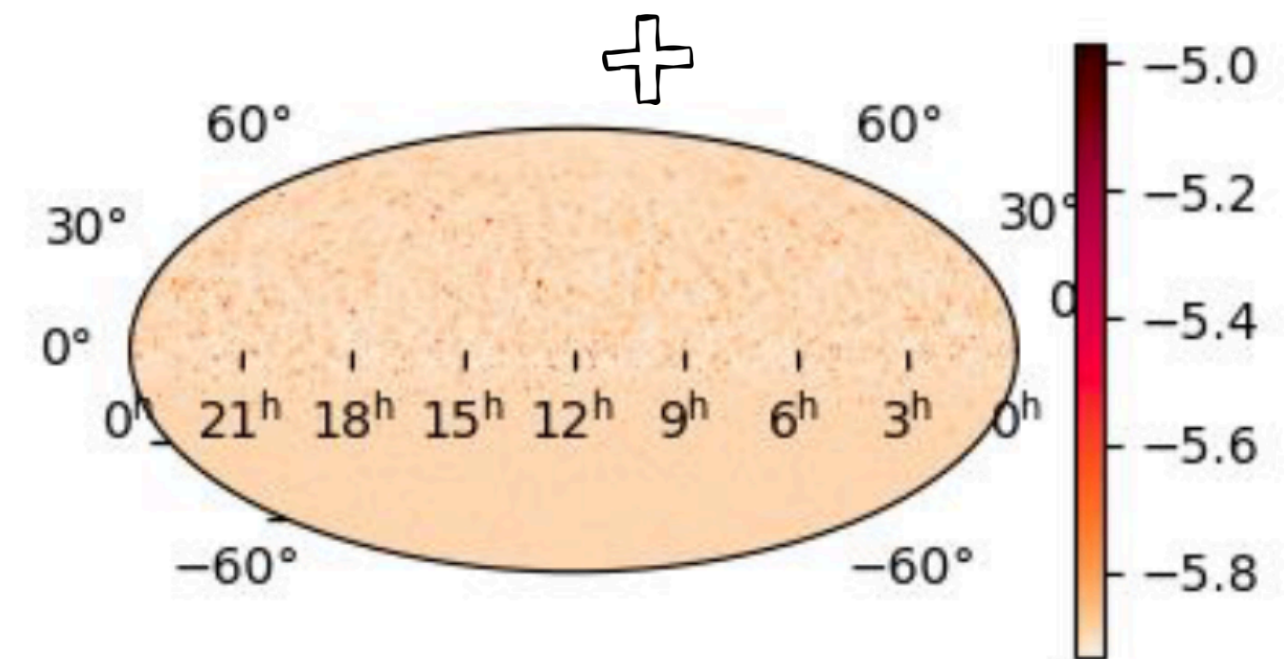


Main steps:

- Perform **background trials**:
 - Scramble neutrinos, GWs, AGNs
 - Compute TS statistic distribution for the null hypothesis
- Assess **sensitivity**:
 - Perform injections and compute fraction of events above given p-value threshold



Example of gravitational-wave skymap
produced with BAYESTAR



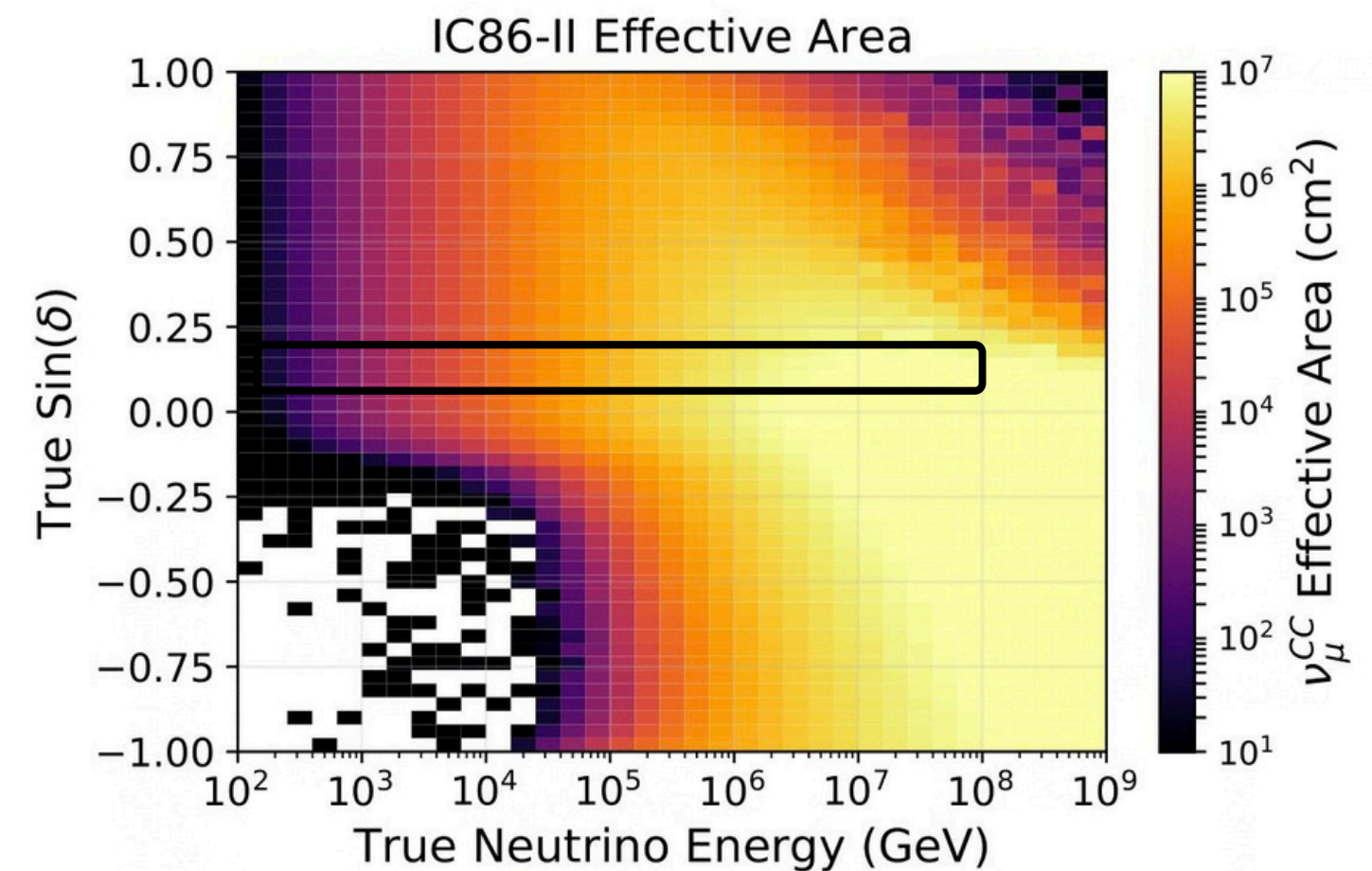
Example of background neutrino skymap
produced with our method

Sensitivity study

For each trial:

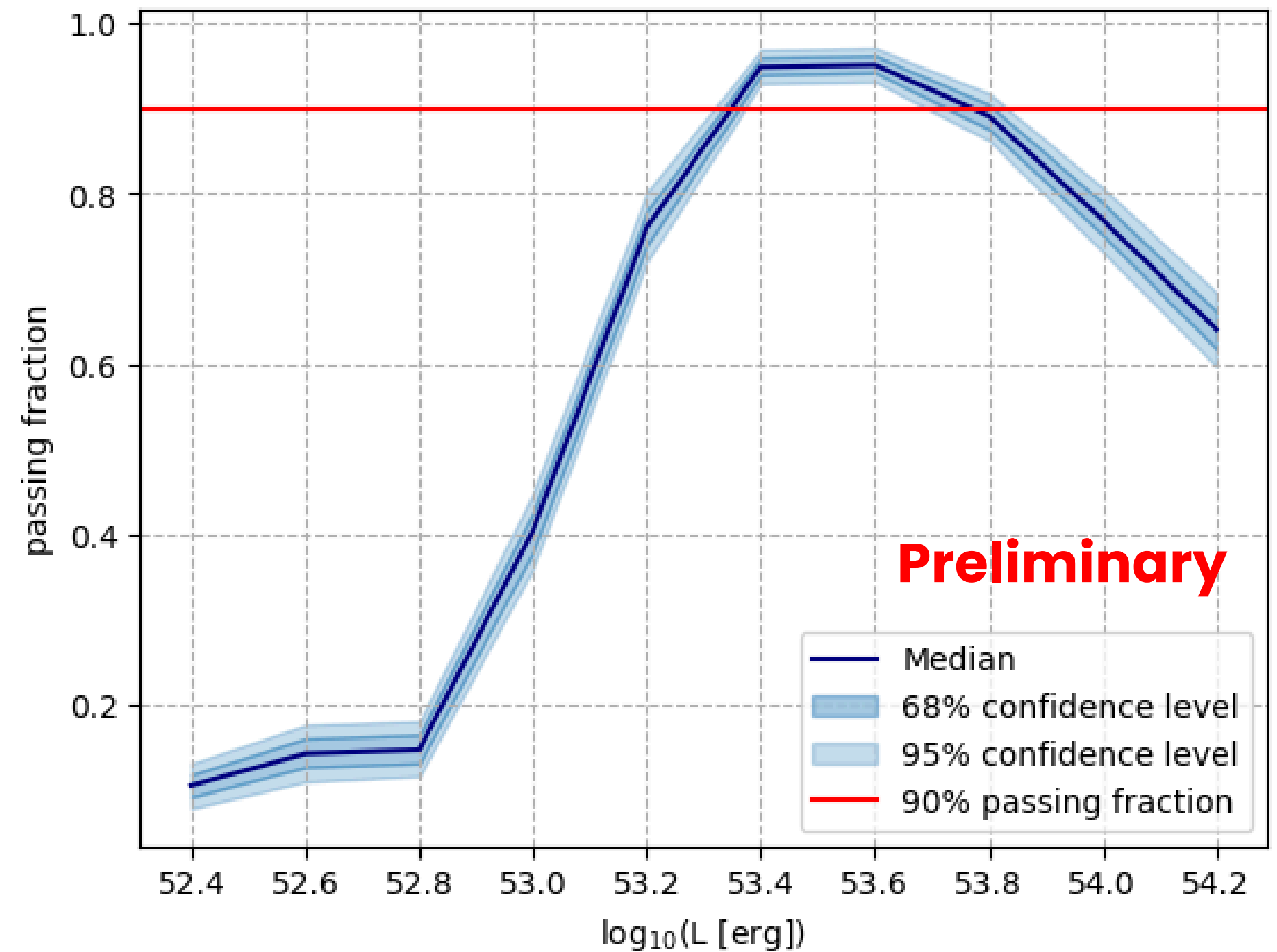
- draw AGN (**dec, distance d_L**)
- simulate GW event using BAYESTAR (**m_1, m_2**)
- inject number of detected neutrinos n_{inj} (**luminosity L , distance d_L**)

- distance **$d_L = 500$ Mpc**
- **$dec = 10^\circ$**
- **$m_1 = m_2 = 30 M_\odot$**
- Scan over neutrino **luminosity**.



Sensitivity study

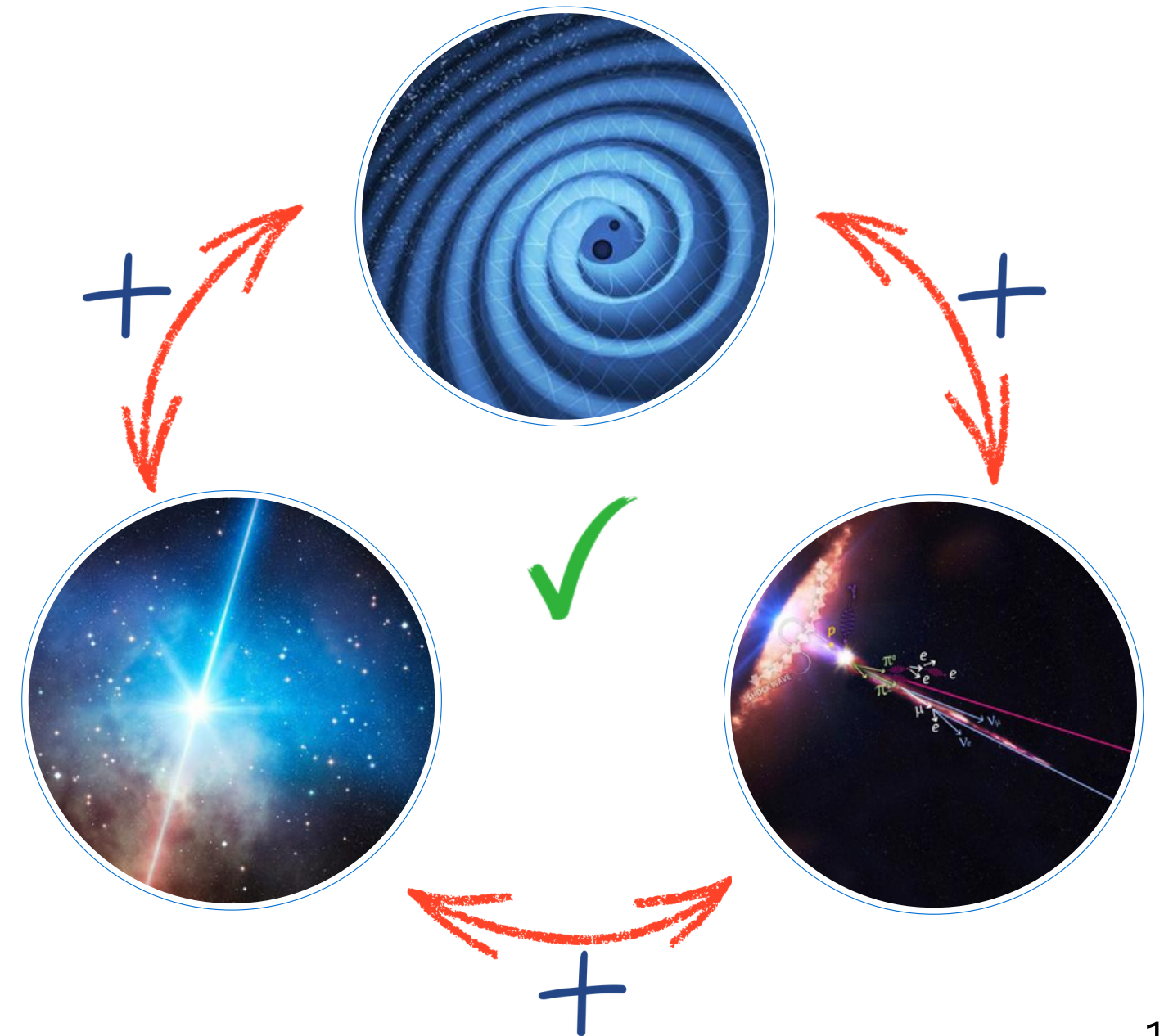
- Compare TS with median loudest background candidate
- 450 trials for each luminosity



Conclusions

- We've assessed the **sensitivity** of the method with public data
- We want to perform a **real search** for O4 and IR1 on subthreshold GW triggers and IceCube neutrino events.

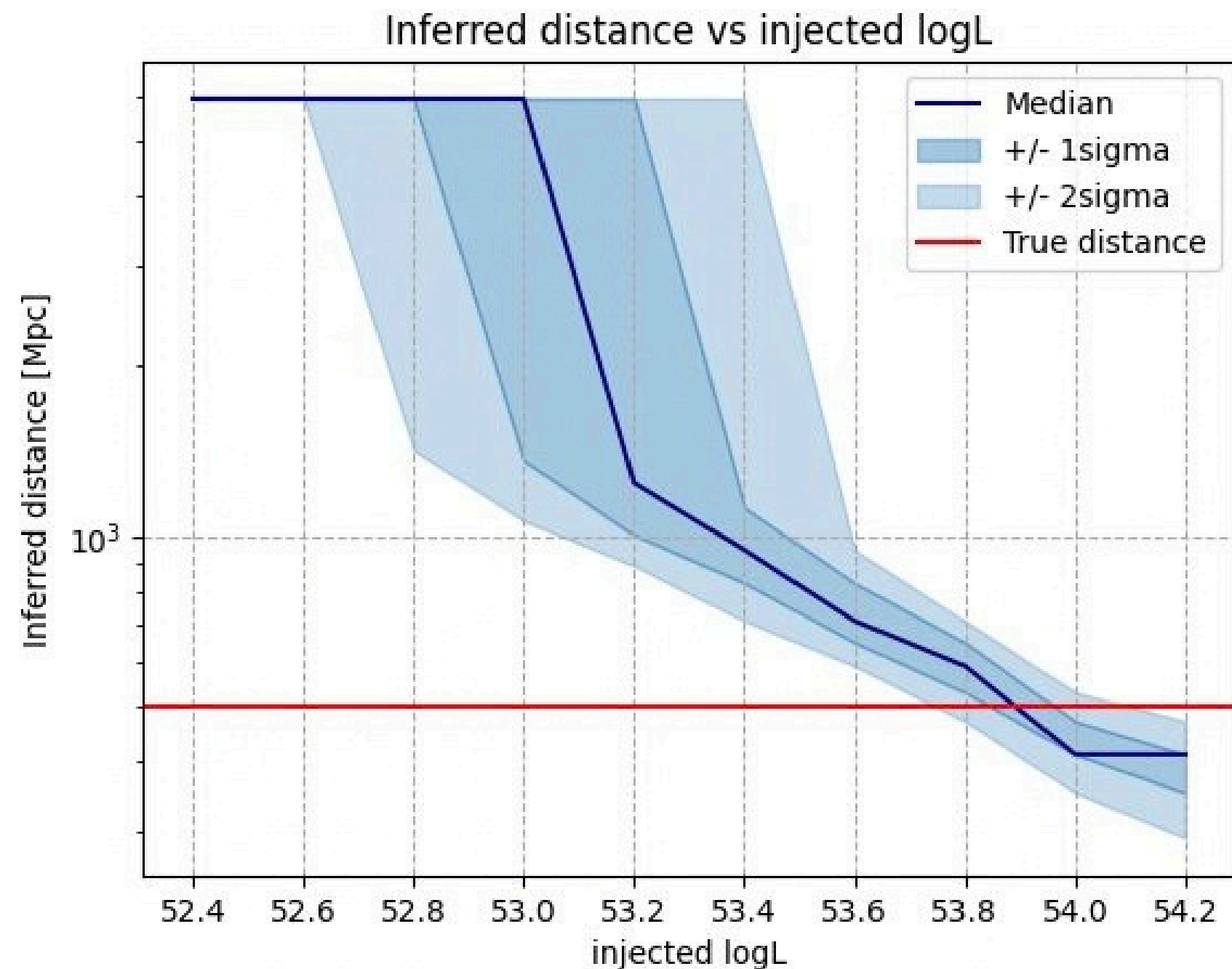
Thank you for the attention!



Backup slides

Inferred source distance

- The test statistic decreases when the inferred distance becomes less than the true distance of the source.
→ the **spatial overlap** decreases.
- Consequence of the prior on luminosity (log-uniform in 10^{48} – 10^{55} erg)
- Sources with higher luminosity are less likely in realistic scenarios

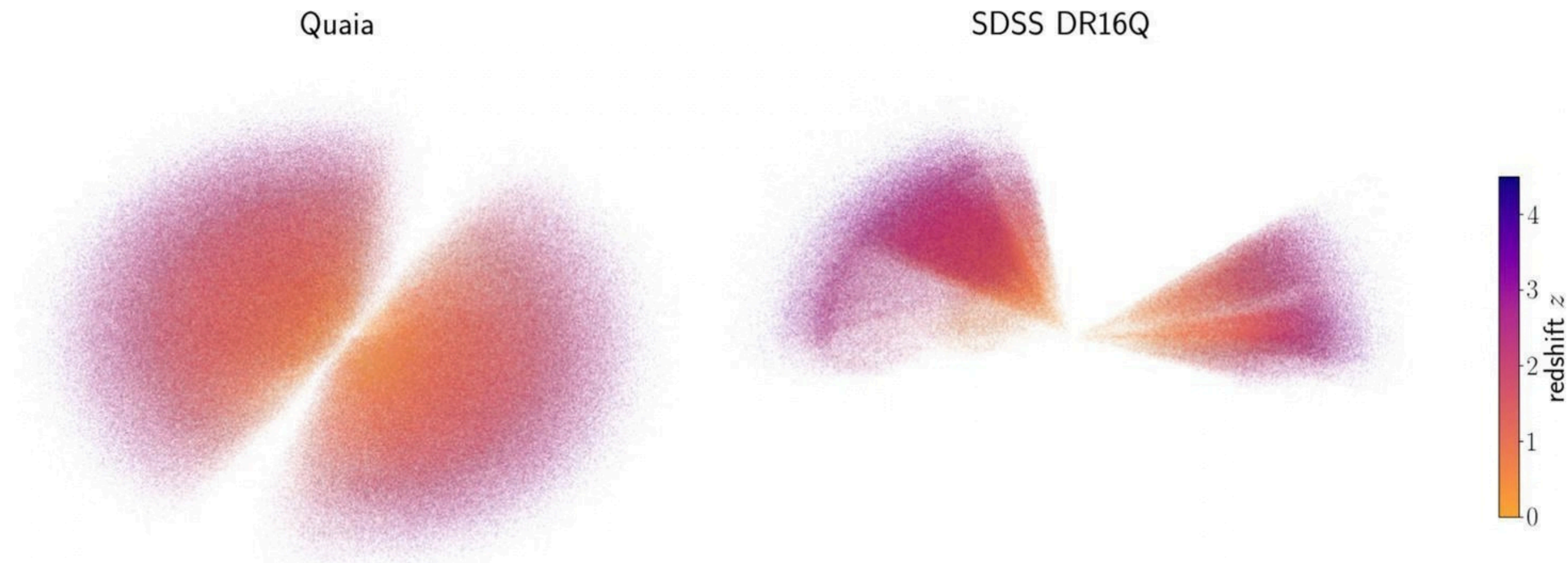


Quaia catalog

Quaia: *Gaia* DR3 quasar candidates (6.6 M) crossmatched with unWISE infrared observations (2.2 B)

755,850 quasars with magnitude $G < 20$ (most between $0 < z < 3$)

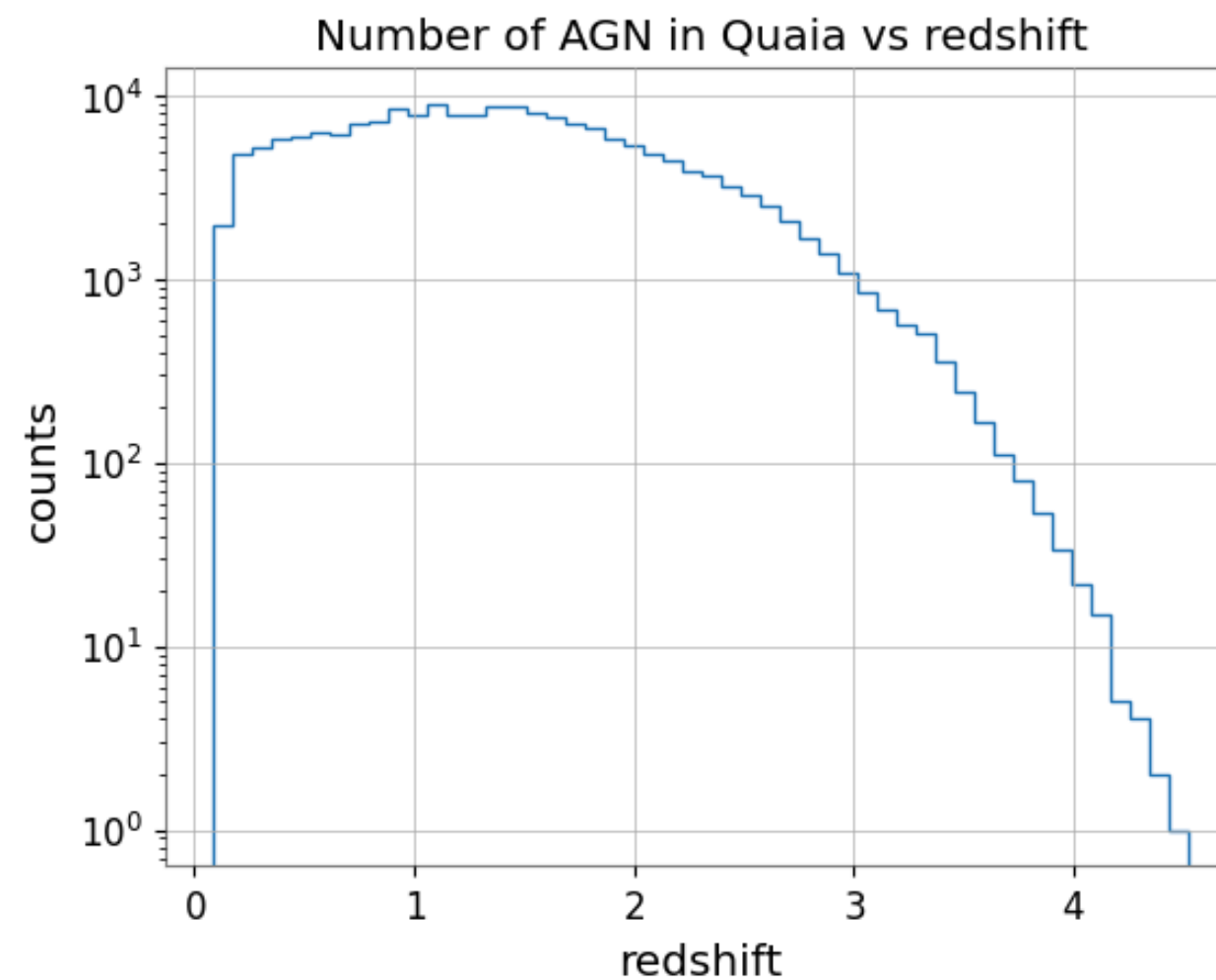
Cleaner sample, better redshift estimate. **All-sky** and highly **complete**.



Quaia catalog

Quaia: *Gaia* DR3 quasar candidates (6.6 M) crossmatched with unWISE infrared observations (2.2 B)

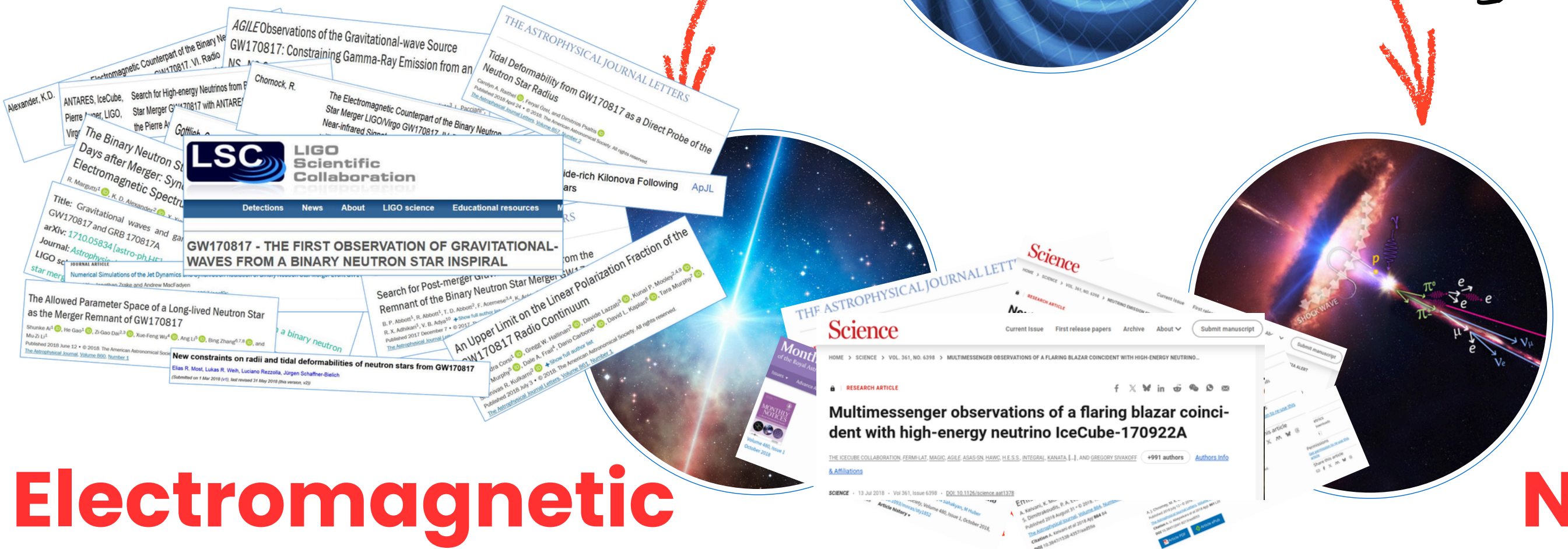
755,850 quasars with magnitude $G < 20$ (most between $0 < z < 3$)



Multi-messenger astronomy

Gravitational Waves

Multi-messenger Observations of a Binary Neutron Star Merger [1]



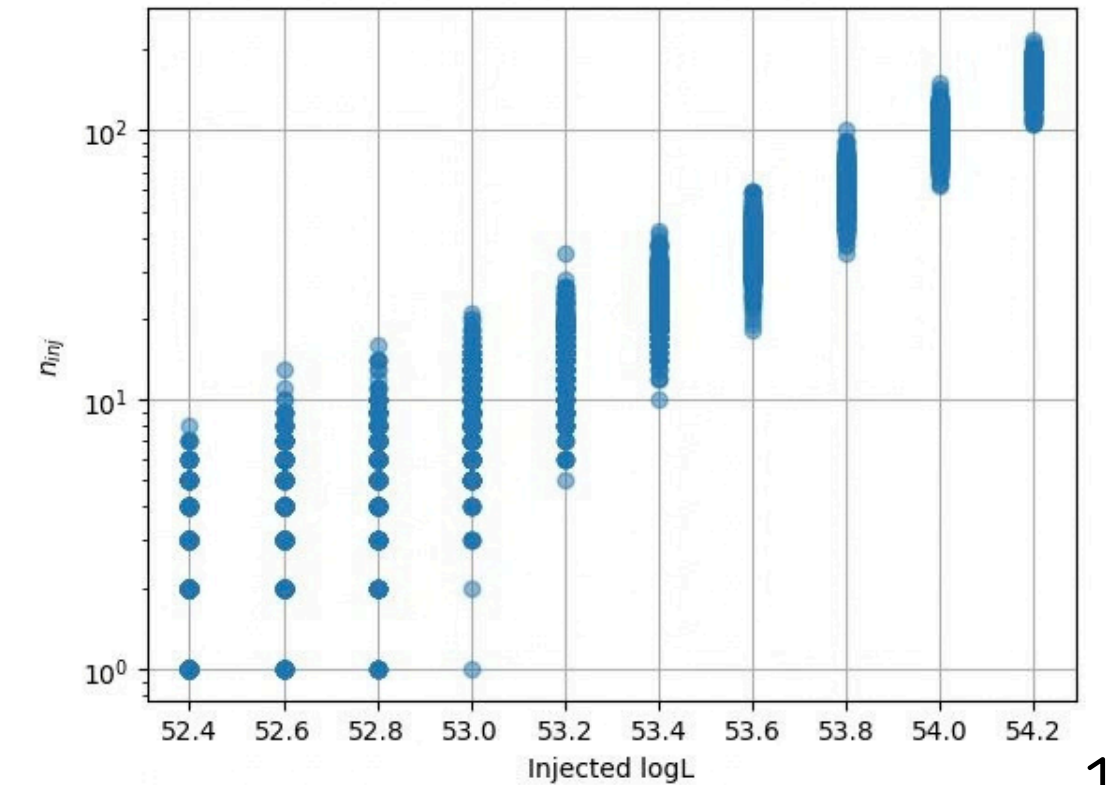
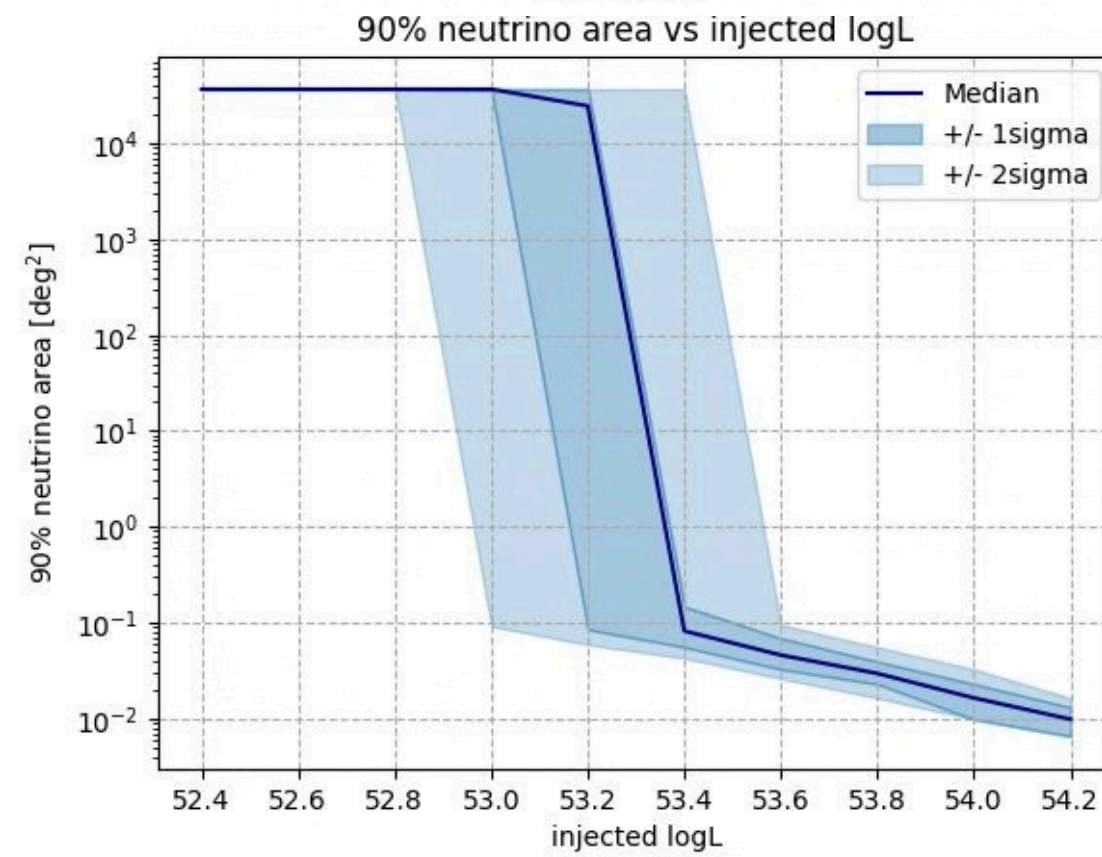
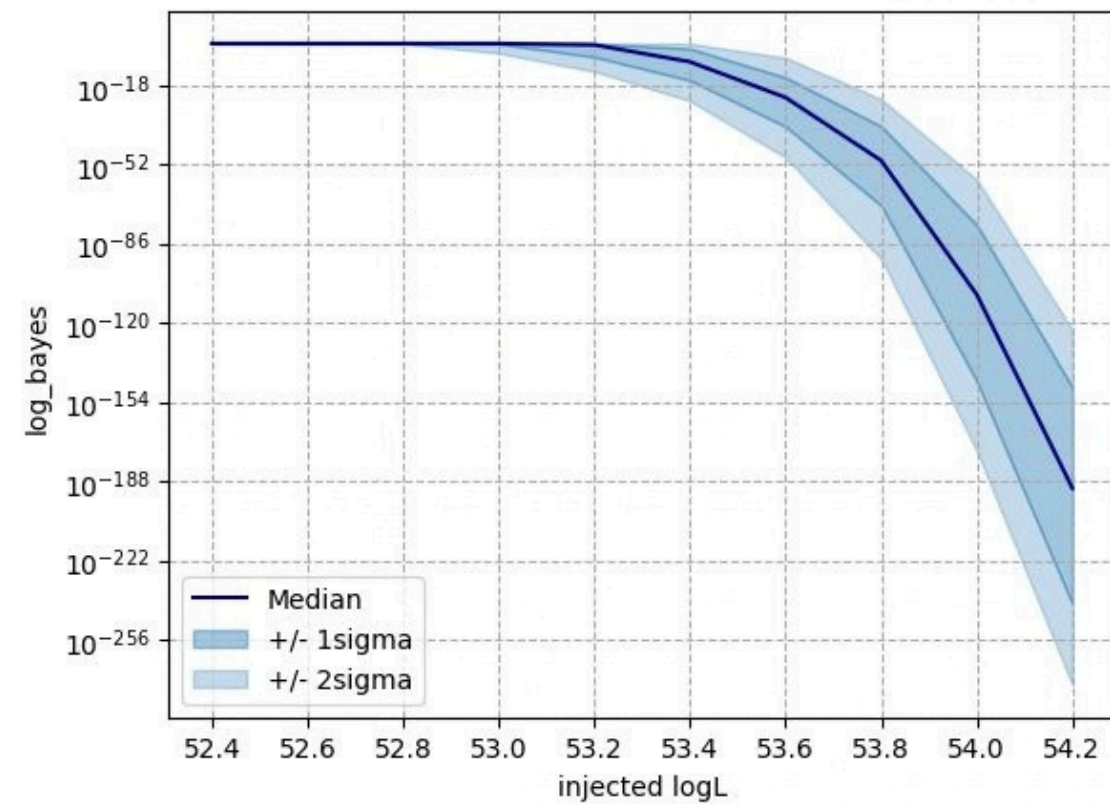
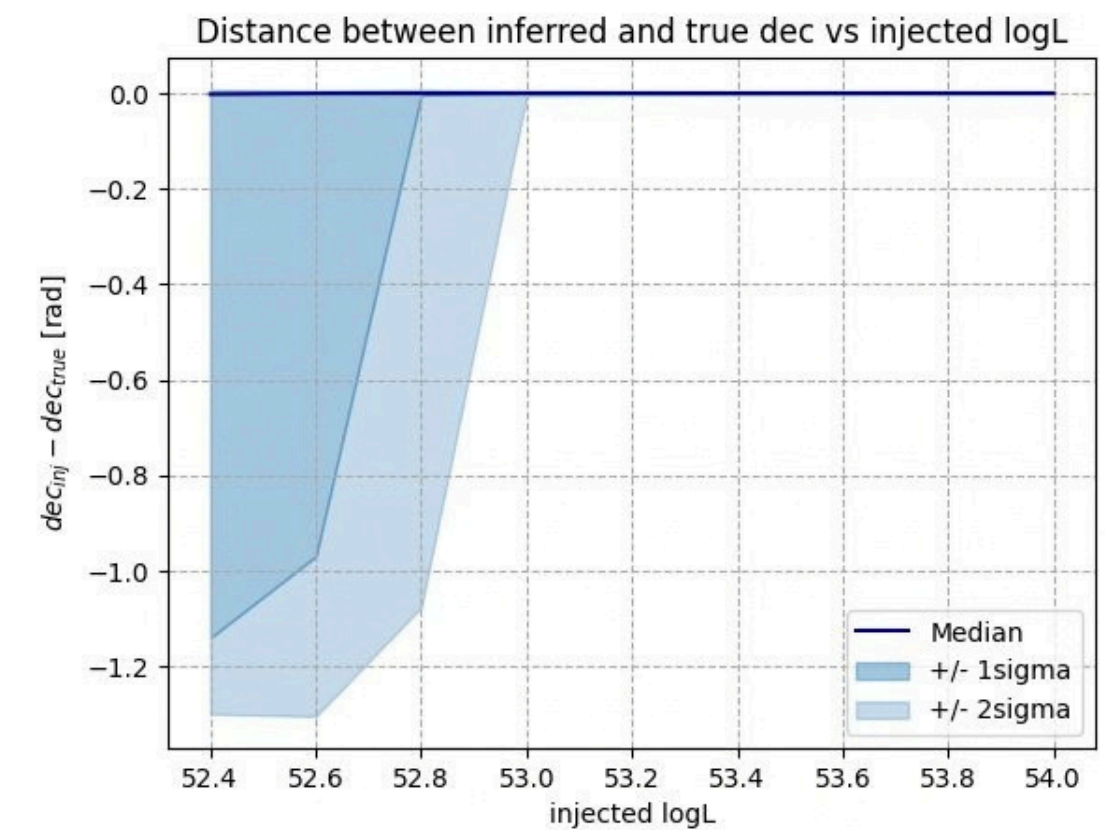
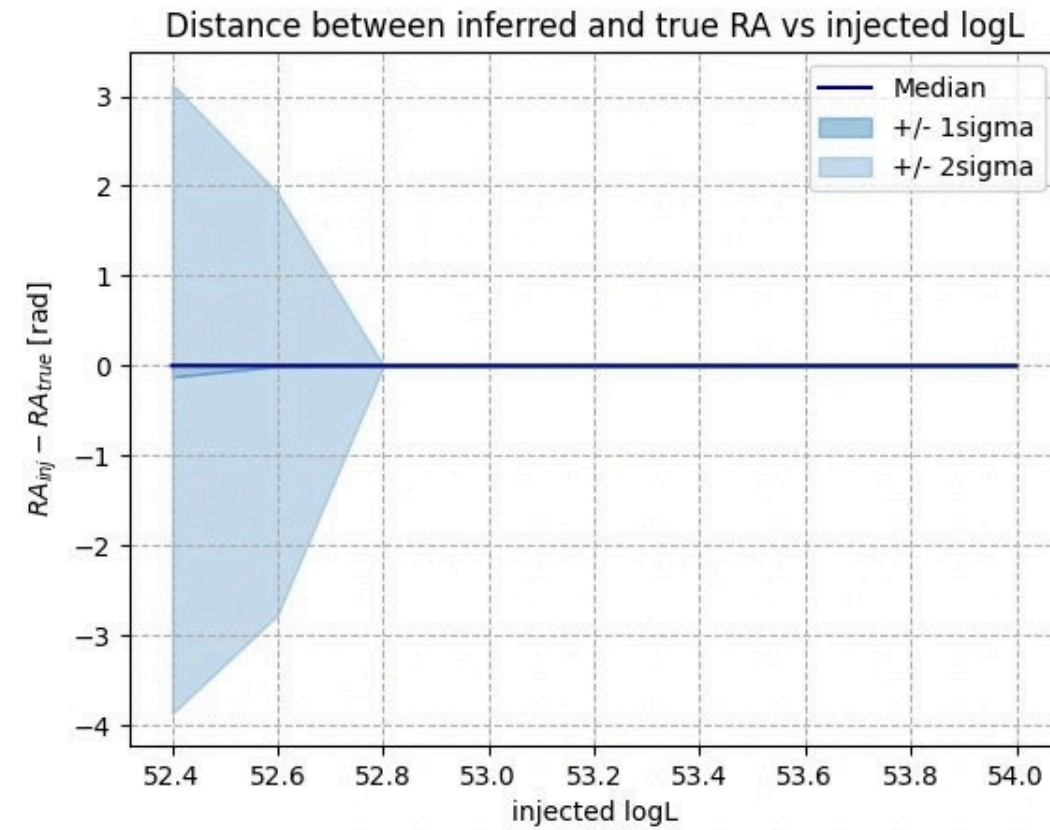
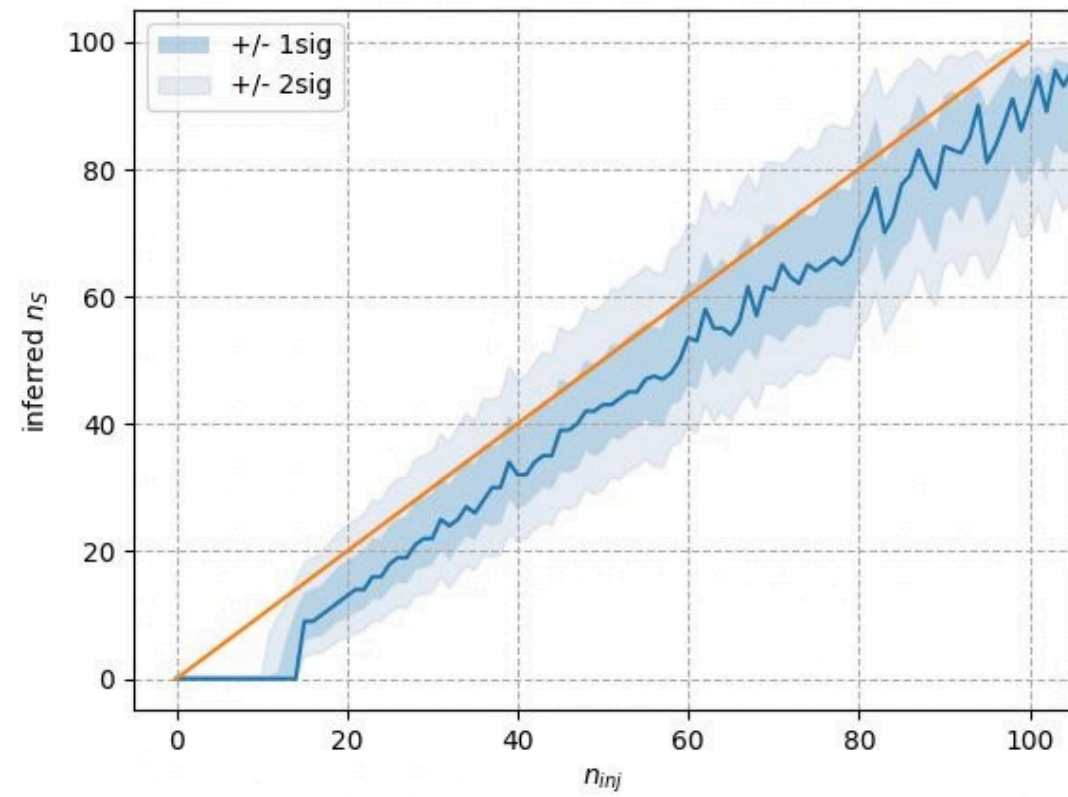
Electromagnetic

Neutrinos

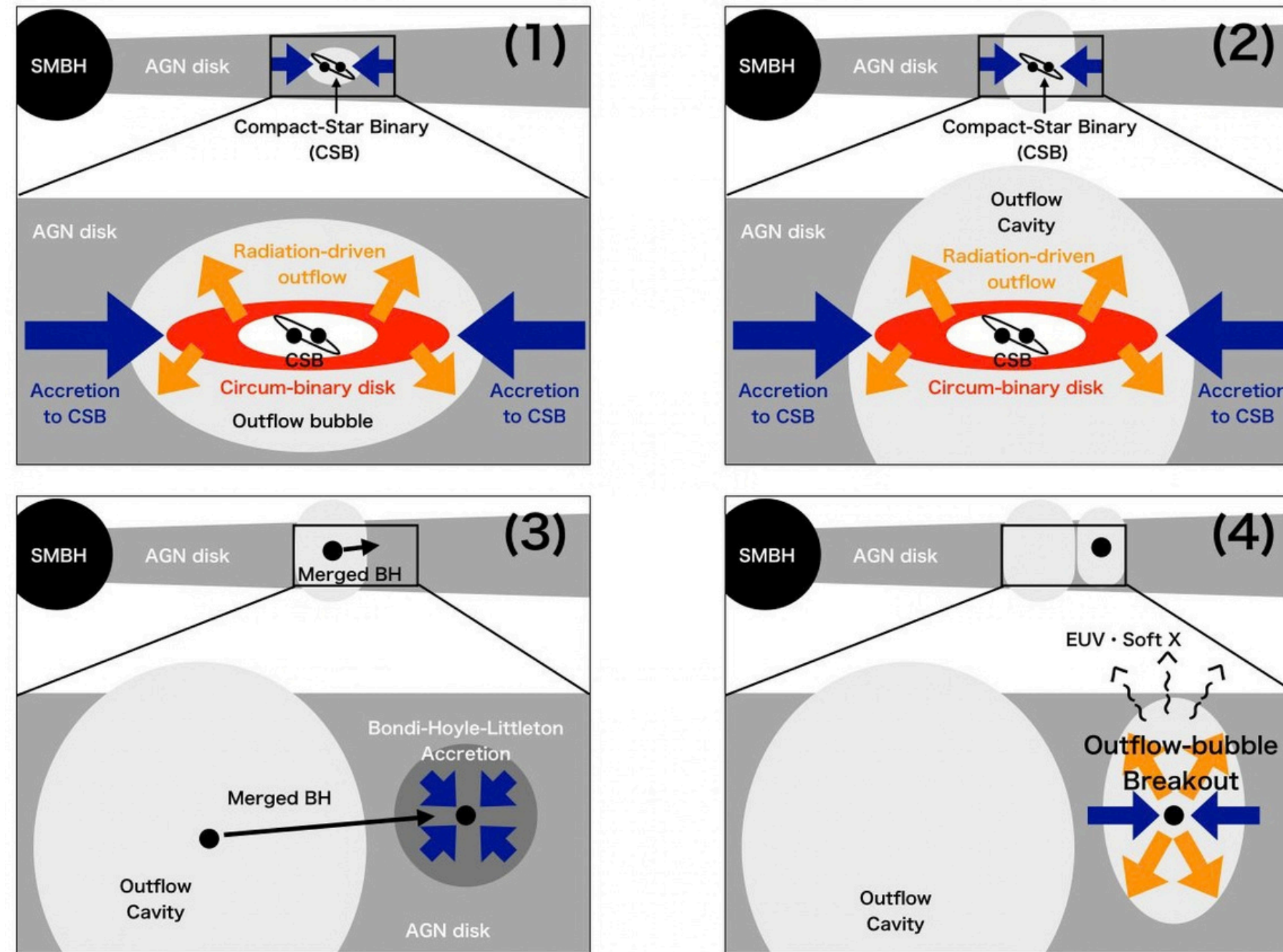
Flaring blazar coincident with high-energy neutrino IceCube-170922A [2]

[1] The IceCube Collaboration, Science 361, eaat1378 (2018). DOI: [10.1126/science.aat1378](https://doi.org/10.1126/science.aat1378)
[2] B. P. Abbott et al., ApJL 848, L12 (2017). DOI: [10.3847/2041-8213/aa91c9](https://doi.org/10.3847/2041-8213/aa91c9)

Neutrino bayesian inference



Model and time delay

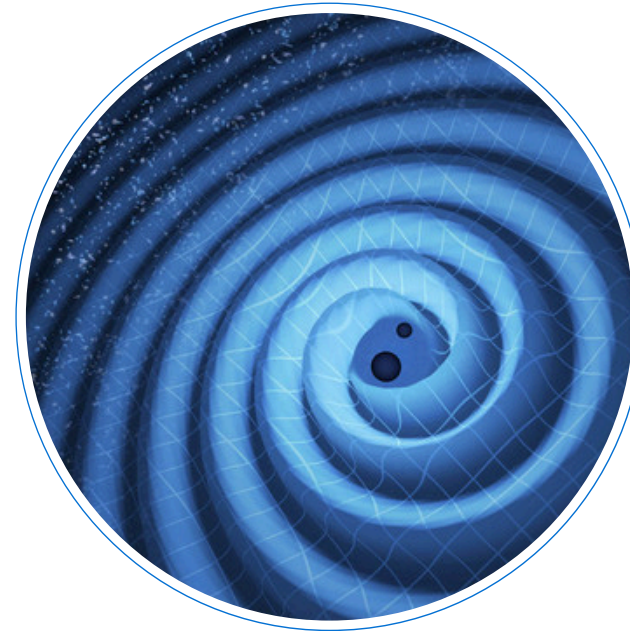


Time delay between GW and
EM/neutrino emission:

$$t_{\text{cro}} \approx r_{\text{cav}} / v_{\text{kick}} \simeq 12 r_{\text{cav},13.5} v_{\text{kick},7.5}^{-1} \text{ day},$$

Gravitational Waves

Multi-messenger Observations of a
Binary Neutron Star Merger [1]



Electromagnetic



Neutrinos

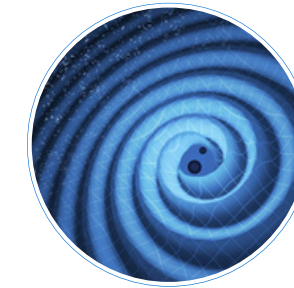
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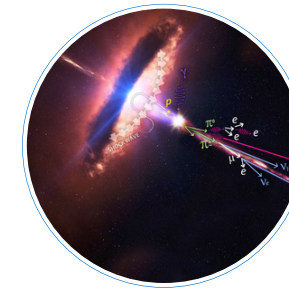
Analysis

Ingredients:

1. **Gravitational waves** from **LIGO-Virgo-KAGRA**



2. High-energy **neutrinos** from **IceCube**



3. **AGN** from **Quiaia** catalog



First step: Bayesian inference on **GW** and **neutrino** data individually



Second step: combine data using a ranking statistic

Neutrino Bayesian Inference

Challenge:

- **Huge time-window** (100 days)
- All-sky

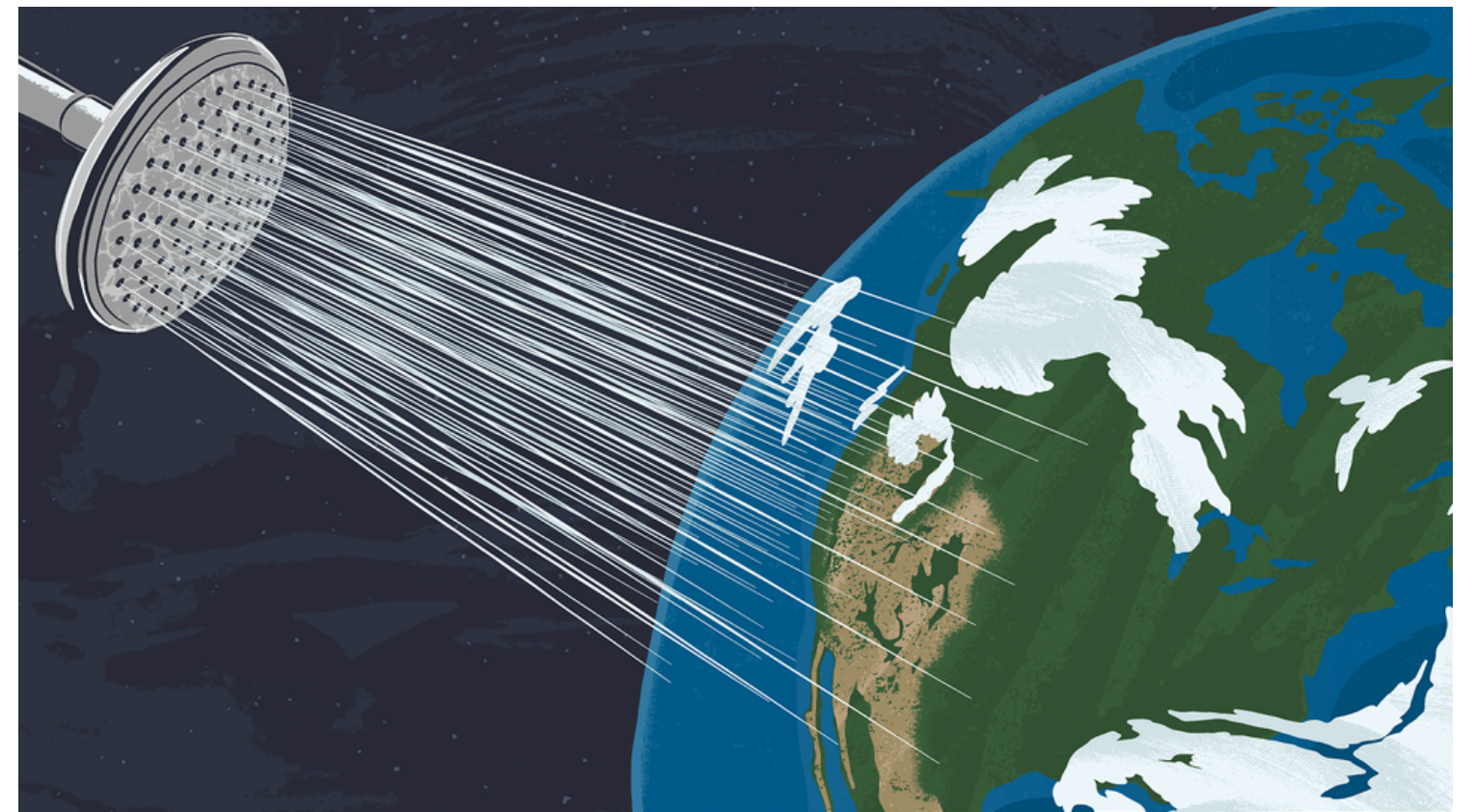


Typical number of background neutrinos: ~30.000

Standard Bayesian inference software struggle to converge.

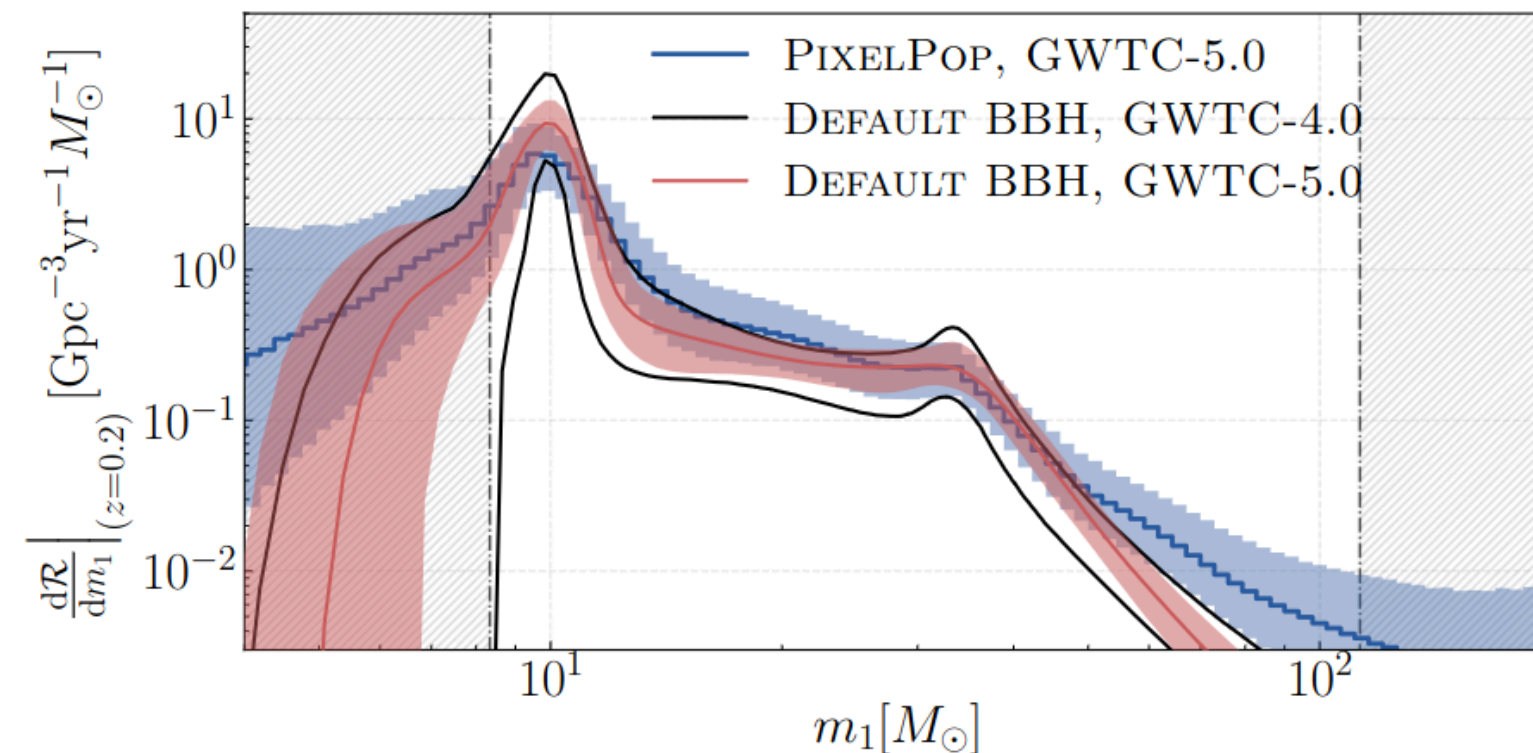
I implemented a method to perform **fast inference** for this problem

From $O(10 \text{ min}) \rightarrow O(\text{min})$



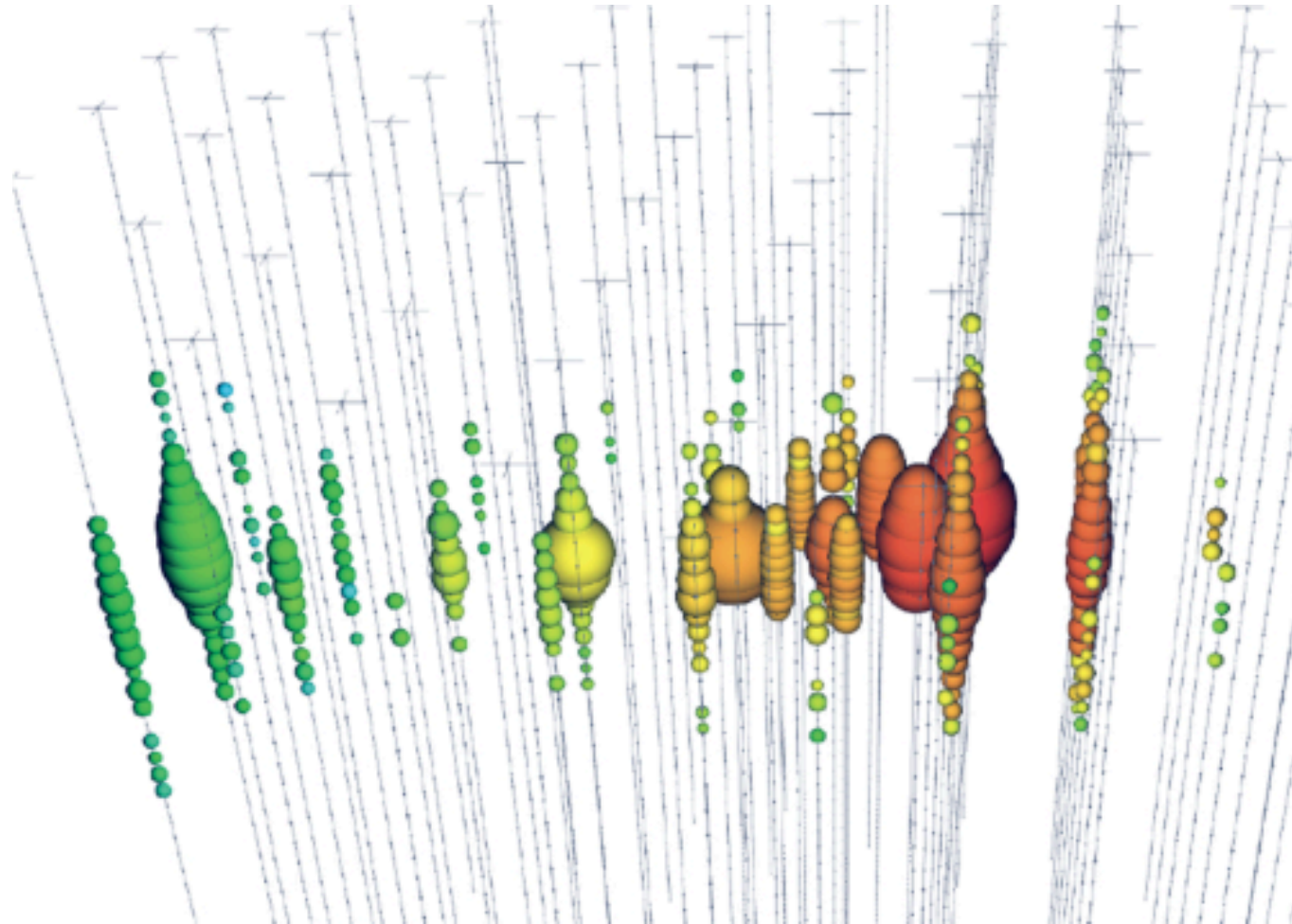
BBH in AGN rate estimates

- McKernan et al (2018): $\sim 10^{-3} - 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Tagawa et al (2020): $\sim 0.02 - 60 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Gröbner et al. (2020): $\sim (0.002 - 18) \text{ Gpc}^{-3} \text{ yr}^{-1}$
- Ford & McKernan (2022): up to $\sim 20 \text{ Gpc}^{-3} \text{ yr}^{-1}$
- GWTC-5 (2026): $27.5 - 49.4 \text{ Gpc}^{-3} \text{ yr}^{-1}$



Neutrino interactions topologies

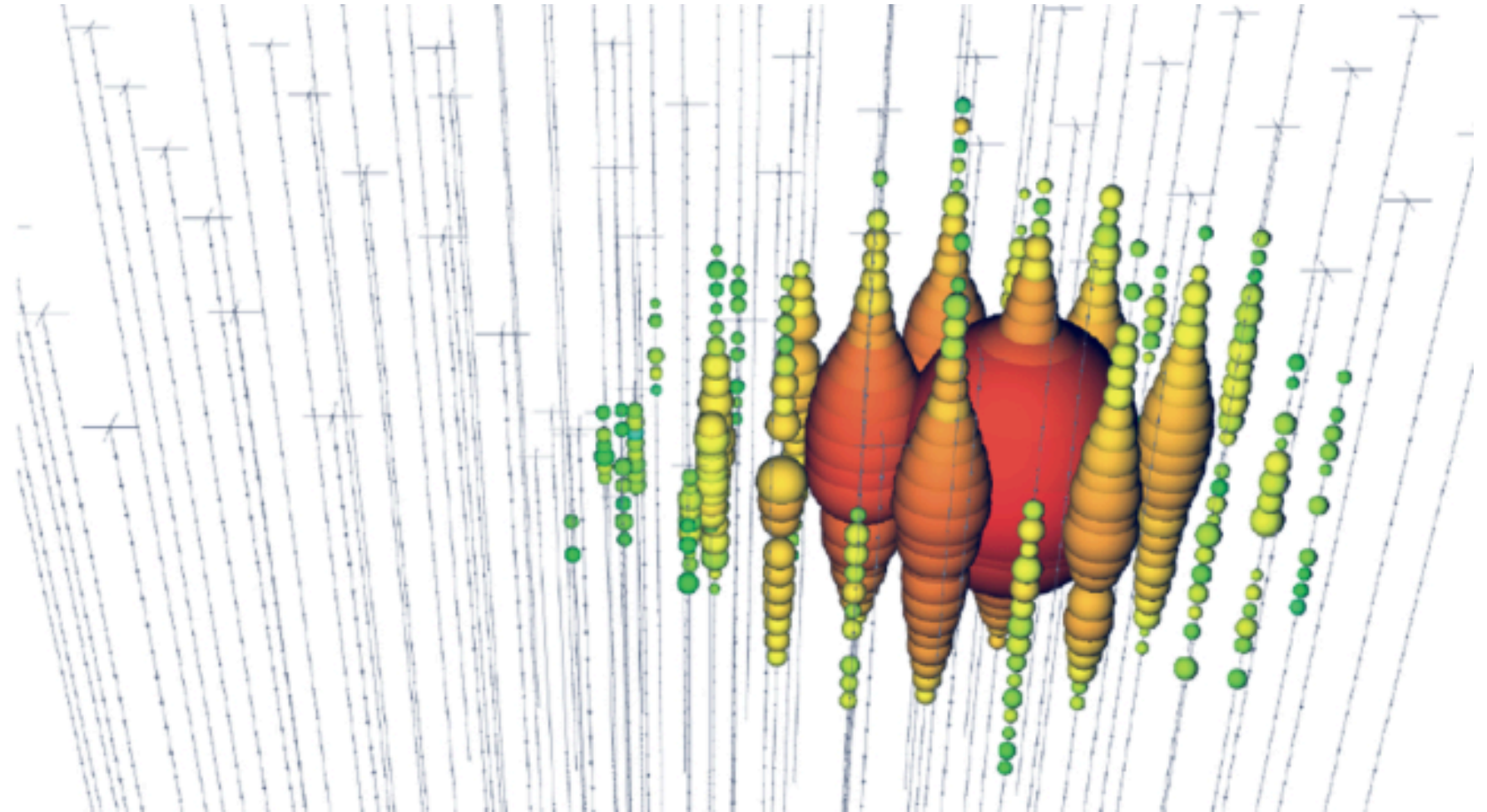
Tracks



$\nu_{\mu} + \text{CC}$

Good direction reconstruction

Cascades



$\nu_e + \text{CC}$

$\nu + \text{NC}$

Good energy reconstruction

Neutrino production

Photo-hadronic: $p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \\ n + \pi^+ \end{cases}$

Hadronic: $p + p \rightarrow \pi^{0,\pm} + X,$



Pion decay:
 $\pi^+ \rightarrow \mu^+ + \nu_\mu$

Muon decay:
 $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

Test statistic

Test statistic is designed to handle non-significant events.

Answers three questions:

$$\Lambda = \frac{I_x}{1 + Q_\nu + Q_{GW} + Q_\nu Q_{GW}}$$



- How much the two messengers overlap?
- How compatible are they with an AGN?
- How confident each messenger is?

What do we need?

- **Posterior distributions** of each messenger,
- **Evidence** of each messenger.

Ashton et al. ApJ 860 62018 (2018) DOI: [10.3847/1538-4357/aabfd2](https://doi.org/10.3847/1538-4357/aabfd2)

Stachie et al. Class. Quantum Grav. 37 175001 (2020) DOI: [10.1088/1361-6382/aba28a](https://doi.org/10.1088/1361-6382/aba28a)

Pillas et al. ApJ 956 56 (2023) DOI: [10.3847/1538-4357/acf458](https://doi.org/10.3847/1538-4357/acf458)

Neutrino formulas

Neutrino point-source likelihood:

$$\mathcal{L}_{S+B}(\vec{x}; n_s) = \prod_{\nu_i} \left[\frac{n_s}{N} \mathcal{S}(\vec{x}; \vec{x}_{\nu_i}) + \left(1 - \frac{n_s}{N} \right) \mathcal{B}(\vec{x}) \right]$$

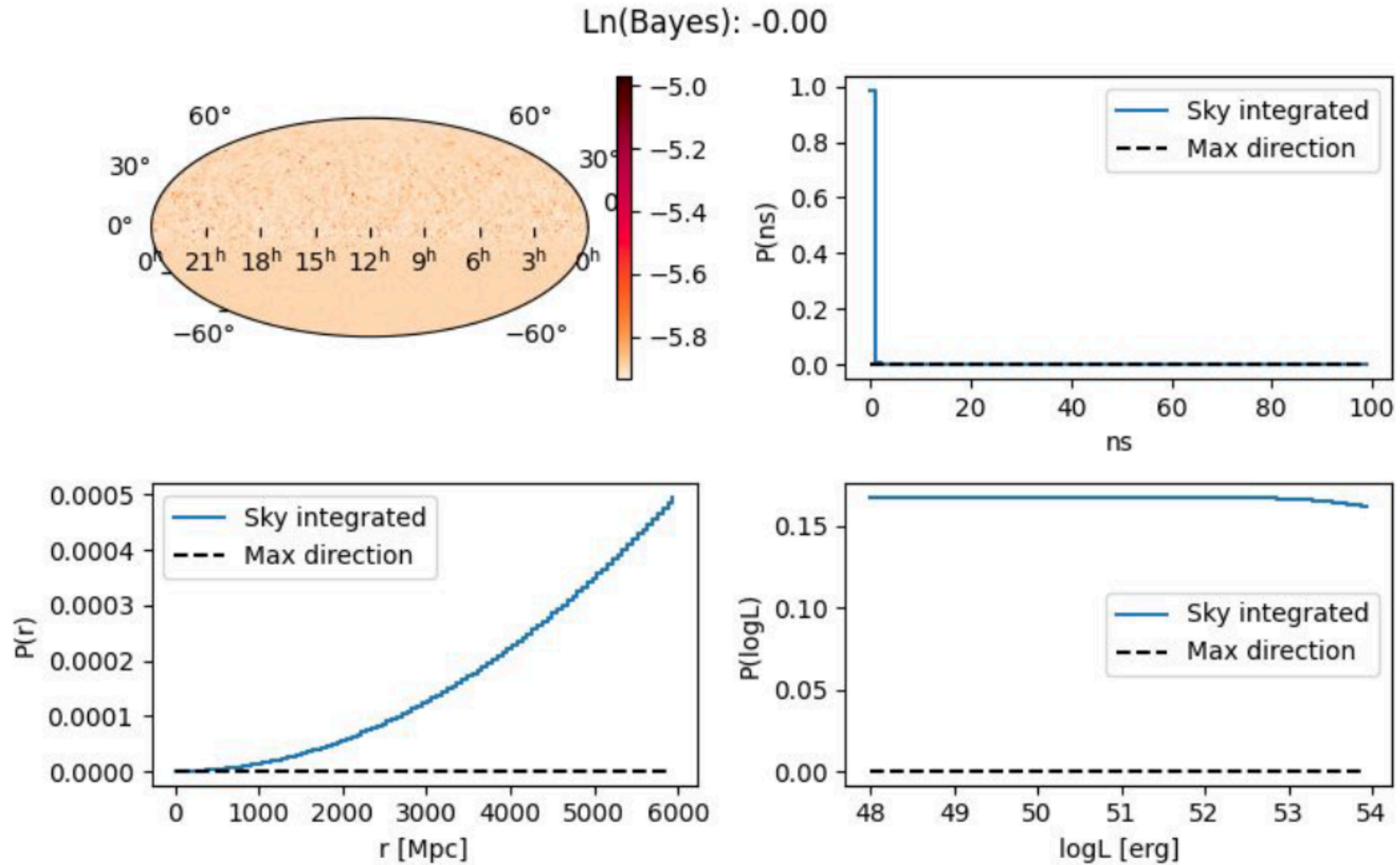
Sum of Signal (S) + Background (B) PDFs. Only spatial dependence
S: Von Mises-Fisher distribution, B: inferred from data

Compute n_s from source distance d_L and luminosity $\log L$:

$$P(\hat{r}, d_L, \log L | D_\nu) \propto \mathcal{L}_{S+B} \left(\hat{r}, n_s = C \cdot \int A_{\text{eff}}(E_\nu, \delta) dE_\nu \cdot \frac{L}{4\pi d_L^2} \right) \times \Pi(d_L) \Pi(\log L)$$

Effective area: equivalent area of detector with 100% detection efficiency

Example results – background



Example results – injecting 30 neutrinos

