

Can we constrain the neutron star merger time from kilonova lightcurves?

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On behalf of the joint LVK/LSST-TVS T_0 task force:

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Motivations

- **Motivation for the project:** LIGO/Virgo/KAGRA collaboration perform different GW searches to look for multi-messenger events e.g. **externally triggered GW searches**
- So far these searches have been done considering other triggers (GRB, Neutrinos, etc) → wish to extend them to kilonovae observed by Vera C. Rubin Observatory **to get ready for IR1!**
- Crucial aspect of all the multi-messenger searches: definition of time window for two events to be considered as coincident; **this is not trivial for kilonovae**

Can we constrain the BNS merger time from kilonova lightcurves? If yes, with which accuracy?

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Kilonova models

What are the differences between them?

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Search for GWs around kilonova candidates

1. Kilonova models

Kilonova: Optical-NIR emission accompanying the nucleosynthesis and decay of heavy elements during the merger

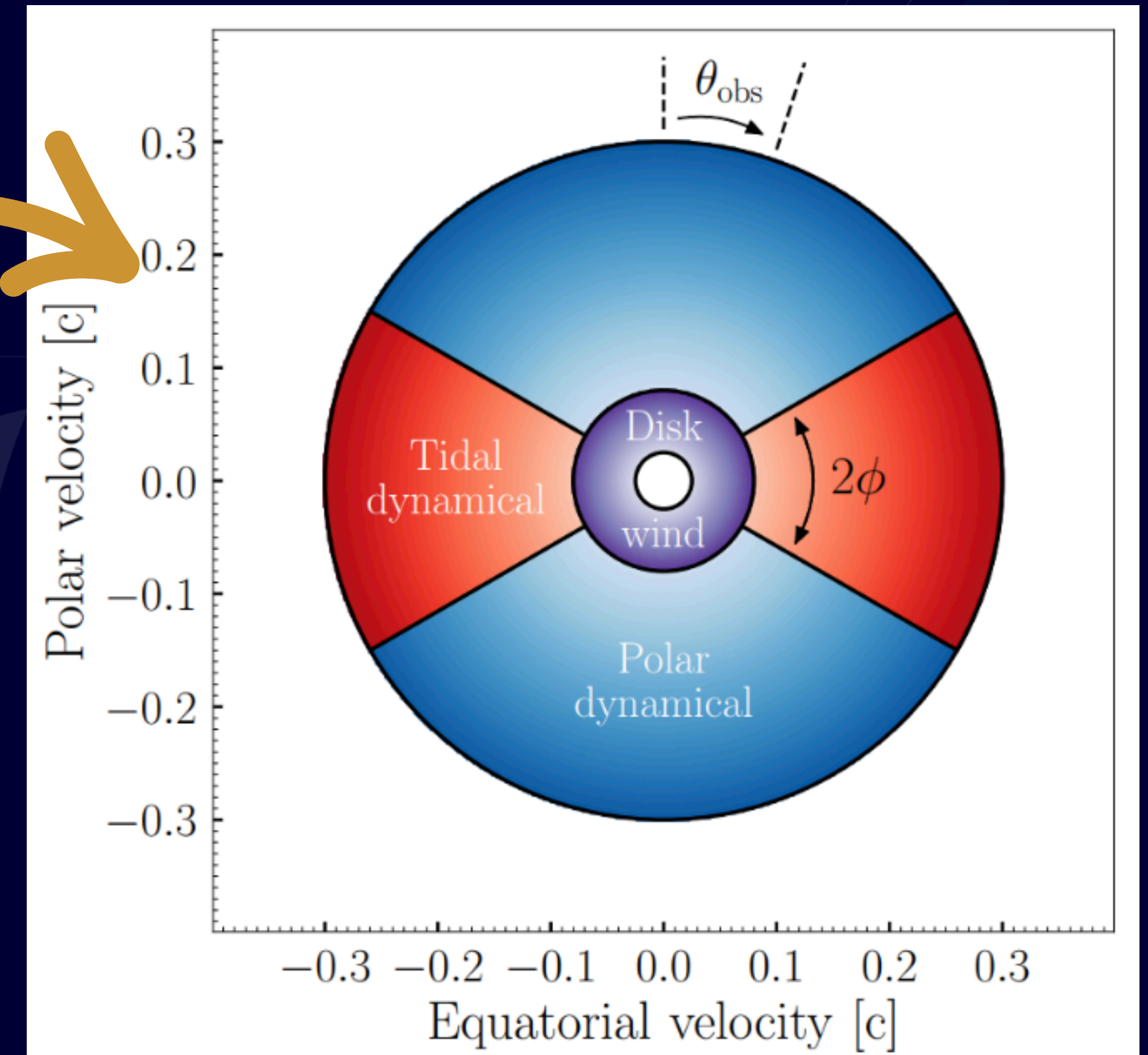
How to model the kilonova luminosity evolution?

- **Grid of Kilonova models**

Kilonova lightcurves for different combinations of ejecta parameters (e.g. mass and velocity) and observer viewing angle imprinted in the kilonova lightcurves

- **Different models created with:**

- semi-analytic codes (Metzger 2020)
- rad. transfer sedona (Kasen+2006, Brethauer+2026)
- **rad. transfer POSSIS (Bulla 2019, 2023)**
- rad. transfer supernu (Wollaeger+2014)



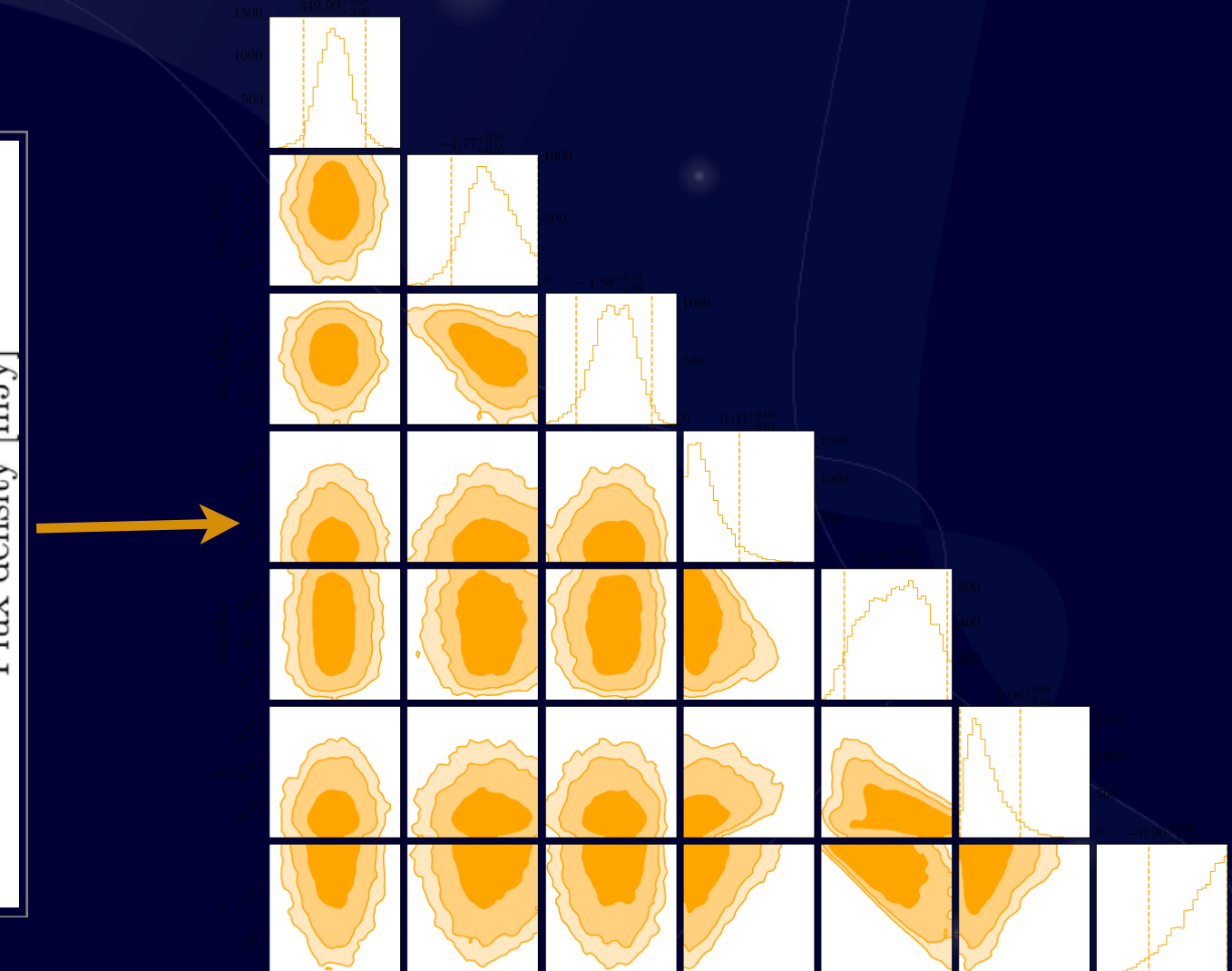
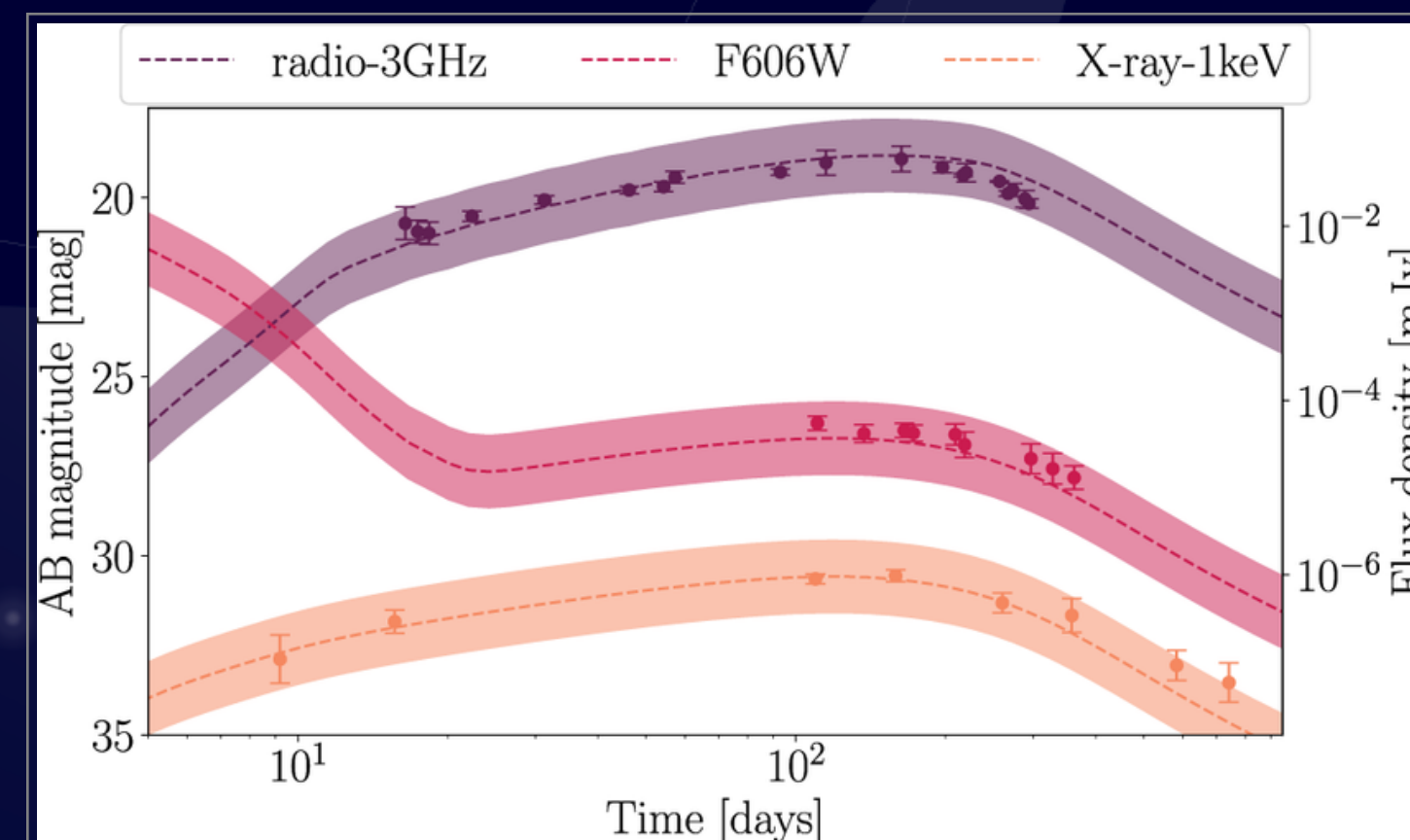
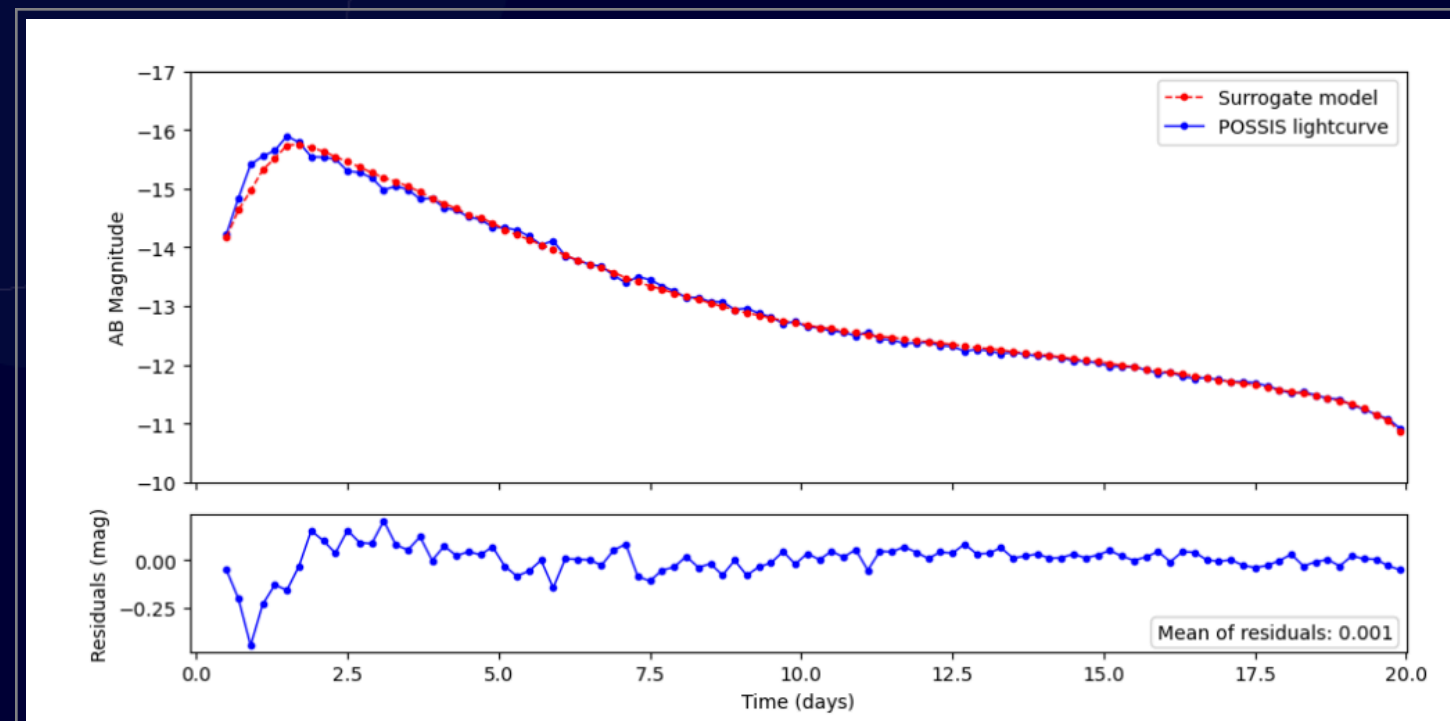
2. T_0 estimation

Inference frameworks:

Light curve fit and parameter inference

Many frameworks can be used:

- **NMMA** (Pang+2023, Rose+2026)
- Redback (Sarin+2024)
- Rift (Lange+2018, Ristic+2022, Peng+2024)
- nessai/bilby (Datrier 2022)



2. T_0 estimation

Can kilonova models
recover the merger time?

With which accuracy?

Which model to use?

To what extent observational
constraints affect the T_0
recovery?

What was done

- **Perform simulations (injection study)**
 - Synthetic kilonova light curve generation and recovery
 - Different observational configuration
 - Optimistic (rich light curve)
 - light curve injected in LSST baseline simulation
- **Use of real data**
 - AT2017gfo
 - GRB with KN candidates (*not presented here*)

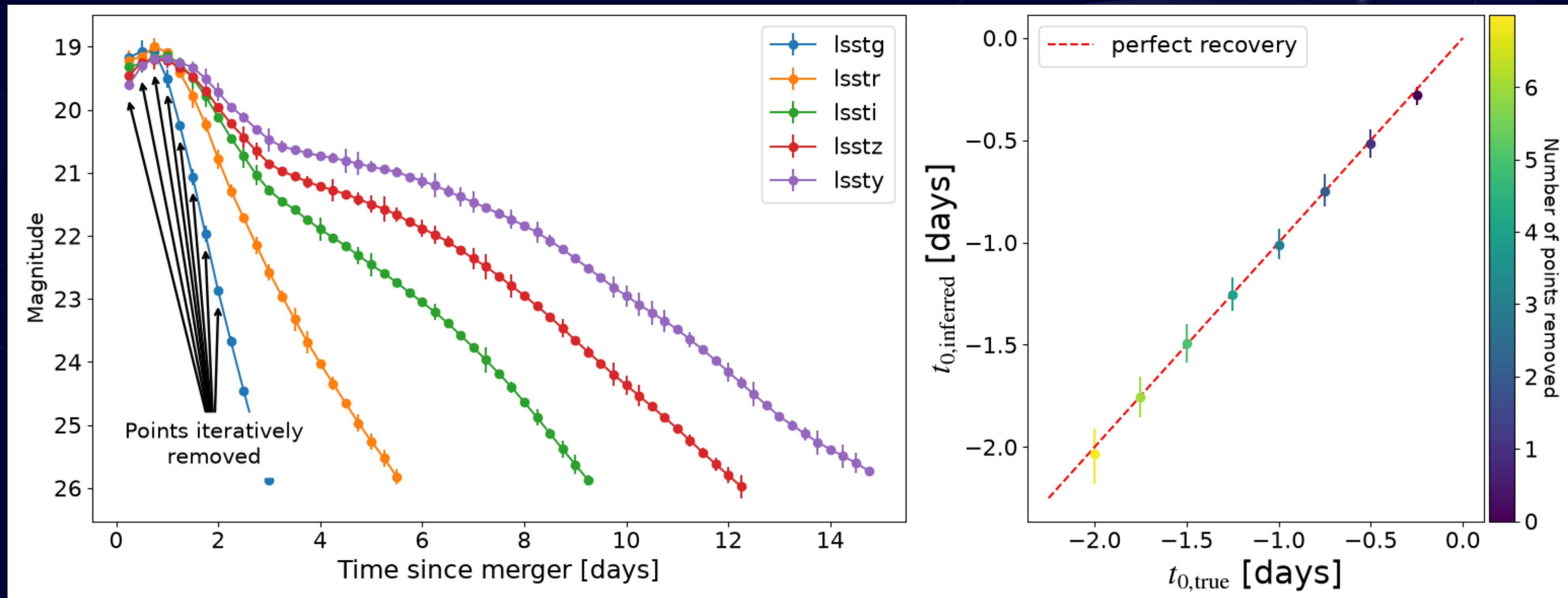
2. T_0 estimation

Injection study

Optimistic observing scenario

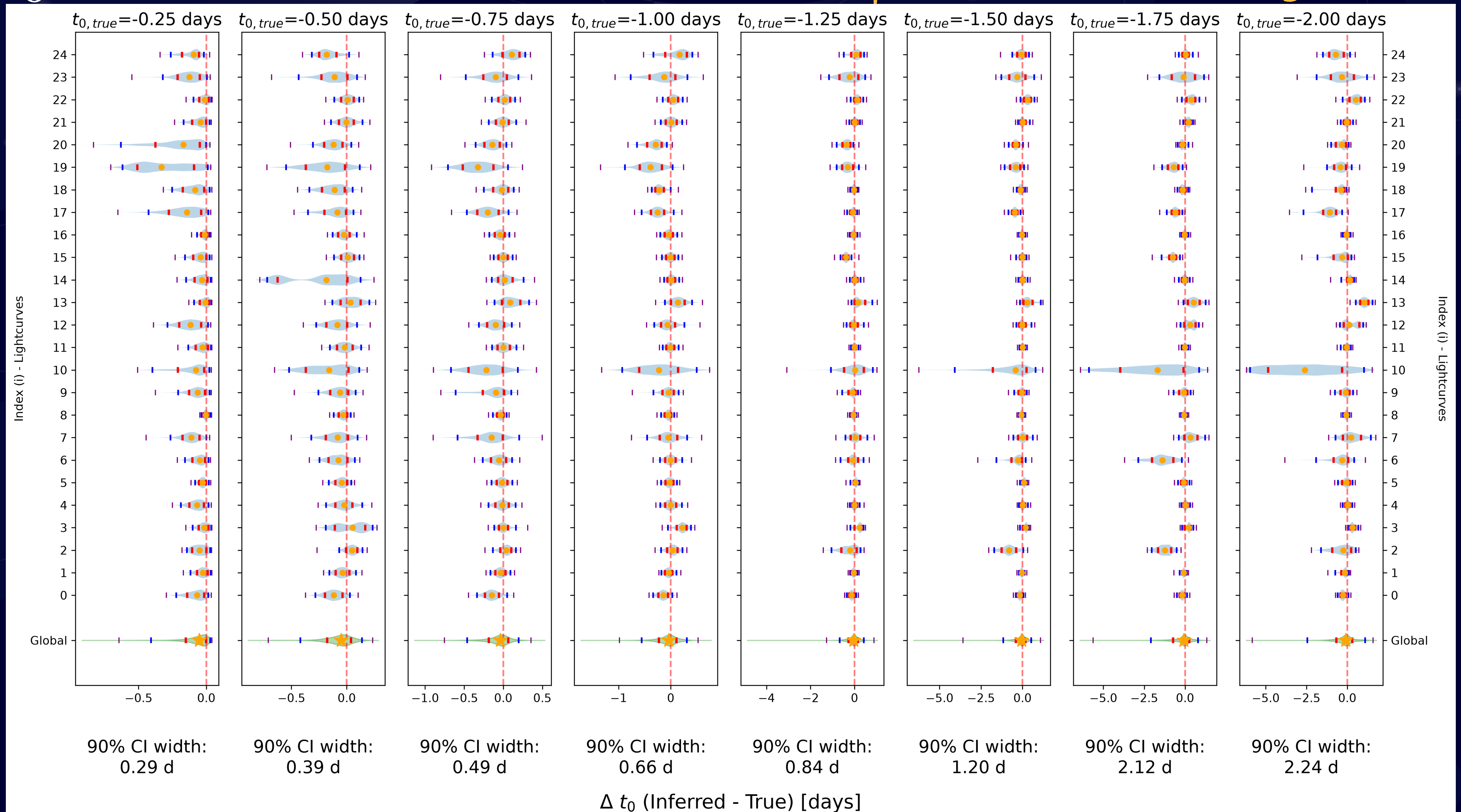
- Same model for KN generation and recovery (Bulla, 2026)
- Assess how accurately the merger time can be recovered as a function of the first detection epoch:
 - Iteratively remove the earliest detection from each synthetic lightcurve
 - Quantify how merger-time inference degrades as early-time observations are lost

Priors covering the model parameter space



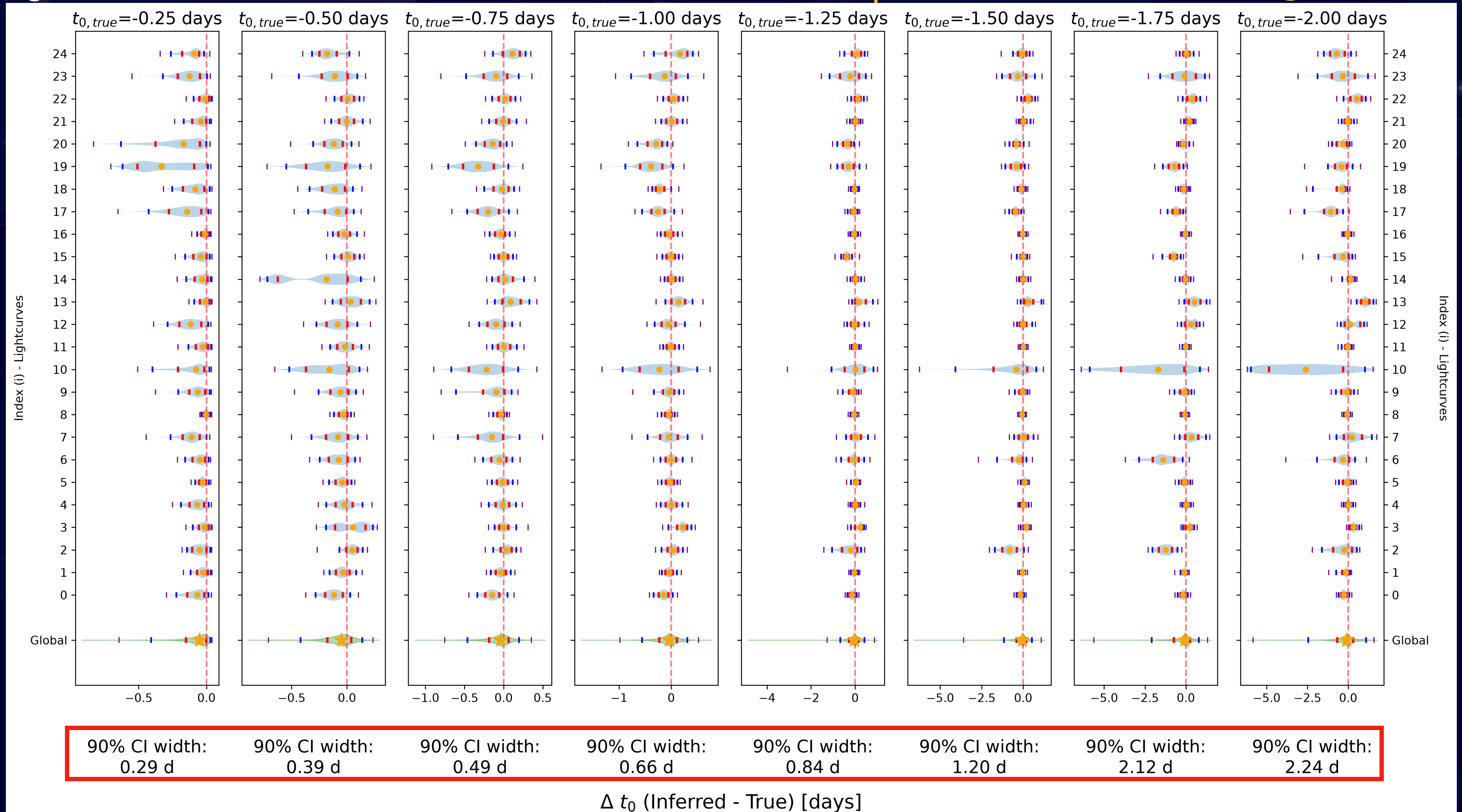
2. T_0 estimation *Injection study*

Optimistic observing scenario



2. T_0 estimation *Injection study*

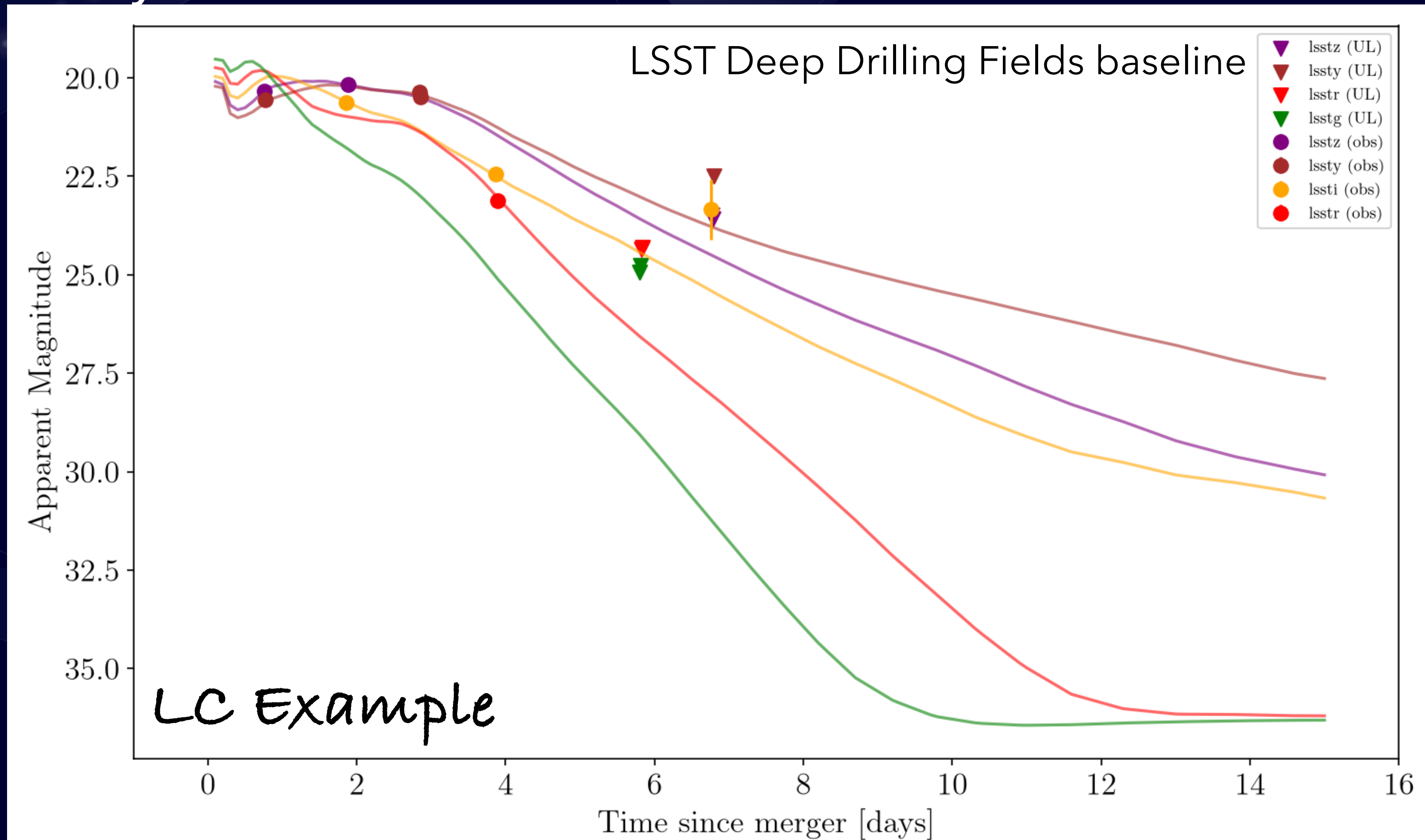
Optimistic observing scenario



2. T_0 estimation

Injection study

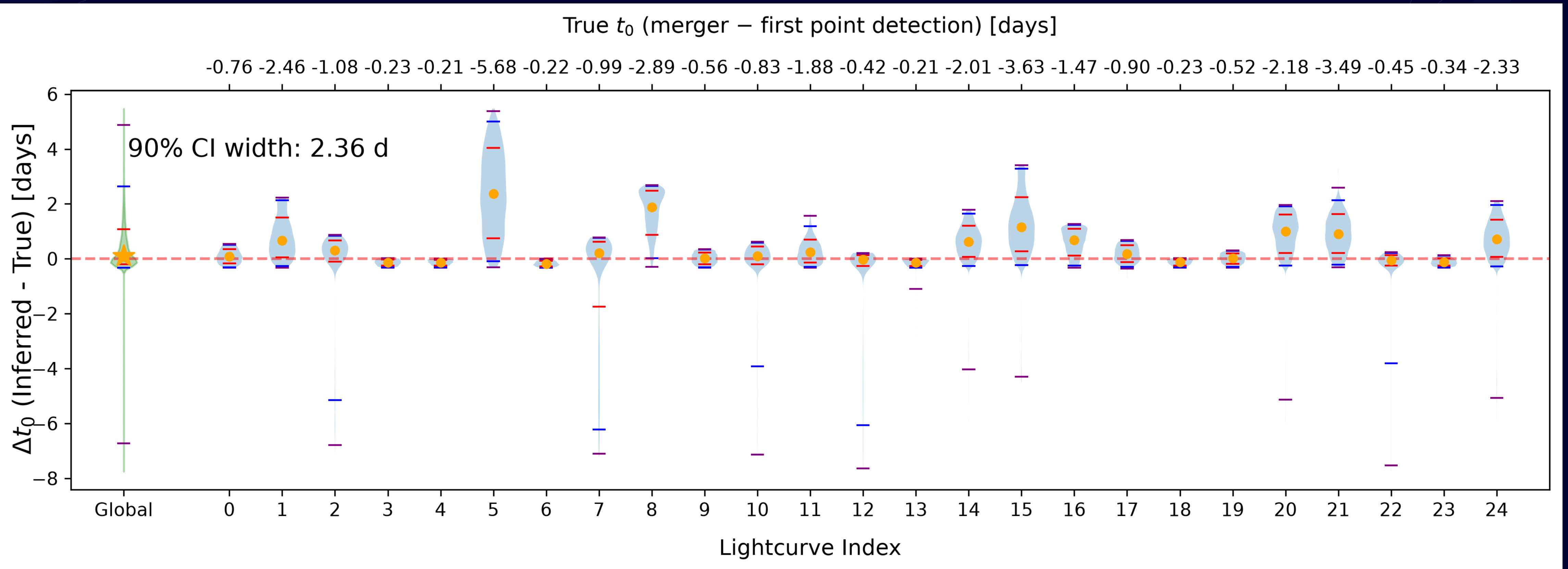
LSST observing scenario



2. T_0 estimation

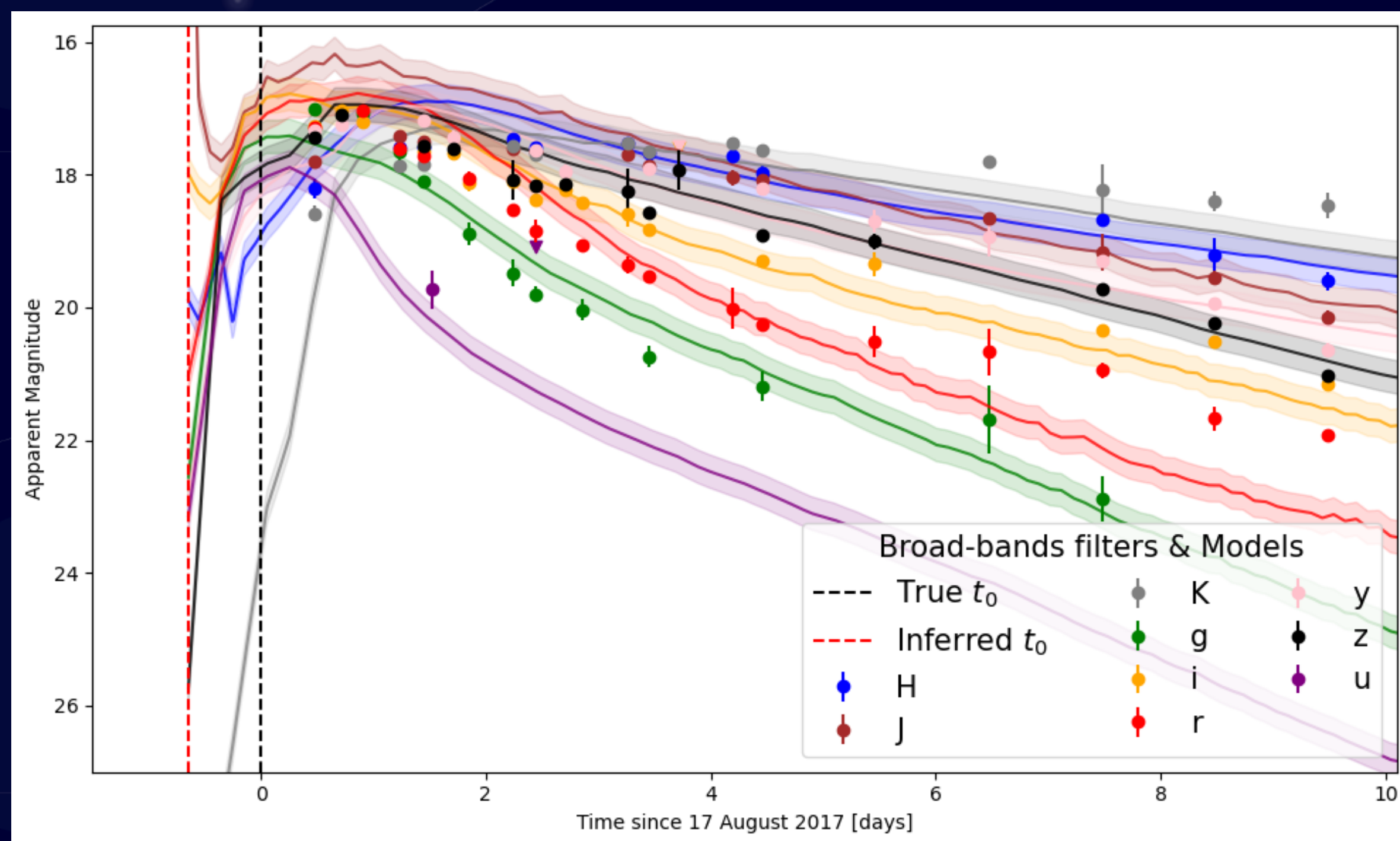
Injection study

LSST observing scenario What if we add an upper limit before the merger time?



2. T_0 estimation

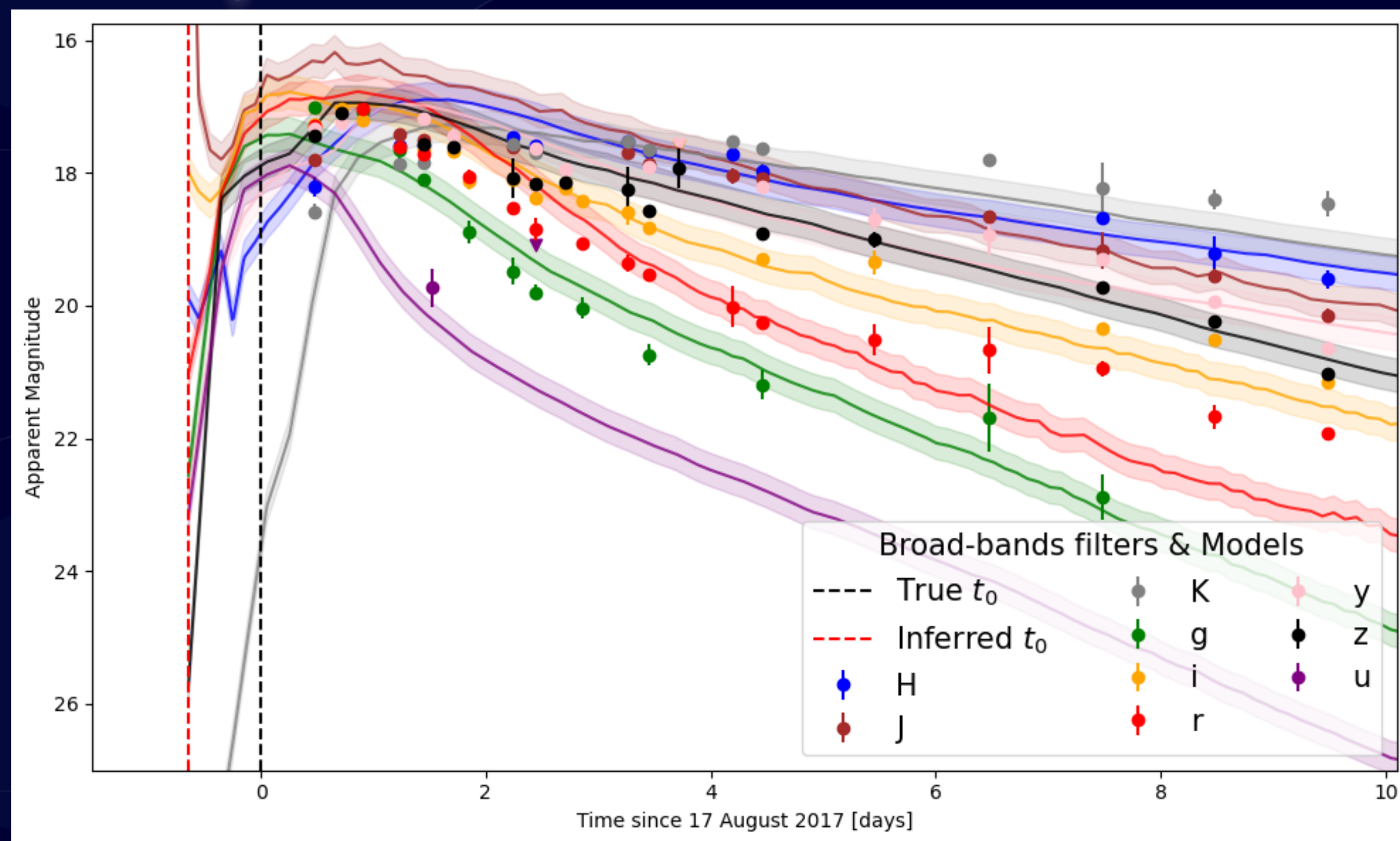
Real data: AT2017gfo



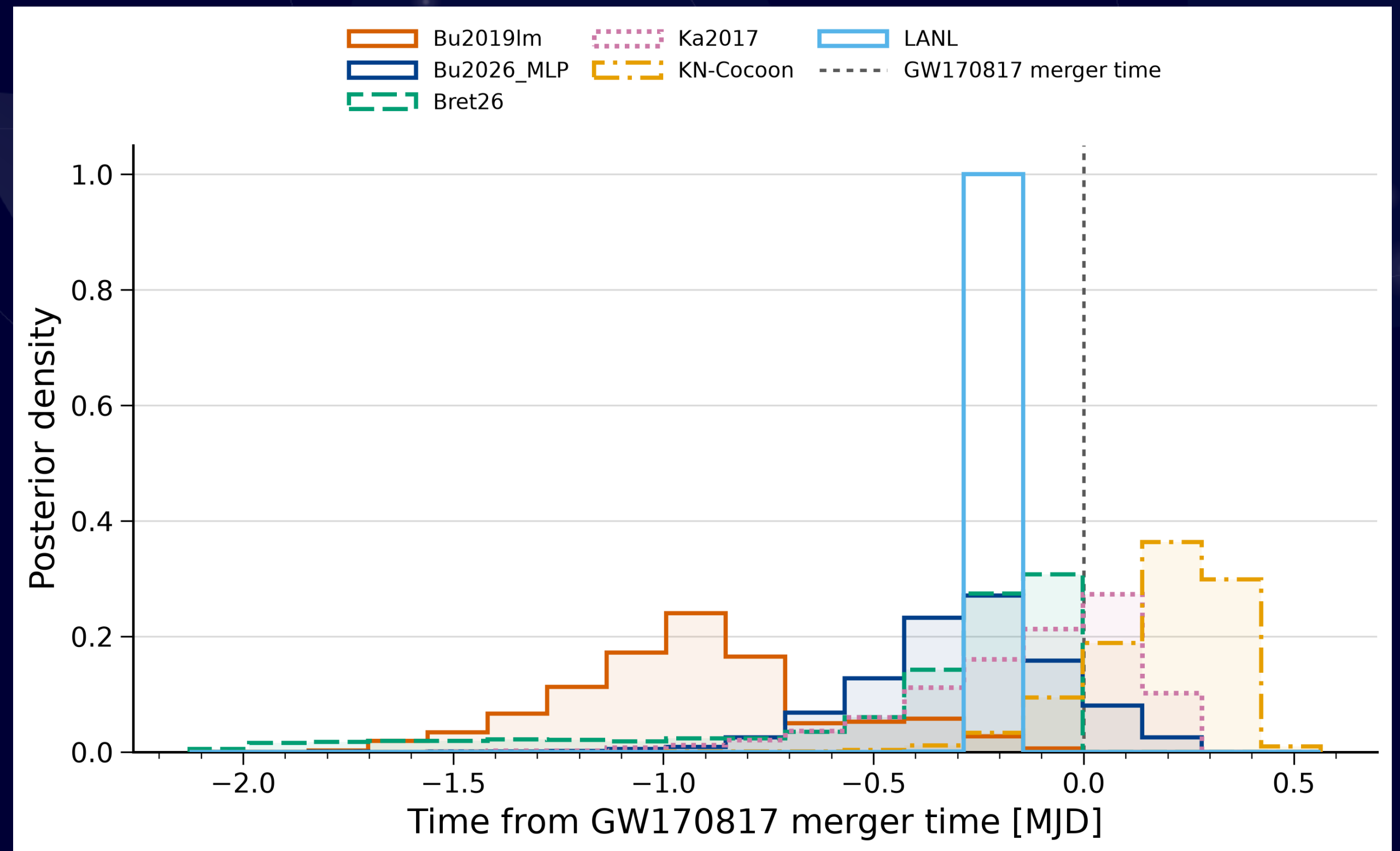
Analysis with Bu2026

2. T_0 estimation

Real data: AT2017gfo



Analysis with Bu2026

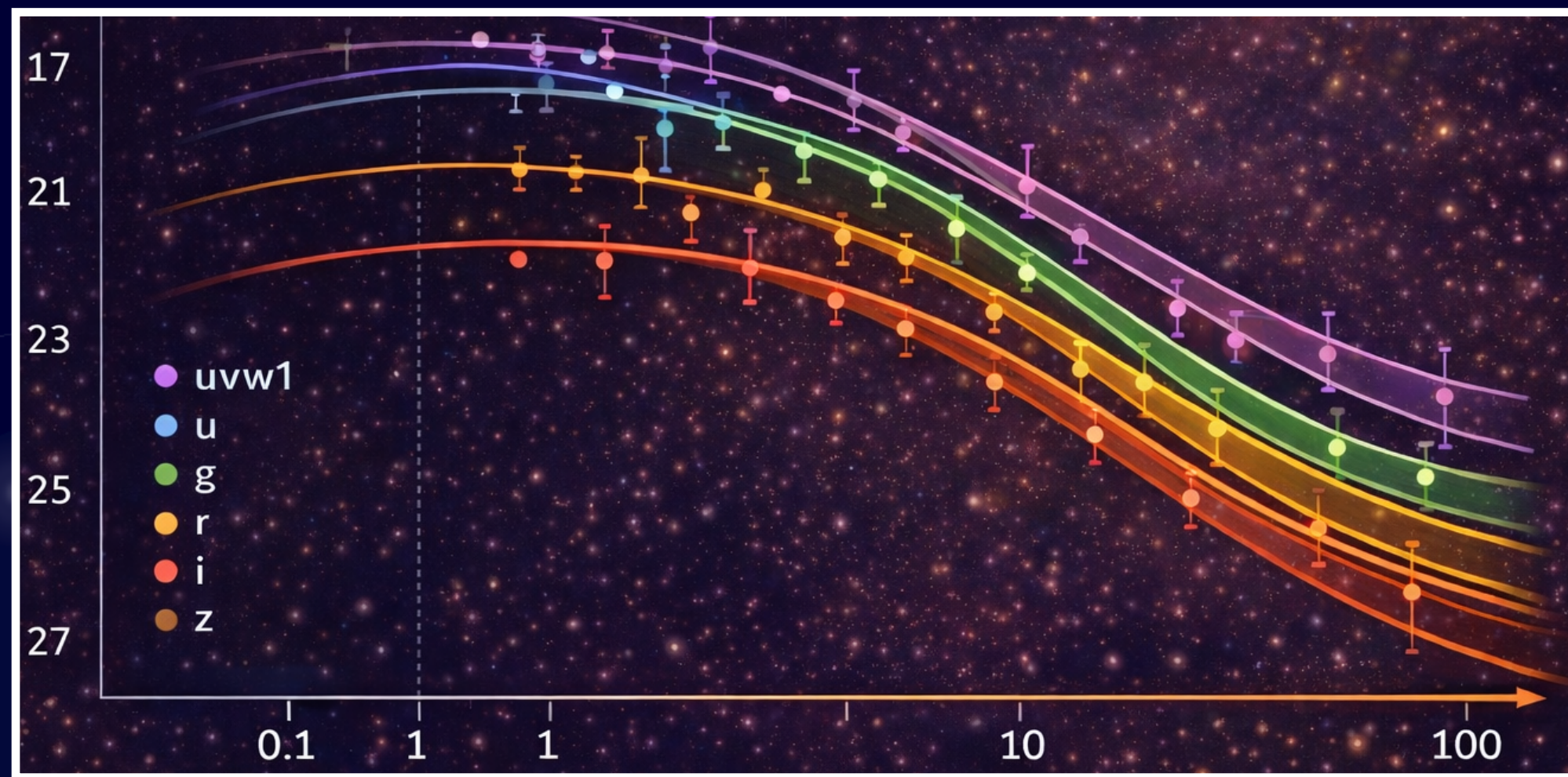


Bu2019Im: overestimated opacity at early times, delaying photon escape and producing a longer rise to maximum light.

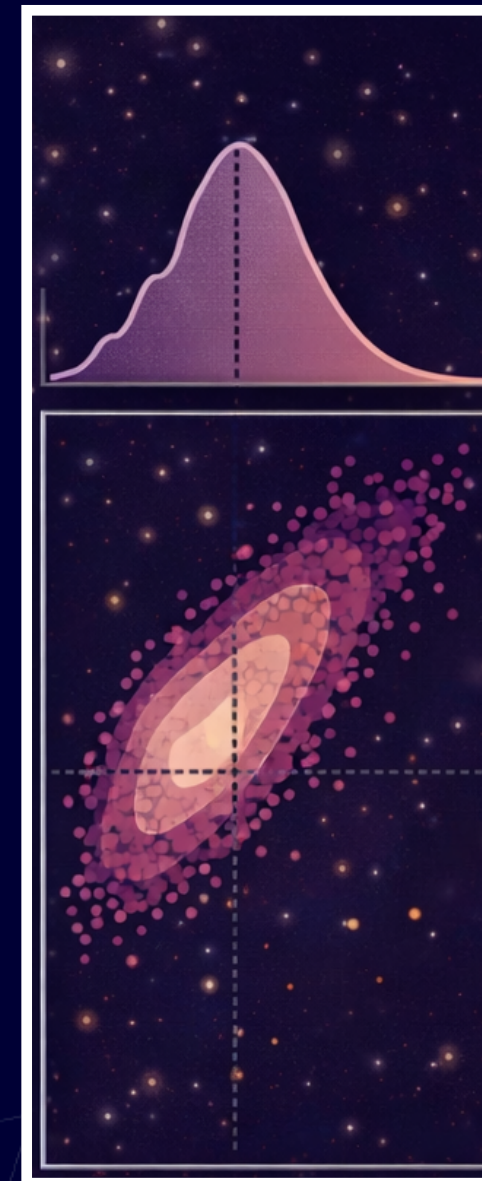
LANL: only analysis with a free model systematic error here, reducing the width of the posterior and slightly shifting it

3. Gravitational-wave targeted search

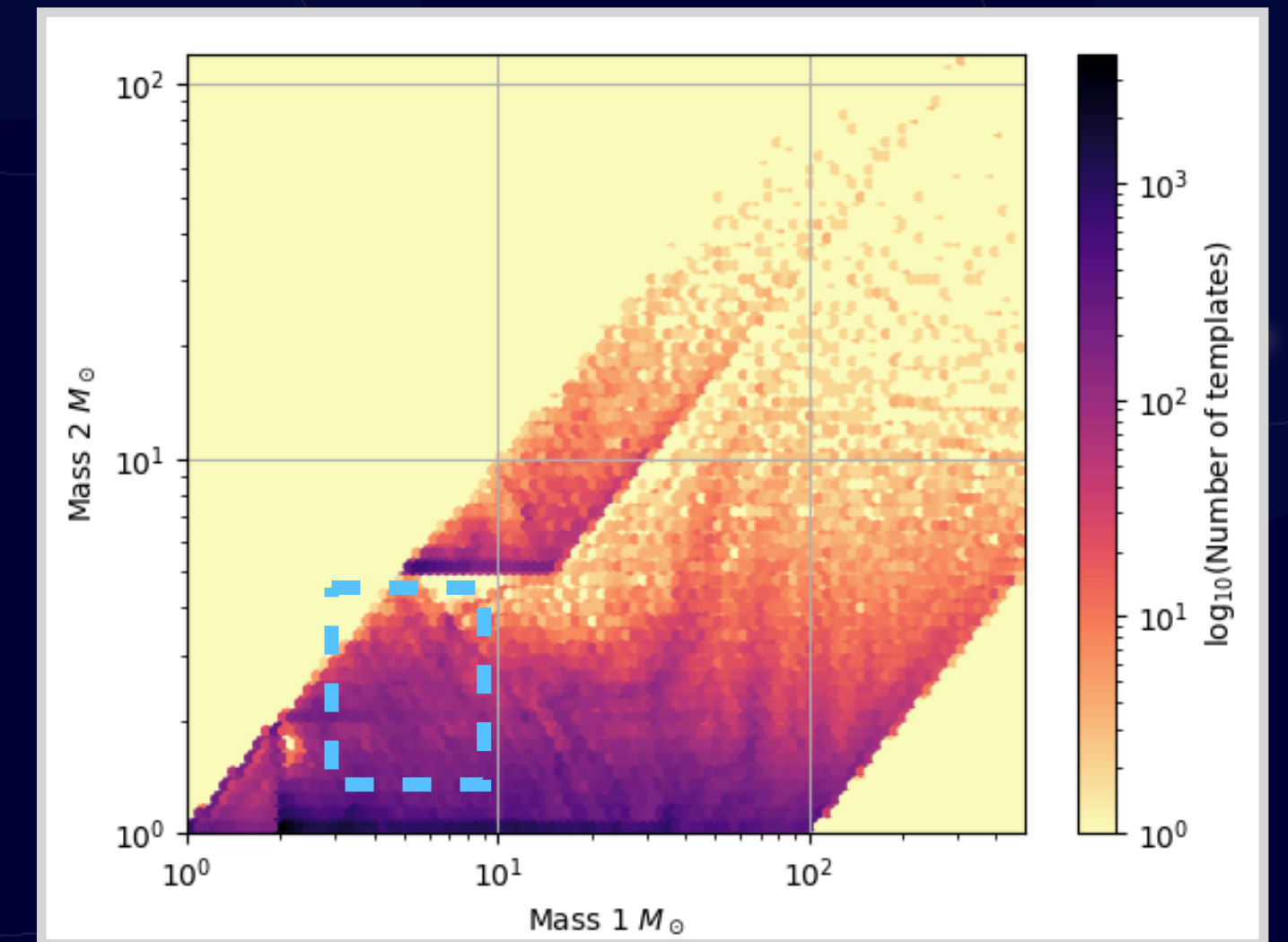
workflow



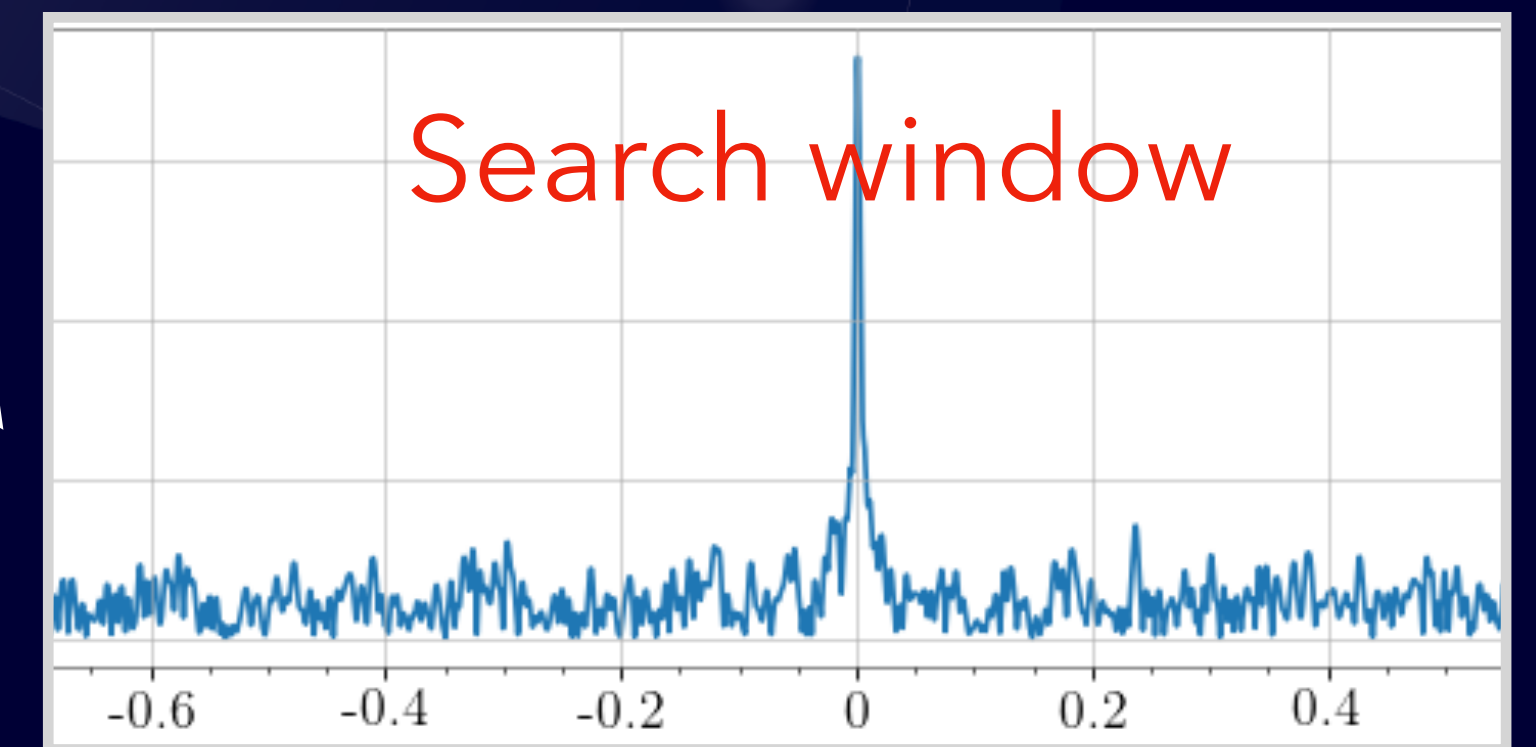
Fit the KN lightcurve



Posterior distribution
of **merger time**,
masses...



Reduce the template bank

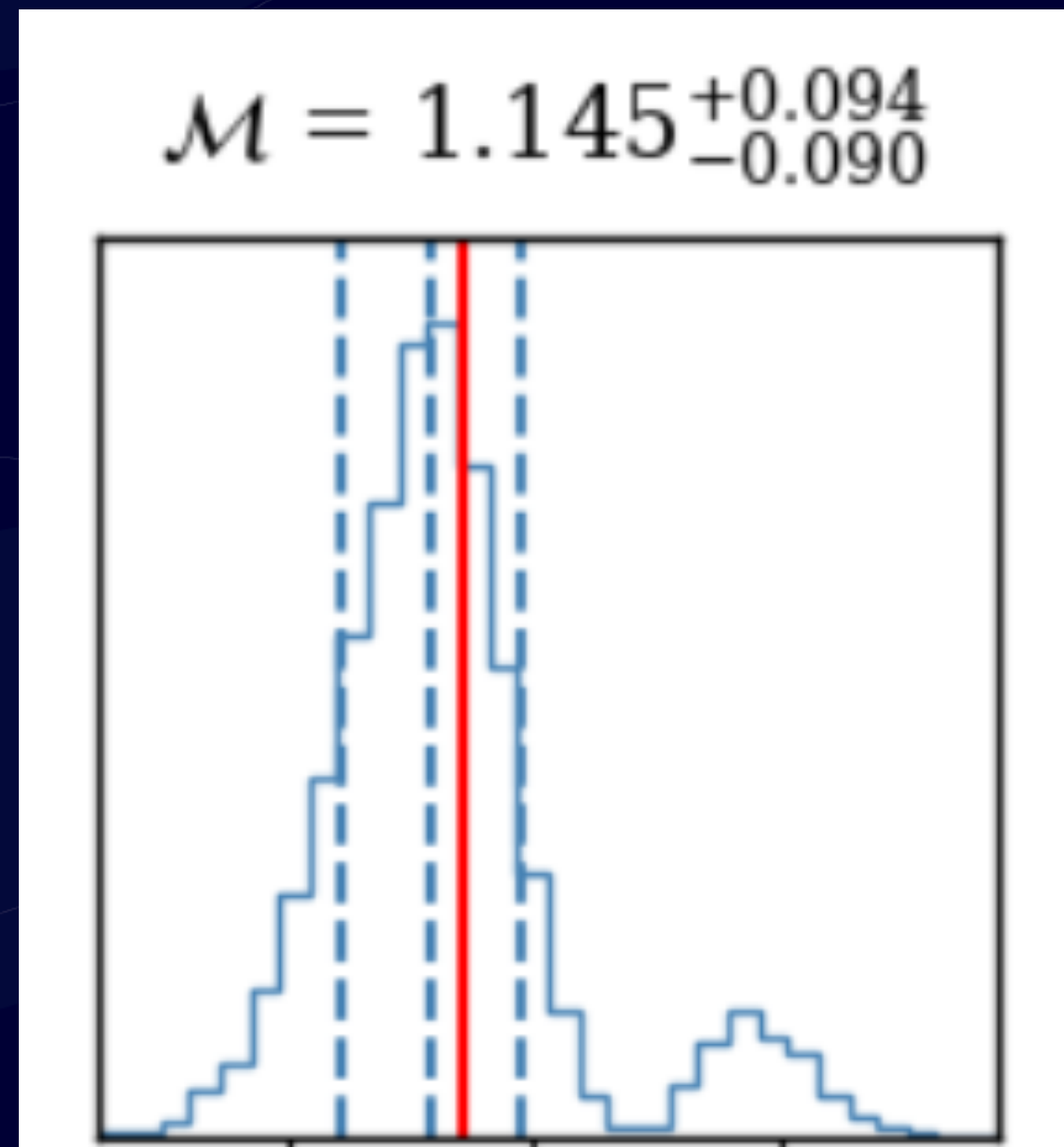


**Define the search window
and search for GW
candidates**

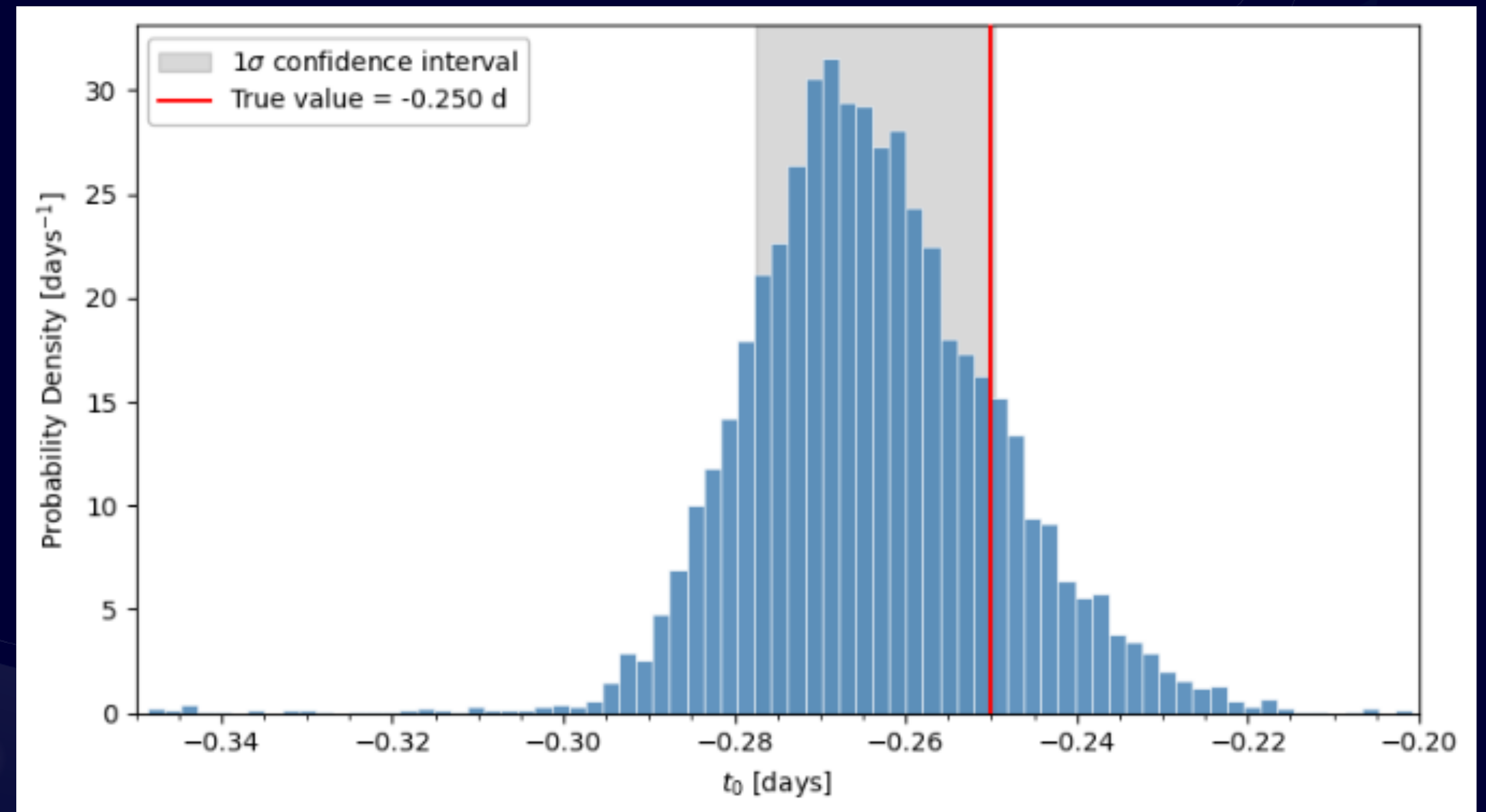
3.

Gravitational-wave targeted search

Test on AT2017gfo



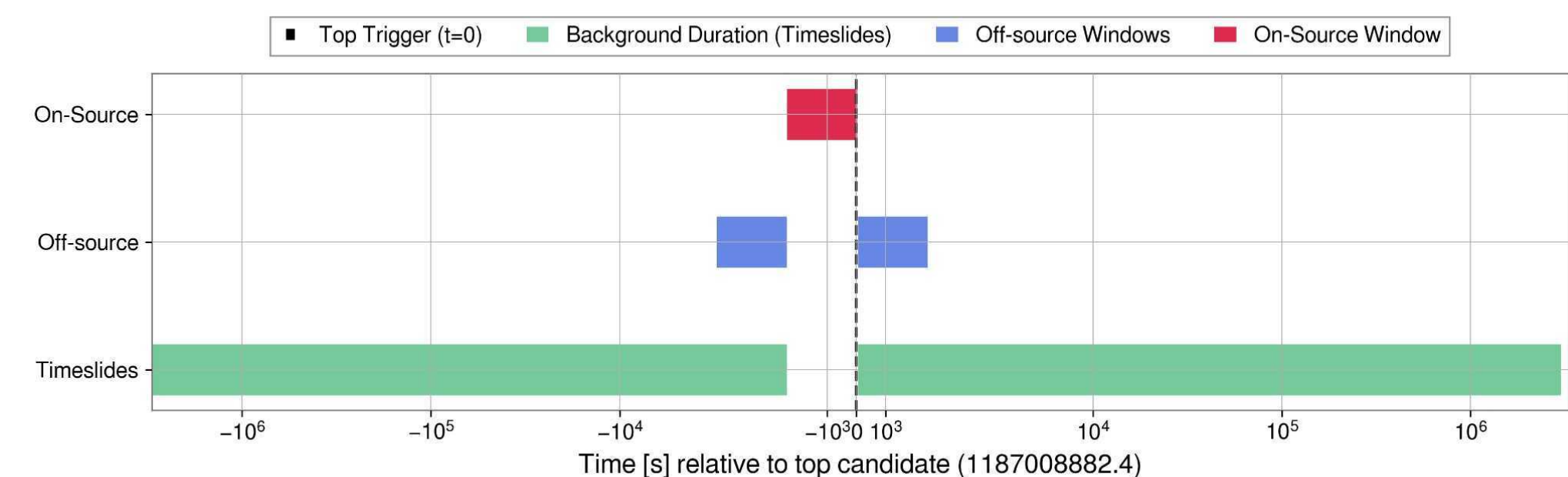
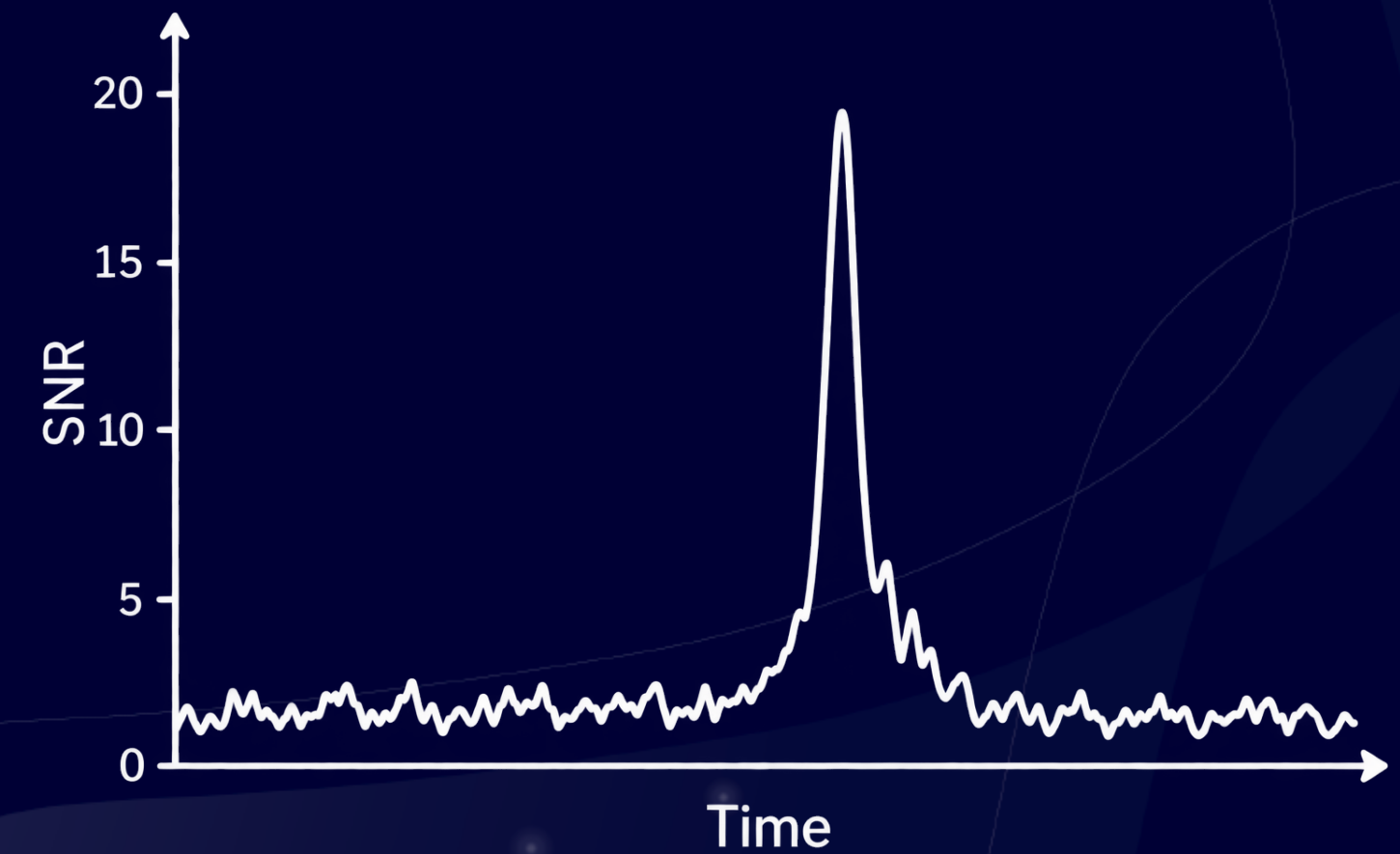
« True » chirp mass
(inferred from GW)



3.

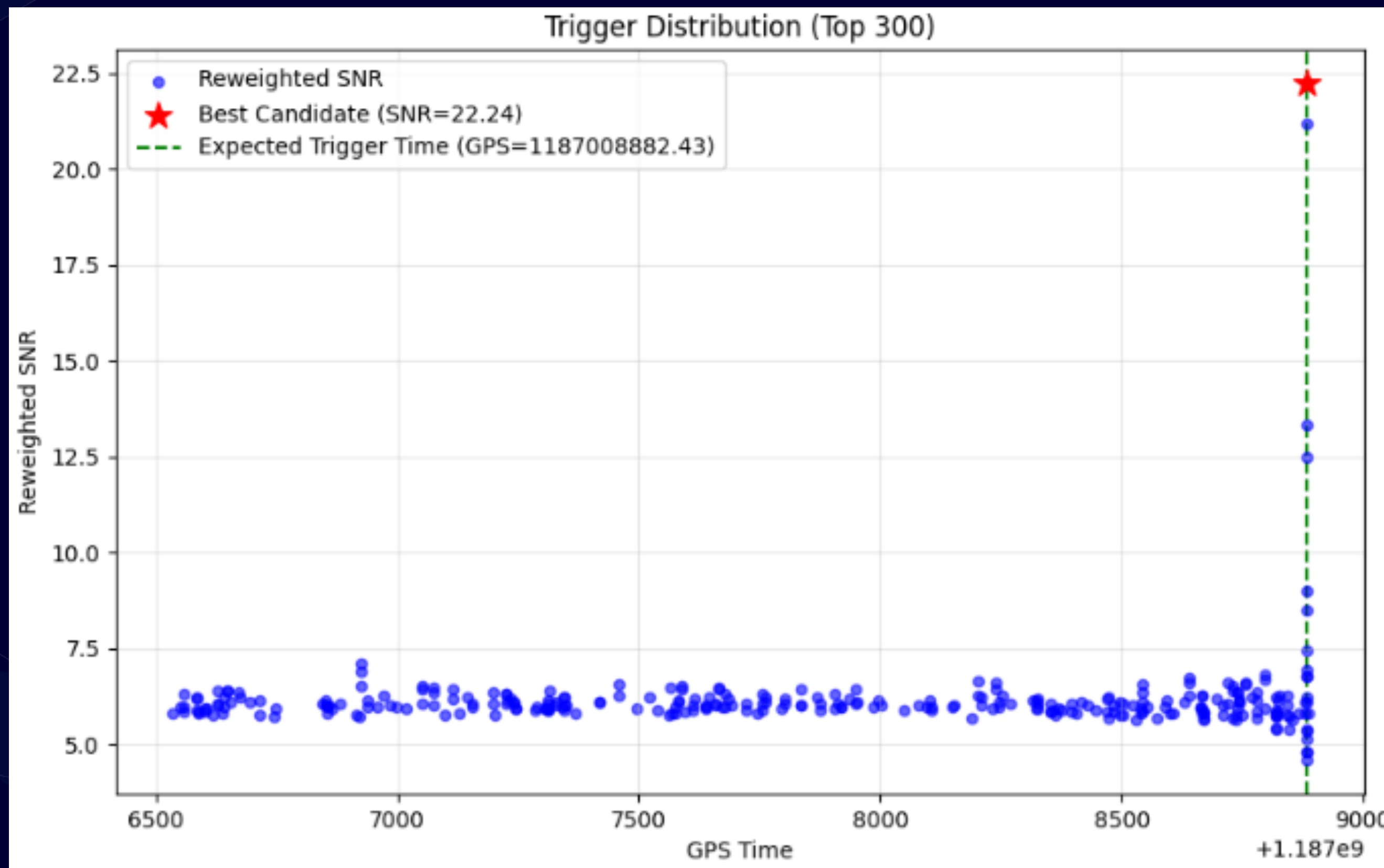
Gravitational-wave targeted search

- **Signal-to-Noise timeseries** computed over the on-source search window using PyCBC pipeline
- **Reduced template bank**
- For large on-source window (hours-day): need to account for the **Earth's rotation** by dividing the on-source into subsegments
- **Background** estimated with **time-slides in a off-source window** → to compute the **significance** of the loudest foreground candidate (p-value)



3. Gravitational-wave targeted search

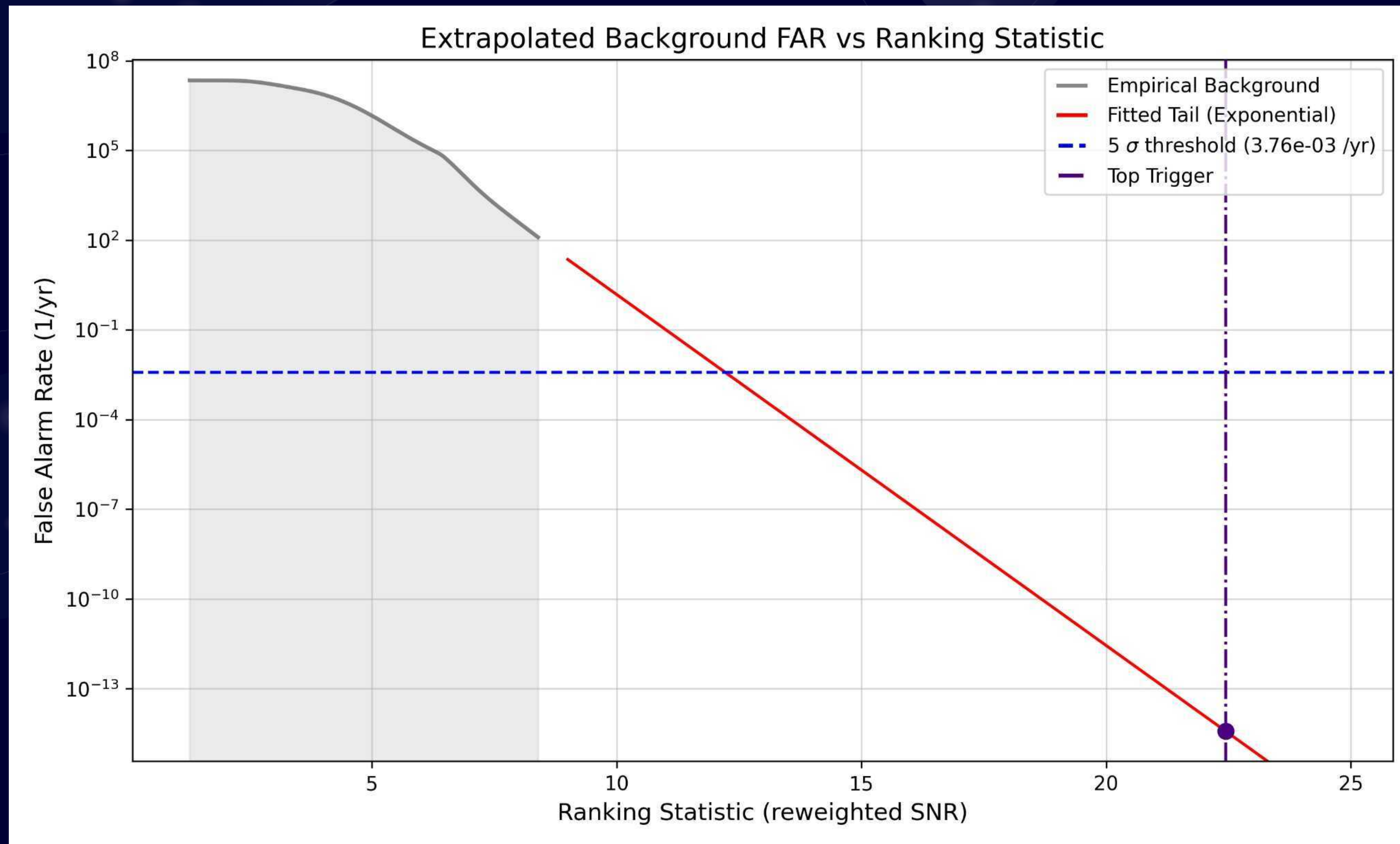
*Real data:
GW170817-
AT2017gfo*



**Preliminary analysis
configuration as a first
test**

3. Gravitational-wave targeted search

*Real data:
GW170817-
AT2017gfo*



**Background
extrapolation
reaching 5σ
significance**

Conclusion

- Best case (GW170817 dataset + 1 fake datapoint in the rising phase): t_0 estimated with an uncertainty <0.2 days
- Best case with LSST: t_0 estimated with an uncertainty of 0.44 days (LC 23)
- Worst case with LSST (no UL before): t_0 estimated with an uncertainty of $\text{several days/ 1 week}$
- Upper limit near the merger improves the results
- An intermediate configuration could be considered: detection by LSST + additional follow-up with external telescopes

Future work

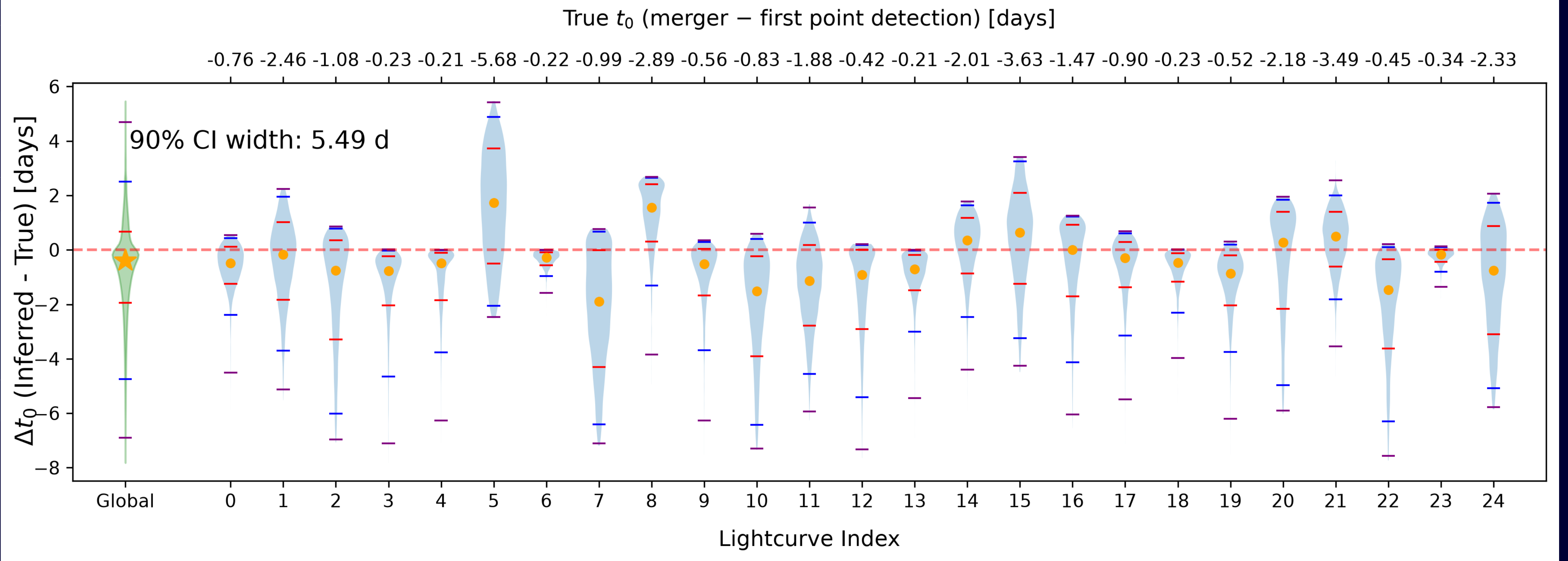
- **Kilonova side:**
 - How can we diagnostic the inference performance?
→ Need to understand which model to choose to infer T_0 during IR1!
- **GW side:**
 - Perform injections study for the GW targeted search
 - Test the speed of the computation on large time windows
 - Tests new methods for background computation

BACKUP

3. T_0 estimation

Injection study

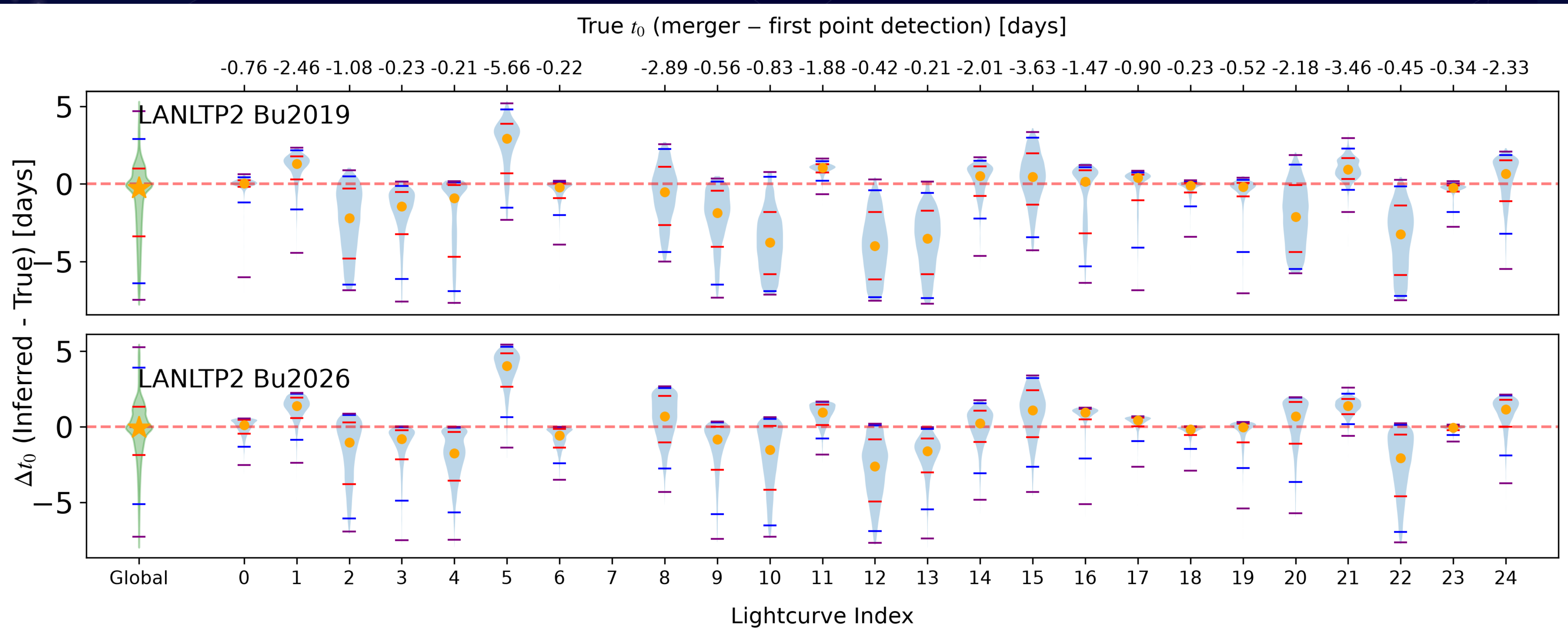
Fixed distance - LSST observing scenario



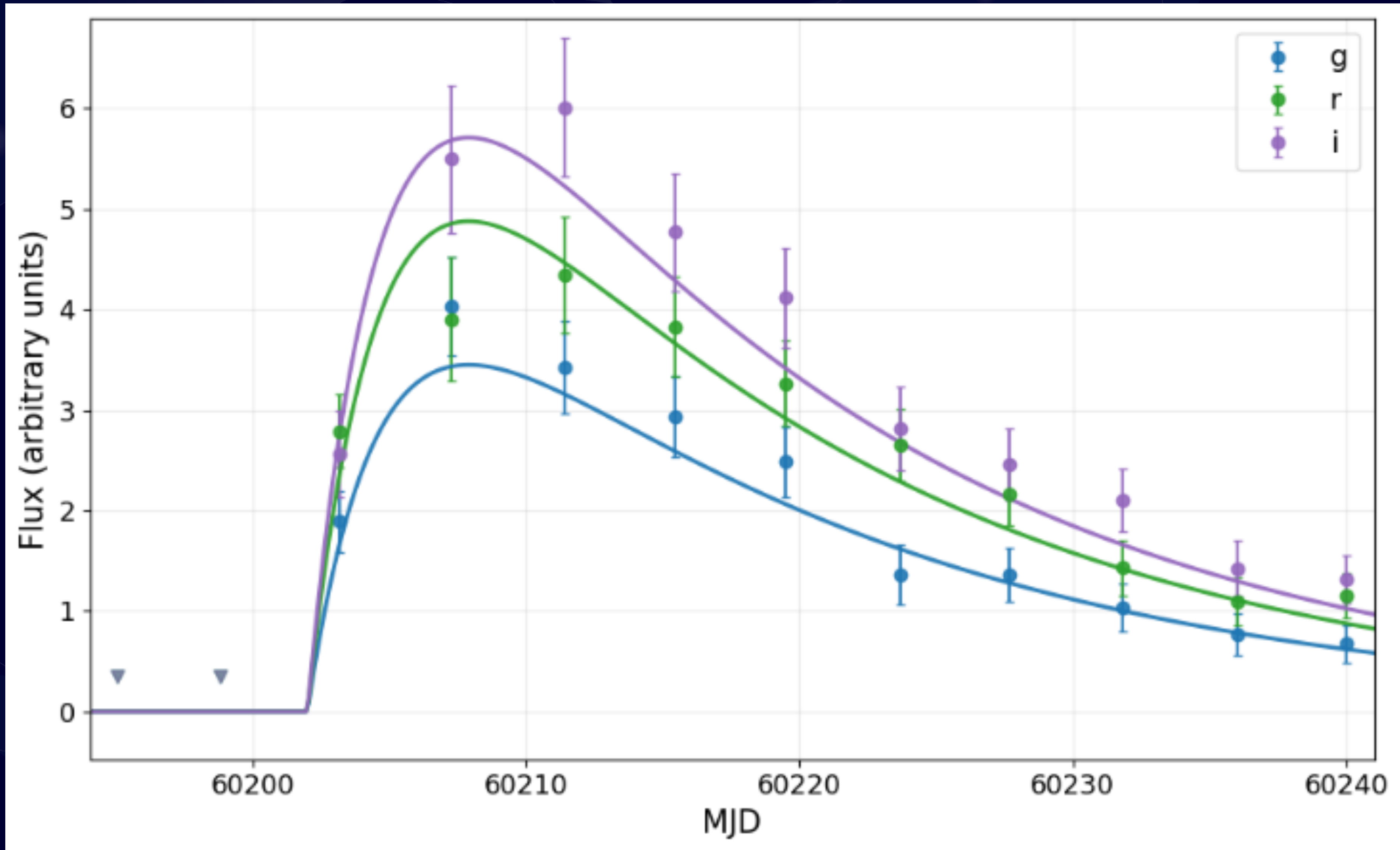
3. T_0 estimation

Injection study

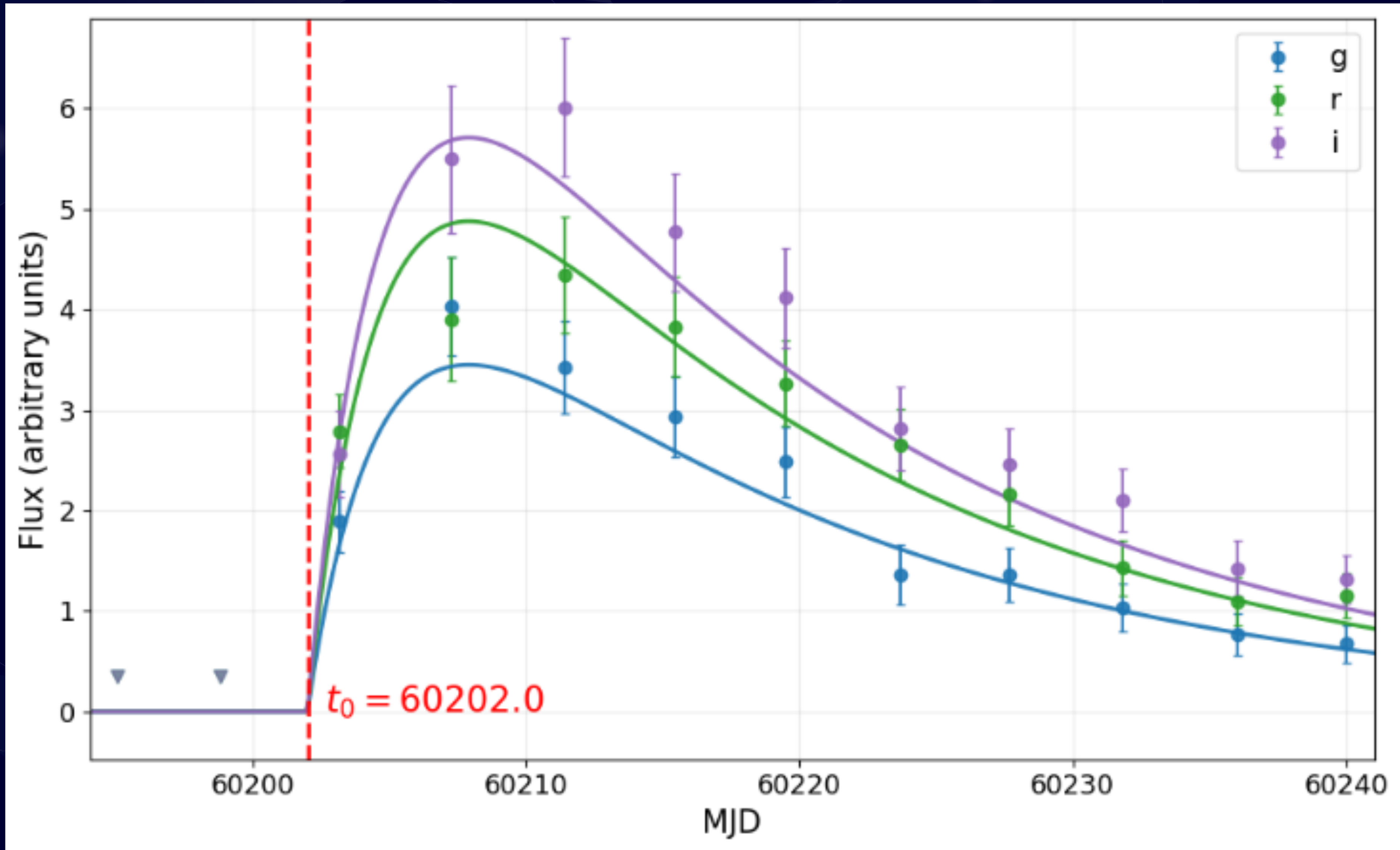
Cross model injection - recovery
LSST observing scenario
LANL KN model injection - Bulla recovery



3. T_0 estimation



3. T_0 estimation



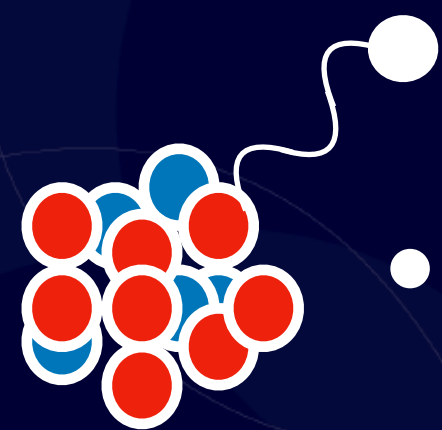
2. Kilonova models

Example Bulla model: light curves computed with POSSIS

(Bulla, 2019 & Bulla, 2026)

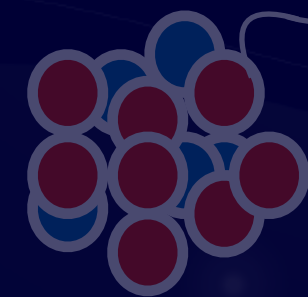
- 3D Monte Carlo code for modeling radiation transport in KN
- Does not solve the radiative transfer equation analytically but rather numerically with Monte Carlo photons representing radiation and propagating through the expanding ejecta → **speed up the computation**
- **Key ingredients:** input **energy** (from radioactive decay of r-process nuclei) and **opacity** (controlling the diffusion of Monte Carlo photons)

Creating photons



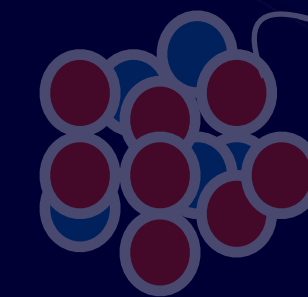
- Inputs:
 - Frequency
 - Energy

Propagating photons



- Optical depth: $\tau = \int \kappa \rho dr$
- Probability of interacting with matter: $P = 1 - e^{-\tau}$

Collecting photons



- Create observables:
 - Spectra
 - Light curves ...

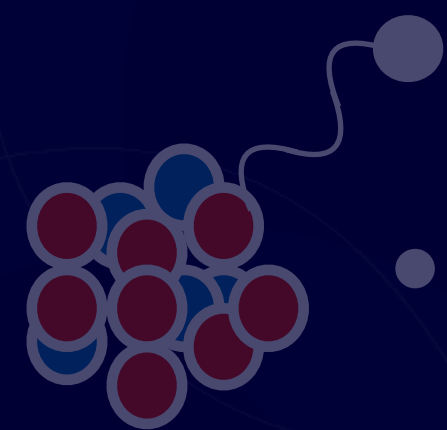
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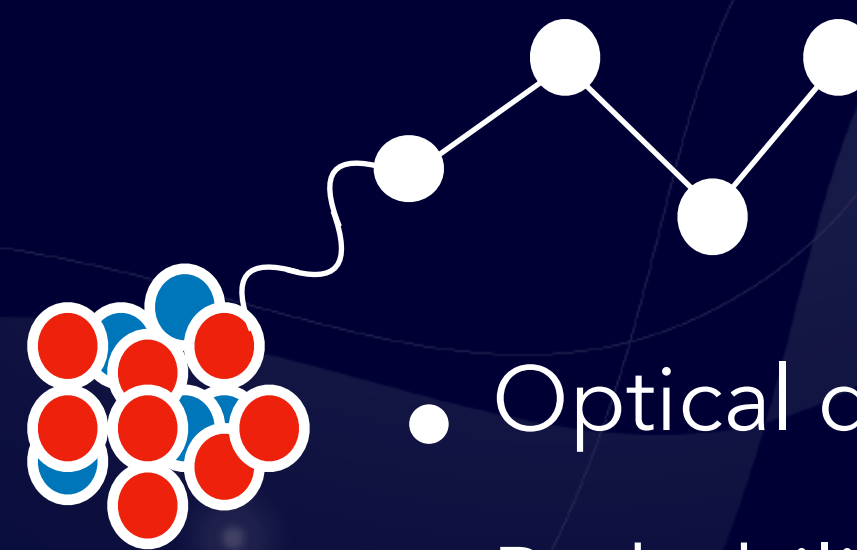
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Creating photons



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Collecting photons



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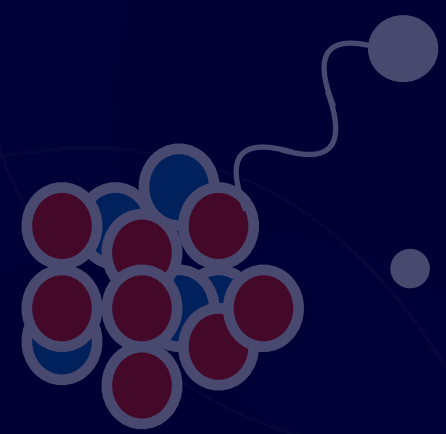
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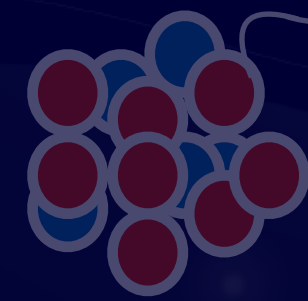
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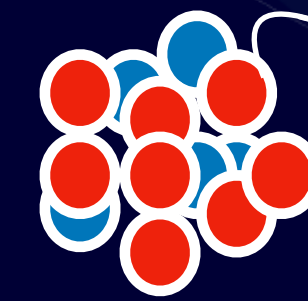
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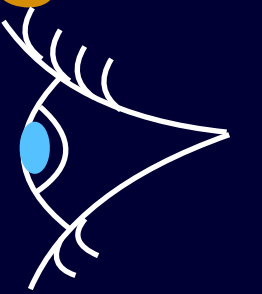


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- Probability of interacting with matter: $P = 1 - e^{-\tau}$

Collecting photons



- Create observables:
 - Spectra
 - Light curves ...



3. T_0 estimation

Focus on Bulla 2026

- Priors:

Parameter	Distribution	Range / Bounds	Use
M_1	Uniform	1, 2.25 [$M_\odot$]	Generation
M_2	Uniform	1, 2.25 [$M_\odot$]	Generation
$\log_{10} M_{\text{ej}}^{\text{dyn}}$	Uniform	-4, -1.302	Analysis
$\log_{10} M_{\text{ej}}^{\text{wind}}$	Uniform	-4, -0.56	Analysis
$v_{\text{ej}}^{\text{dyn}}$	Uniform	0.12 – 0.35 [c]	Both
$v_{\text{ej}}^{\text{wind}}$	Uniform	0.05 – 0.15 [c]	Both
Y_e^{dyn}	Uniform	0.15 – 0.35	Both
Y_e^{wind}	Uniform	0.2 – 0.4	Both
θ	Sine	0 – $\pi/2$ [rad]	Both
D_L	Uniform _{cv}	10 – 200 [Mpc]	Generation
D_L	Uniform	10 – 300 [Mpc]	Analysis
σ_{sys}	Uniform	0.3 – 2	Analysis

2. T_0 estimation

Injection study

Also investigated in the paper *but not presented here*:

- 1) fixed distance → slight improvement
- 2) cross model injection-recovery → good recovery

2. T_0 estimation

Real data: AT2017gfo

Also investigated in the paper *but not presented here*:

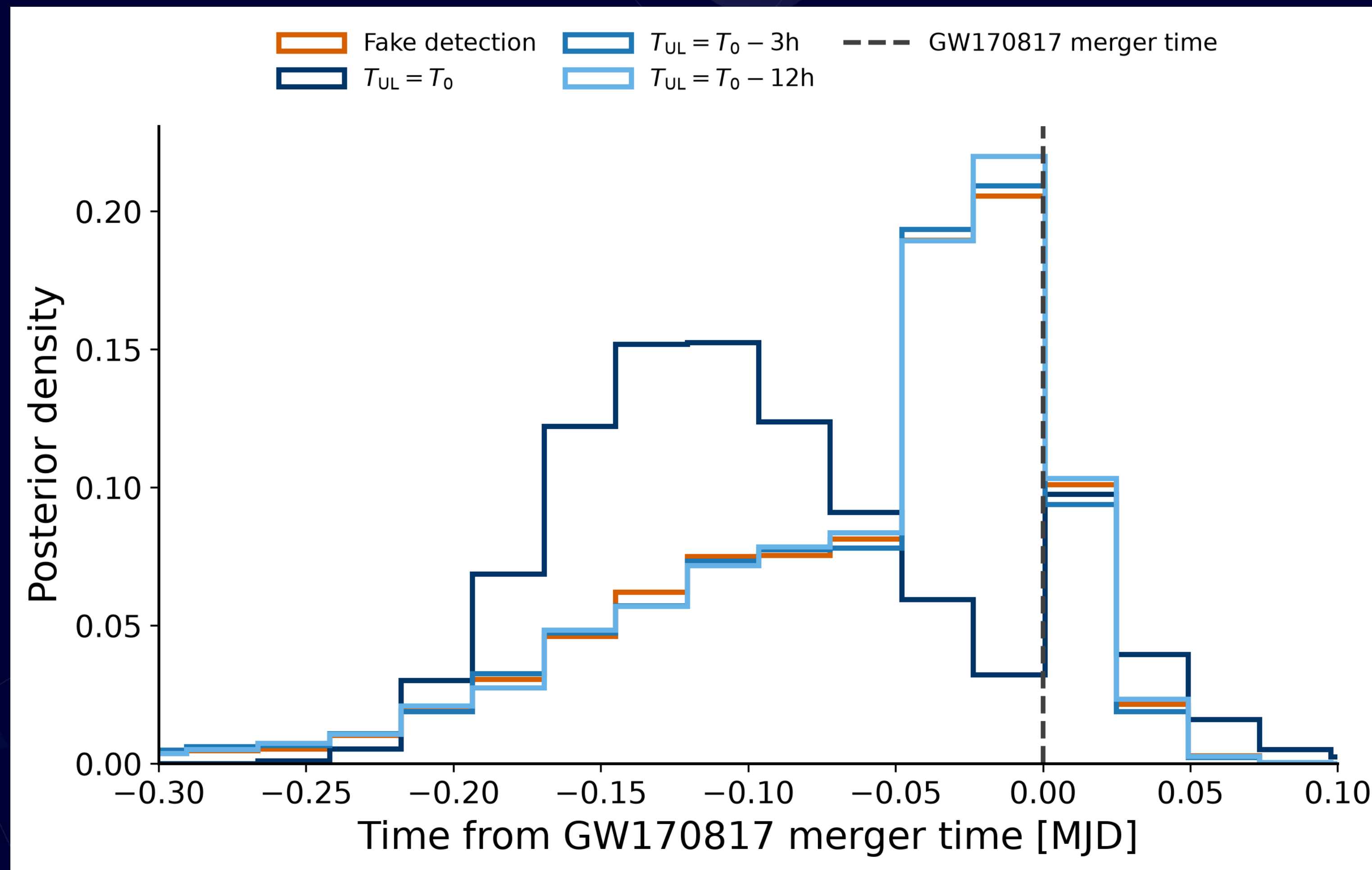
1) « What if we had a detection in AT2017gfo rising phase? »

2) « What if we had upper limit before the merger? »

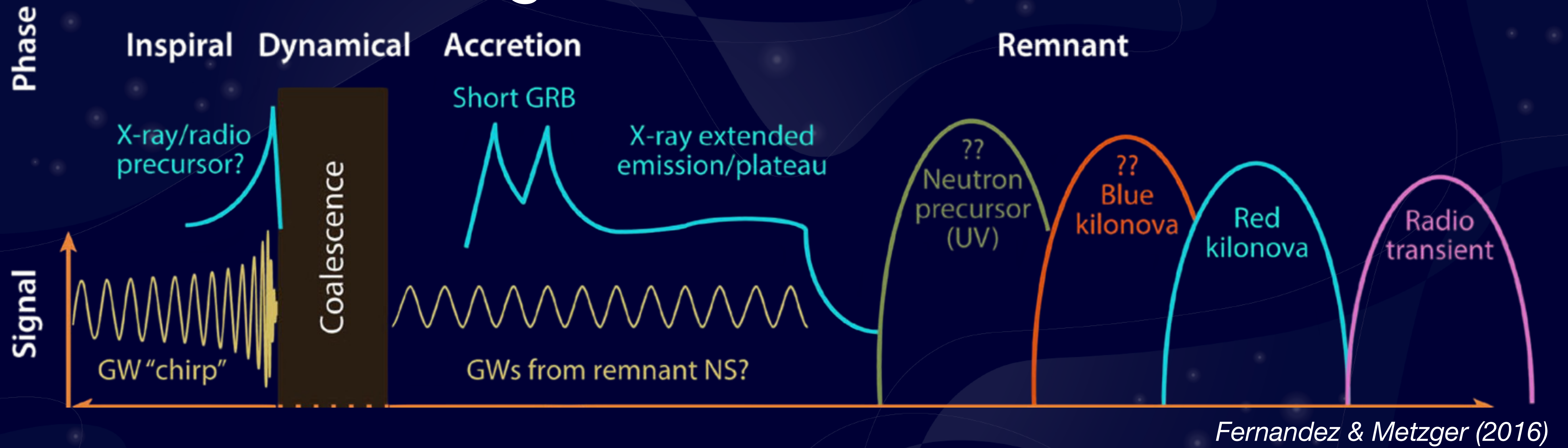
→ **best case scenario: good t_0 recovery and uncertainty of 0.03 days**

3. T_0 estimation

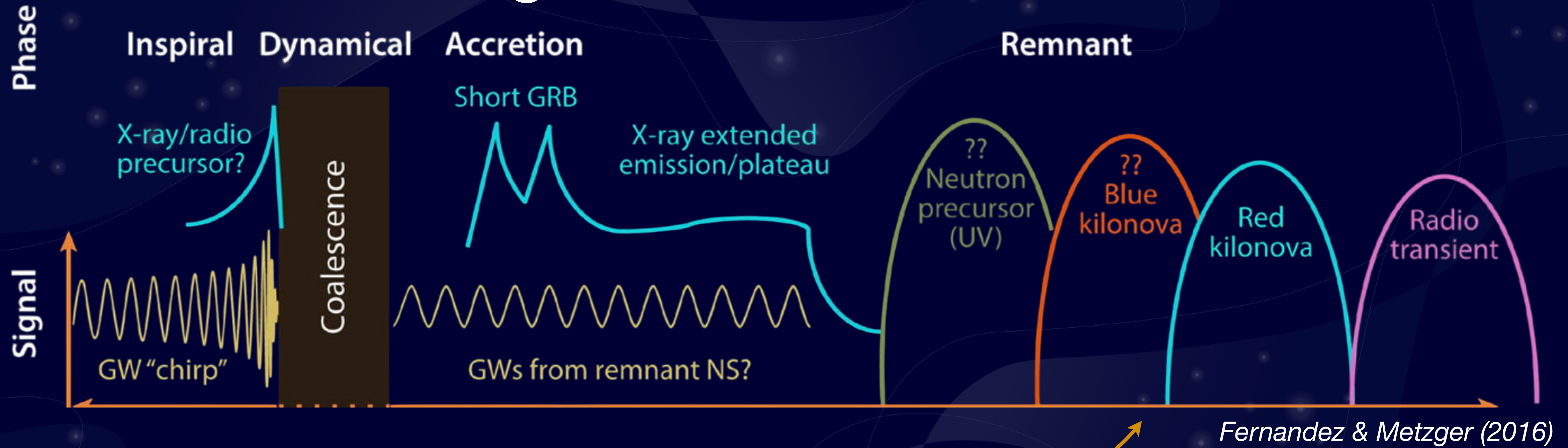
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1. Neutron star mergers



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Kilonova: Optical-NIR emission accompanying the nucleosynthesis and decay of heavy elements during the merger

