Kilonova modelling: from r-process yields in binary neutron star mergers to population studies

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The discovery of GW170817

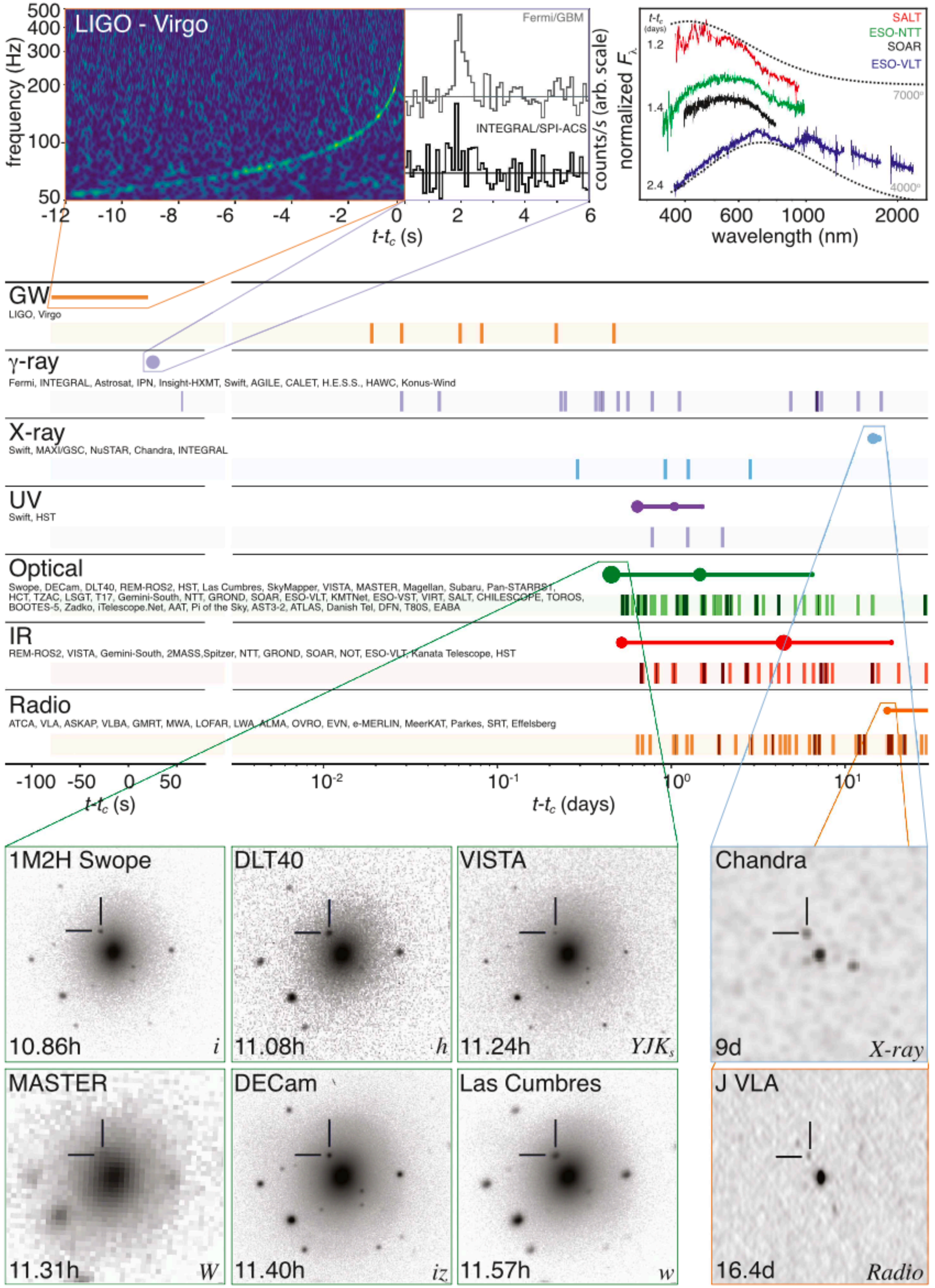
- First detection of gravitational waves (GWs) and electromagnetic radiation from a binary neutron star (BNS) merger

- Observational campaign: LIGO-Virgo (network of three interferometers) and more than 50 telescopes

- Direct evidence that BNS mergers power short gamma-ray bursts (GRBs) and kilonovae (KNe)

- Profound impact on many research areas

  [e.g. Abbott + PRL 2018; Pian + Nature 2017; Smartt + Nature 2017; Abbott + Nature 2017]

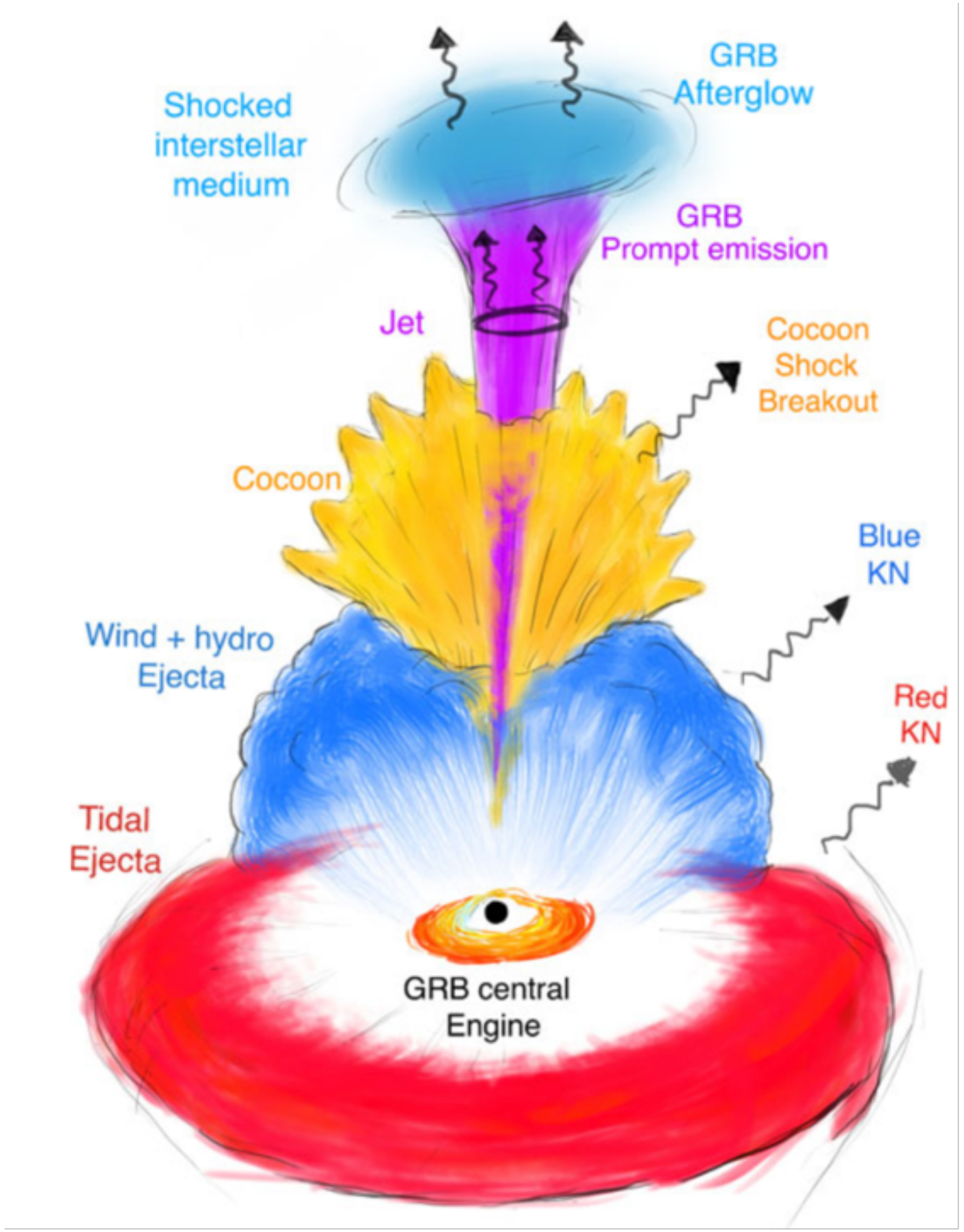


Credits: LVK collaboration, APJL, 2017

Kilonovae

- Ejection of neutron rich matter → heavy elements nucleosynthesis via rapid neutron capture (r-process)
- Thermal EM emission powered by nuclear decay of freshly synthesised heavy elements
- Dynamical ejecta / wind / secular ejecta
- Merger microphysics (Equation of State of nuclear matter and weak interactions) → ejecta and remnant properties → KN signal

[e.g. Metzger + LRR 2019]

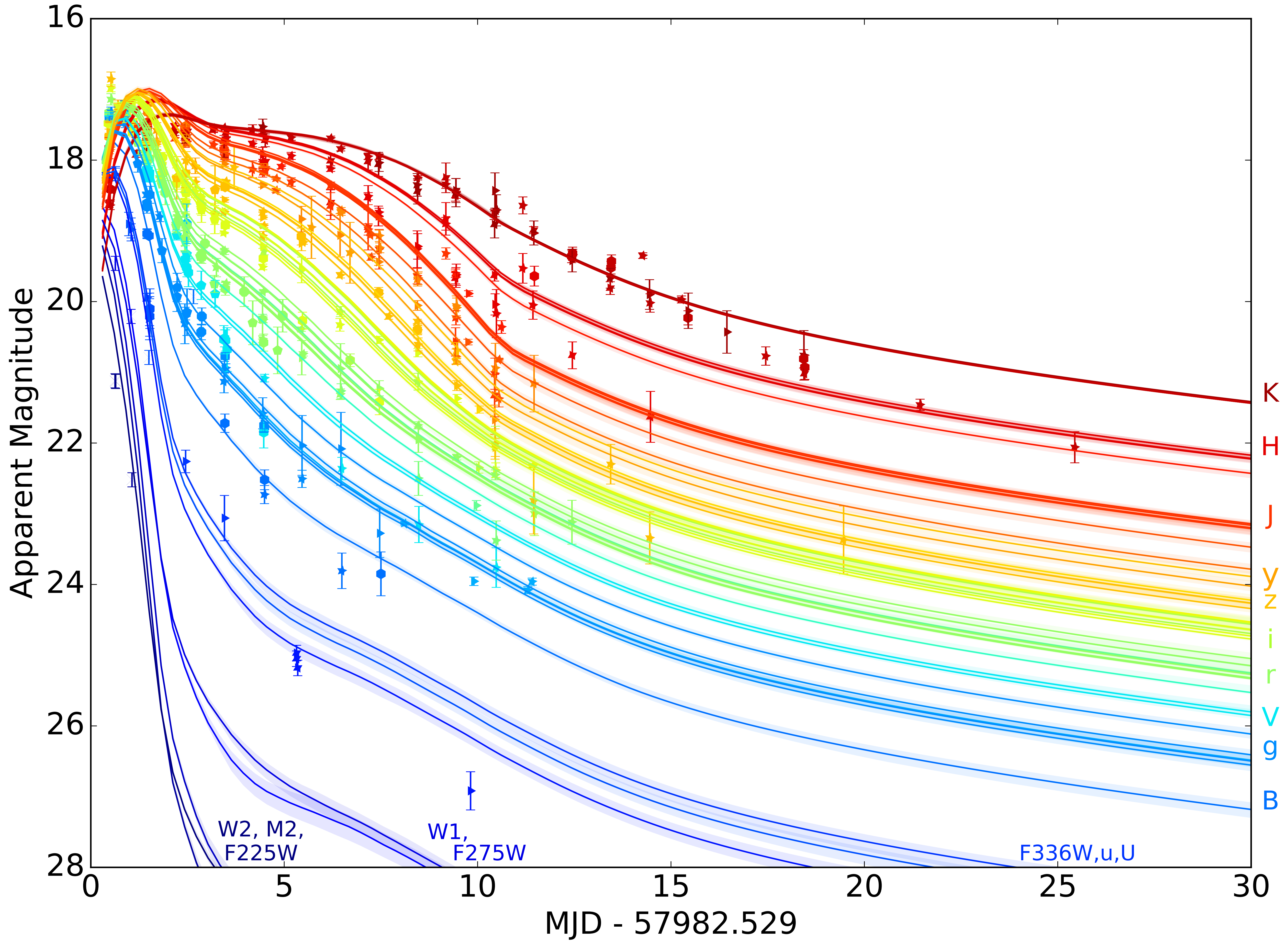


Credits: Stefano Ascenzi

The detection of AT2017gfo

- AT2017gfo → KN associated with GW170817
- UV/optical/NIR signal, faint and rapidly evolving (1 week), distinct colour evolution
- Theoretical predictions long before AT2017gfo

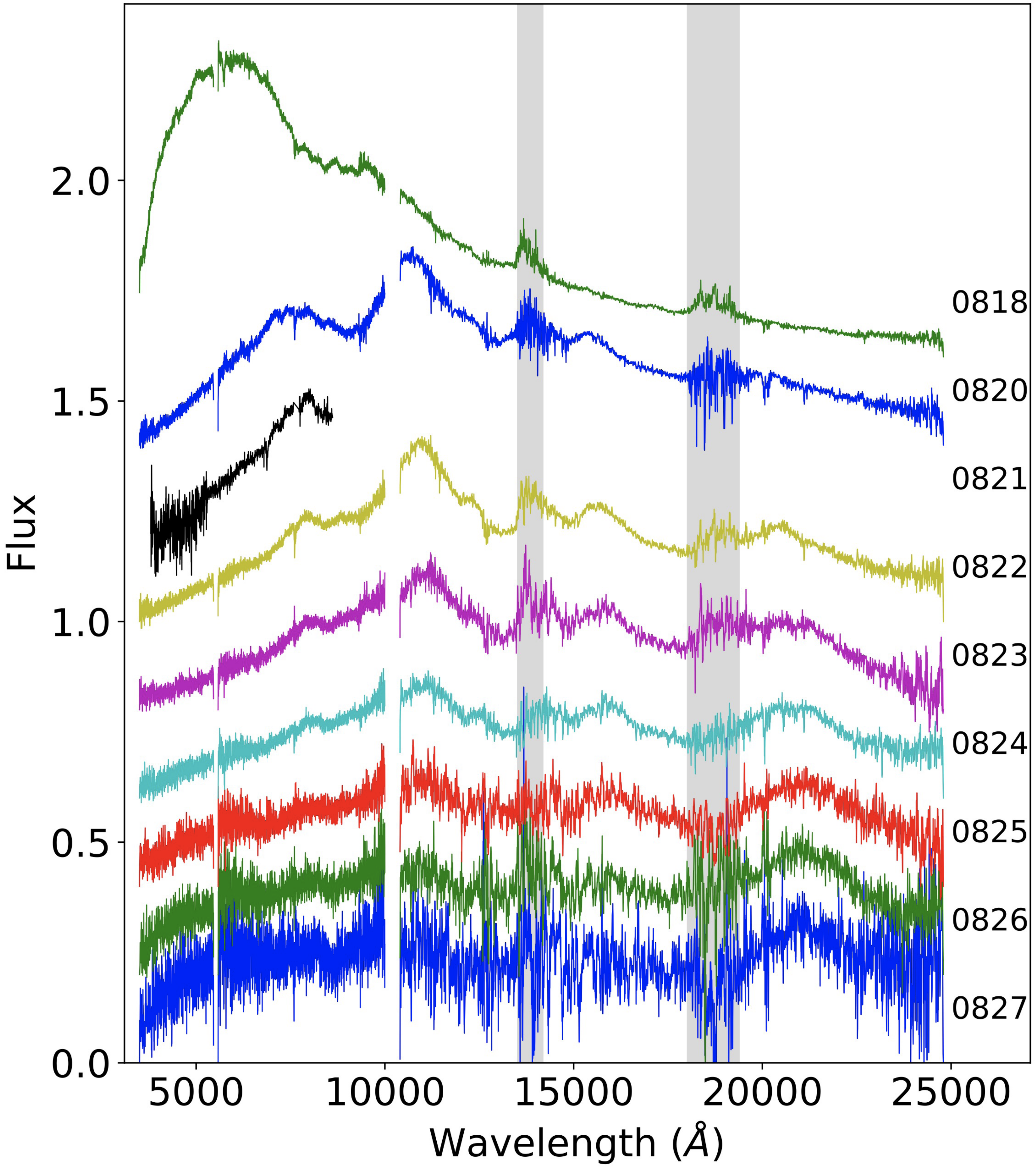
[Li & Paczyński 1998; Kulkarni 2005; Metzger + 2010; Kasen + 2013; Barnes & Kasen 2013; Grossman + 2014]



Credits: Villar et al., APJL, 2017

The detection of AT2017gfo

- Precise sky-localisation $\simeq 28\ \text{deg}^2 \rightarrow$ effective and prompt follow up with optical/ NIR telescopes
- Small lum. distance $\simeq 40$ Mpc $\rightarrow$ galaxy targeting strategy and candidate identification
- Deep multi-wavelength photometry and spectroscopy $\rightarrow$characterisation of KN candidate
- Theoretical predictions on colour evolution, timescale, luminosity $\rightarrow$ crucial to recognise KN signature

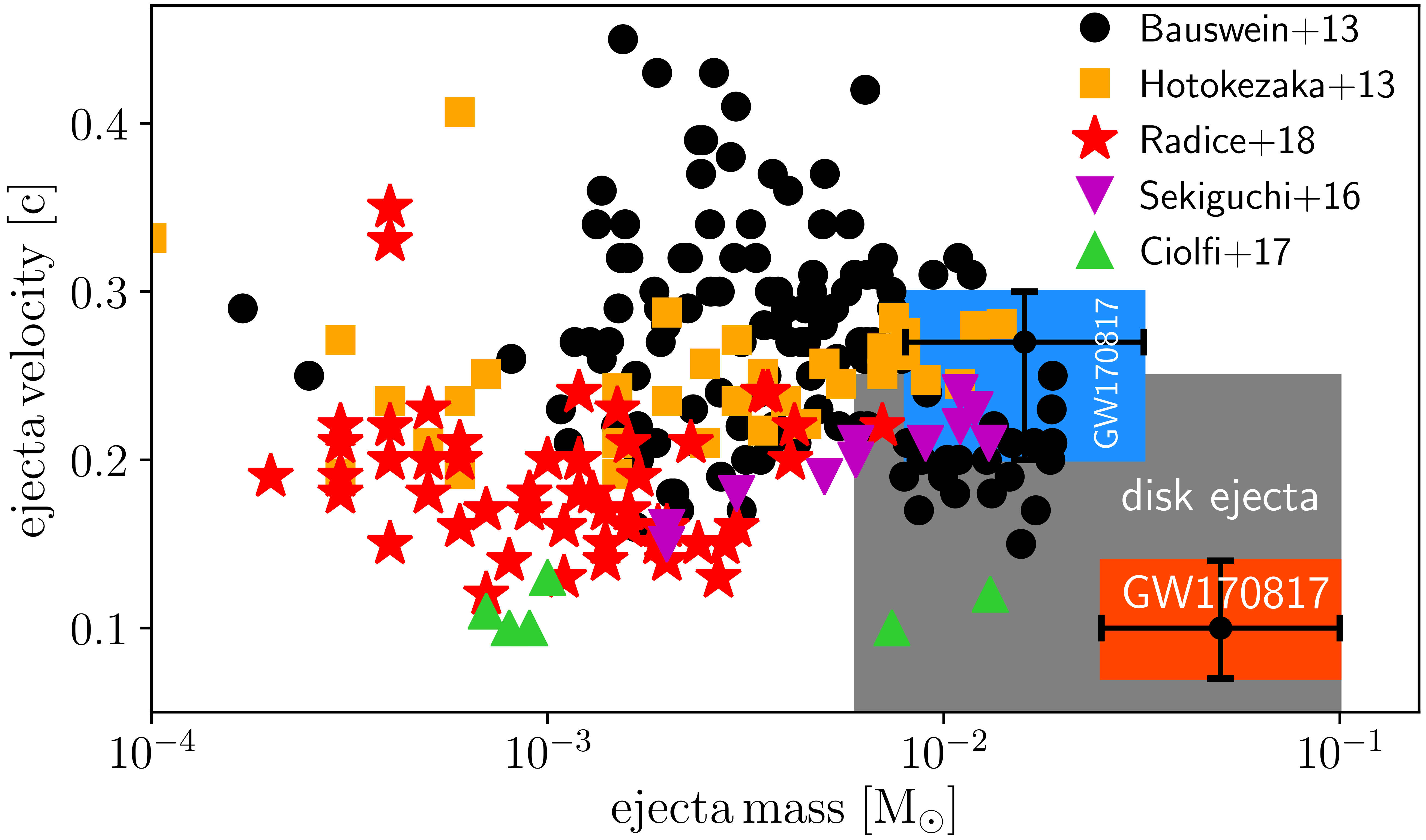


Credits: Pian et al., Nature, 2017

AT2017gfo: challenges for the interpretation

- Still many open questions on ejecta properties, heavy-elements nucleosynthesis, spectral features

- KN signal features strongly depend on merger microphysics and heavy-elements nucleosynthesis → **need to advance our understanding of microphysics**



Credits: Siegel, EPJA, 2019

More challenges: GW190425

- Second GW signal from inspiral of a BNS merger
- Poor sky-localisation
- No EM counterpart identified
- High total and chirp mass
- Origin? Remnant? EM emission?

	GW170817	**GW190425**
Primary mass M_1	1.36 - 1.60 $M_\odot$	1.60 - 1.87 $M_\odot$
Secondary mass M_2	1.16 - 1.36 $M_\odot$	1.46 - 1.69 $M_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $M_\odot$	$1.44^{+0.02}_{-0.02}$ $M_\odot$
Mass ratio q	0.73 - 1.00	0.8 - 1.0
Total mass $M_{\rm tot}$	$2.73^{+0.04}_{-0.01}$ $M_\odot$	$3.3^{+0.1}_{-0.1}$ $M_\odot$
Luminosity distance D_L	39^{+7}_{-14} Mpc	159^{+69}_{-72} Mpc
Inclination angle $\theta_{\rm JN}$	151^{+15}_{-11} deg	-
Tidal deformability $\Lambda_{1.4}$	190^{+390}_{-120}	-
Combined tidal deformability $\tilde{\Lambda}$	300^{+500}_{-190}	≤ 600

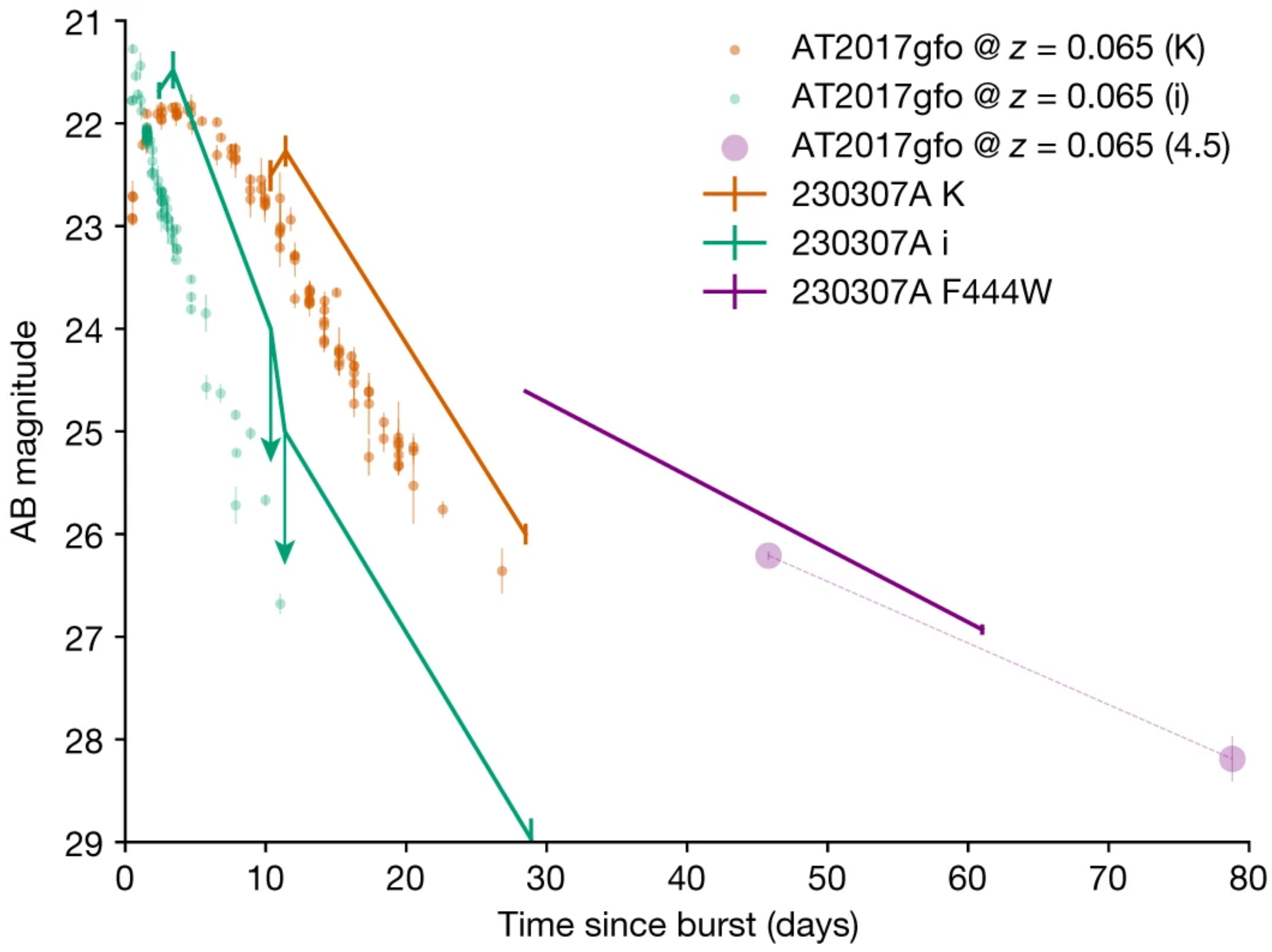
More challenges: KNe and GRBs

- Expected from theory: association between KNe and short GRBs

- A few observational evidences
  [e.g. Gompertz et al. 2018, Rossi et al. 2020]

- Evidence before AT2017gfo: GRB 130603B
  [Berger, Fong & Chornock 2013b; Tanvir et al. 2013]

- However, recently indications of KN emission in long-duration GRBs: GRB 211211A and GRB 230307A
  [Rastinejad et al. 2022; Troja et al. 2022; Mei et al. 2022; Levan et al. 2023]



Credits: Levan et al., Nature, 2023

Prospects for GW/KN joint detections

- Next runs of LVKI → expected detection of a few BNS mergers
  [Abbott + 2020, 2023; Colombo + 2022]

- Einstein Telescope (ET) and Cosmic Explorer (CE) → 10^5 BNS mergers per year up to $z \simeq 5 - 10$, large number of events with much better parameter estimation
  [Maggiore + 2020; Evans + 2021; Branchesi + 2023]

- Next-generation optical and NIR telescopes as Vera Rubin, ELT and WST → enhance chances of KN detection and characterisation

Prospects for GW/KN joint detections

- Current and next runs of LVKI → expected detection of a few up to several tens of BNS mergers
  [Abbott + 2020, 2023; Colombo + 2022]

- Einstein Telescope (ET) and Cosmic Explorer (CE) → 10^5 BNS mergers per year up to $z \simeq 5 - 10$, large number of events with much better parameter estimation
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Access science prospects through number of joint detections and their properties

Define effective follow up strategies and optimal instrument designs

This talk

BNS nucleosynthesis

Investigate impact of neutrino winds on BNS merger nucleosynthesis
&
Produce public available database of r-process yields

1

Loffredo et al. in prep.

BNS population properties

Evaluating prospects for GW/KN detections by next-generation observatories considering present uncertainties in BNS merger rate, NS mass distribution and EOS

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Loffredo et al. A&A 2025

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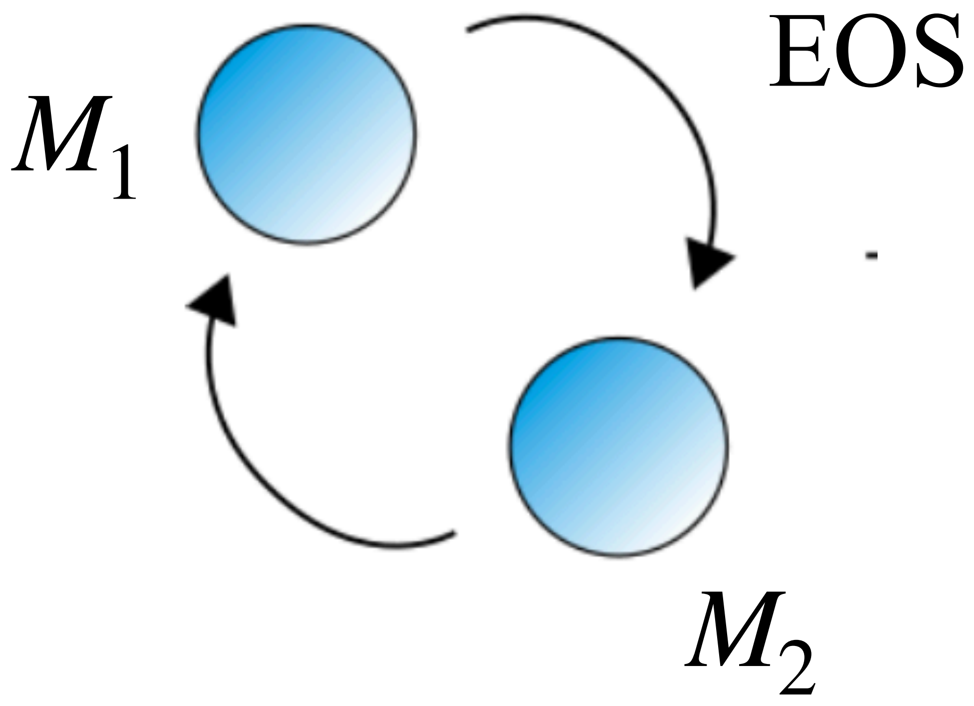
Tracing r-process nucleosynthesis in BNS mergers

1

Sample of BNS mergers with different initial conditions (masses, mass ratios, Equation of State)



Tracing r-process nucleosynthesis in BNS mergers

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Sample of BNS mergers with different initial conditions (masses, mass ratios, Equation of State)

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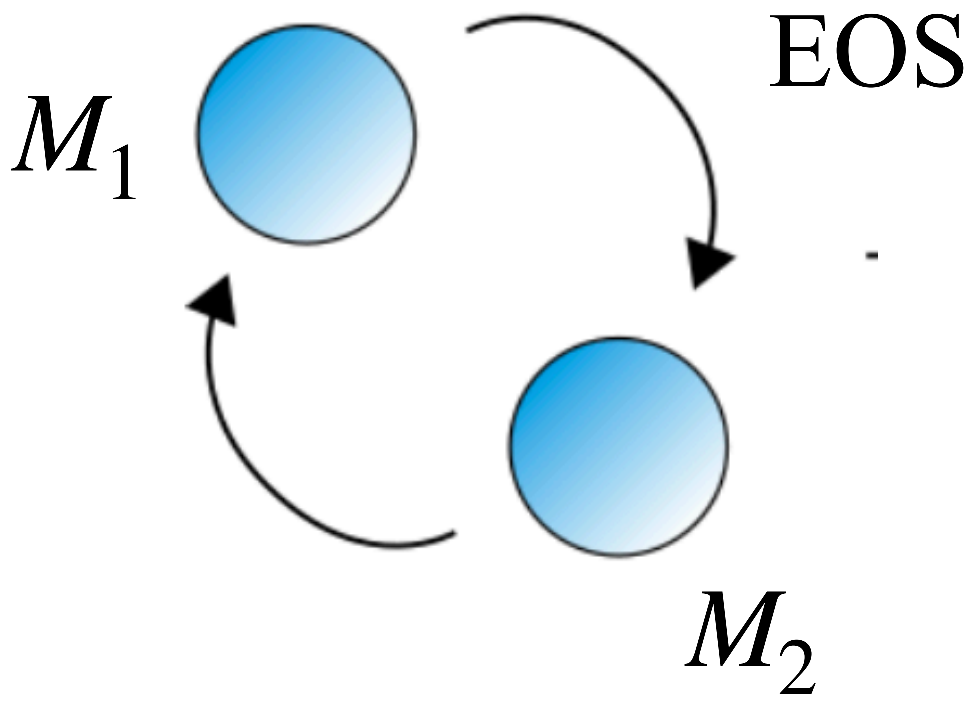
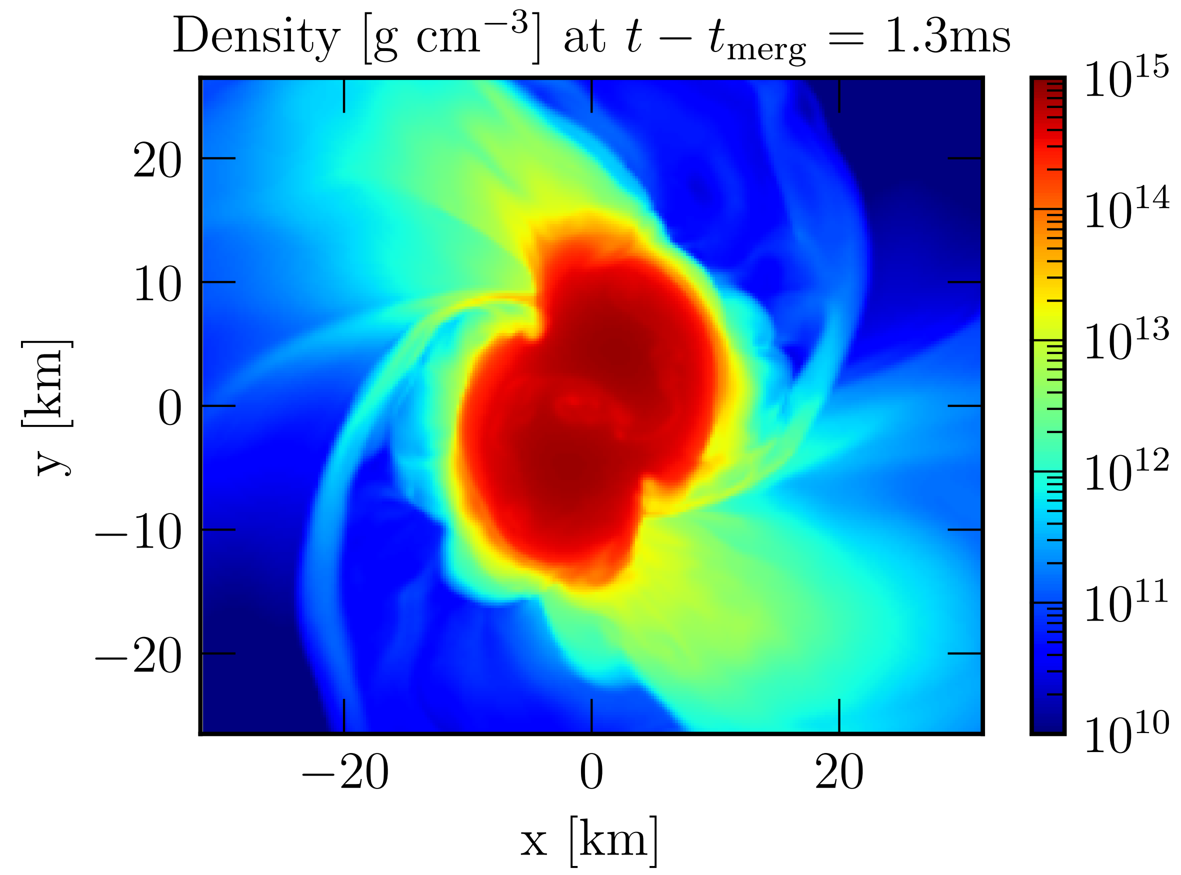
2

Numerical relativity simulations of the merger → flux of ejected matter and tracer particles





Tracing r-process nucleosynthesis in BNS mergers

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Sample of BNS mergers with different initial conditions (masses, mass ratios, Equation of State)

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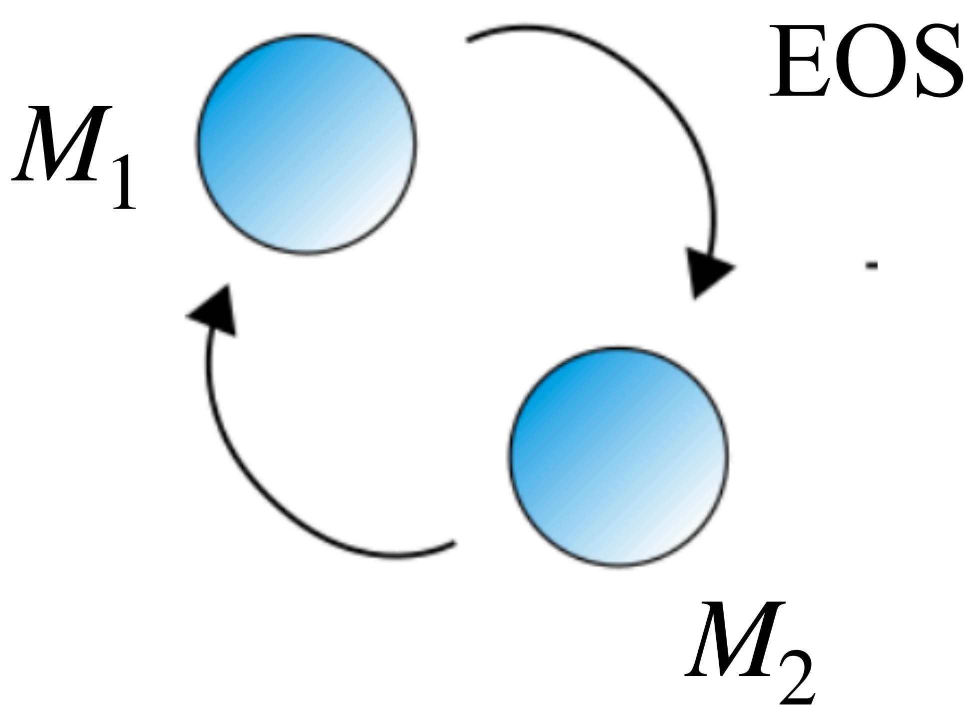
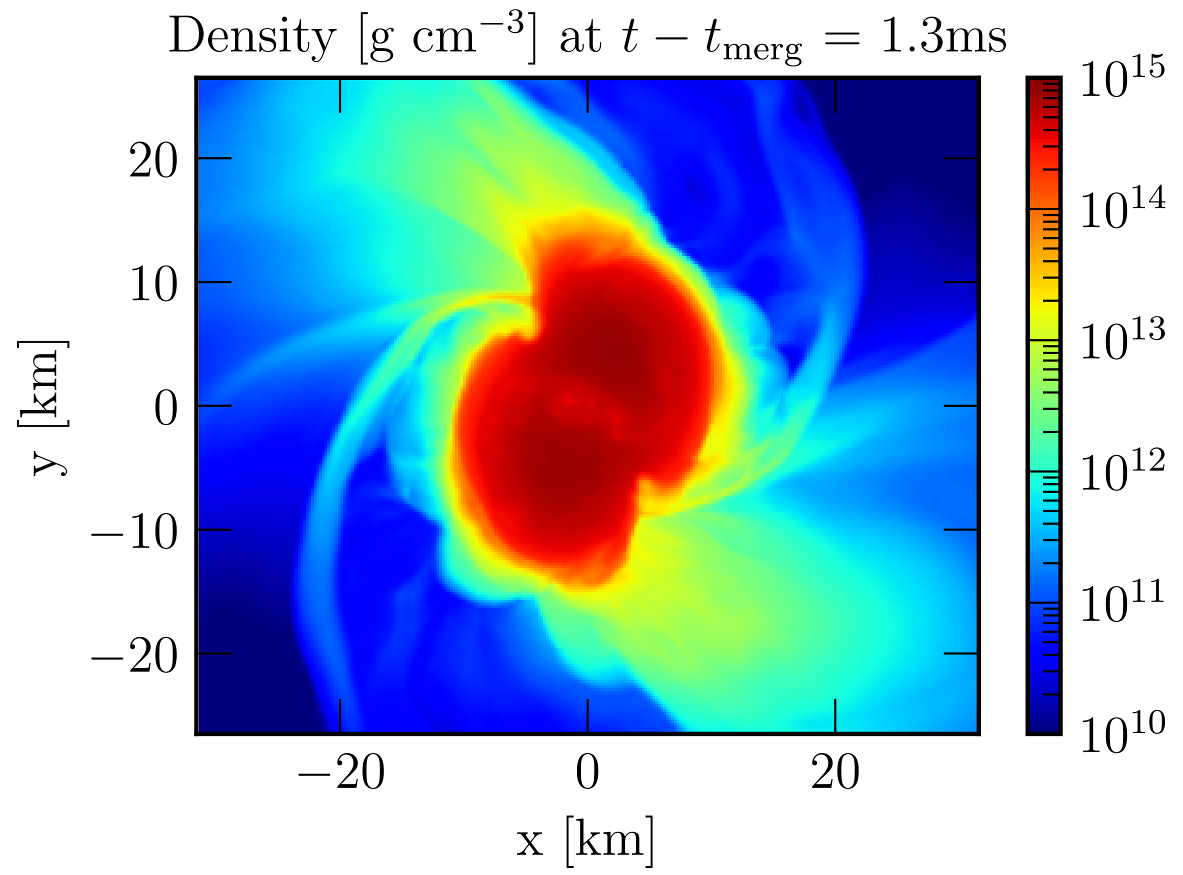
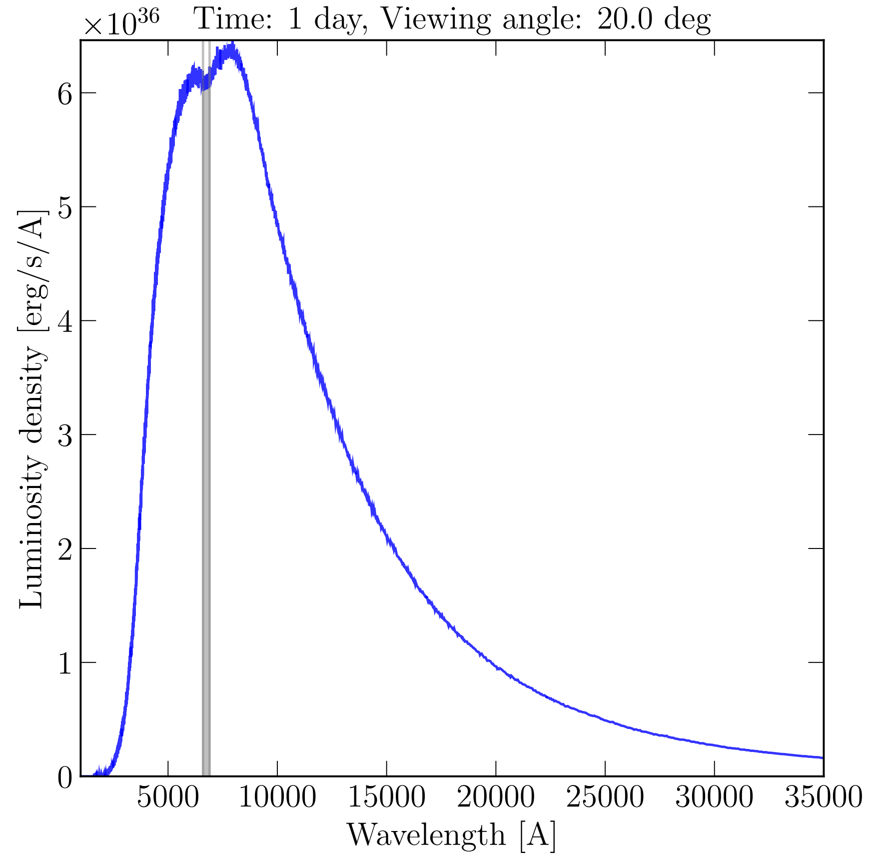
→

3

Compute the nucleosynthesis → get nuclear yields for each merger







Numerical relativity simulations of BNS mergers

Why?

- Predict the merger outcome (GW signal, collapse time, ejected matter, …)
- Interpret observations and constrain the nuclear EOS

How?

- GR Equations + relativistic hydrodynamics
- Microphysics → nuclear Equation of State (EOS), weak reactions with neutrinos, …
- Magnetic fields

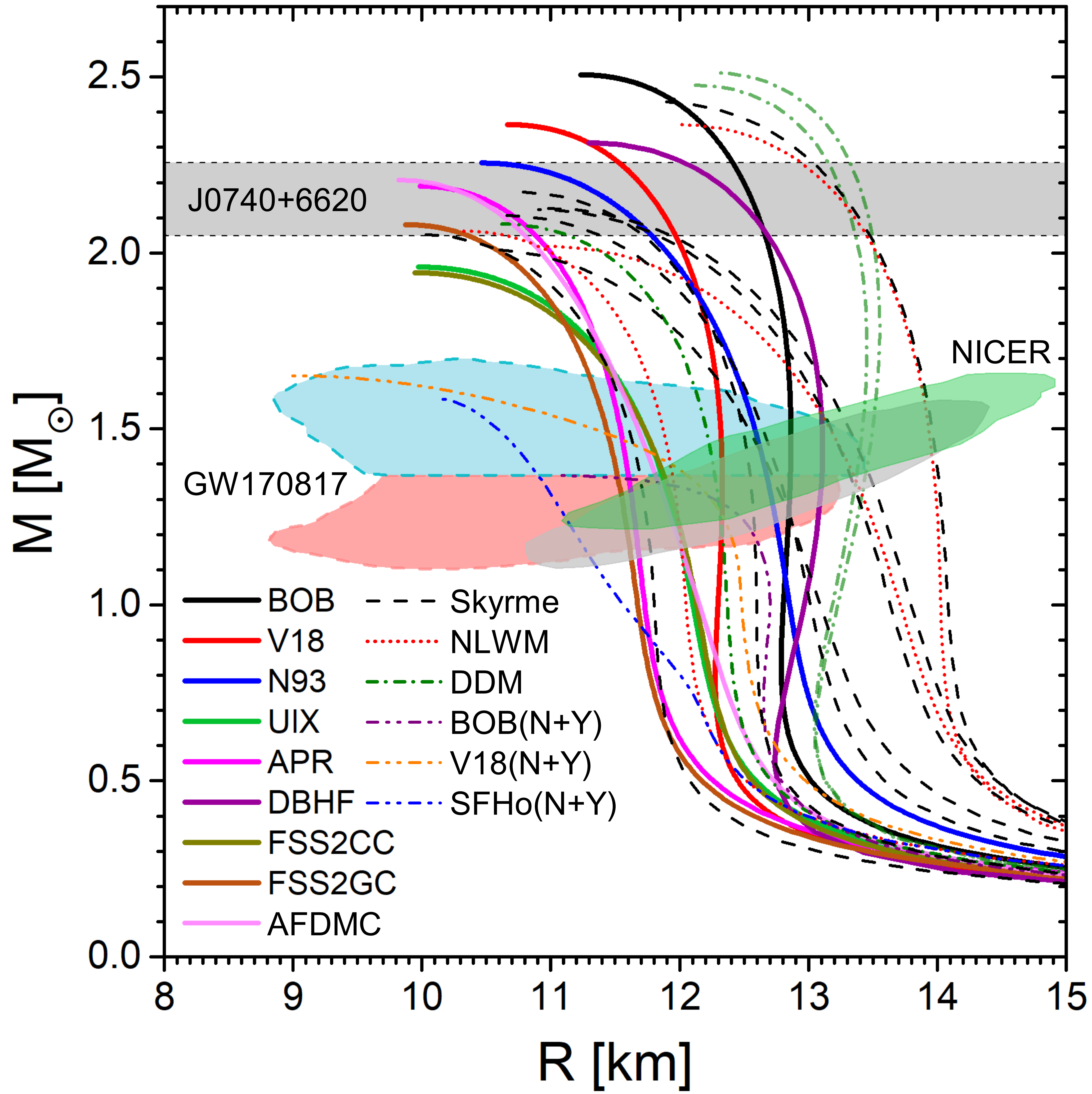
The equation of state of nuclear matter

- Equation of state (EOS): relation between state variable (e.g. matter density, temperature) and other thermodynamic variables (e.g. pressure)

- The nuclear EOS is uncertain

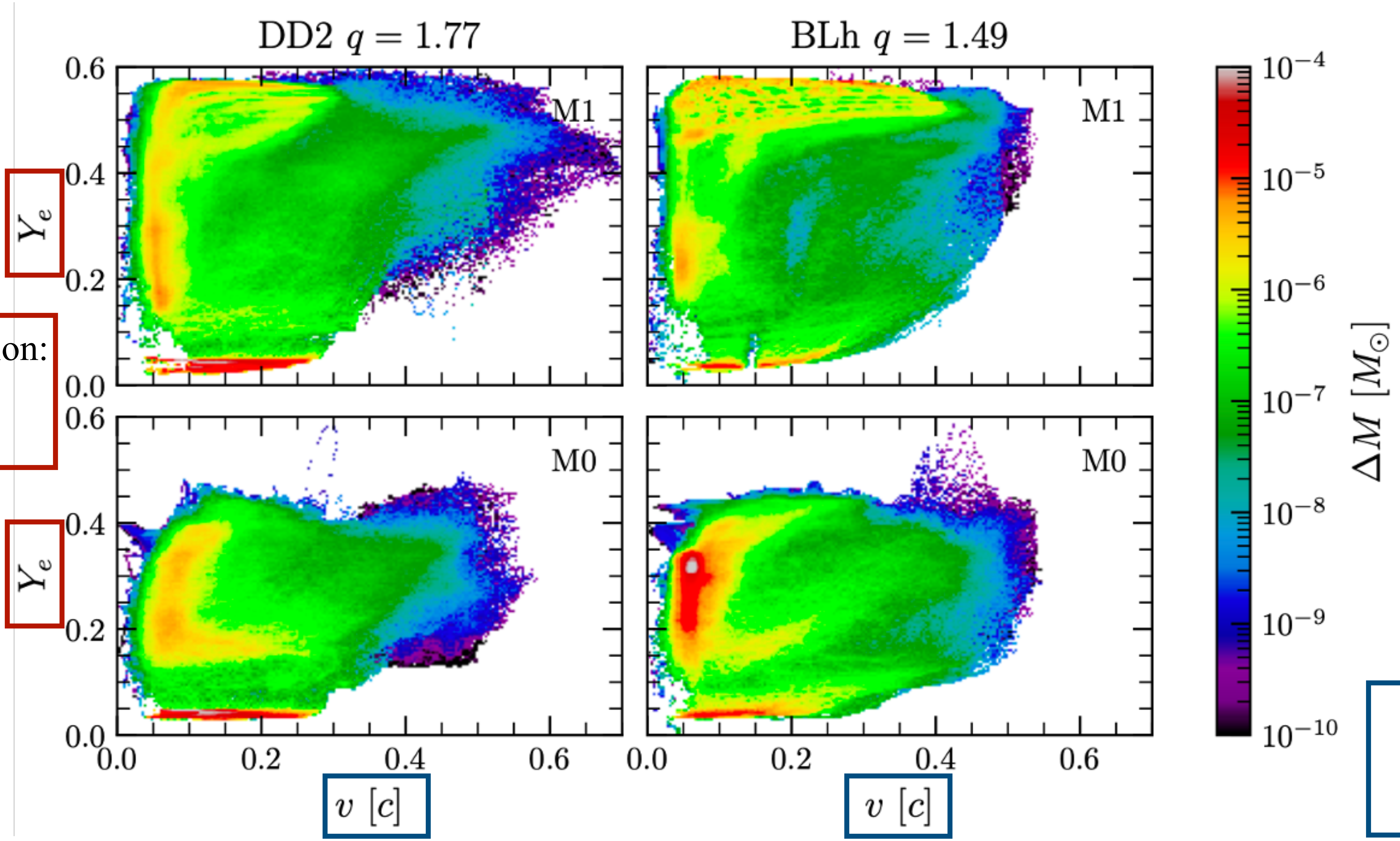
- Modelling of nuclear interaction and relevant degrees of freedom: neutrons, protons, pions, quarks, muons, …

- The relevant degrees of freedom depend on the temperature other than the density



Credits: Burgio et al., PPNP, 2021

Impact of the EOS and neutrino treatment on the ejecta



Electron fraction:

$$Y_e = \frac{n_e}{n_b}$$

Velocity of ejected matter

Credits: Bernuzzi et al., 2024

E.g. Foucart+16,20; Radice+22; Kiuchi+23; Just+23; Ricigliano+24; Bernuzzi+24; Sneppen+24; Jacobi+25

Impact of the EOS and neutrino treatment on the ejecta

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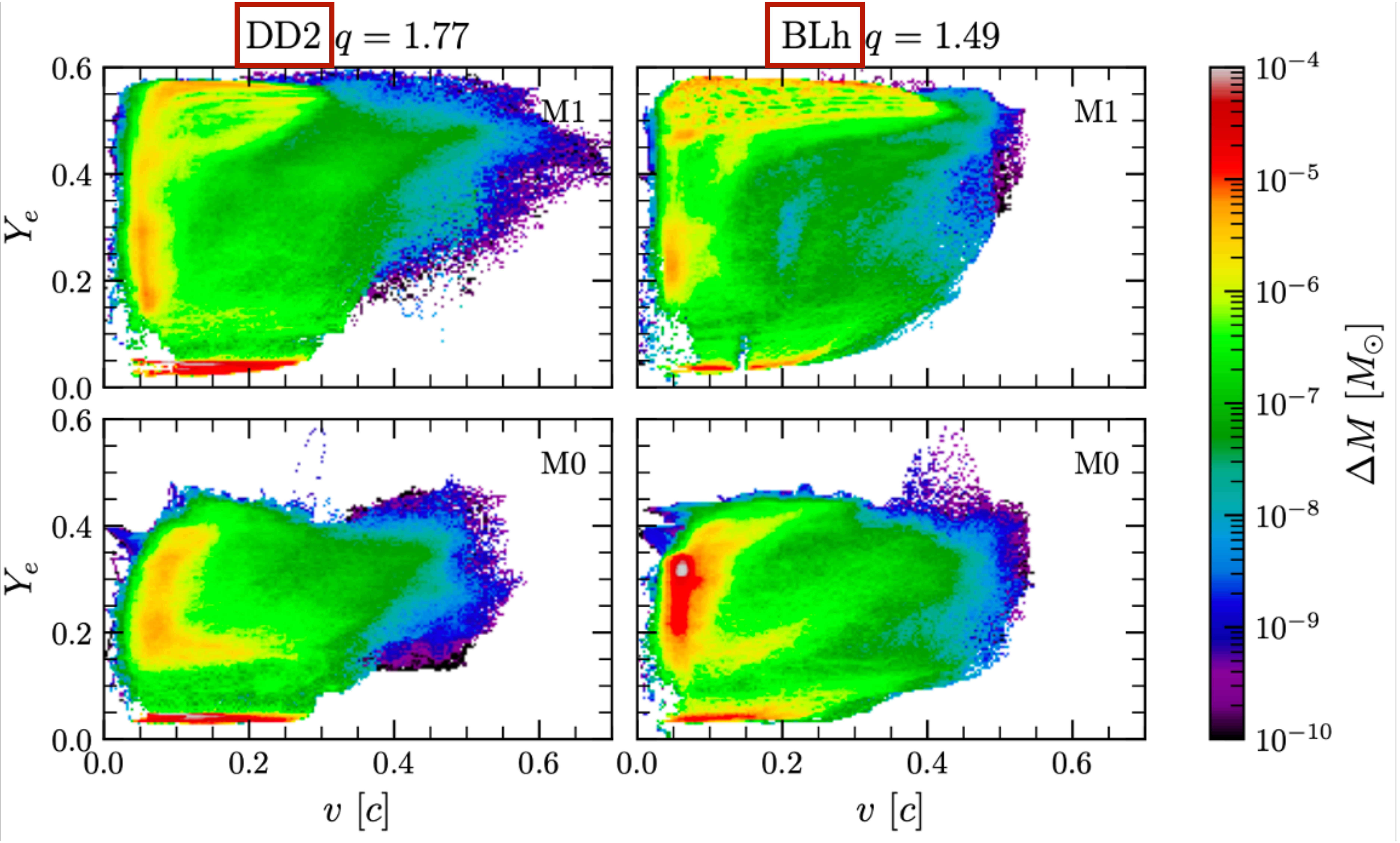

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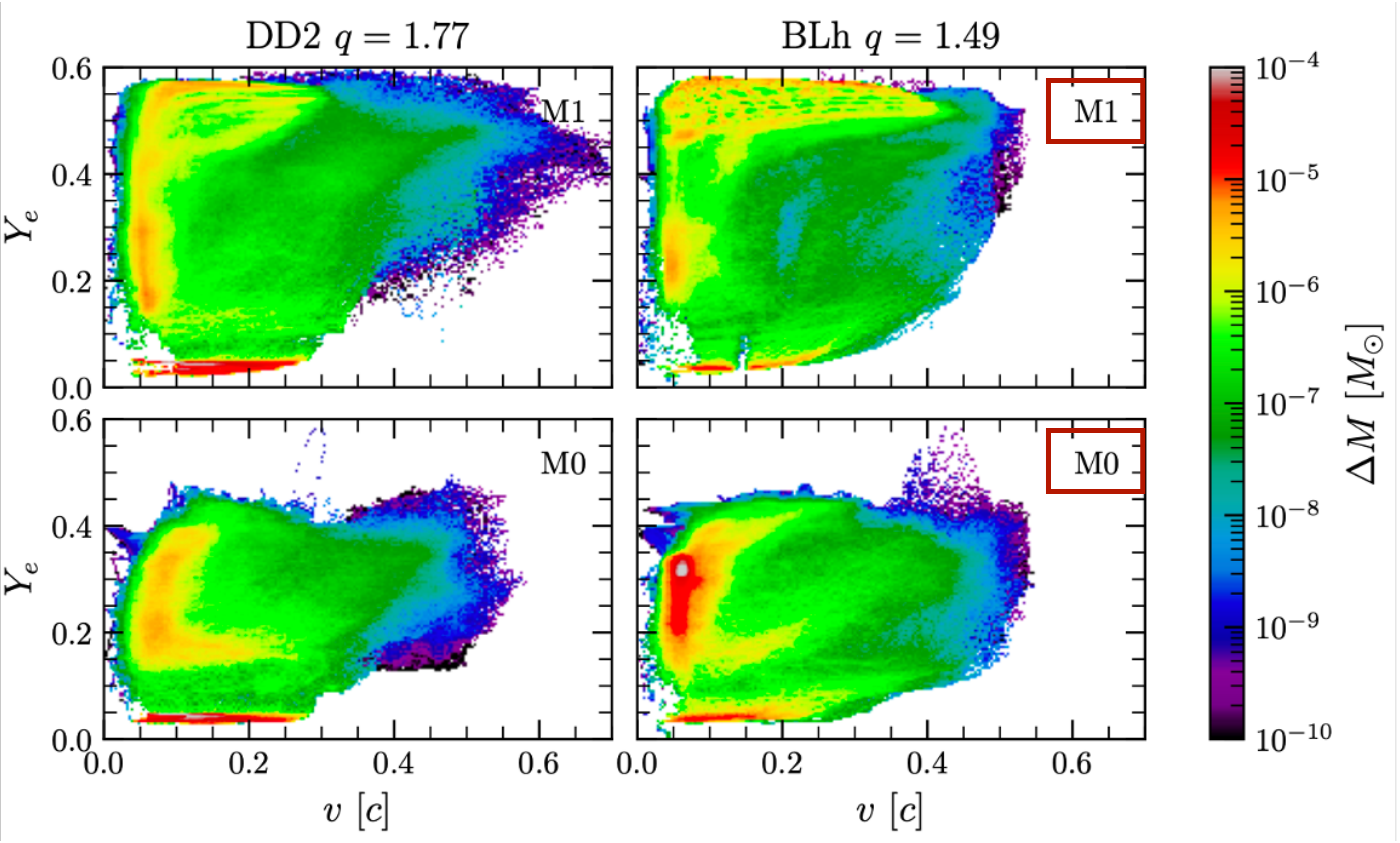

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Tracing r-process nucleosynthesis in BNS mergers

Aims

- Investigate impact of neutrino winds on the nucleosynthesis
- Produce publicly available database of r-process yields varying BNS mass ratio and EOS

Method

- Set of 10 BNS merger simulations with different masses, EOSs and mass ratios
- Neutrino treatment: **M1 gray scheme** [Radice+22]
- Extract **tracer** particles for ejecta
- Compute nucleosynthesis with WinNet [Reichert+23]

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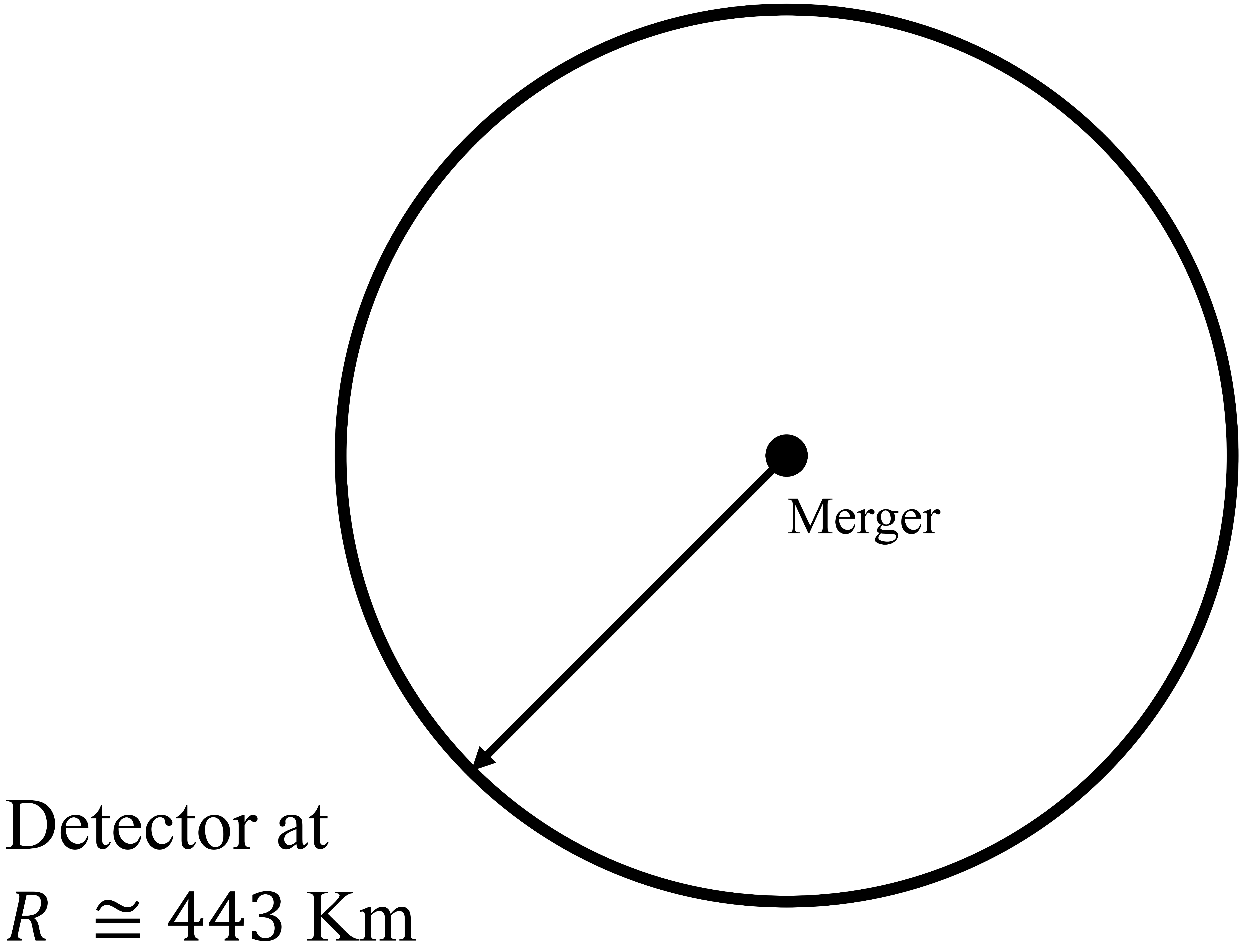
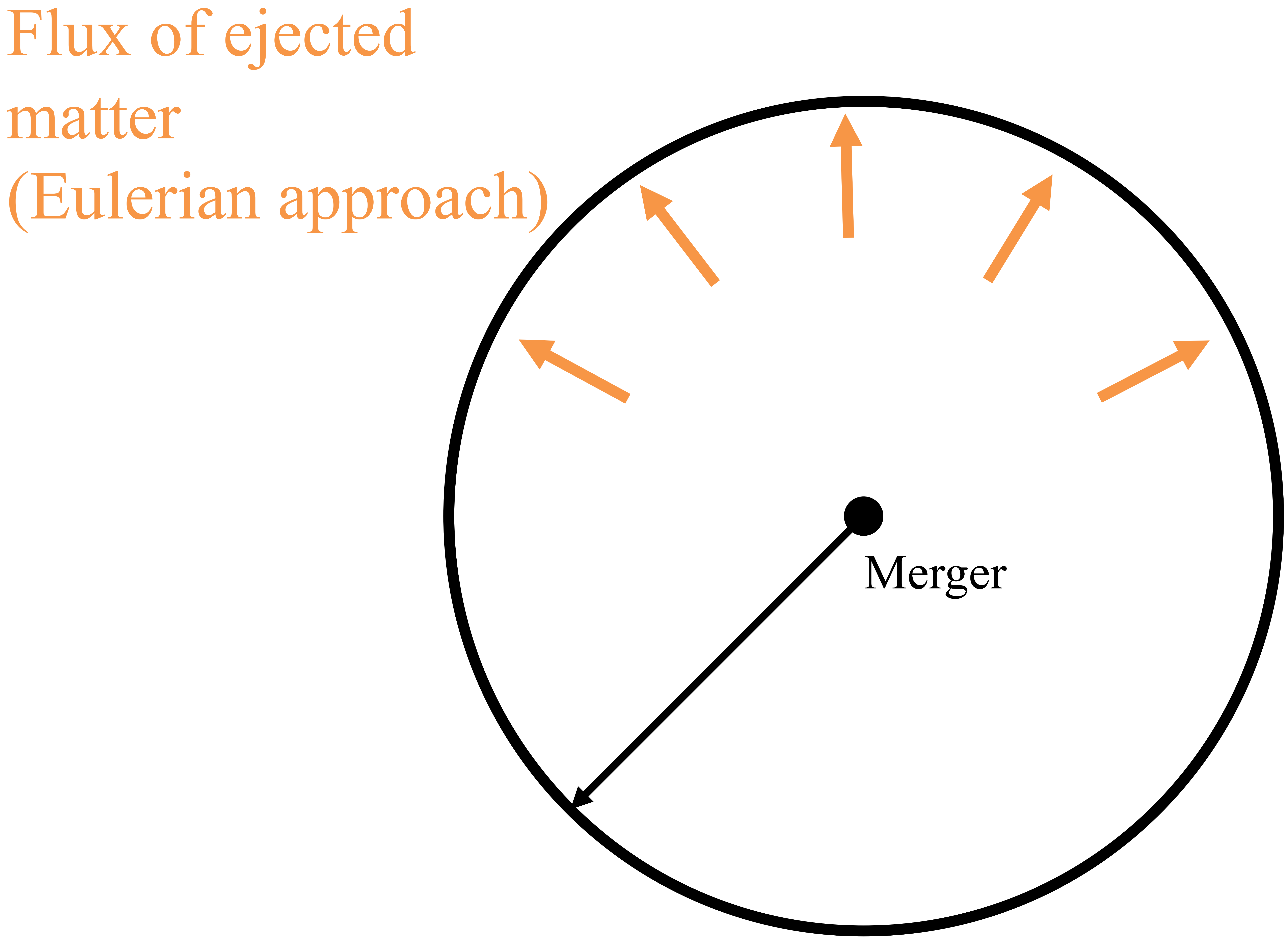
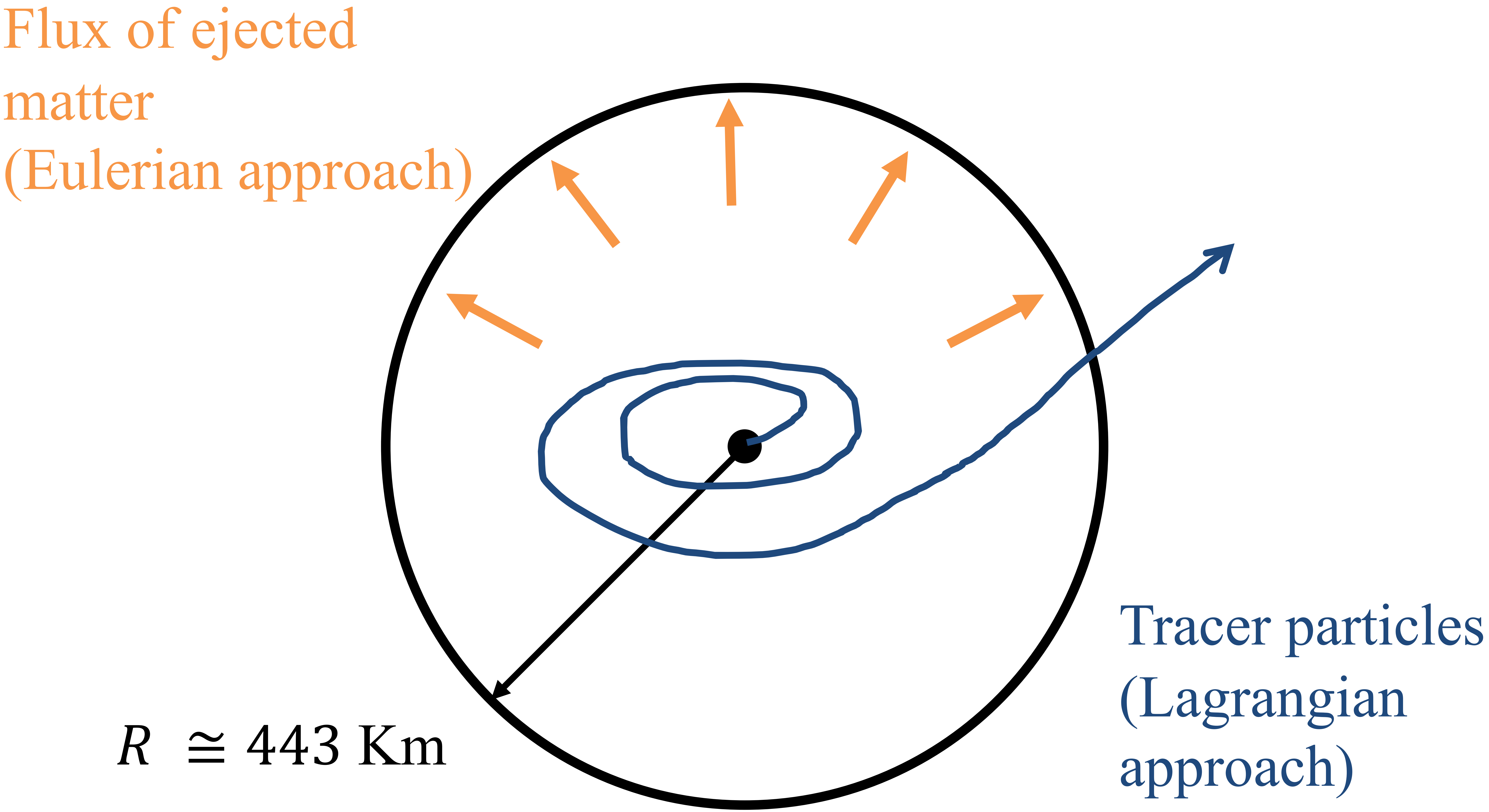
SFHo EOS and unitary mass ratio

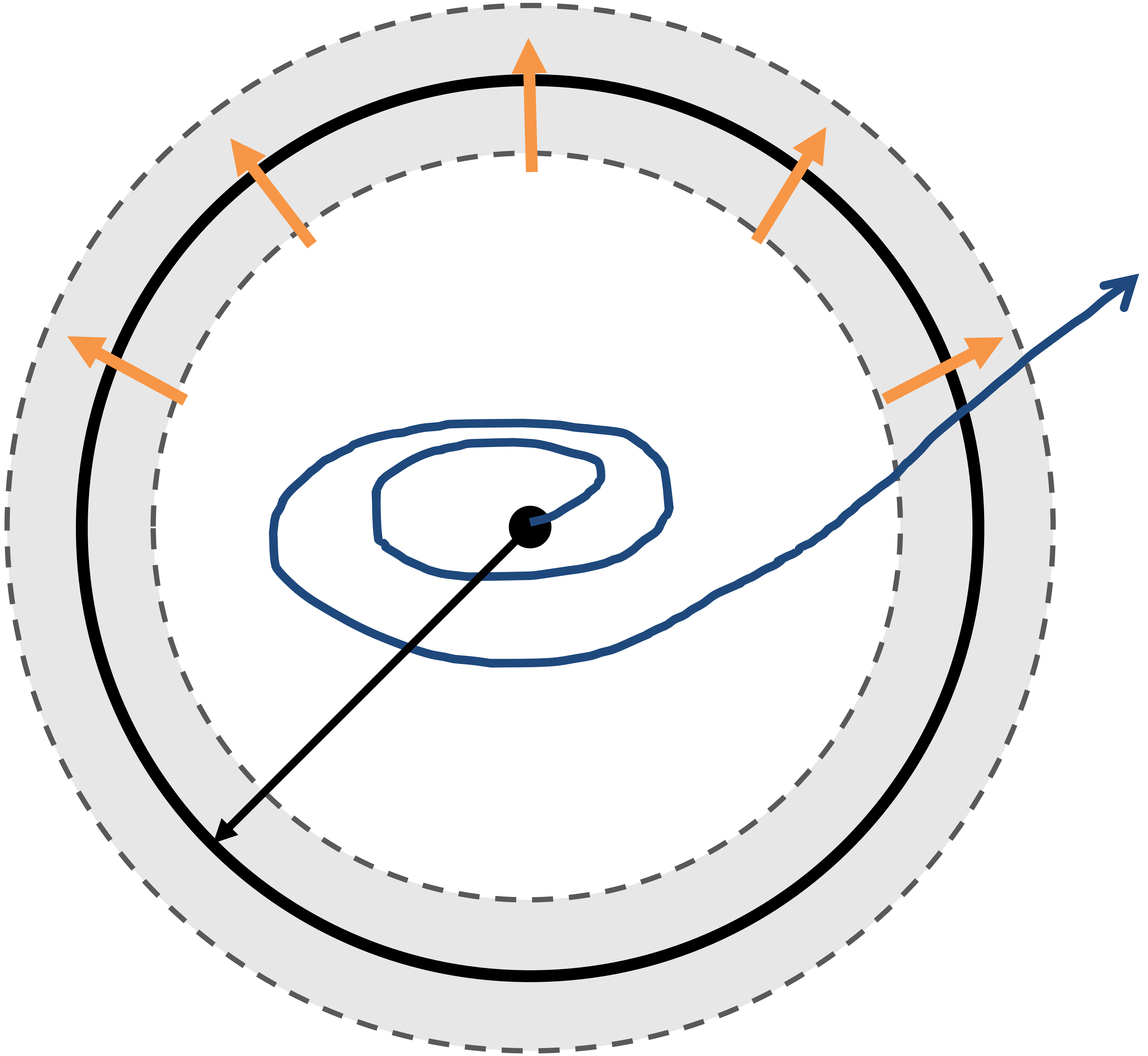
- Compute nucleosynthesis with WinNet [Reichert+23]


Merger
Detector at
$R \cong 443$ Km

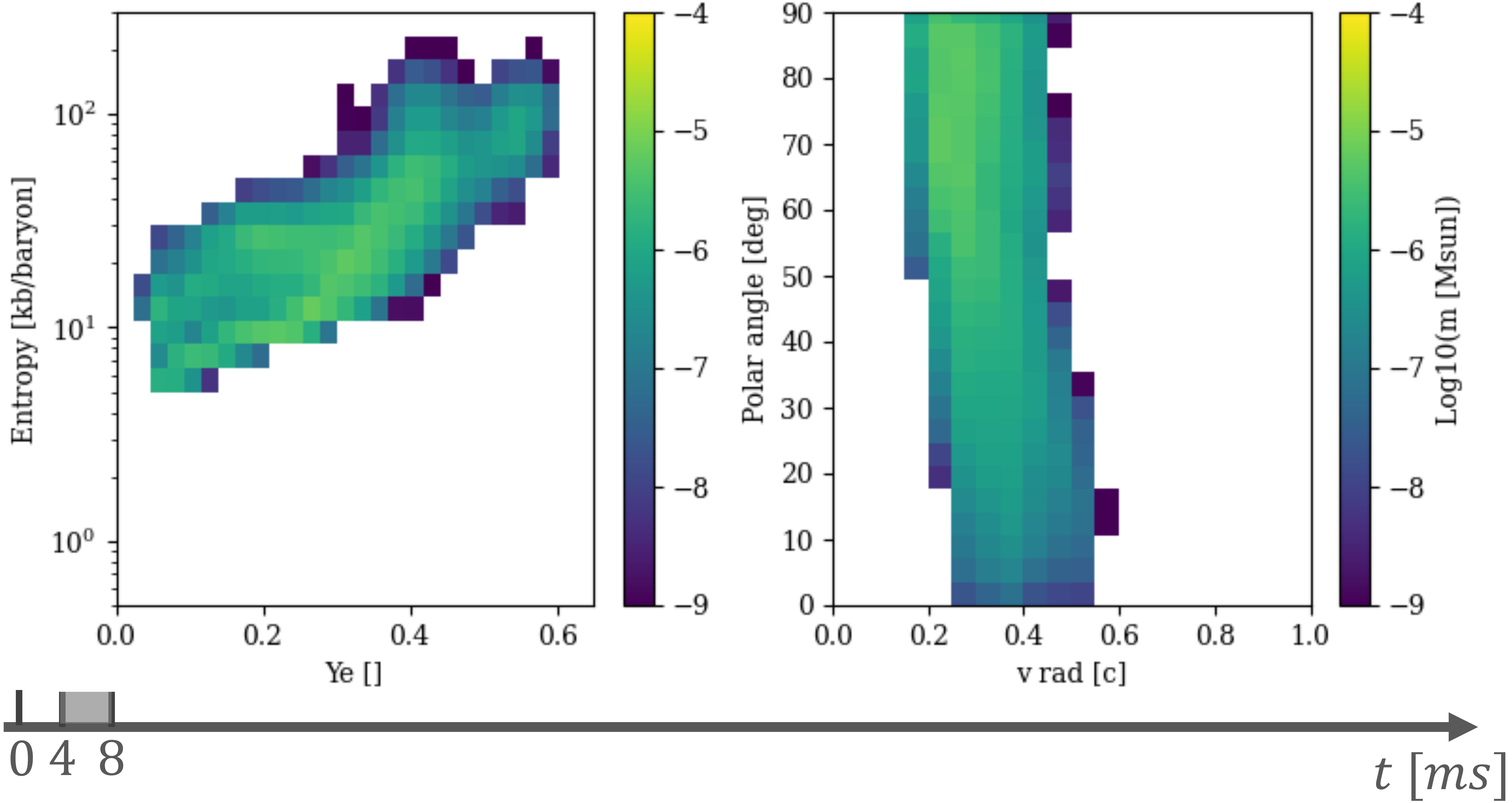

Flux of ejected matter
(Eulerian approach)
Merger


Flux of ejected matter
(Eulerian approach)
$R \cong 443$ Km
Tracer particles
(Lagrangian approach)

Time windows $\Delta t_1, \ldots, \Delta t_n$

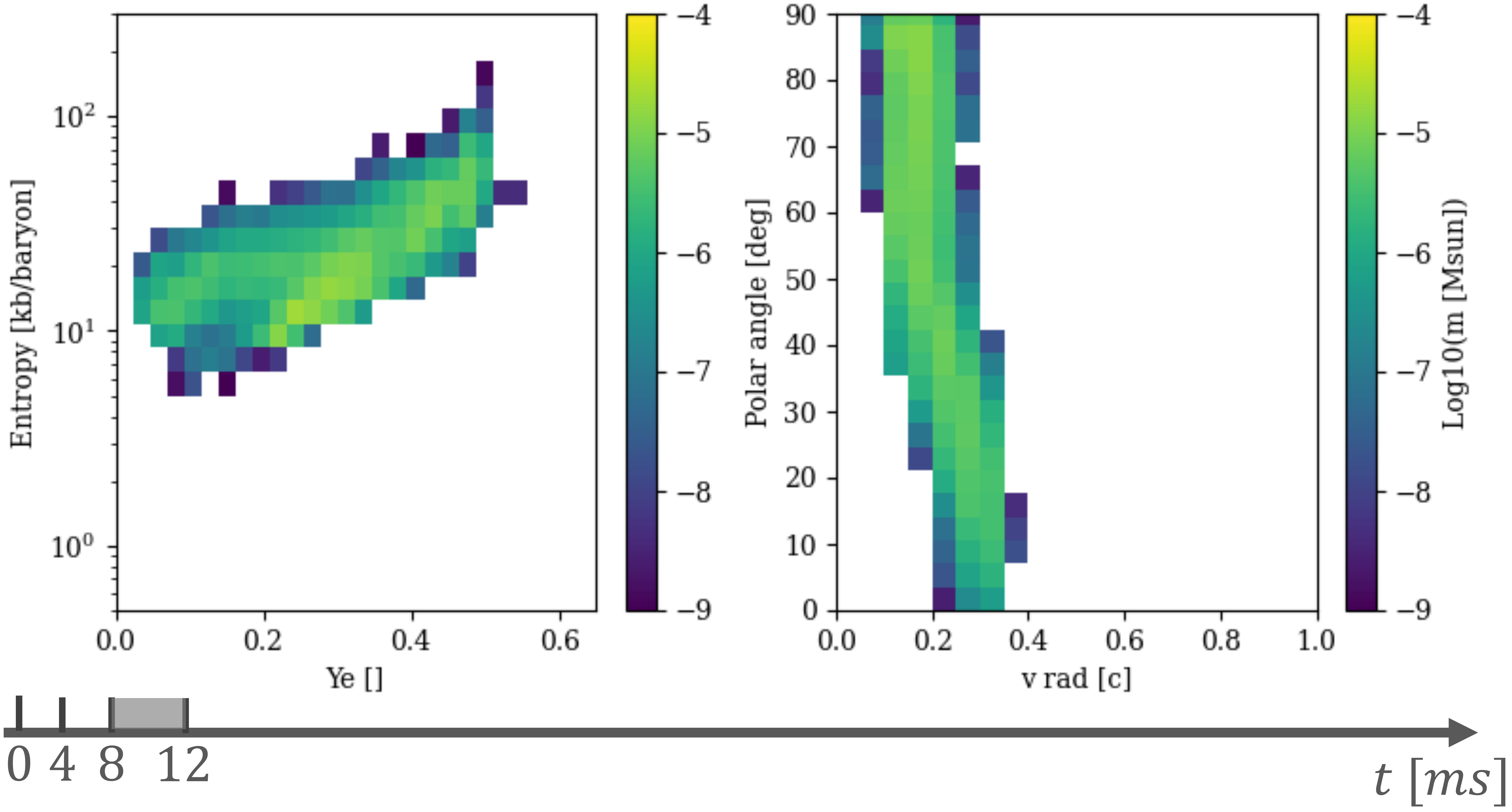


Ejecta analysis



Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

Ejecta analysis



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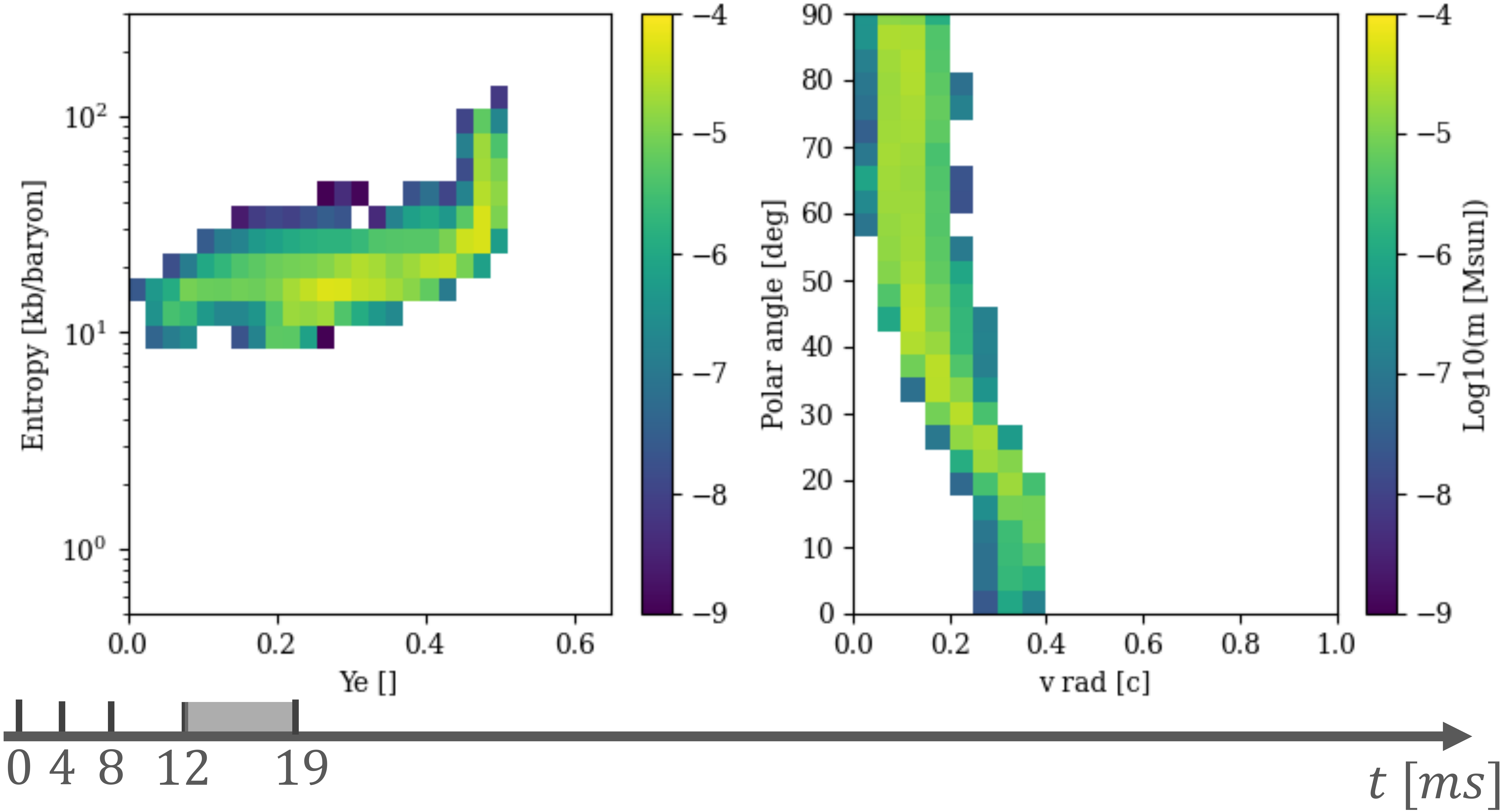

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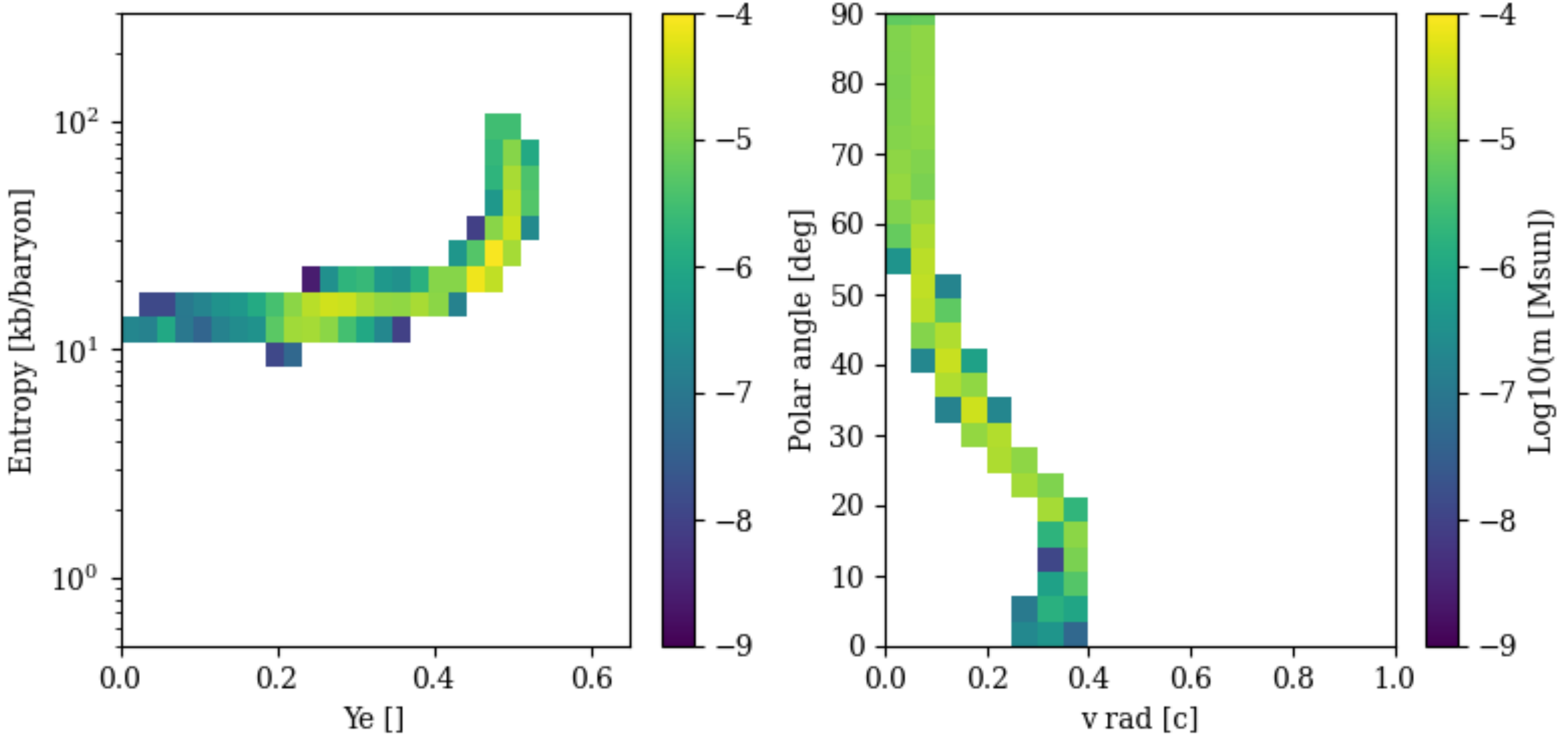

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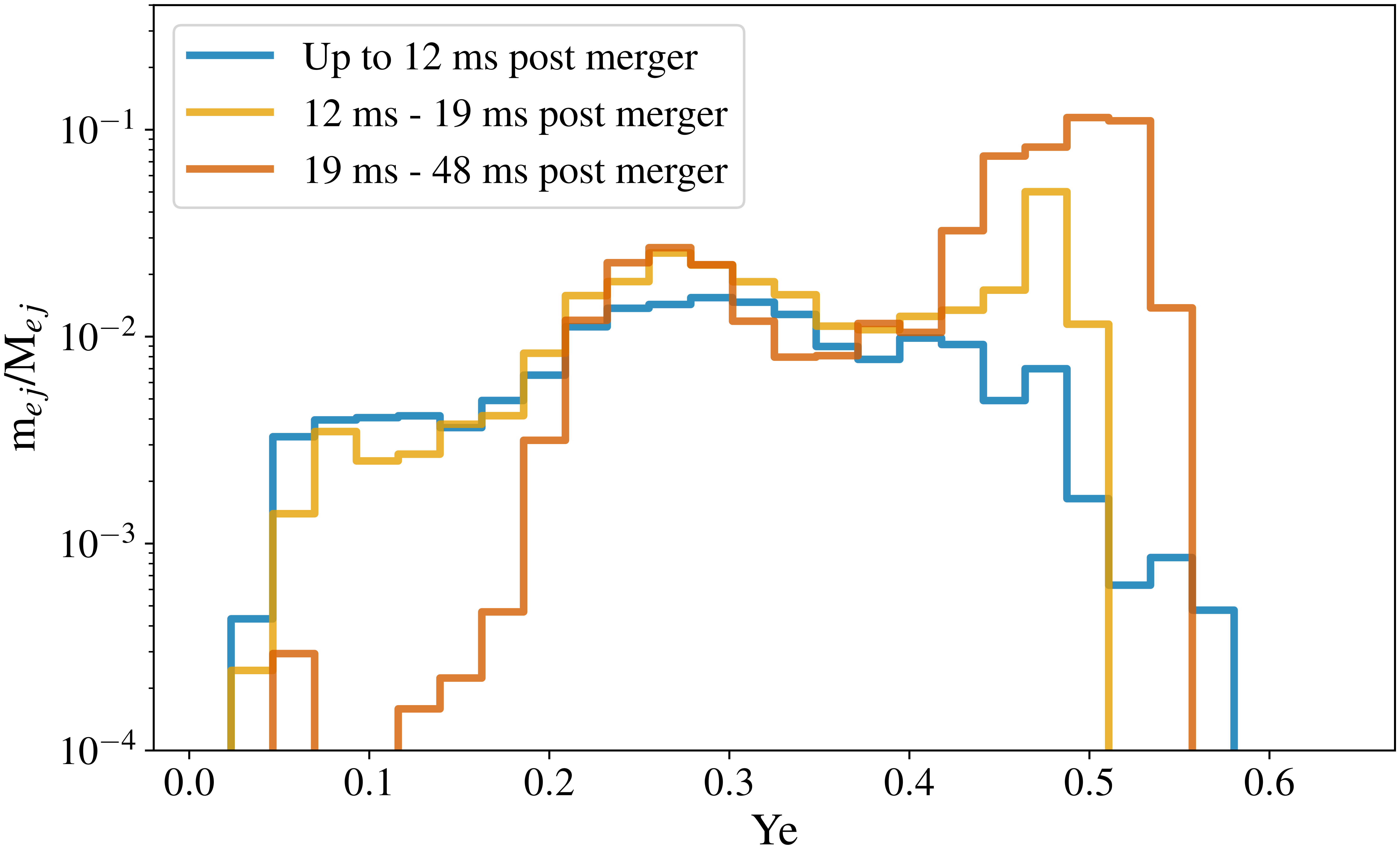
Ejecta analysis: Ye distribution



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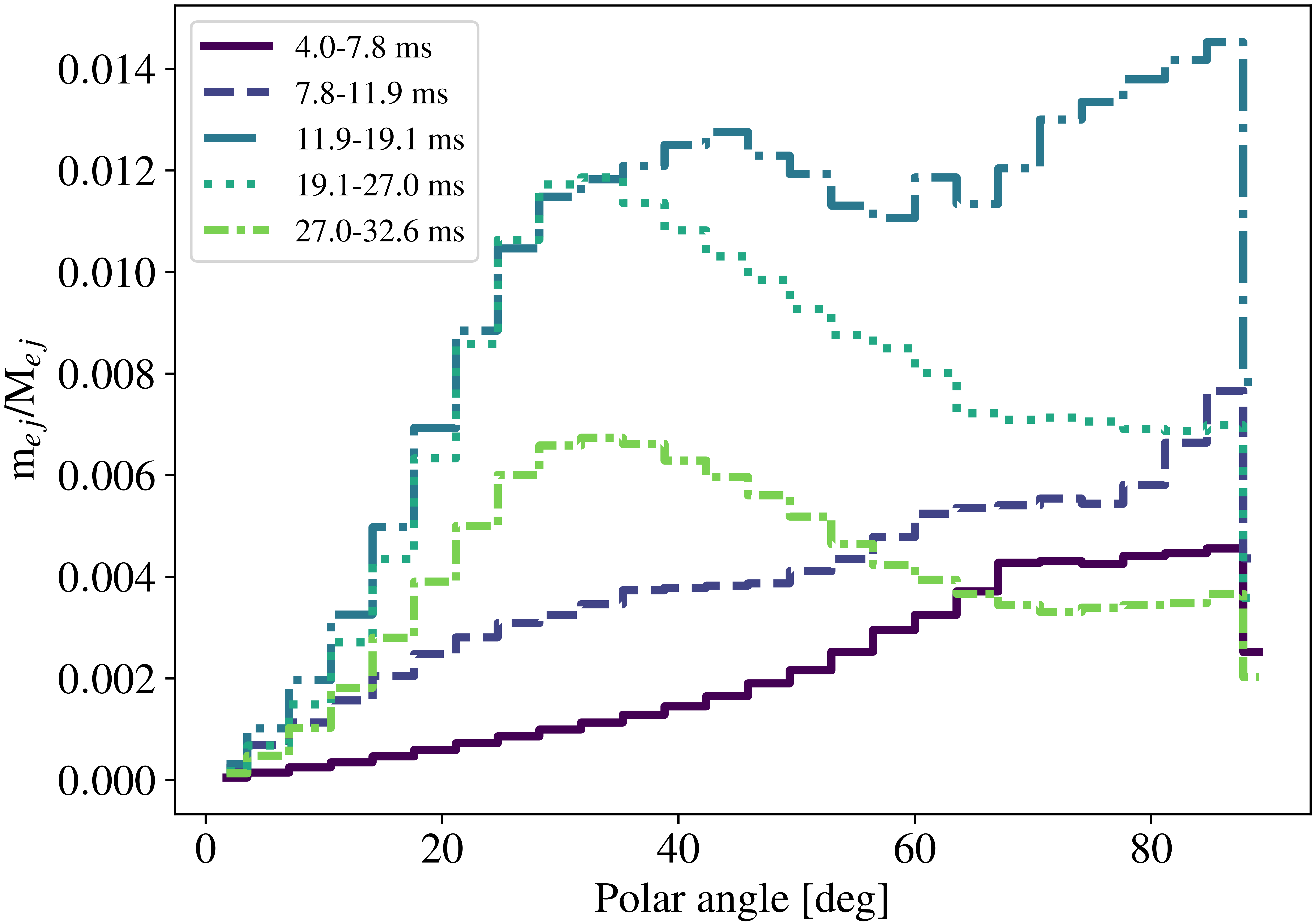
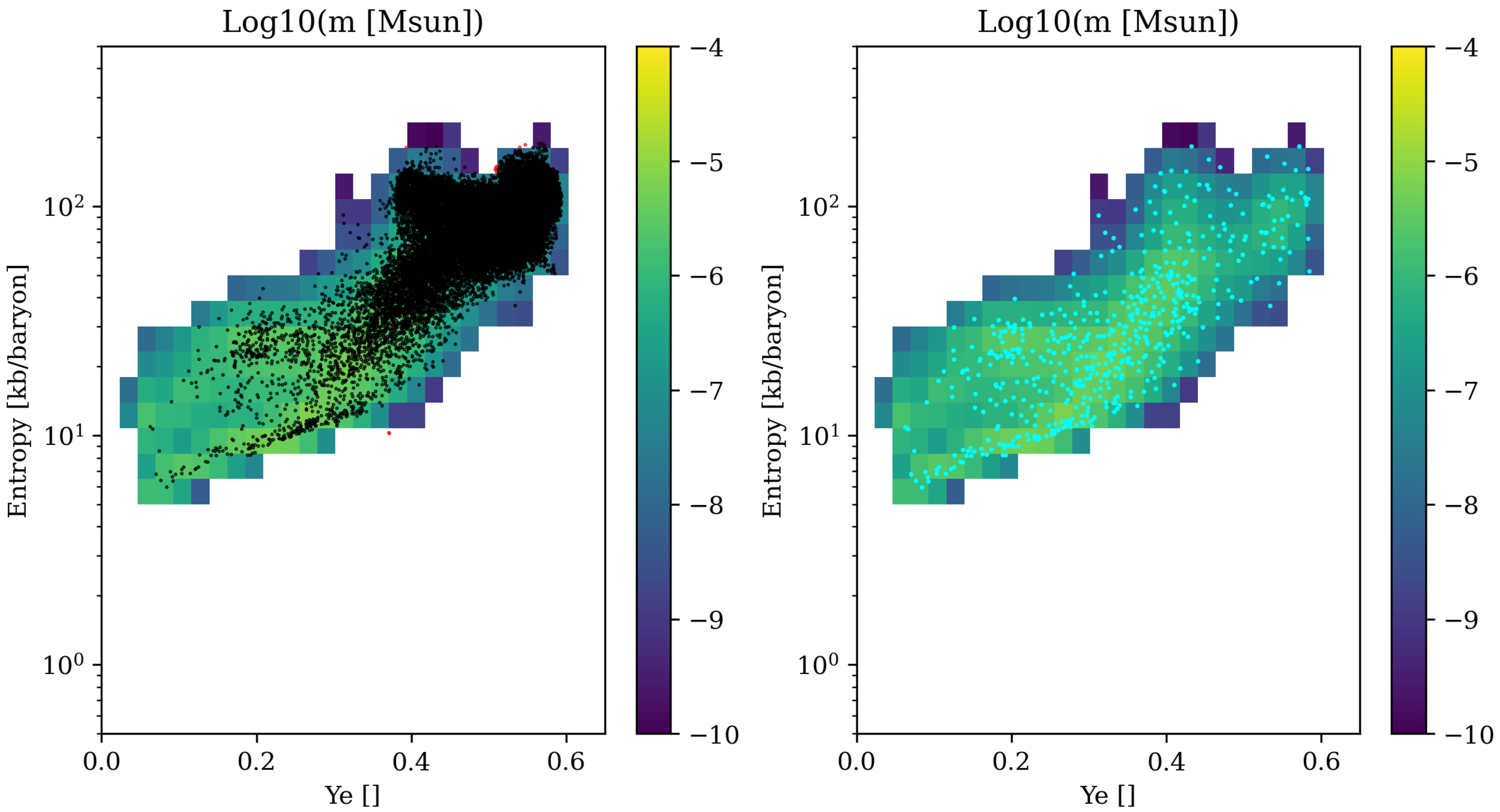
Ejecta analysis: angular distribution



Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

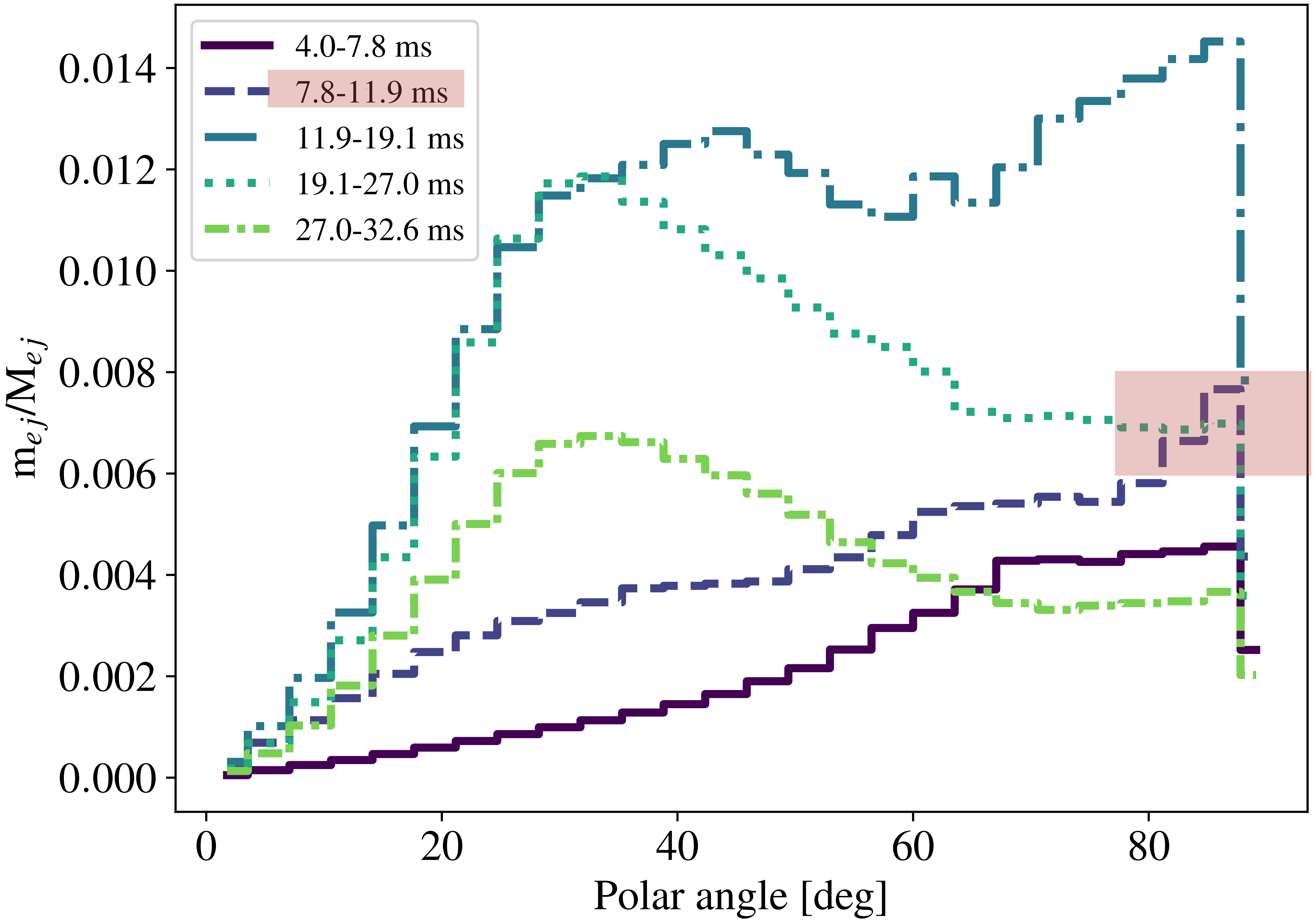
Tracer extraction

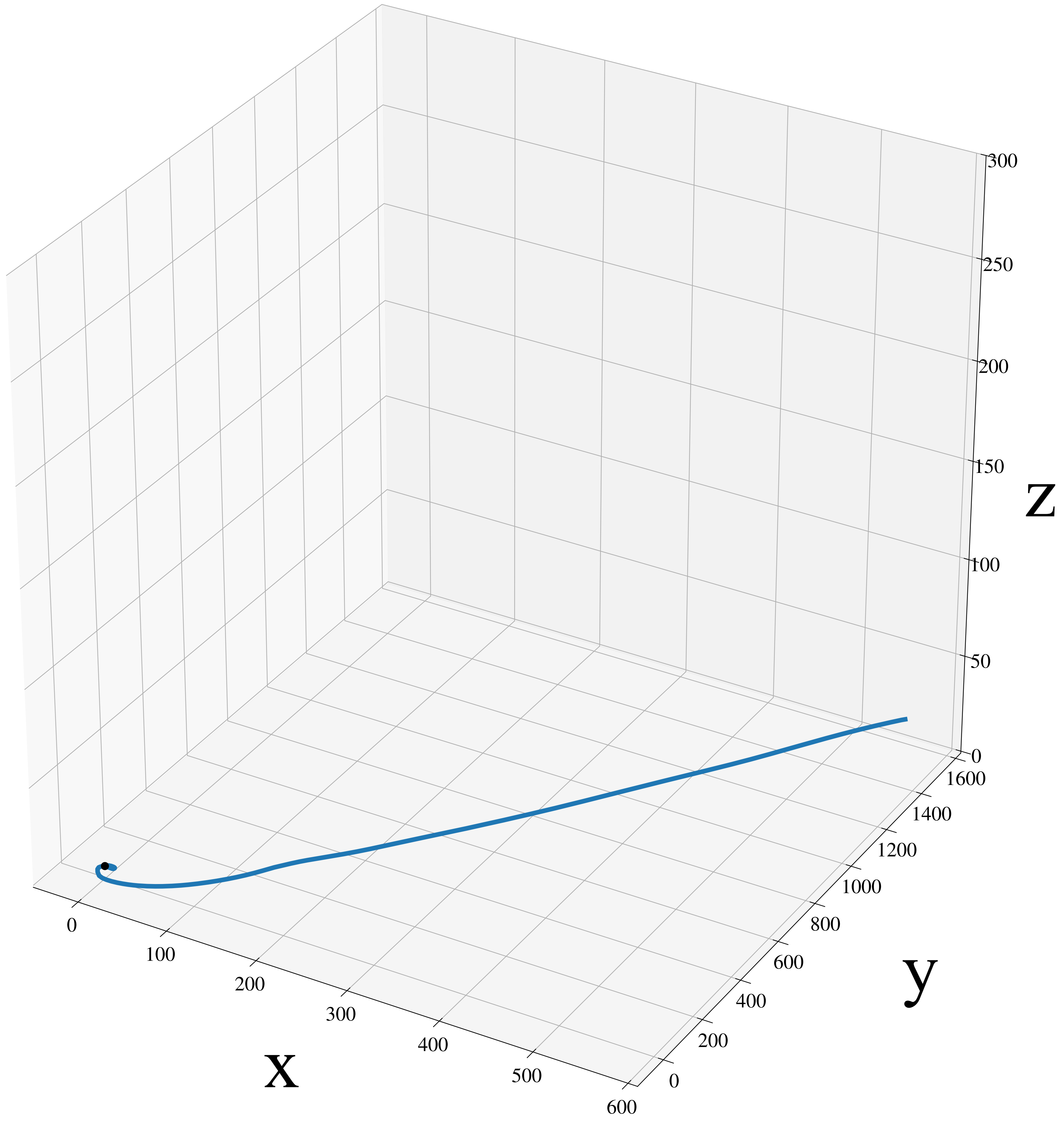


From 2.6×10^5 to 3×10^3 tracers: mass weighted extraction per time window

Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

$$Y_e(t_{merger}) = 0.10$$

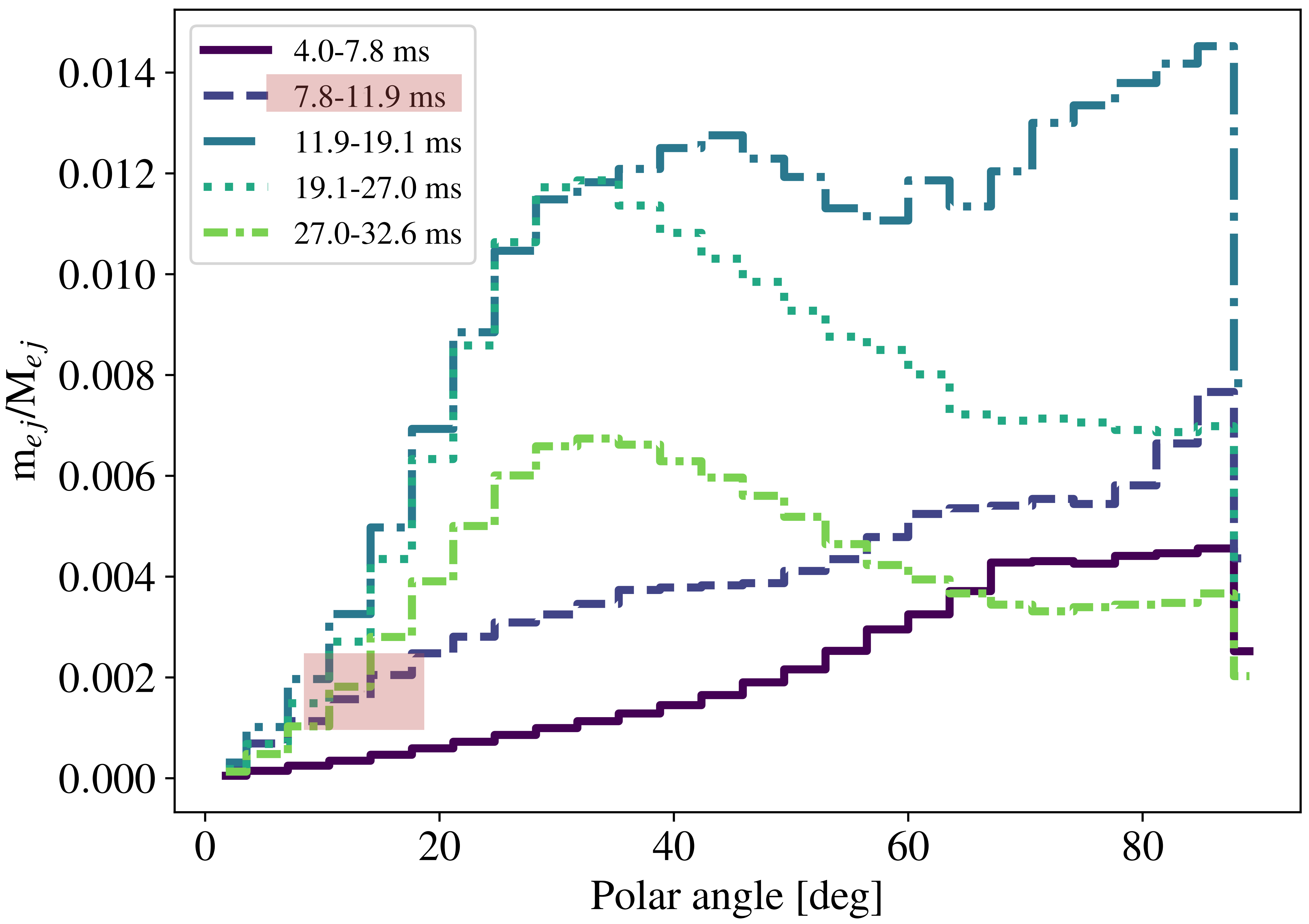


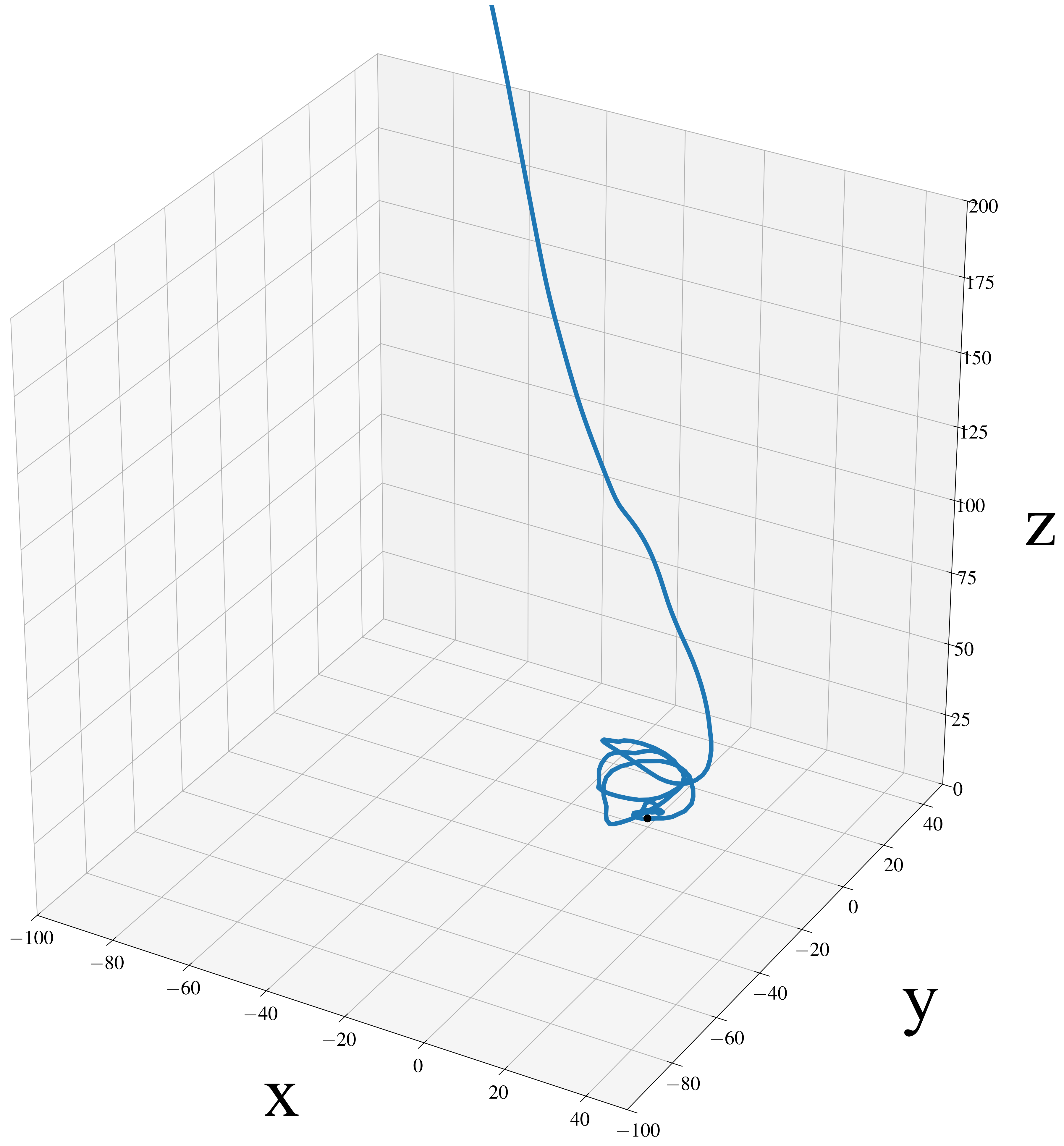


$$Y_e(t_{fin}) = 0.06$$

Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

$$Y_e(t_{merger}) = 0.10$$

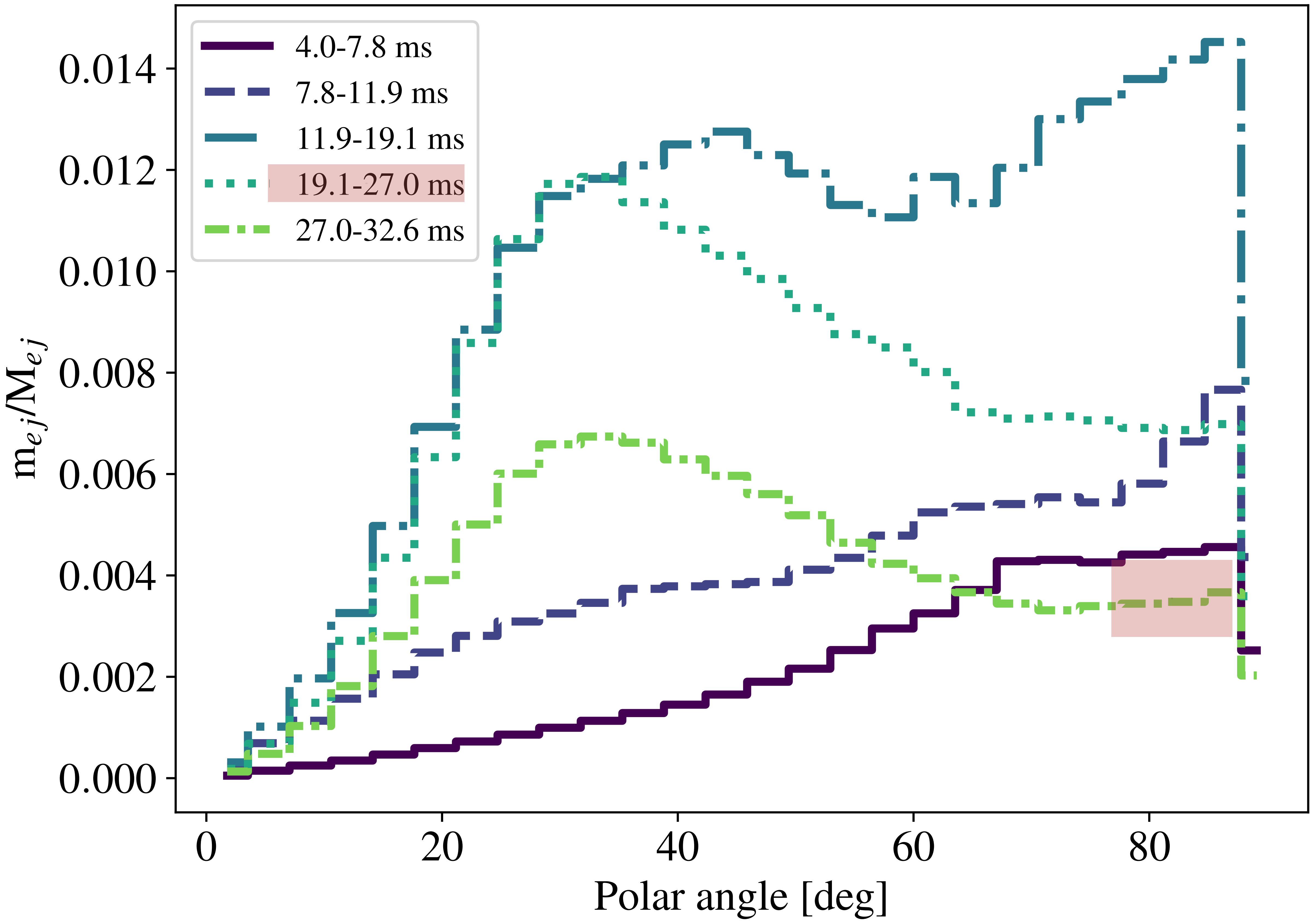


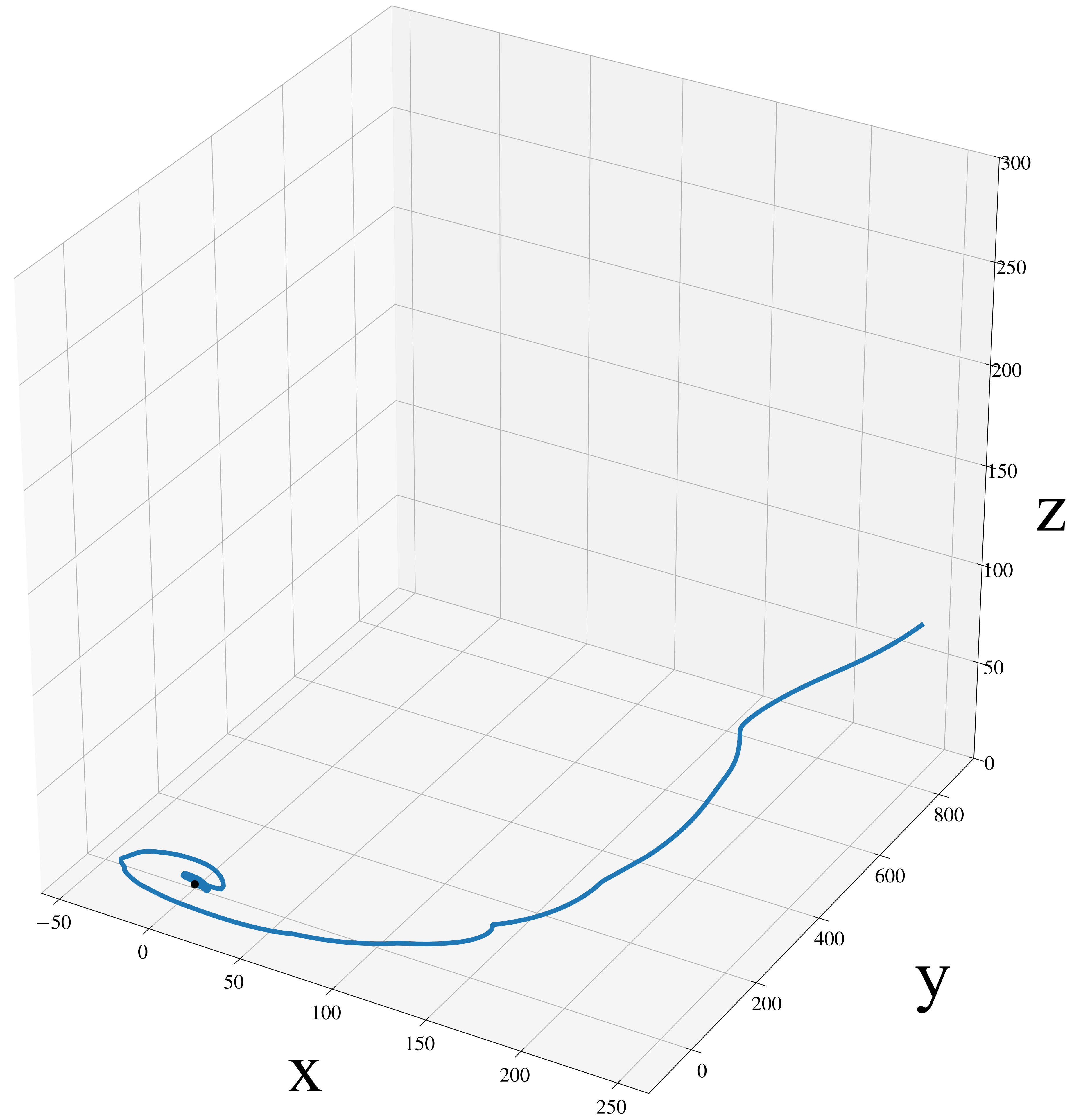


$$Y_e(t_{fin}) = 0.49$$

Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

$$Y_e(t_{merger}) = 0.10$$

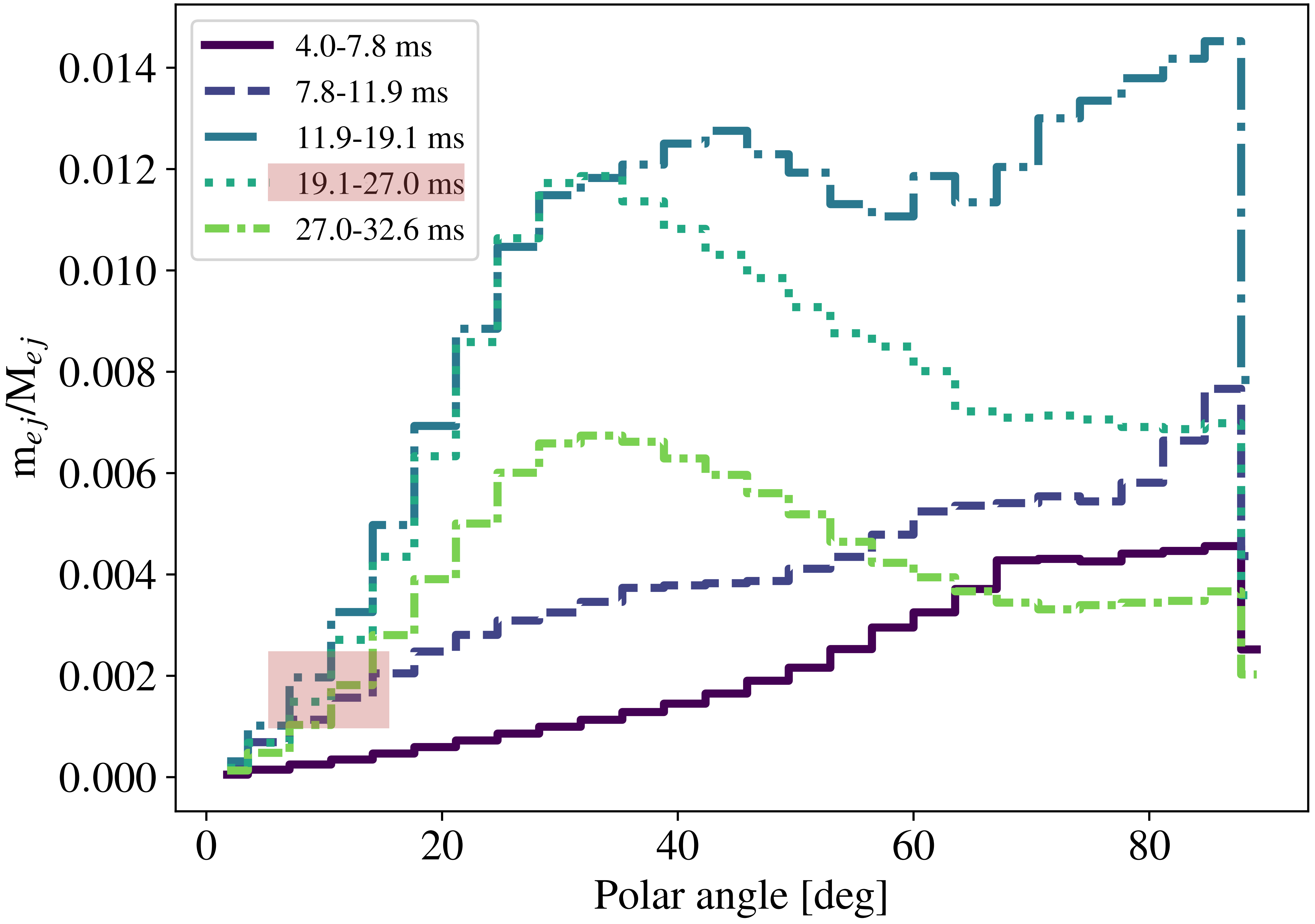


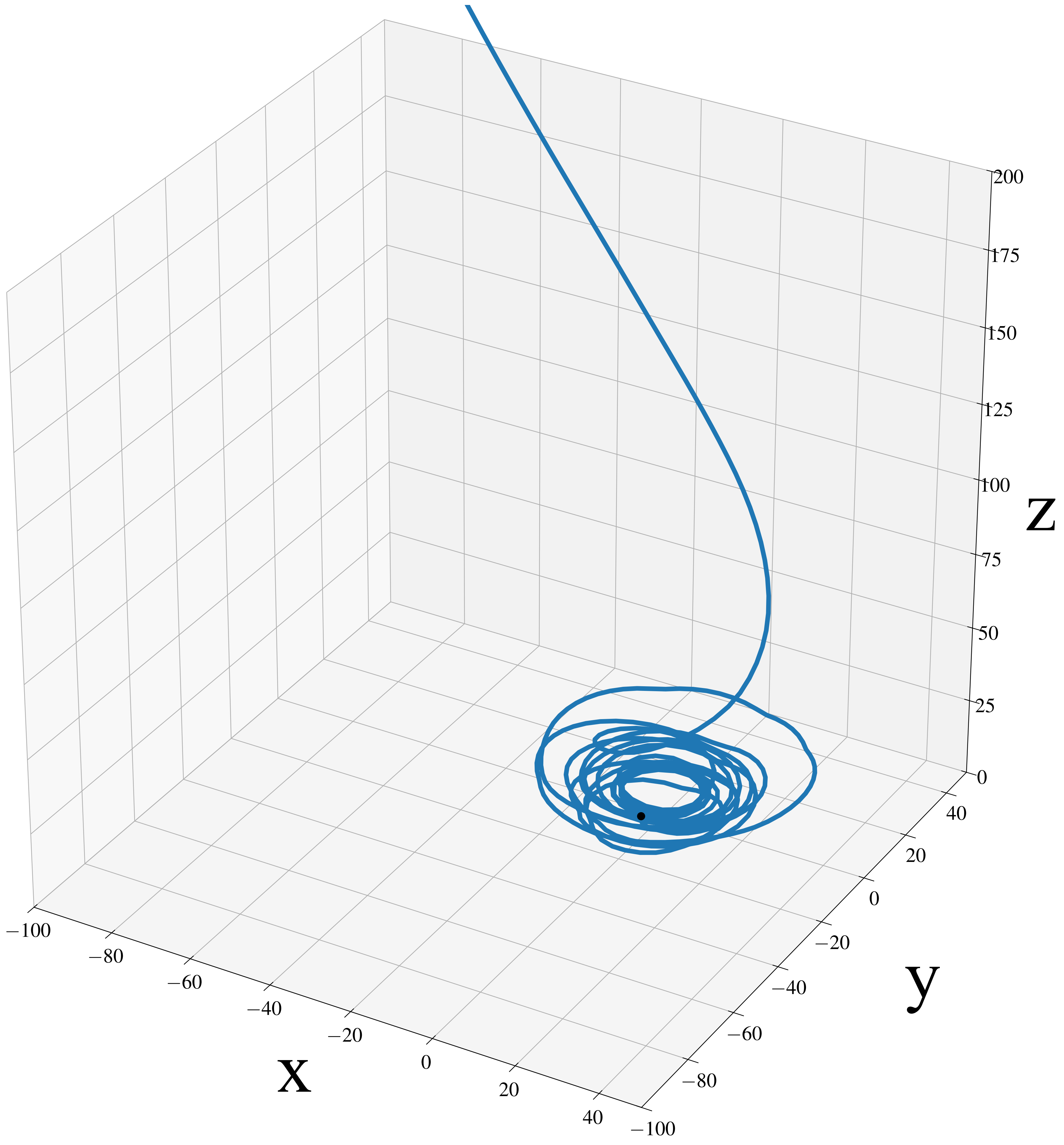


$$Y_e(t_{fin}) = 0.29$$

Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

$$Y_e(t_{merger}) = 0.10$$





$$Y_e(t_{fin}) = 0.5$$

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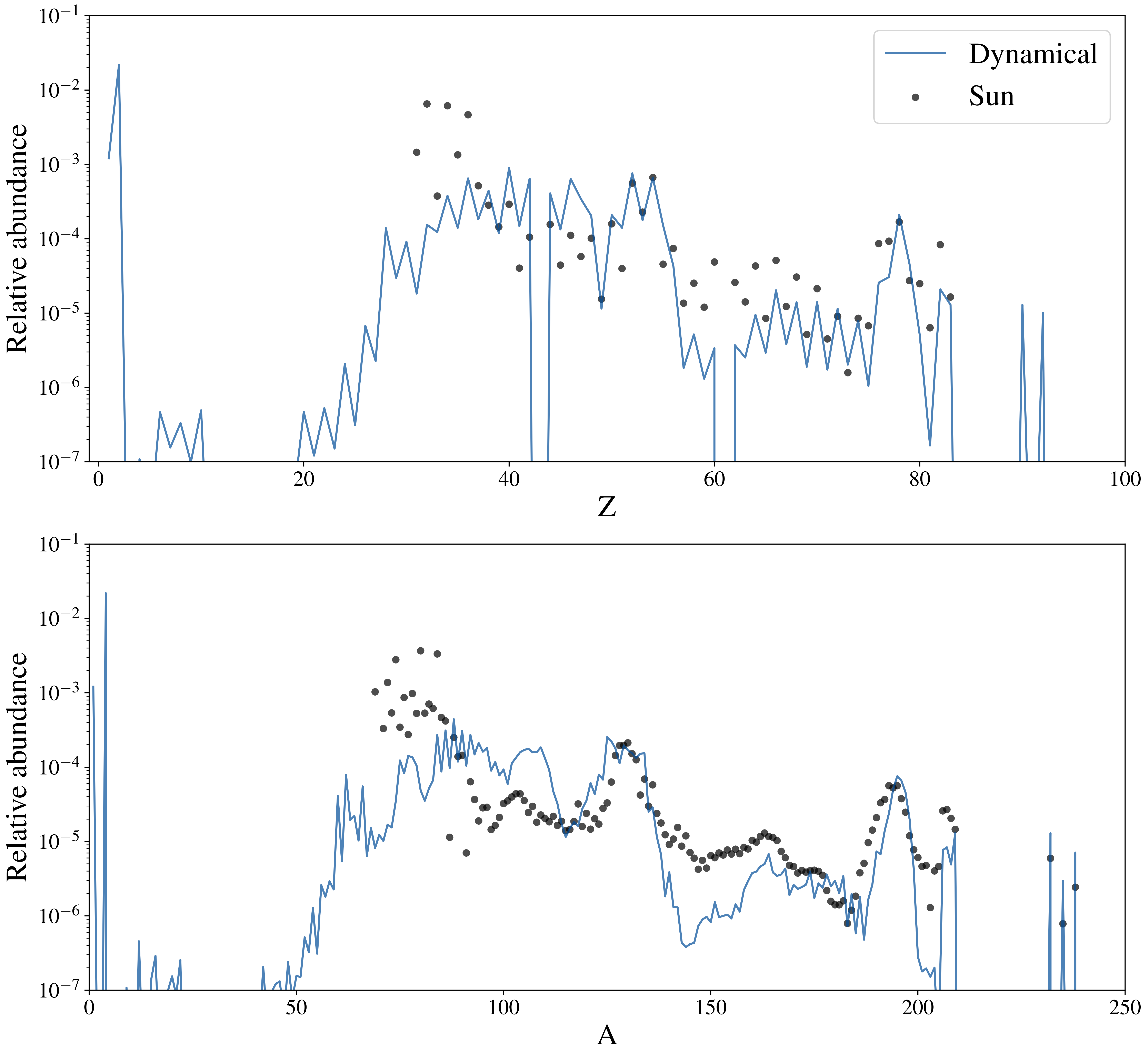

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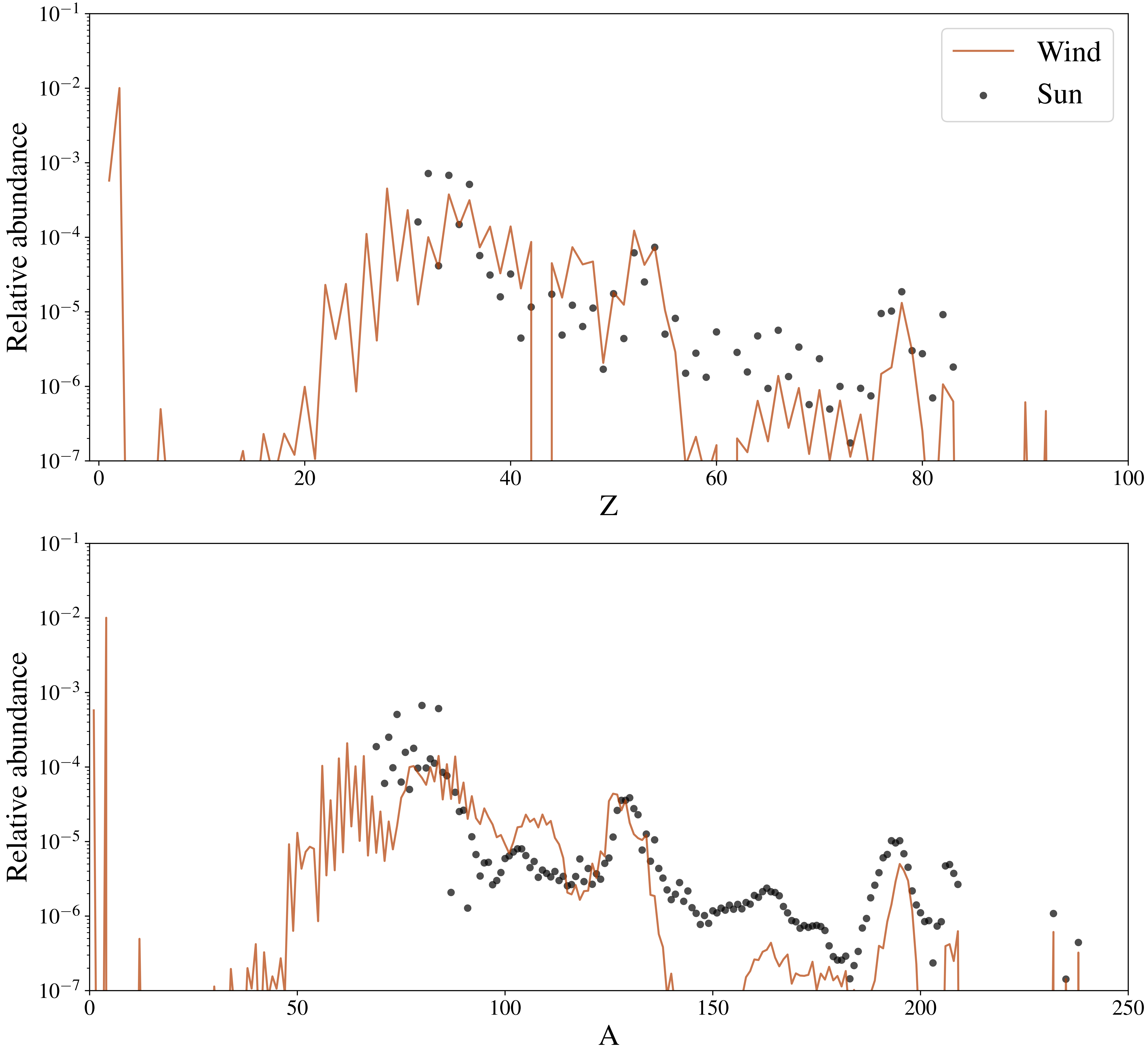
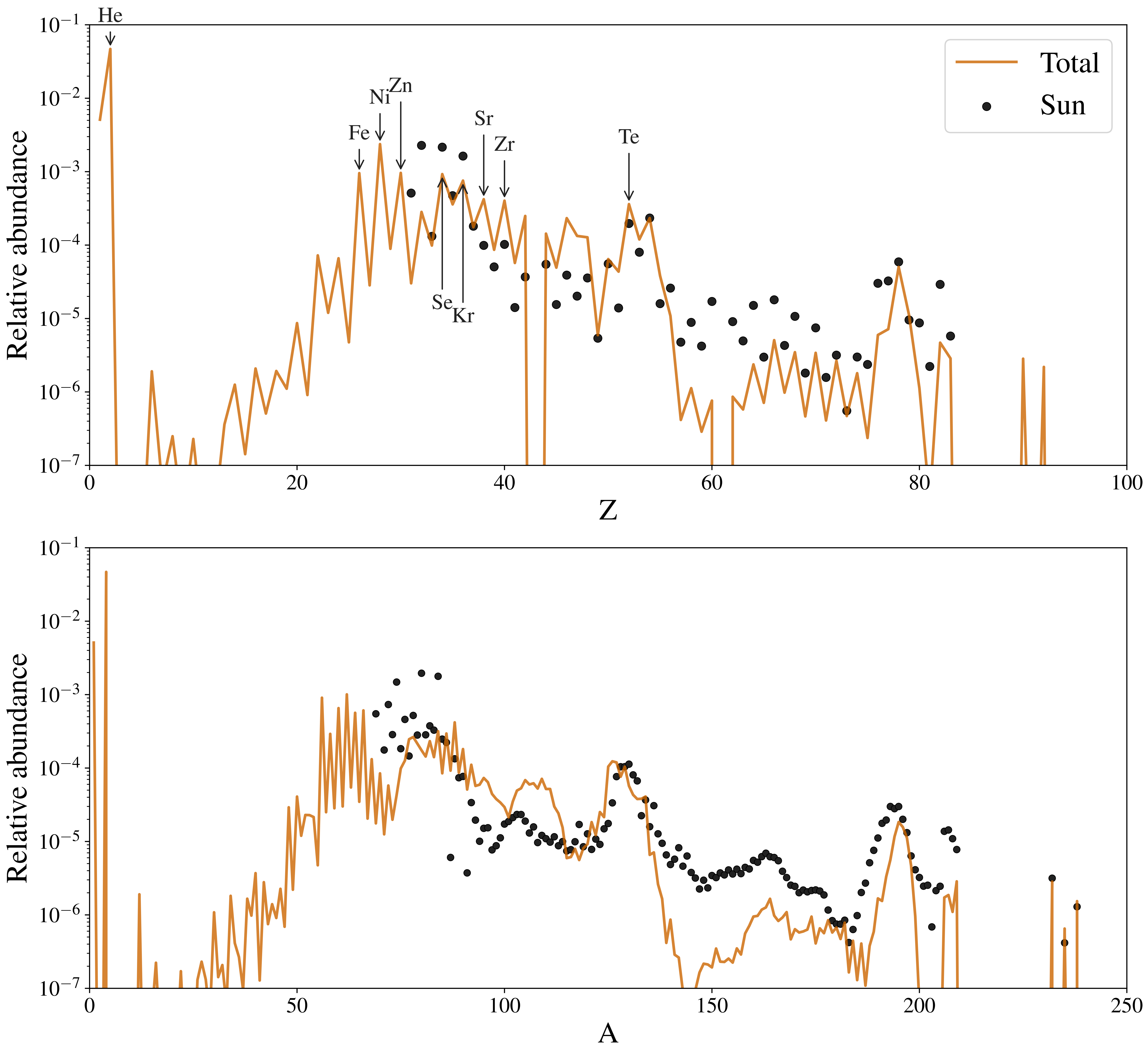


Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

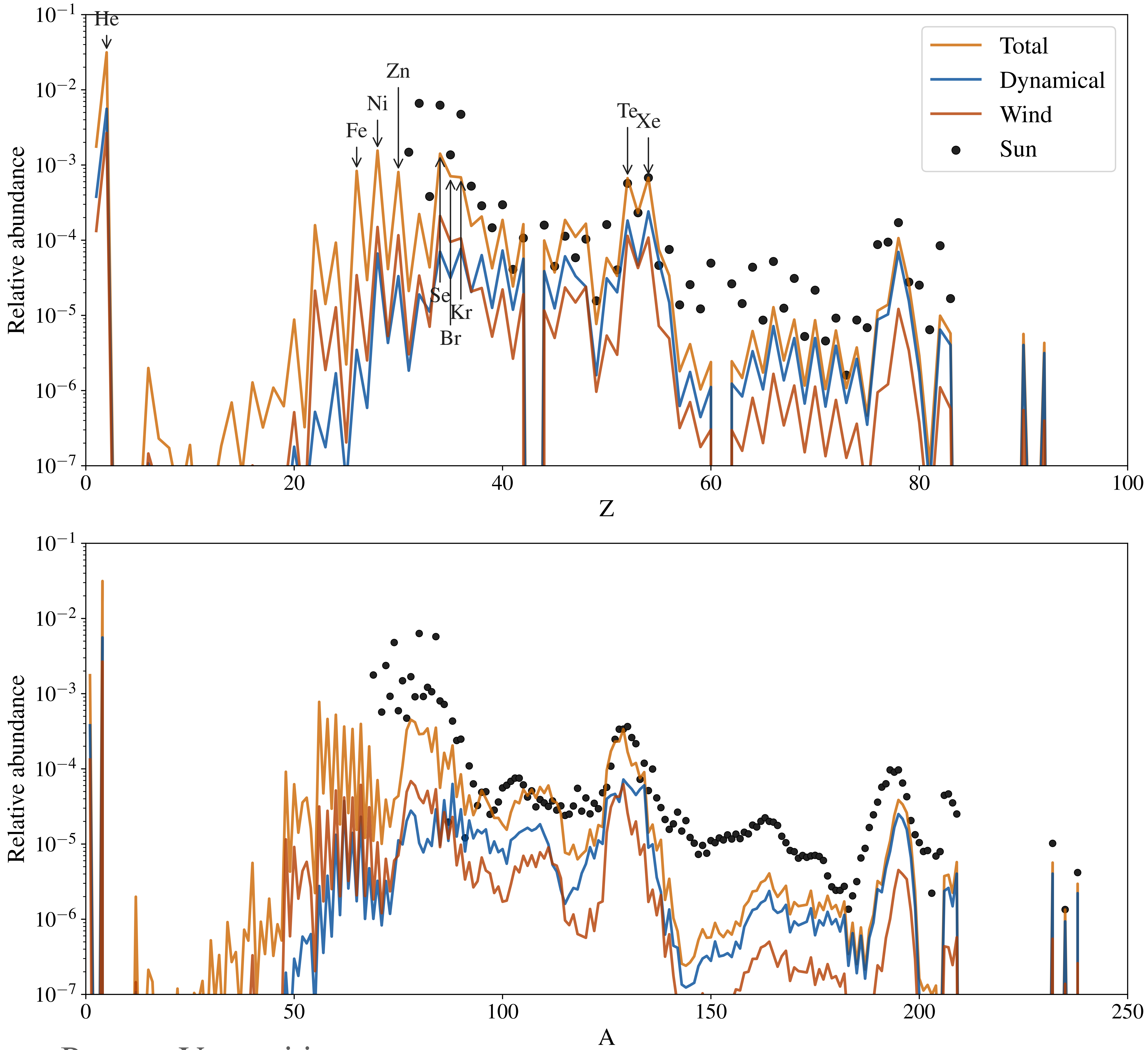
Iron group elements among the most abundant!

See also Domoto+2021, Perego+2022, Sneppen+2024, Jacobi+2025



Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

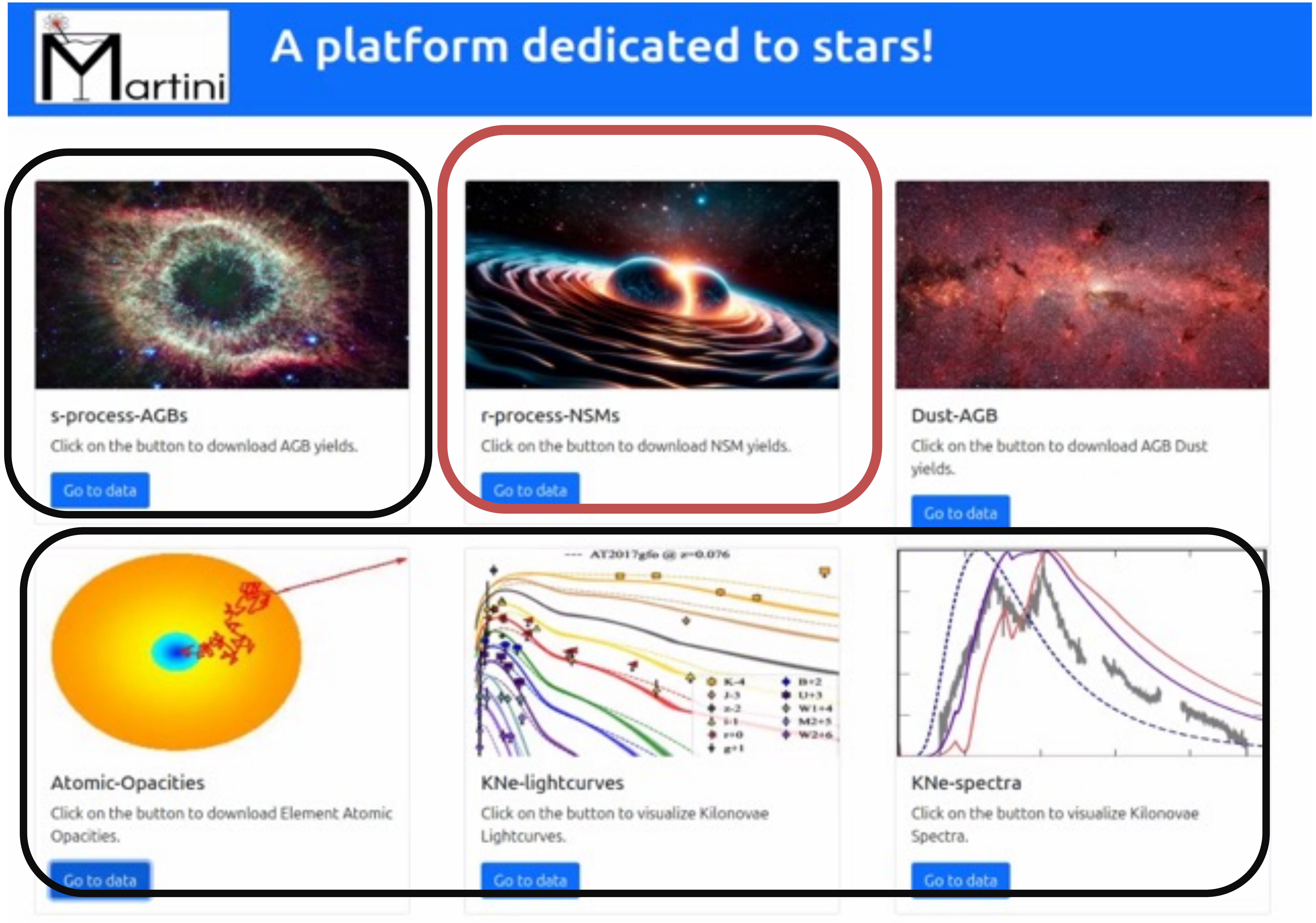
Iron group elements among the most abundant, irrespective of the EOS



DD2 EOS, unitary mass ratio

Loffredo, Cristallo, Guercilena, Perego, Vescovi in prep.

F.R.U.I.T.Y.



Bezmalinovich's talk coming soon…

Key points - 1

- Dynamical ejecta: production of elements in 2nd and 3rd peak.
- Neutrino wind: production of lighter elements.
- Iron group elements among the most abundant irrespective of the EOS.
- Nuclear input physics?
- Asymmetric mass ratios?
- Role of oscillations?

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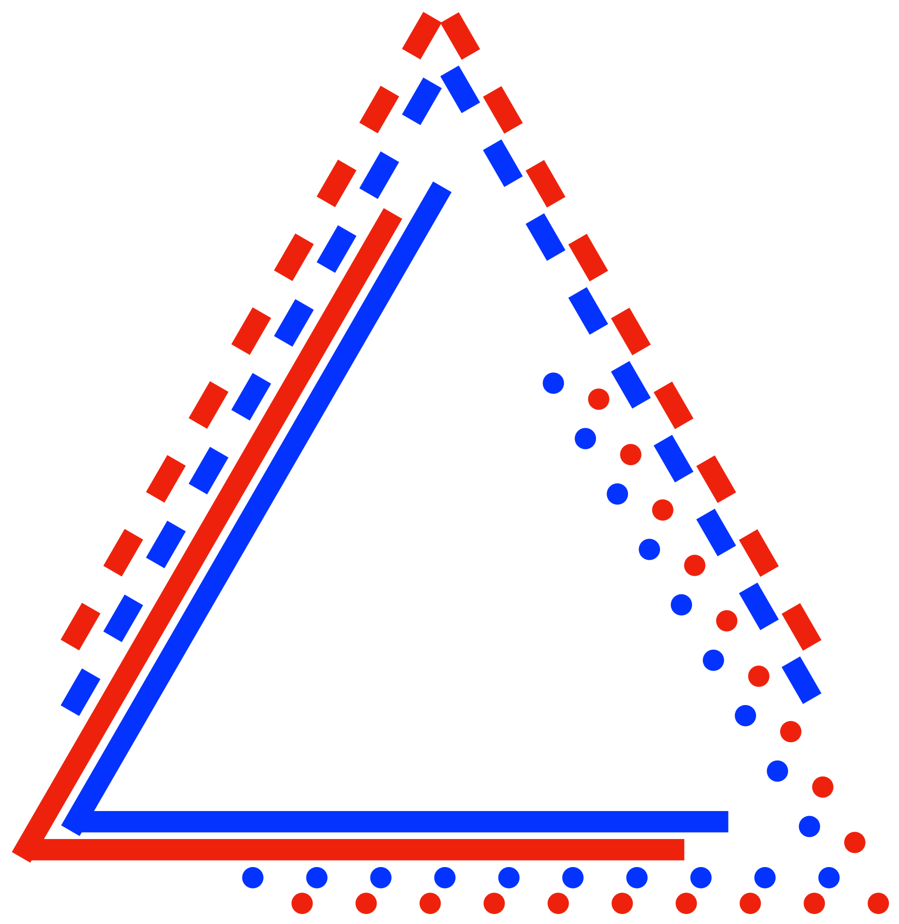
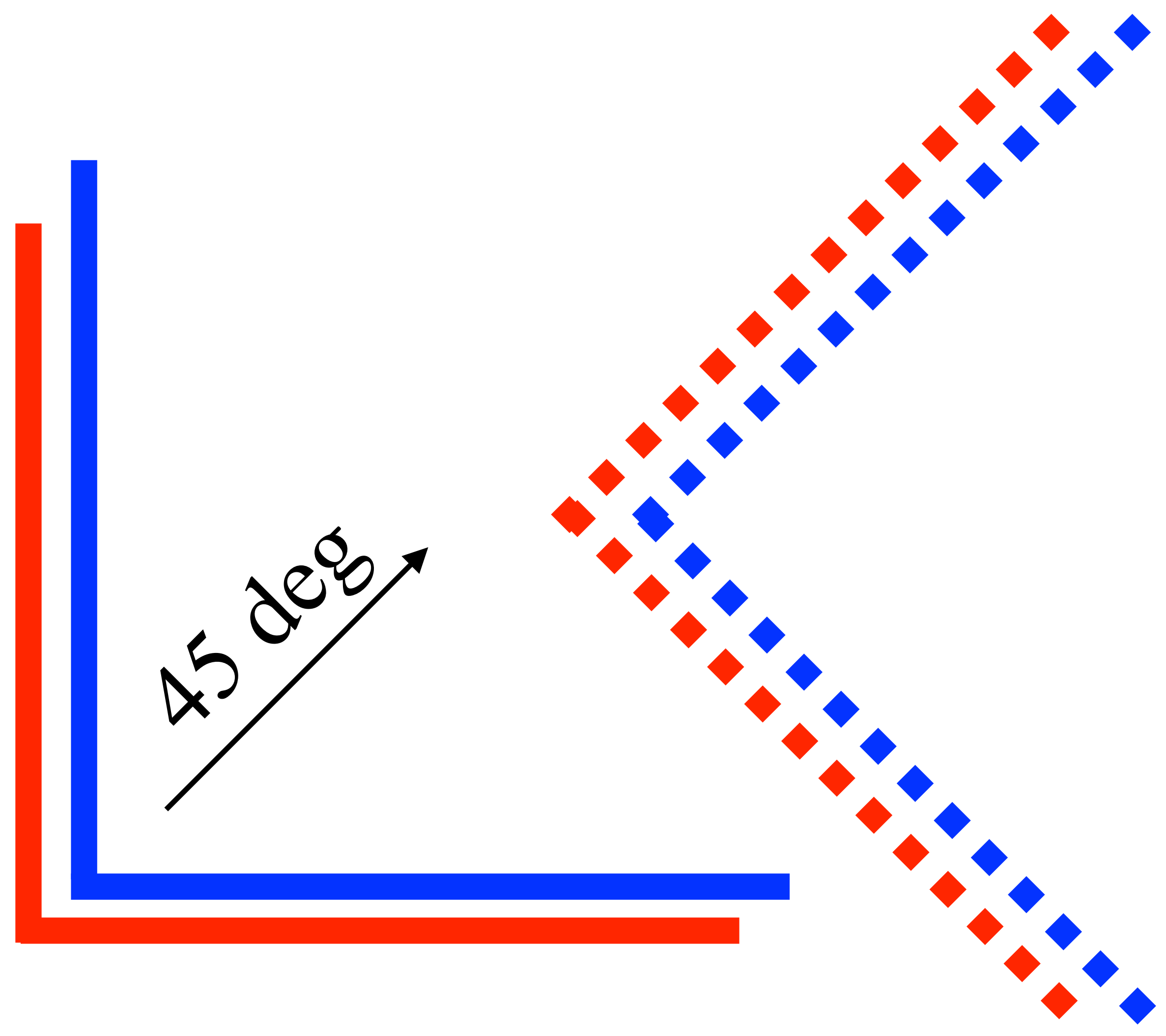
Loffredo et al. A&A 2025

The Einstein Telescope

- Next-generation GW detector, triangular shape, underground
- Reference design → triangular-shaped, 10 km arms, xylophone configuration with high-frequency and low-frequency lasers
- Geometries → 2L vs Δ
- See Branchesi et al. JCAP 2023 and Abac et al. arXiv:2503.12263





Prospects for GW/optical joint detections

Assessing prospects for GW and optical detection from BNS mergers considering:

- ET alone or in a network with LVKI / 1CE / 2CEs
- Realistic follow-up strategies with the Vera Rubin Observatory
- Effect of present uncertainties in BNS population properties and NS microphysics
- Difference in KNe emerging from less massive BNS (GW170817) and more massive BNS (GW190425)

LIGO VIRGO KAGRA

COSMIC EXPLORER

ET EINSTEIN TELESCOPE

VERA C. RUBIN OBSERVATORY

Loffredo, Hazra, Dupletsa et al., A&A, 2025

The entire methodology

STEP 1

Population of isolated BNS mergers

COSMORATE SEVN

↓

Properties of each BNS (masses, redshift, sky-position, inclination, …)

The entire methodology

STEP 1

Population of isolated BNS mergers

COSMORATE SEVN

↓

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STEP 2

Assign waveform approximant to each merger & perform parameter estimation for each GW detector

GWFISH

↓

Number of detected mergers, source parameters, and errors (e.g. sky-loc.)

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Modelling of KN emission

KN light curve for each detected merger

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STEP 3

Modelling of KN emission

↓

KN light curve for each detected merger

STEP 4

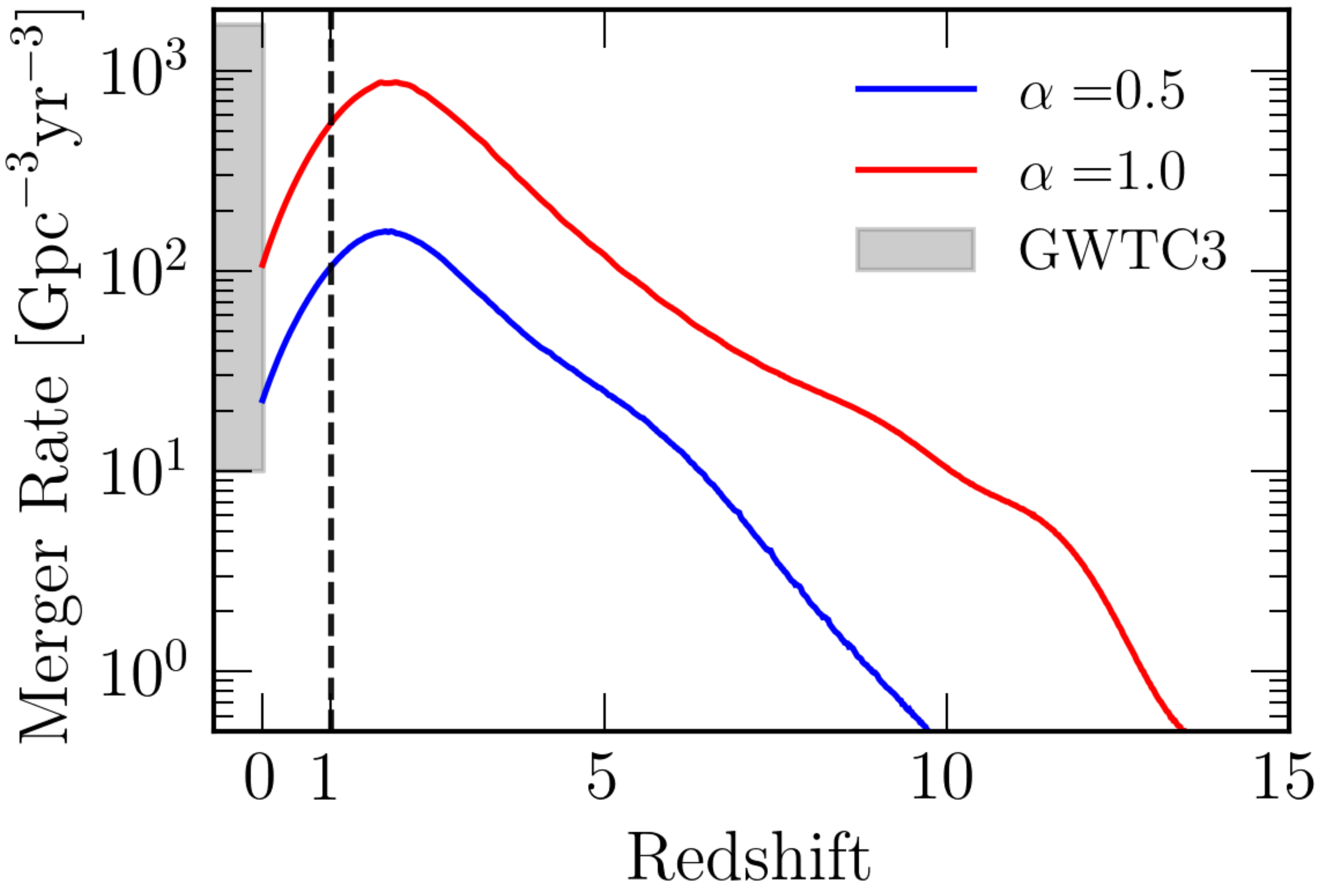
Follow up strategy (mosaic) with Rubin of events within a certain sky-loc.

↓

Number of KNe detected in *g* and *i*

Step 1 - BNS merger populations

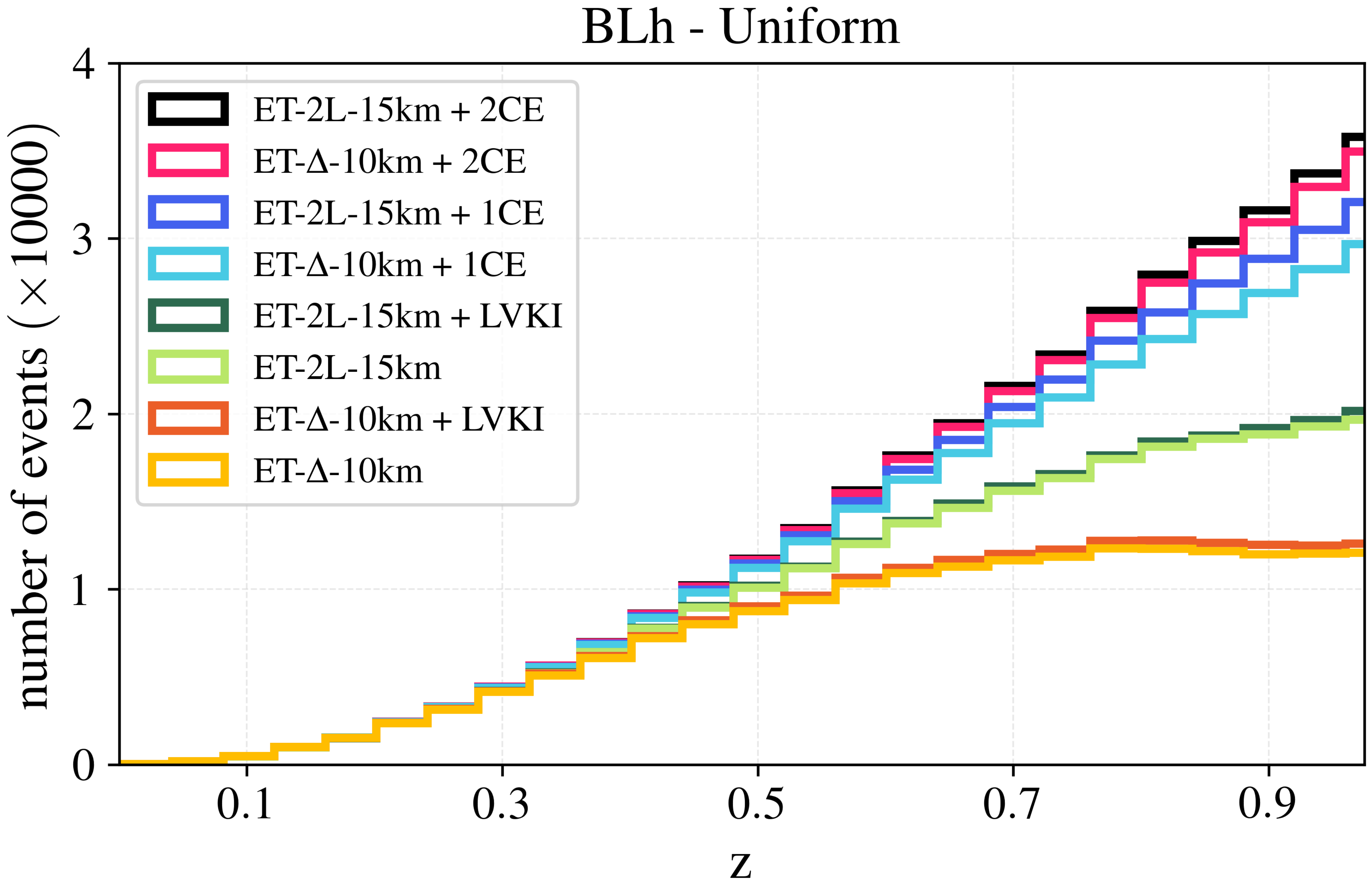
- Pessimistic population (blue) → $\mathscr{R}_{\mathrm{BNS}} = 23\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ and $\alpha = 0.5$
- Fiducial population (red) → $\mathscr{R}_{\mathrm{BNS}} = 107\ \mathrm{Gpc}^{-3}\ \mathrm{yr}^{-1}$ and $\alpha = 1.0$
- BNS up to redshift $z = 1$, randomly distributed in the sky, random inclination
- NS EOS? APR4 (more compact NSs) and BLh (less compact NSs)
- NS mass distribution? Gaussian and uniform



Loffredo, Hazra, Dupletsa, et al., A&A, 2025

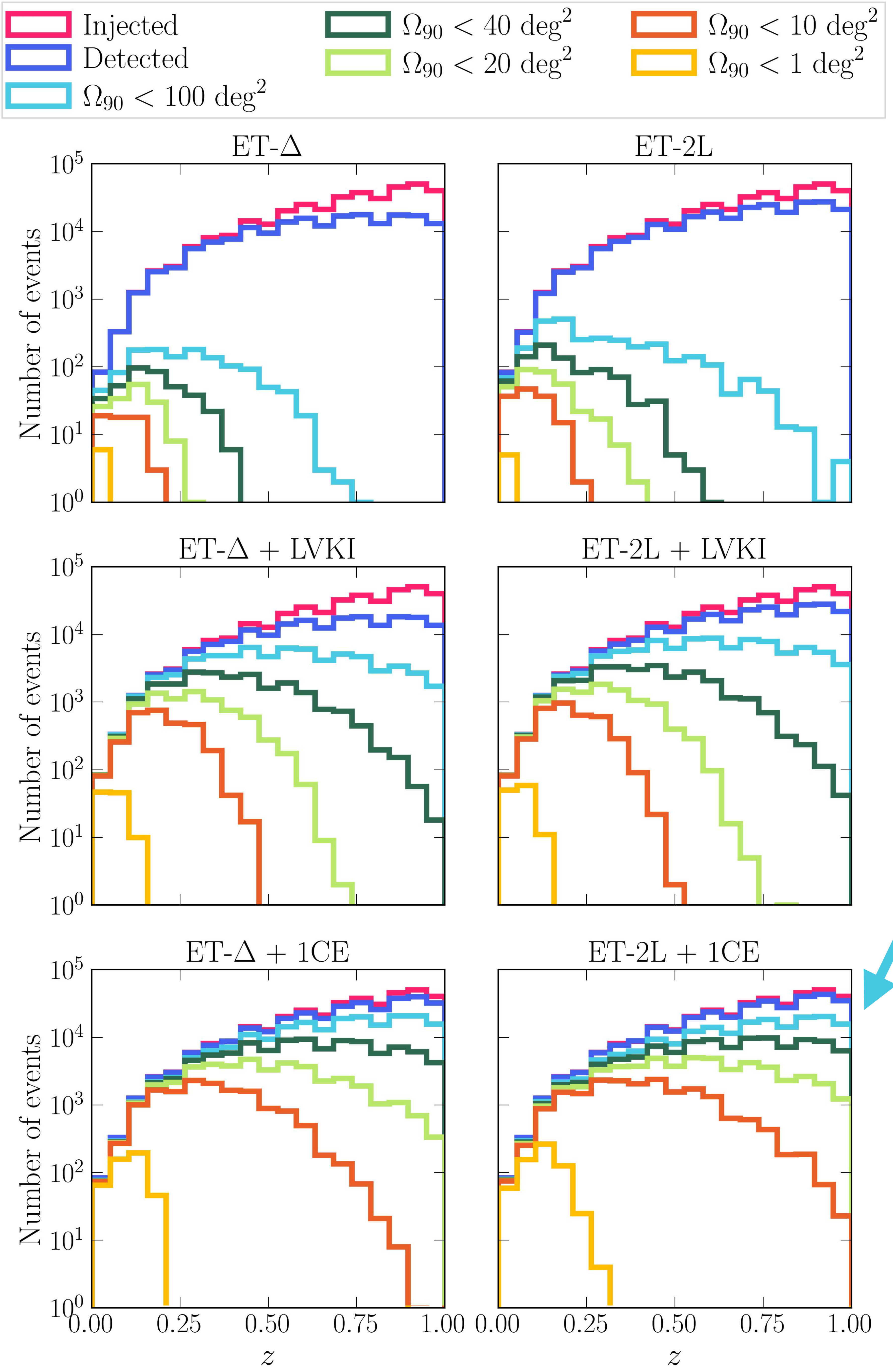
Step 2 - Simulating GW detections

- Two ET configurations: **2L** and **Δ**
- GW networks → ET, ET + LVKI (O5 sens.), ET + 1CE (40 km), ET + 2CE (USA, Australia)
- 64 simulations for 10 years of mergers



- Local merger rate: dominant source of uncertainty in GW detection rate (factor 5)
- NS mass distribution: 25% more detections for uniform NS mass distr. wrt Gaussian
- EOS: less than 5% impact on detection rate

Loffredo, Hazra, Dupletsa, et al., A&A, 2025



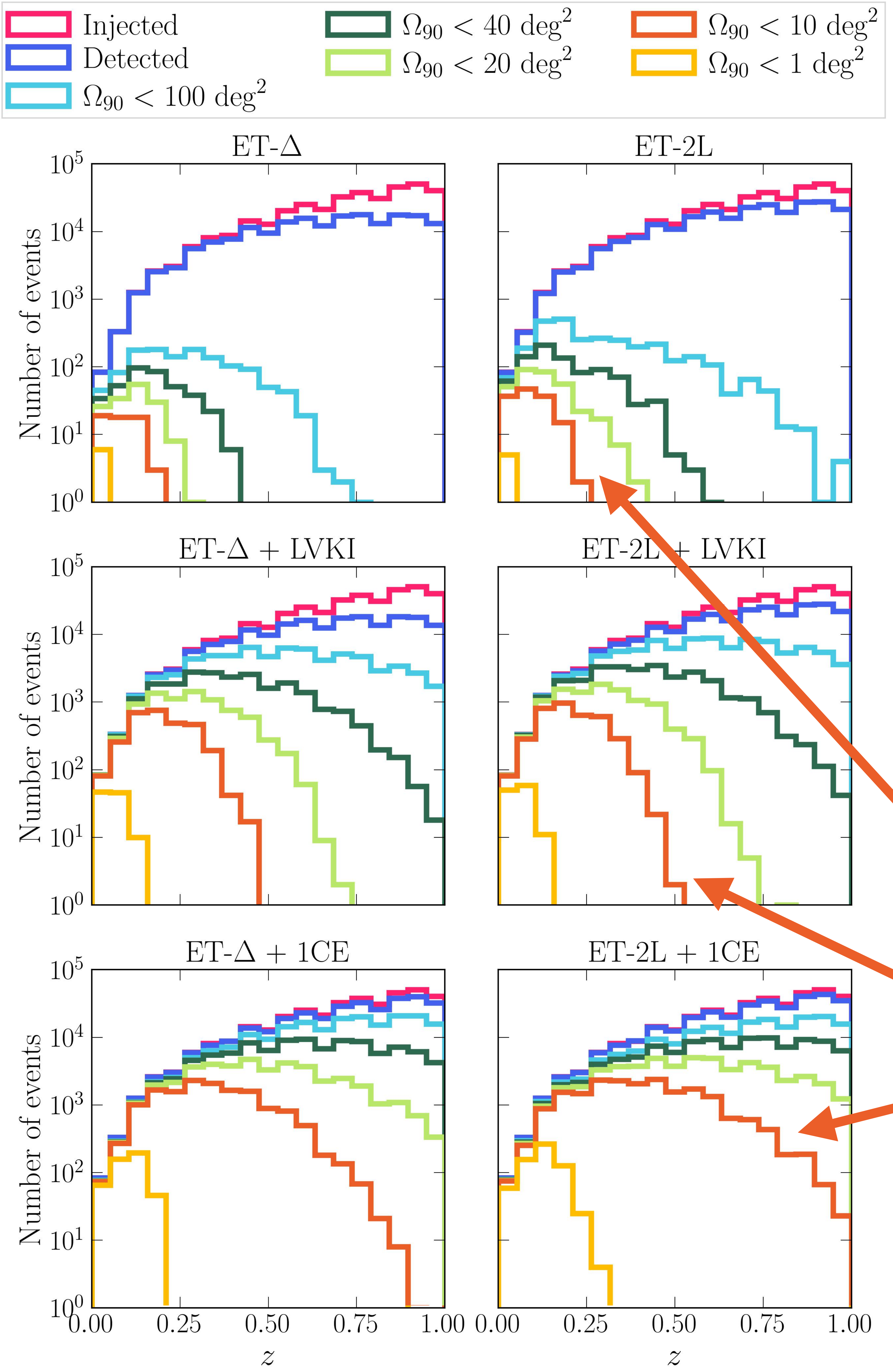
Injected/Detected

- ET-2L 30% more detections wrt ET-triangle
- ET+LVKI negligible increase of detections wrt ET
- ET + CE about a factor 2 increase of detections wrt ET

Relatively well localised events

- ET-2L twice detections wrt ET-triangle
- $O(10^2)$ per year by ET
- $O(10^3)$ per year by ET+LVKI
- $O(10^4)$ per year by ET+CE

FIDUCIAL POPULATION



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FIDUCIAL POPULATION

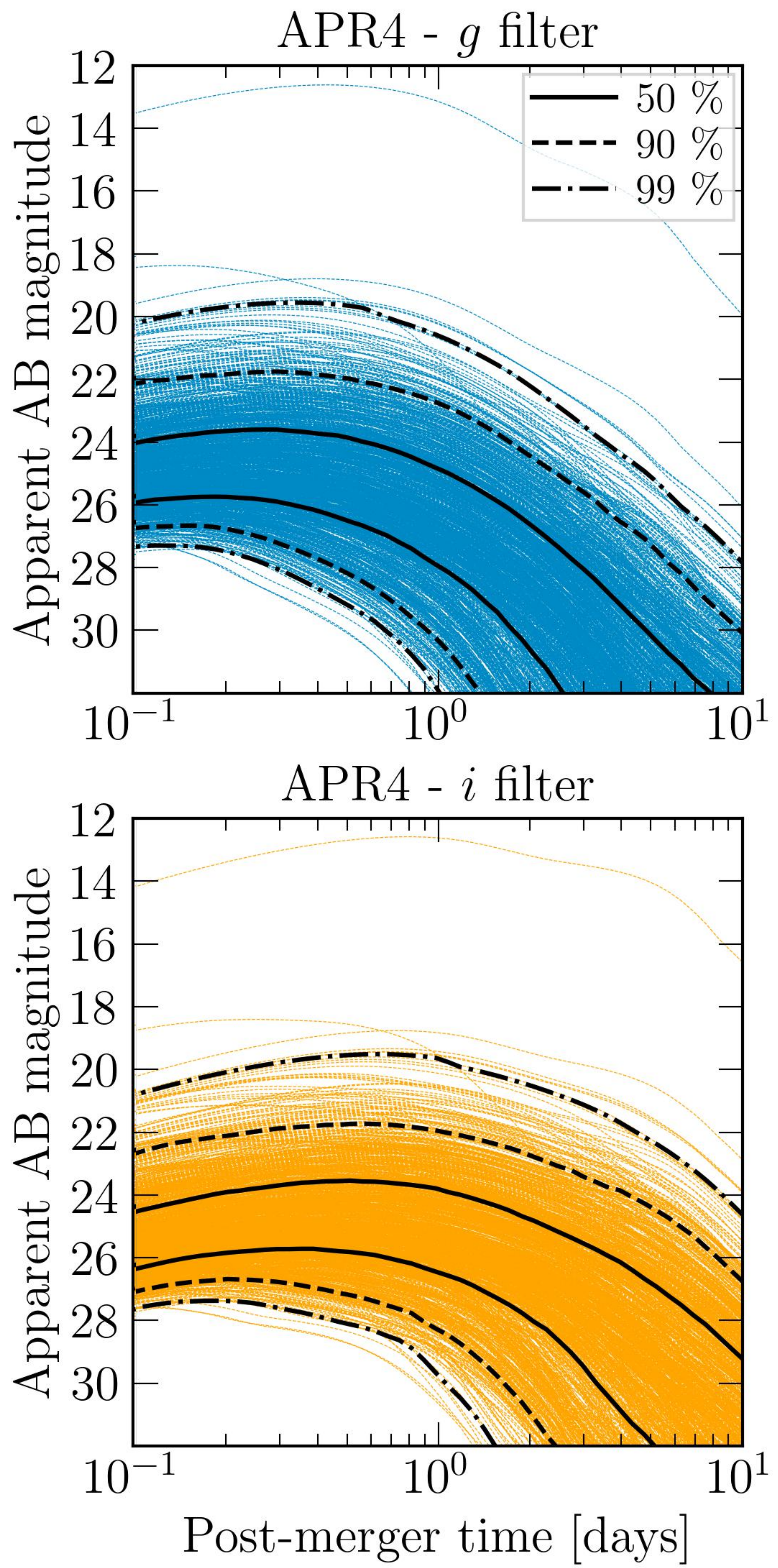
Well localised events (< 10 deg^2)

- ET-2L three times detections wrt ET-triangle
- A few per year by ET
- $O(10^2)$ per year by ET+LVKI
- Networks enable localisation up higher z

FIDUCIAL POPULATION

Step 3 - KN modelling

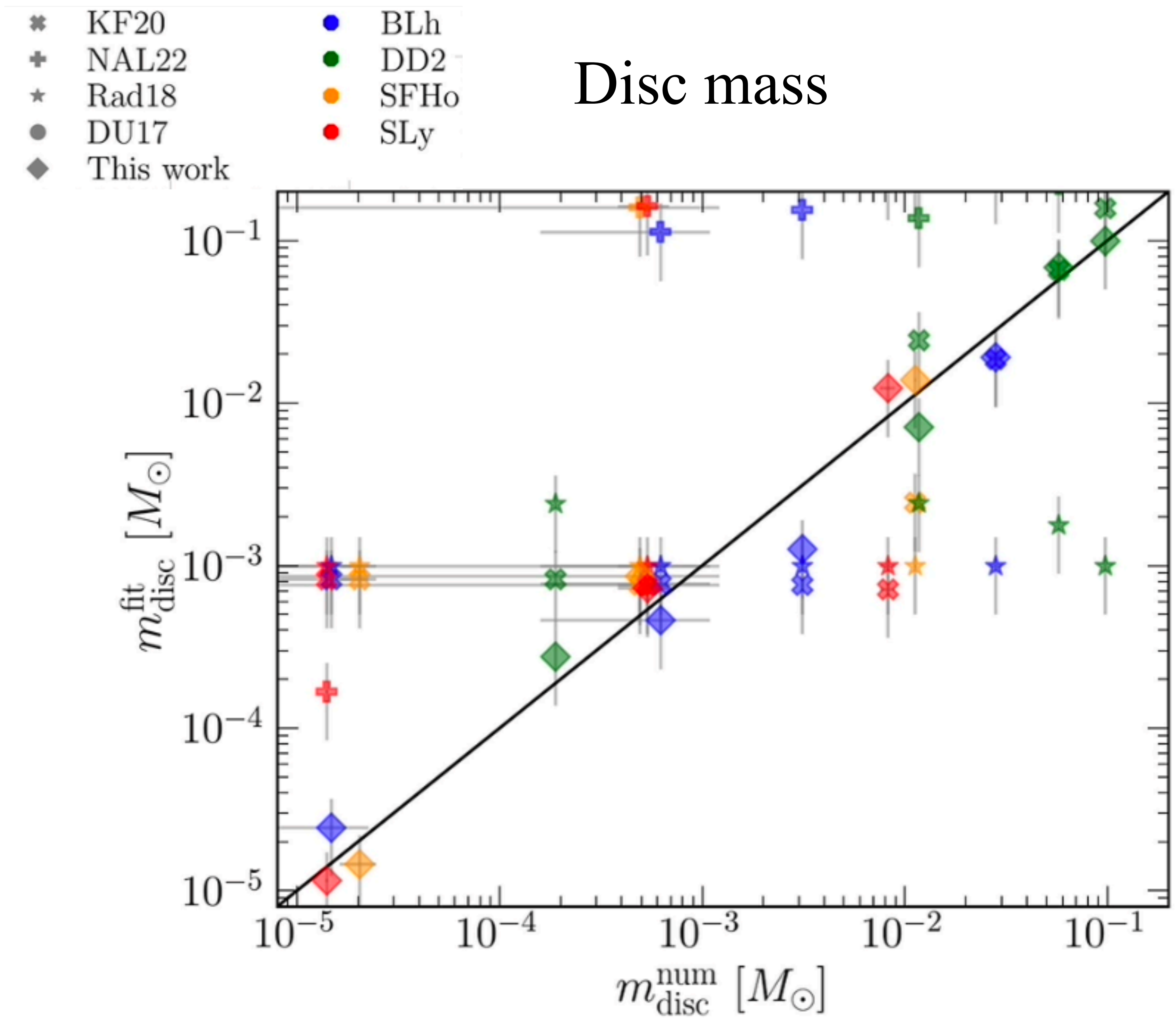
- Multi-component ejecta: dynamical + spiral wind + secular
- Ejecta from numerical relativity informed fits
- Prompt collapse mass threshold M_{thr} from NR informed fits
  [Perego + 2022; Kashyap + 2022]
- Below M_{thr} → fitting formulas calibrated on GW170817
  [Radice + 2018; Krüger & Foucart 2020; Nedora + 2019]
- Above M_{thr} → new fitting formulas calibrated on GW190425
  [Loffredo + 2025; Camilletti + 2022]



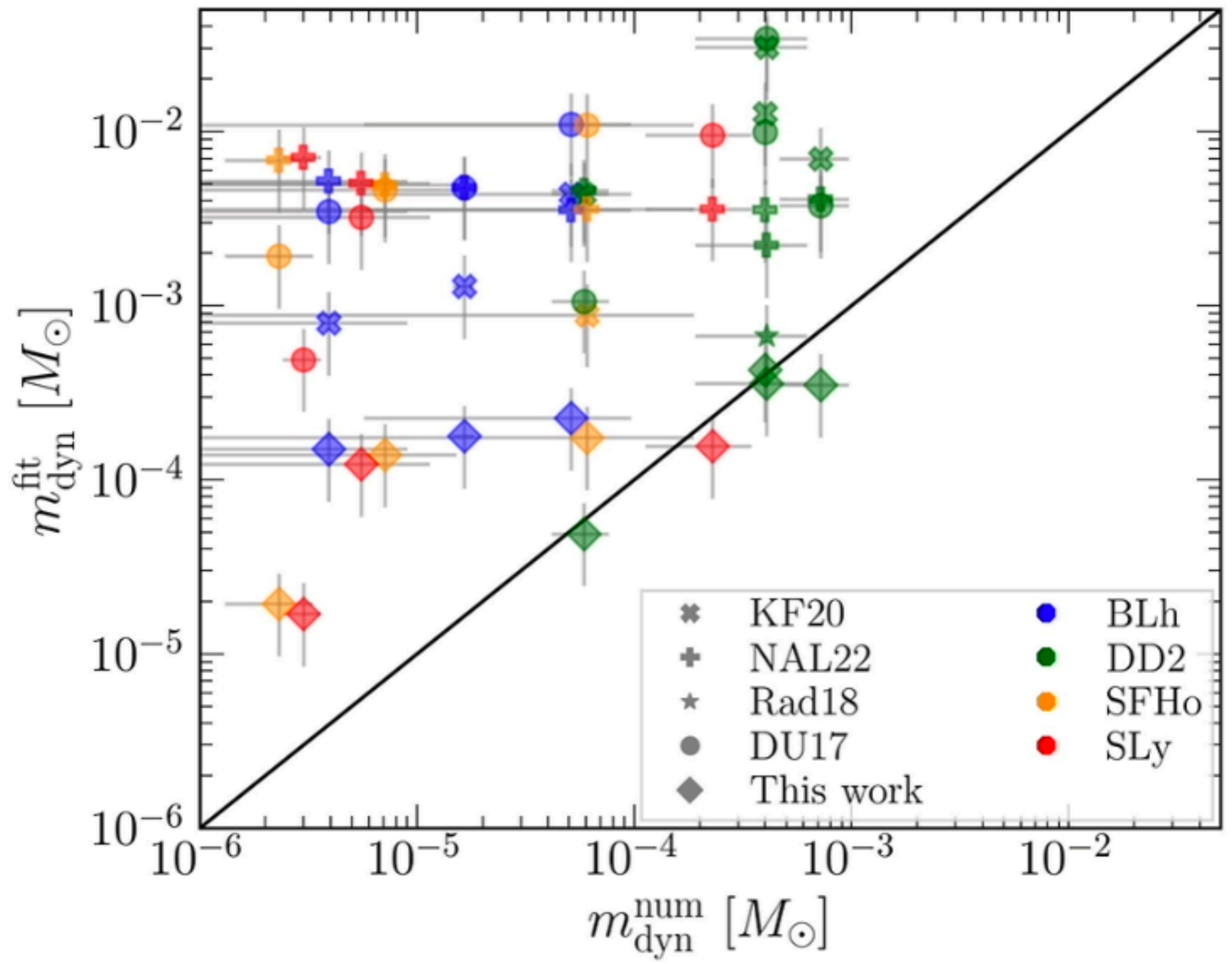
Loffredo, Hazra, Dupletsa, et al., A&A, 2025

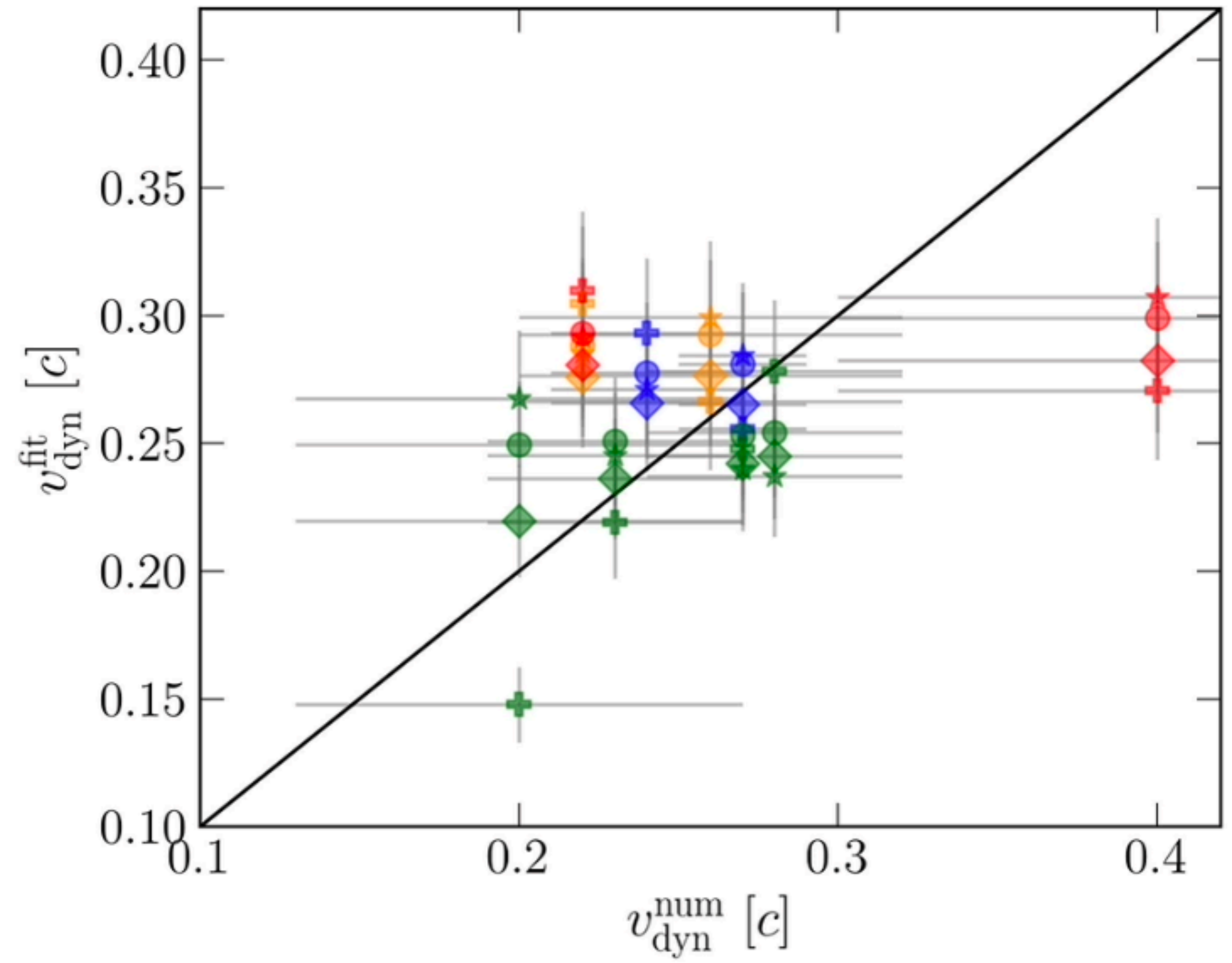
Comparison of fits

Disc mass

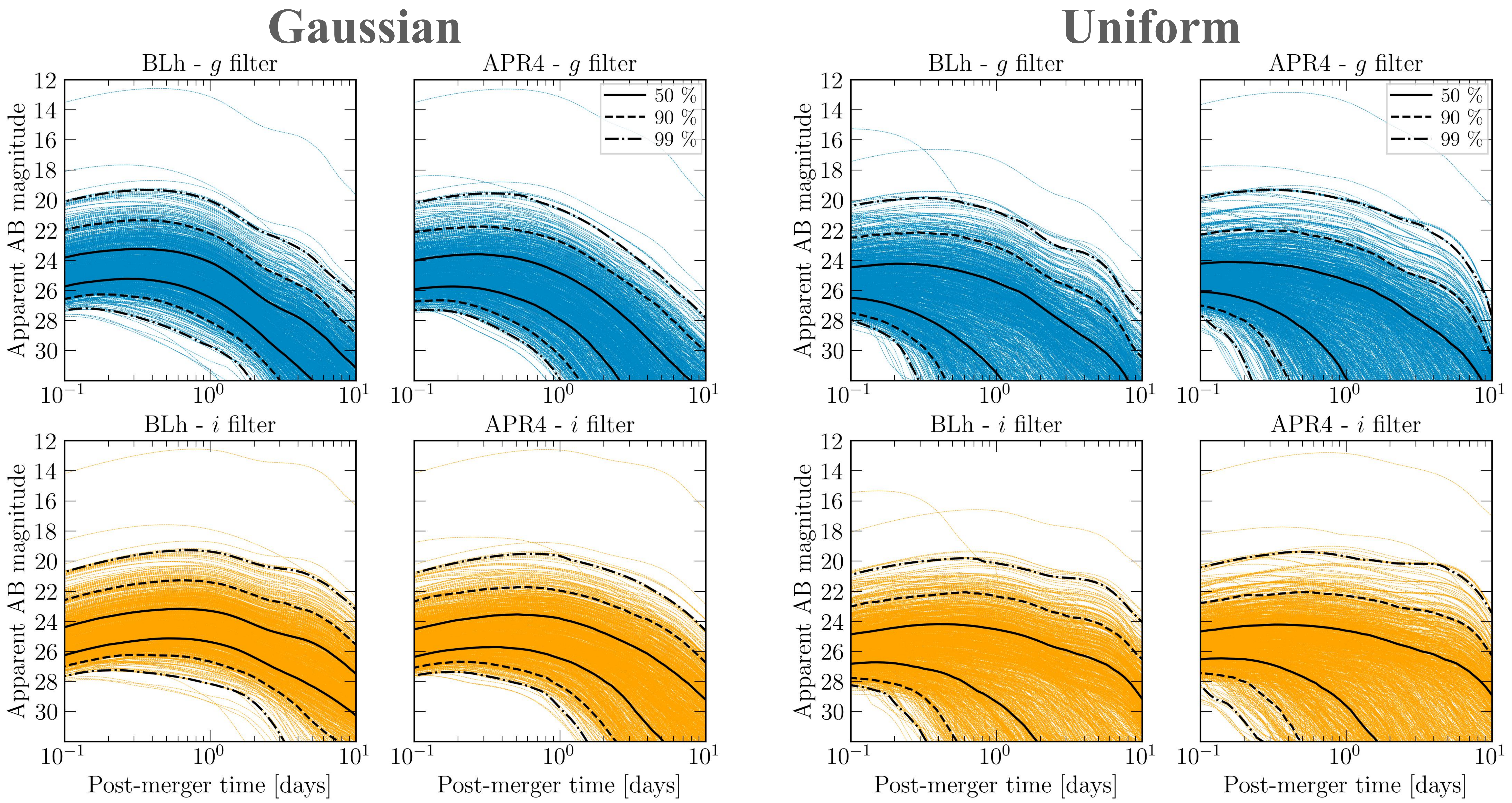


Loffredo, Hazra, Dupletsa, et al., A&A, 2025





Dynamical Ejecta (mass and velocity)

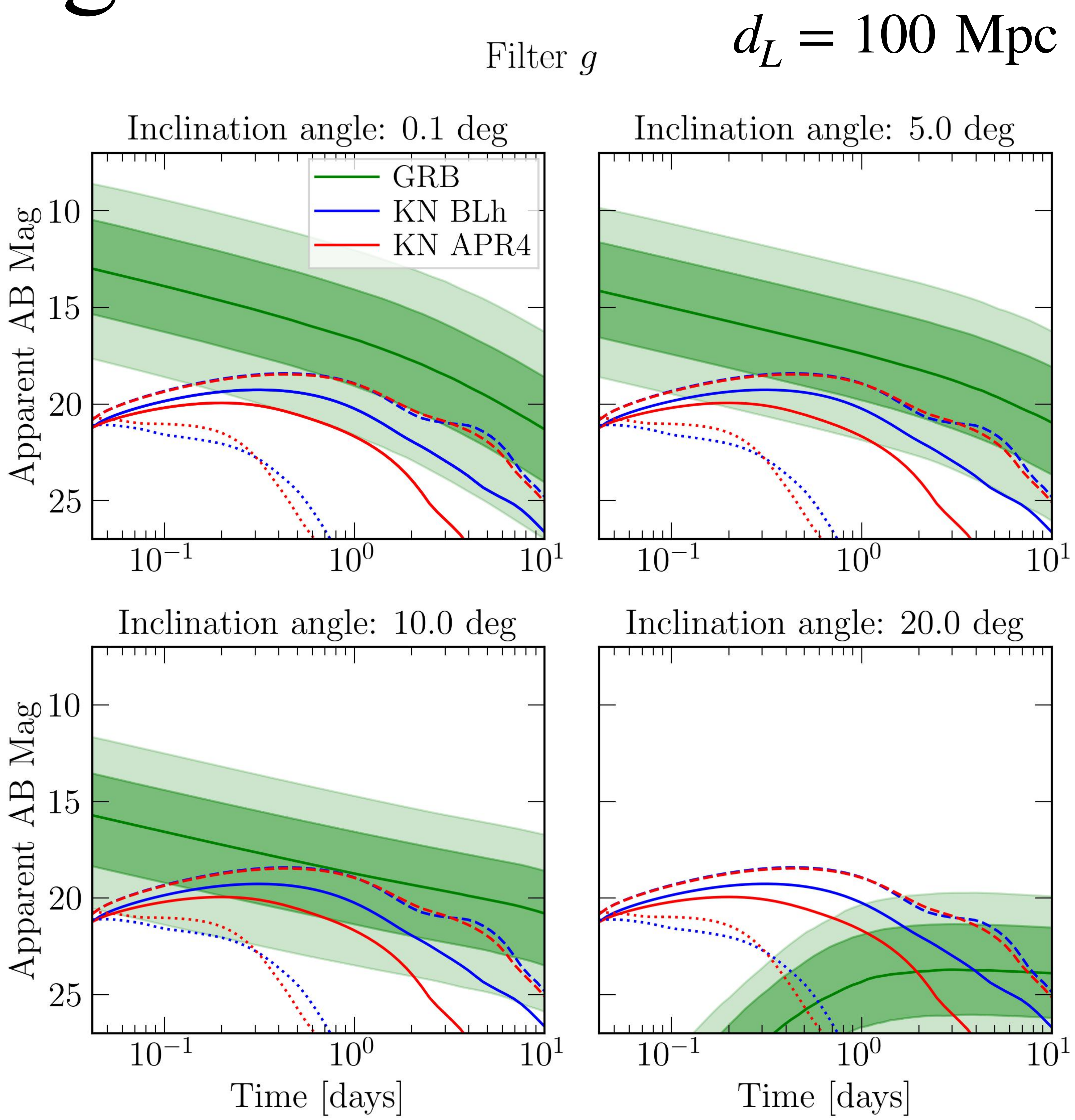


BLh EOS → At the peak LC brighter by half to one magnitude and evolving more slowly than APR4

Uniform NS mass distr. → high mass systems, prompt collapse, fainter lightcurves than Gaussian

Step 3 - GRB optical afterglow

- Consistent with observed range of optical fluxes of short GRBs [Kann + 2011]
- Fraction of BNS producing relativistic jet calibrated on sample of observed GRB [Ronchini + 2022]
- Afterglow outshines KNe for viewing angles < 15deg
- KNe dominate early emission at viewing angles > 20deg
- Brightest KNe overcome a non-negligible portion of the afterglows at any angle a few hours after merger



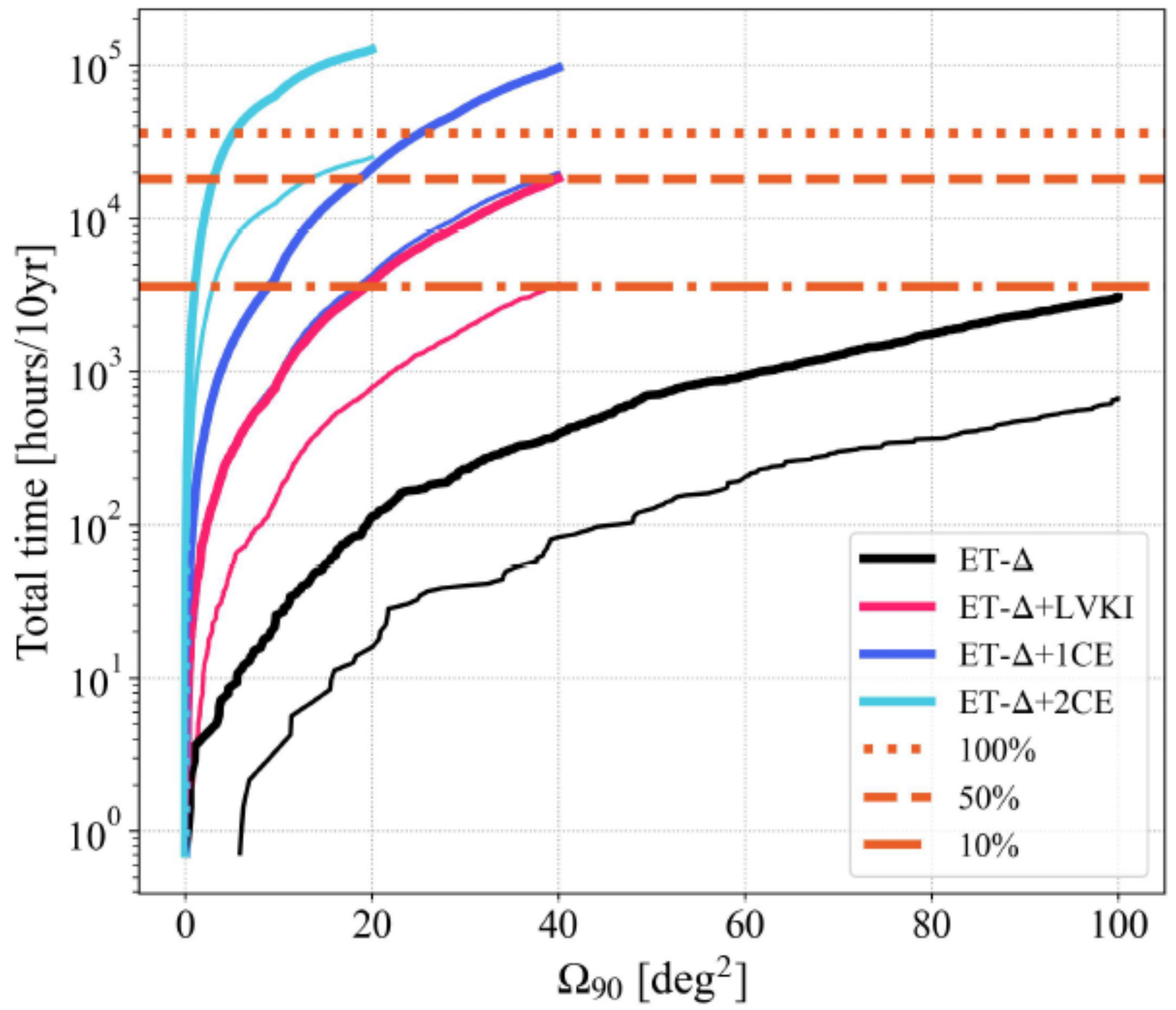
Loffredo, Hazra, Dupletsa, et al., A&A, 2025

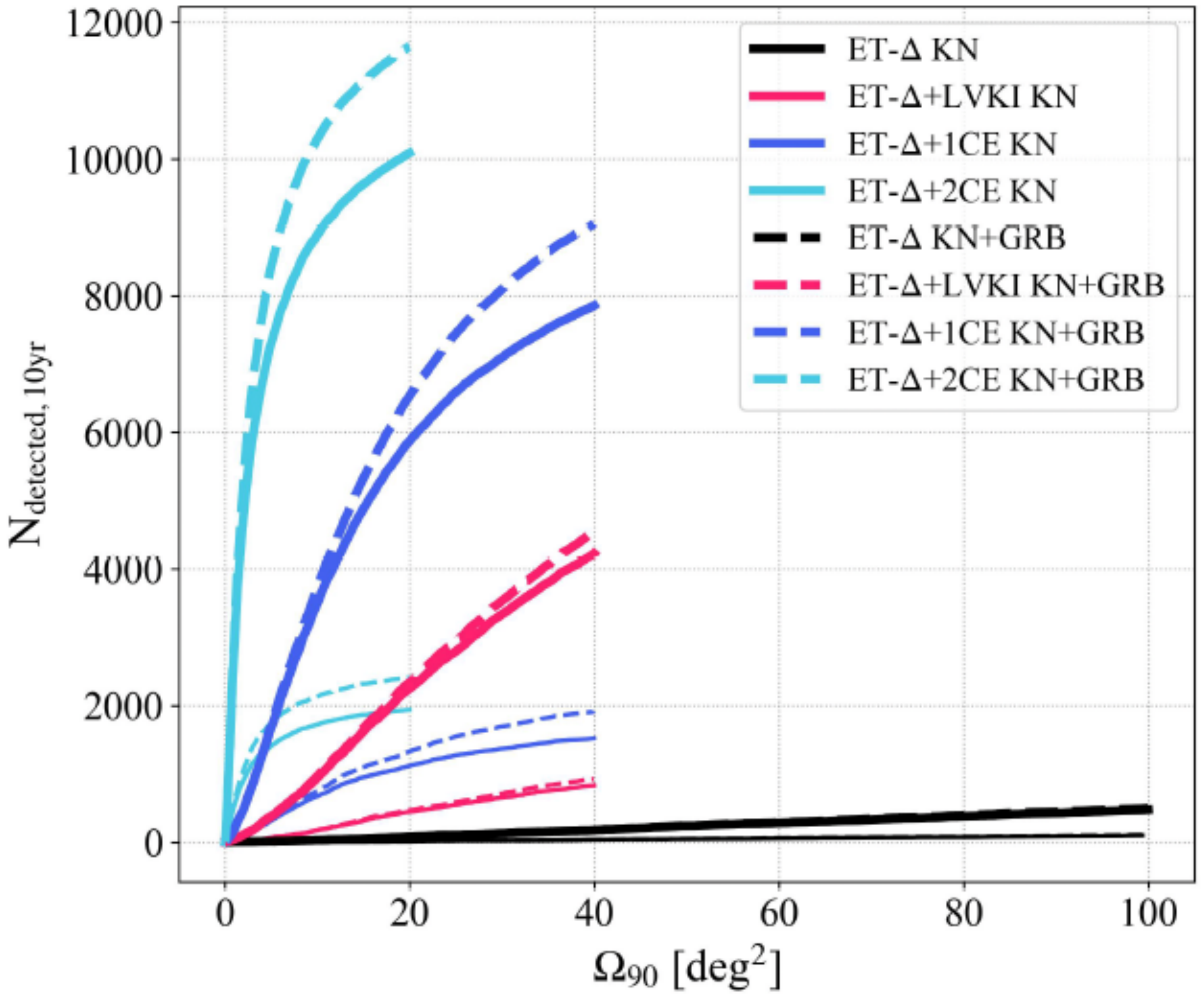
Step 4 - Rubin's follow-up

- Events in Rubin's footprint and localised better than a certain $\Delta\Omega_{90}$
- KN follow-up → filters *g* and *i*, mosaic to scan the error region, 600s each pointing (corresponding to lim mag 26.53 in *g* and 25.59 in *i*)
- Two epochs of observations over two/three nights (detection when at least two filters detections in one epoch)

> - ET → Rubin 10-100 KNe per year
> - ET+LVKI → Rubin detection increase by one order of magnitude wrt ET
> - ET+1CE → Rubin detection increase by 3 wrt ET+LVKI (limited by Rubin detection efficiency for KNe)

Loffredo, Hazra, Dupletsa, et al., A&A, 2025





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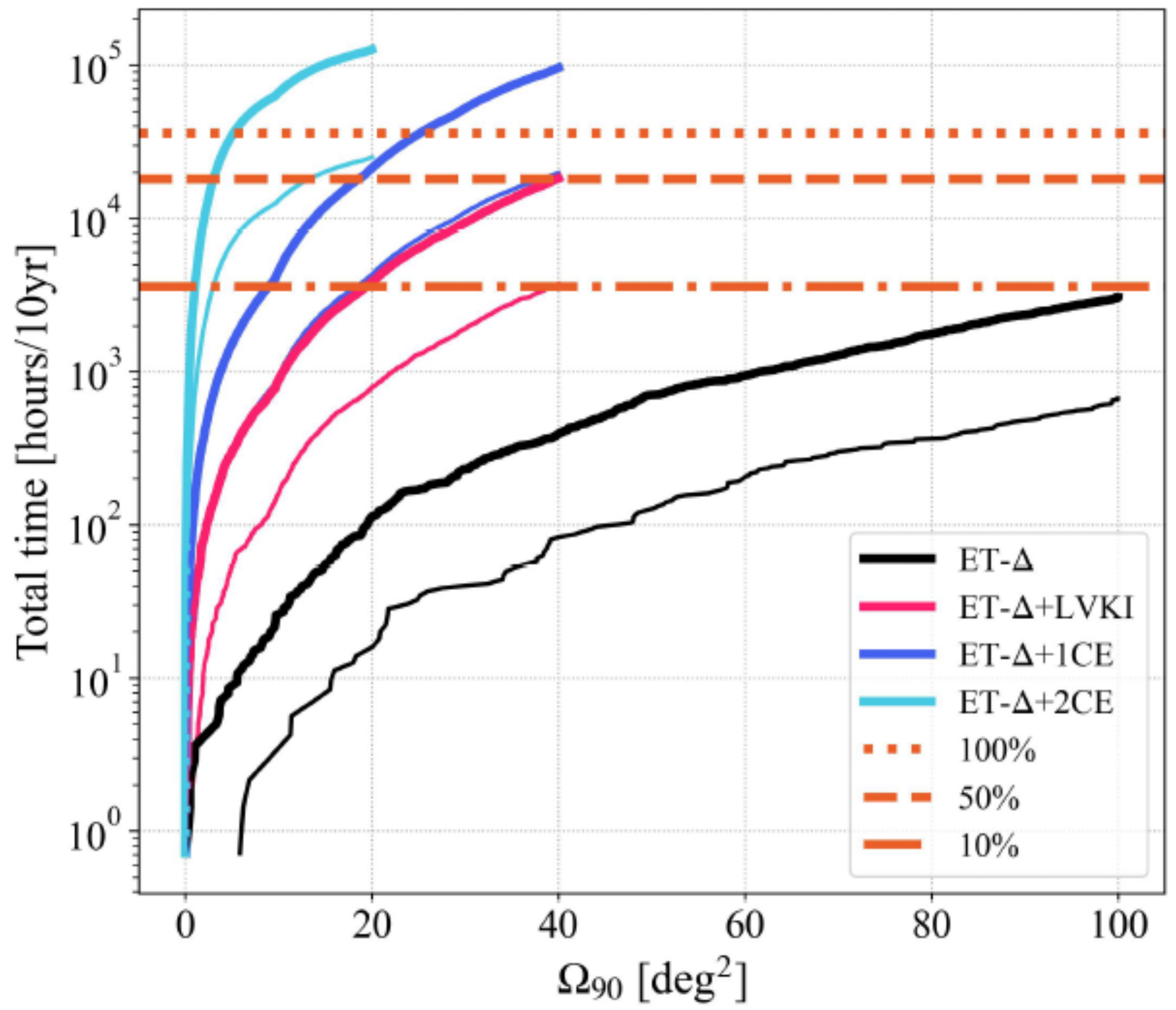
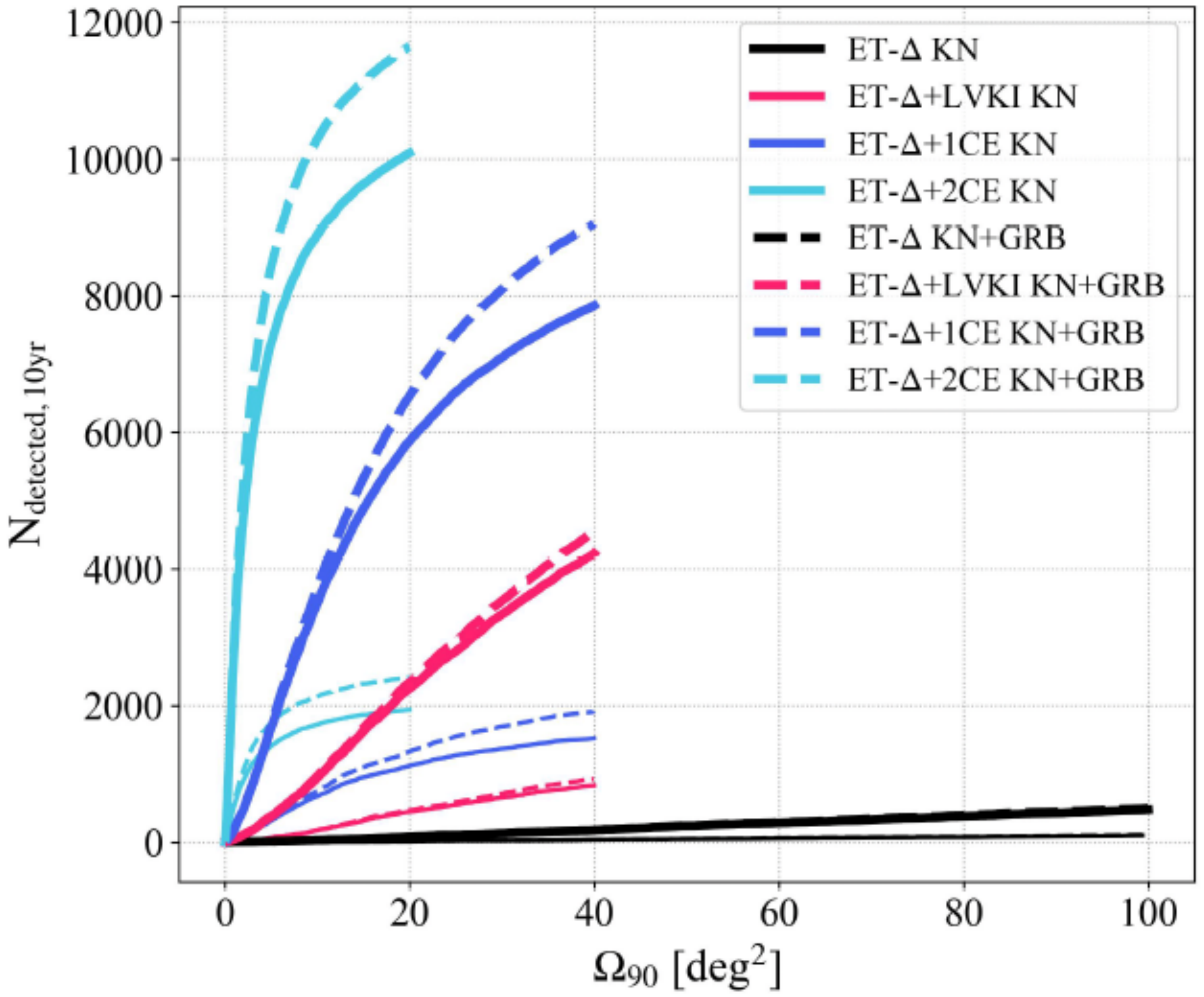
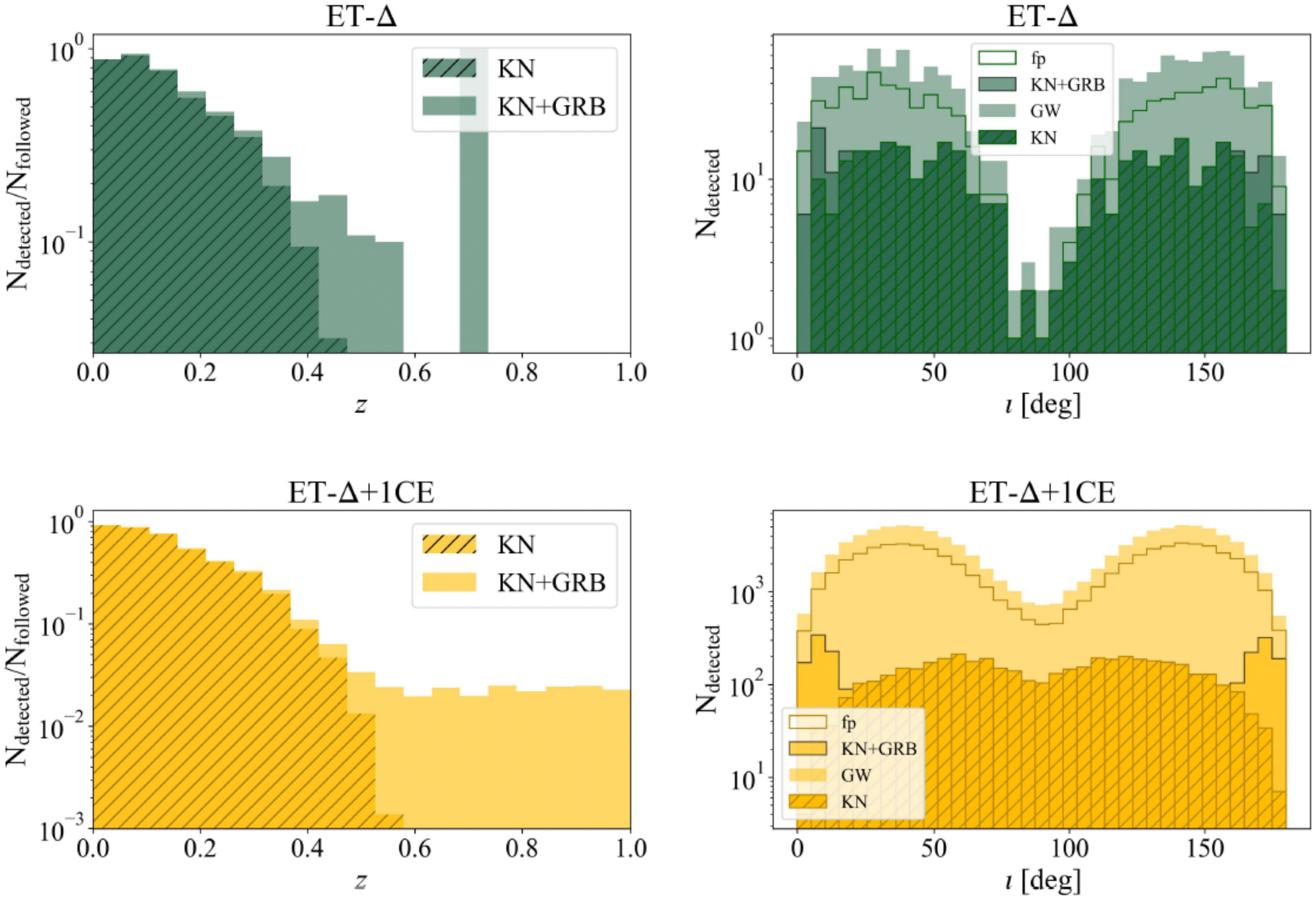
> - Uncertainty in absolute number of KN detections dominated by BNS merger local rate
> - NS mass distr., EOS, and KN modelling affect detection rate to much lesser extent and interplay in complex way → challenging to disentangle individual effects

Loffredo, Hazra, Dupletsa, et al., A&A, 2025





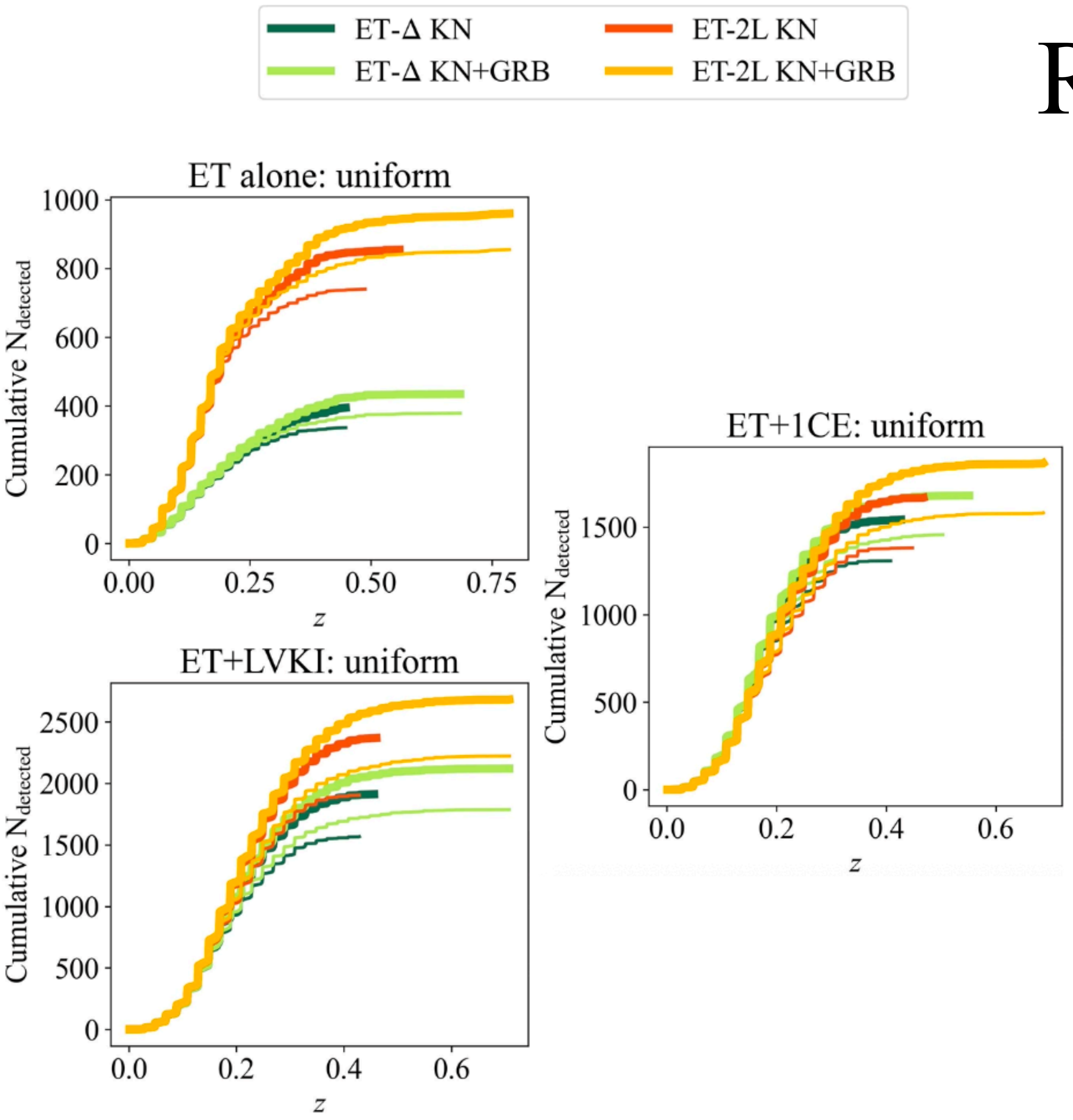
Rubin’s detection efficiency



Efficiency drops at 30% already at redshift $z \sim 0.3$
→ no gain from improved localisation accuracy at high z for KNe detection, big gain for GRB afterglow detection

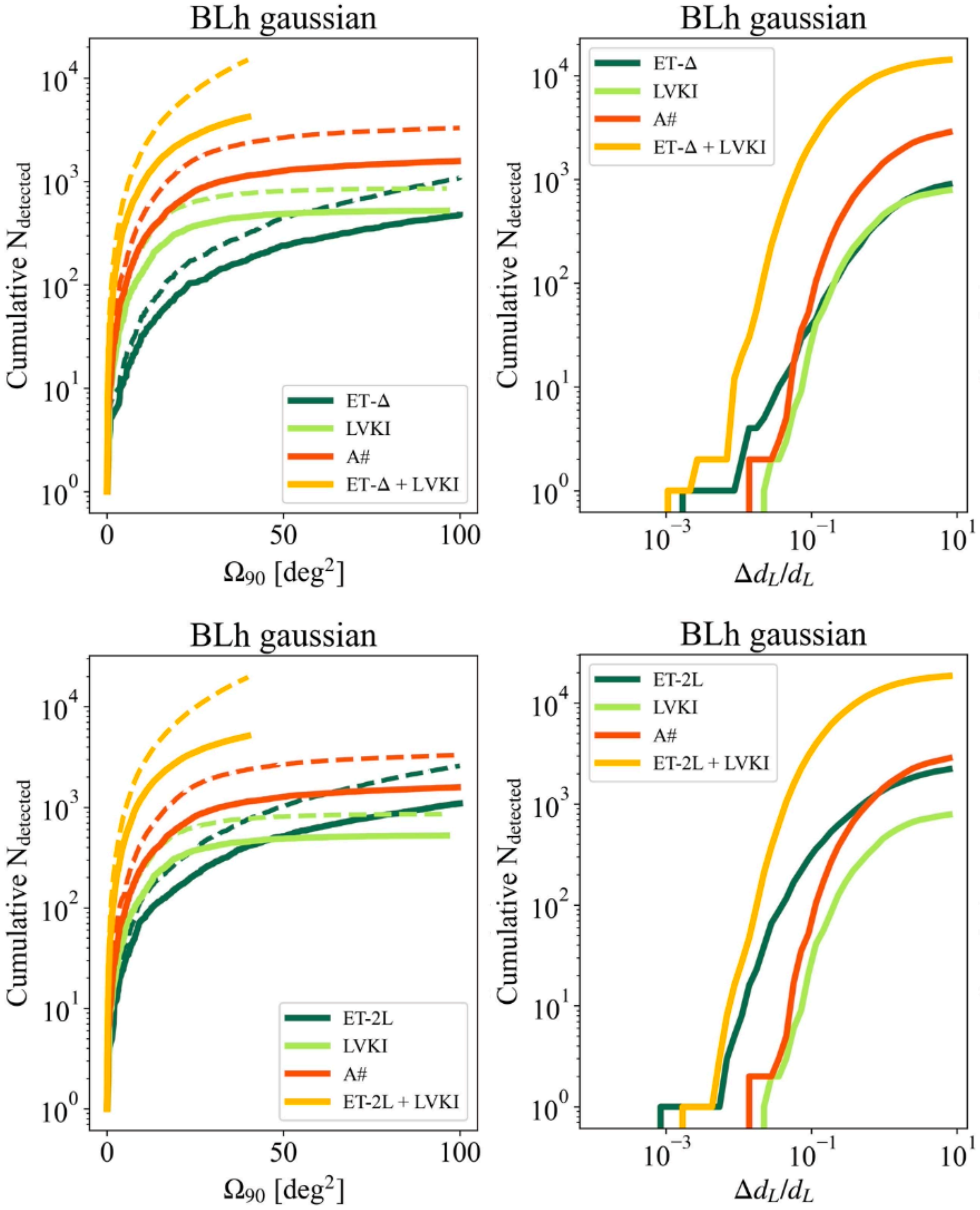
Loffredo, Hazra, Dupletsa, et al., A&A, 2025

Rubin’s deeper observations



- Cumulative number of joint detections for Rubin’s pointing of 600s (thin lines) vs 1200s (thick lines)
- Limited increase in absolute number of joint detections (less than 25%)
- Increase in Rubin’s observing time (from 20% to 50% for ET alone)
- Enhanced probability to detect KN at higher redshift

Loffredo, Hazra, Dupletsa, et al., A&A, 2025



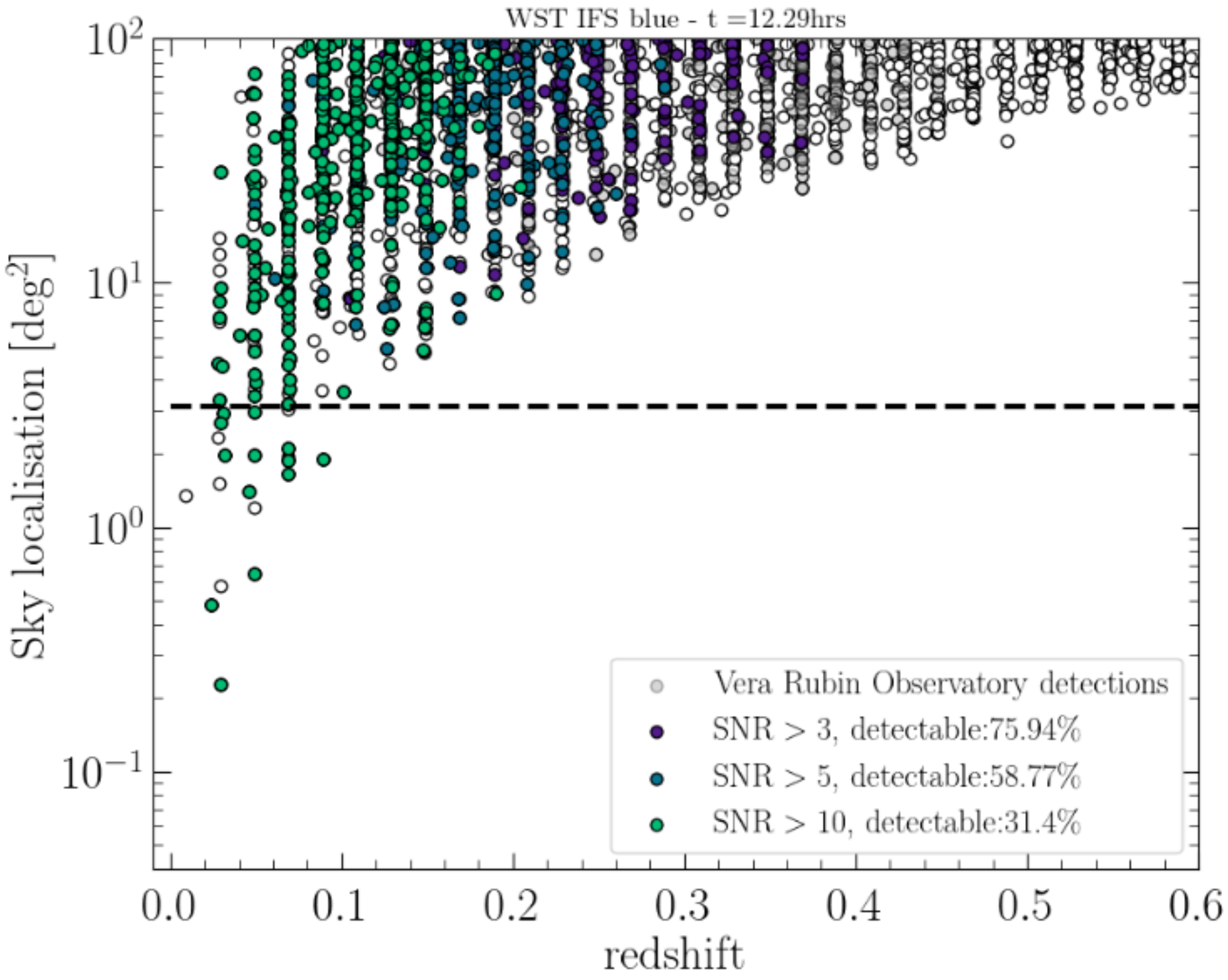
Comparison with LVKI and 3A#

- Rubin operating with 3A# outperforms ET-Triangle by a factor 3-4
- Rubin operating with ET-2L outperforms LVKI and approaches 3A#
- ET alone: much better estimates of source parameters, eg. luminosity distance

Loffredo, Hazra, Dupletsa, et al., A&A, 2025

Synergy ET and WST

- WST → next-generation wide field spectroscopic telescope, large FoV, MOS & giant IFS
- Joint GW/KN detections up to $z < 0.2$ with SNR > 10
- Joint GW/KN detections up to $z \sim 0.4$ with SNR > 3 - 5

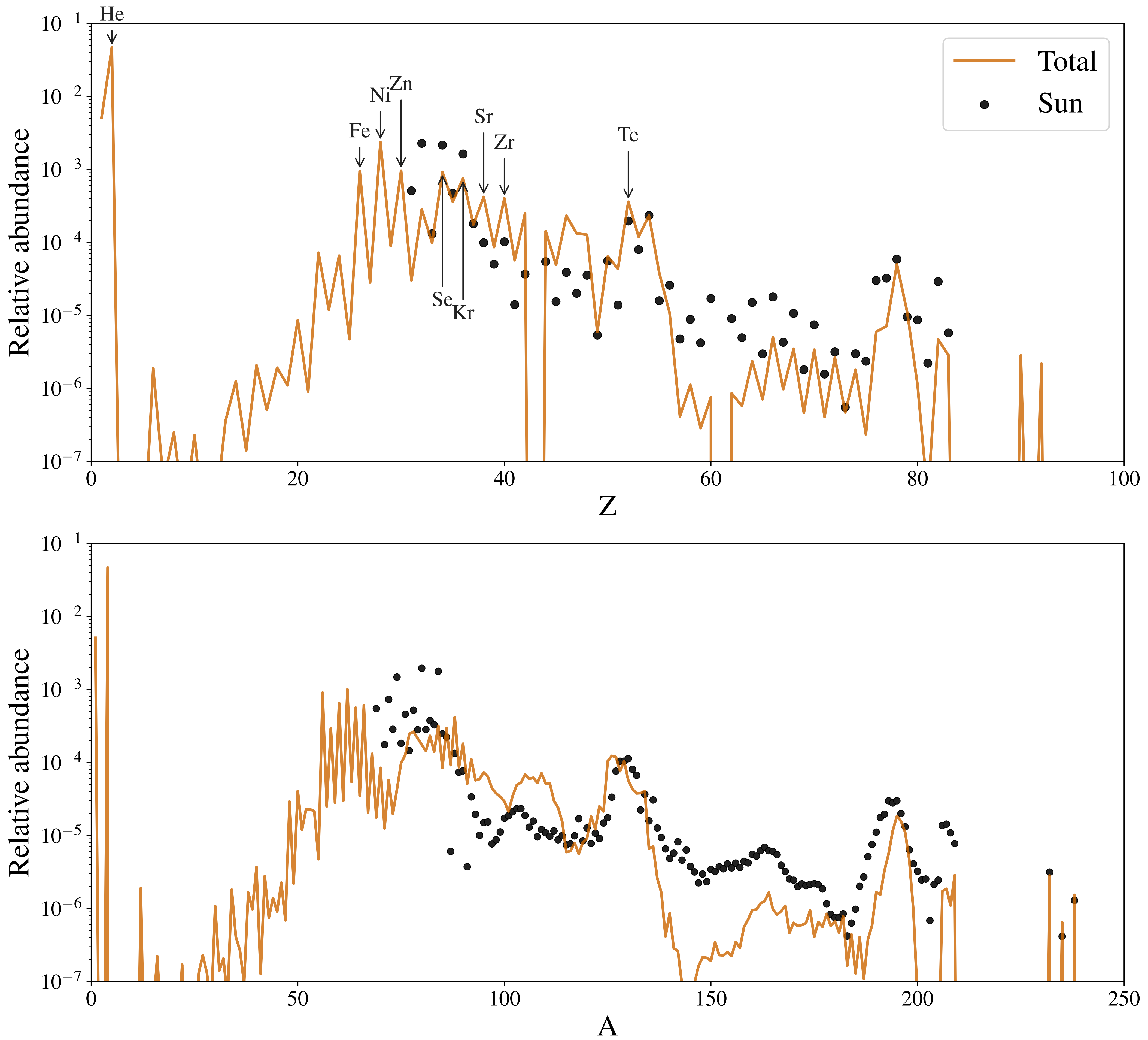


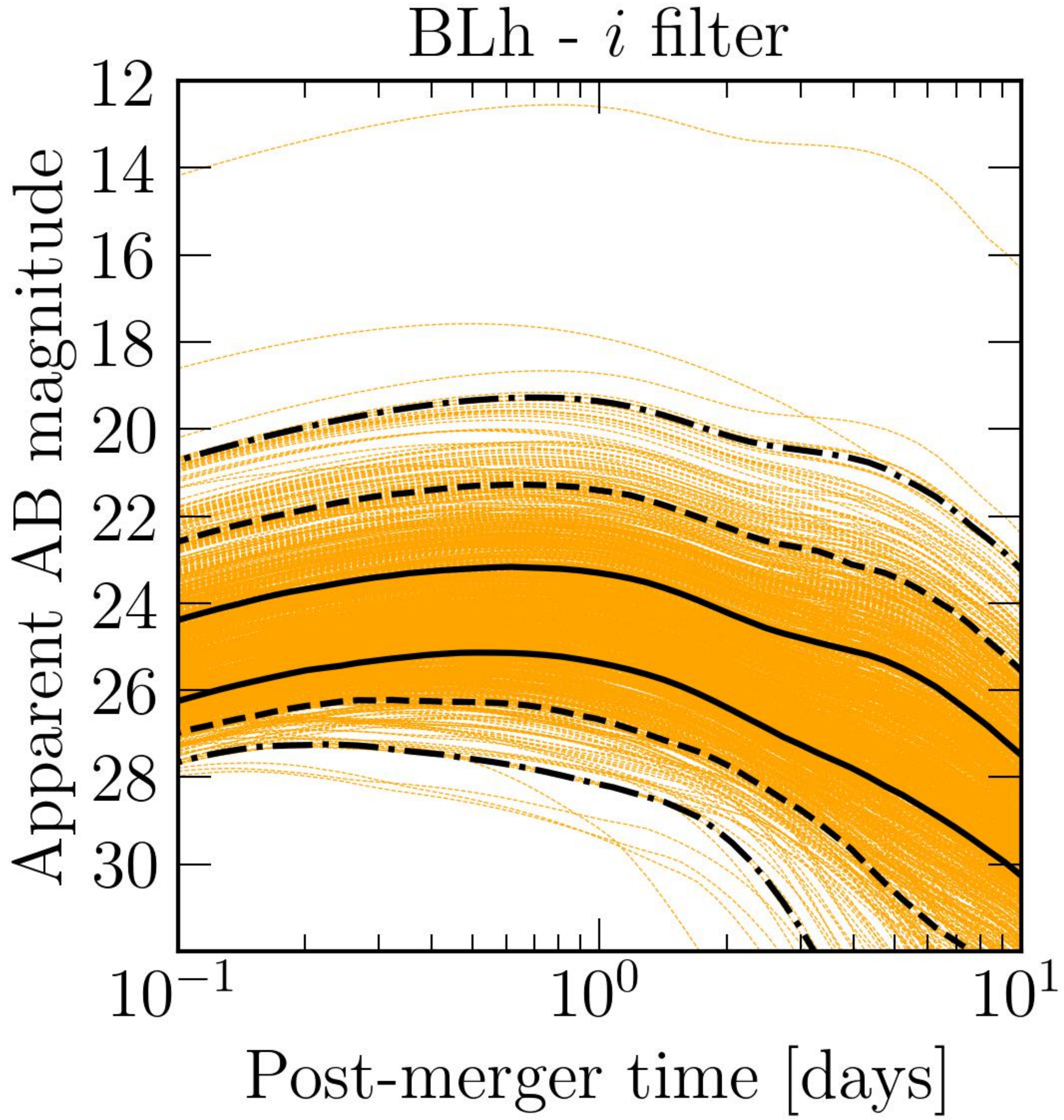
Bisero, Vergani, Loffredo et al., arXiv:2507.02055v1

Key points - 2

- ET alone operating with Rubin: will enable detection of 10-100 KNe per year
- ET in a network of current or next-gen detectors: several hundreds of KNe per year
- Largest source of uncertainty: BNS merger rate
- ET in a network → extremely large number of alerts → need to optimise observational strategy on specific science cases (e.g. priority based on SNR / distance / component masses…)

Kilonova modelling: from r-process yields in binary neutron star mergers to population studies





Thank you