Illuminating neutrons star mergers with the radiative transfer code POSSIS

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Mattia Bulla

with: A. Neuweiler, S. Anand, L. Nativi, P. T. H. Pang, M. W. Coughlin, T. Dietrich, I. Tews, M. Shrestha, A. Goobar, S. Rosswog, S. Covino, M. Tanaka, K. Kyutoku and many more

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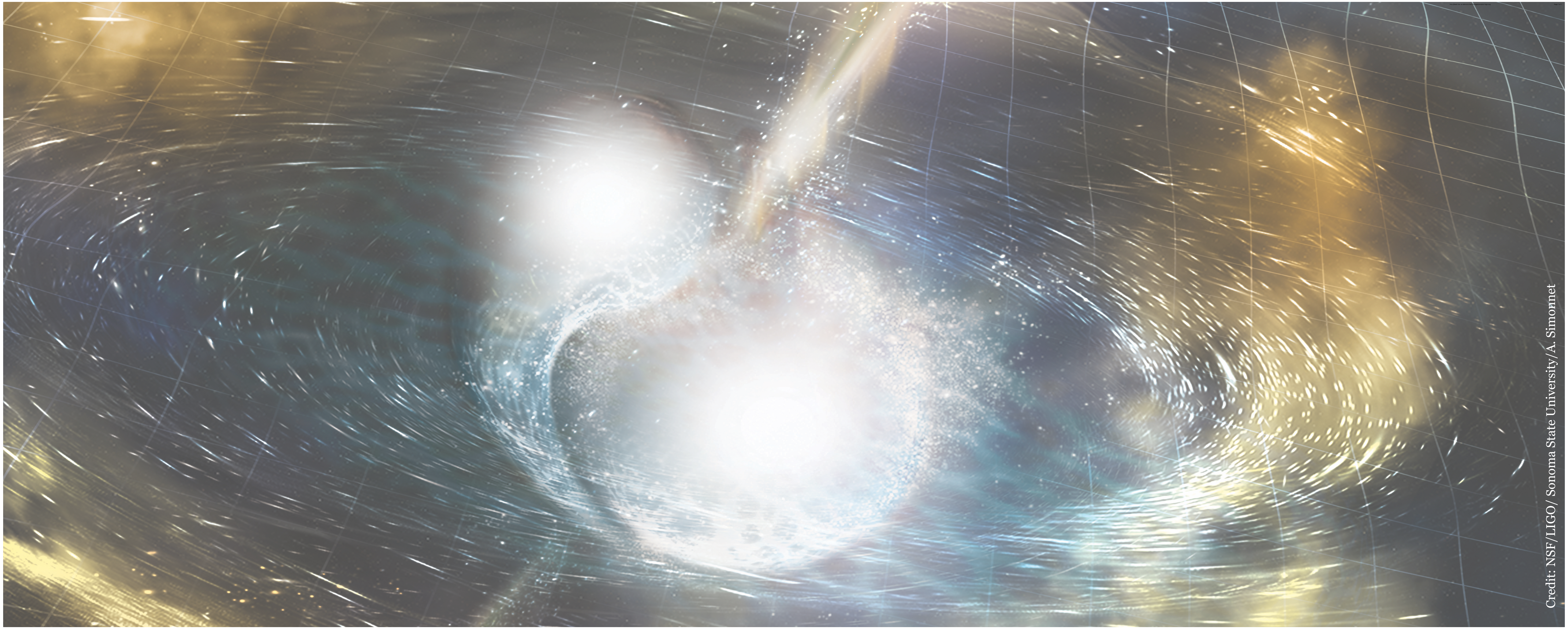
INAF Osservatorio Astronomico d'Abruzzo



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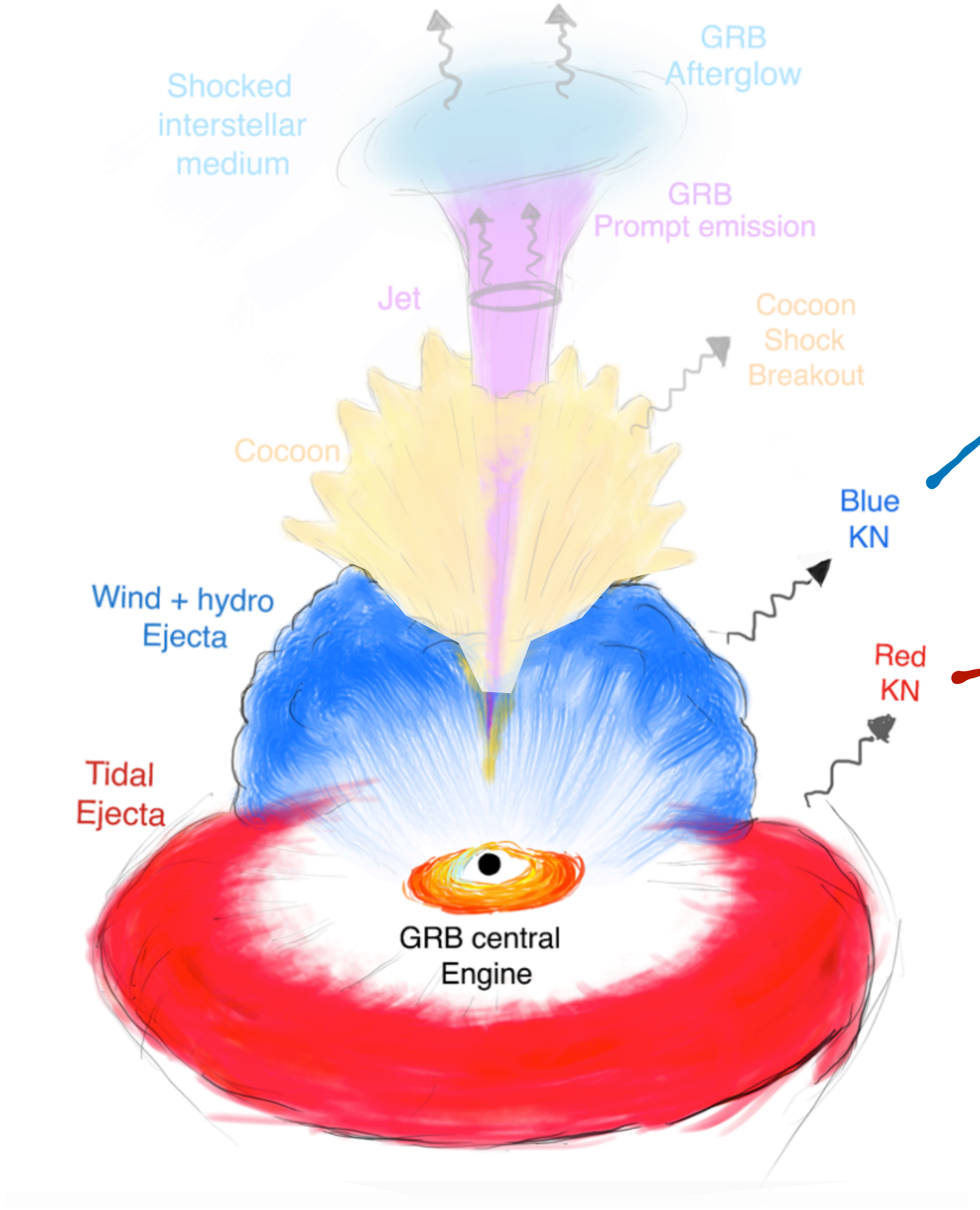
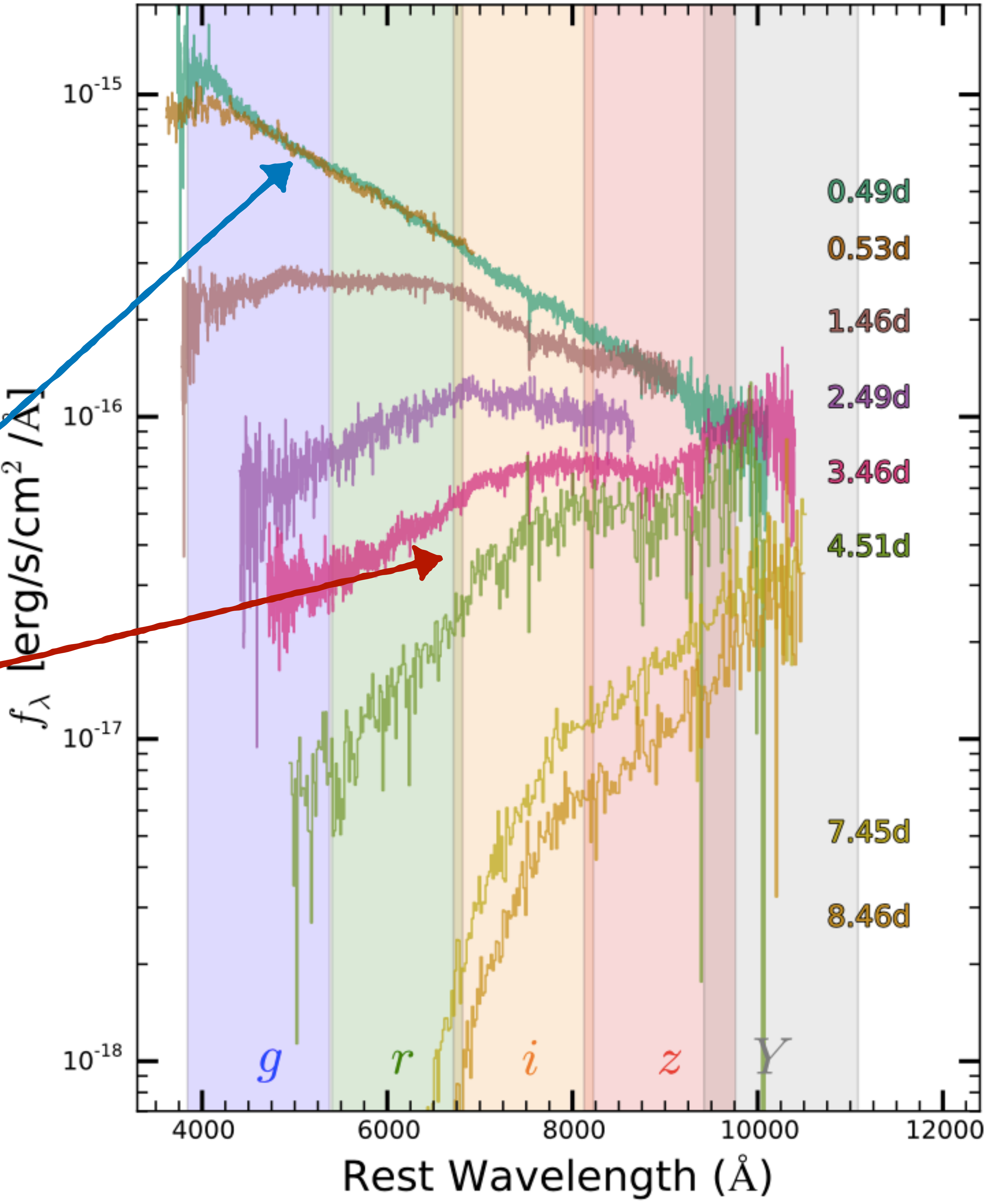
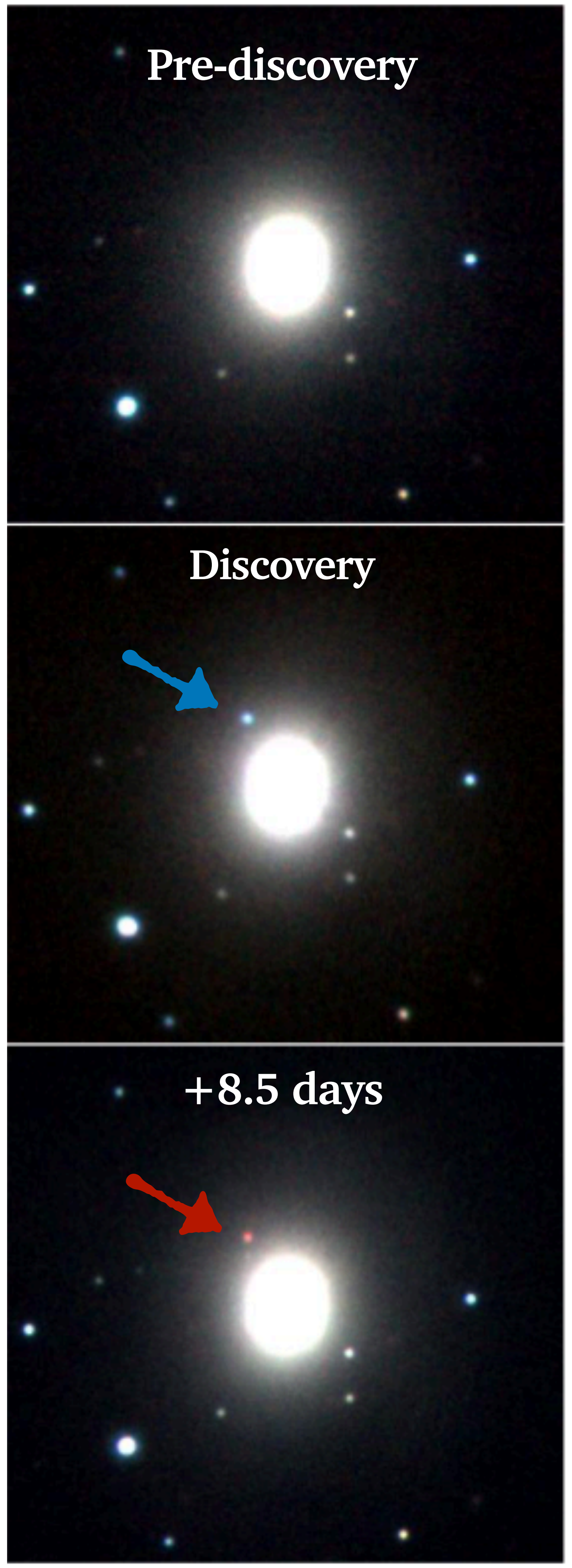
A red and a blue kilonova from GW170817



[Ascenzi+2021, Journal of Plasma Physics]



[Shappee+2017, Science]



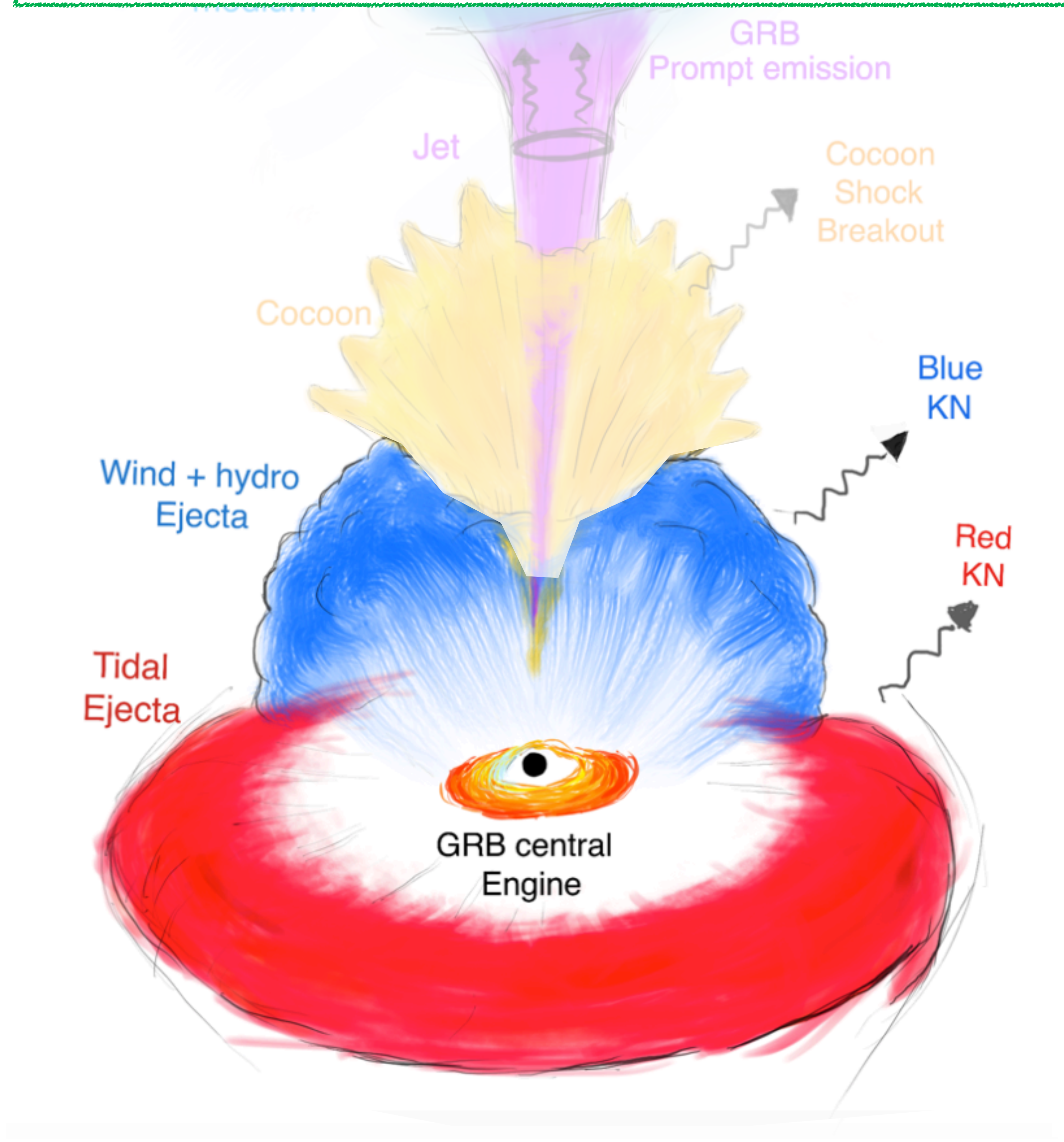
[Tanvir+2017, ApJ]

A red and a blue kilonova from GW170817

Parameters for red and blue KNe are extracted from **1D** and/or **semi-analytical** modelling

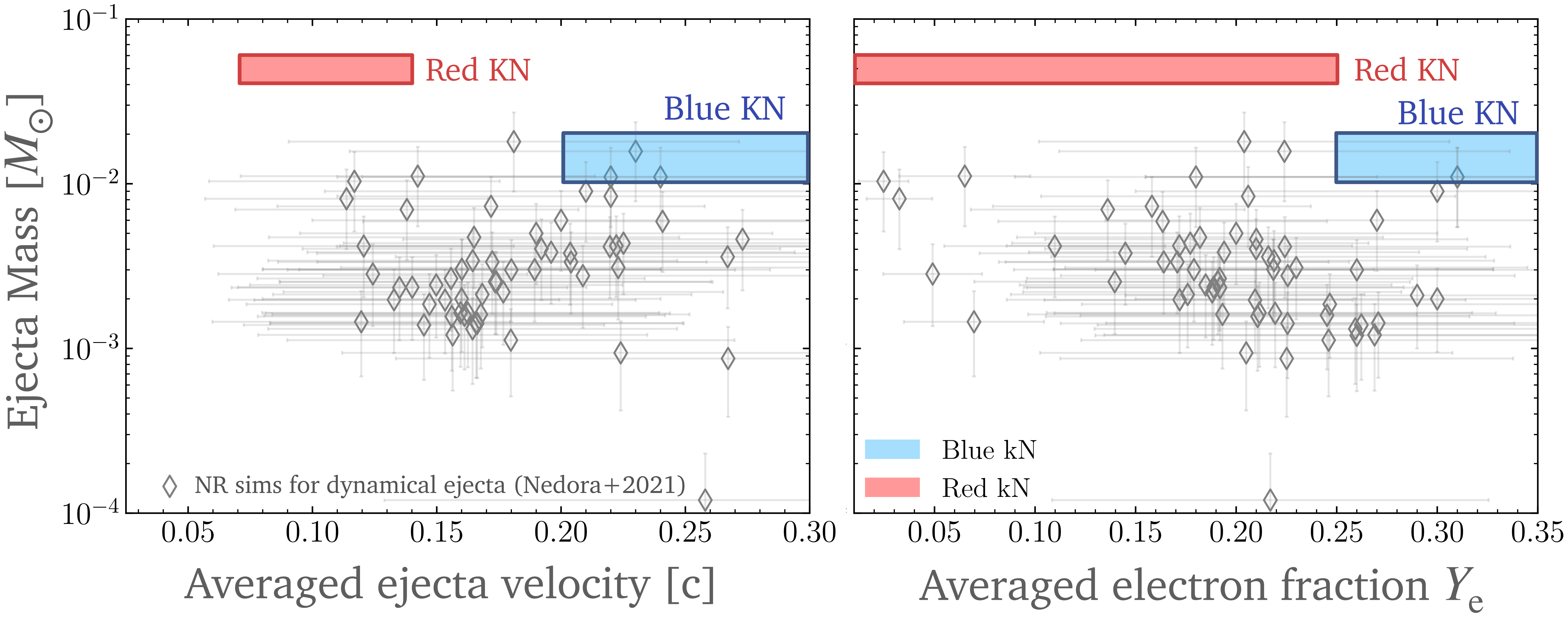
No geometry | No viewing angle dependence | No reprocessing

Simple heating rates (e.g. uniform) | Simple thermalisation efficiencies (e.g. uniform+constant) | Simple opacities (e.g. uniform+grey)



[Ascenzi+2021, Journal of Plasma Physics]

Masses for both red KN and blue KN are larger than predicted by NR simulations



Parameters for Red and Blue KN from [Siegel 2019, Eur. Phys. J. A.]

Kilonova modelling with POSSIS

A 3D Monte Carlo radiative transfer code to model explosive transients

[MB+2015, MNRAS; MB 2019, MNRAS; MB 2023, MNRAS]

Creating photons

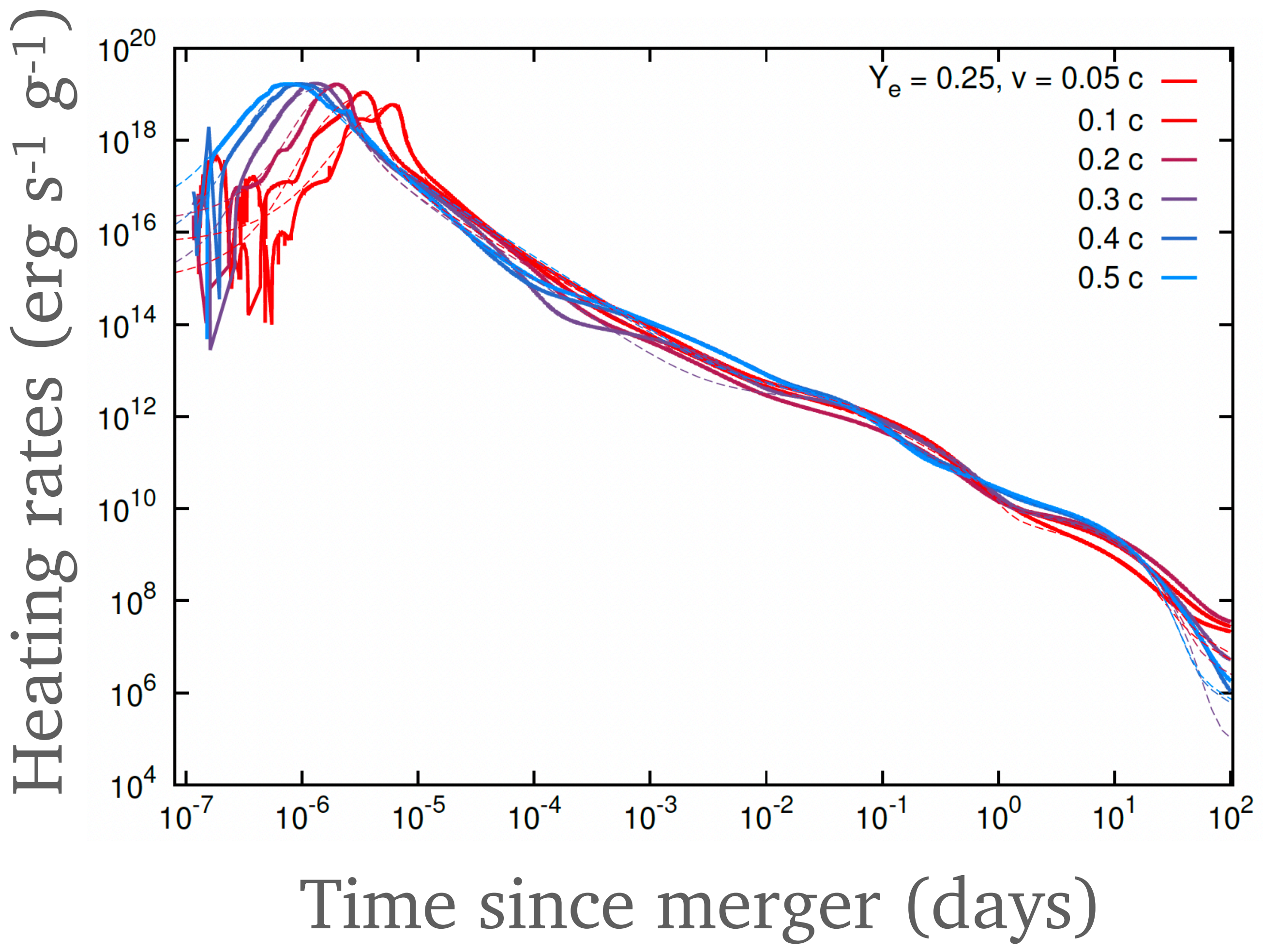
Frequency

From temperature + opacity

Energy

Nuclear heating rates

Thermalisation efficiencies



Stokes parameters

from Rosswog & Korobkin 2022 as a function of Y_e and velocity

from Barnes+2016 and Wollaeger+2018 as a function of density and for each species (α, β, γ, fission)

Kilonova modelling with POSSIS

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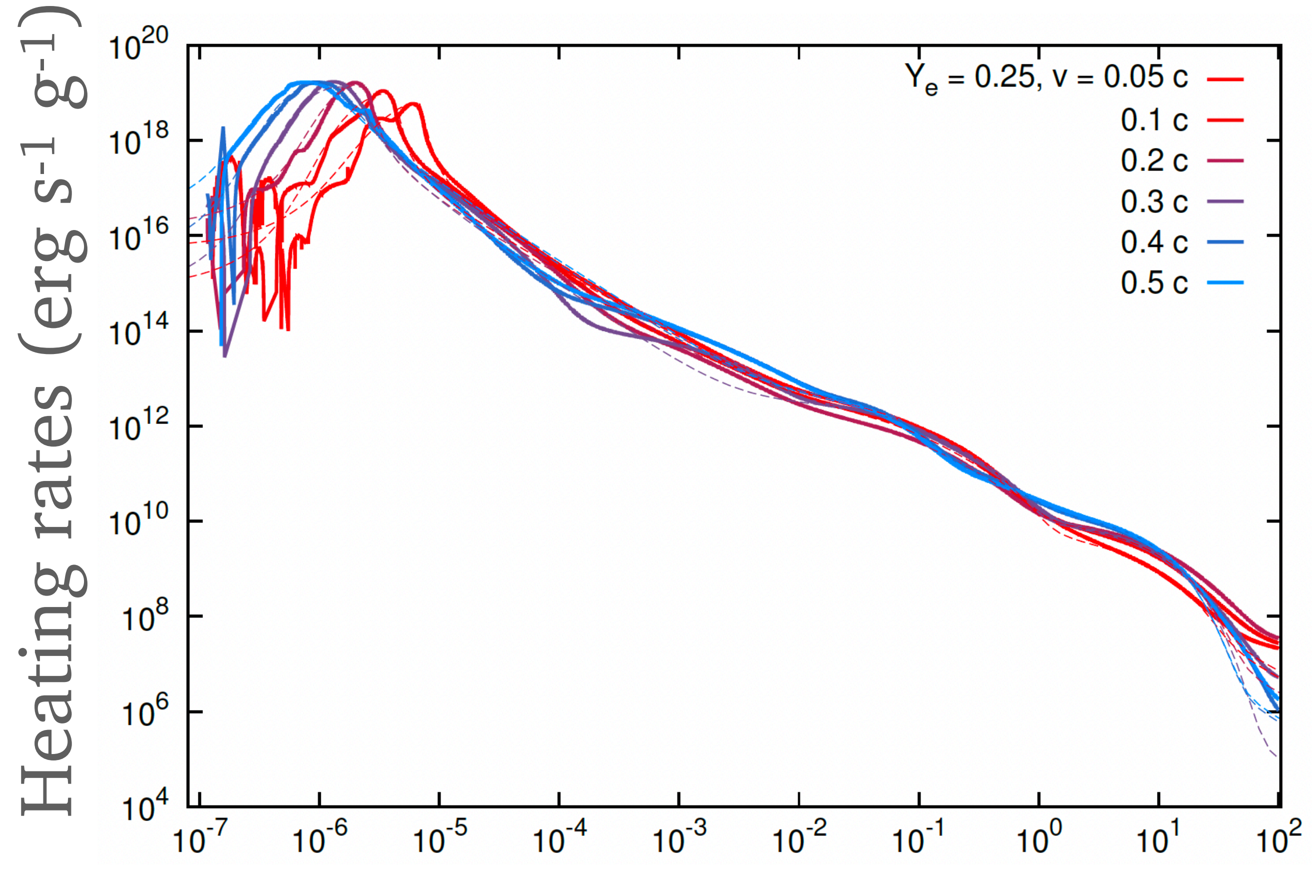


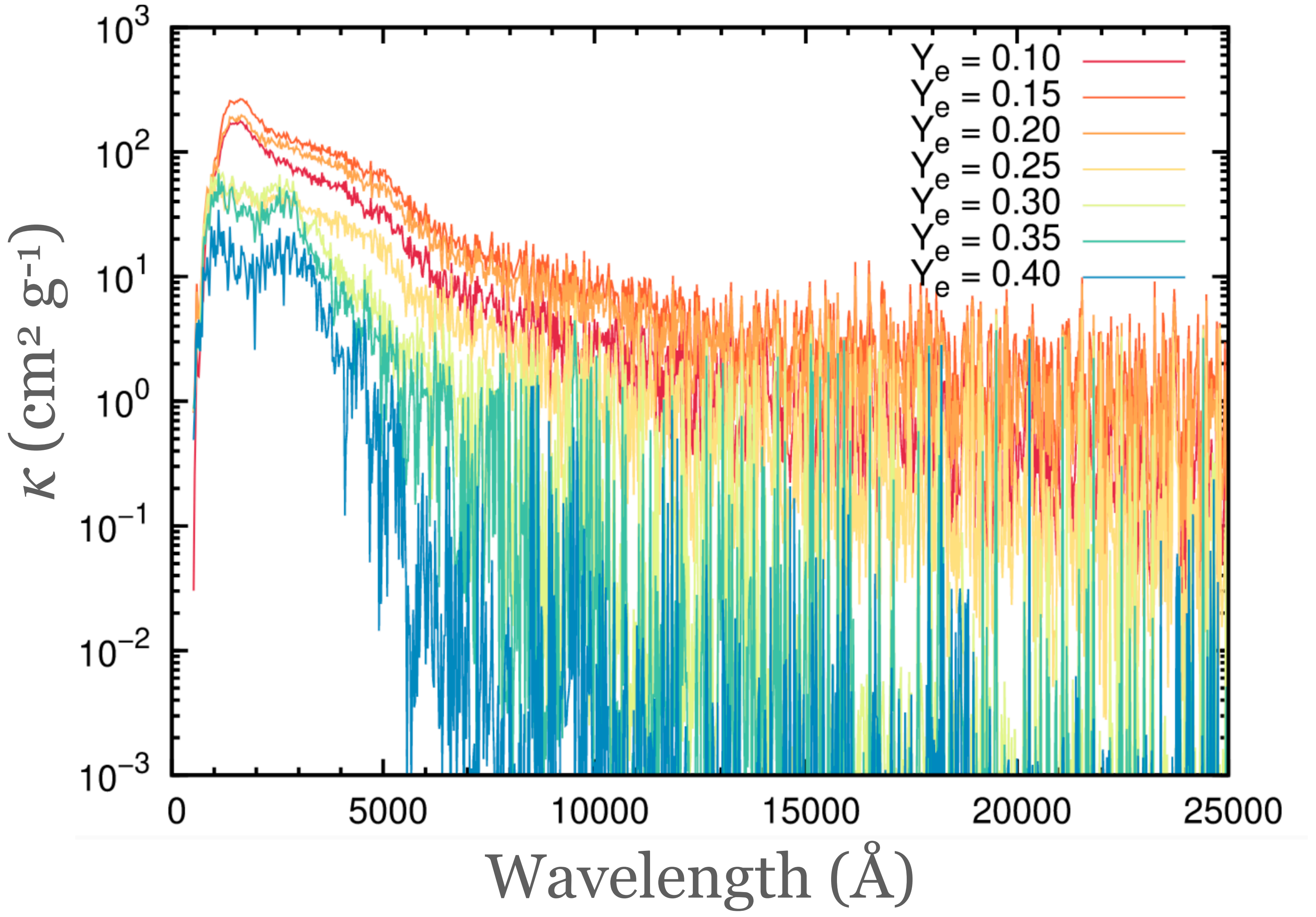
Stokes parameters

Propagating photons

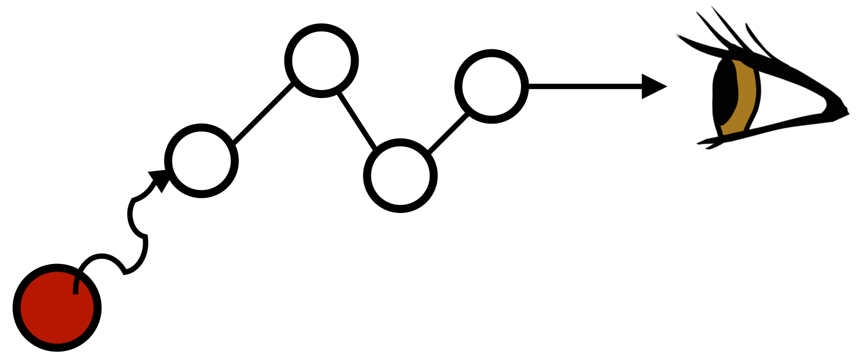
Opacity

$$\tau = \int \kappa \, \rho \, dr \qquad P_{\text{interaction}} = 1 - e^{-\tau}$$

Main source of opacity in KNe: bound-bound → $\kappa(\lambda)$ opacities from Tanaka+2020 as a function of ρ, T, Y_e and time



Kilonova modelling with POSSIS



A 3D Monte Carlo radiative transfer code to model explosive transients

[MB+2015, MNRAS; MB 2019, MNRAS; MB 2023, MNRAS]

Help yourself!
Modelled grids available at
https://github.com/mbulla/kilonova_models

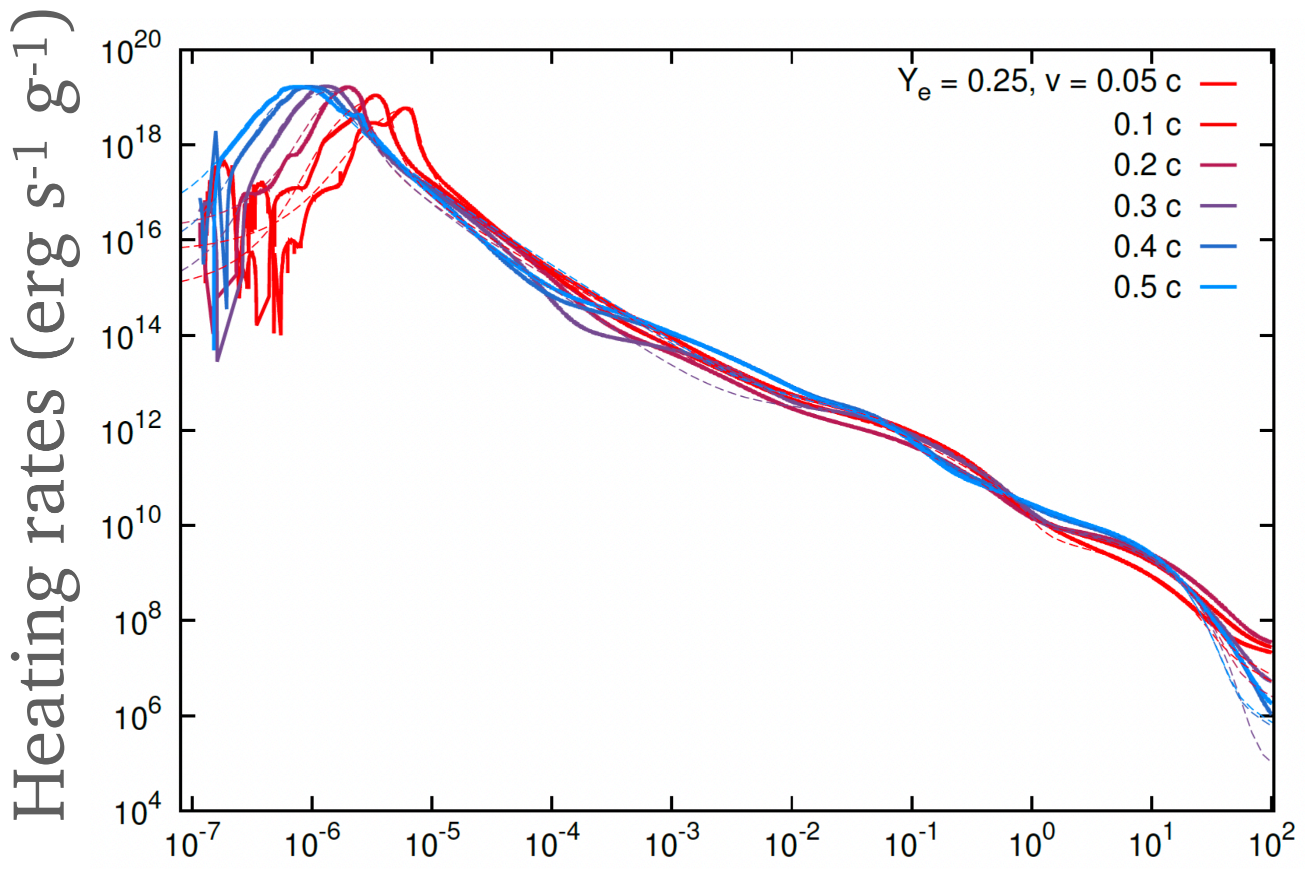
Creating photons

Frequency

From temperature + opacity

Energy

Nuclear heating rates
Thermalisation efficiencies



Time since merger (days)

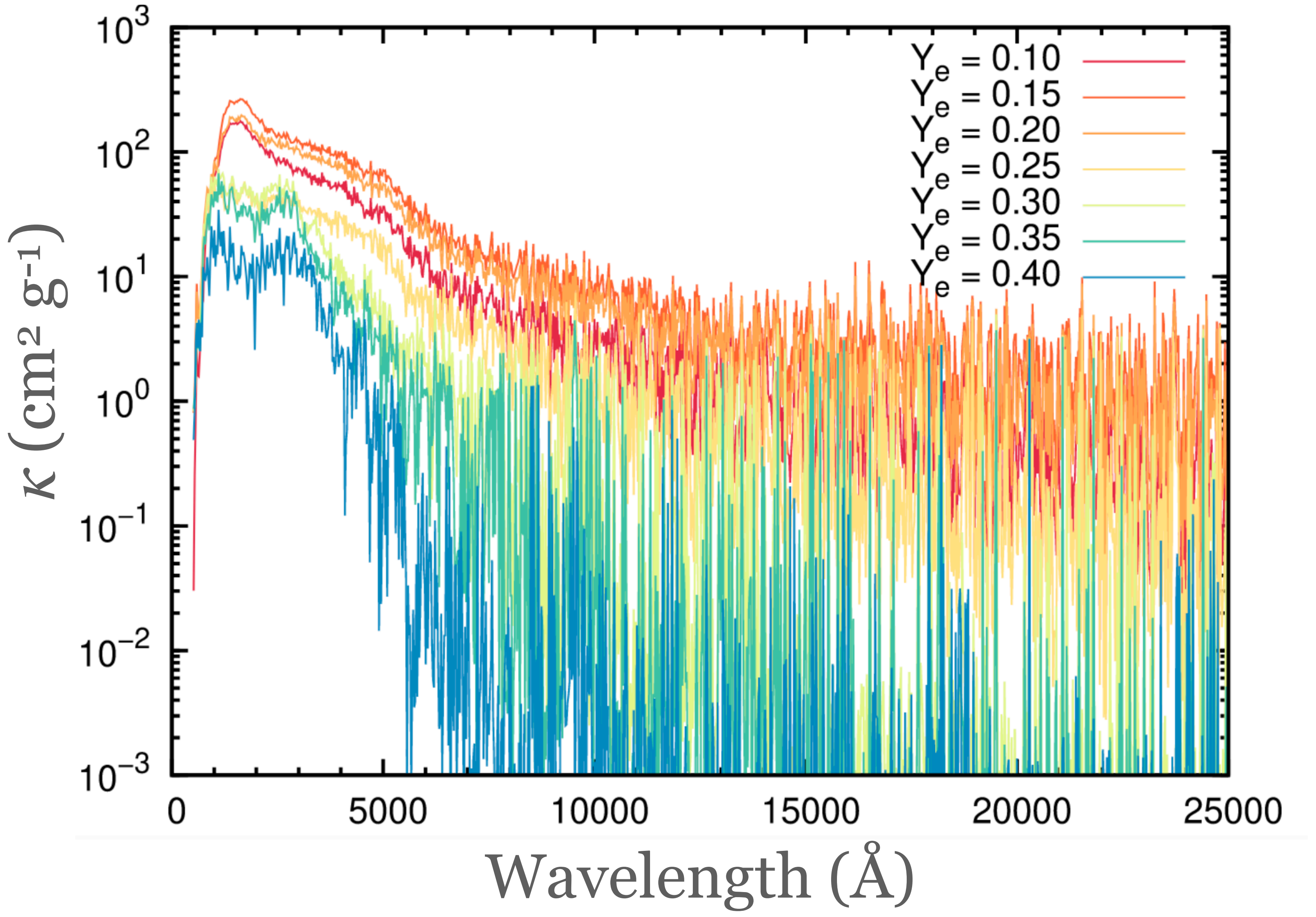
Stokes parameters

Propagating photons

Opacity

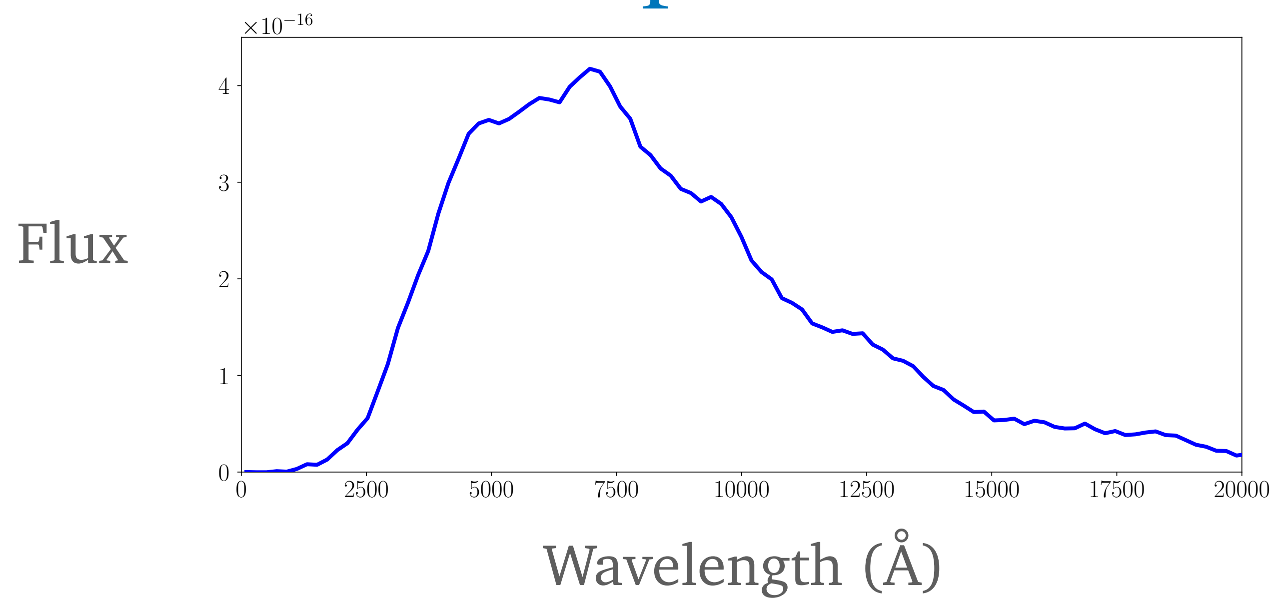
$$\tau = \int \kappa \, \rho \, dr \qquad P_{\mathrm{interaction}} = 1 - e^{-\tau}$$

Main source of opacity in KNe: bound-bound

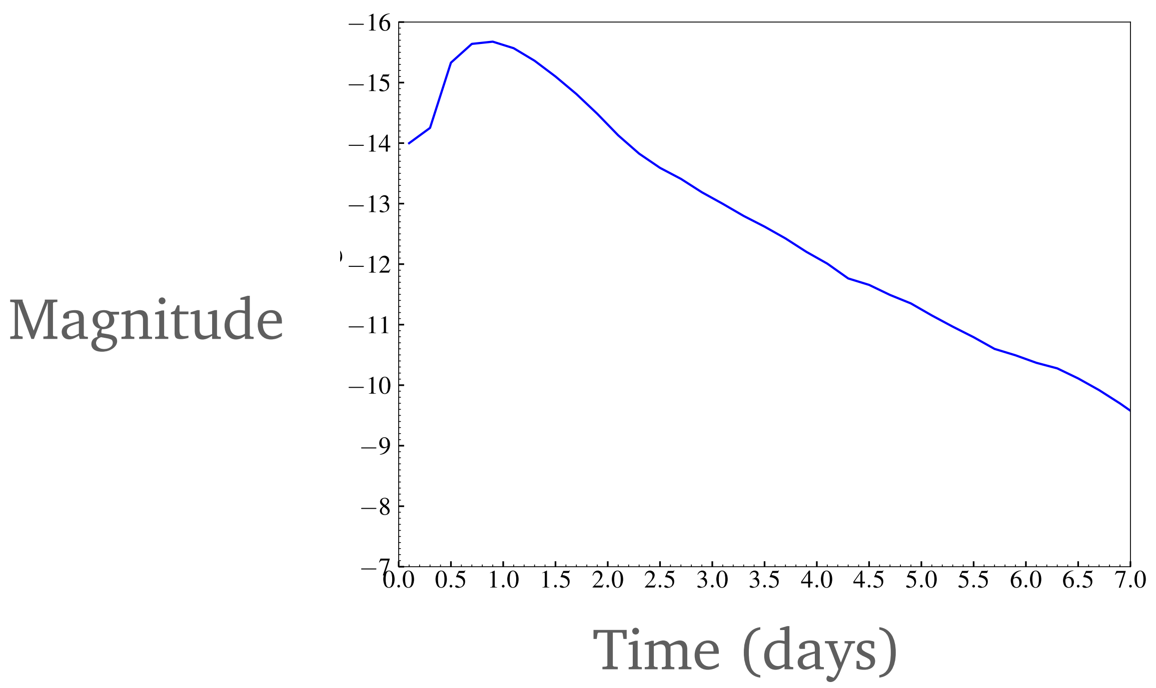


Collecting photons

Spectra



Light curves

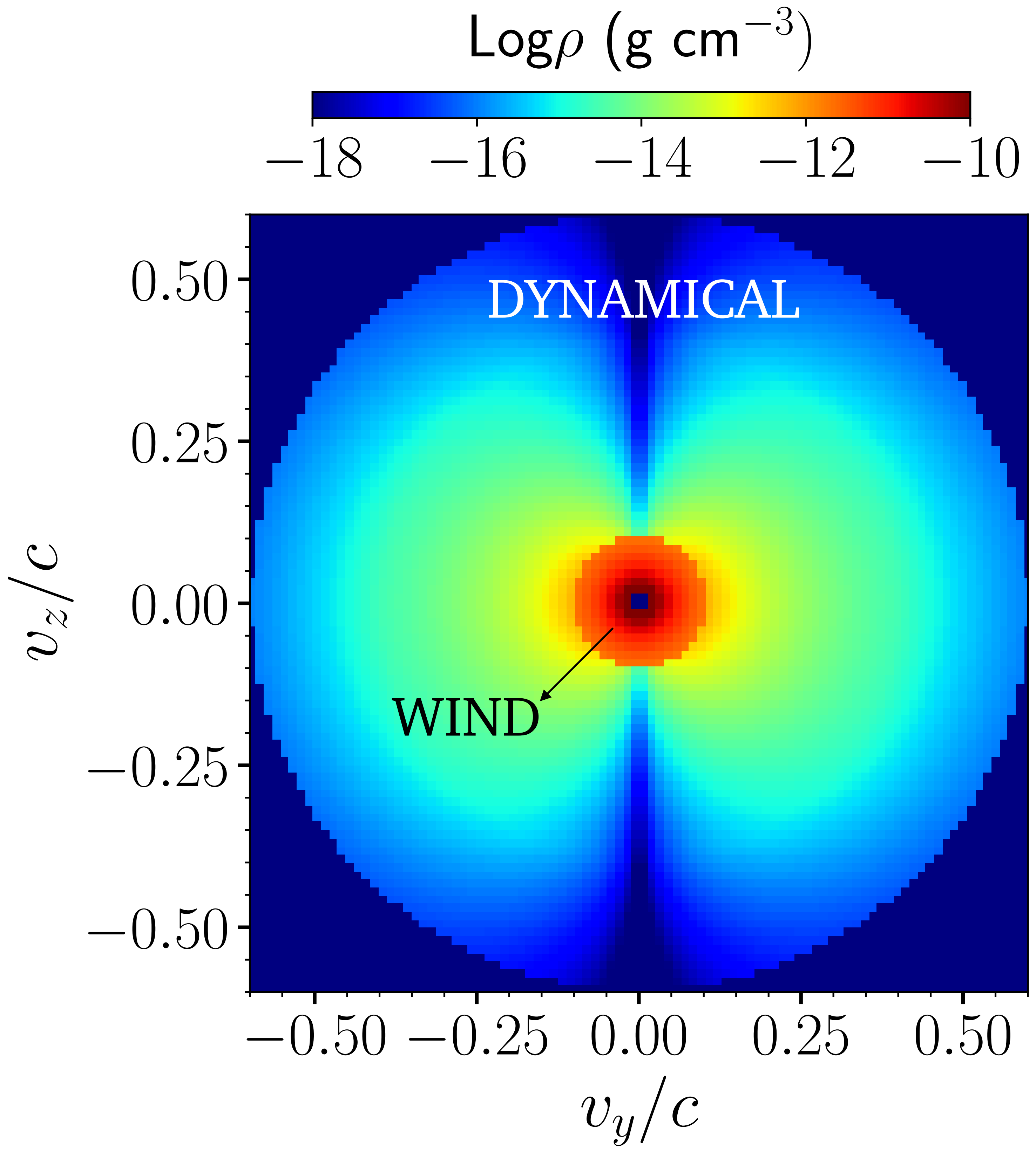


Polarization

Ejecta: density and Y_e distribution at t_0

Idealised

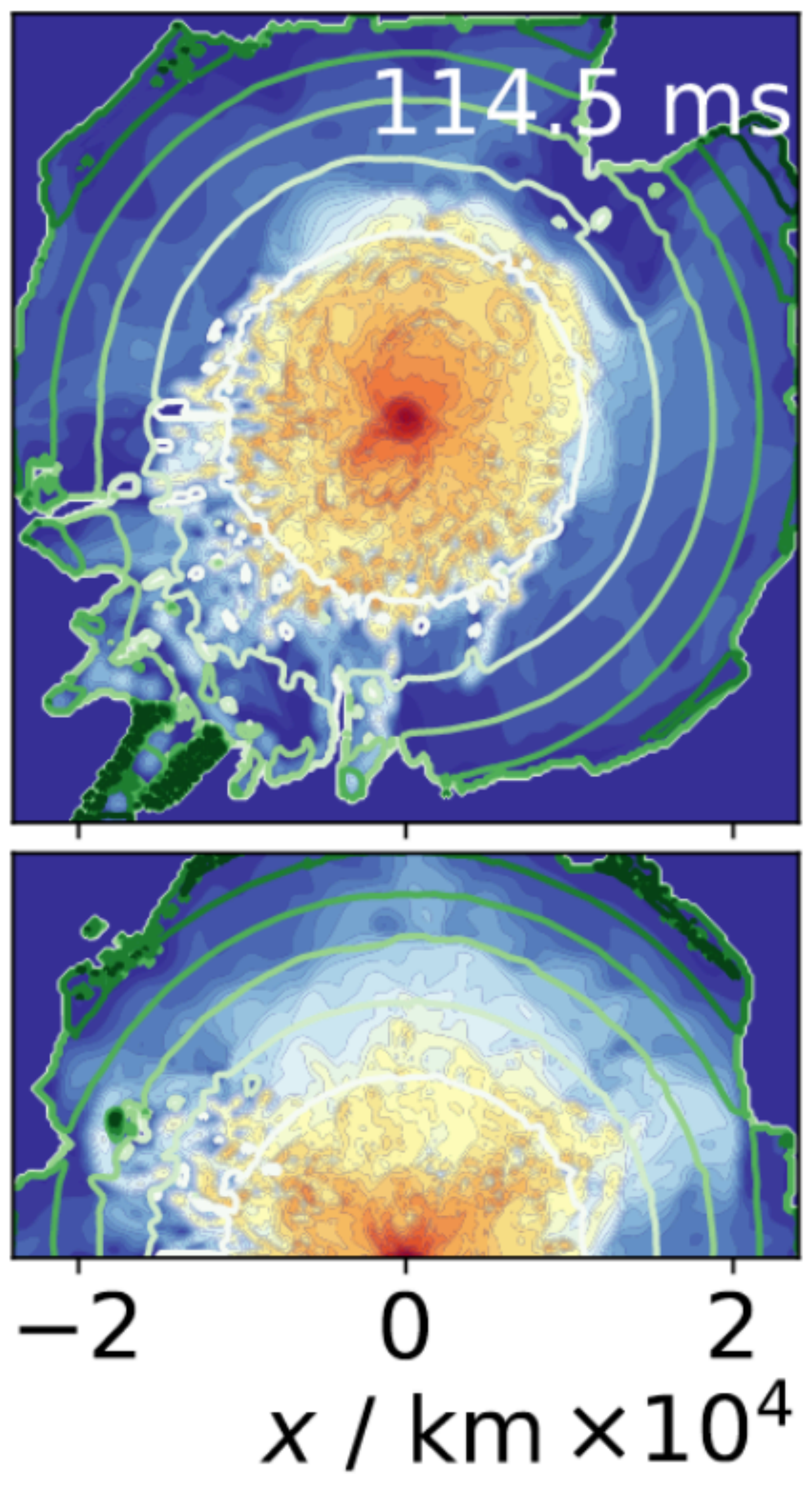
Large grids of models (~1000)
Typical runtime/model ~ 100-500 CPUh



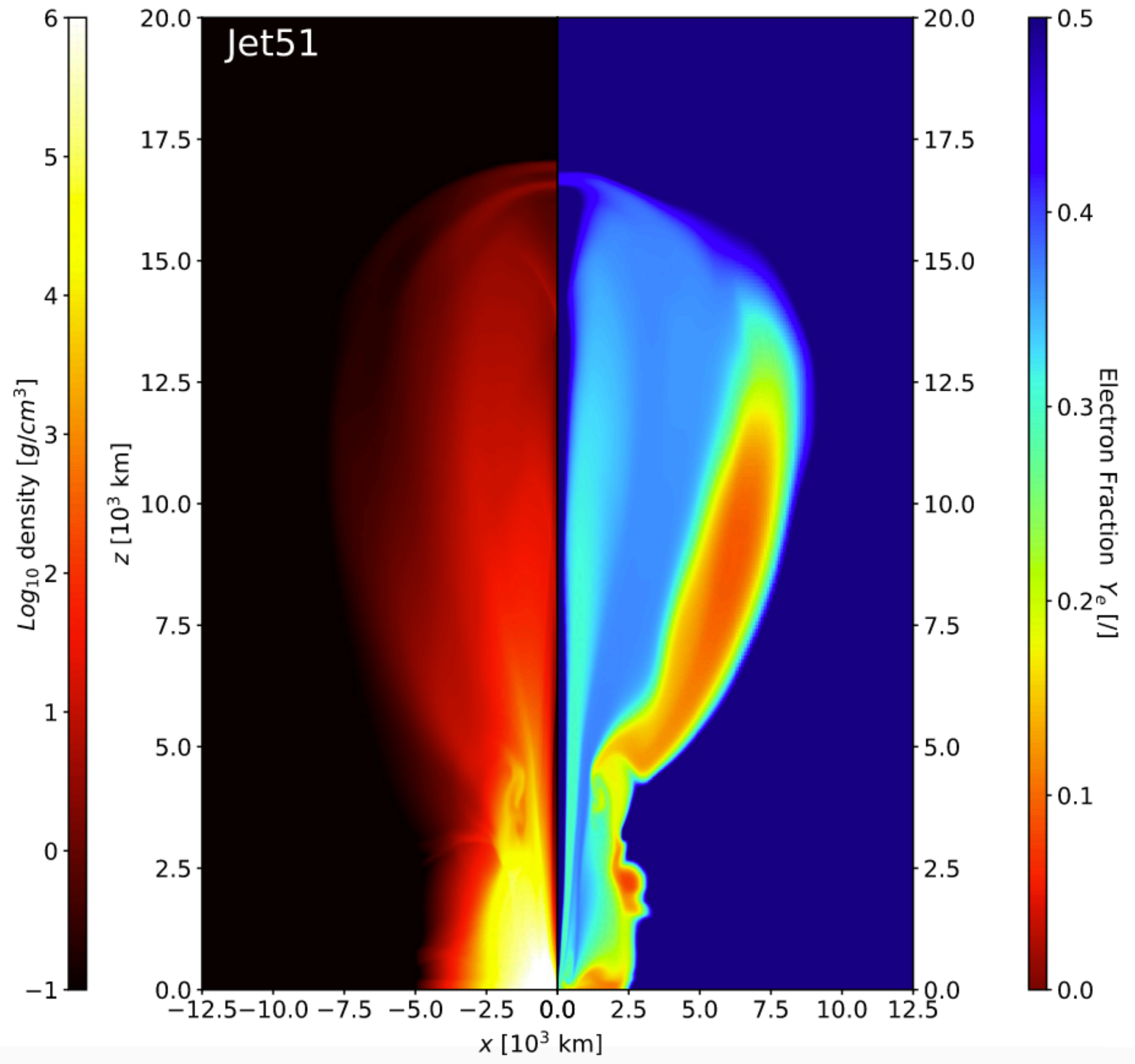
[MB 2023, MNRAS]

Numerical simulations

From numerical-relativity and/or hydrodynamic simulations



[Neuweiler, Dietrich, MB+2023, PRD]



[Nativi, MB+2021, MNRAS]

Role of heating rates/therm. efficiencies/opacities

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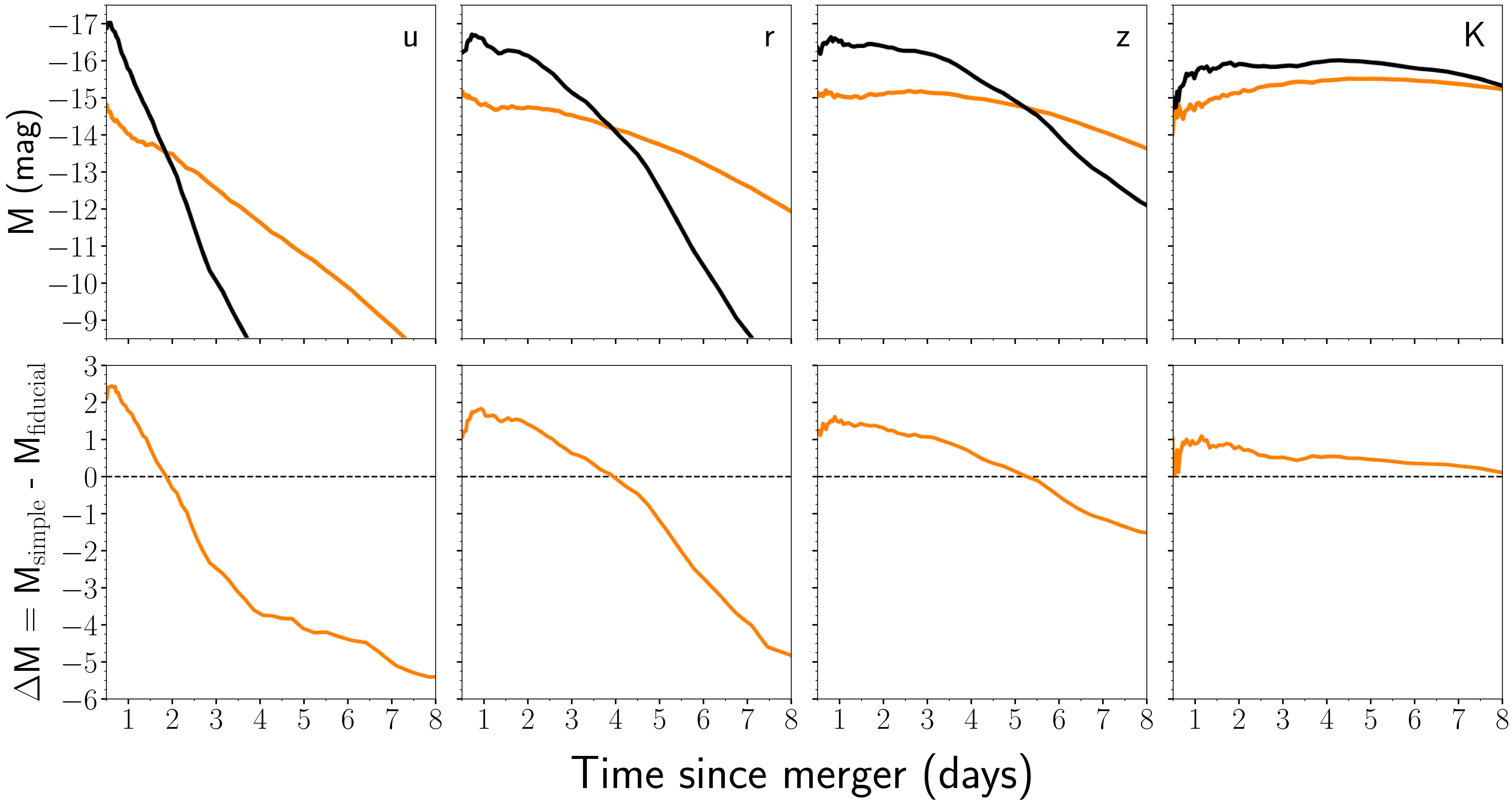
[MB 2023, MNRAS]

Fiducial model

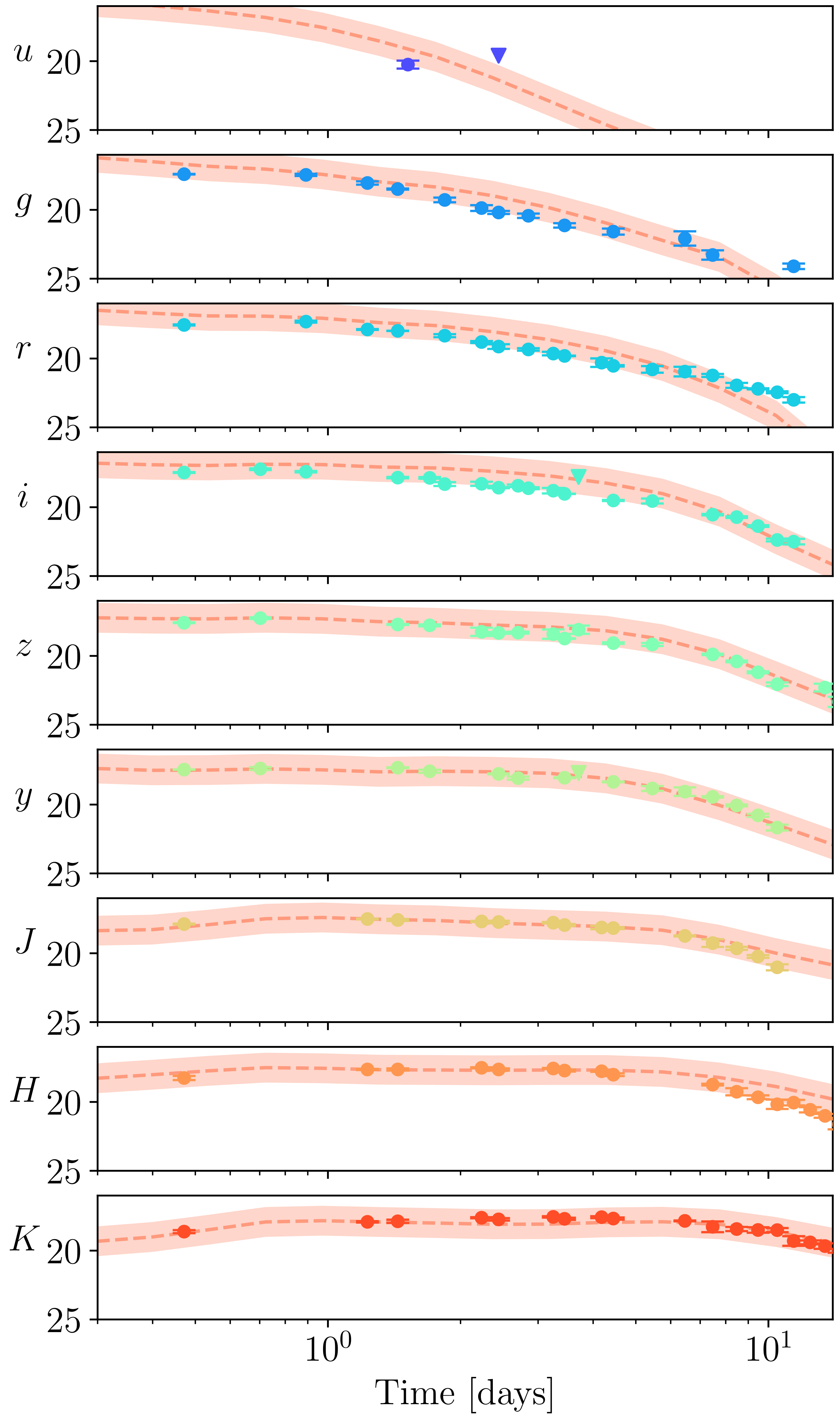
Simple model

- <u>Uniform</u> heating rates (Korobkin+2012)
- <u>Uniform</u> & <u>constant</u> thermalisation efficiencies (0.5)
- <u>Grey</u> opacities (red+blue+purple)

Face-on view (jet/polar axis)



Parameter inference on GW170817/AT2017gfo



[Anand, Pang, MB+, arXiv:2307.11080]

6D GRID WITH POSSIS

[1024 models, 11264 different KNe]

Dynamical ejecta: $M_{ej,dyn}$, $<v_{ej,dyn}>$, $<Y_{e,dyn}>$

Wind ejecta: $M_{ej,wind}$, $<v_{ej,wind}>$

Viewing angle θ_{obs}

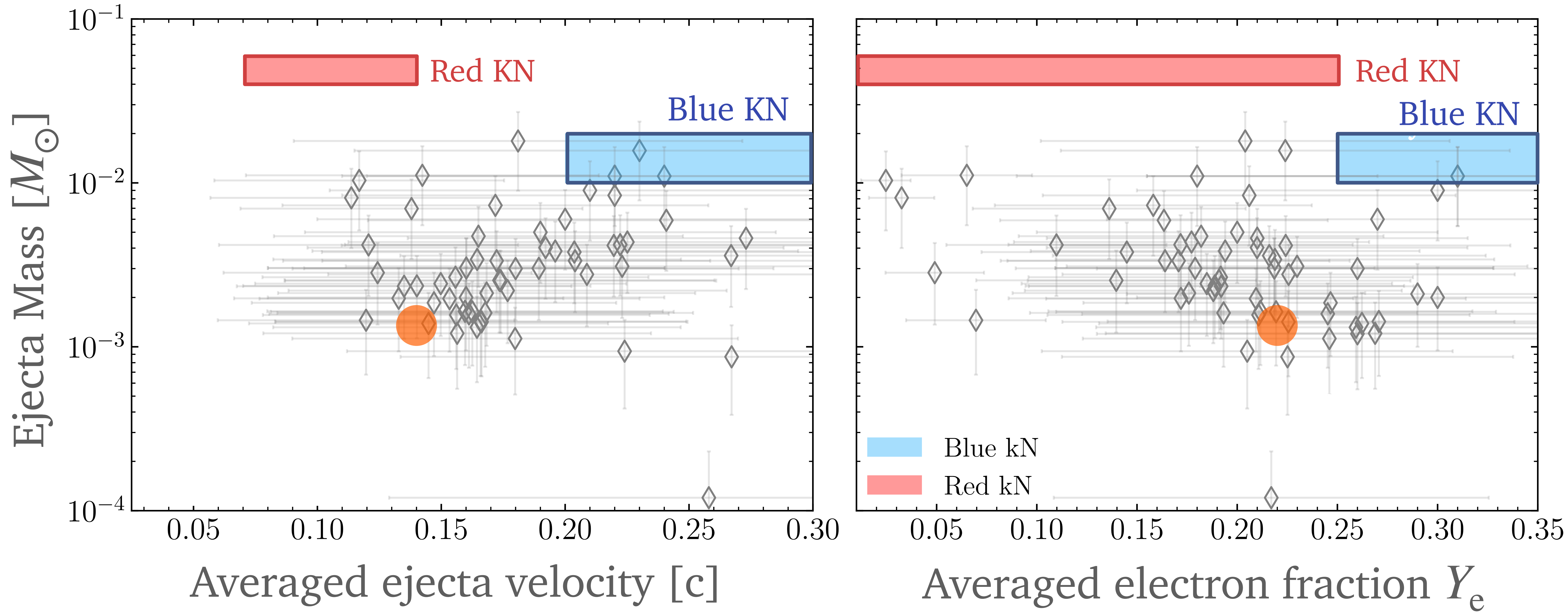
INTERPOLATION WITH NMMA

NMMA

https://github.com/nuclear-multimessenger-astronomy/nmma

[Dietrich, Coughlin, Pang, MB+2020, Science]

[Pang, Dietrich, Coughlin, MB+2023, arXiv:2205.08513]



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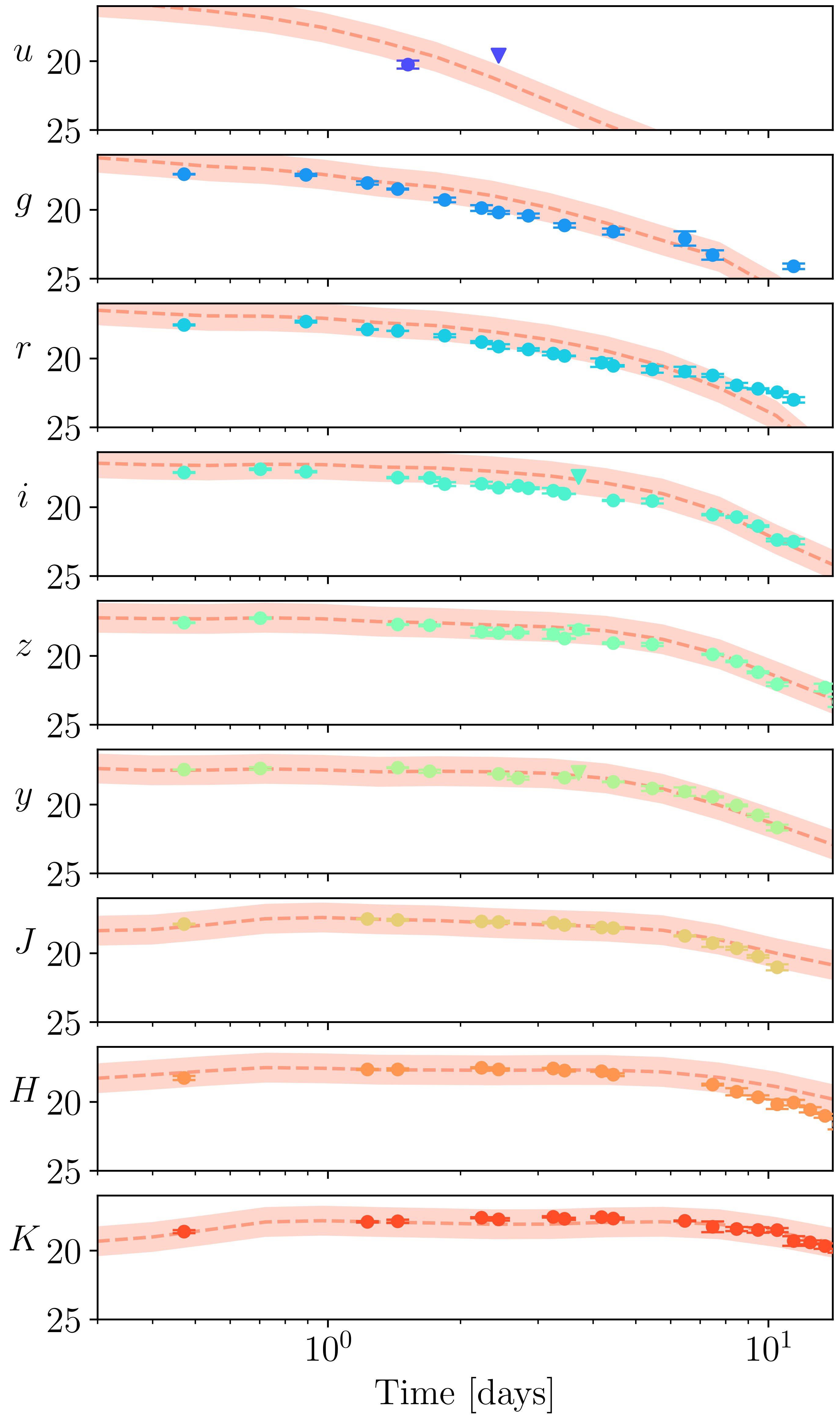

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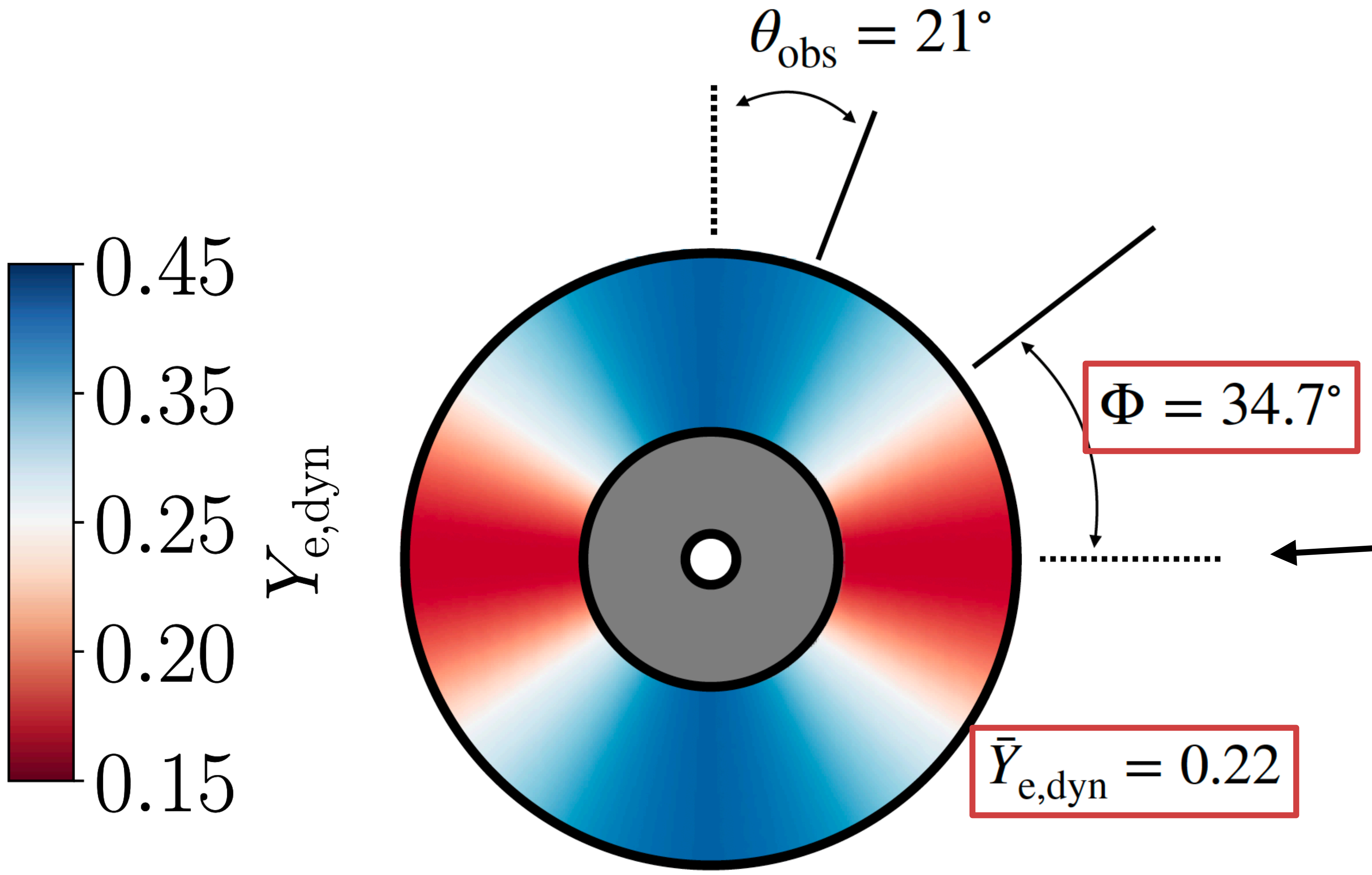

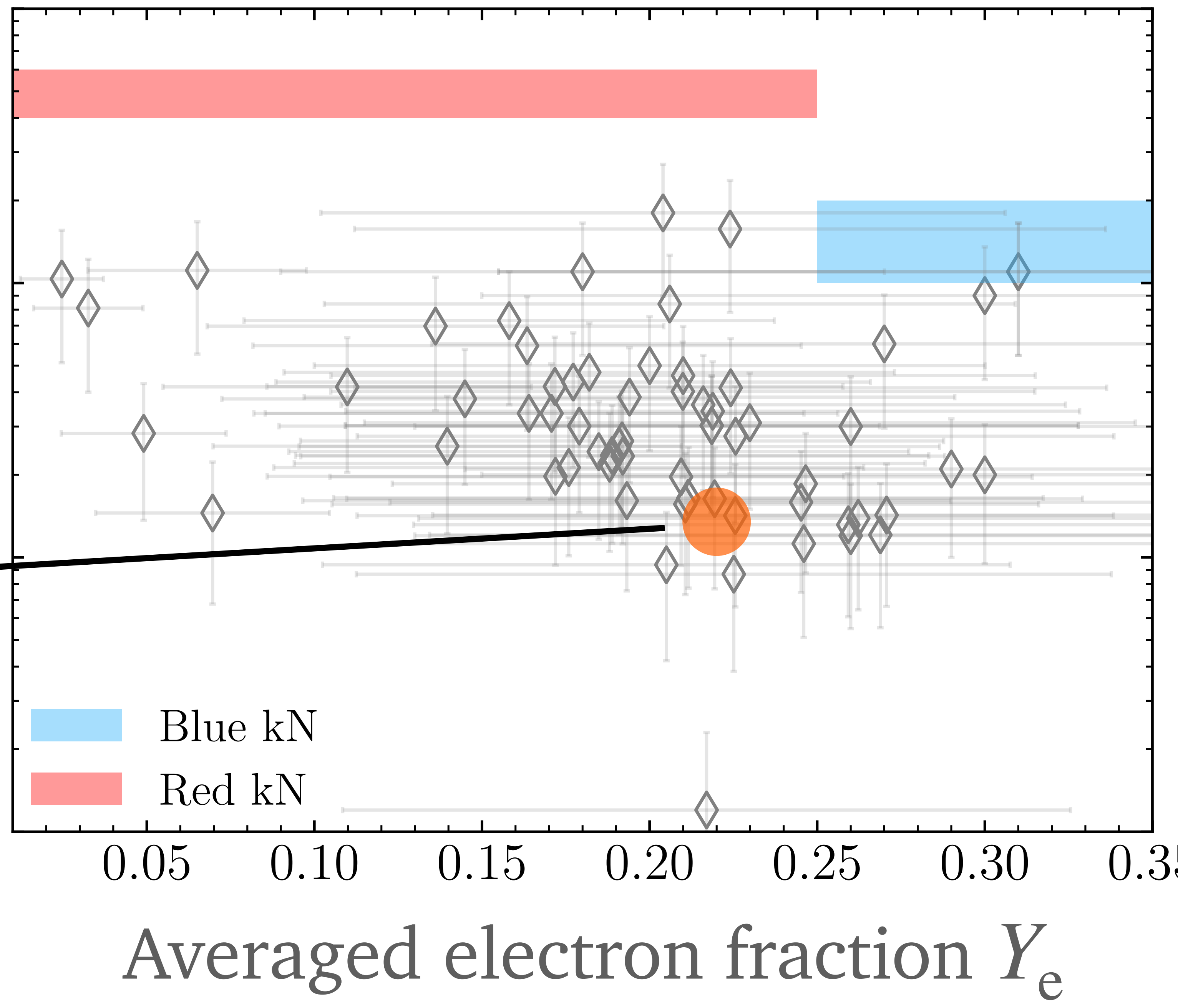

cf. with 'spherical KN' claim by Sneppen+2023

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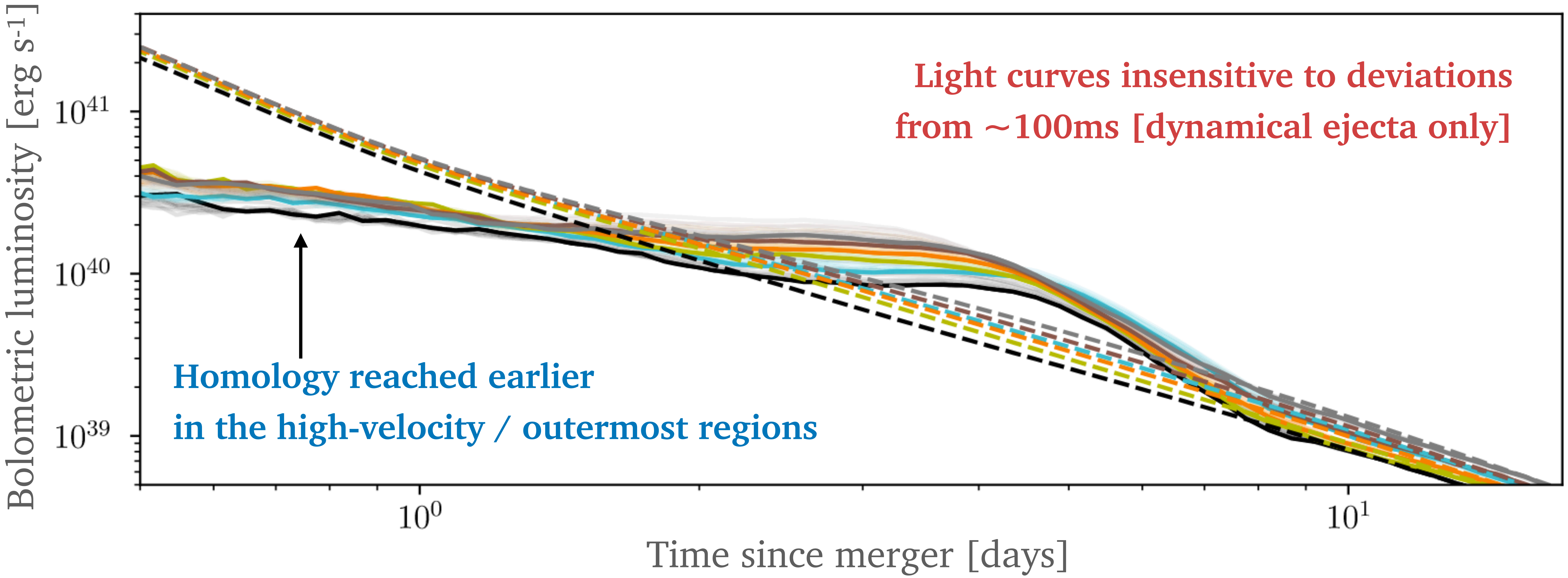
Homologous expansion and kilonovae

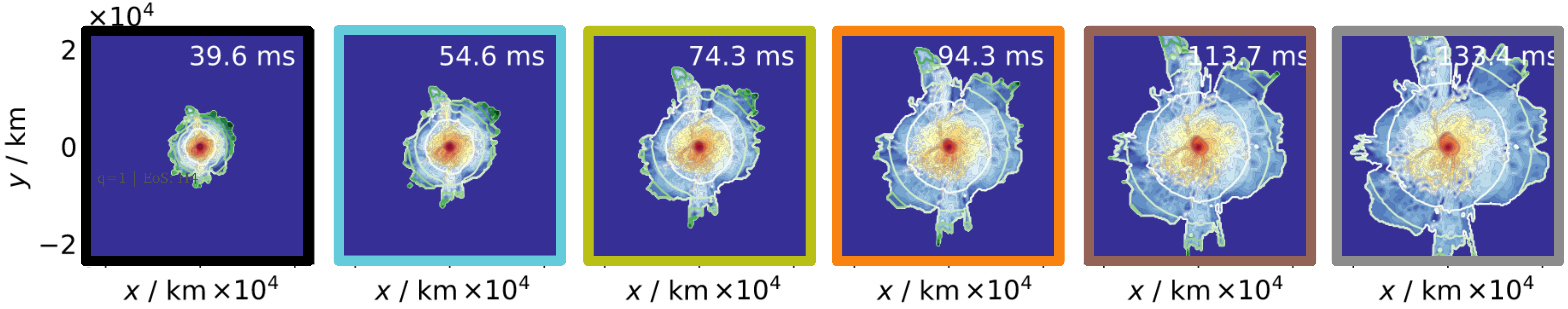


[Neuweiler, Dietrich, MB+2023, PRD]

Simulations with the BAM code (Brugmann+08, Thierfelder+2011)

See also:

- Markin+ arXiv:2304.11642: Merger of a NS with a sub-solar BH
- Schianchi+ arXiv:2307.04572: M1 scheme



The impact of jets on the ejecta and kilonova

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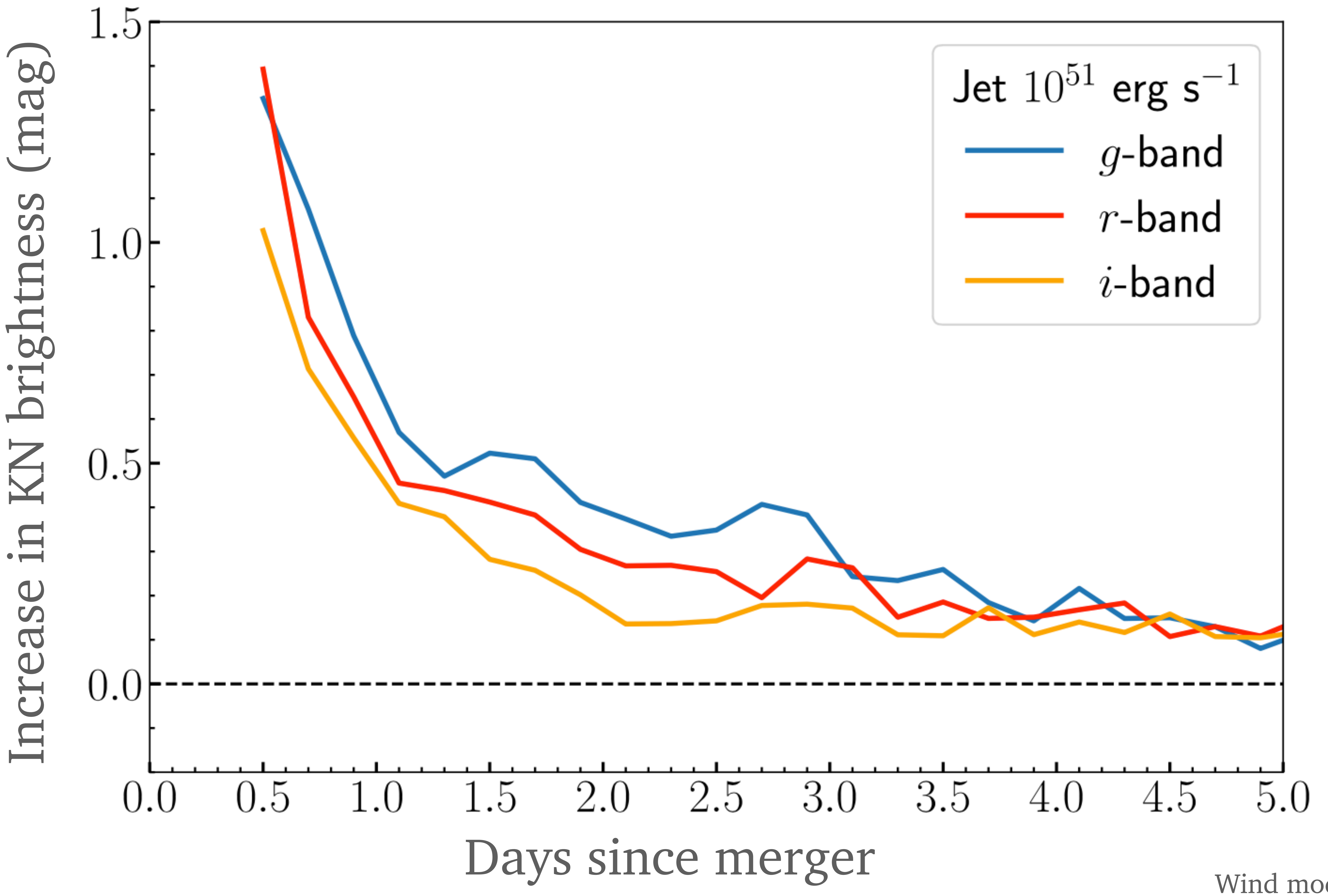
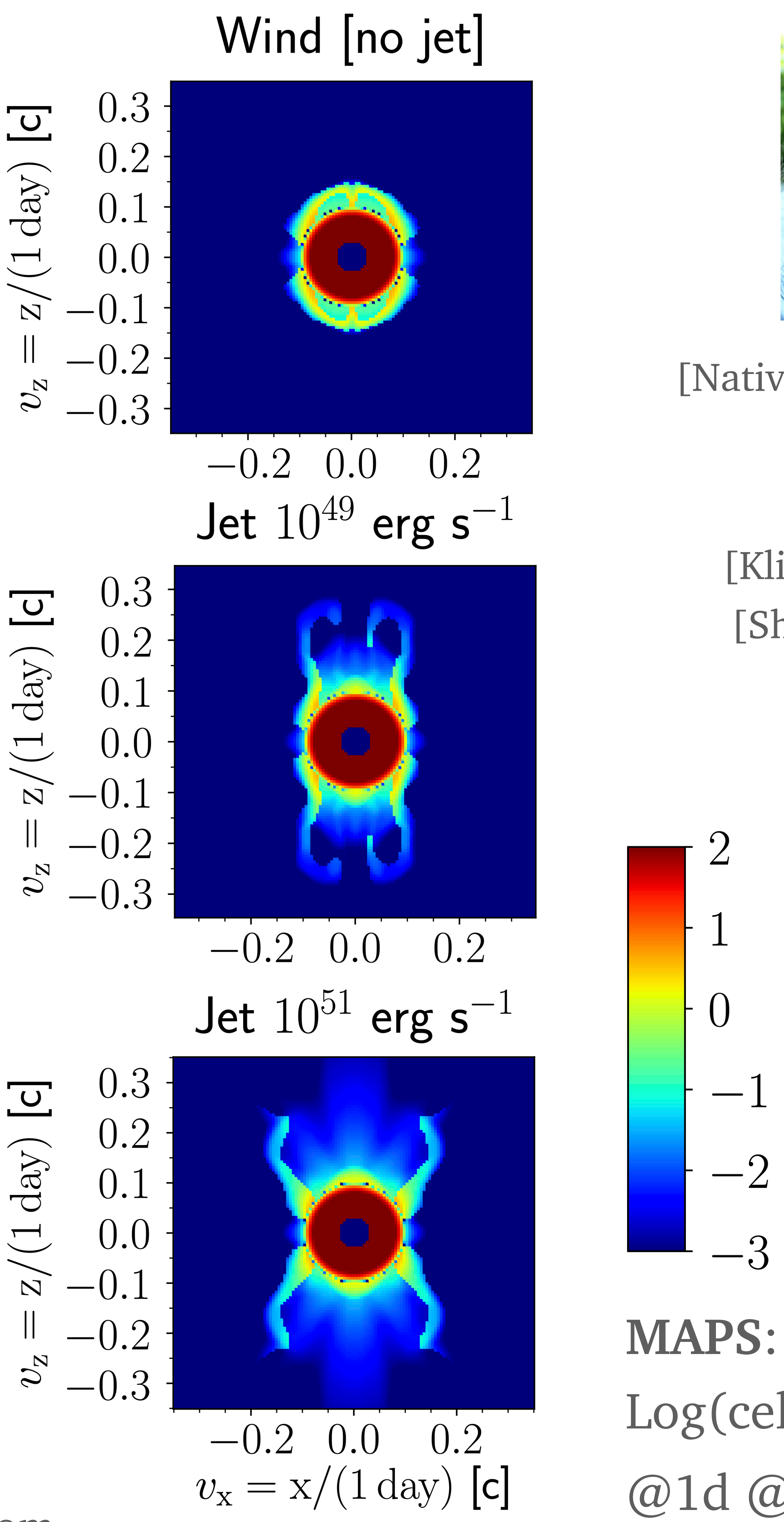
Jets make kilonovae brighter and bluer at early times





Wind models from [Perego+2014, MNRAS]

[Nativi, MB+2021, MNRAS]

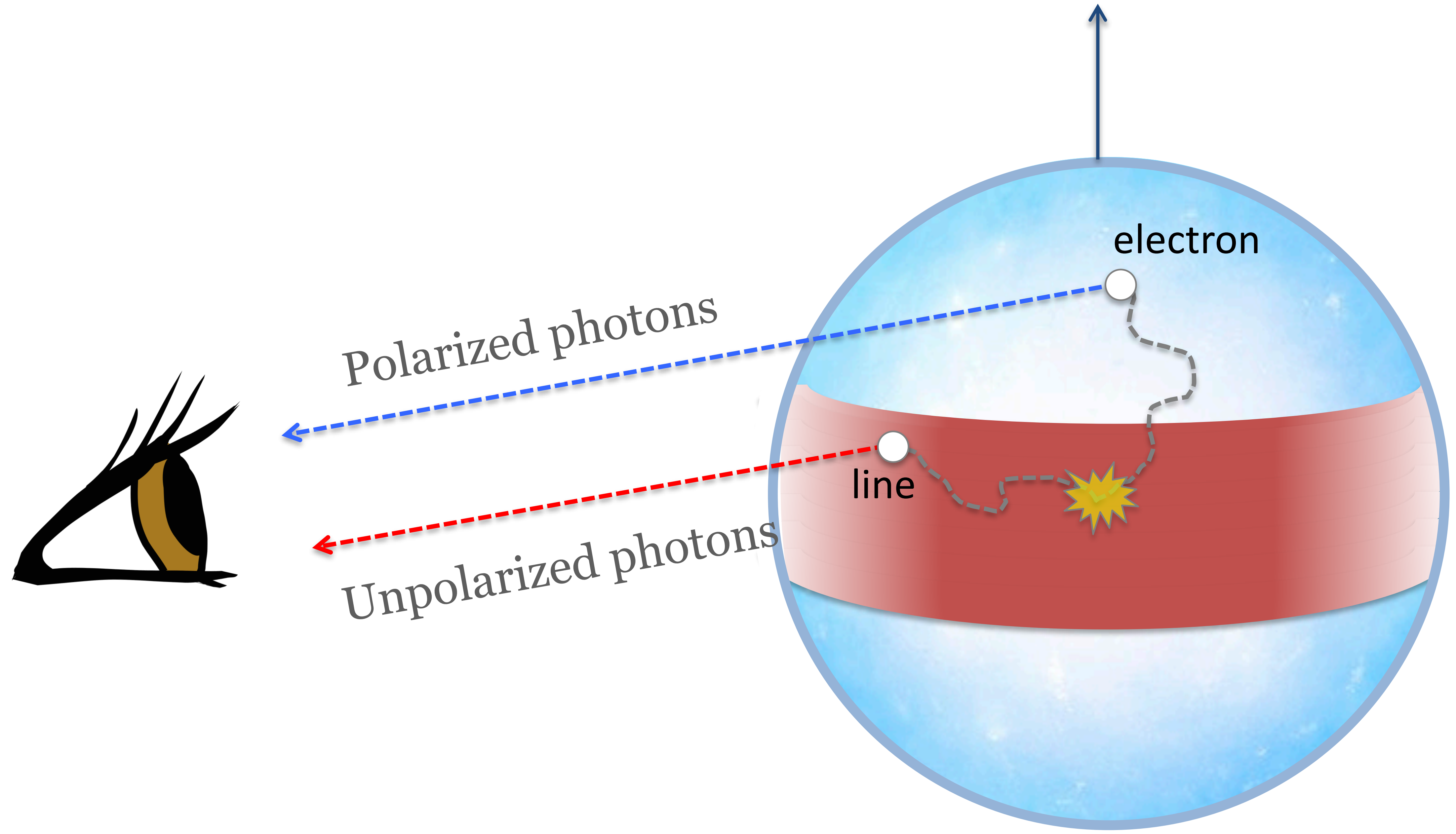
see also
[Klion+2021, MNRAS]
[Shrestha, MB+2023]

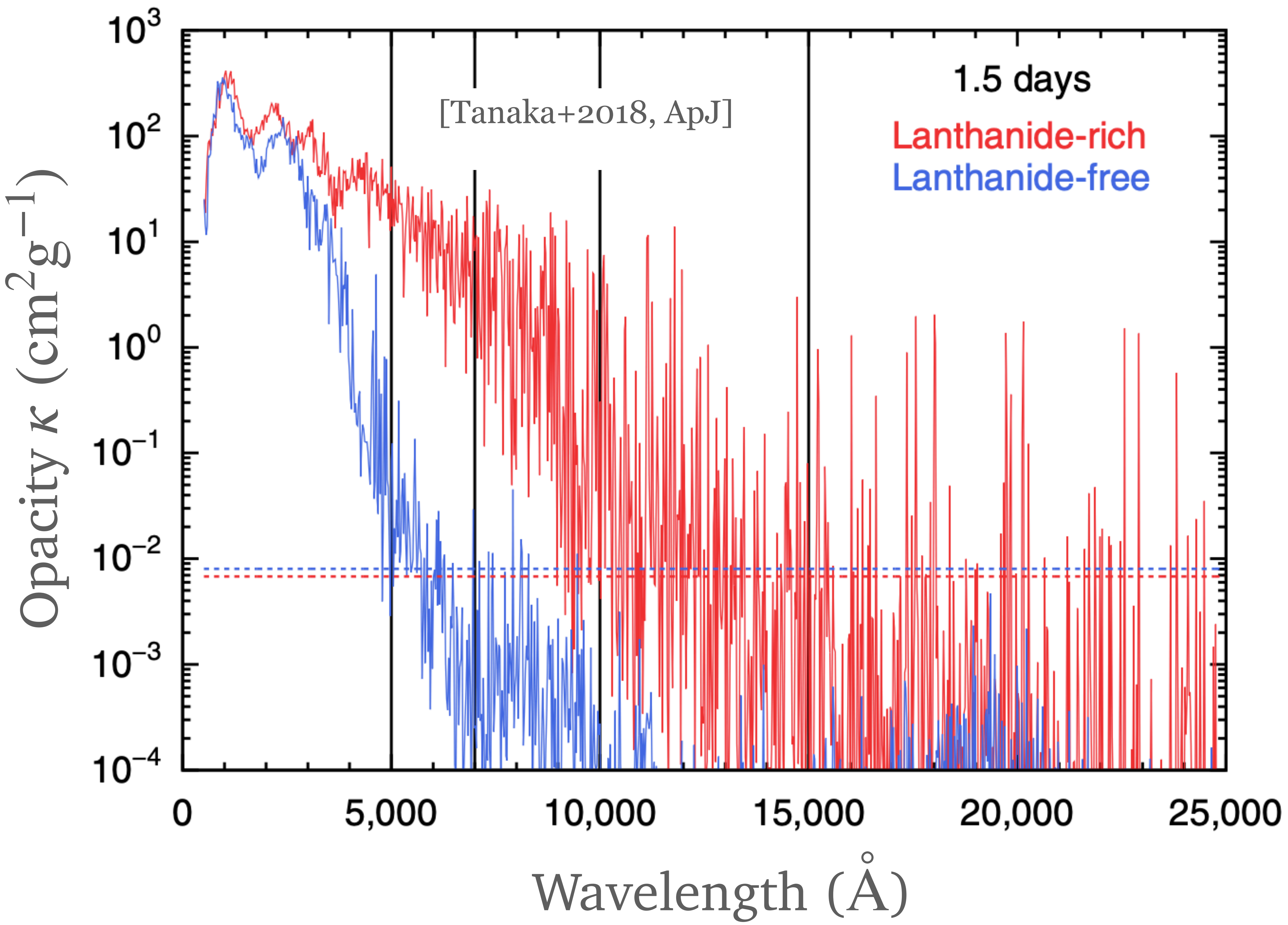
MAPS:
Log(cell optical depth)
@1d @5000Å

(Linearly) polarized kilonovae from NS mergers

[MB+2019, Nature Astronomy] (BNS)
[MB+2021, MNRAS] (BHNS)
[Shrestha, MB+2023] (BNS with jets)

Polarization is sensitive to opacities





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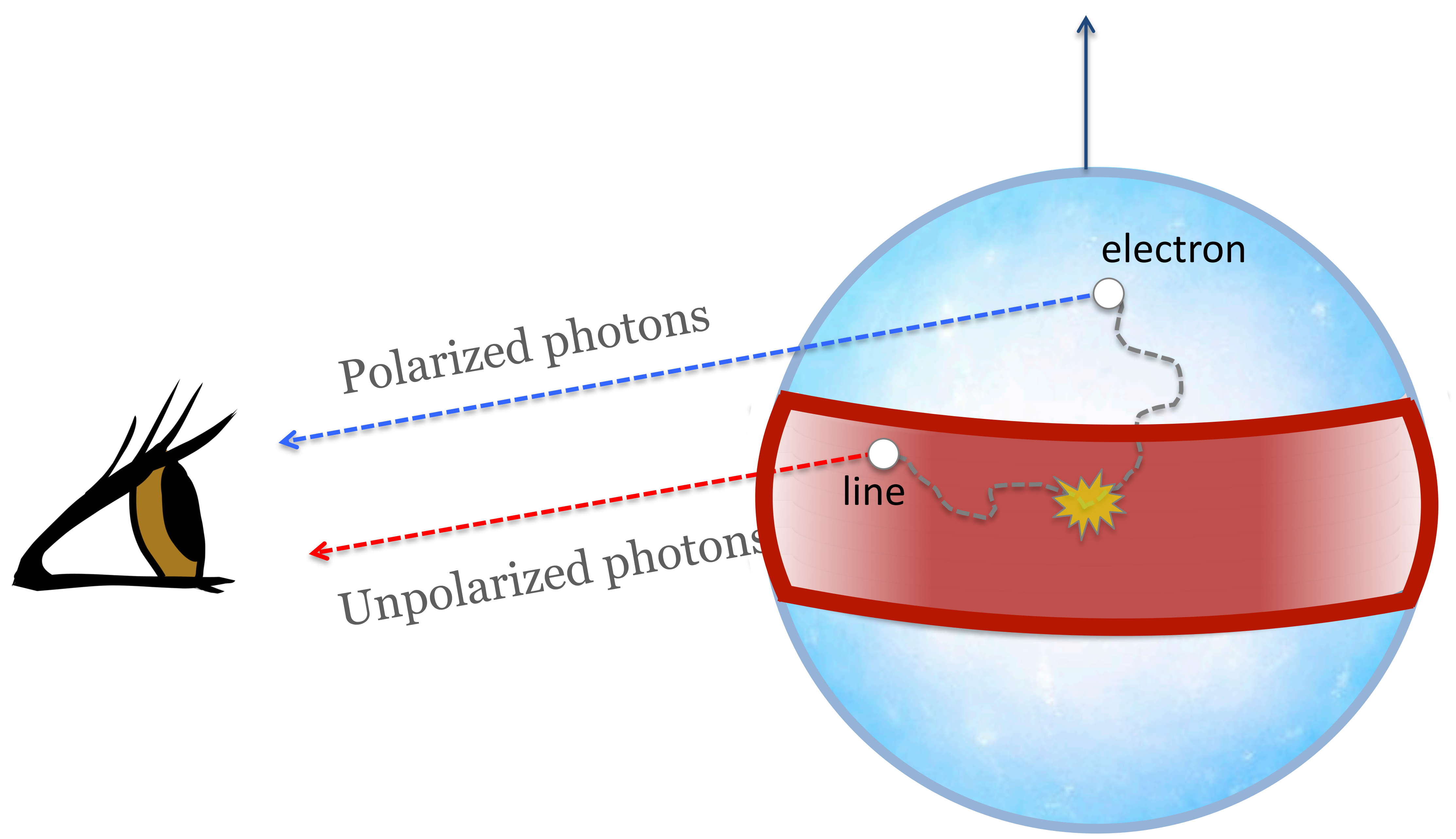
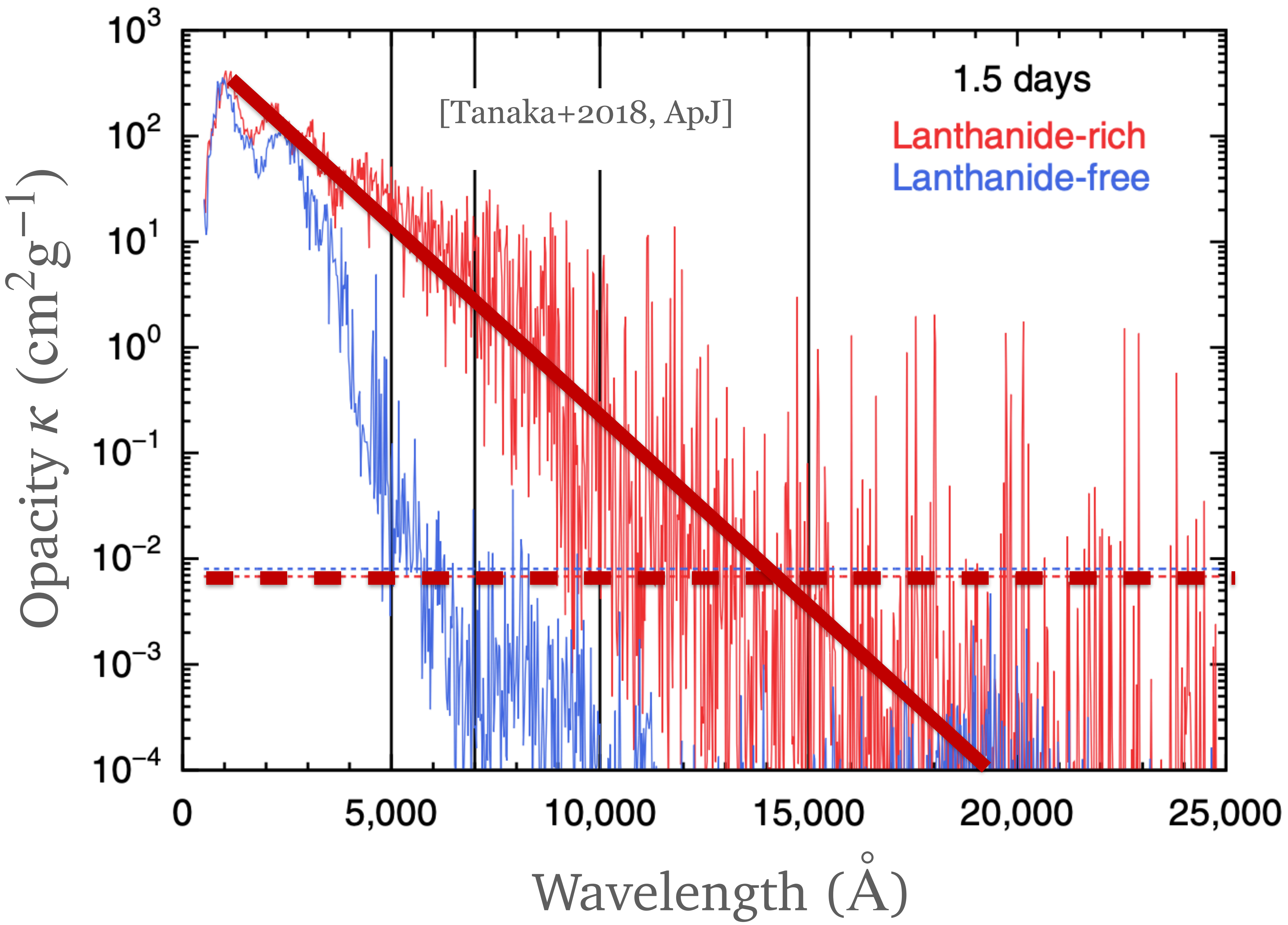


Lanthanide-rich composition

Electron scattering << [depolarising] line absorption

NO optical polarised light!



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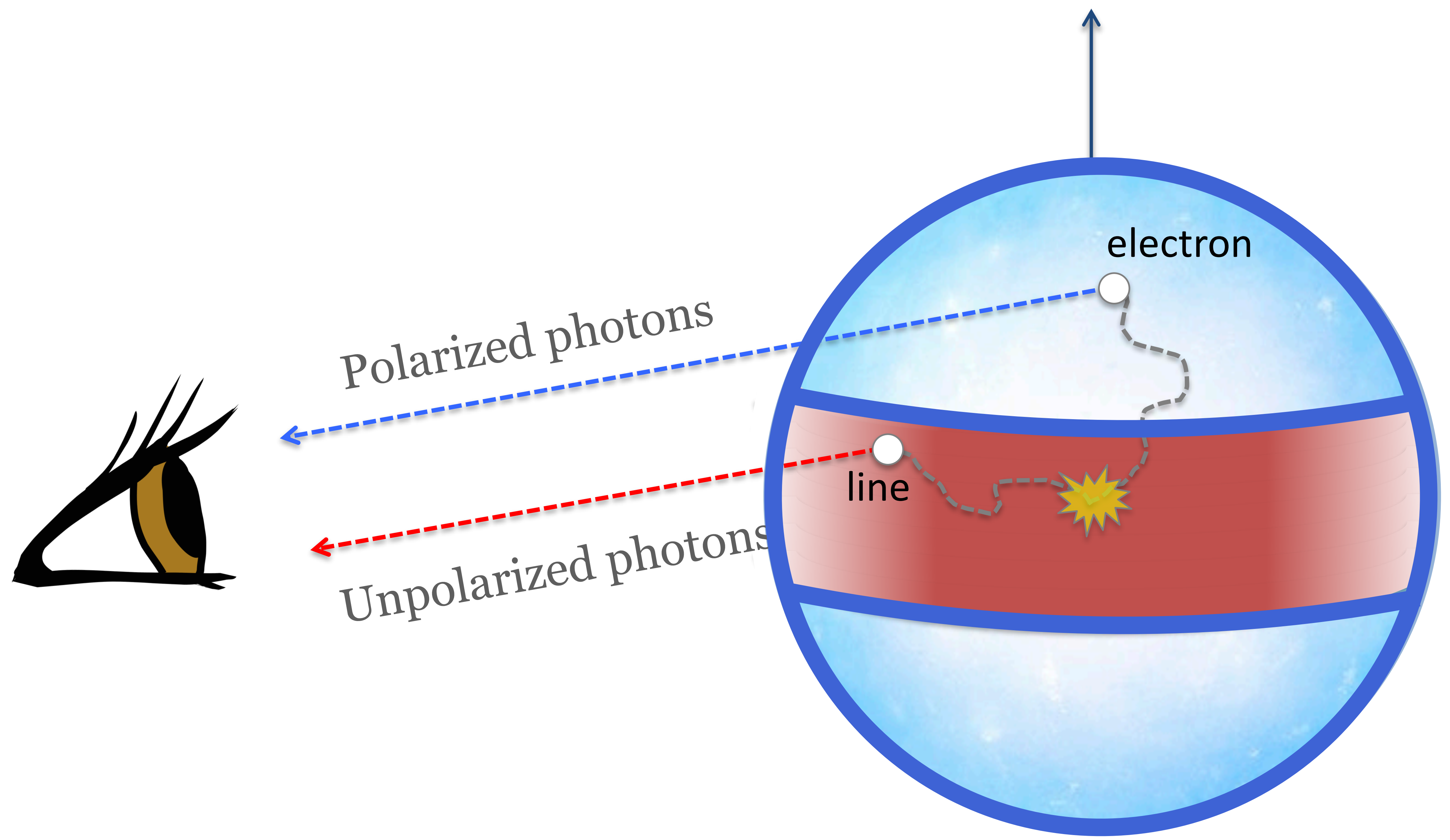
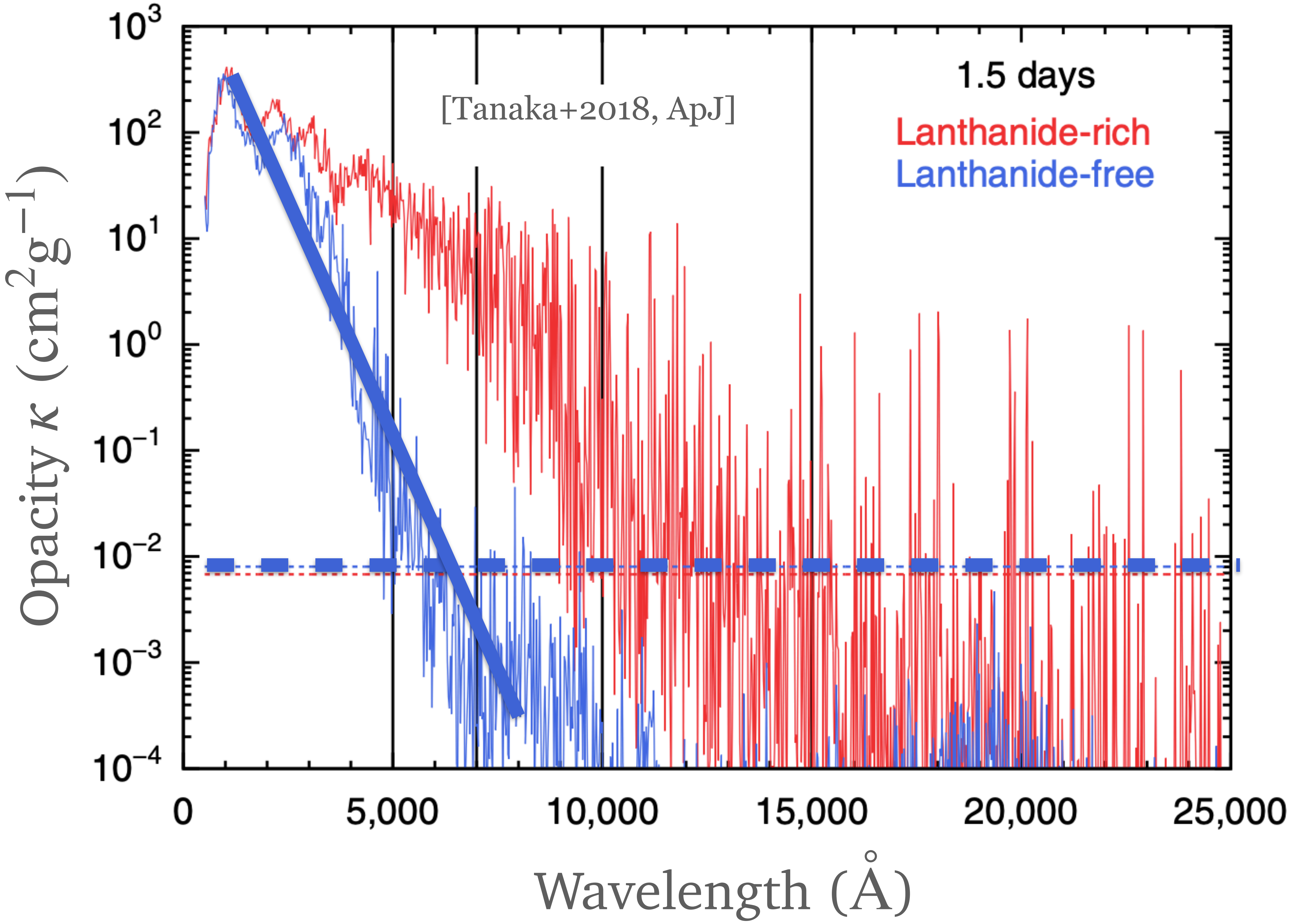


Lanthanide-poor composition

Electron scattering ≳ [depolarising] line absorption

Polarised light in optical/IR!



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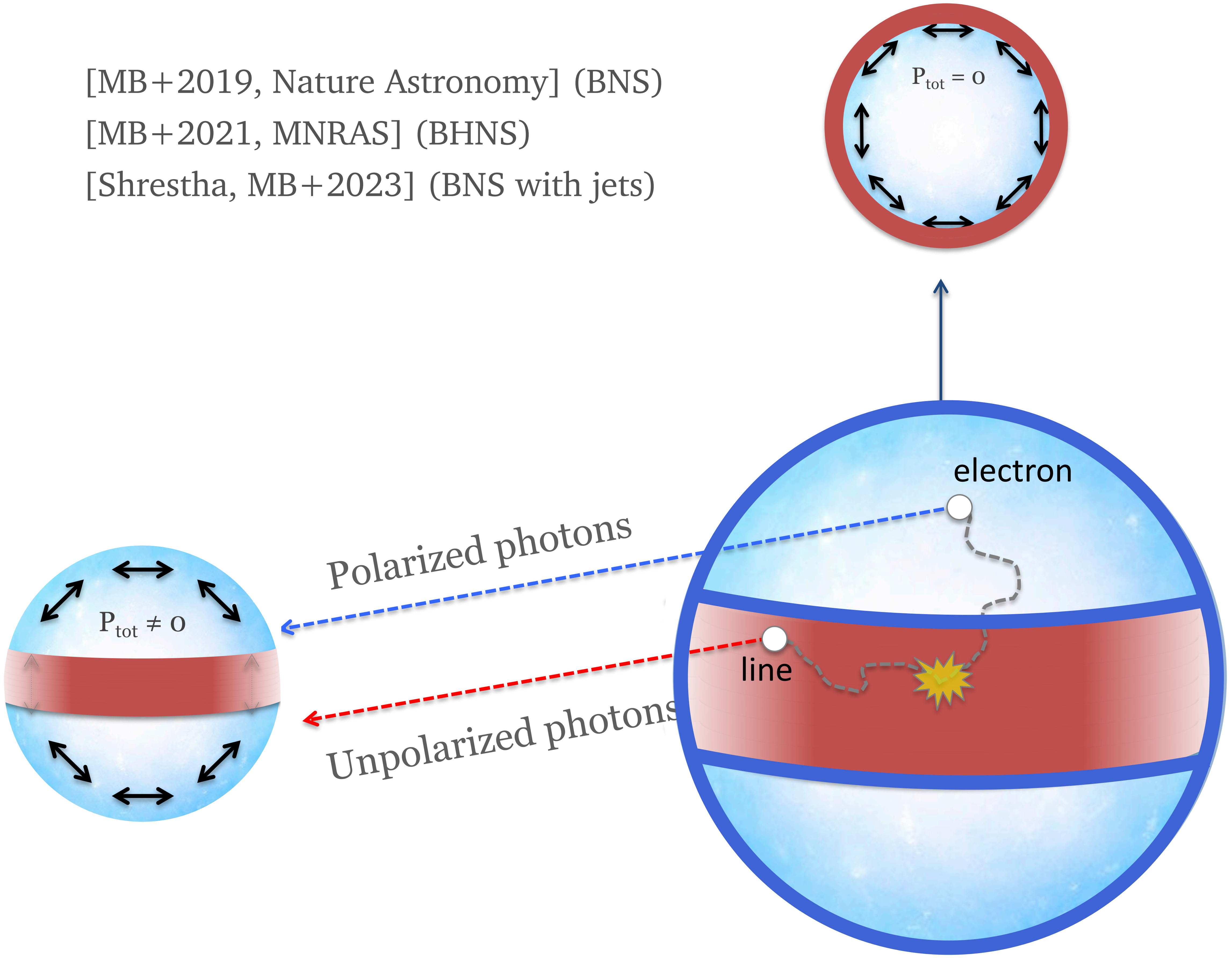

Polarization is sensitive to the **geometry** and the **viewing angle**

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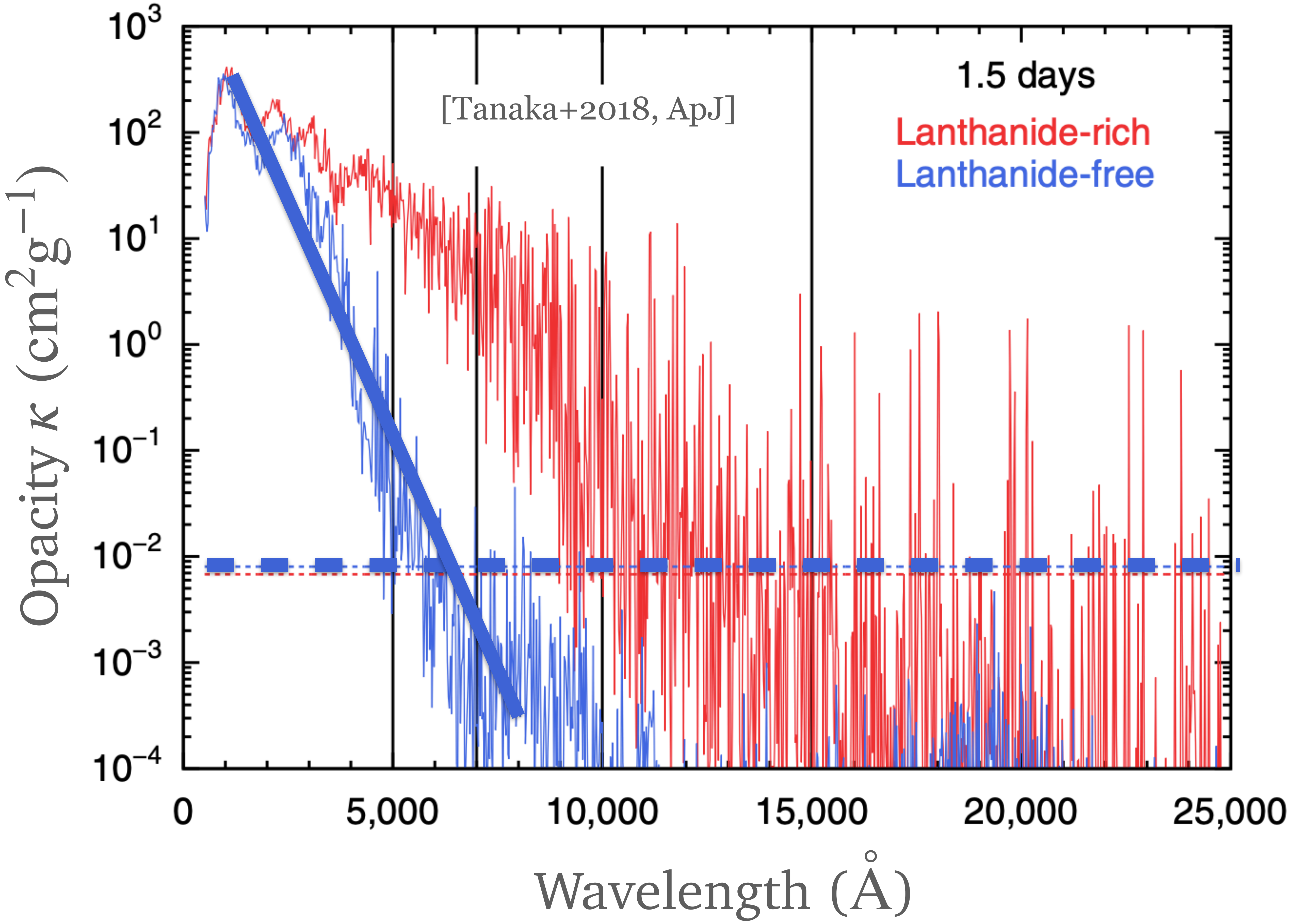

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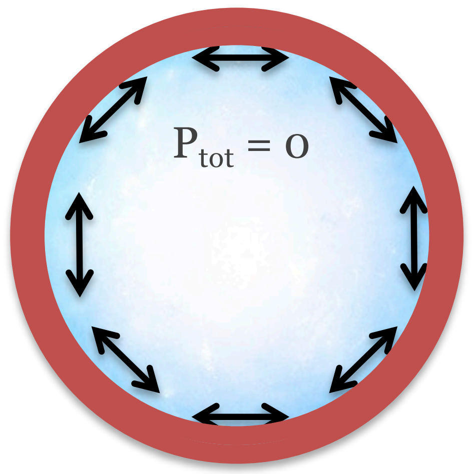
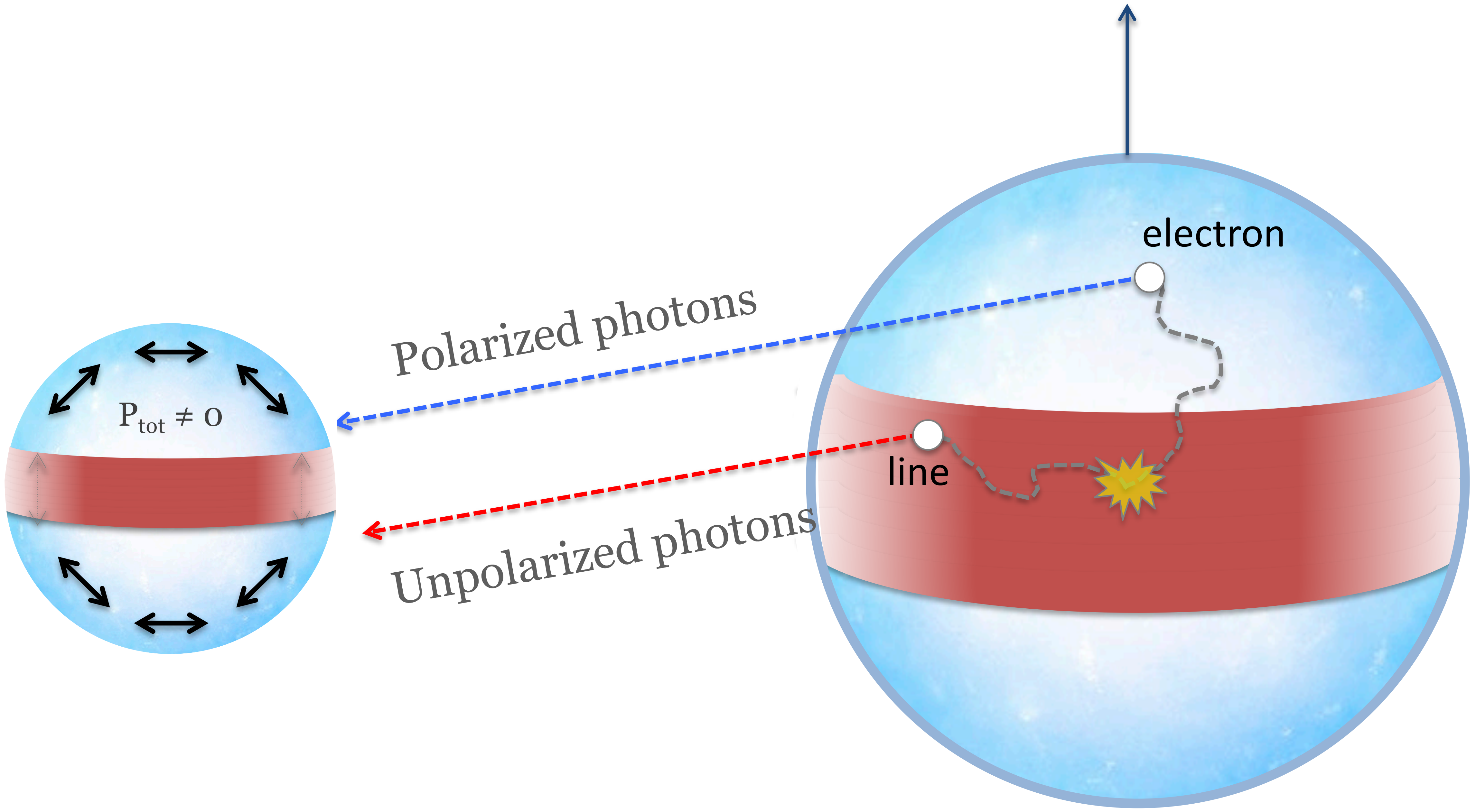




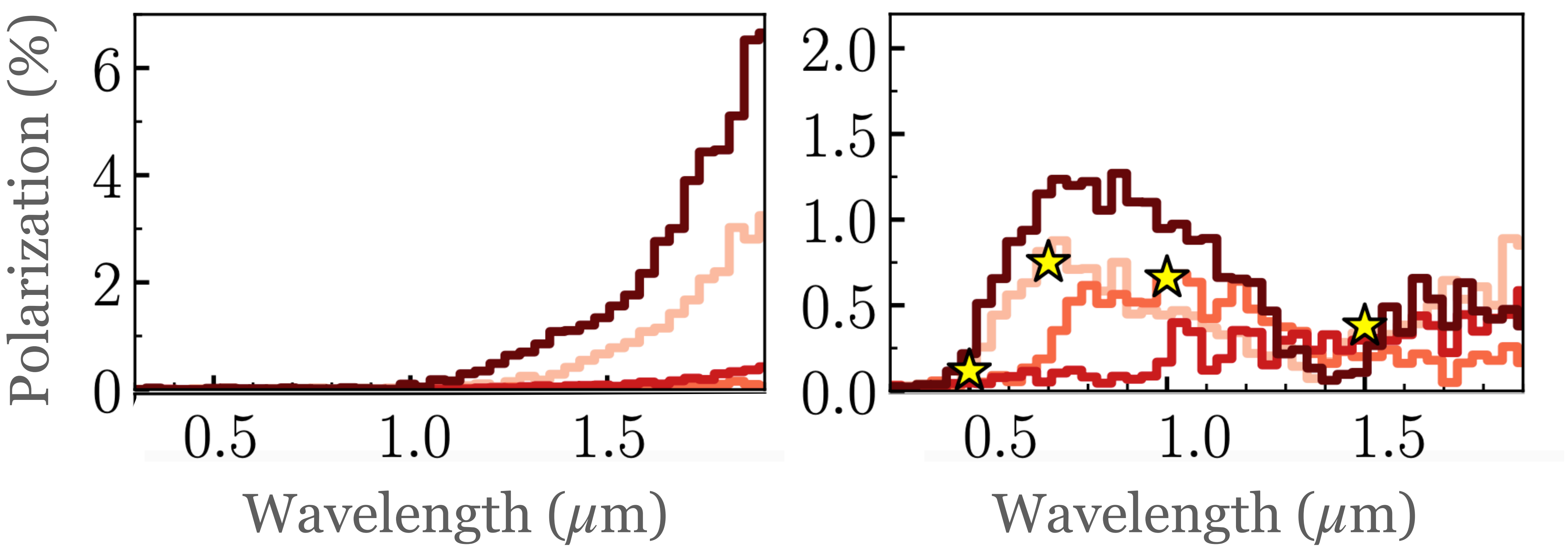
Polarization is sensitive to the **geometry** and the **viewing angle**

Take aways

- Polarization as smoking gun for presence of lanthanide-poor component
- Polarization levels up to ~1% in the optical
- Polarization levels up to ~5% in the near-infrared
- Rapid decay with time (due to recombination)

Lanthanide-rich dynamical ejecta
[Kyutoku+2015, PRD]

Lanthanide-rich dynamical ejecta
+lanthanide-poor disk-wind



[MB+2021, MNRAS]