Let there be light

Kilonovae from radiative transfer simulations of neutron star mergers

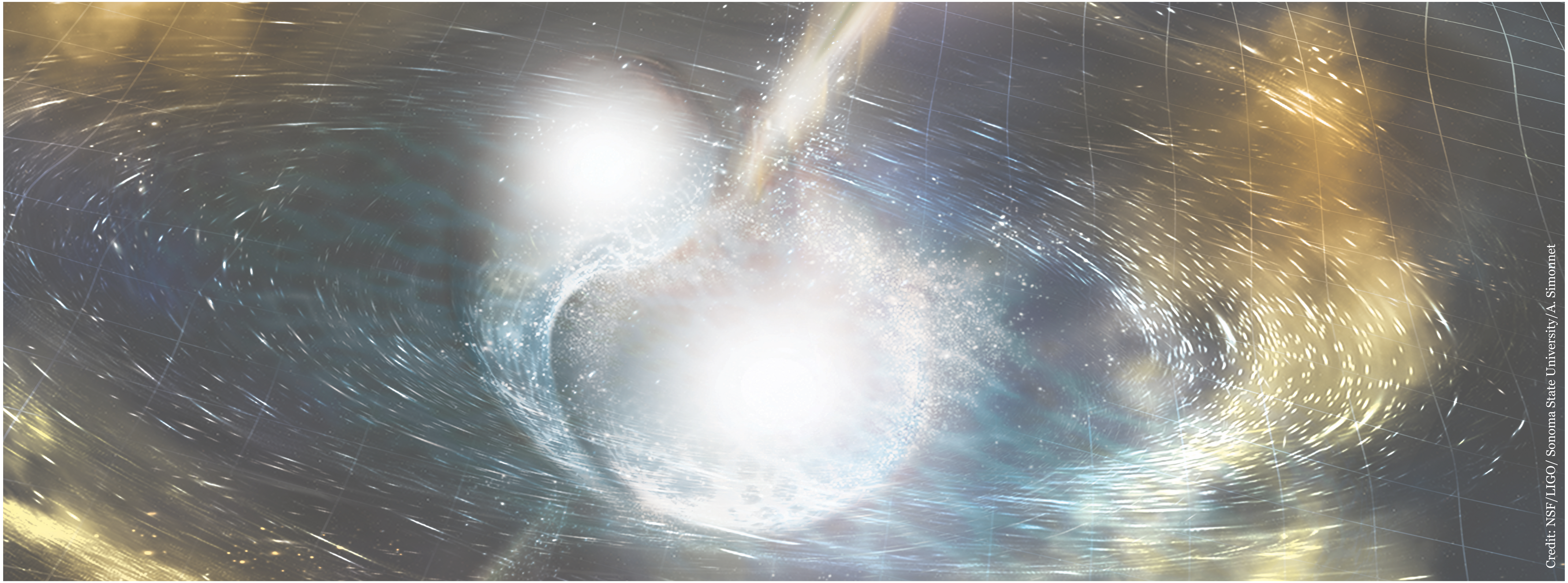
Mattia Bulla

Stockholm University

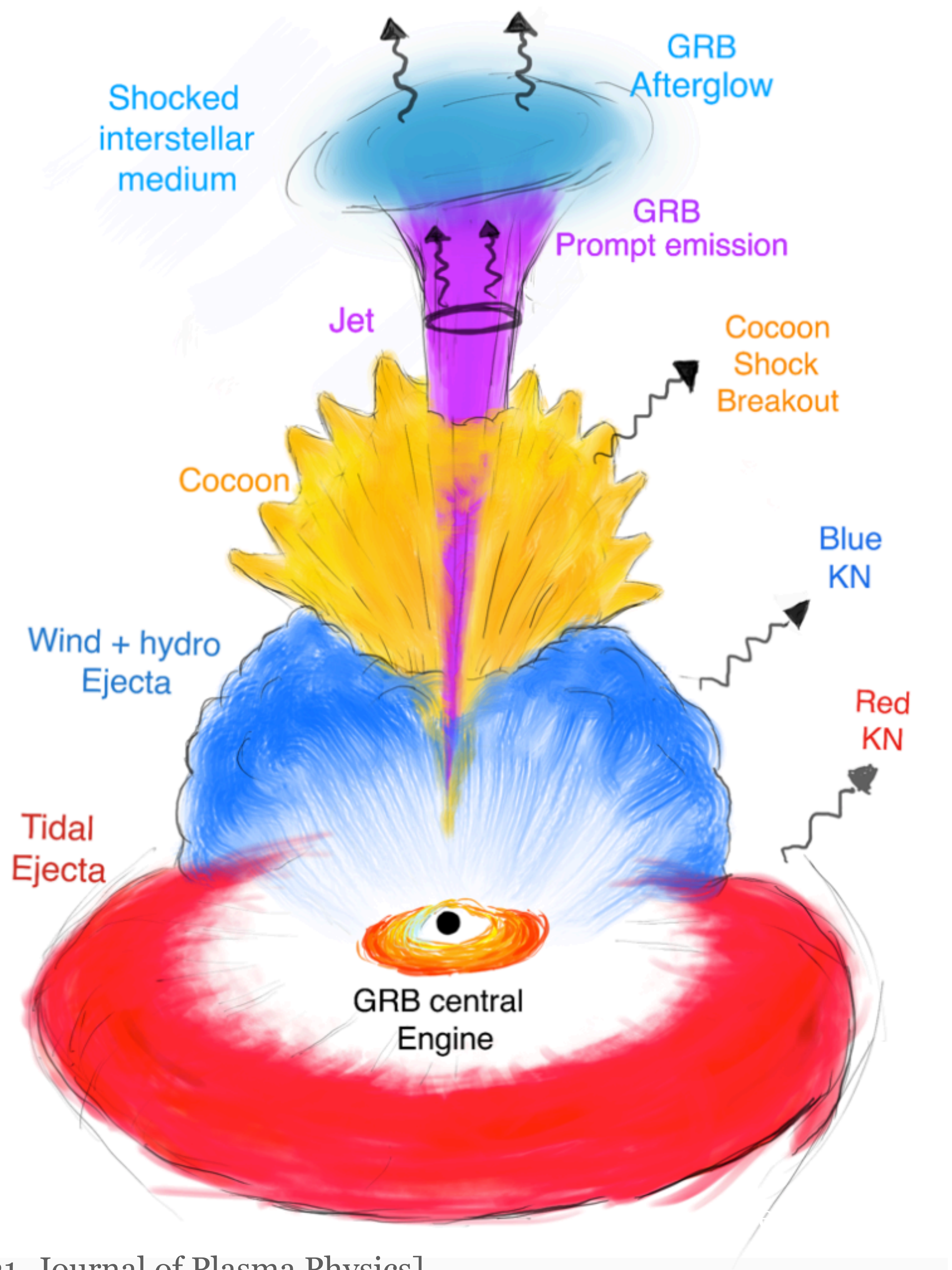
Oskar Klein centre

Vetenskapsrådet
Swedish Research Council

with: A. Sagues-Carracedo, L. Nativi, S. Dhawan, A. Goobar, S. Rosswog,
L. Issa, S. Anand, P. T. H. Pang, M. Shrestha, I. Andreoni, M. W. Coughlin, T. Dietrich, I. Tews, S. Covino, M. Tanaka, K. Kyutoku + many more

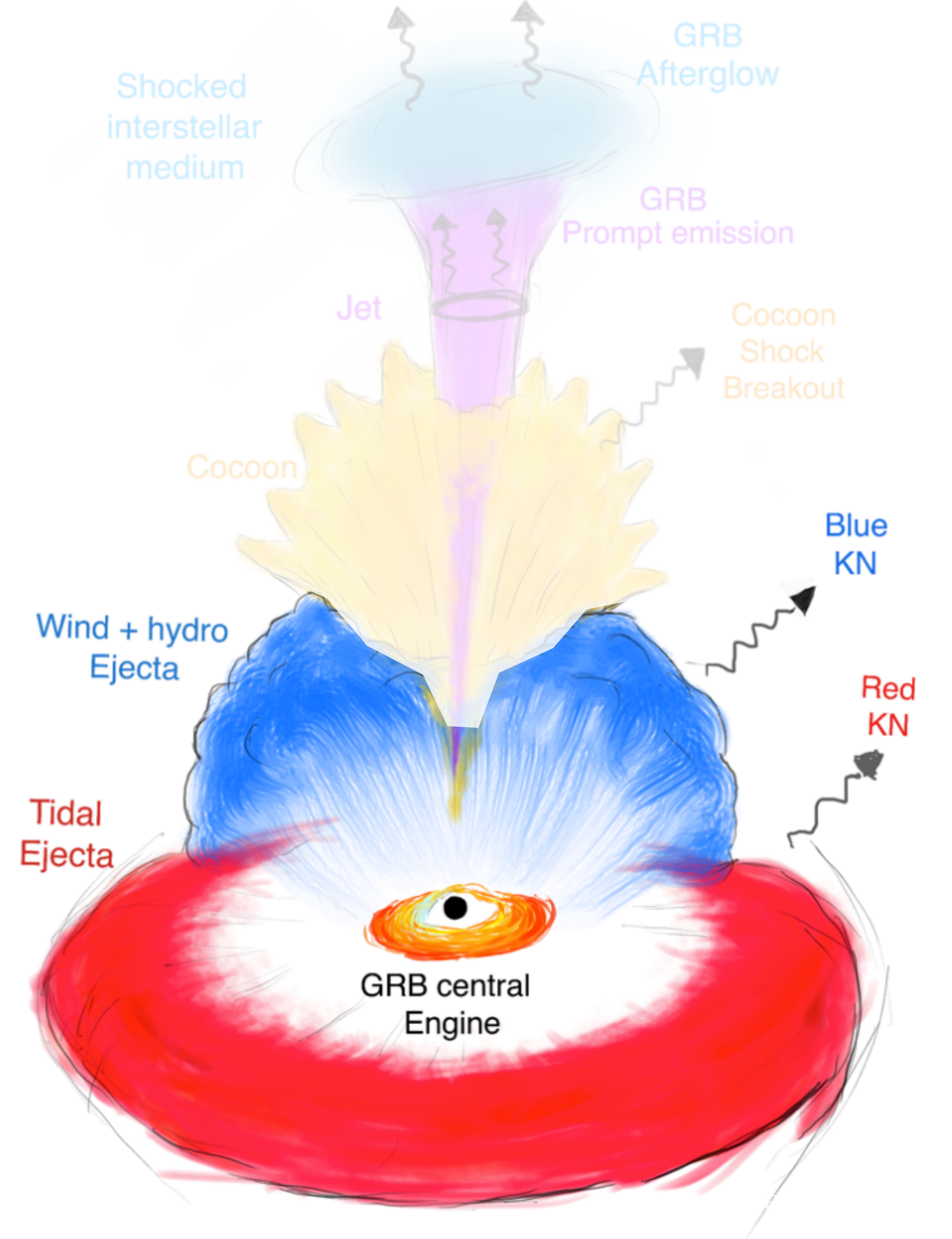


NS mergers and EM counterparts



[Ascenzi+2021, Journal of Plasma Physics]

NS mergers and kilonovae



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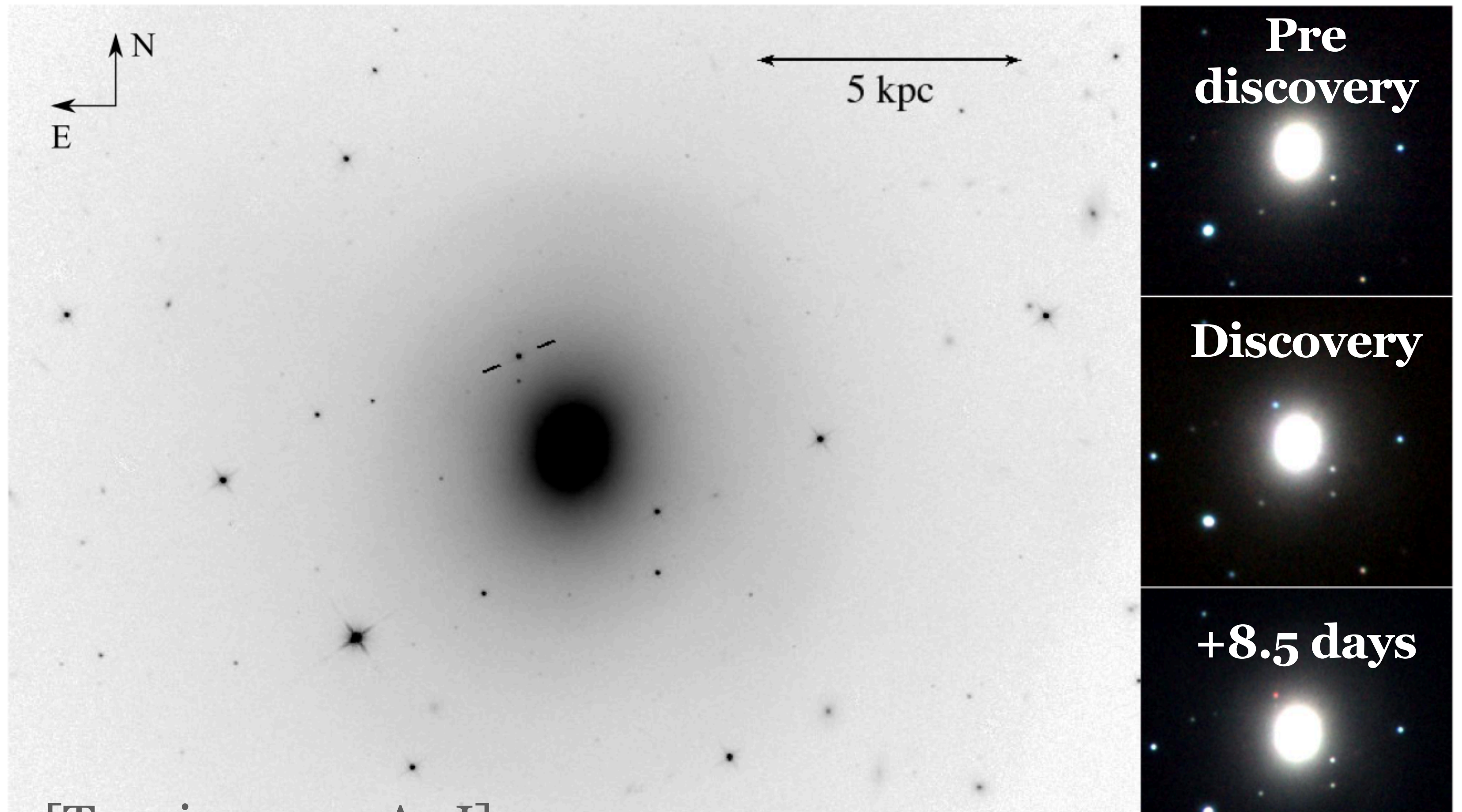
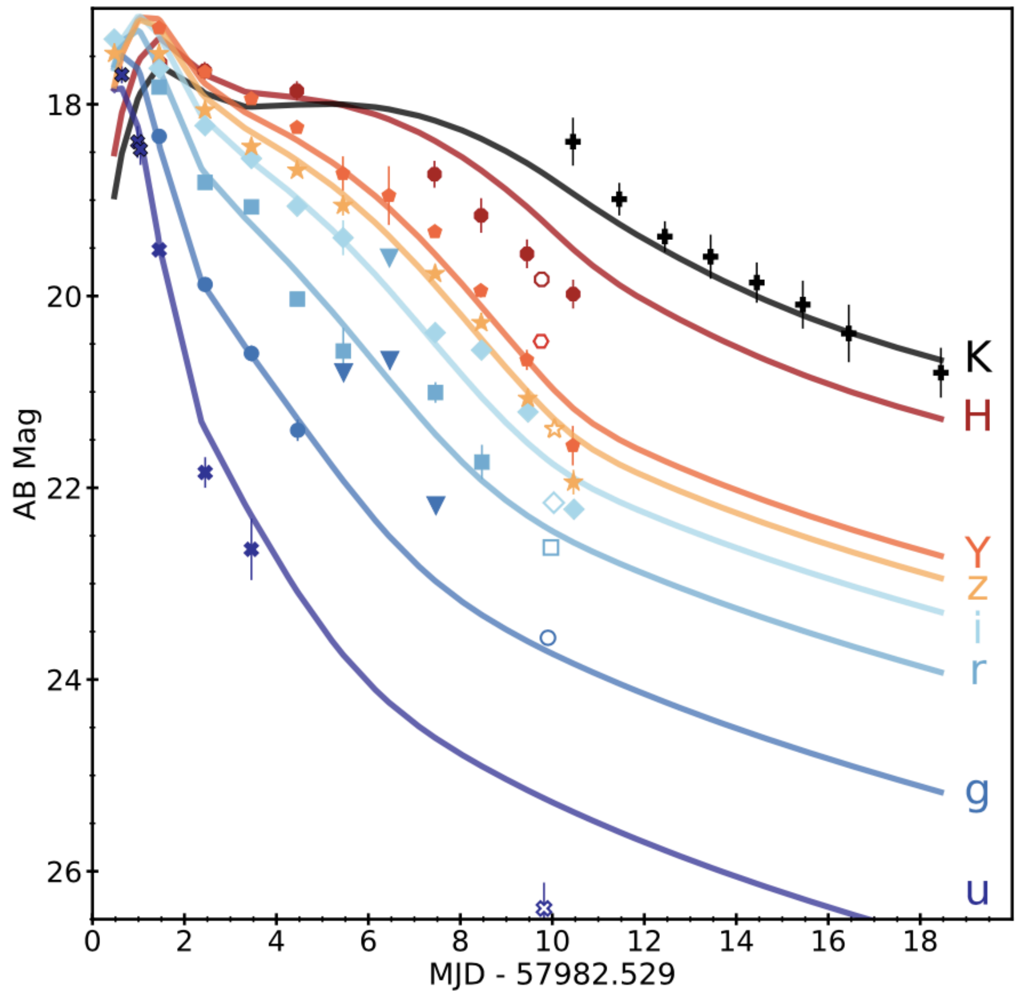
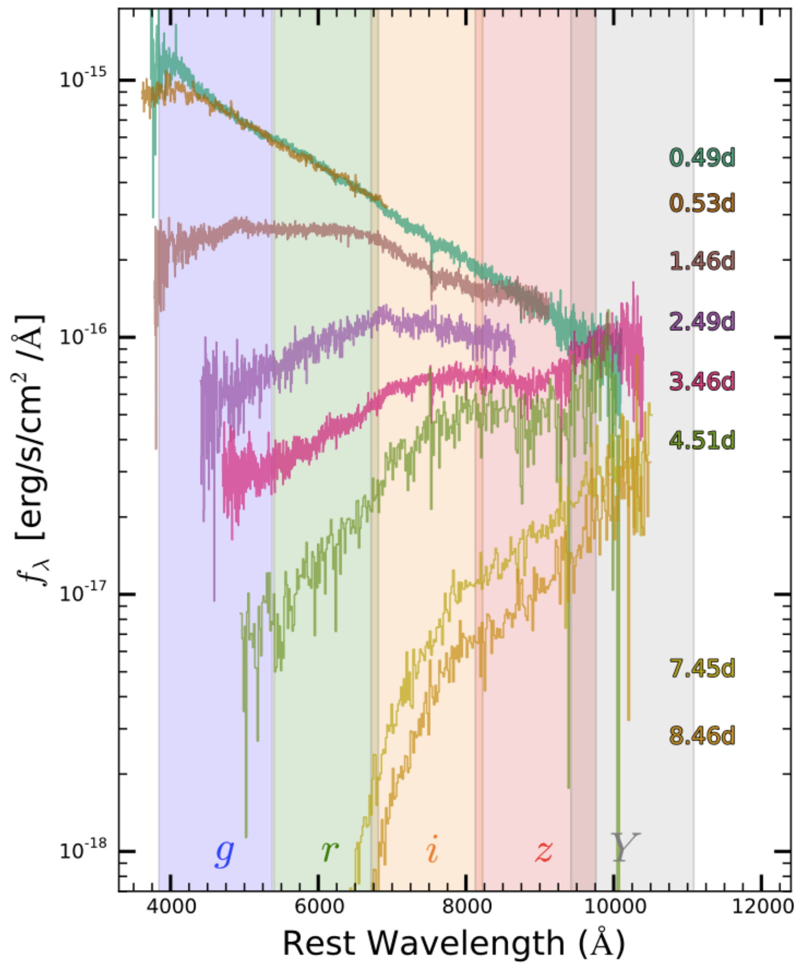


[Tanvir+2017, ApJ]

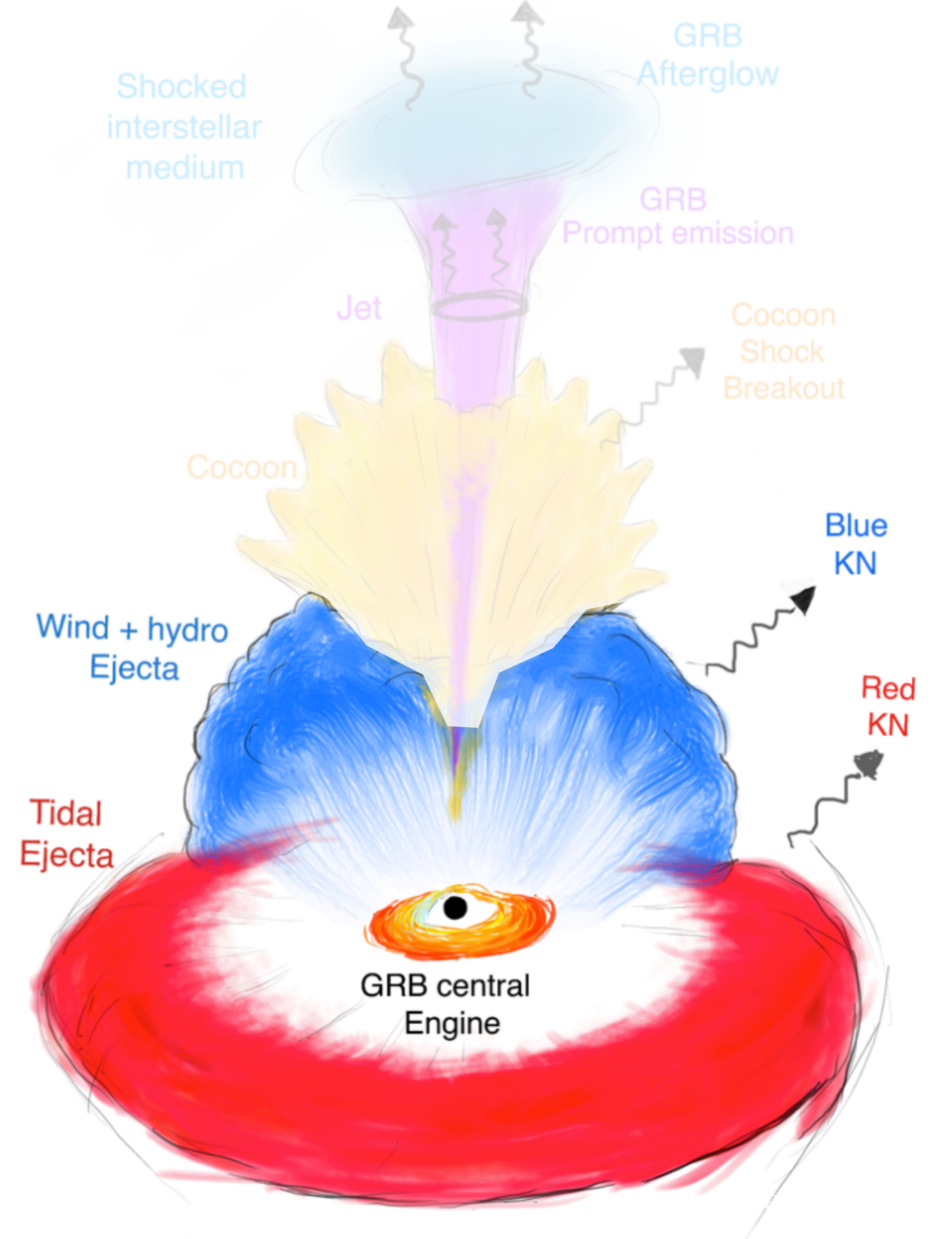


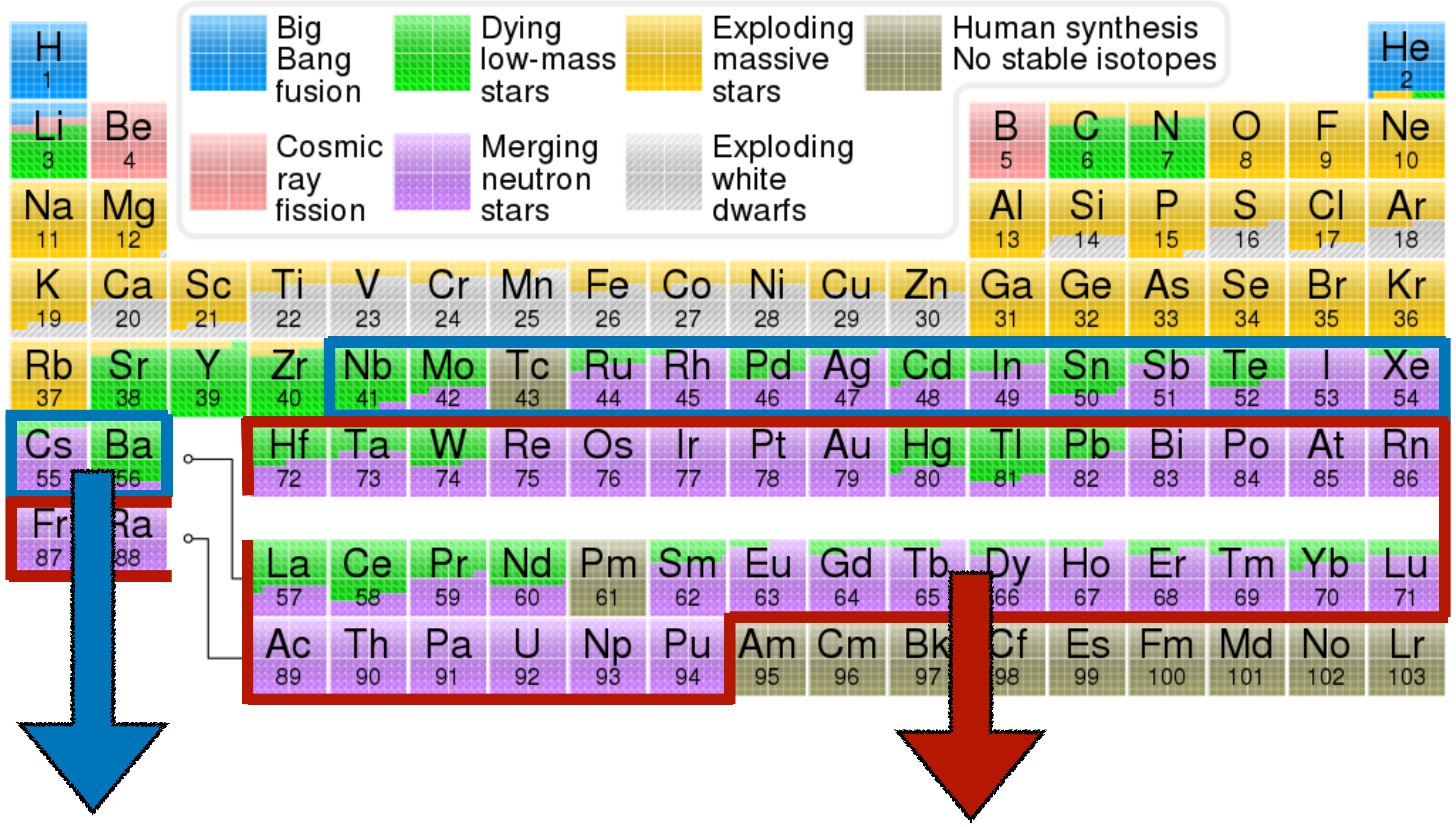
[Cowperthwaite+2017, ApJ]



[Shappee+2017, Science]

NS mergers and kilonovae





Blue KN

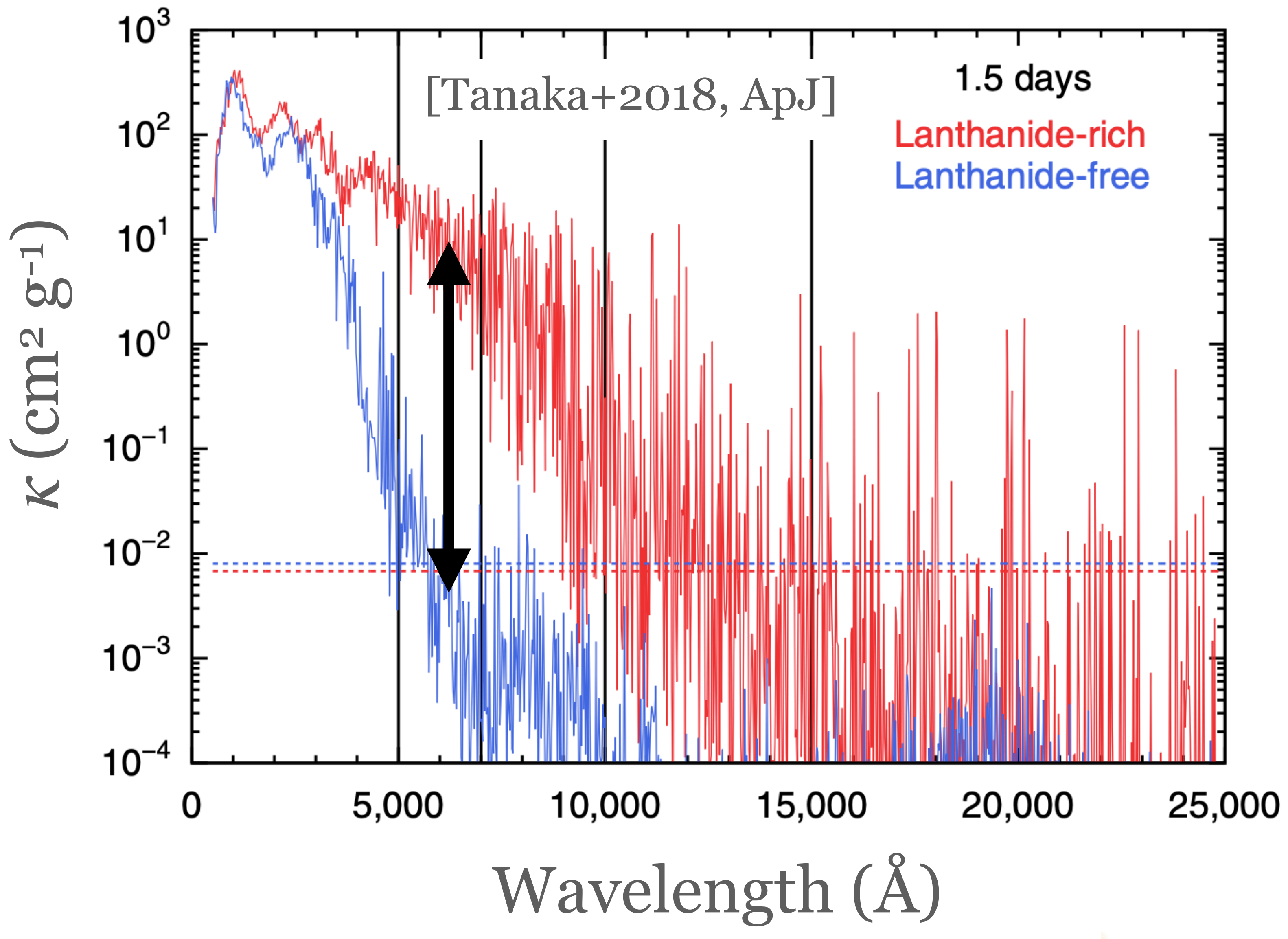
$Y_e \gtrsim 0.25$

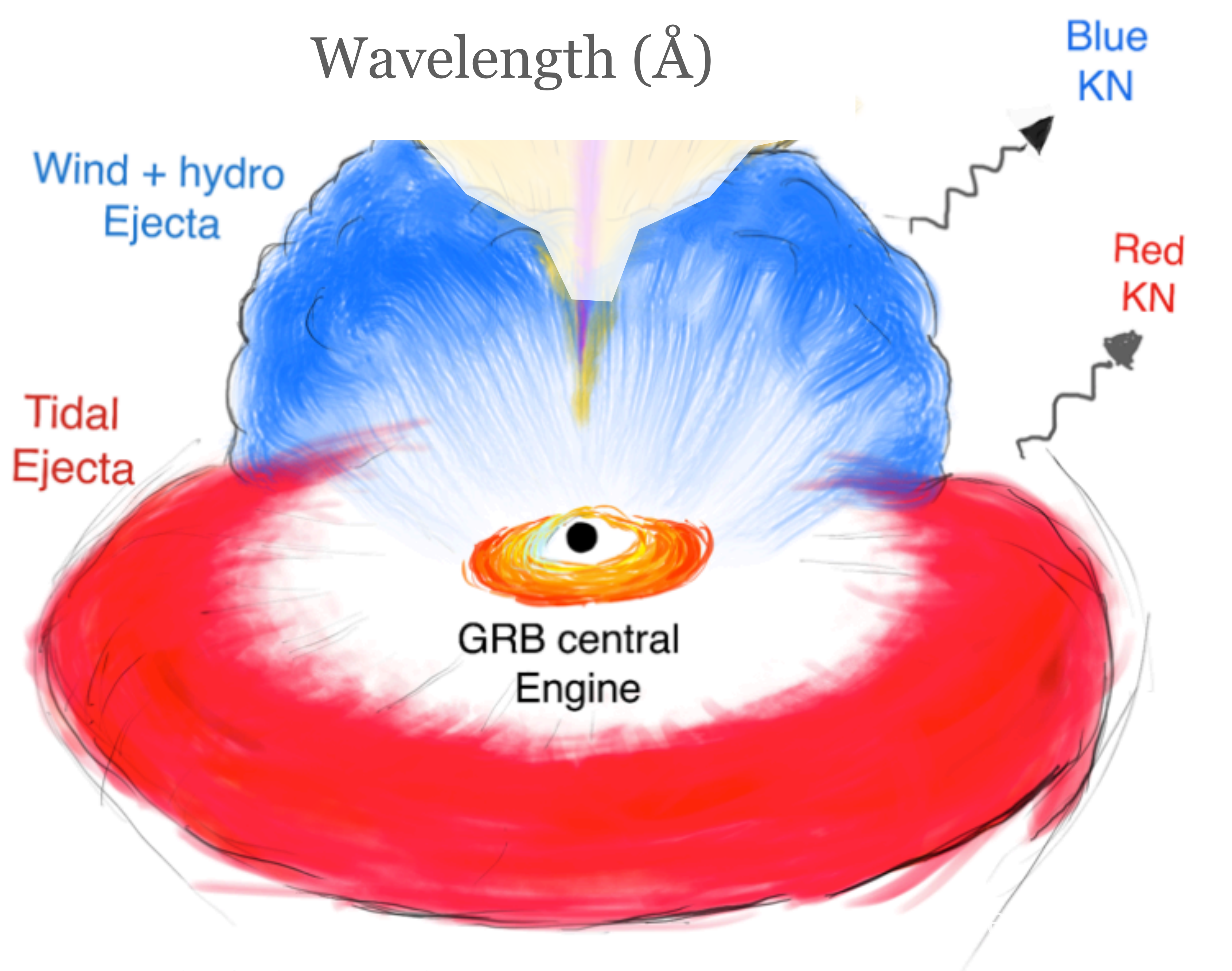
Red KN

$Y_e \lesssim 0.25$

[Ascenzi+2021, Journal of Plasma Physics]

NS mergers and kilonovae





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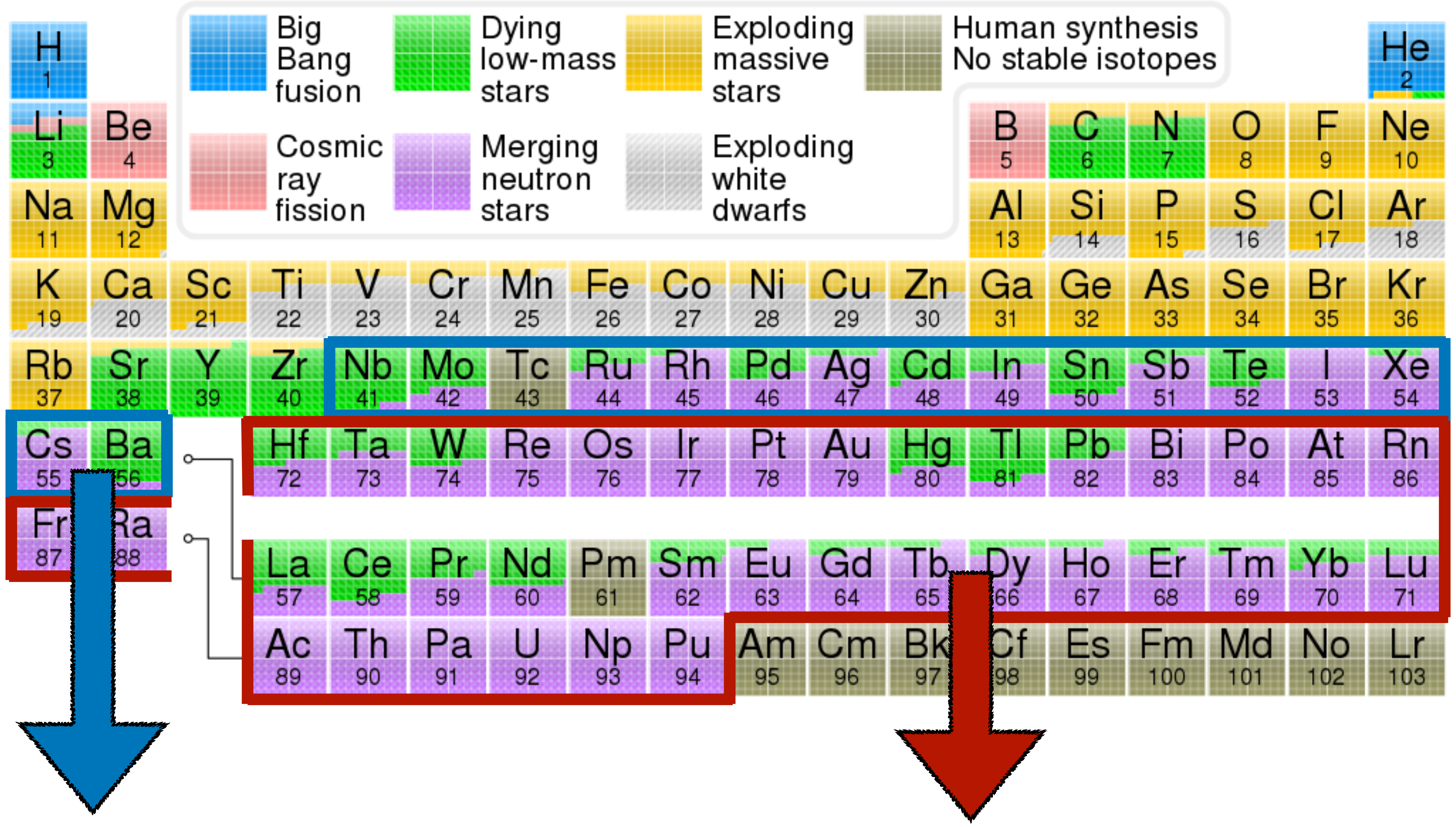


Blue KN

$Y_e \gtrsim 0.25$

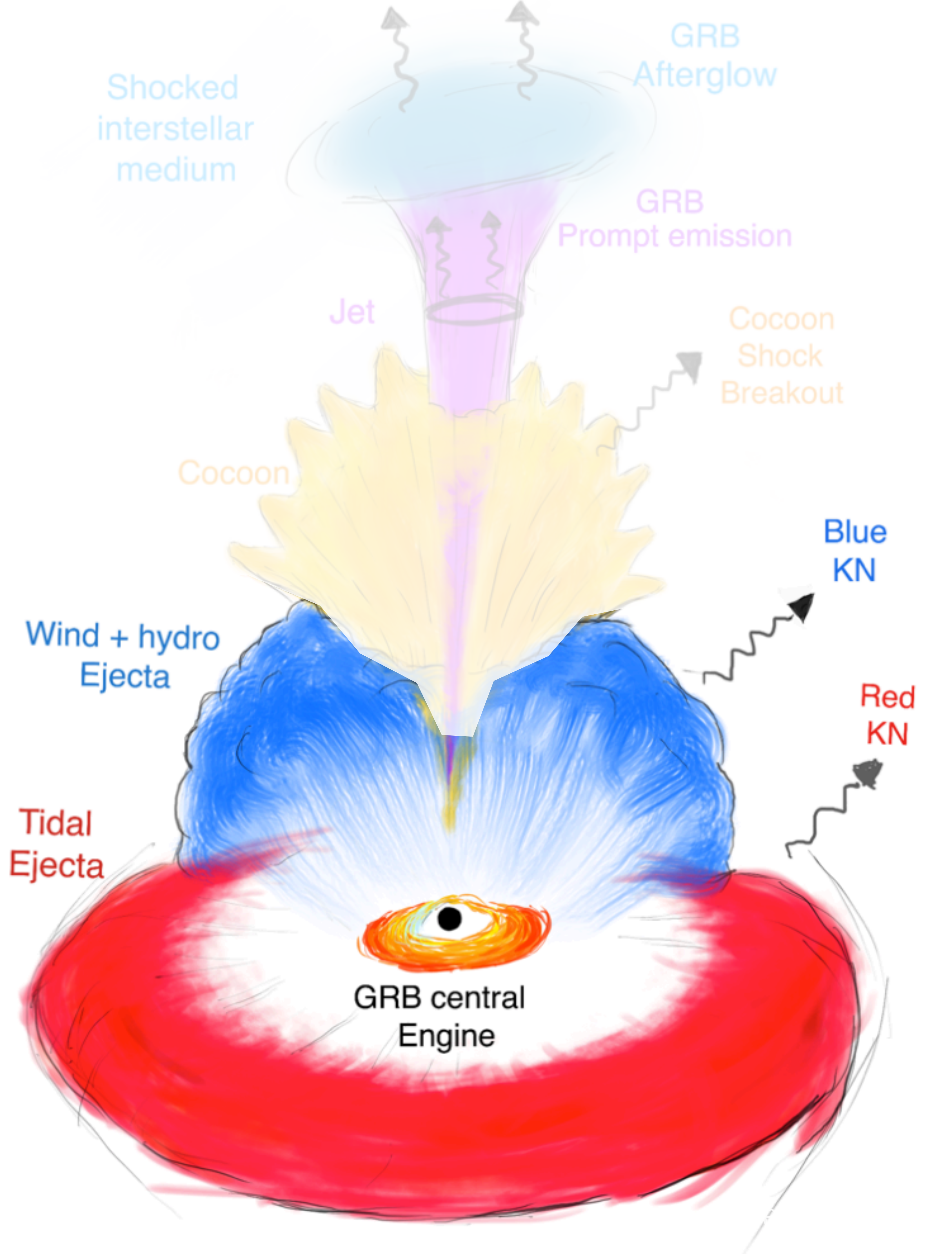
Low opacities

Red KN

$Y_e \lesssim 0.25$

High opacities

NS mergers and kilonovae



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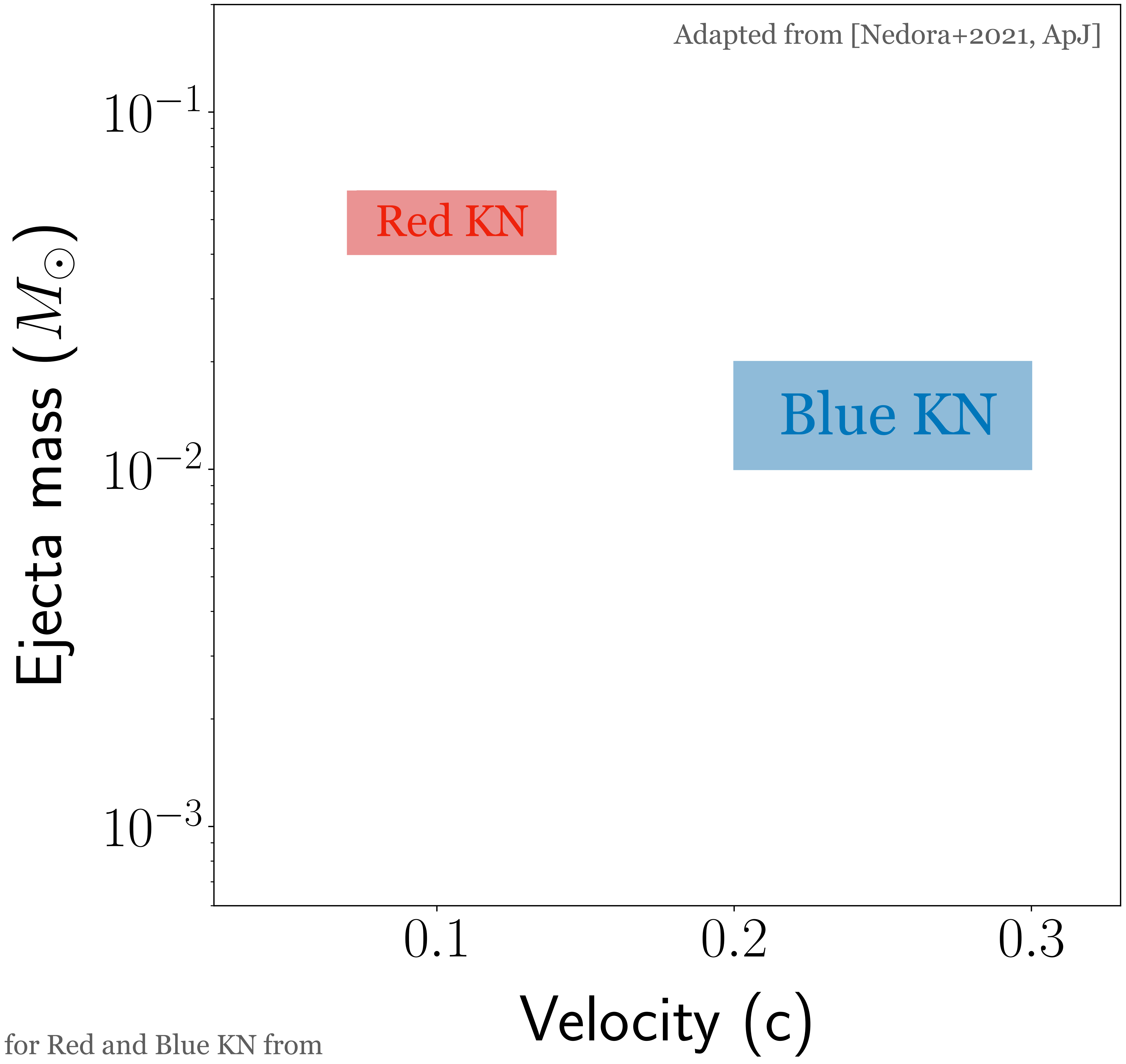
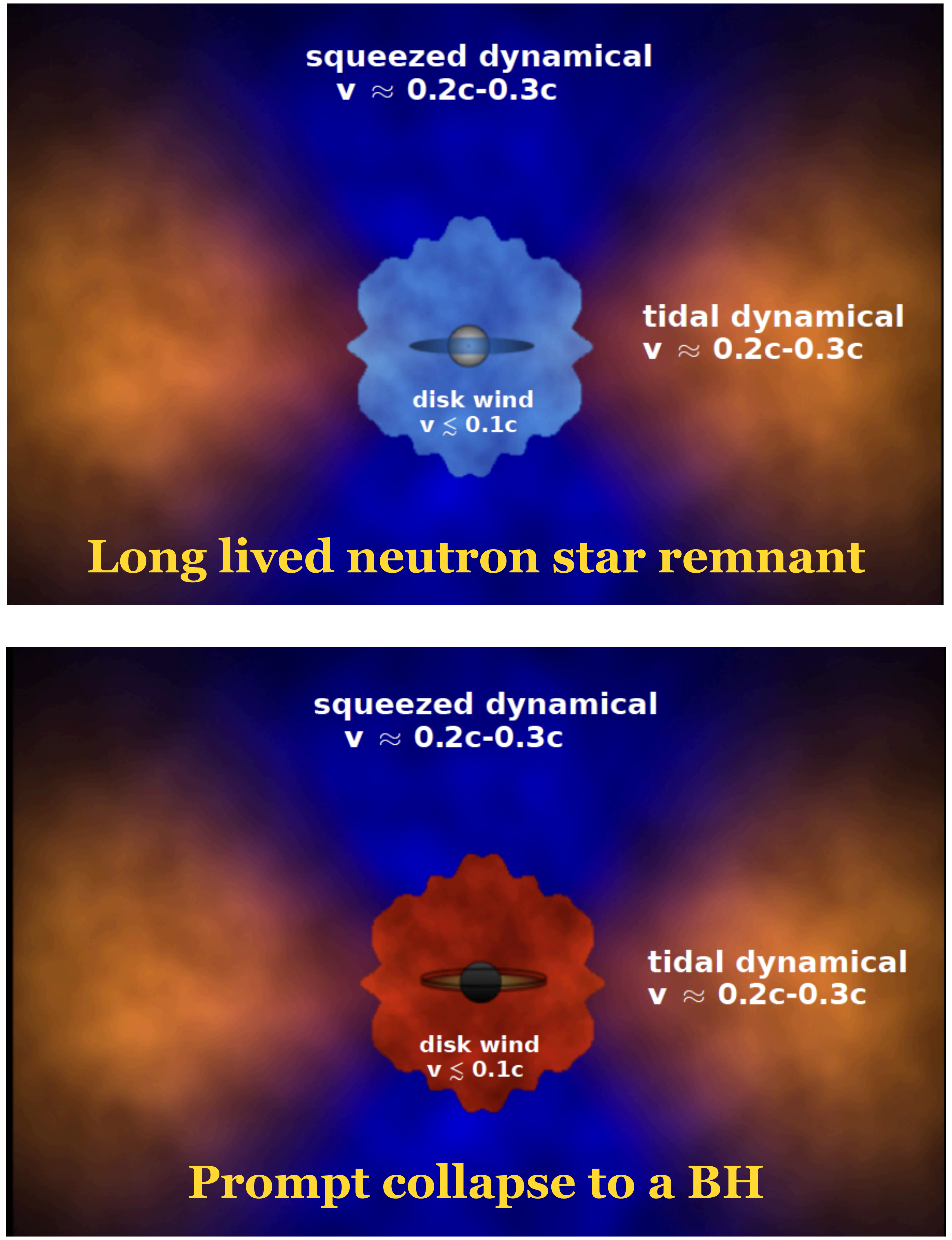
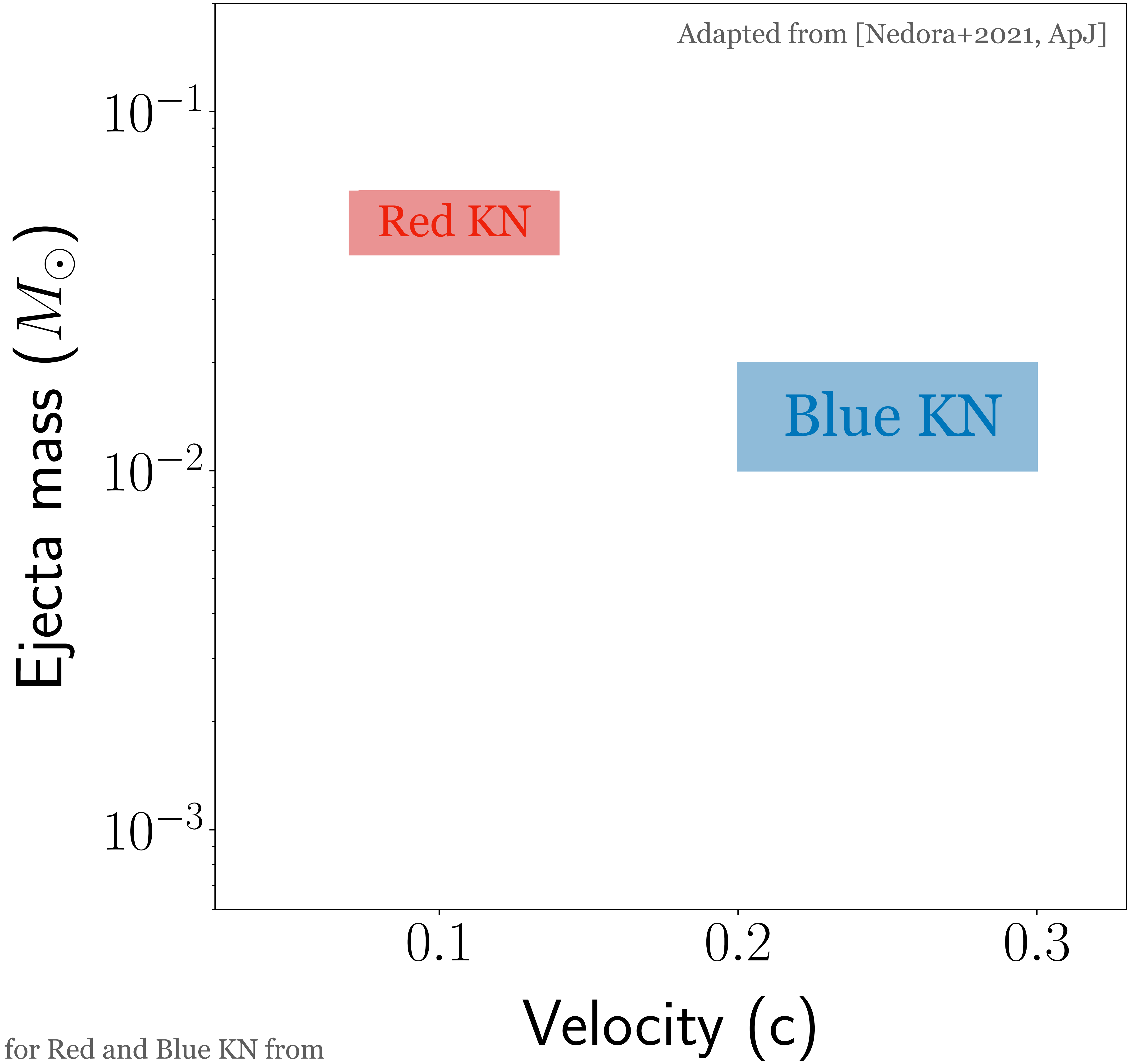


Parameters for Red and Blue KN from
[Siegel 2019, Eur. Phys. J. A.]

NS mergers and kilonovae





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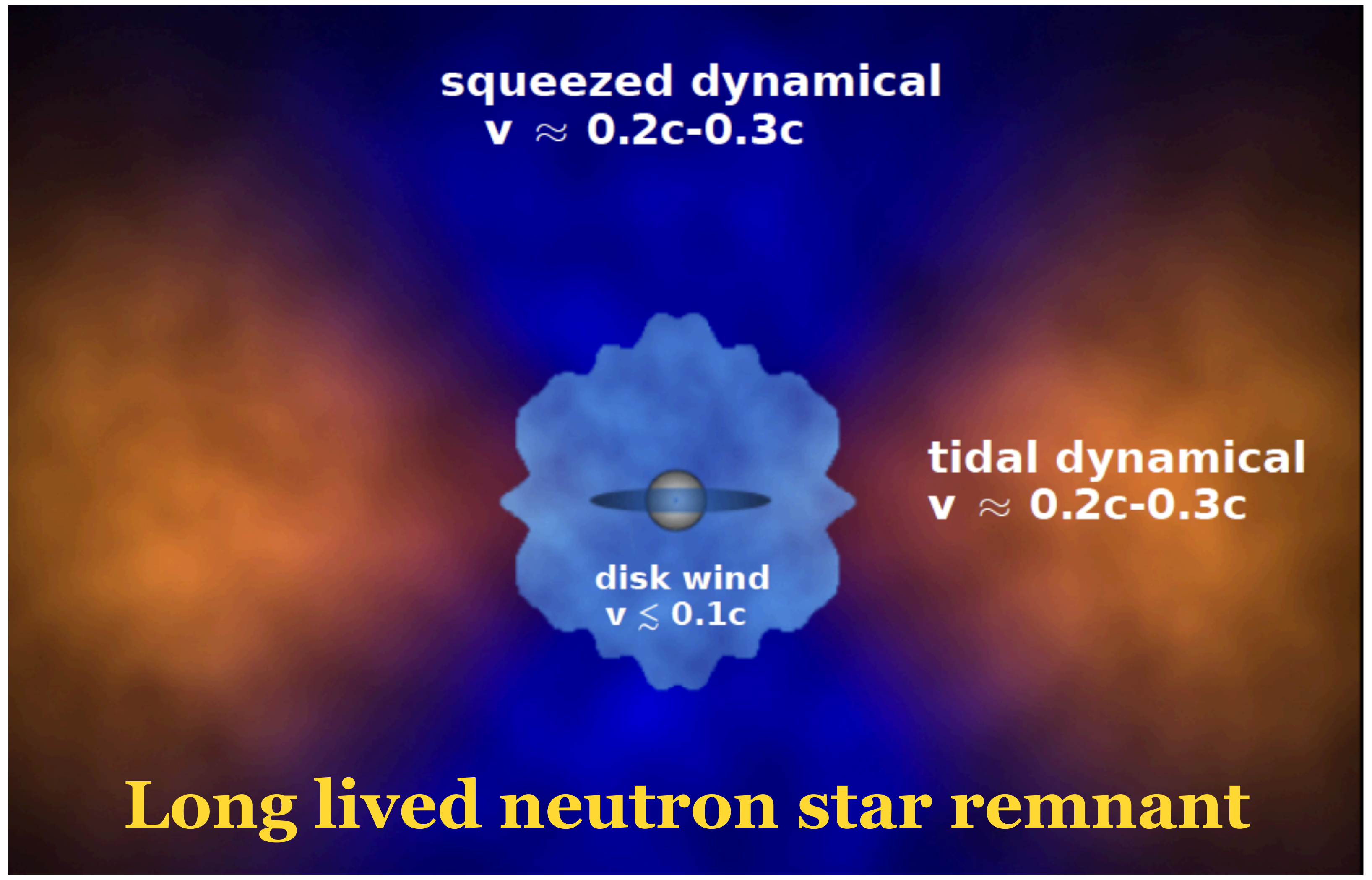

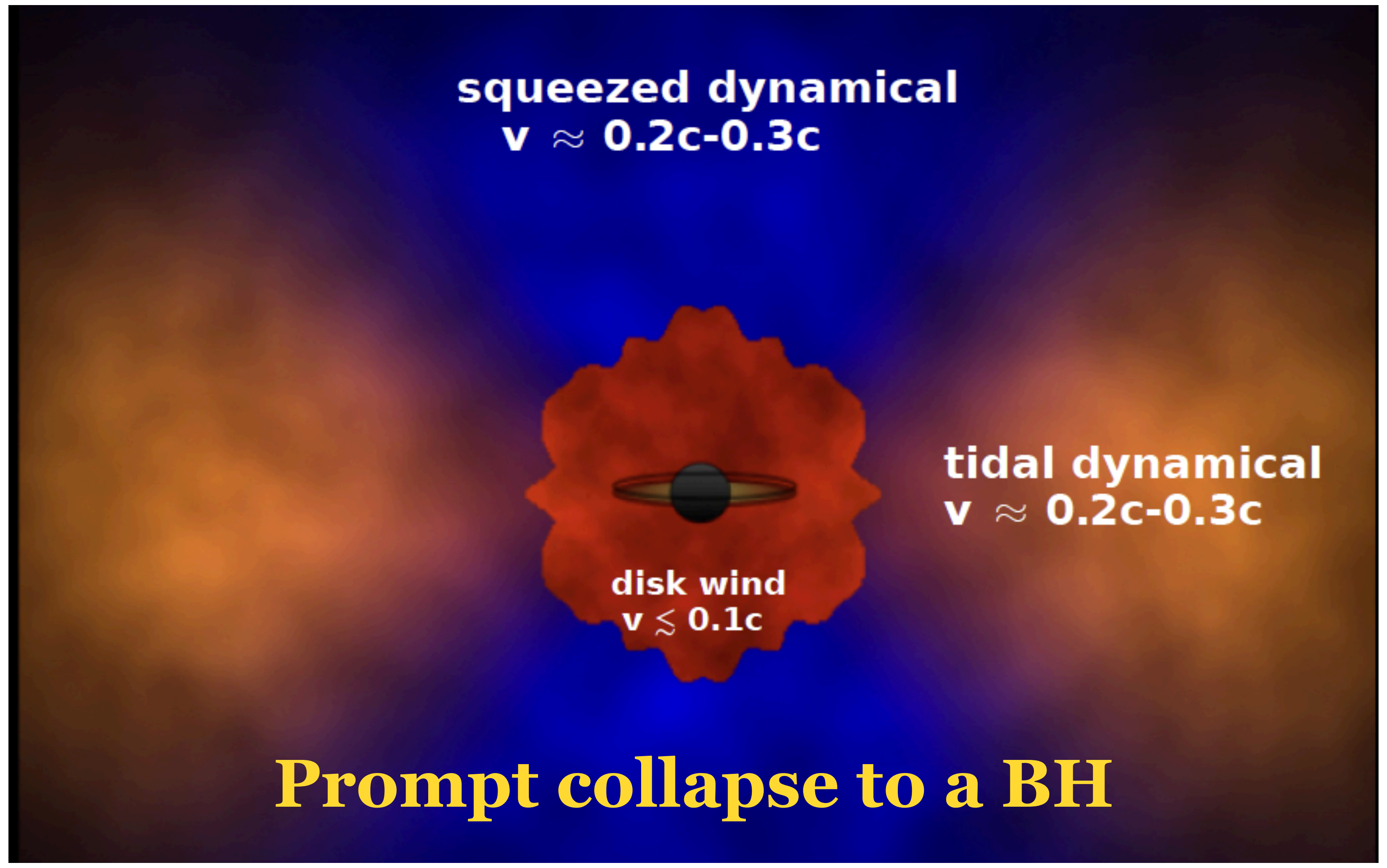

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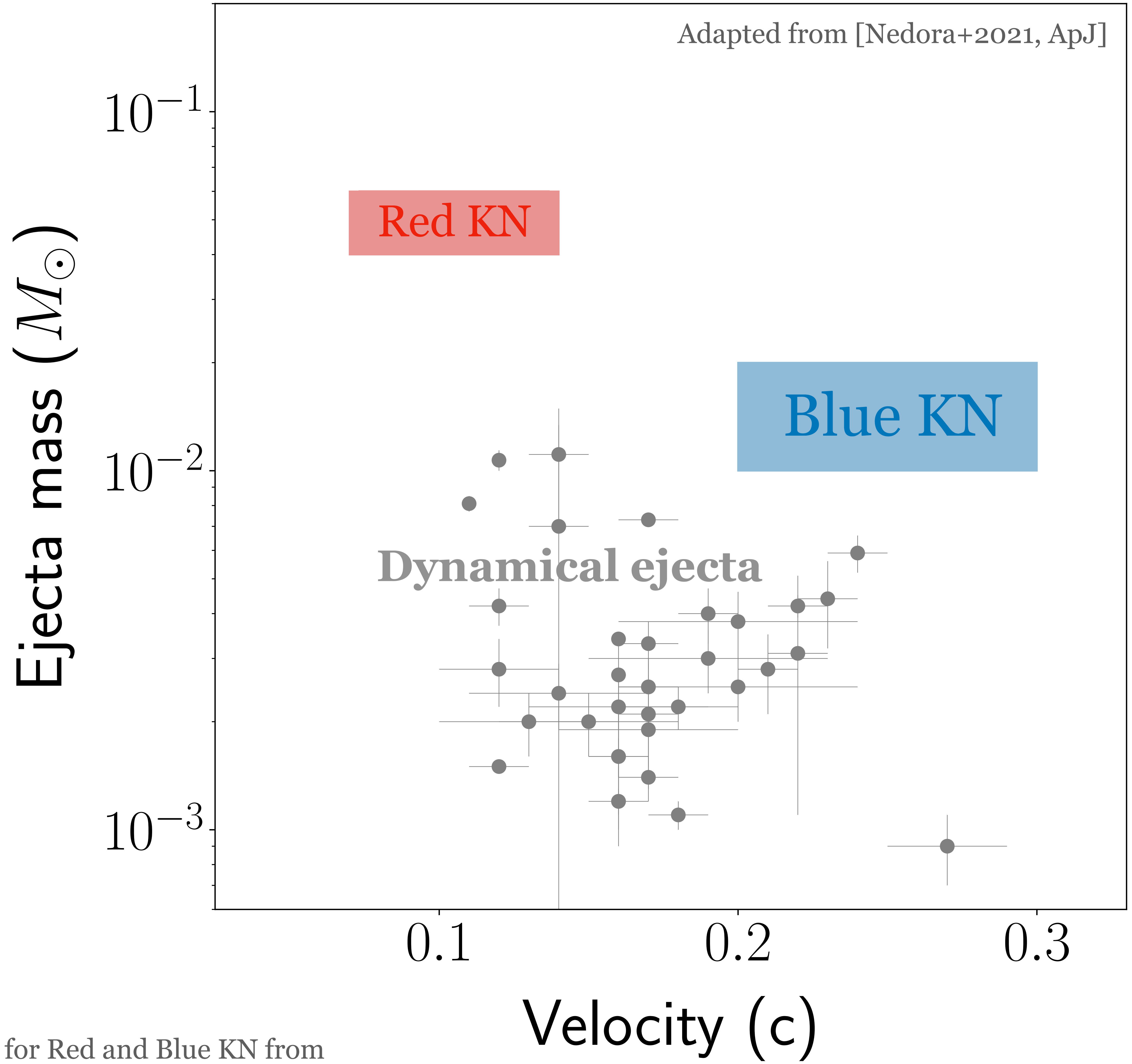

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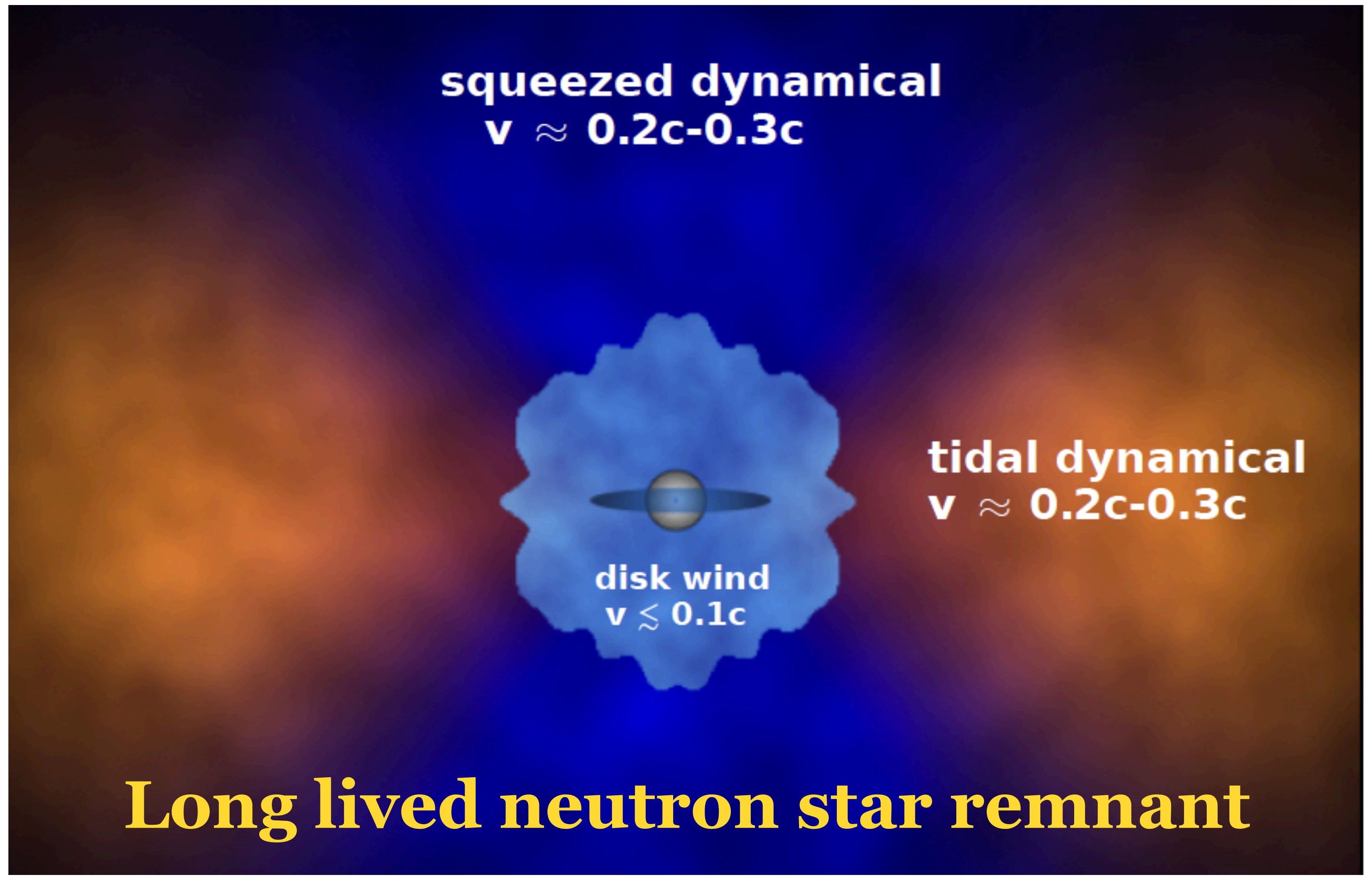

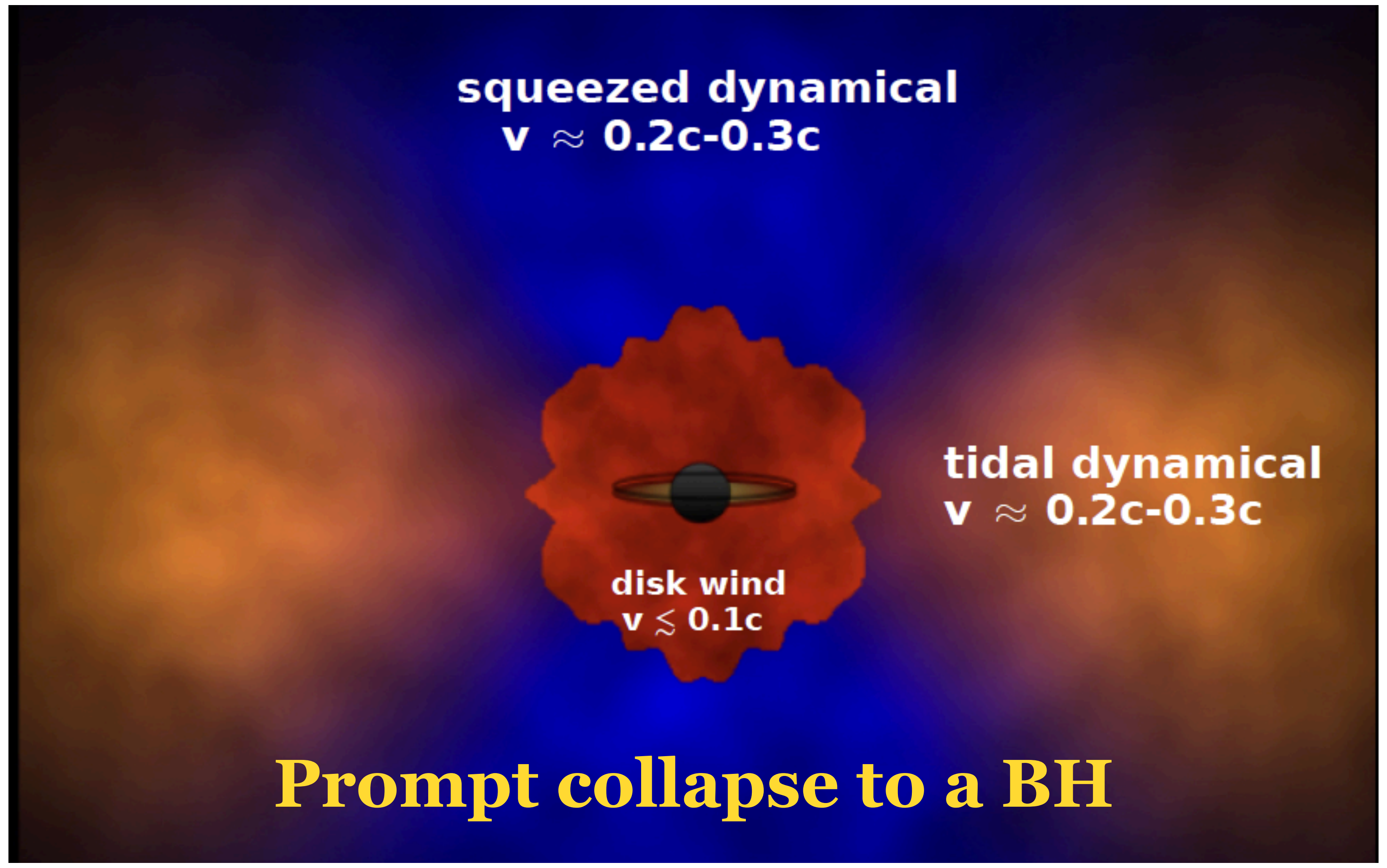

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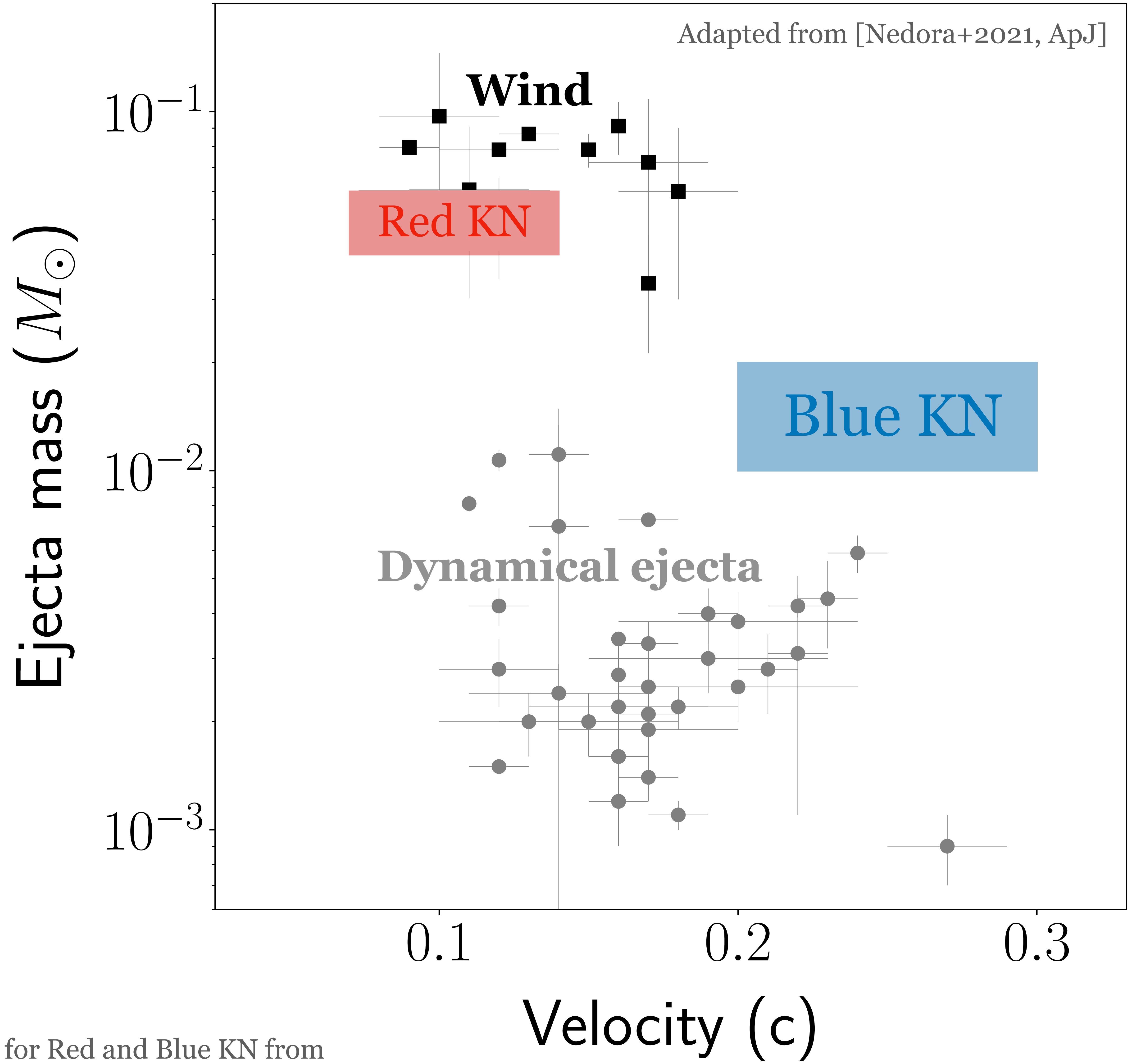

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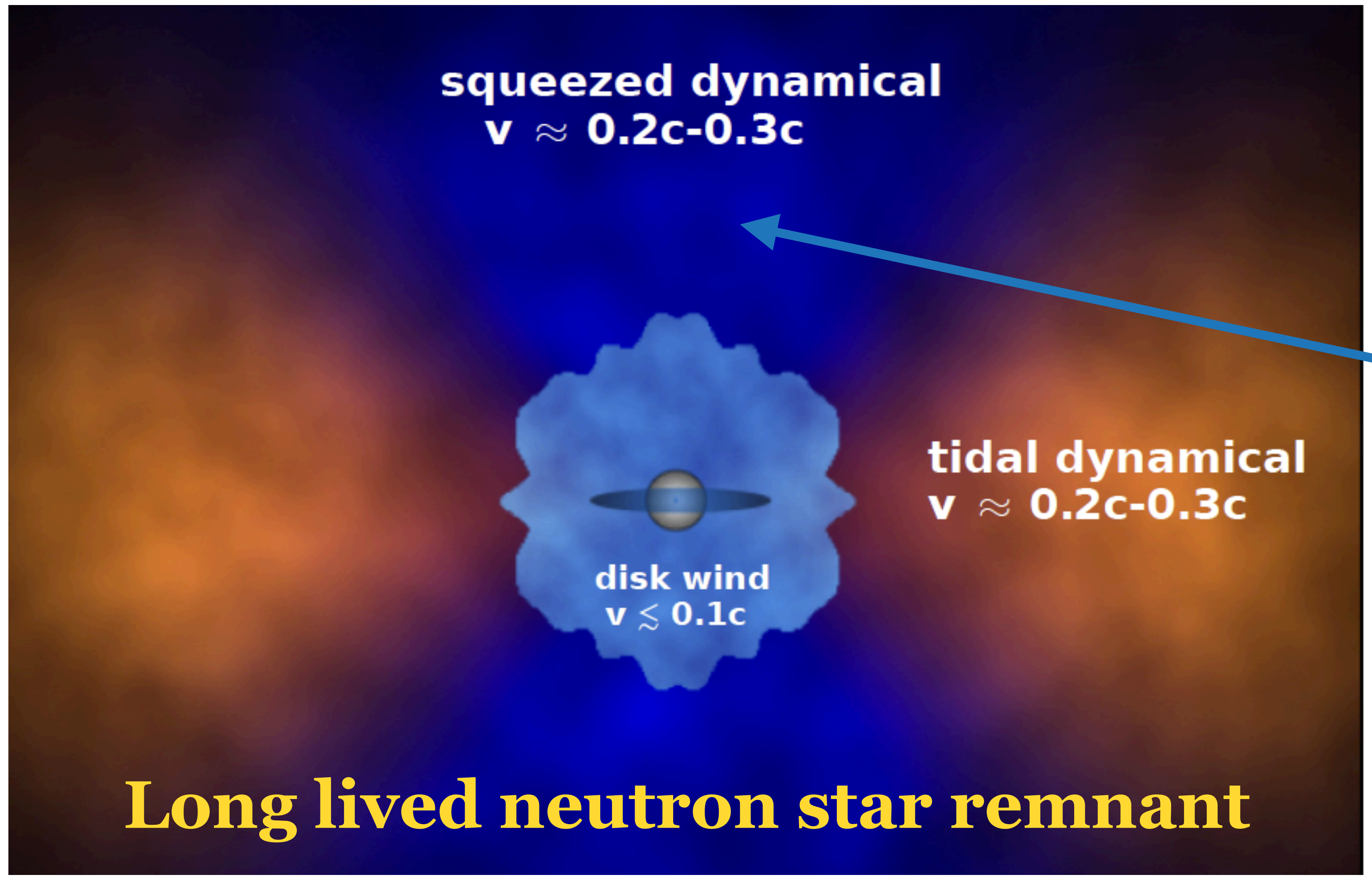

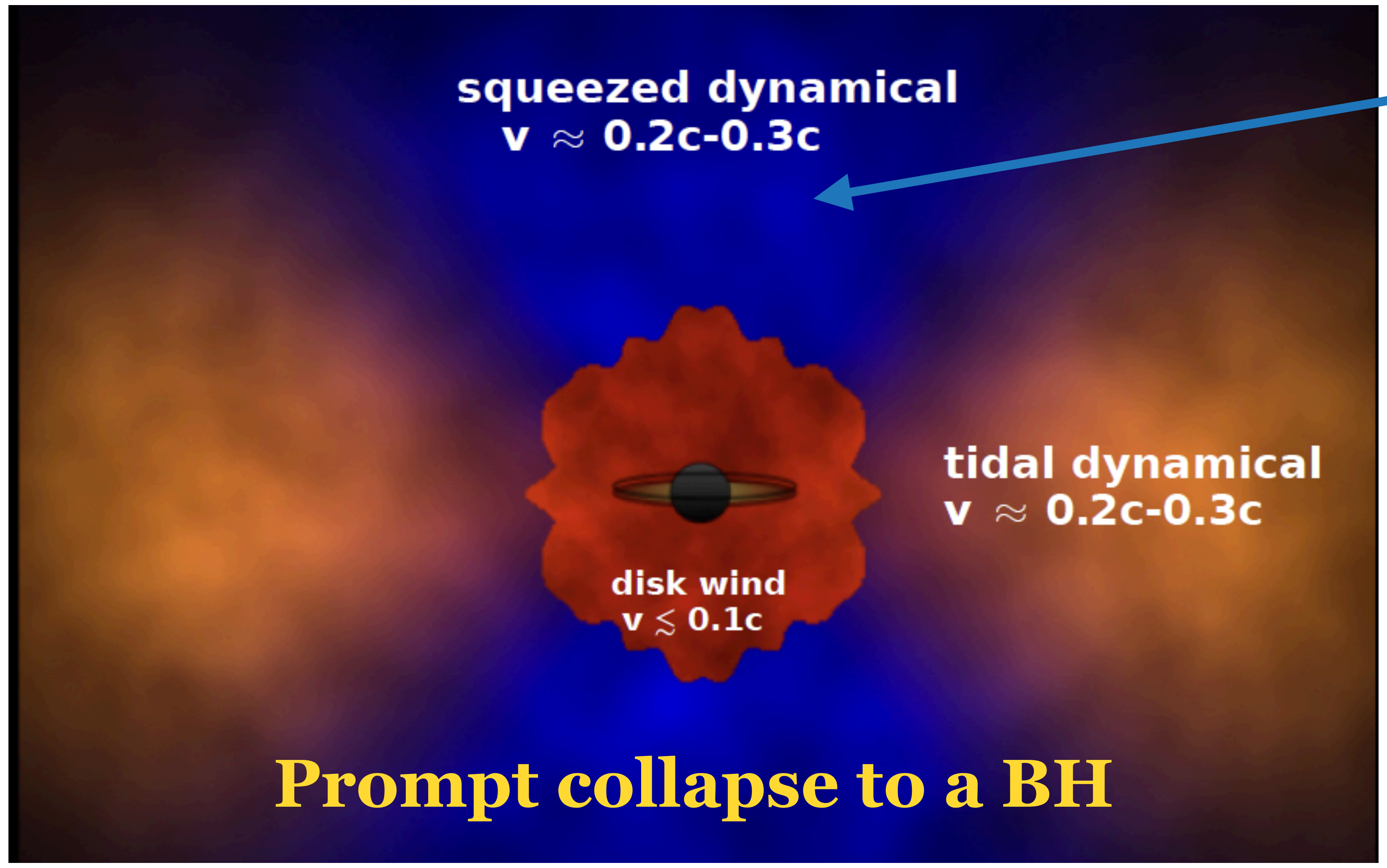

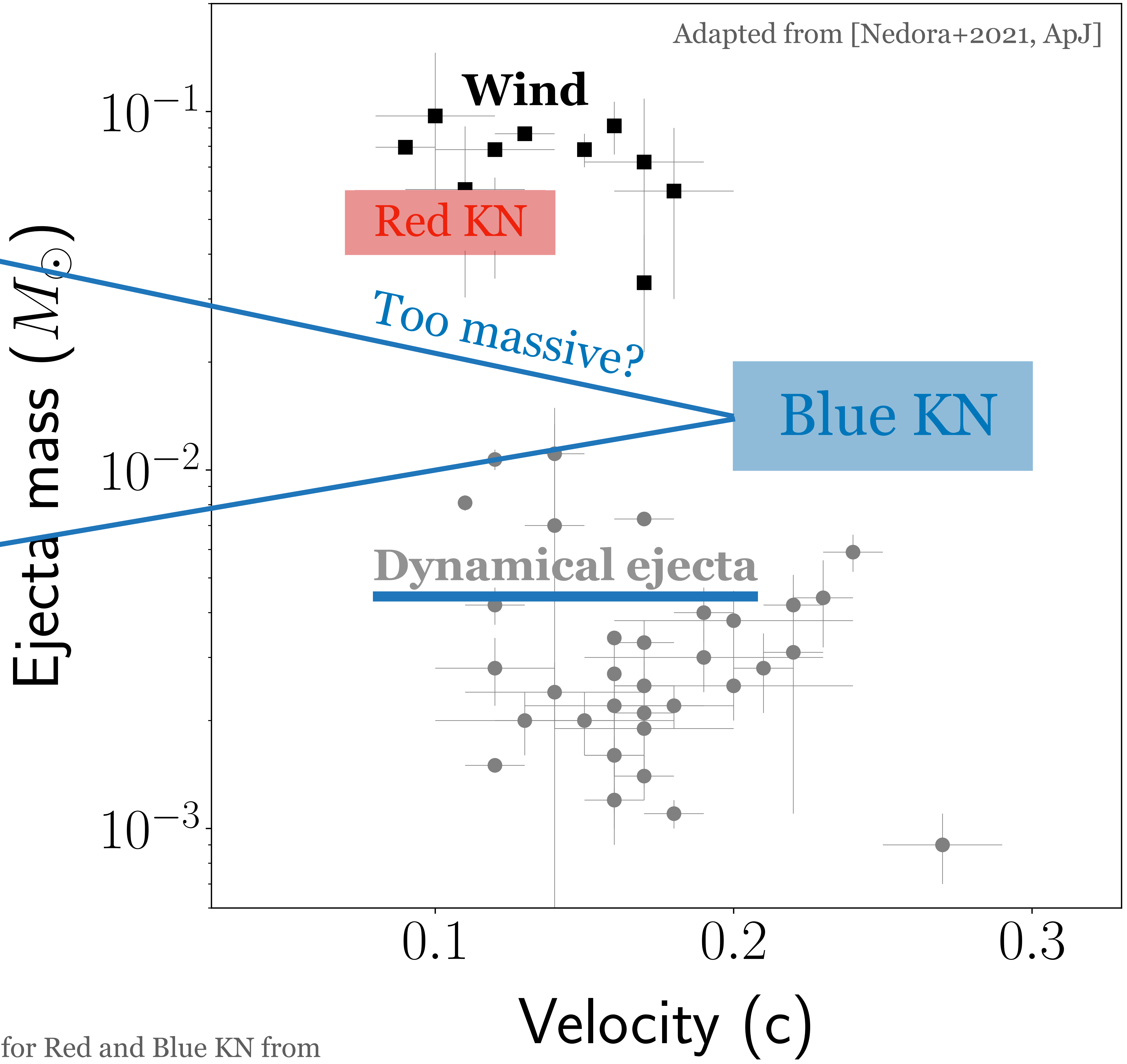

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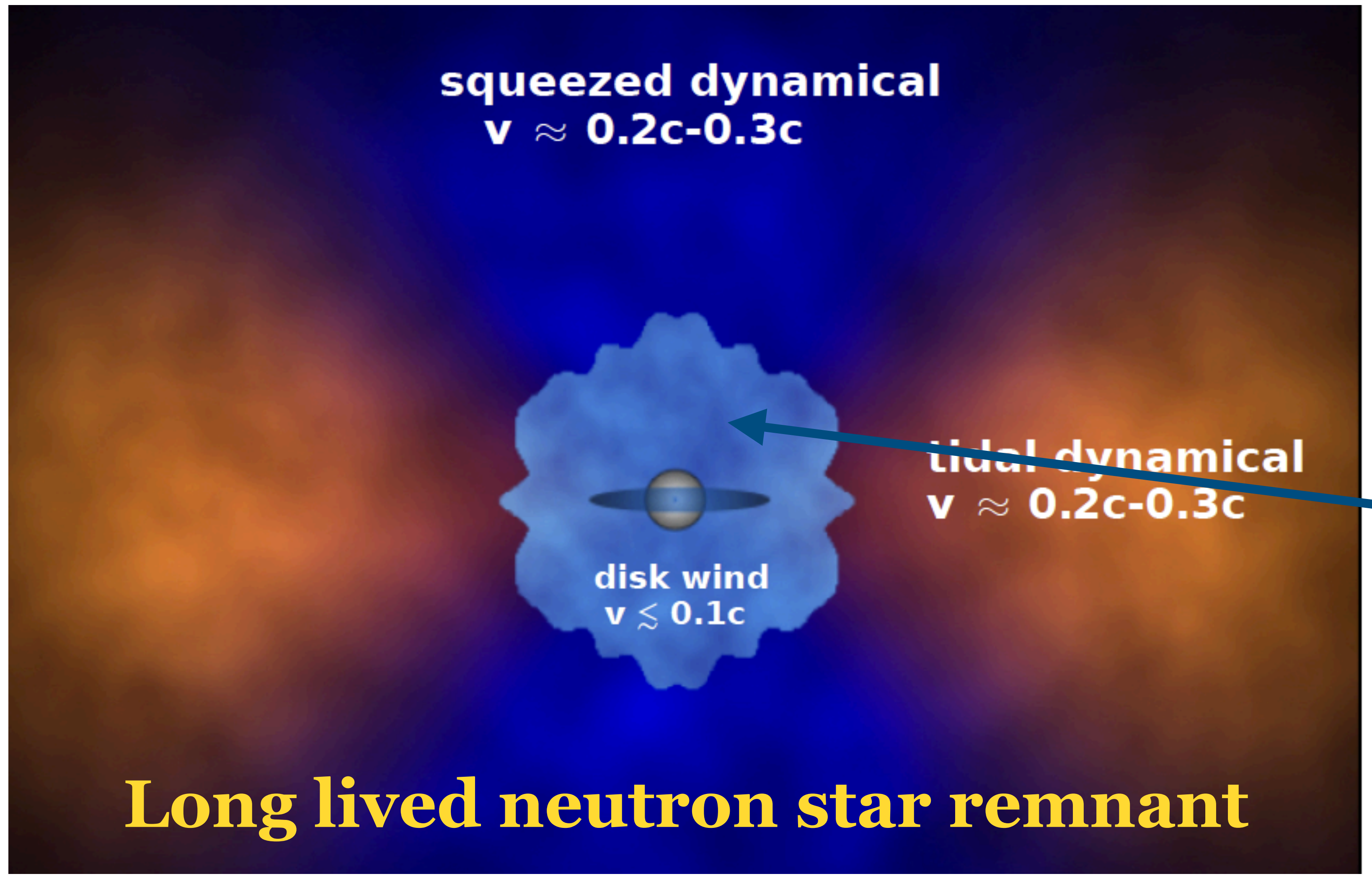
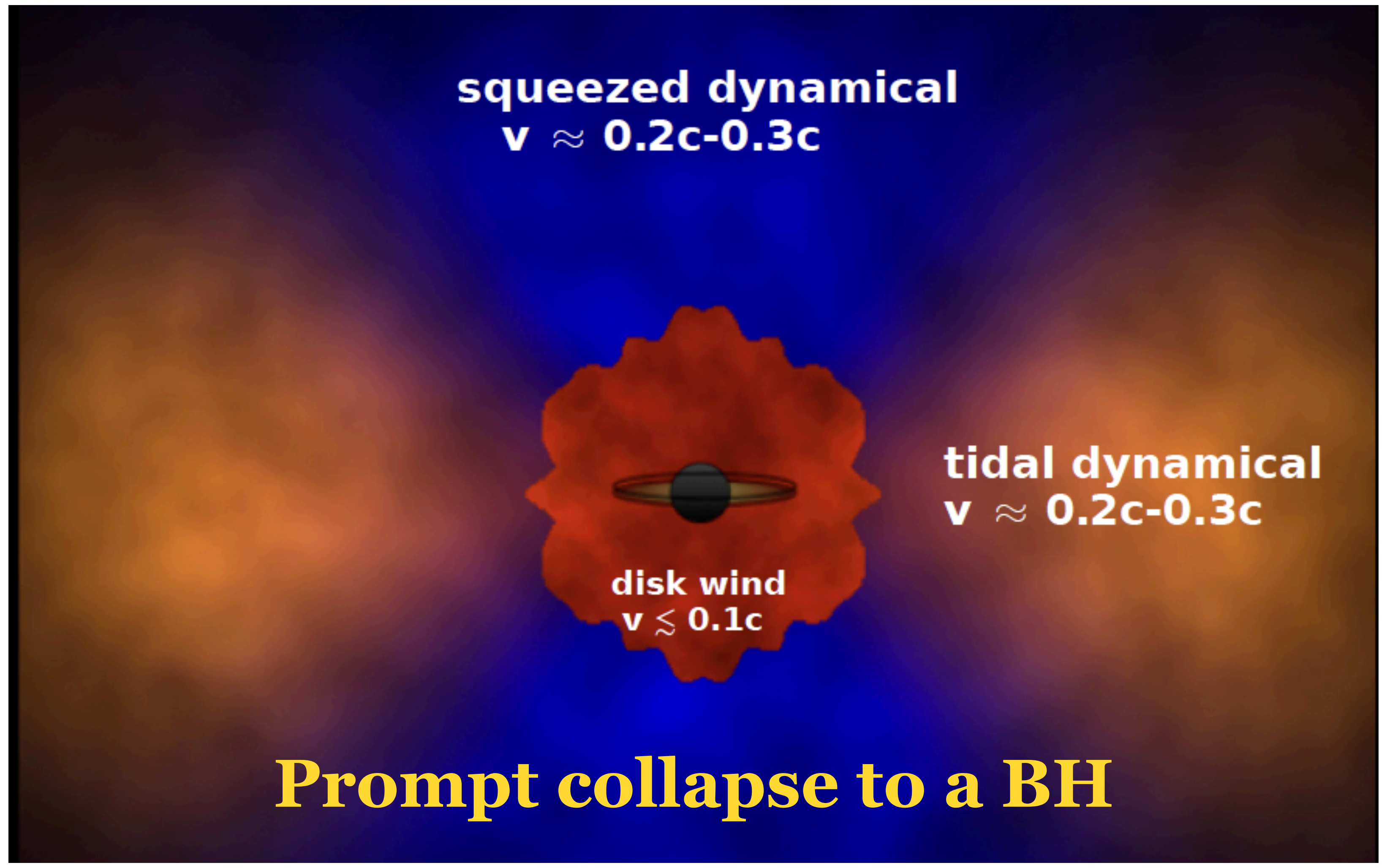
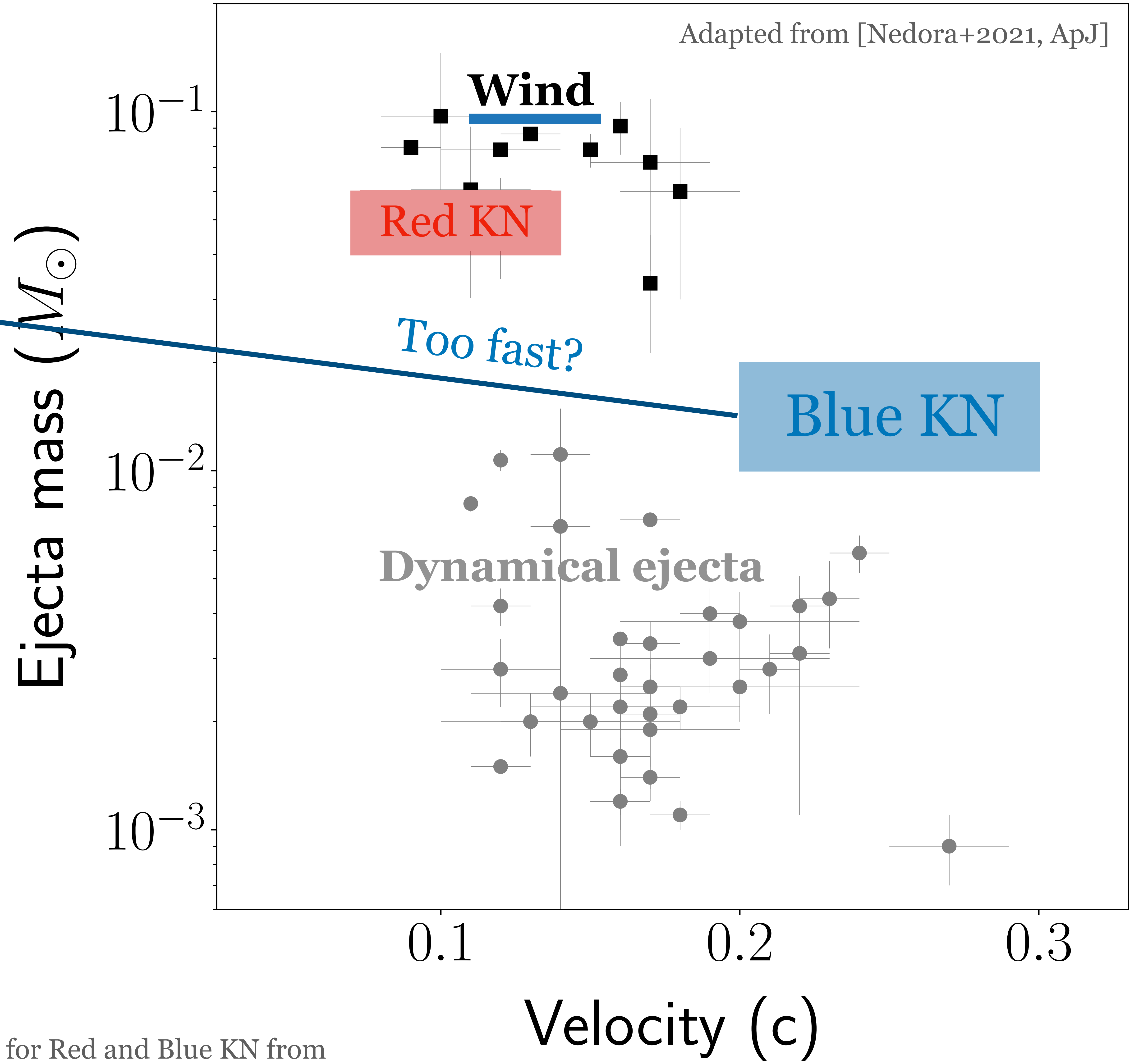
NS mergers and kilonovae

See Steven Fahlman's talk on Thursday







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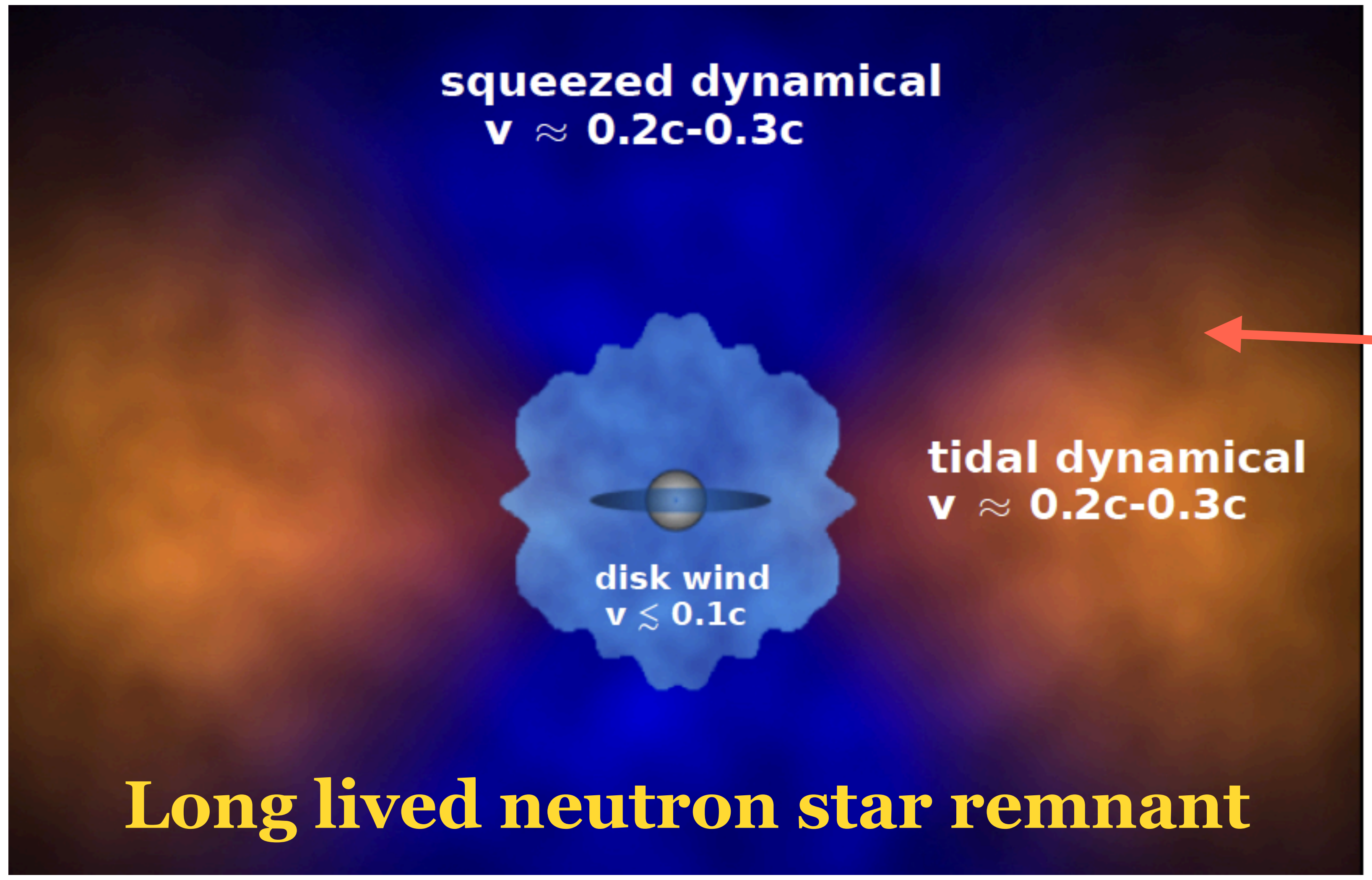

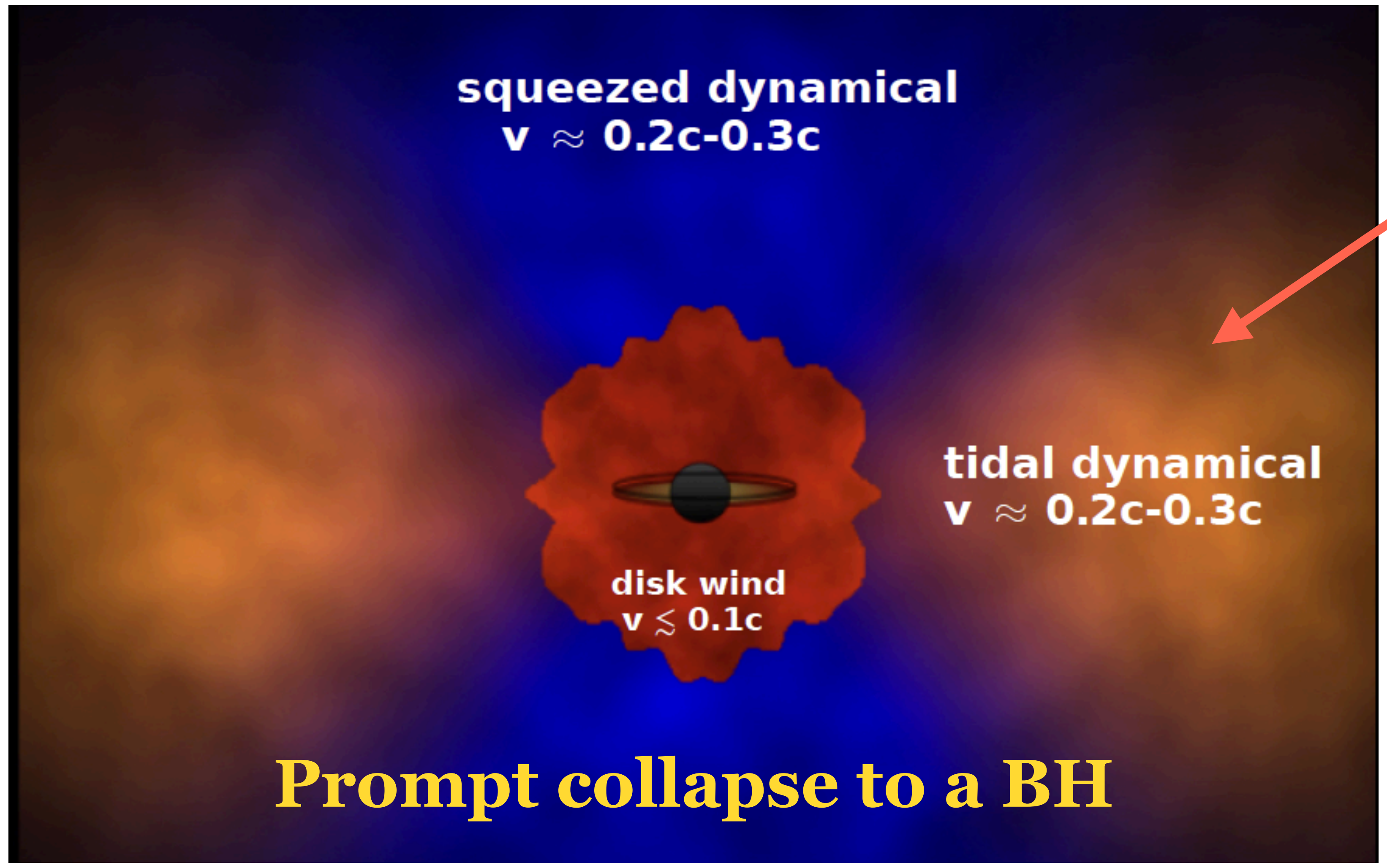

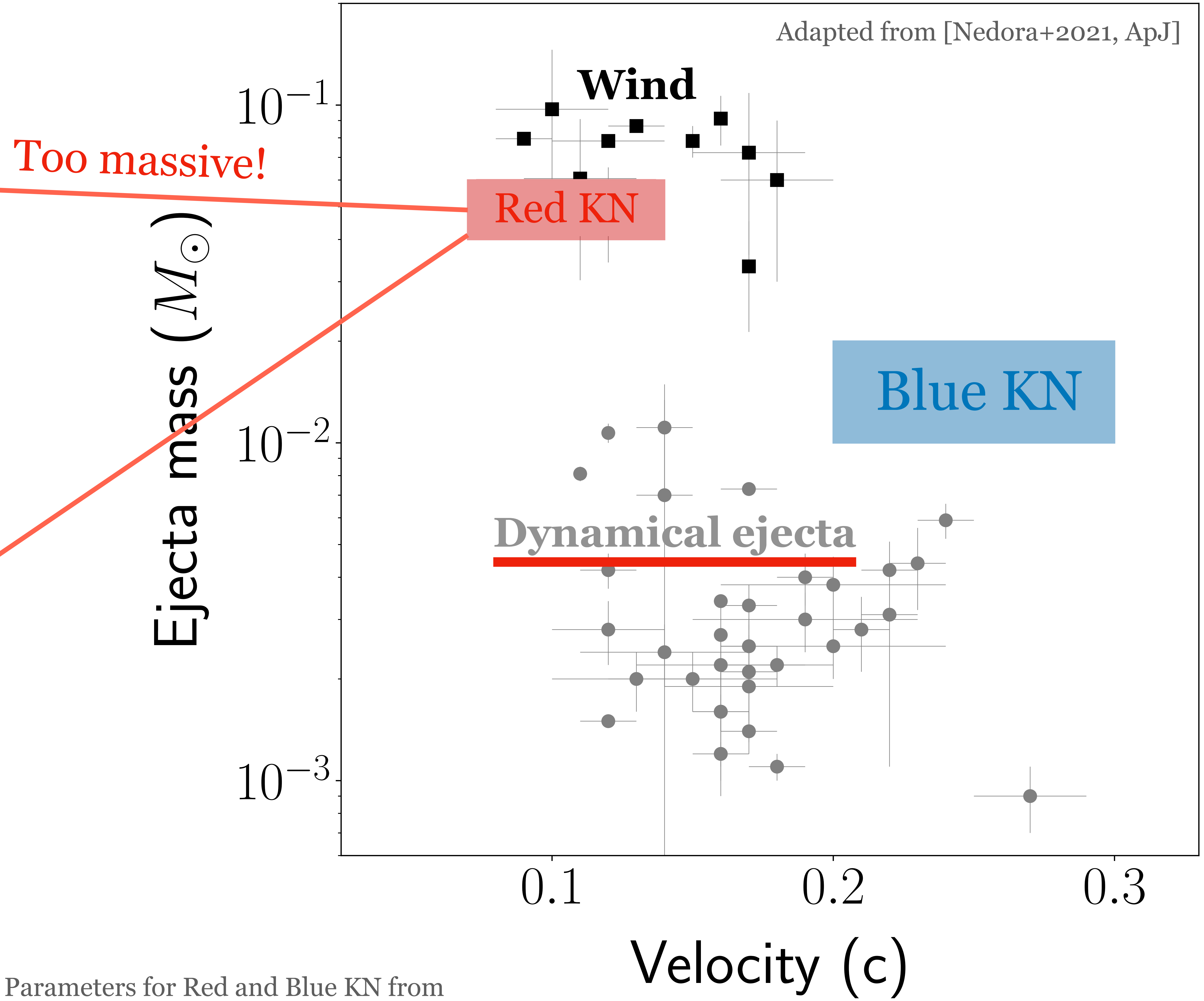

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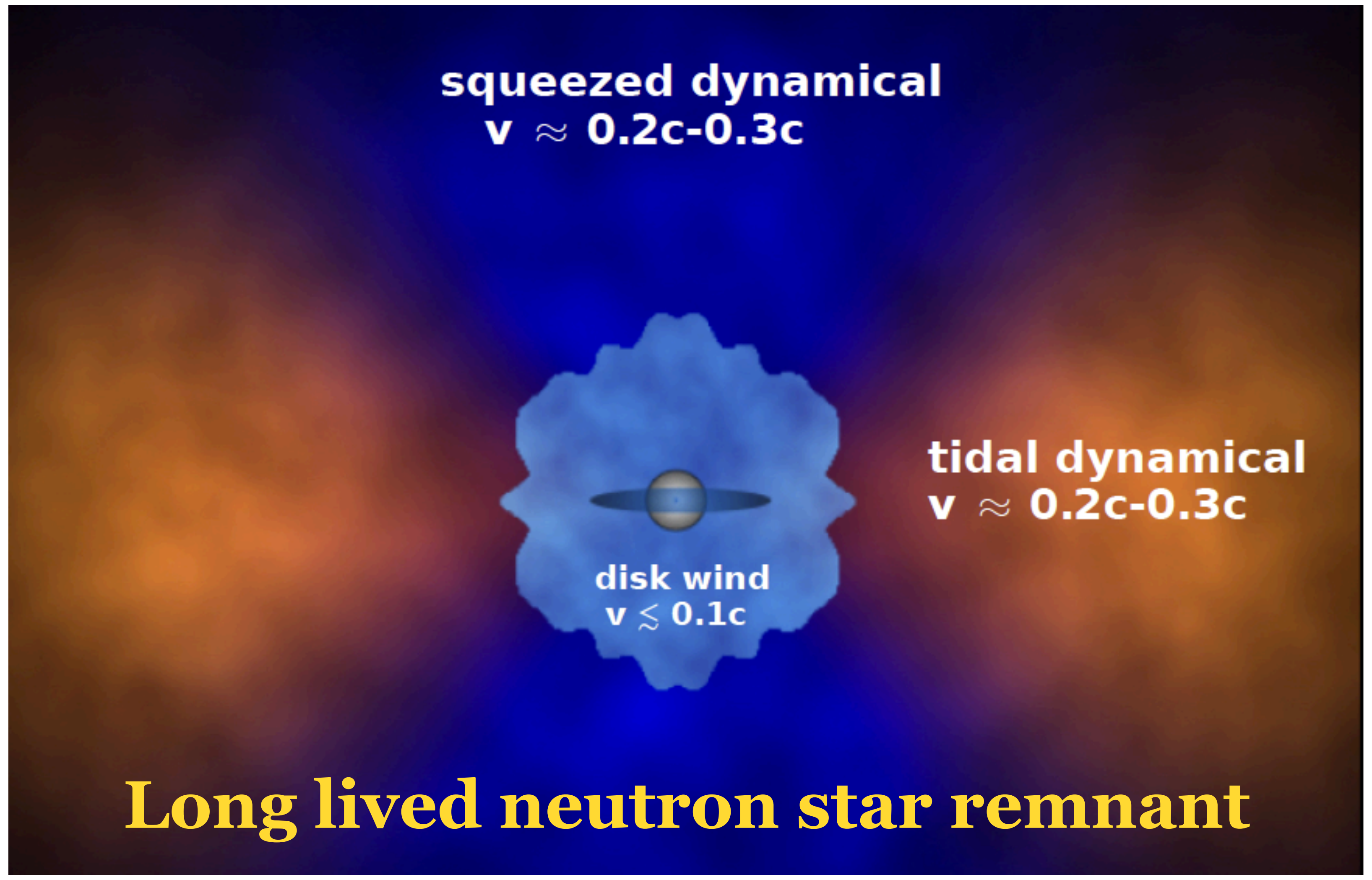
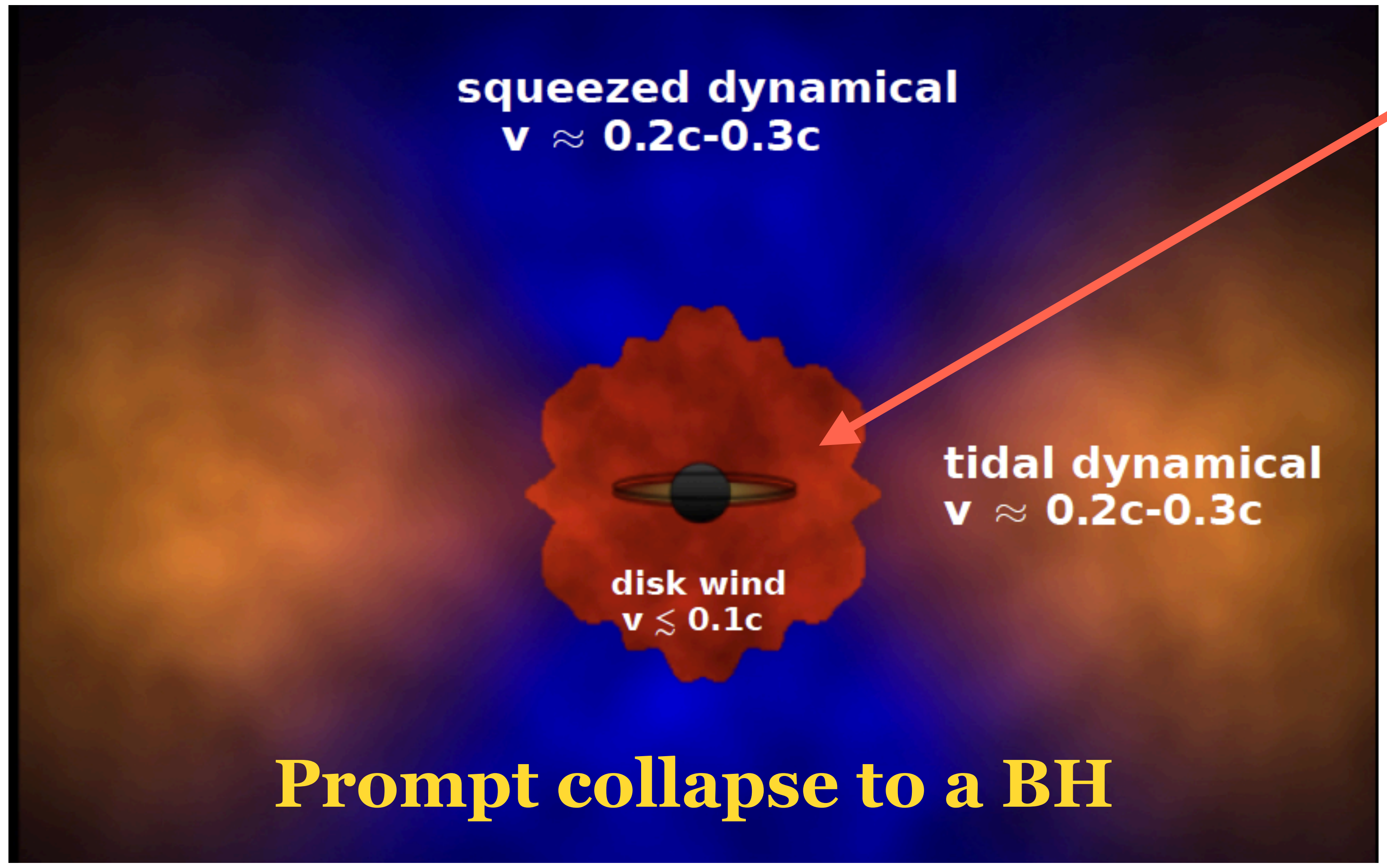
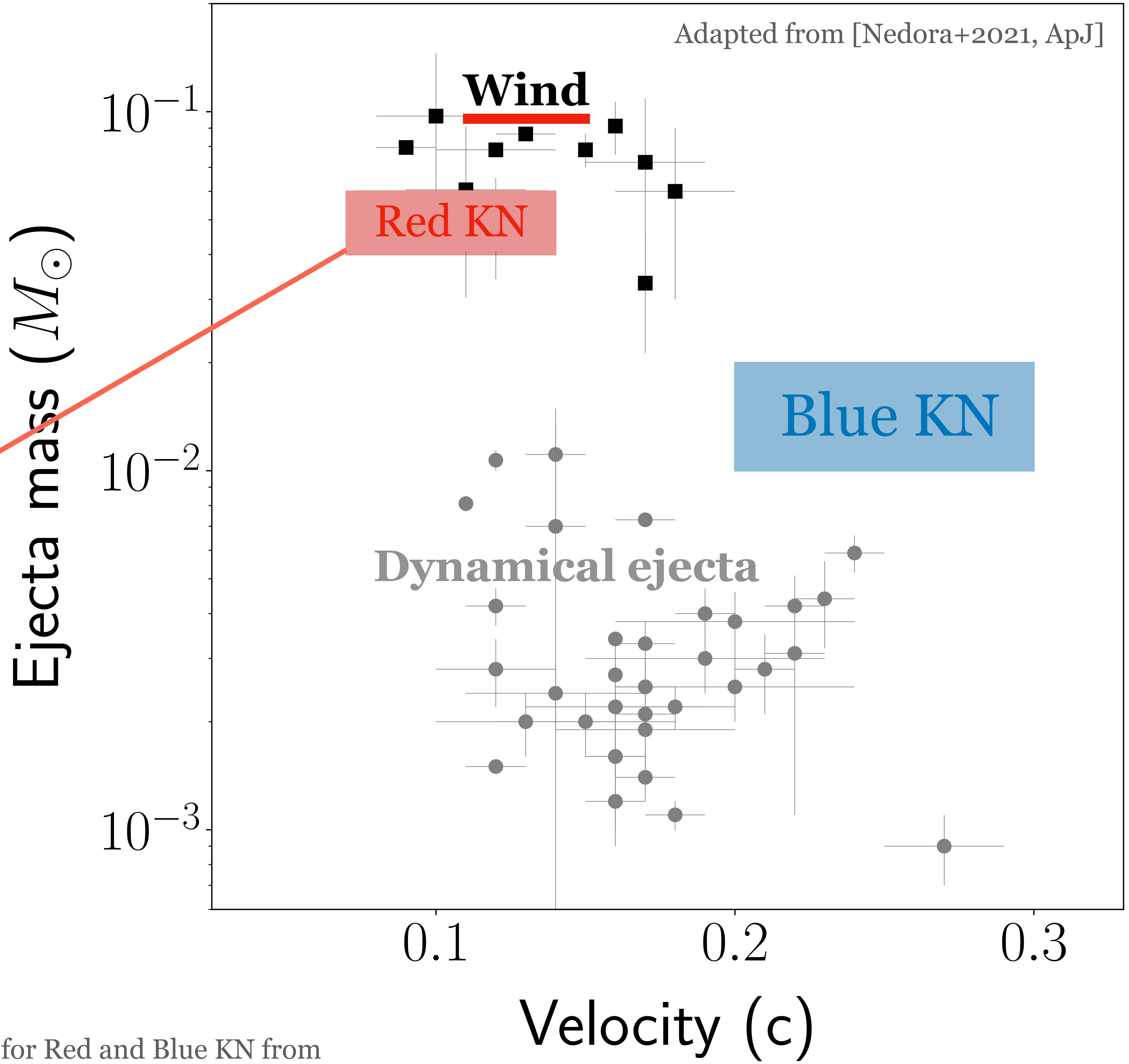




Ok



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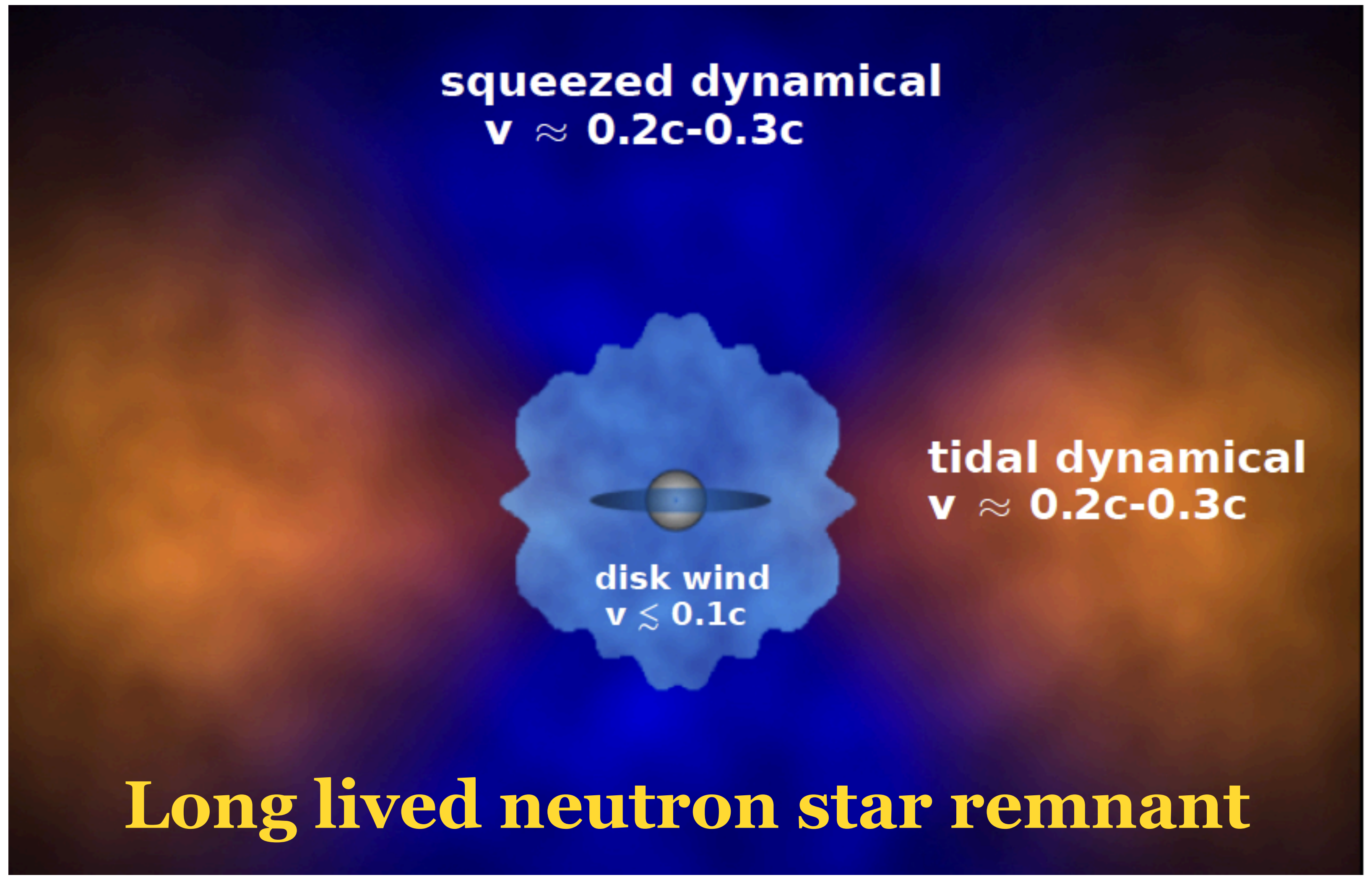

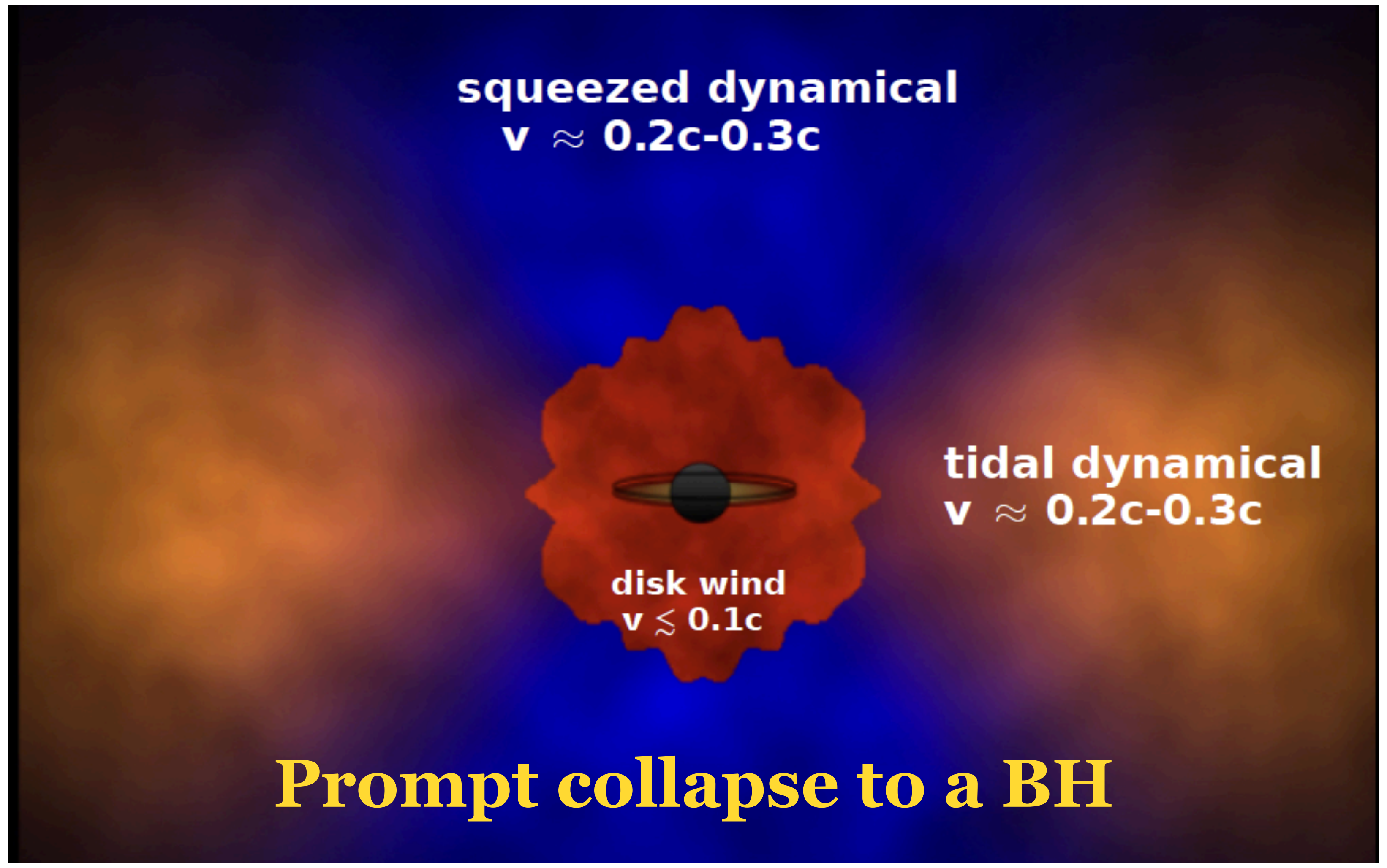

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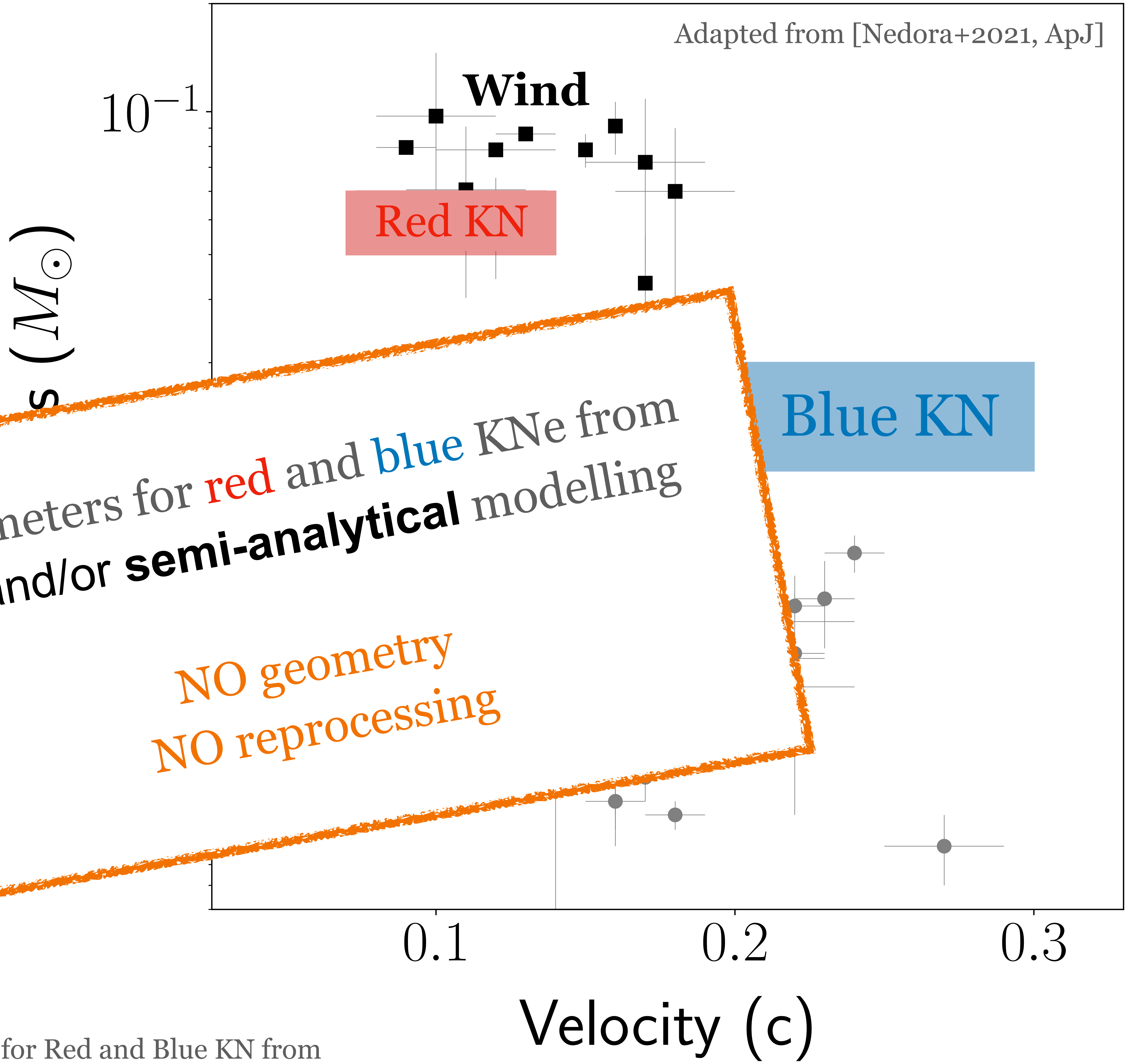

Parameters for red and blue KNe from
1D and/or **semi-analytical** modelling

NO geometry
NO reprocessing

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

POSSIS

A 3D Monte Carlo radiative transfer code to model kilonovae

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

POSSIS

A 3D Monte Carlo radiative transfer code to model kilonovae

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Creating photons

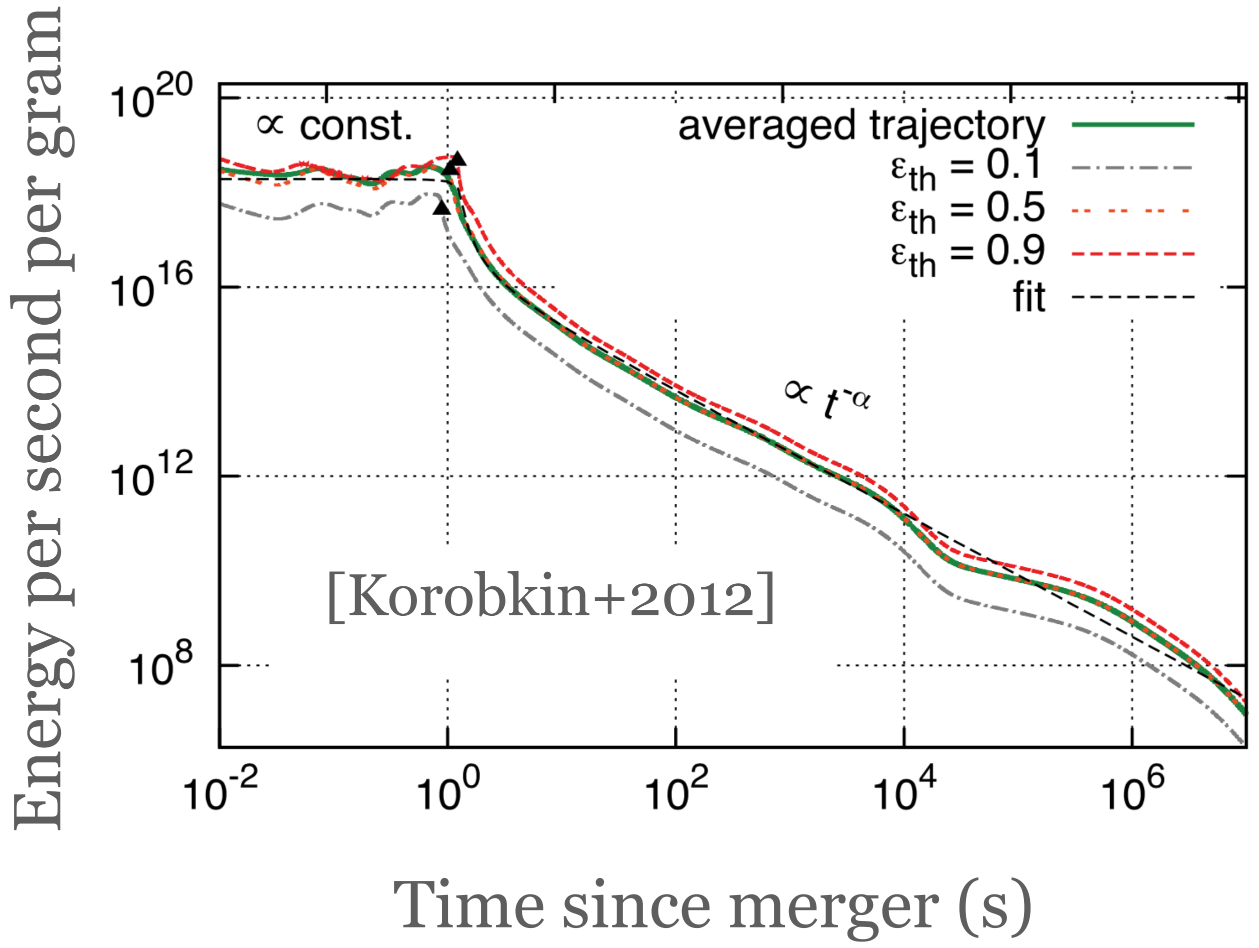
Frequency

From temperature

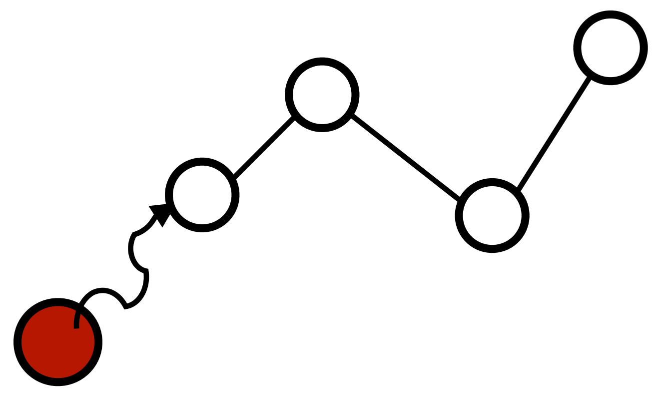
Energy

Nuclear heating rates

Thermalisation efficiencies



Stokes parameters



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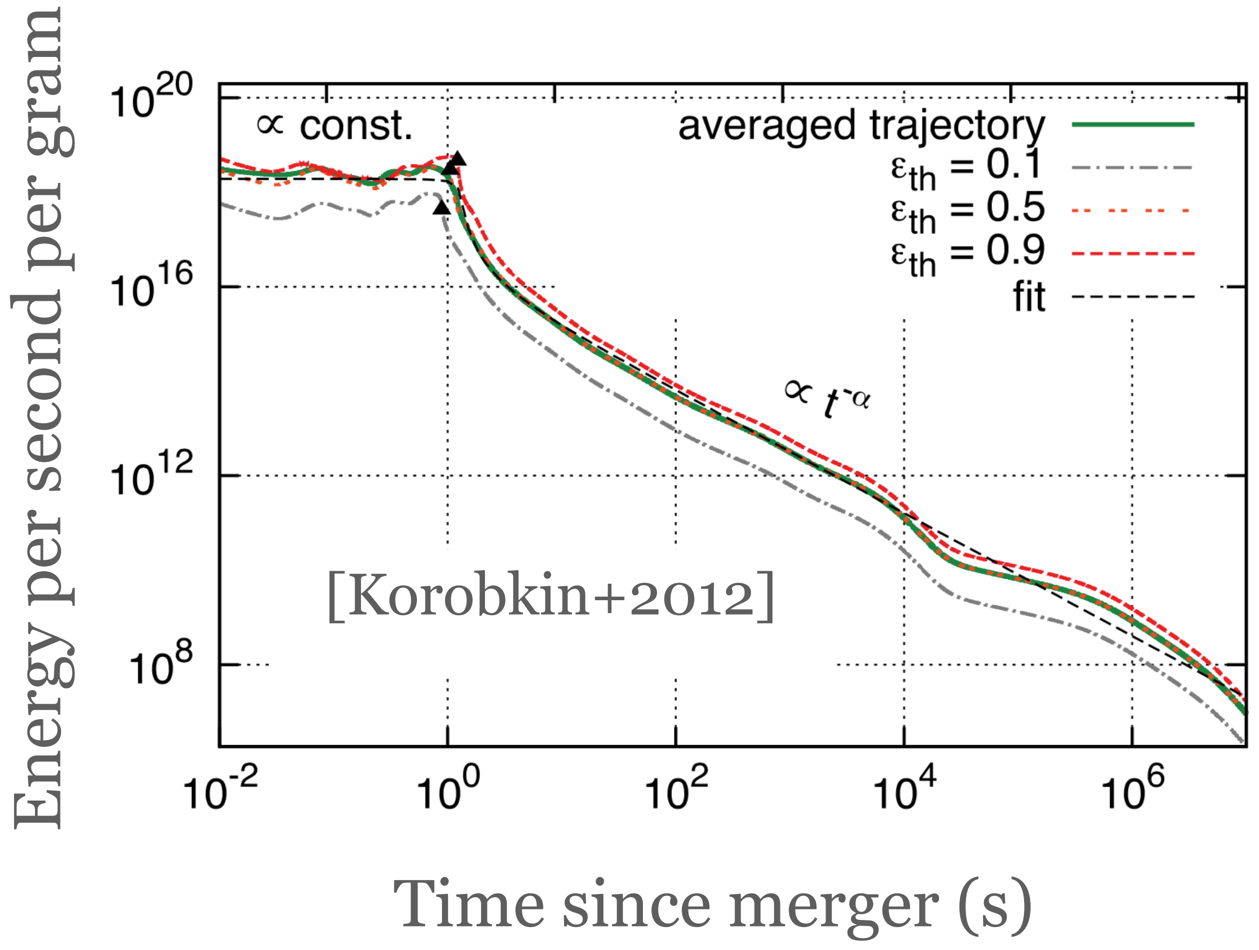


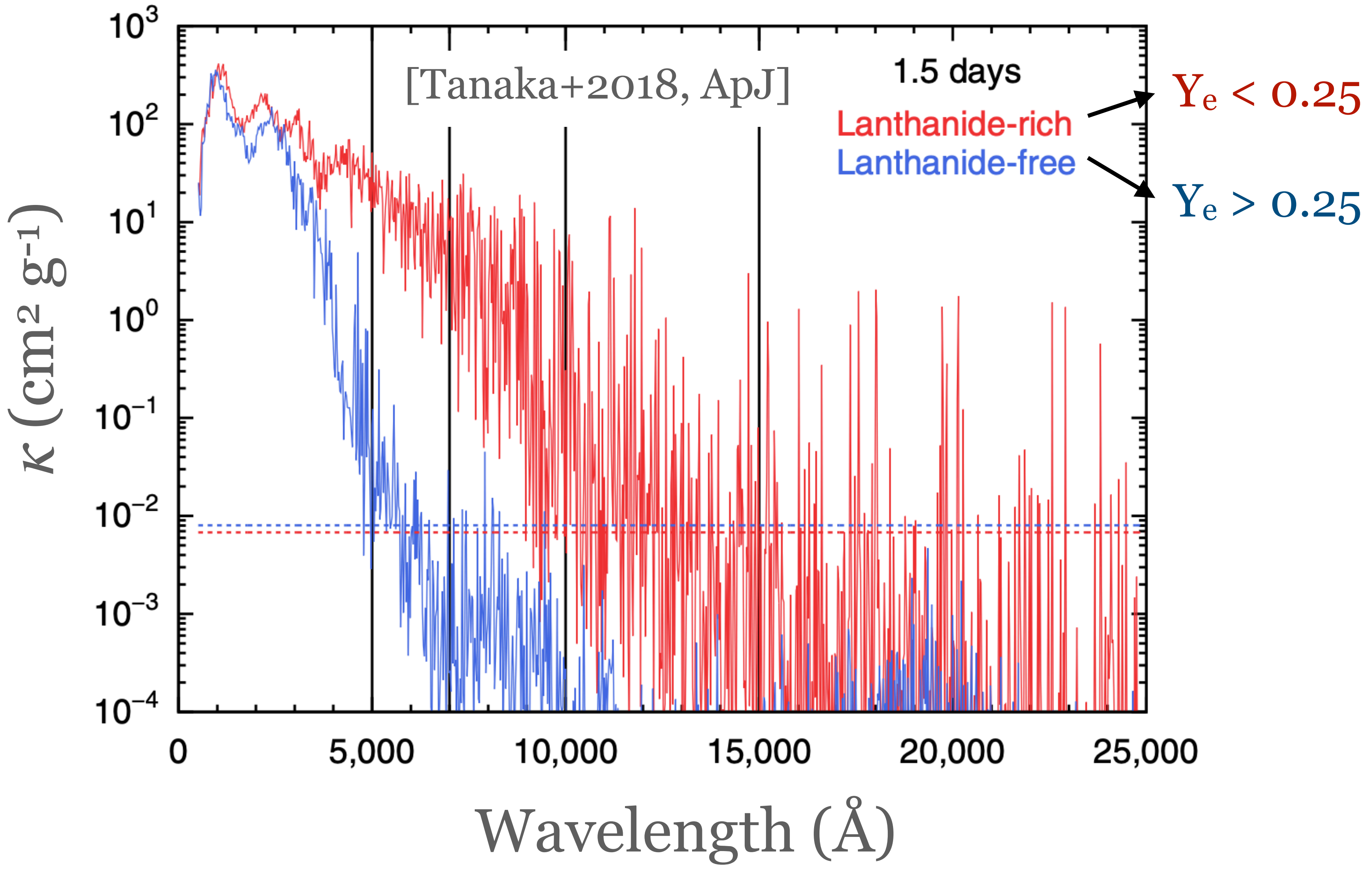
Stokes parameters

Propagating photons

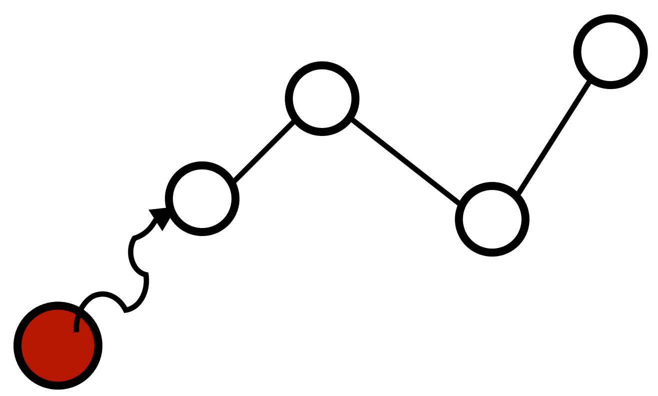
Opacity

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

Main source of opacity in KNe: bound-bound



POSSIS



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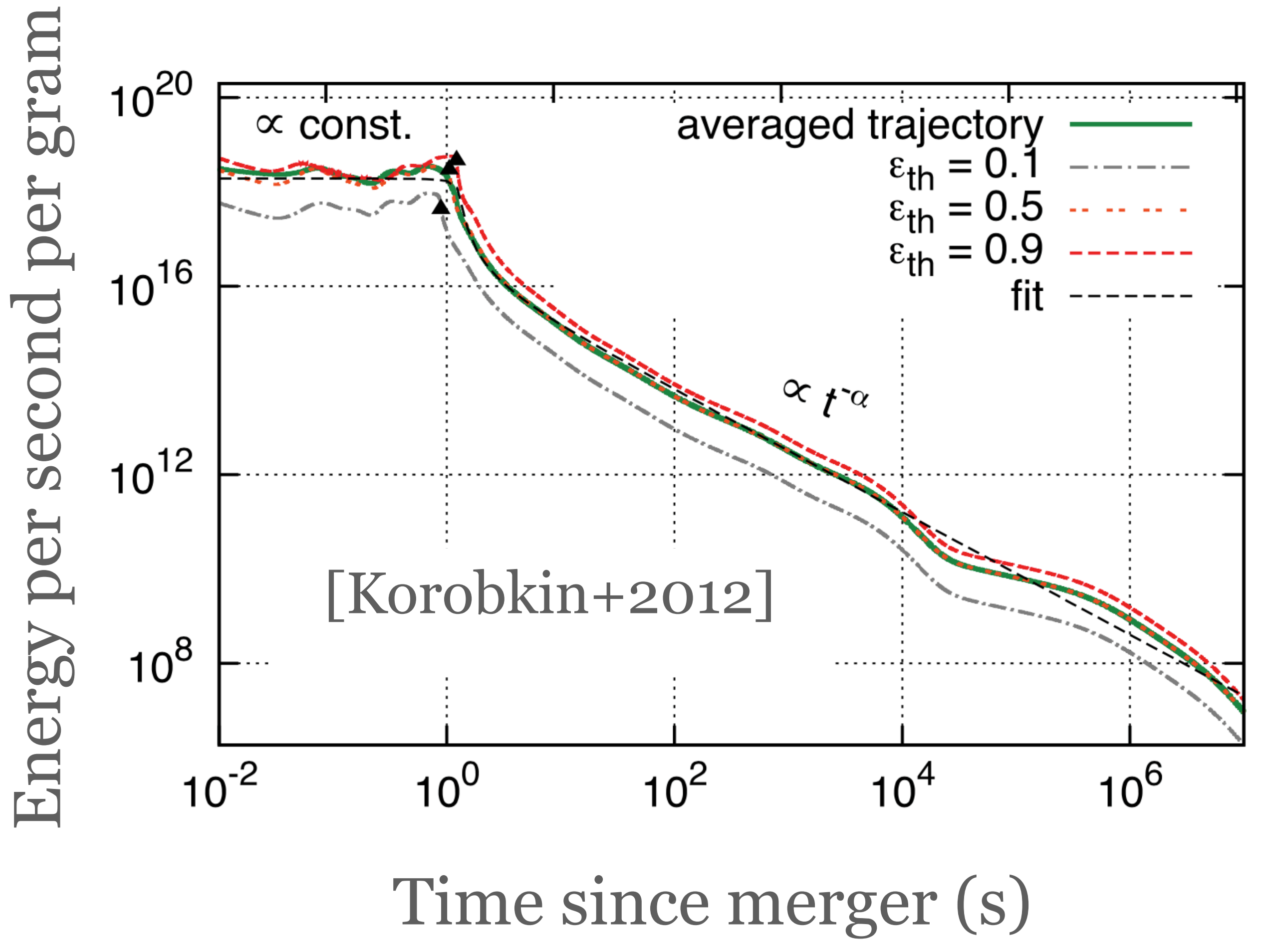

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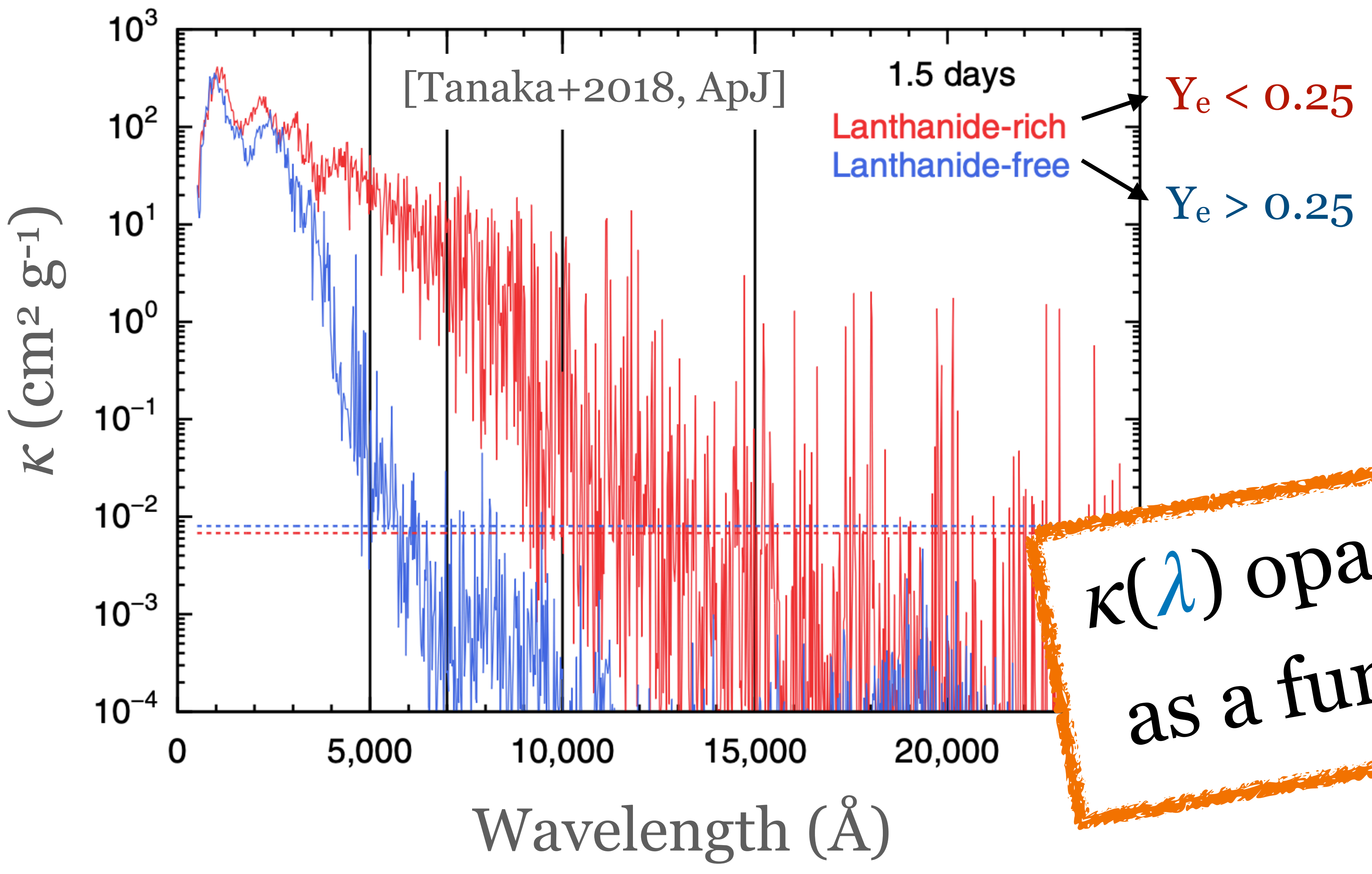
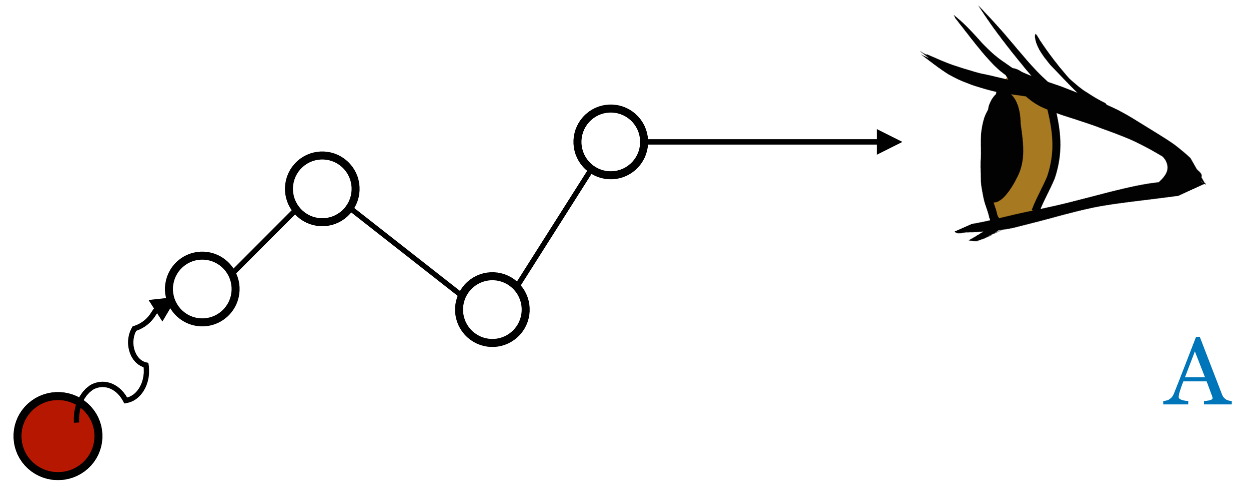


$\kappa(\lambda)$ opacities from Tanaka+2020 as a function of ρ, T, Y_e and time



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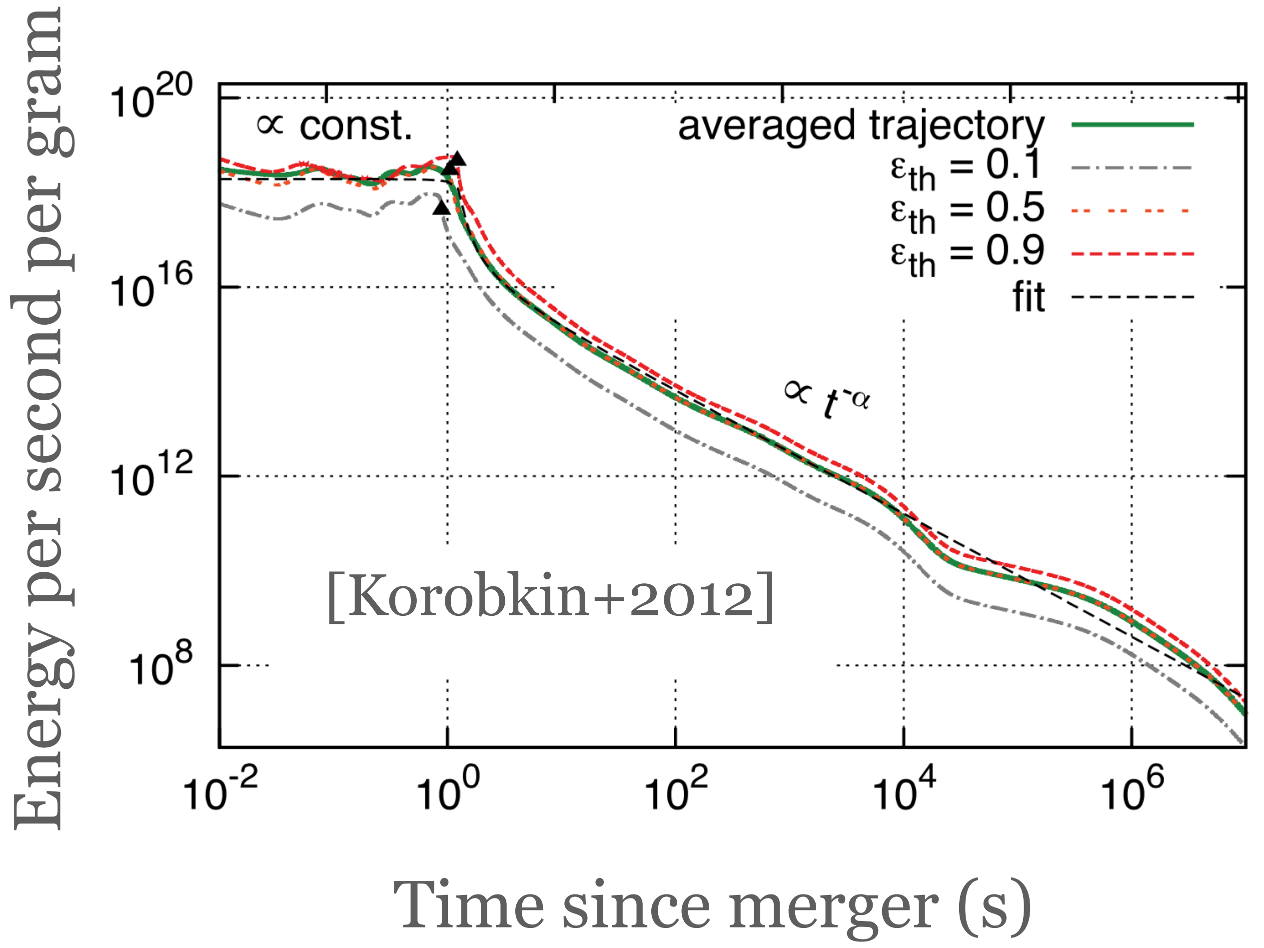

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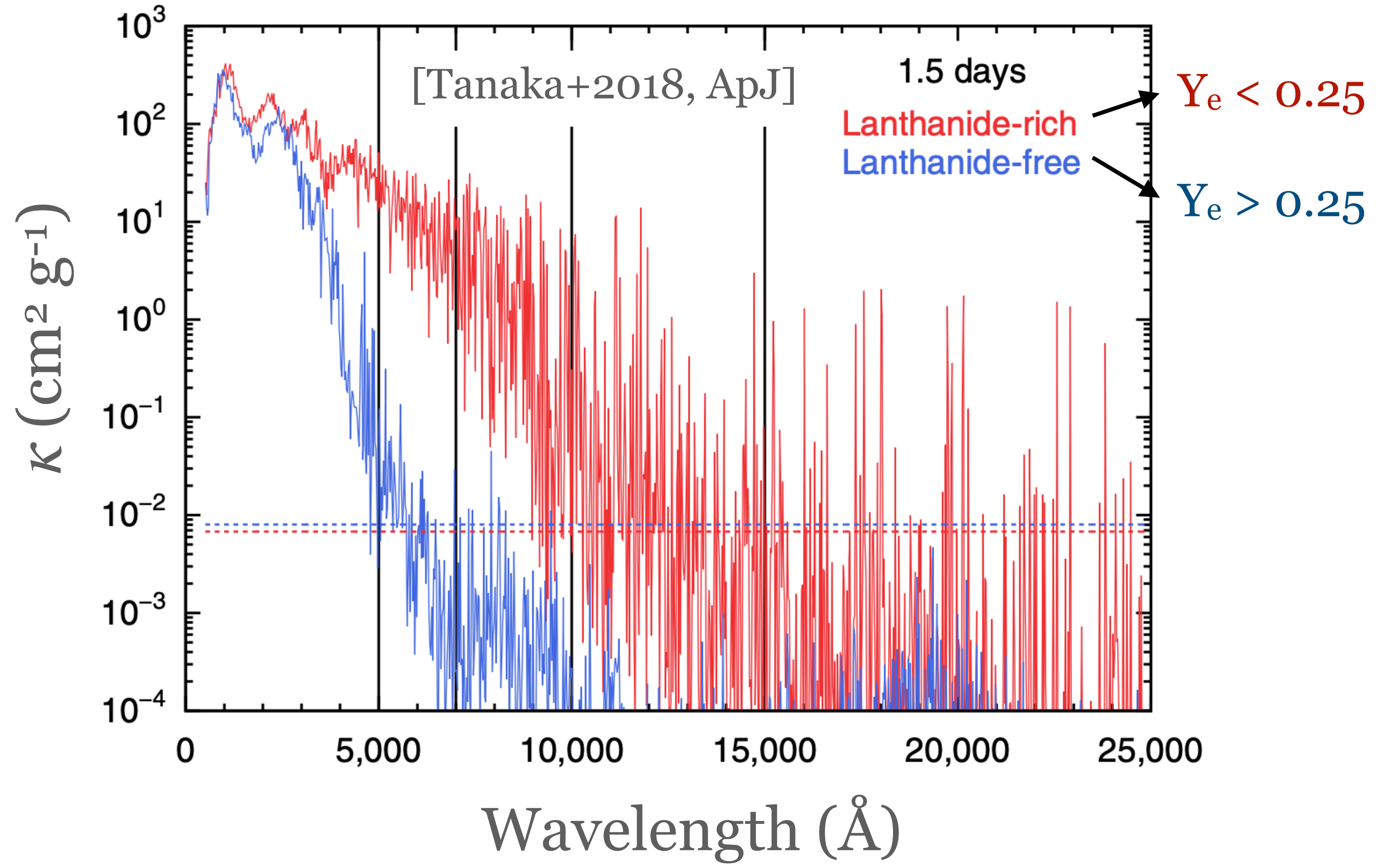
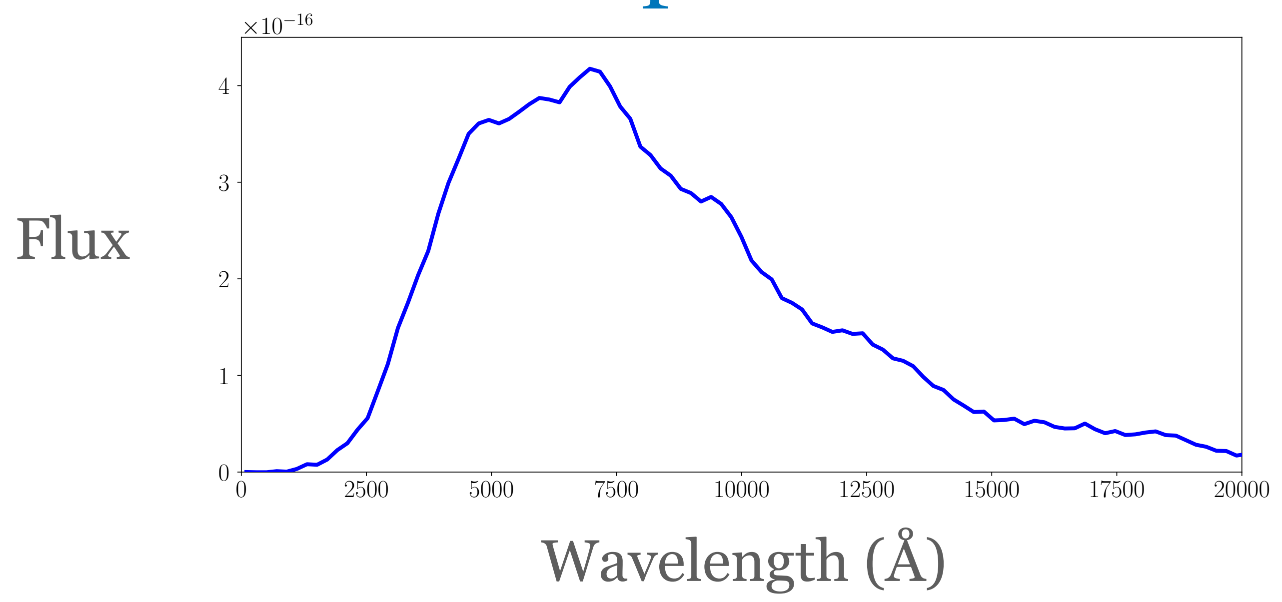
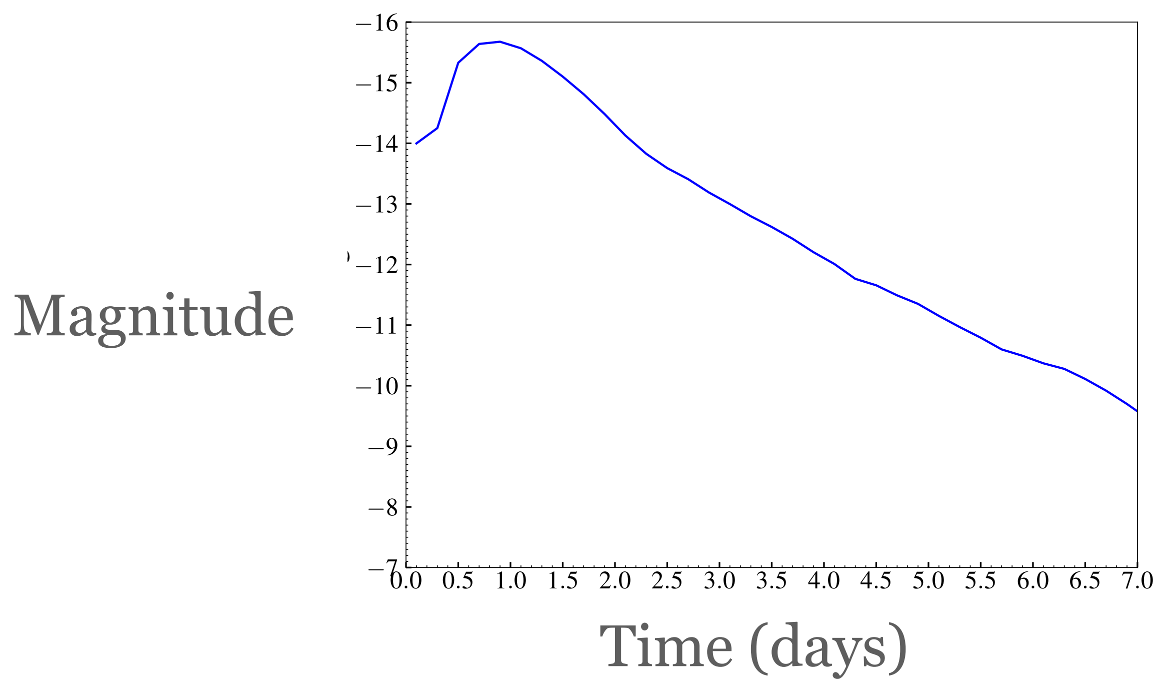


Collecting photons

Spectra



Light curves



Polarization

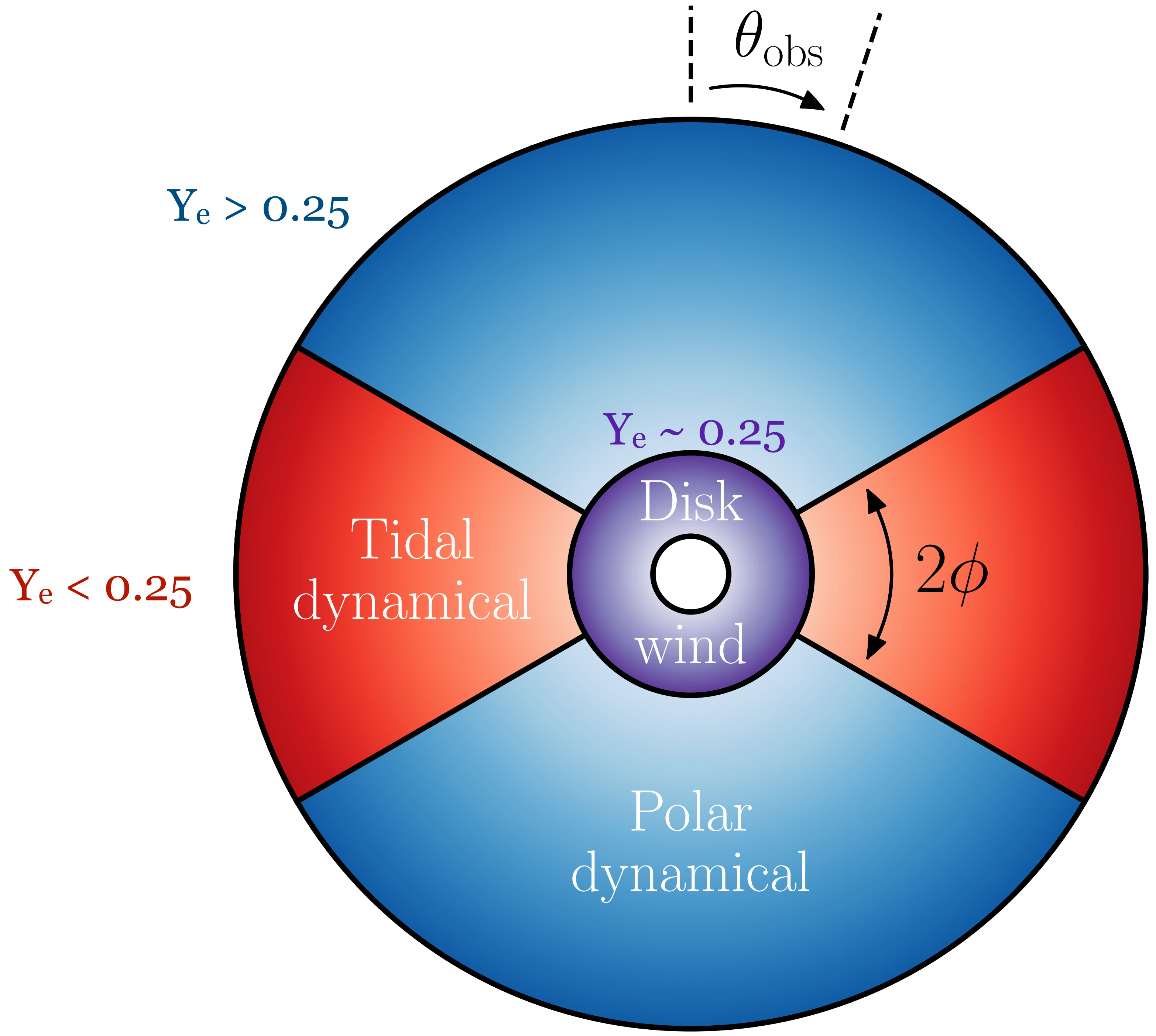
POSSIS

A 3D Monte Carlo radiative transfer code to model kilonovae

[**MB**+2015; **MB** 2019]

Neutron Star - Neutron Star

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

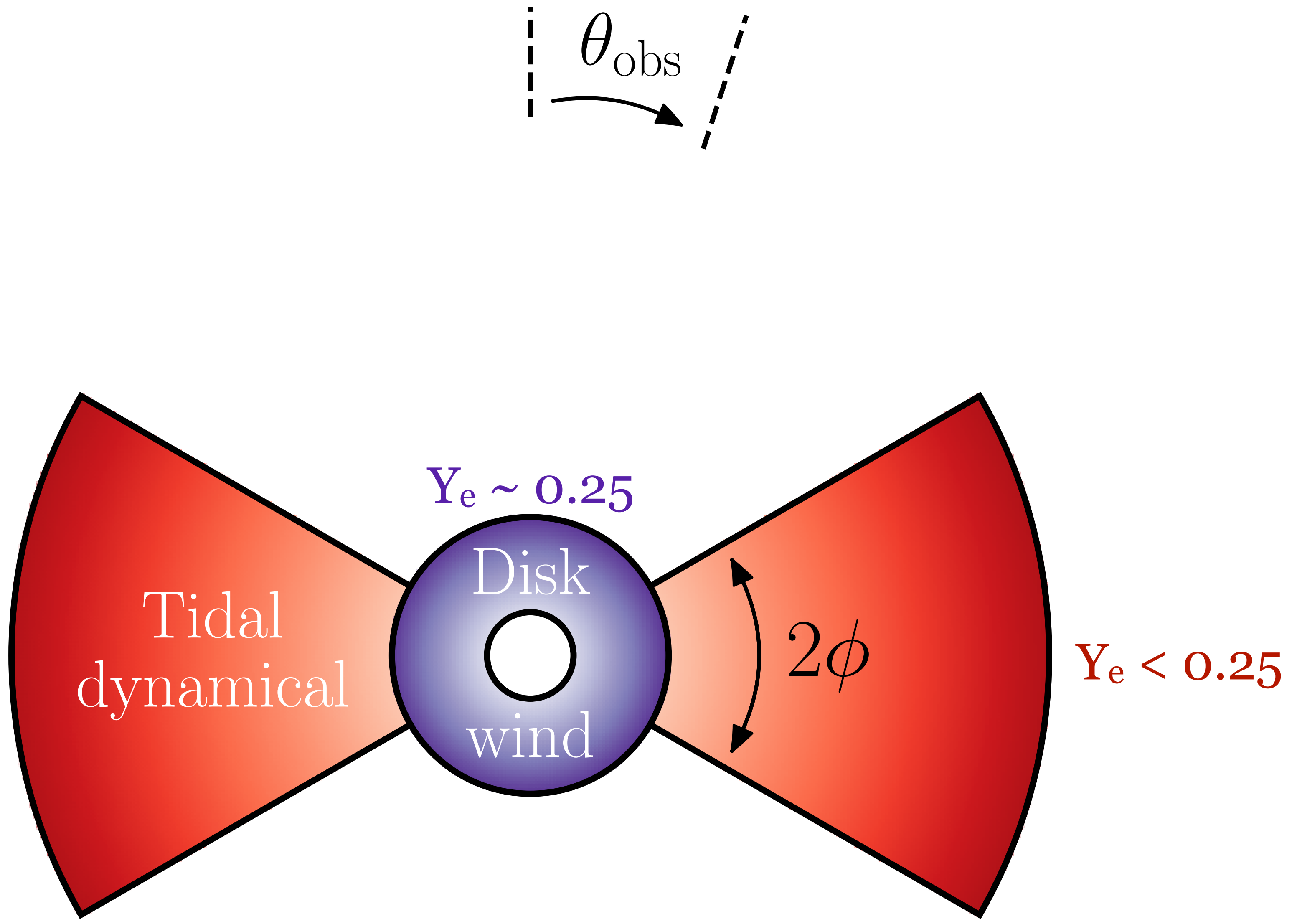


1540 models

varying ejecta masses ($M_{ej,dyn}$, $M_{ej,wind}$),
half-opening angles (ϕ) and viewing angle (θ_{obs})

Black Hole - Neutron Star

[Anand, Coughlin, Kasliwal, **MB**+2020, Nature Astronomy]



891 models

varying ejecta masses ($M_{ej,dyn}$, $M_{ej,wind}$),
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POSSIS

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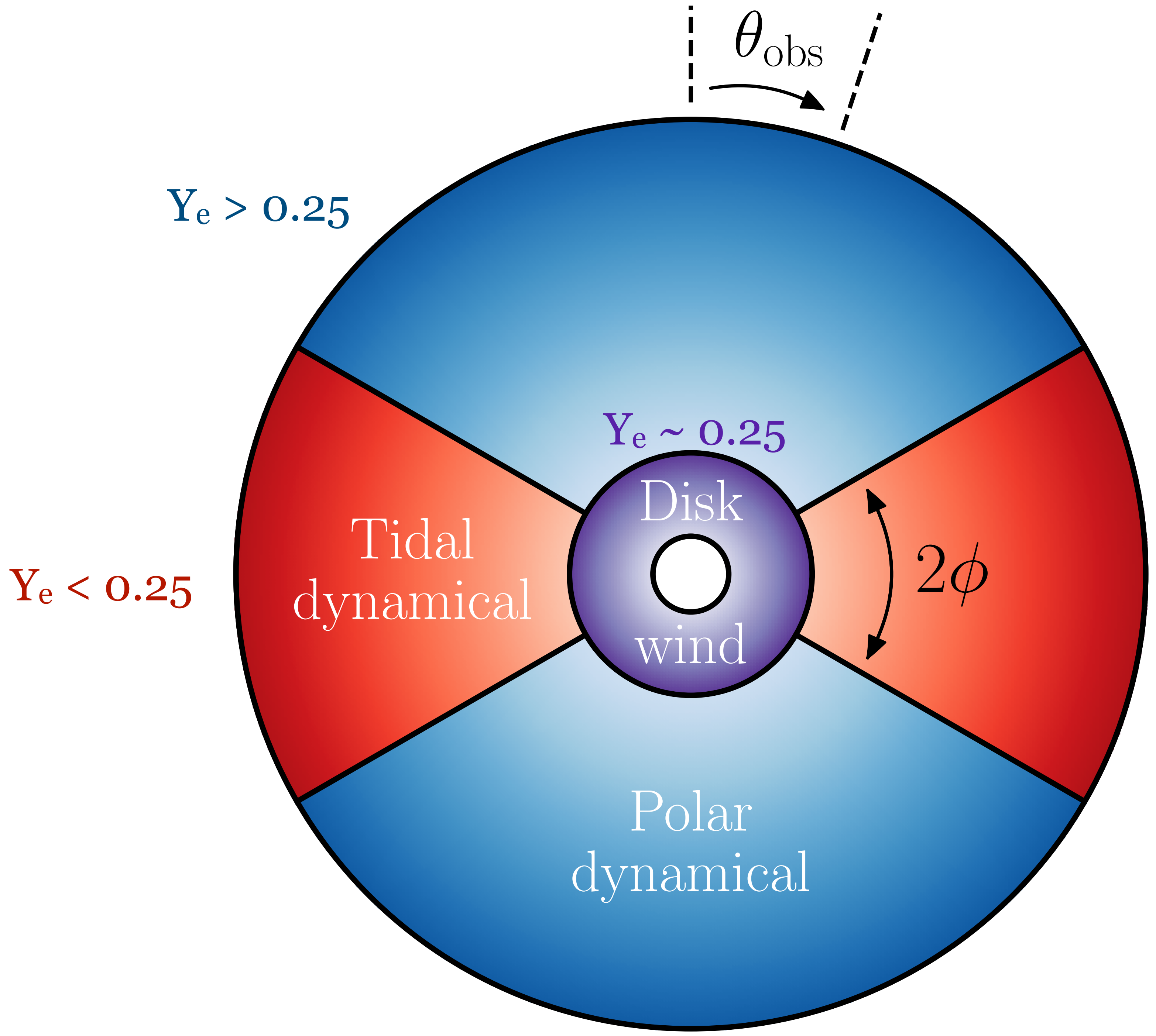

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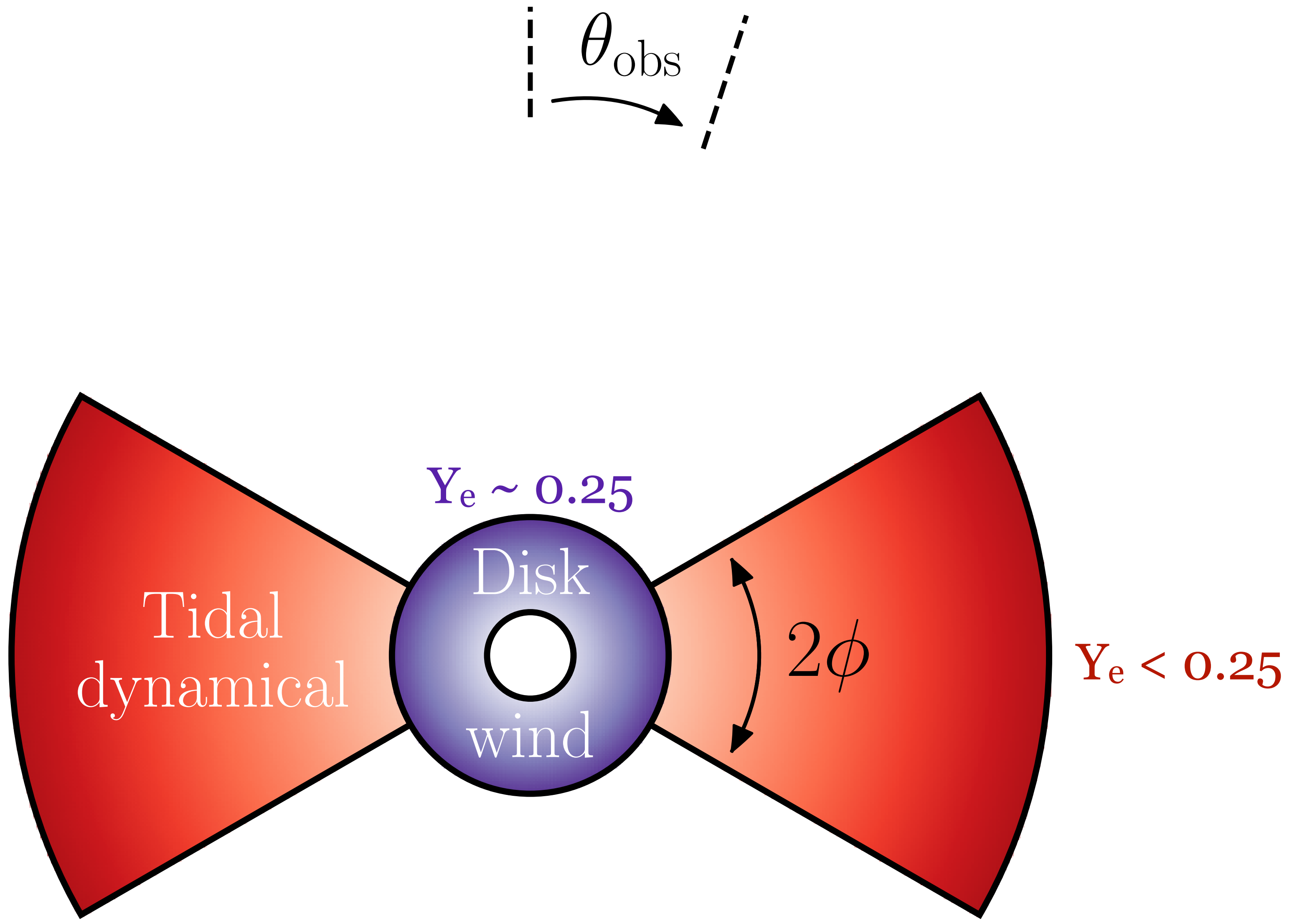

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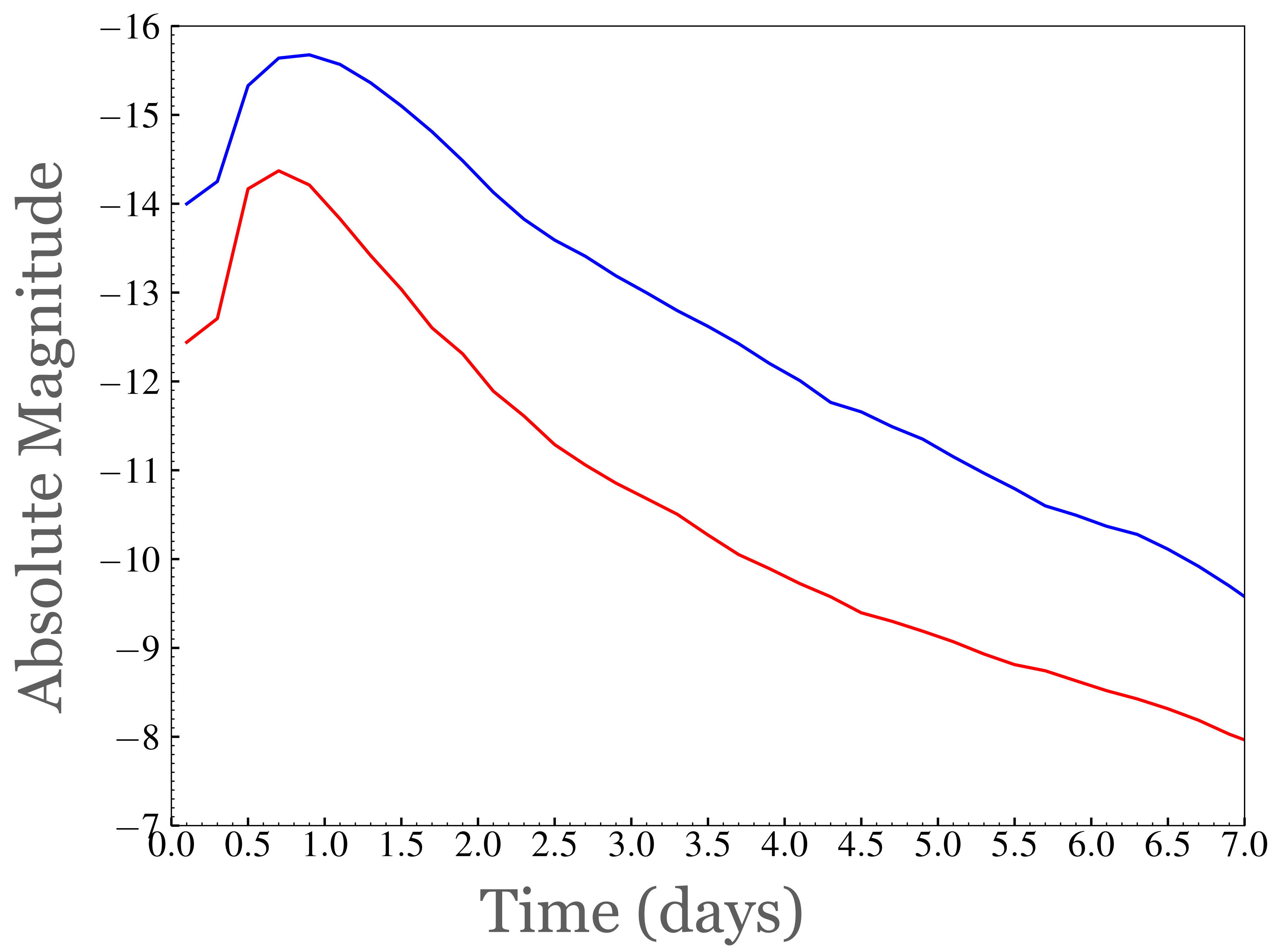
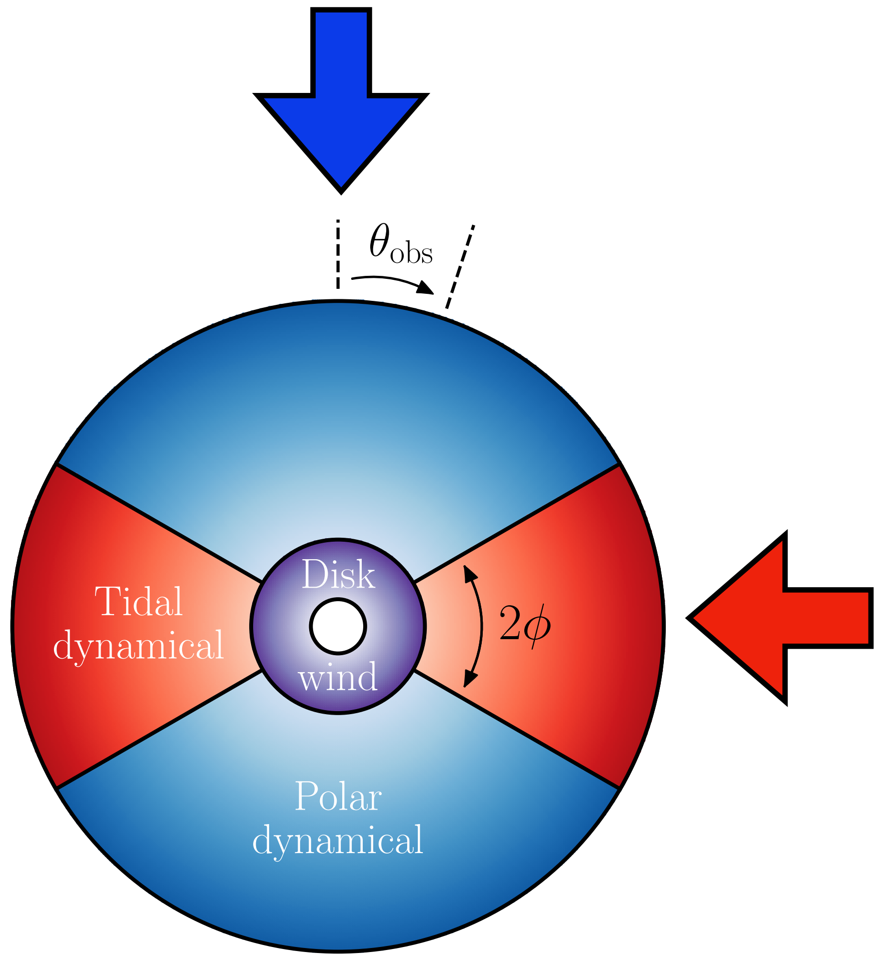
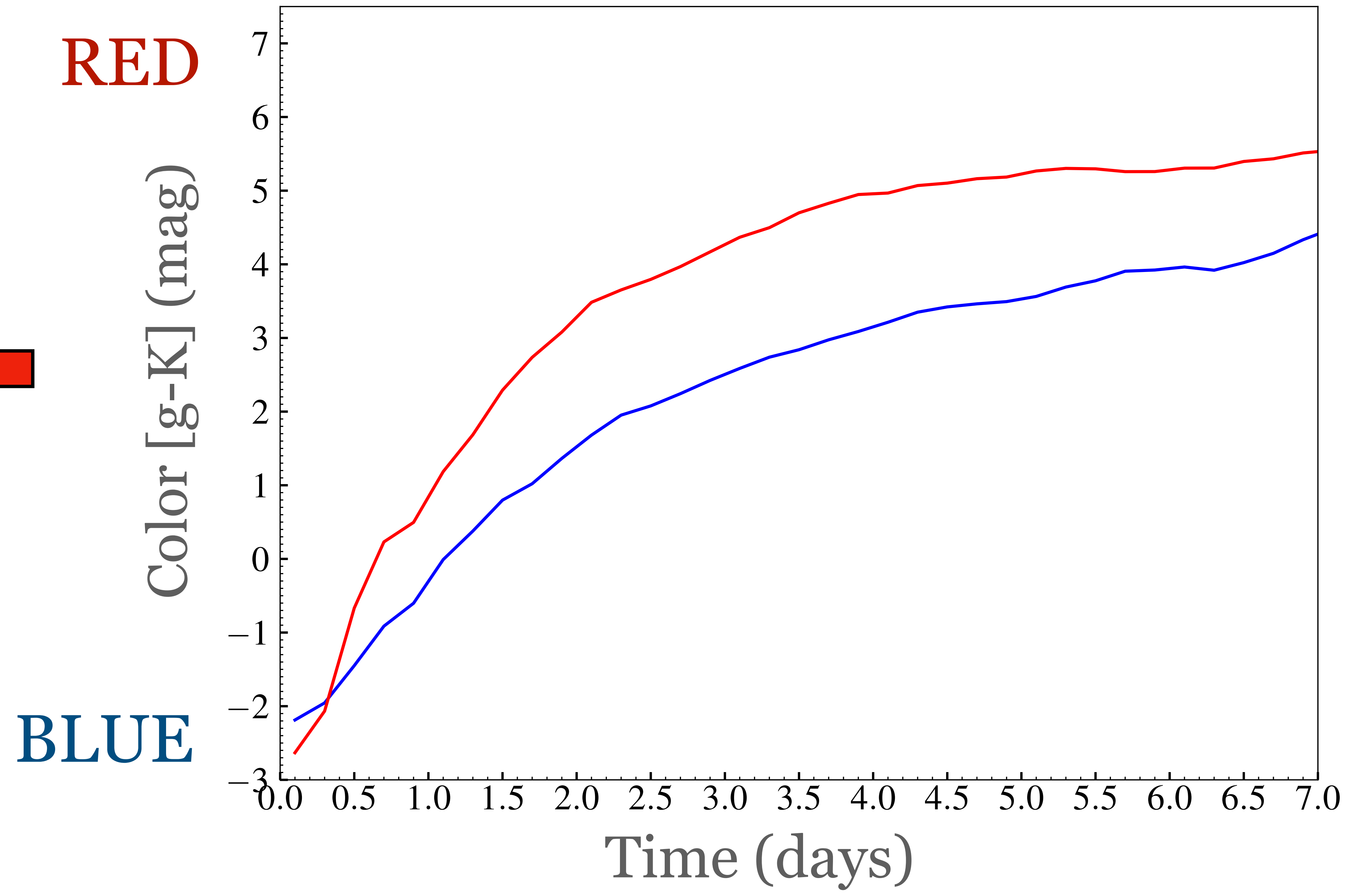
POSSIS

Viewing-angle dependence

Kilonovae viewed face-on ($\theta_{\mathrm{obs}} = 0°$, jet axis) are brighter and bluer compared to kilonovae viewed edge-on ($\theta_{\mathrm{obs}} = 90°$, merger plane)







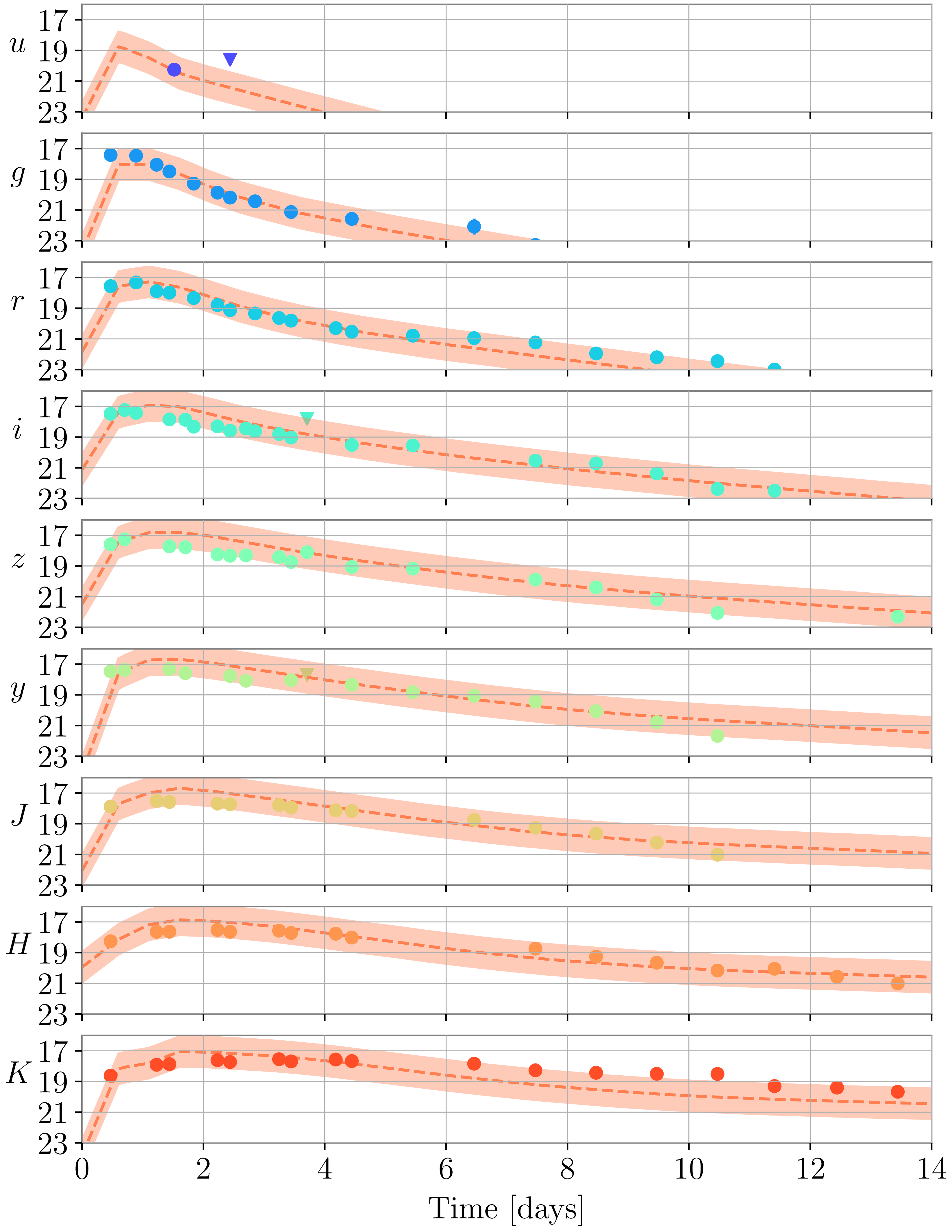
A fit to the kilonova AT2017gfo

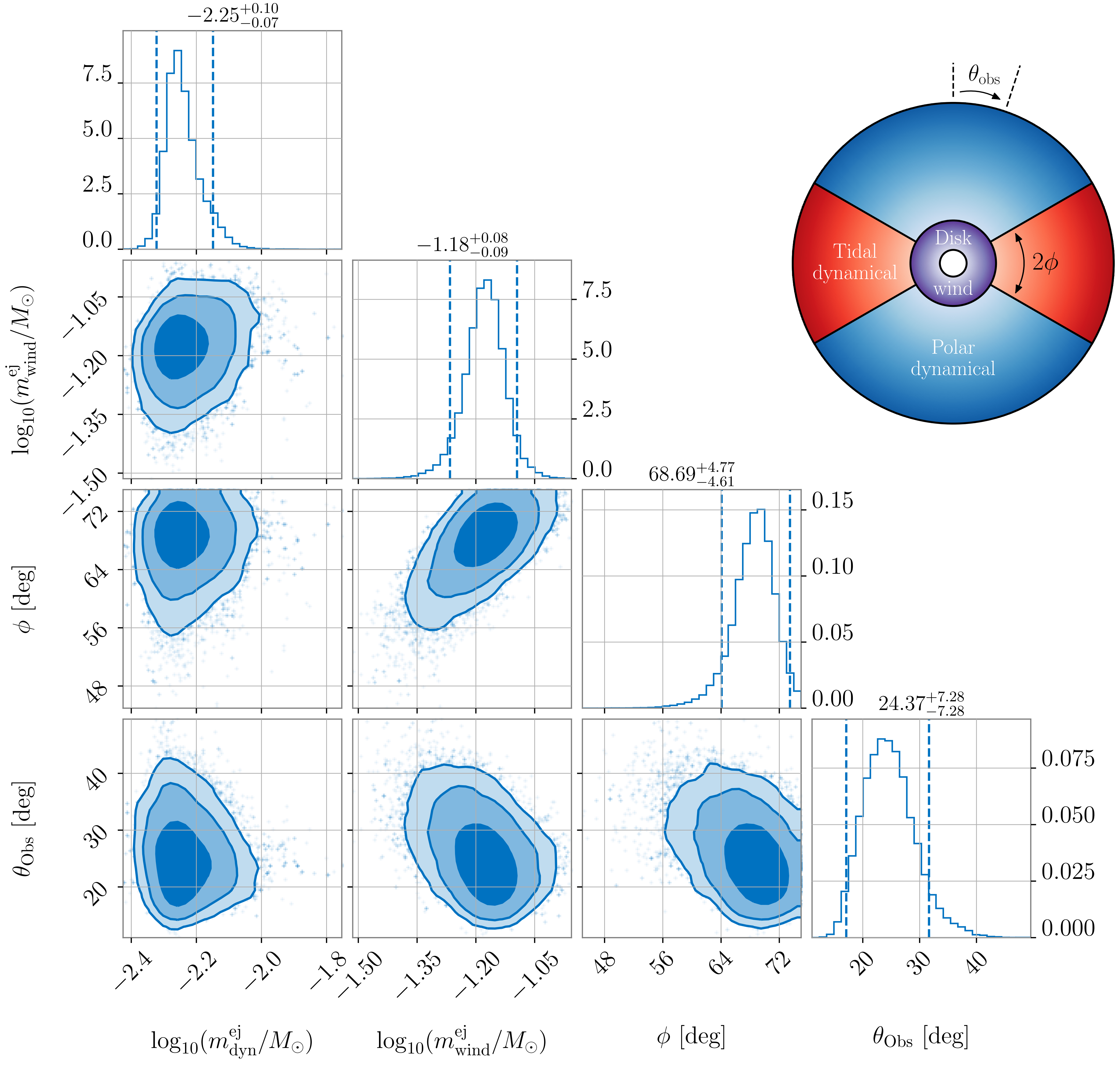
Interpolation scheme using Gaussian Process Regression or Neural Networks

Gaussian Process Regression
[Coughlin..**MB**..+2020, PRR]

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

Neural Networks
[Almualla, Ning, **MB**+2021, arXiv:2112.15470]





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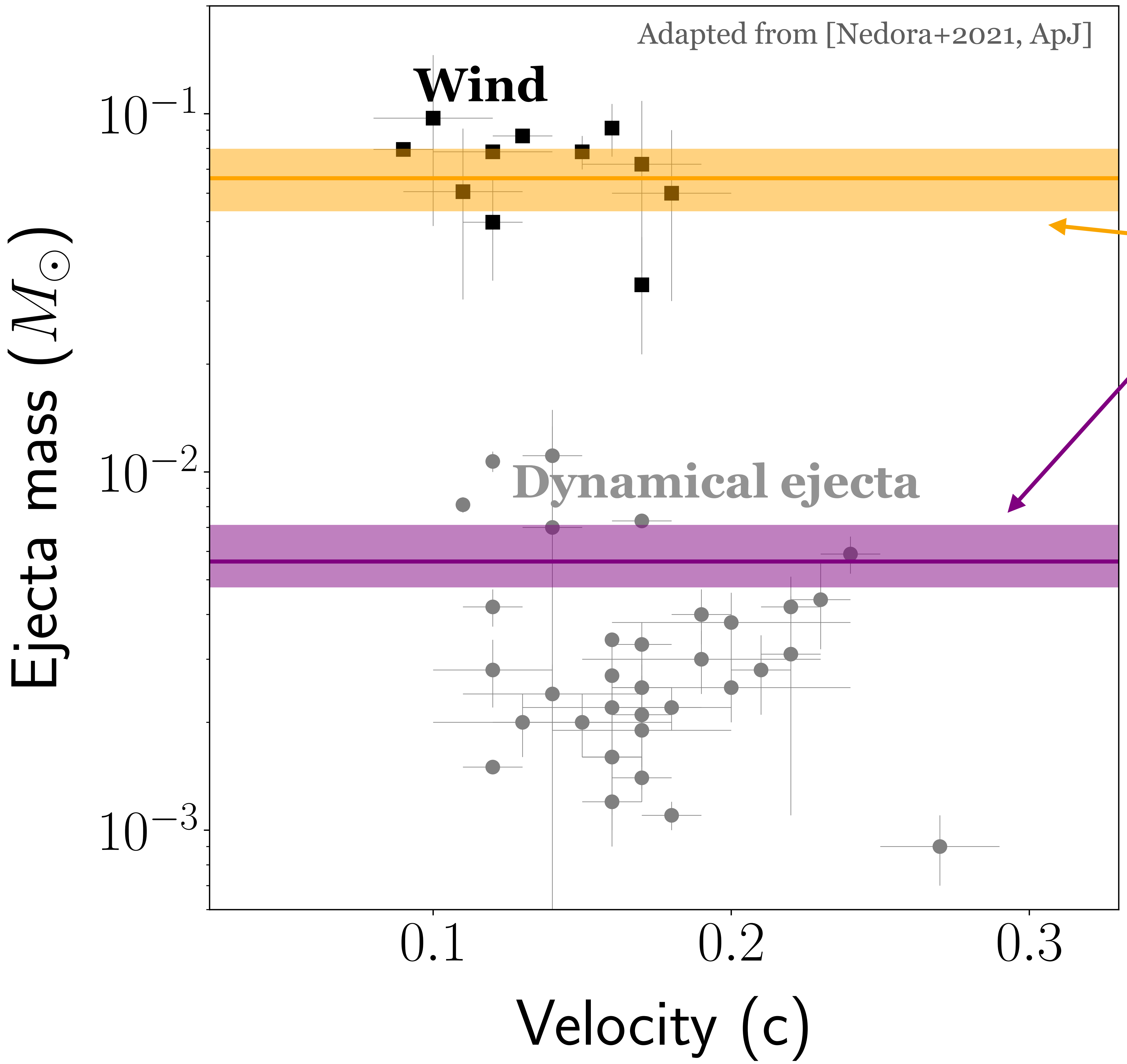

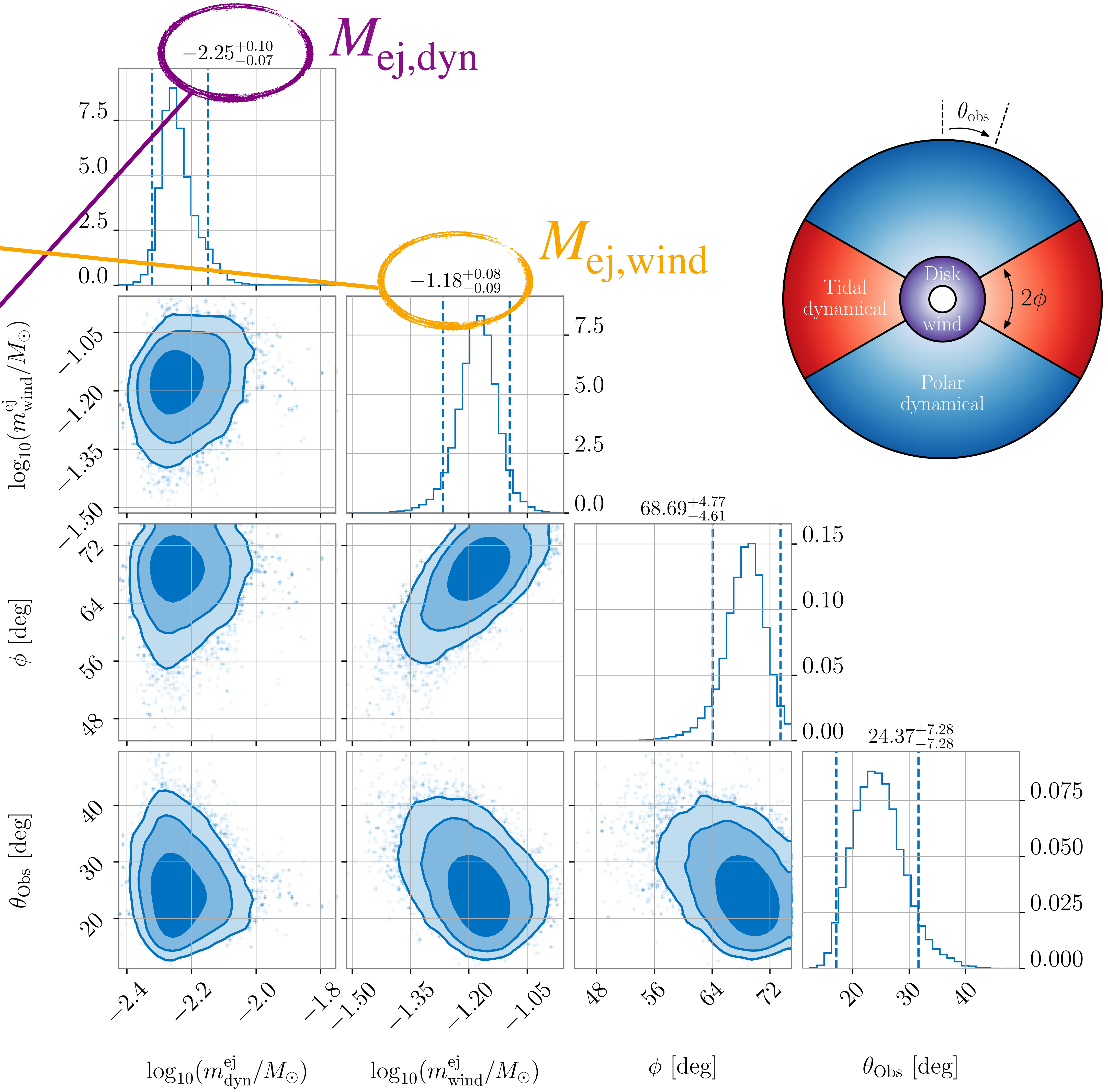

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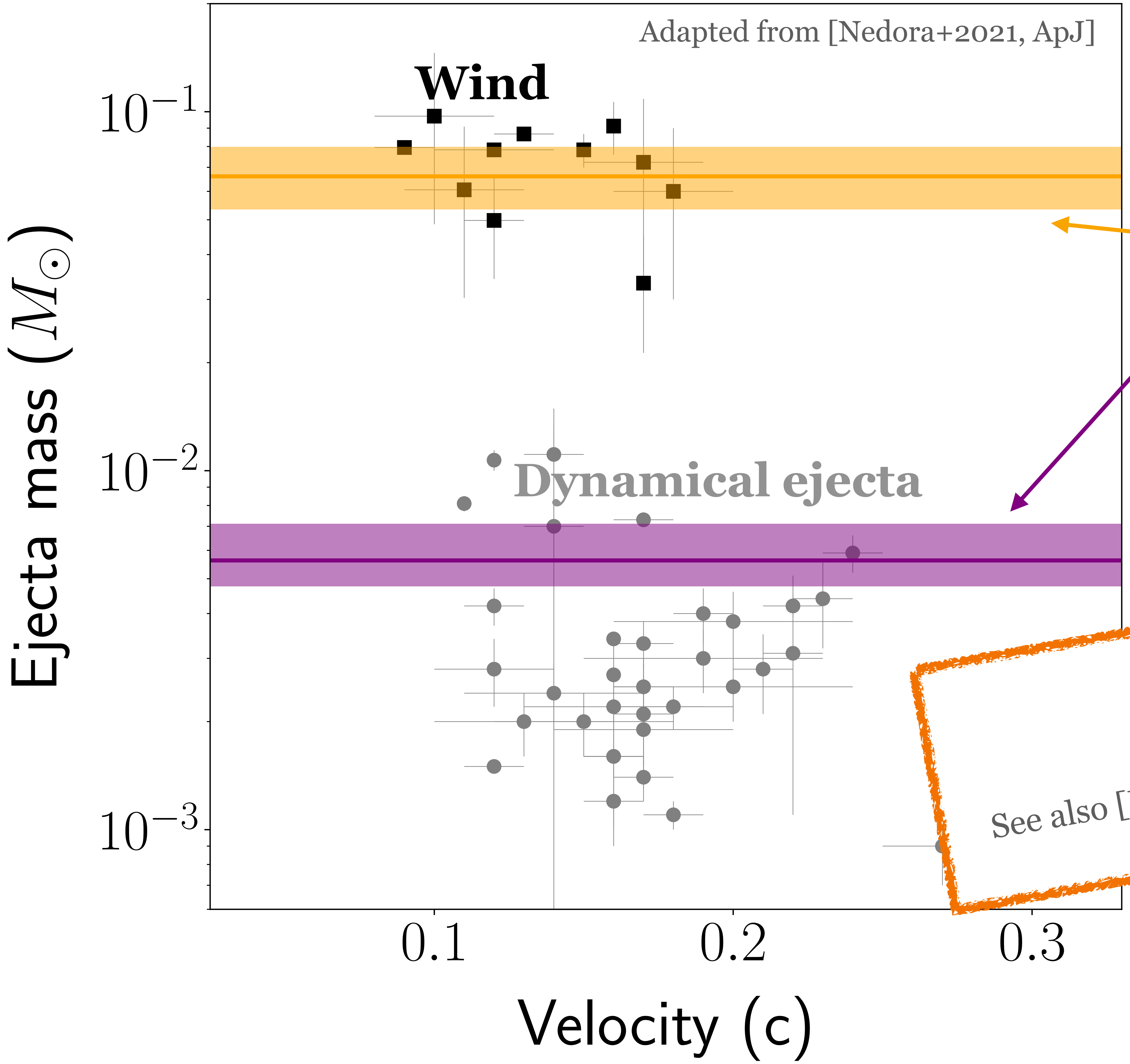
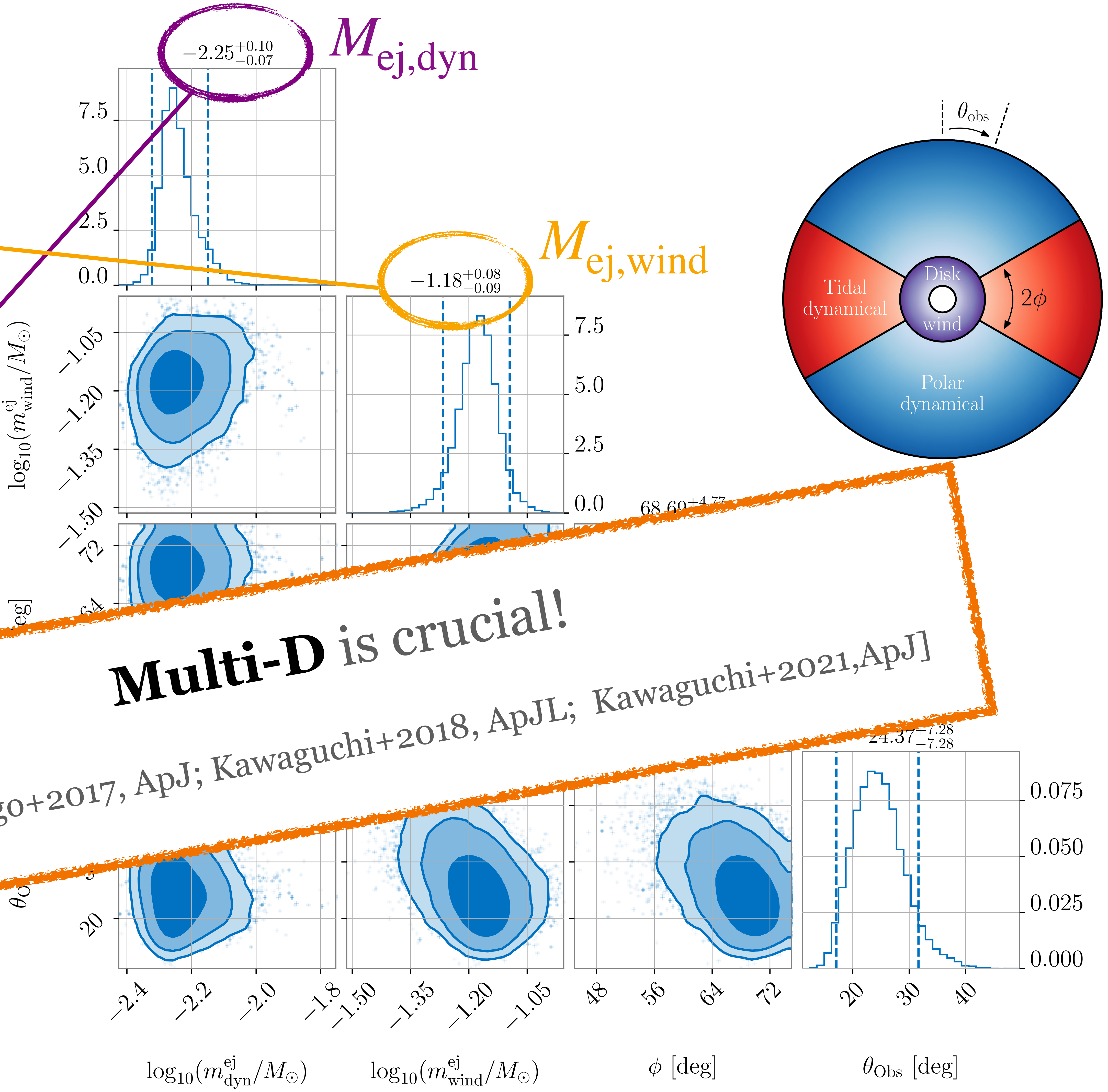




Multi-D is crucial!

See also [Perego+2017, ApJ; Kawaguchi+2018, ApJL; Kawaguchi+2021,ApJ]

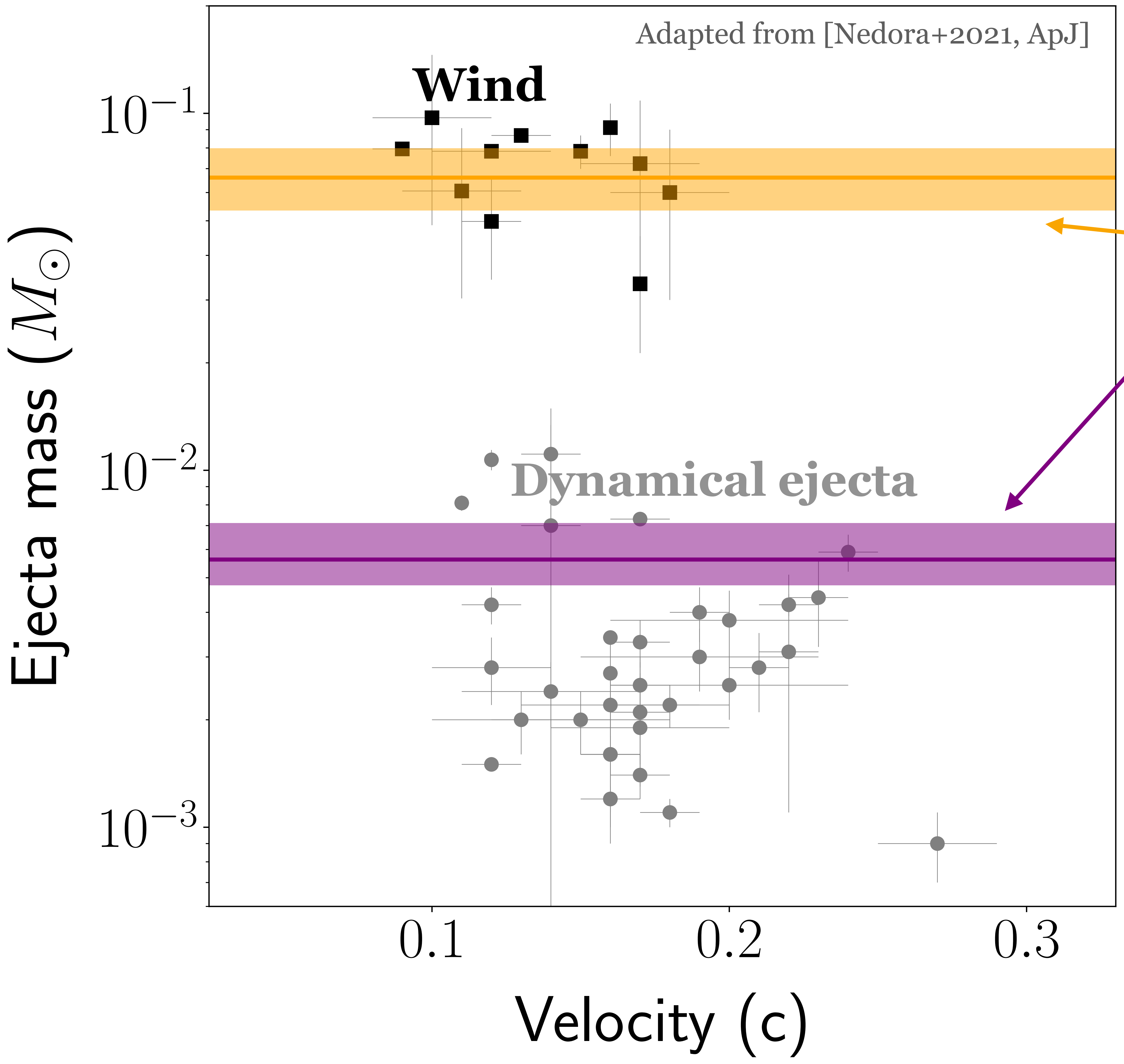
A fit to the kilonova AT2017gfo

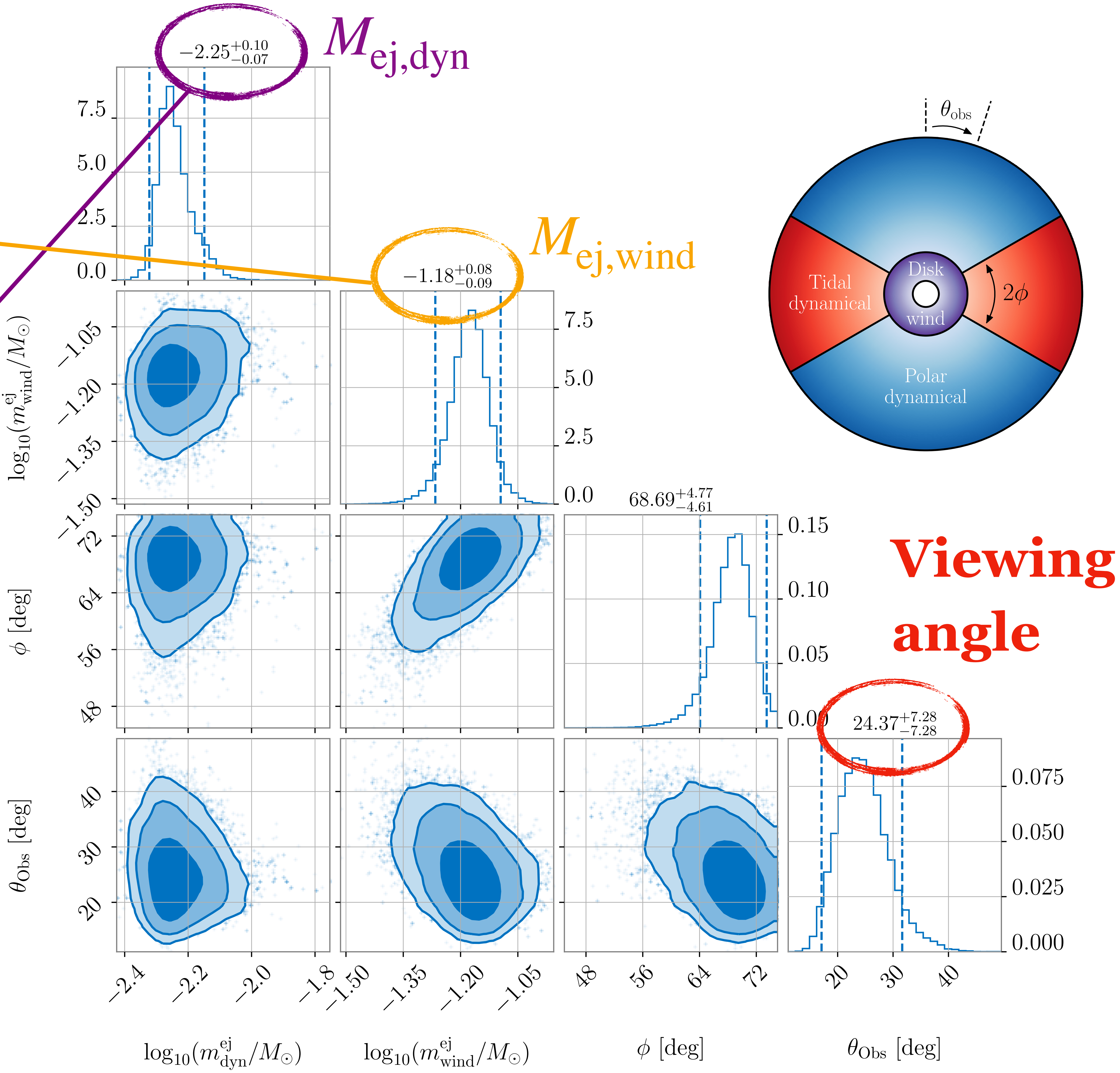
Interpolation scheme using Gaussian Process Regression or Neural Networks

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

Gaussian Process Regression
[Coughlin..**MB**..+2020, PRR]

Neural Networks
[Almualla, Ning, **MB**+2021, arXiv:2112.15470]



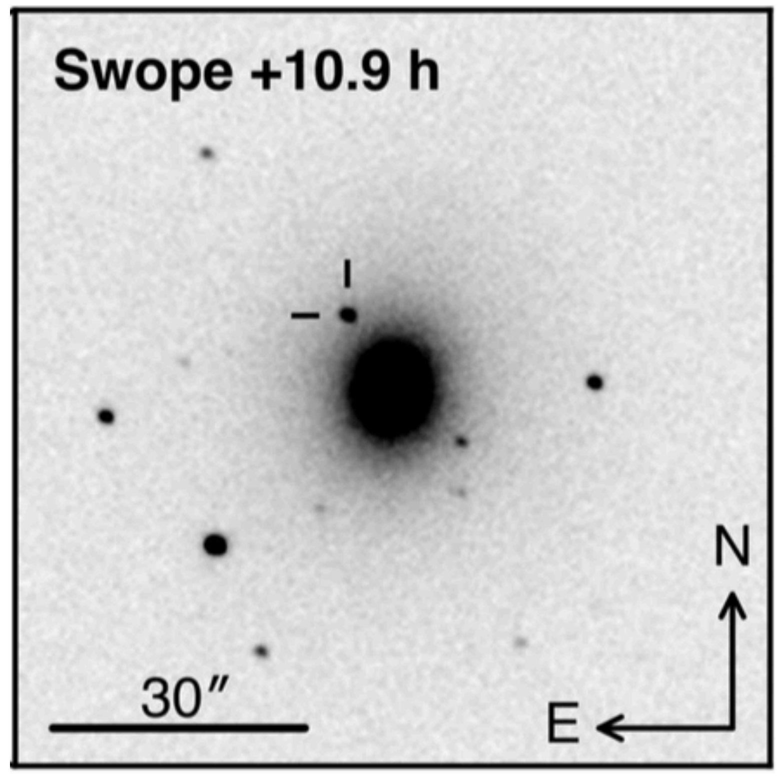


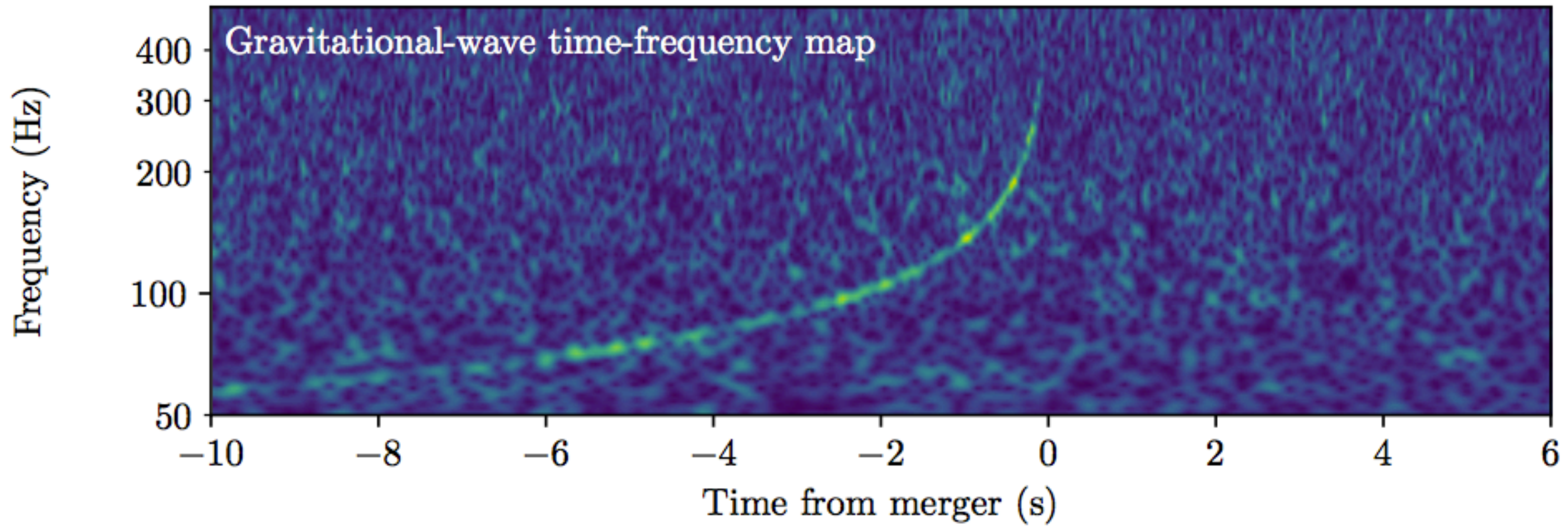
The Hubble constant H_0

Gravitational Waves as Standard Sirens

[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

$$H_0 = \frac{\text{Velocity}}{\text{Distance}} = \frac{[\text{speed of light}] \cdot \text{Redshift}}{\text{Distance}}$$





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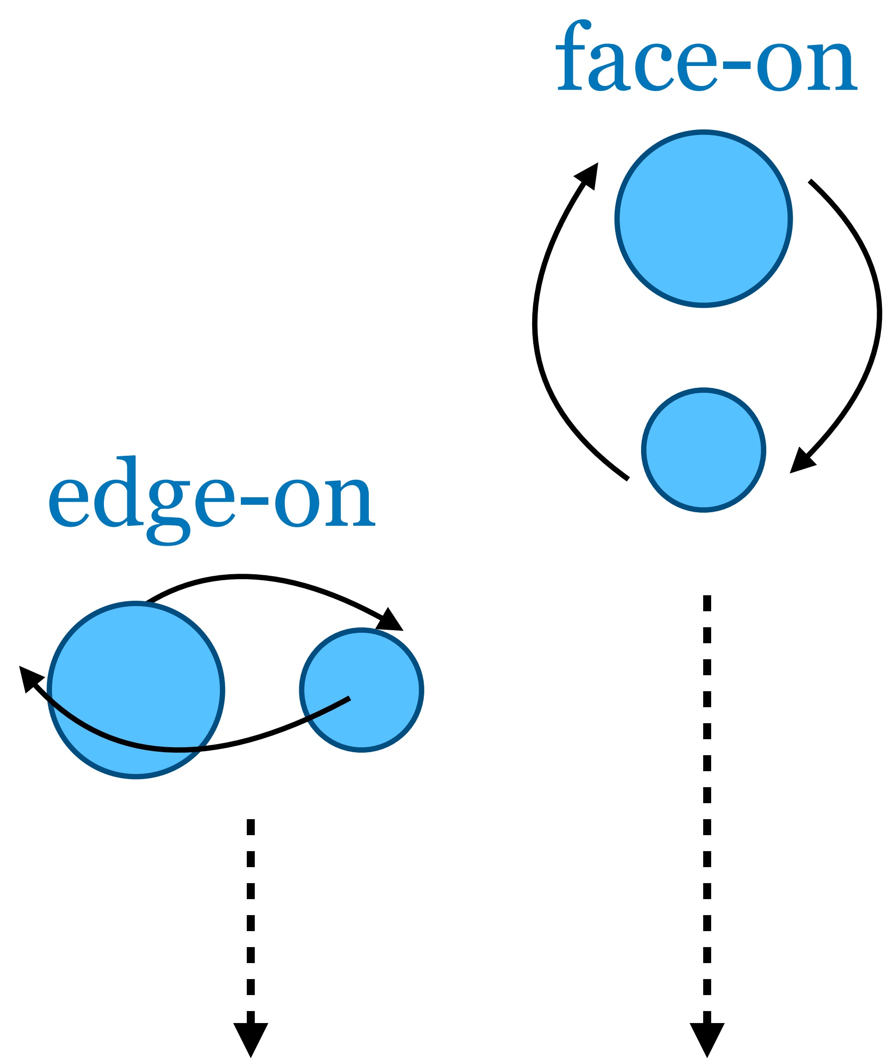

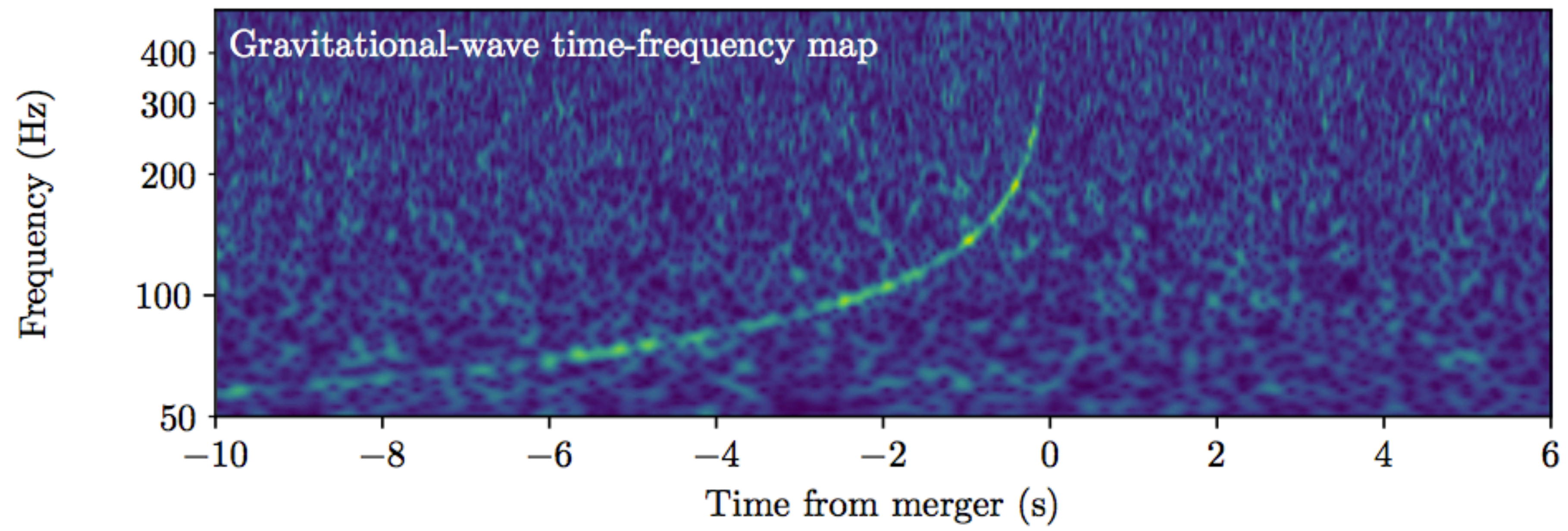

The Hubble constant H_0

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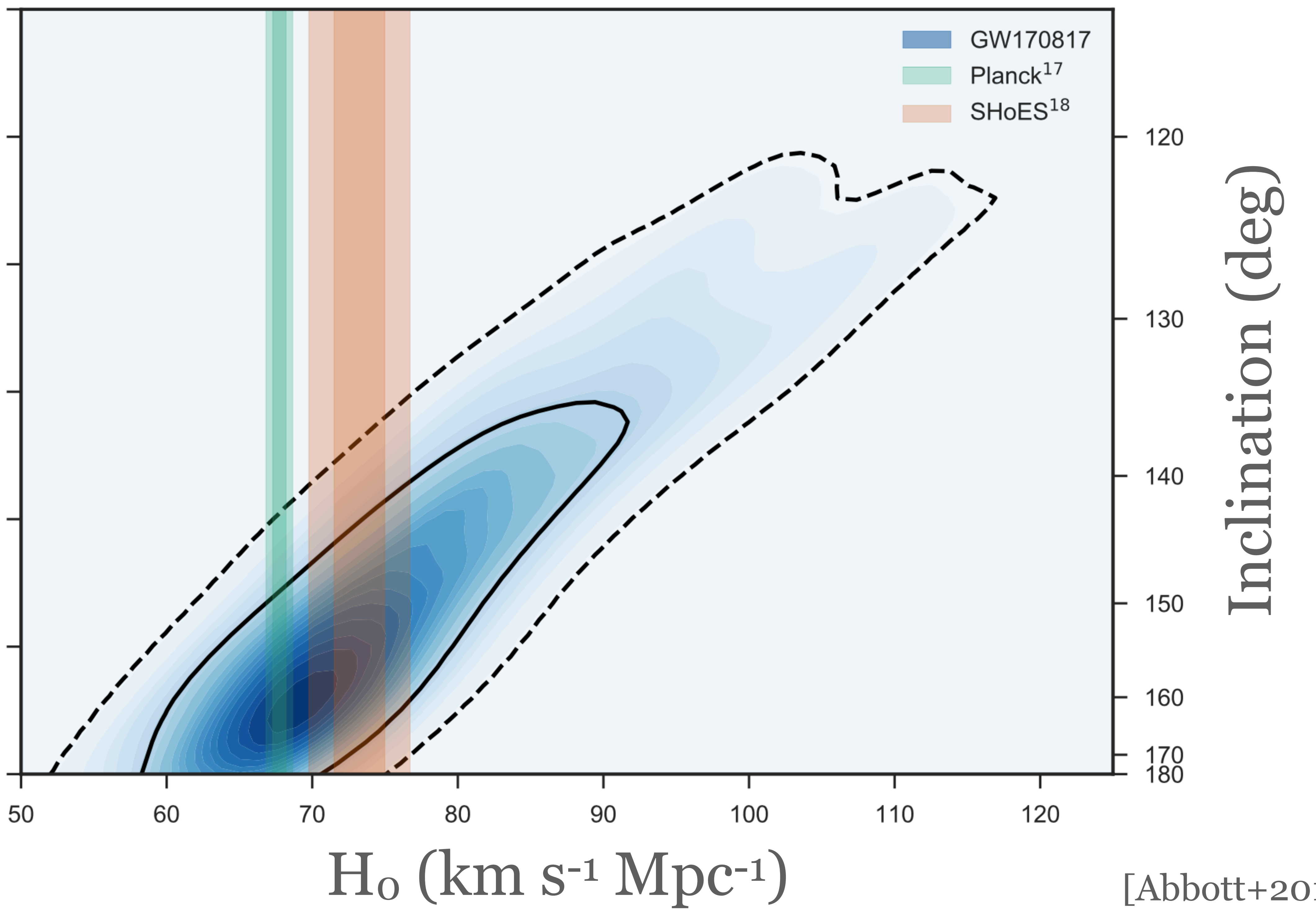
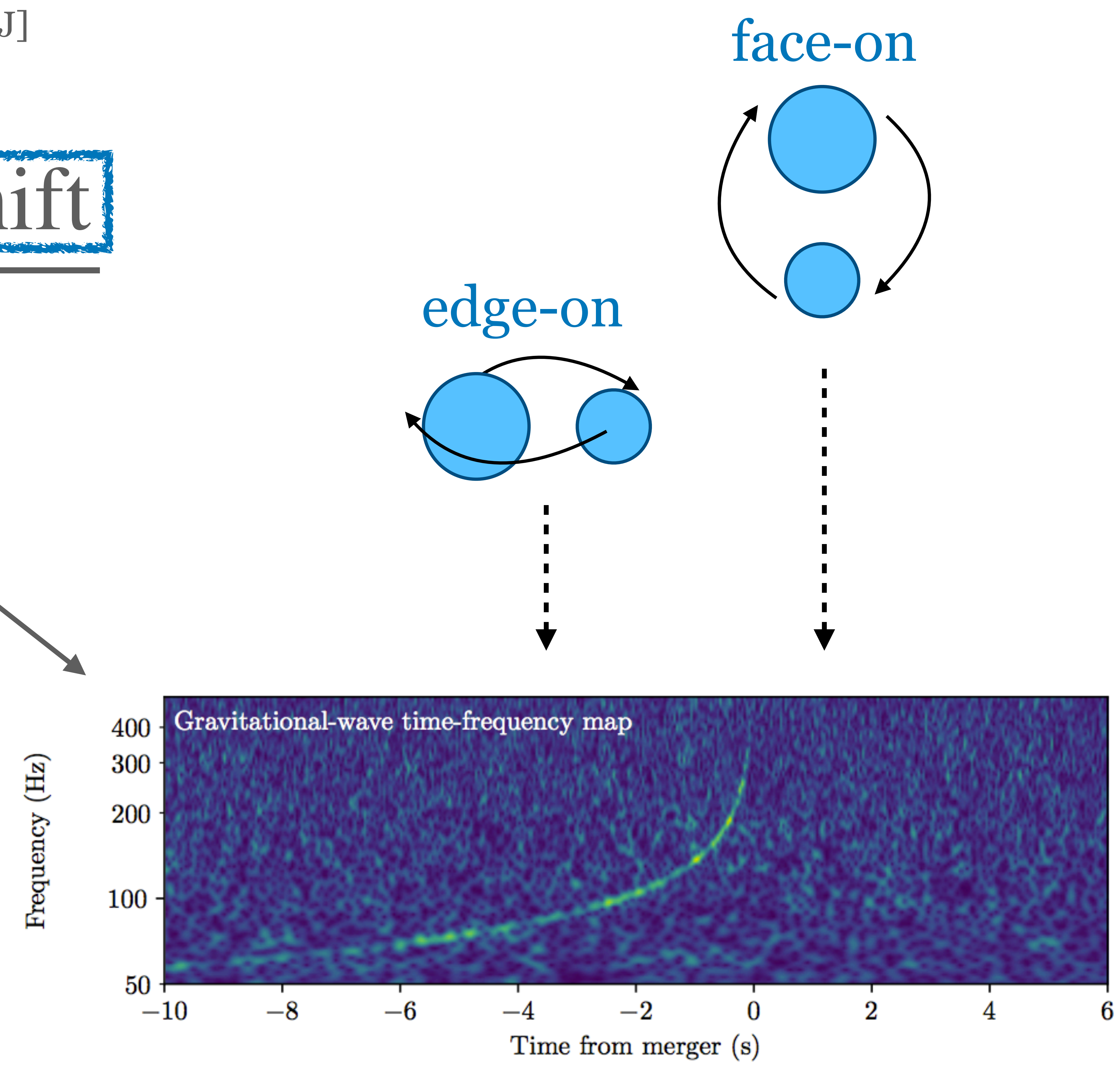


[Abbott+2017, Nature]



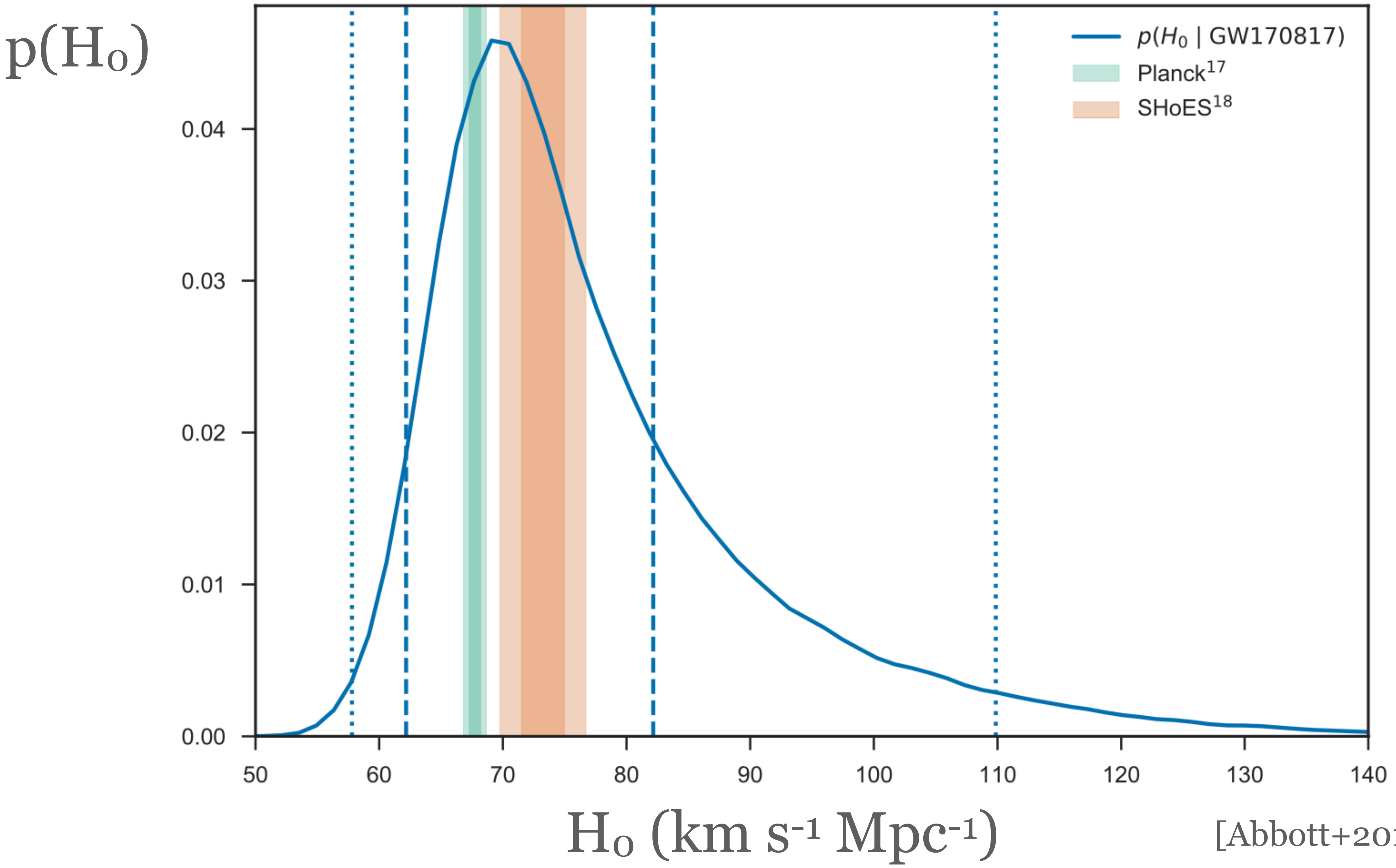
$$H_0 = 70.0^{+12.0}_{-8.0}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$

The Hubble constant H_0

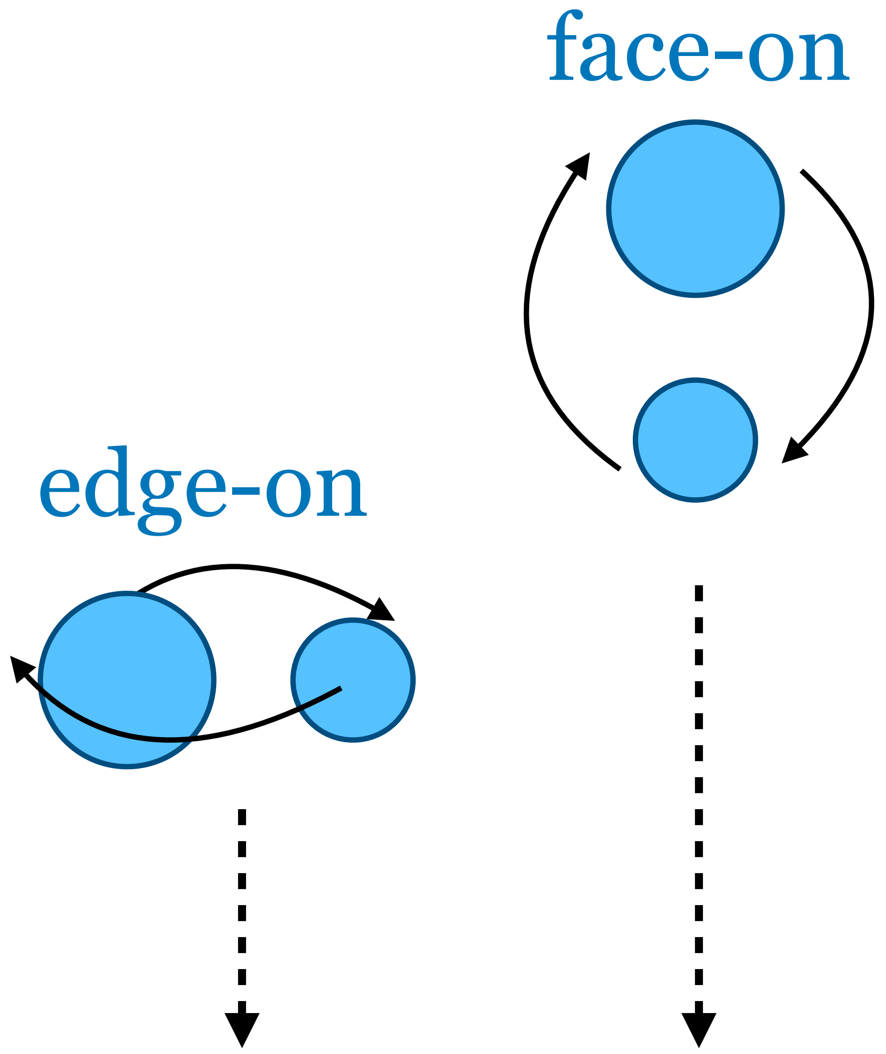
Gravitational Waves as Standard Sirens

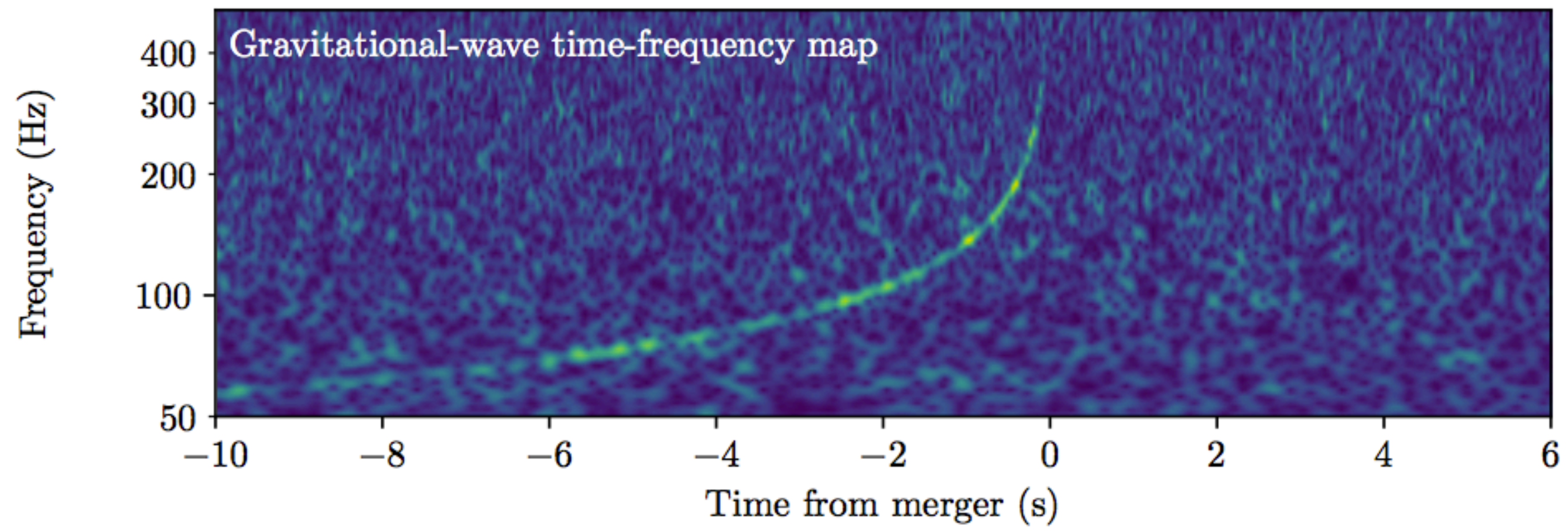
[Schutz 1986, Nature; Holz & Hughes 2005, ApJ]

$$H_0 = \frac{\text{Velocity}}{\text{Distance}} = \frac{[\text{speed of light}] \cdot \text{Redshift}}{\text{Distance}}$$



[Abbott+2017, Nature]





$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

The Hubble constant H_0

24% improvement on H_0

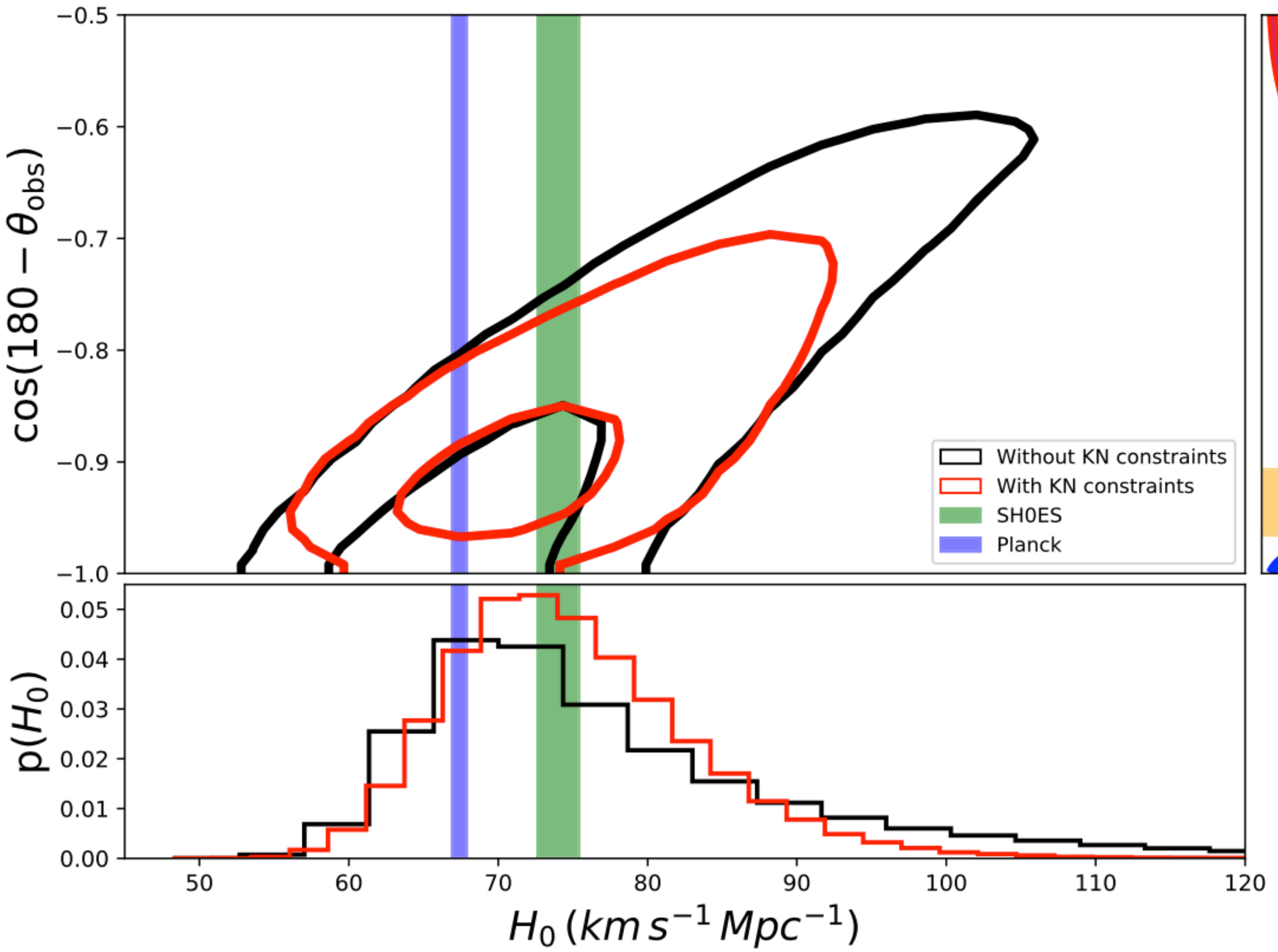
[Dhawan, **MB**+2020, ApJ]

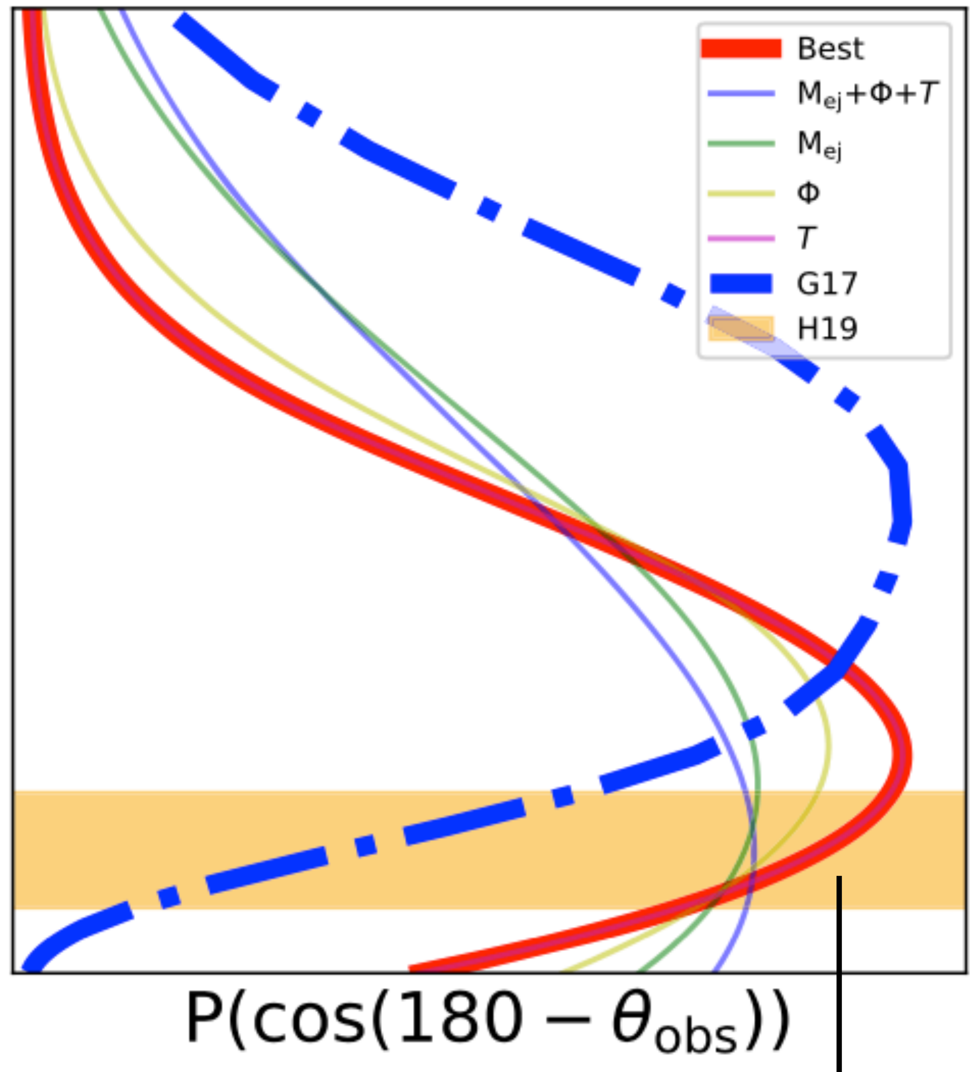
GW only

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

GW + kilonova

$$H_0 = 72.4^{+7.9}_{-7.3}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

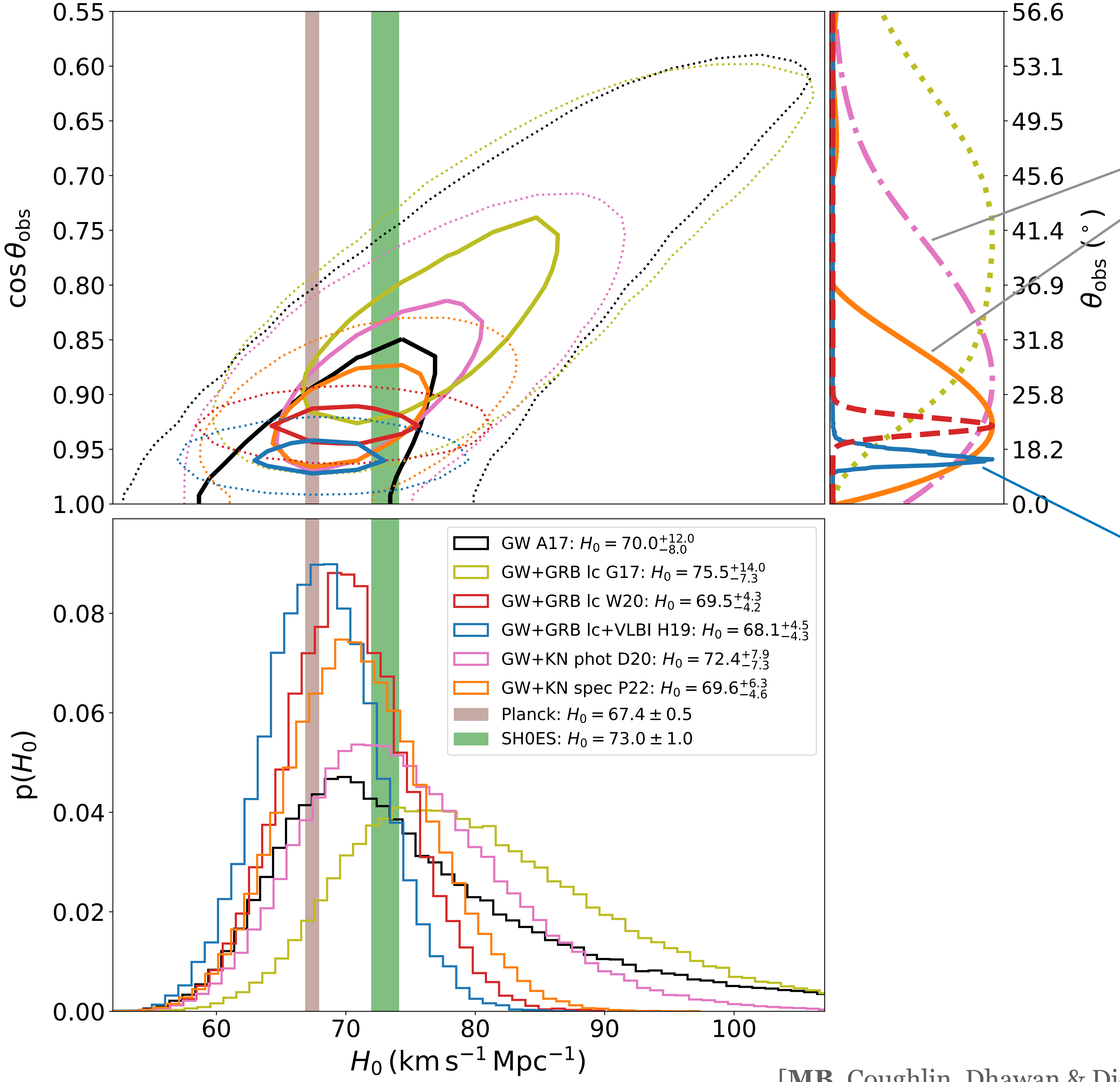




~25 deg
from the pole

see also [Coughlin...**MB**...+2020, Nature Communications]

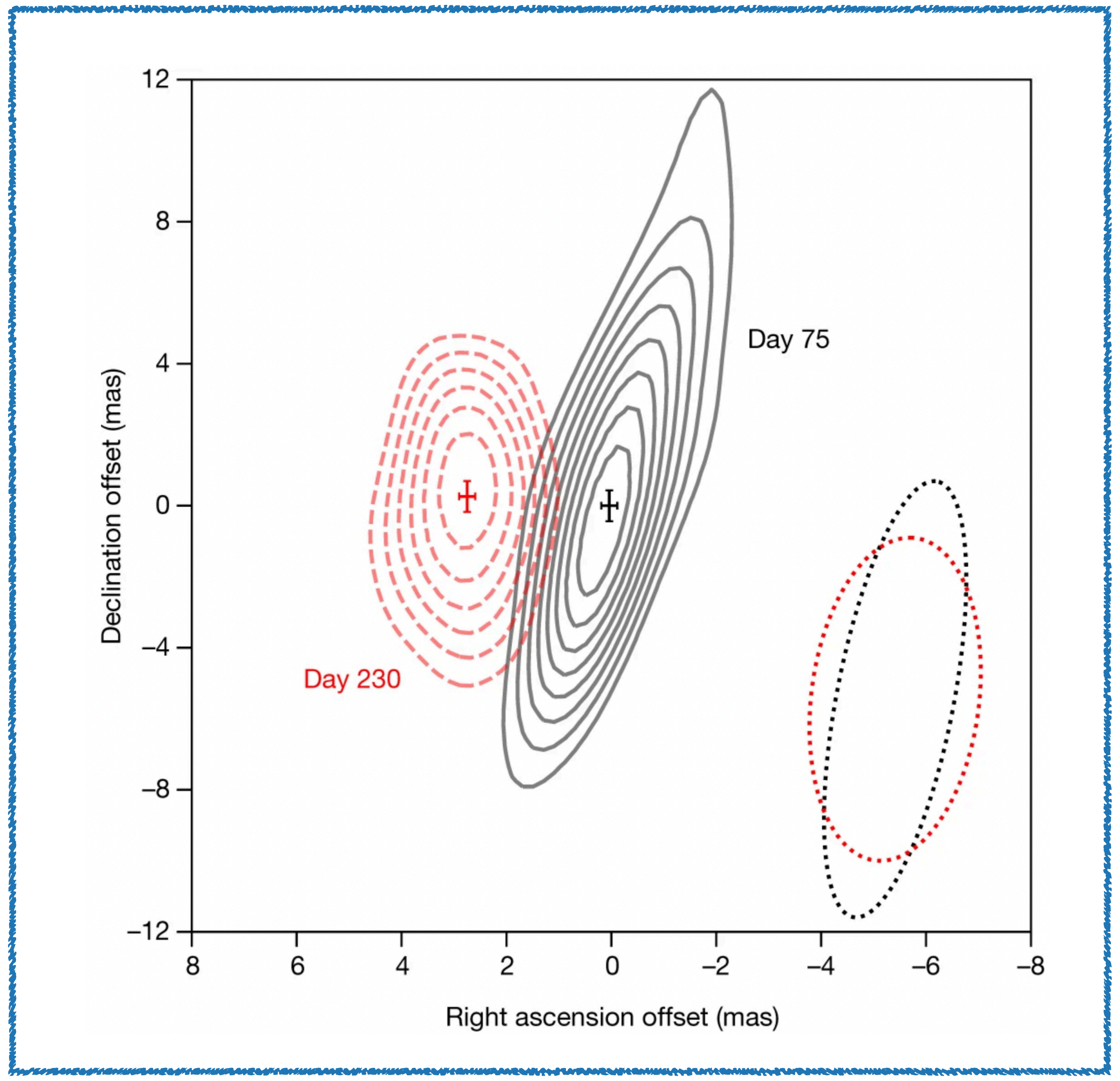
The Hubble constant H_0



Kilonova

Superluminal motion

[Mooley+2018, Nature]
[Hotokezaka+2019, NatAstro]

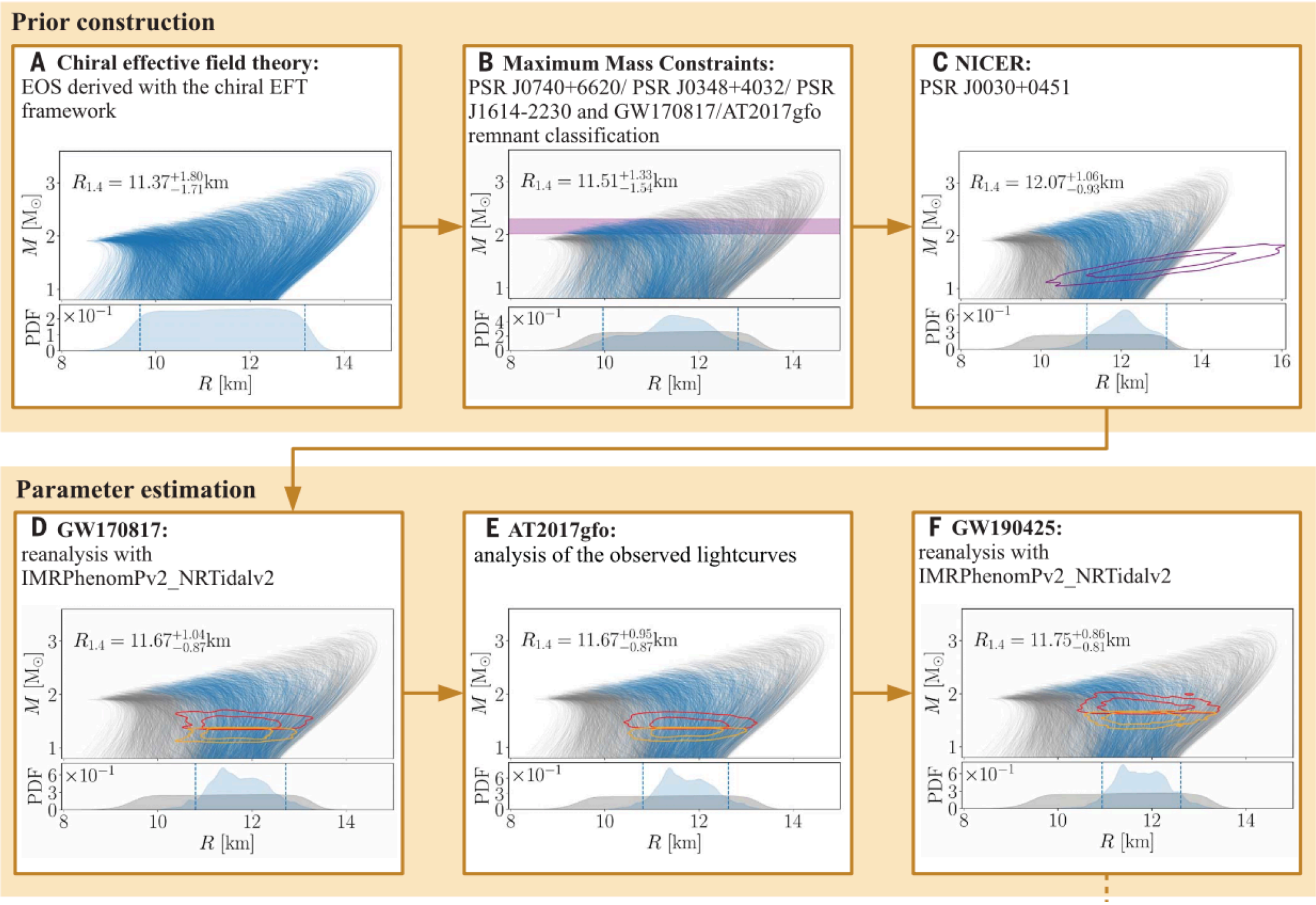


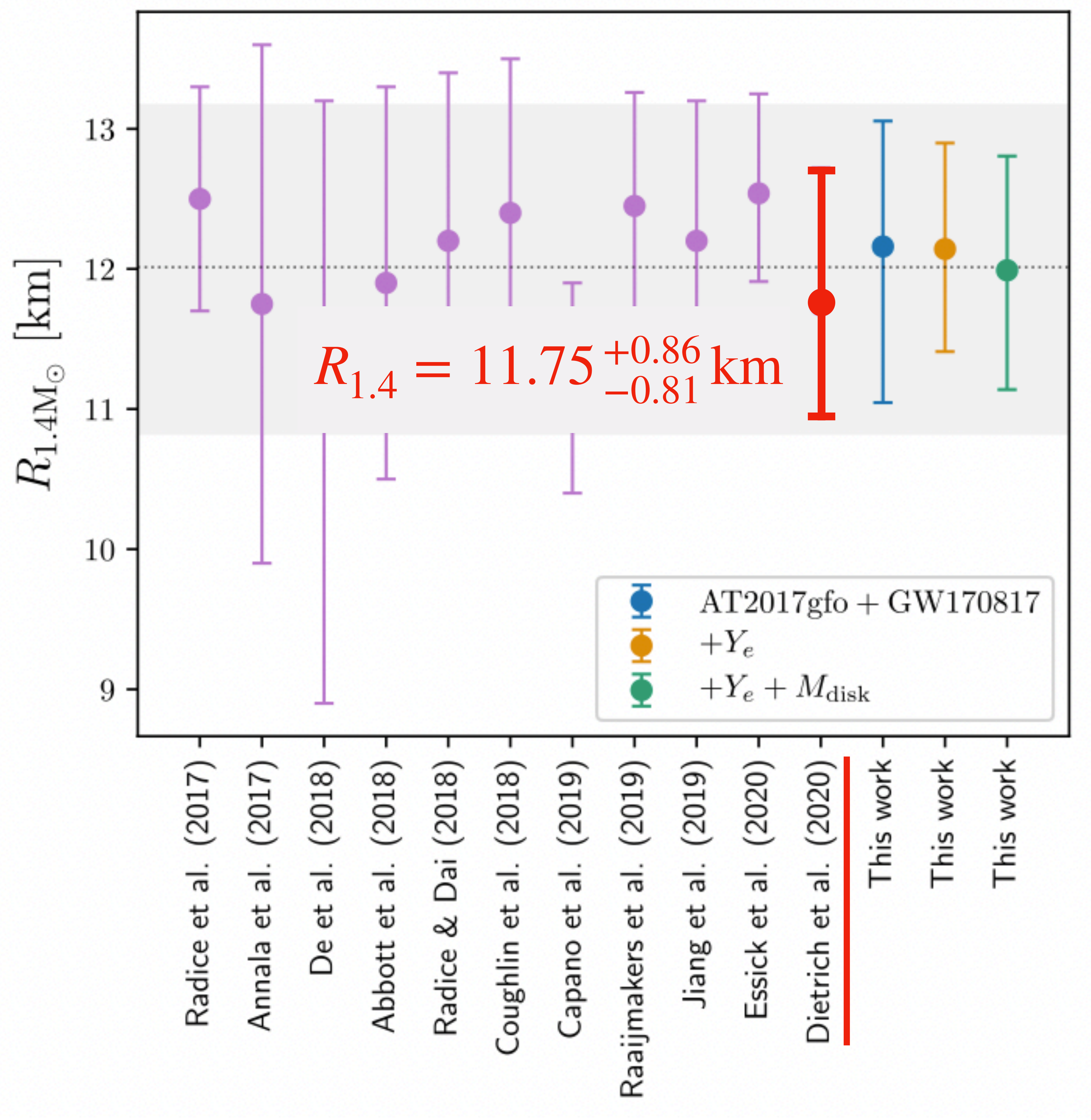
[**MB**, Coughlin, Dhawan & Dietrich 2022, Universe]

NMMA: A framework to rule them all

A nuclear-physics multi-messenger bayesian framework

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





[Breschi+2021,MNRAS]

NMMA: A framework to rule them all

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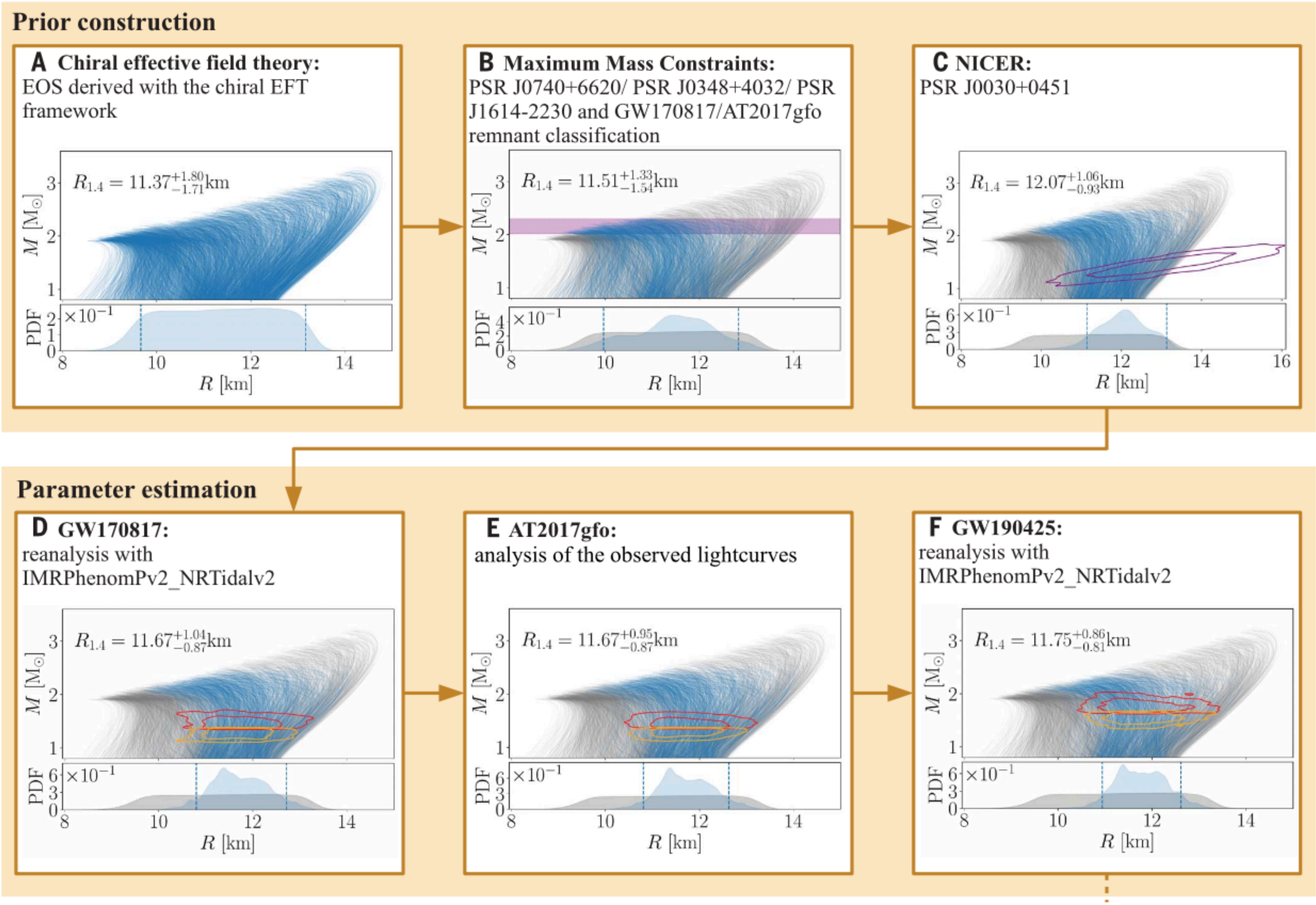
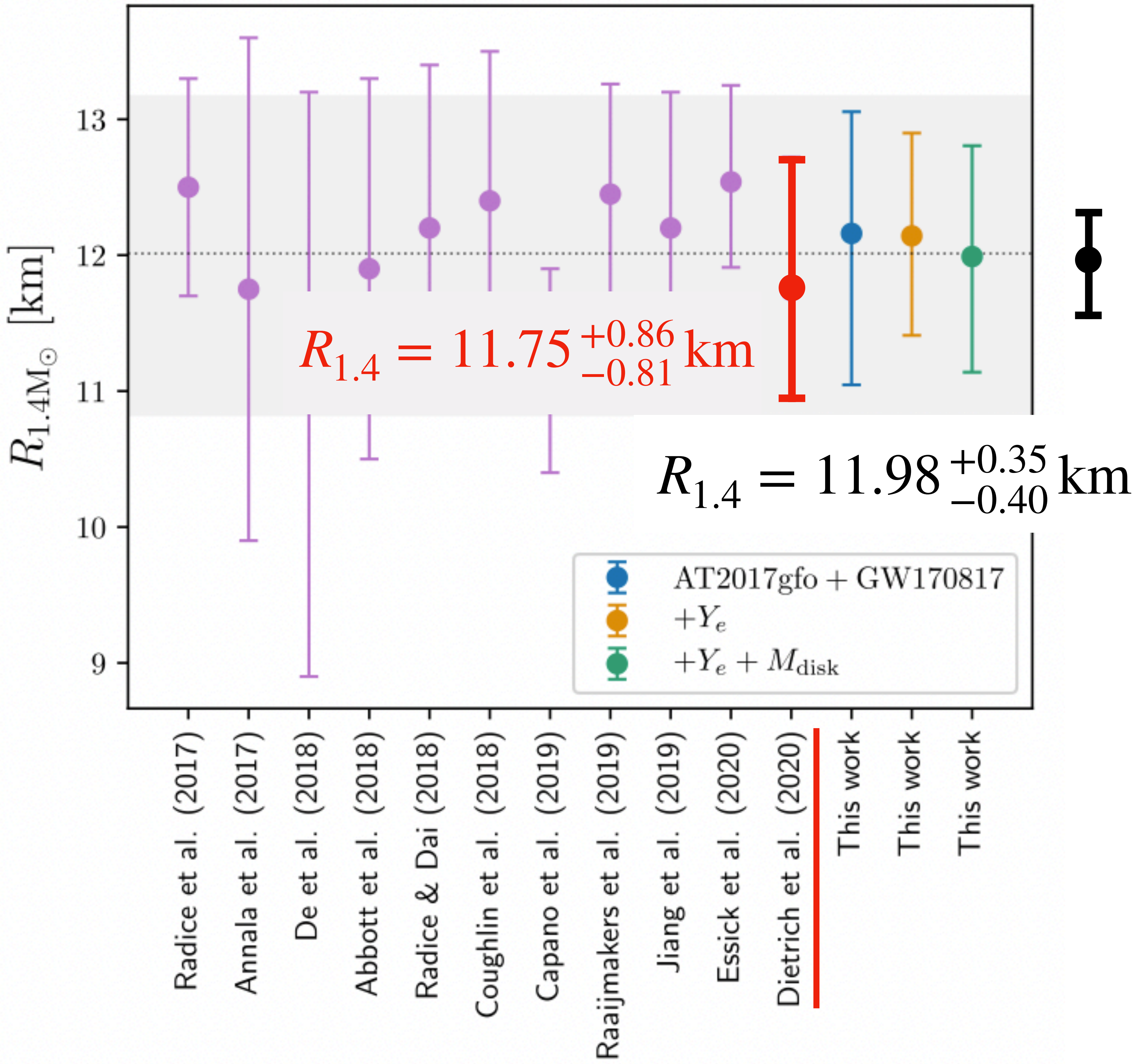
[Dietrich, Coughlin, Pang, **MB**+2020, Science]



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



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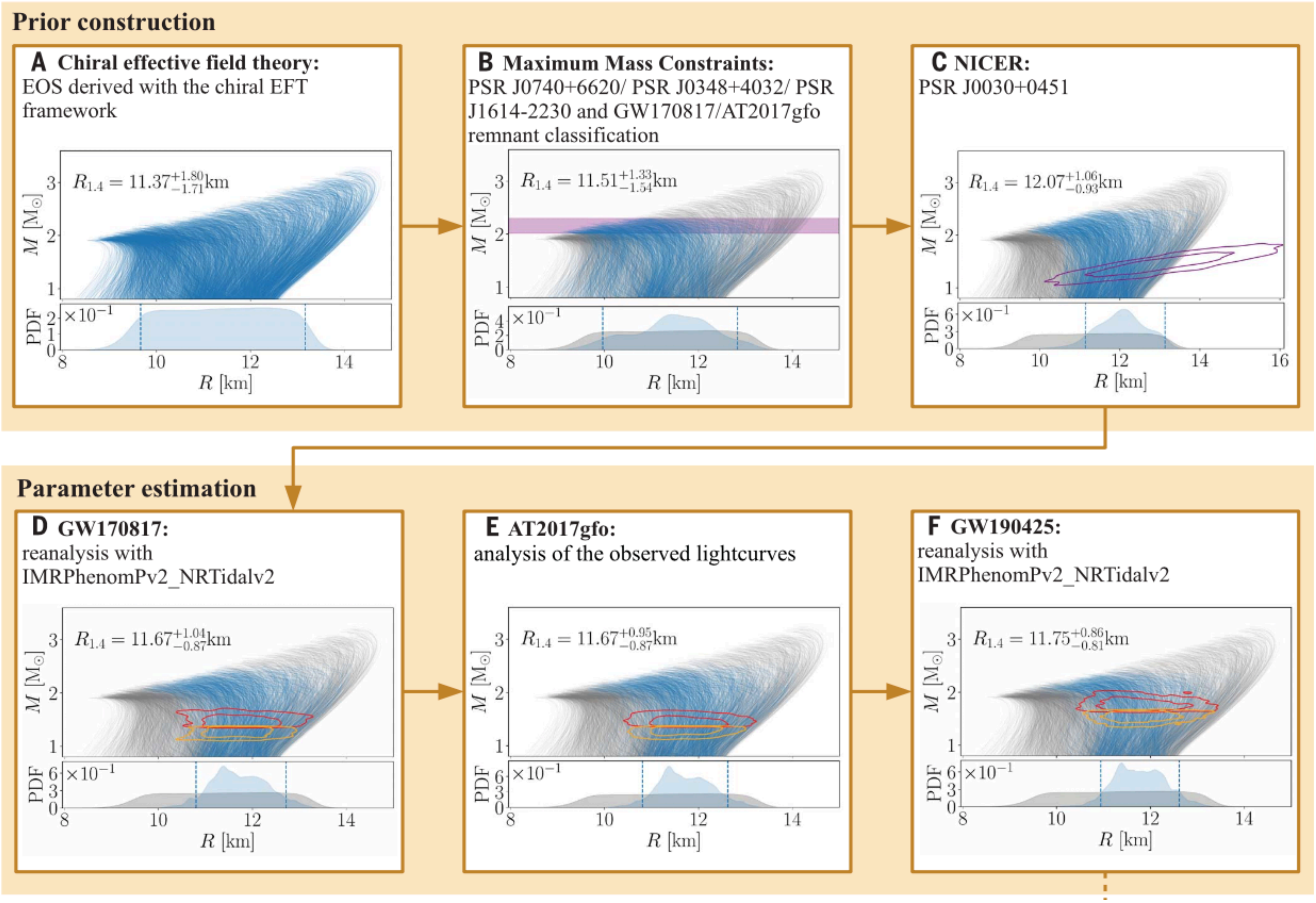
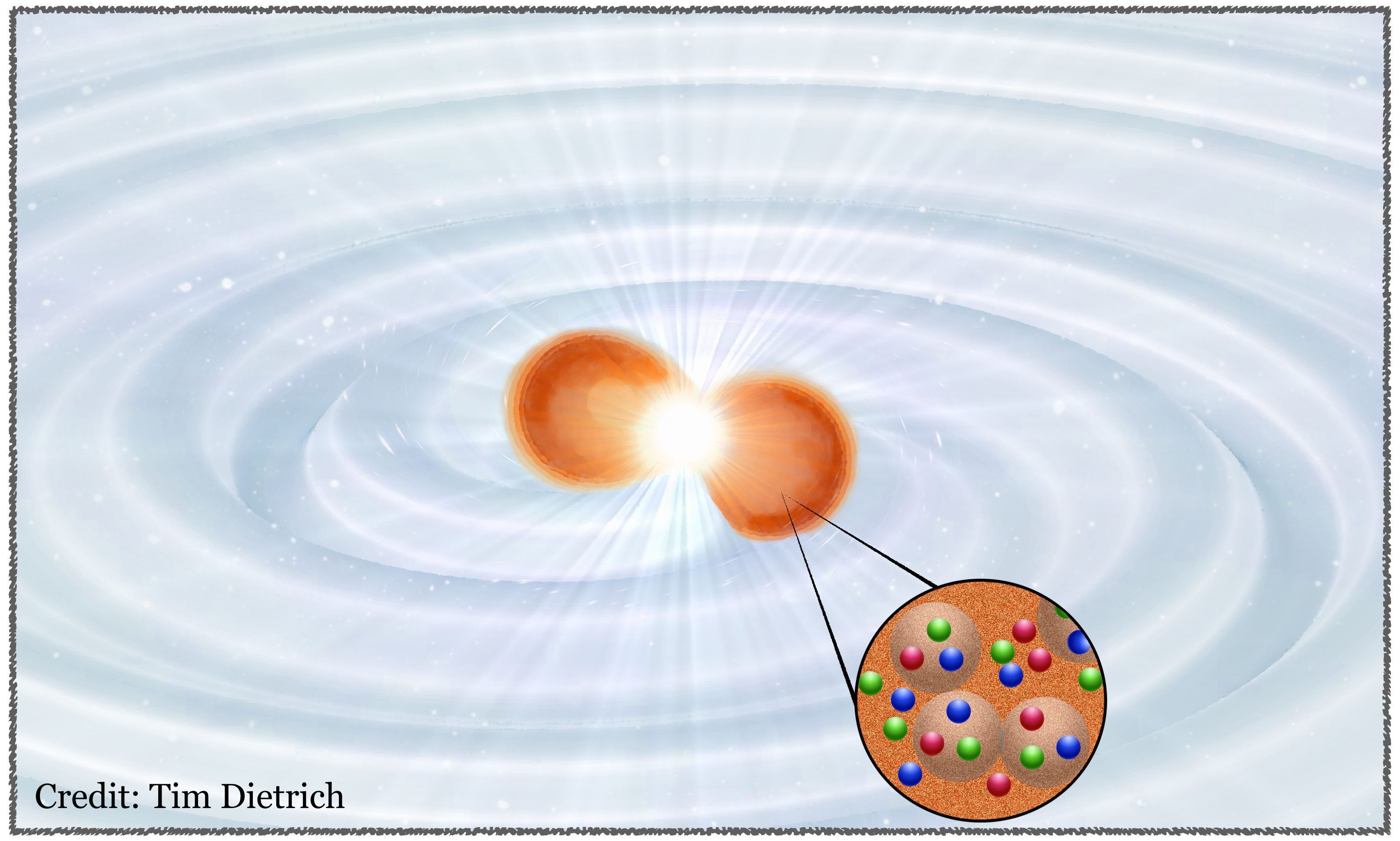
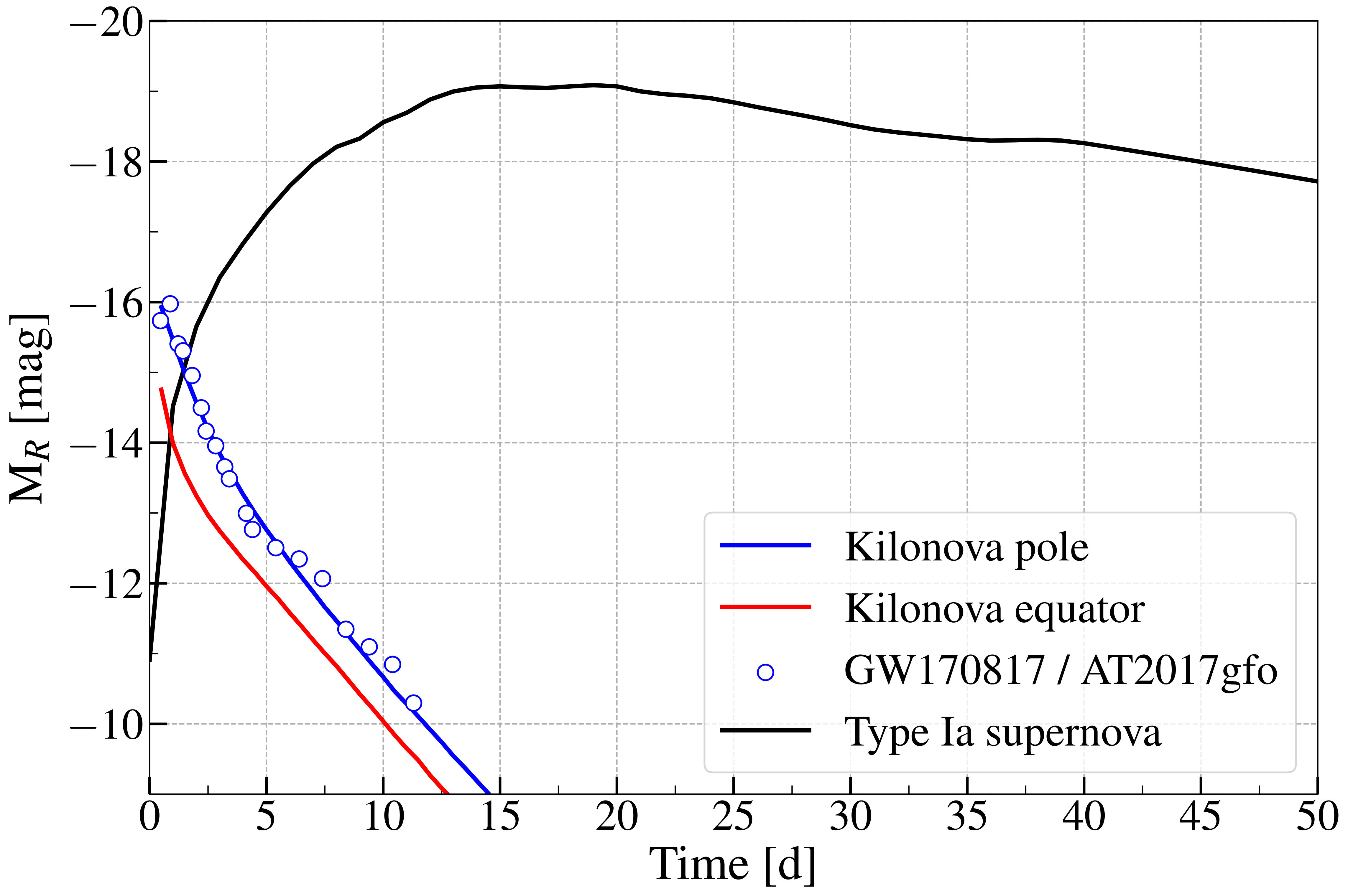




- GW190814 as a BBH [Tews..**MB**..+2021, ApJL]
- Adding PSRJ0740+6620 [Pang, Tews, Coughlin, **MB**+2021, ApJ]
- Kilonova searches [Andreoni...**MB**...+,2021,ApJ]
- MM observations + HIC [Huth...**MB**...+, Nature, in press]
- GRB211211A, in prep.

See Achim's talk on Tuesday

Hunting for kilonovae in O3

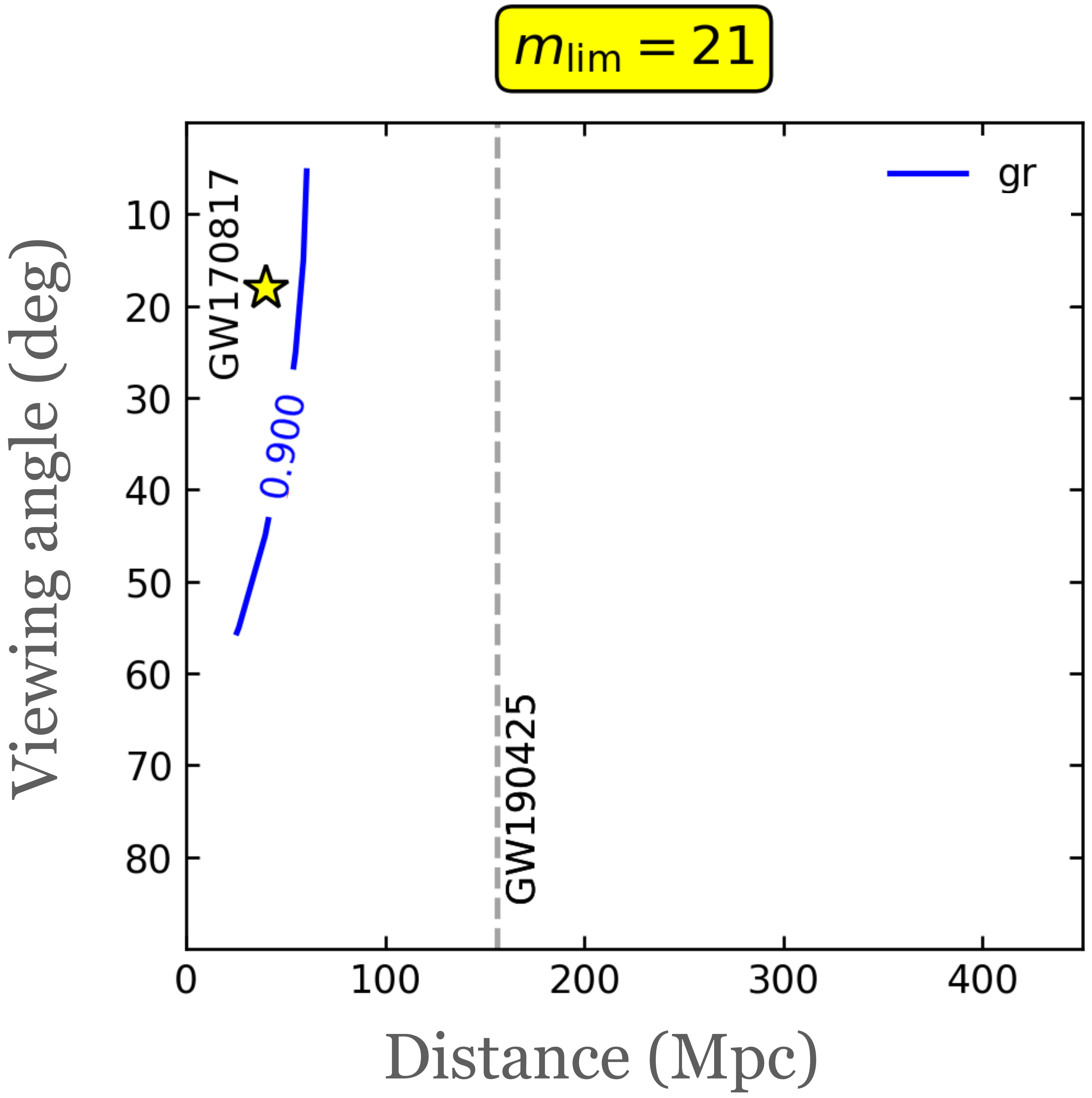


Name	Localization	Distance	Class
GW190425	7461 deg^2	156 ± 41 Mpc	BNS
S190426c	1131 deg^2	377 ± 100 Mpc	NSBH
GW190814	23 deg^2	267 ± 52 Mpc	NSBH
S190901ap	14,753 deg^2	241 ± 79 Mpc	BNS
S190910d	2482 deg^2	632 ± 186 Mpc	NSBH
S190910h	24,264 deg^2	230 ± 88 Mpc	BNS
S190923y	2107 deg^2	438 ± 133 Mpc	NSBH
S190930t	24,220 deg^2	108 ± 38 Mpc	NSBH
S191205ah	6378 deg^2	385 ± 164 Mpc	NSBH
S191213g	4480 deg^2	201 ± 81 Mpc	BNS
S200105ae	7373 deg^2	283 ± 74 Mpc	NSBH
S200115j	765 deg^2	340 ± 79 Mpc	NSBH
S200213t	2326 deg^2	201 ± 80 Mpc	BNS
GW170817	30 deg^2	40 Mpc	BNS

[Kasliwal..**MB**..,+2020, ApJ]

Detectability of kilonovae

[Sagues-Carracedo, **MB**, Feindt & Goobar 2021, MNRAS]

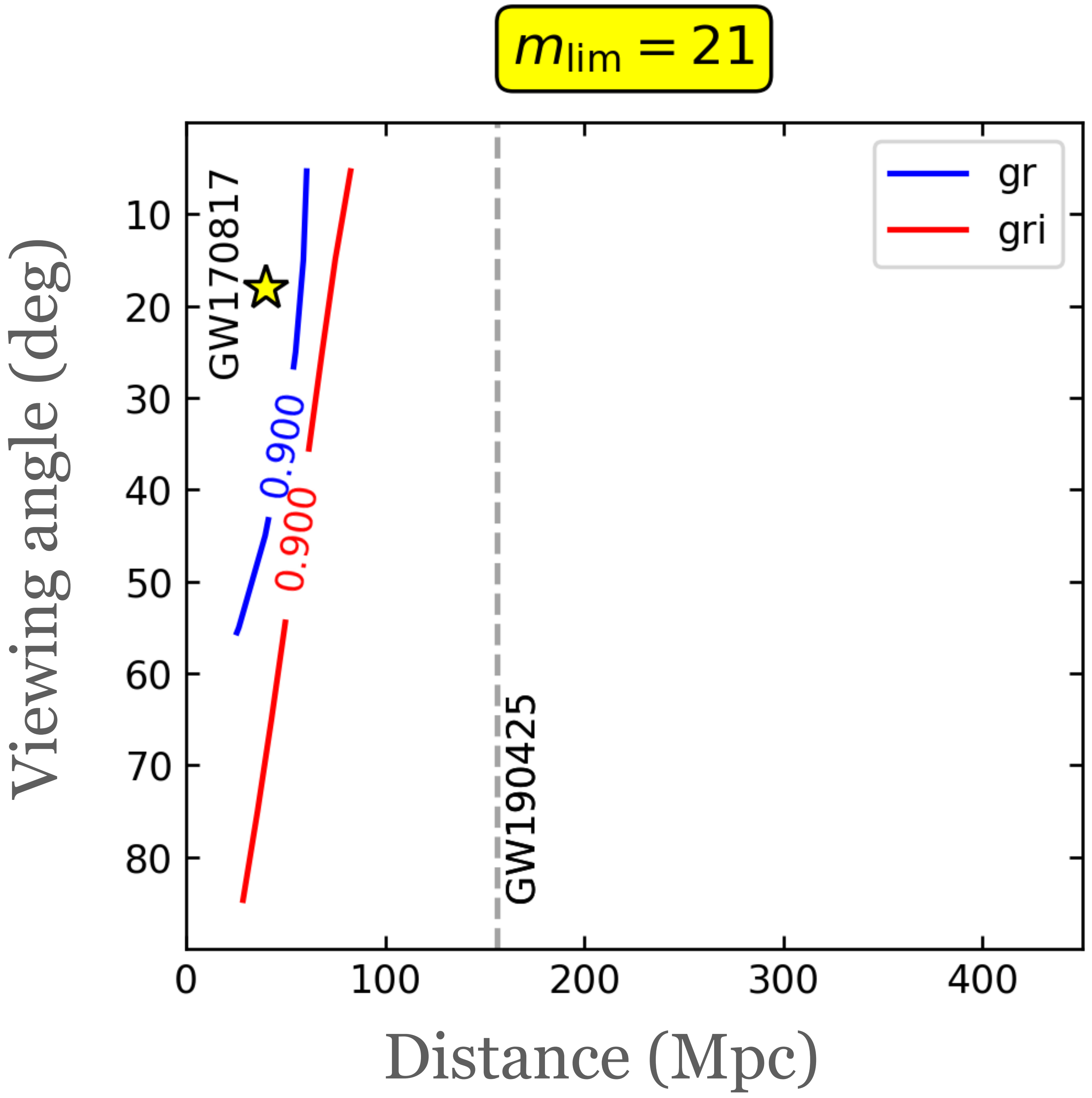


see also [Coughlin, Dietrich, Antier, **MB**+2020a, MNRAS / Coughlin..**MB**..+2020b, MNRAS / Almualla..**MB**..+2021,MNRAS]

Detectability of kilonovae

Go red!

[Sagues-Carracedo, **MB**, Feindt & Goobar 2021, MNRAS]

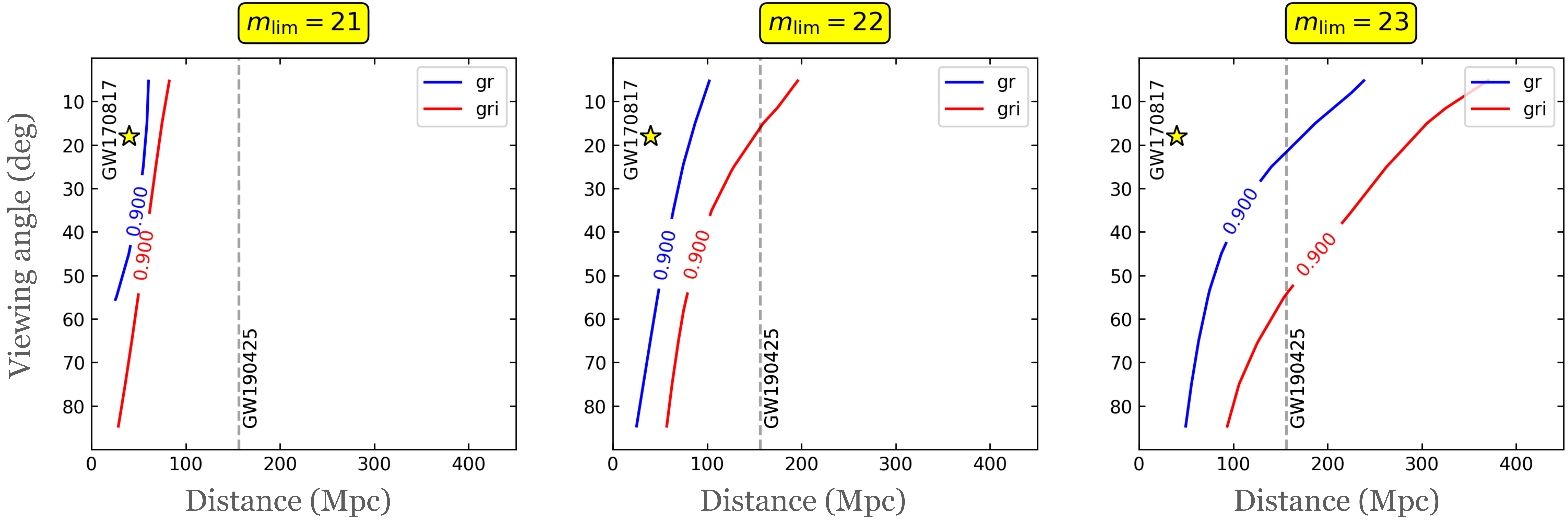


see also [Coughlin, Dietrich, Antier, **MB**+2020a, MNRAS / Coughlin..**MB**..+2020b, MNRAS / Almualla..**MB**..+2021,MNRAS]

Detectability of kilonovae

Go red! Go deep!

[Sagues-Carracedo, **MB**, Feindt & Goobar 2021, MNRAS]



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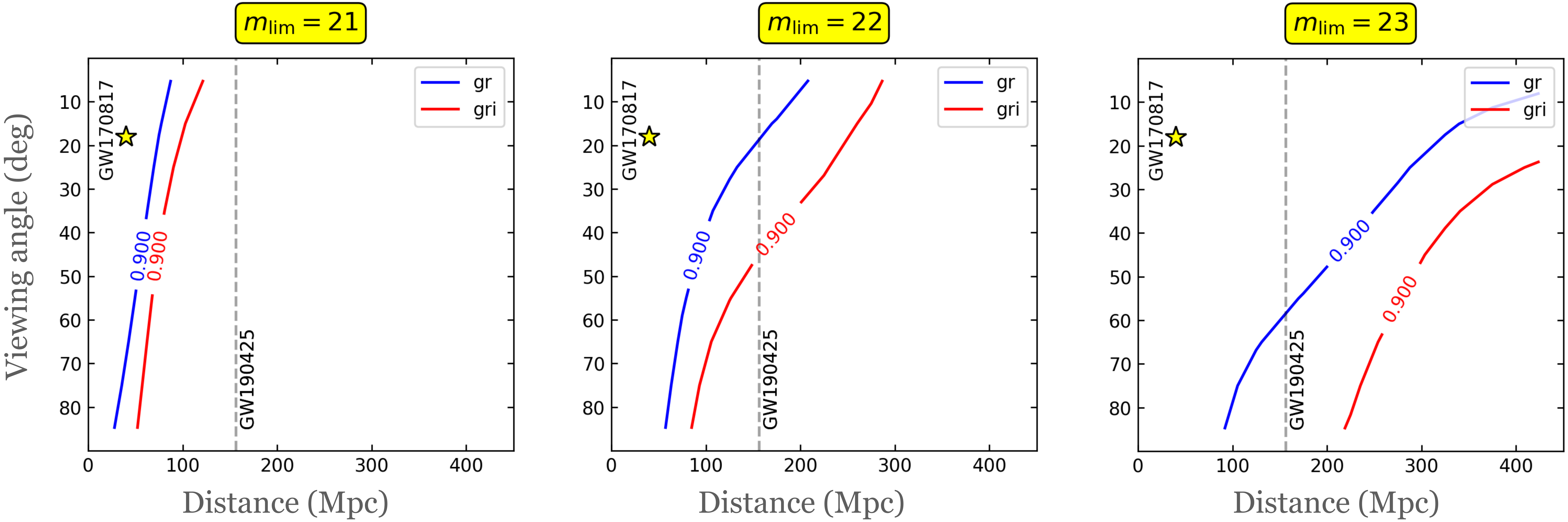
Detectability of kilonovae

Go red! Go deep! Be quick!

[Sagues-Carracedo, **MB**, Feindt & Goobar 2021, MNRAS]



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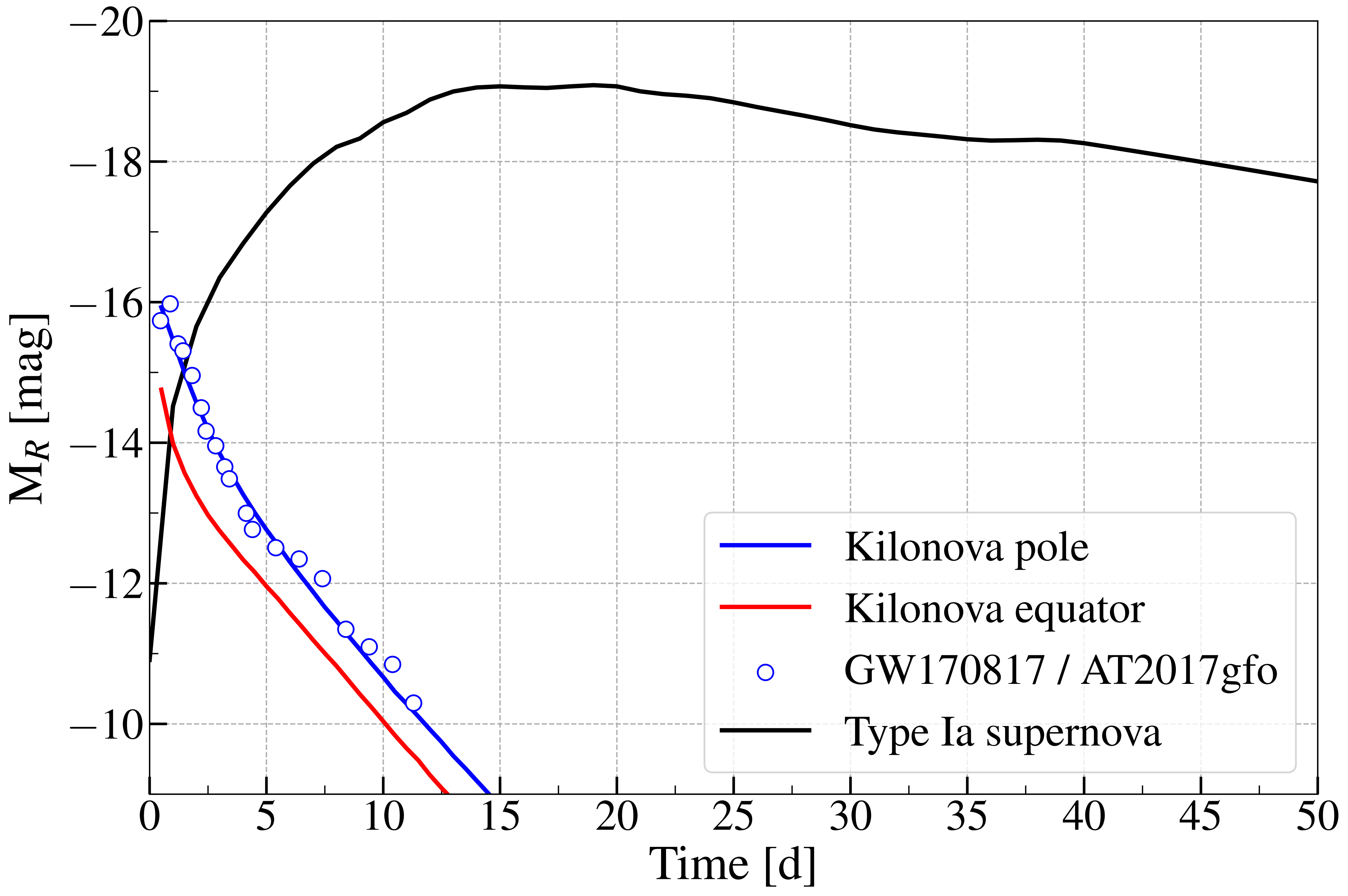
Hunting for kilonovae in O3



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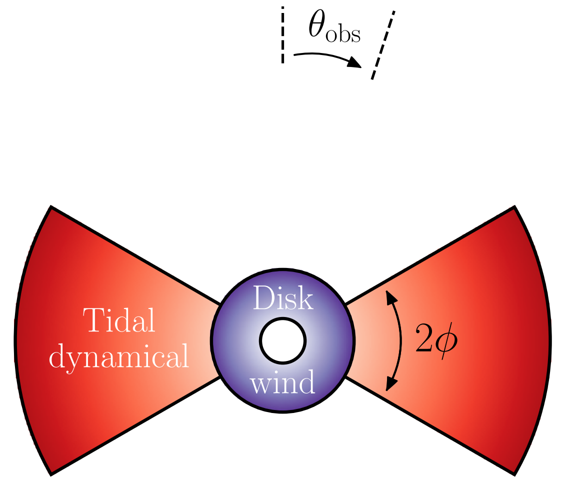
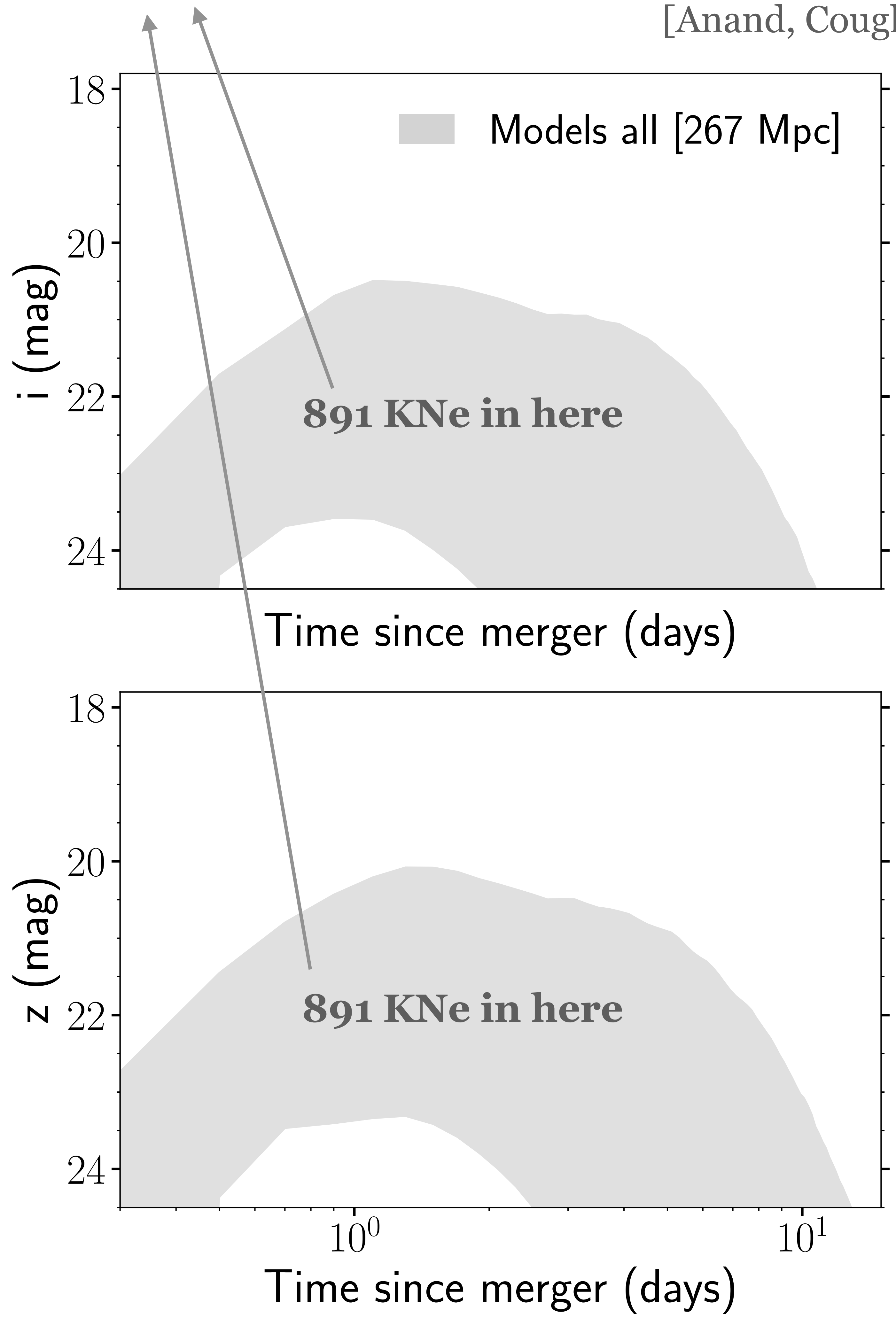
[Kasliwal..**MB**..,+2020, ApJ]

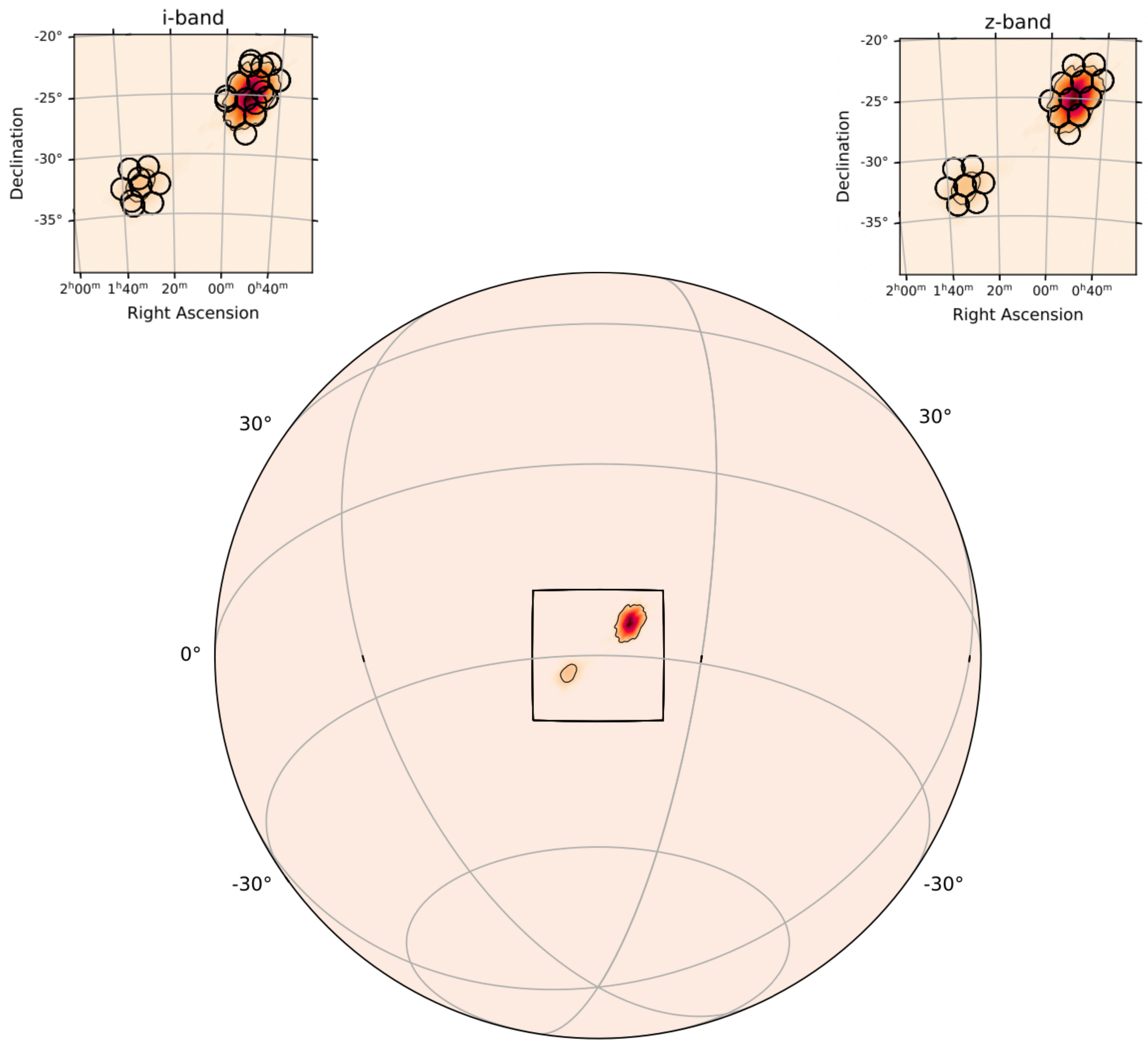


Hunting for kilonovae in O3

Constraining the parameter space of models from non-detections

[Anand, Coughlin, Kasliwal, **MB** +2020, Nature Astronomy] [Andreoni..**MB**..+2020a, ApJ]





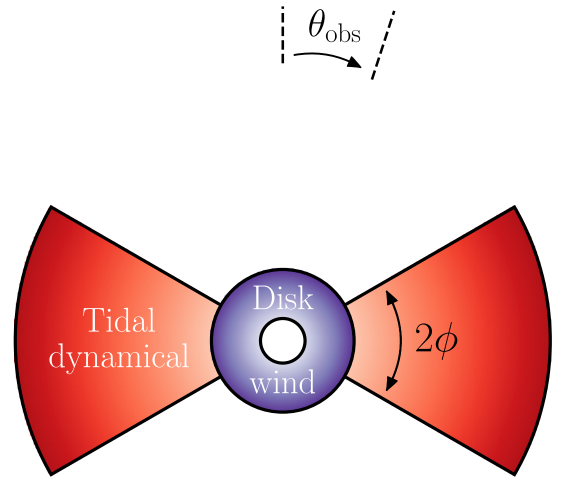
S190814bv
(now GW190814)

23 deg^2
267 Mpc

Possible NS-BH

see also [Coughlin..**MB**..+2020ab, MNRAS / Ackley..**MB**..+2020, A&A / Andreoni..**MB**..+2020b, ApJ / Kasliwal..**MB**..,+2020, ApJ / Andreoni..**MB**..,+2021, ApJ]

Hunting for kilonovae in O3



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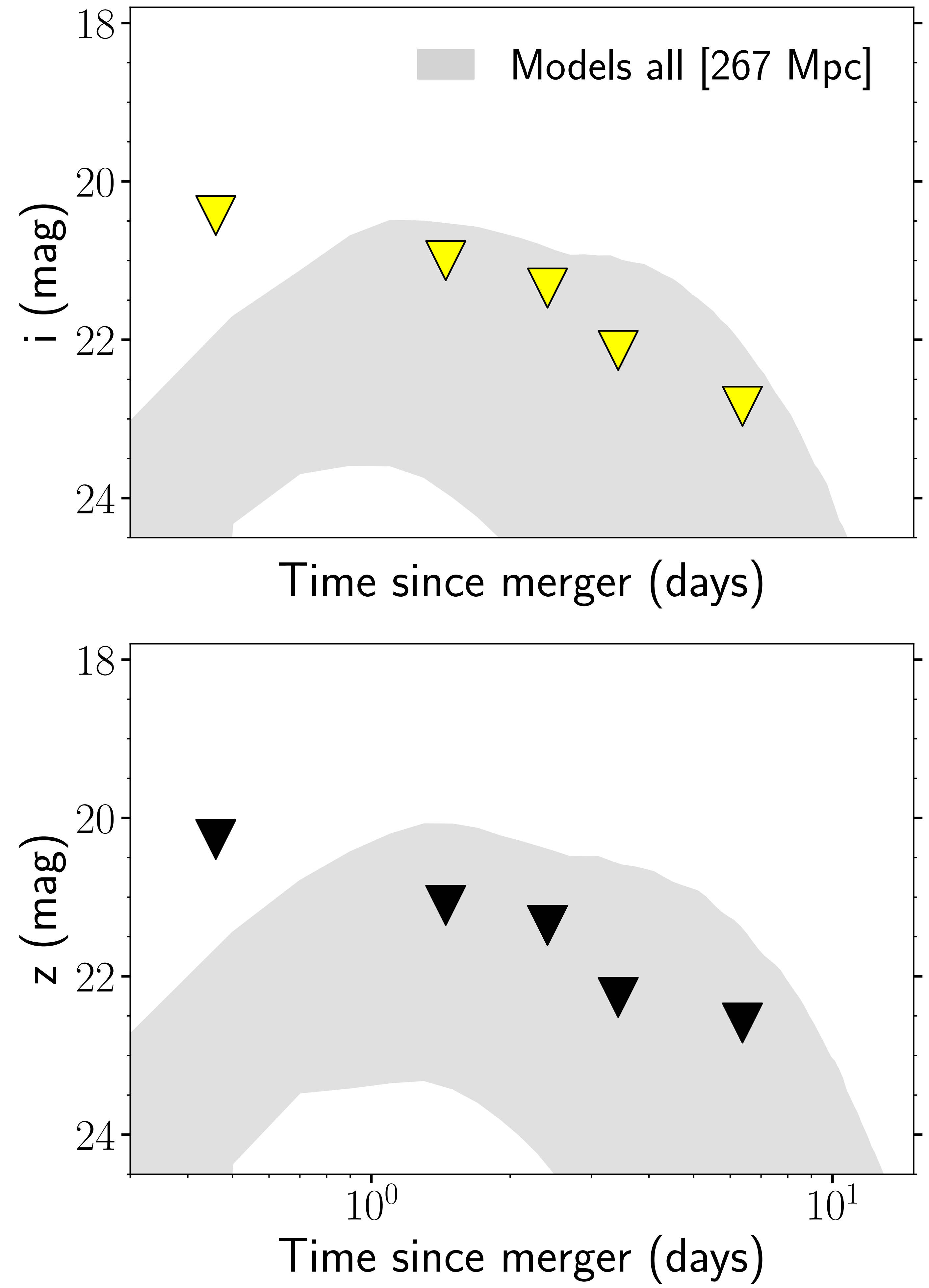
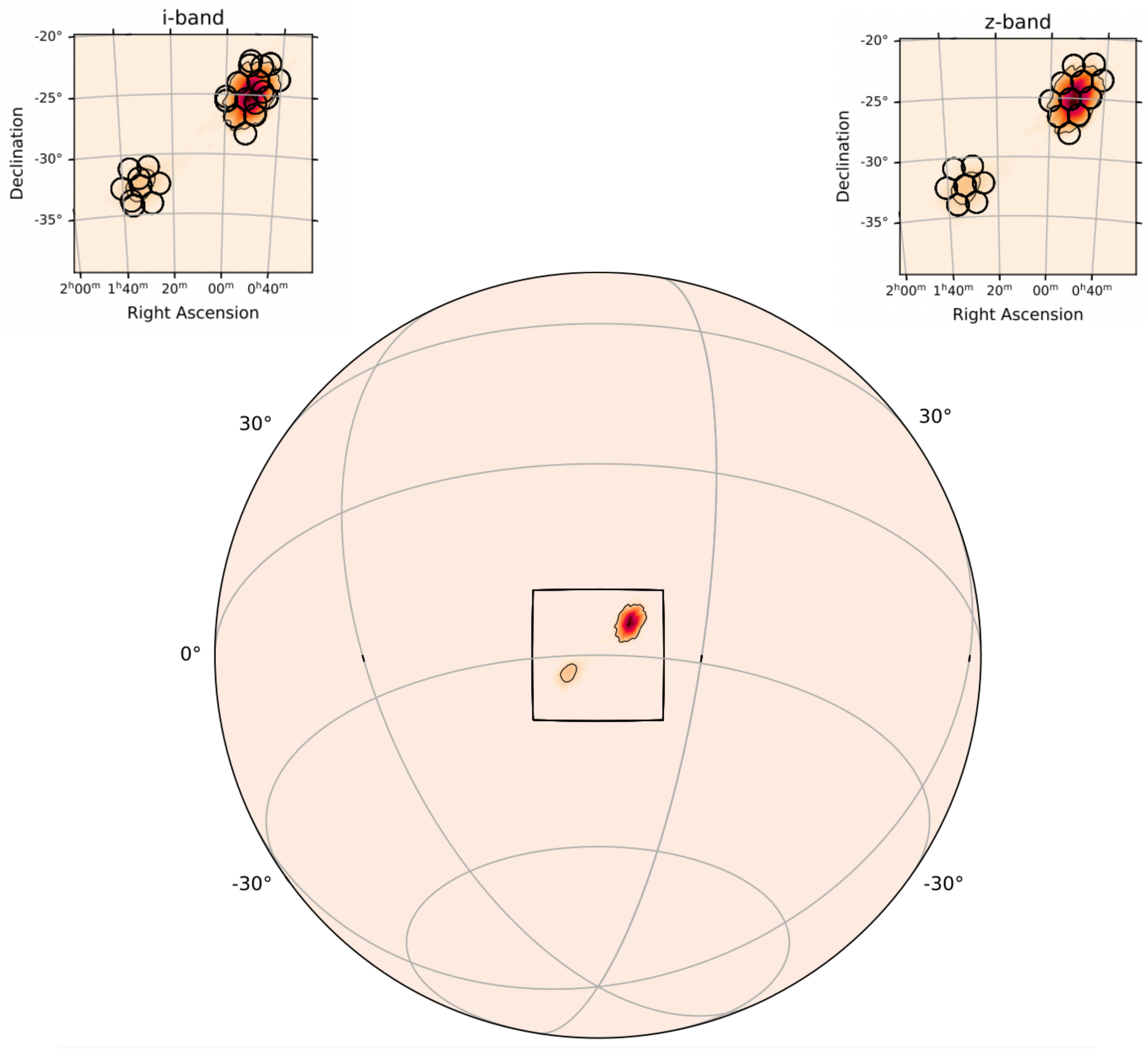


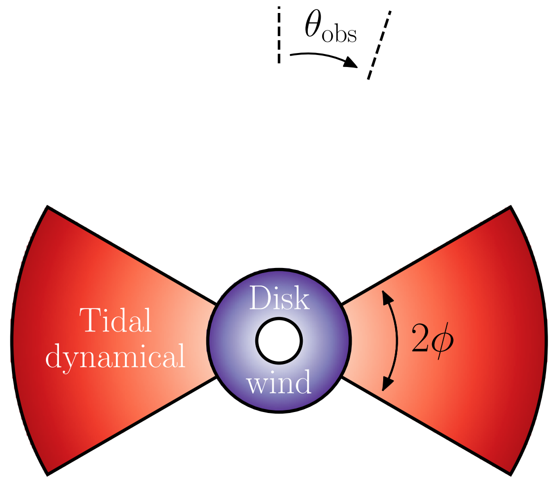


S190814bv
(now GW190814)

23 deg^2
267 Mpc

Possible NS-BH

see also [Coughlin..**MB**..+2020ab, MNRAS / Ackley..**MB**..+2020, A&A / Andreoni..**MB**..+2020b, ApJ / Kasliwal..**MB**..,+2020, ApJ / Andreoni..**MB**..,+2021, ApJ]



Hunting for kilonovae in O3

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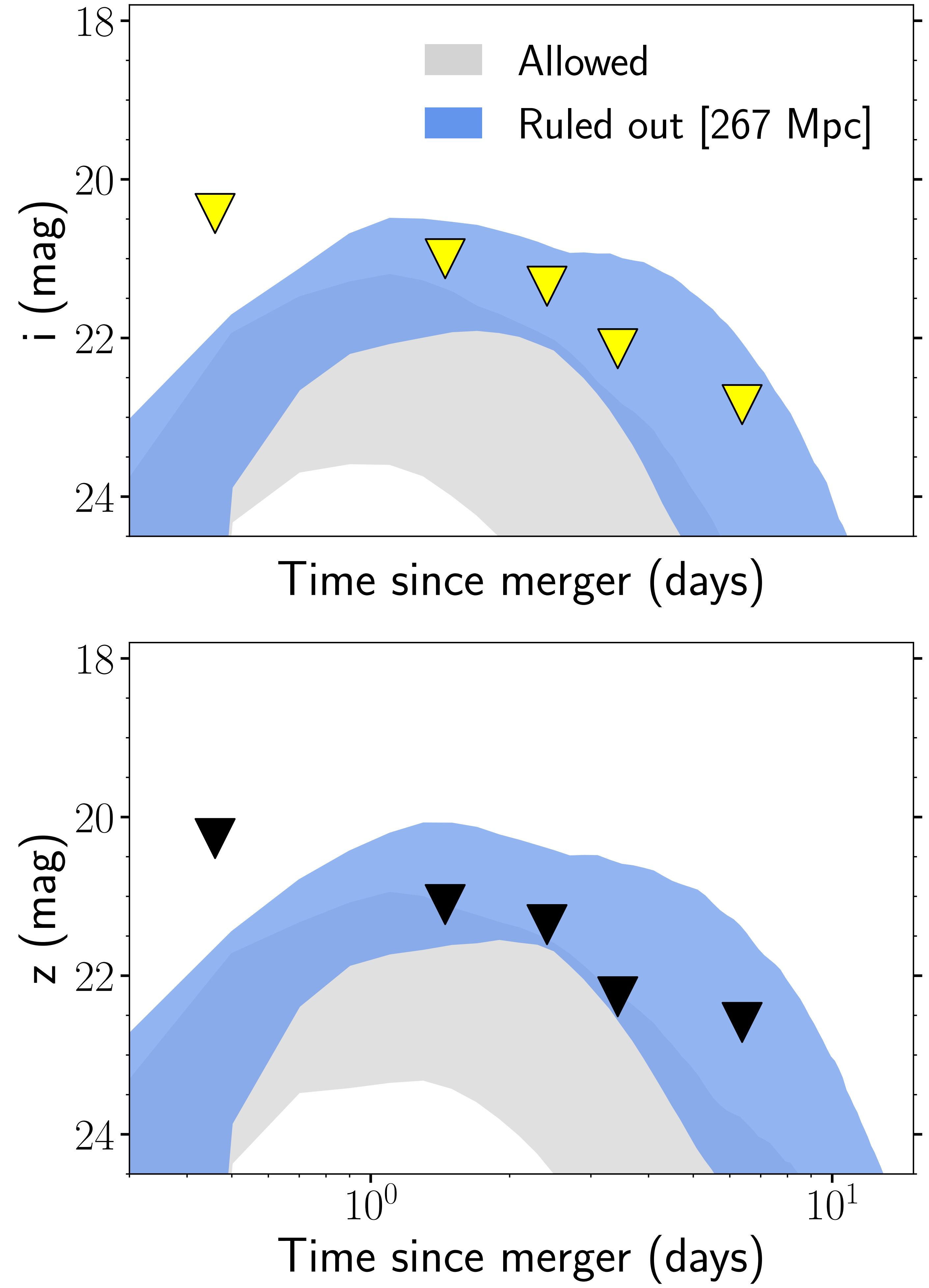
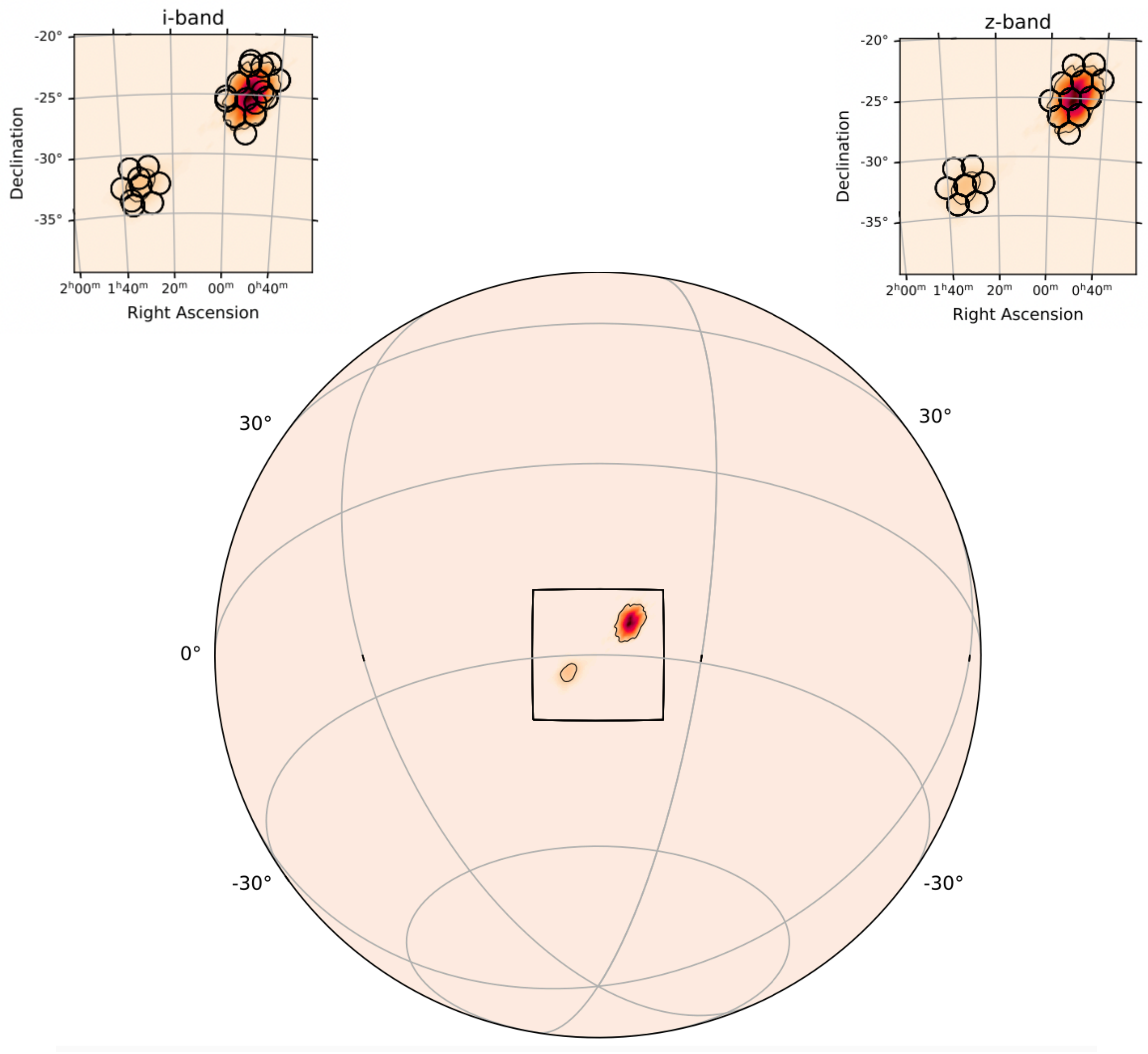
[Anand, Coughlin, Kasliwal, **MB** +2020, Nature Astronomy] [Andreoni..**MB**..+2020a, ApJ]





S190814bv
(now GW190814)

23 deg^2
267 Mpc

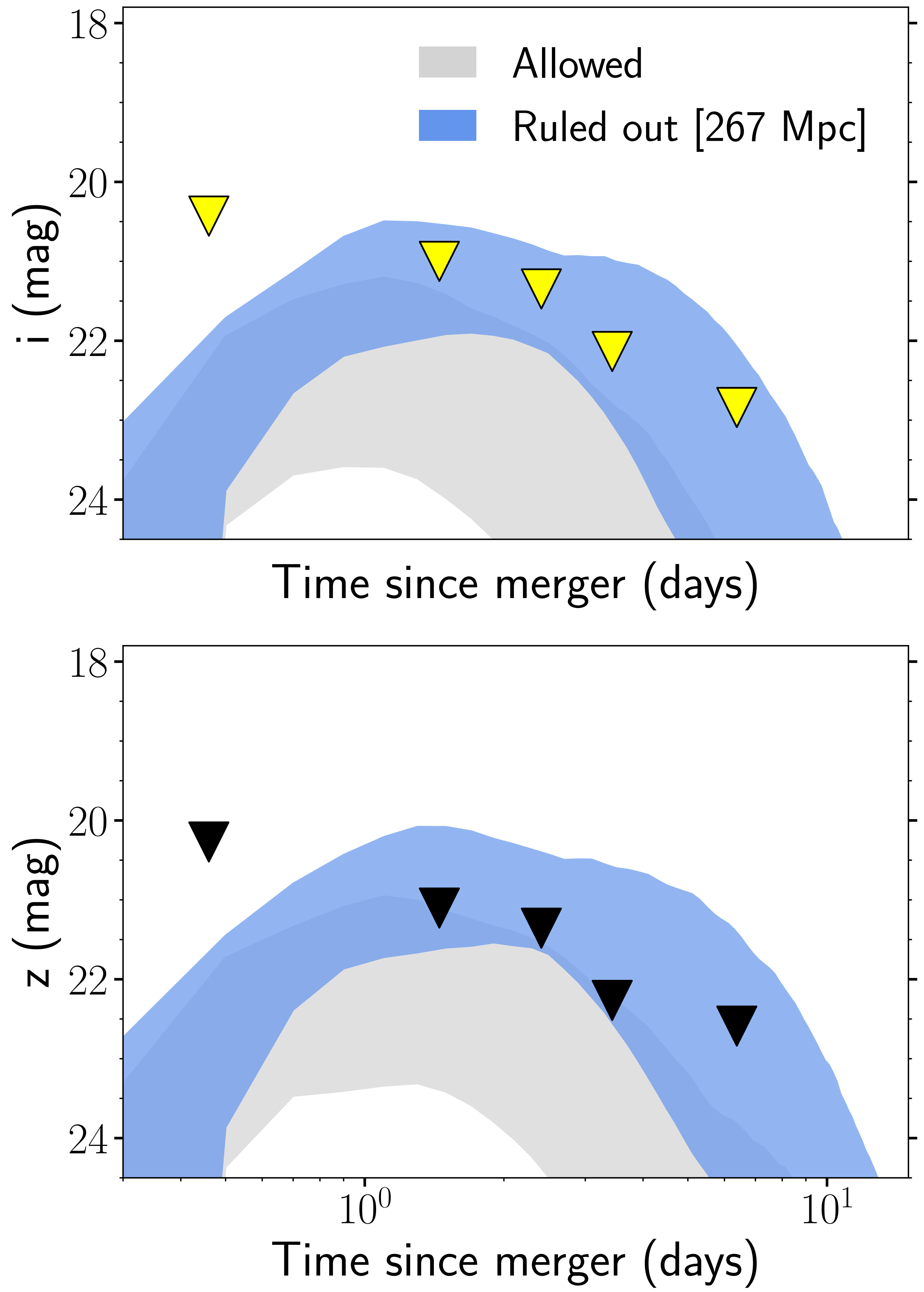
Possible NS-BH

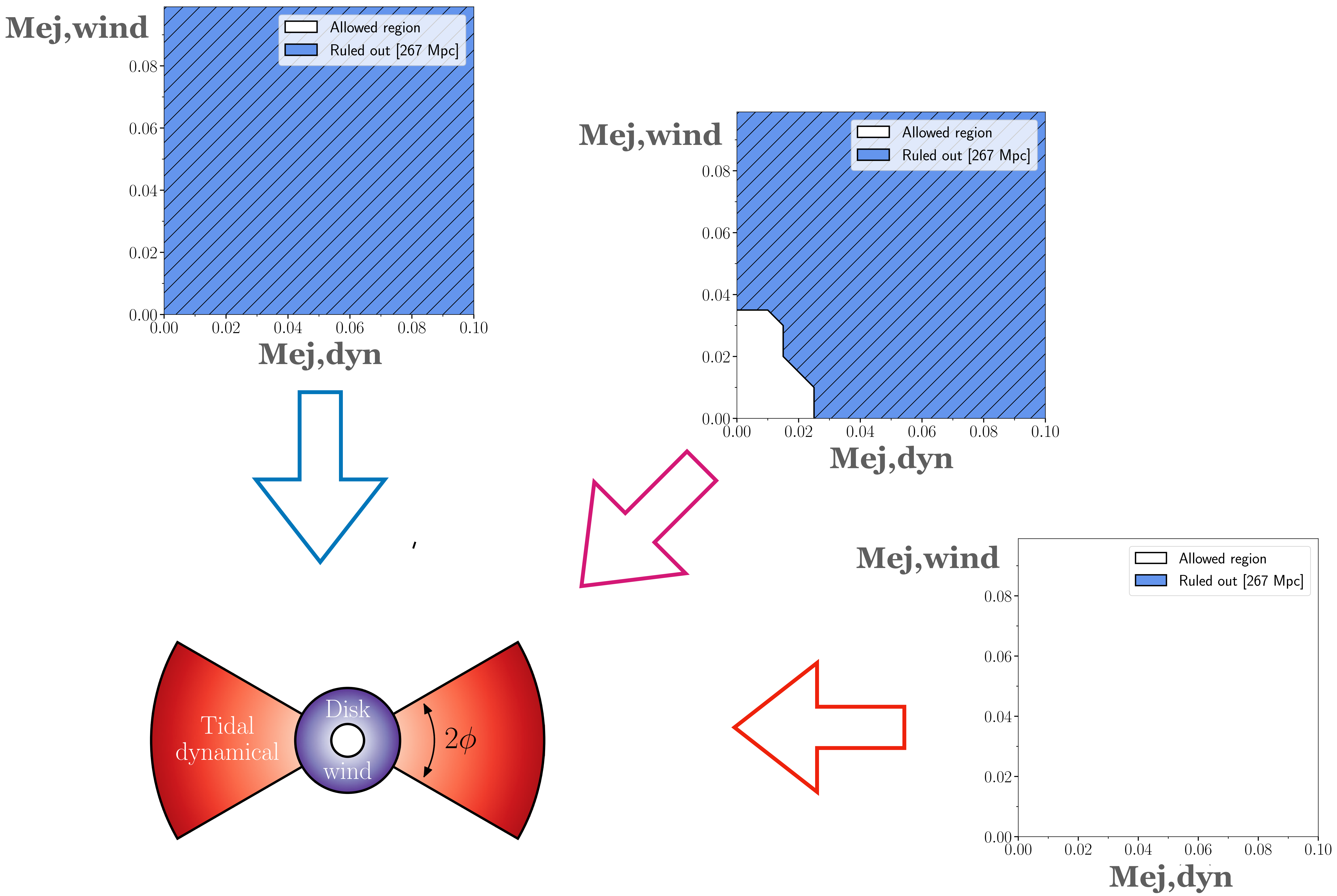
see also [Coughlin..**MB**..+2020ab, MNRAS / Ackley..**MB**..+2020, A&A / Andreoni..**MB**..+2020b, ApJ / Kasliwal..**MB**..,+2020, ApJ / Andreoni..**MB**..,+2021, ApJ]

Hunting for kilonovae in O3

Constraining the parameter space of models from non-detections

[Anand, Coughlin, Kasliwal, **MB** +2020, Nature Astronomy] [Andreoni..**MB**..+2020a, ApJ]





see also [Coughlin..**MB**..+2020ab, MNRAS / Ackley..**MB**..+2020, A&A / Andreoni..**MB**..+2020b, ApJ / Kasliwal..**MB**..,+2020, ApJ / Andreoni..**MB**..,+2021, ApJ]

Hunting for kilonovae in O3

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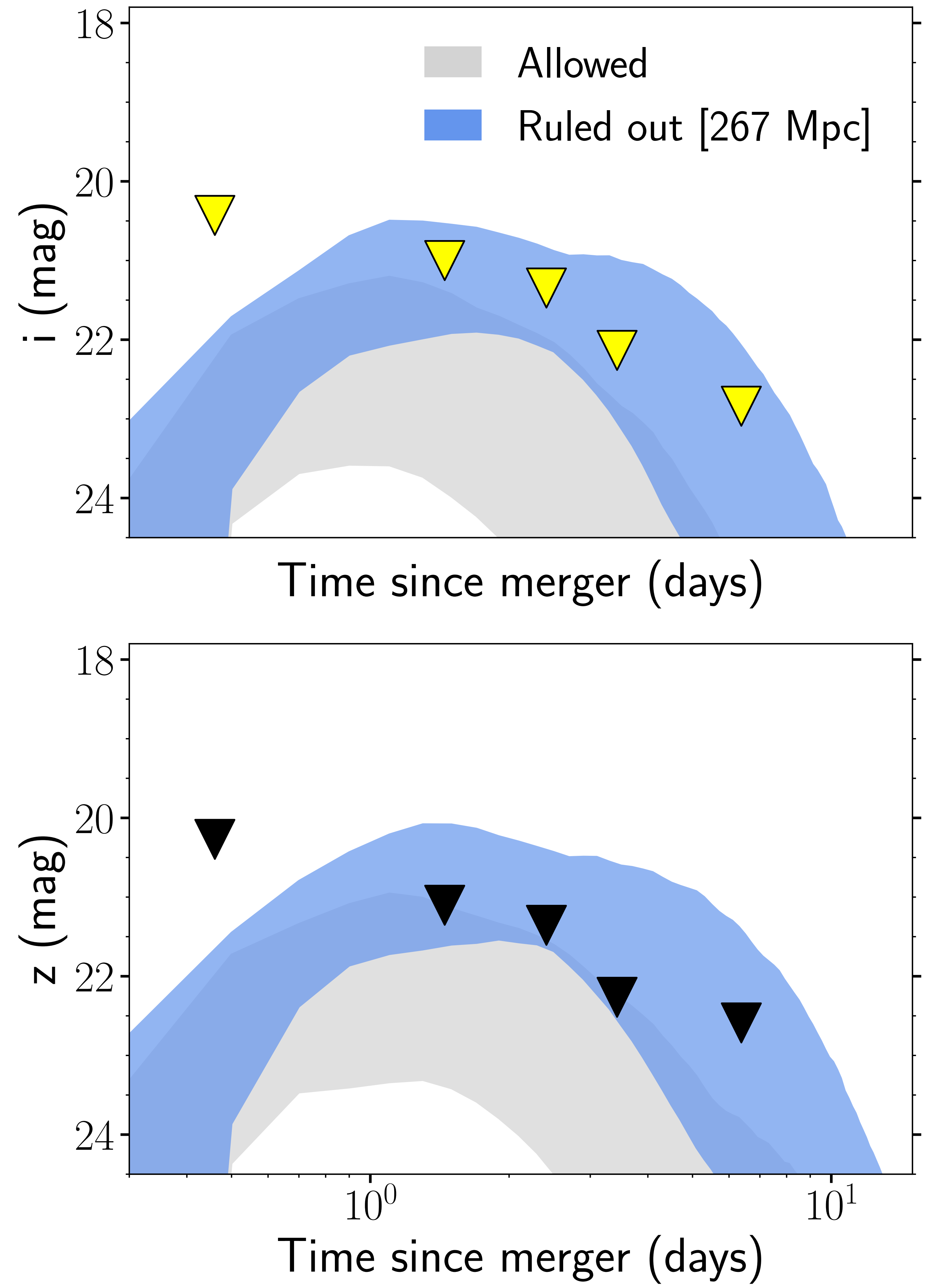
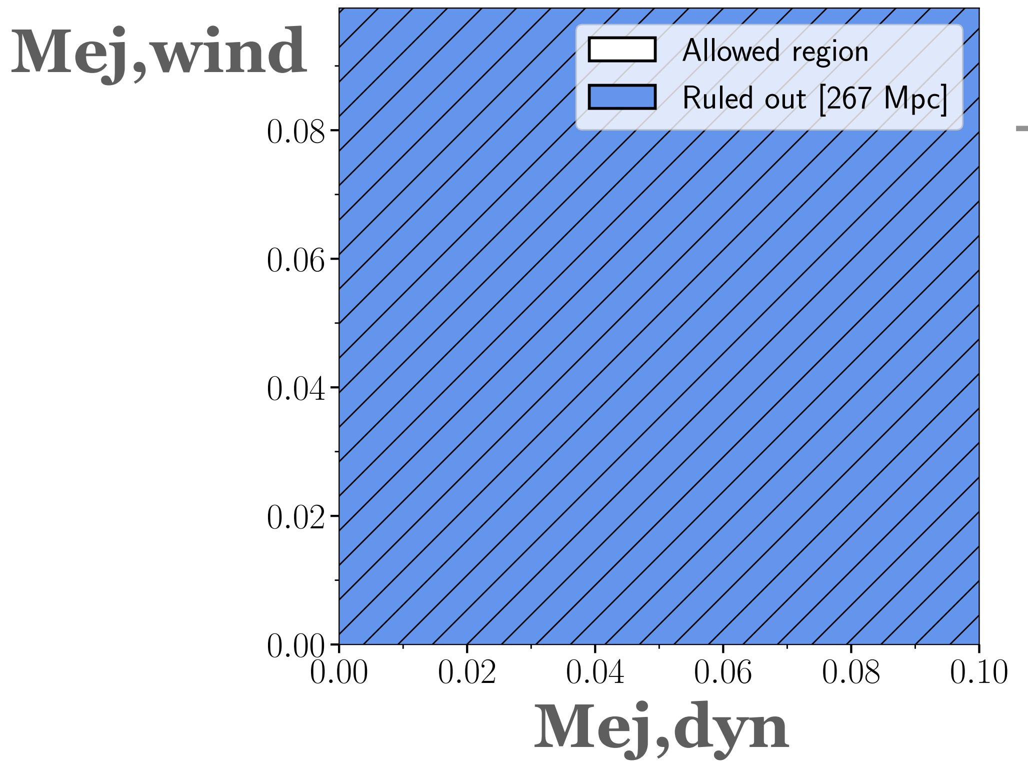
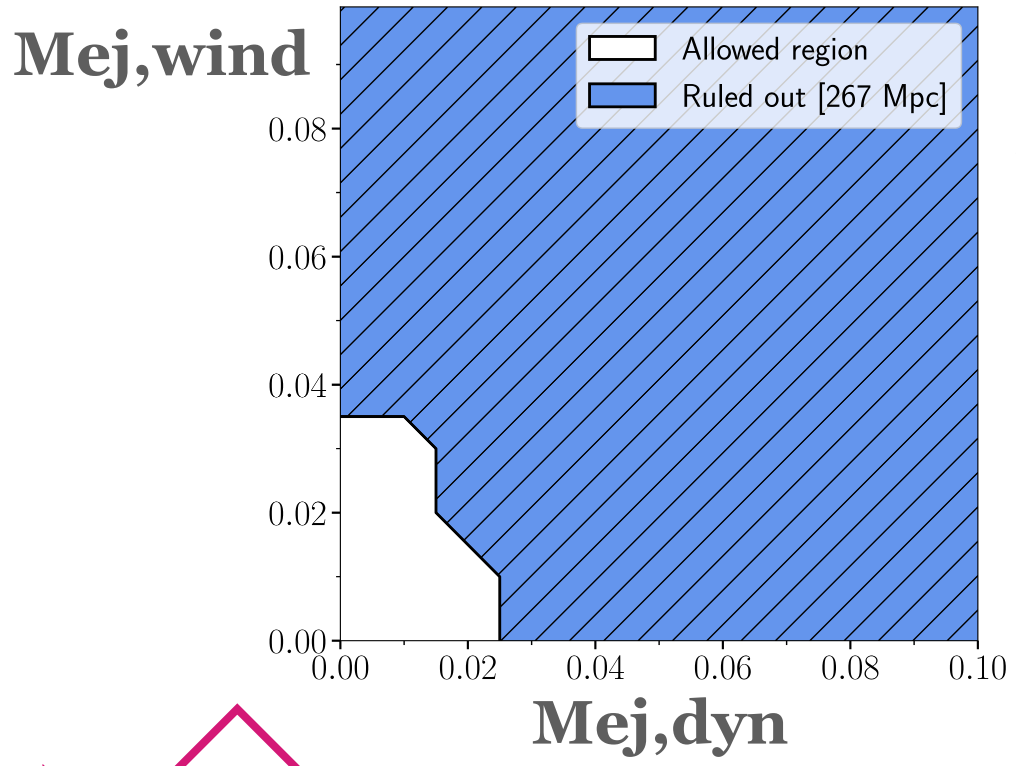
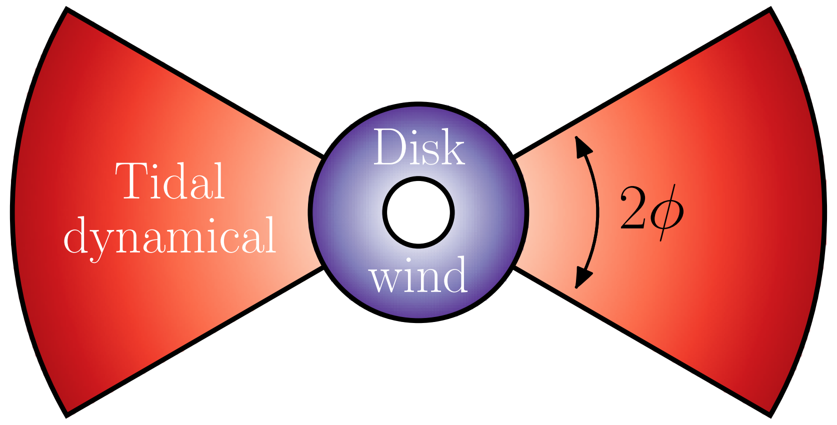
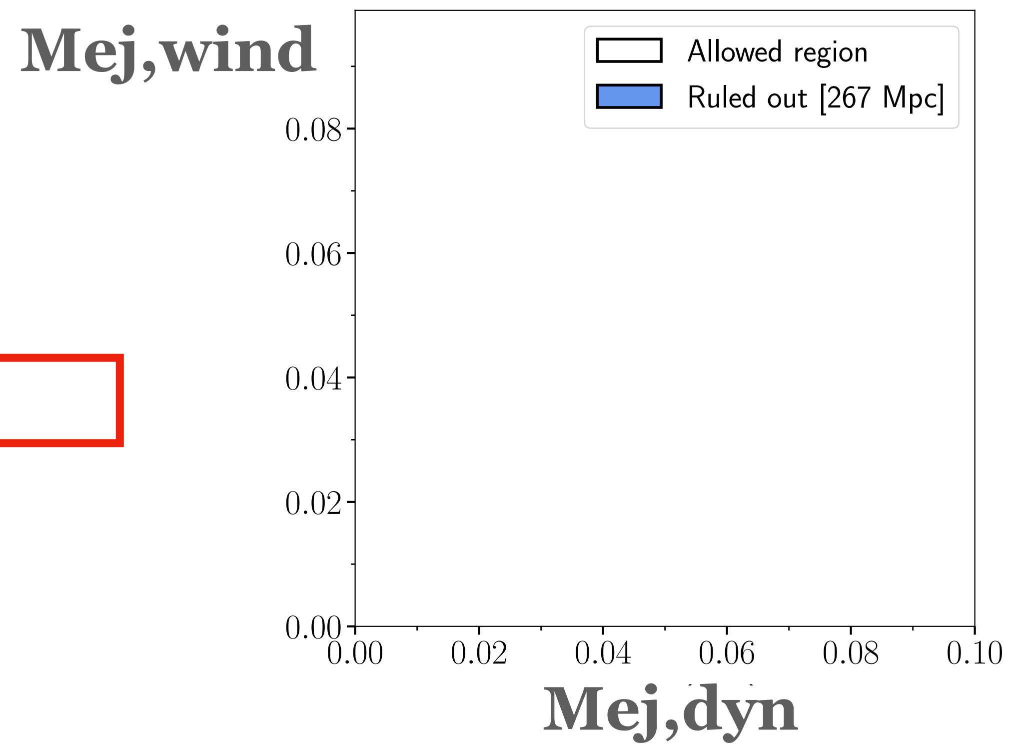






Rule out systems with low mass ratio, high BH spin or large NS radii

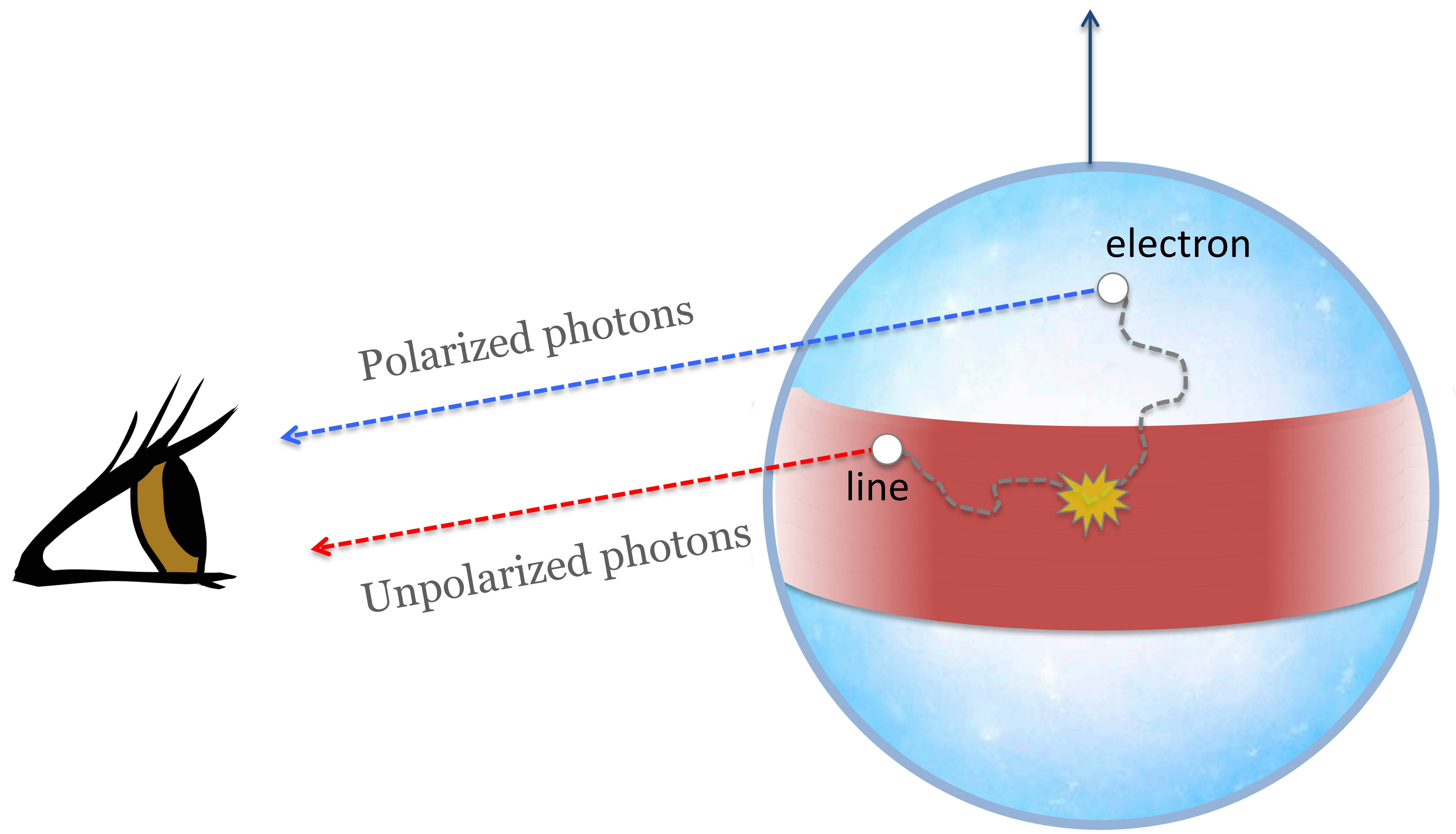




see also [Coughlin..**MB**..+2020ab, MNRAS / Ackley..**MB**..+2020, A&A / Andreoni..**MB**..+2020b, ApJ / Kasliwal..**MB**..,+2020, ApJ / Andreoni..**MB**..,+2021, ApJ]

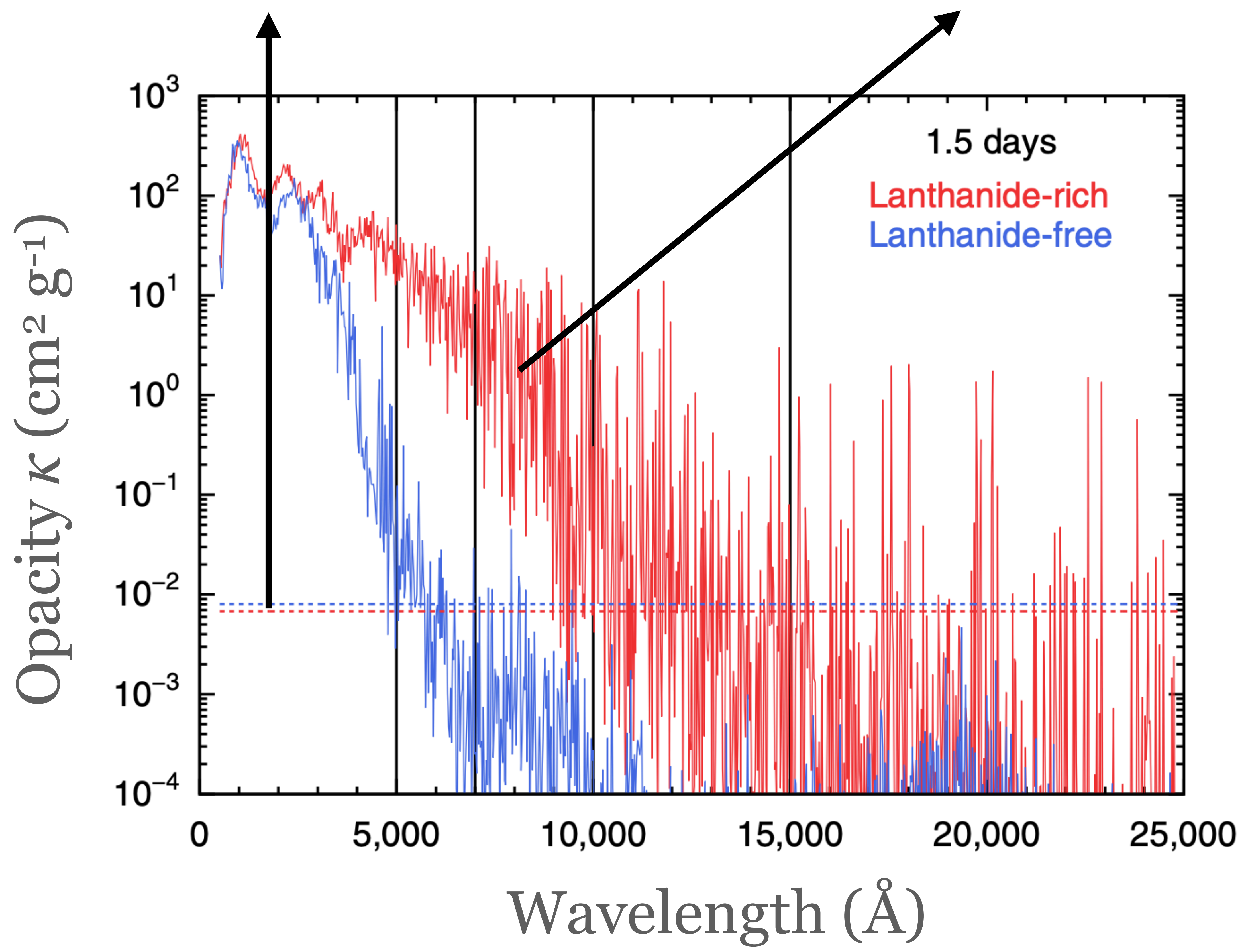
Polarization signal

Constraining the viewing angle and the presence of a lanthanide-free component



Electron scattering << Line absorption

Polarizing Depolarizing



[Tanaka+2018, ApJ]

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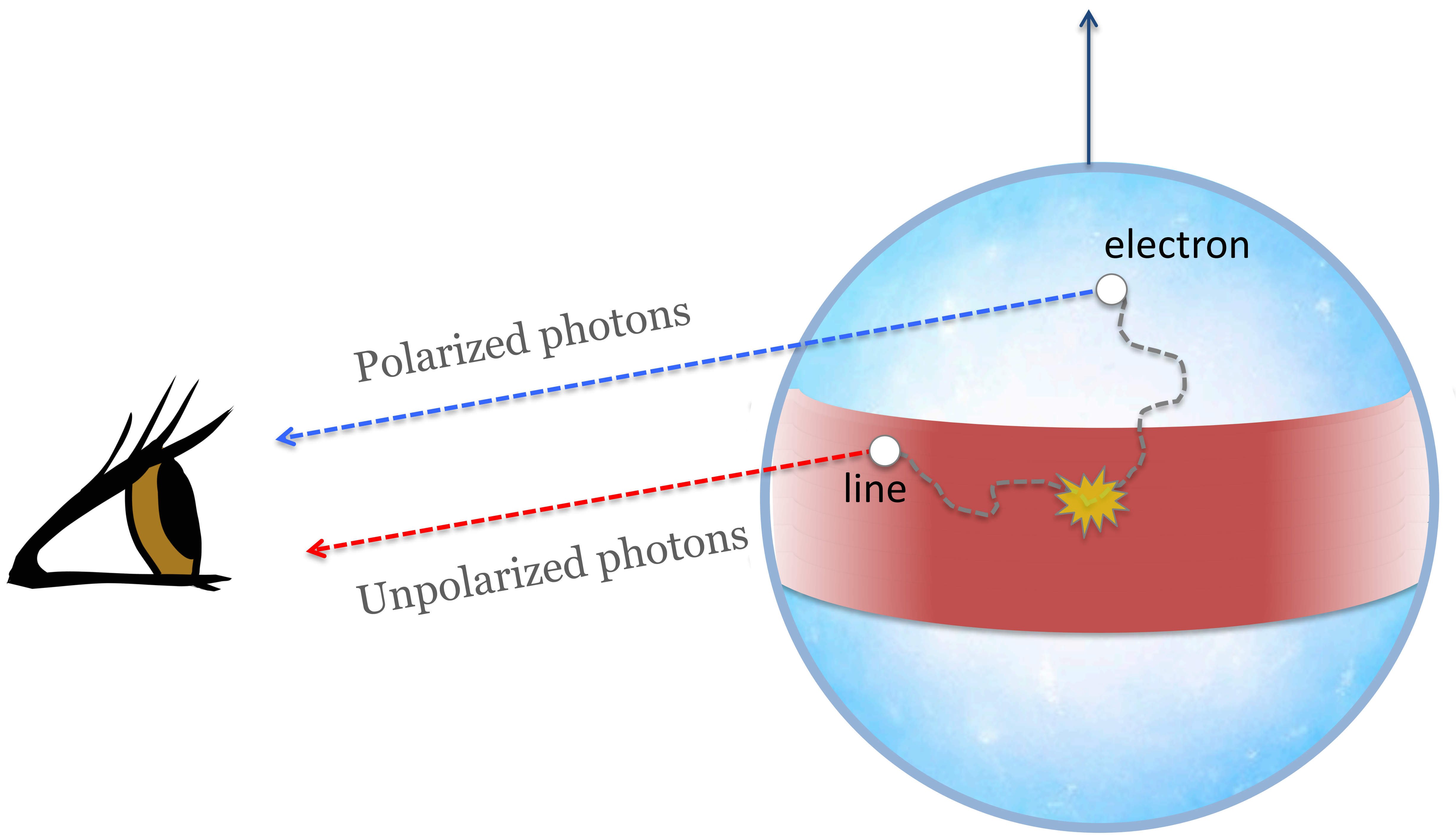
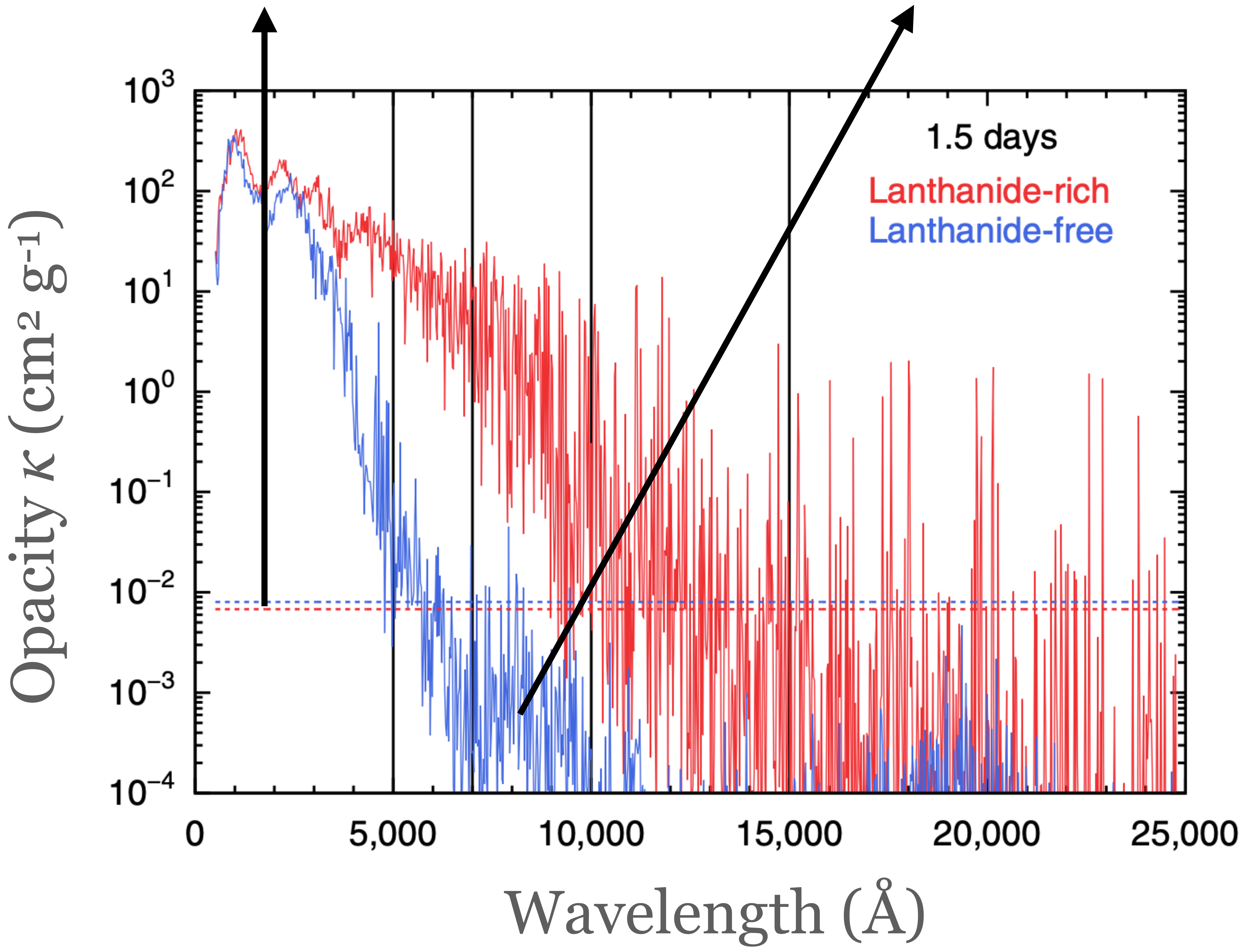
Constraining the viewing angle and the presence of a lanthanide-free component



Electron scattering $\gtrsim$ Line absorption

Polarizing   Depolarizing



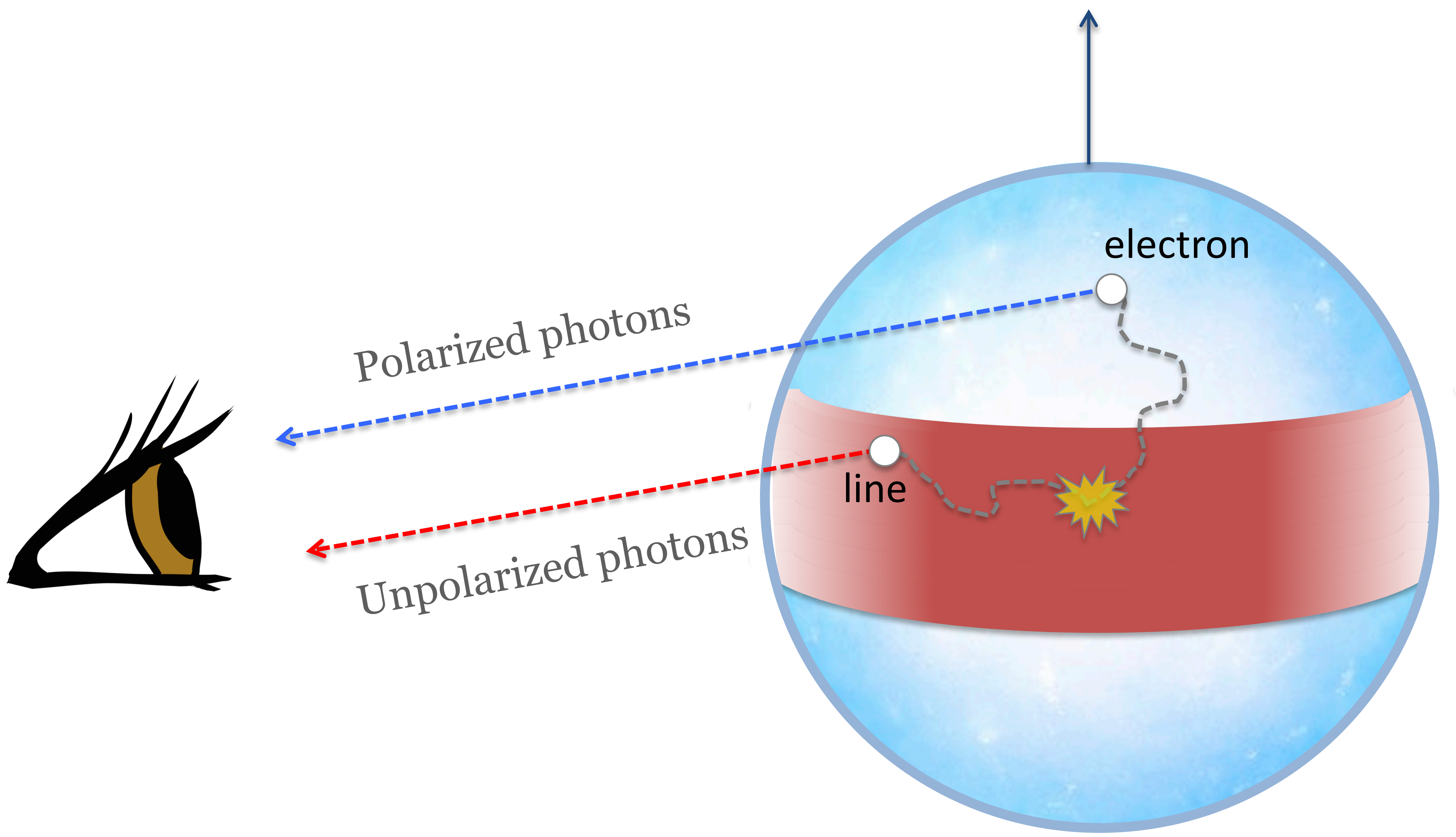
[Tanaka+2018, ApJ]

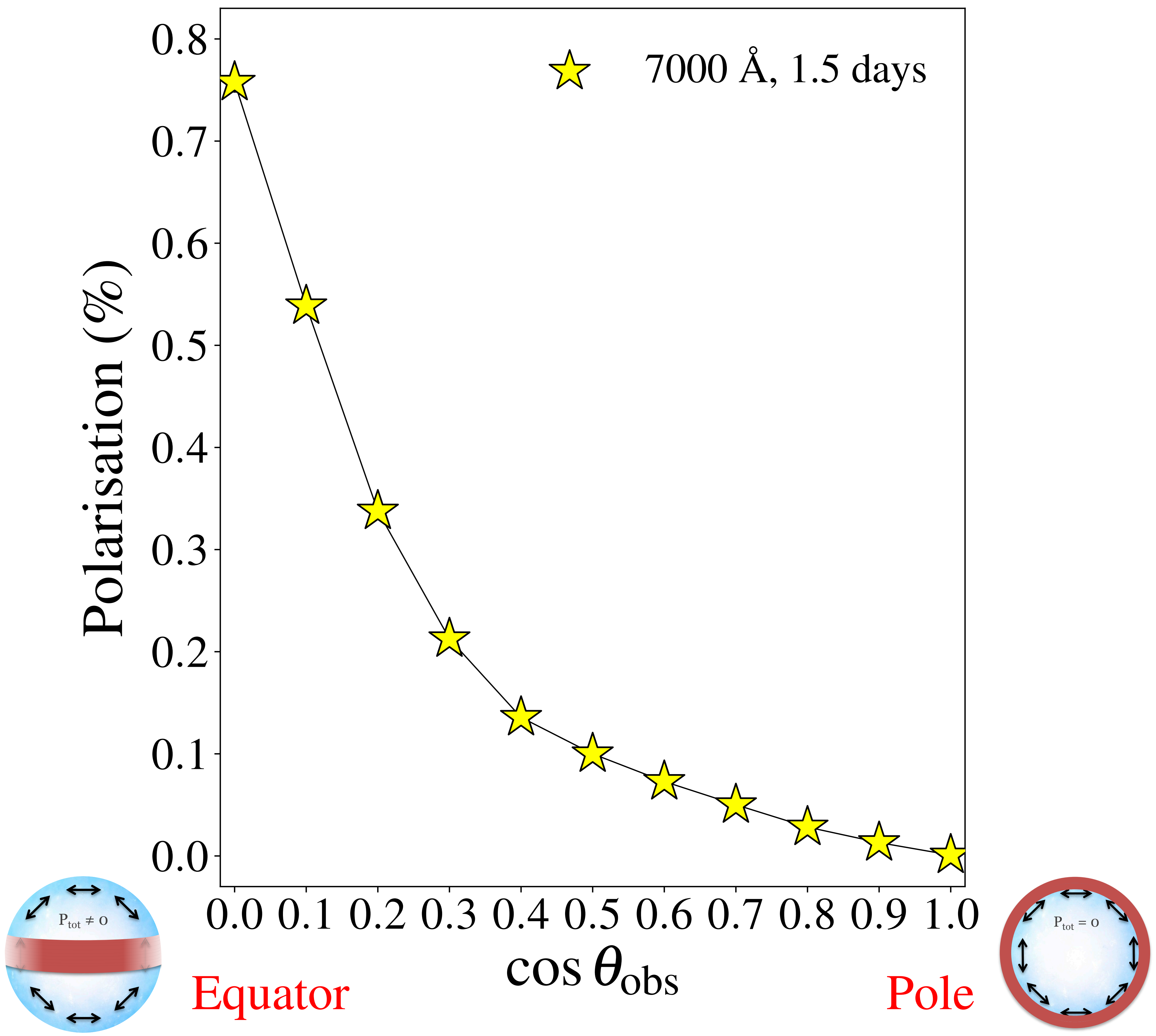
Polarization signal

Constraining the viewing angle and the presence of a lanthanide-free component

NS+NS

[**MB**+2019, Nature Astronomy]



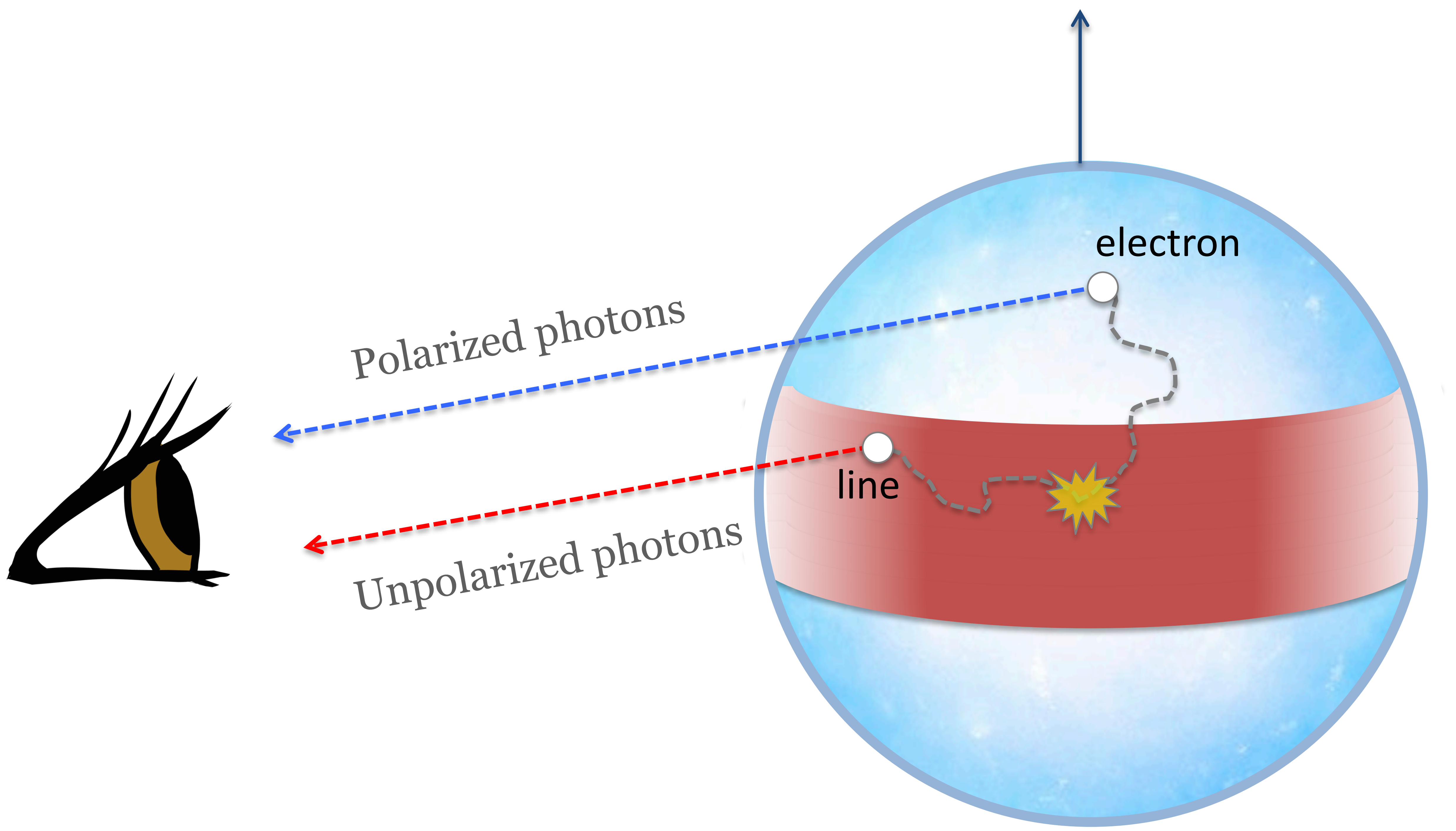


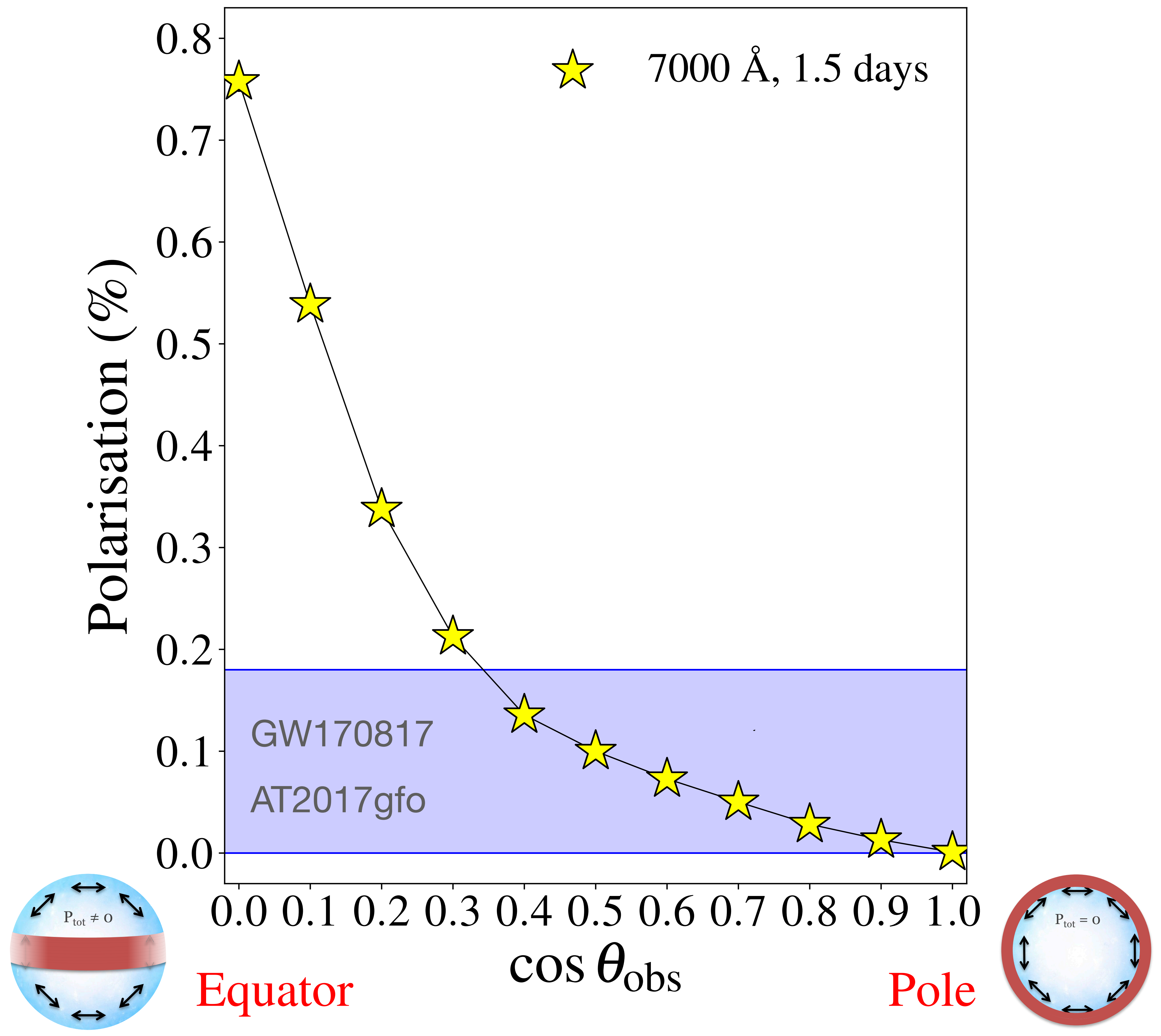
Polarization signal

Constraining the viewing angle and the presence of a lanthanide-free component

NS+NS

[**MB**+2019, Nature Astronomy]



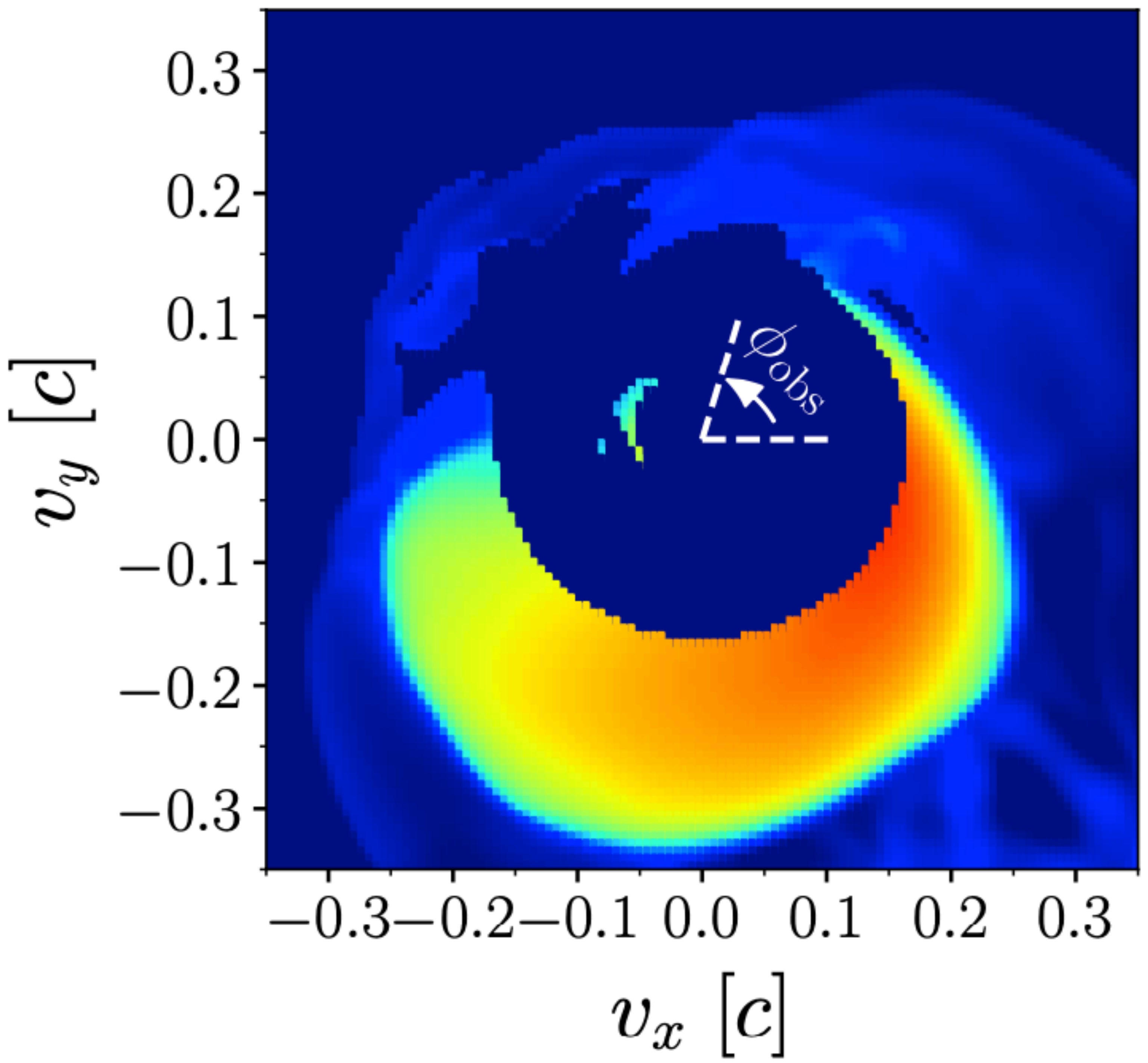


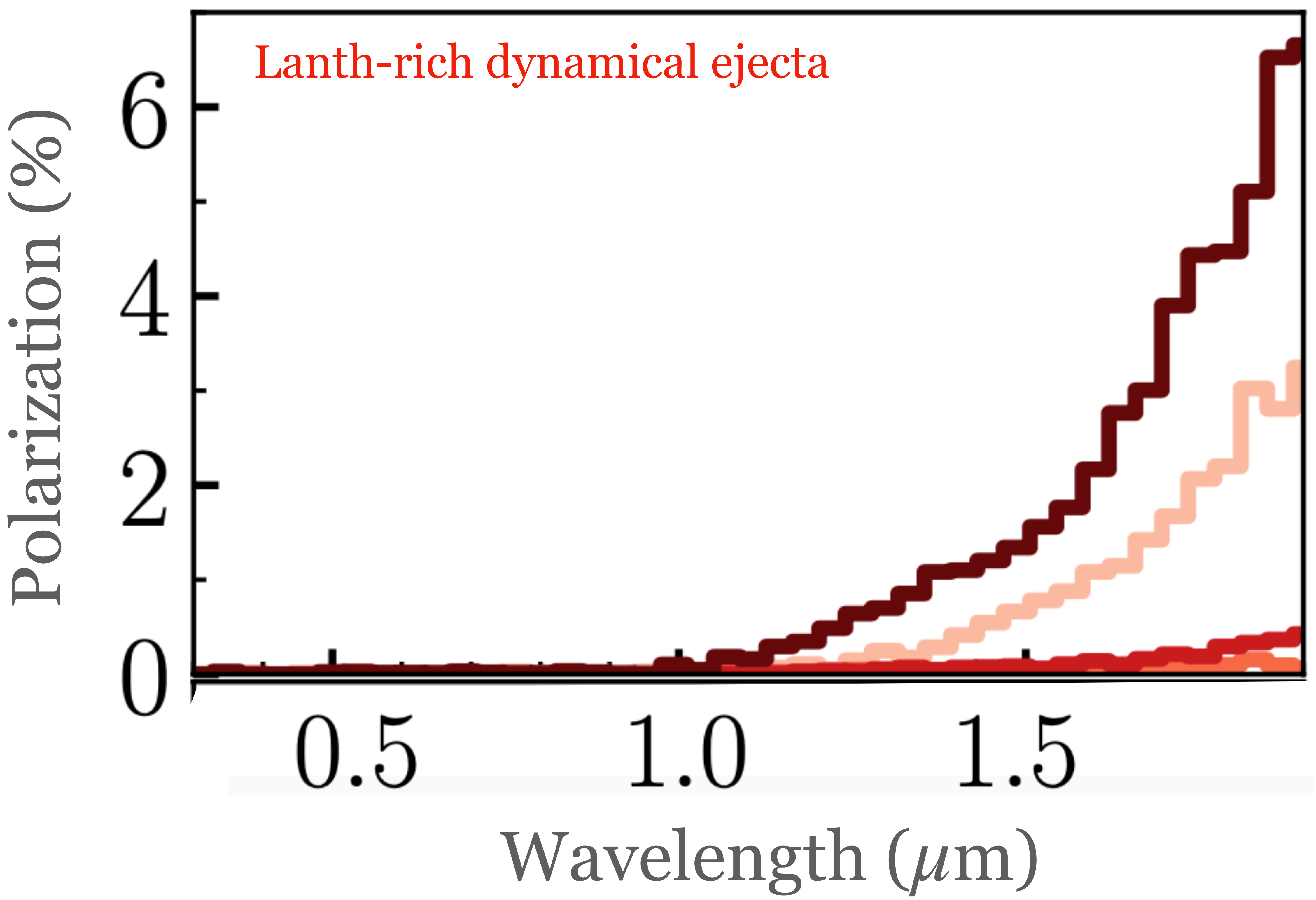
Polarization signal

Constraining the presence of a lanthanide-free component

BH+NS

[**MB**+2021, MNRAS]





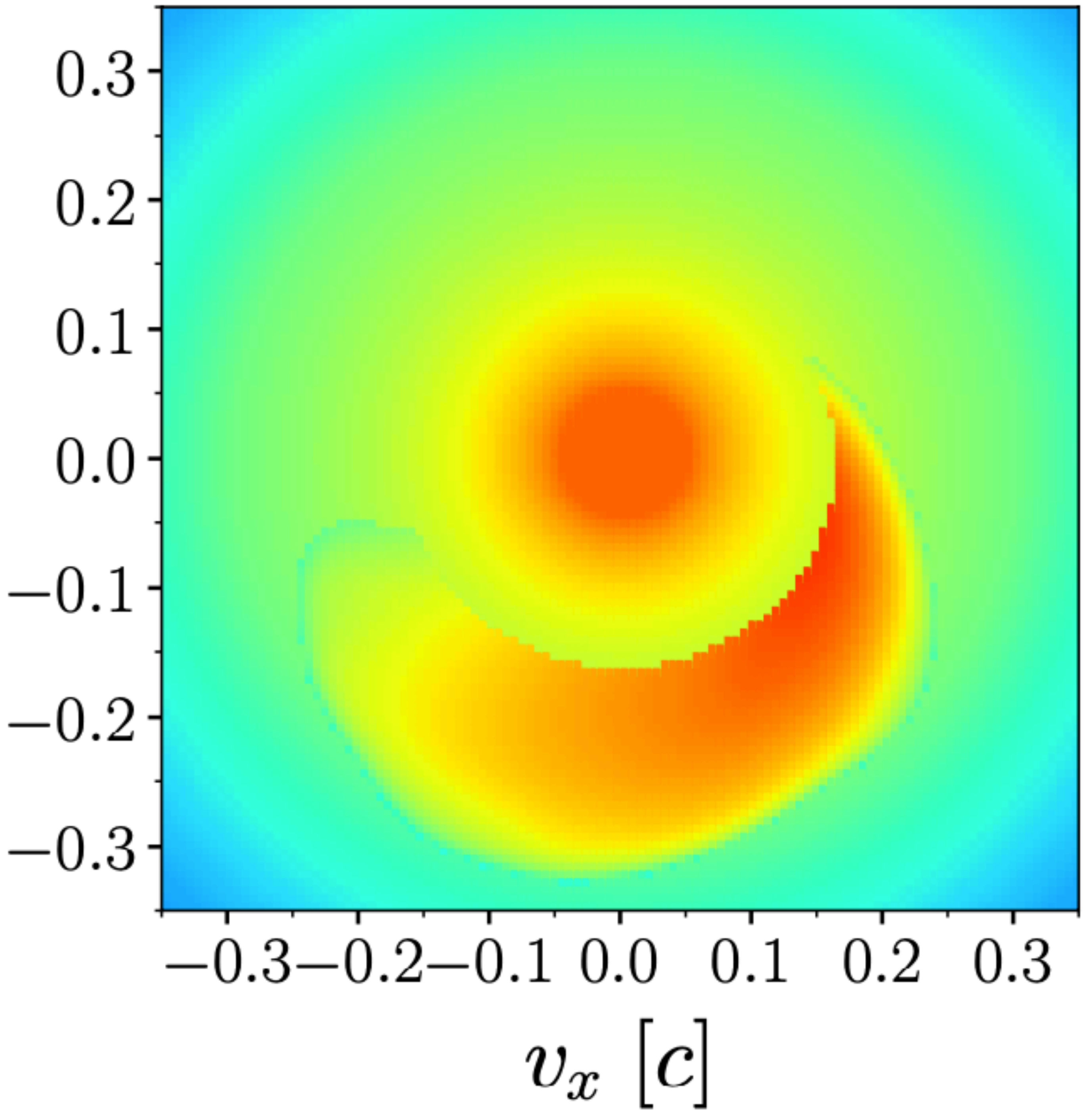
Model for dynamical ejecta from [Kyutoku+2015, PRD]

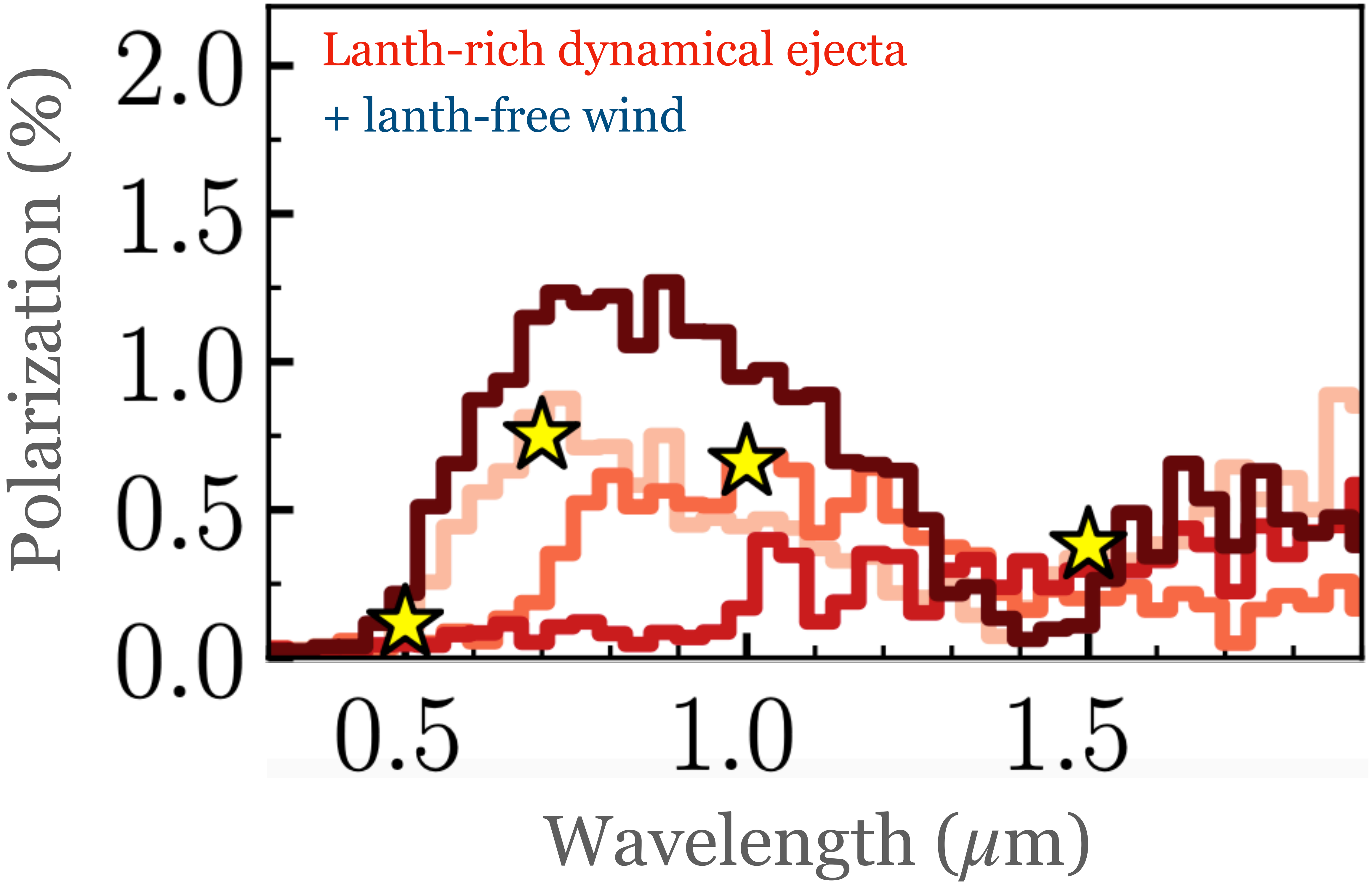
Polarization signal

Constraining the presence of a lanthanide-free component

BH+NS

[**MB**+2021, MNRAS]



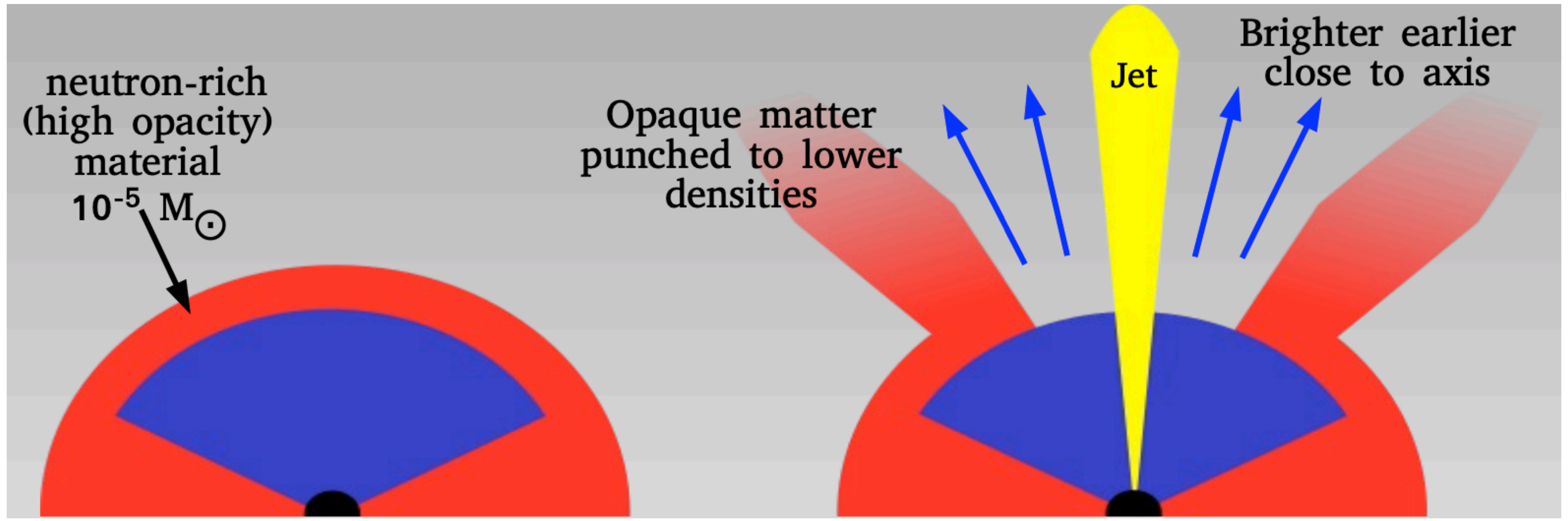


Model for dynamical ejecta from [Kyutoku+2015, PRD]

Jet-ejecta interaction

Making kilonovae brighter and bluer

[Nativi, **MB**, Lundman, Rosswog+2021, MNRAS]

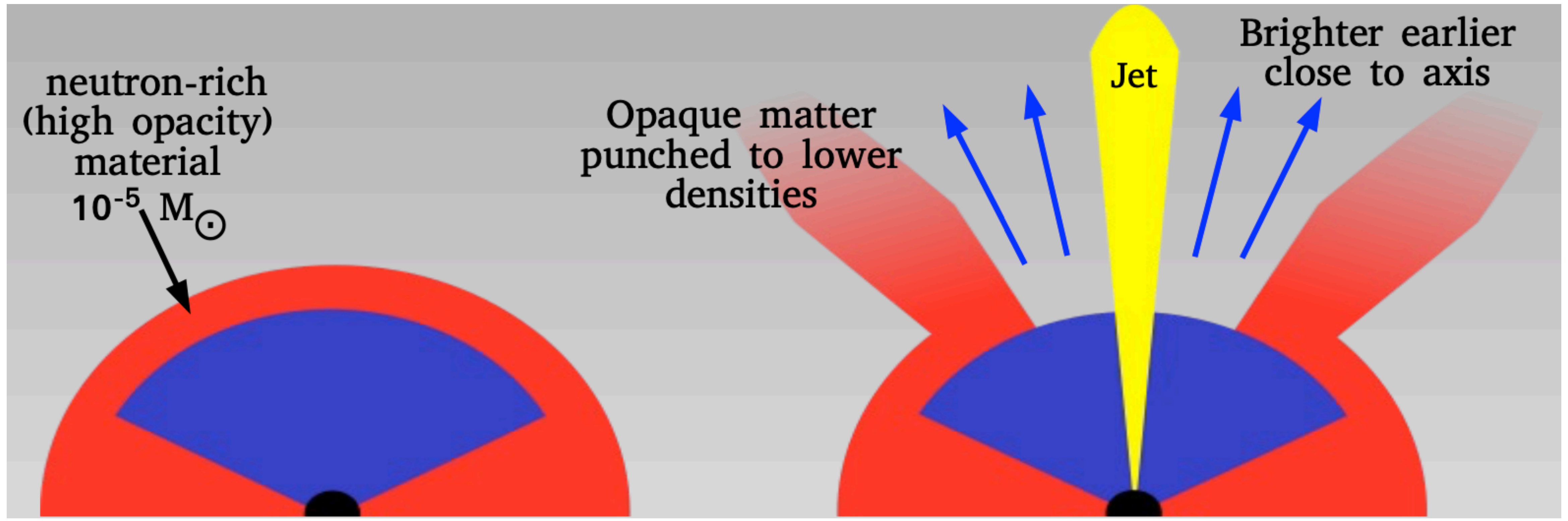


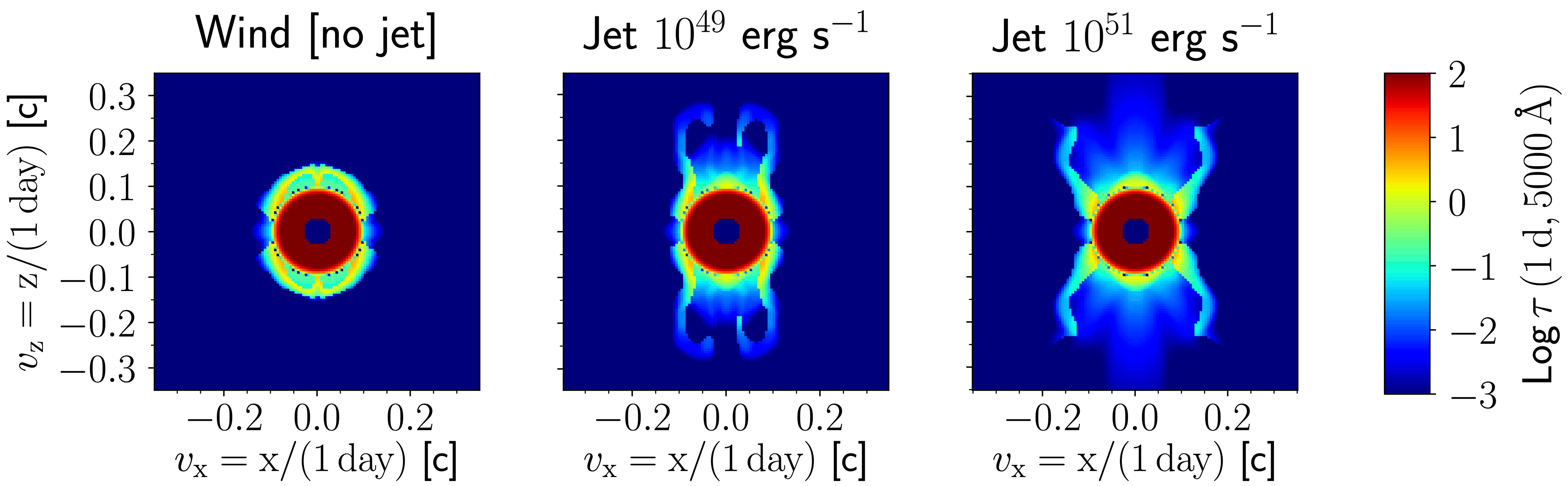
see also [Klion, Duffert, Kasen & Quataert 2021, MNRAS]

Jet-ejecta interaction

Making kilonovae brighter and bluer

[Nativi, **MB**, Lundman, Rosswog+2021, MNRAS]





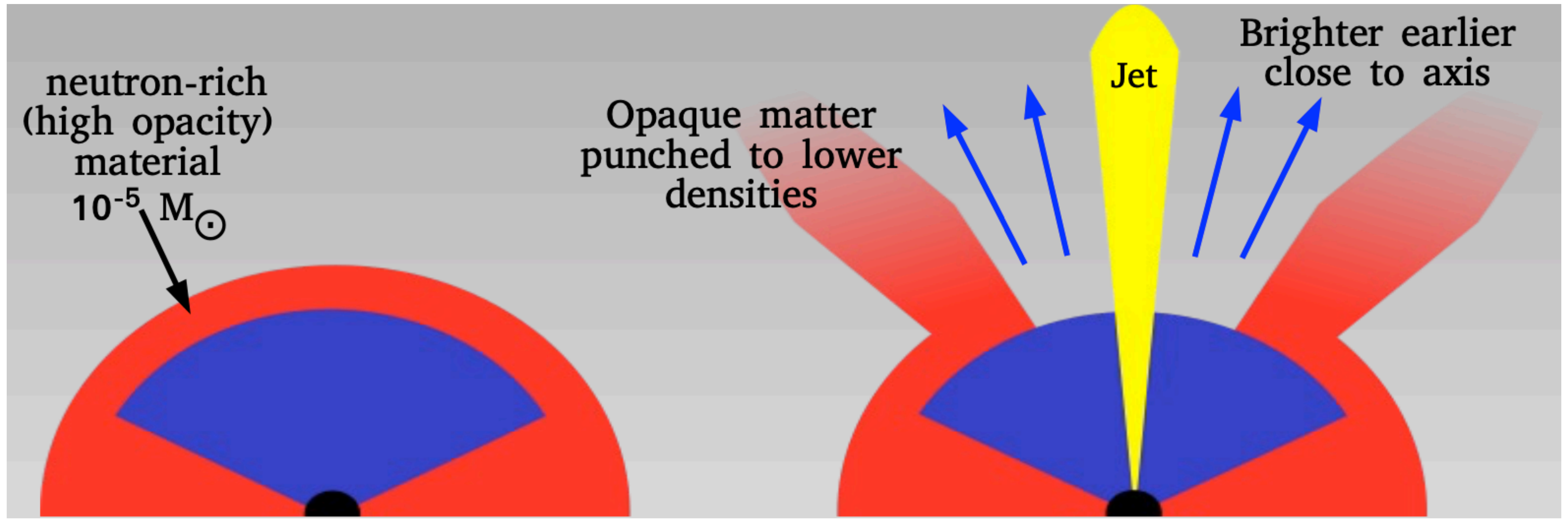
Wind models from [Perego+2014, MNRAS]

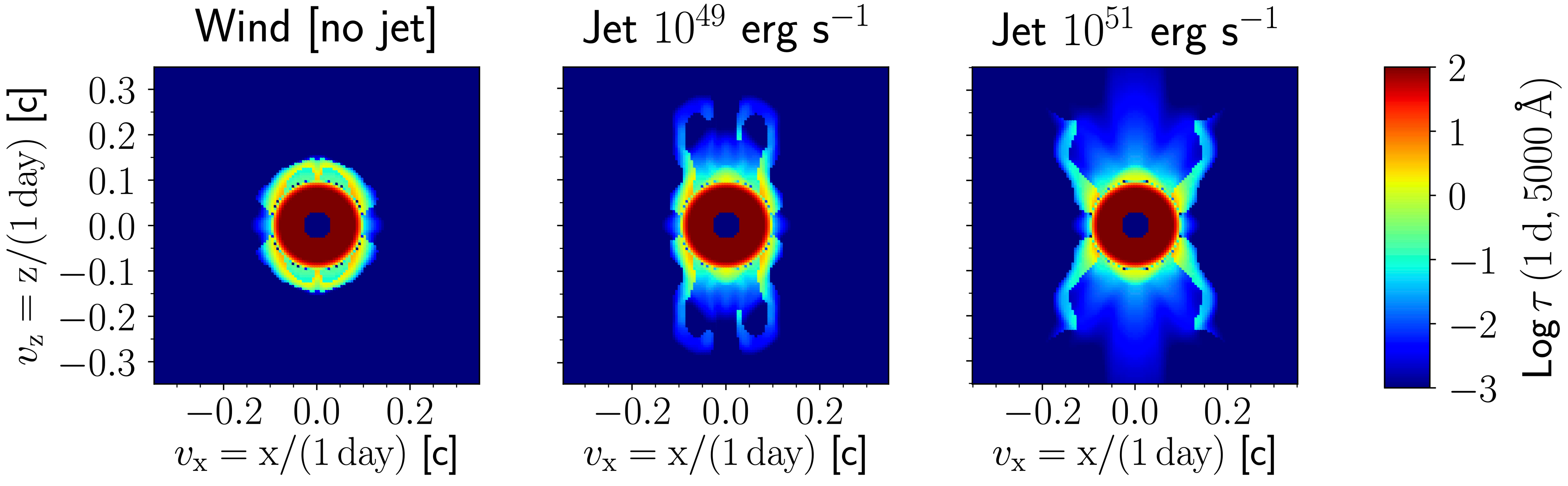
see also [Klion, Duffert, Kasen & Quataert 2021, MNRAS]

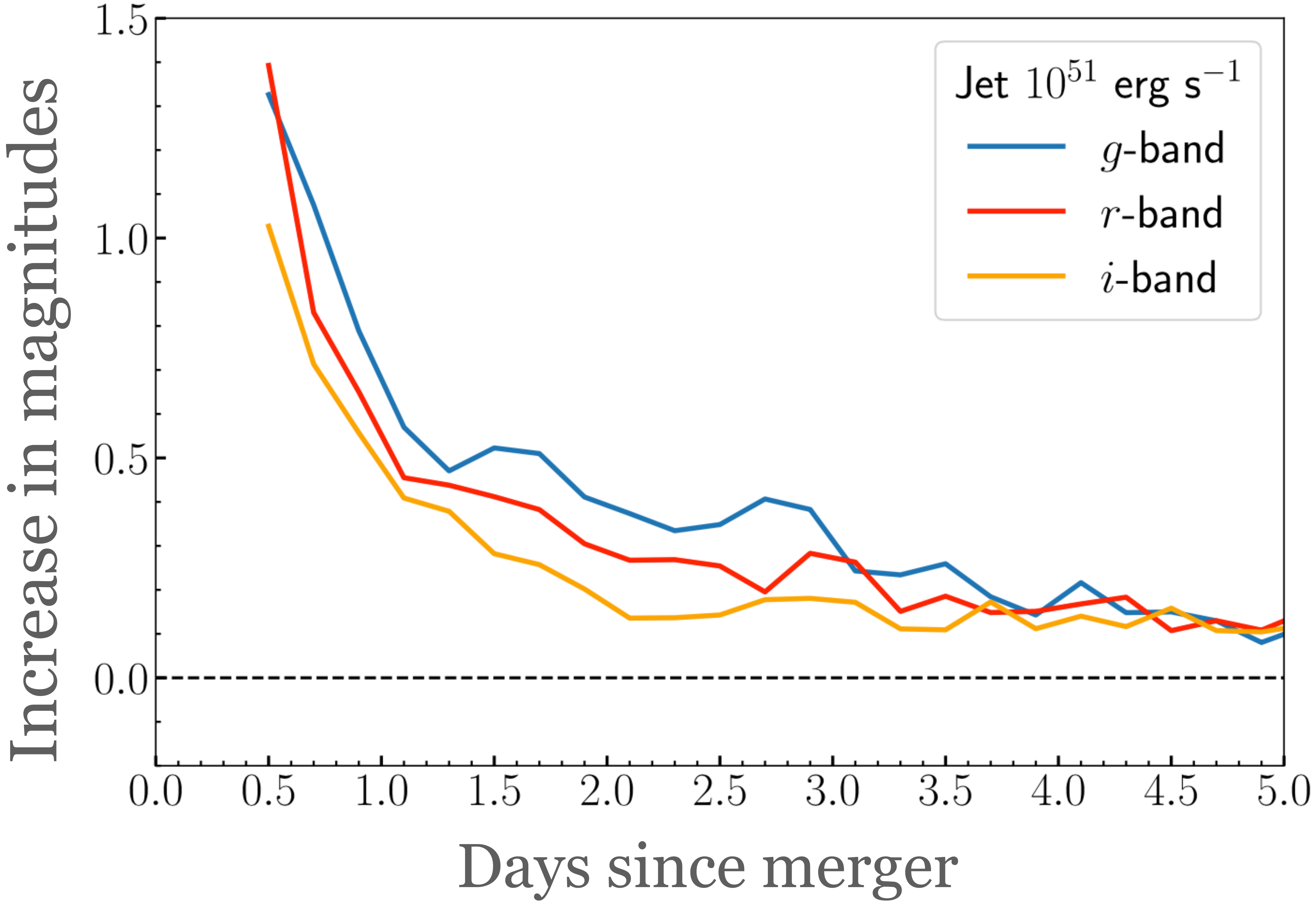
Jet-ejecta interaction

Making kilonovae brighter and bluer

[Nativi, **MB**, Lundman, Rosswog+2021, MNRAS]







Wind models from [Perego+2014, MNRAS]

see also [Klion, Duffert, Kasen & Quataert 2021, MNRAS]

Thank you!