Spectral insights into kilonovae

-- Rapid evolution --

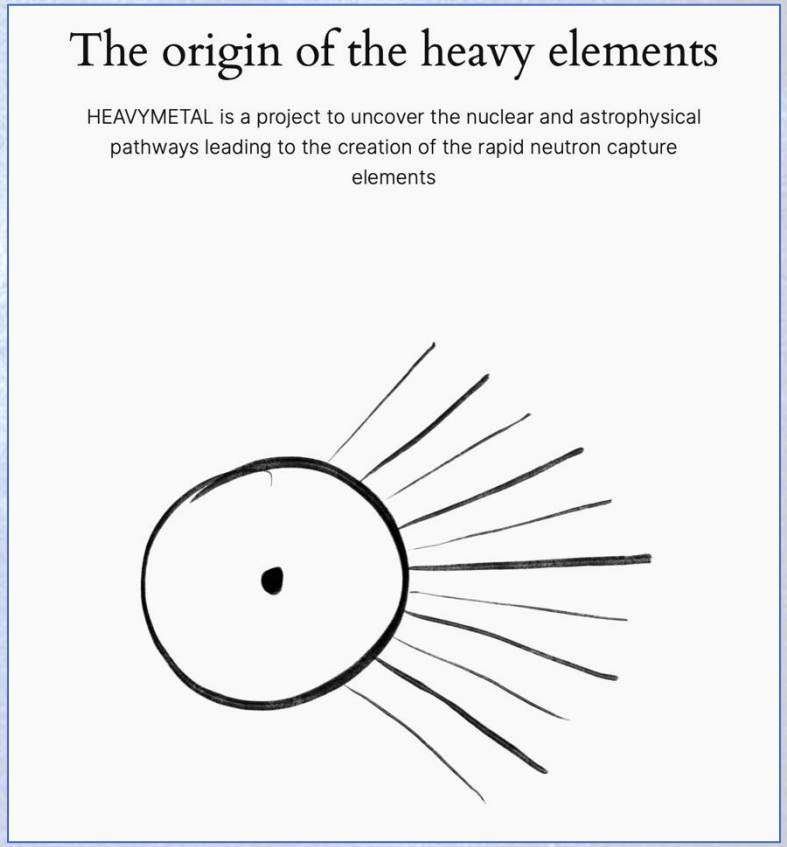
Presented by Albert Sneppen

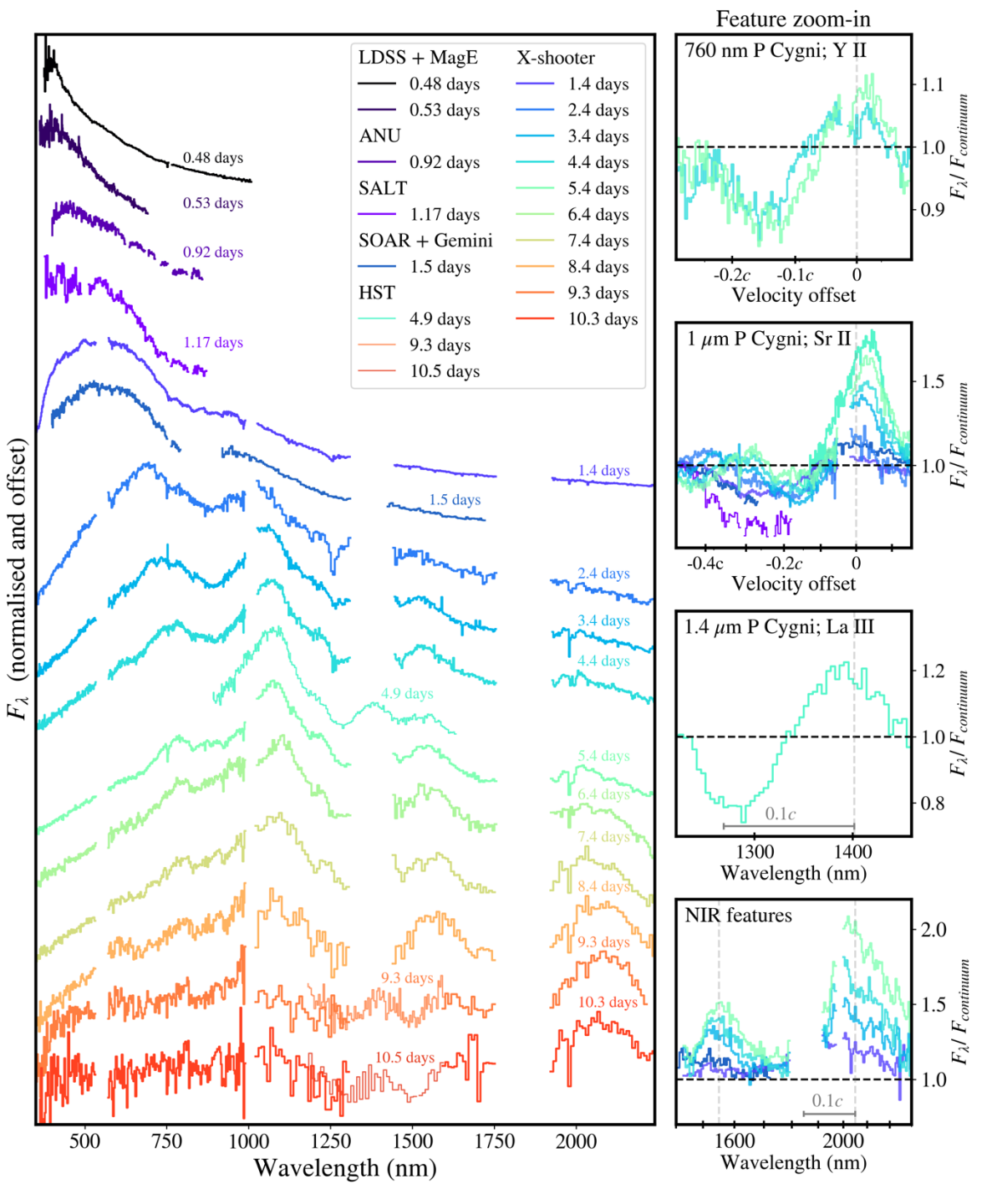
PhD student at the Cosmic DAWN Center, Denmark

YITP, week 4

Work done in collaboration with

Rasmus Damgaard, Darach Watson, Stuart Sim, Andreas Bauswein, Oliver Just, James Gillanders, Ehud Nakar, Dovi Poznanski, Gabriel Martinez-Pinedo, Kasper E. Heintz, Nicholas Vieira, Petri Vaisanen, Antoine Mohoro, Daniele Malesani, Luke Shingles, Christine Collins





A unified spectral series of AT2017gfo

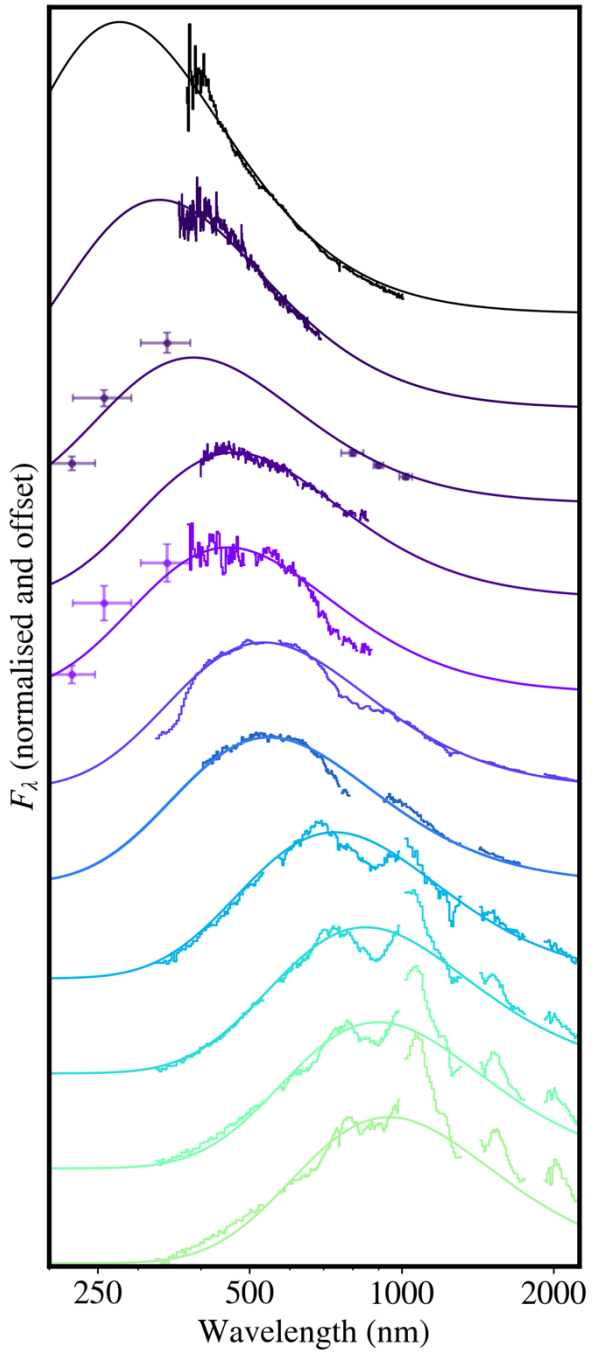
Fig. 1 from Sneppen et al (2024b) - unified spectral data-series can be found at https://github.com/Sneppen/Kilonova-analysis

Data from LDSS + MagE [Shappee et al, 2017], ANU [Andreoni et al, 2017], SALT [Buckley et al, 2018], X-shooter [Pian et al, 2017; Smartt et al, 2017], SOAR [Chornock et al, 2017], Gemini [Nicholl et al, 2017], HST [Tanvir et al, 2017]

The rapid evolution

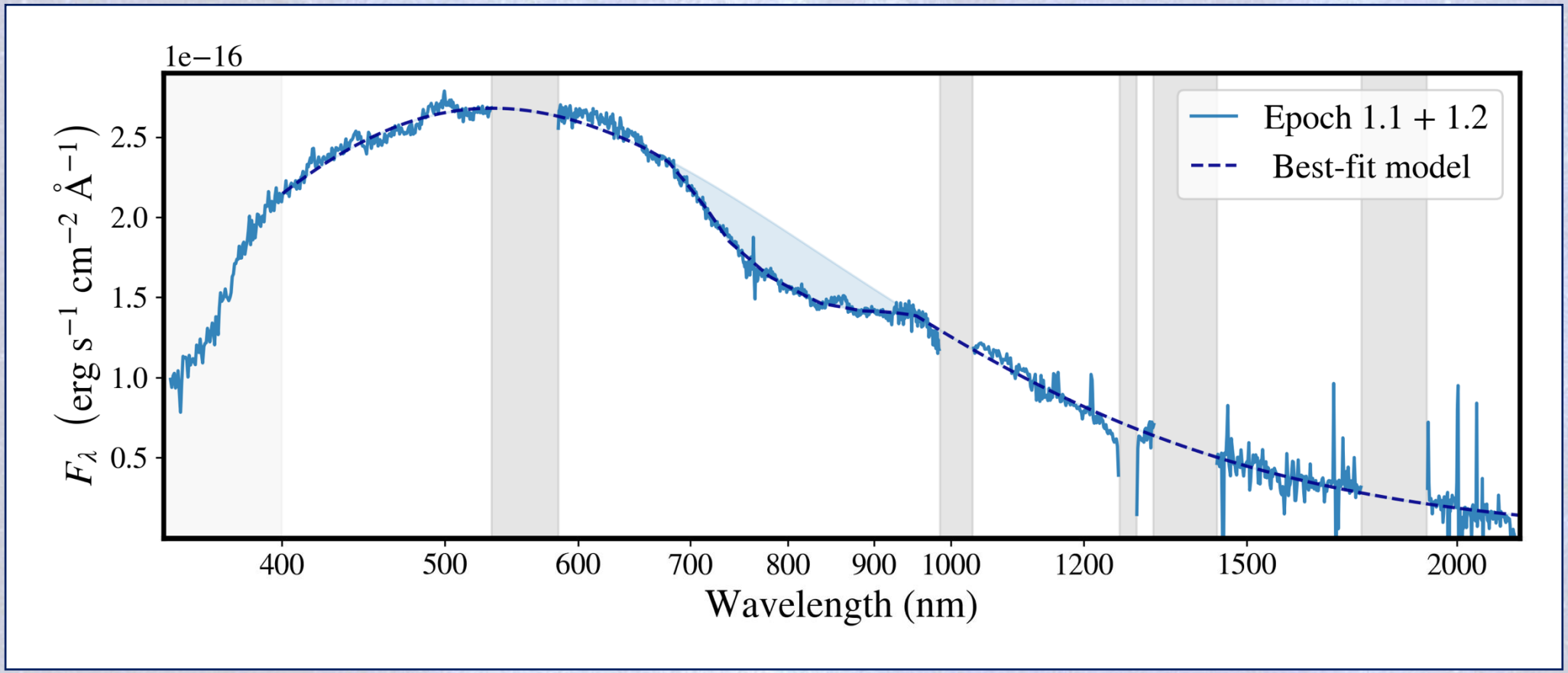
Sneppen et al (2024b), Table 1, blackbody temperatures

Time (days)	Telescope/Instrument	T_{obs} (K)	Publication
0.48	Magellan/LDSS	$11\,000^{+3400}_{-900}$ [1]	Shappee et al. (2017)
0.53	Magellan/MagE	9300 ± 300 [1]	Shappee et al. (2017)
0.92	ANU/WiFeS	6800 ± 200 [2]	Andreoni et al. (2017)
1.17	SALT/RSS	6400 ± 110	Buckley et al. (2018)
1.43	VLT/X-shooter	5440 ± 60	Pian et al. (2017)
1.45	VLT/X-shooter	5380 ± 60	Sneppen et al. (2023a)
1.47	SOAR/GHTS, Gemini/FLAMINGOS-2	5330 ± 60	Nicholl et al. (2017), Chornock et al. (2017)
2.42	VLT/X-shooter	3940 ± 50	Smartt et al. (2017)
3.41	VLT/X-shooter	3420 ± 40	Pian et al. (2017)
4.40	VLT/X-shooter	3330 ± 40	Smartt et al. (2017)
5.40	VLT/X-shooter	3070 ± 40	Pian et al. (2017)



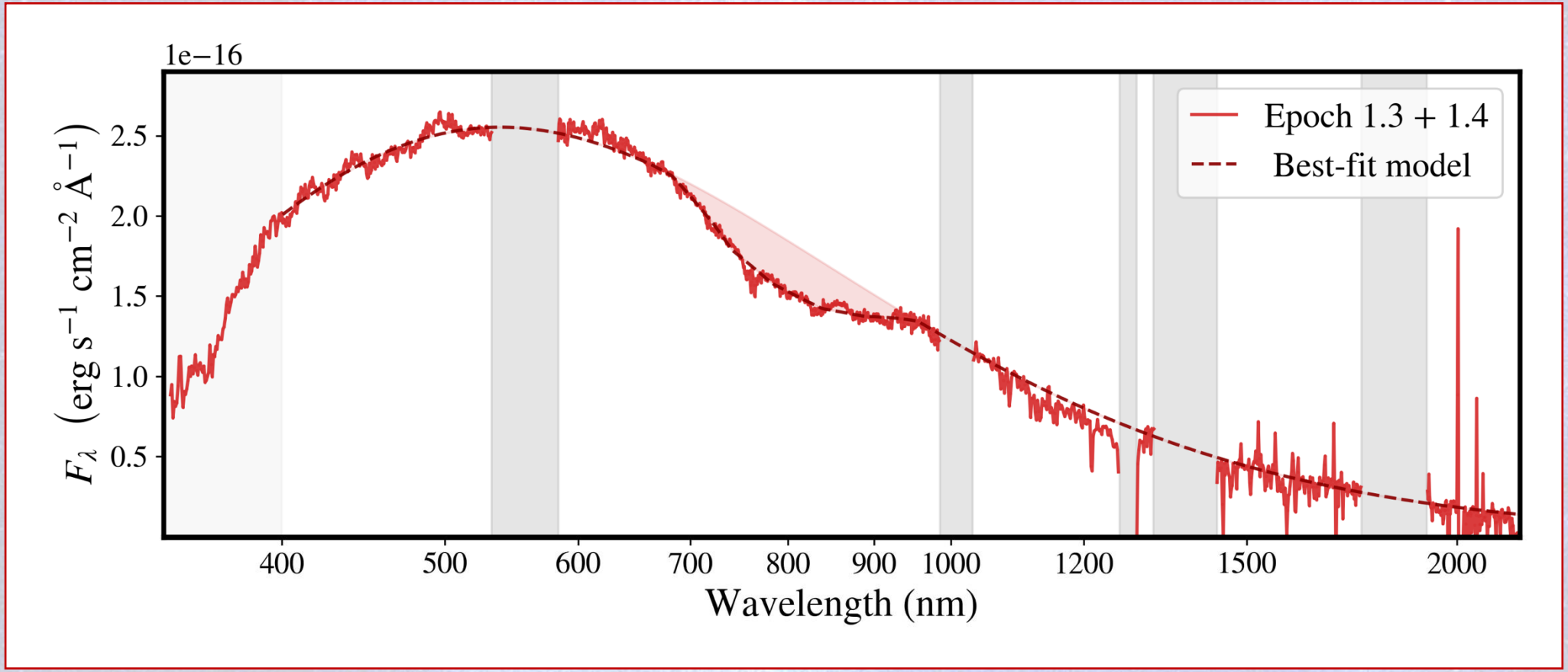
Sneppen et al. (2024b)

1.43 days post-merger



Sneppen et al (2024a), sub-epoch reduction of X-shooter spectra

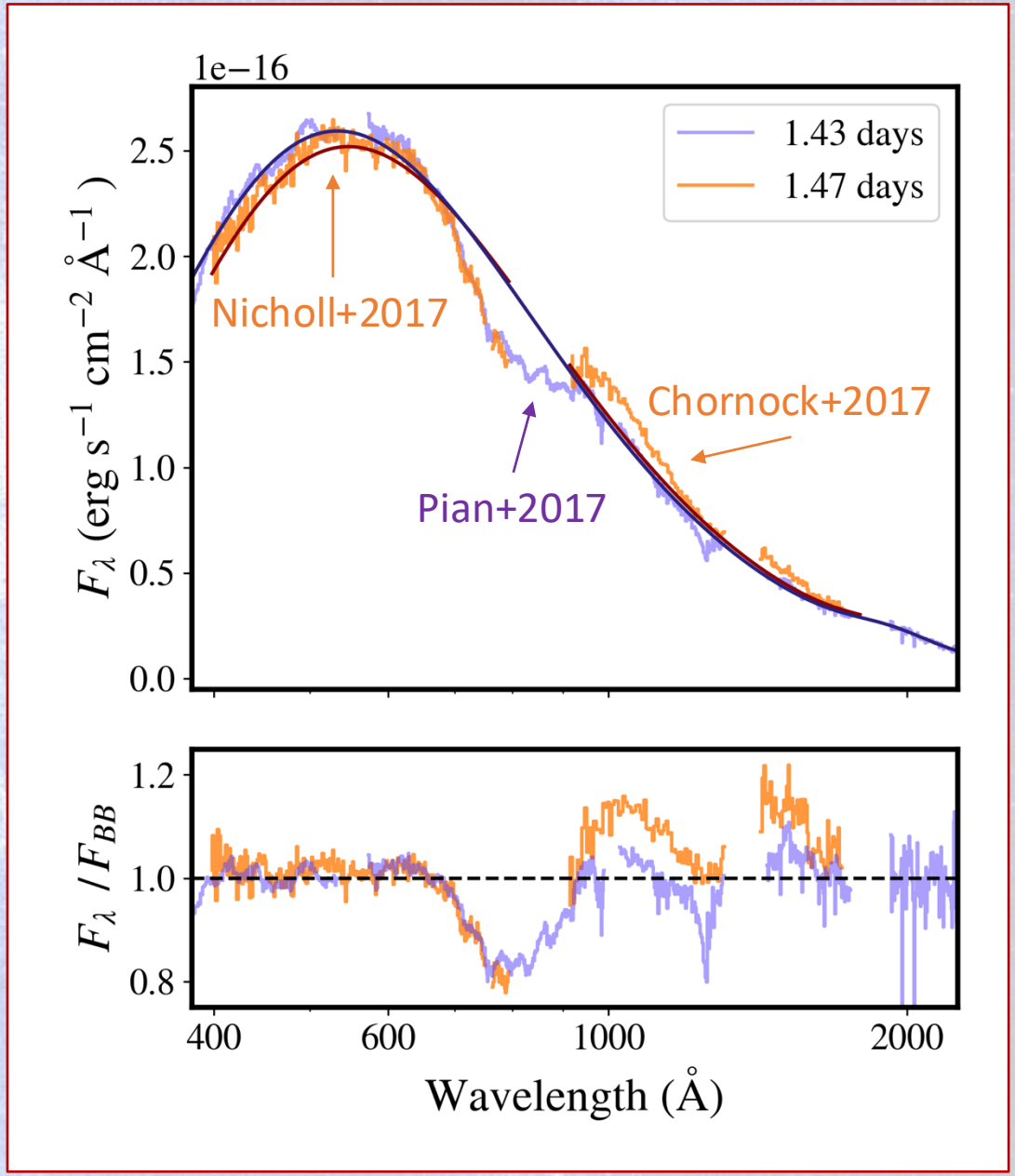
1.43+0.02 days post-merger



Sneppen et al (2024a), sub-epoch reduction of X-shooter spectra

1.43-1.47 days

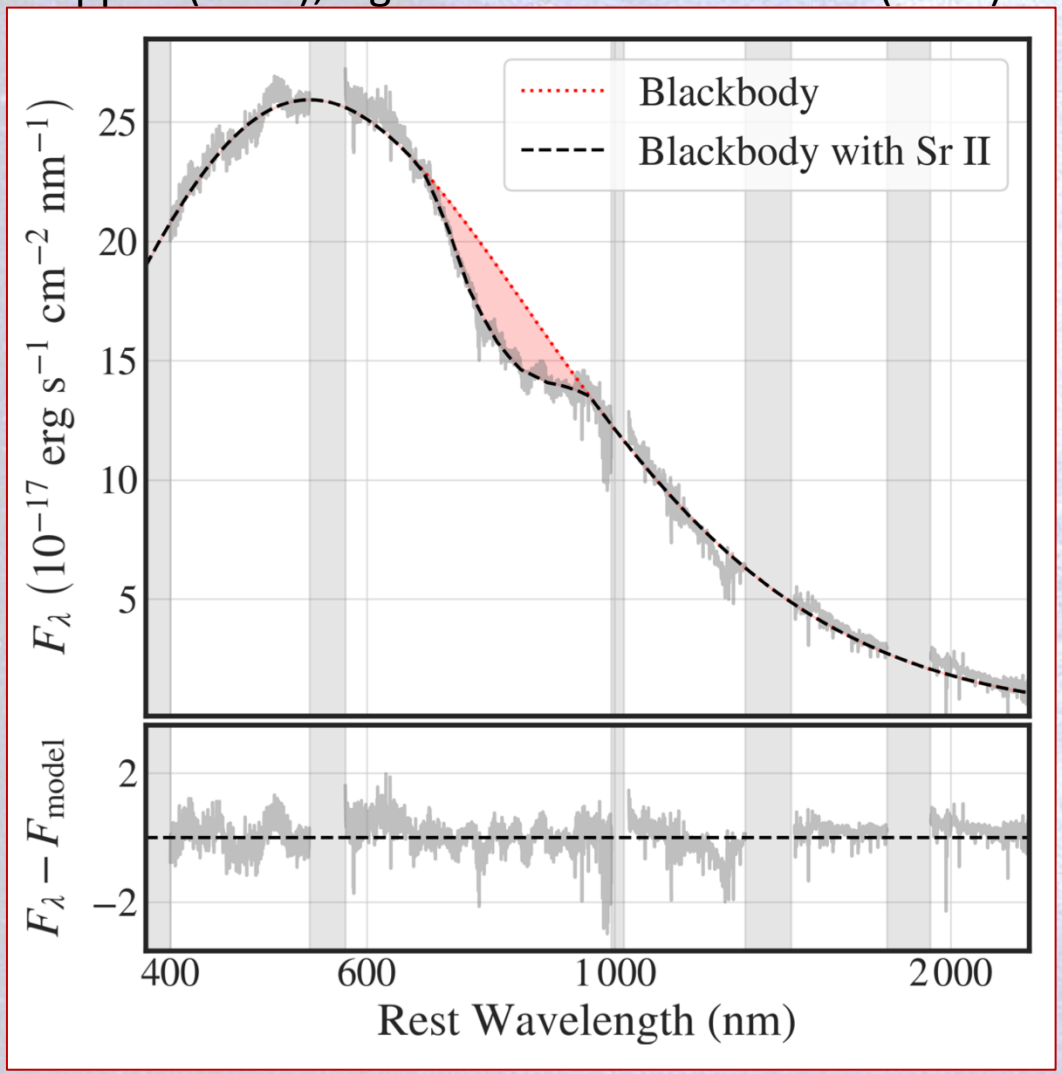
Time (days)	Telescope/Instrument	T_{obs} (K)		Publication
0.48	Magellan/LDSS	$11\,000^{+3400}_{-900}$	[1]	Shappee et al. (2017)
0.53	Magellan/MagE	9300 ± 300	[1]	Shappee et al. (2017)
0.92	ANU/WiFeS	6800 ± 200	[2]	Andreoni et al. (2017)
1.17	SALT/RSS	6400 ± 110		Buckley et al. (2018)
1.43	VLT/X-shooter	5440 ± 60		Pian et al. (2017)
1.45	VLT/X-shooter	5380 ± 60		Sneppen et al. (2023a)
1.47	SOAR/GHTS, Gemini/FLAMINGOS-2	5330 ± 60		Nicholl et al. (2017), Chornock et al. (2017)
2.42	VLT/X-shooter	3940 ± 50		Smartt et al. (2017)
3.41	VLT/X-shooter	3420 ± 40		Pian et al. (2017)
4.40	VLT/X-shooter	3330 ± 40		Smartt et al. (2017)
5.40	VLT/X-shooter	3070 ± 40		Pian et al. (2017)



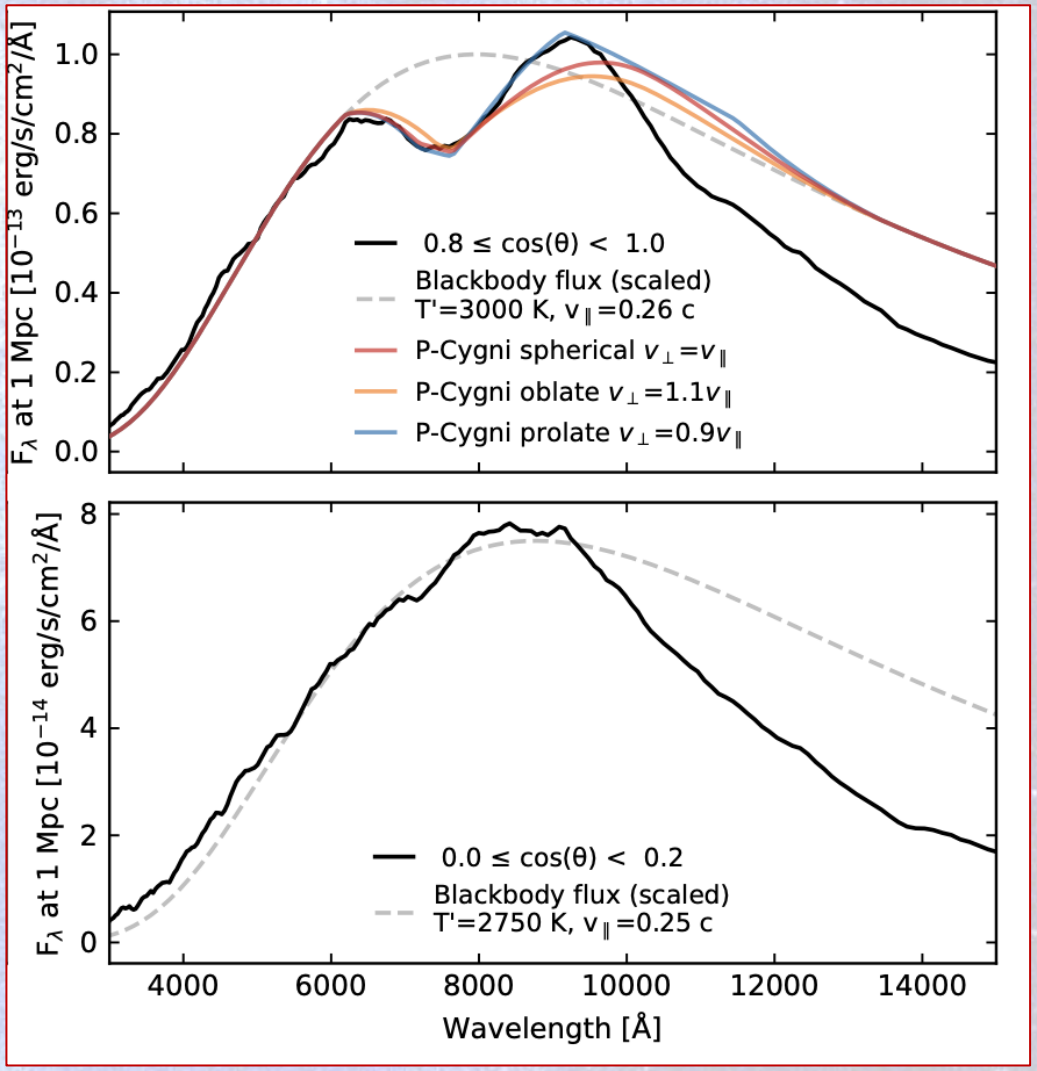
Sneppen et al. (2024b)

The blackbody spectrum

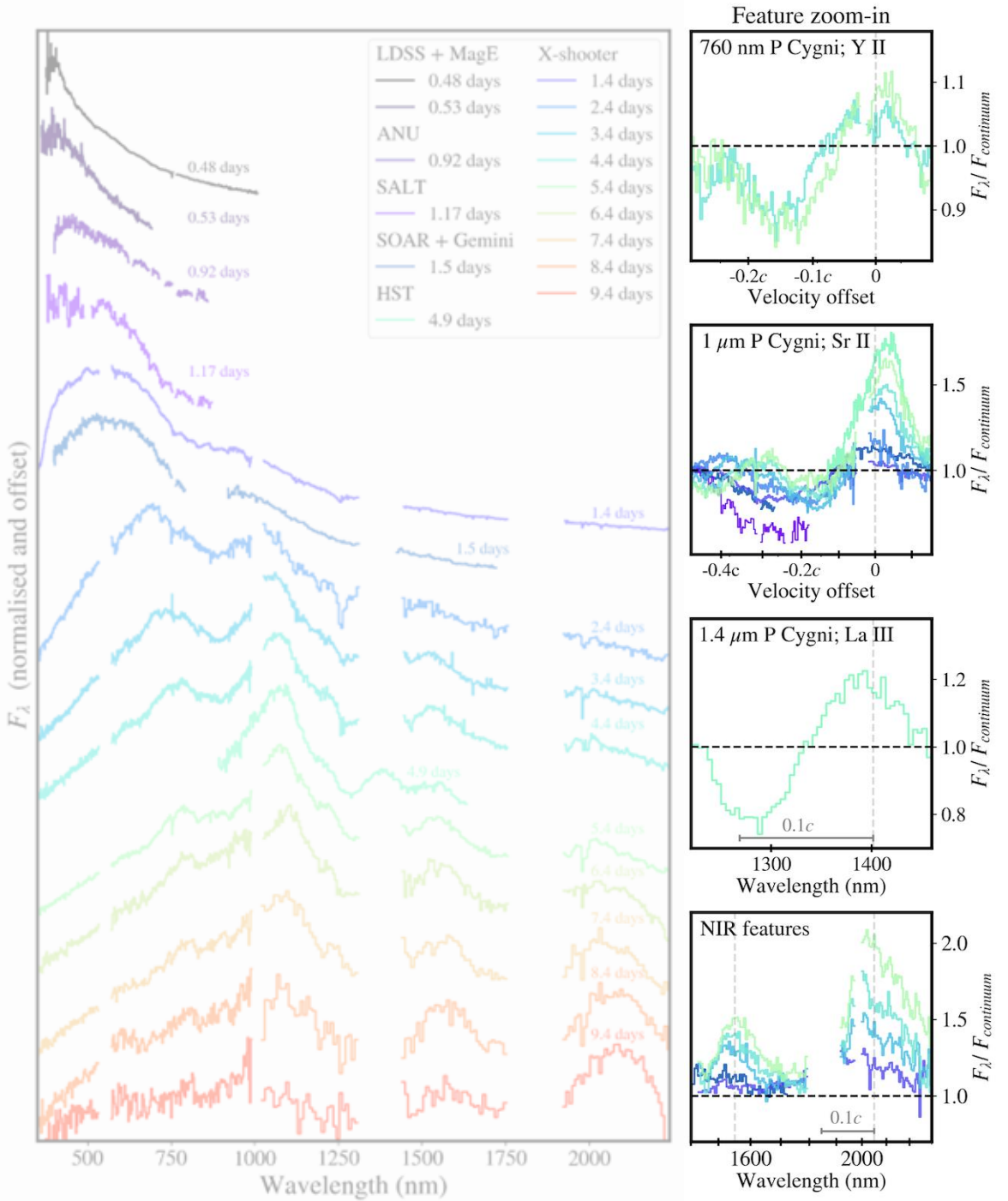
Sneppen (2023), Fig. 6 – see also Sadeh et al (2025)



Collins et al (2024)



Spectral features



Sneppen et al (2024b)

Spectral features from individual elements

Reproduced and extended with systematic analyses using radiative transfer codes with more atomic line data:

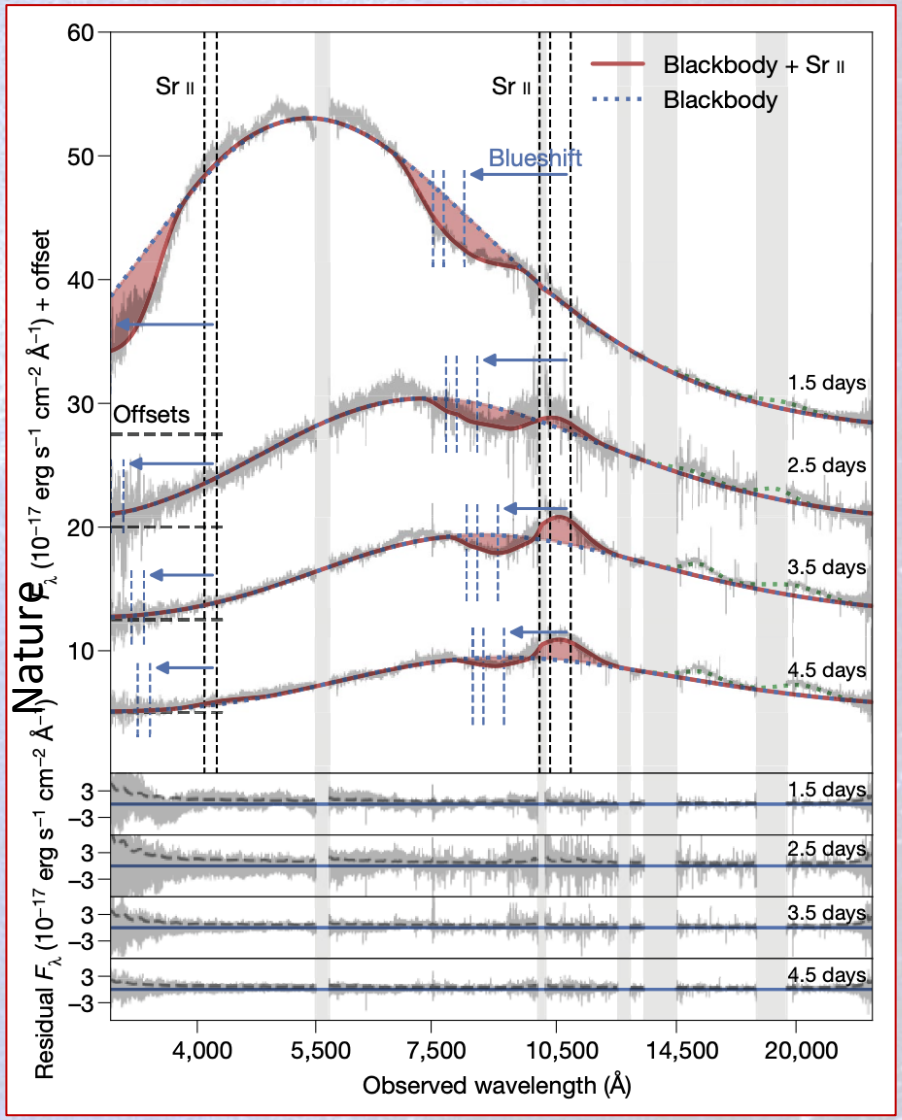
- Domoto et al. (2021)
- Gillanders et al. (2022)
- Vieira et al. (2023)
- Sneppen et al (2023b)

Additionally, accounting for the full 3D spatial and time dependence of the density with line-by-line opacity:

- Shingles et al. (2023)

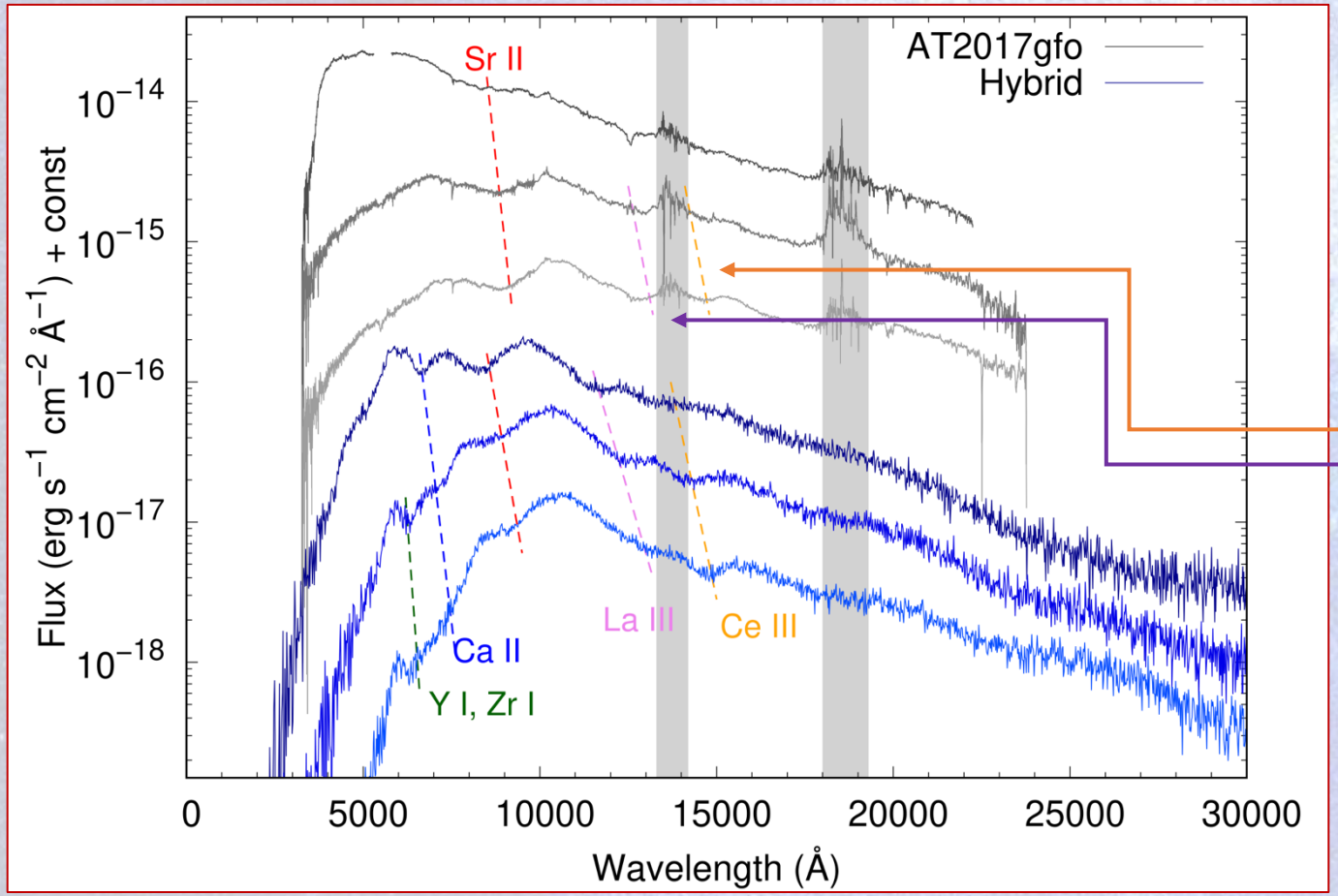
and NLTE feasibility in

- Pognan et al (2023)
- Tarumi et al (2023)
- Brethauer et al (2025)
- Arya et al (in prep)
- Chiba et al (in prep)



Watson et al. (2019), Nature

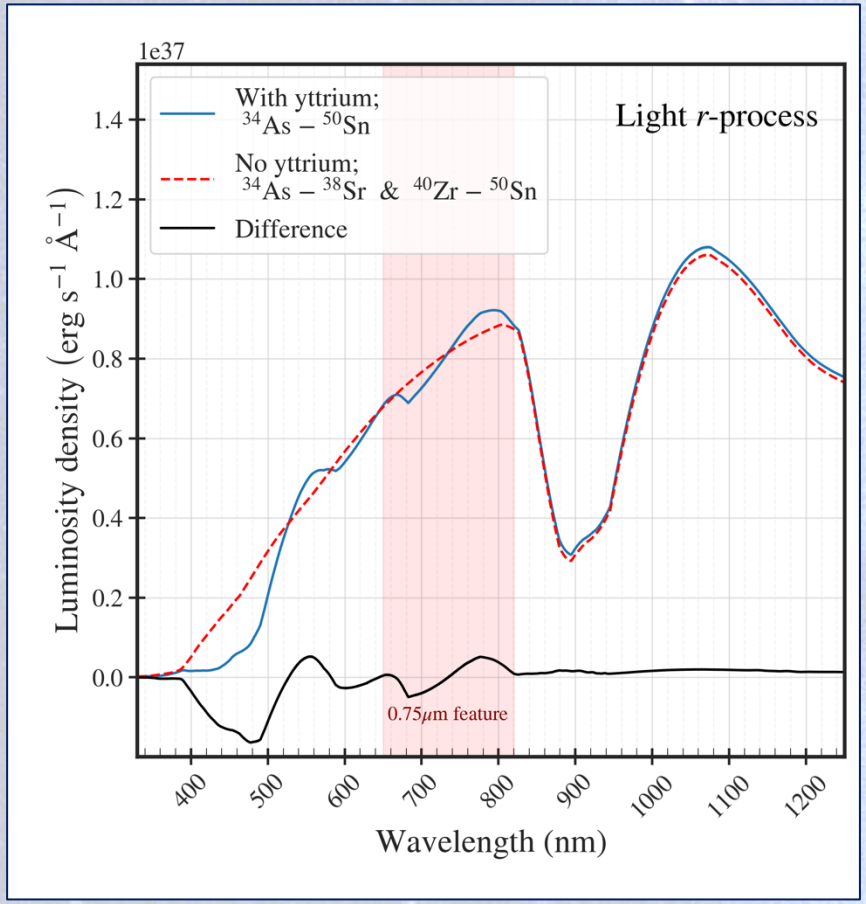
NIR spectral wiggles



Signatures of La III and Ce III from wiggles at 12 000 – 14 000 Å

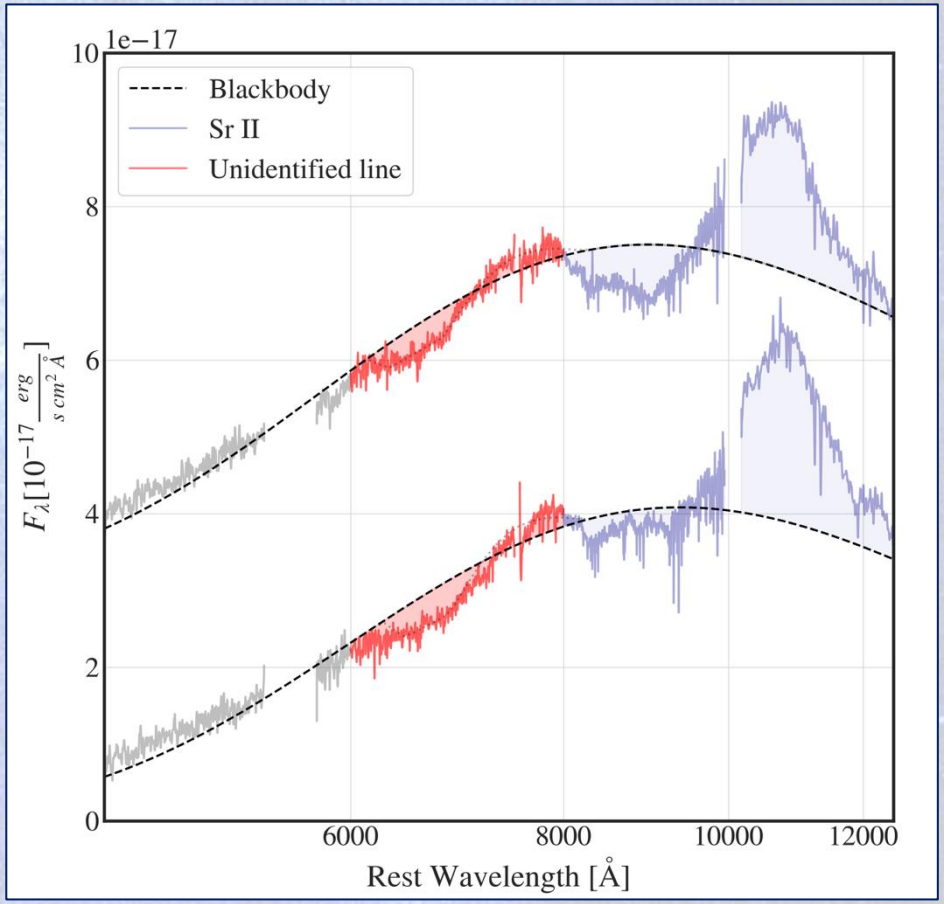
Domoto et al. (2022, 2023),
see also Gd III contribution in Rahmouni et al (2025)

Feature at 750 nm from Yttrium



1) The presence of Sr II requires Y II to be present.

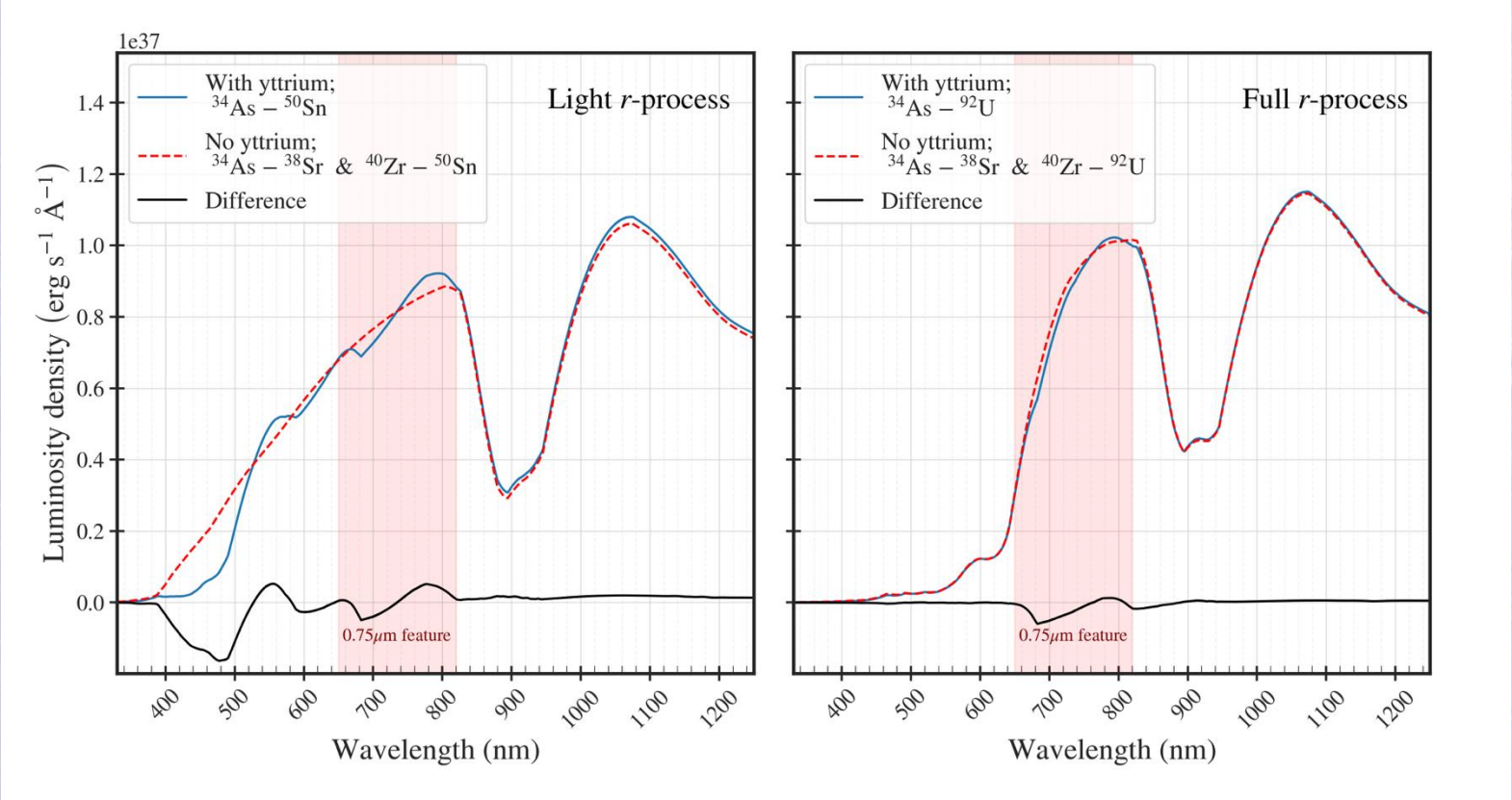
2) If Y II is present the line transitions $4d5p\text{-}4d^2$ will produce a P Cygni around 750 nm

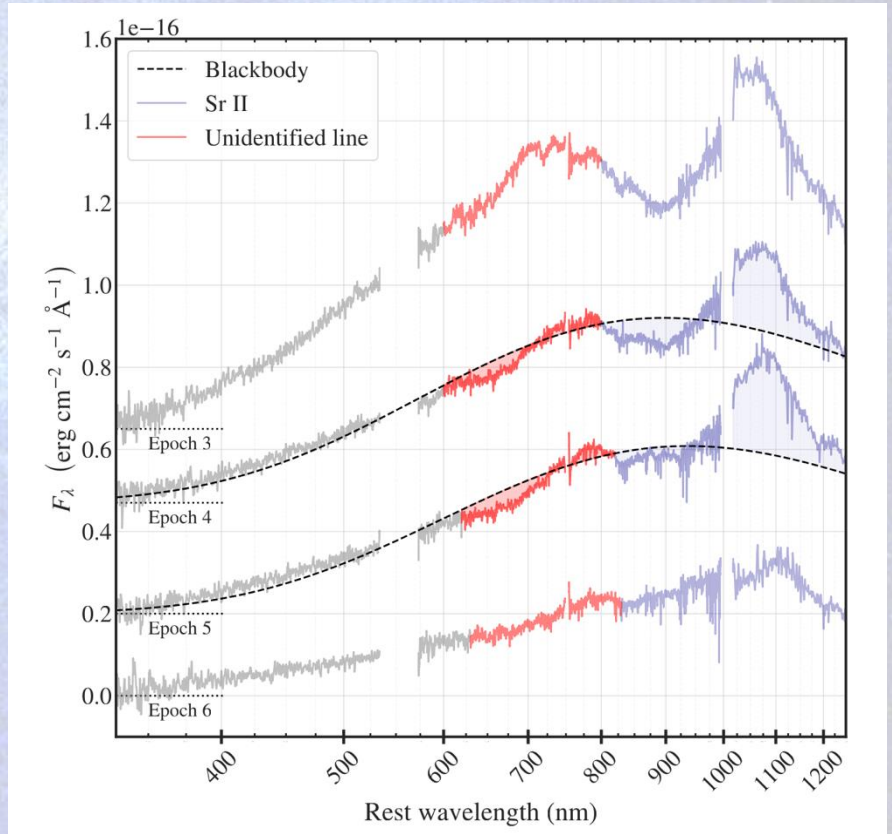


Sneppen & Watson (2023), A&A

See also Shingles et al (2023), Tak et al (2024), Pognan et al (2024), Banerjee et al (2025)

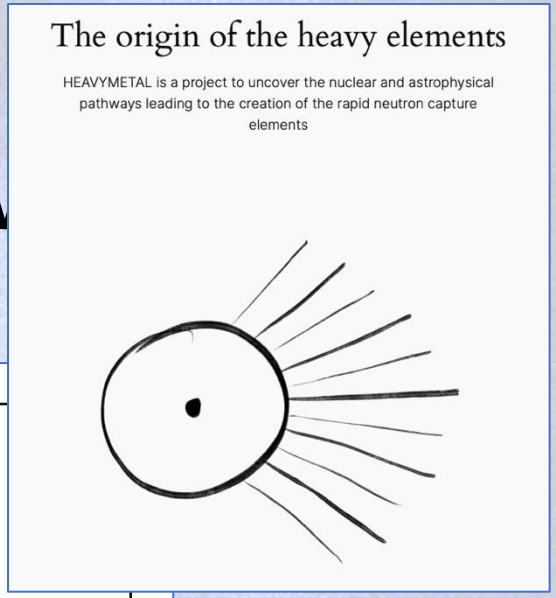
Y II constraining the optical line-blanketing?

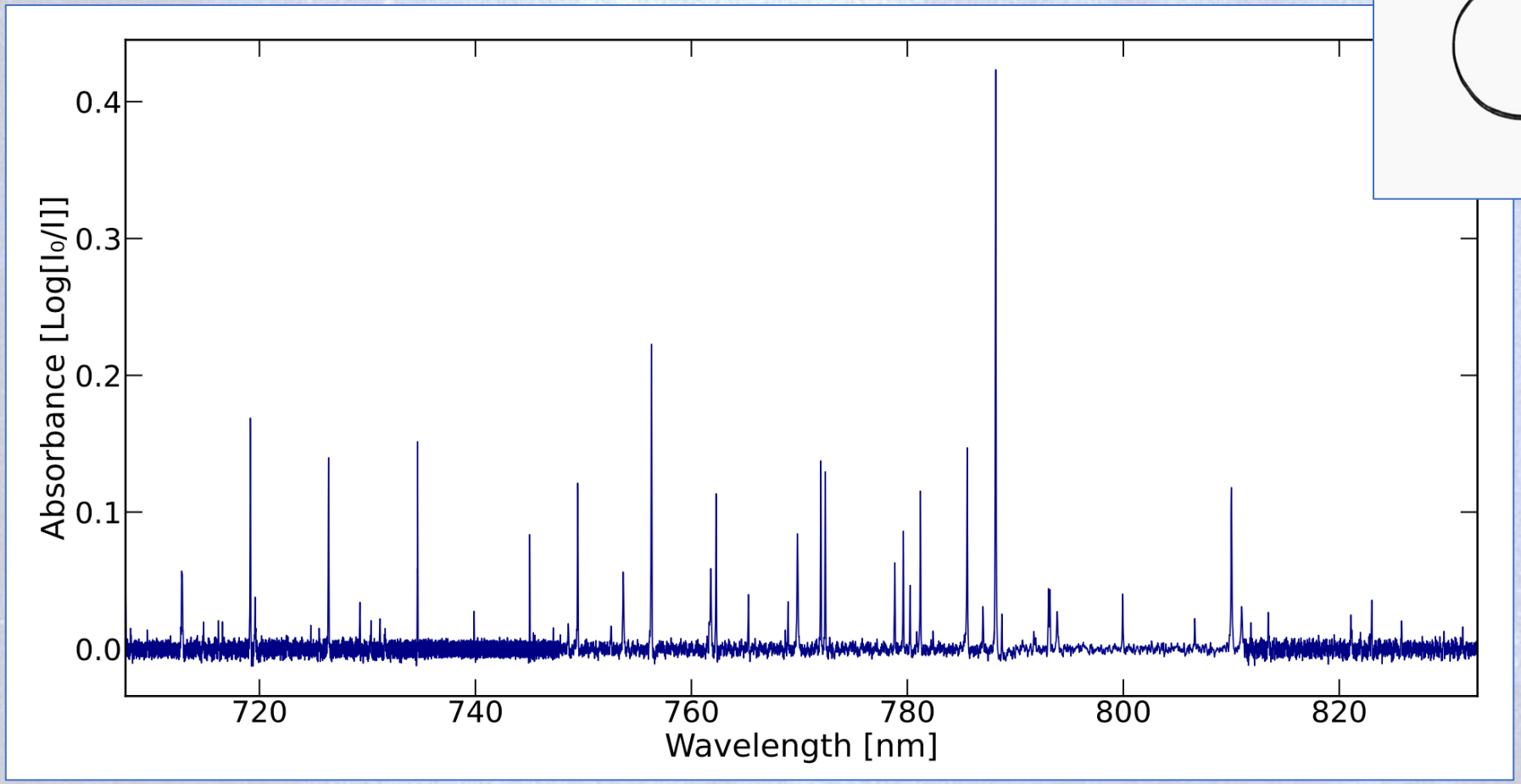




Sneppen & Watson (2023)

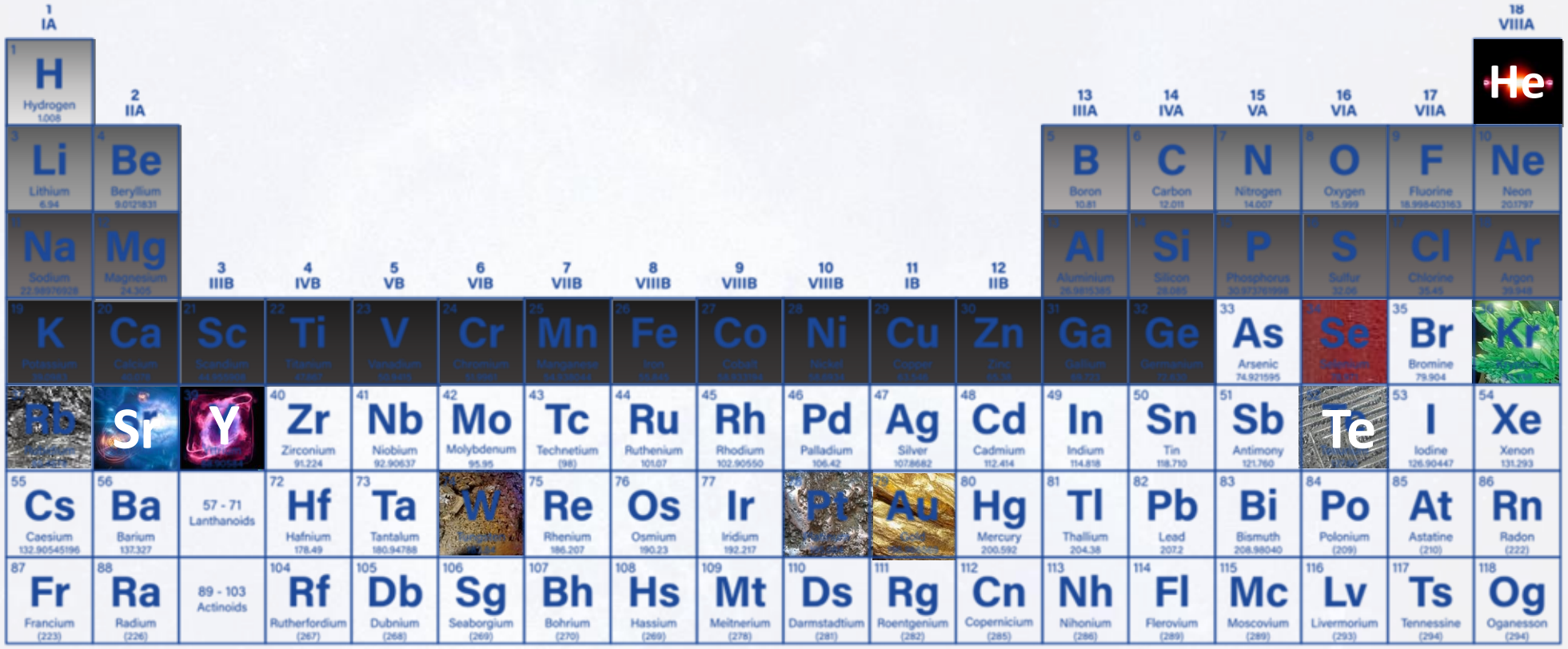
Atomic data from ‘heavymetal’ underv





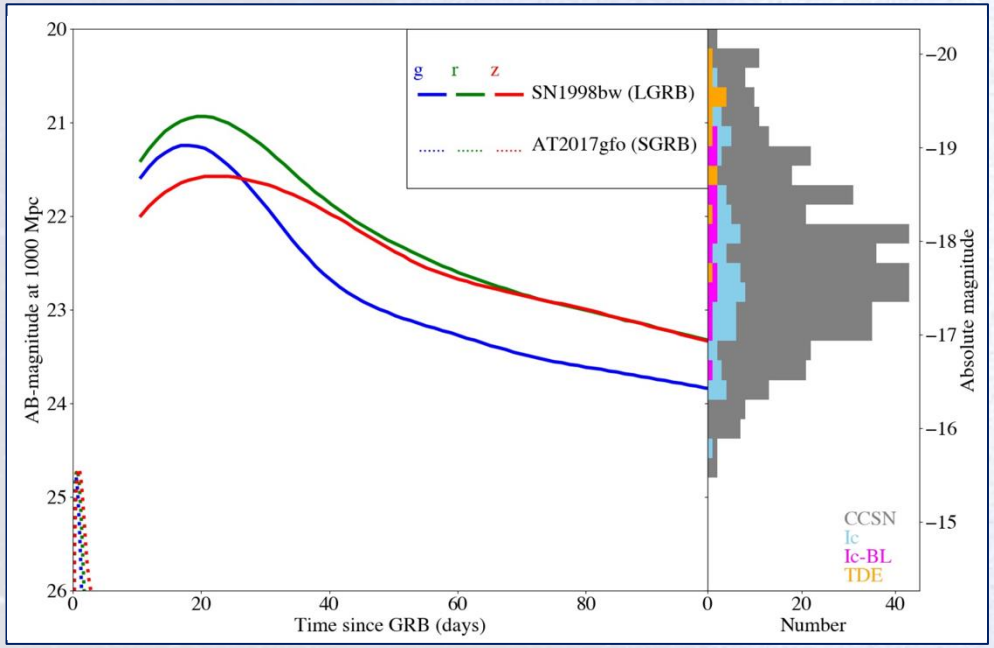
Dowd et al (2025)

See
Sr [Watson et al (2019)],
Pt, Au [Gillanders et al (2021)],
La, Ce [Domoto et al (2022,23)],
Y [Sneppen & Watson (2023)],
Te [Hotokezaka et al (2023),
Gillanders et al (2023),
Mulholland et al (2026)],
Rb [Pogan et al (2023)],
He [Tarumi et al (2023),
Sneppen et al (2024)],
W, Se [Hotokezaka et al (2022)],
W [McCann et al (2024)],
Gd [Rahmouni et al (2025)],
Kr [Jerkstrand et al (2025)],
Th [Domoto et al (2025)],



The information *hiding* in the emergence of spectral feature

Rapidly evolving transient



from Levan et al. (2023)

Large velocities / long time-delays

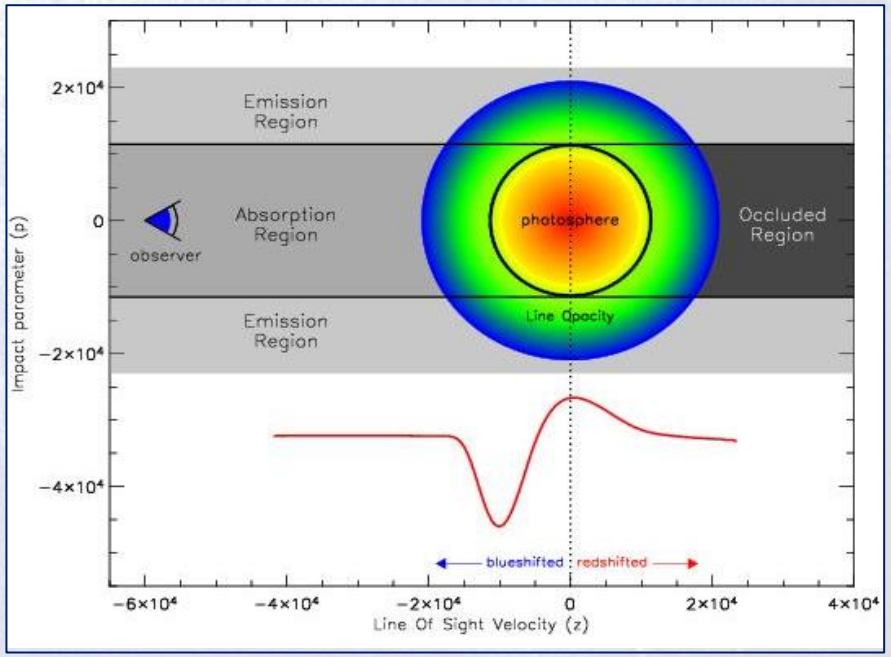
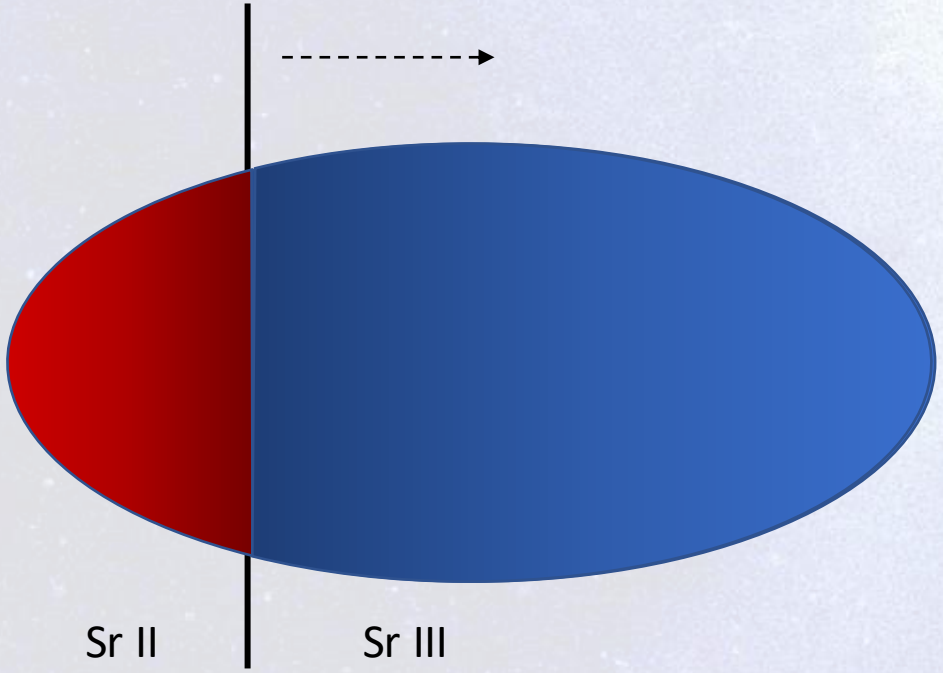


illustration from Dan Kasen

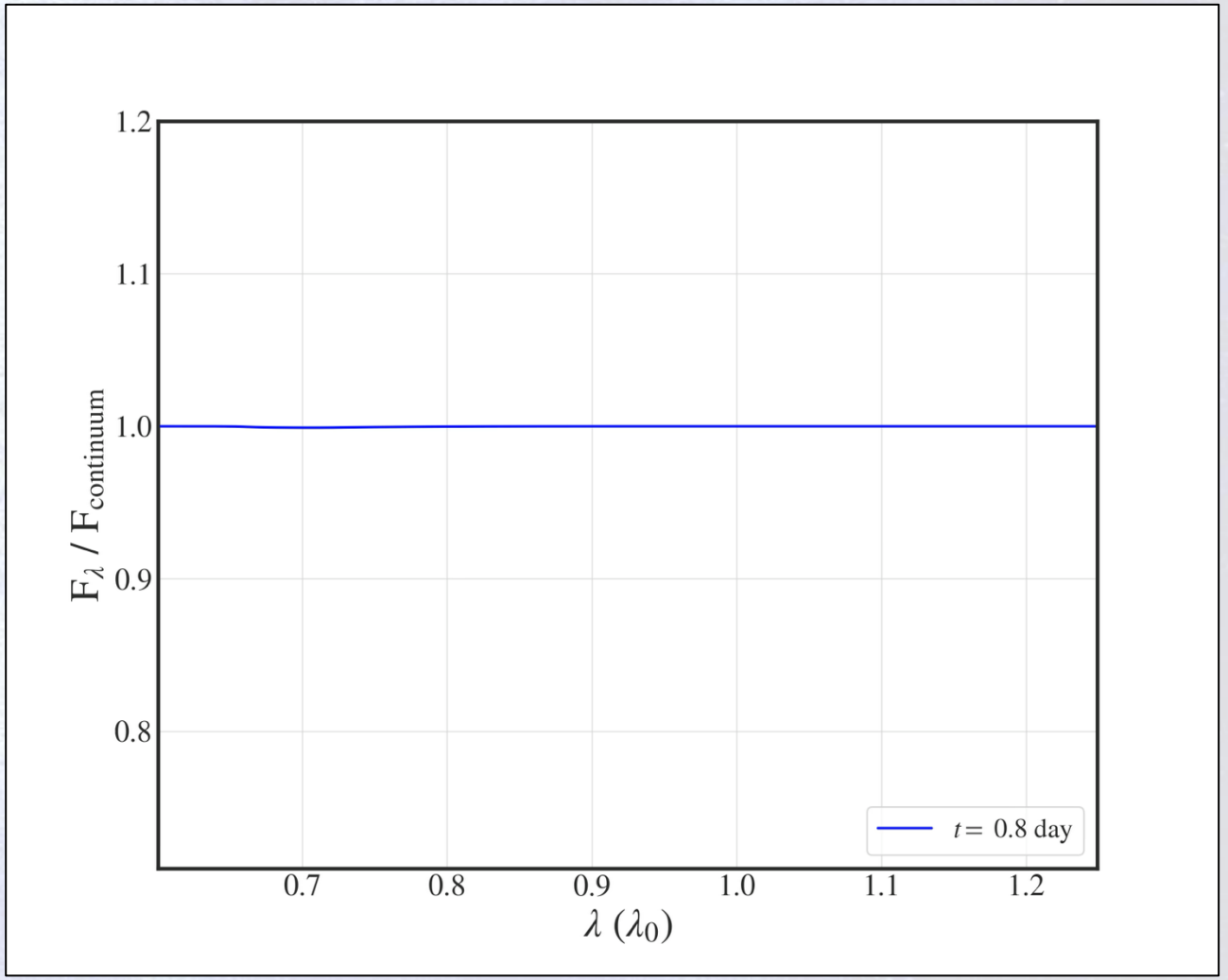
How lines emerge in KNe

$$\frac{n_{Sr\ III}}{n_{Sr\ II}} = \frac{2}{\lambda^3}\frac{g_{Sr\ III}}{g_{Sr\ II}}\frac{1}{n_e}e^{-\frac{E_{ionize}}{k_B T}}$$

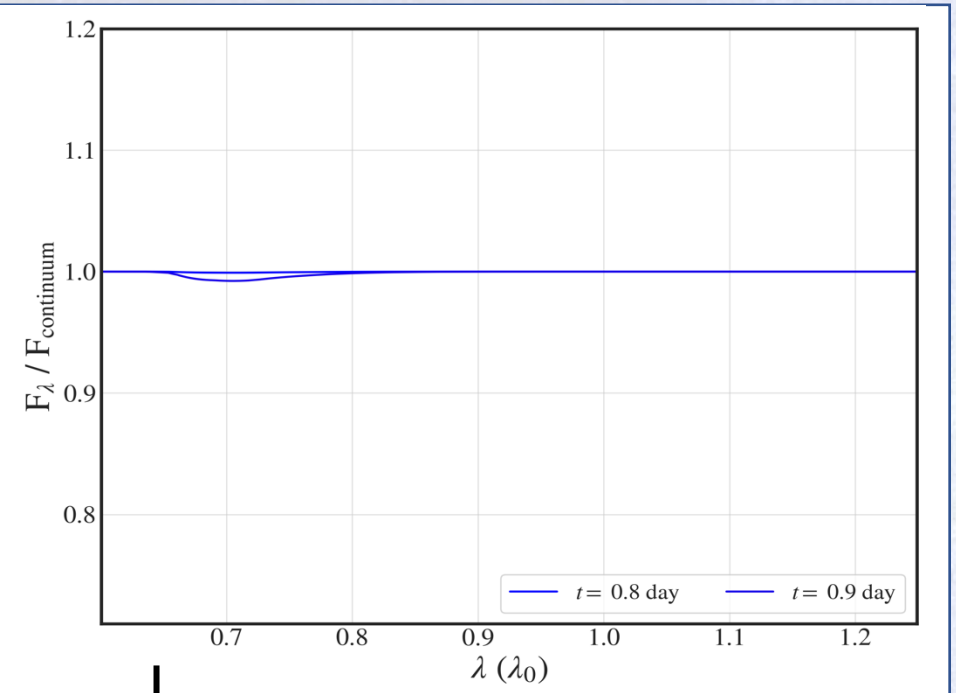
Saha Equation

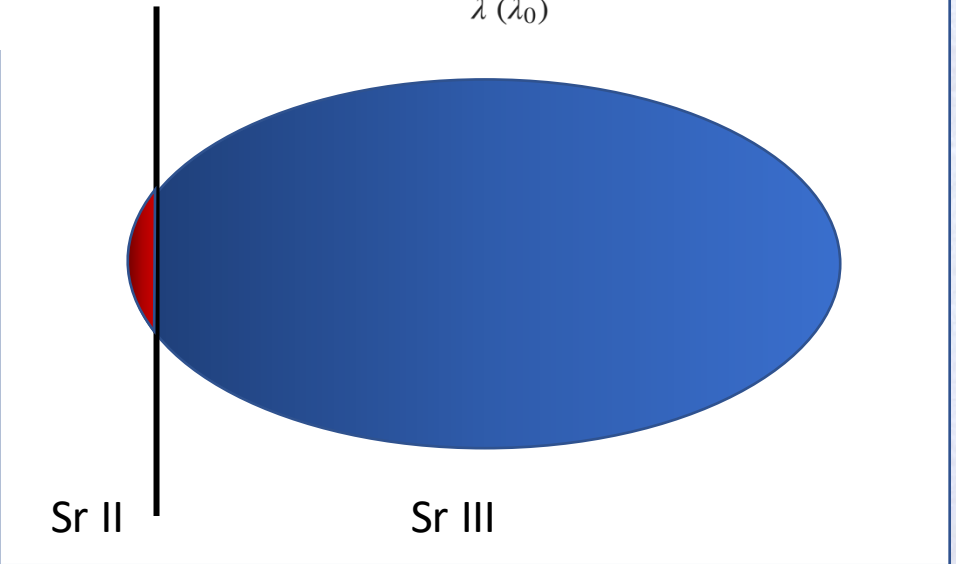


Sneppen et al (2024a)

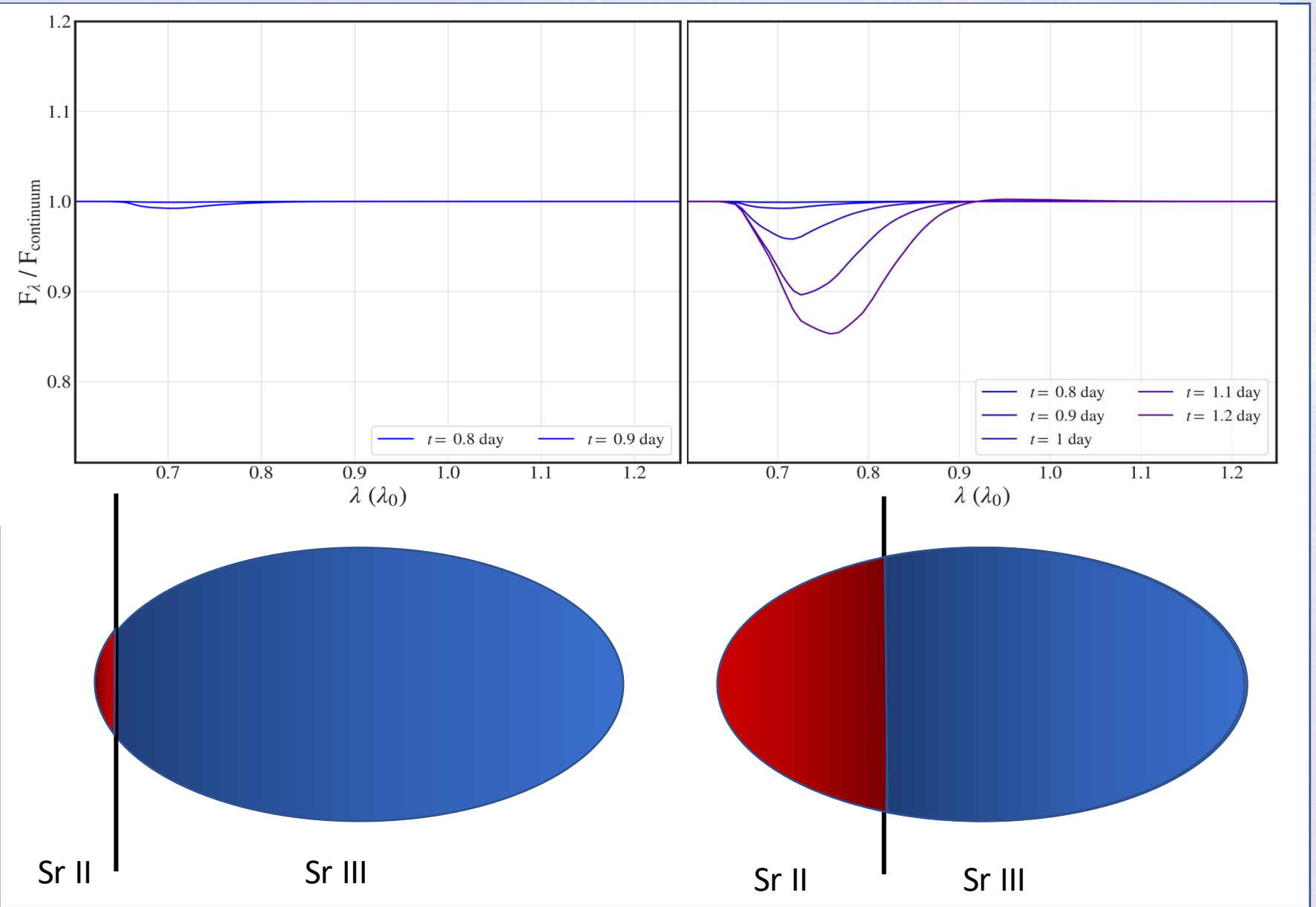


A recombination wave moving through the ejecta

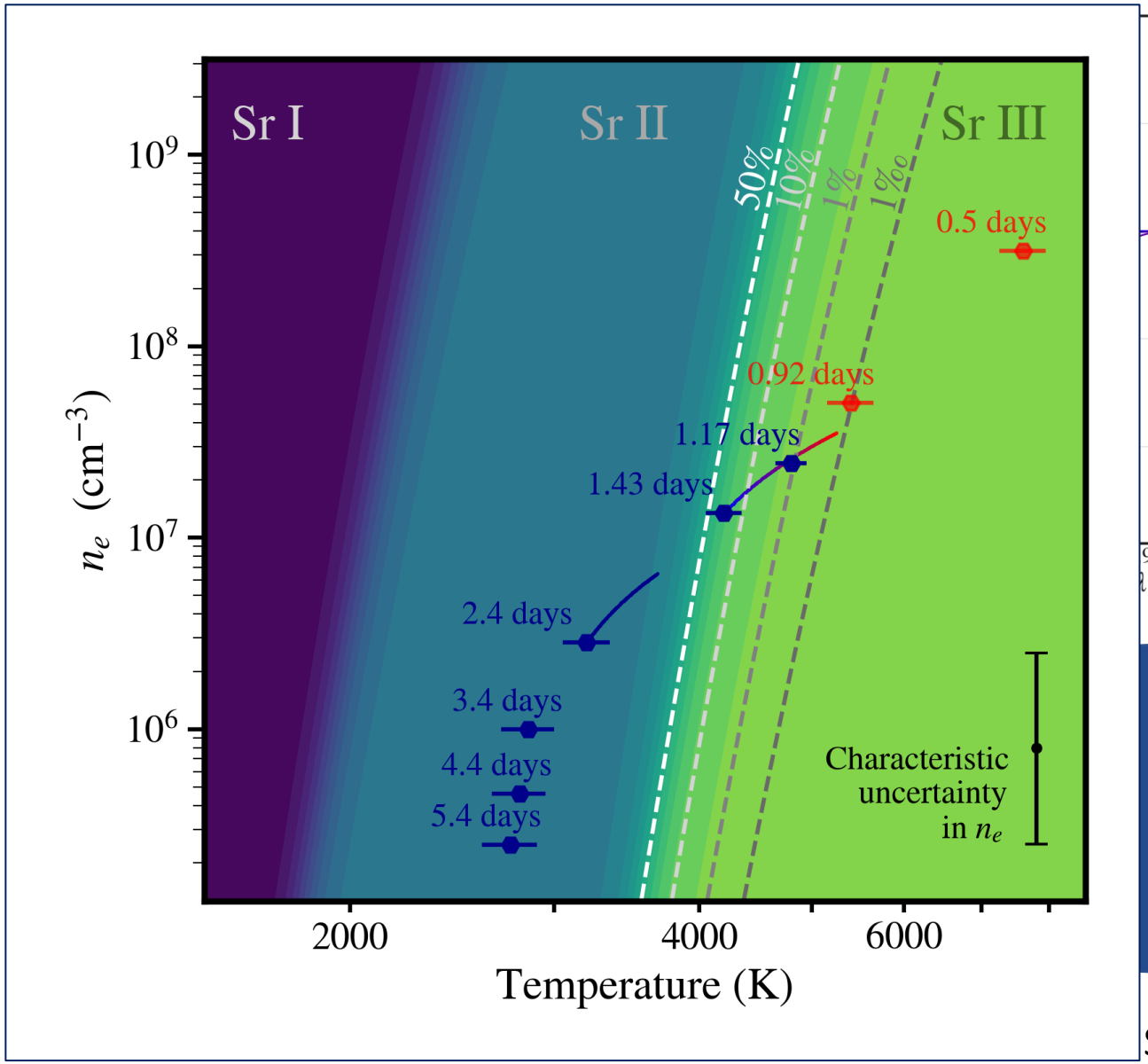


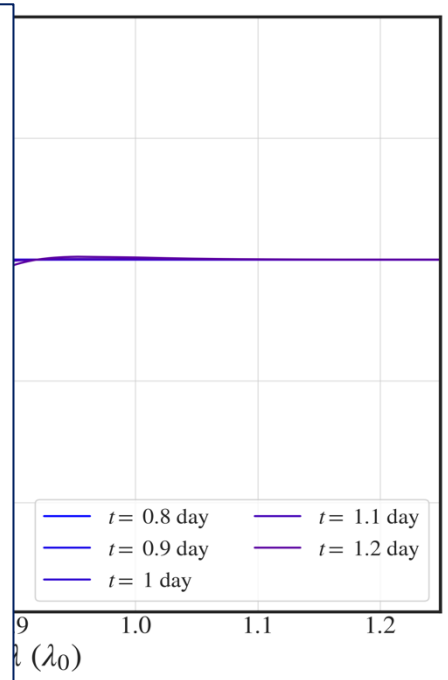


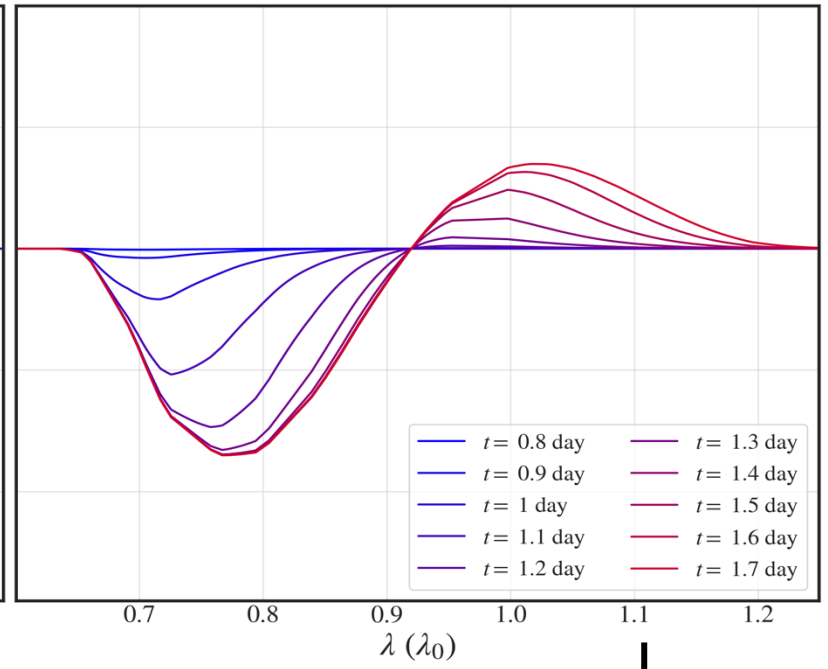
A recombination wave moving through the ejecta

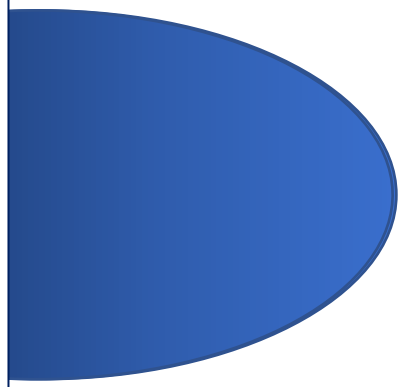


A recombination wave moving through the ejecta

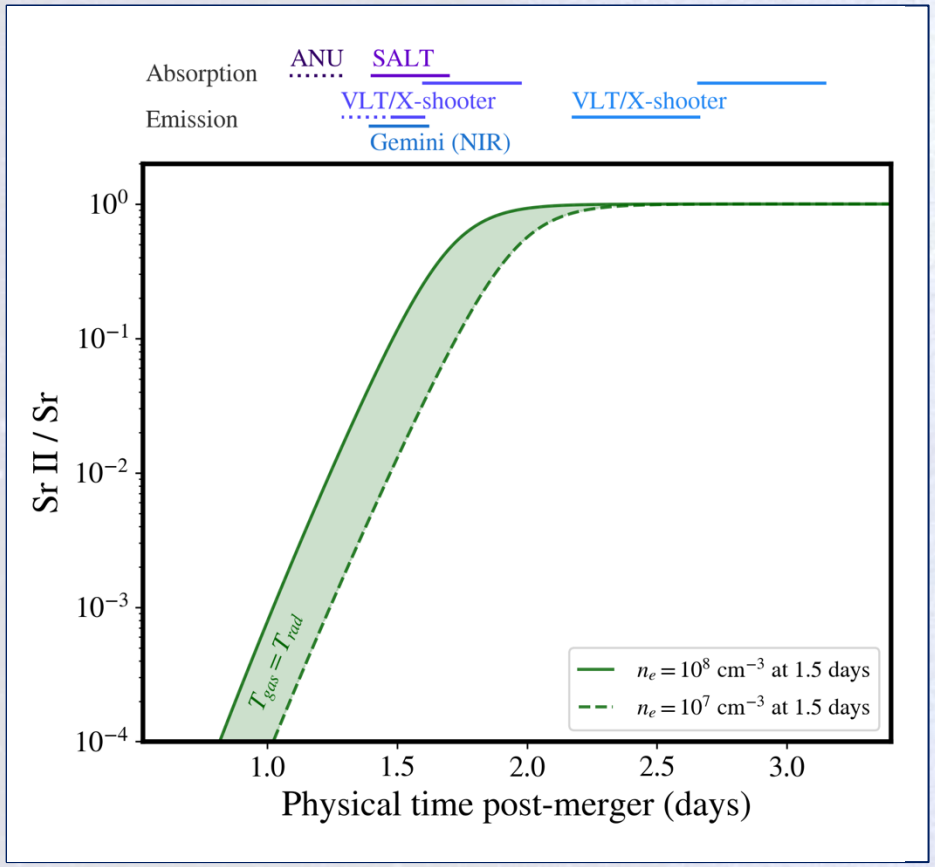




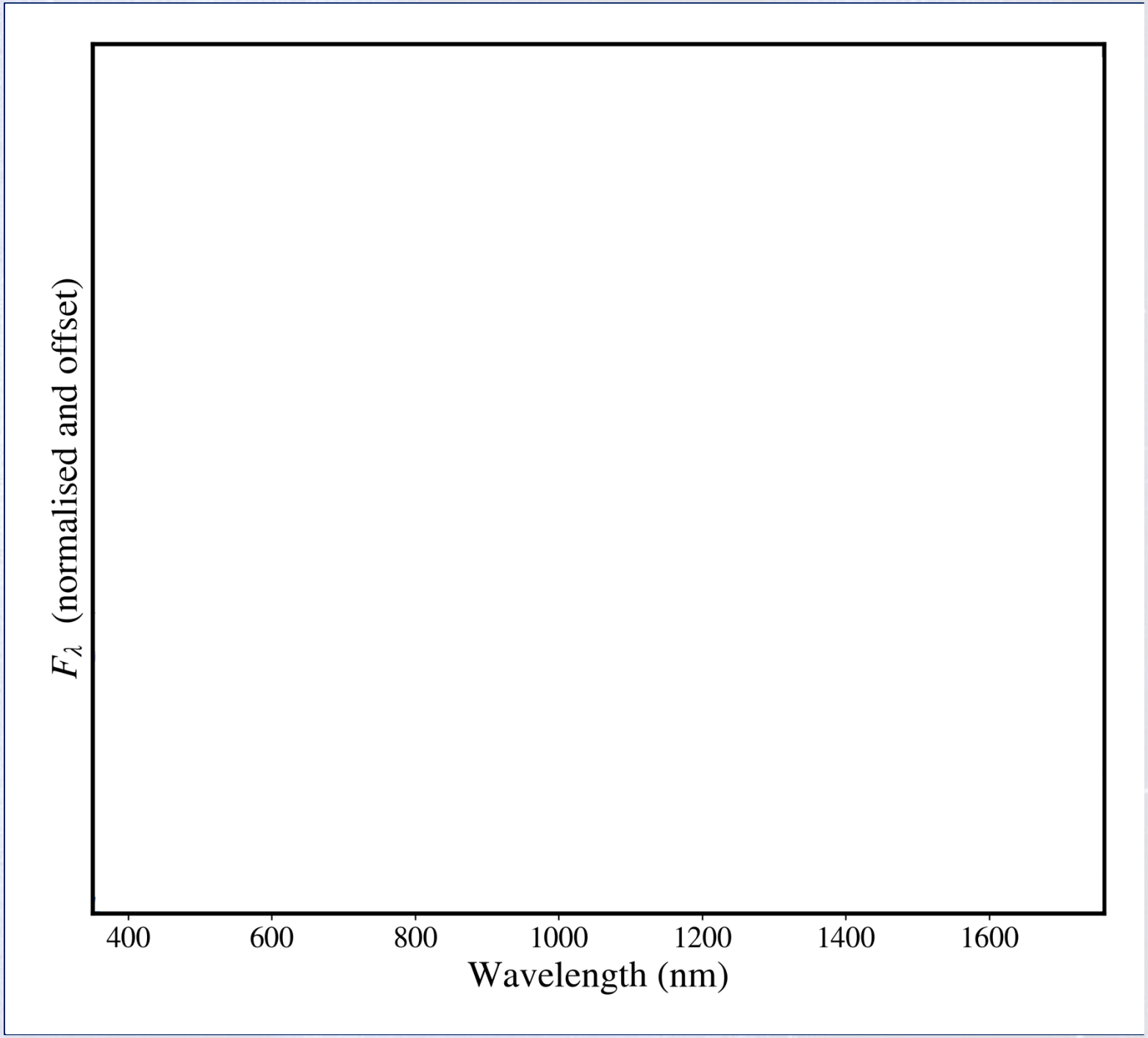




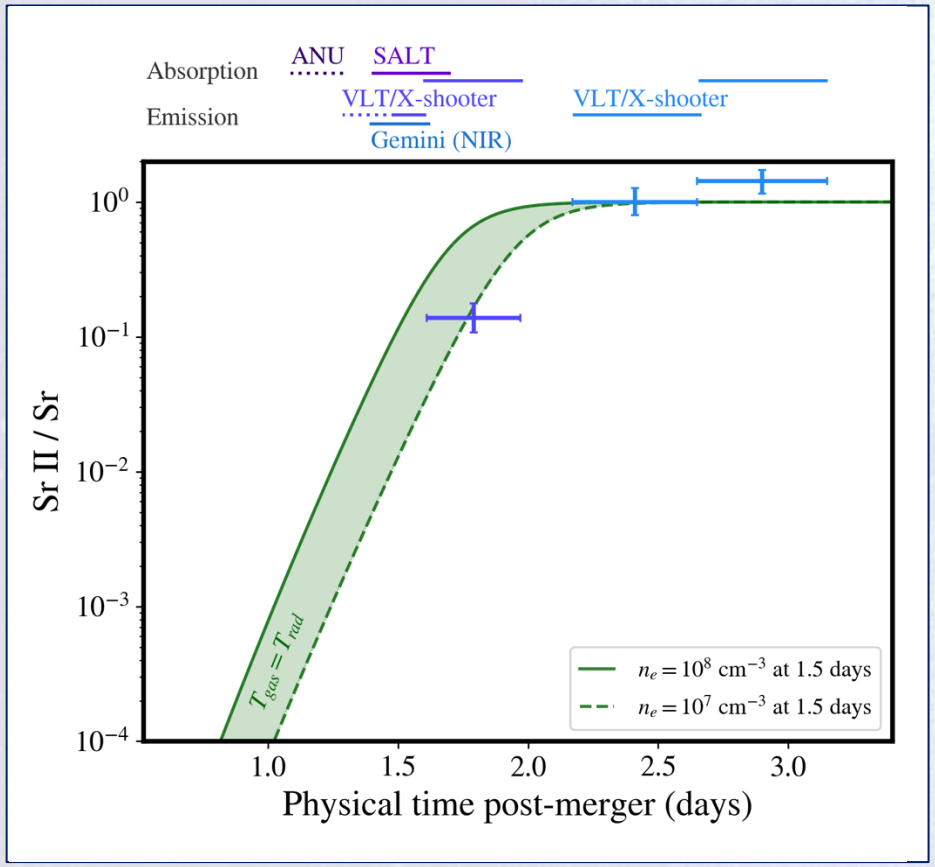
… A prediction we can now test!



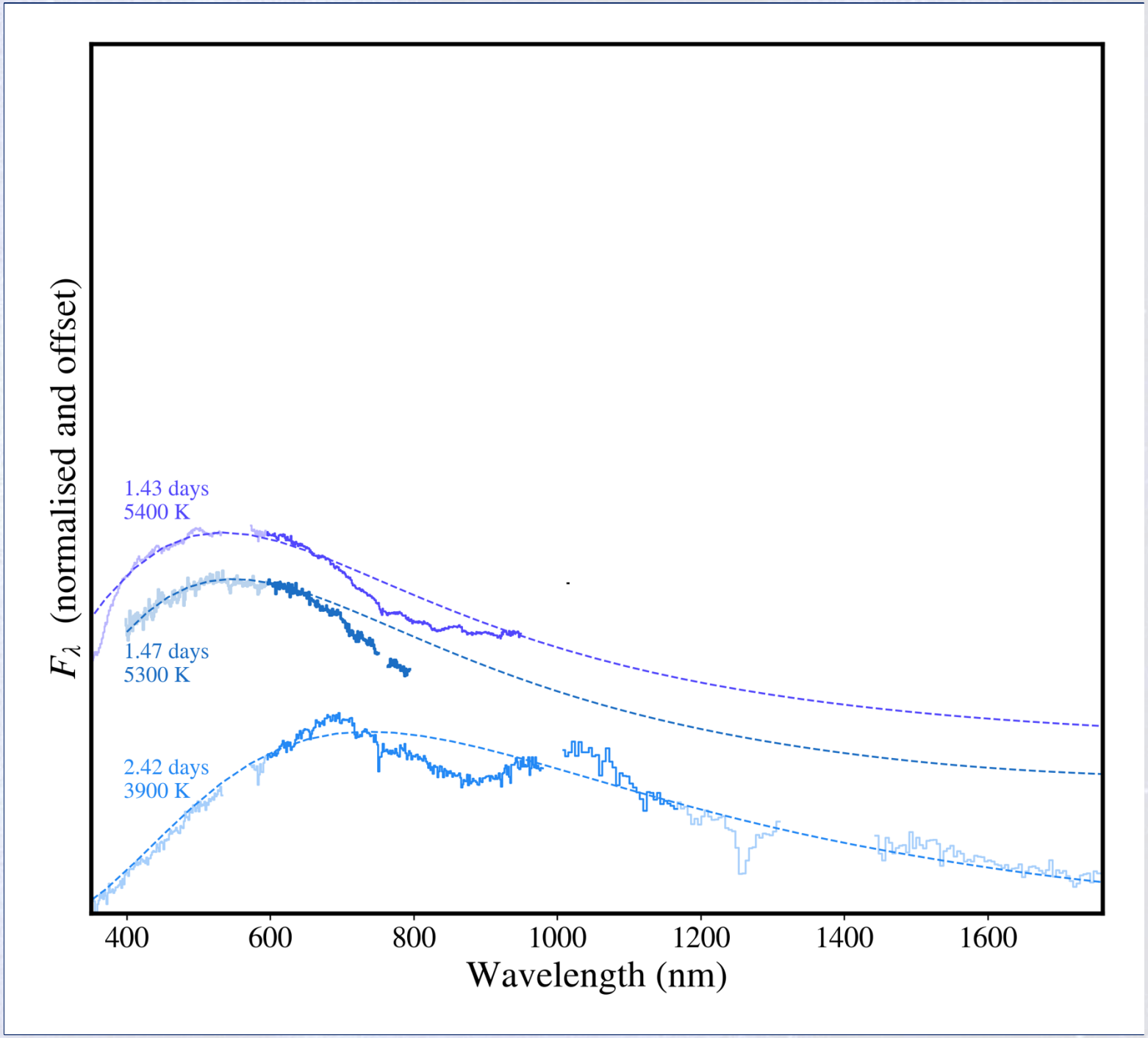
Sneppen et al (2024b)



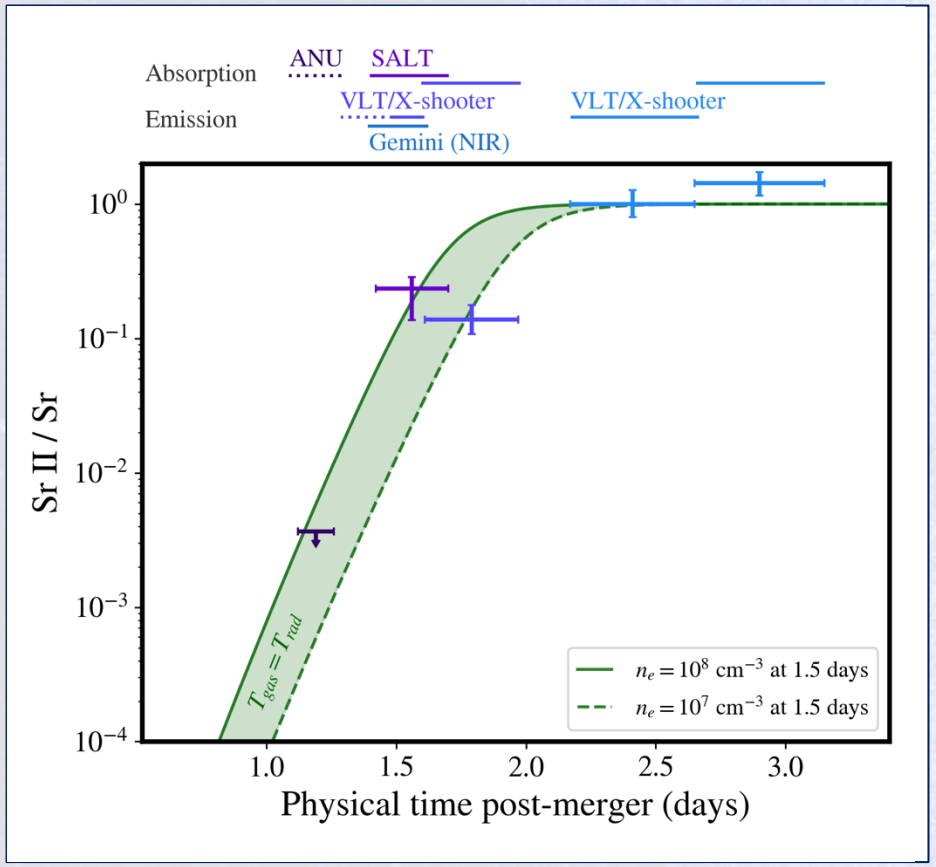
… A prediction we can now test!

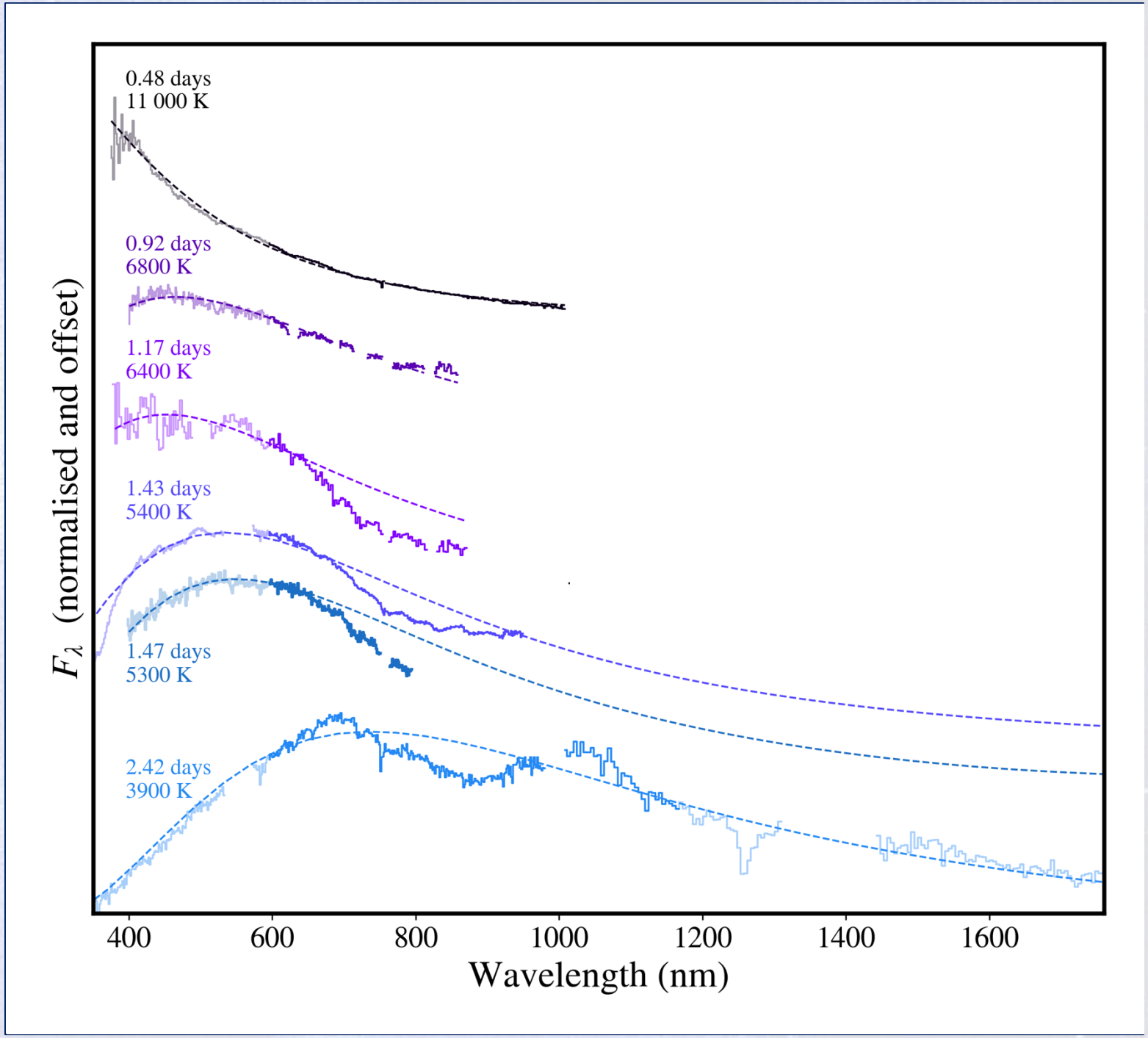


Sneppen et al (2024b)



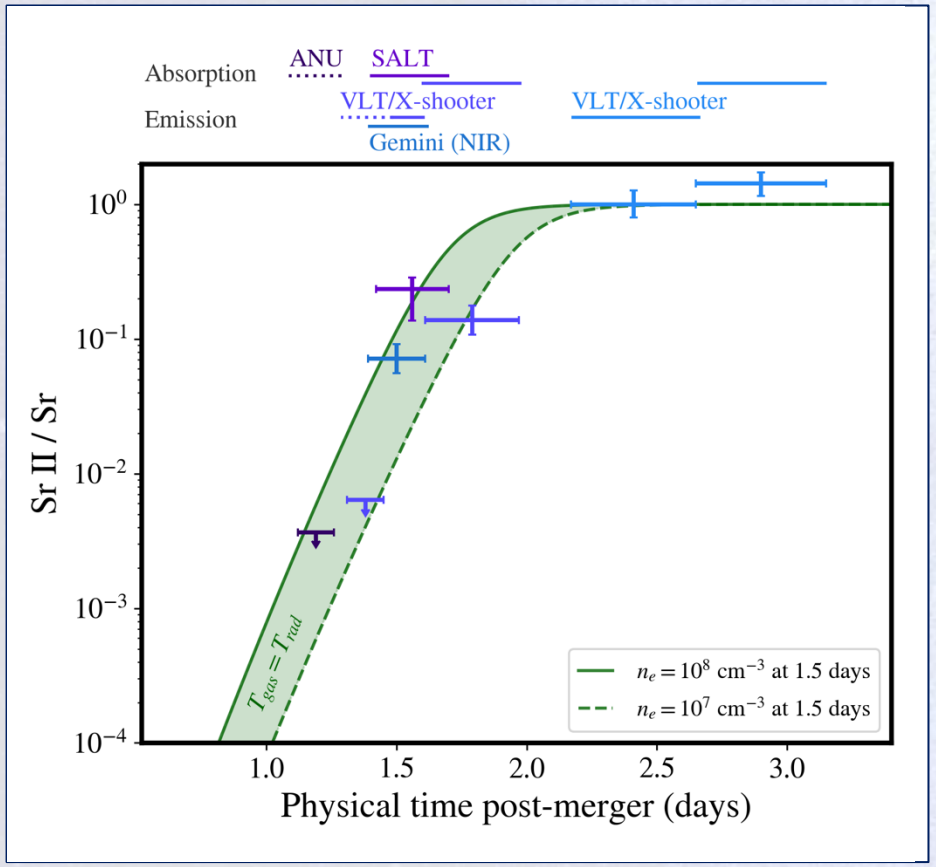
… A prediction we can now test!

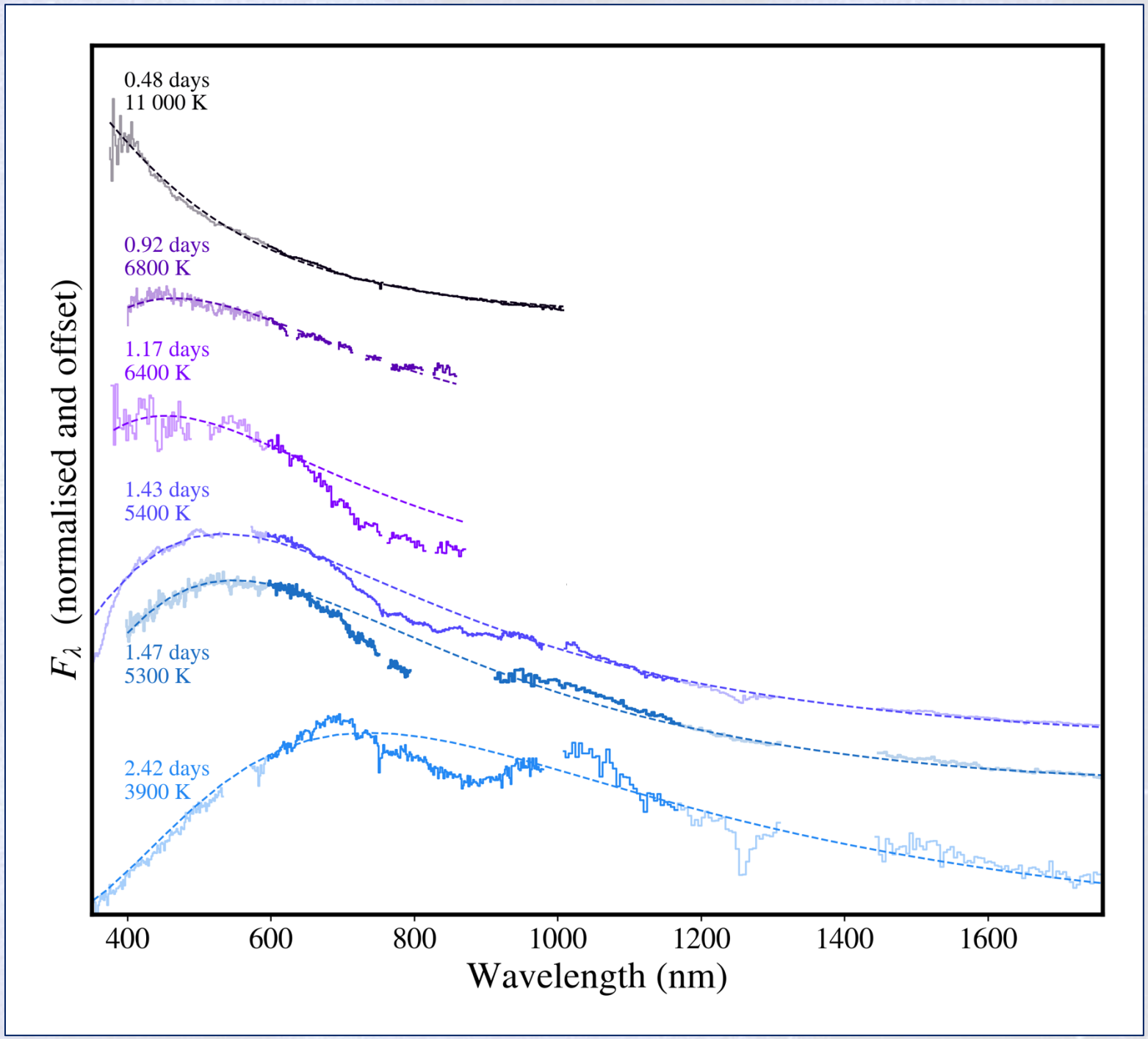




Sneppen et al (2024b)

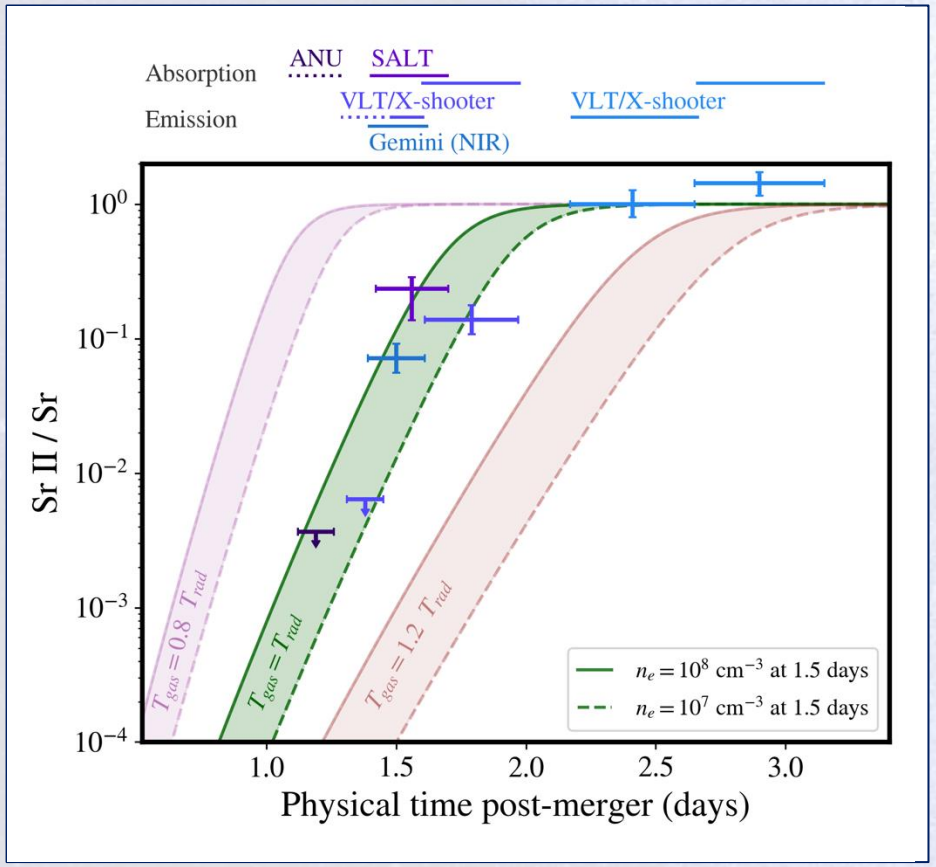
… A prediction we can now test!



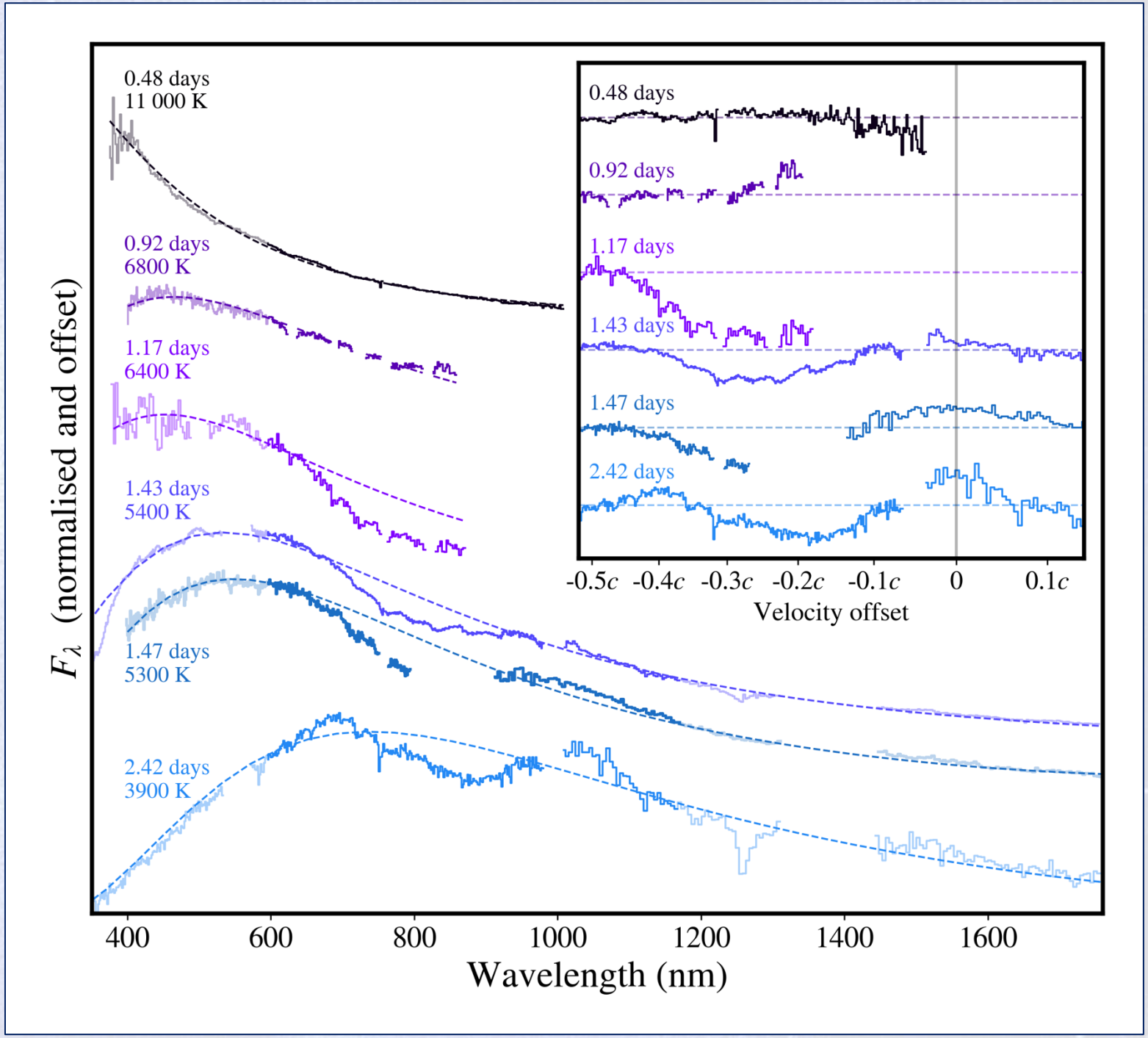


Sneppen et al (2024b)

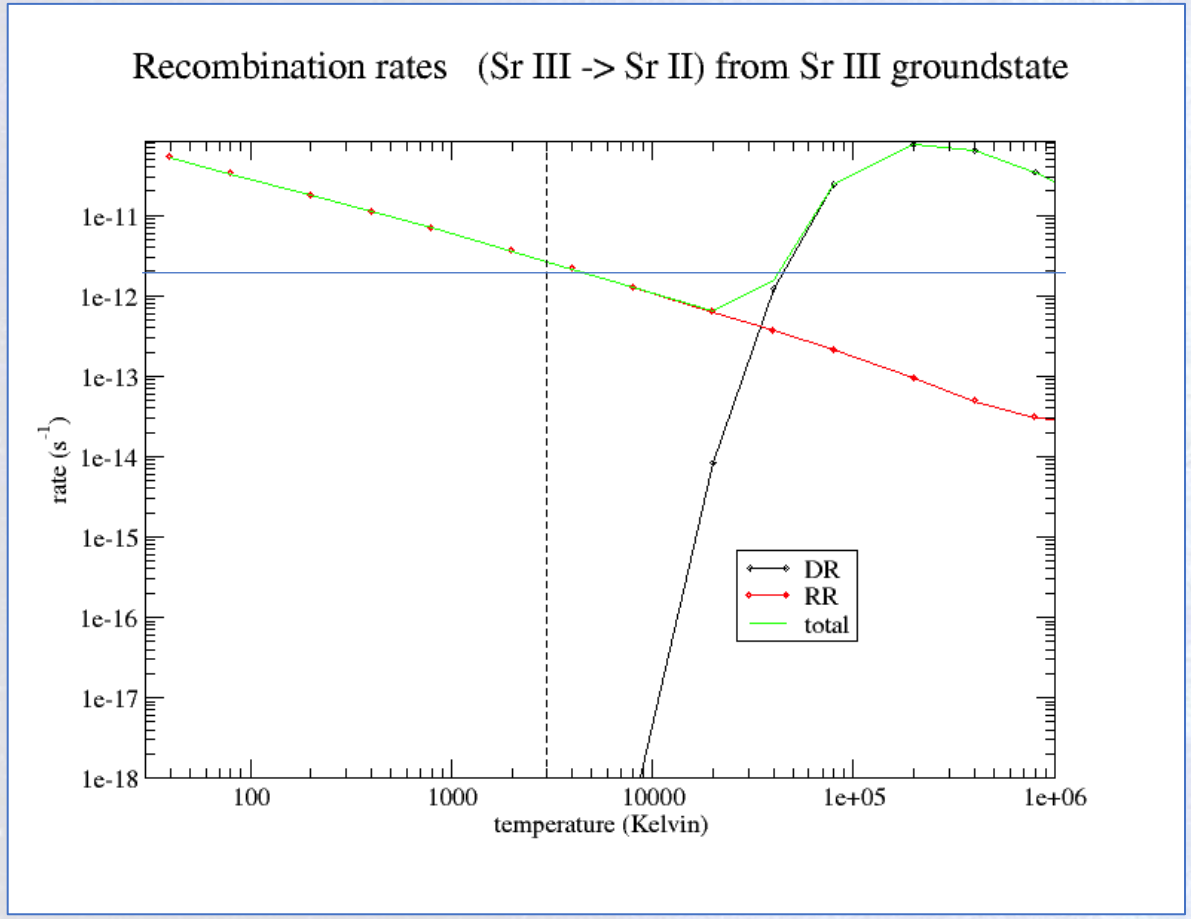
… A prediction we can now test!



Sneppen et al (2024b)



Local estimate of the KN electron-density



Data from C. Balance, Sneppen et al (2024b)

Local estimate of electron density:

$$n_e \alpha_{Sr\ III} > \frac{1}{t_{rec}}$$

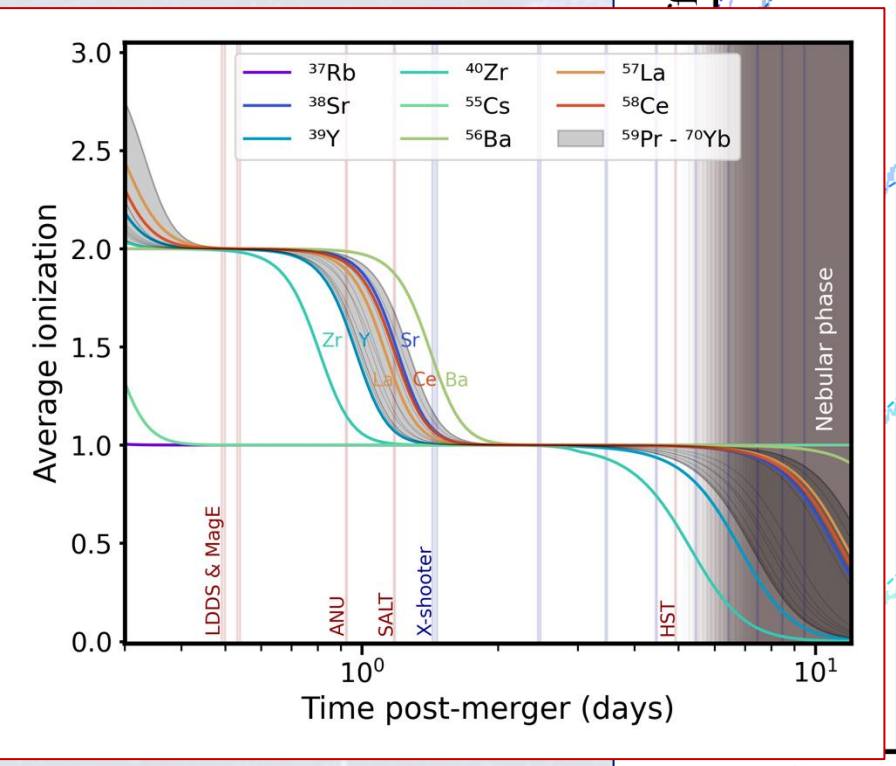
Formation in **absorption**

at **t ≈1.3-1.5 days**

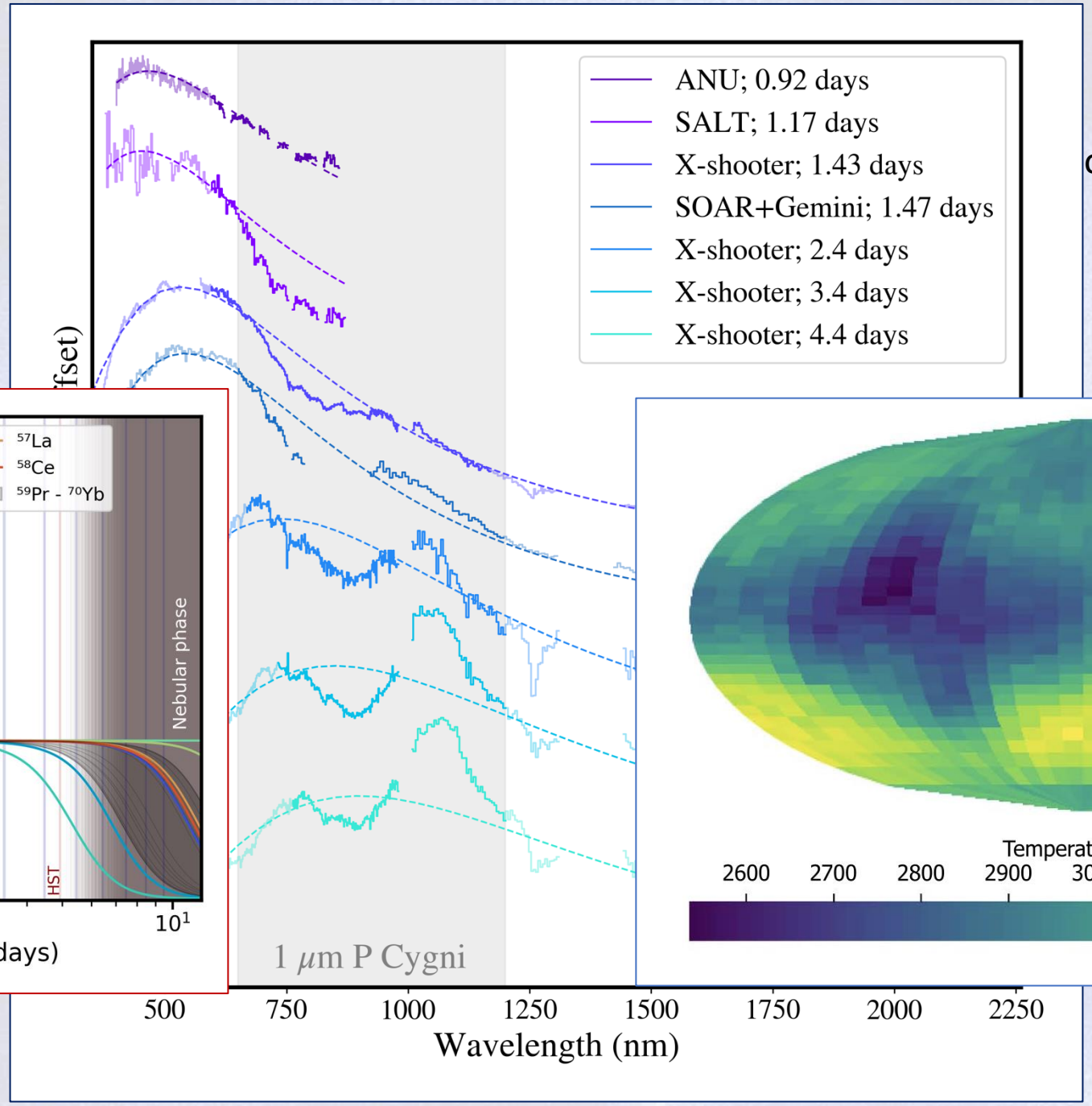
in physical time.

ormation in **emission** around

1.43-1.47 days post-merger



Sneppen et al (2024b)



Shingles et al (2023)

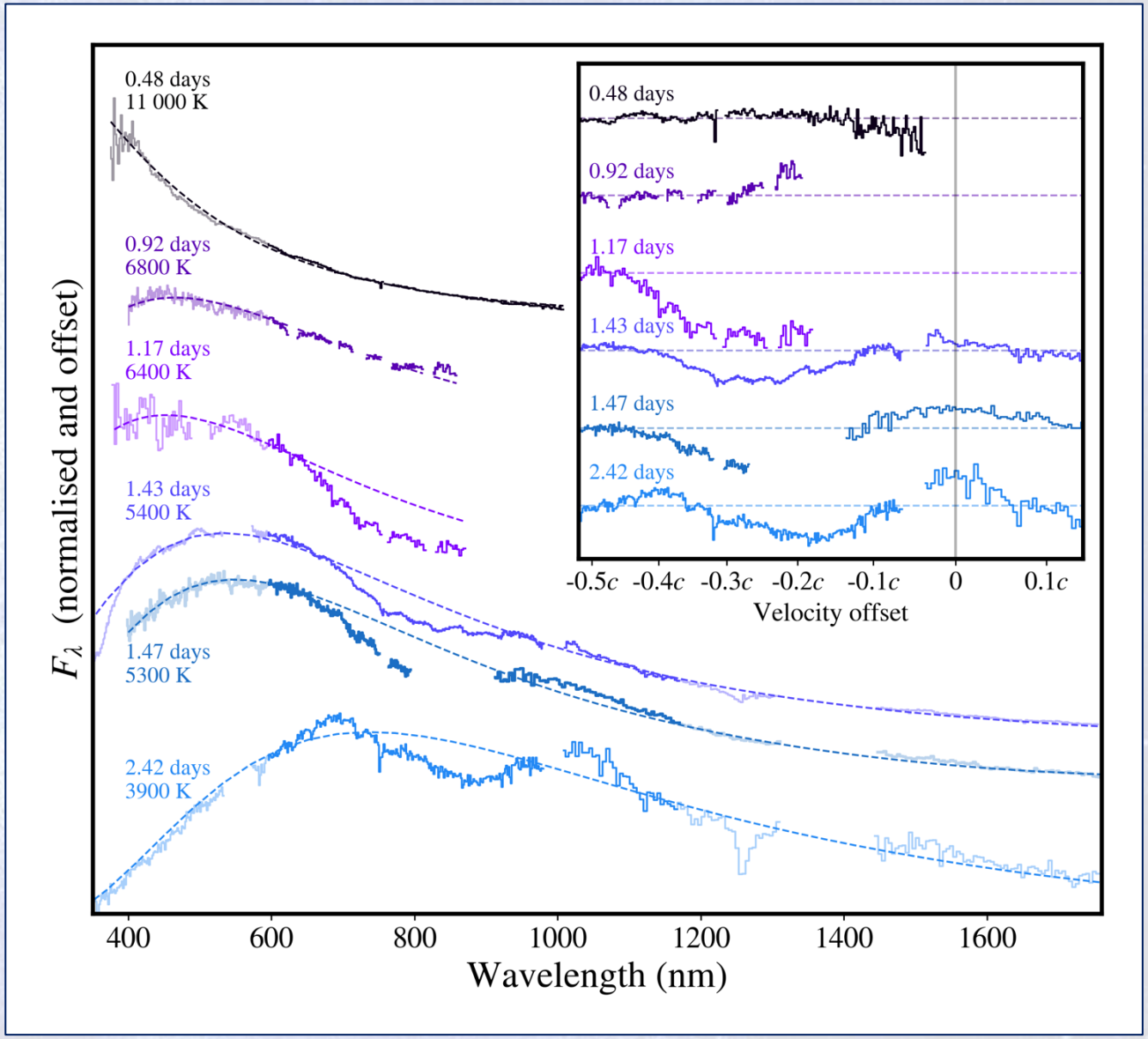
Take-aways from emergence

1) One should consider the temporal aspect even in interpreting an individual spectrum. We can see reverberation/recombination waves in the ejecta.

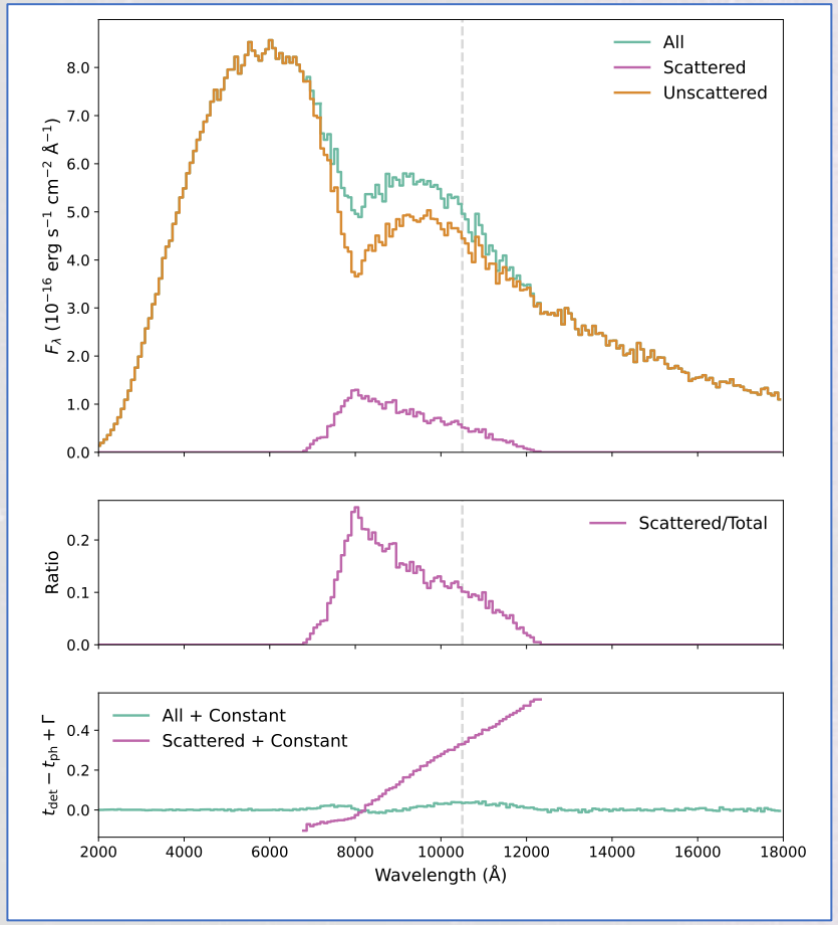
2) A feature's emergence and evolution provides direct observational test of LTE and nLTE line-IDs!

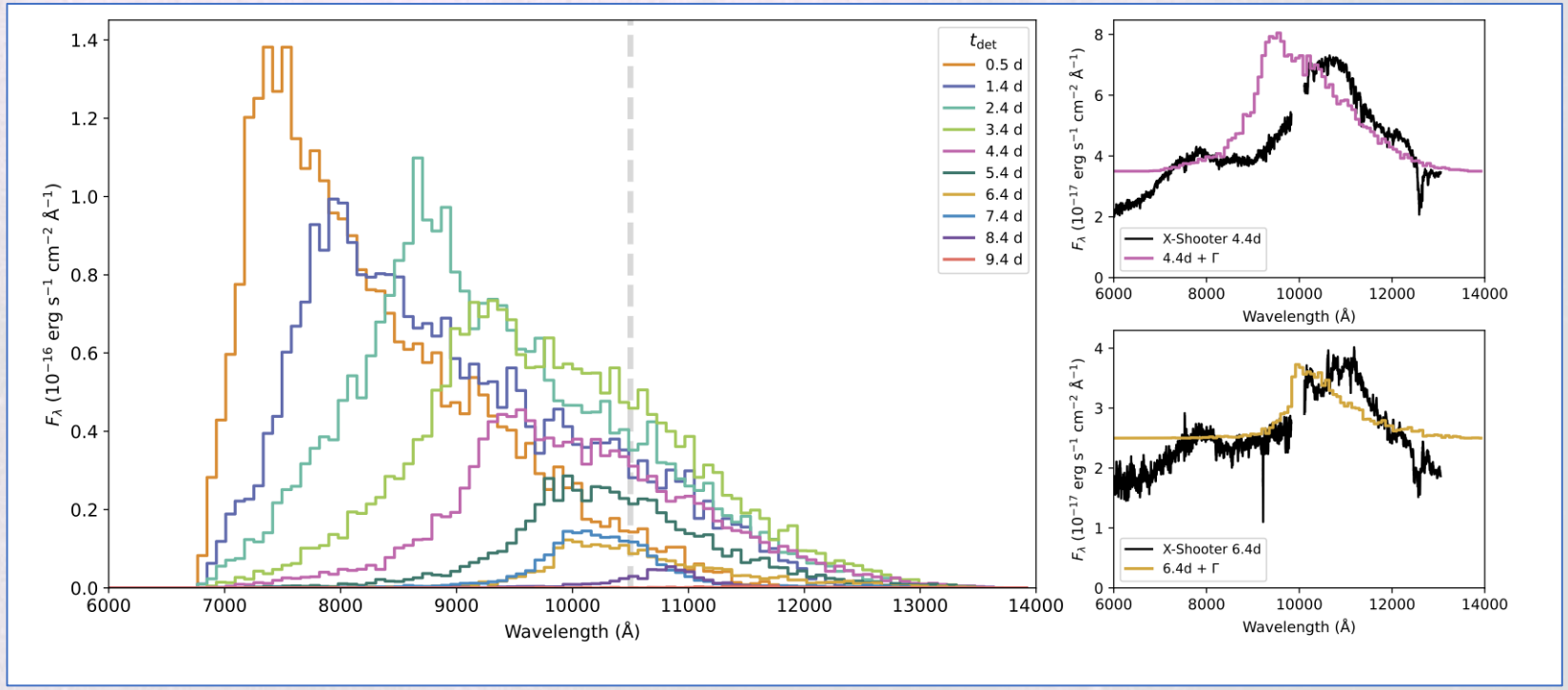
3) We are within 5% of the radiation-field inferred from the observed blackbody.

4) We can constrain n_e from recombination timescale; $n_e \sim 10^8 cm^{-3}$.



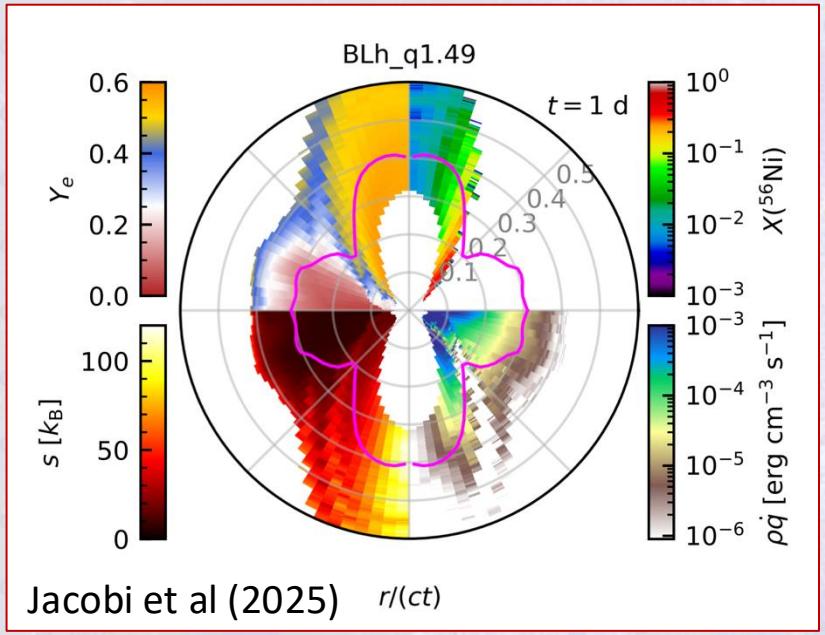
Reverberation in first principles modelling





See Poster 11 -- F. McNeill et al (2026), in press

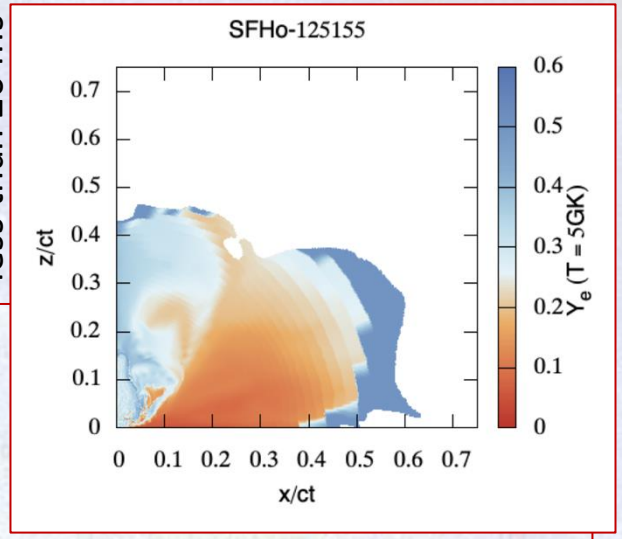
Pathway to helium

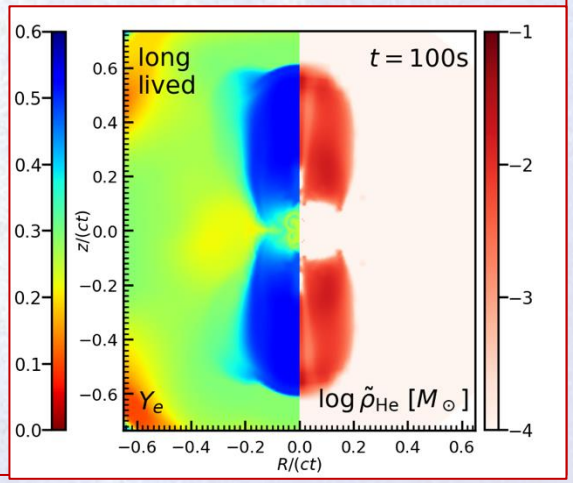


Jacobi et al (2025)

Sneppen, Just, Bauswein et al

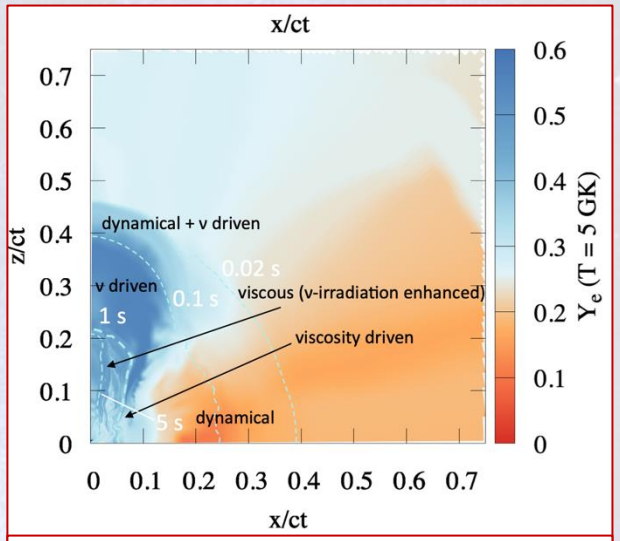
Kawaguchi et al (2023)
less than 20 ms



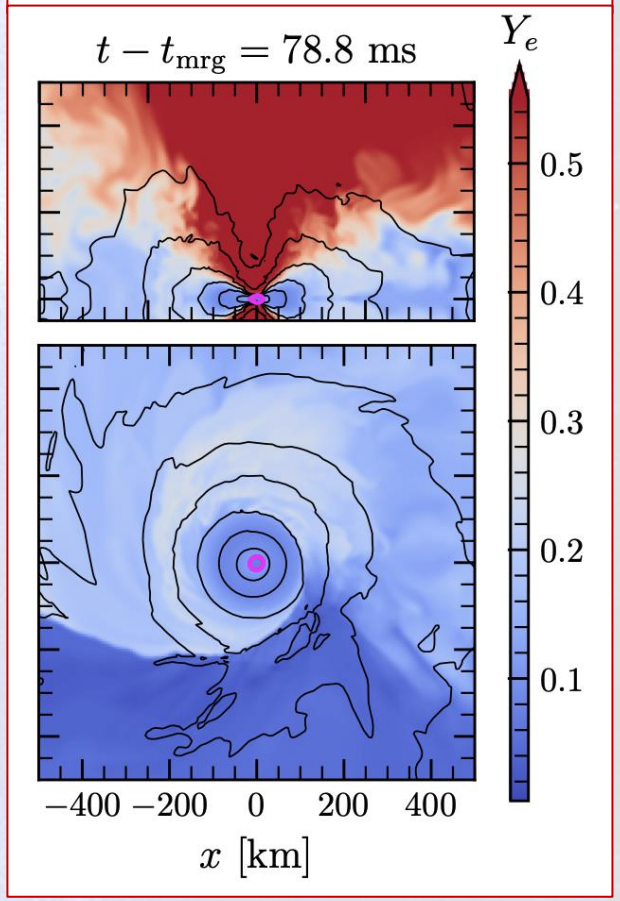


Model from Just et al (2023)

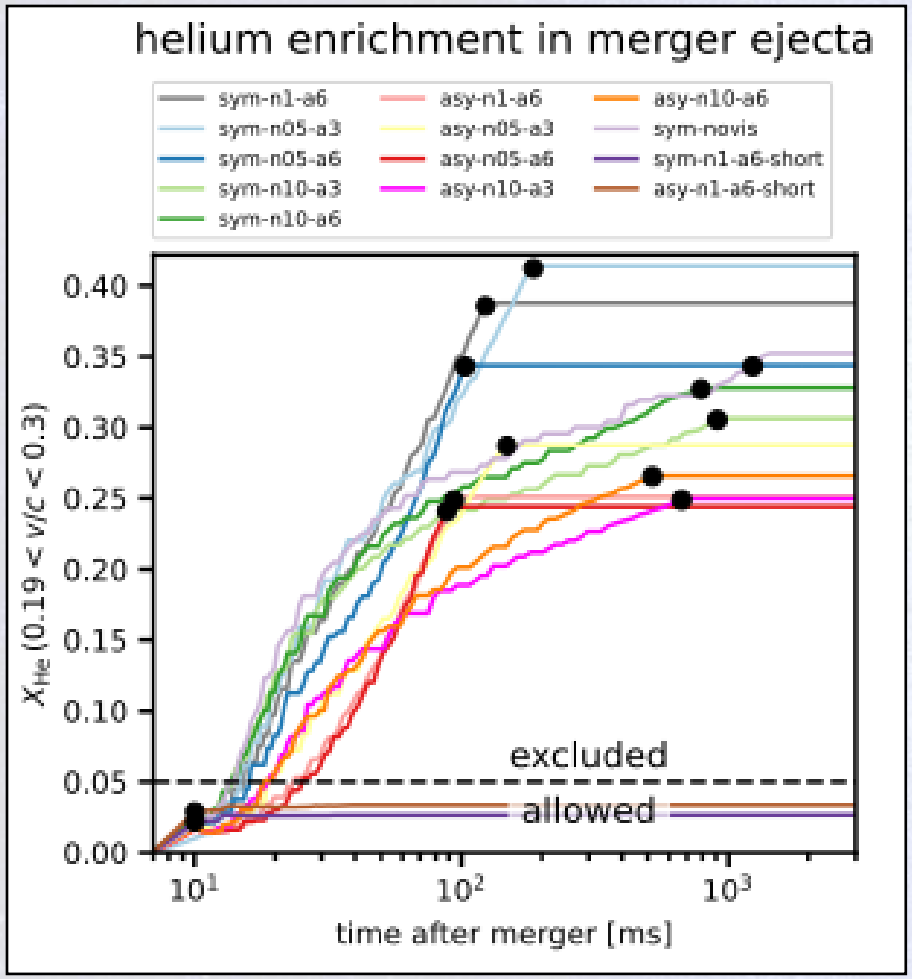
Kawaguchi et al (2022)
More than 0.5 s



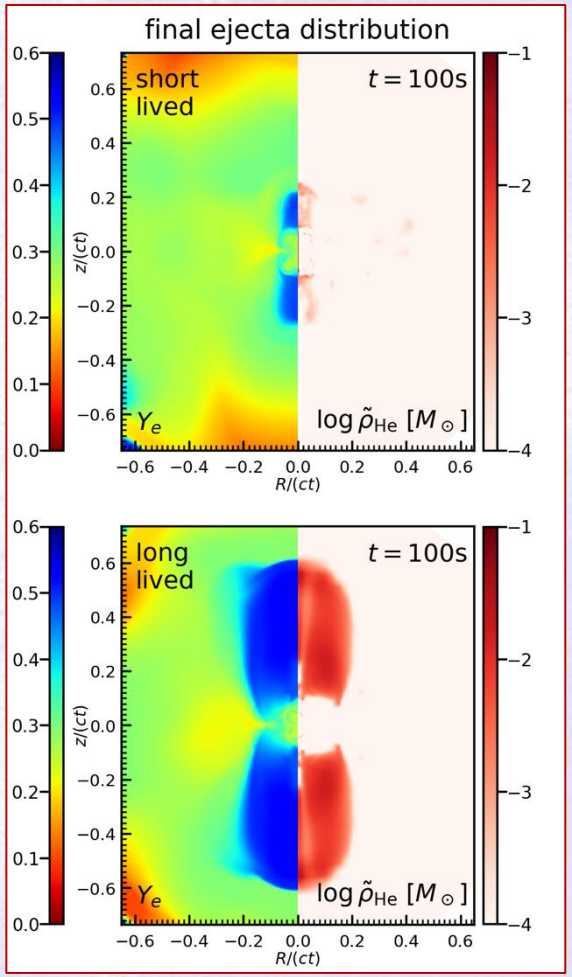
Bernuzzi et al (2024)



Helium production in neutron-star mergers



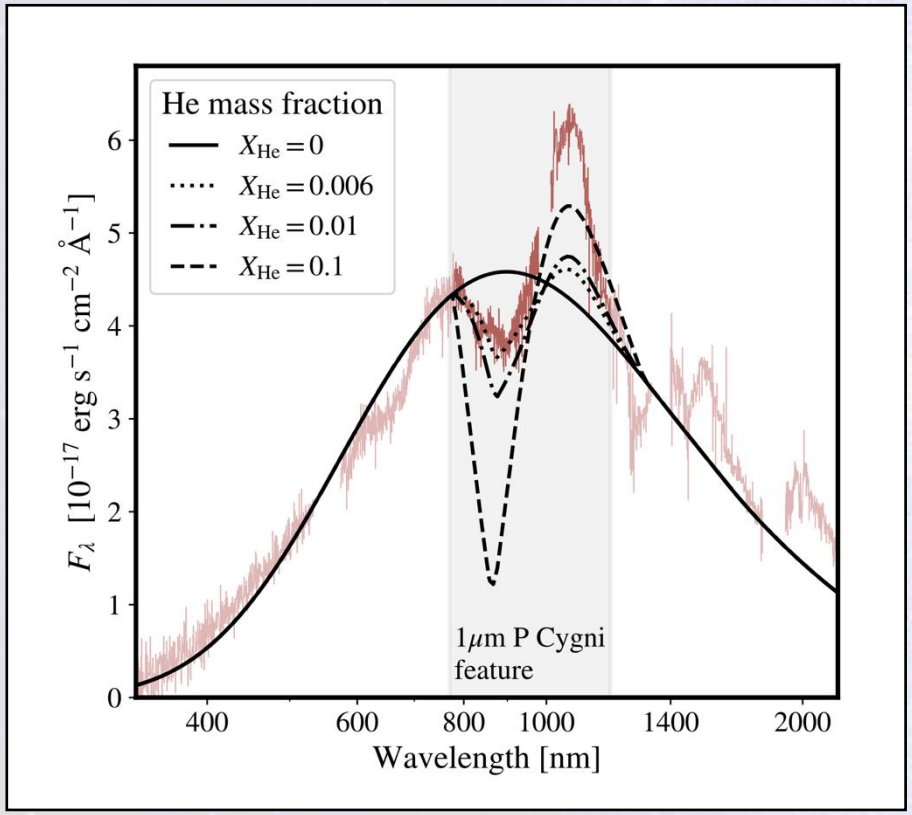
Sneppen, Just, Bauswein et al

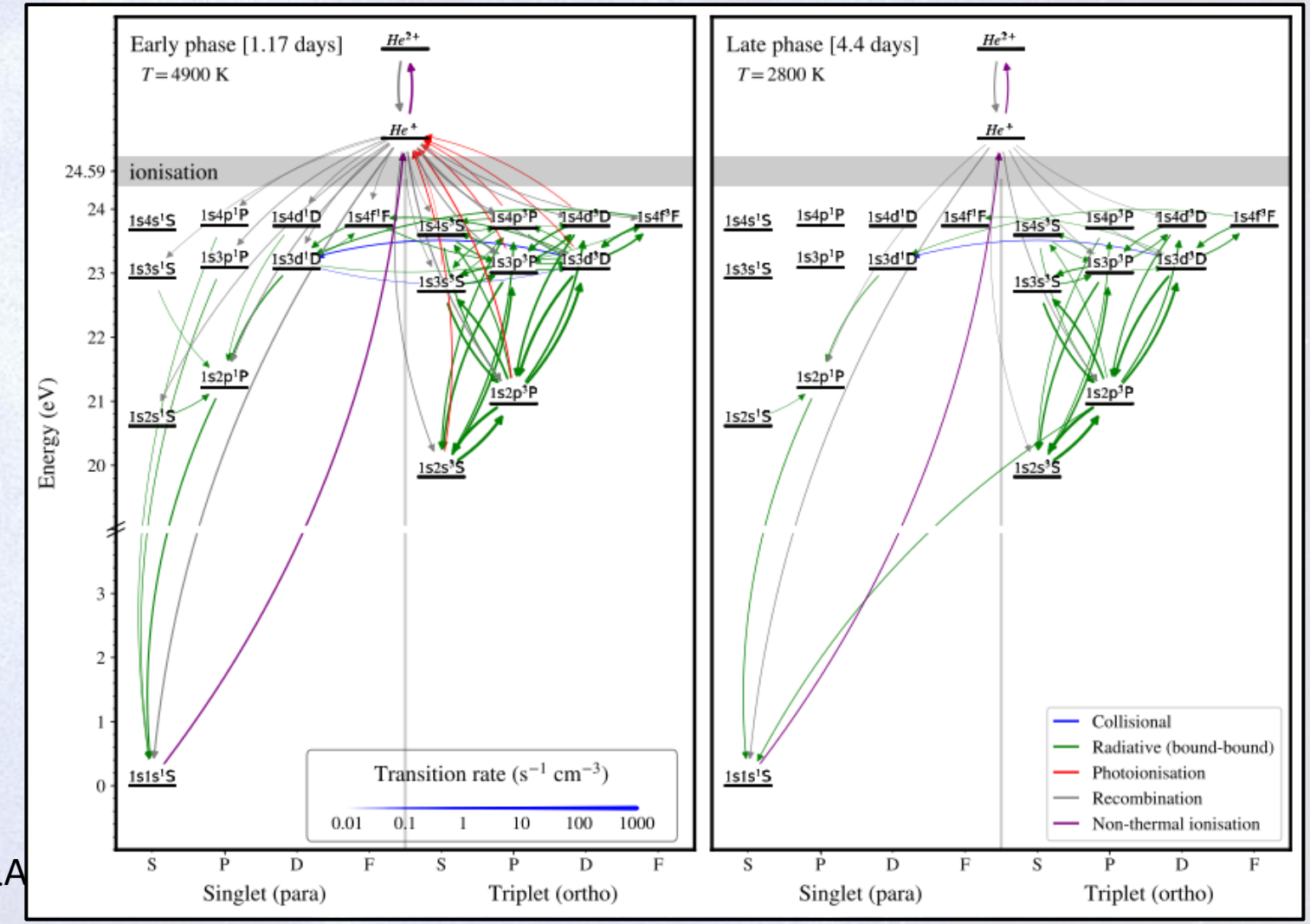


X_{He} - Helium mass fraction

Ie. fraction of mass which will end up as helium particles

He features should* be visible around 4-5 days…



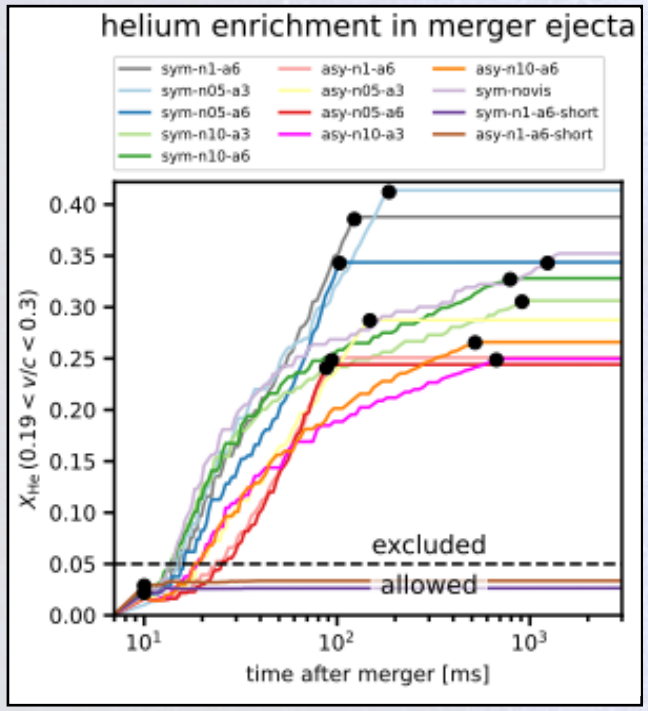


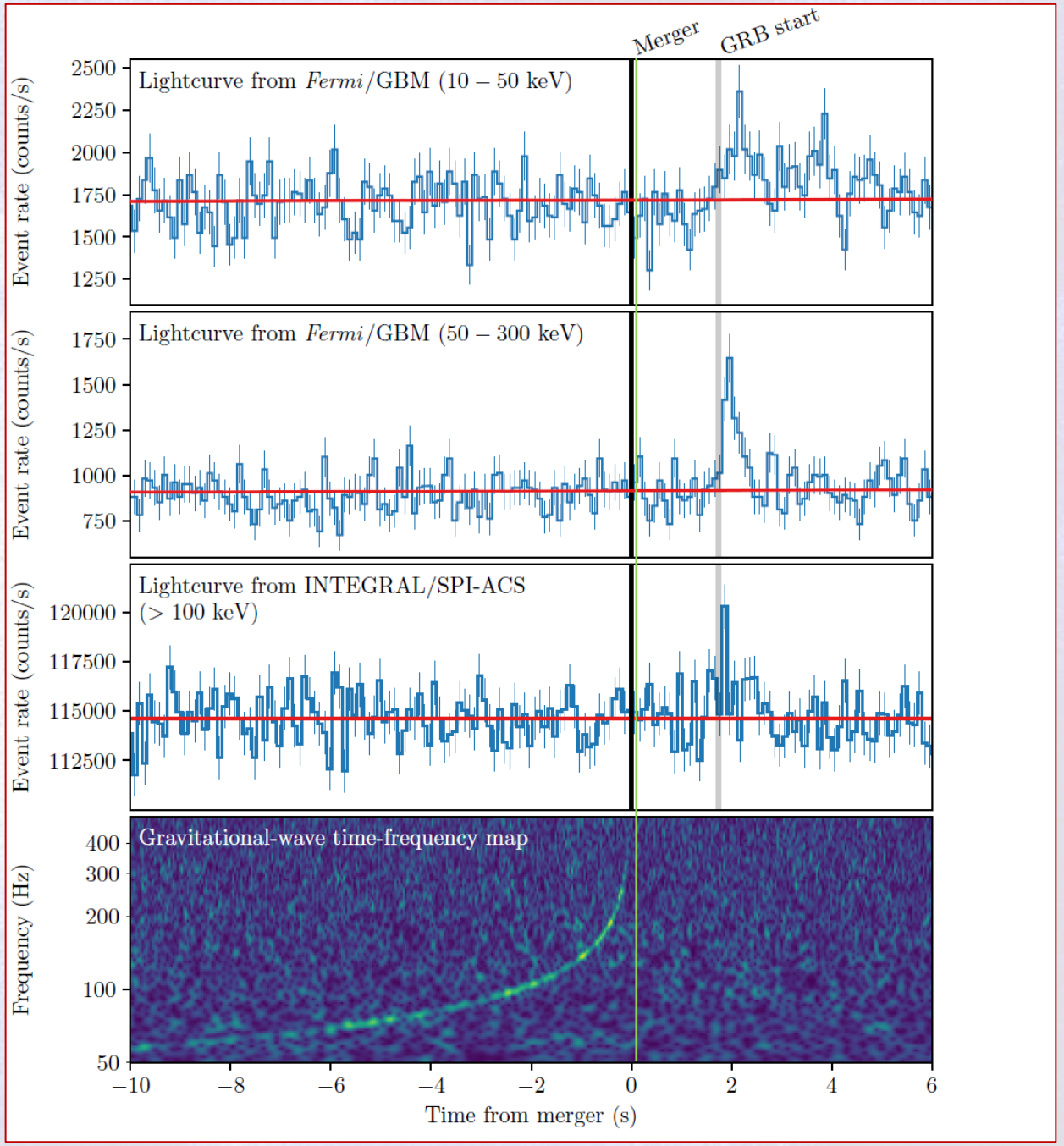
Sneppen, Damgaard & Watson et al (2024), A&A

sGRB implication

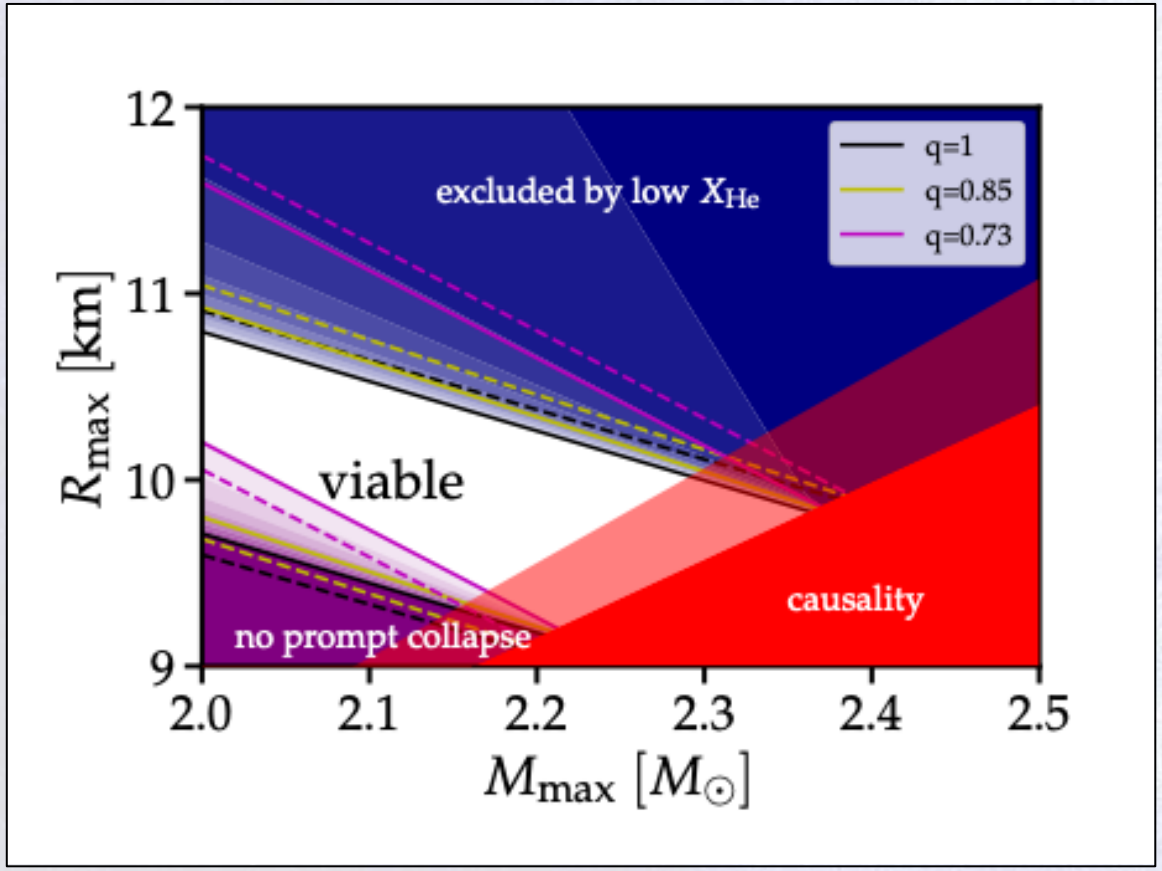
$t_{BH} \ll t_{GRB,start} - t_{GW}$

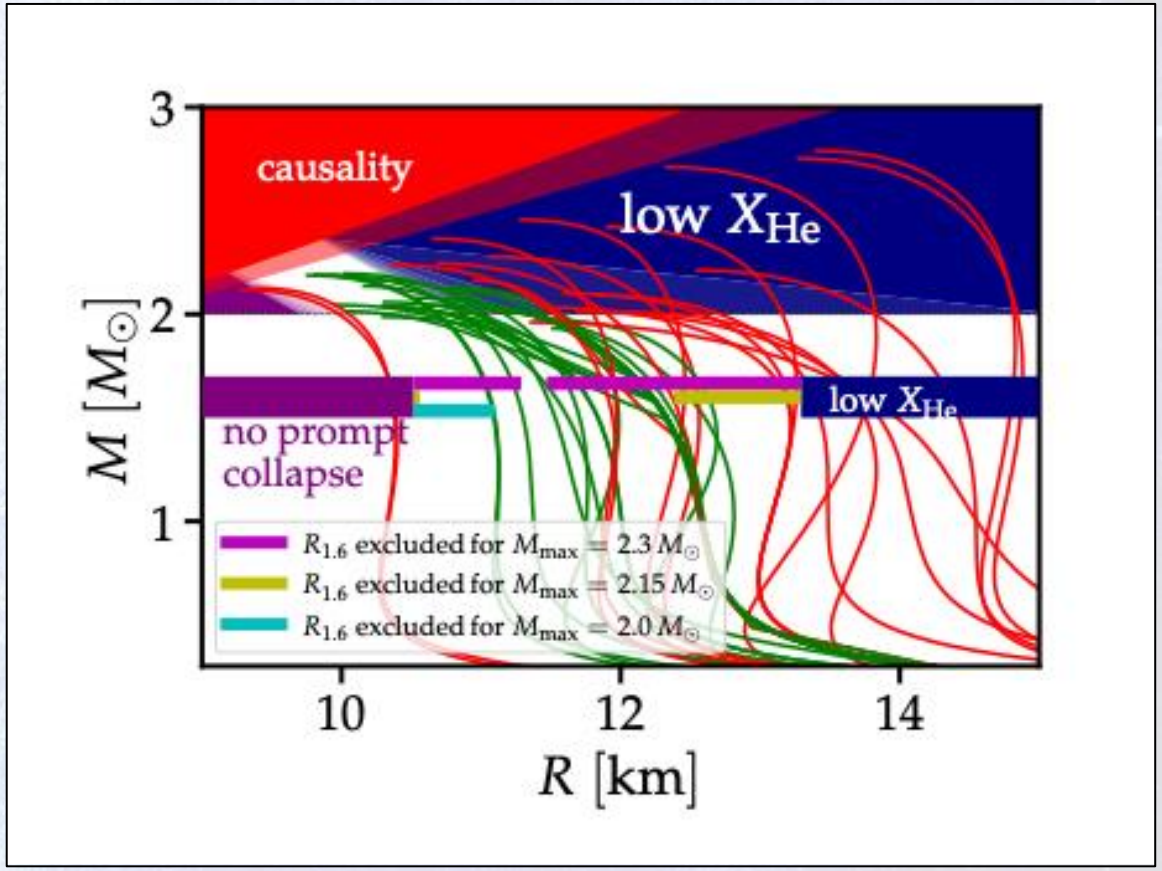
favours a Blandford–Znajek process (Black-hole torus engine) driving the jet.





Implications for nuclear equation of state



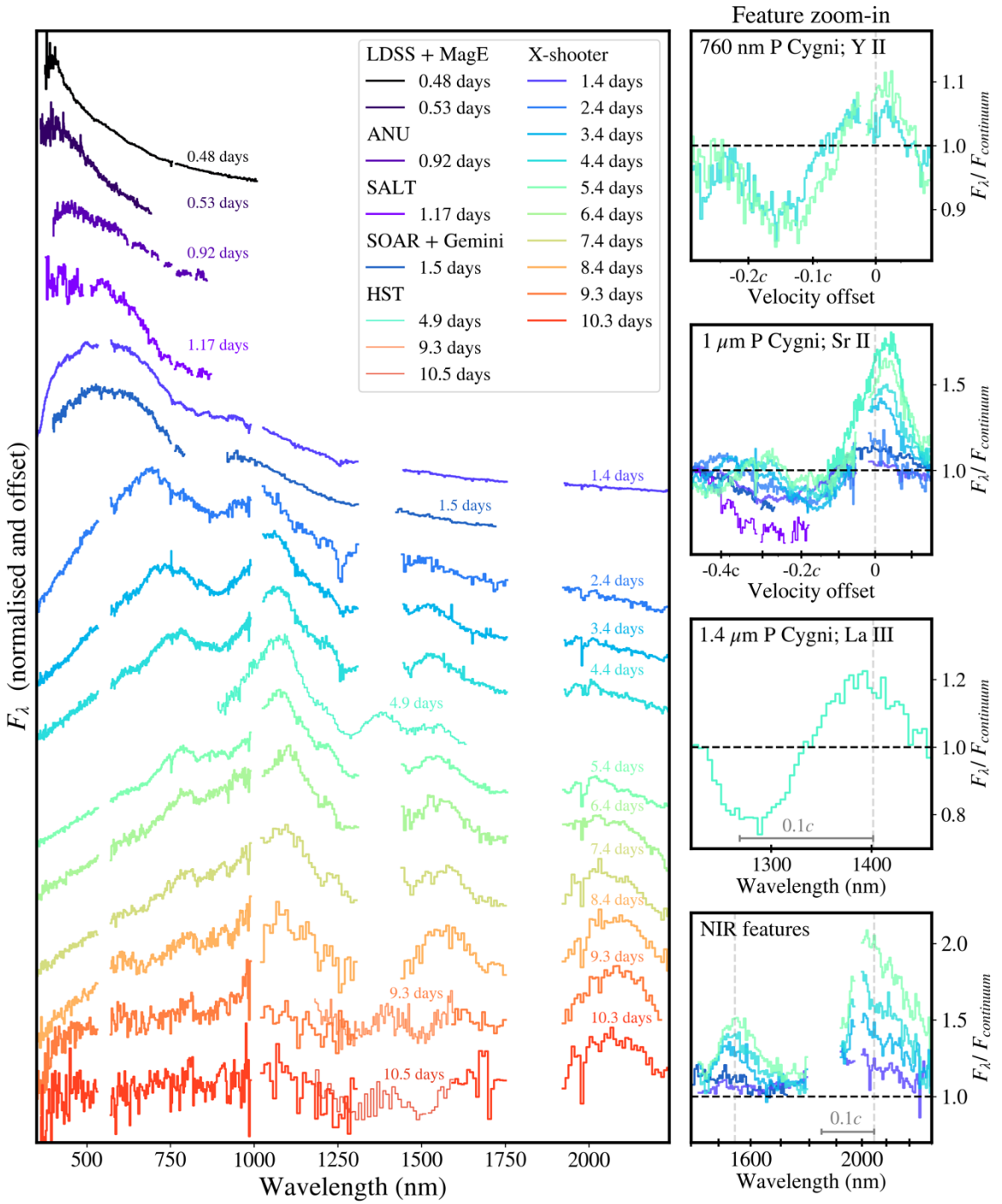


Sneppen et al (2024)

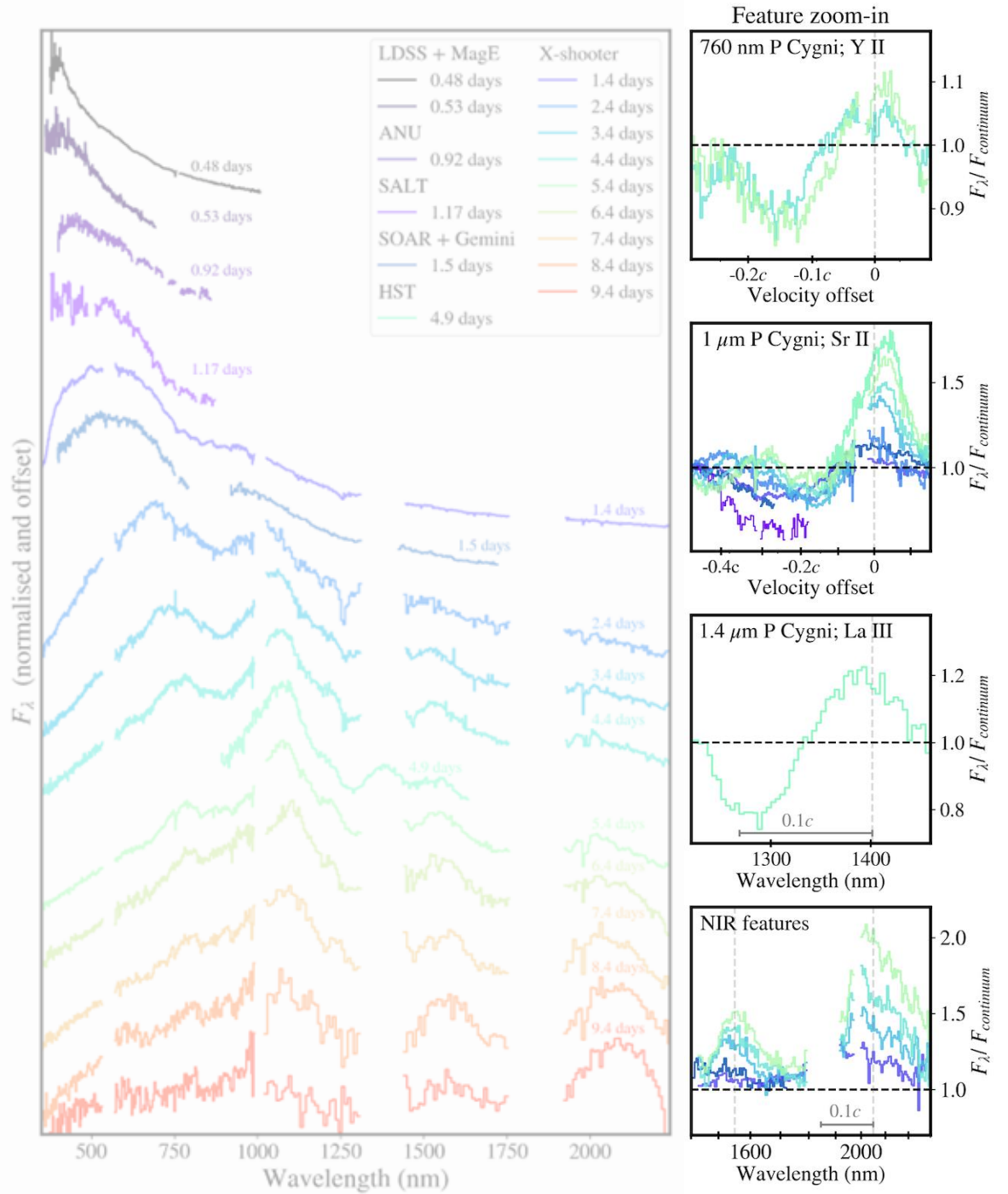
Thank you

Unified spectral data-series can be found at
https://github.com/Sneppen/Kilonova-analysis

Fig. 1 from Sneppen et al (2024b); Data from LDSS + MagE [Shappee et al, 2017], ANU [Andreoni et al, 2017], SALT [Buckley et al, 2018], X-shooter [Pian et al, 2017; Smartt et al, 2017], SOAR [Chornock et al, 2017], Gemini [Nicholl et al, 2017], HST [Tanvir et al, 2017]

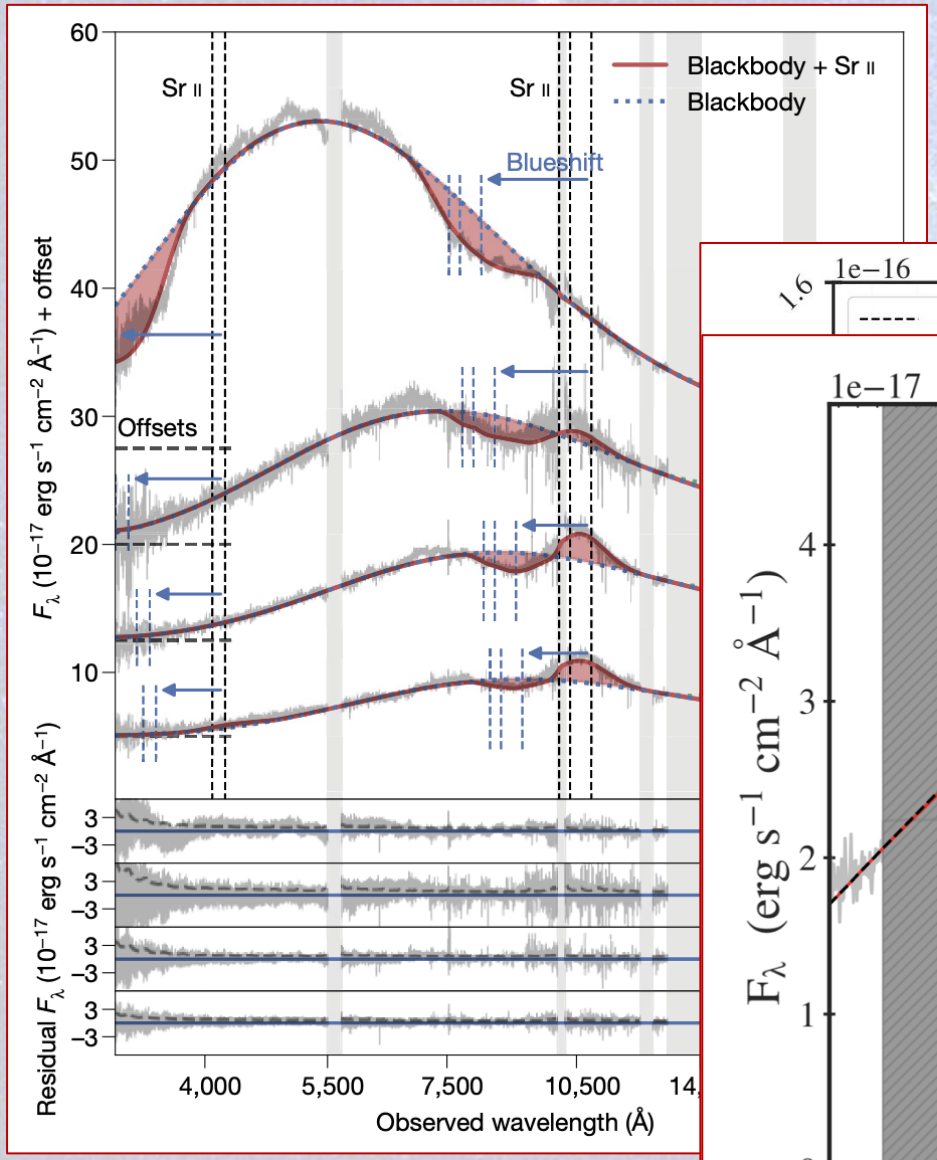


Ubiquity of P Cygni

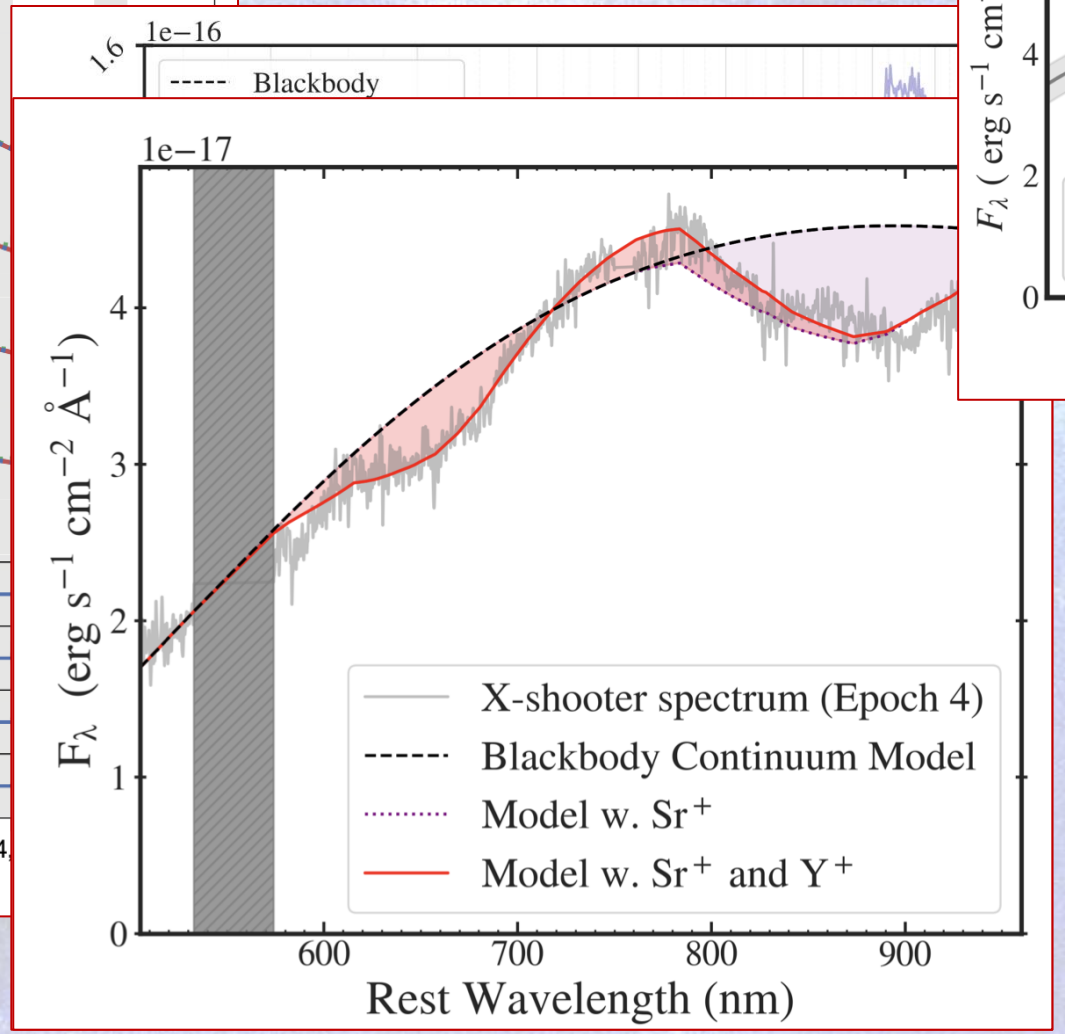


Sneppen et al (2024b)

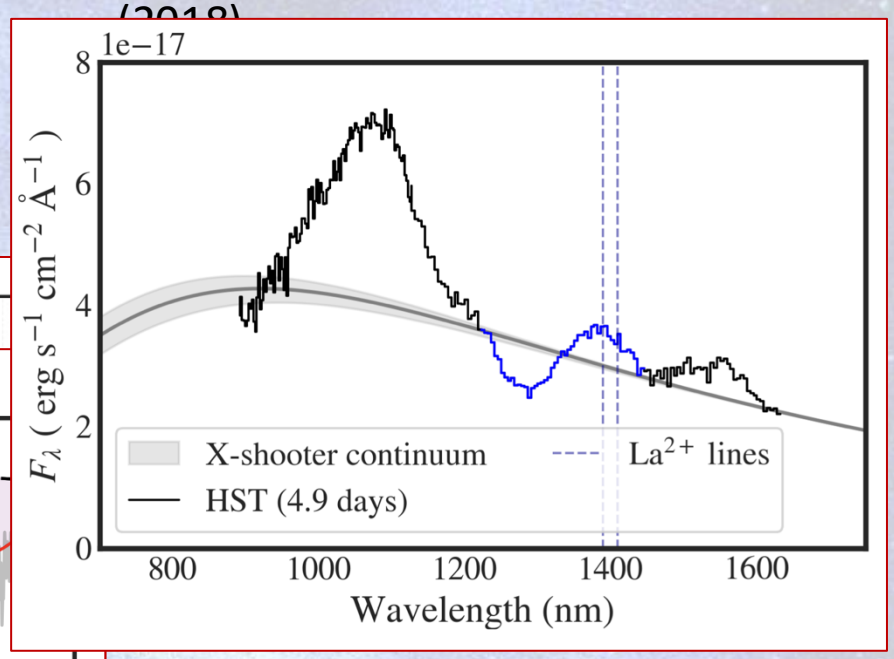
Data from Pian et al (2017), Smartt et al (2017), Tanvir et al (2018)



Watson et al. (2019)



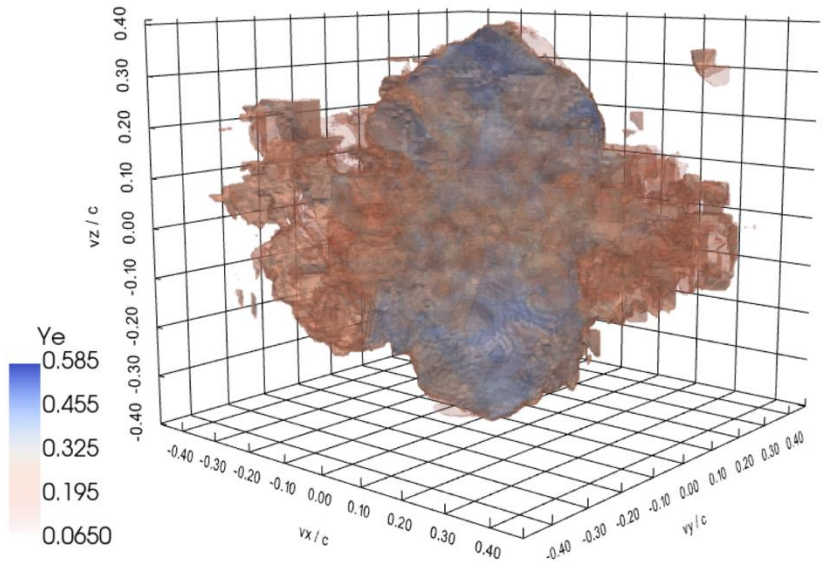
Sneppen et al. (2023b)

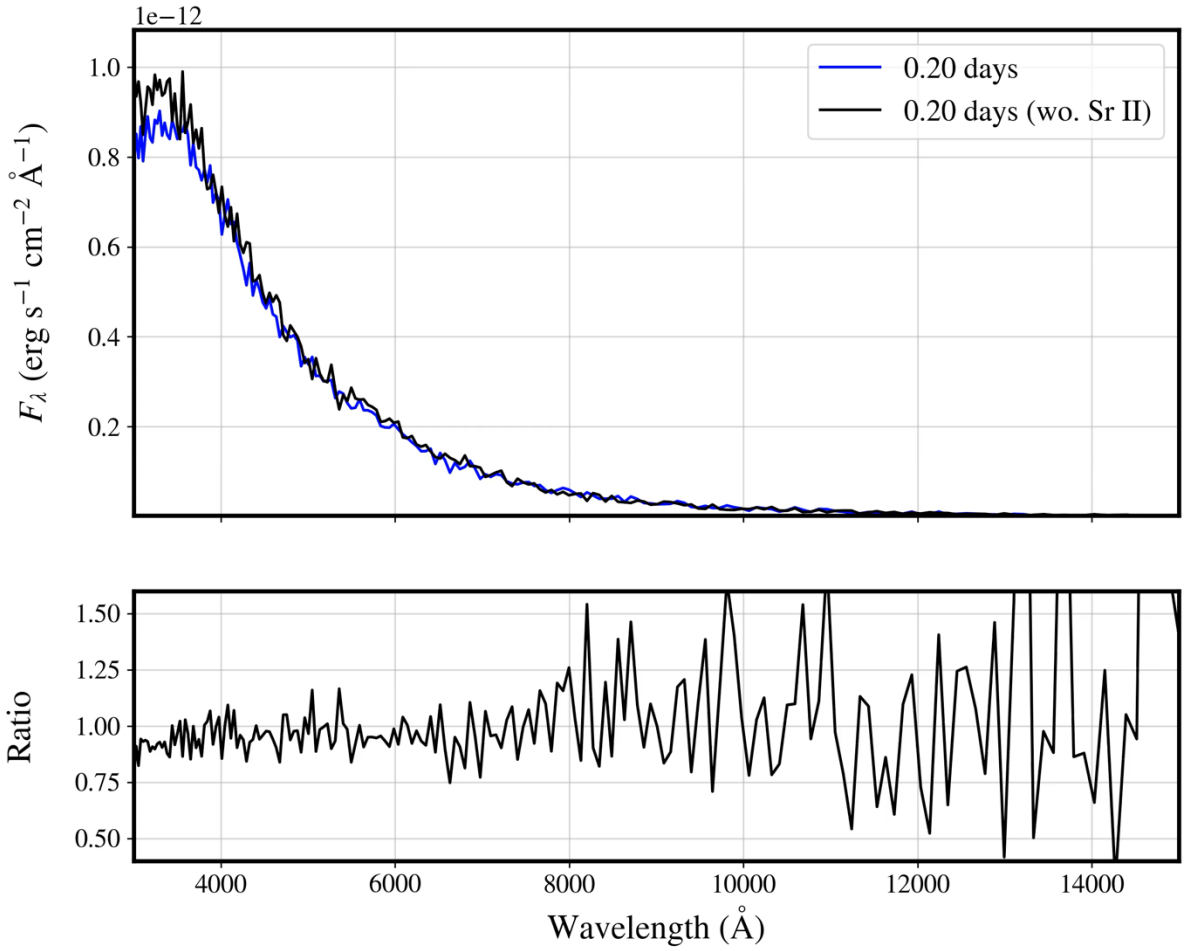


La III proposed in Domoto et al (2022)

[Plot from Sneppen et al. (2024b)]

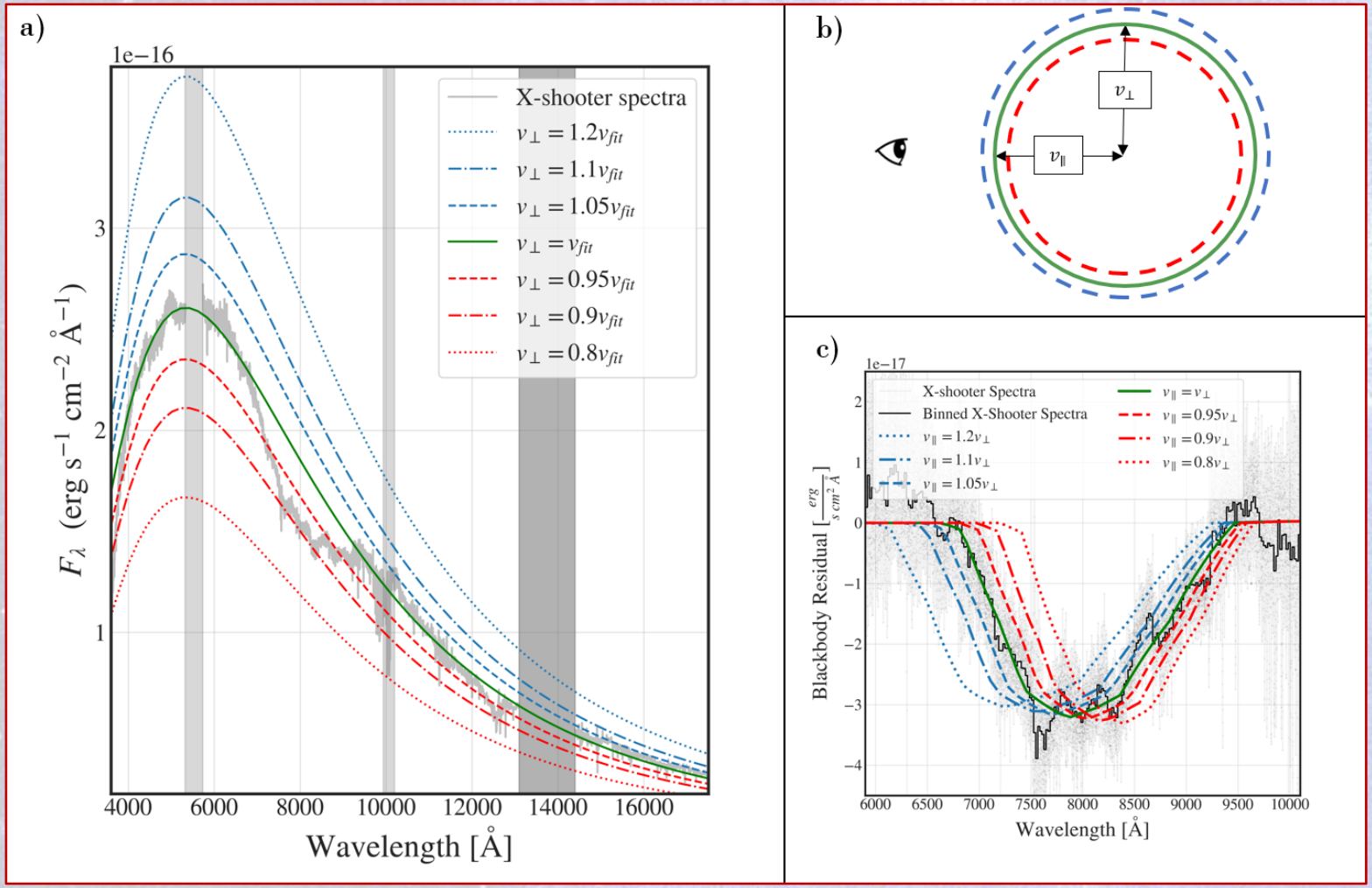
“Kilonova in a computer”





See
Shingles et al (2023)
Collins et al (2024)

The Expanding Photosphere Method



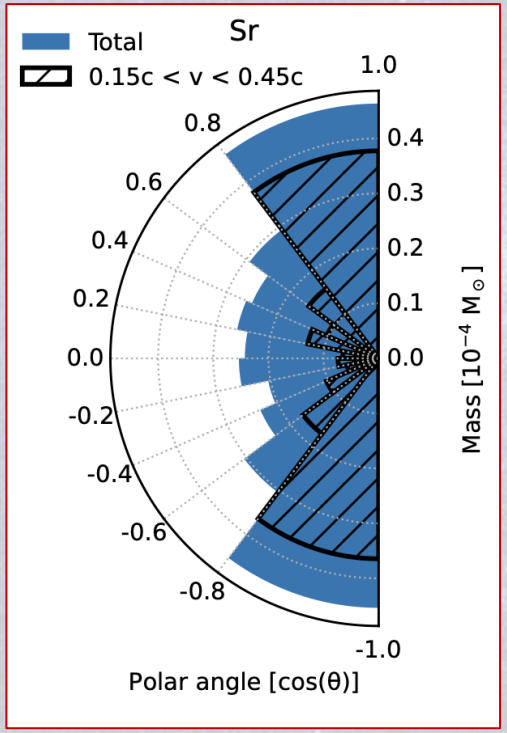
Sneppen et al (2023)

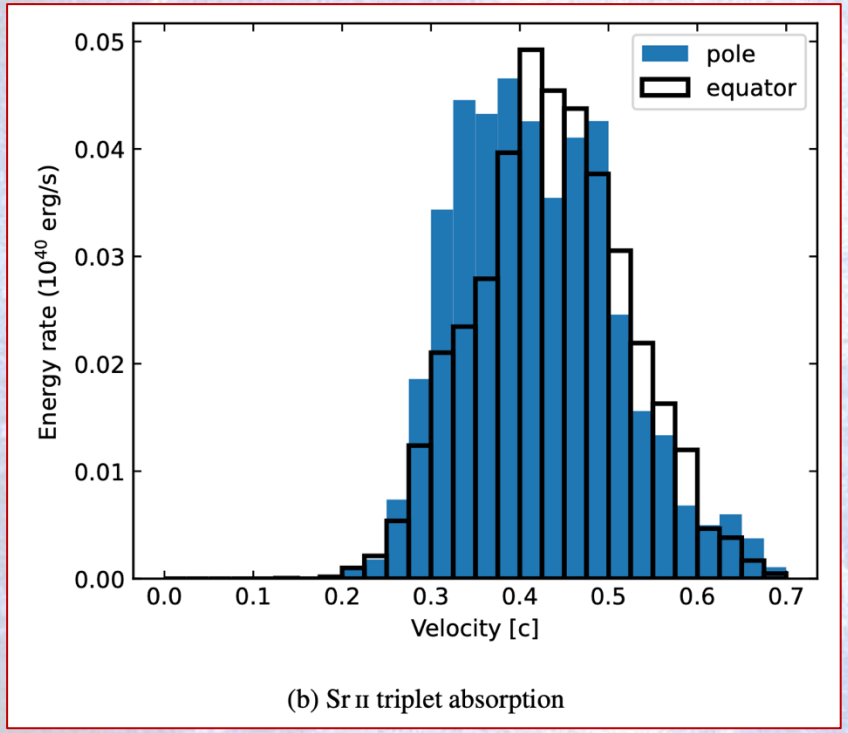
$v_\perp$: The cross-sectional velocity (inferred from the continuum luminosity)

$v_\parallel$: The velocity along the line-of-sight (inferred from the 1 μm P Cygni)

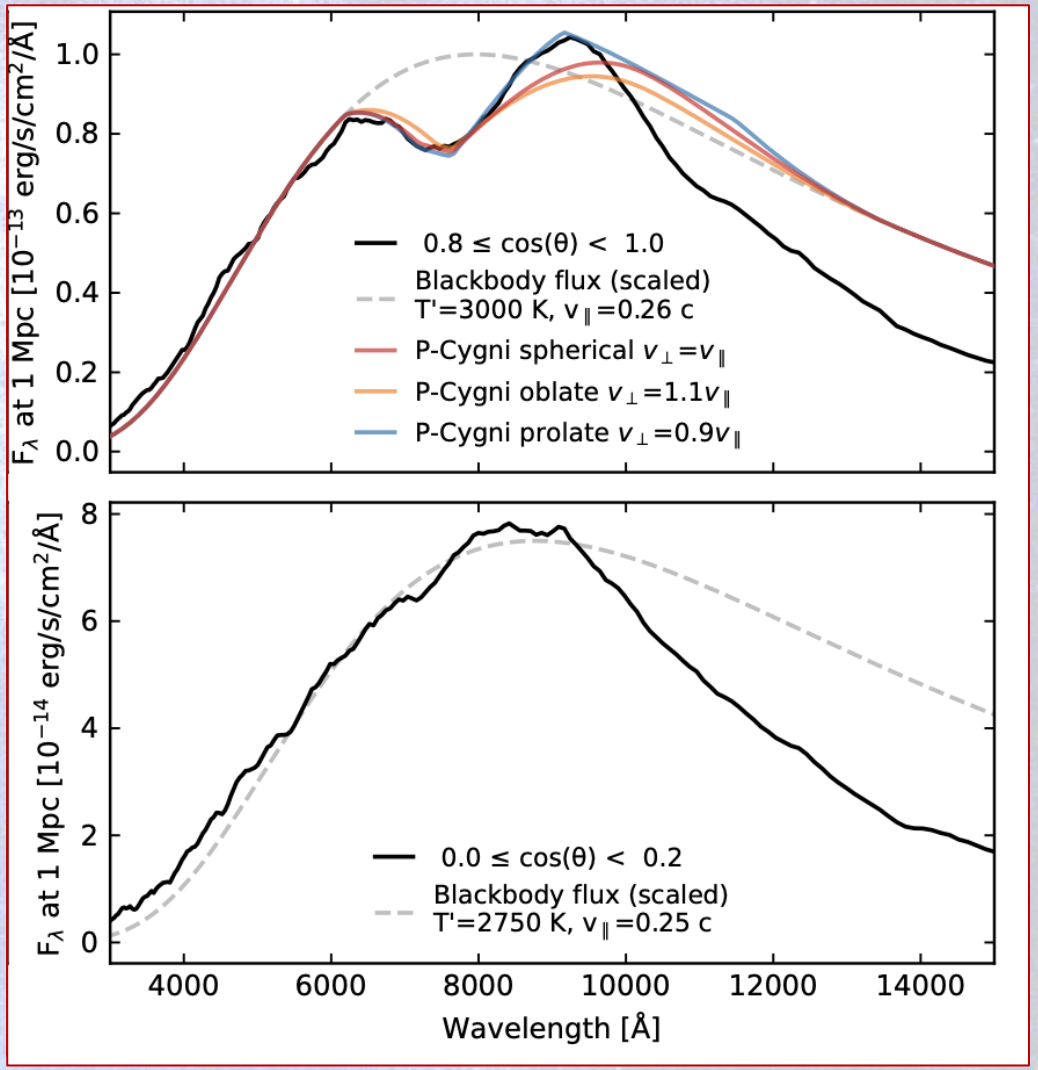
$$\Upsilon = \frac{v_\parallel - v_\perp}{v_\parallel + v_\perp}$$

Sphericity sufficient -- but is it neccesary?



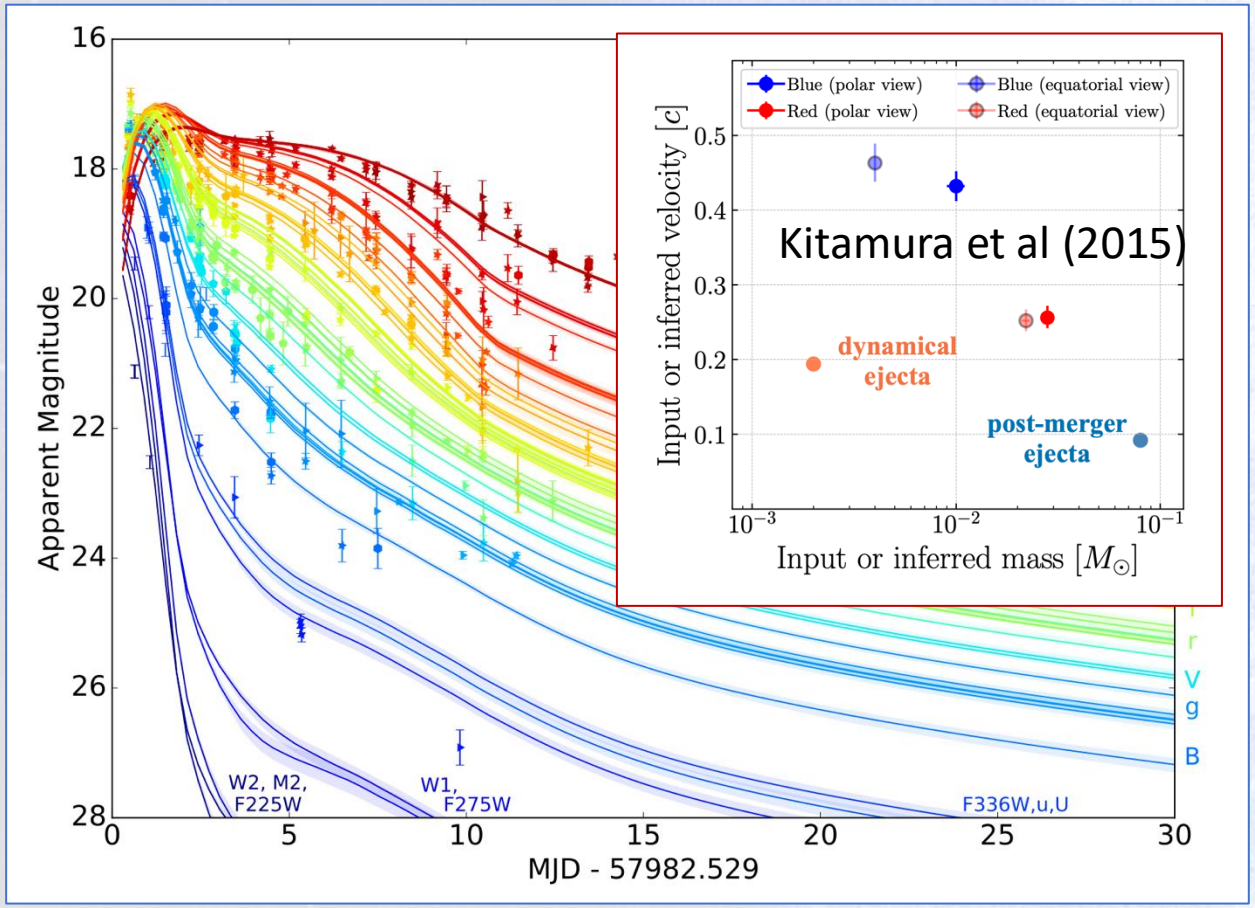


(b) Sr II triplet absorption

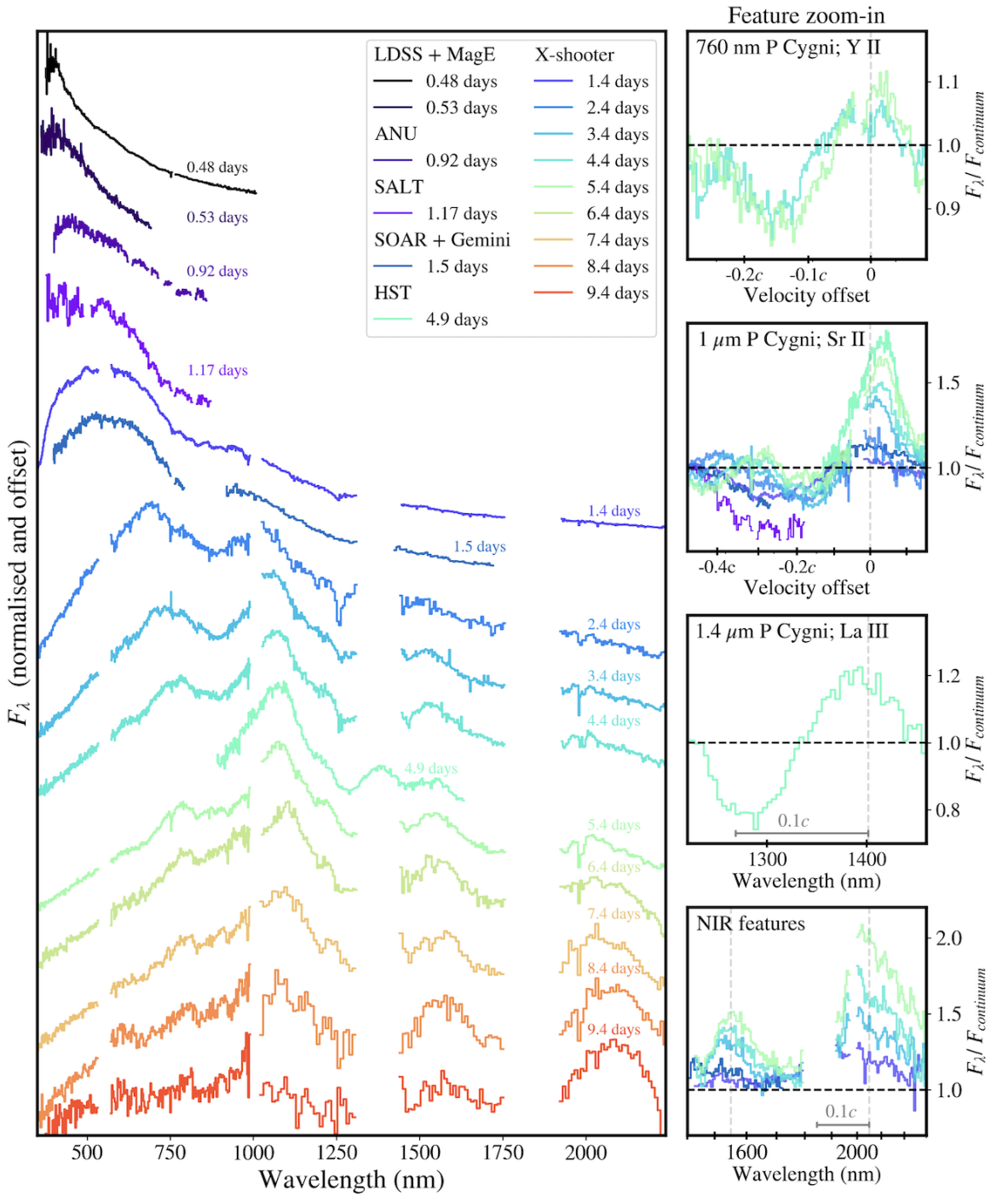


Collins et al (2024)

Red/blue KNe



Villar et al (2017)



Sneppen et al (2024b)

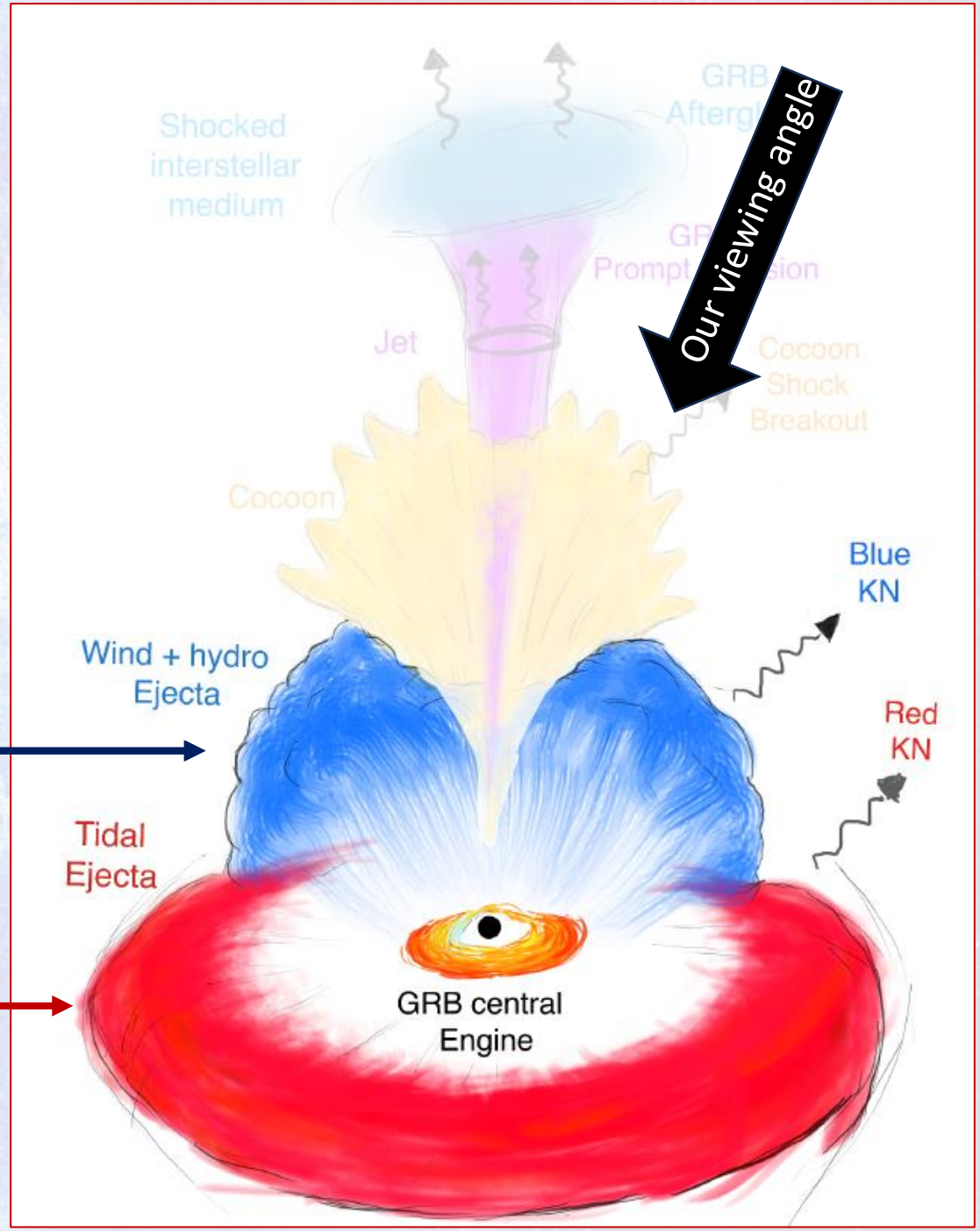
Kilonova models

Various ejection mechanisms characterised

by

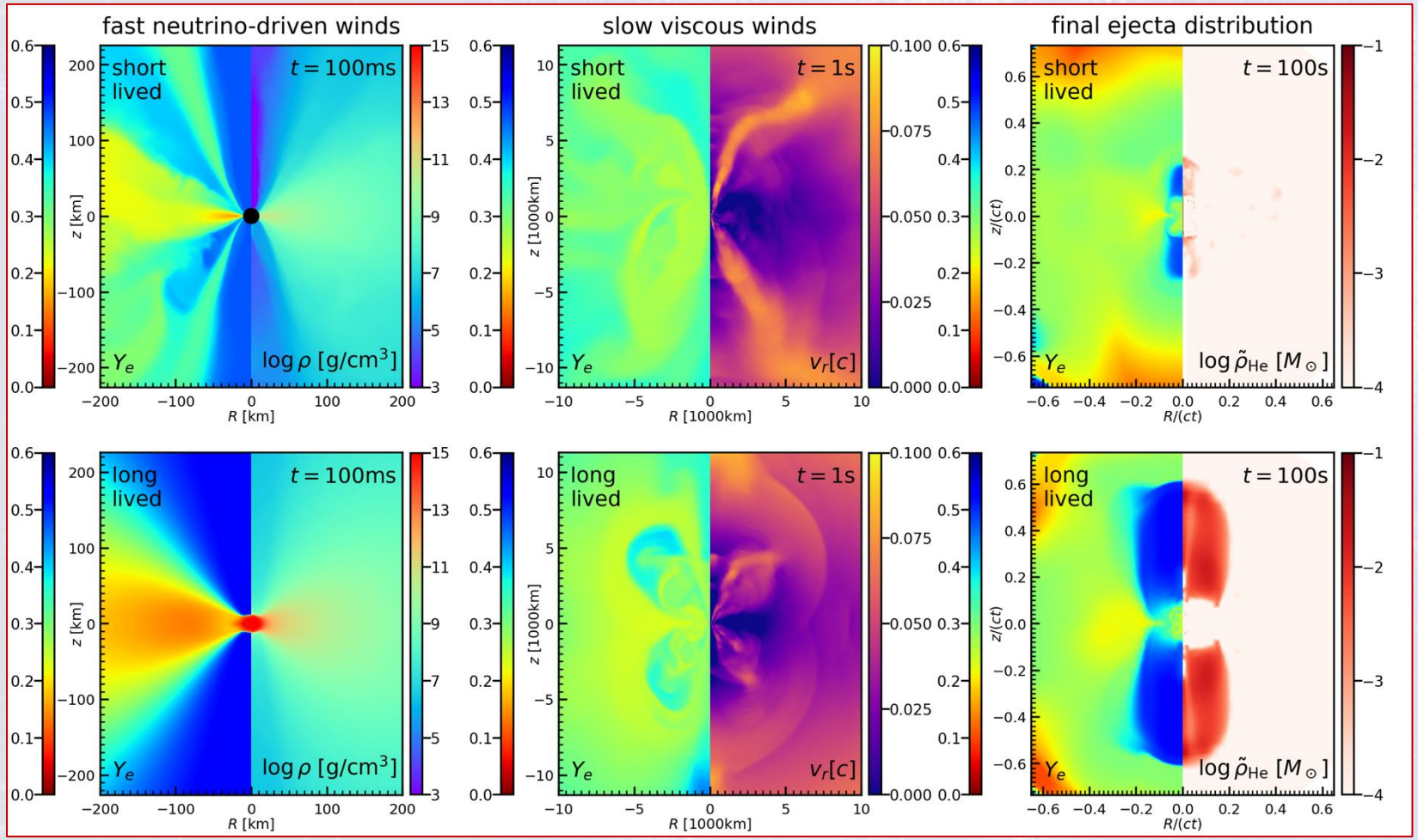
different nucleosynthethic ~~conditions~~

- Shocked ~~interface~~
- Tidal tail
- Neutrino driven winds
- Magnetic field
- BH Torus ejecta



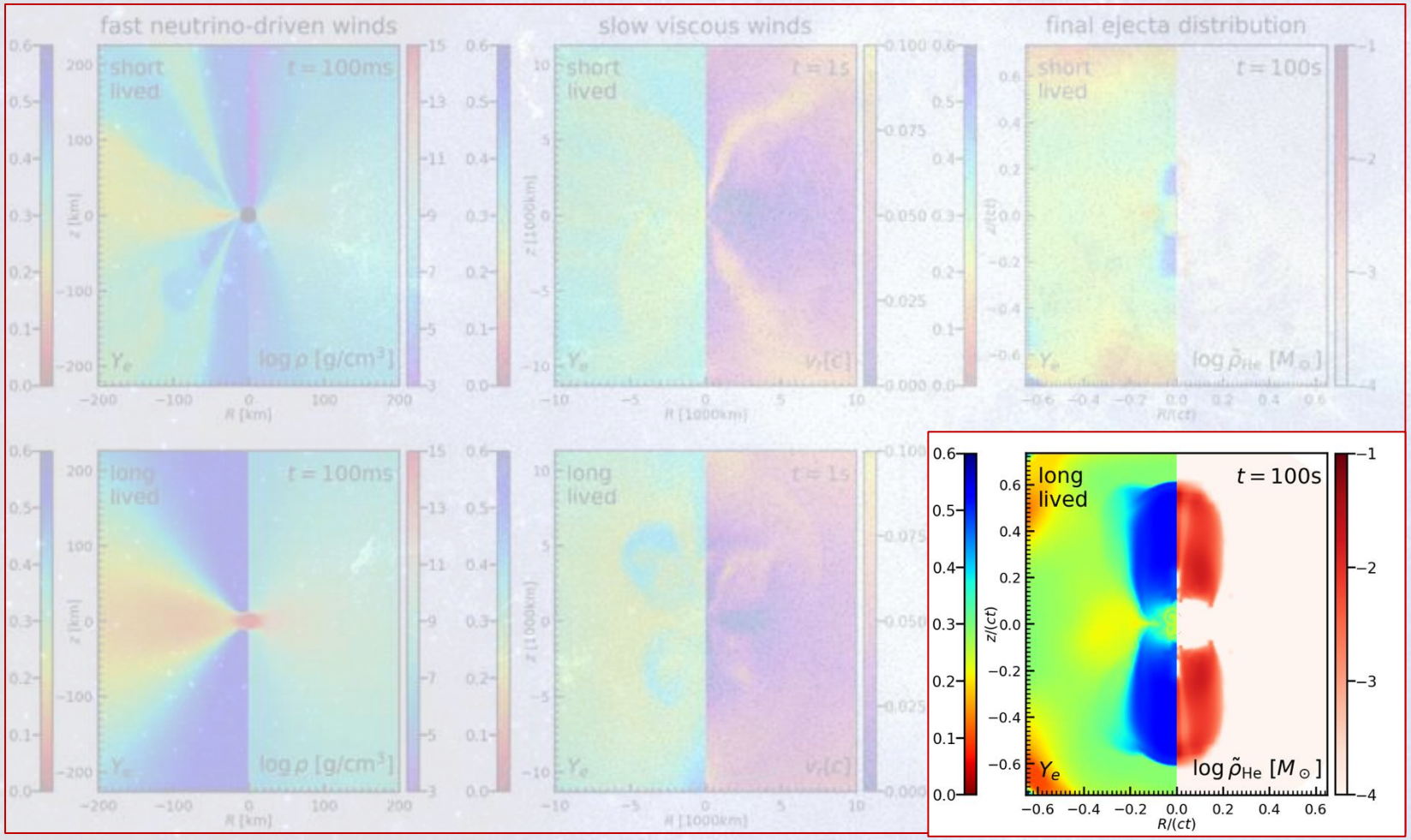
Ascenzi et al (2021)

Pathways to asphericity



Sneppen, Just, Bauswein et al

Pathways to asphericity



Sneppen, Just, Bauswein et al

Helium NLTE Modelling

For NLTE KN deep dive see also:

Pognan et al (2022,2023,2025),

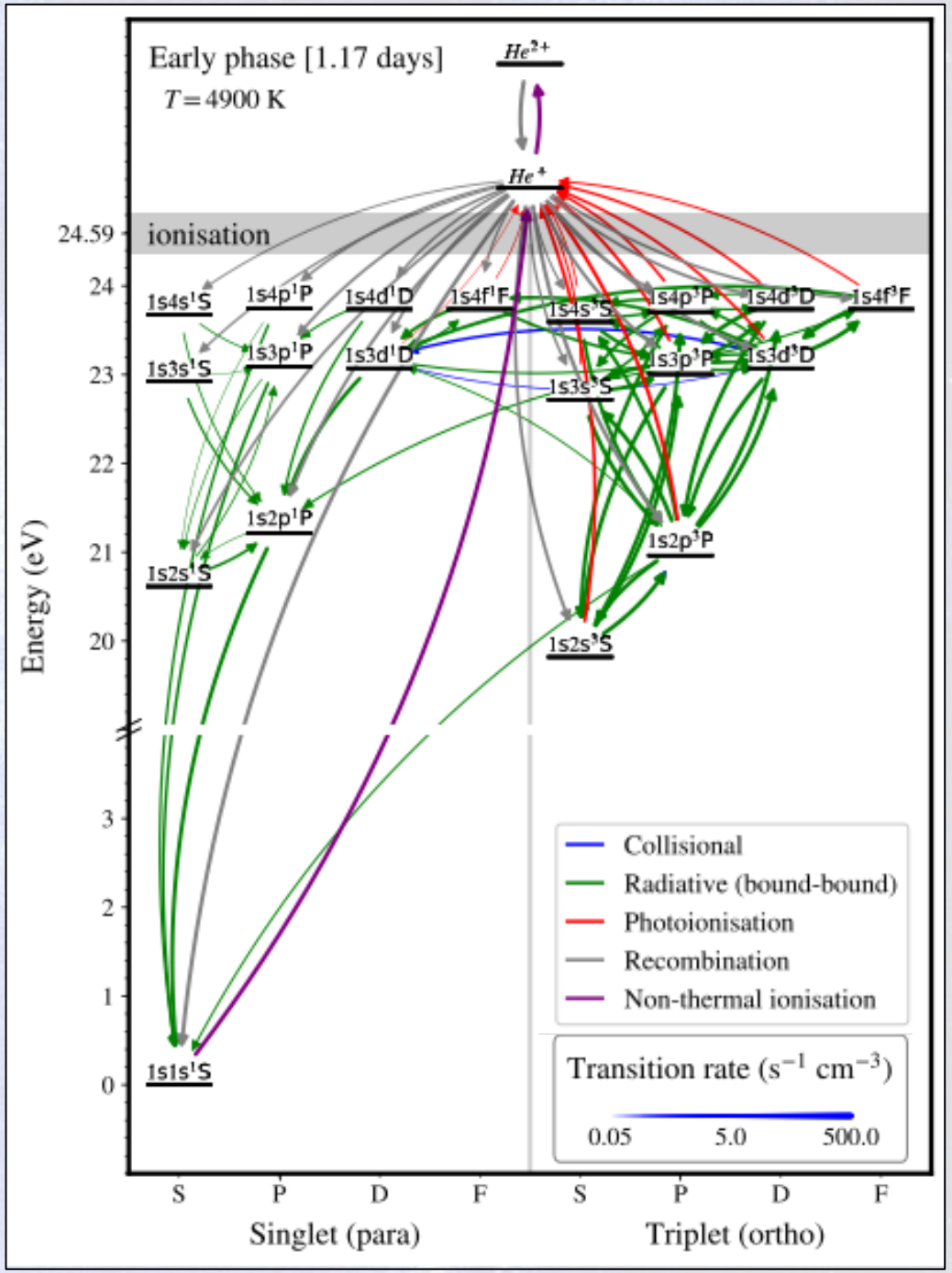
Tarumi et al (2023),

Brethauer et al (2025),

Jerkstrand (2025)

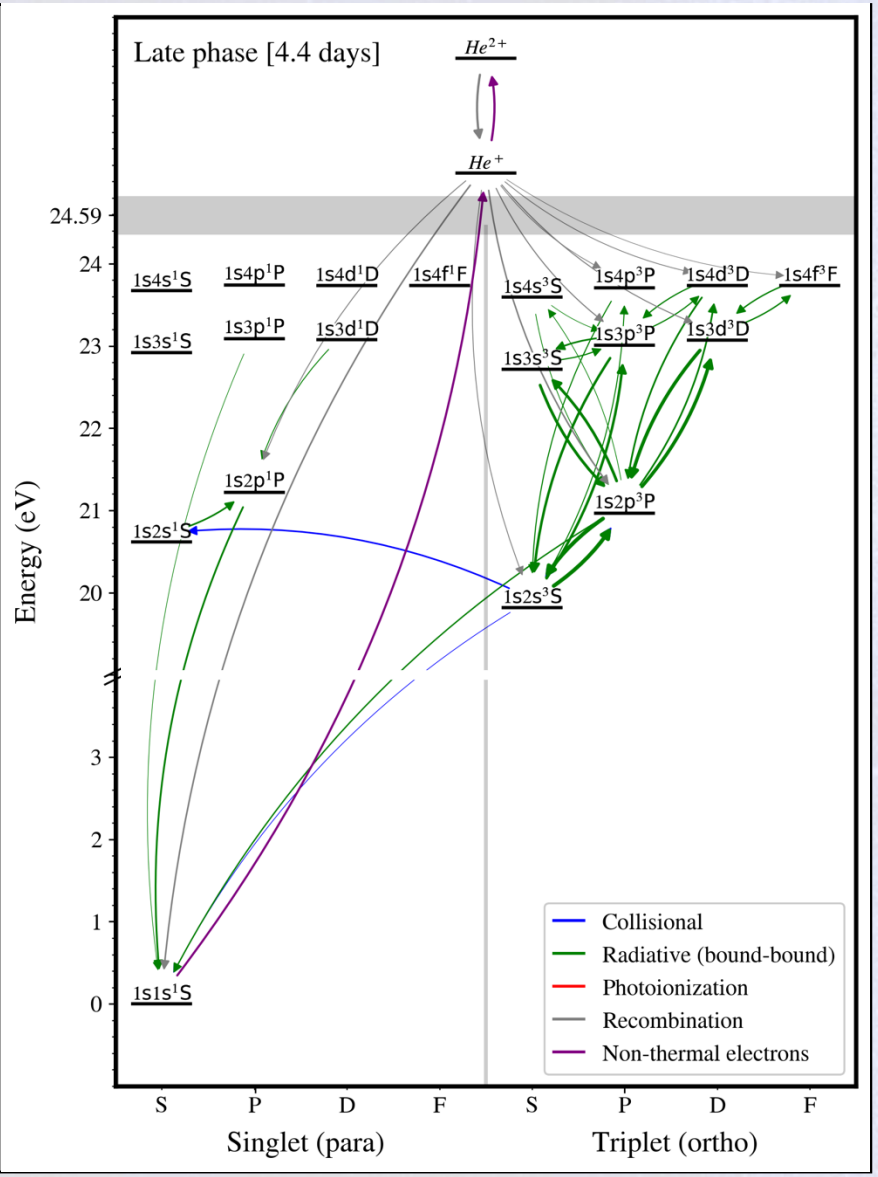
And upcoming work:

Arya et al (2026)

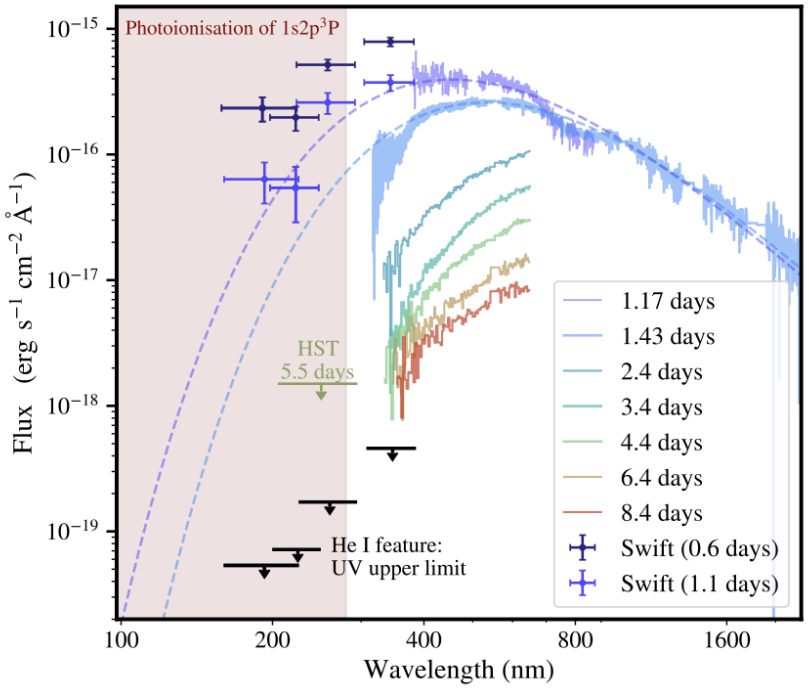


Sneppen, Damgaard & Watson et al (2024), A&A

Are such He abundances consistent with observati



At early times - no constraining power:



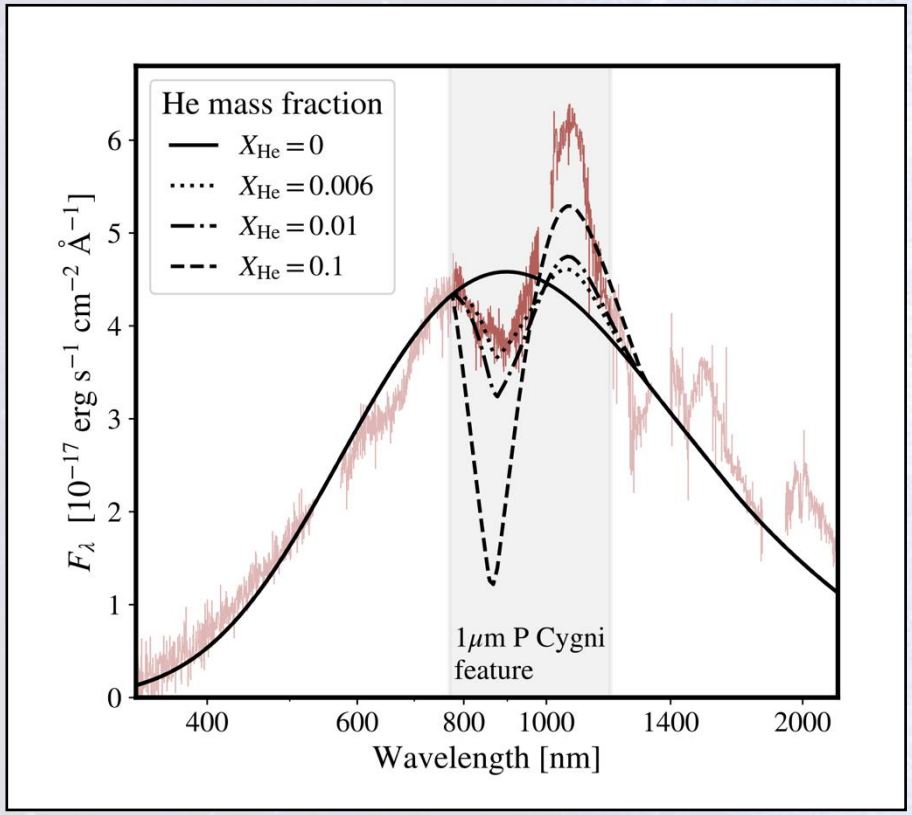
At around 4-5 days an ejecta primarely He by number should become observable

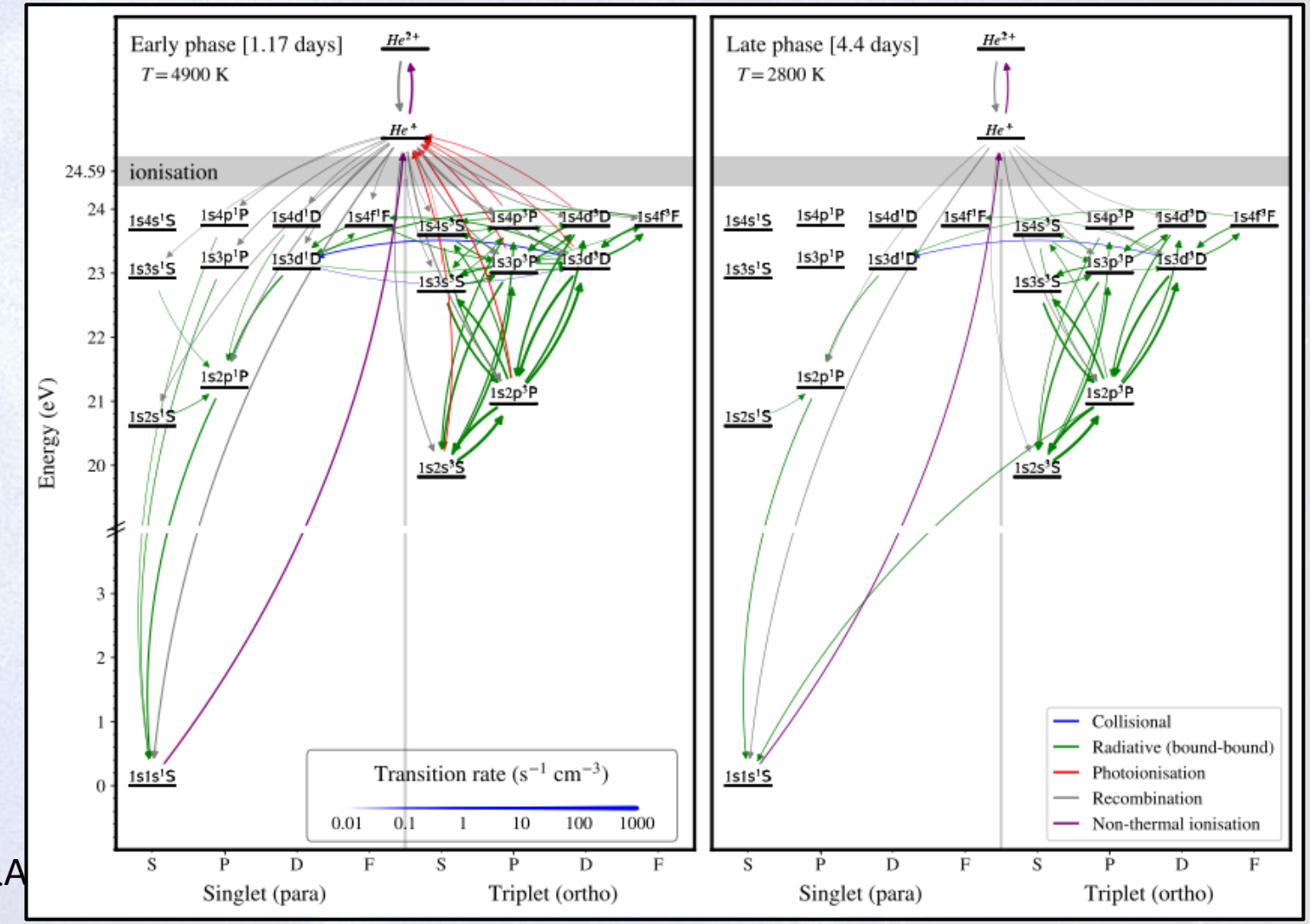
See:

Helium features are inconsistent with the spectral evolution of the kilonova AT2017gfo

Albert Sneppen[1,2], Rasmus Damgaard[1,2], Darach Watson[1,2], Christine E. Collins[3], Luke Shingles[3] and Stuart A. Sim[4]

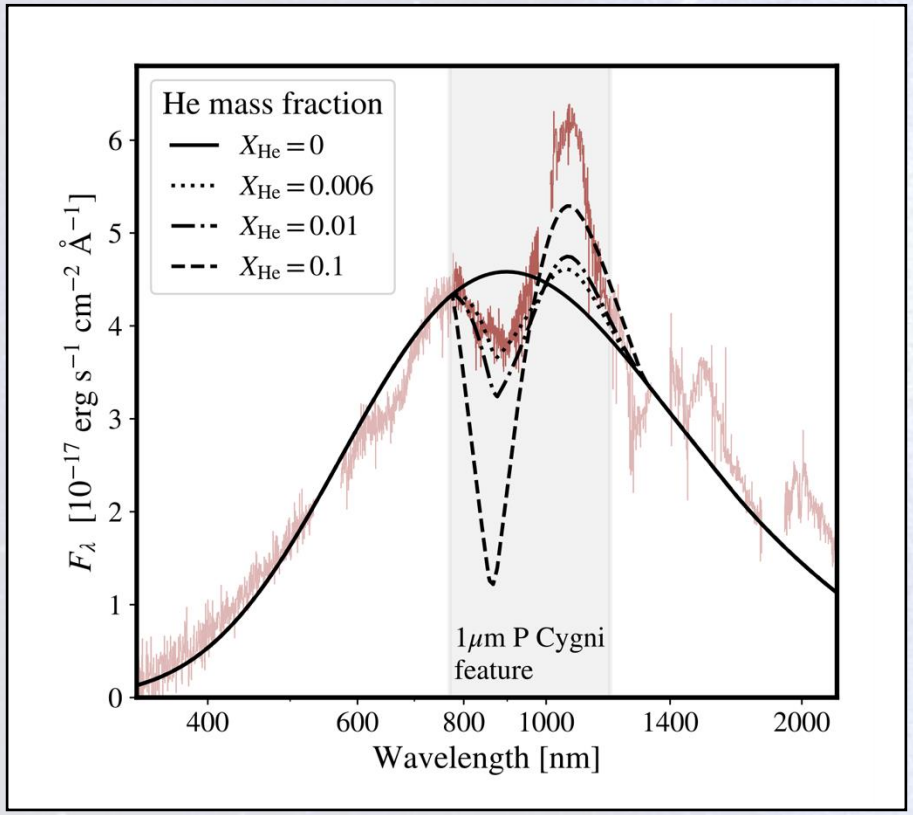
He features should* be visible around 4-5 days…

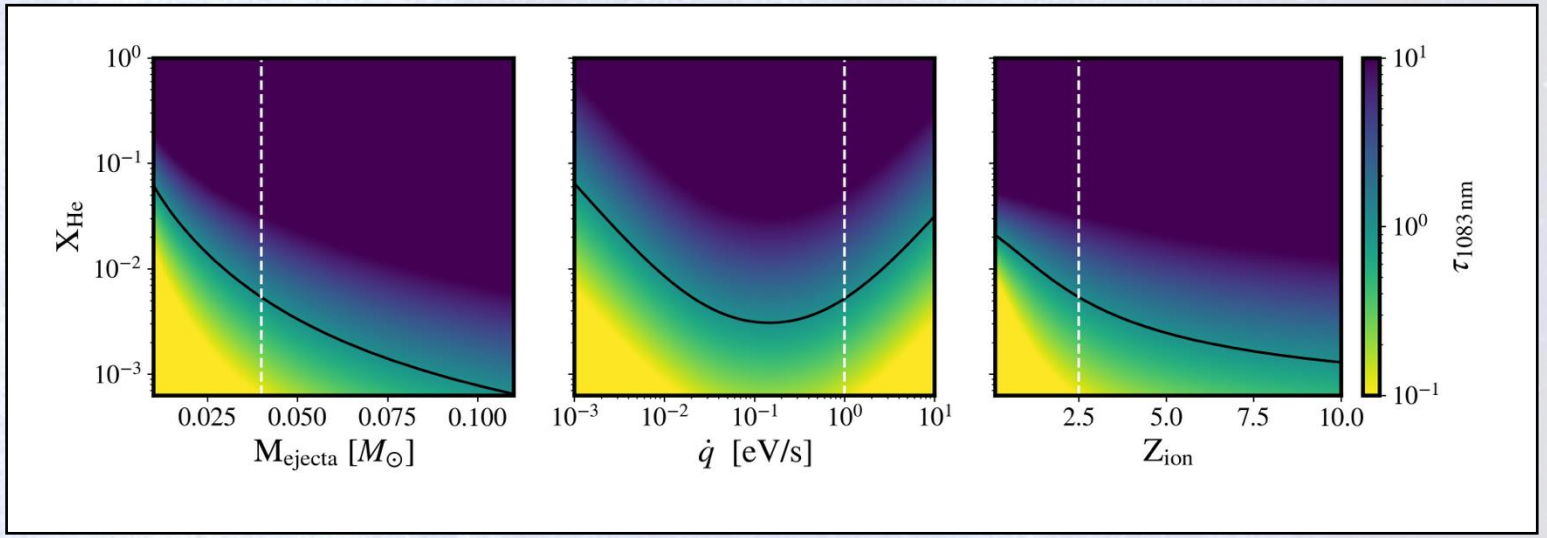




Sneppen, Damgaard & Watson et al (2024), A&A

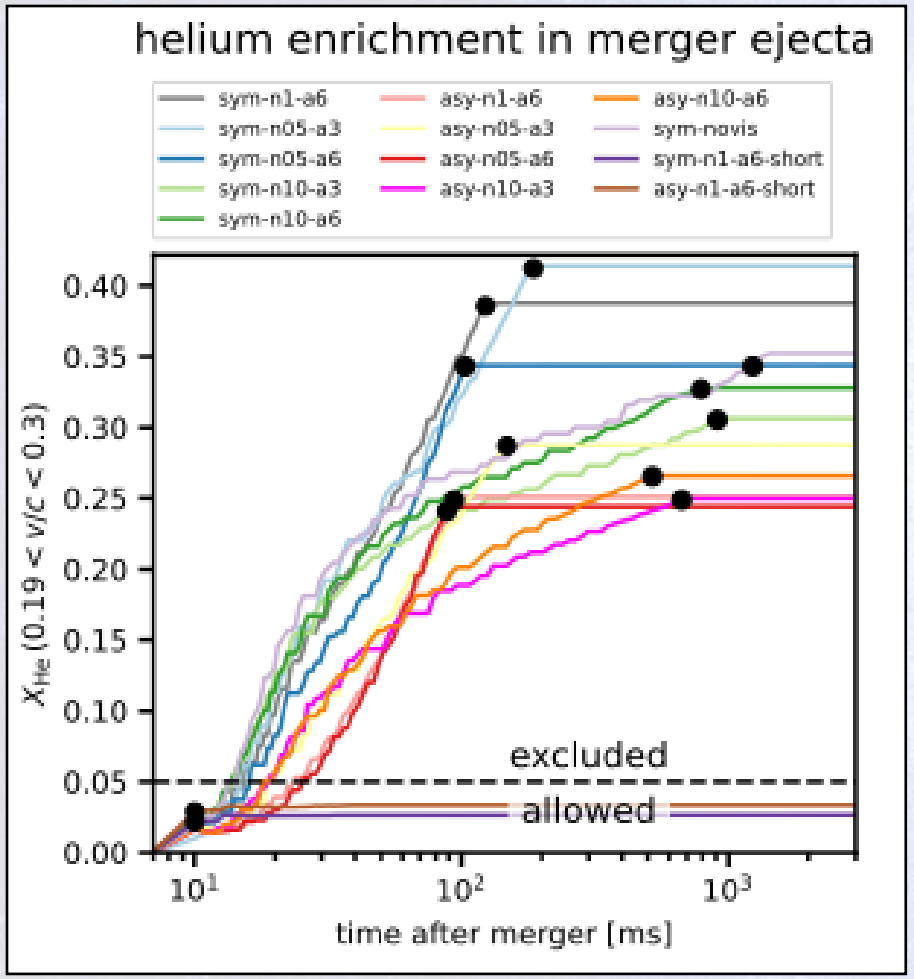
For both methods $X_{He} < 0.05$

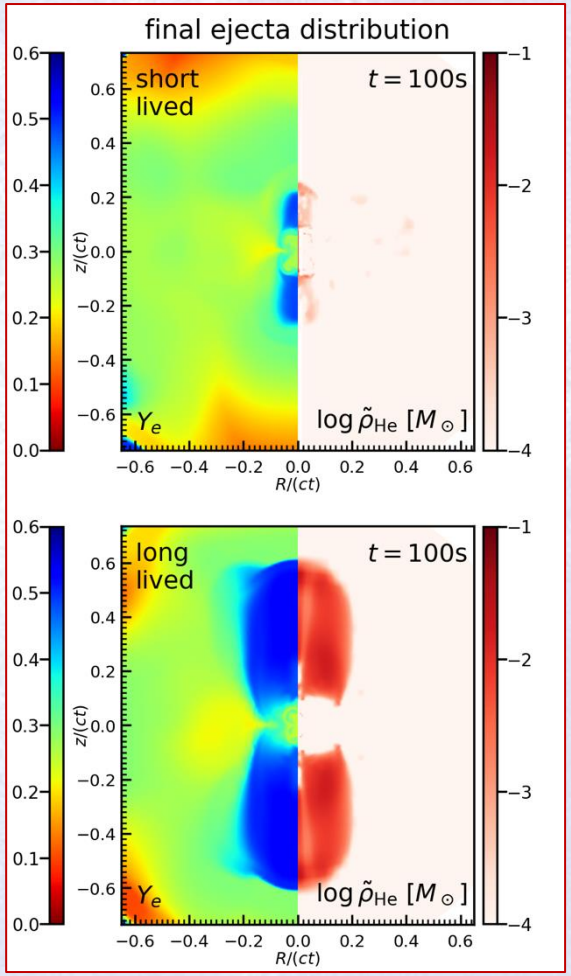




Sneppen, Just & Bauswein et al

Helium production in neutron-star mergers

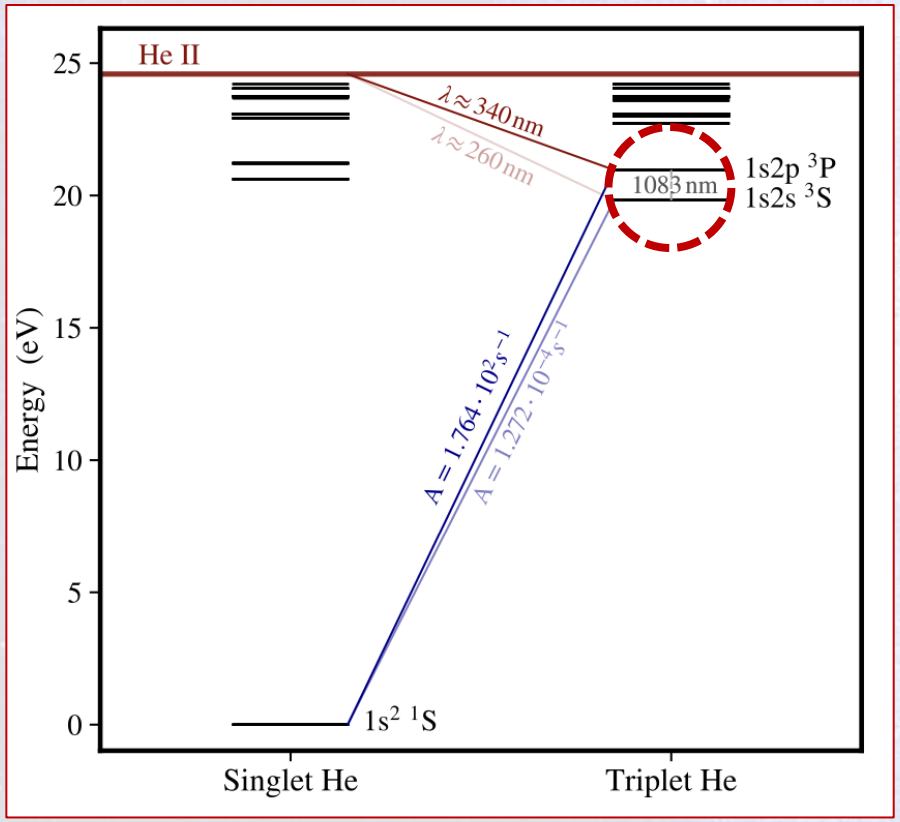


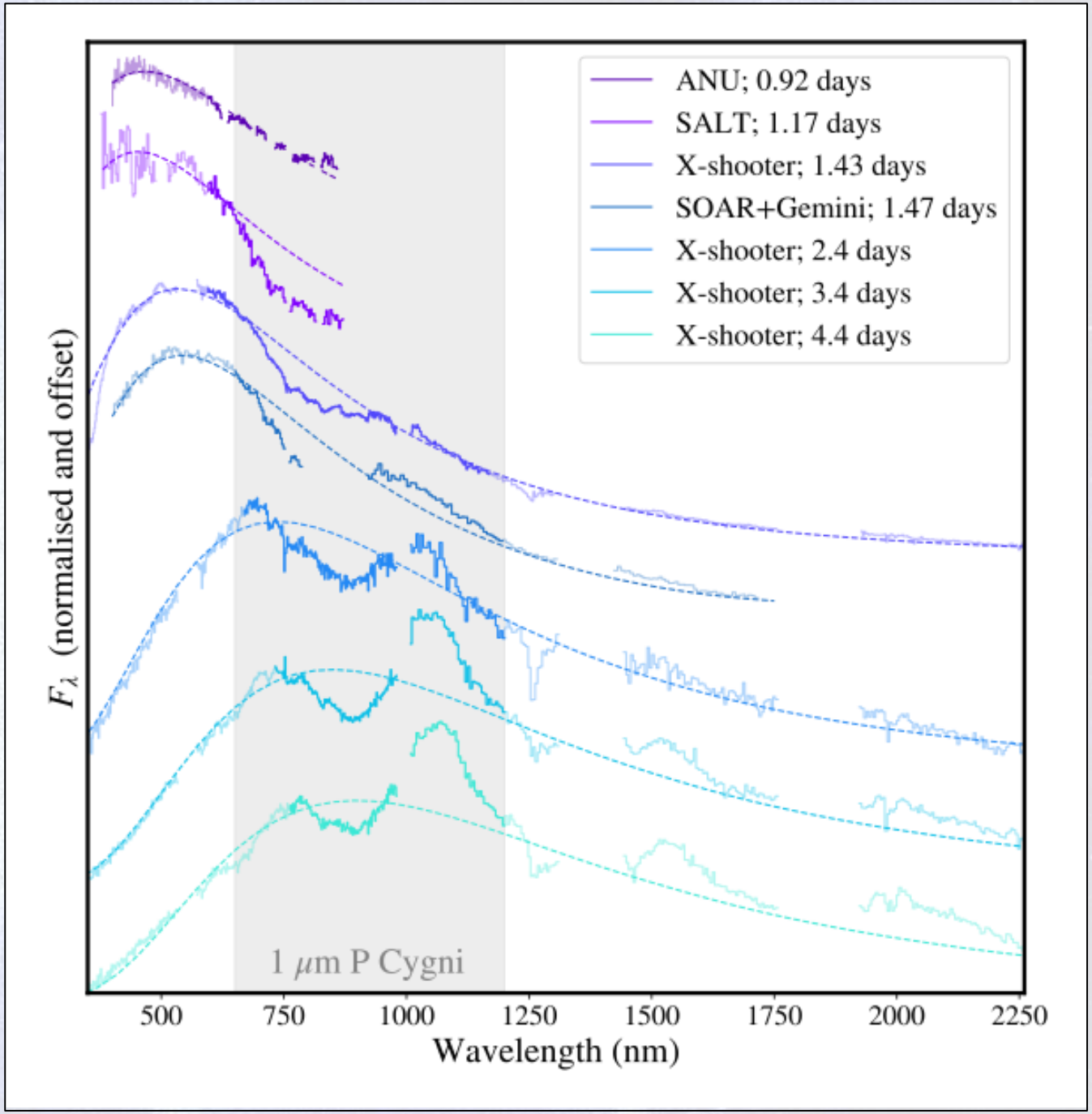


Timescale of black hole formation, τ_{BH}, was rapid – within 20-30 ms.

Sneppen et al (2024)

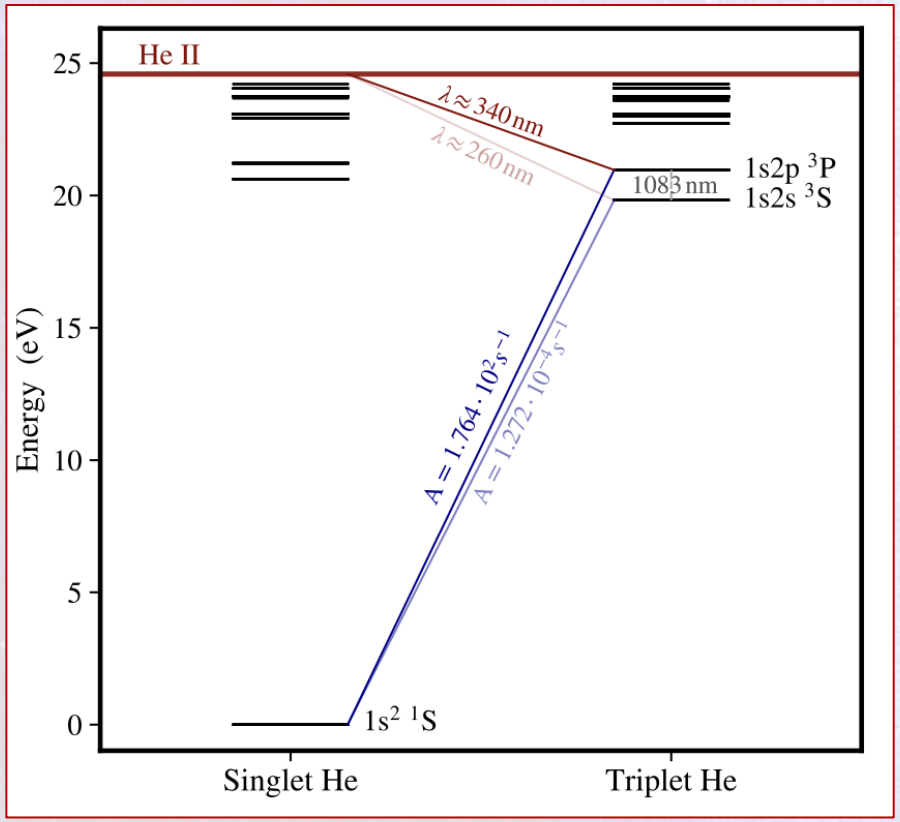
He I - 1 μm feature?

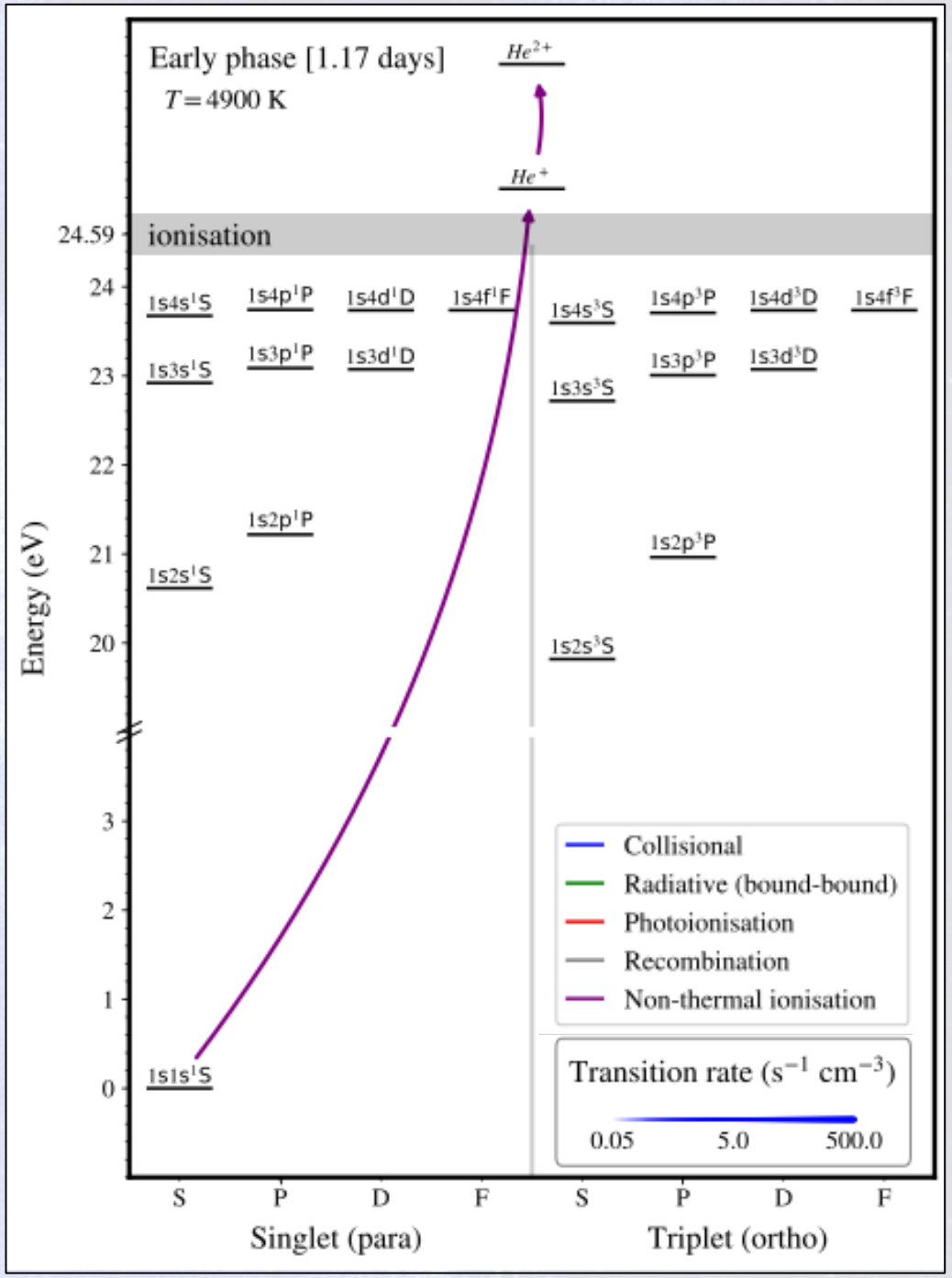




Sneppen, Damgaard & Watson et al (2024), A&A

Helium NLTE Modelling





Sneppen, Damgaard & Watson et al (2024), A&A

Helium NLTE Modelling

For NLTE KN deep dive see also:

Pognan et al (2022,2023,2025),

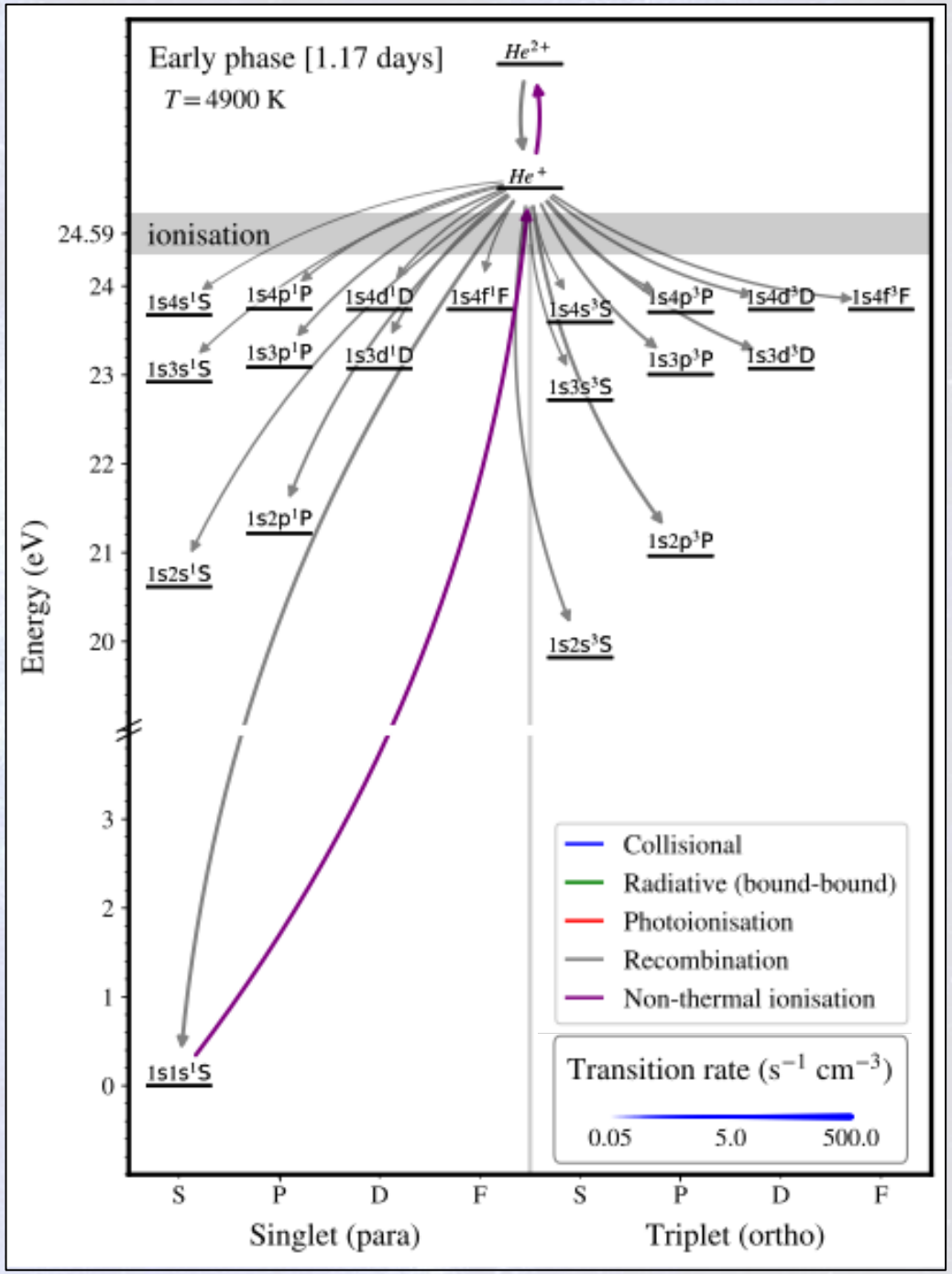
Tarumi et al (2023),

Brethauer et al (2025),

Jerkstrand (2025)

And upcoming work:

Arya et al (2026)



Sneppen, Damgaard & Watson et al (2024), A&A

Helium NLTE Modelling

For NLTE KN deep dive see also:

Pognan et al (2022,2023,2025),

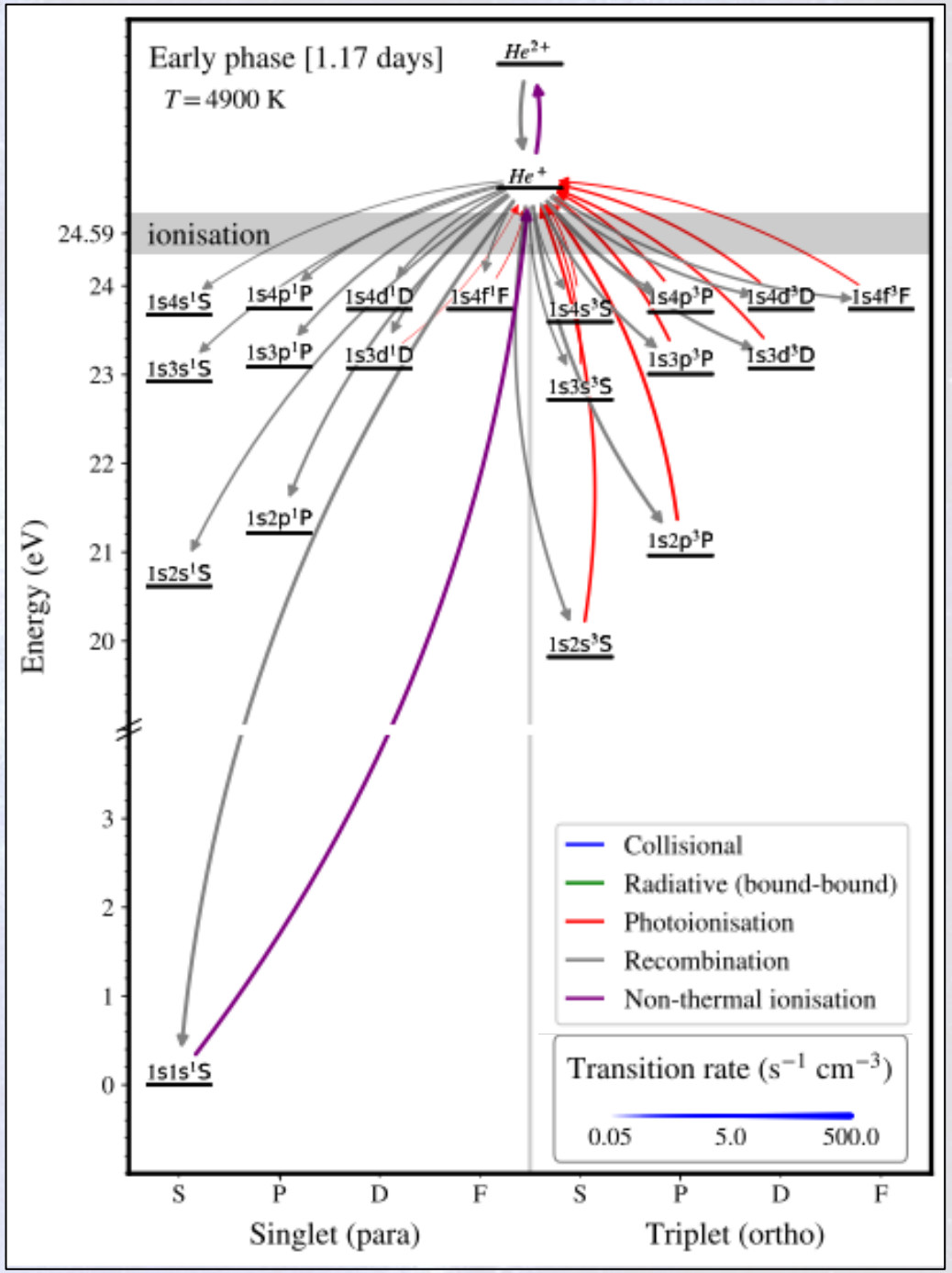
Tarumi et al (2023),

Brethauer et al (2025),

Jerkstrand (2025)

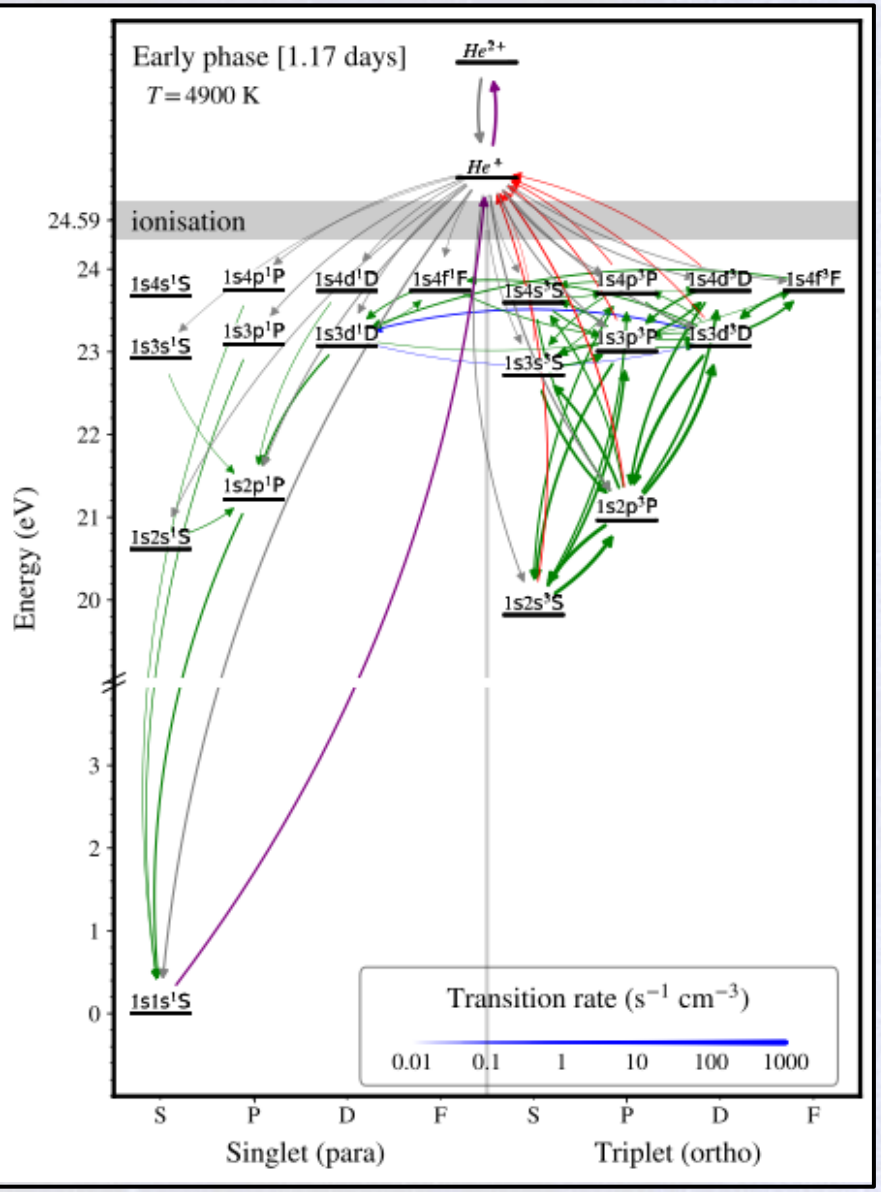
And upcoming work:

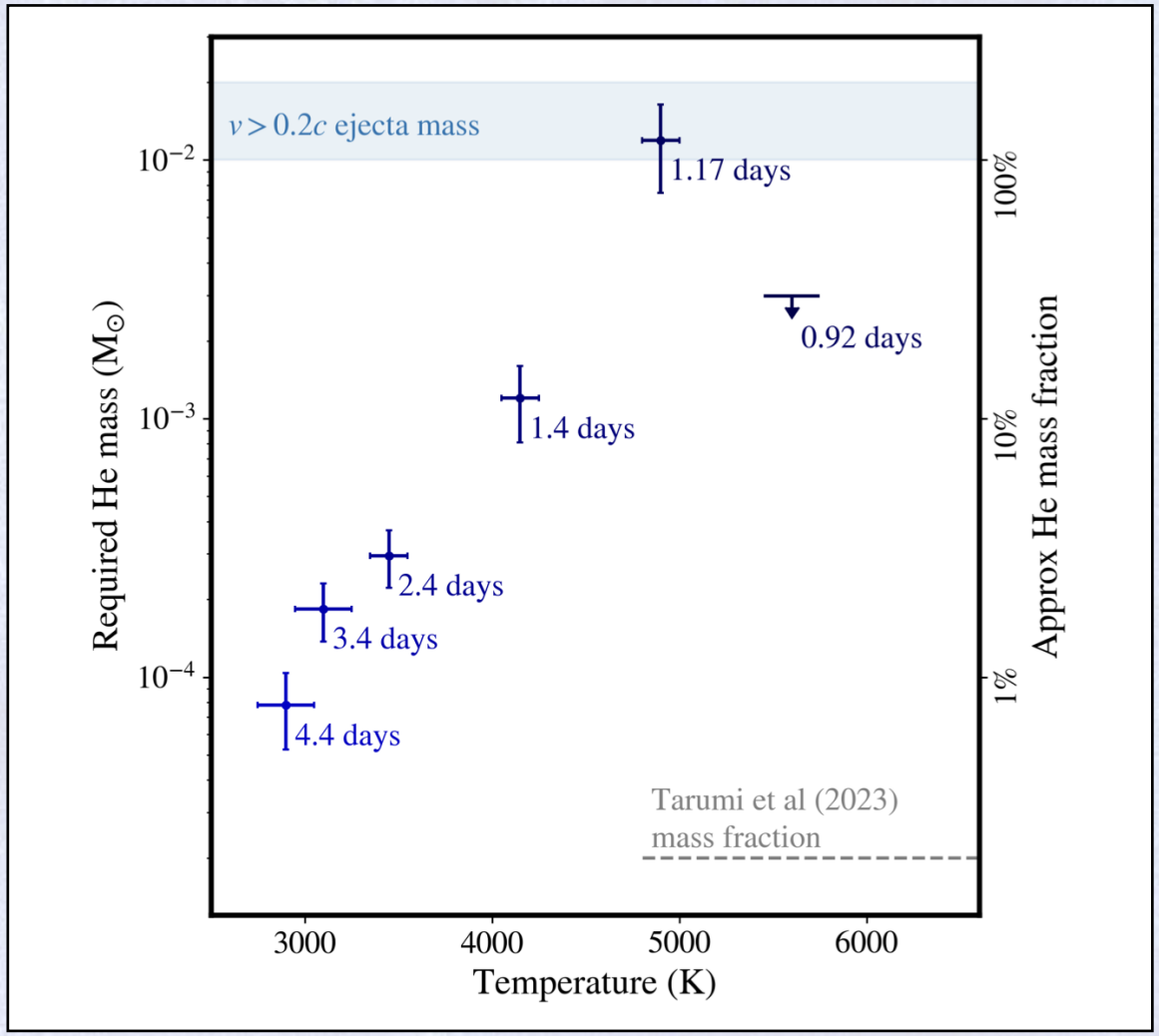
Arya et al (2026)



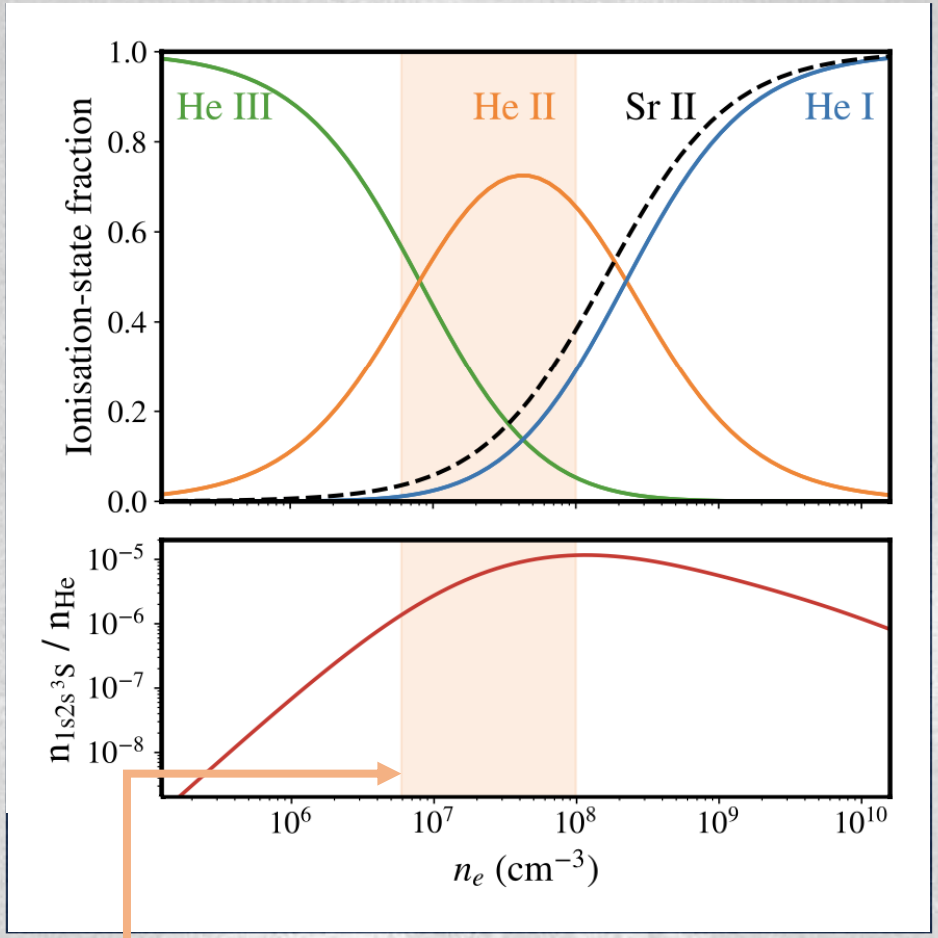
Sneppen, Damgaard & Watson et al (2024), A&A

Early / High-velocity helium constraints





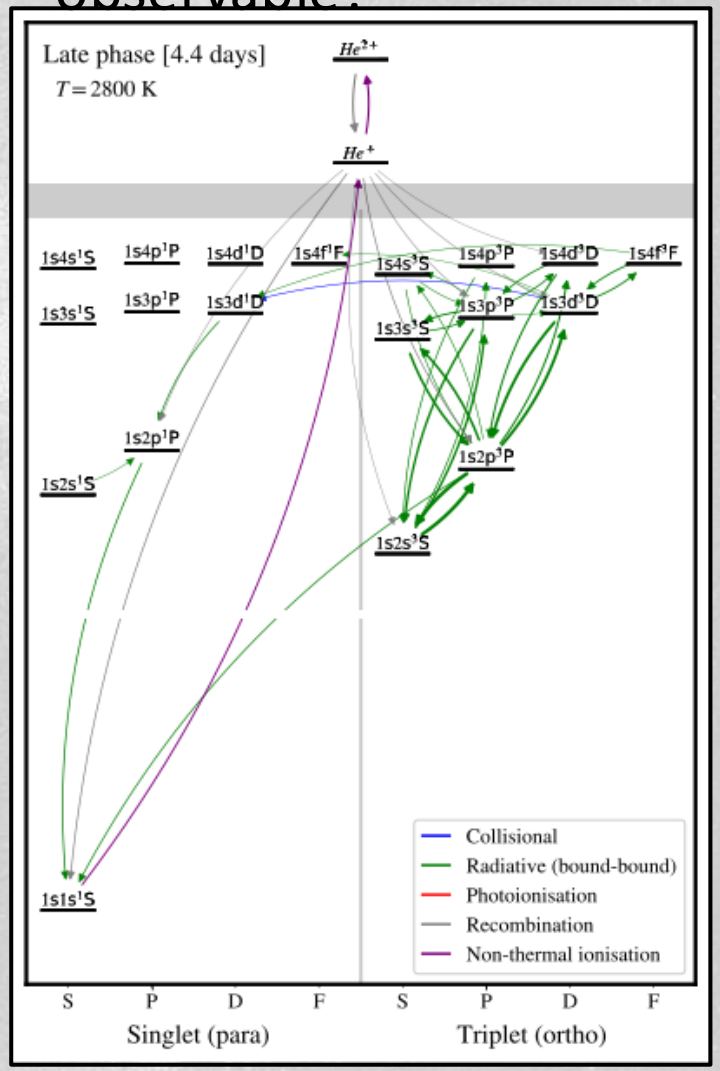
Sneppen, Damgaard & Watson et al (2024), A&

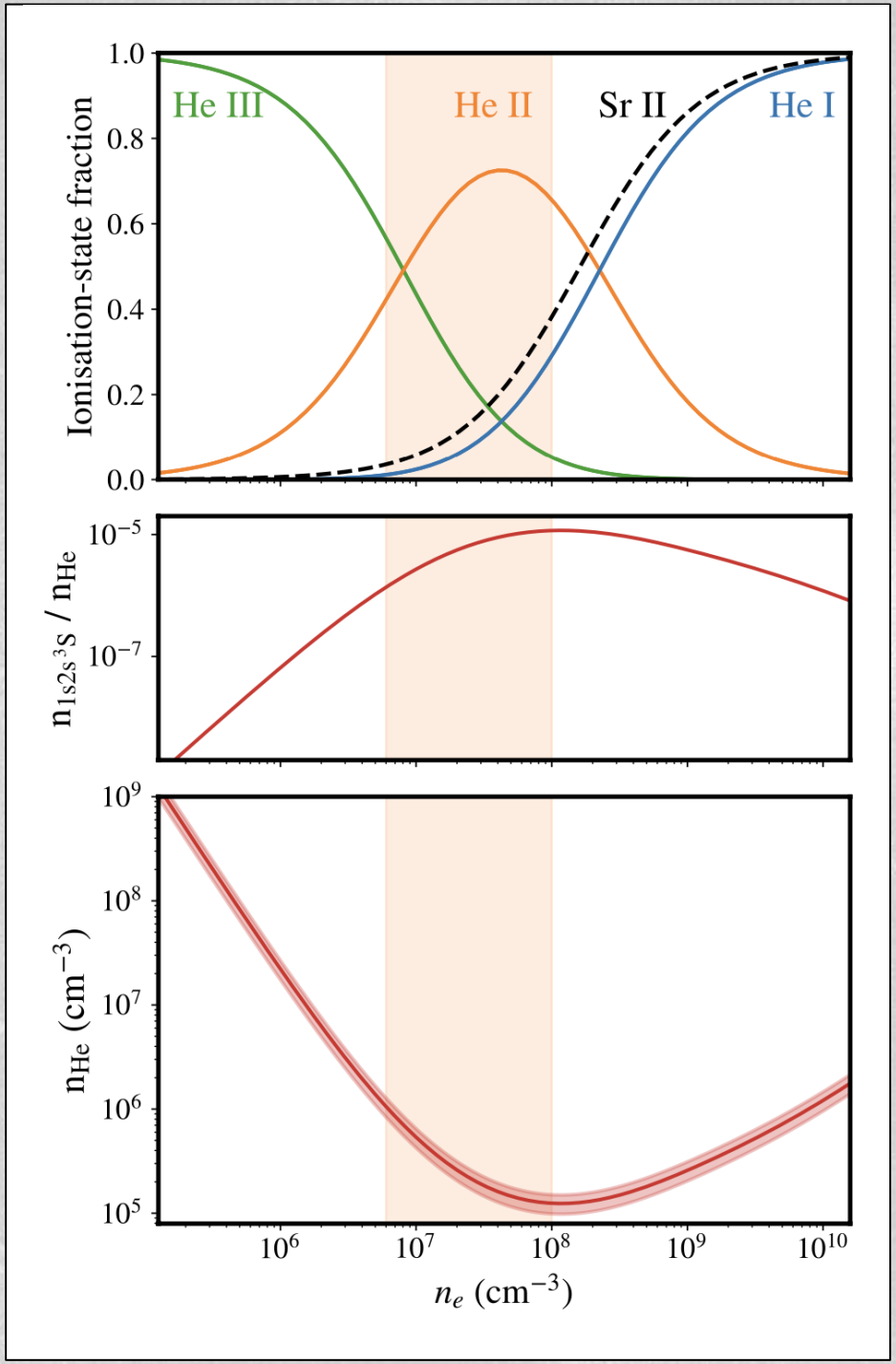


n_e constrained from

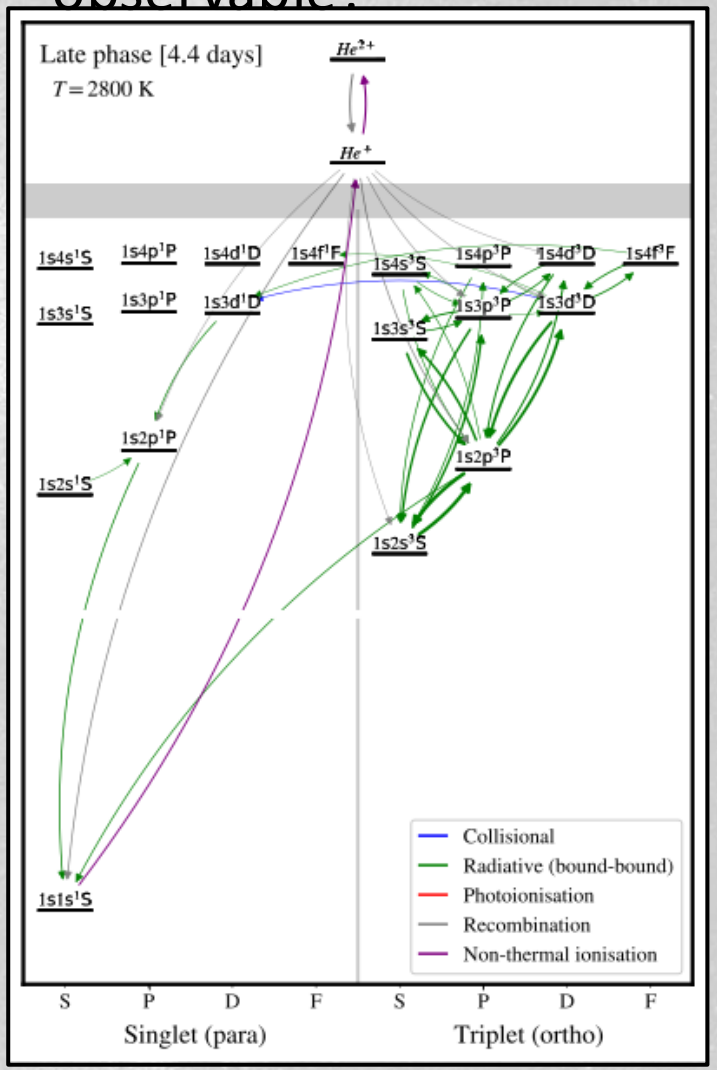
- Recombination timescale
- Existence of other features
- Mass + ionisation arguments

Under what conditions must He I be observable?

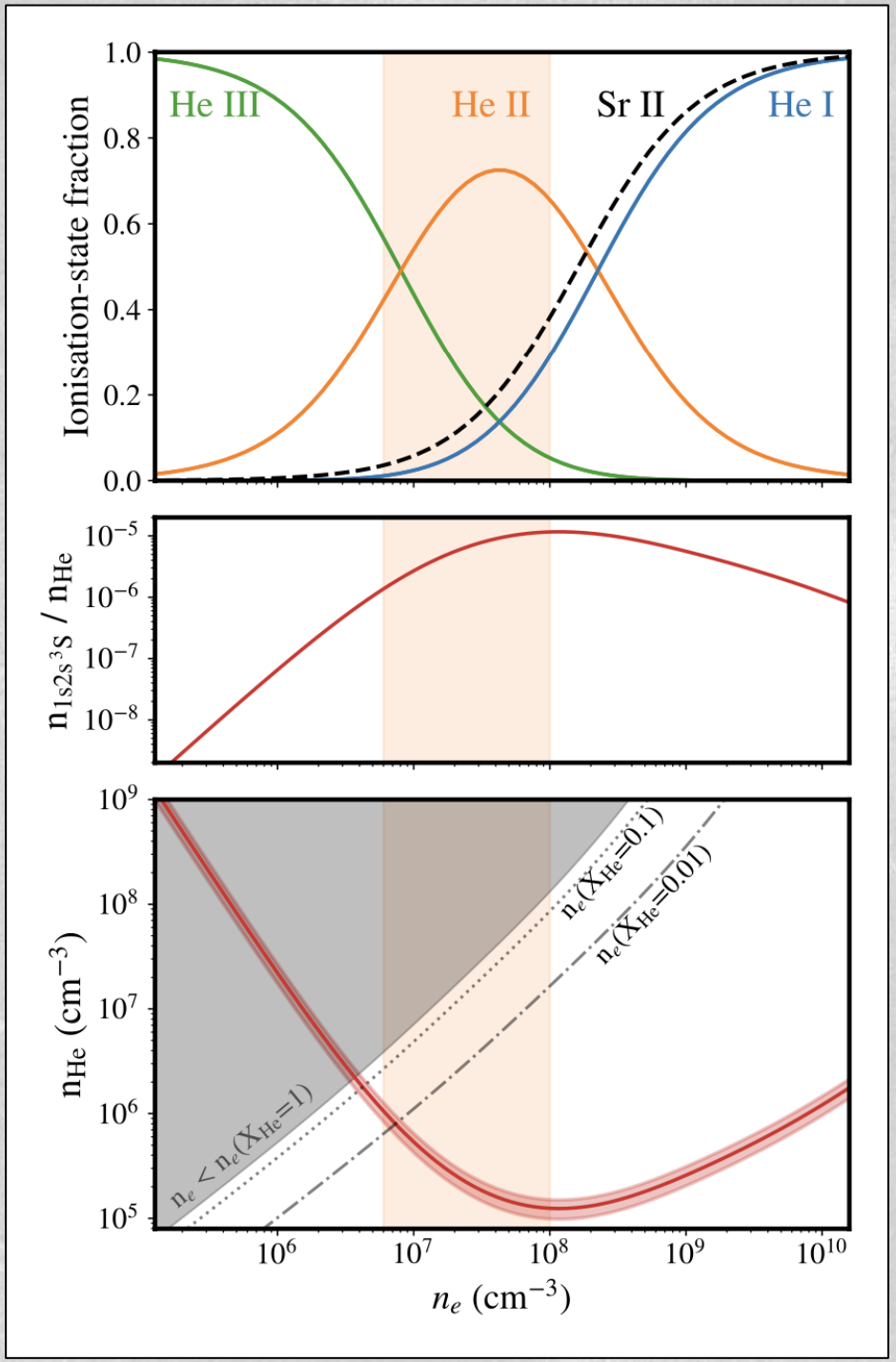




Under what conditions must He I be observable?



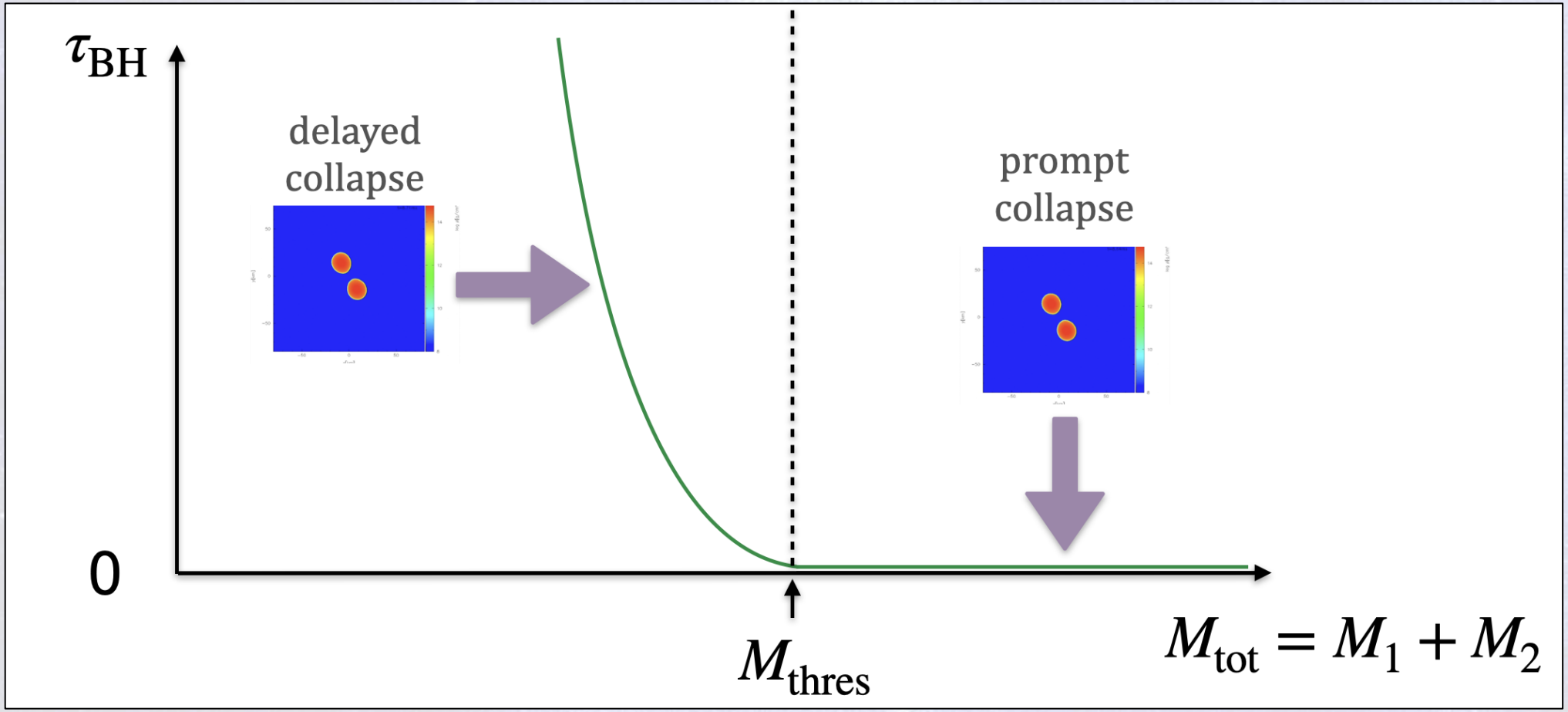
Compare n_{He} with M_{ej}
$\rightarrow X_{He}$



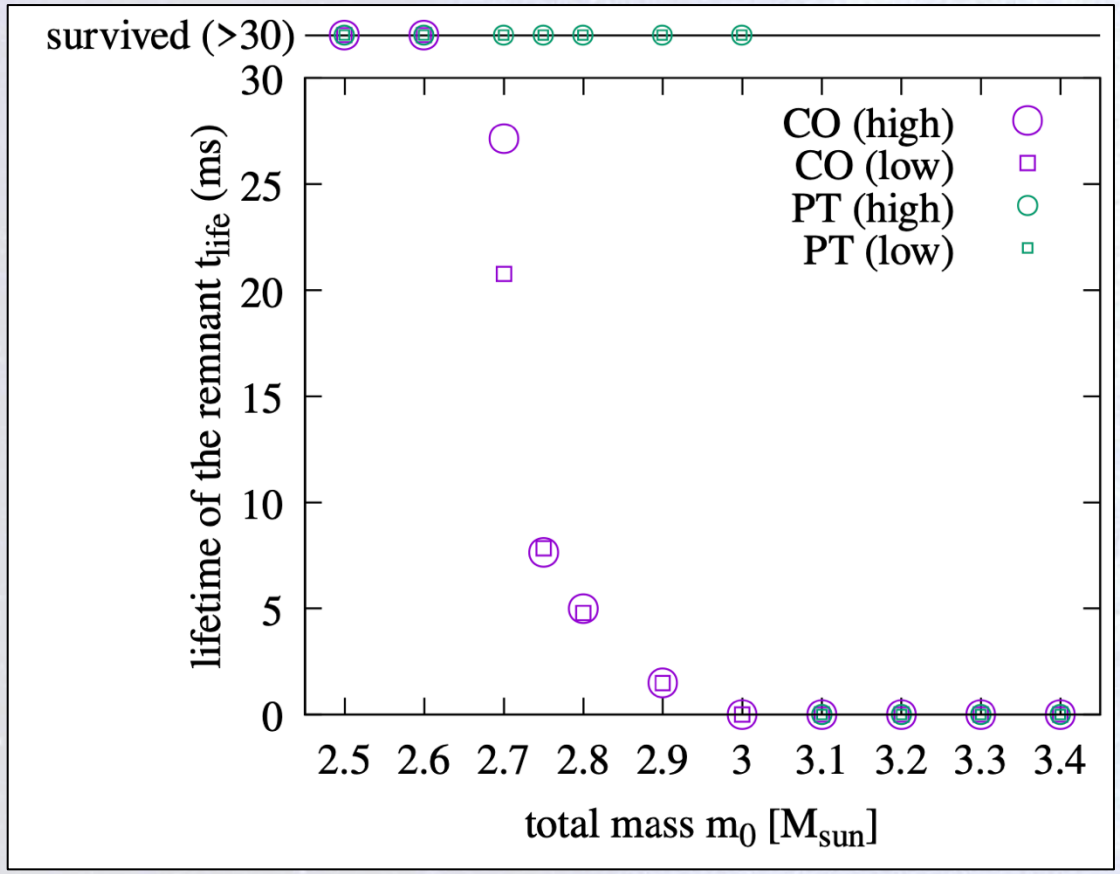
Compare n_e with n_{He}
$\rightarrow X_{He}$

Sneppen, Just & Bauswein et al

Connecting remnant lifetime with the EOS

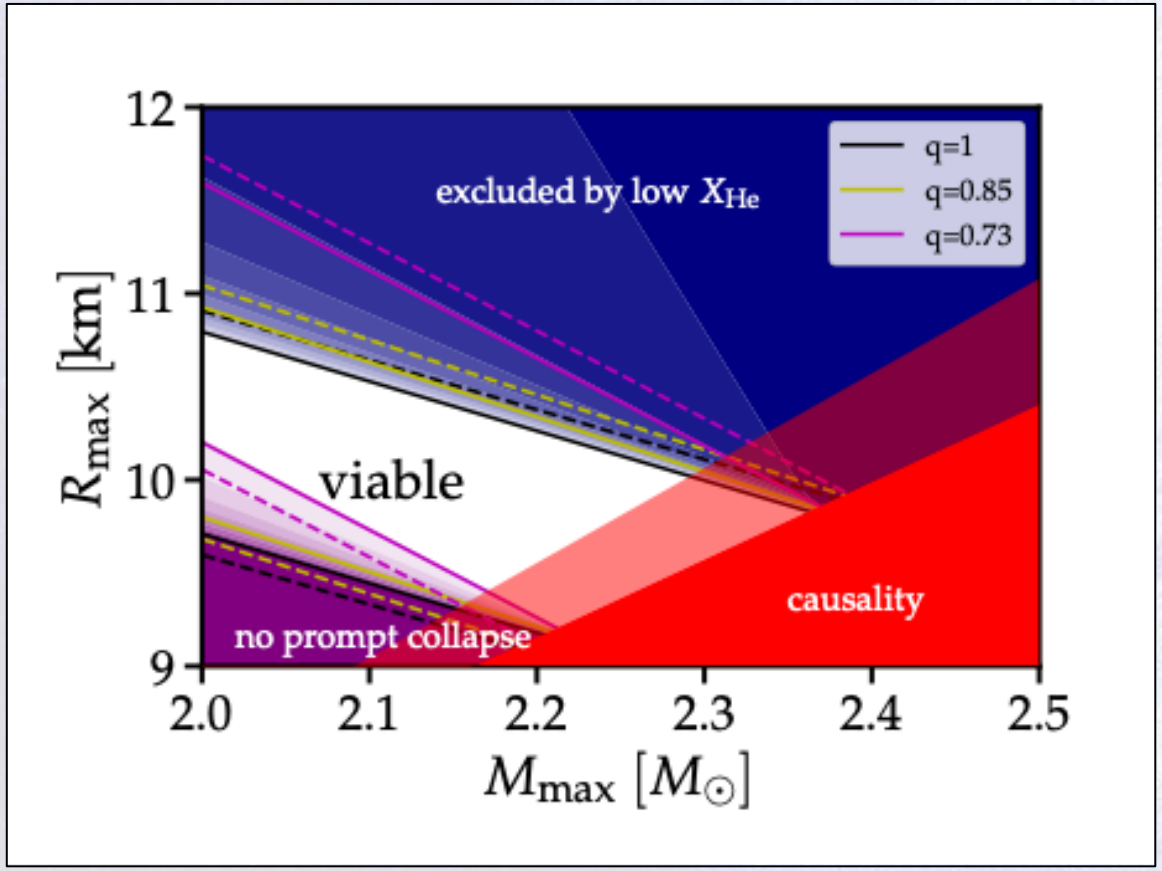


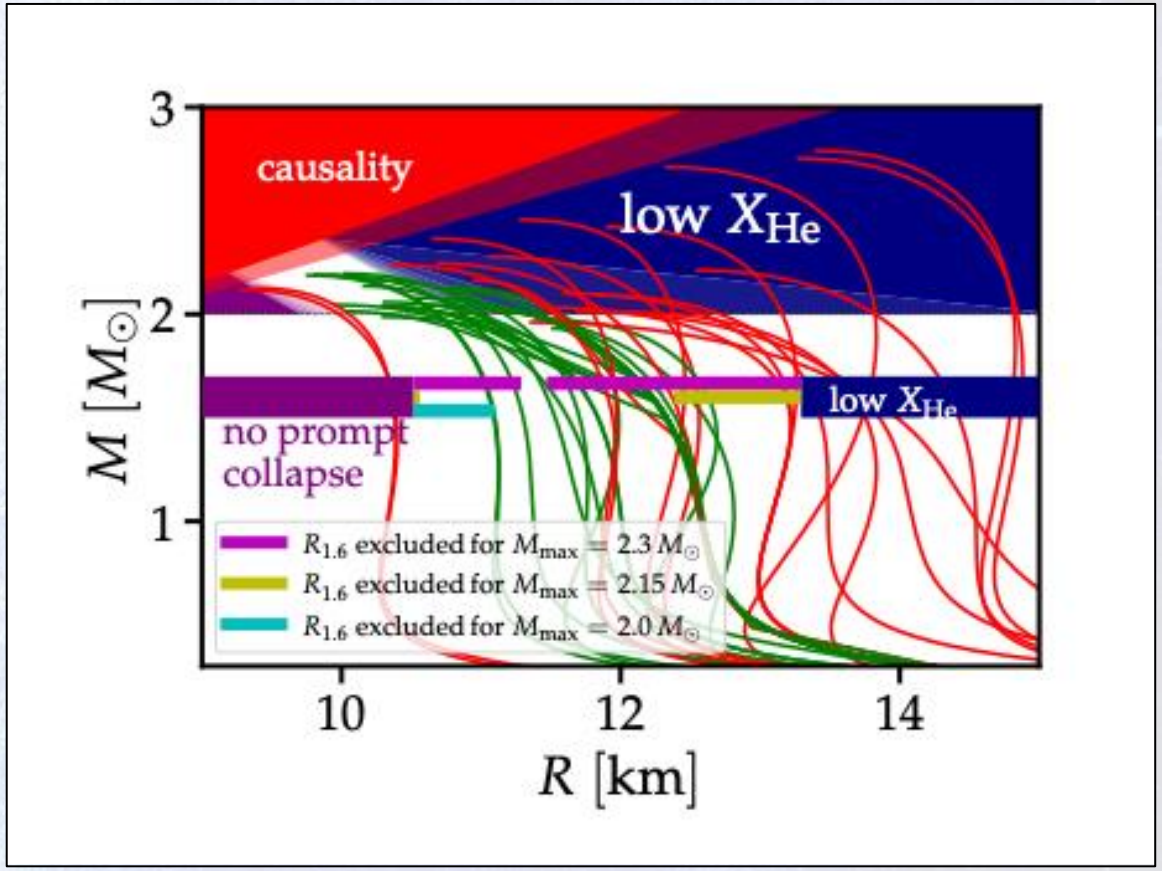
Connecting remnant lifetime with the EOS



Fujimoto et al (2025)

Implications for nuclear equation of state



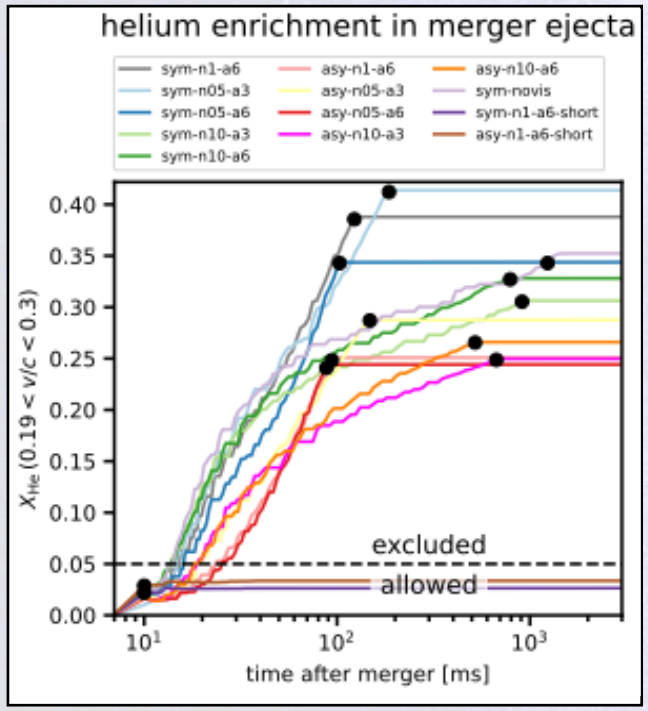


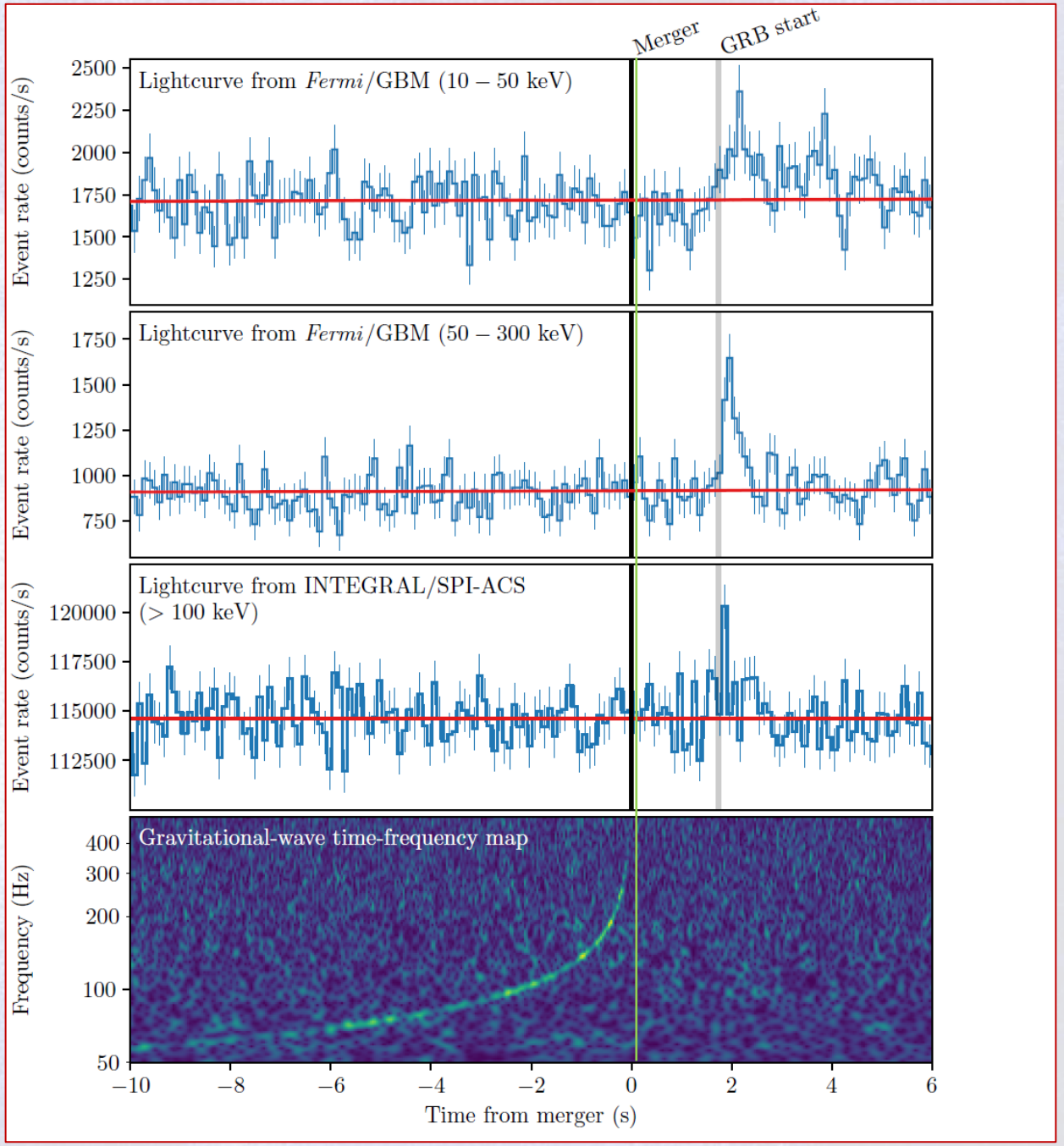
Sneppen et al (2024)

sGRB implication

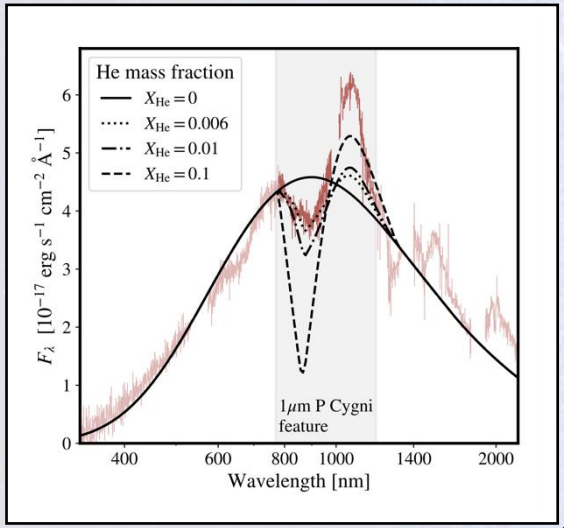
$t_{BH} \ll t_{GRB,start} - t_{GW}$

favours a Blandford–Znajek process (Black-hole torus engine) driving the jet.



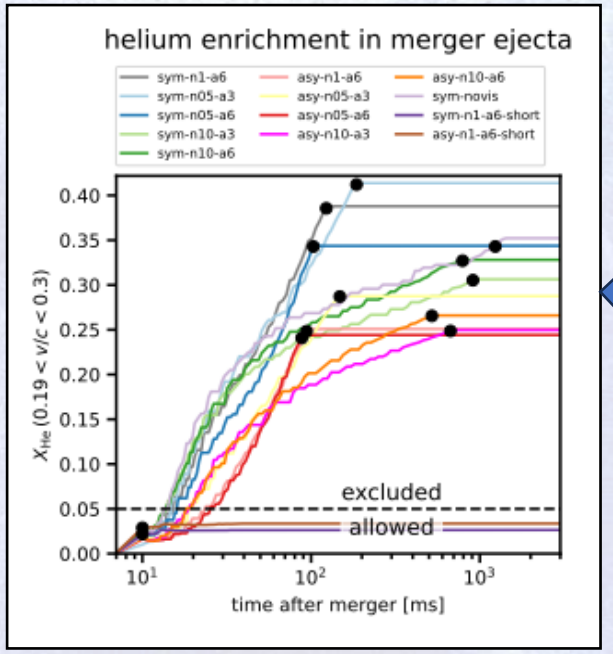


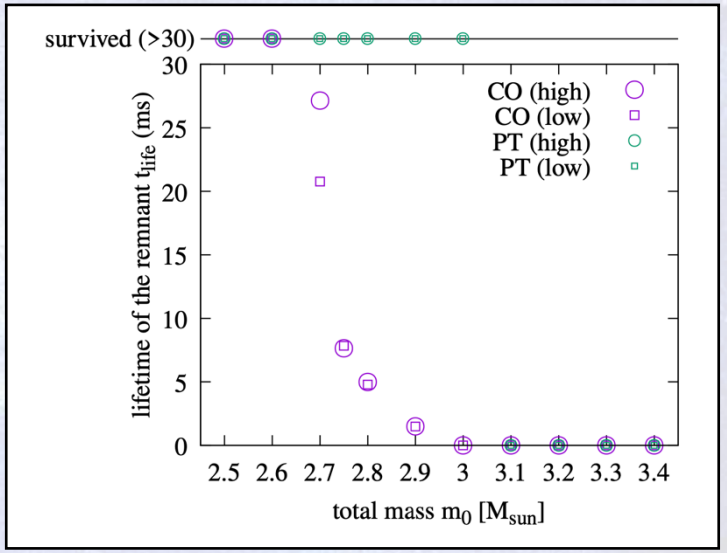
Propogated uncertainties



Radiative transfer

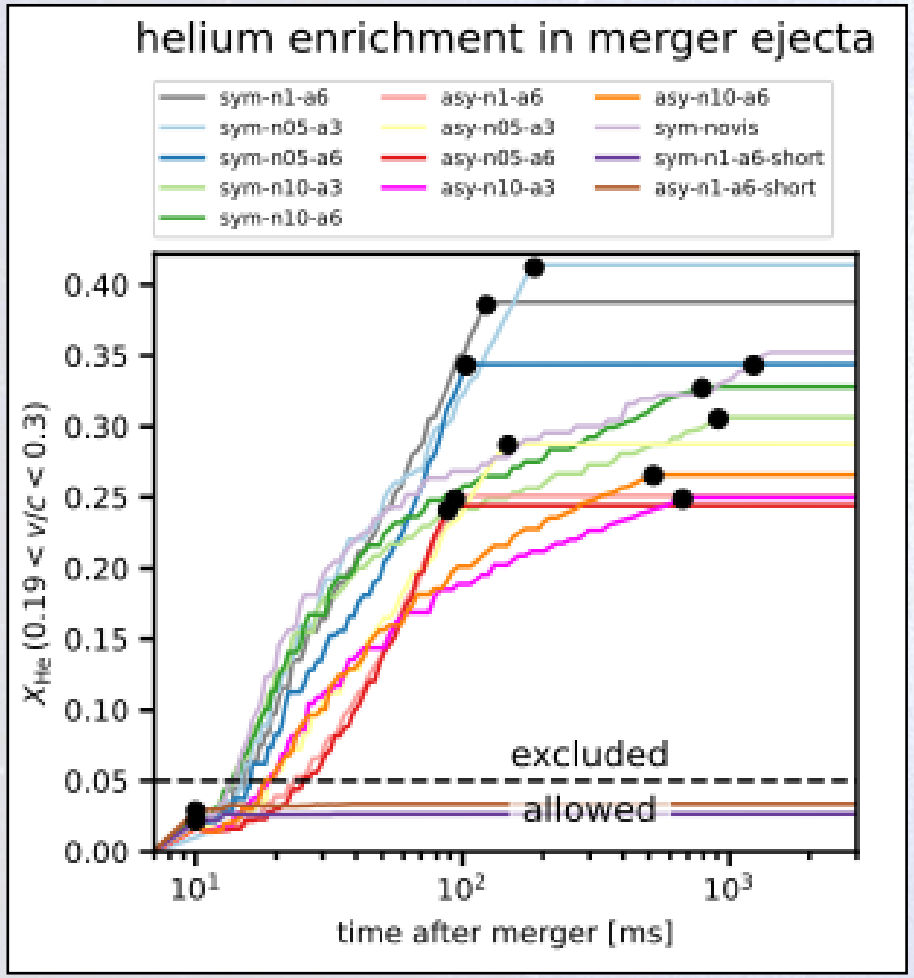
Hydro-merger models

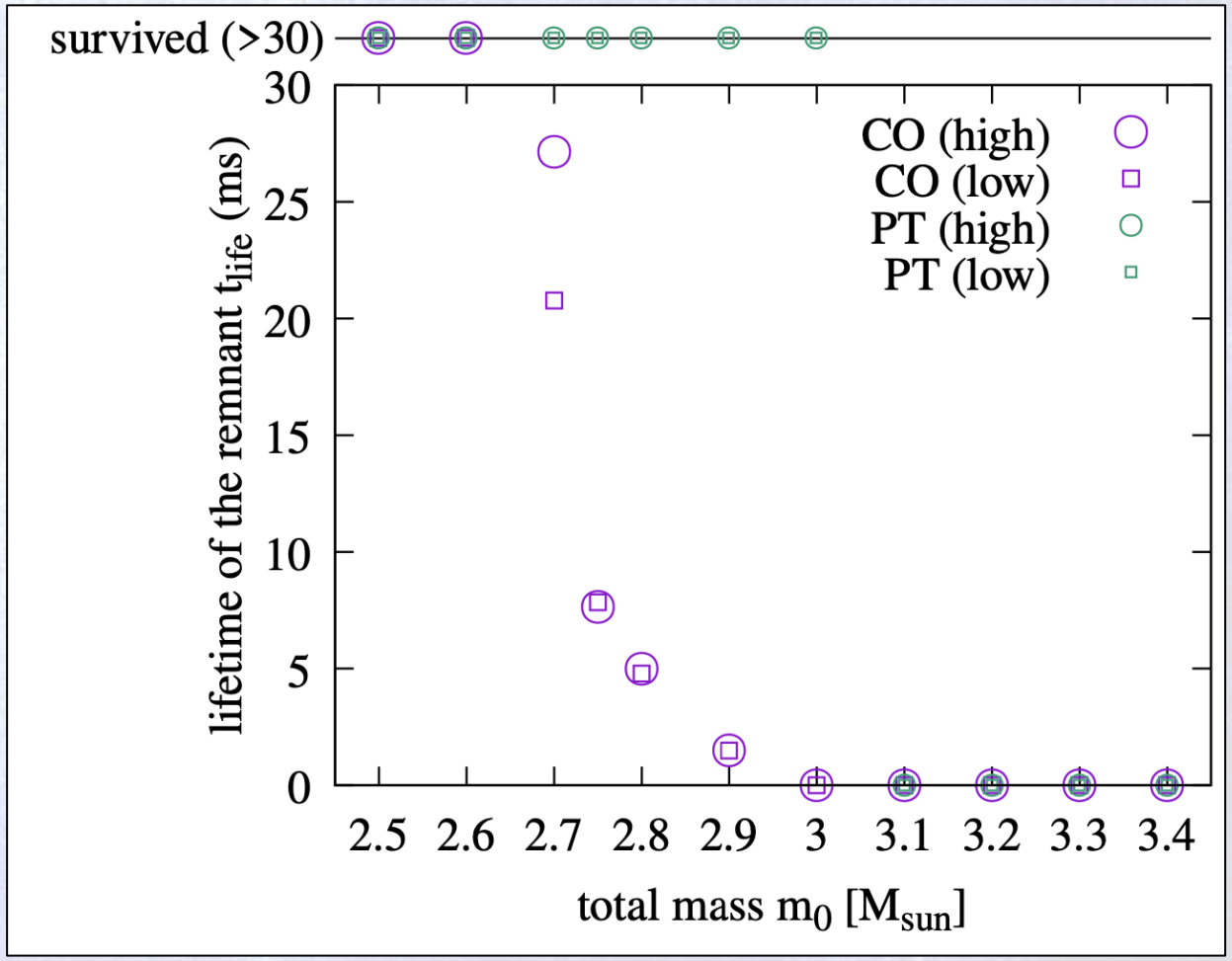


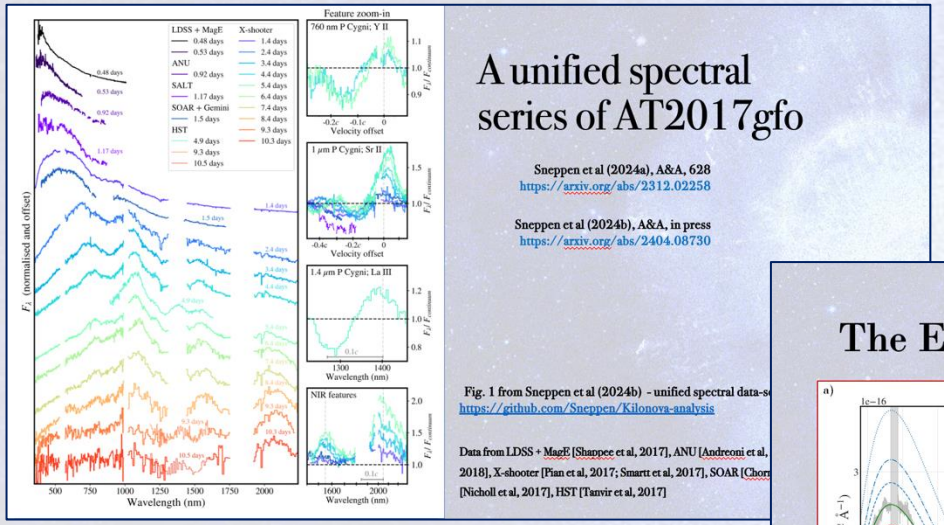


Lifetime to EoS constraints

Steep dependencies helps EoS constraints







A unified spectral series of AT2017gfo

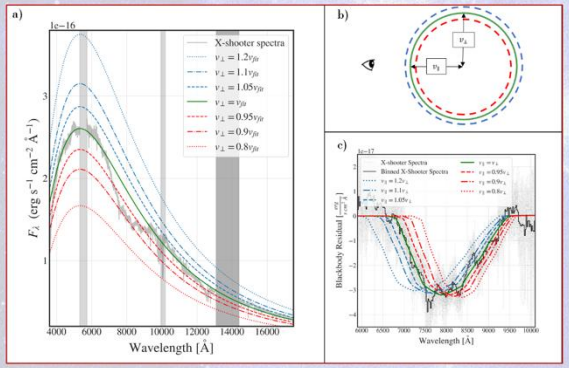
Sneppen et al (2024a), A&A, 628
https://arxiv.org/abs/2312.02258

Sneppen et al (2024b), A&A, in press
https://arxiv.org/abs/2404.08730

Fig. 1 from Sneppen et al (2024b) - unified spectral data-s
https://github.com/Sneppen/Kilonova-analysis

Data from LDSS + MagE [Shappee et al, 2017], ANU [Andreoni et al, 2018], X-shooter [Pian et al, 2017; Smartt et al, 2017], SOAR [Chor [Nicholl et al, 2017], HST [Tanvir et al, 2017]

The Expanding Photosphere Method

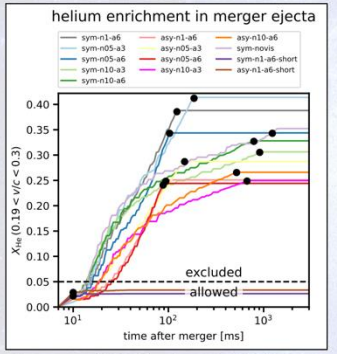


Sneppen et al (2023)

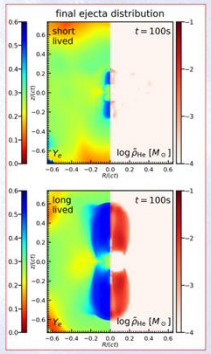
$v_\perp$: The cross-sectional velocity (inferred from the continuum luminosity)

$v_\parallel$: The velocity along the line-of-sight (inferred from the 1 μm P Cygni)

Helium production in neutron-star mergers



Sneppen et al (2024), submitted to PRX



X_{He} - Helium mass fraction

Ie. fraction of mass which will end up as helium particles

Thank you

Fig. 1 from Sneppen et al (2024b) - unified spectral data-series at https://github.com/Sneppen/Kilonova-analysis

Data from LDSS + MagE [Shappee et al, 2017], ANU [Andreoni et al, 2017], SALT [Buckley et al, 2018], X-shooter [Pian et al, 2017; Smartt et al, 2017], SOAR [Chornock et al, 2017], Gemini [Nicholl et al, 2017], HST [Tanvir et al, 2017]