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Plesso Area della Ricerca CNR

Kilonovae: the cosmic foundries of heavy elements

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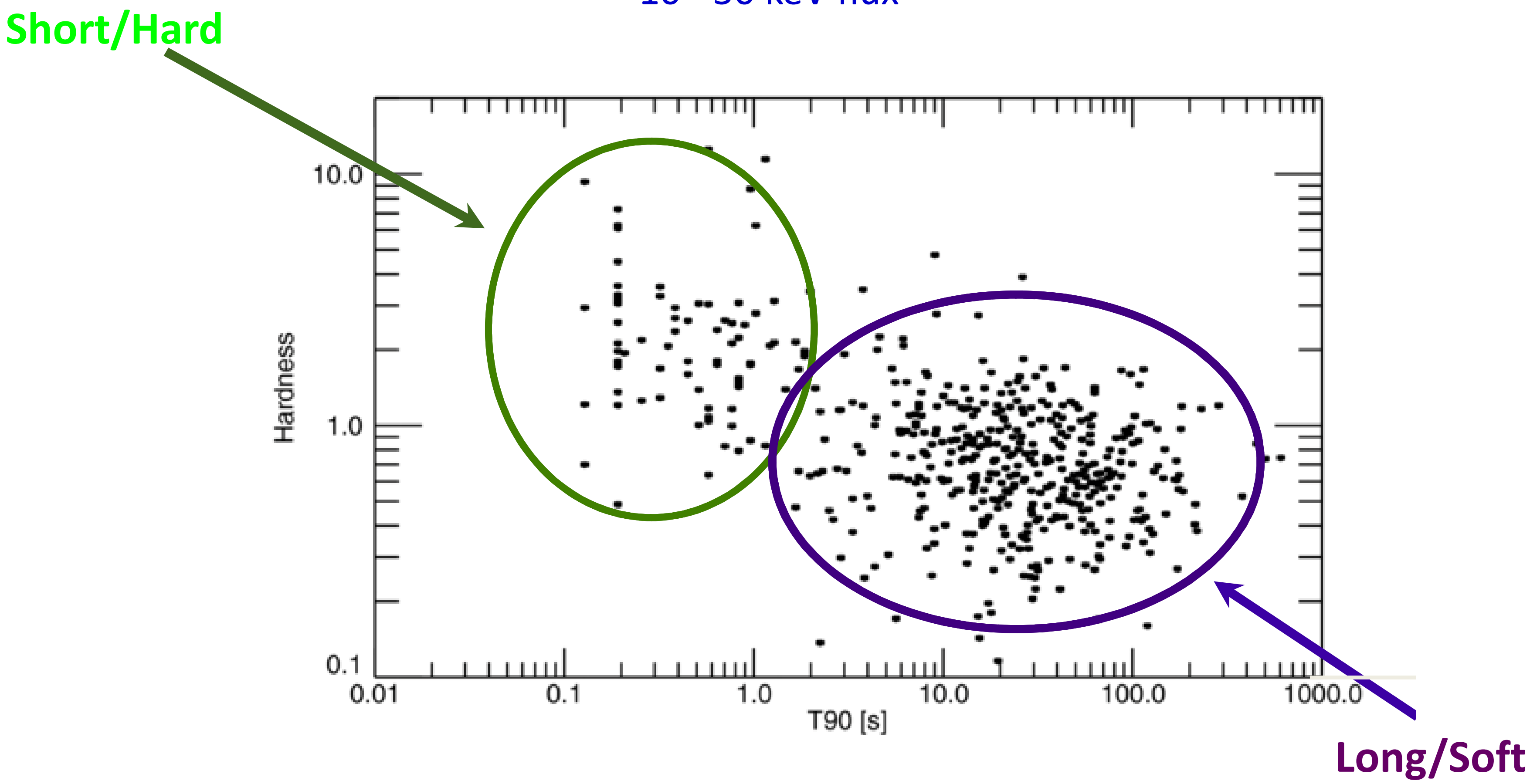
A double neutron star merger is expected to produce:

1) a GW signal at ~1-1000 Hz (nearly isotropic)
2) a short GRB (highly directional and anisotropic)
3) r-process nucleosynthesis (nearly isotropic)

Lattimer & Schramm 1974; Eichler et al. 1989; Li & Paczynski 1998

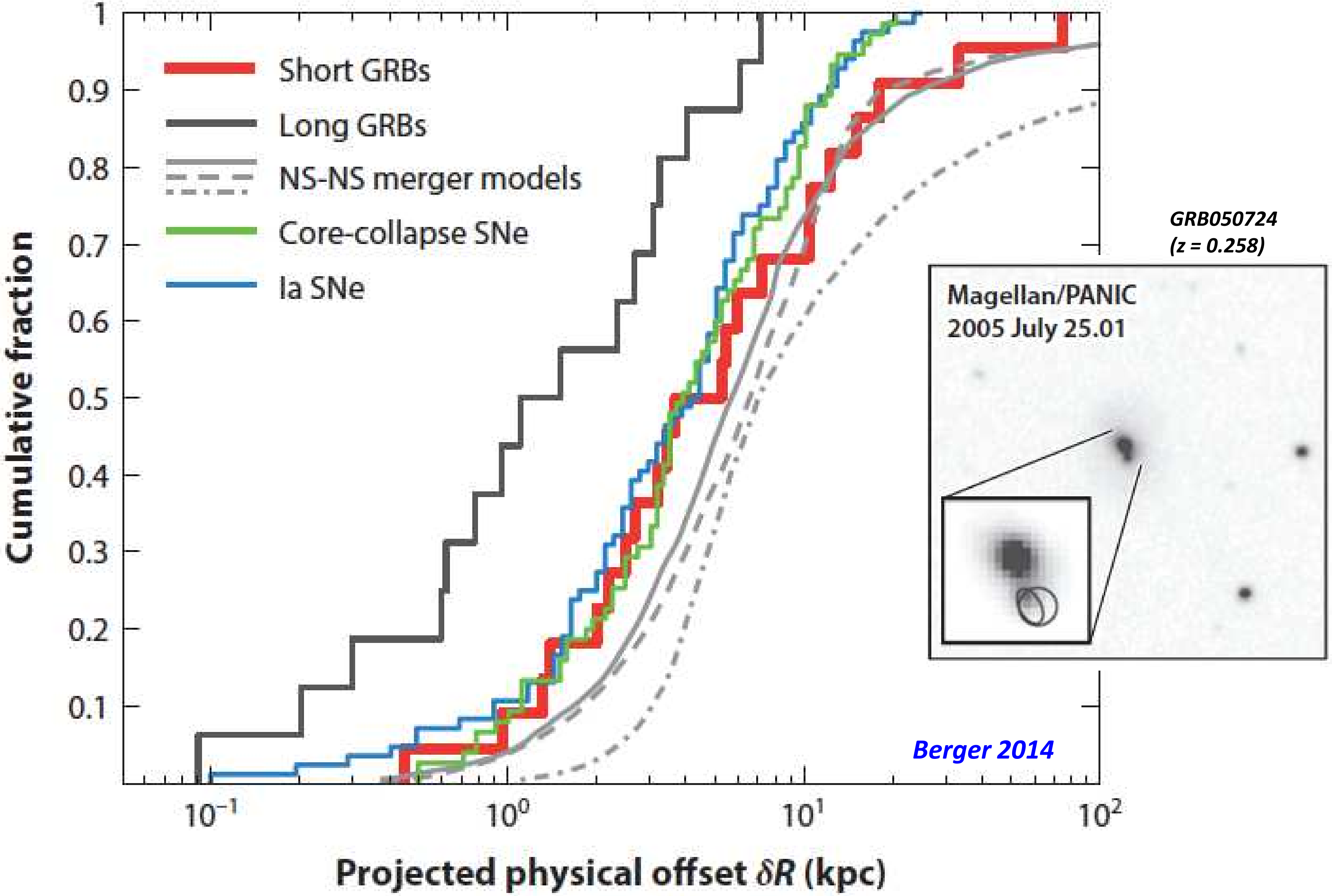
Hardness-Duration Classification of GRBs

$$H = \frac{50 - 300 \text{ keV flux}}{10 - 50 \text{ keV flux}}$$

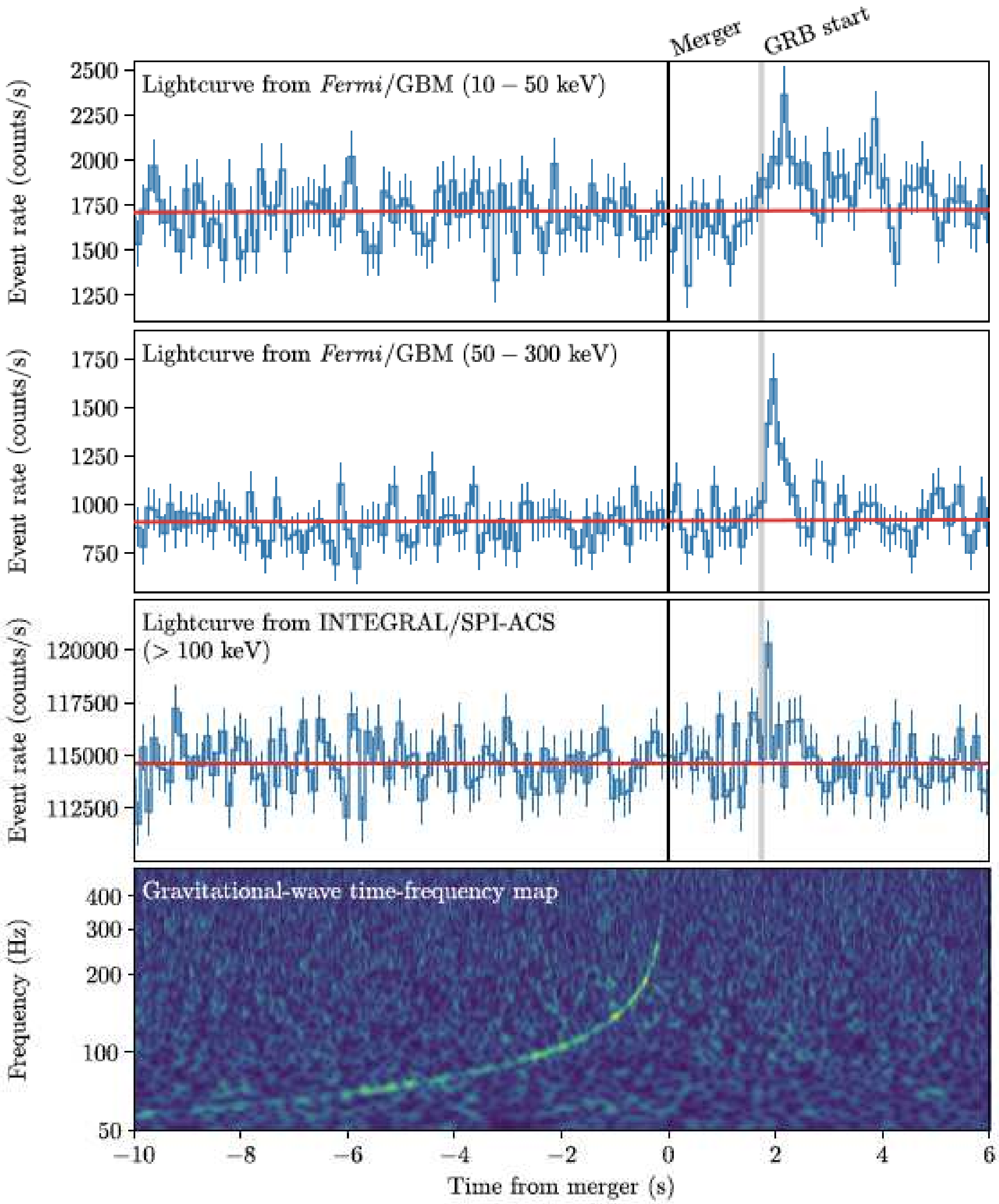


Kouveliotou+1993; von Kienlin+2014

Cumulative distribution of projected offsets of various explosions with respect to their host centers



Berger 2014

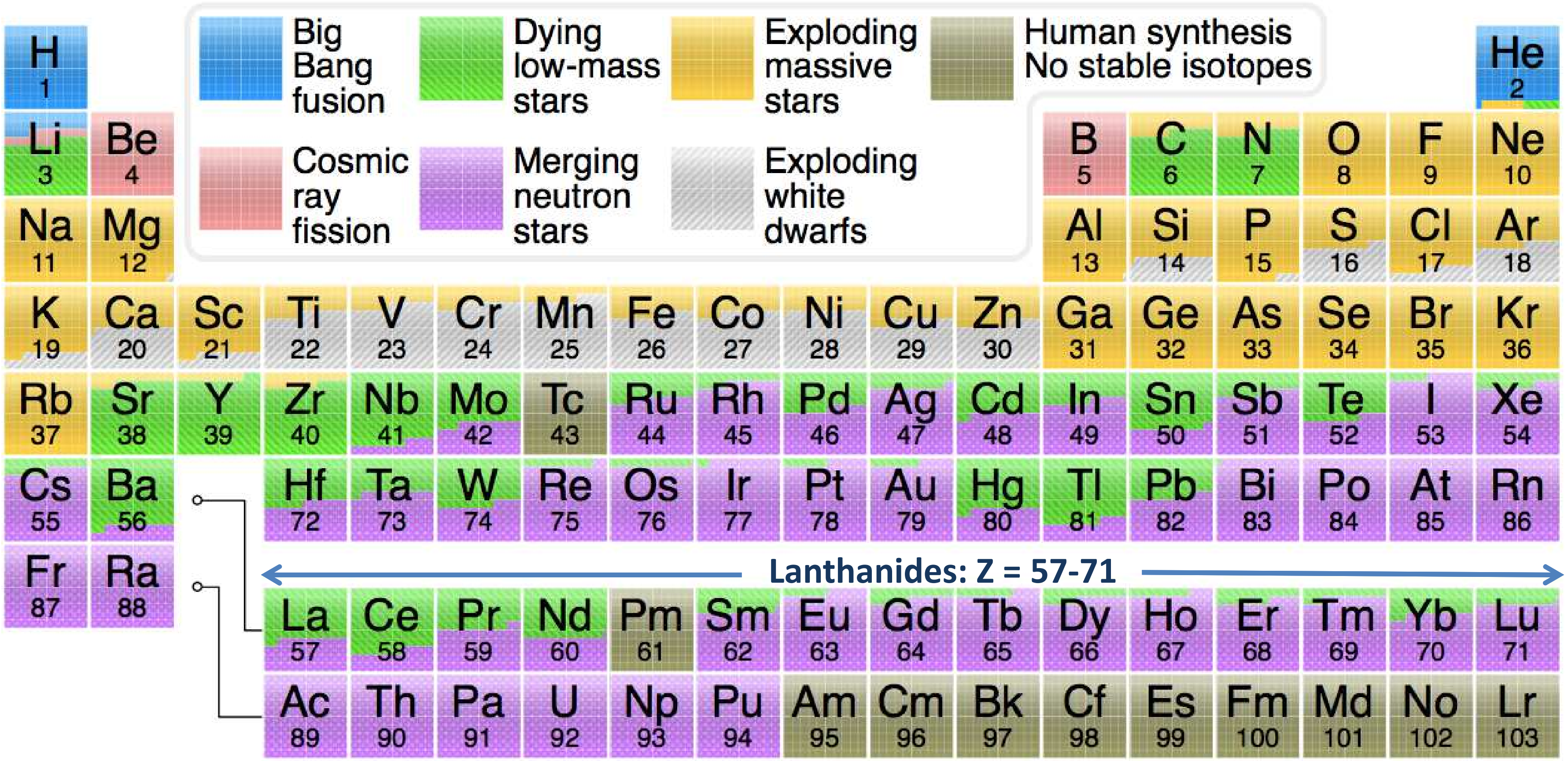


GW170817 and GRB170817A

The short GRB170817A lags GW signal by 1.7s: is this timescale related to the engine or to the plasma outflow?

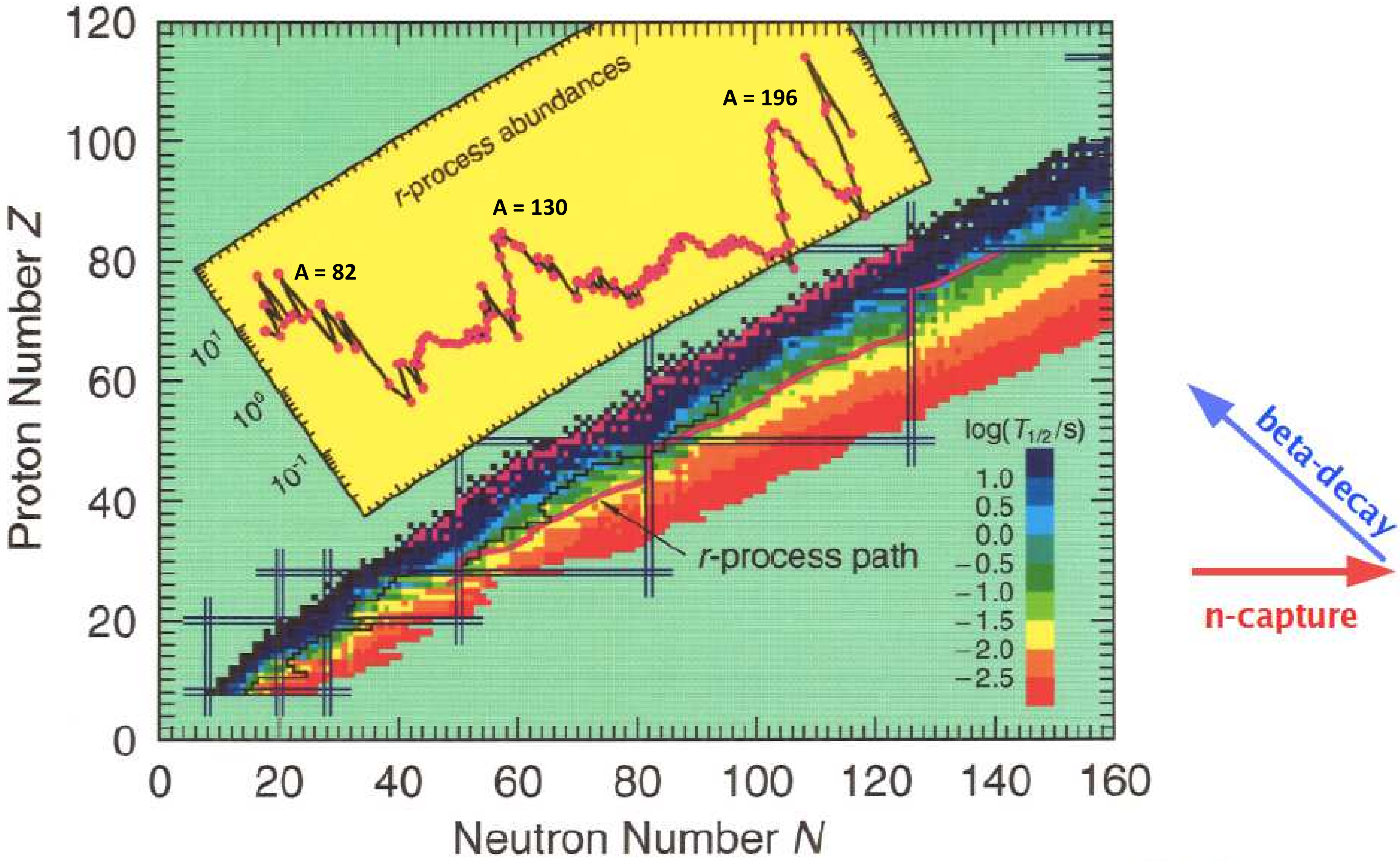
Abbott et al. 2017;
Savchenko et al. 2017;
Fermi Collaboration 2017

Periodic table of elements



https://en.wikipedia.org/wiki/R-process

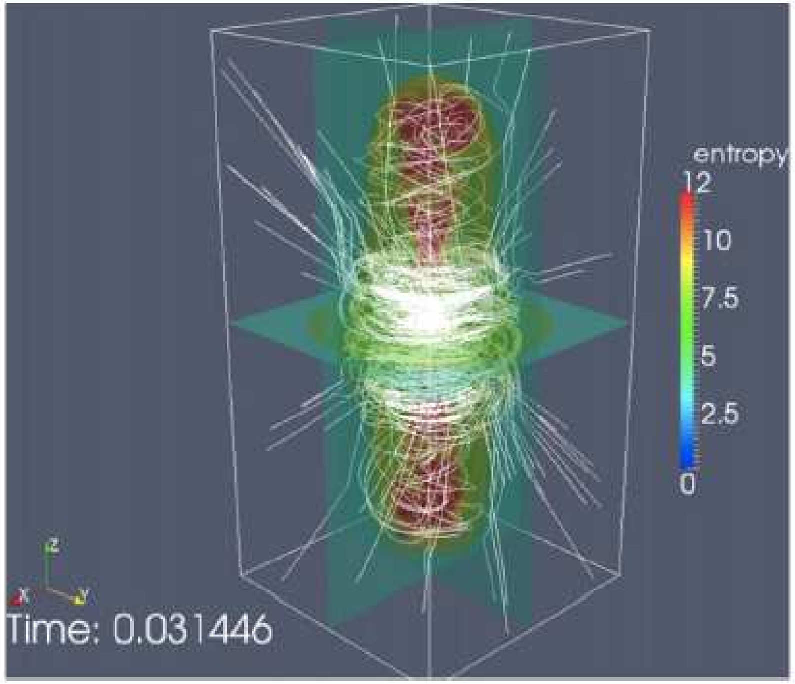
s- and r-Process Nucleosynthesis



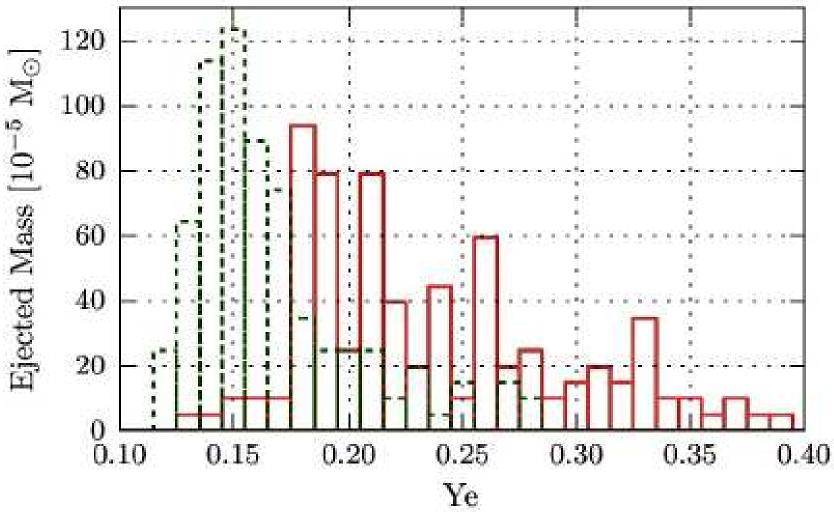
Courtesy: K.-L. Kratz

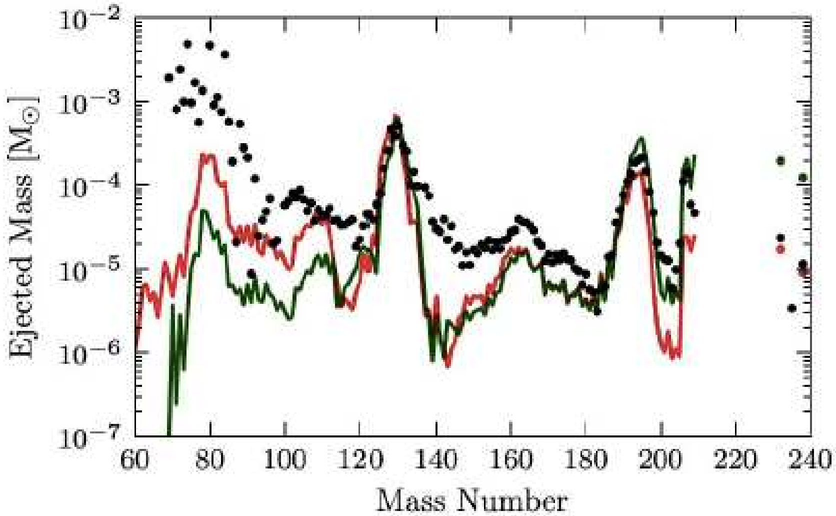
Jet-Supernova Models as r-process Sites?

- MHD-driven polar 'jets" could sweep out n-rich matter.
- Requires extremely fast matter ejection, extremely rapid rotation and extremely strong magnetic fields in pre-collapse stellar cores.
- Should be very rare event; maybe 1 of 1000 stellar core collapses?



Winteler et al., ApJL 750 (2012) L22





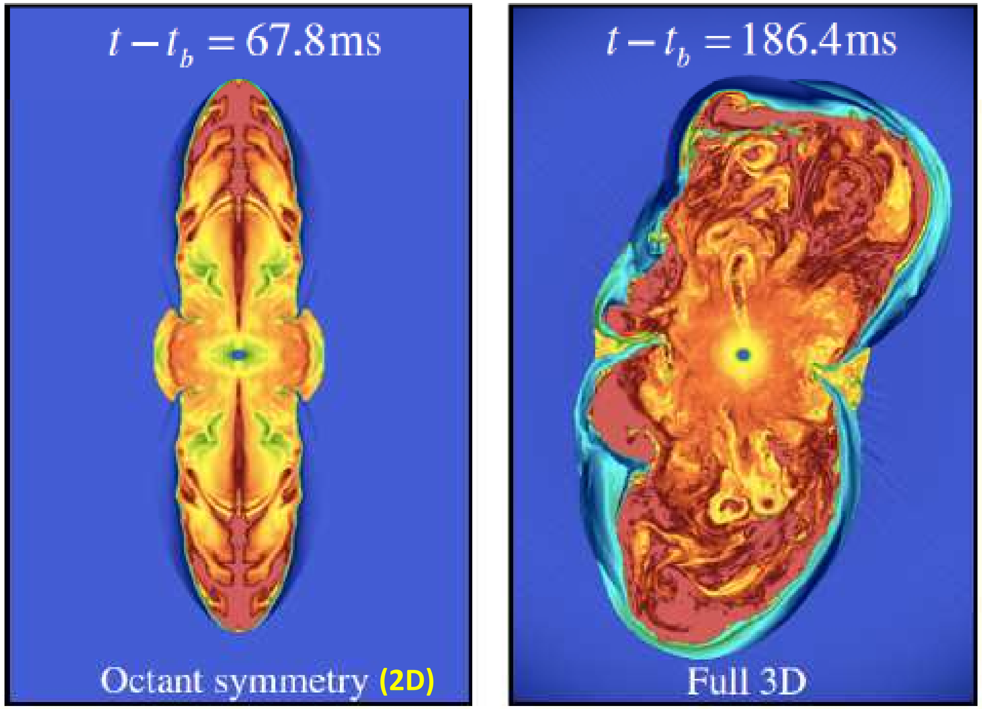
From Th. Janka, 2016

Jet-Supernova Models as r-process Sites?

BUT:

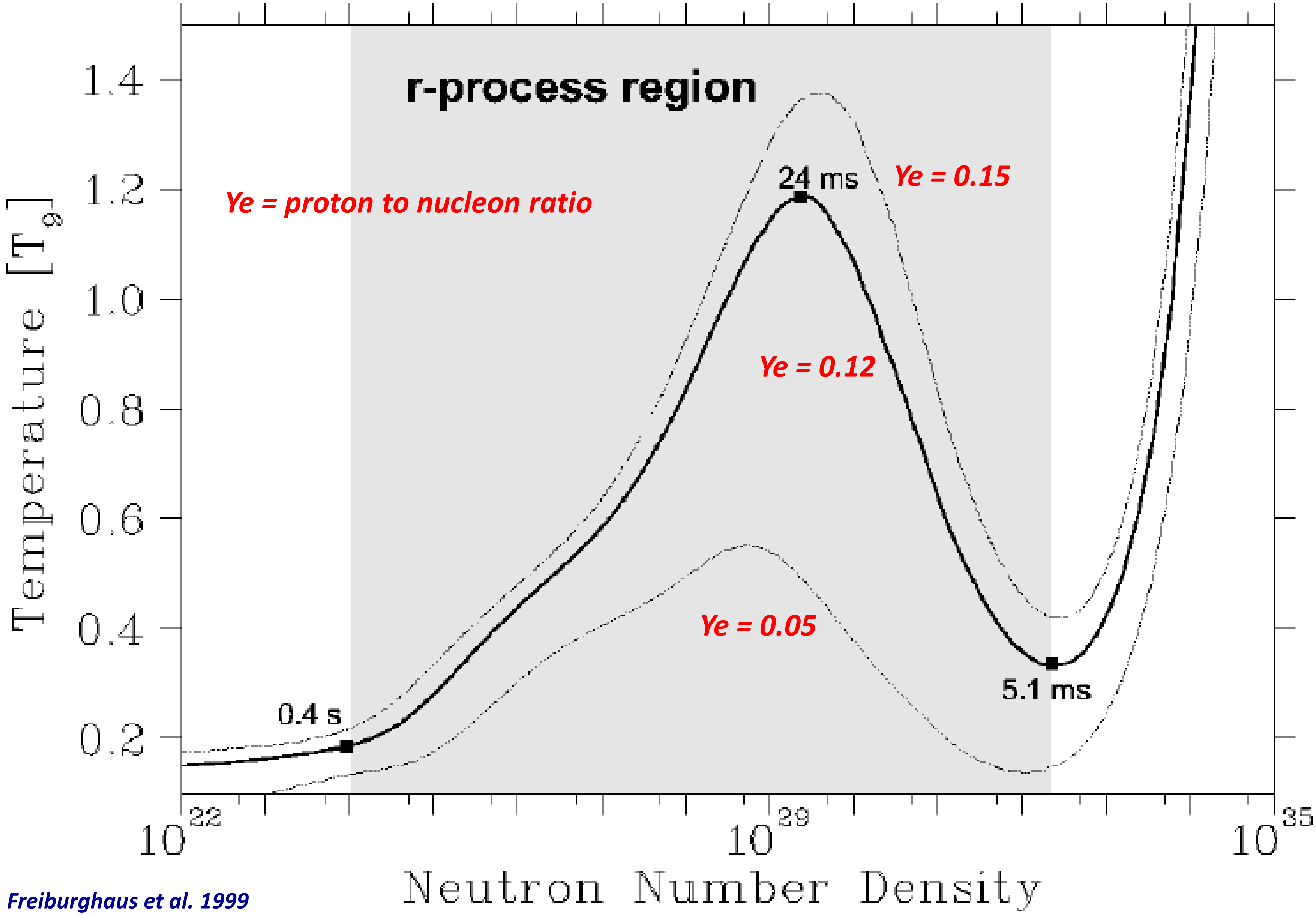
- MHD-driven polar "jets" in 3D develop kink instability.
- Assumed initial conditions not supported by stellar pre-collapse models.
- Dynamical scenario does not provide environment for robust r-process.

From Th. Janka, 2016



Mösta et al., ApJL 785 (2014) L29

Conditions during decompression of NS material



Freiburghaus et al. 1999

Short GRB130603B

(z = 0.356)

Kilonova:

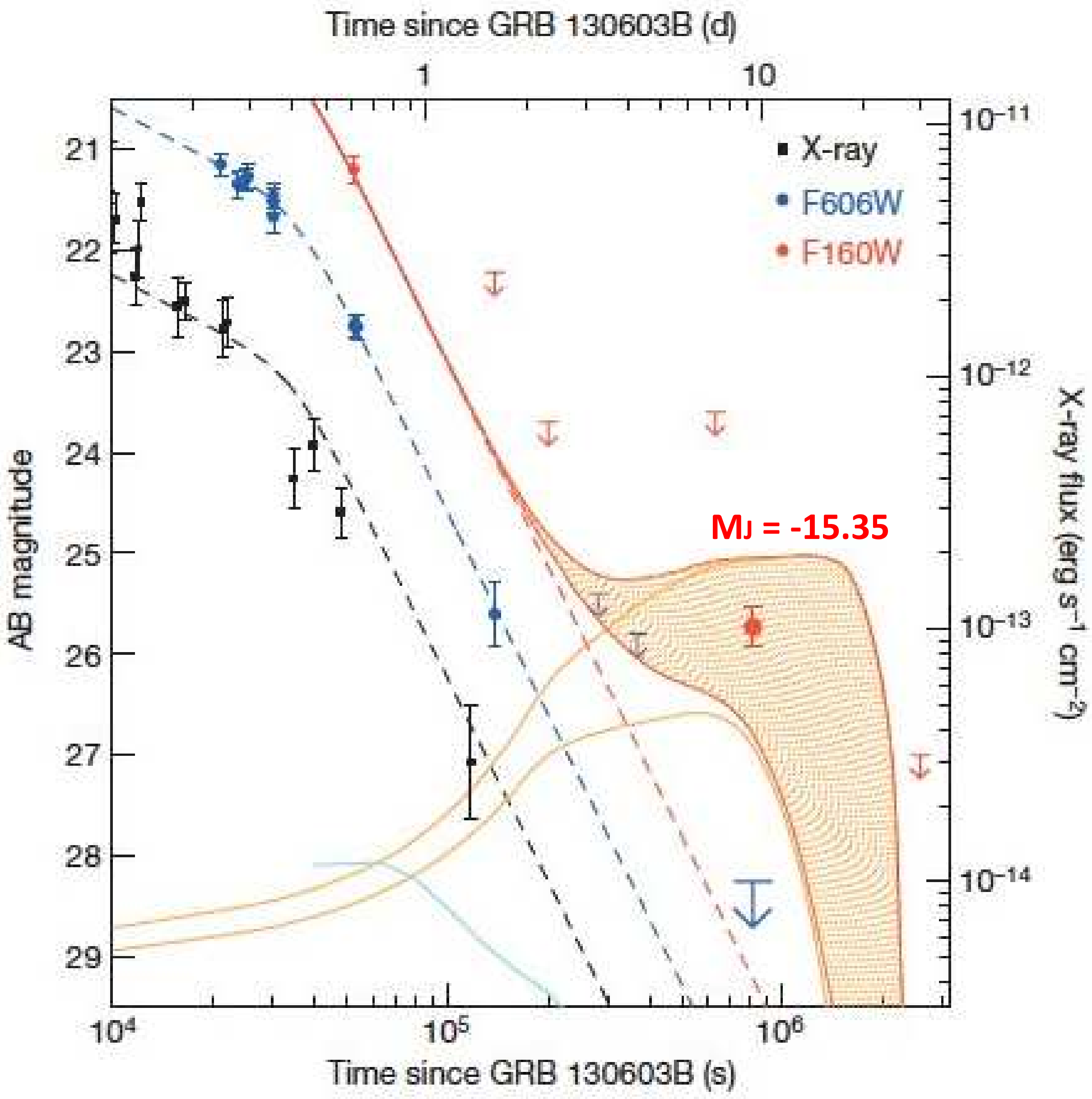
Ejection of r-process material from a NS merger (0.01-0.1 Mo) (Barnes & Kasen 2013)

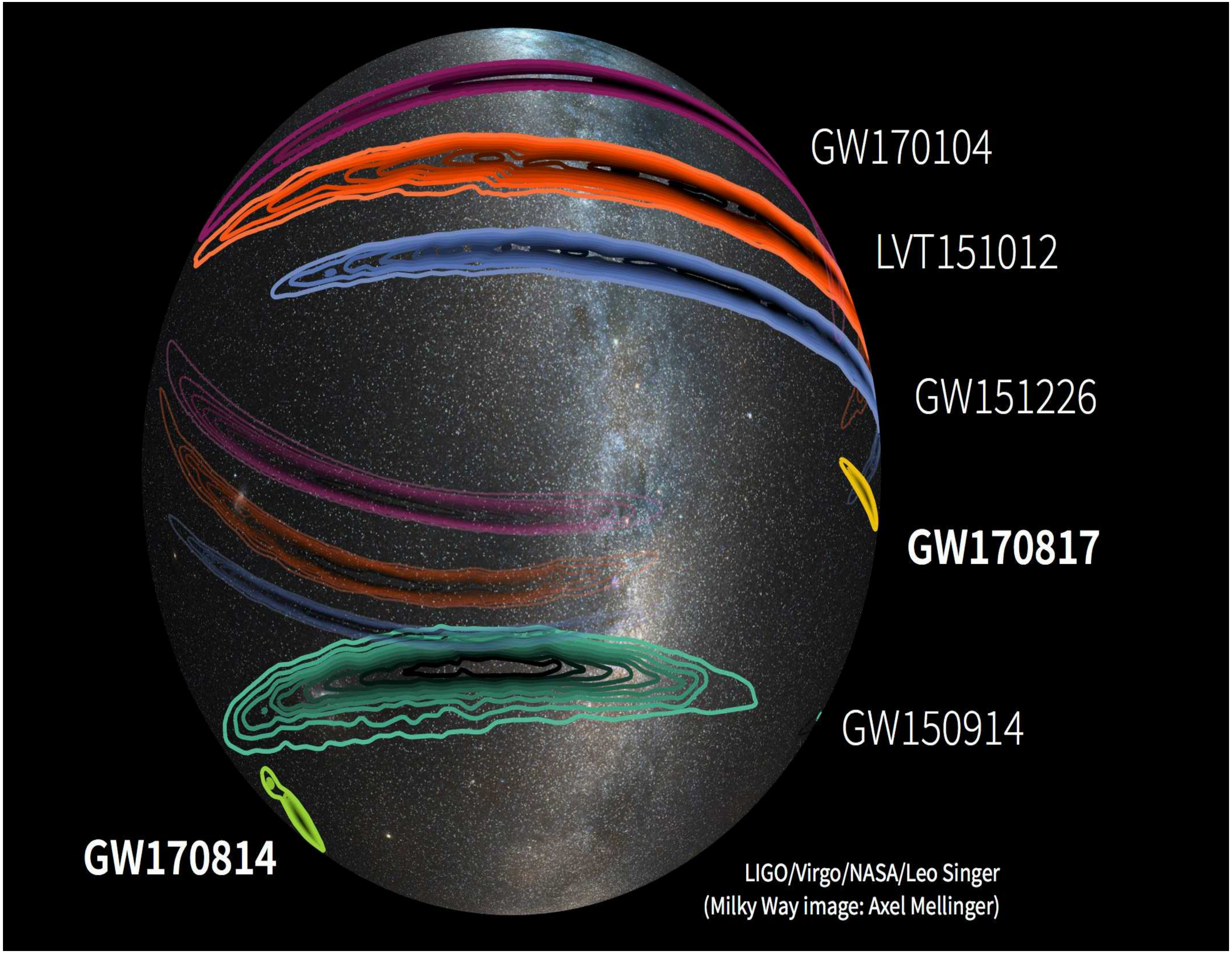
$M_H \approx -15$

$M_R \approx -13$

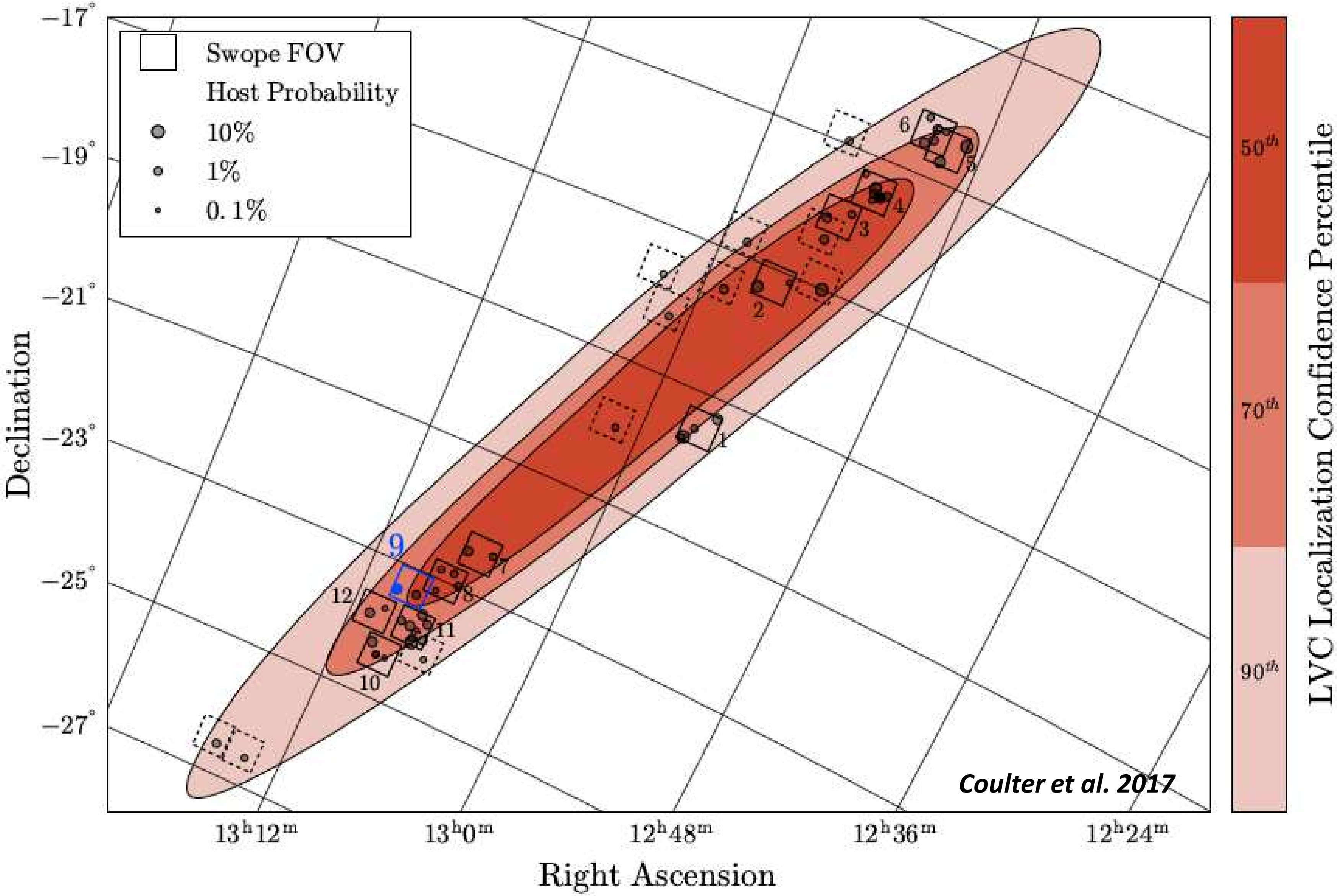
Tanvir et al. 2013;

Berger et al. 2013



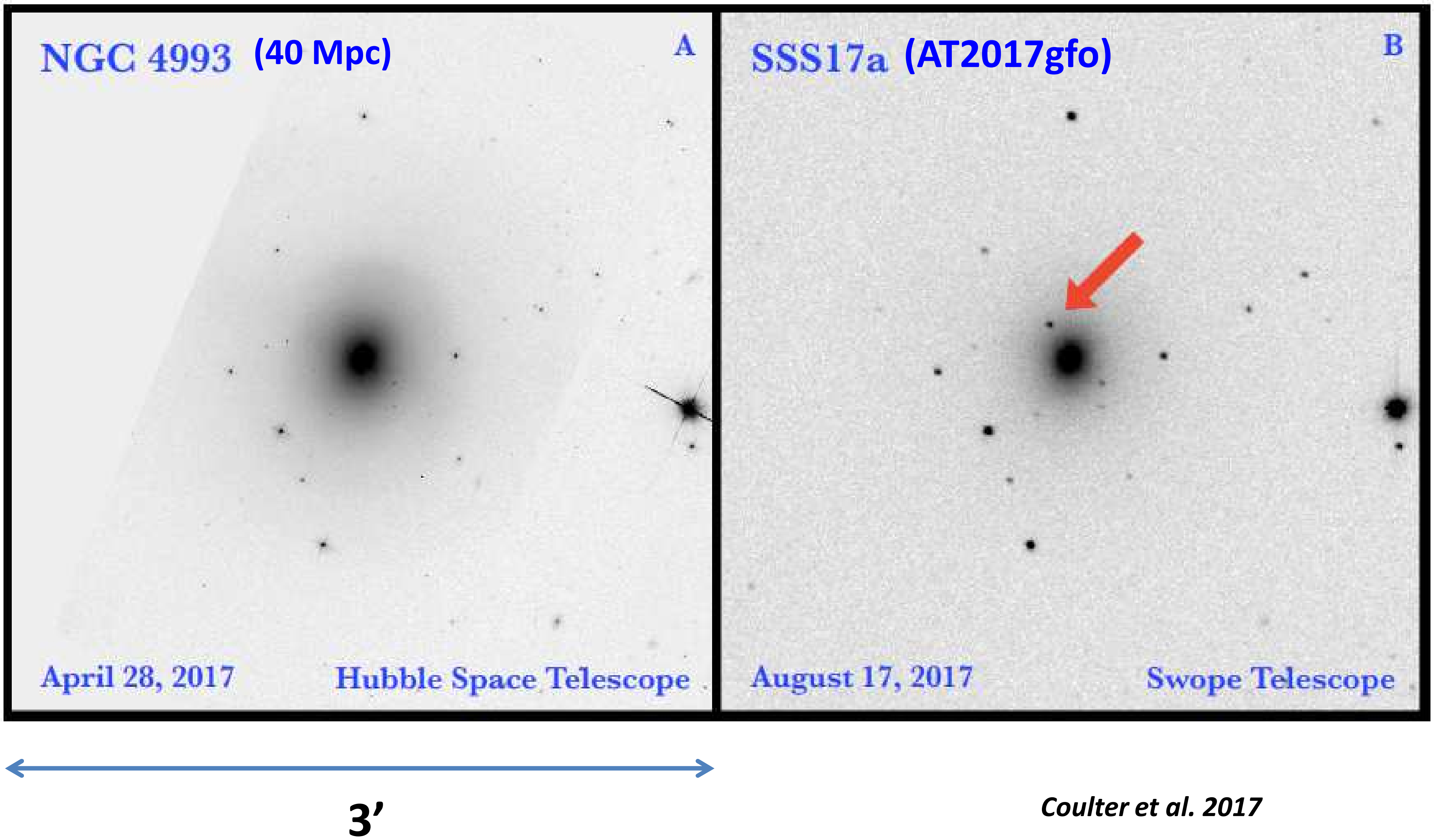

GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Search for GW170817 optical counterpart: GW error regions and Swope 1m pointings



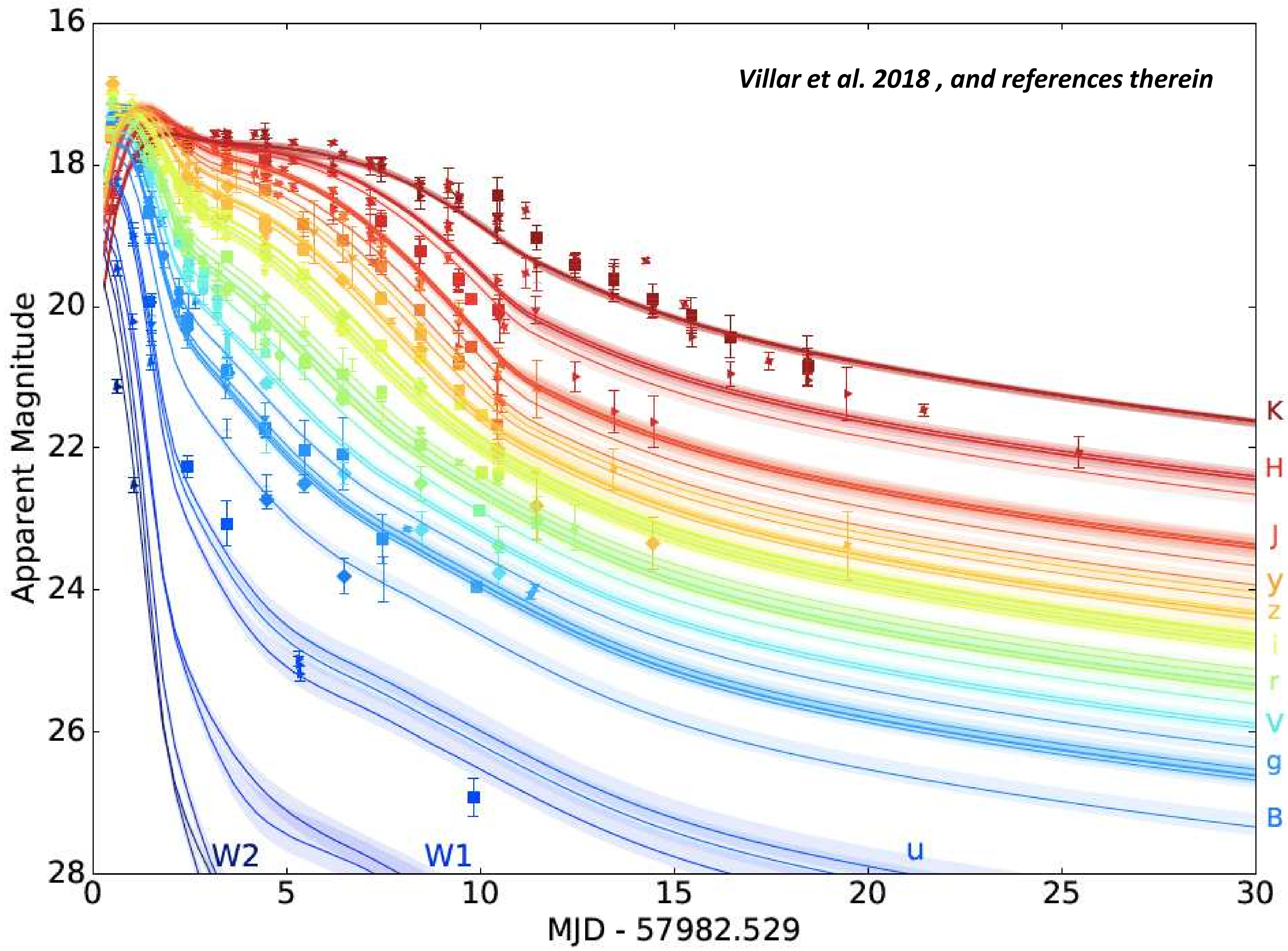
Coulter et al. 2017

Comparison of Swope discovery image with archival HST image

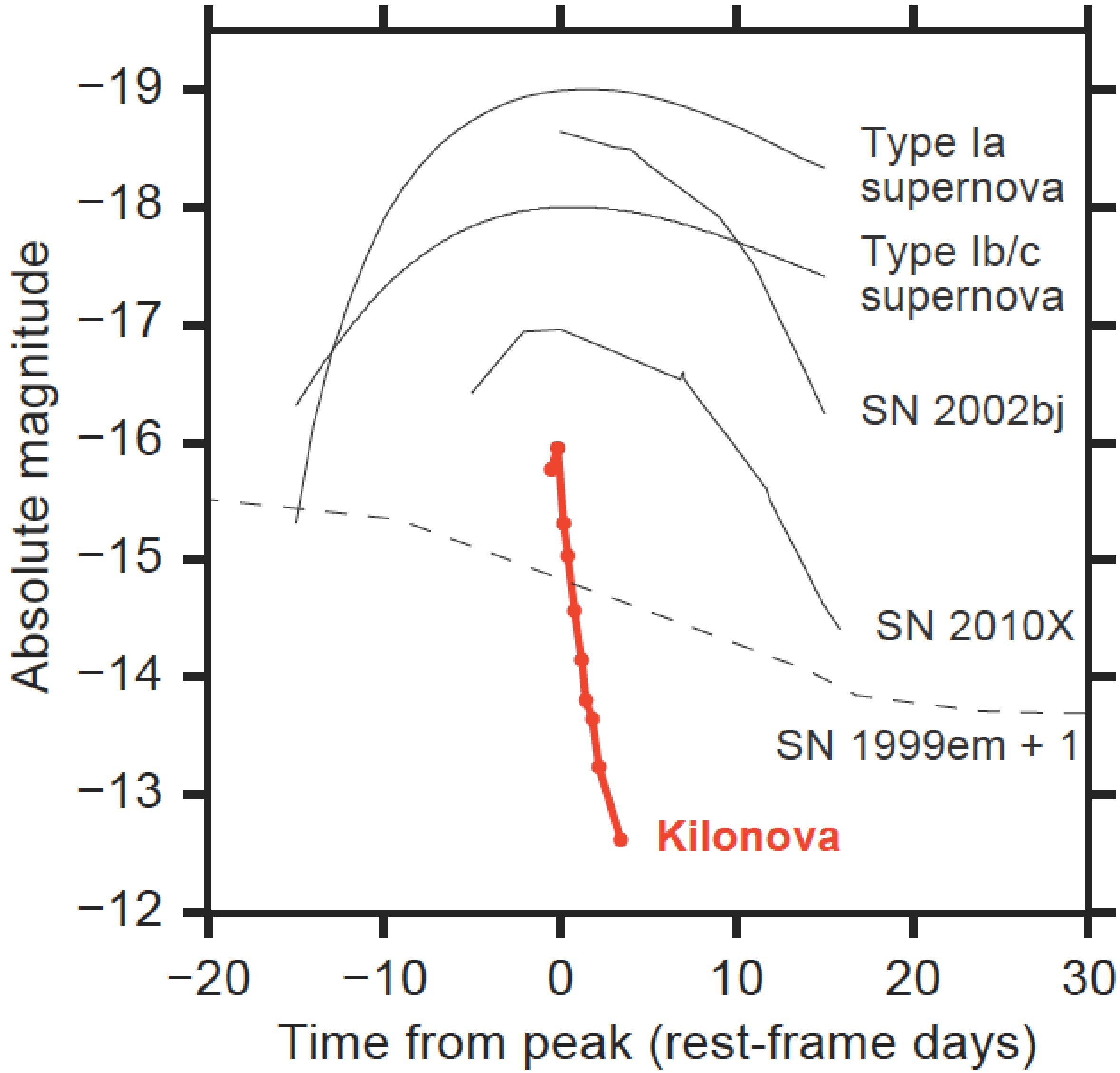


Coulter et al. 2017

Optical and near-infrared light curves of GW170817 / AT2017gfo

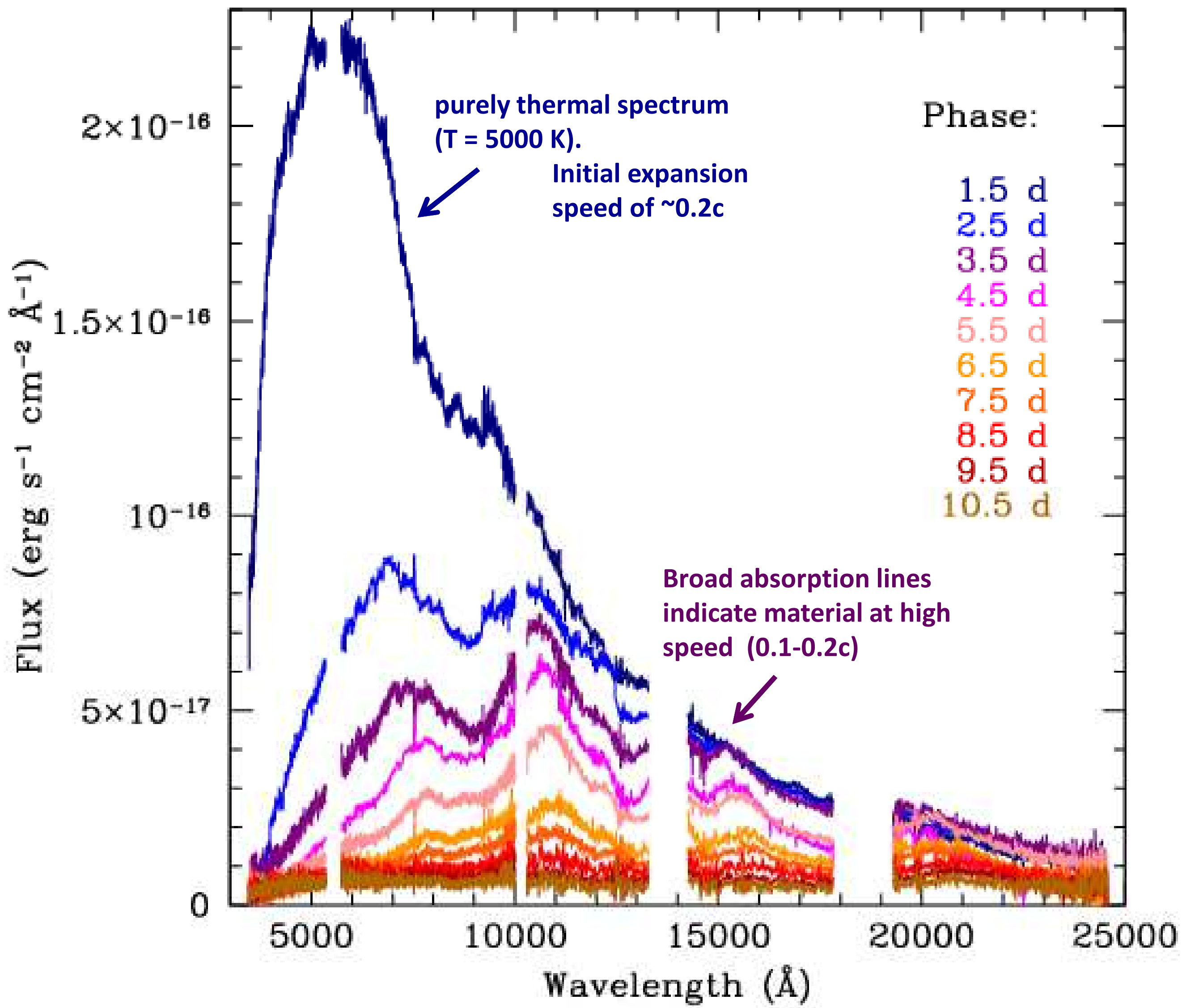


AT2017gfo evolves much more rapidly than any supernova



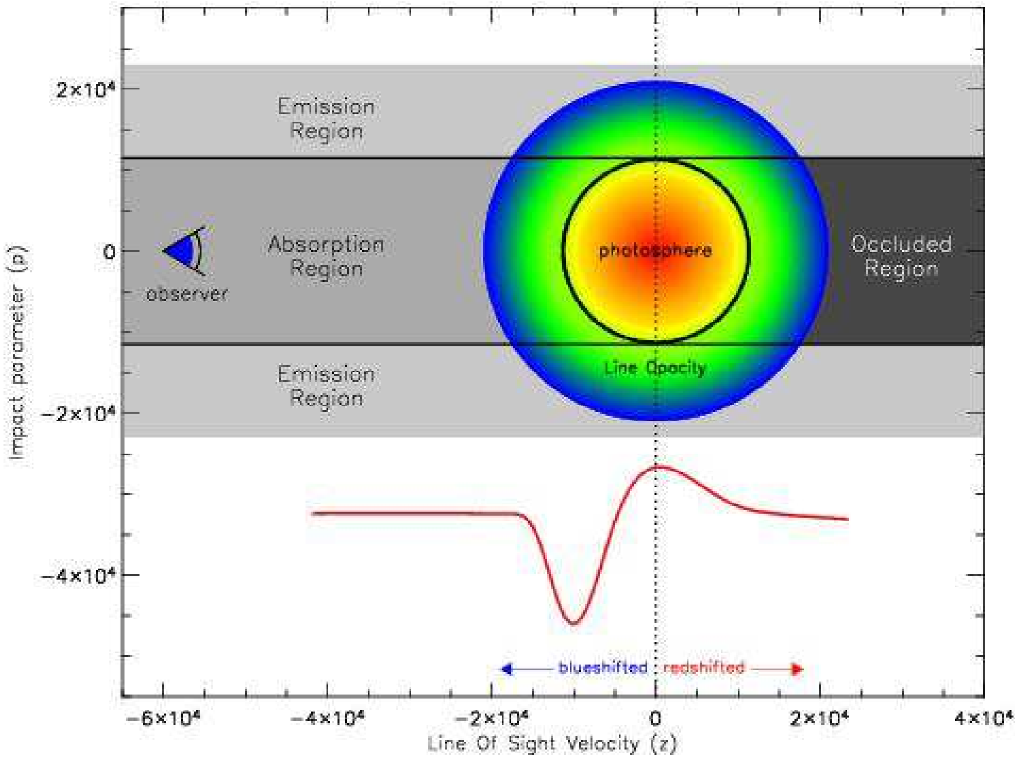
Arcavi et al. 2

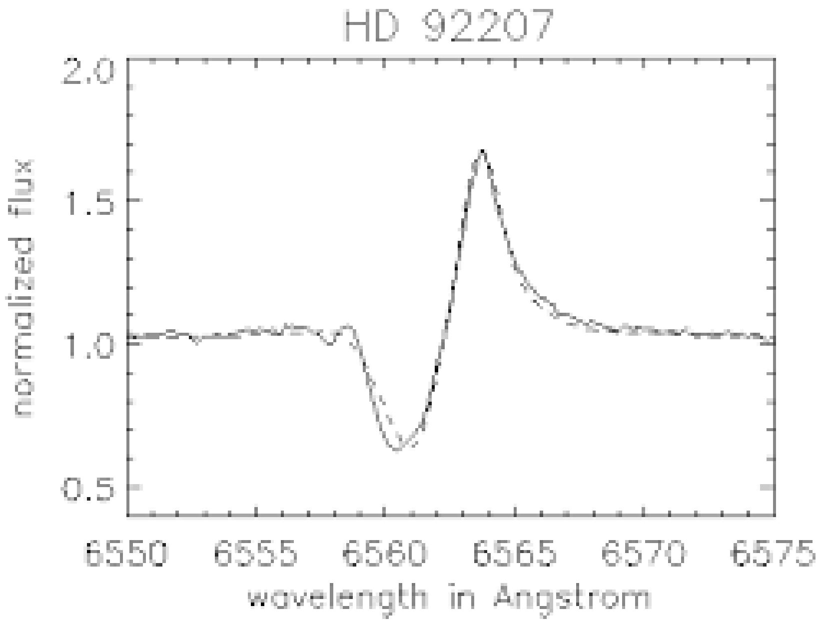
ESO VLT X-Shooter spectral sequence of kilonova GW170817



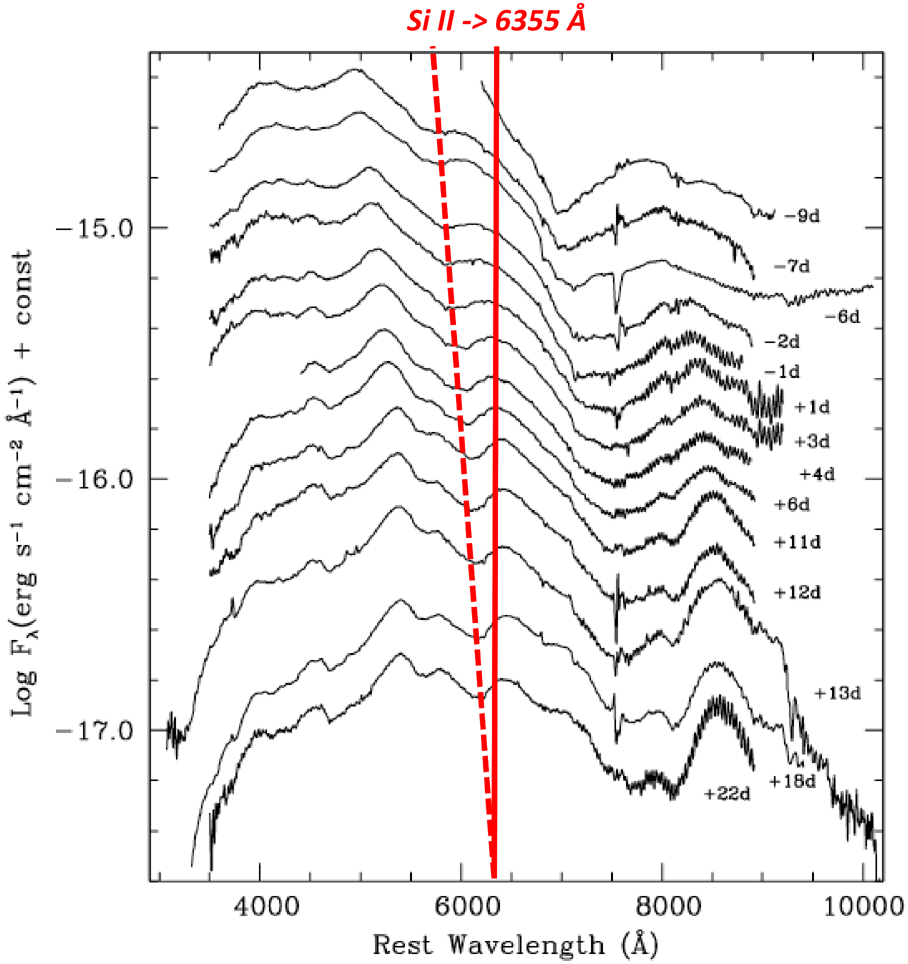
Pian et al. 2017; Smartt et al. 2017

Receding photosphere: P-Cygni profile of absorption lines





Supernova spectral evolution: the photosphere (τ ~ 1) recedes with time (SN1998bw, 35 Mpc)



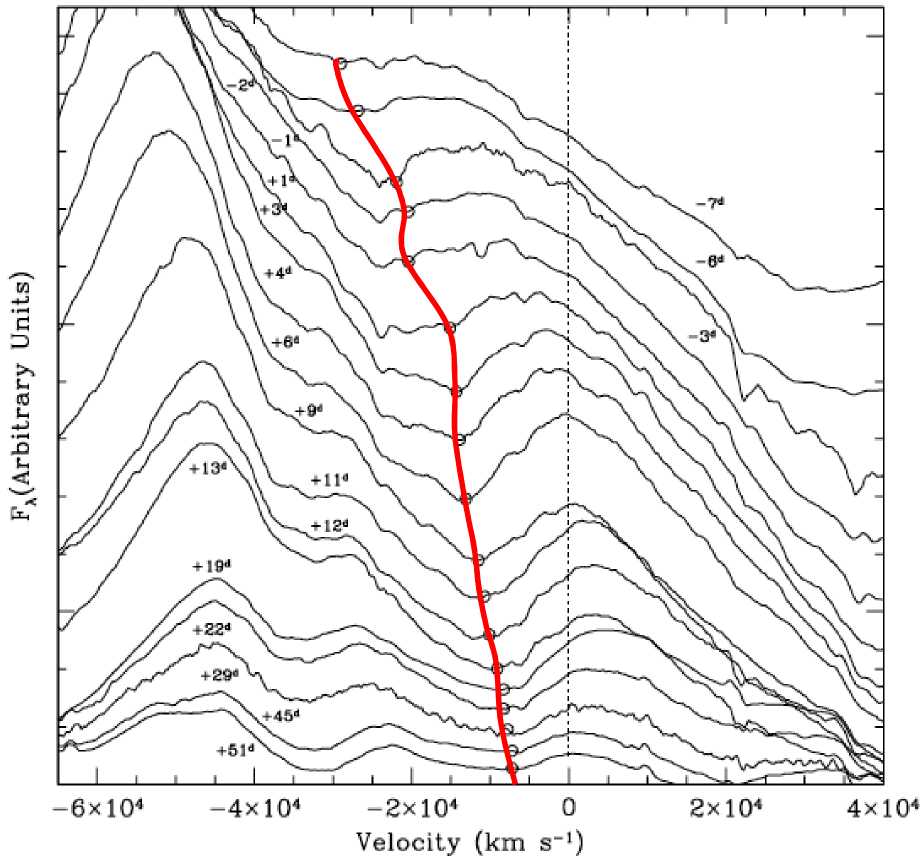
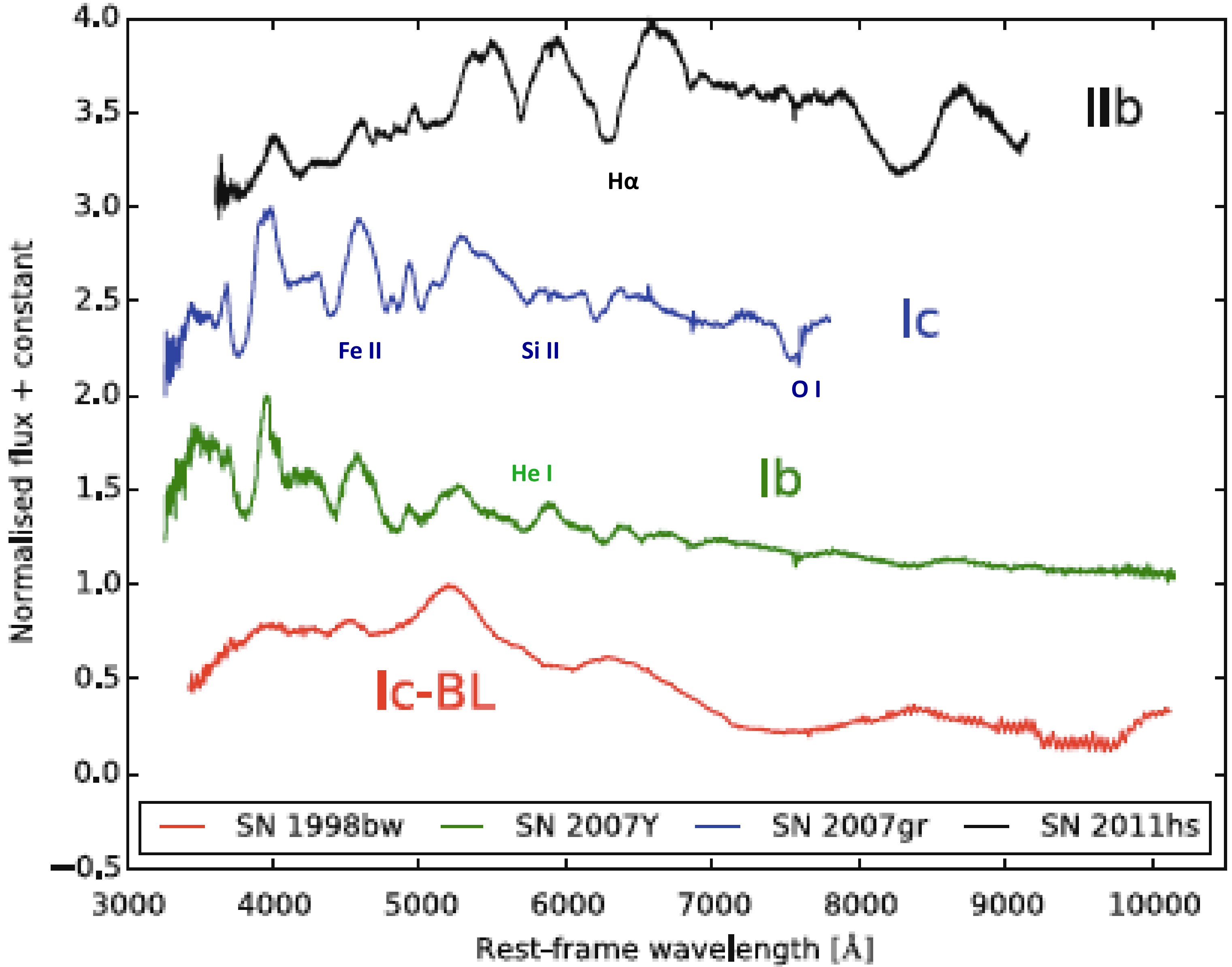


FIG. 4.—Evolution of the Si II λ6355 region. The empty circles mark the value that has been assumed to represent the photospheric velocity.

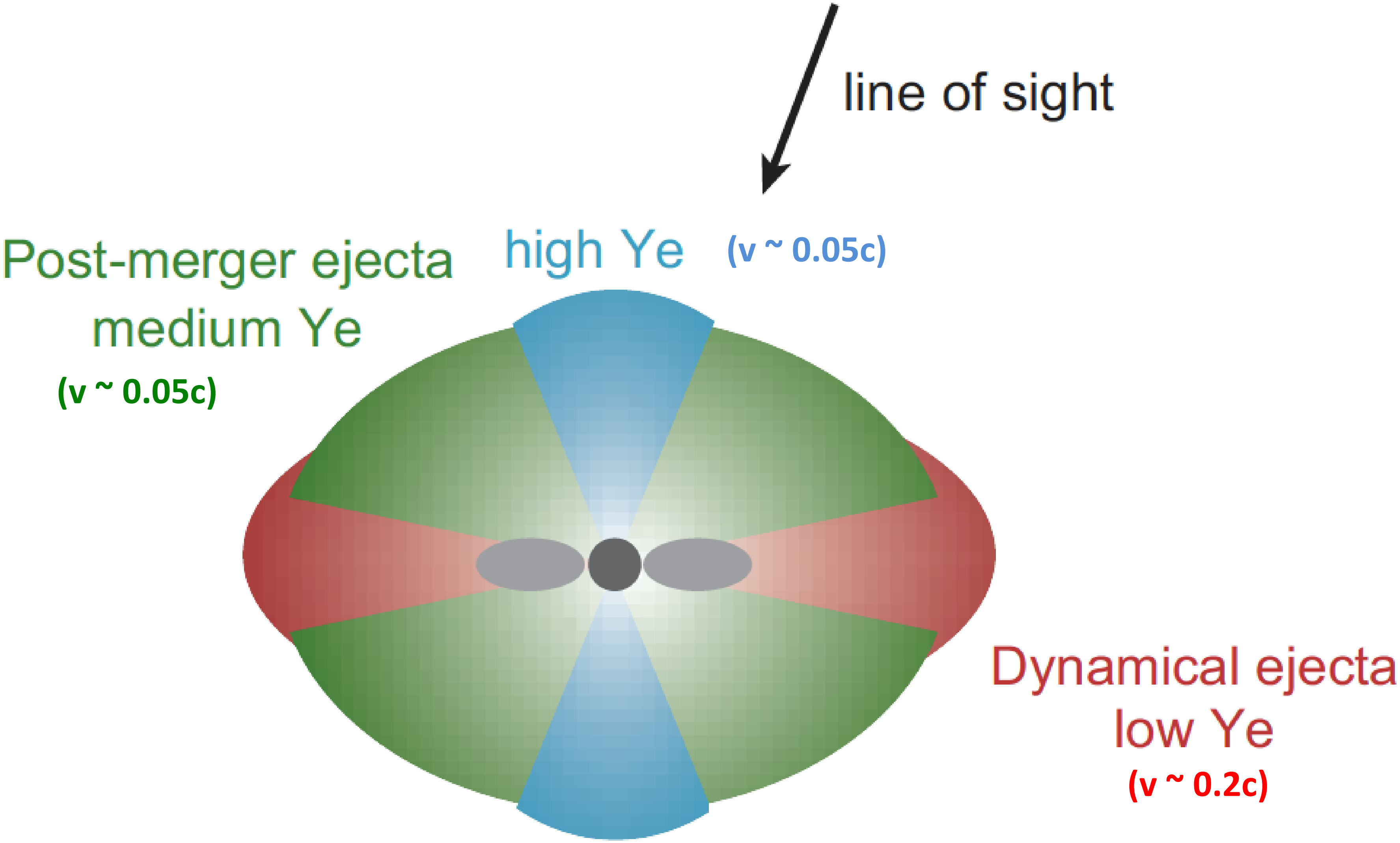
Patat et al. 2001

Typical spectra of Stripped-envelope core-collapse SNe



Pian & Mazzali 2017

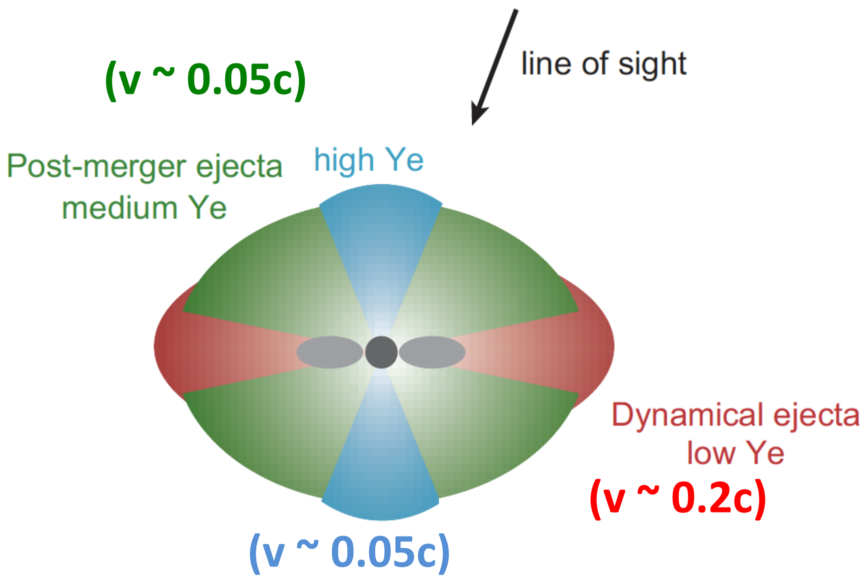
Geometry of 3-component model for kilonova

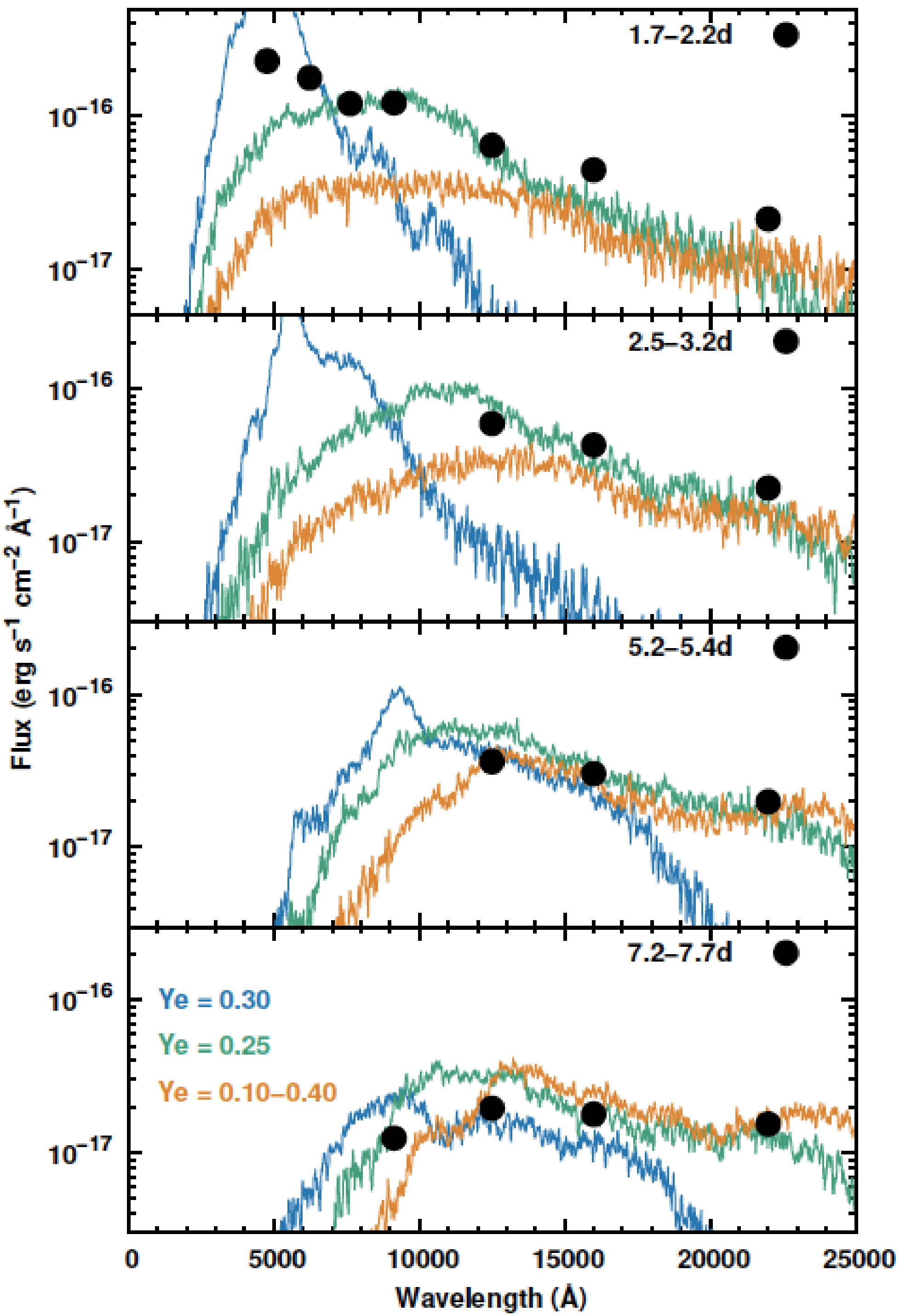


Tanaka et al. 2017, PASJ

Geometry of 3-component model for kilonova and resulting spectra

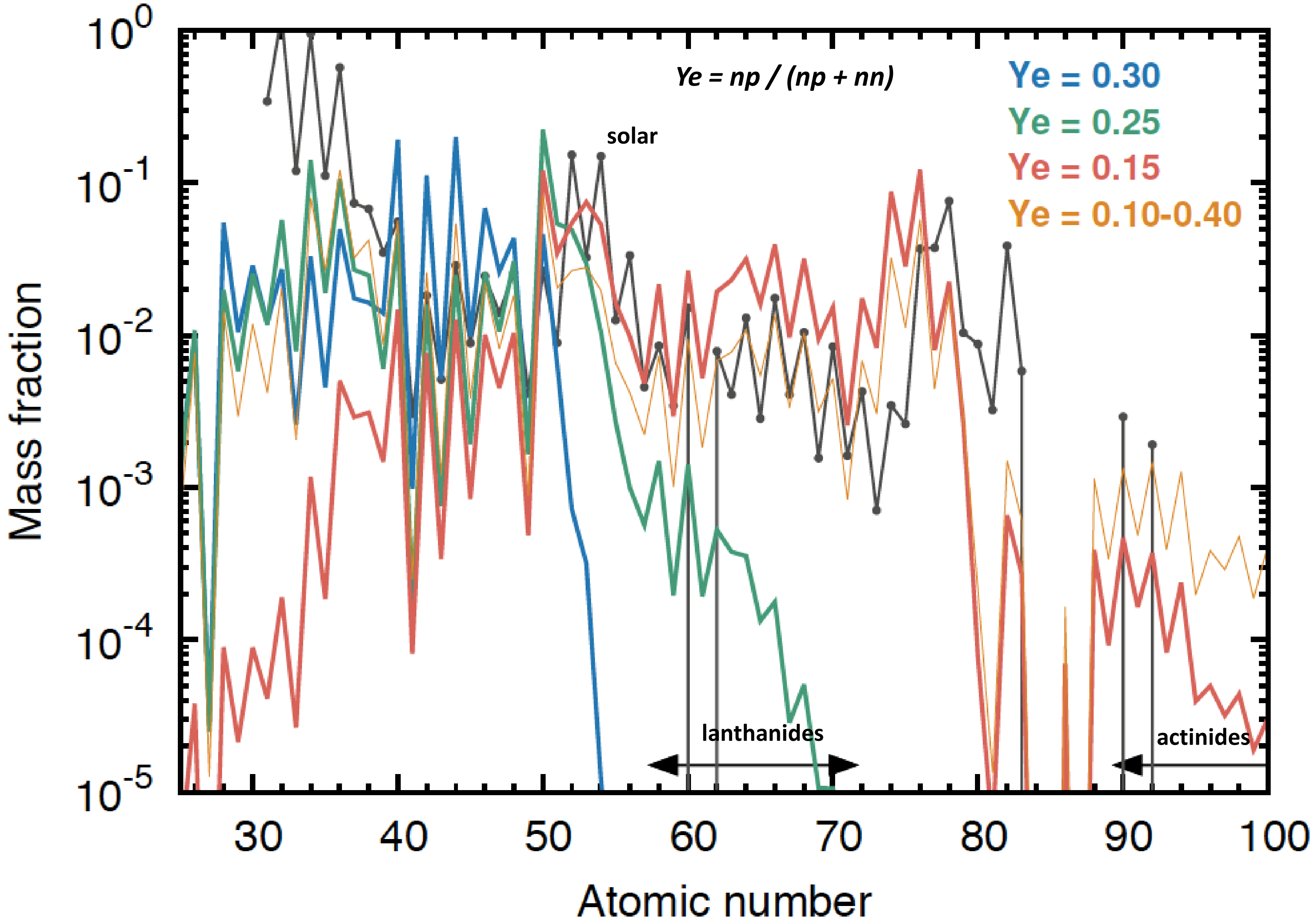
M_{ej} ~ 0.03





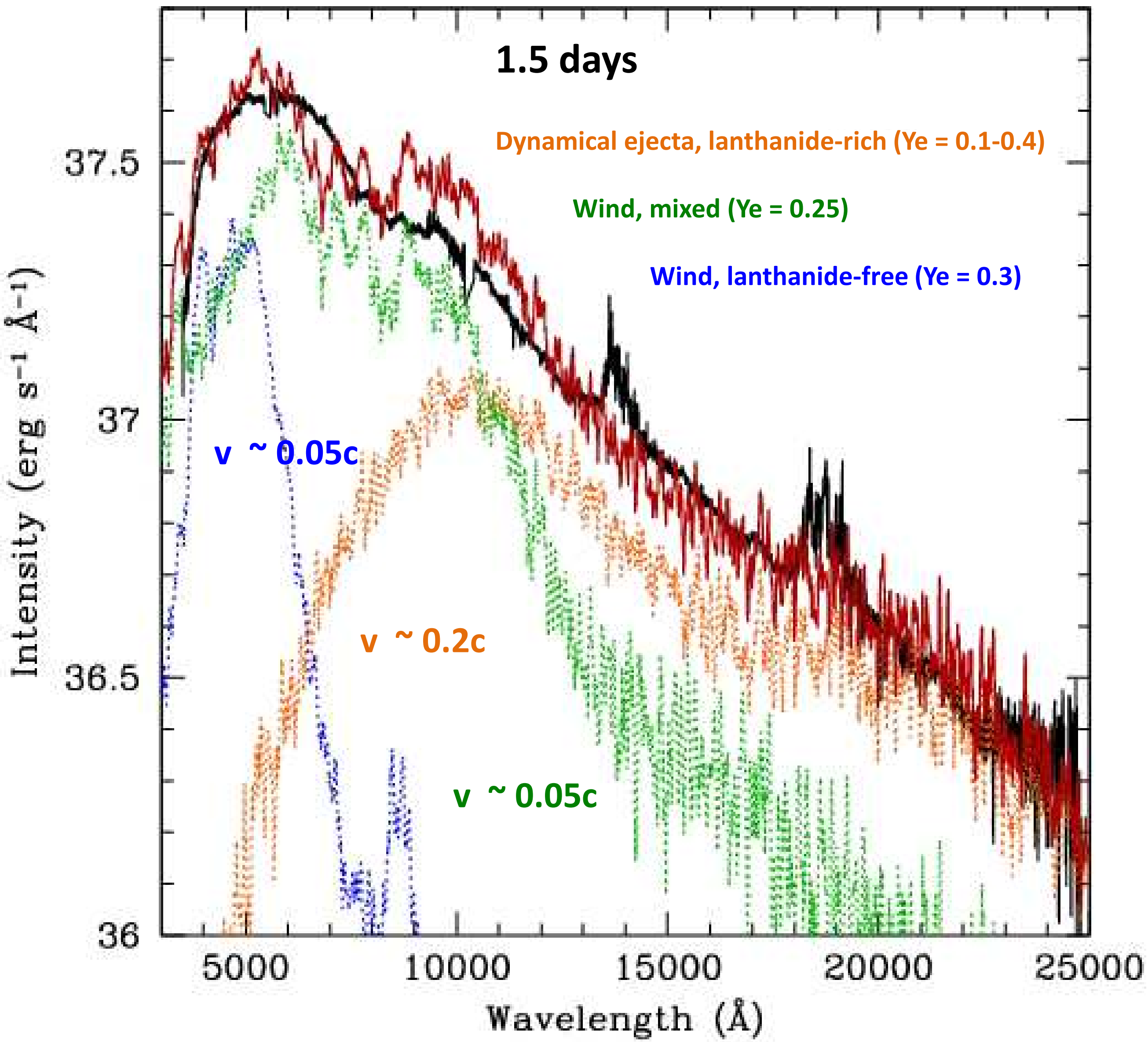
Tanaka et al. 2017, Utsumi et al. 2017

Element abundances at 1 day after merger

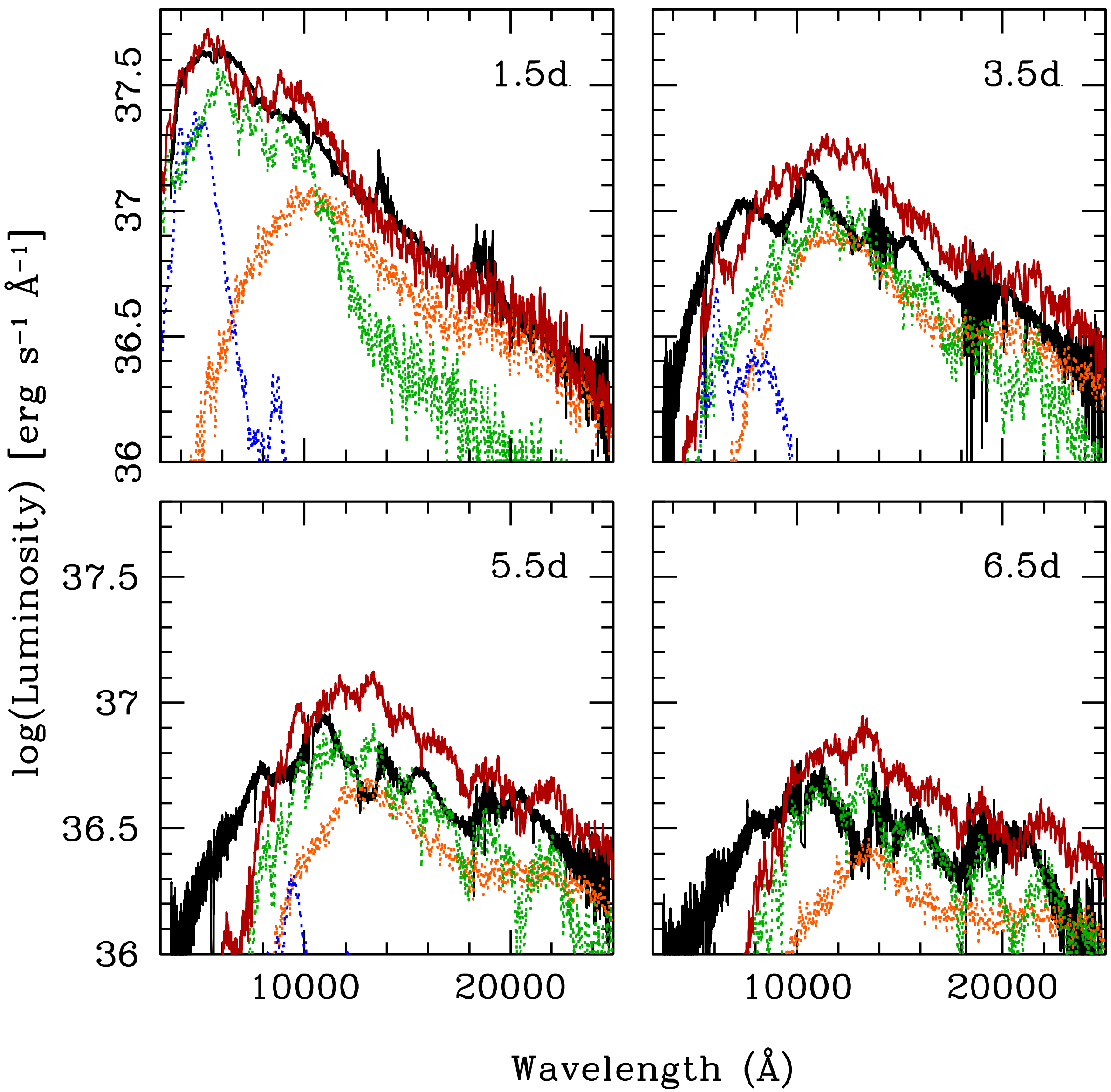


Tanaka et al. 2017, PASJ

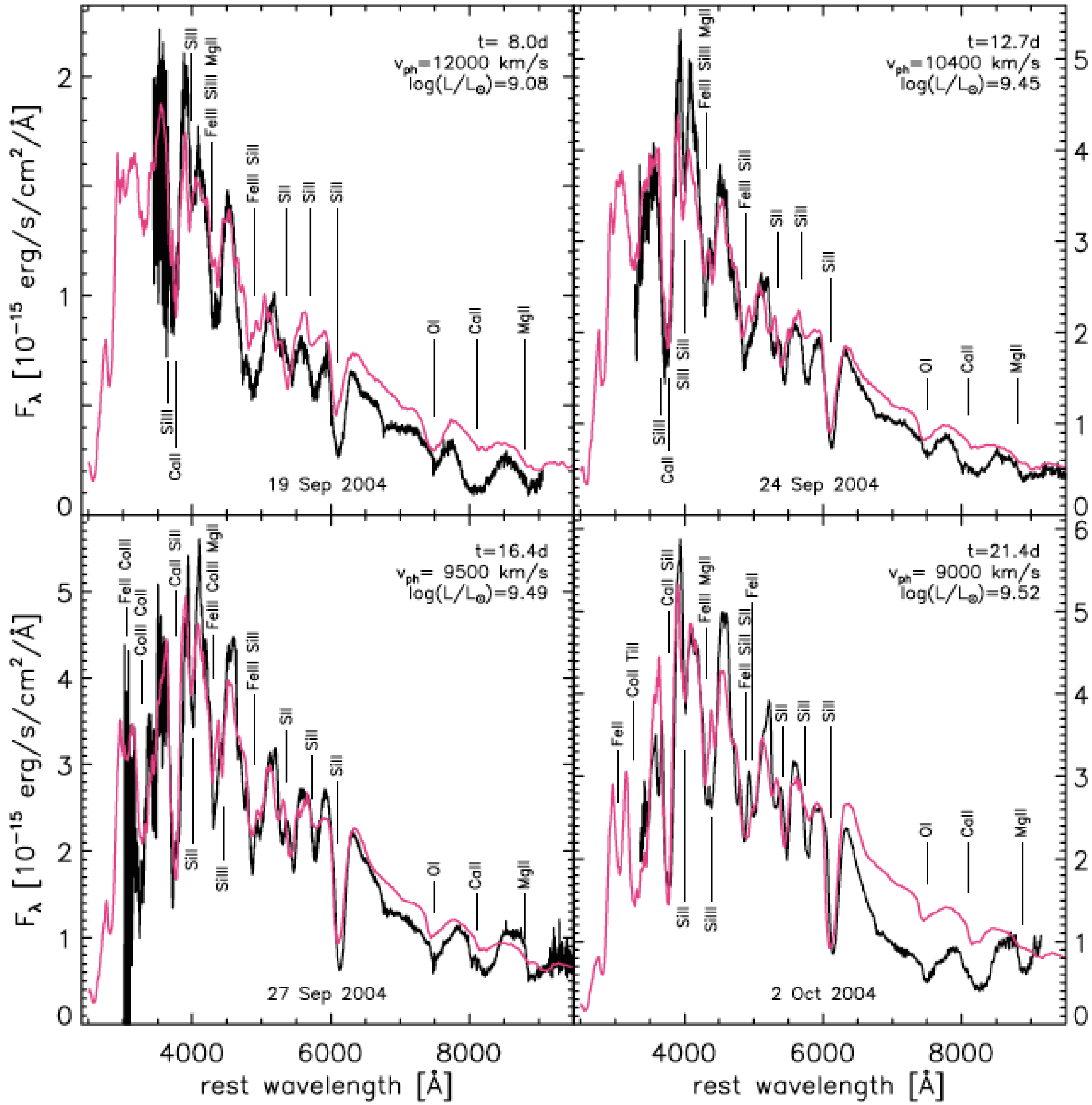
Kilonova 3-component model for AT2017gfo



Kilonova 3-component model for AT2017gfo: ejecta mass is 0.03-0.05 solar masses



An example of a _good_ spectral fit (SN2004eo)



Mazzali et al. 2008

Conclusions

Optical/infrared emission from AT2017gfo is the first direct proof that neutron star mergers are r-process factories.

The preliminary models require an ejecta mass of 0.03-0.05 Msun, and more than one kilonova component, with different proportions of species (lanthanide-rich vs lanthanide-free).

More realistic atomic models and opacities are necessary, to be used with density structure profiles, nuclear reaction networks and radiative transport codes.

Study of NS EoS can be addressed with joint GW and EM information: dynamical ejecta should be larger for more asymmetric mergers (i.e. with bigger mass ratios); moreover larger remnant mass implies lower ejecta. On the other hand, it's not clear how ejecta mass depends on EoS.