Nidia's Fest
Massive Stars and Supernovae
8 Nov 2018

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OSSERVATORIO DI ASTROFISICA E SCIENZA DELLO SPAZIO DI BOLOGNA
Plesso Area della Ricerca CNR

Kilonovae as cosmic foundries of heavy elements

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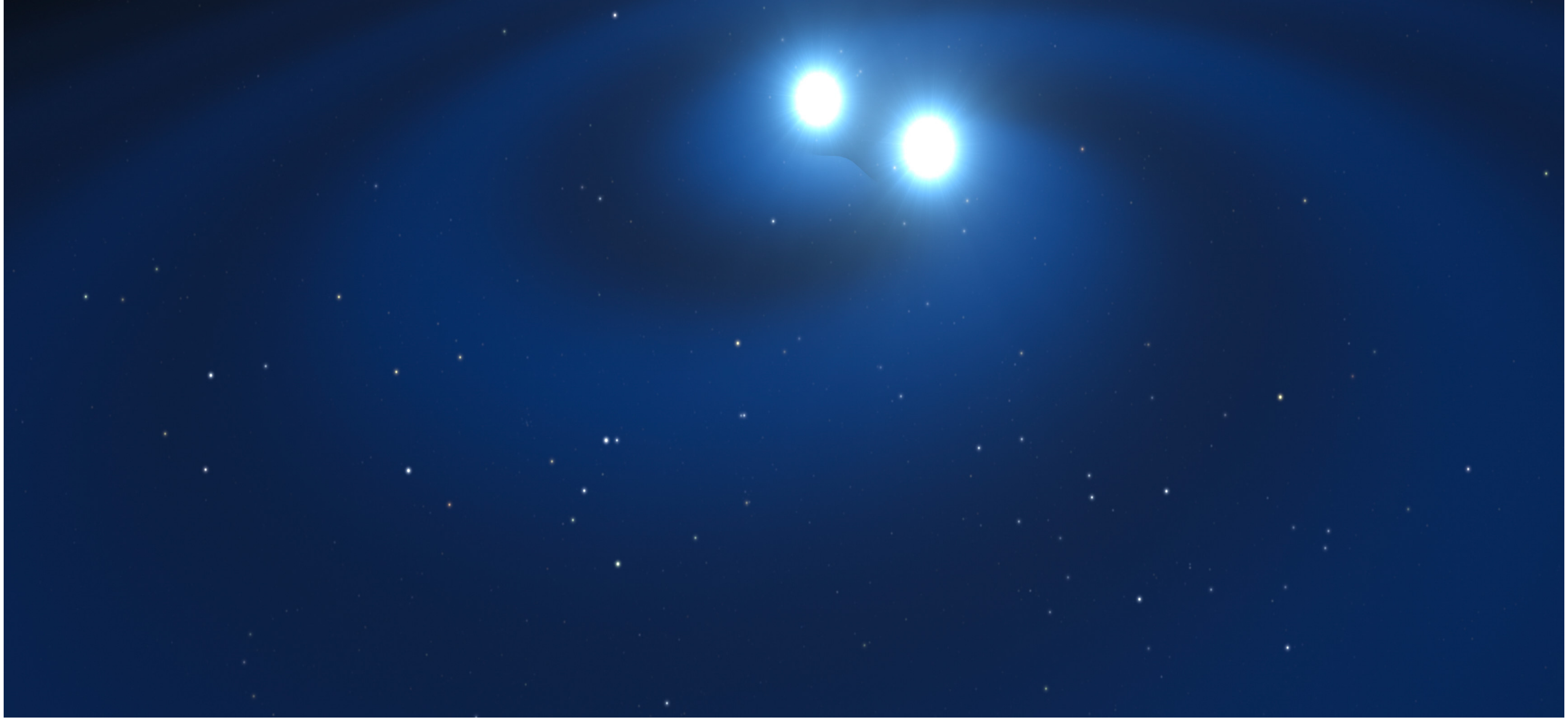
Collaborators: M. Tanaka, J. Selsing, P. Mazzali, E. Cappellaro et al.

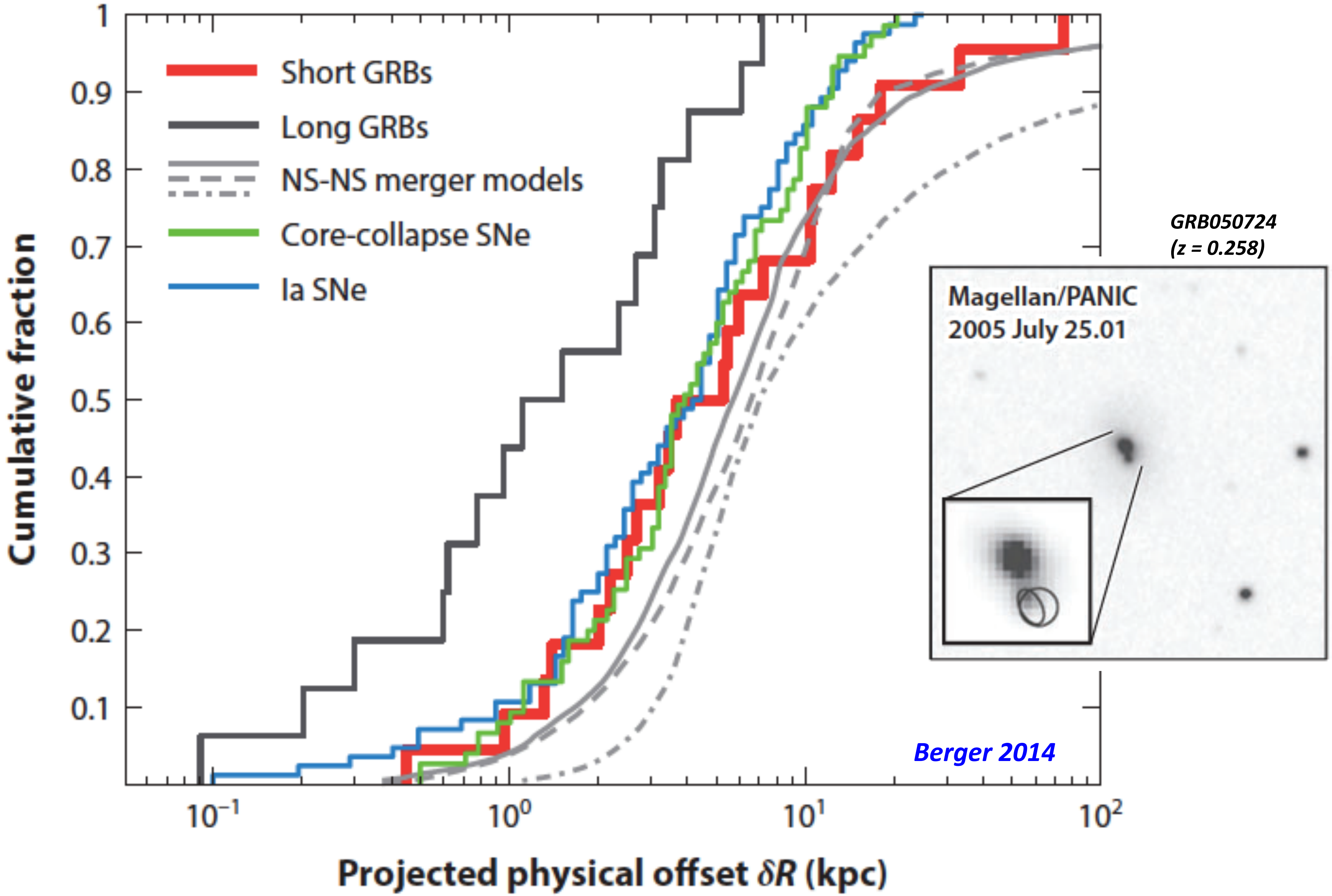
A double neutron star merger is expected to produce:

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



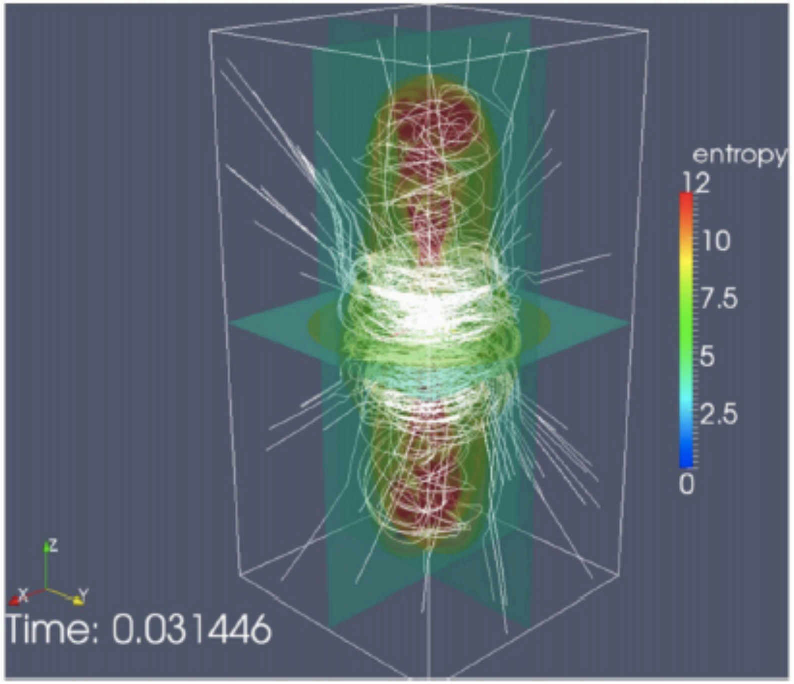
Cumulative distribution of projected offsets of various explosions with respect to their host centers



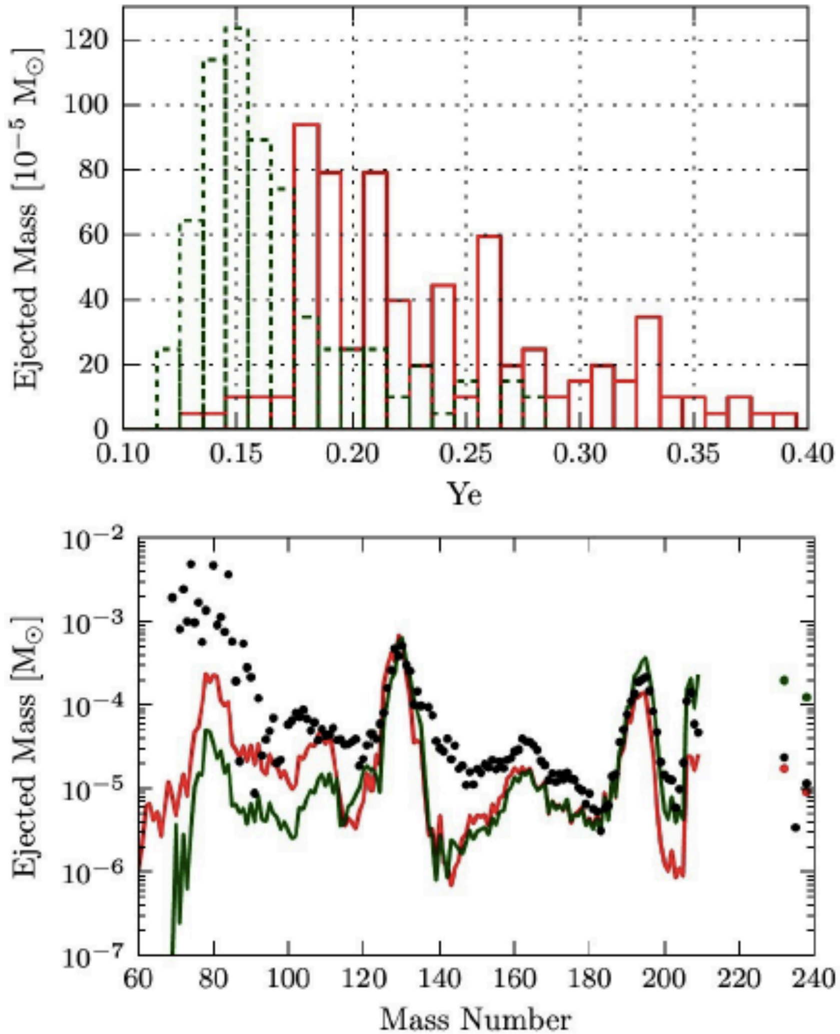
Berger 2014

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



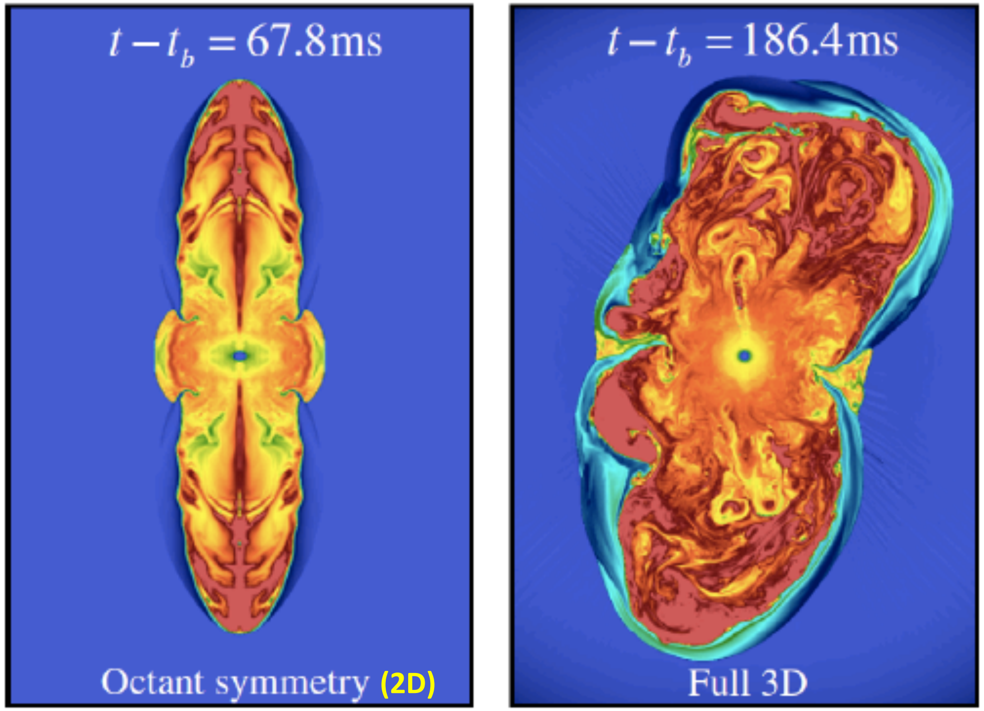
Courtesy: Th. Janka, 2016

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

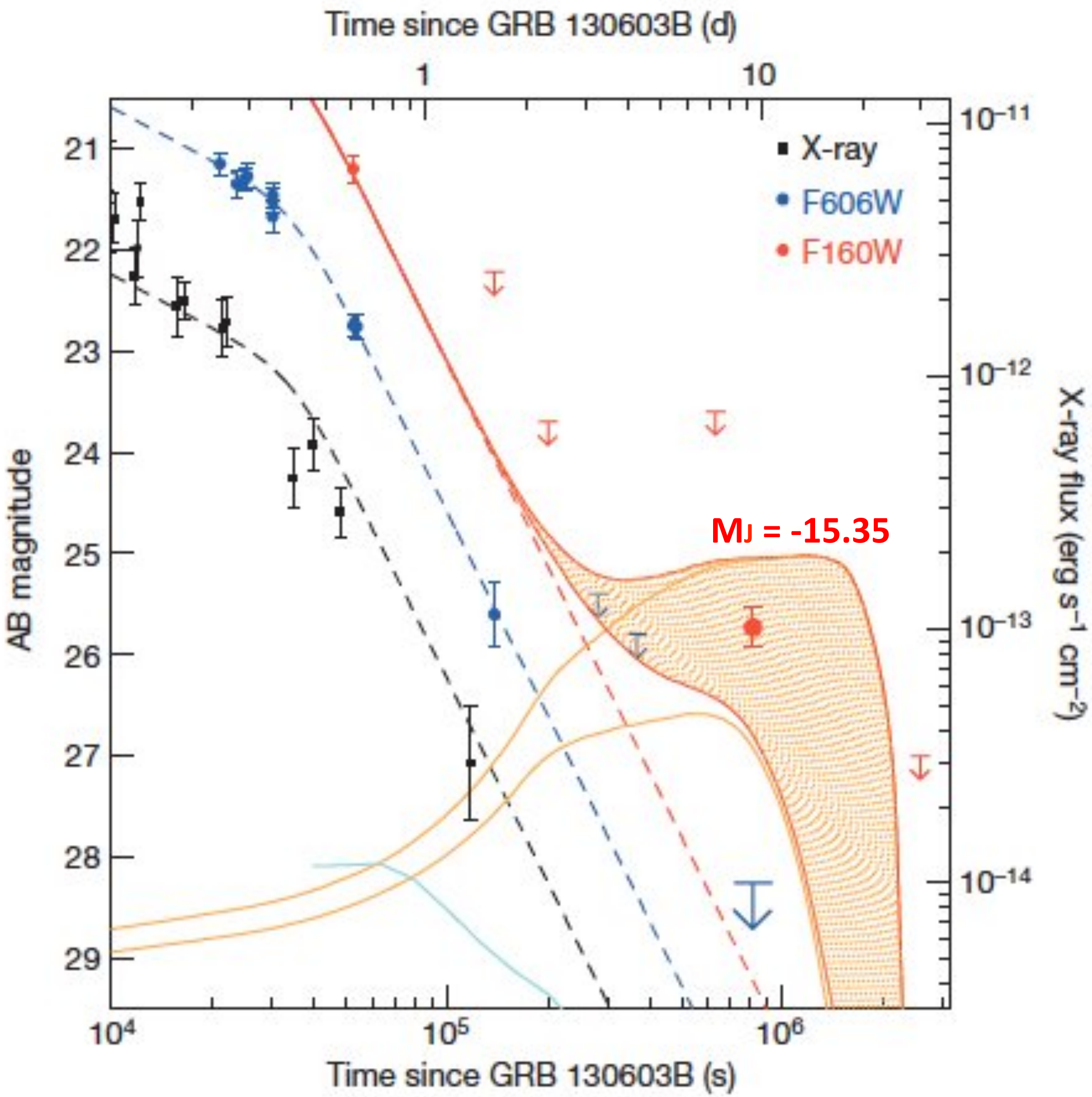
Short GRB130603B
(z = 0.356)

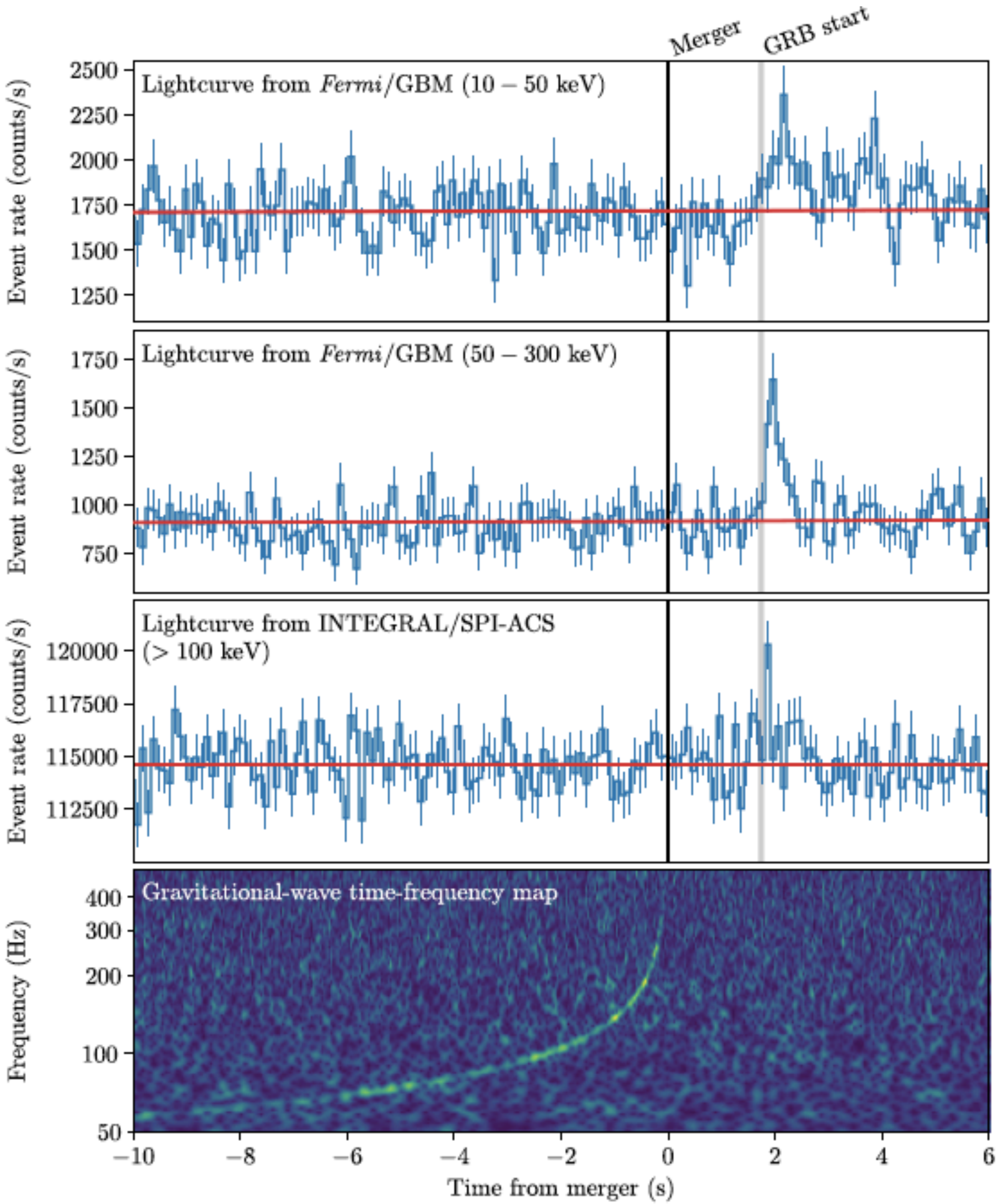
<u>Kilonova</u>:
Ejection of r-process material from a NS merger (0.01-0.1 Mo) (Barnes & Kasen 2013)

$M_H \approx -15$

$M_R \approx -13$

Tanvir et al. 2013;
Berger et al. 2013

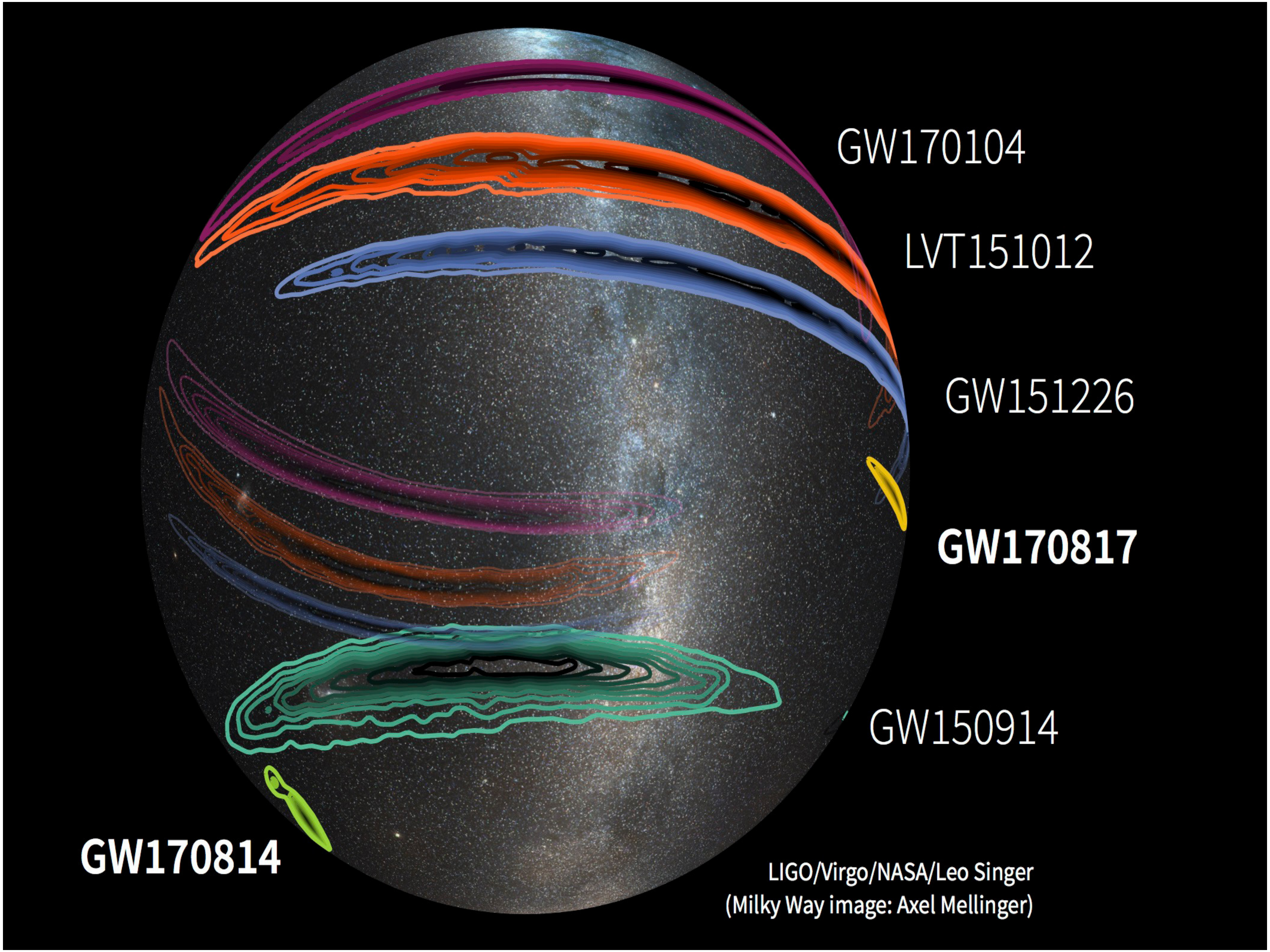




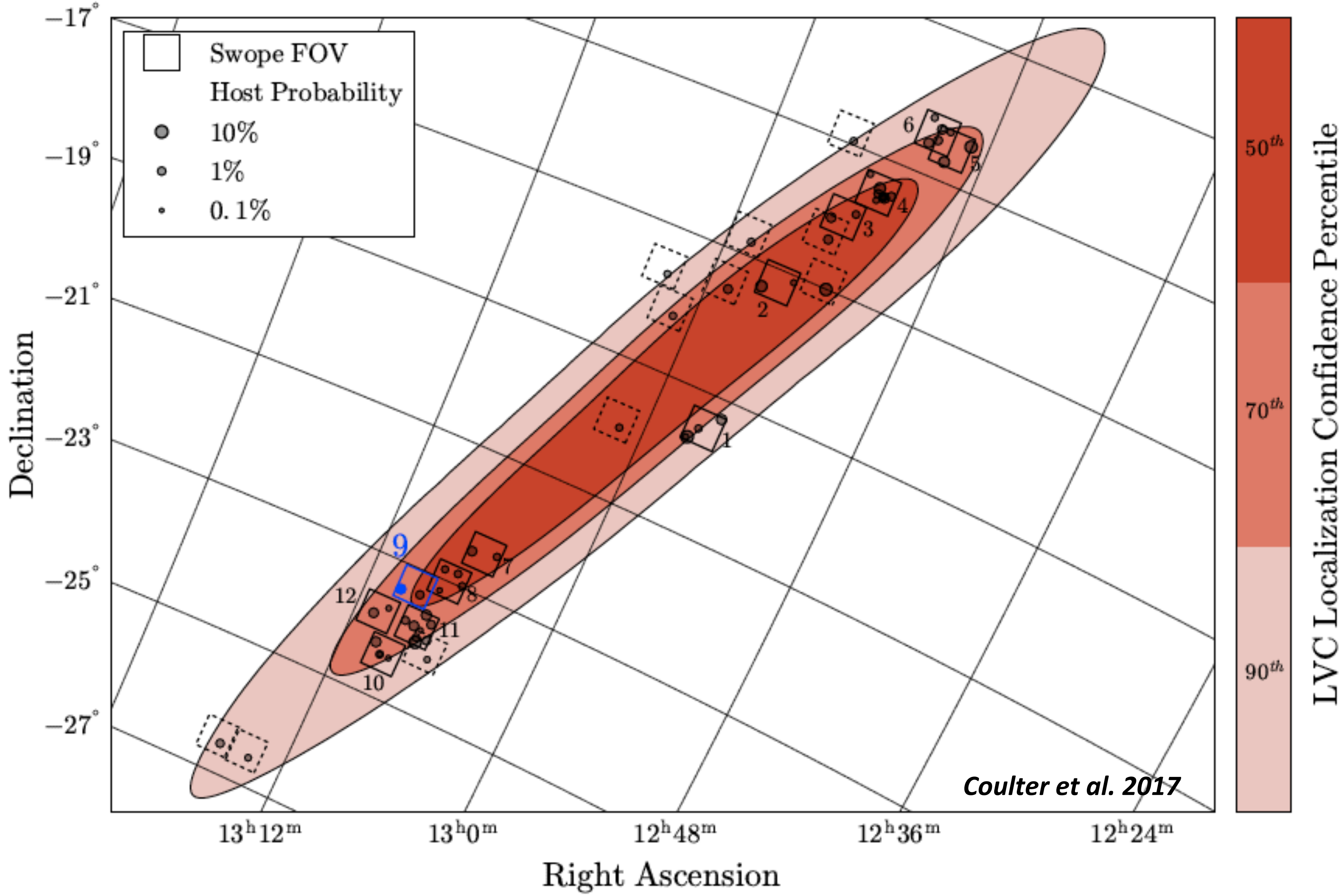
GW170817 and GRB170817A

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

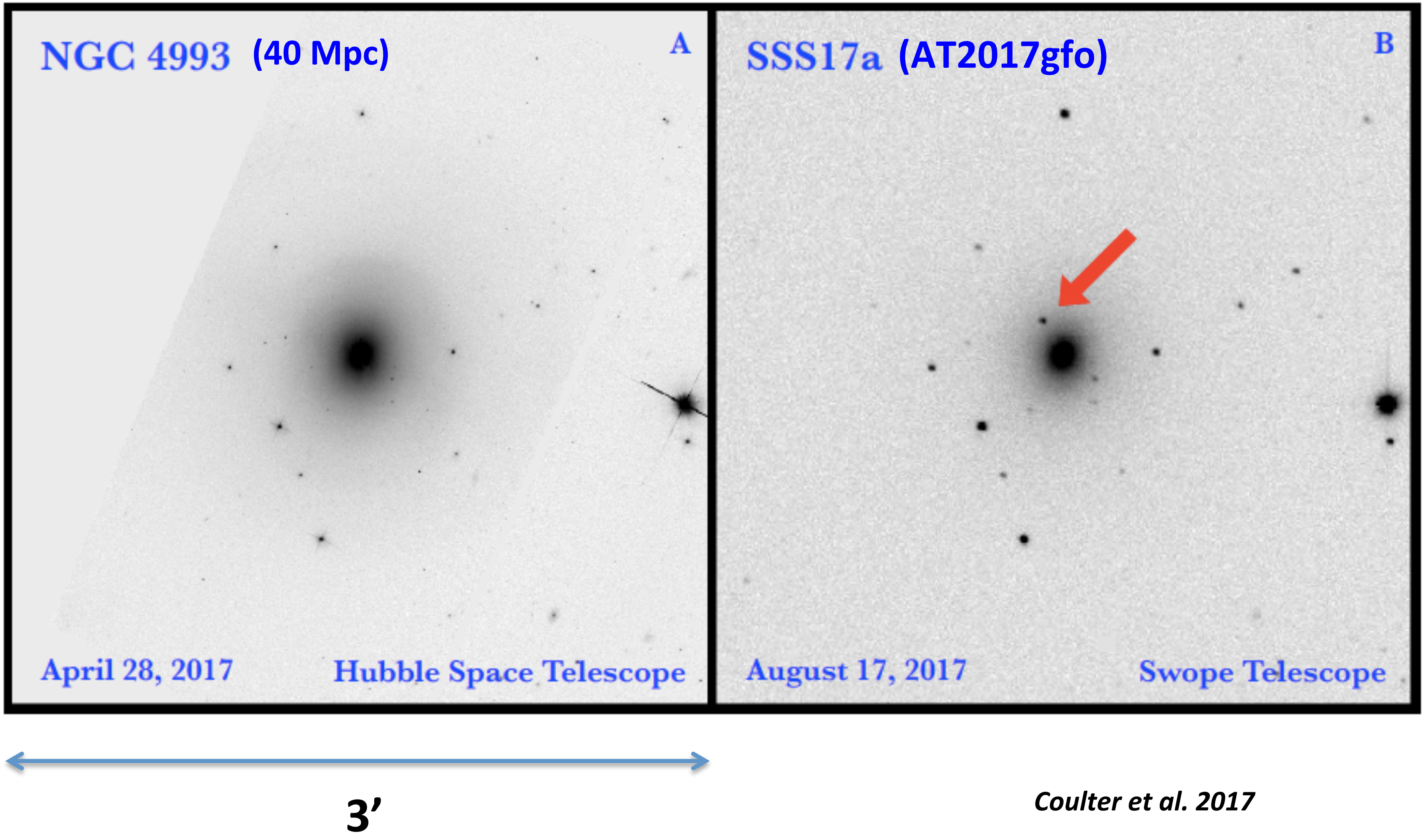
Abbott et al. 2017;
Savchenko et al. 2017;
Fermi Collaboration 2017


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

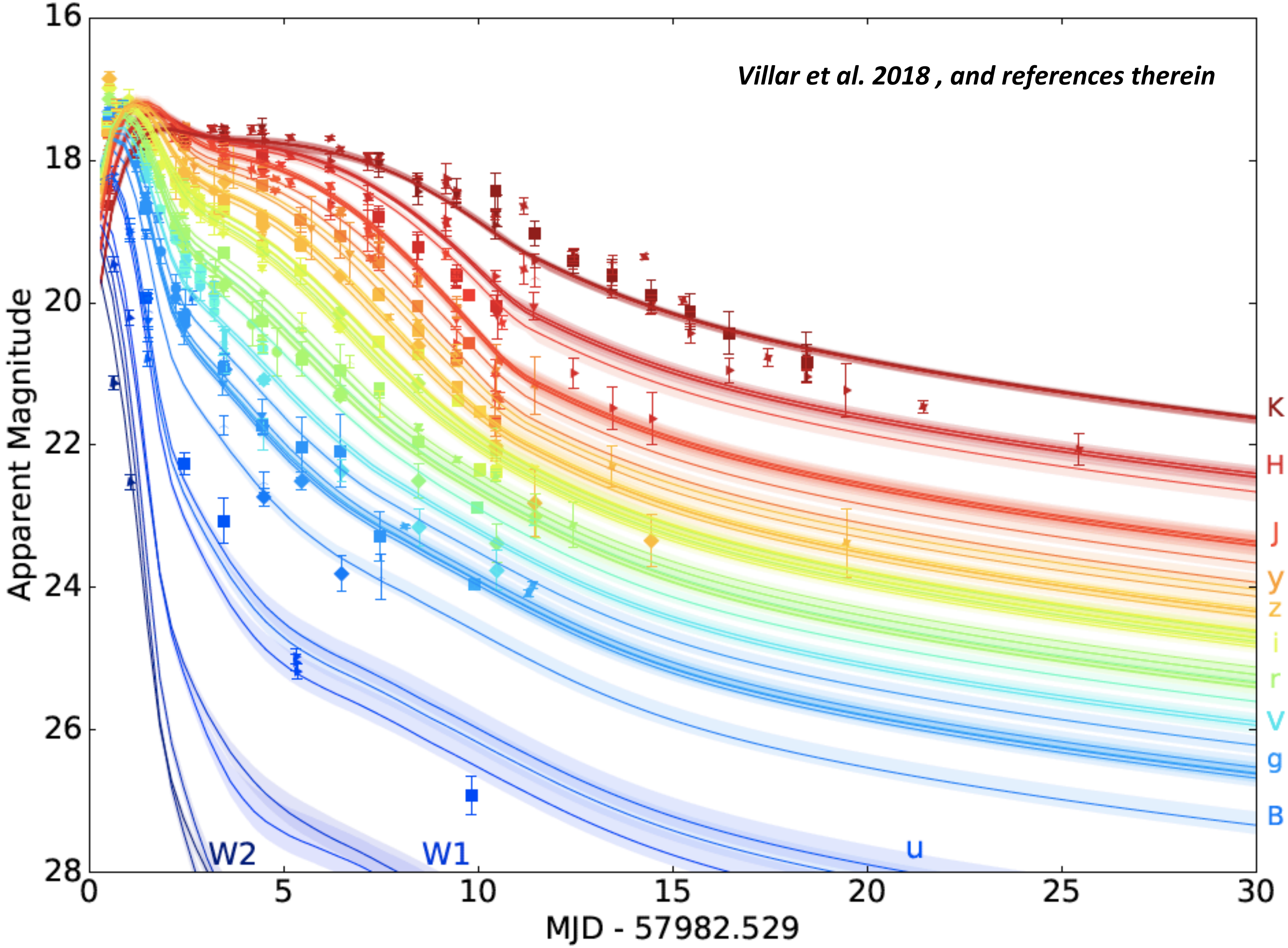


Comparison of Swope discovery image with archival HST image

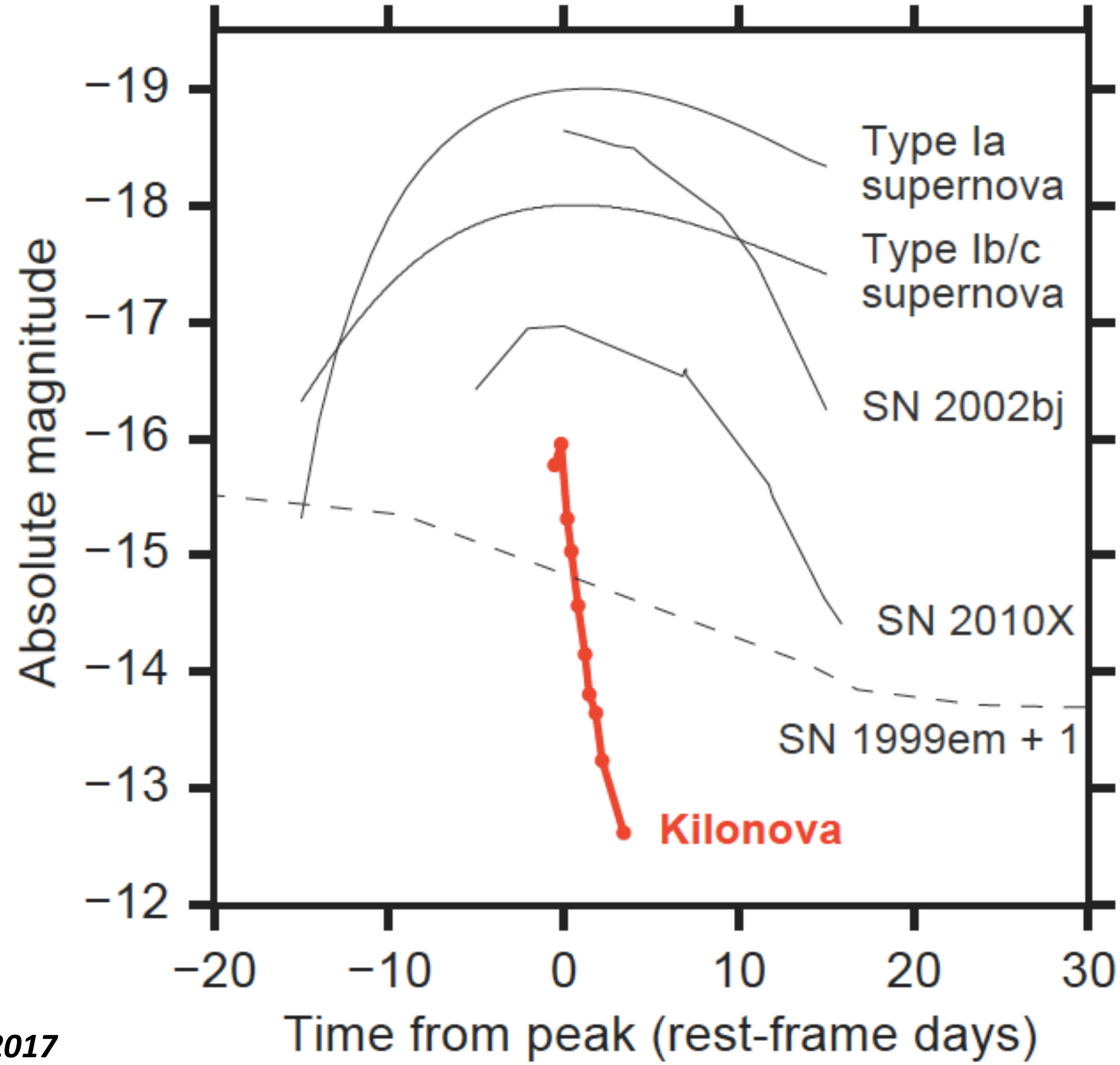


Coulter et al. 2017

Optical and near-infrared light curves of GW170817 / AT2017gfo

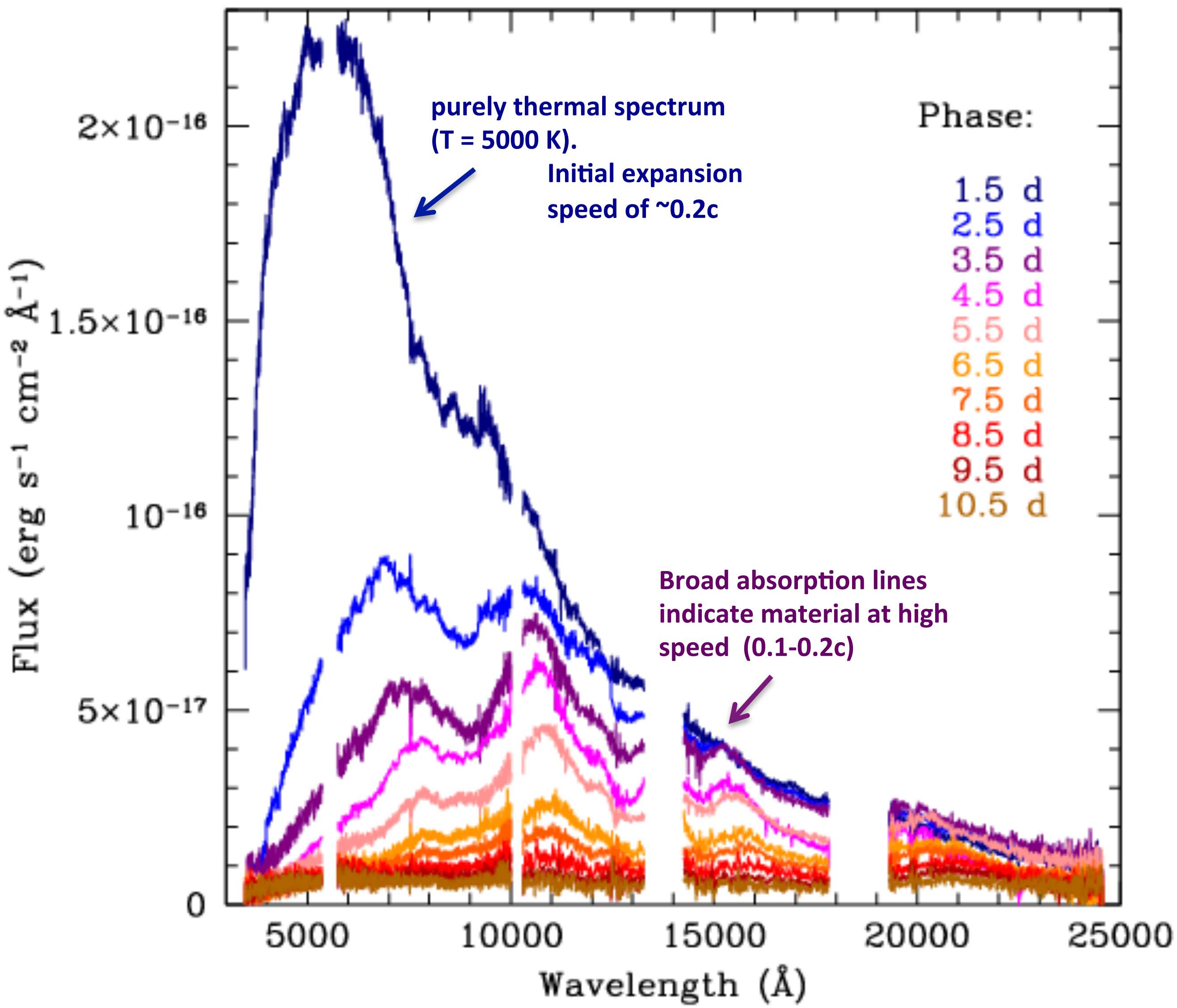


AT2017gfo evolves much more rapidly than any supernova



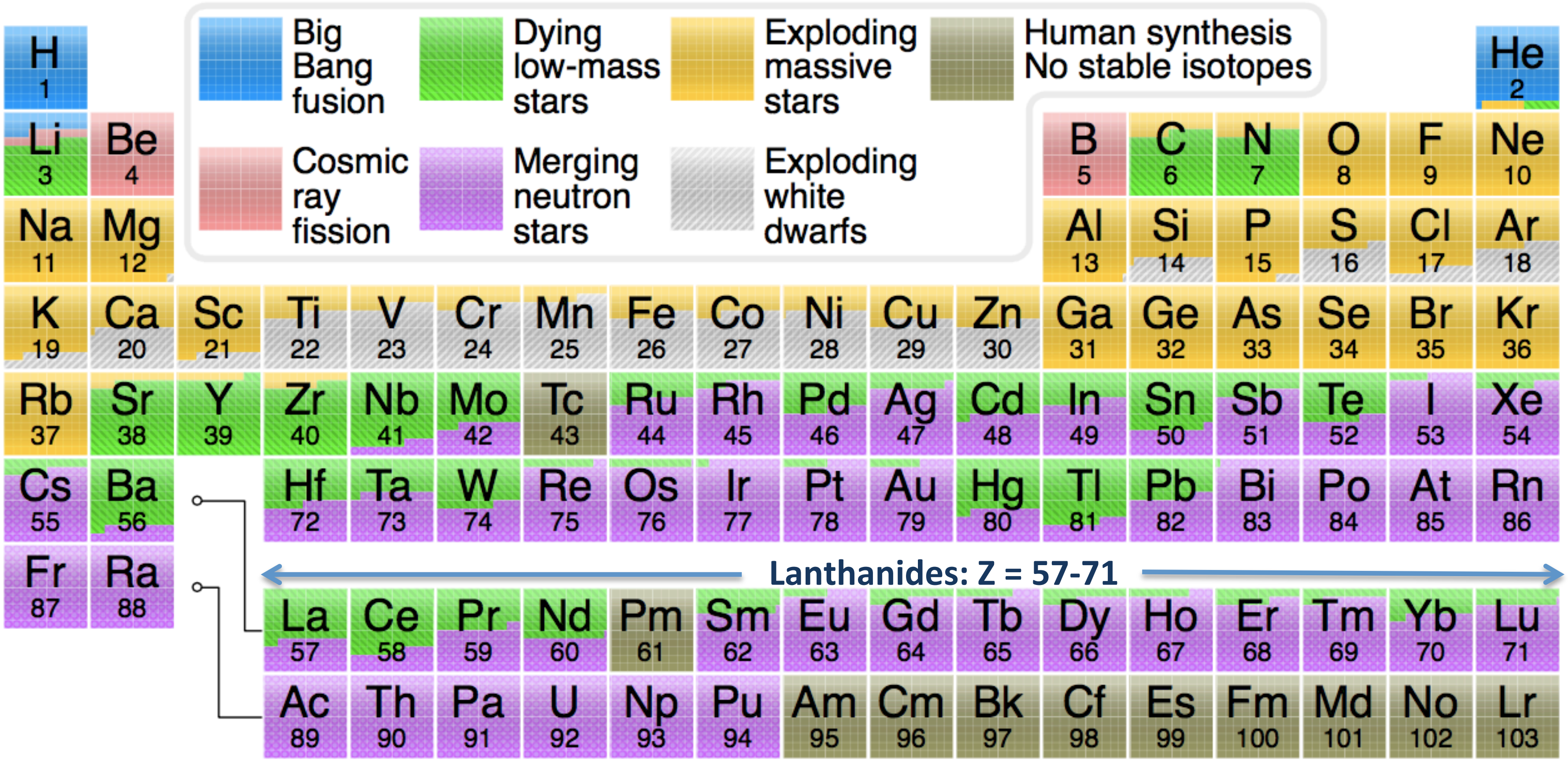
Arcavi et al. 2017

ESO VLT X-Shooter spectral sequence of kilonova GW170817



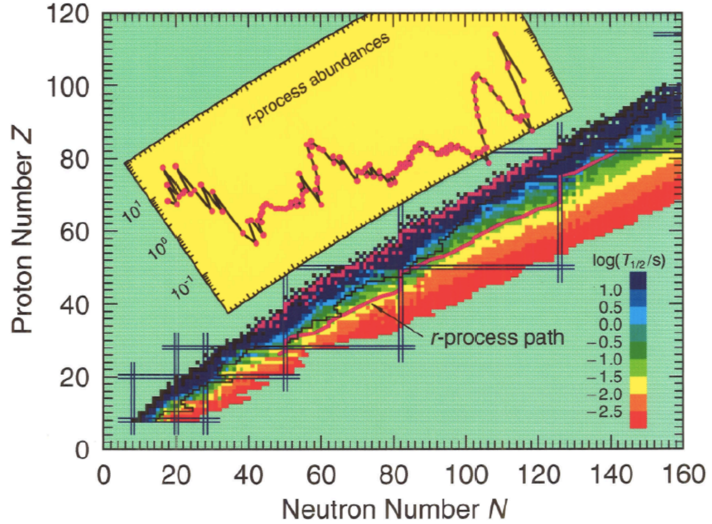
Pian et al. 2017; Smartt et al. 2017

Periodic table of elements

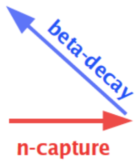


https://en.wikipedia.org/wiki/R-process

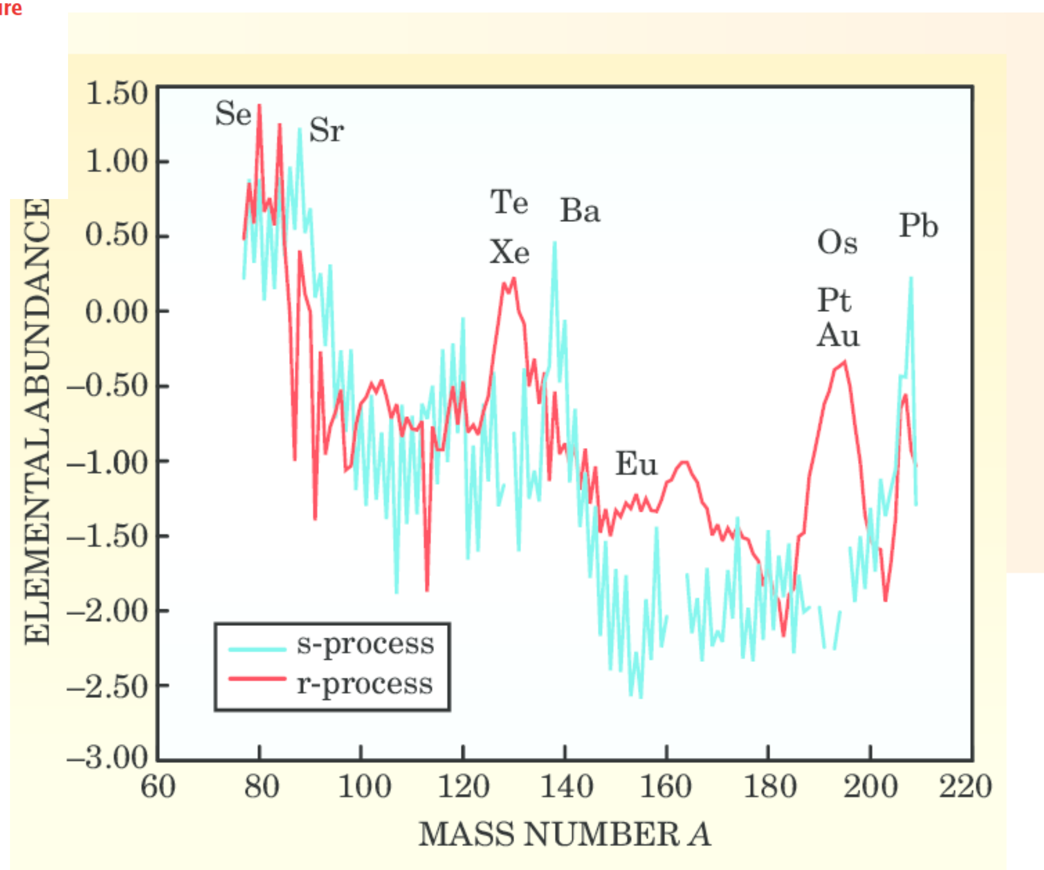
s- and r-Process Nucleosynthesis



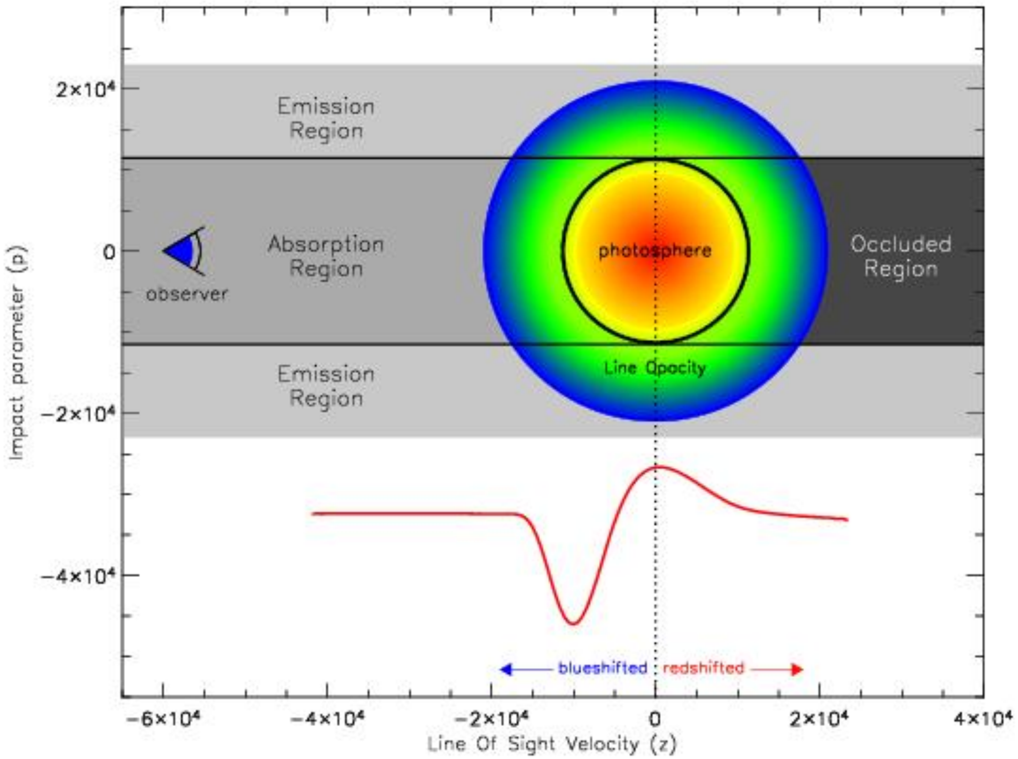
Courtesy: K.-L. Kratz

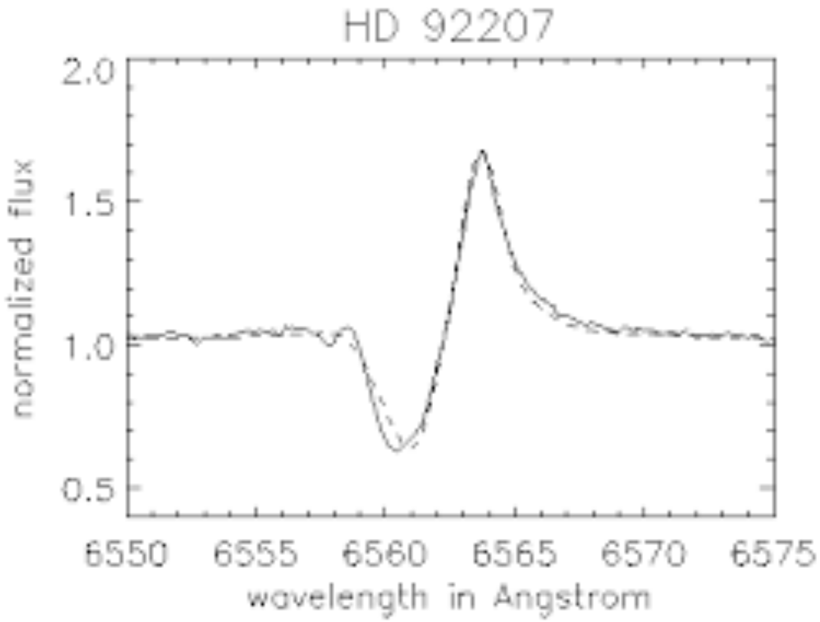


Solar system abundances of heavy elements produced by r-process and s-process neutron capture.

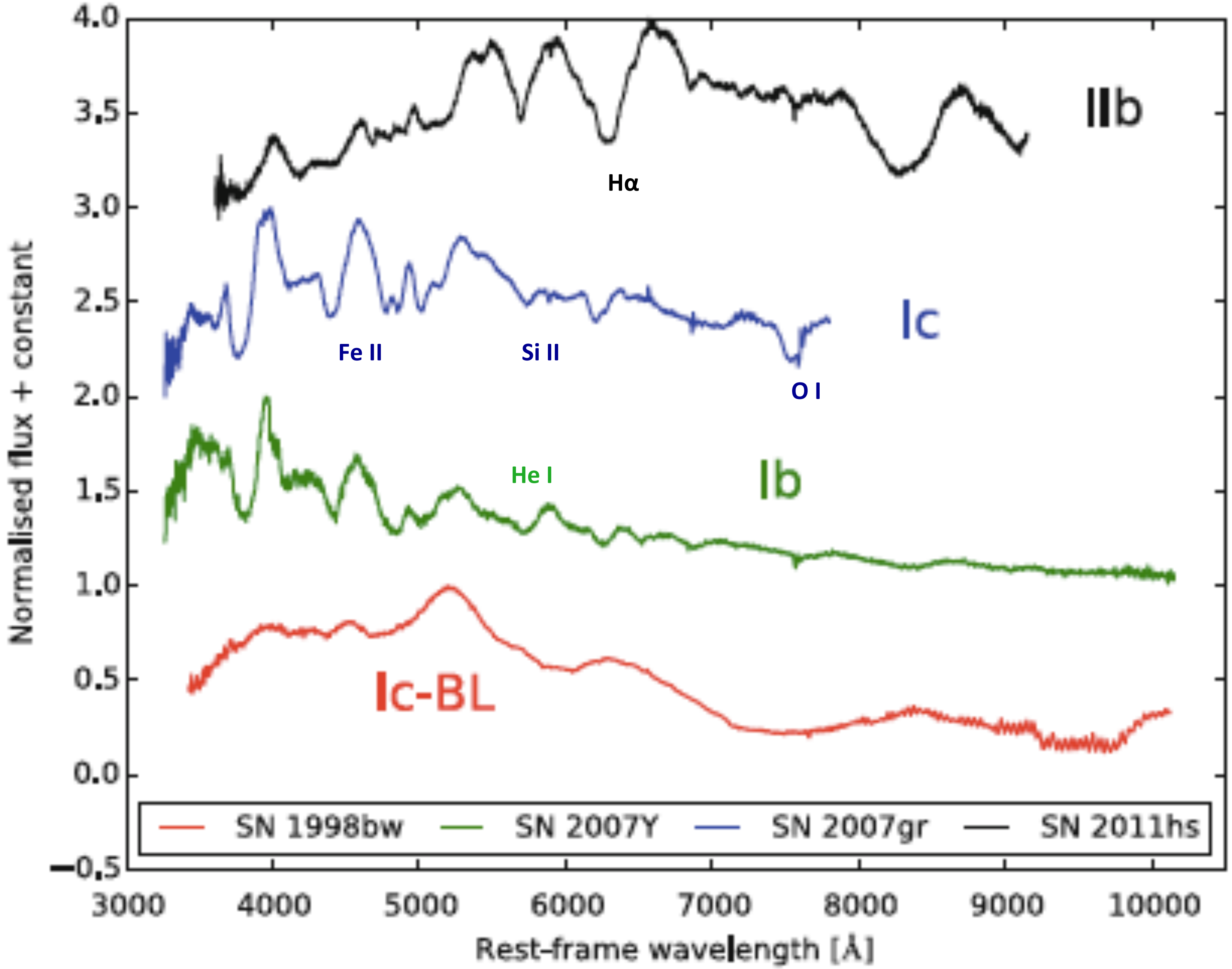


Receding photosphere: P-Cygni profile of absorption lines





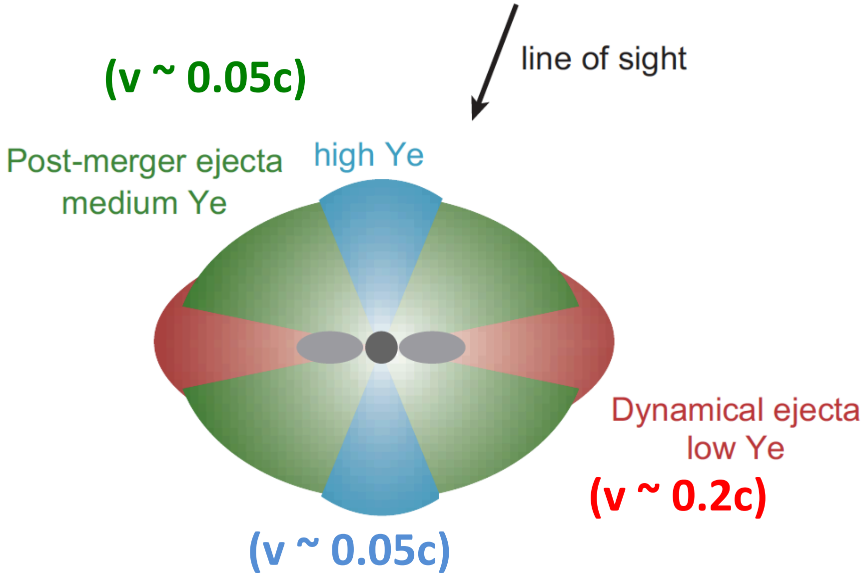
Typical spectra of Stripped-envelope core-collapse SNe



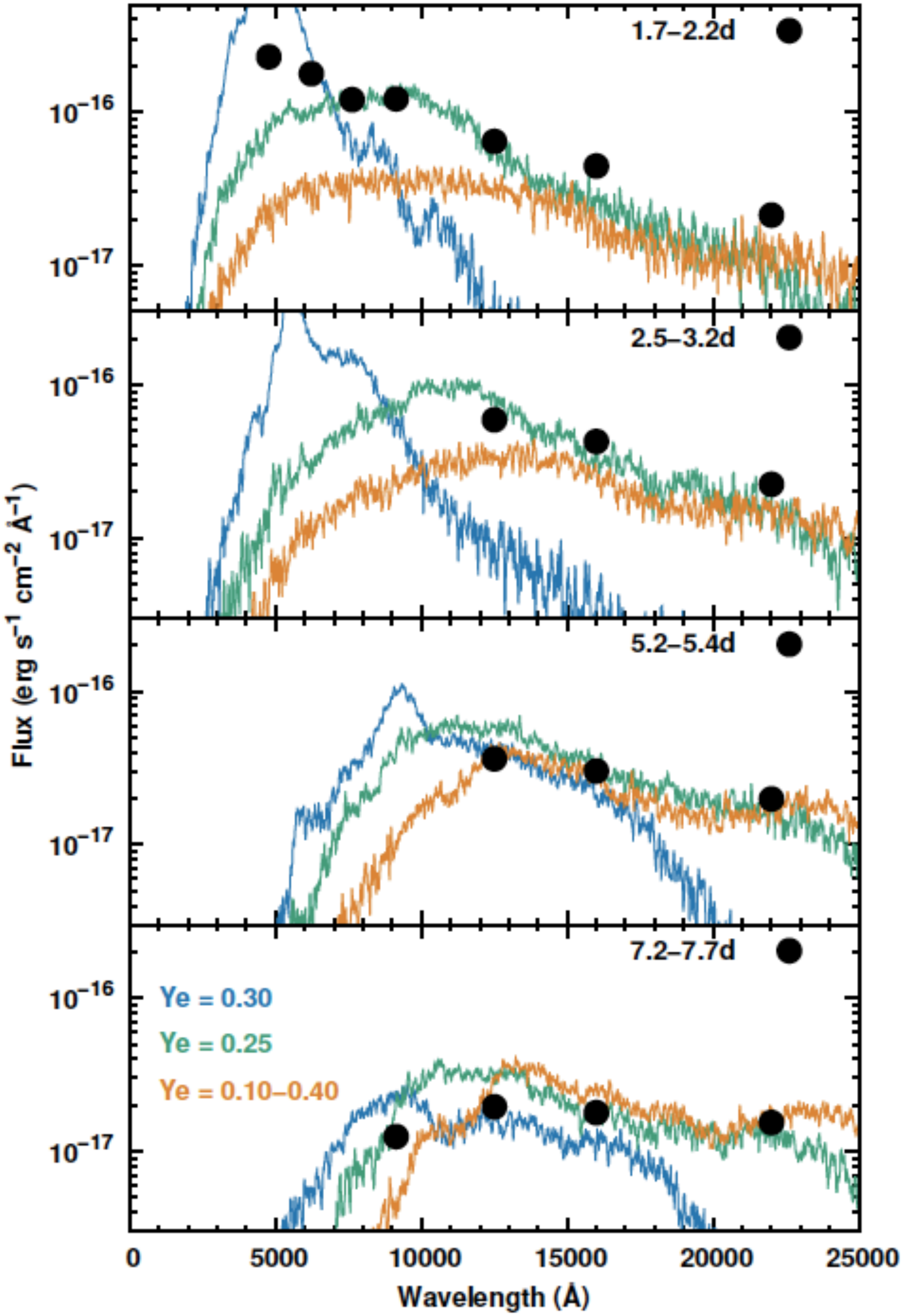
Pian & Mazzali 2017

Geometry of 3-component model for kilonova and resulting spectra

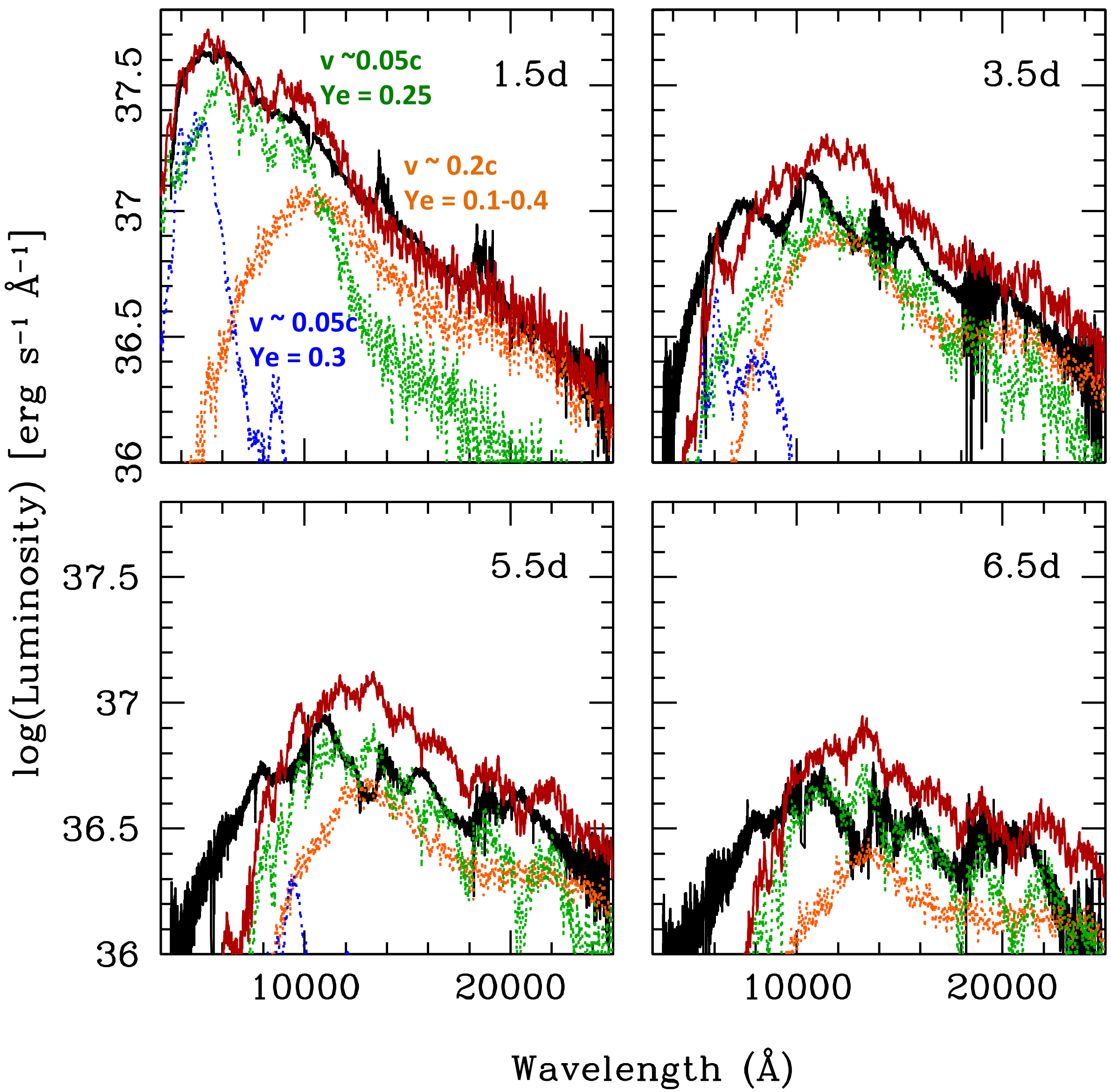
$M_{ej} \sim 0.03$



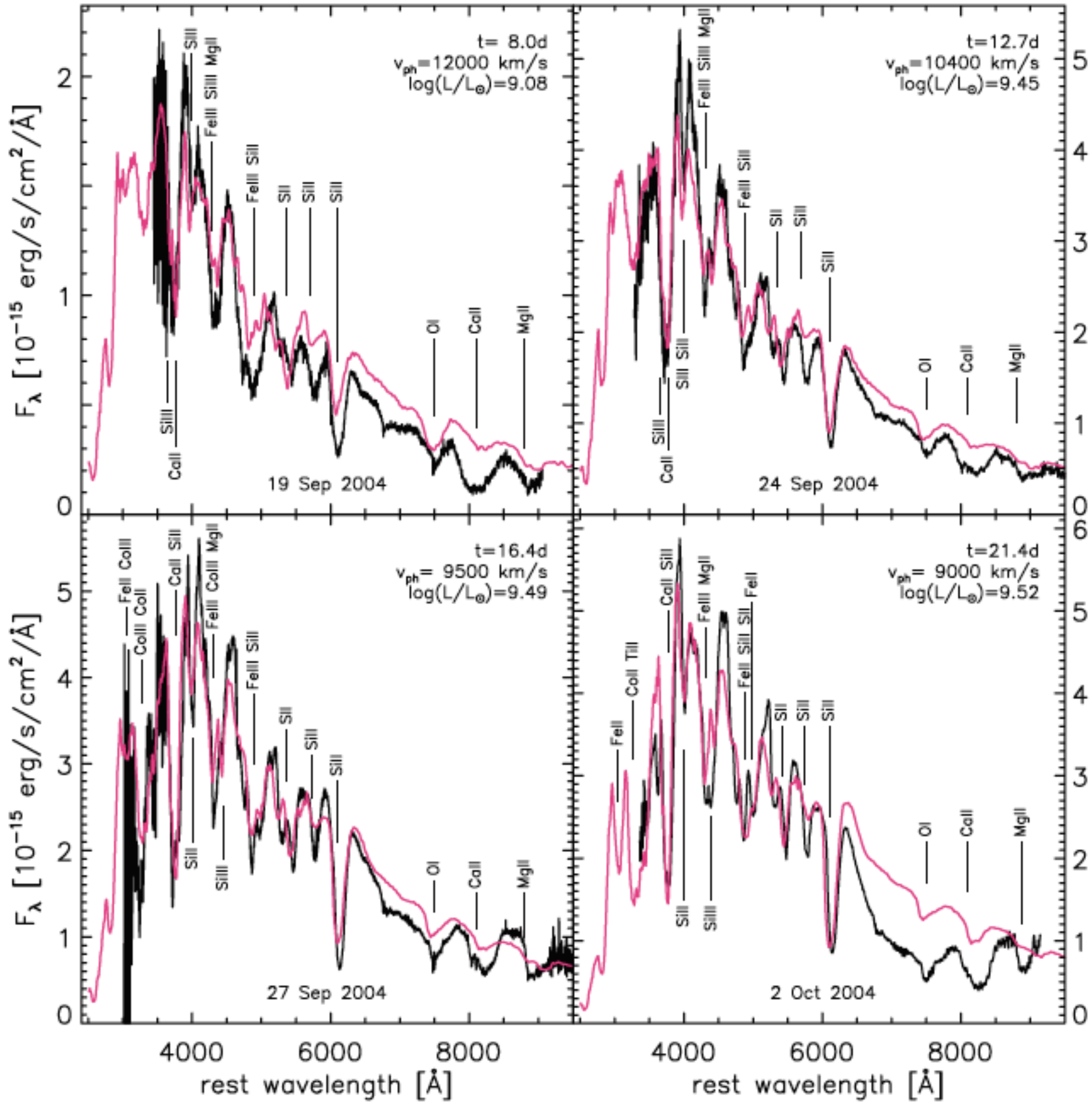
Tanaka et al. 2017, Utsumi et al. 2017



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

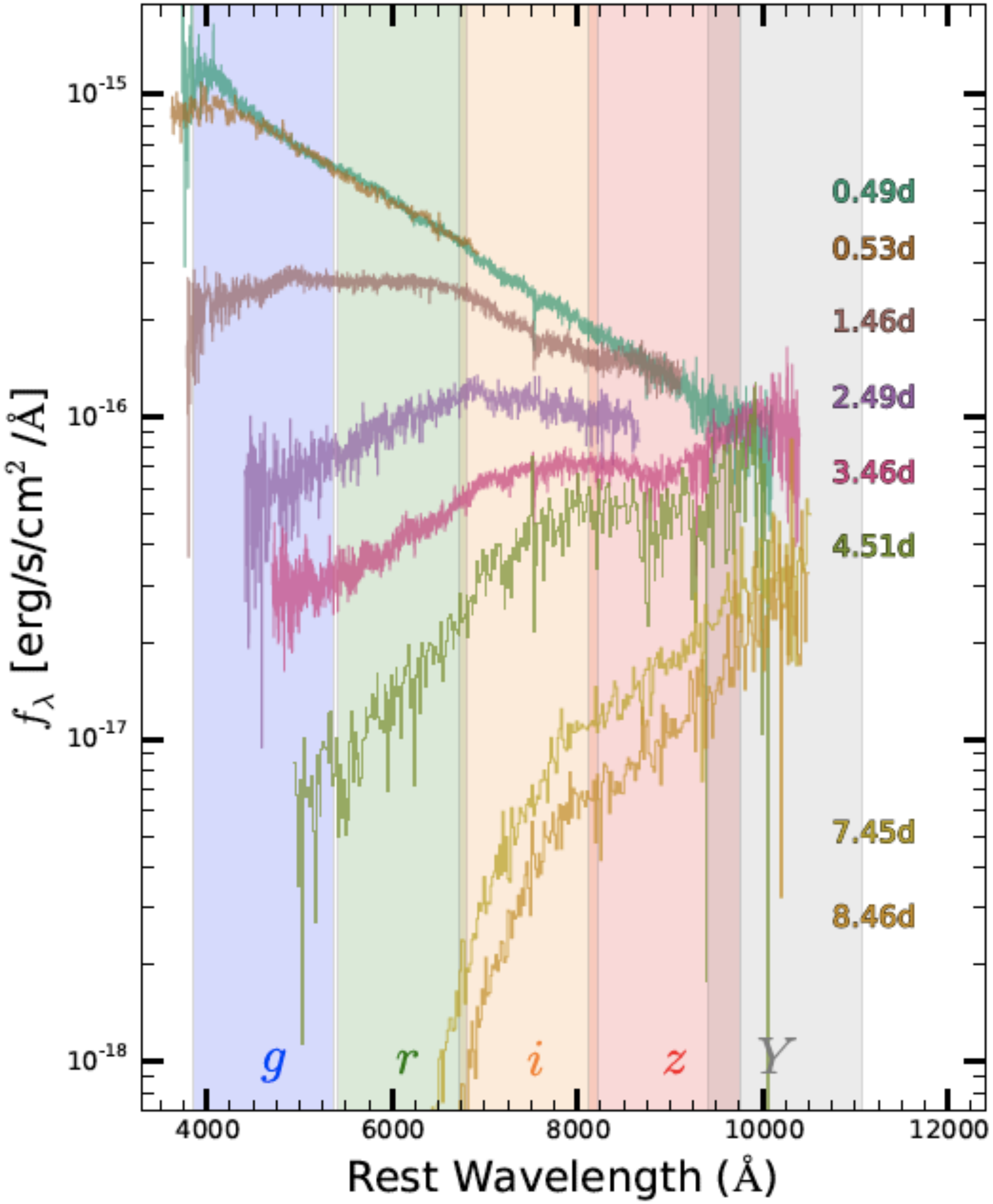


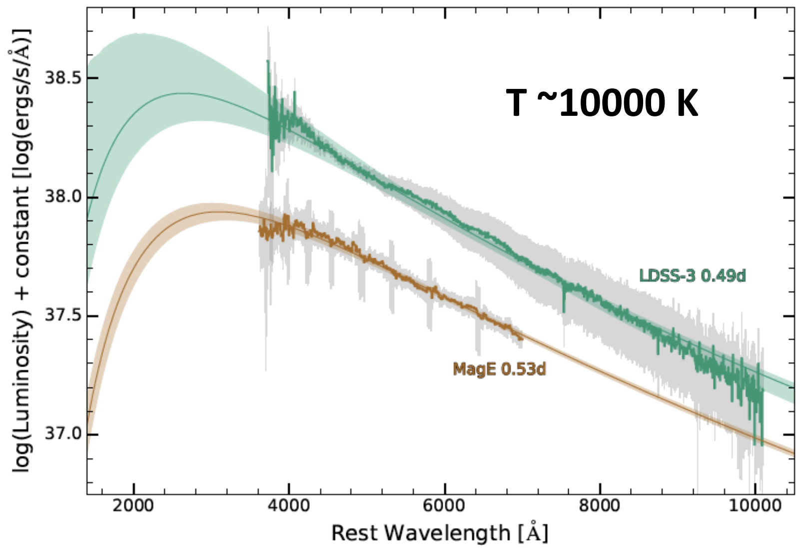
An example of a _good_ spectral fit (SN2004eo)



Mazzali et al. 2008

Magellan spectral sequence of AT2017gfo



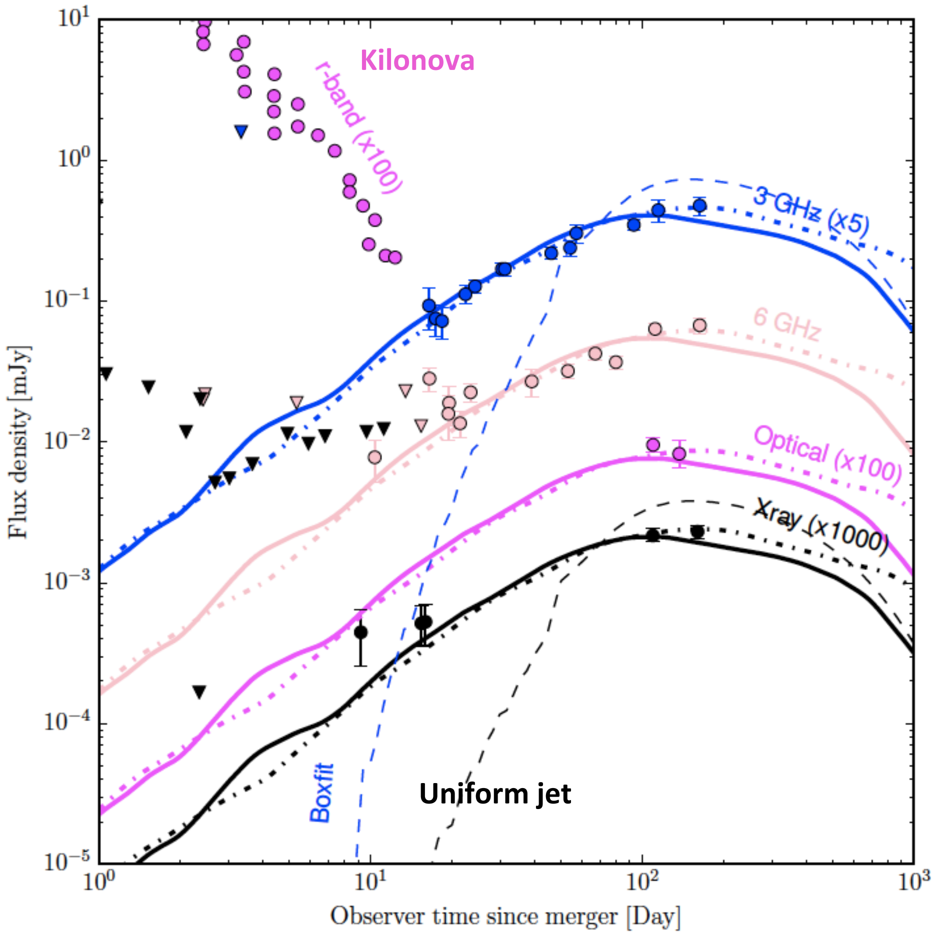


Early spectra set a constraint on initial photospheric speed

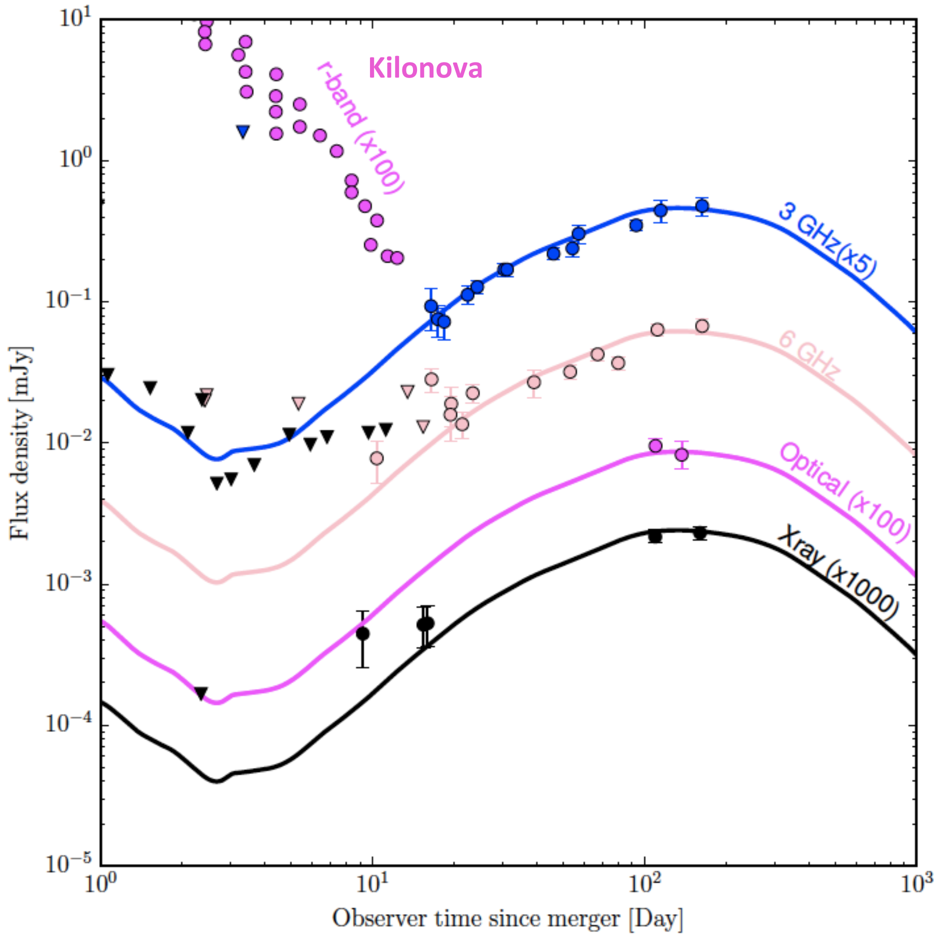
Shappee, Simon, Drout, Piro, Morrell et al. 2017

GRB170817A: multiwavelength LCs and emission models.
A structured off-axis jet or a quasi-isotropic outflow are preferred

Narrow engine

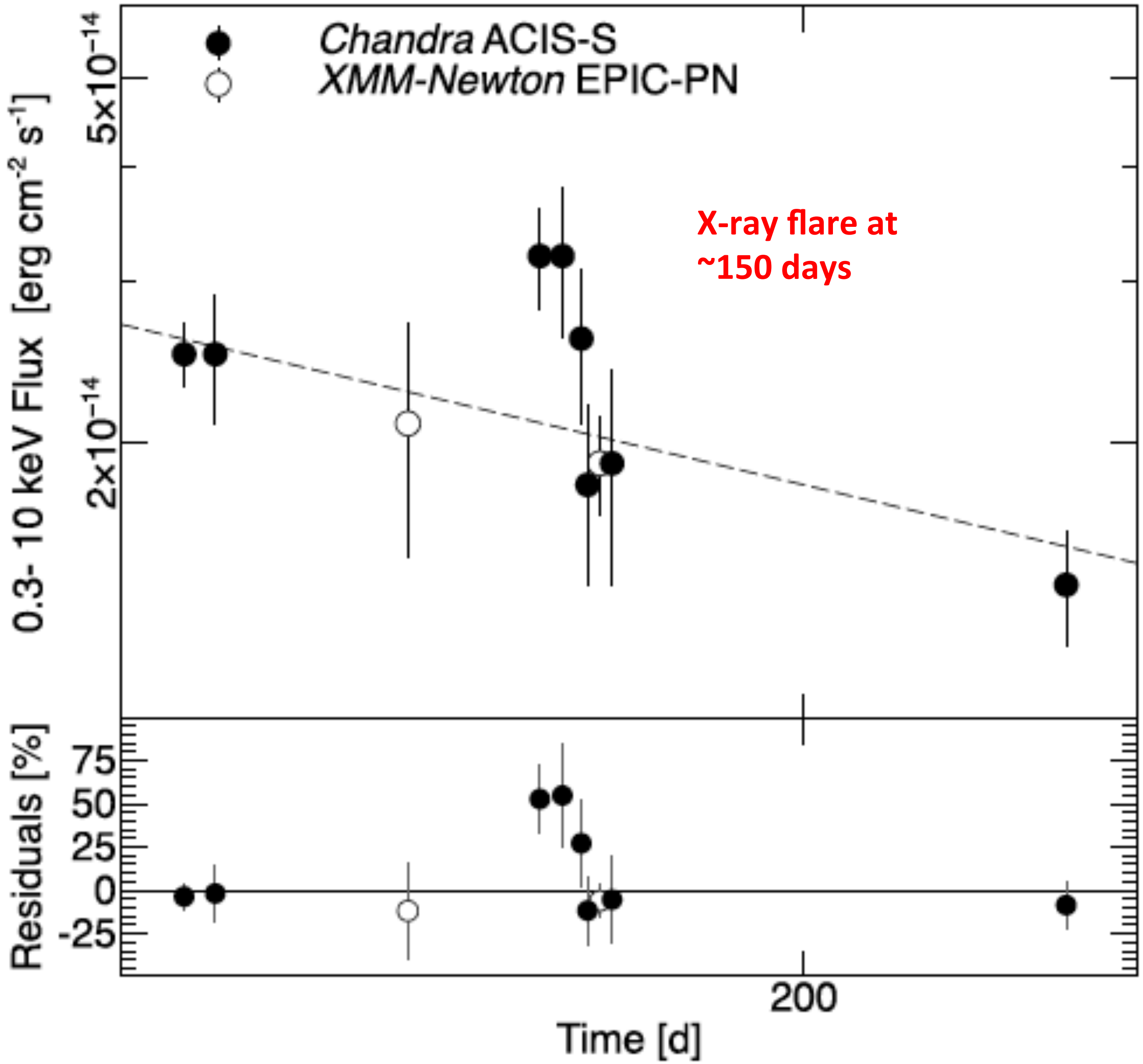


Wide engine



Xie, Zrake, MacFadyen 2018

What is the remnant of the GW170817 merger?



Piro et al. 2018

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.

Late-epoch X-ray flare may contain precious information on remnant.

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.