Gravitational-waves, ElectroMagnetic and dark-MAtter Physics Workshop

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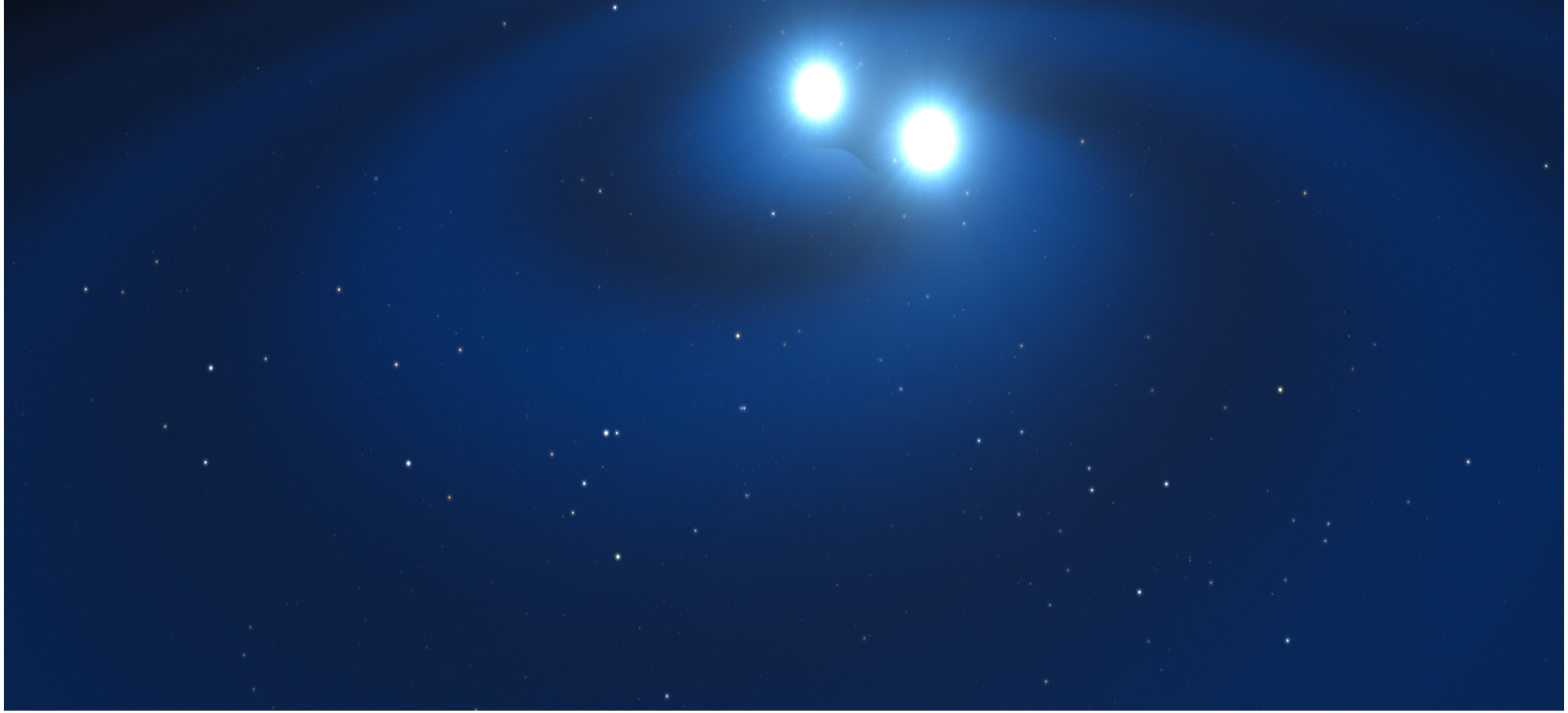
Kilonovae: the cosmic foundries of heavy elements

Elena Pian
INAF - Astrophysics and Space Science Observatory, Bologna, Italy

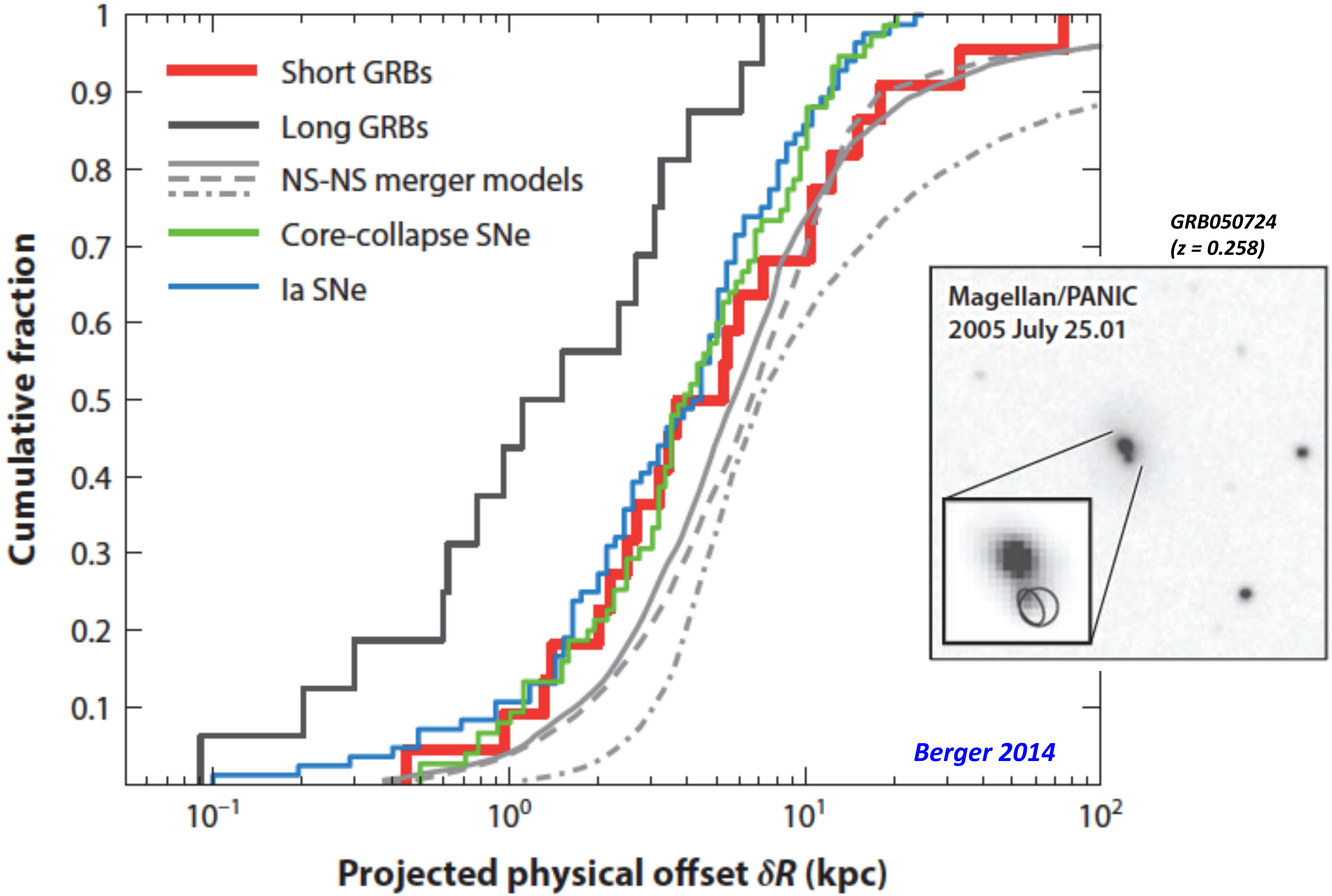
A double neutron star merger is expected to produce:

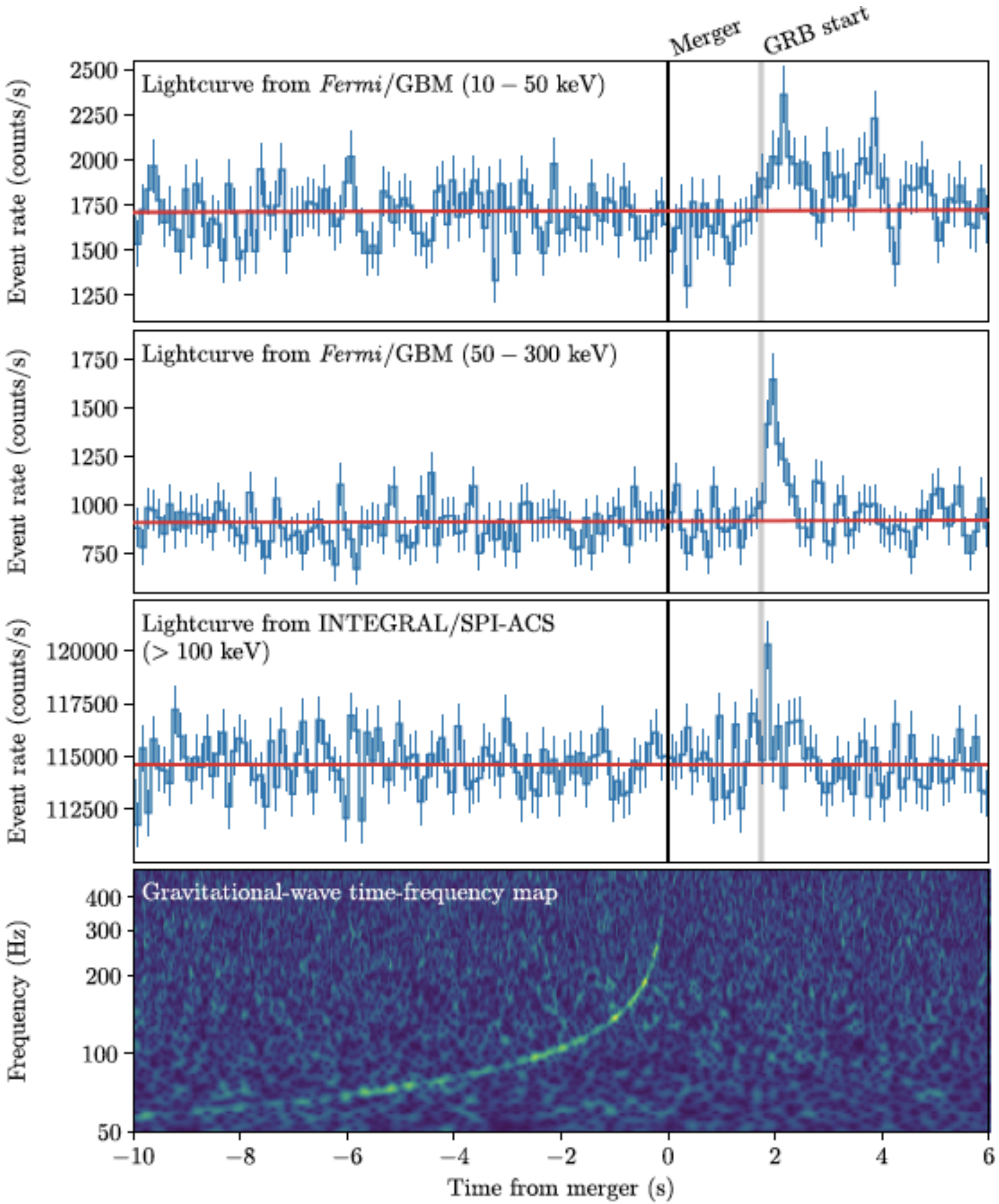
1) a GW signal at ~1-1000 Hz (nearly isotropic)
2) a short GRB (highly directional and anisotropic)
3) r-process nucleosynthesis (nearly isotropic)

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



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



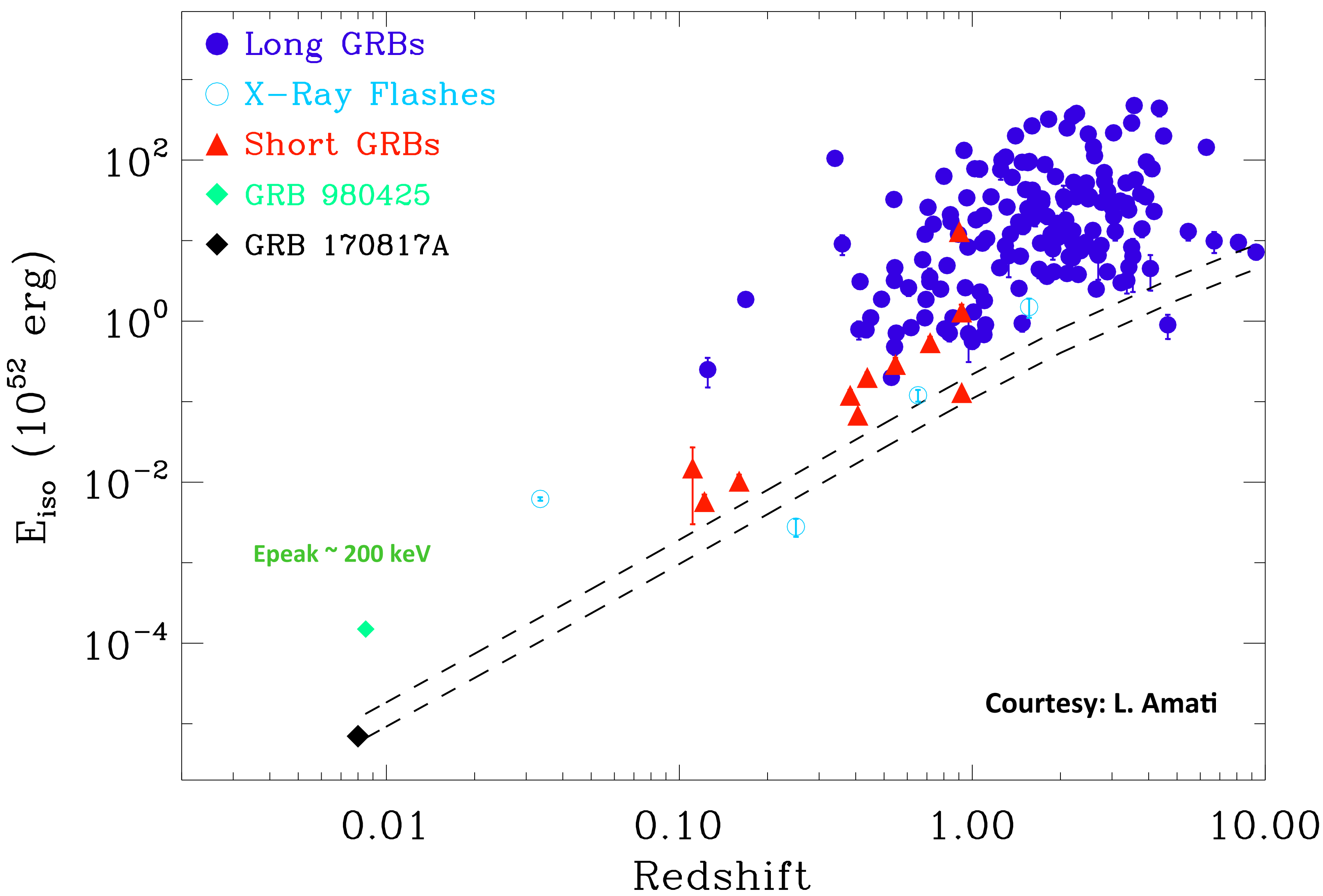


GW170817 and GRB170817A

The short GRB170817A lags GW signal by 1.7s: is this timescale related to the engine or to the plasma outflow? First of all it tells us that GW and light propagation speeds differ by less than 1 part in e15

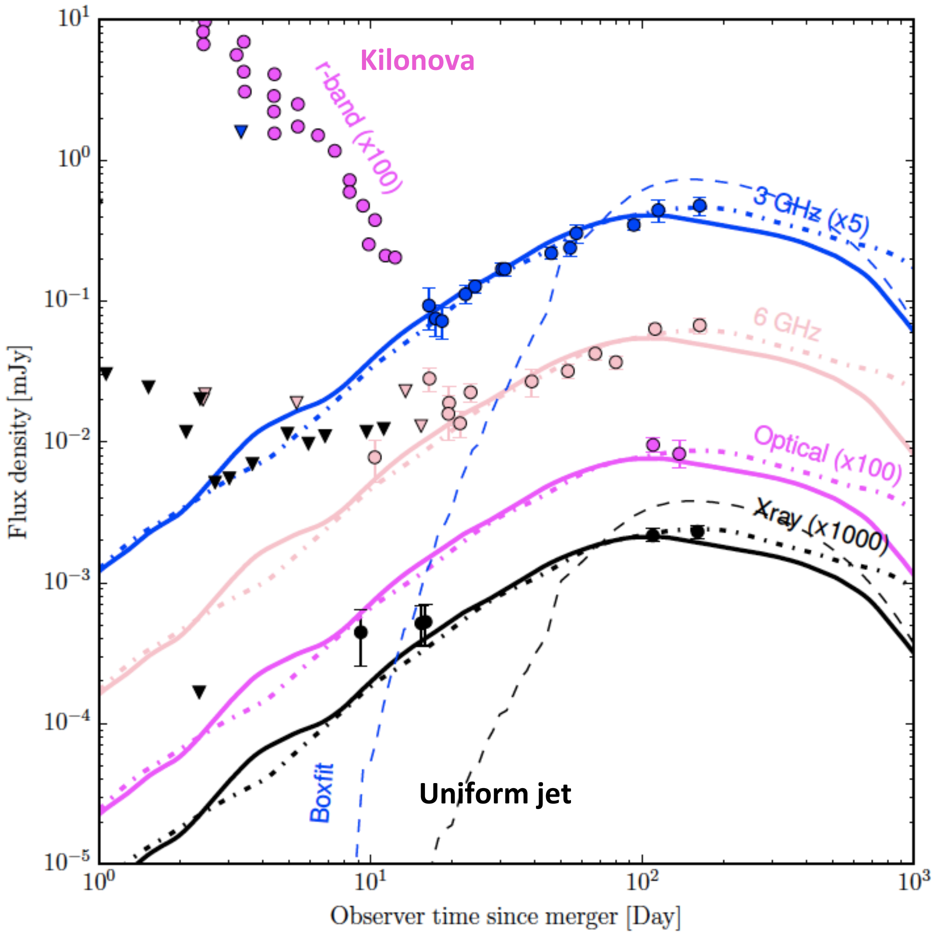
Abbott et al. 2017; Savchenko et al. 2017; Fermi Collaboration 2017

Energy output of GRBs

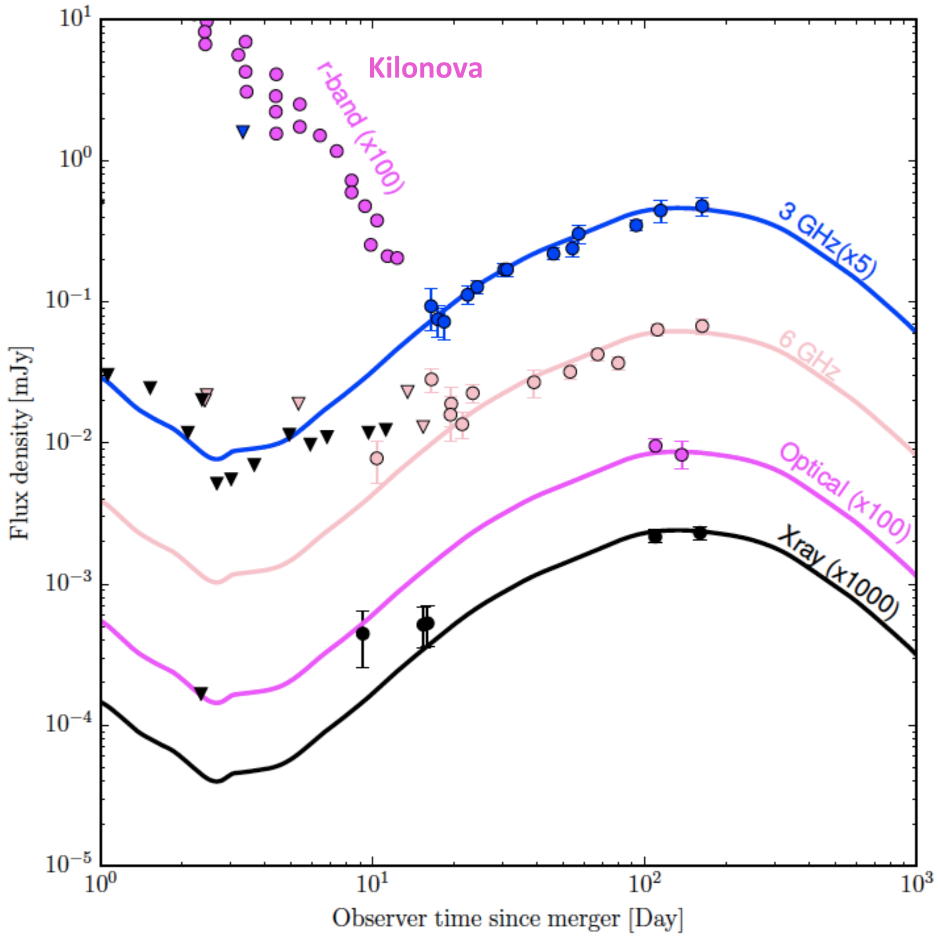


GRB170817A: multiwavelength LCs and emission models.
A structured off-axis jet or a quasi-isotropic outflow are preferred

Narrow engine



Wide engine



Xie, Zrake, MacFadyen 2018

Short GRB130603B

(z = 0.356)

Kilonova:

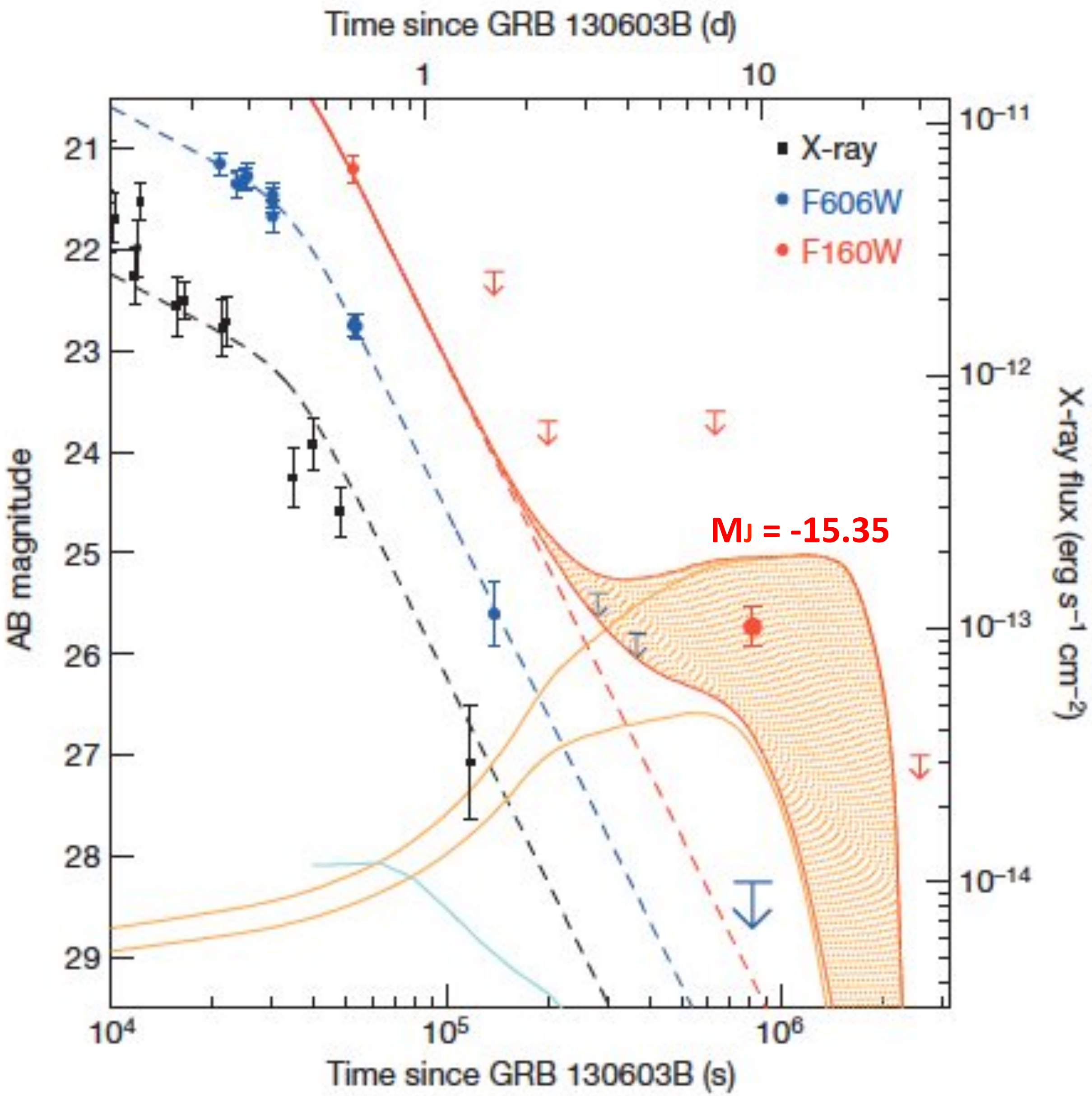
Ejection of r-process material from a NS merger (0.01-0.1 Mo) (Barnes & Kasen 2013)

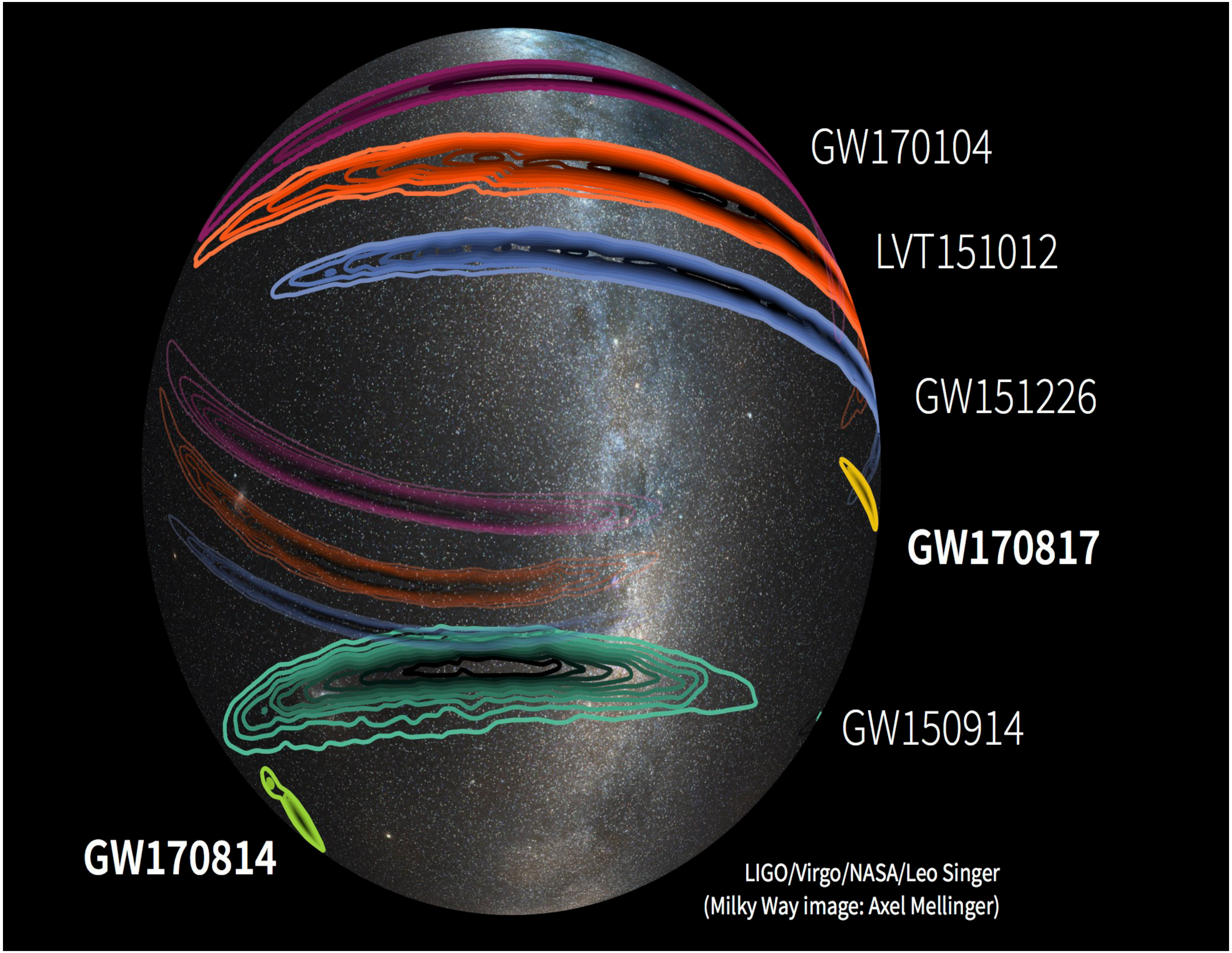
$M_H \approx -15$

$M_R \approx -13$

Tanvir et al. 2013;

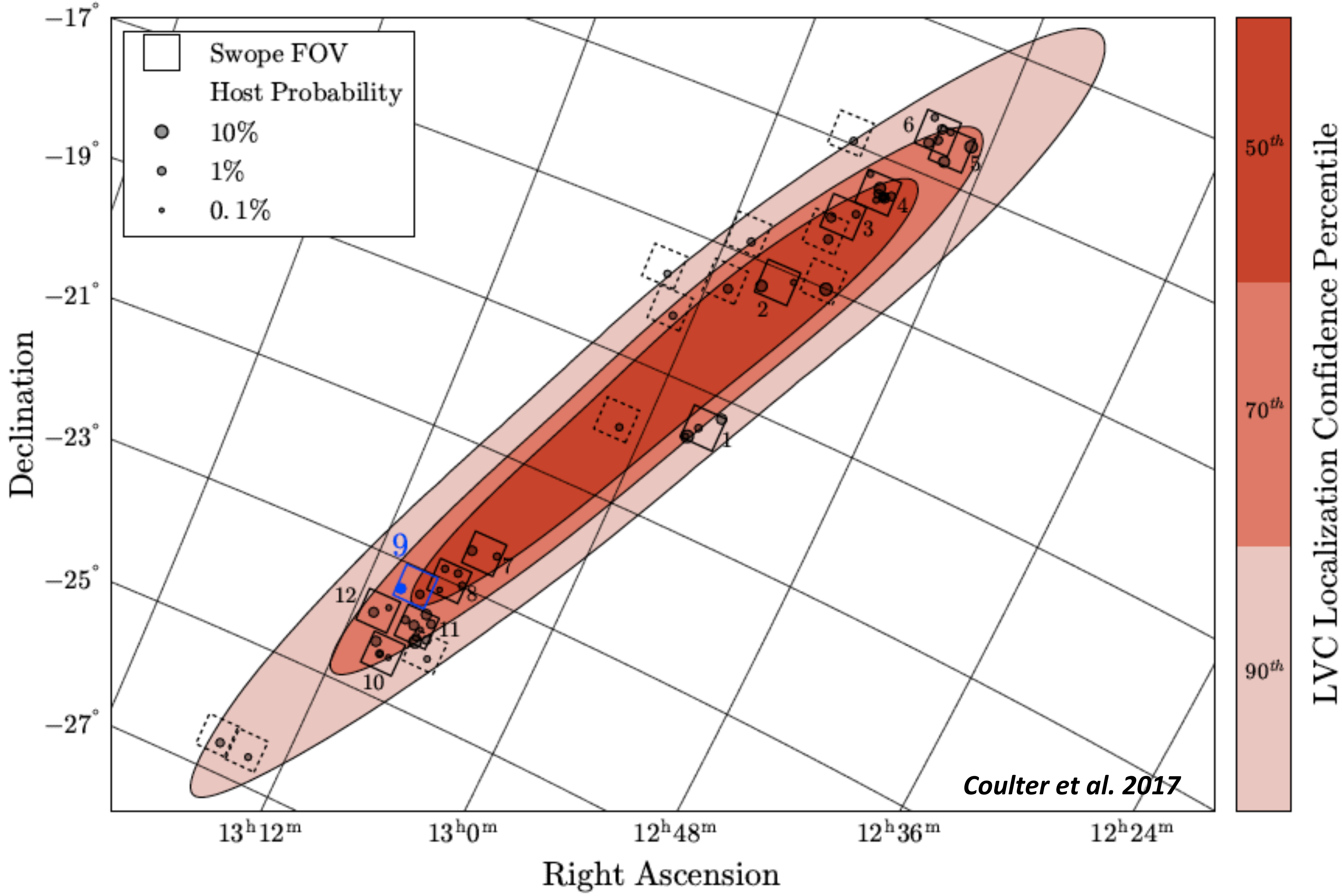
Berger et al. 2013



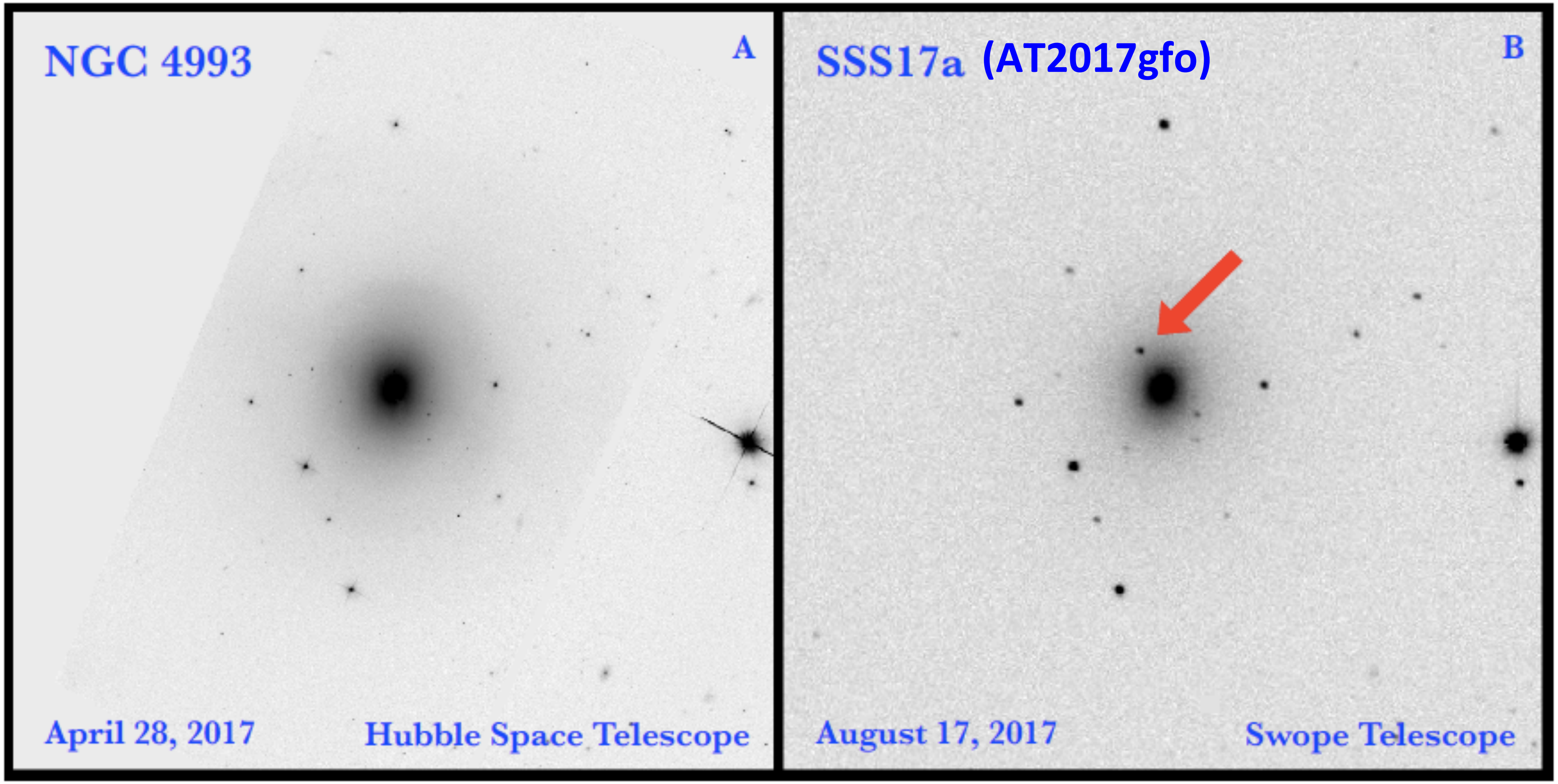


GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

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

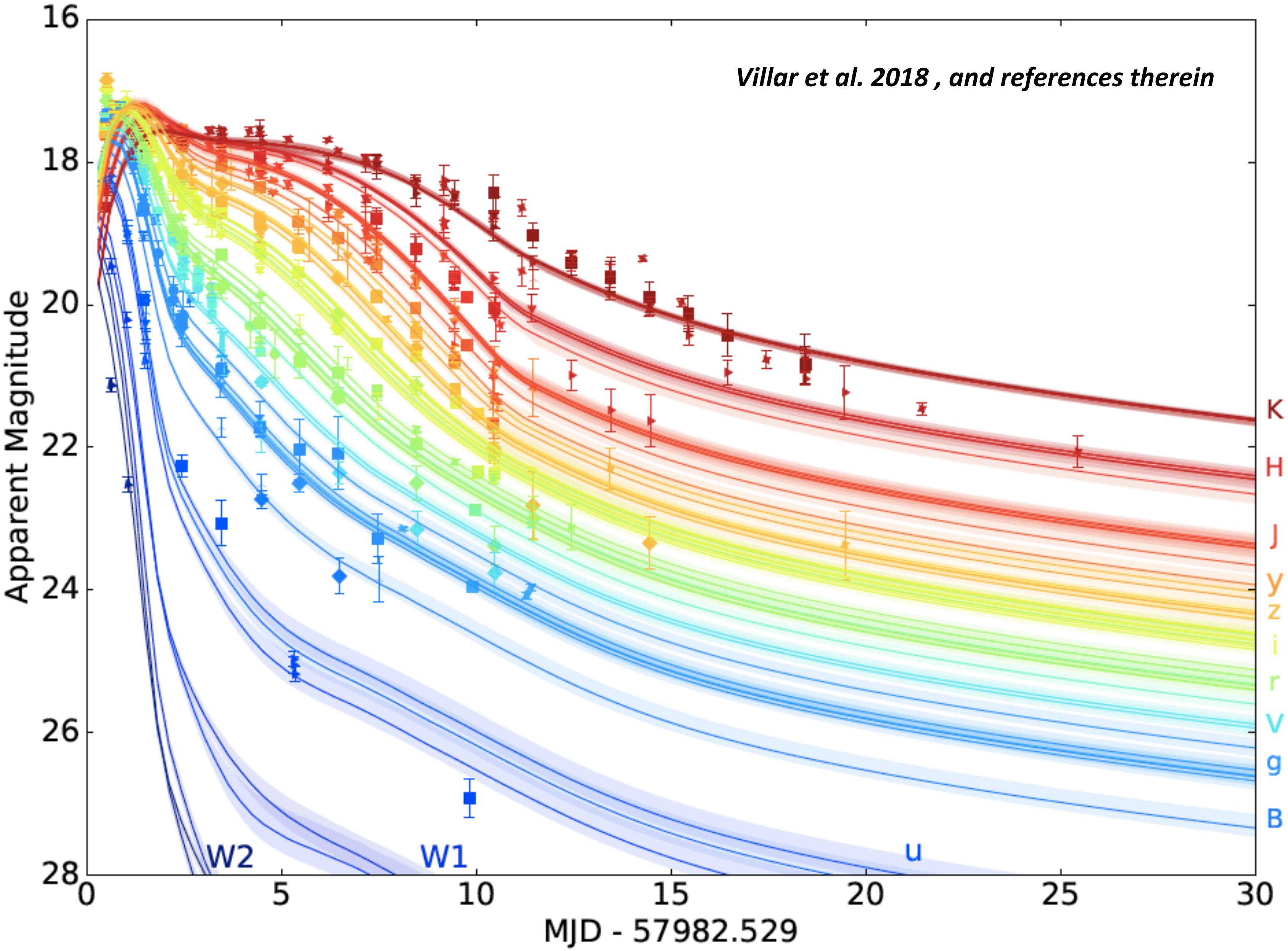


Comparison of Swope discovery image with archival HST image

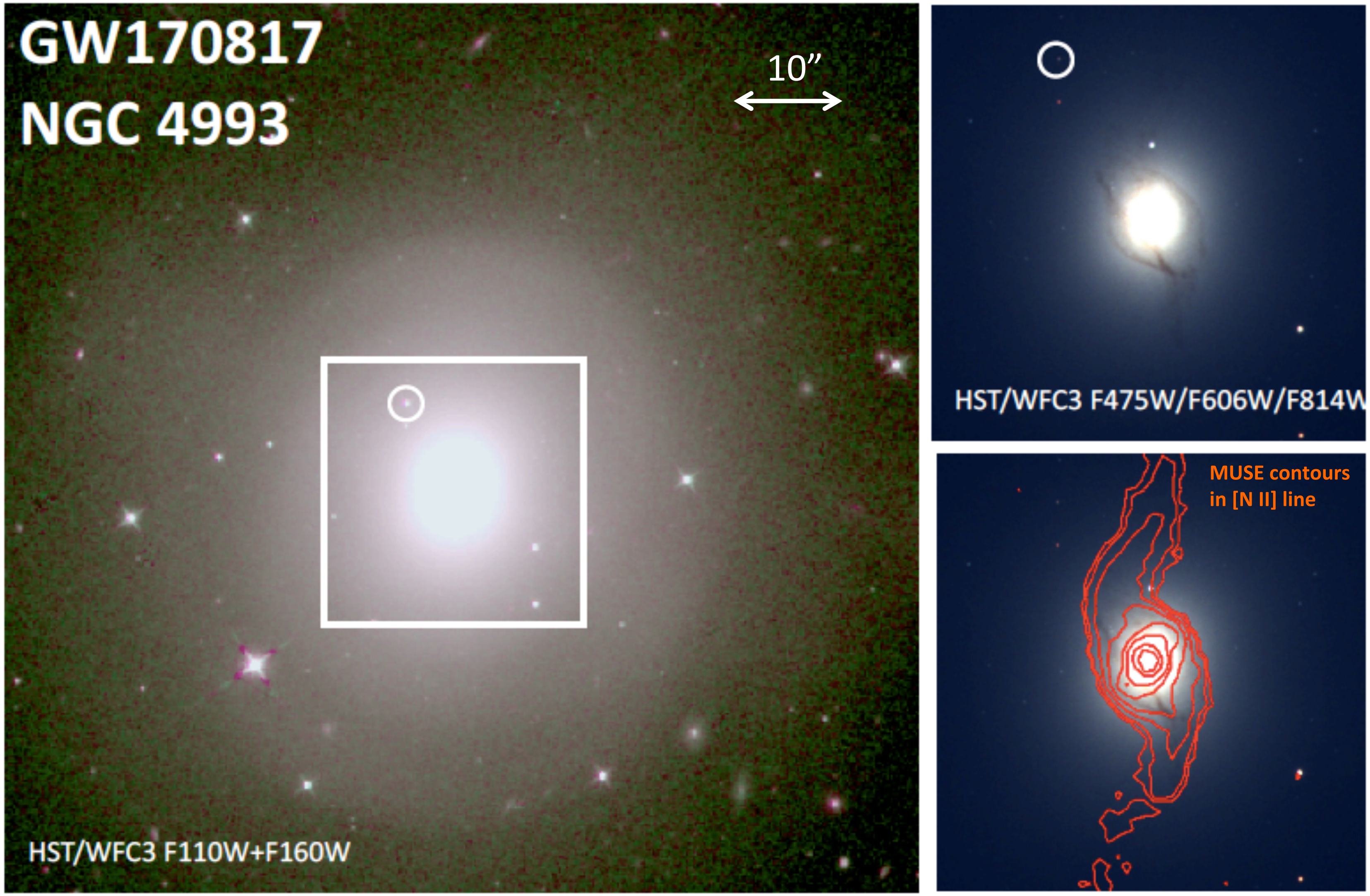


Coulter et al. 2017

Optical and near-infrared light curves of GW170817 / AT2017gfo

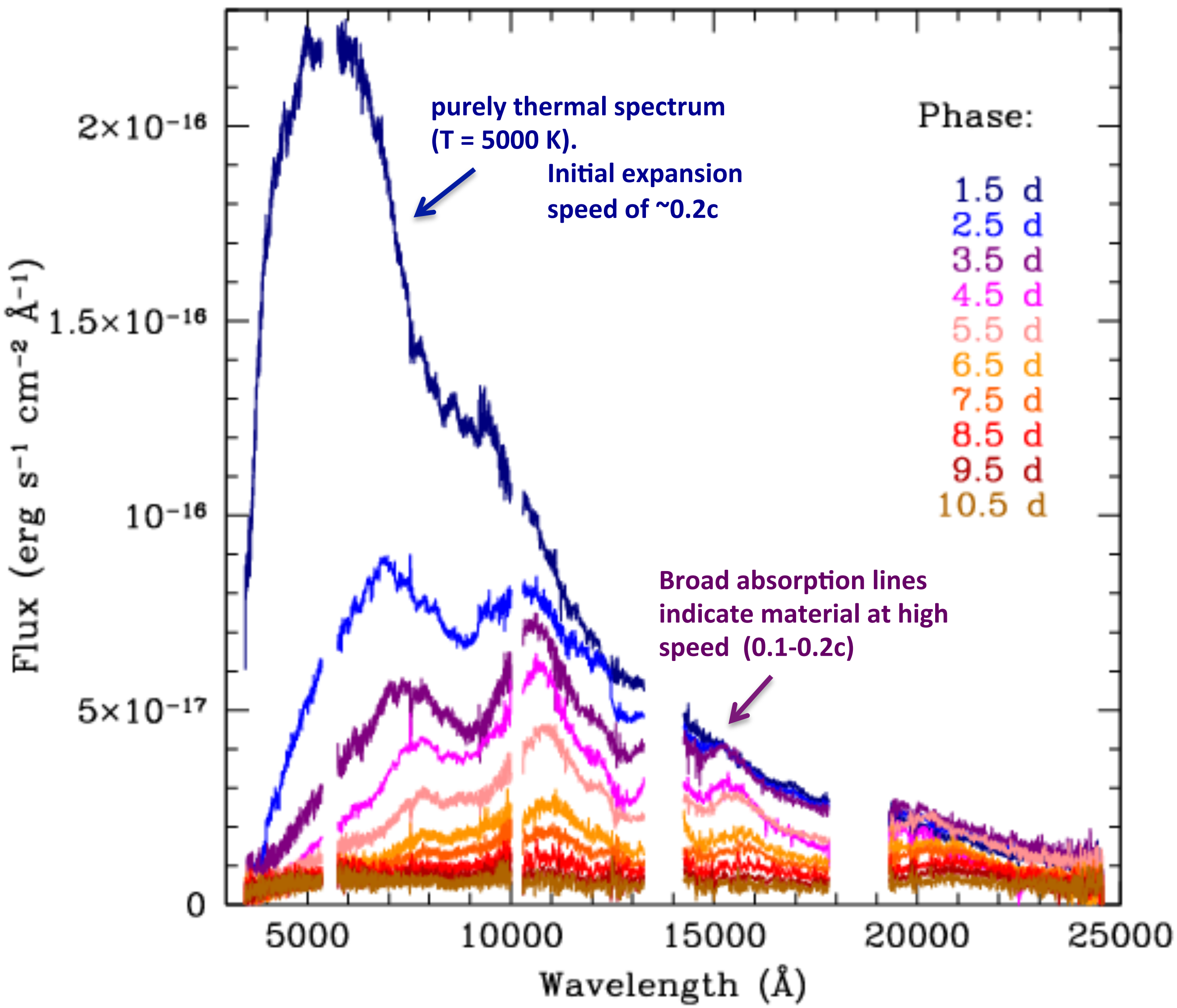


Host of GW170817: Lenticular galaxy NGC 4993 (40 Mpc)



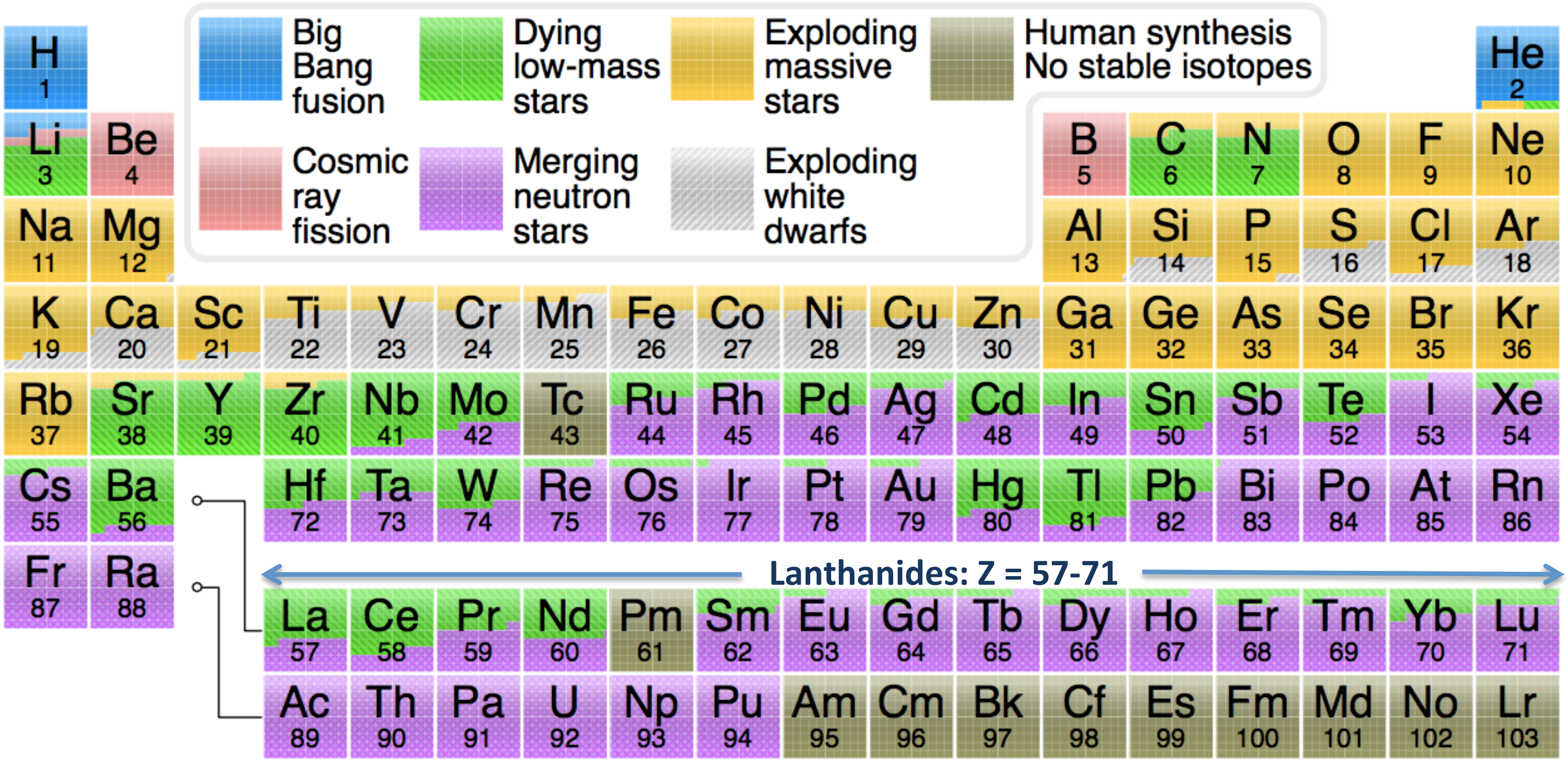
Levan et al. 2017

ESO VLT X-Shooter spectral sequence of kilonova GW170817



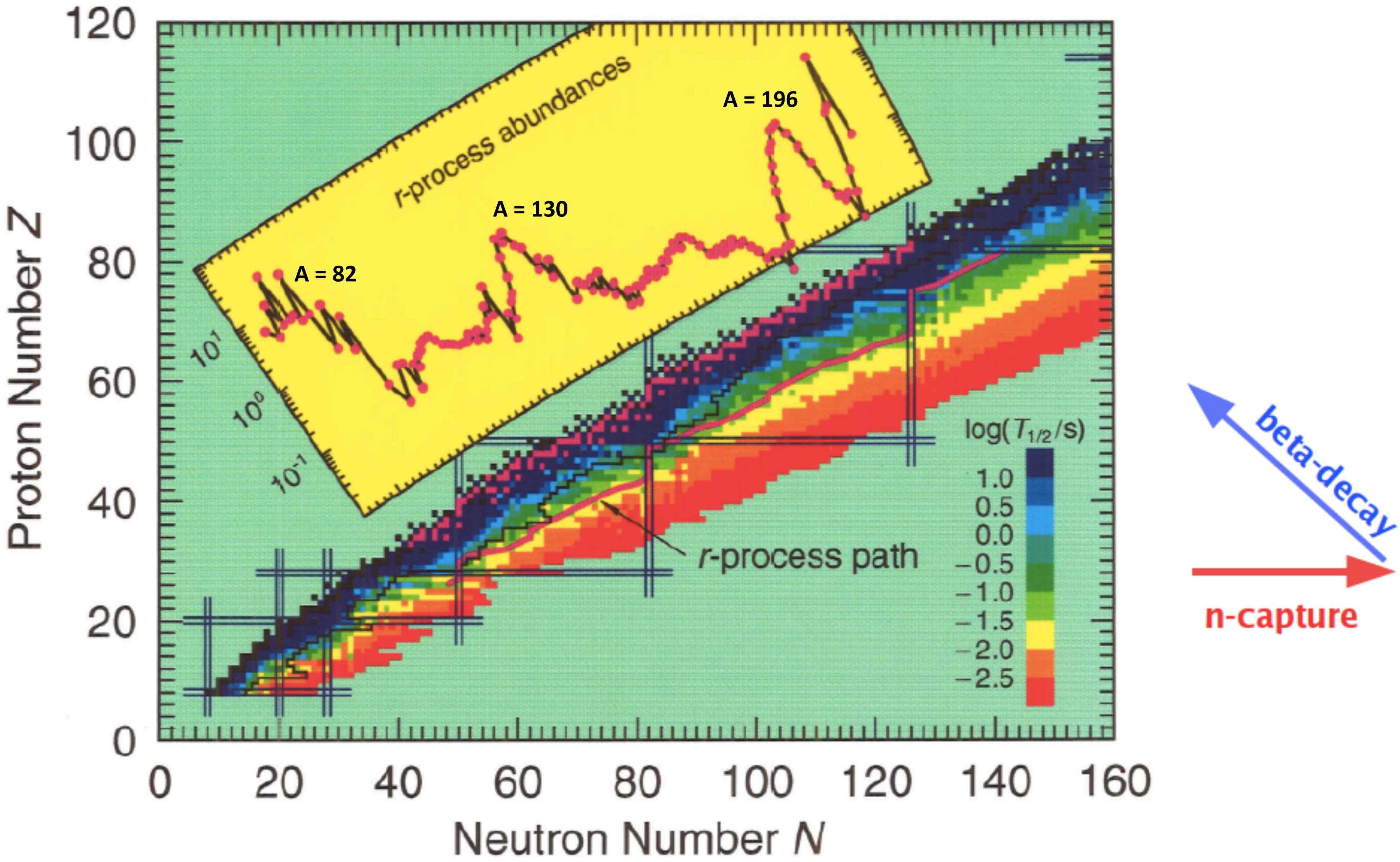
Pian et al. 2017; Smartt et al. 2017

Periodic table of elements



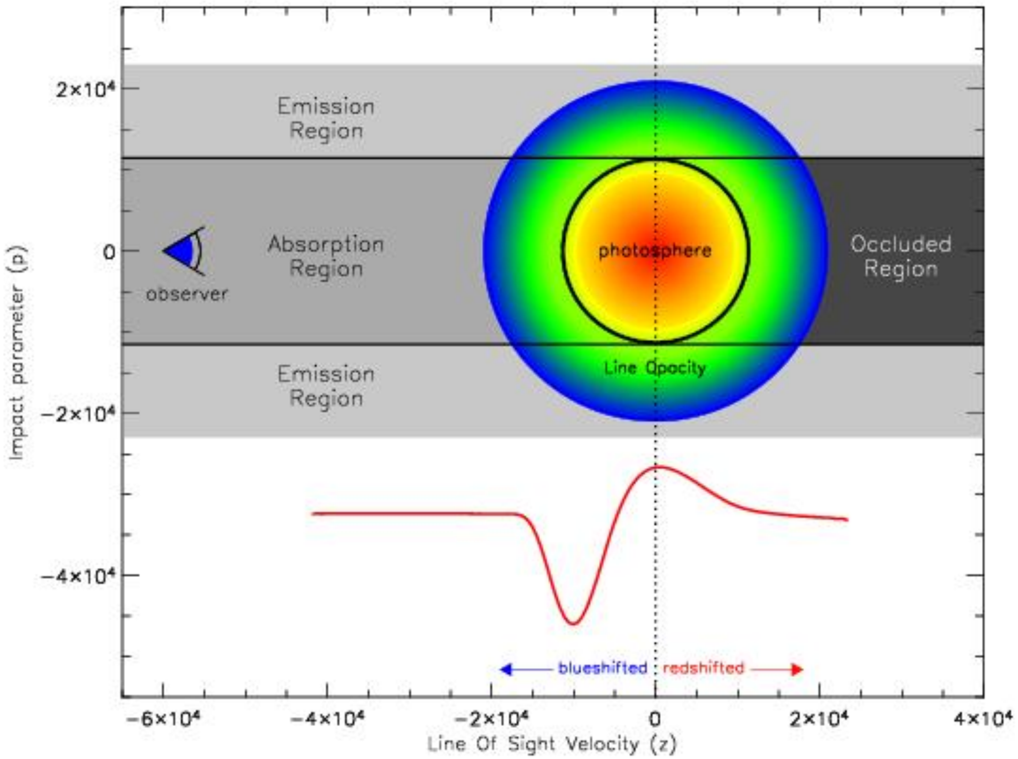
https://en.wikipedia.org/wiki/R-process

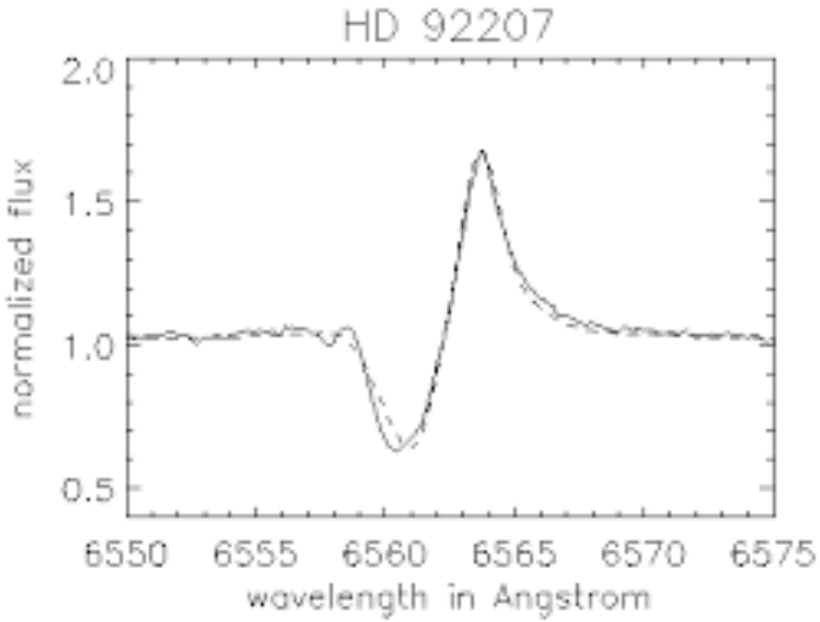
s- and r-Process Nucleosynthesis



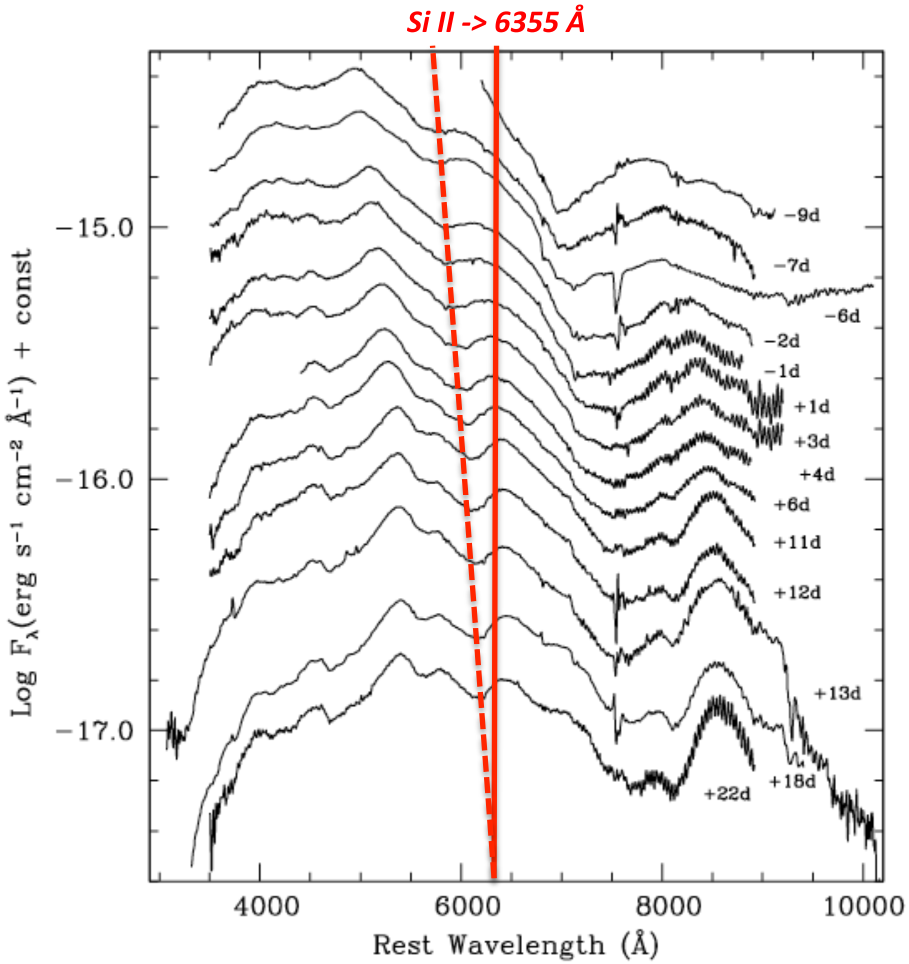
Courtesy: K.-L. Kratz

Receding photosphere: P-Cygni profile of absorption lines





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



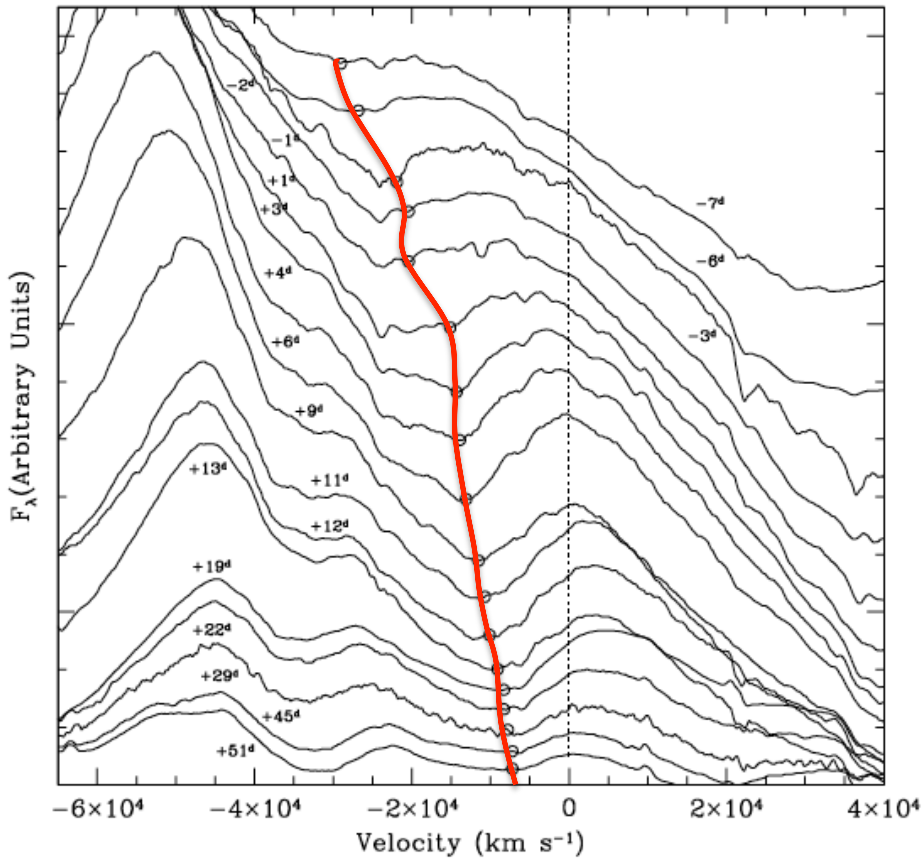
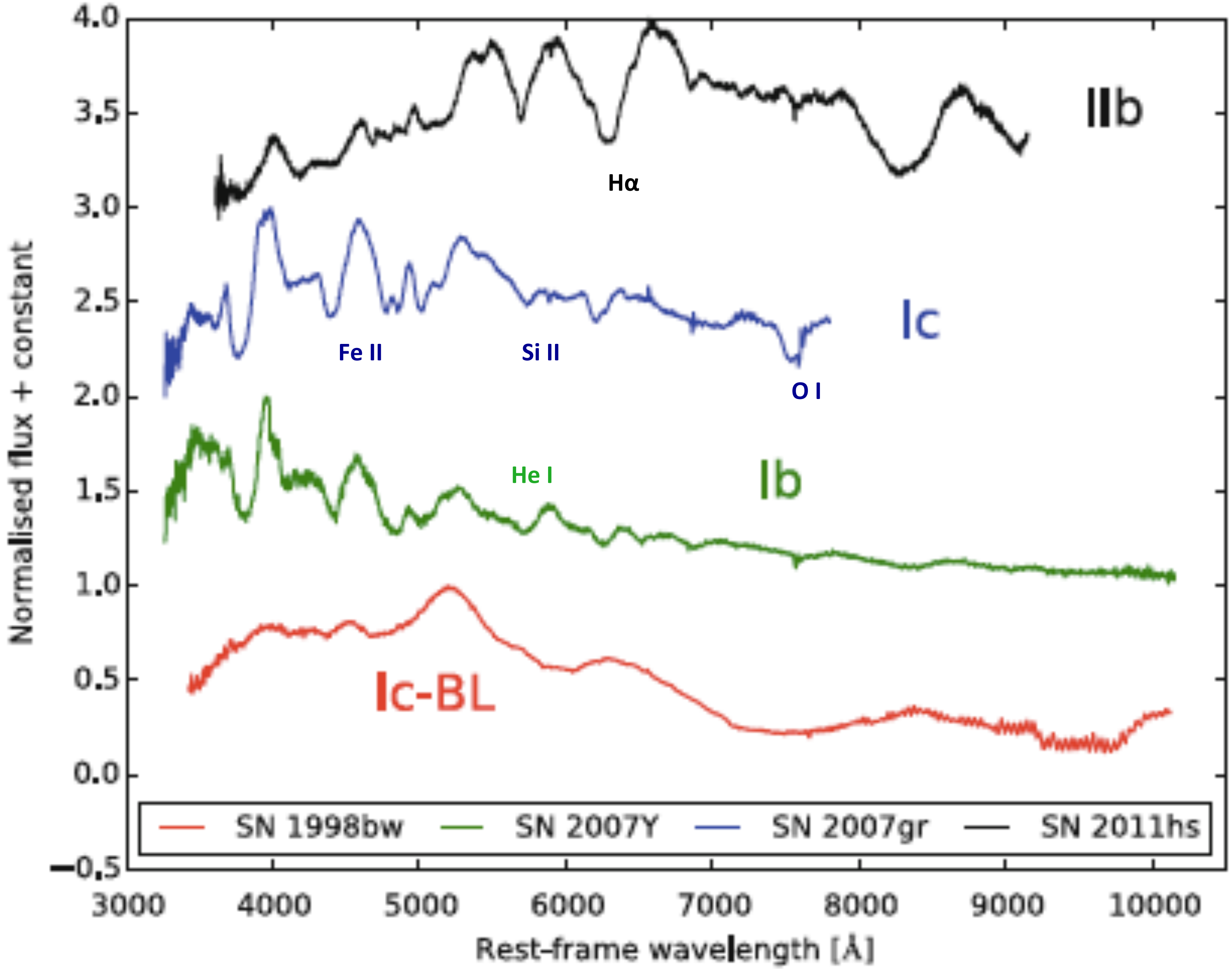


FIG. 4.—Evolution of the Si II λ6355 region. The empty circles mark the value that has been assumed to represent the photospheric velocity.

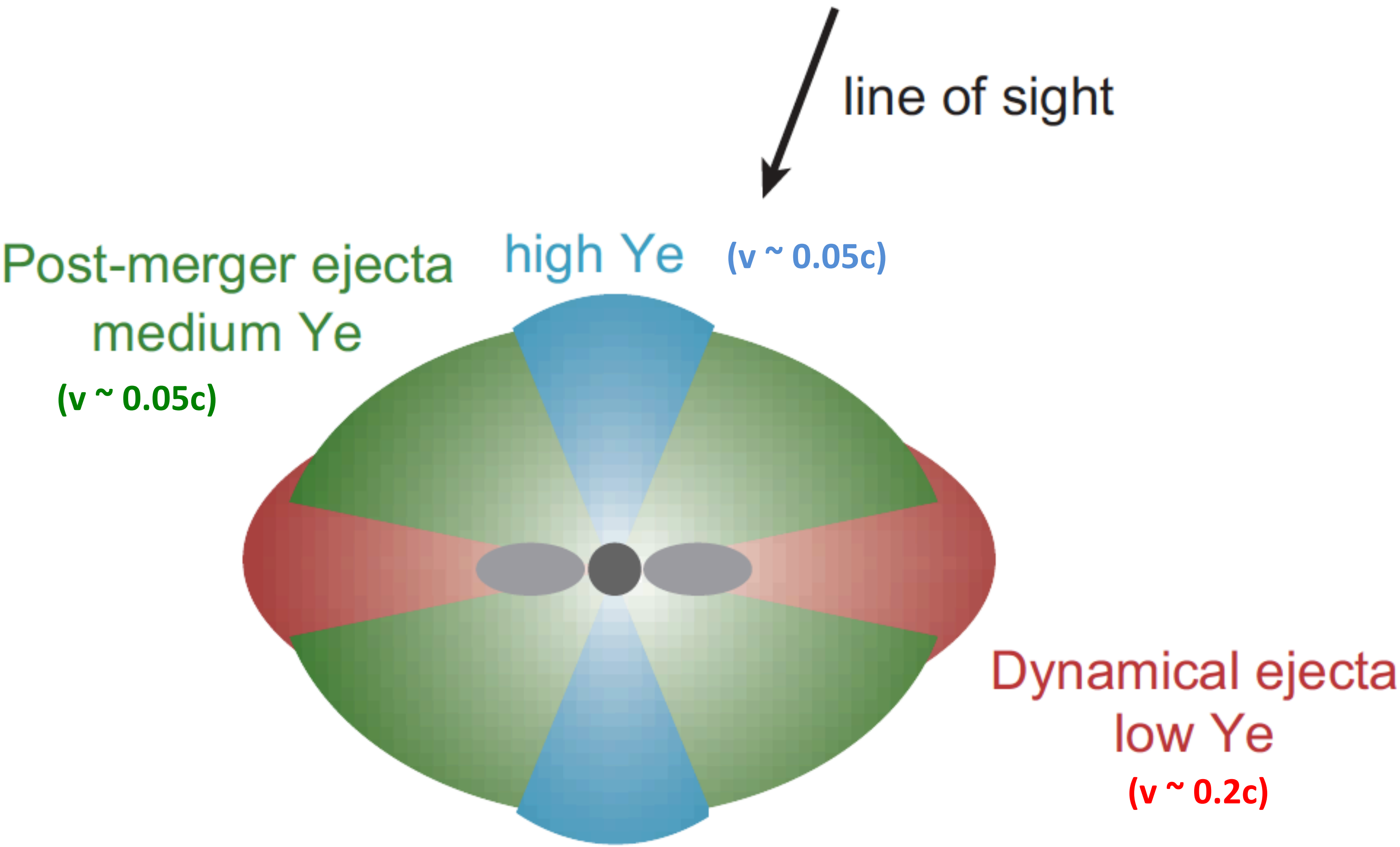
Patat et al. 2001

Typical spectra of Stripped-envelope core-collapse SNe



Pian & Mazzali 2017

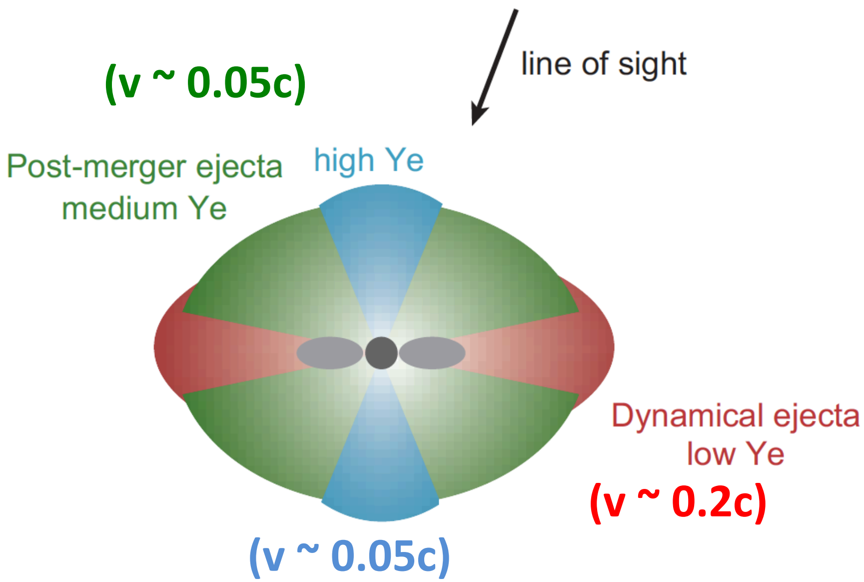
Geometry of 3-component model for kilonova

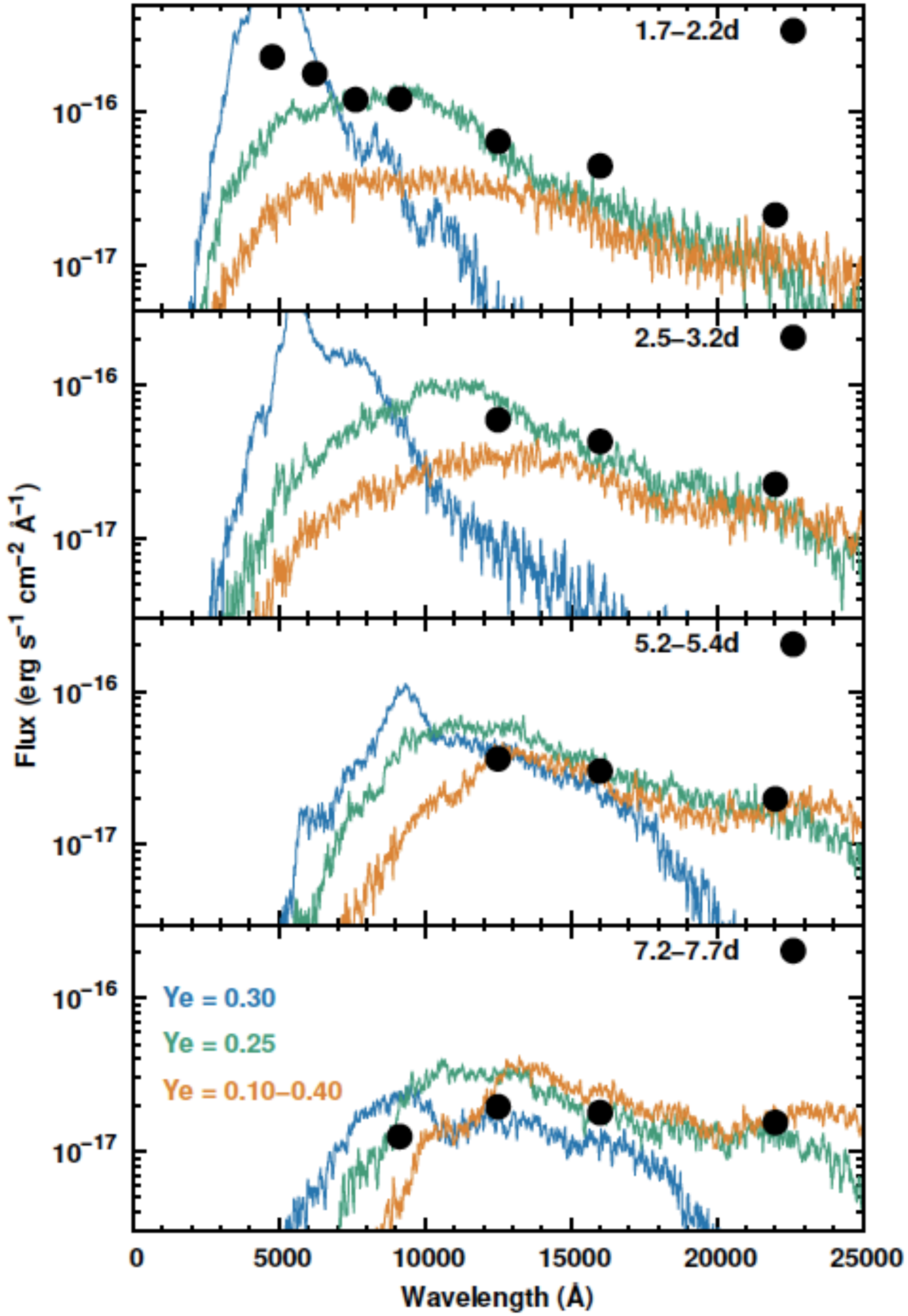


Tanaka et al. 2017, PASJ

Geometry of 3-component model for kilonova and resulting spectra

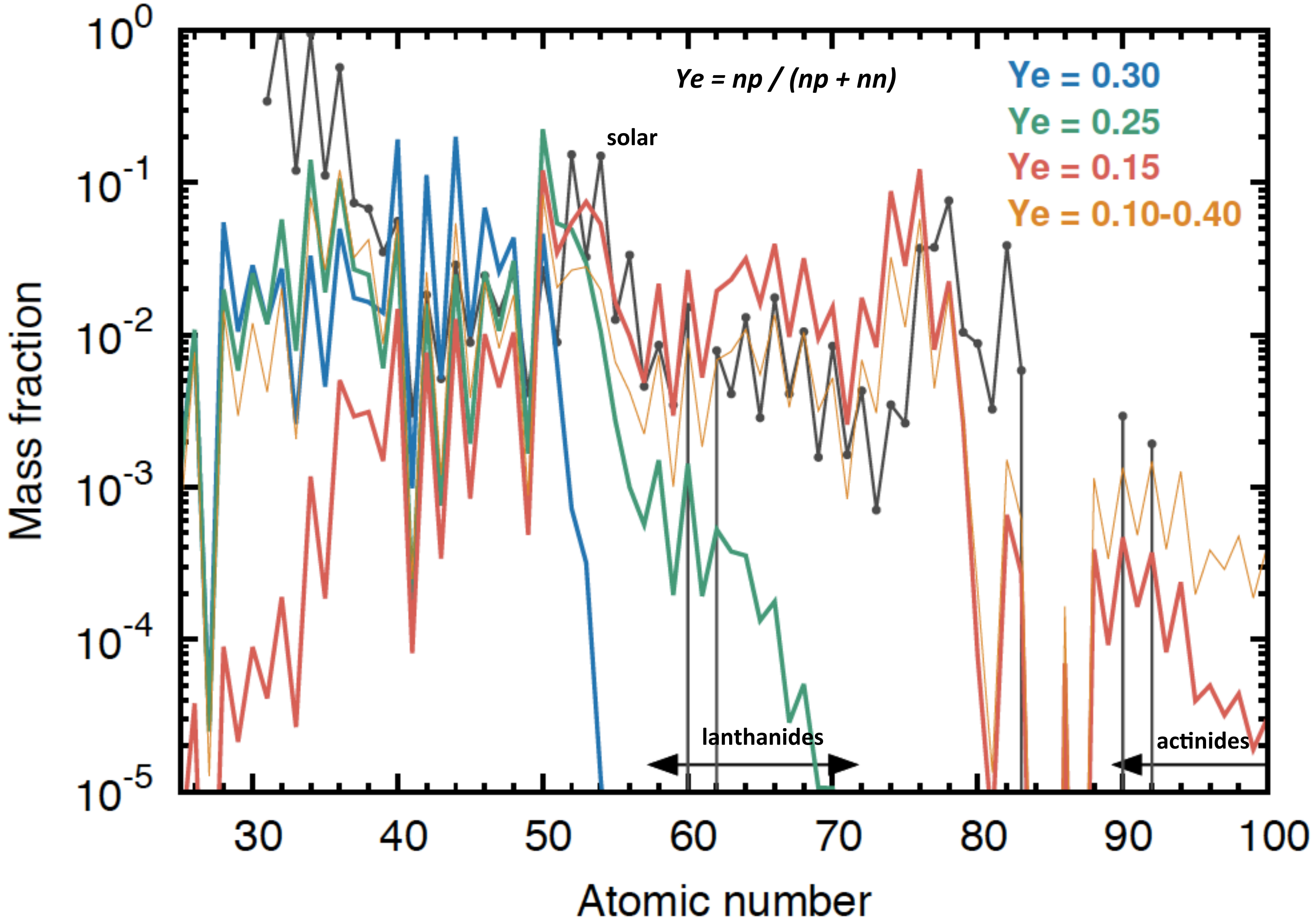
M_{ej} ~ 0.03





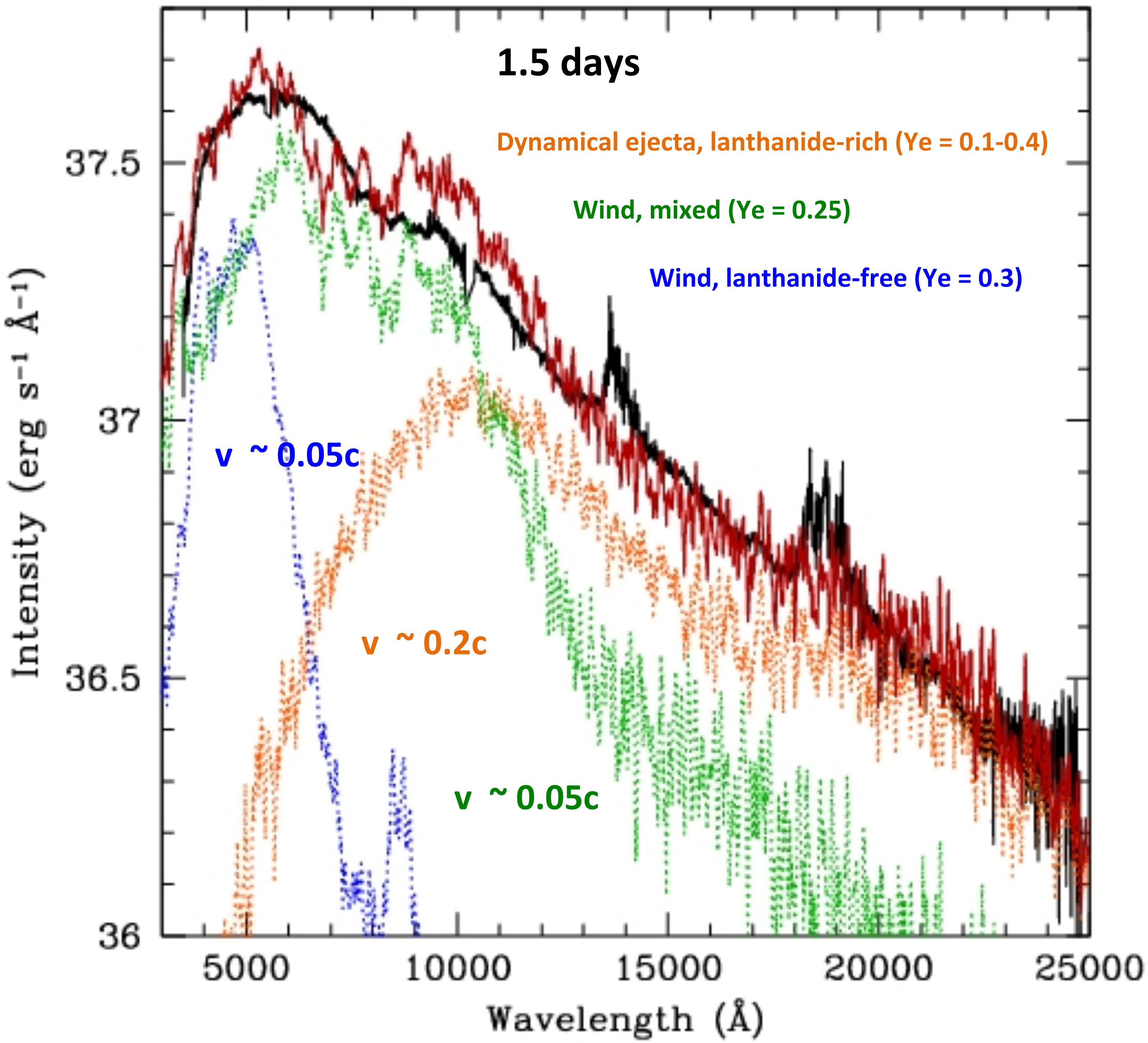
Tanaka et al. 2017, Utsumi et al. 2017

Element abundances at 1 day after merger

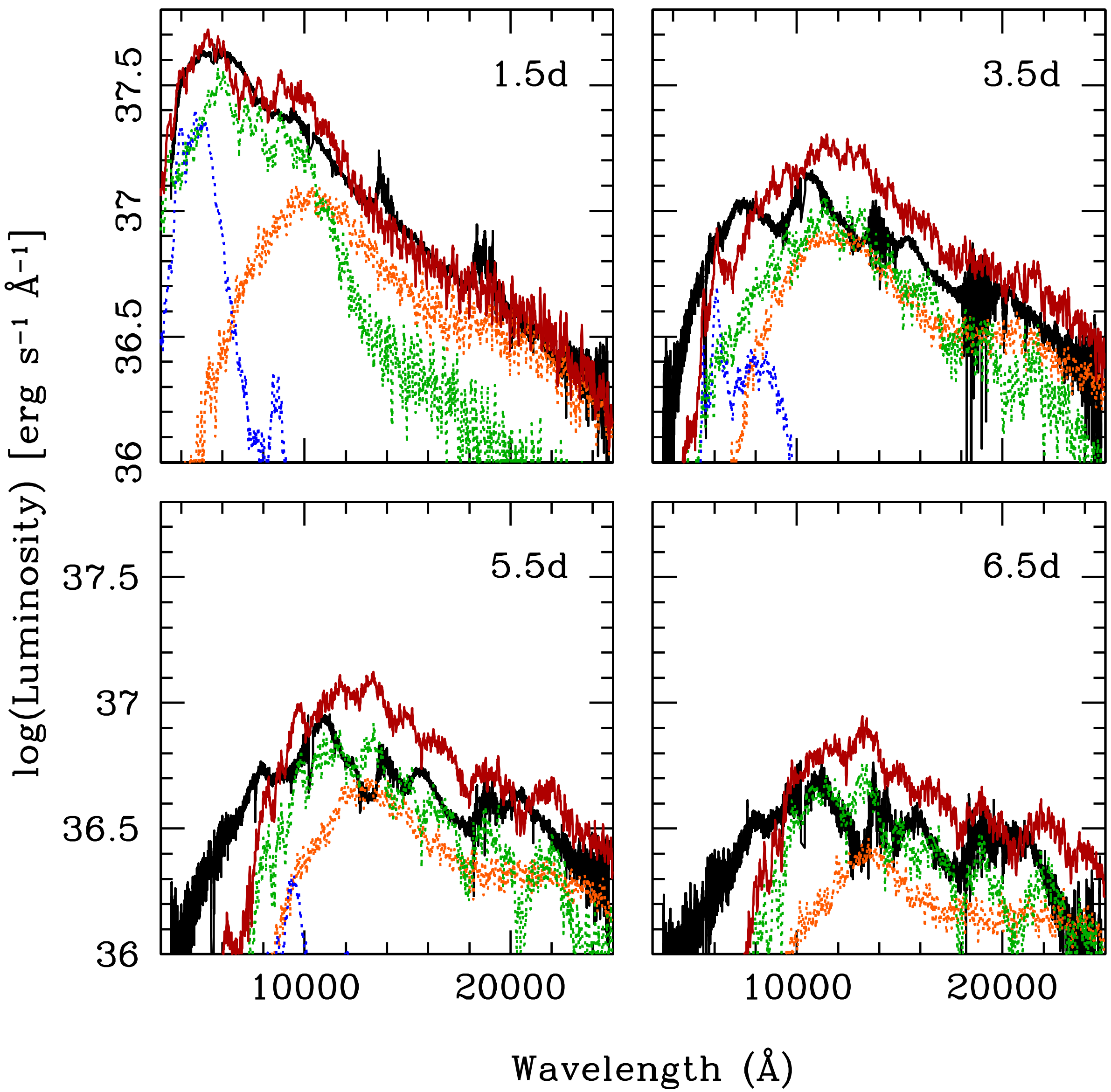


Tanaka et al. 2017, PASJ

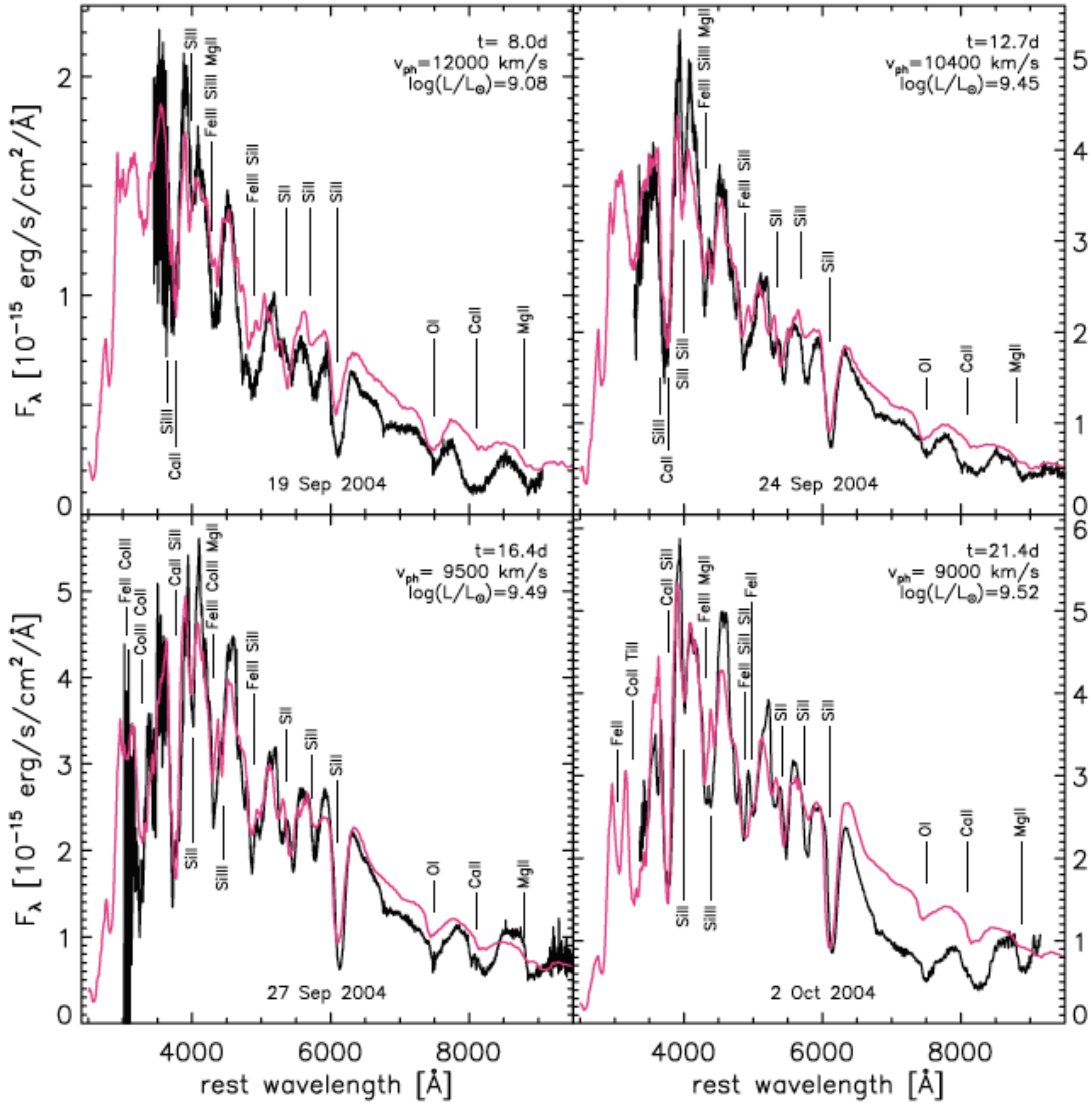
Kilonova 3-component model for AT2017gfo



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

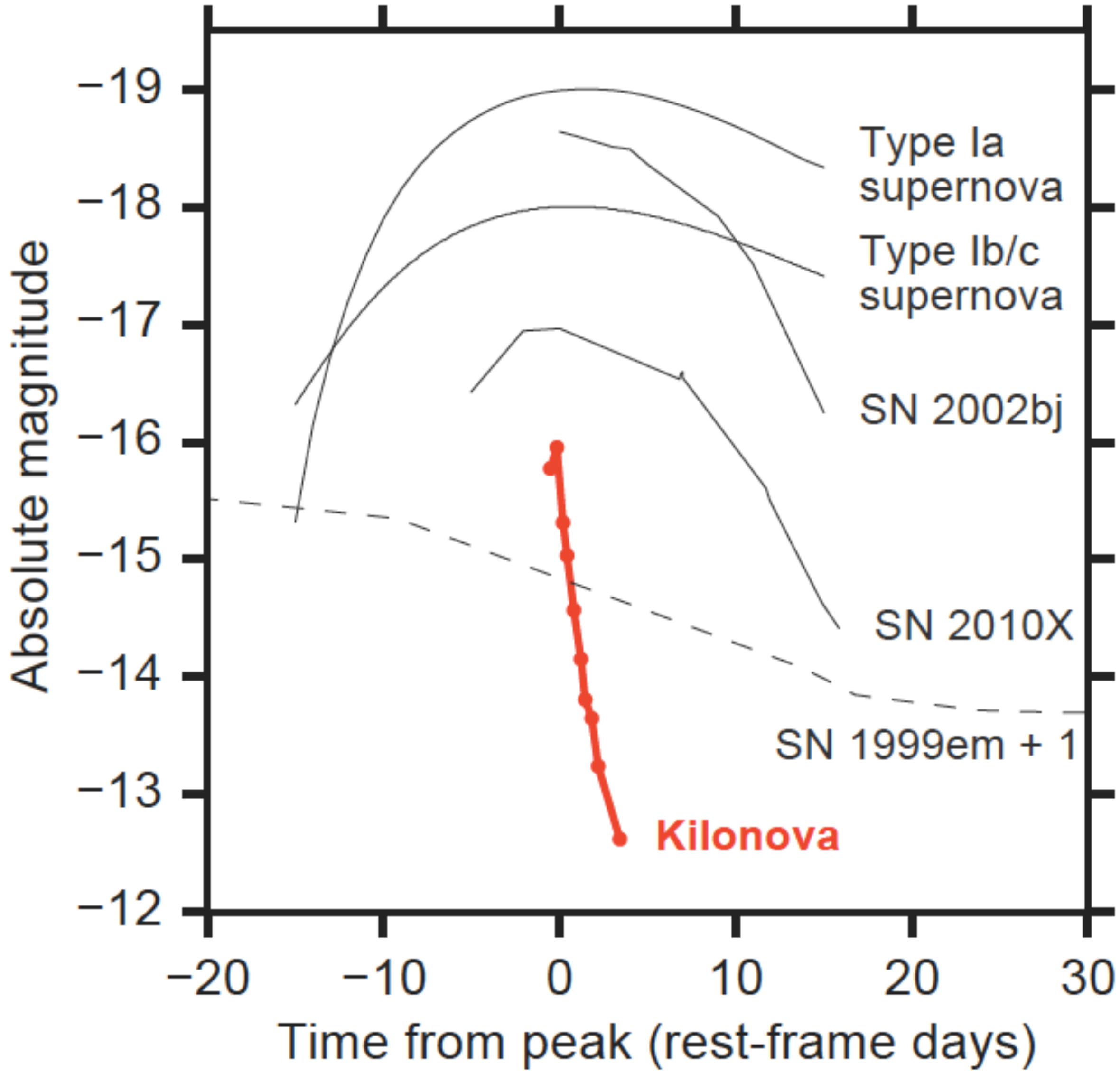


An example of a _good_ spectral fit (SN2004eo)



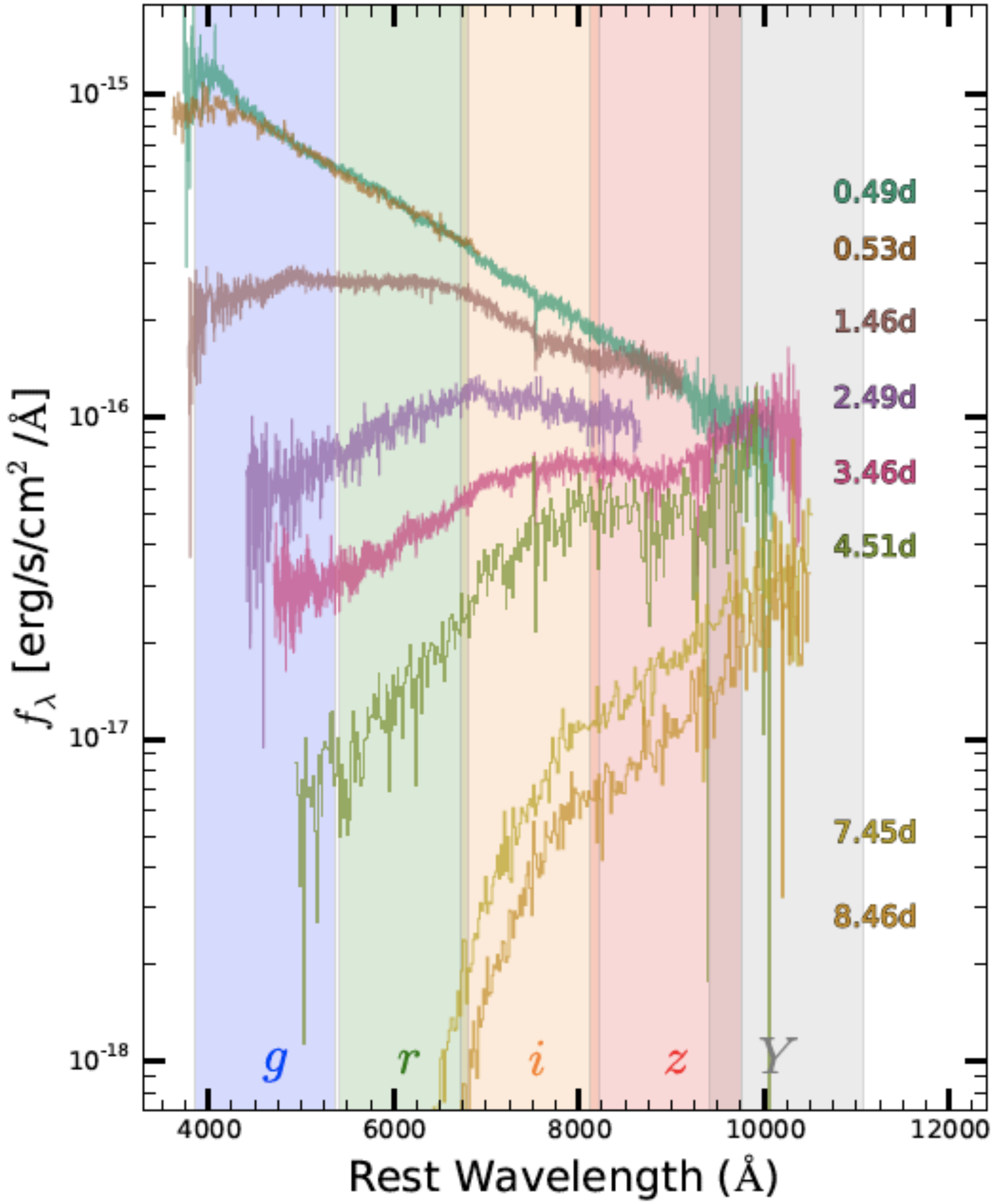
Mazzali et al. 2008

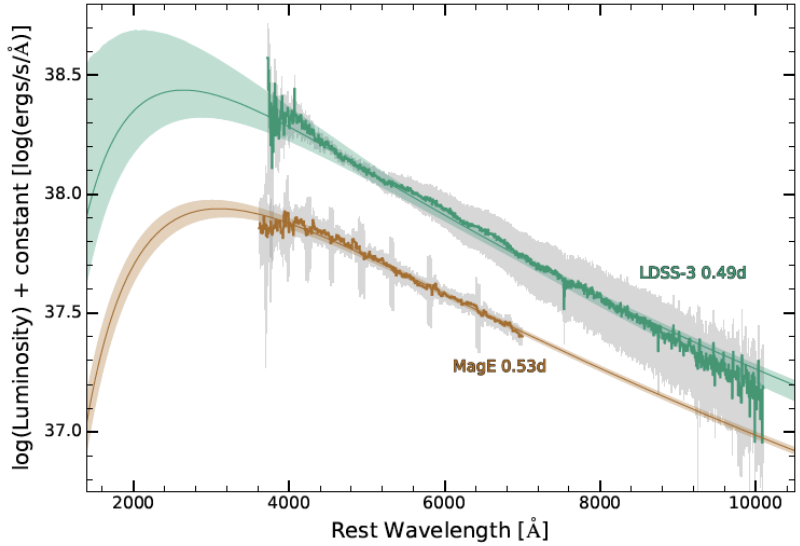
AT2017gfo evolves much more rapidly than any supernova



Arcavi et al. 2

Magellan spectral sequence of kilonova GW170817



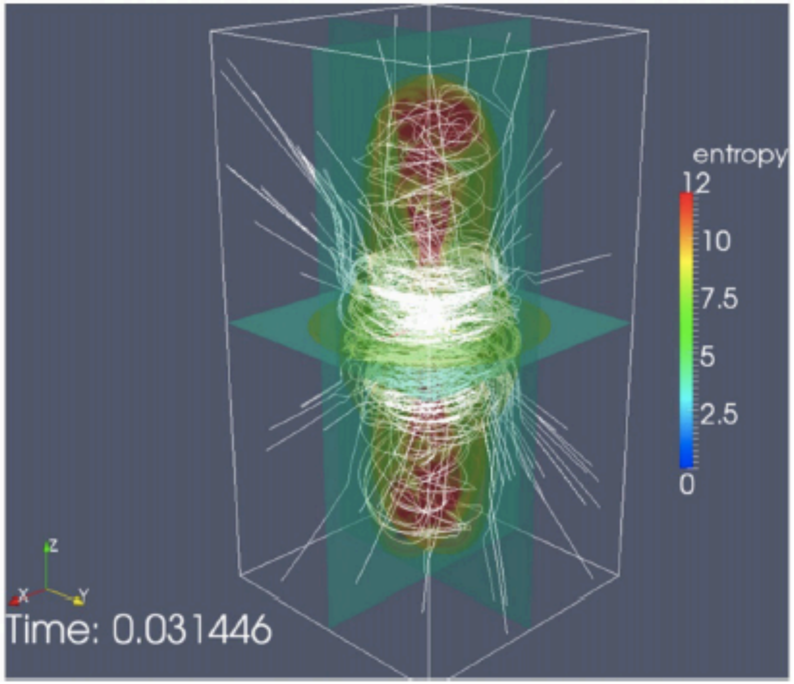


spectra at < 1 day indicate temperature of ~10000 K

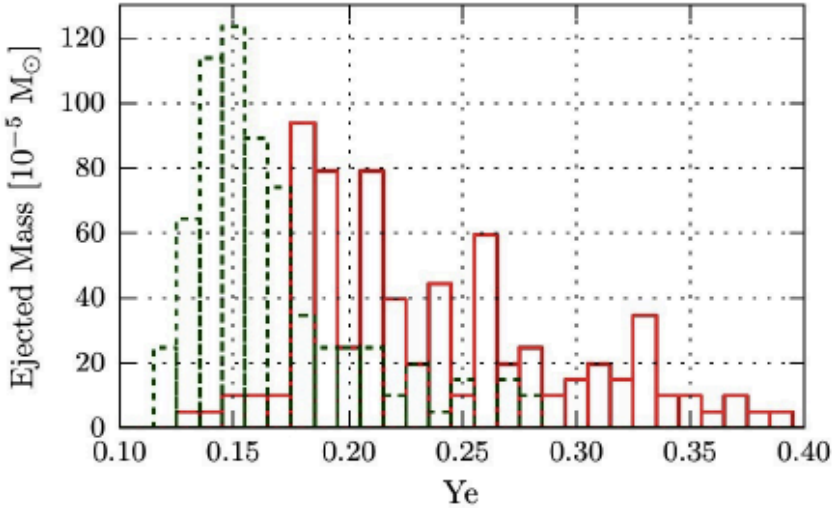
Shappee et al. 2017

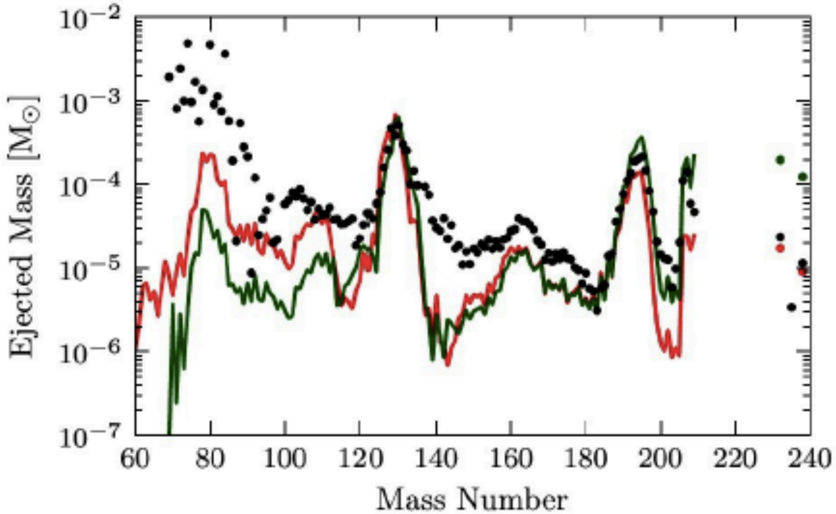
Jet-Supernova Models as r-process Sites?

- 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





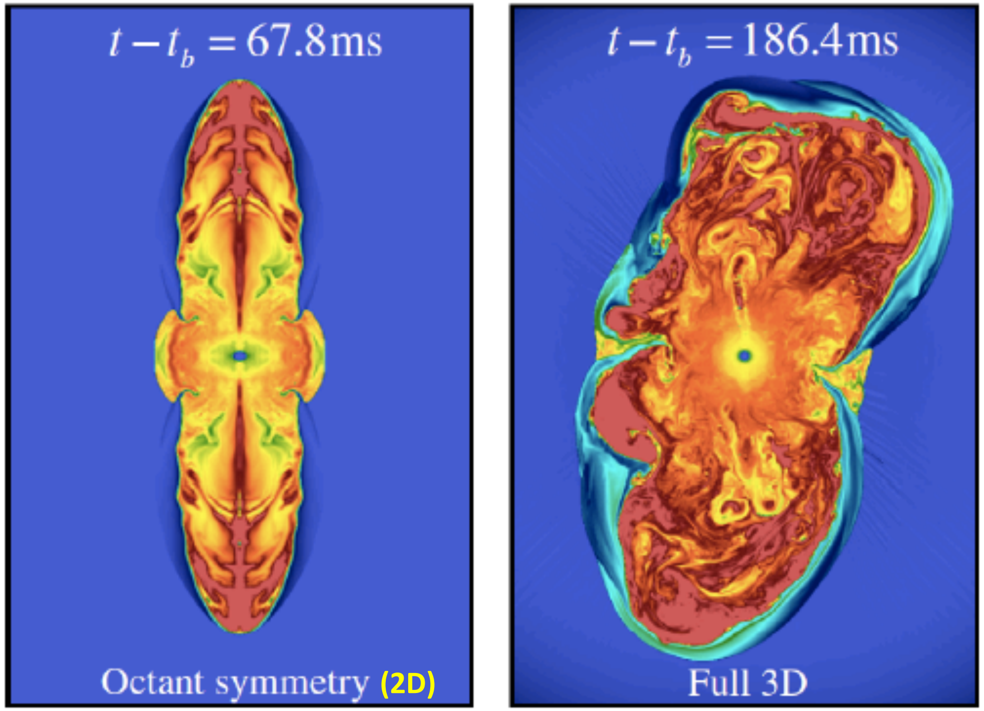
From Th. Janka, 2016

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

Conclusions

While GWs from binary stellar BH mergers should not produce any EM signal, binary neutron star mergers produce kilonova light and spectra -> first direct proof that neutron star mergers are r-process factories.

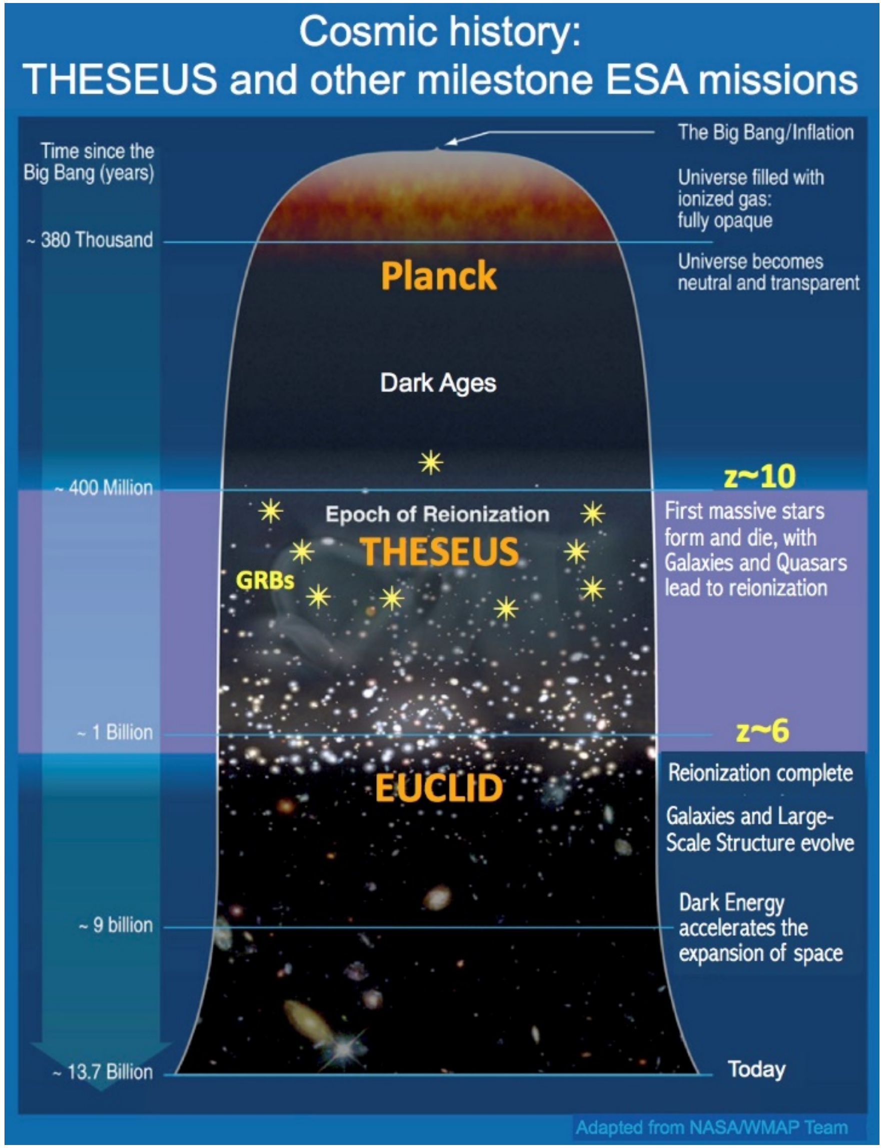
The preliminary models require more than one kilonova component, with different proportions of species (lanthanide-rich vs lanthanide-free). The ejecta are about 0.03-0.05 solar masses.

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

Fundamental problem of NS EoS can be addressed with joint GW and EM information: dynamical ejecta should be larger for smaller NS radii (i.e. softer EoS) and for asymmetric NS masses; moreover larger remnant mass implies lower ejecta.

THESEUS

https://www.isdc.unige.ch/theseus/



Medium-size mission (M5) within the **Cosmic Vision Programme, selected by ESA on 2017 May 7 to enter an assessment phase study**

4 Soft X-ray Imager (SXI, 0.3 – 6 keV),
~1sr FOV, location accuracy < 1-2'

0.7m InfraRed Telescope (IRT, 0.7 – 1.8 μm)
10'x10' FOV, fast response, imaging and spectroscopy capabilities

X-Gamma rays Imaging Spectrometer (XGIS, 2 keV – 20 MeV),

coded-mask cameras based on Si diodes coupled with CsI crystal scintillator, ~1.5sr FOV, location accuracy of ~5' in 2-30 keV