INAF ISTITUTO NAZIONALE DI ASTROFISICA
OAS BOLOGNA

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Kilonovae: the cosmic foundries of heavy elements (Part II)

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yesterday problem:

How many neutrinos where liberated in SN1987A explosion?
And how many reached Earth?

Solution:

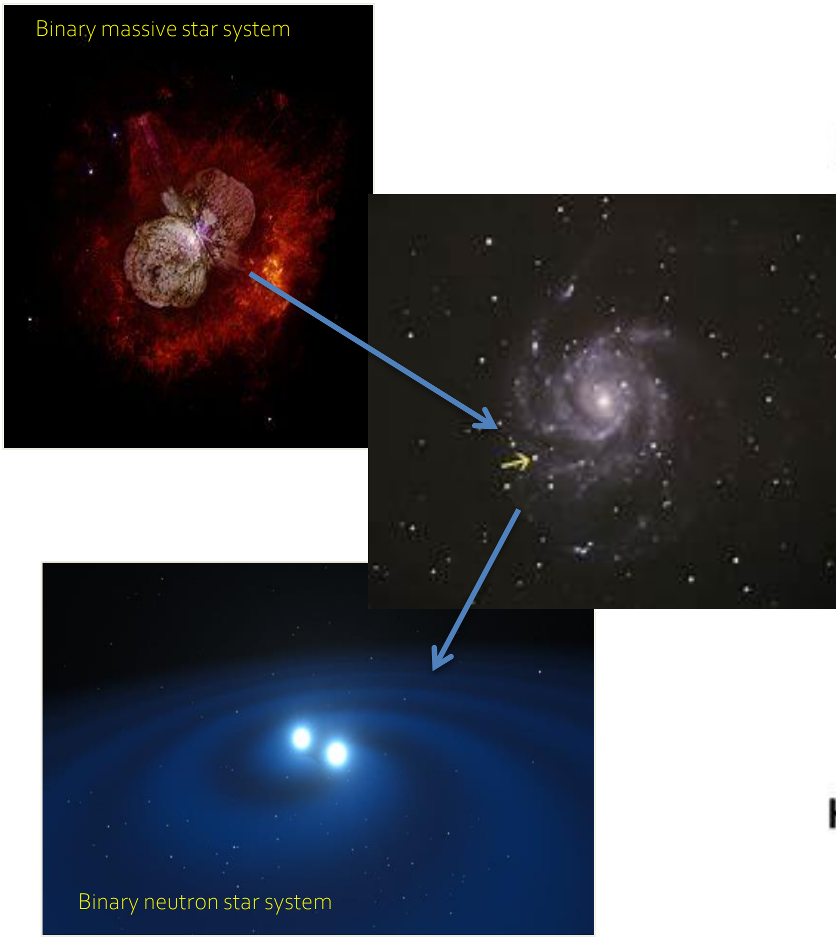
Mass of NS remnant: 1.4 solar masses,
Where 1 solar mass = 2E33 g

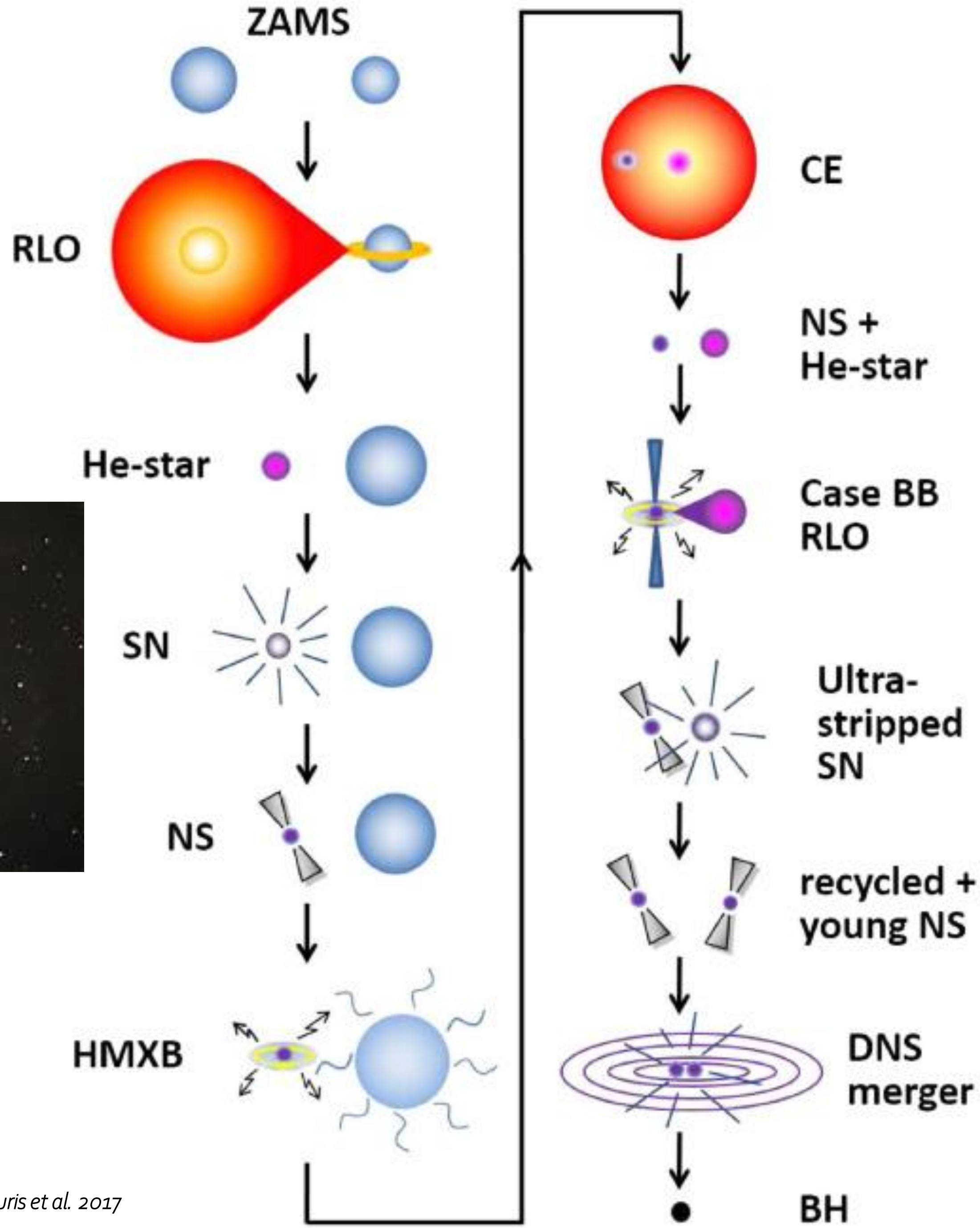
Mass of proton m_p: 1840 * m_e,
Where m_e = 9.1E-28 g

N_nu = N_protons = M_remnant / m_p =
1.4 solar masses / (1840 x m_e) ~ 2 E57 neutrinos
This is a lot of energy! Neutrinos carry away 99% of NS binding energy, E53 erg

At 50 kpc distance, the neutrinos that reached the detectors are
2E57 / (4pi d^2) ~ 6 E9 neutrinos, *but only a dozen detected!*

Evolution of a binary massive (> 8 Msun) star system: supernova explosion and double neutron star remnant





Tauris et al. 2017

Expected rate of double neutron star mergers:

$\sim$300-3000 /Gpc^3/yr

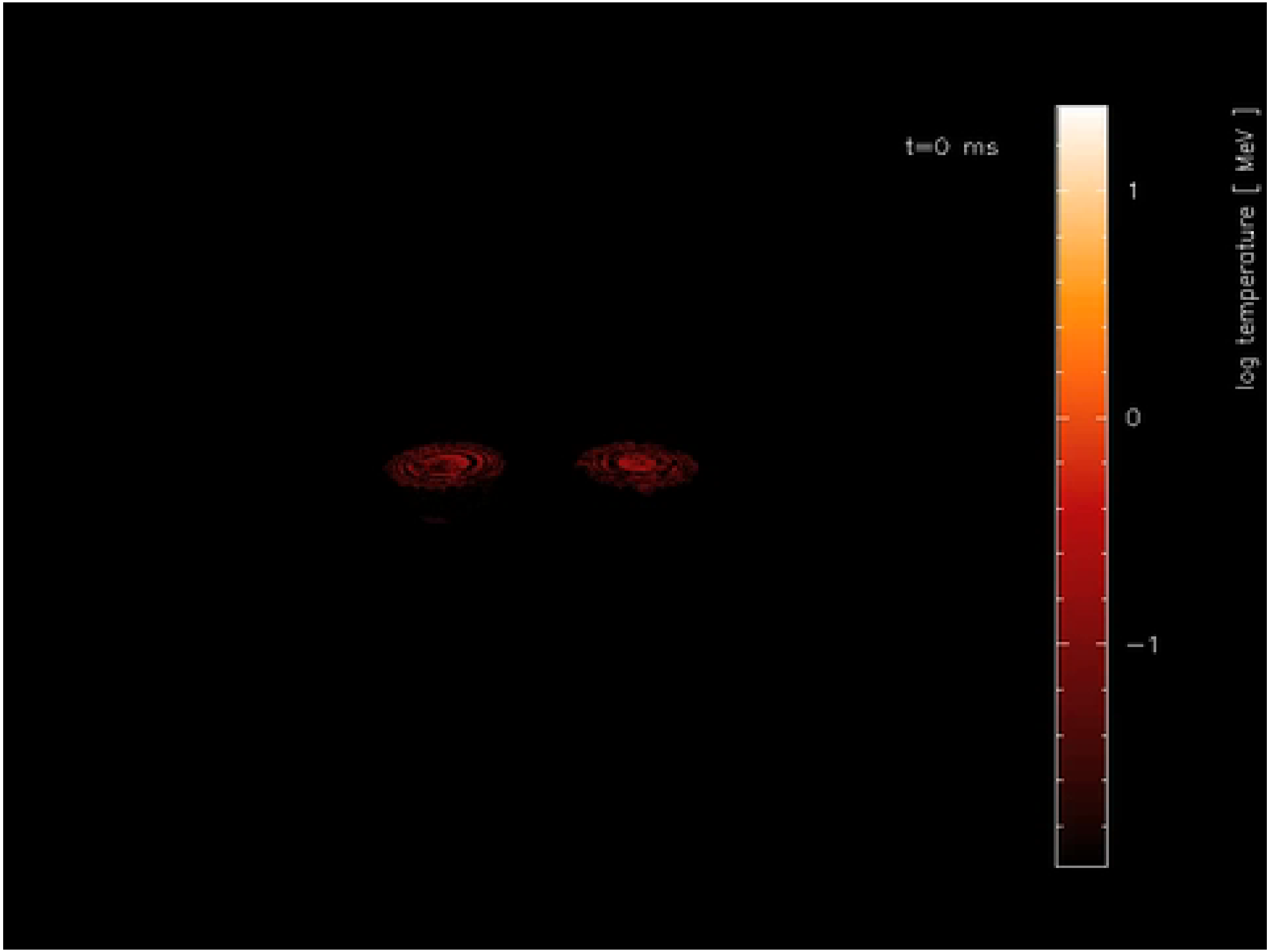
Abbott et al. 2020

A double neutron star merger is expected to produce:

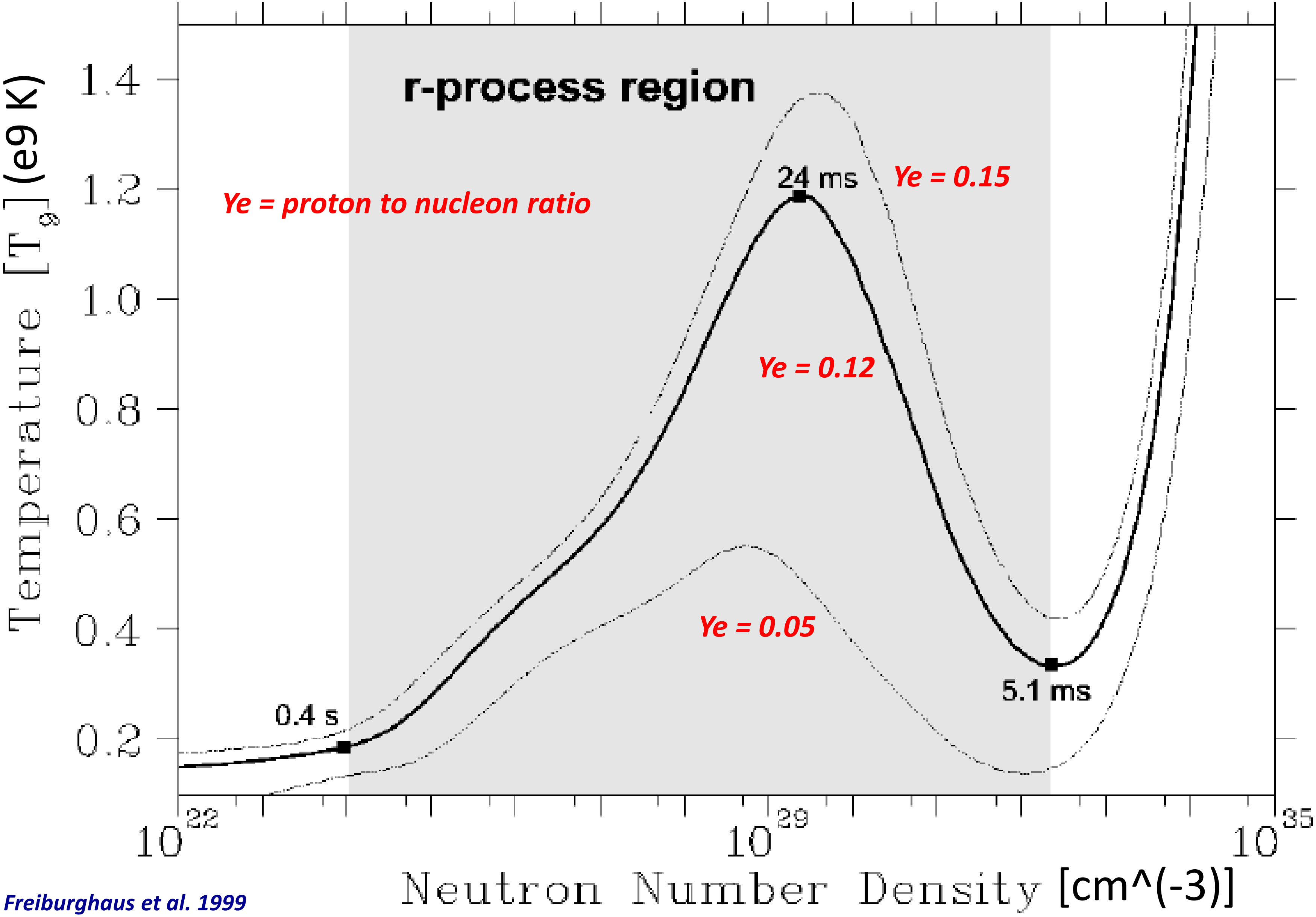
1) a GW signal at $\sim$1-1000 Hz (nearly isotropic)
2) a short GRB (highly directional and anisotropic)
3) r-process nucleosynthesis (nearly isotropic)
4) a MeV neutrino burst

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

Simulation of the merger of a 1.3 and a 1.4 Msun neutron stars (S. Rosswog, http://compact-merger.astro.su.se)

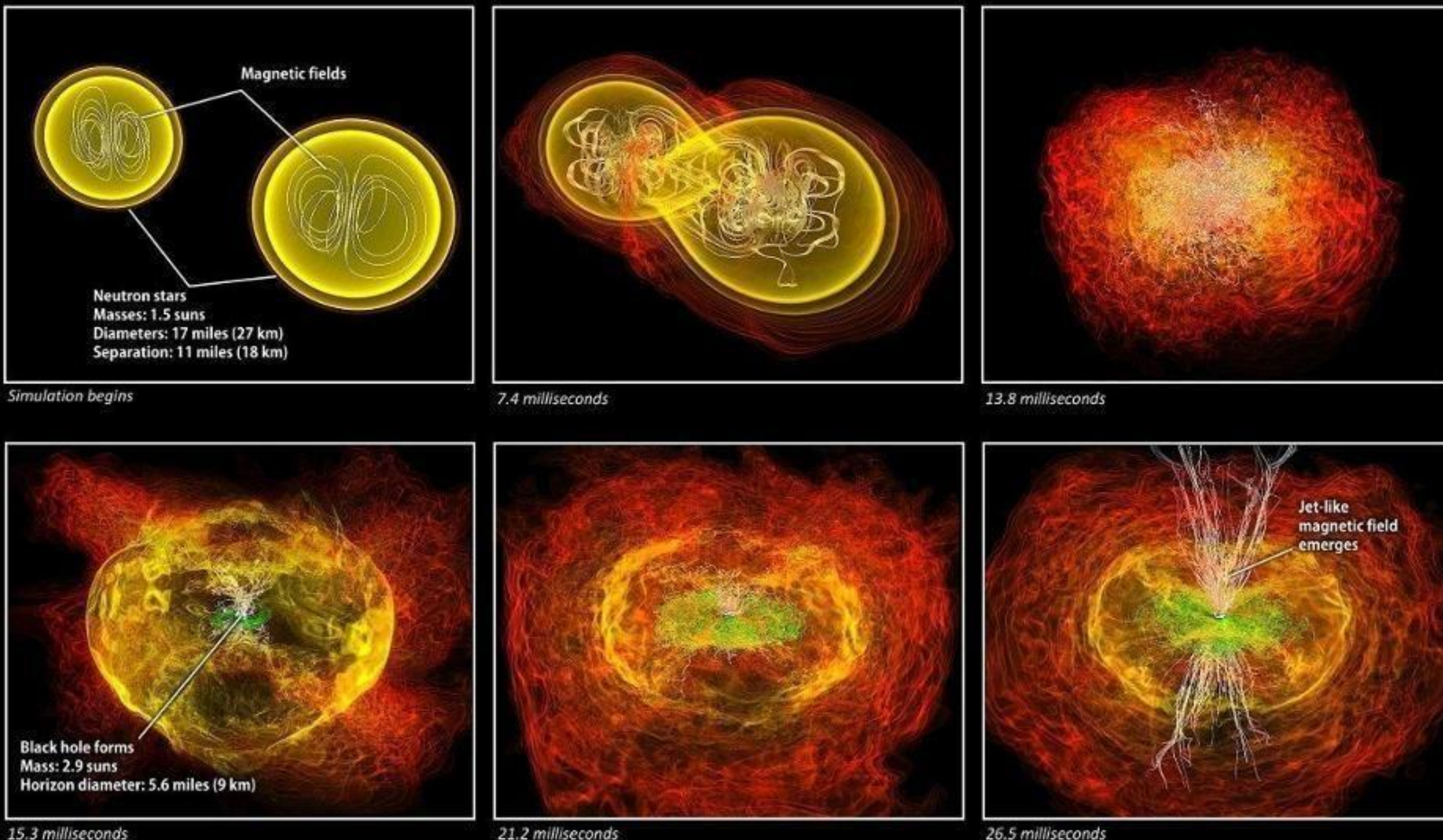


Conditions during decompression of NS material



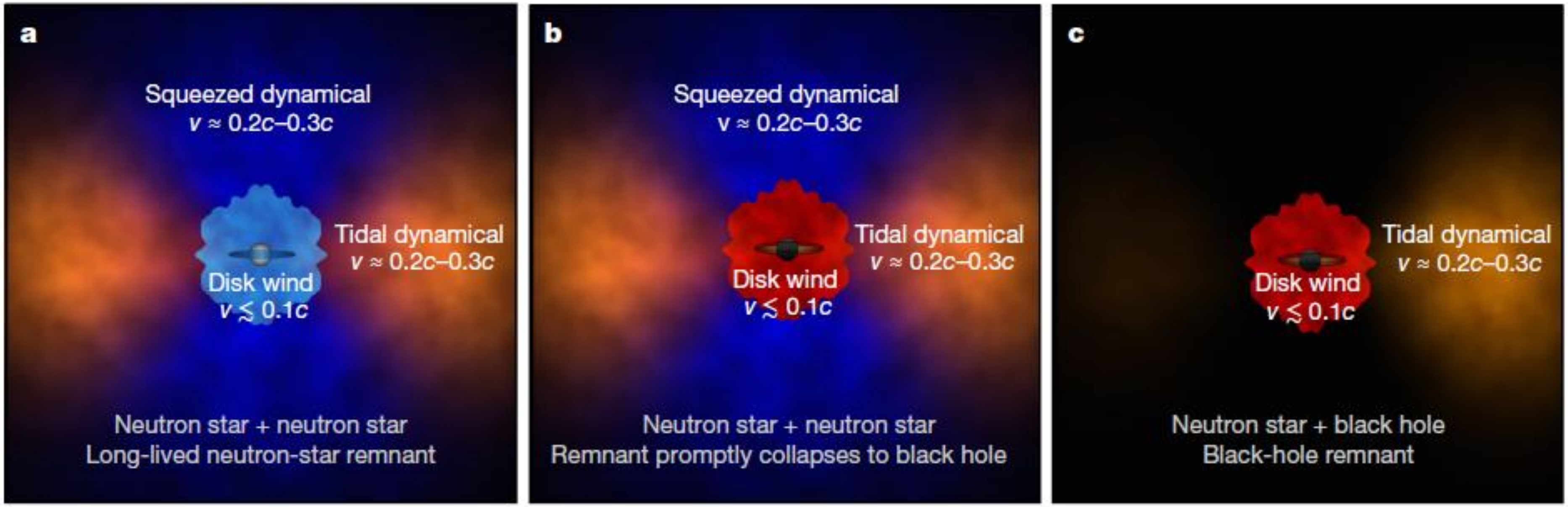
Freiburghaus et al. 1999

Crashing neutron stars can make gamma-ray burst jets



Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla

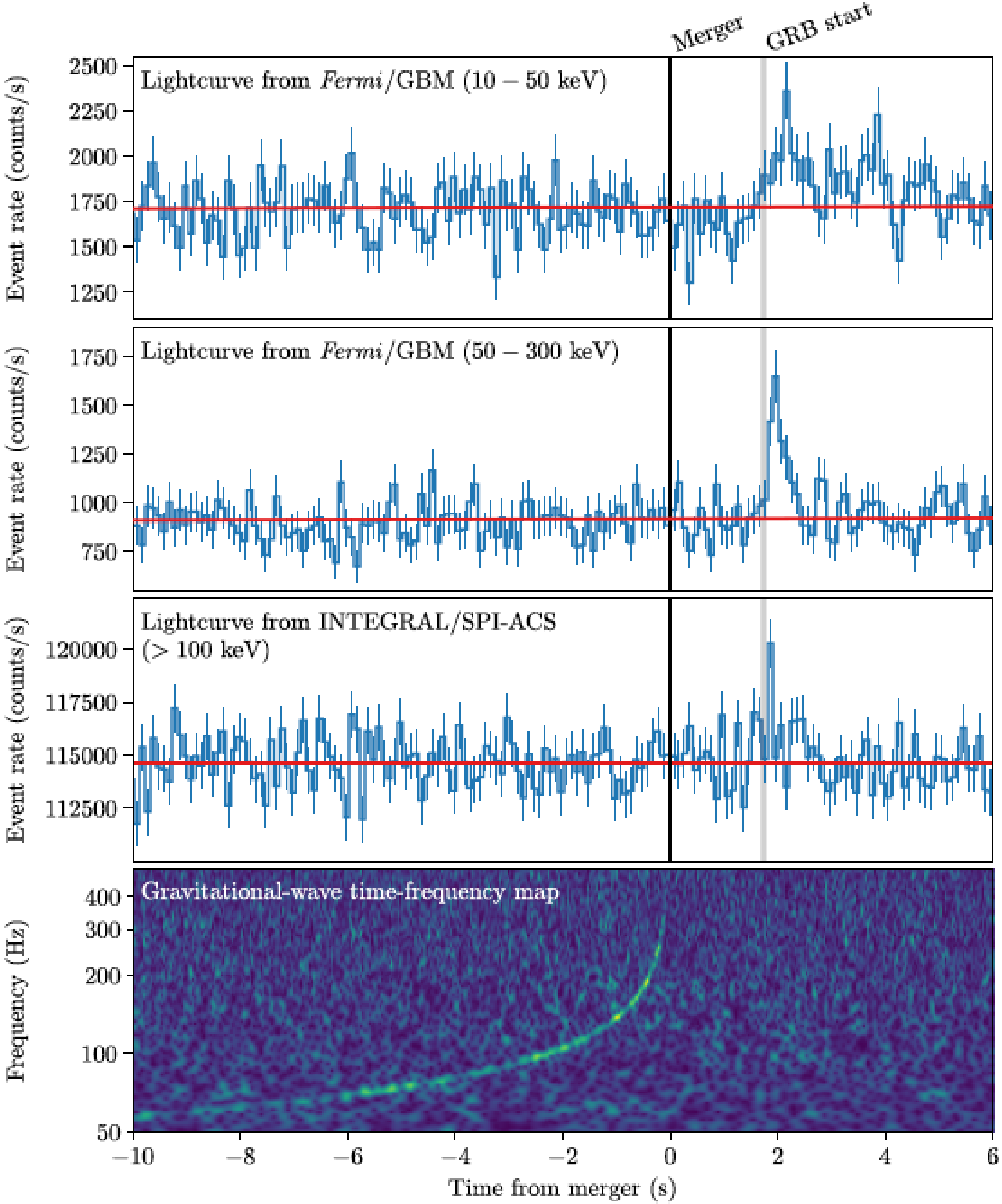
Kilonova scenarios (Kasen et al. 2017)



regions of heavy r-process elements radiate red/infrared light
regions of light r-process elements radiate blue/optical light

During the merger, tidal forces peel off tails of matter, forming a torus of heavy r-process ejecta in the plane of the binary. Material squeezed into the polar regions during the stellar collision can form a cone of light r-process material.

If the remnant survives as a hot neutron star for tens of milliseconds, its neutrino irradiation lowers the neutron fraction and produces a blue wind.

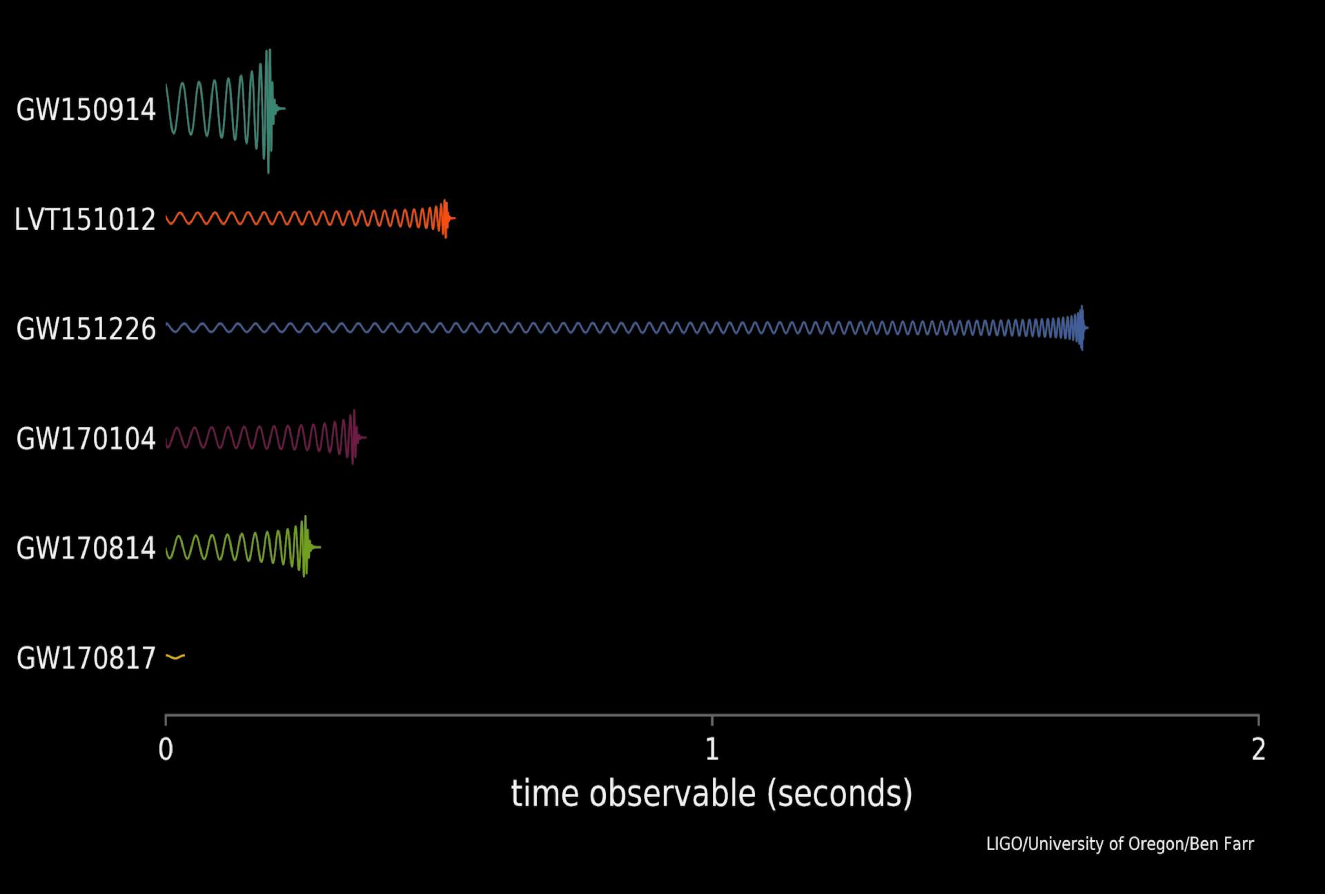


GW170817 and GRB170817A

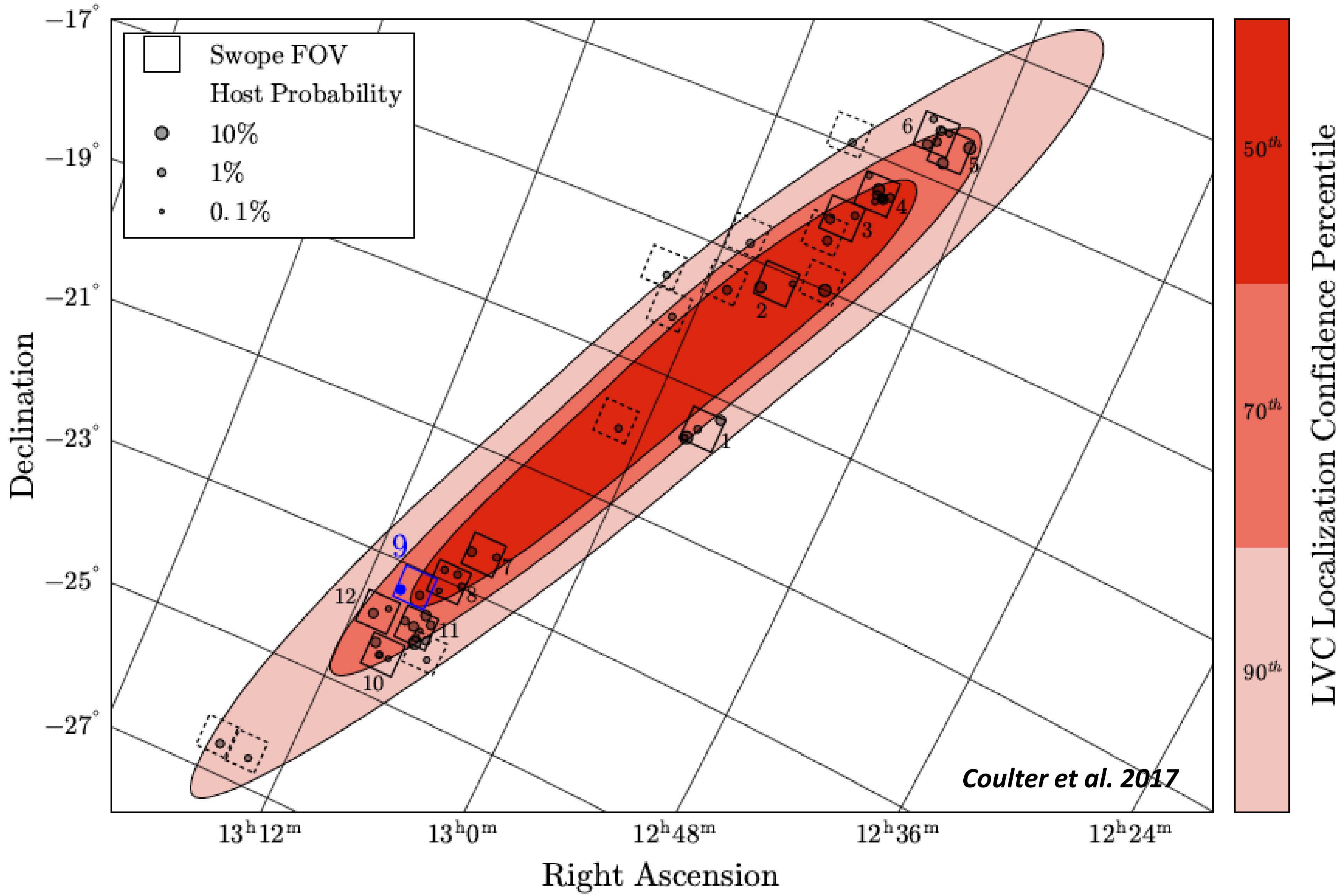
The short GRB170817A lags GW signal by 1.7s: is this timescale related to the engine or to the plasma outflow? As a minimum, it tells us that GW and light propagation speeds differ by less than 1 part in e15.

Epeak ~200 keV (GBM)

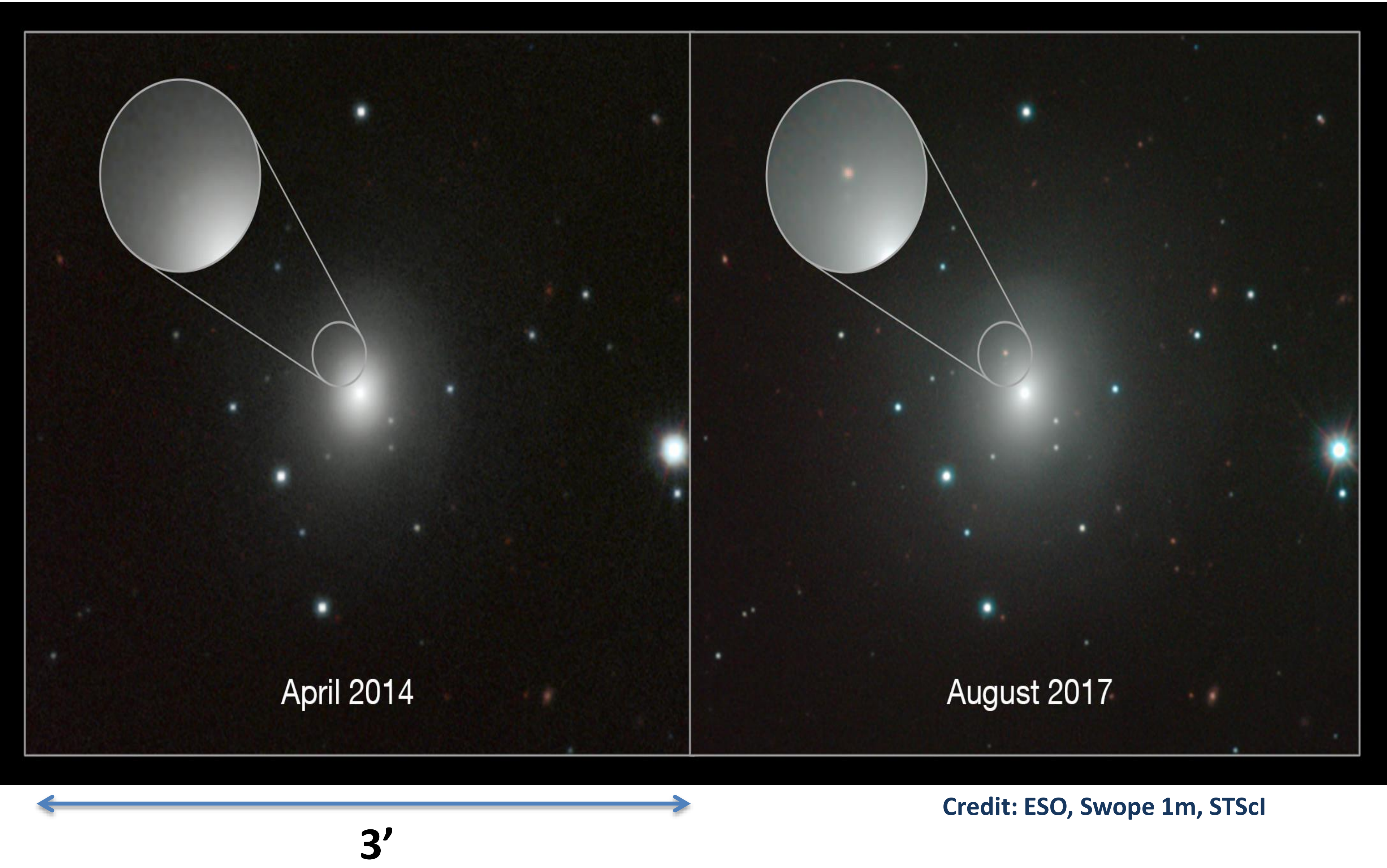
Abbott et al. 2017;
Savchenko et al. 2017;
Fermi Collaboration 2017


GW150914
LVT151012
GW151226
GW170104
GW170814
GW170817
0
1
2
time observable (seconds)
LIGO/University of Oregon/Ben Farr

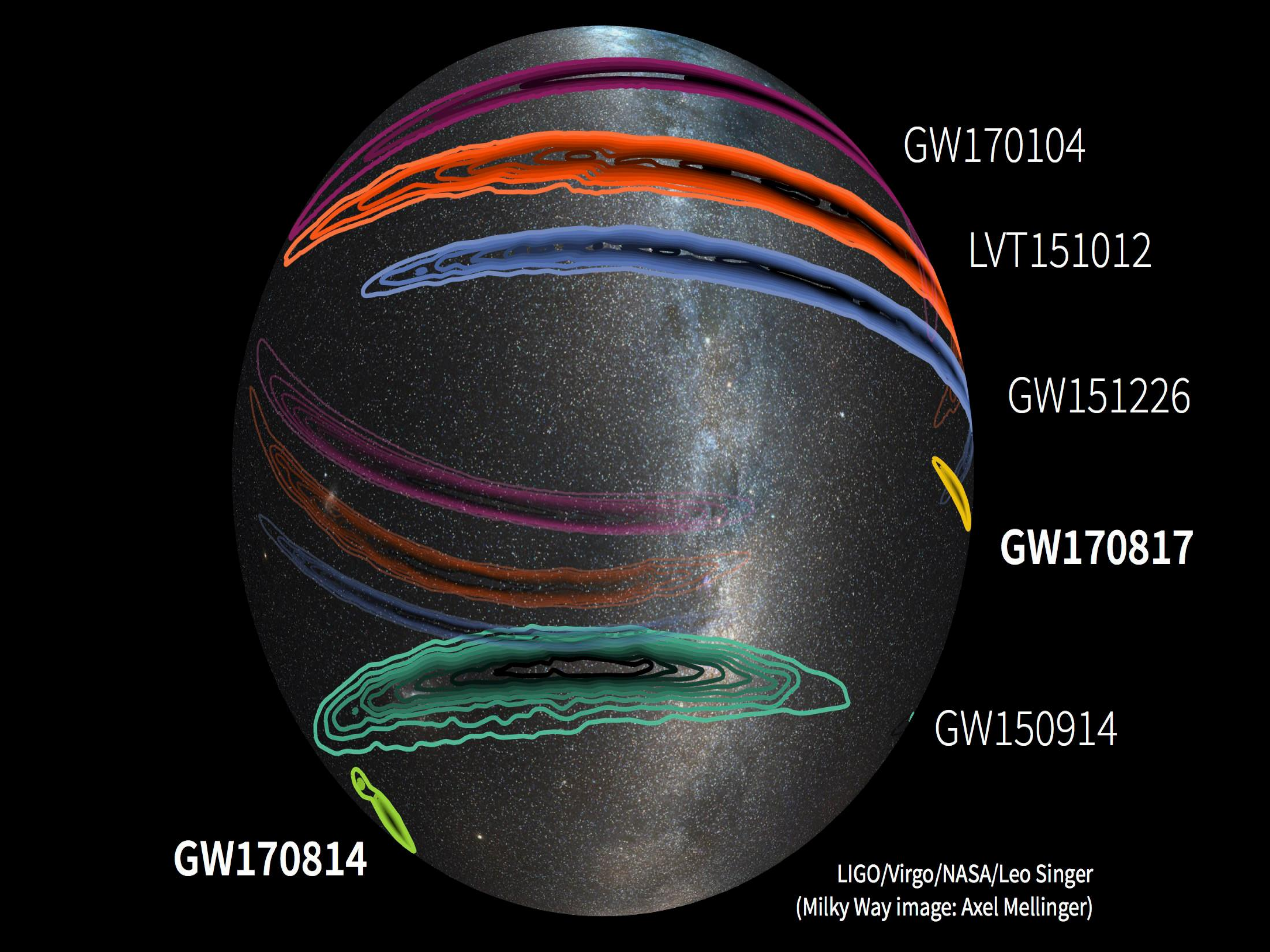
Search for GW170817 optical counterpart: GW error regions and Swope 1m pointings



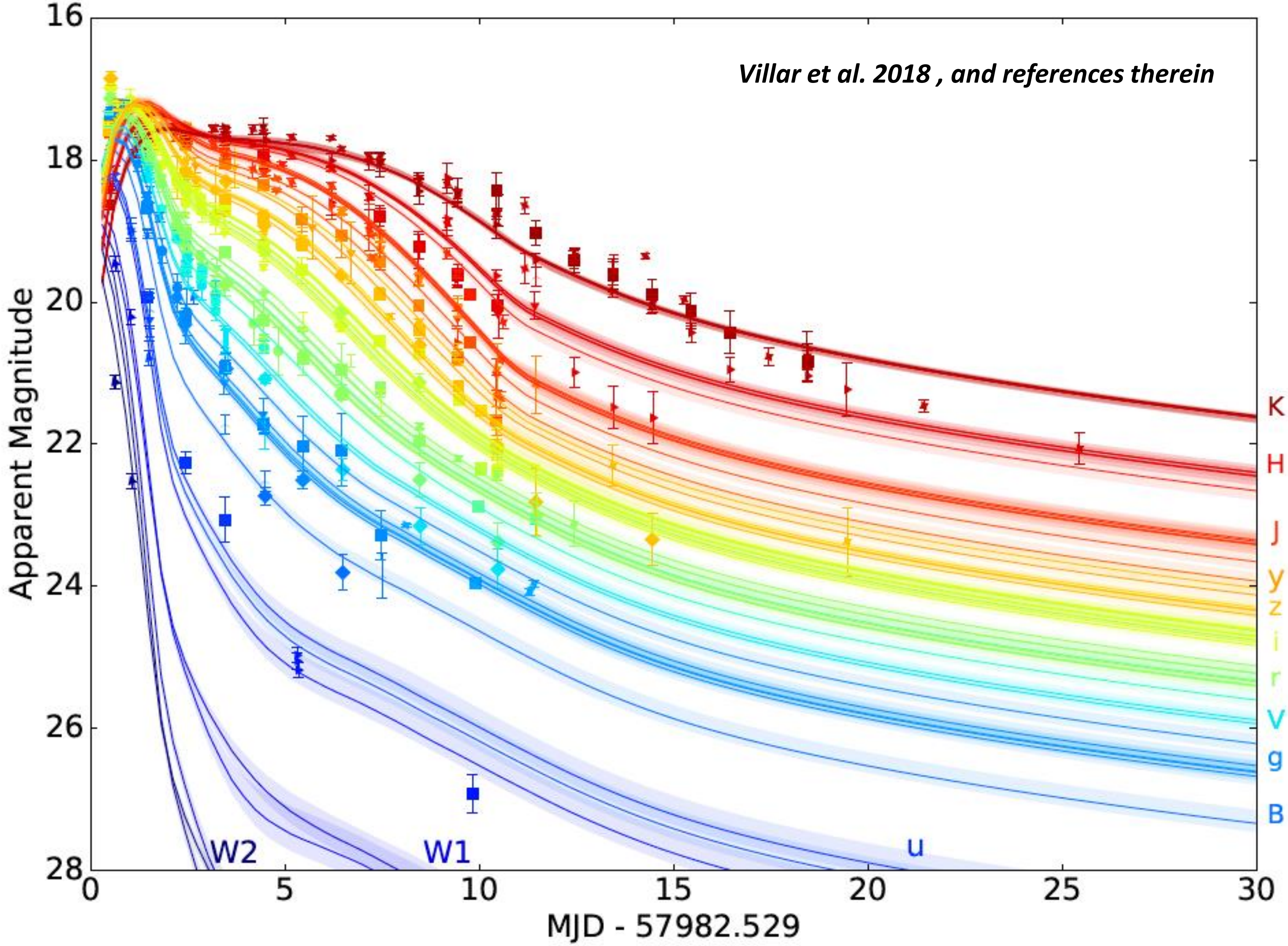
Detection of optical source <u>AT2017gfo</u> associated with GW signal GW170817 in NGC 4993 (40 Mpc = 130 million light years)



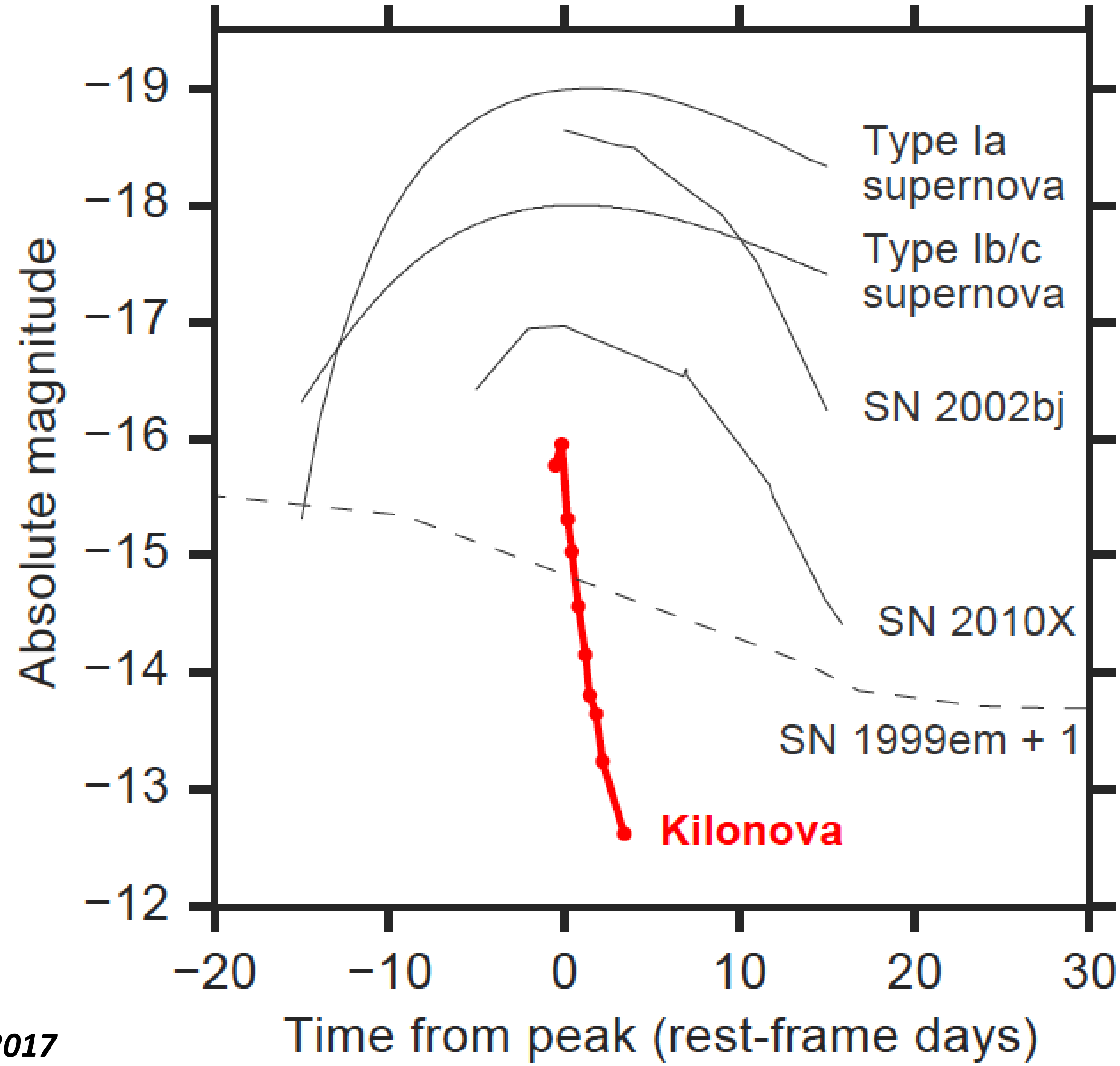
Credit: ESO, Swope 1m, STScI


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

Optical and near-infrared light curves of GW170817 / AT2017gfo

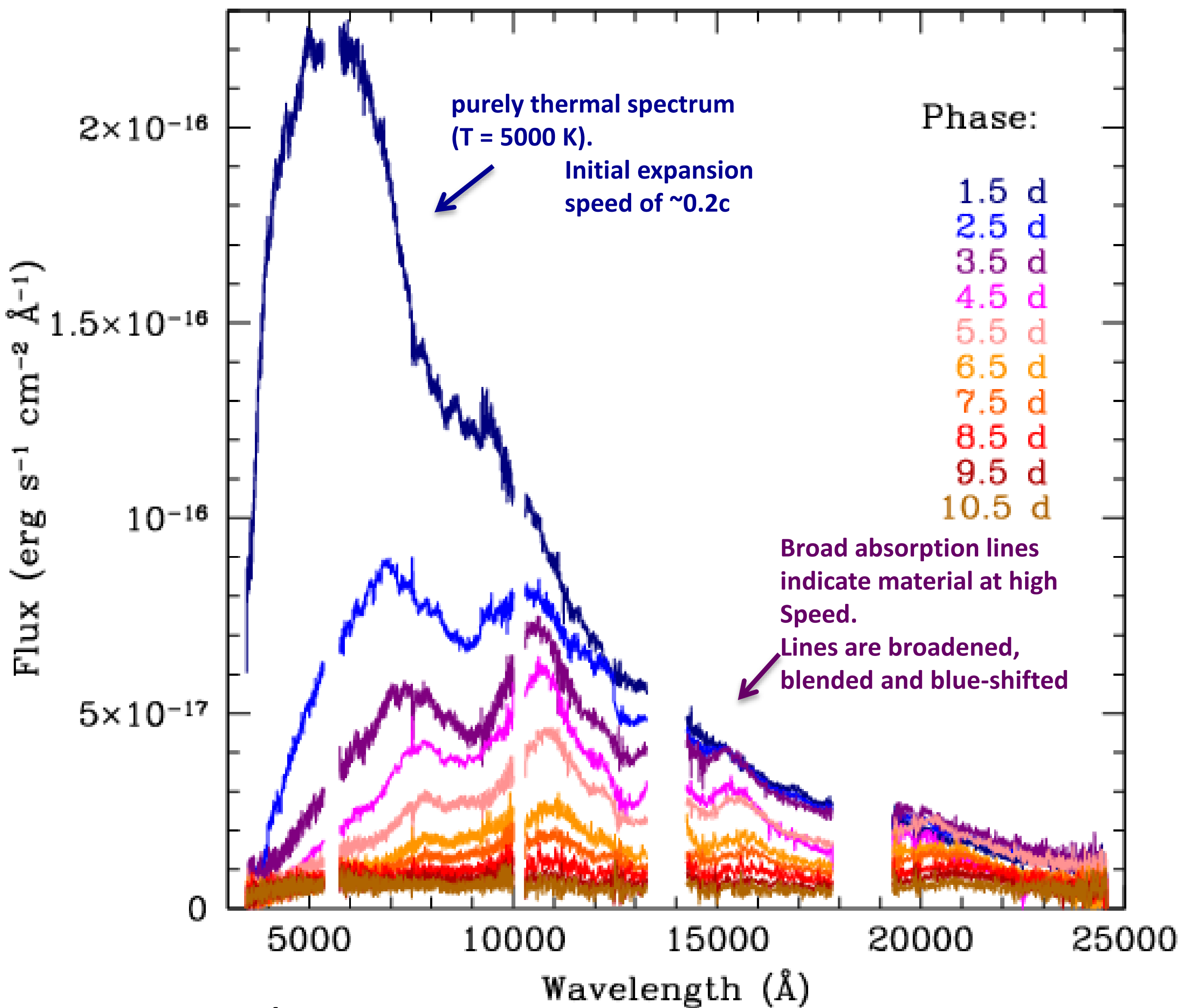


AT2017gfo evolves much more rapidly than any supernova



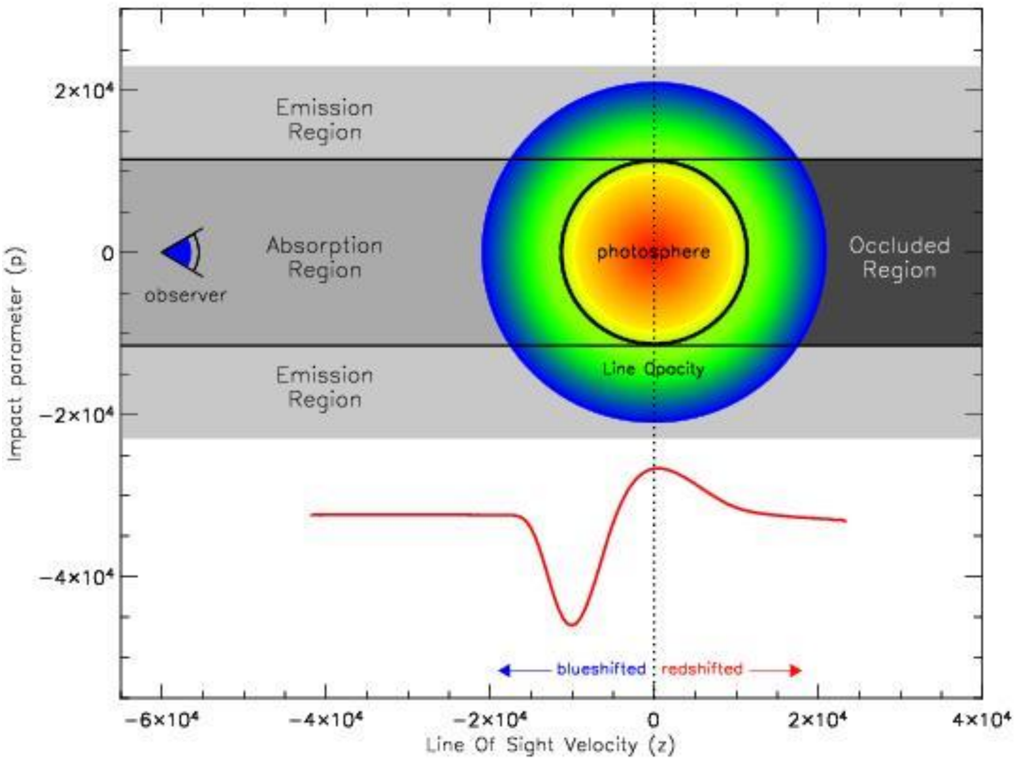
Arcavi et al. 2017

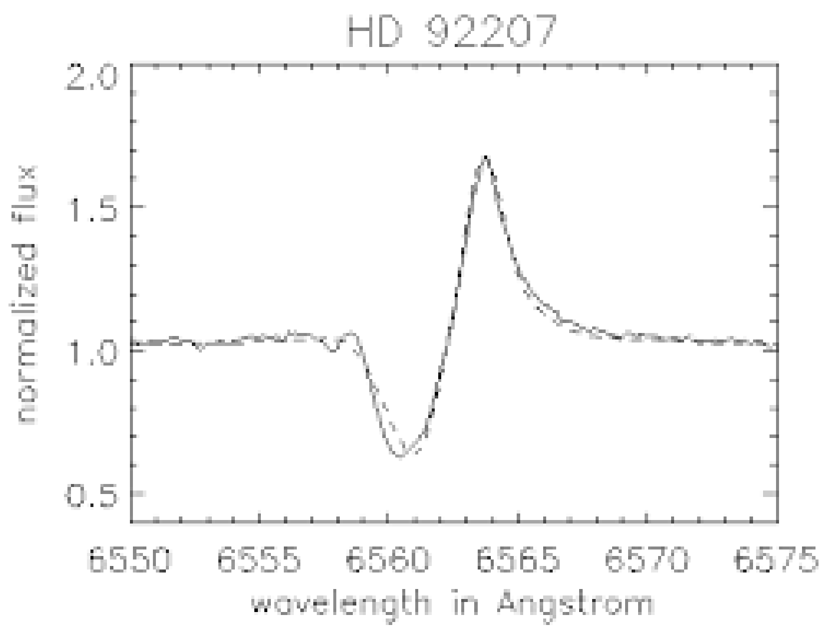
ESO VLT X-Shooter spectral sequence of kilonova GW170817



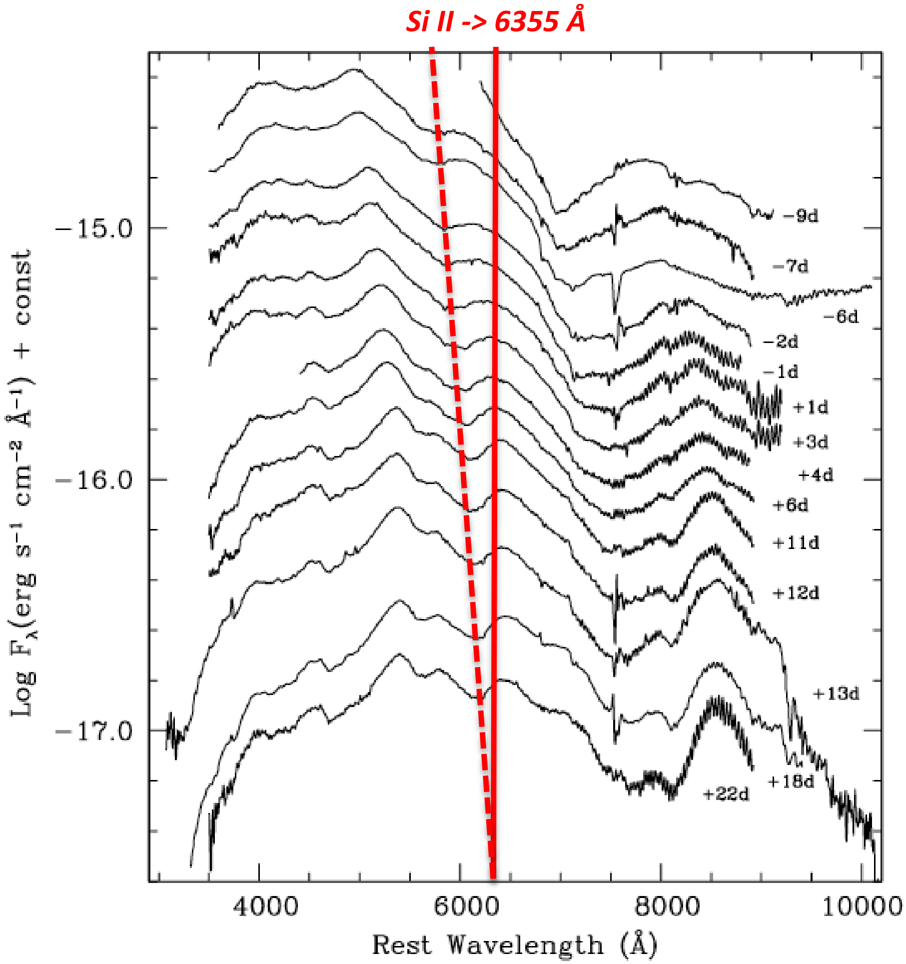
Pian et al. 2017; Smartt et al. 2017

Receding photosphere: P-Cygni profile of absorption lines





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



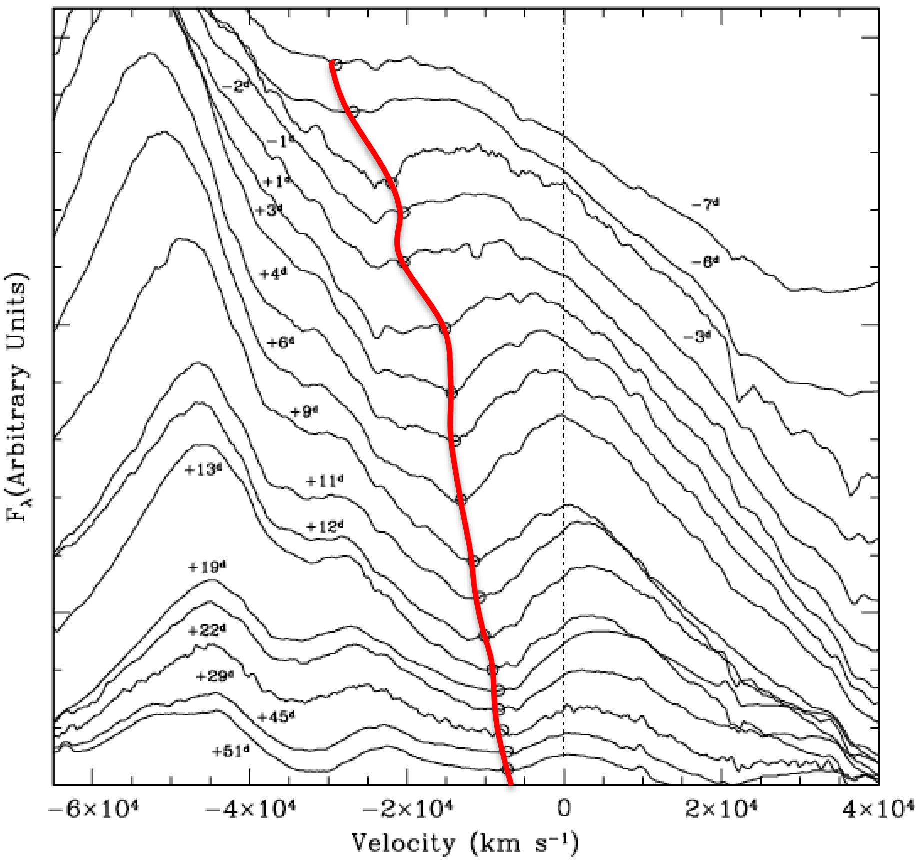
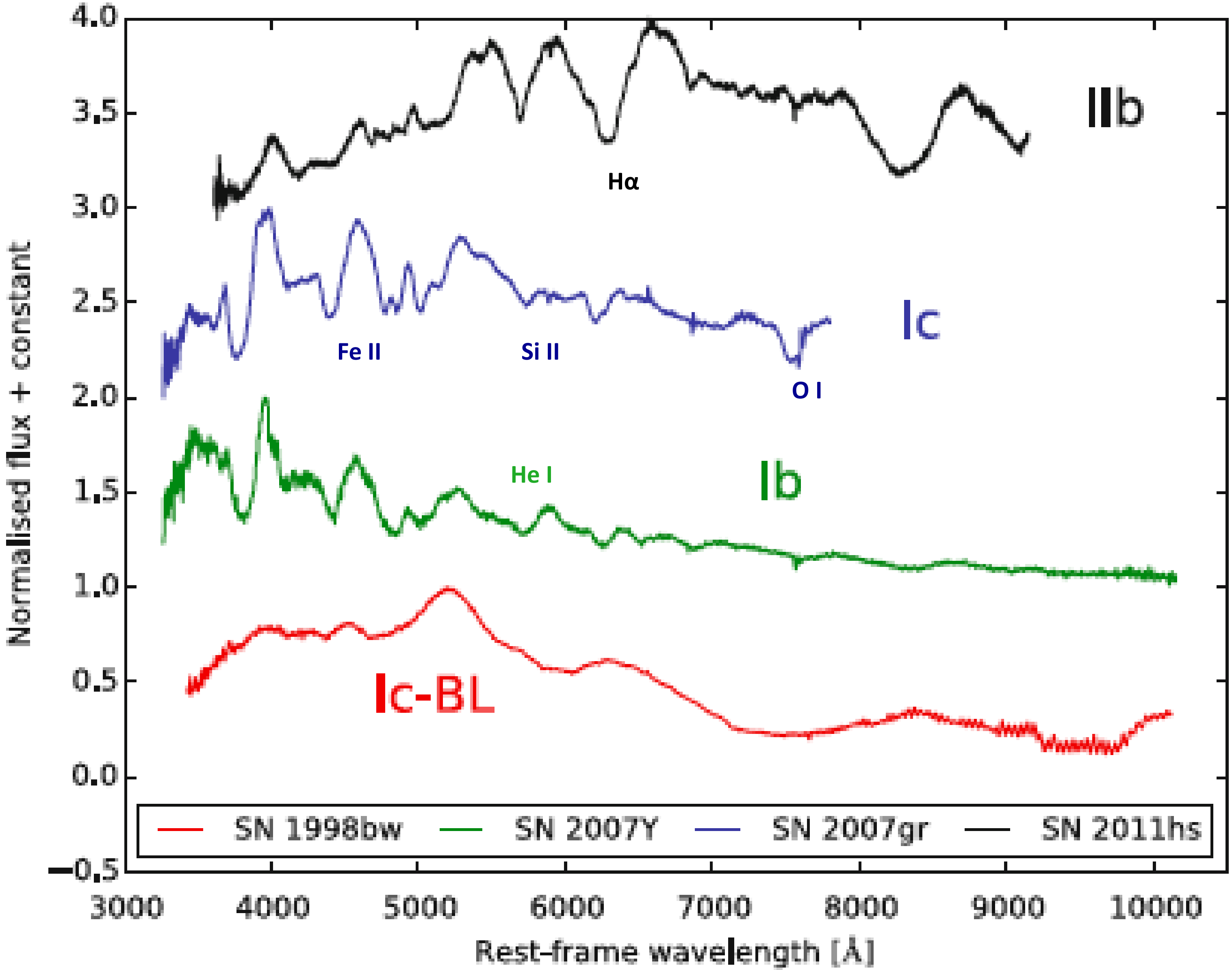


FIG. 4.—Evolution of the Si II λ6355 region. The empty circles mark the value that has been assumed to represent the photospheric velocity.

Patat et al. 2001

Typical spectra of Stripped-envelope core-collapse SNe



Pian & Mazzali 2017

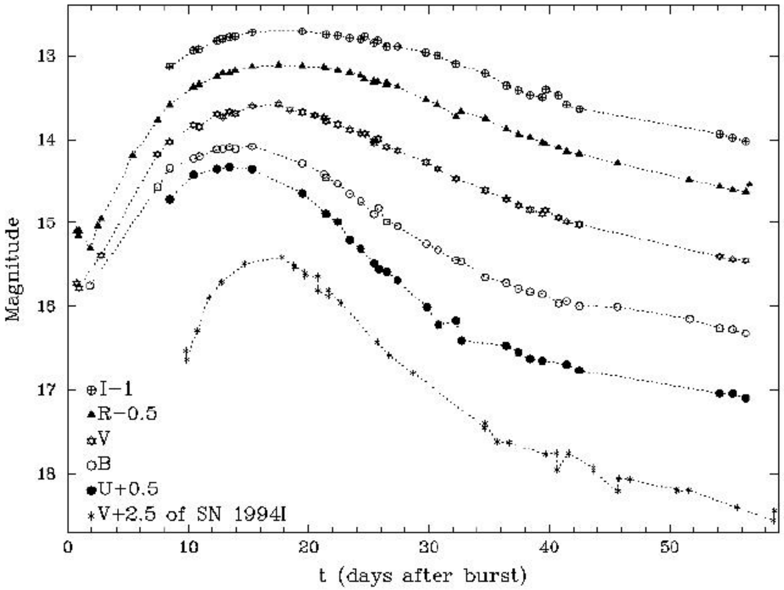
GRB980425
Supernova 1998bw (Type Ic)

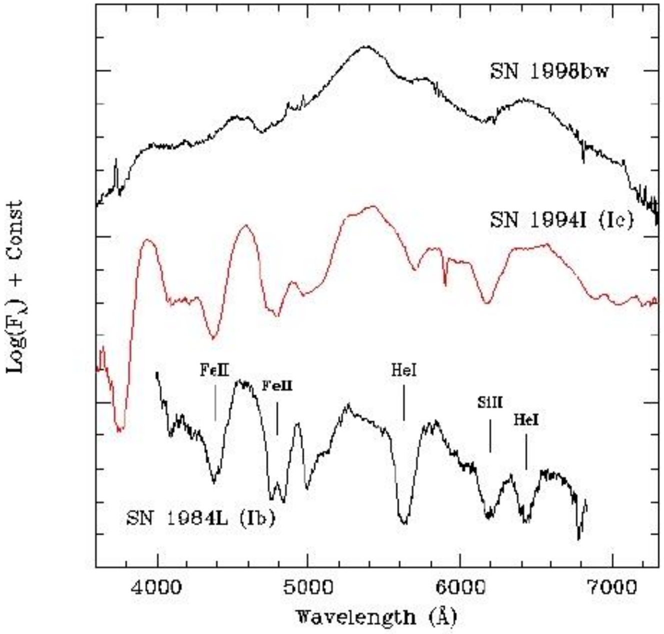
SN 1998bw in Spiral Galaxy ESO184-G82

z = 0.0085

ESO PR Photo 39a/98 (15 October 1998)

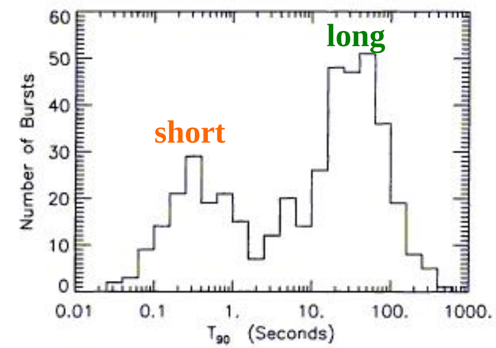
© European Southern Observatory

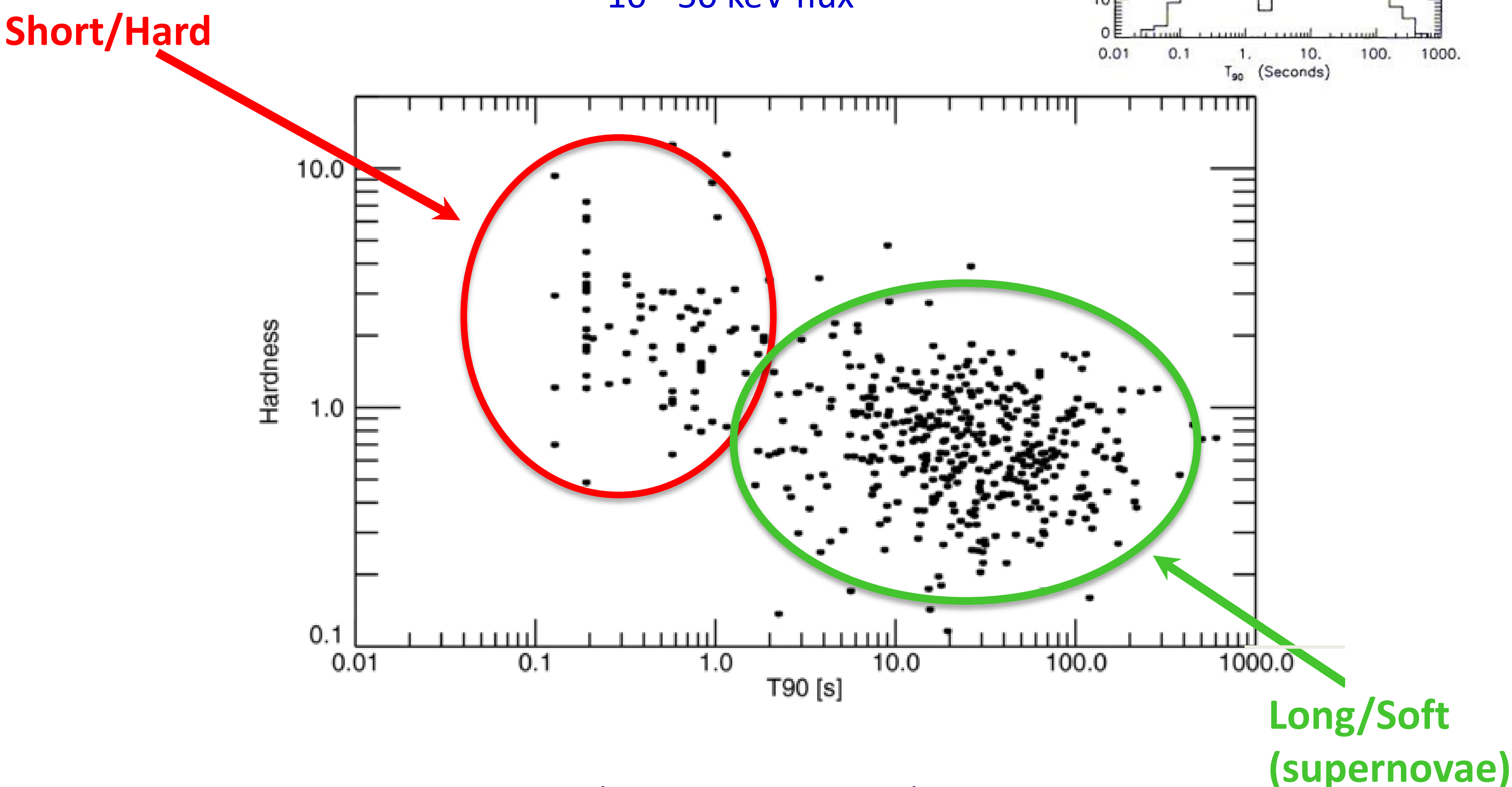




Hardness-Duration Classification of GRBs

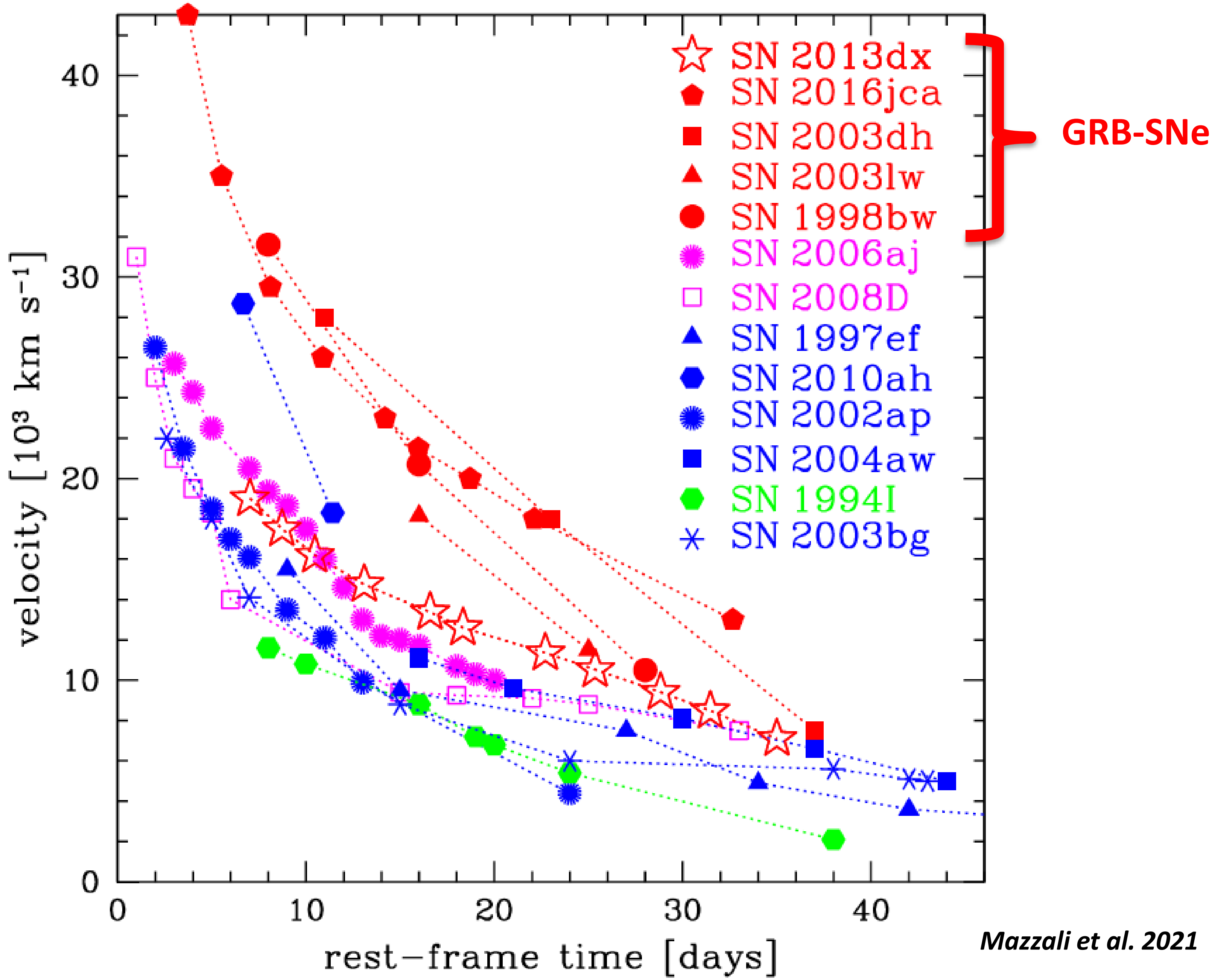
$$H = \frac{50 - 300 \text{ keV flux}}{10 - 50 \text{ keV flux}}$$





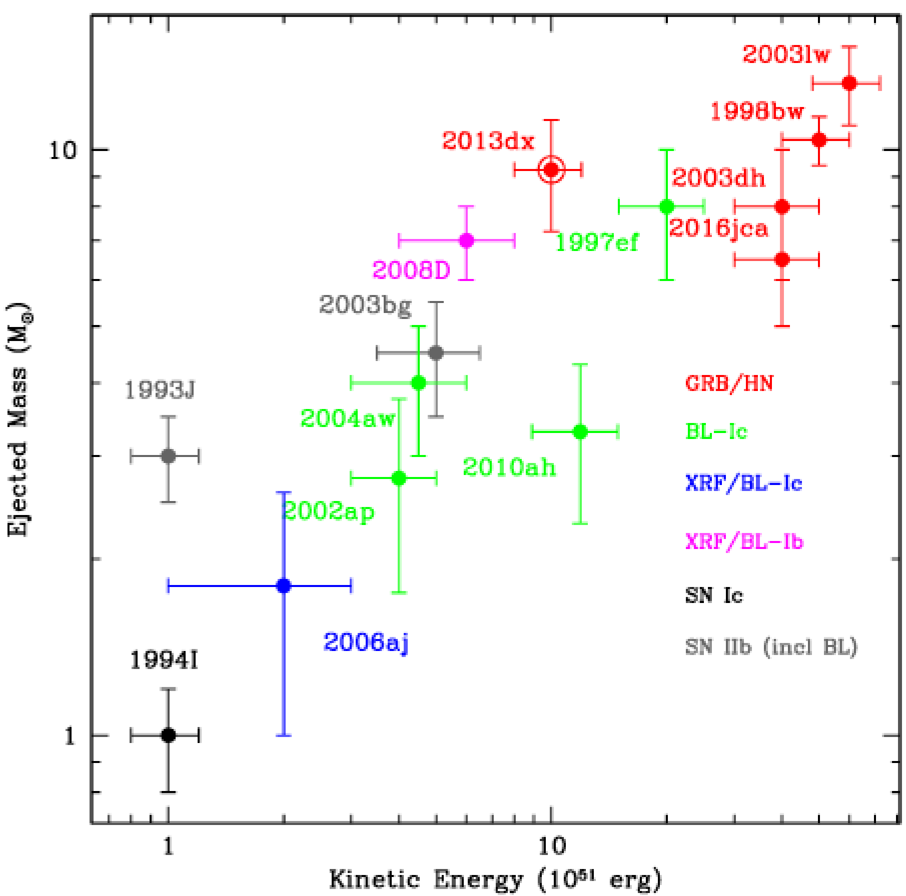
Kouveliotou+1993; von Kienlin+2014

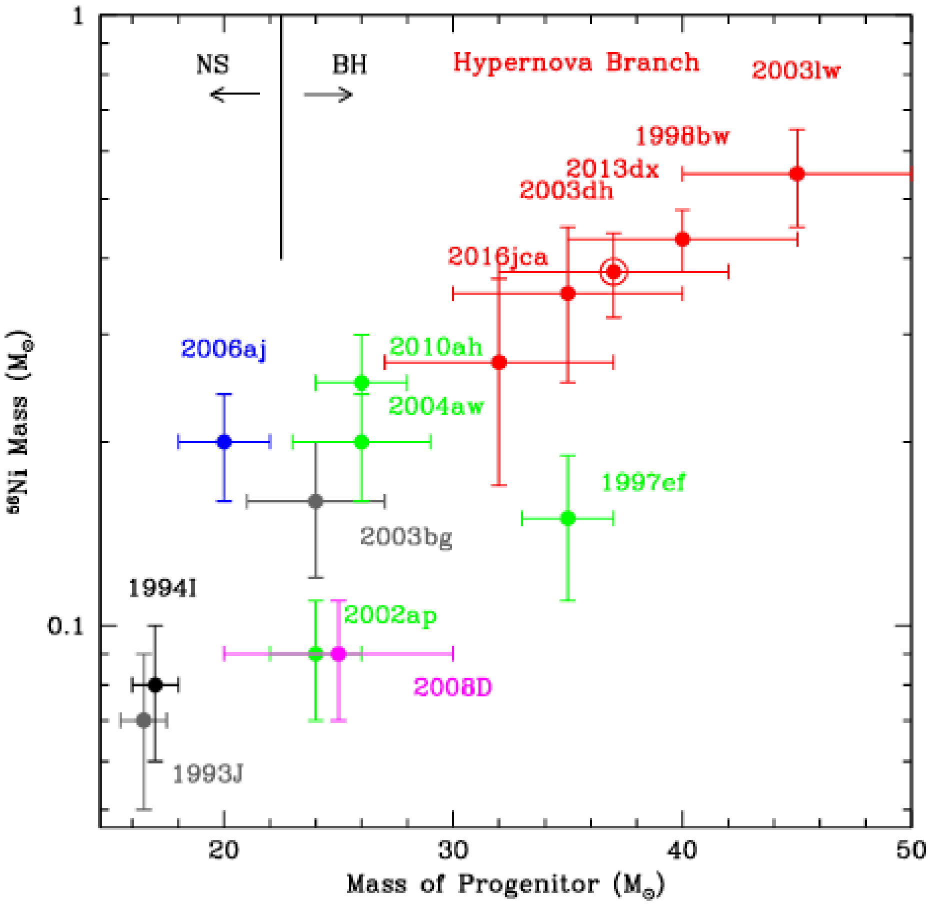
Photospheric velocities of core-collapse Supernovae



Mazzali et al. 2021

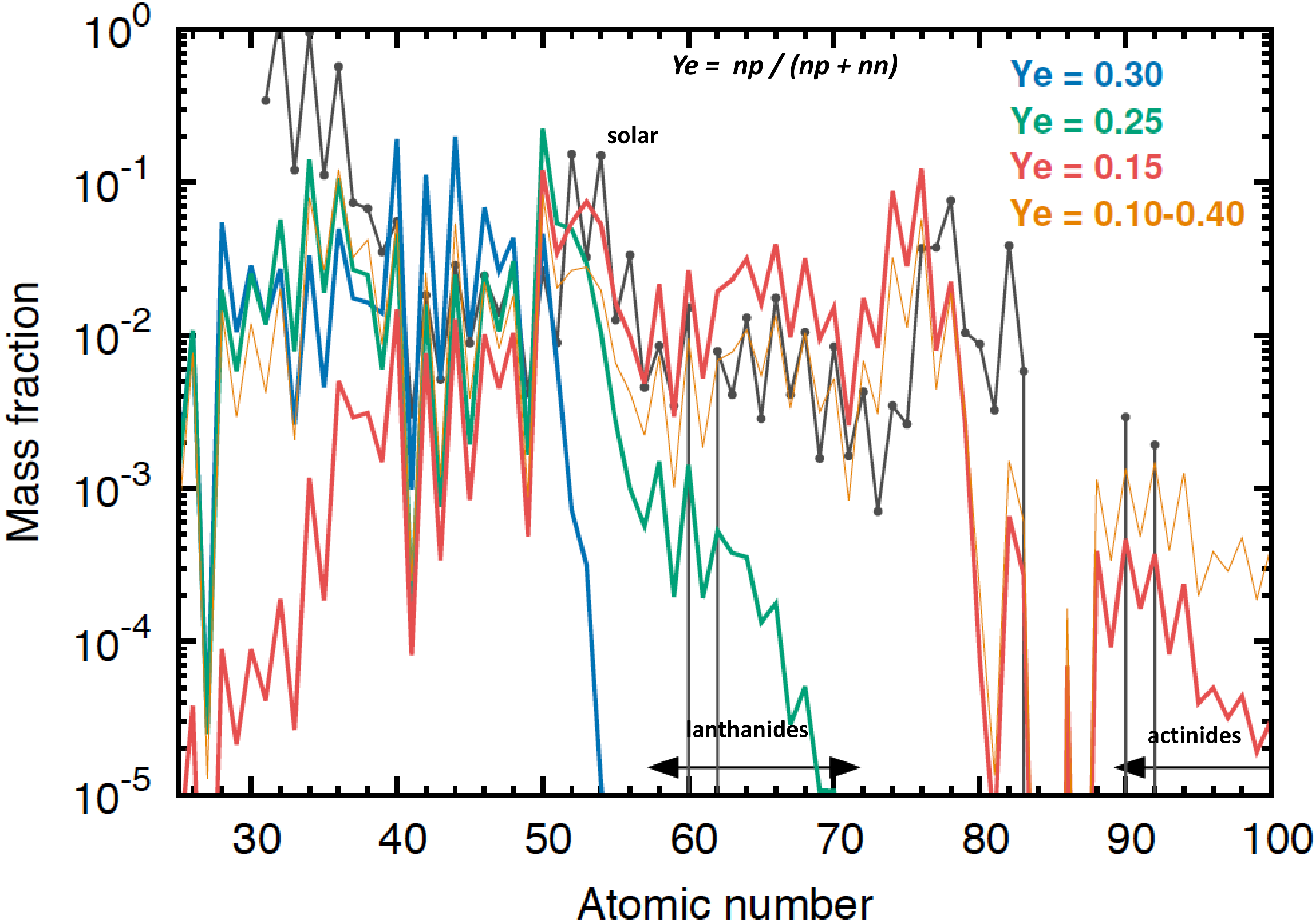
Physical properties of core-collapse supernovae





Mazzali et al. 2021

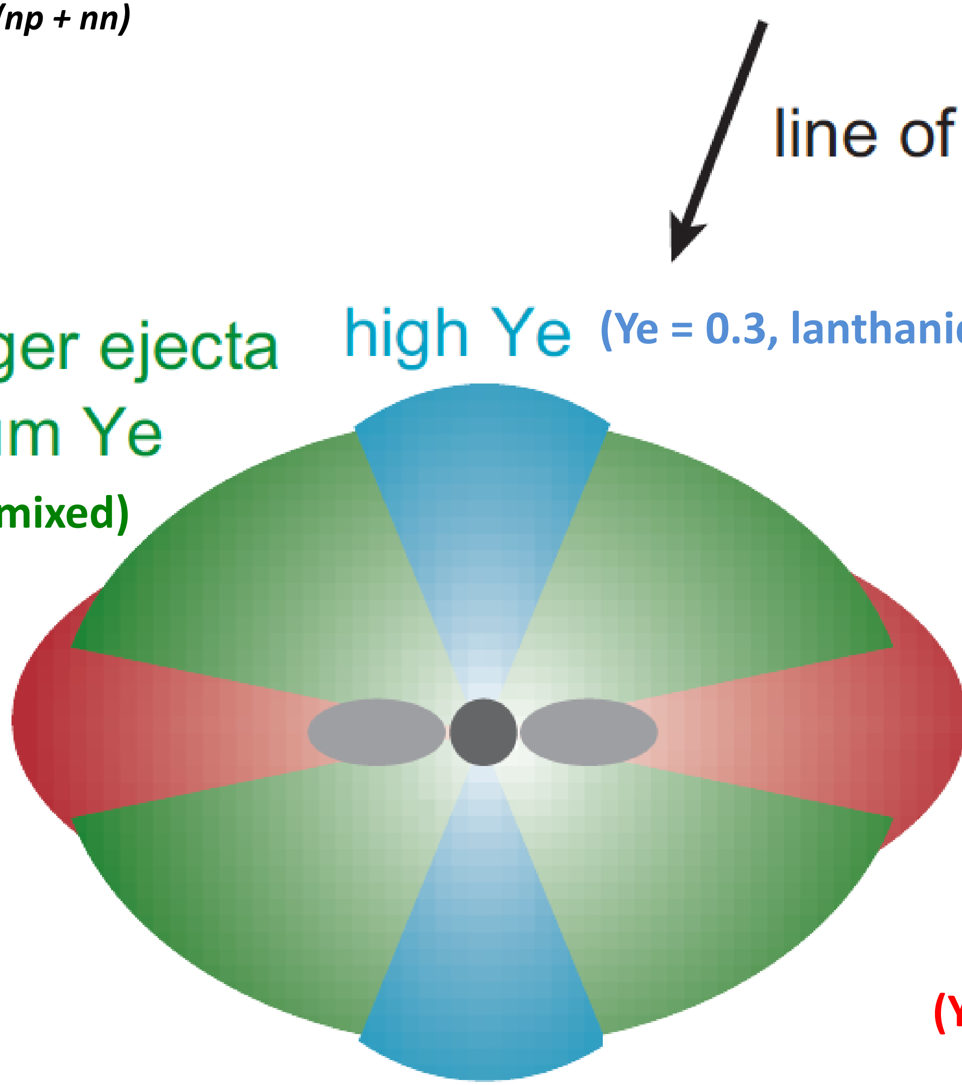
Element abundances at 1 day after DNS merger



Tanaka et al. 2017, PASJ

Geometry of 3-component model for kilonova

Ye = np / (np + nn)



(Ye = 0.3, lanthanide-poor)

v ~ 0.05c

(Ye = 0.25, mixed)

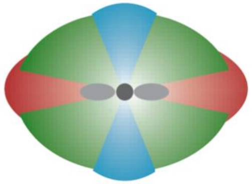
v ~ 0.05c

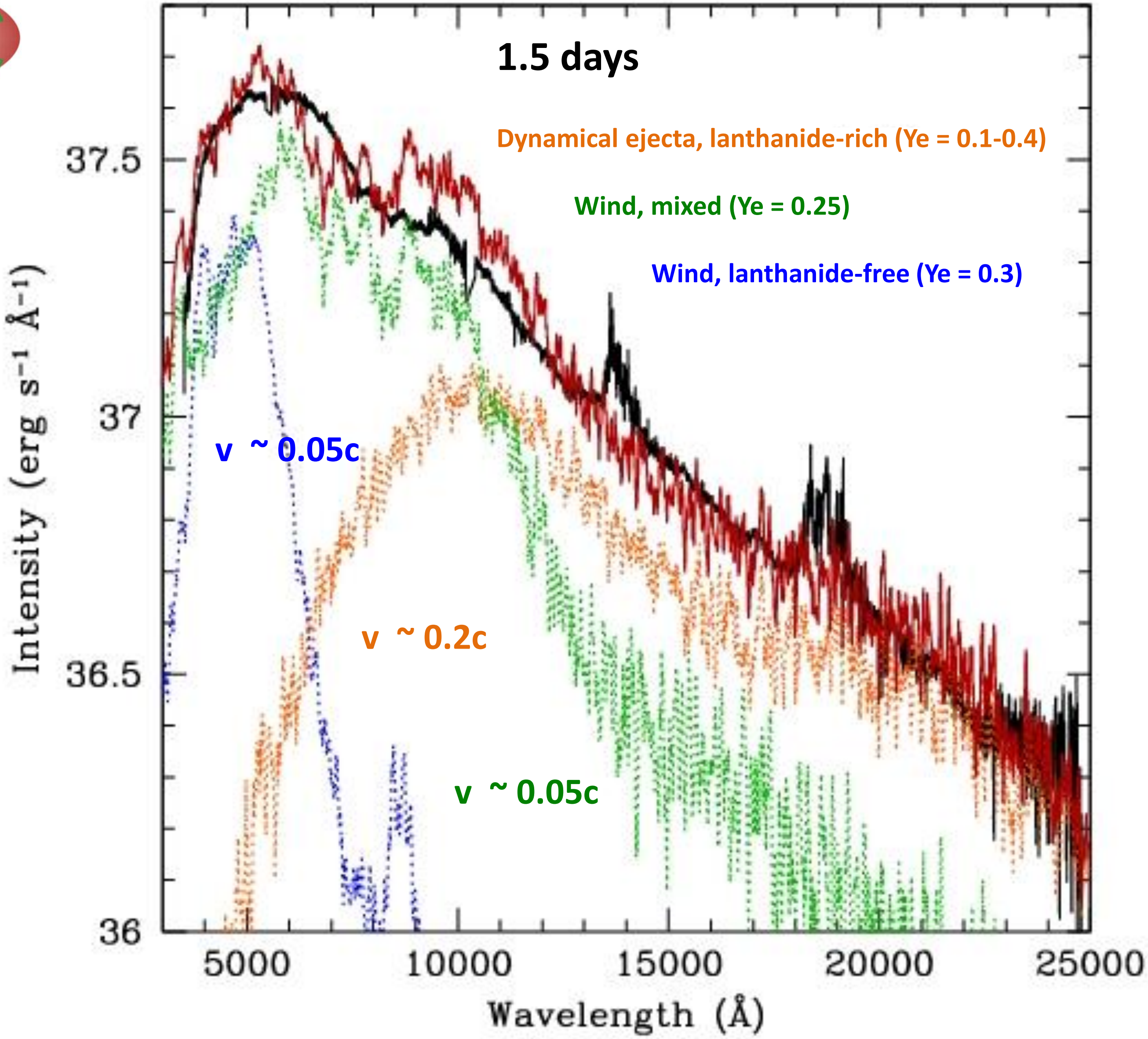
(Ye = 0.1, lanthanide-rich)

v ~ 0.2c

Tanaka et al. 2017, PASJ

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





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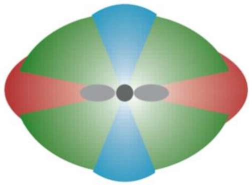
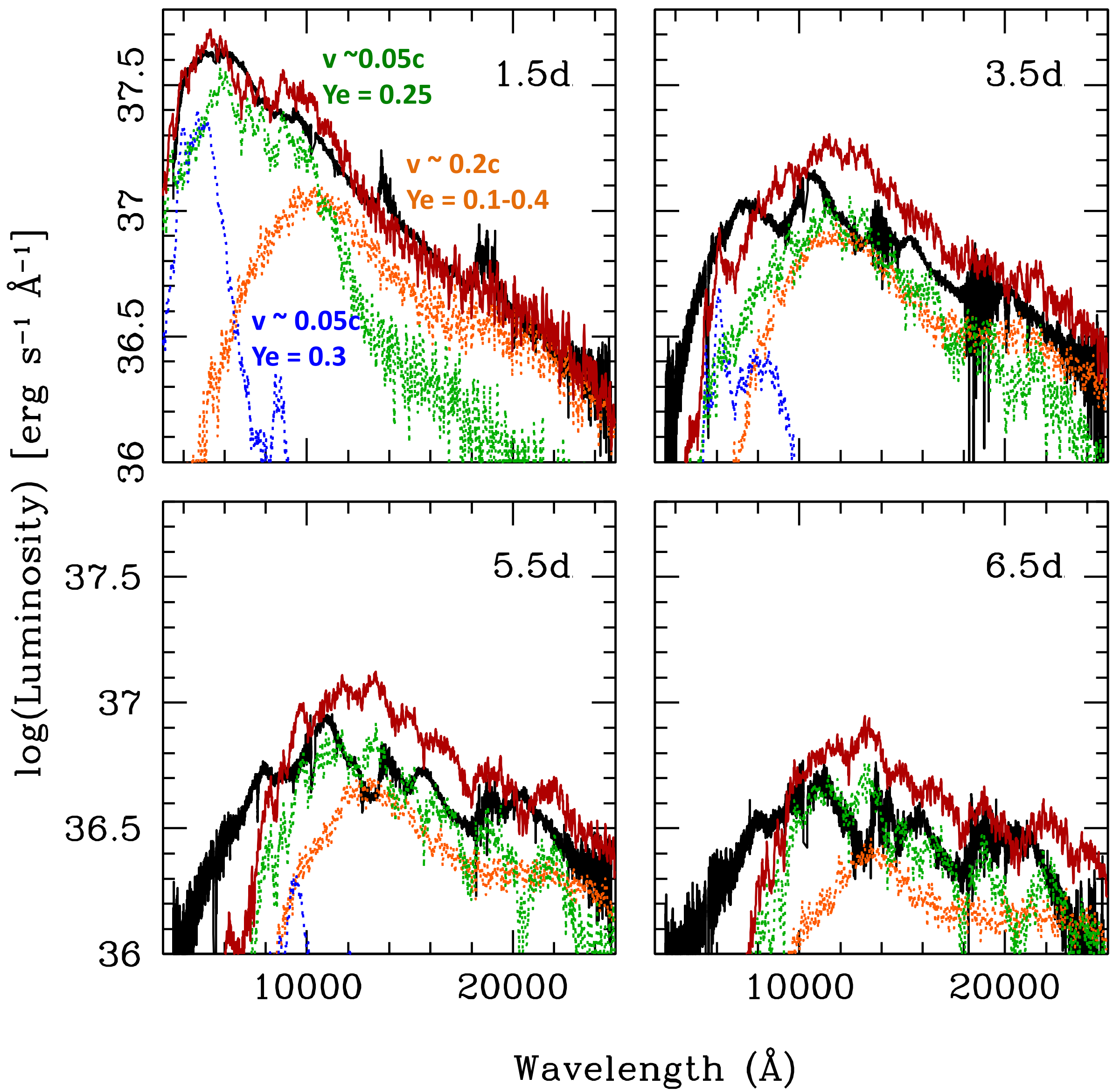
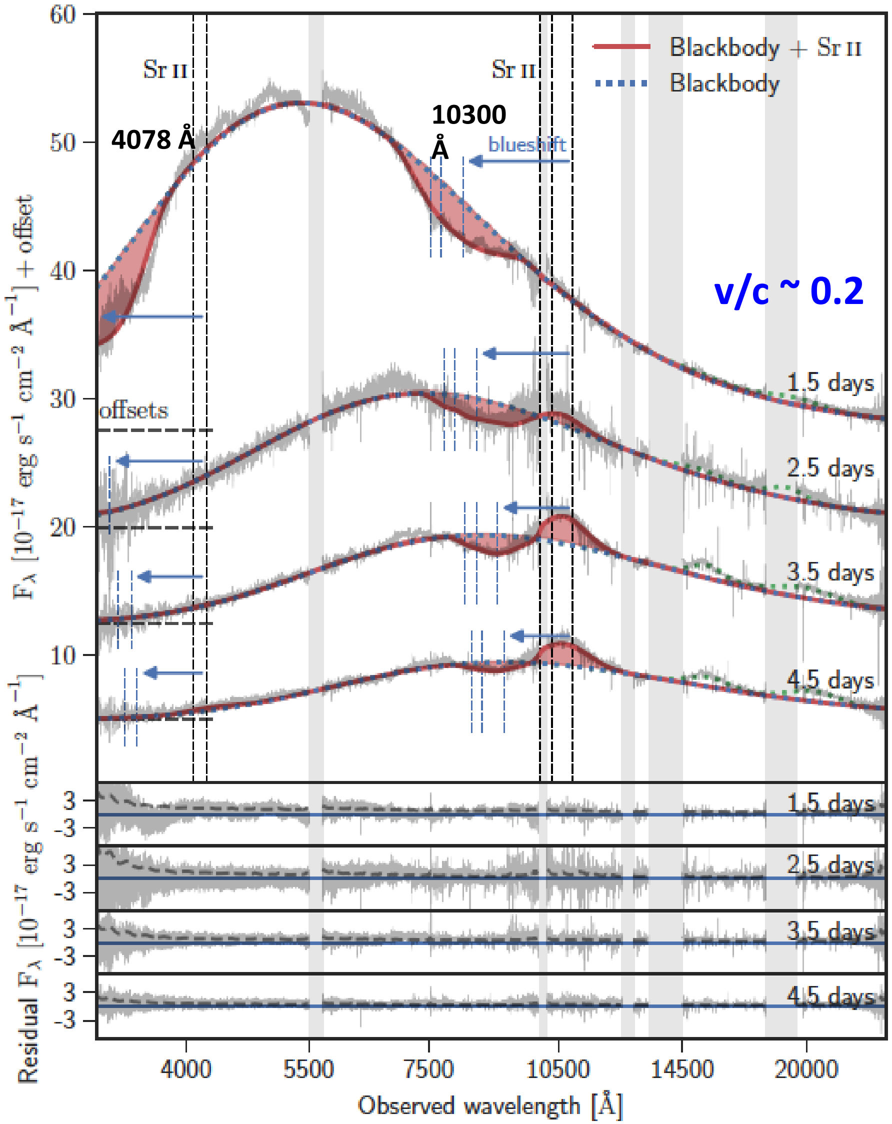




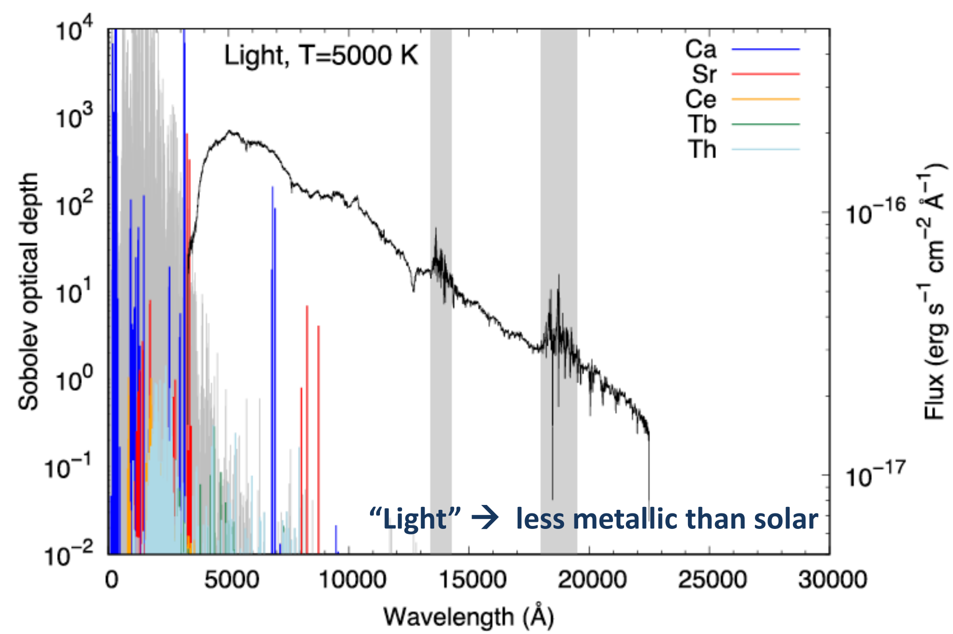
Poor spectral fits: less than optimal knowledge of atomic opacities

X-Shooter spectra of AT2017gfo (40 Mpc) with modeled Sr II lines



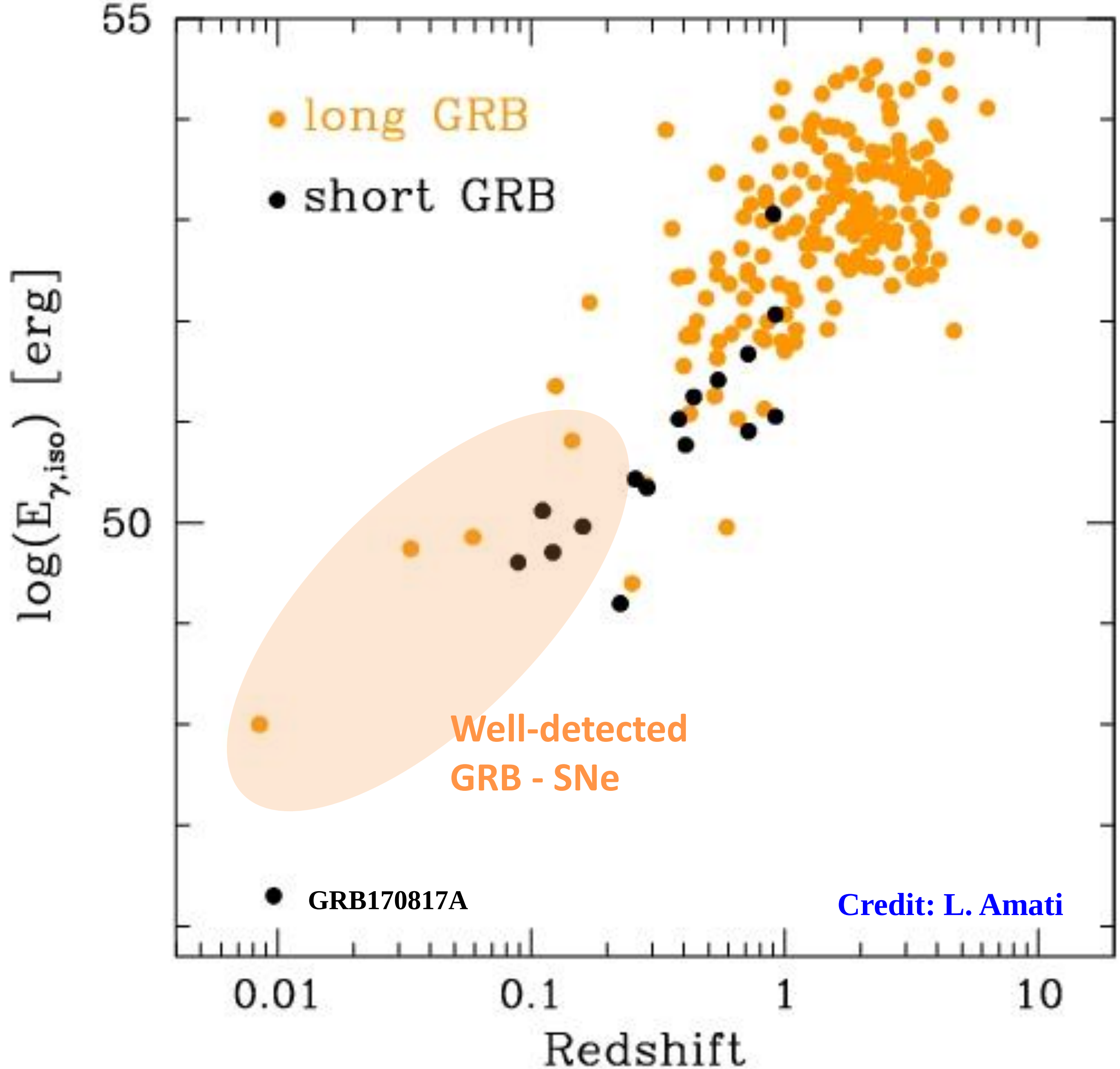
Watson et al. 2019

The presence of the Sr II triplet points to neutron-poor material, as Sr is a relatively low-Z (Z = 38) r-process element

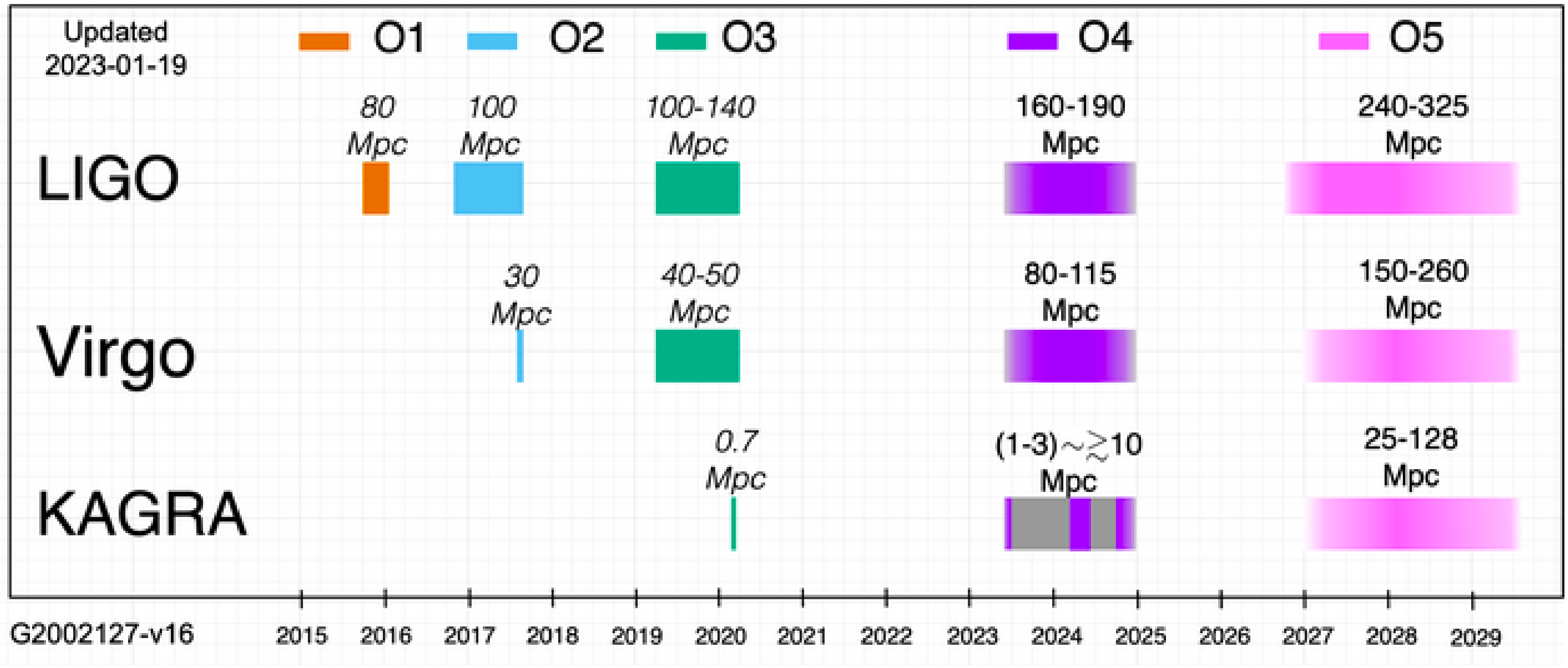


Domoto et al. 2021,2022

Isotropic irradiated γ–ray energy vs redshift



Timeline of future observing runs of Ligo/Virgo/Kagra interferometers



https://observing.docs.ligo.org/plan/

Conclusions

Binary massive star systems evolve to binary neutron star systems that merge after some hundred million years producing a multi-messenger signal: short GRB, multiwavelength afterglow, optical/infrared kilonova, GWs, MeV neutrinos.

With the exception of neutrinos, all the above was detected in the event GW170817 in NGC4993 (40 Mpc).

The kilonova spectra show broad absorption lines that reveal presence of atomic species ejected at very large speed (20-30% of light speed) and synthesized via rapid neutron capture (r-process).

Identification of individual lines is compounded by line blending and enormous number of transitions.
Attempts have been made to identify most probable atomic transitions, and to model atomic structures and opacities, but these need to be benchmarked experimentally (e.g. via laser-produced-plasmas).

Tentative evidence of Sr II was reported.