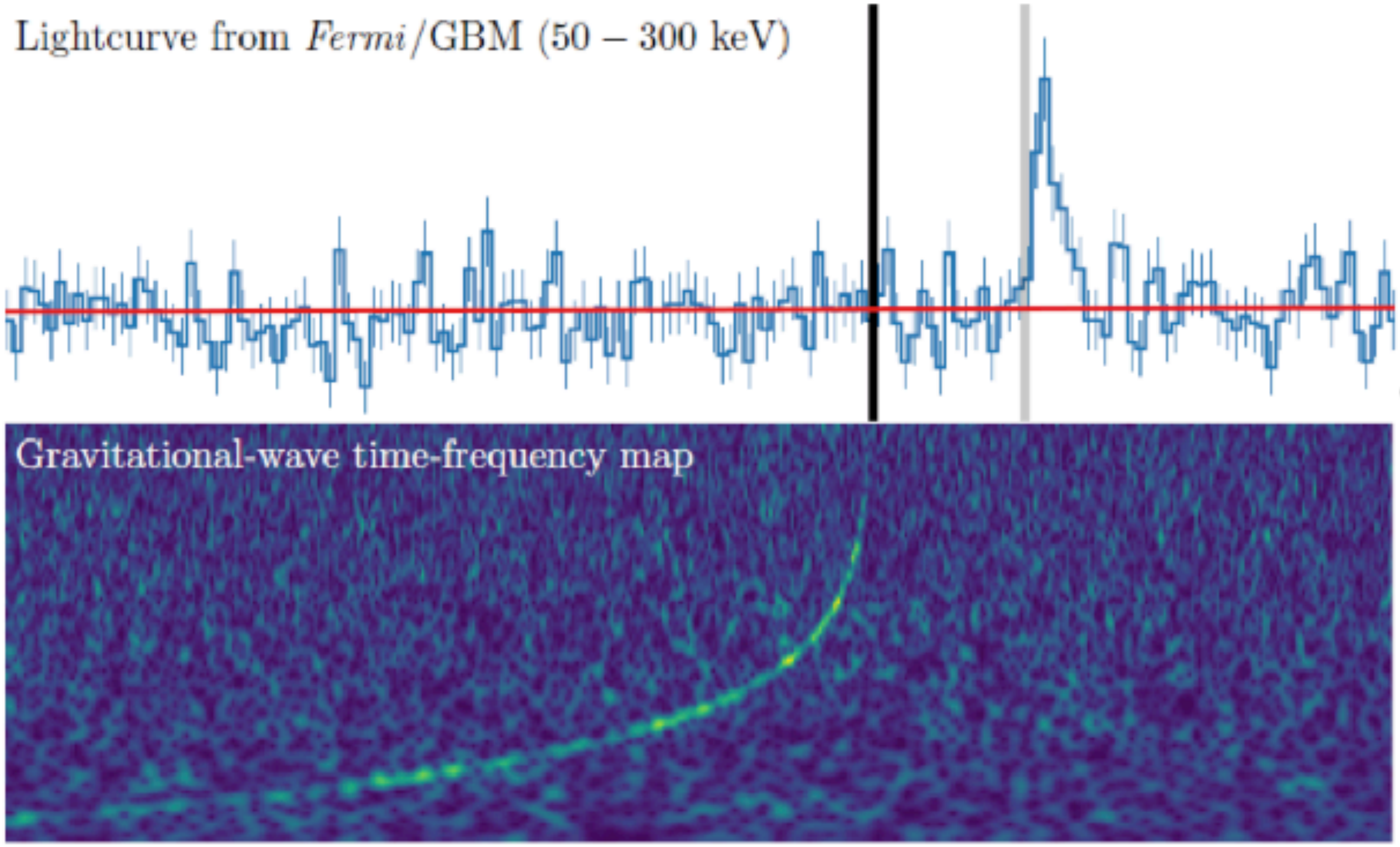
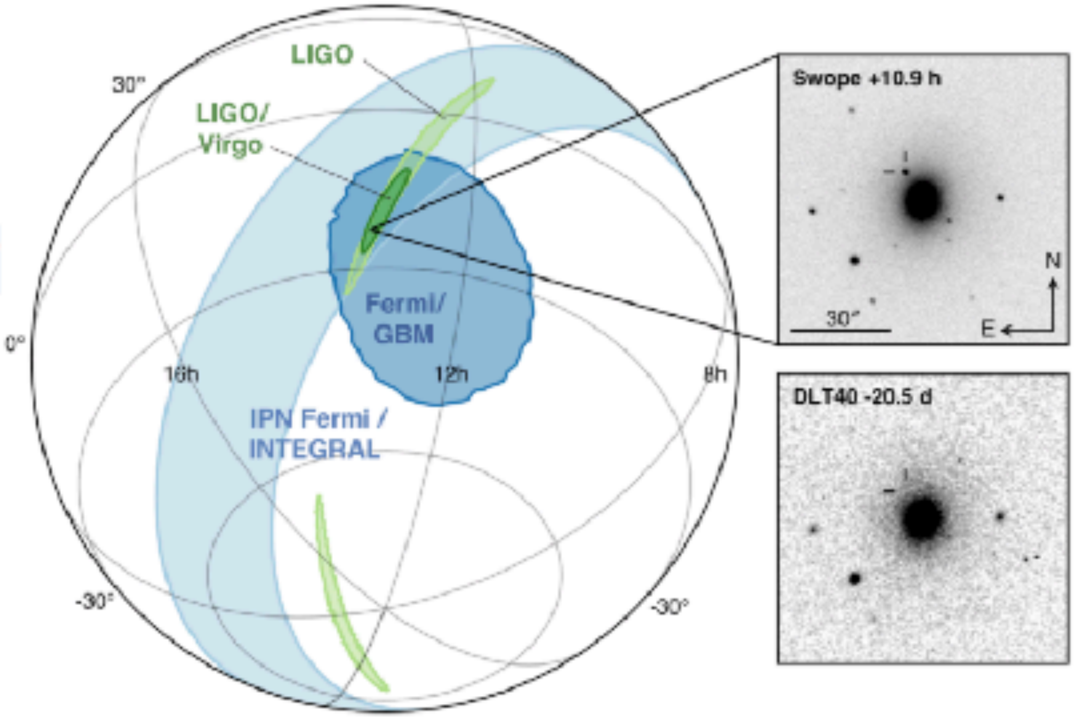
GW170817: Electromagnetic Wave Observations

Masaomi Tanaka
(National Astronomical Observatory of Japan)

The first observations of GWs from neutron star merger
and
The first observations of electromagnetic waves from GW sources

“Multi-messenger“ astronomy

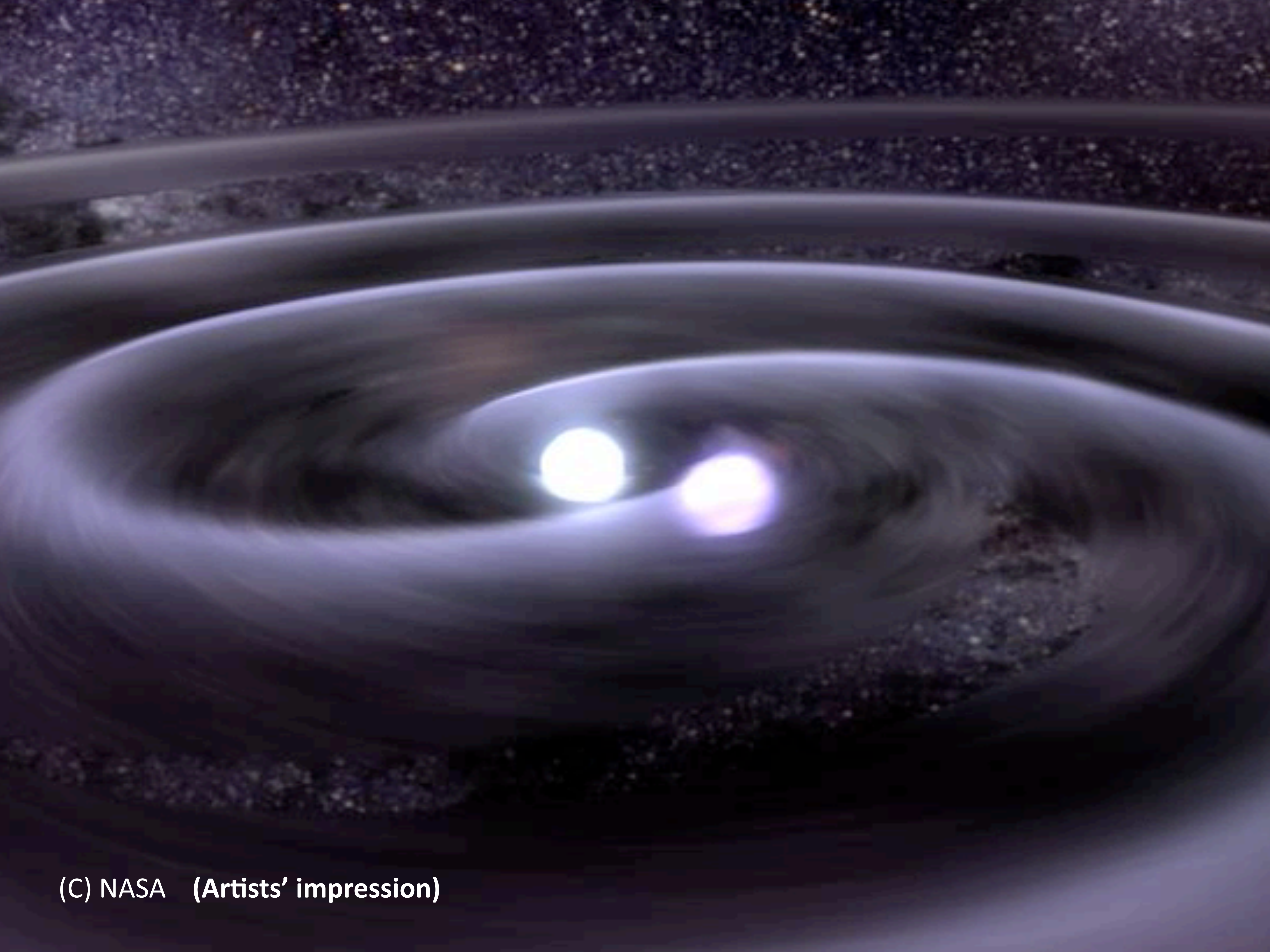




http://www.ligo.org

GW170817: Electromagnetic Wave Observations

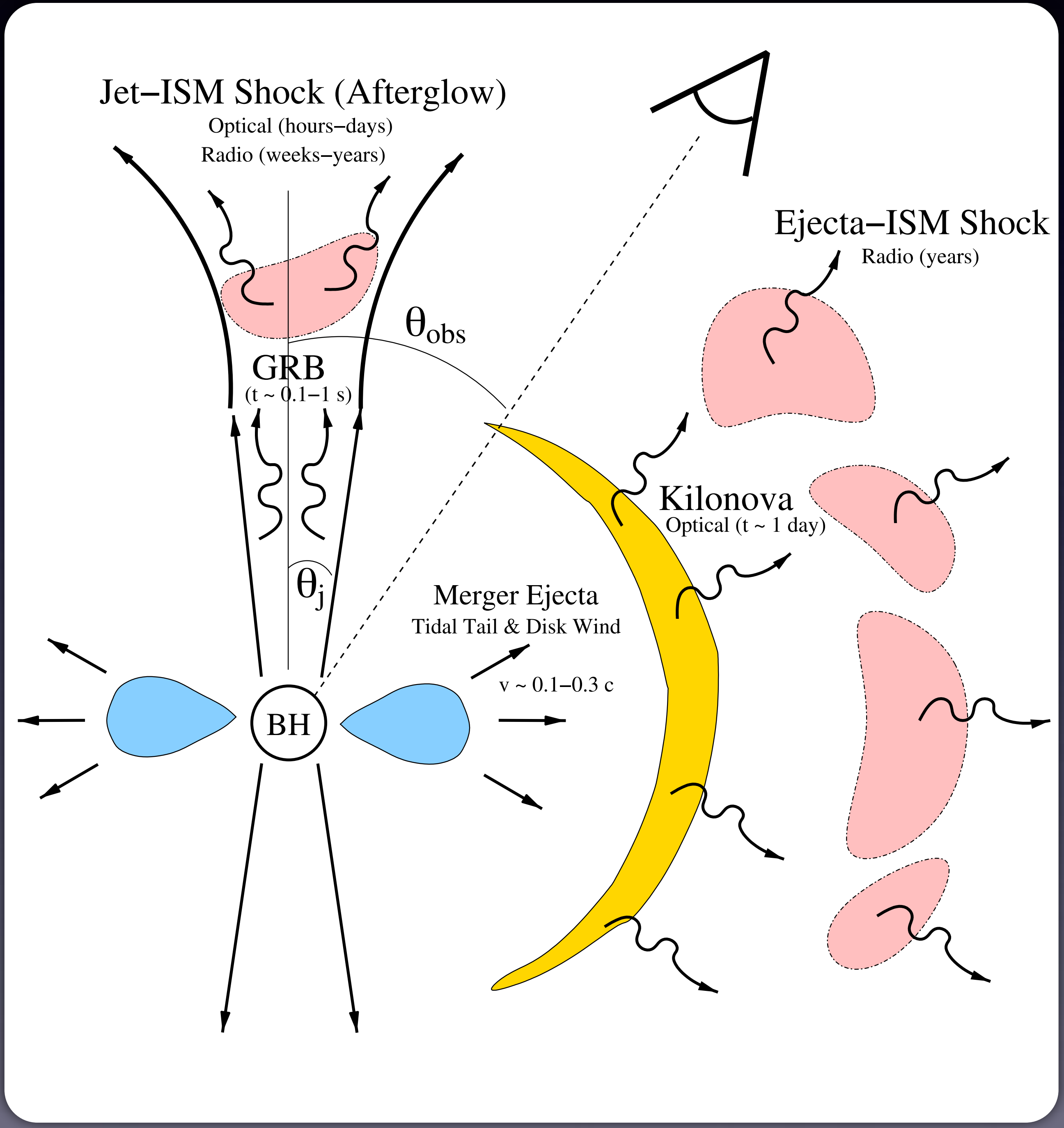
- What was expected
- What was observed



(C) NASA **(Artists' impression)**

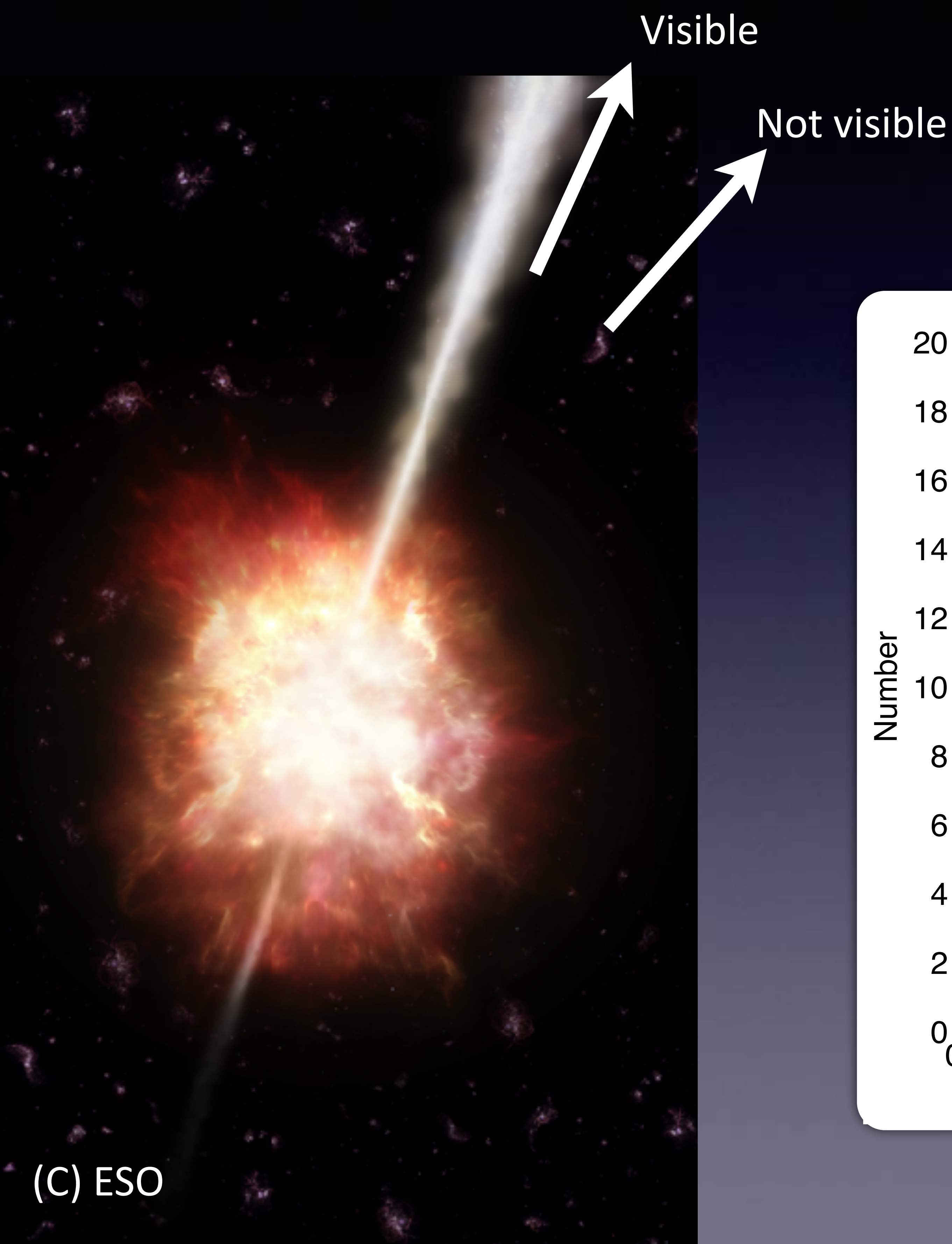
Electromagnetic signature from compact binary merger (NS-NS or BH-NS)

- X-ray/gamma-ray
- Radio
- Optical/NIR

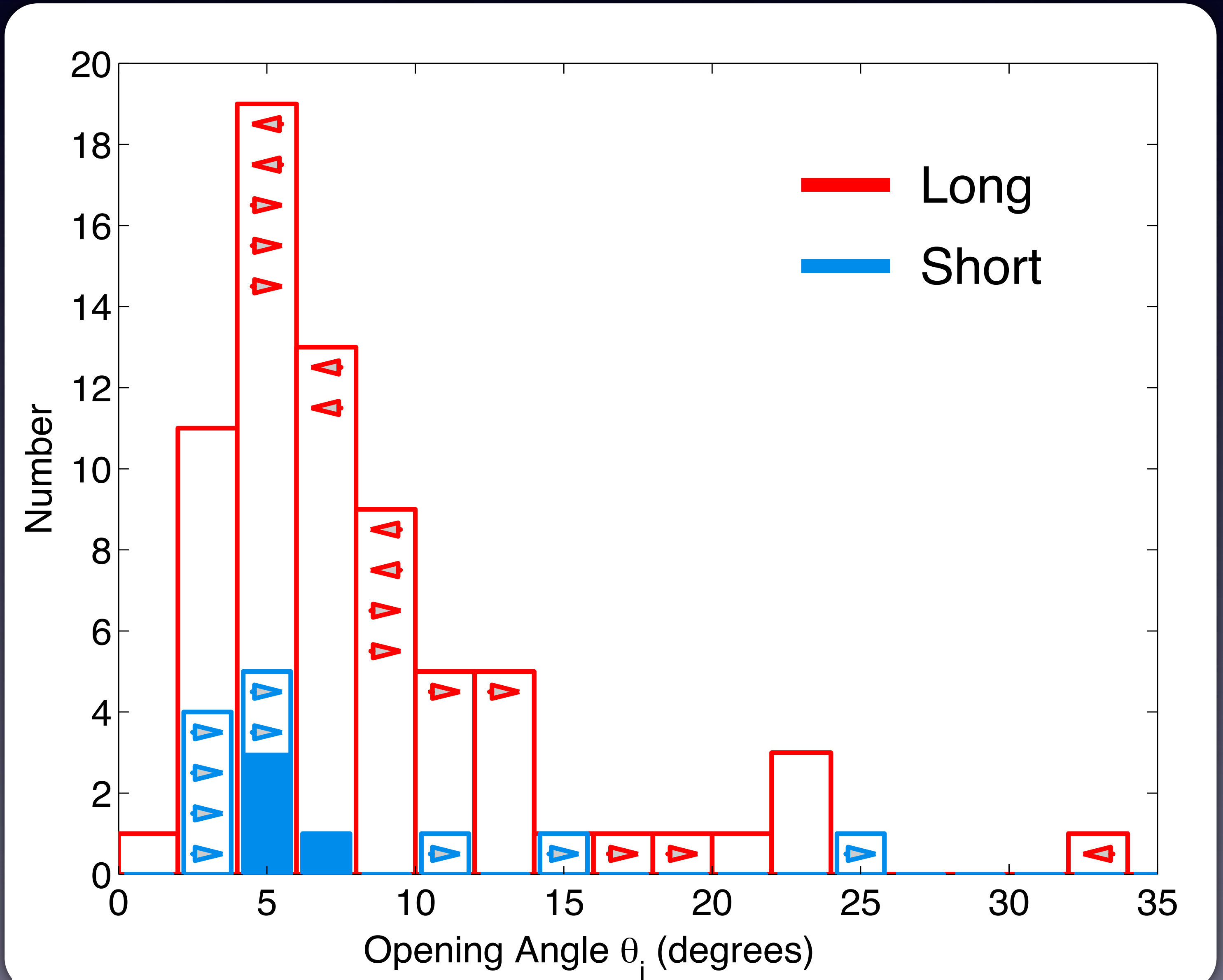


Metzger & Berger 2012

Short gamma-ray burst (GRBs)



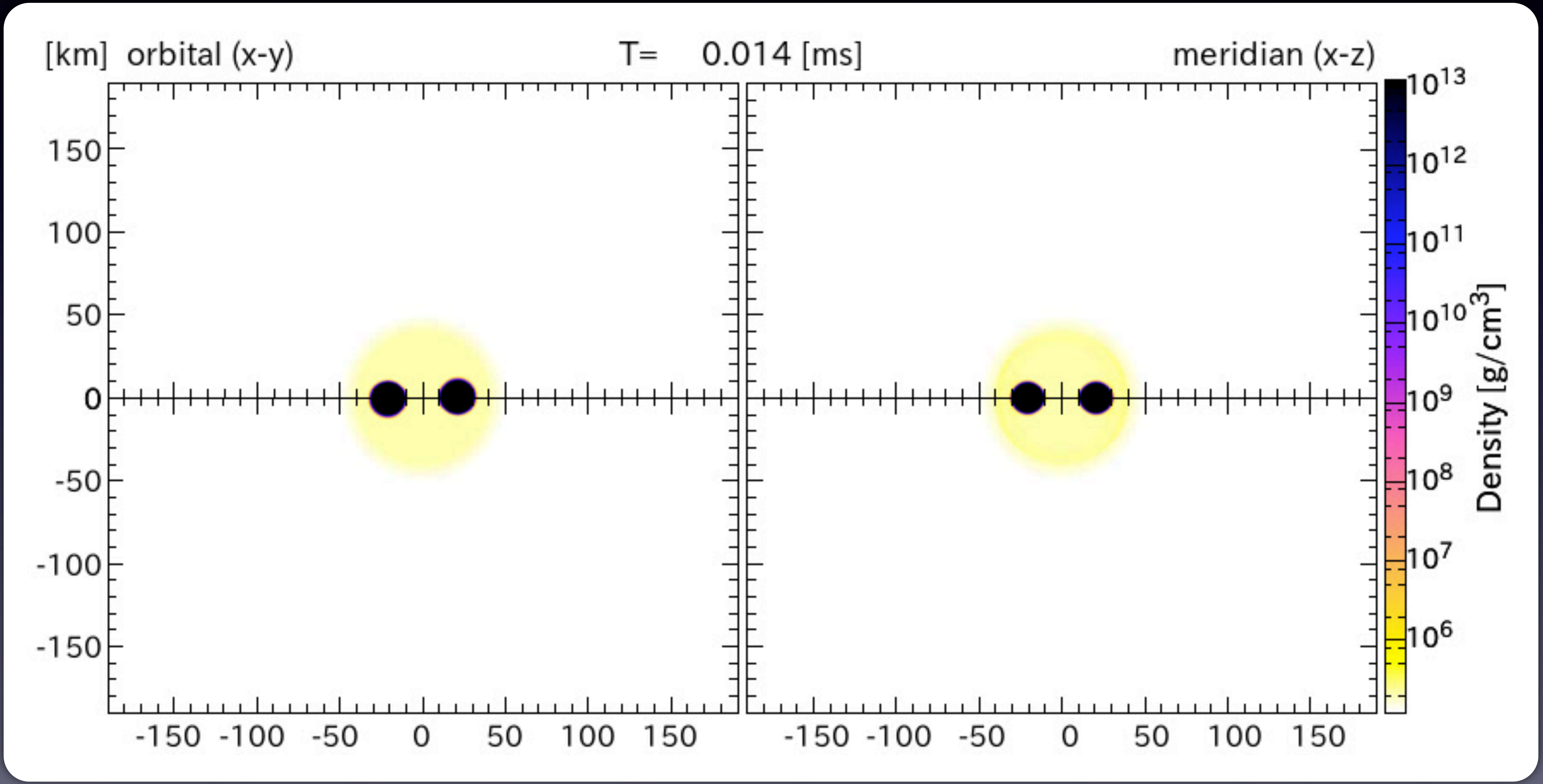
Opening angle ~ 10 deg
=> probability ~ a few %



Fong+14

Mass ejection from NS merger: (1) dynamical ejection

Top view | **Side view**



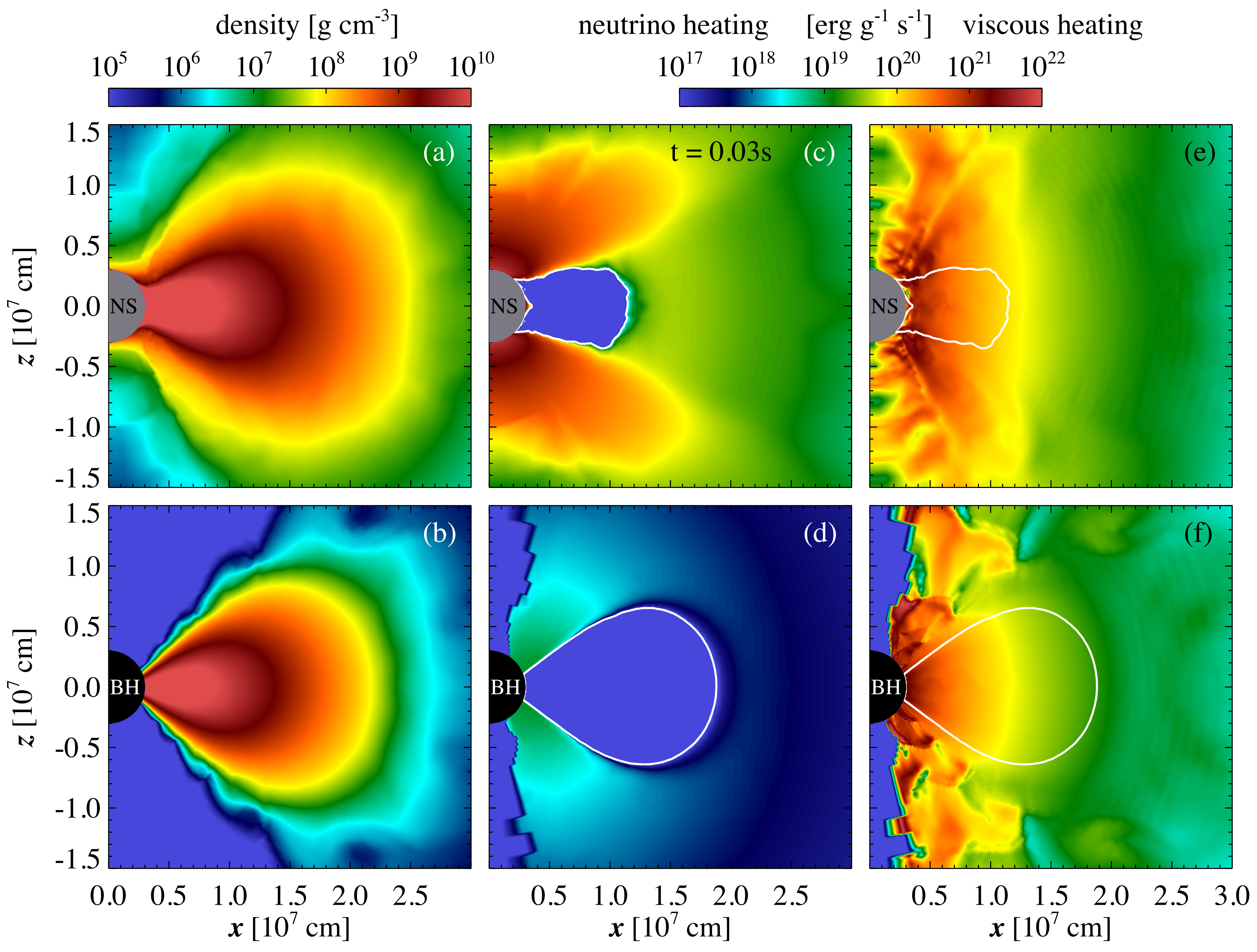
Sekiguchi+15, 16

- Tidal disruption
- Shock heating

$M \sim 10^{-3} - 10^{-2}$ Msun

$v \sim 0.1 - 0.2\ c$

Mass ejection from NS merger: (2) post-merger ejection



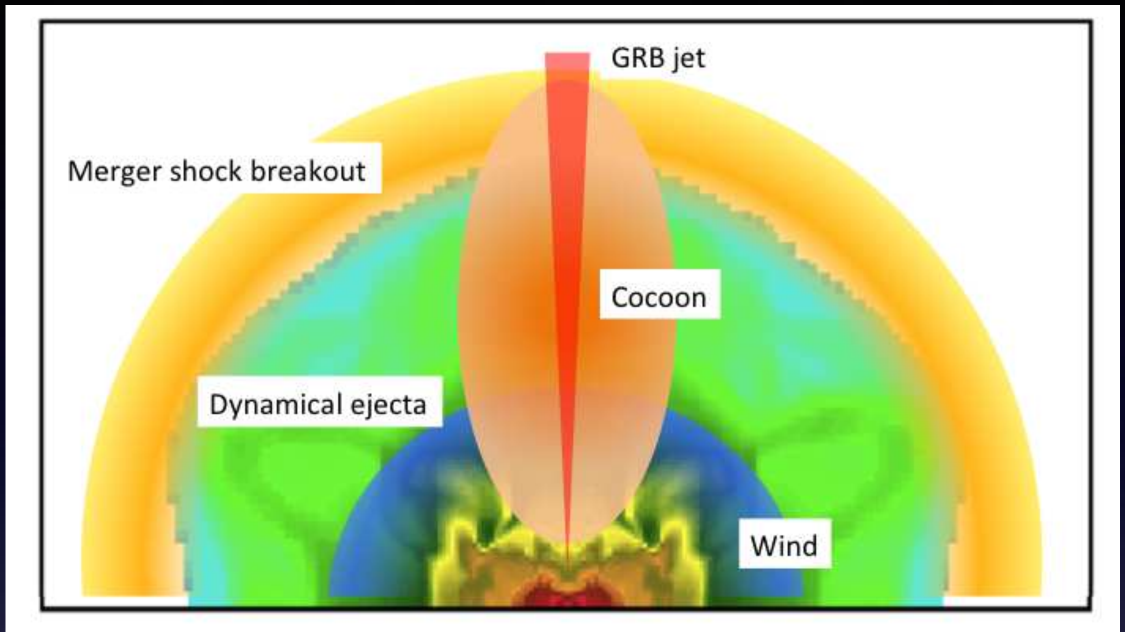
Fernandez+15

- **Viscous heating in the disk**
- **Neutrino heating**

M ~ 10^{-3} - 10^{-2} Msun

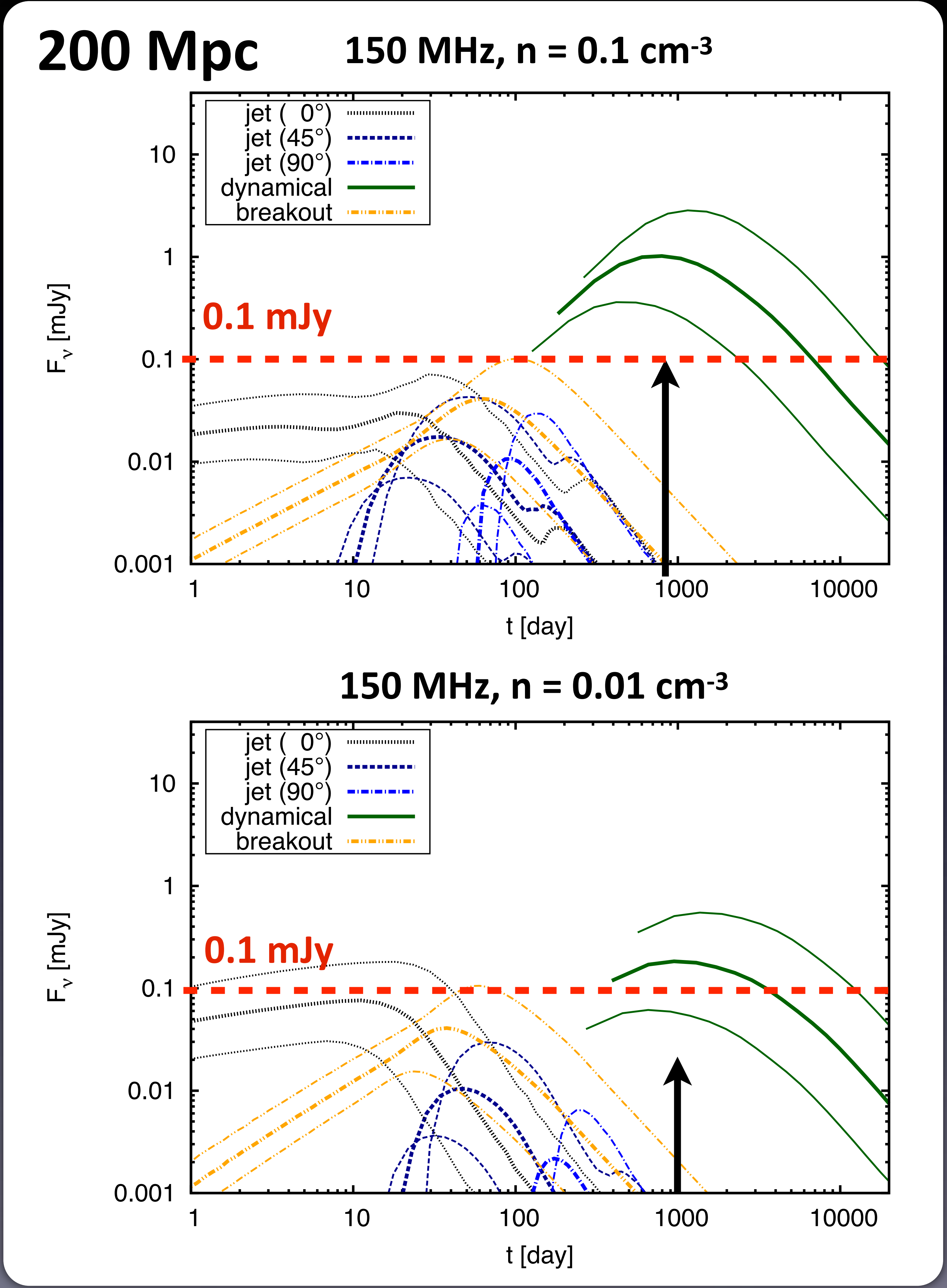
v ~ 0.05c

Radio emission



- Delayed by ~> years
- Too faint?
  (low environment density)
- Low contamination rate

Hotokezaka & Piran 2015, MNRAS, 450, 1430



Electromagnetic signature from compact binary merger (NS-NS or BH-NS)

- X-ray/gamma-ray

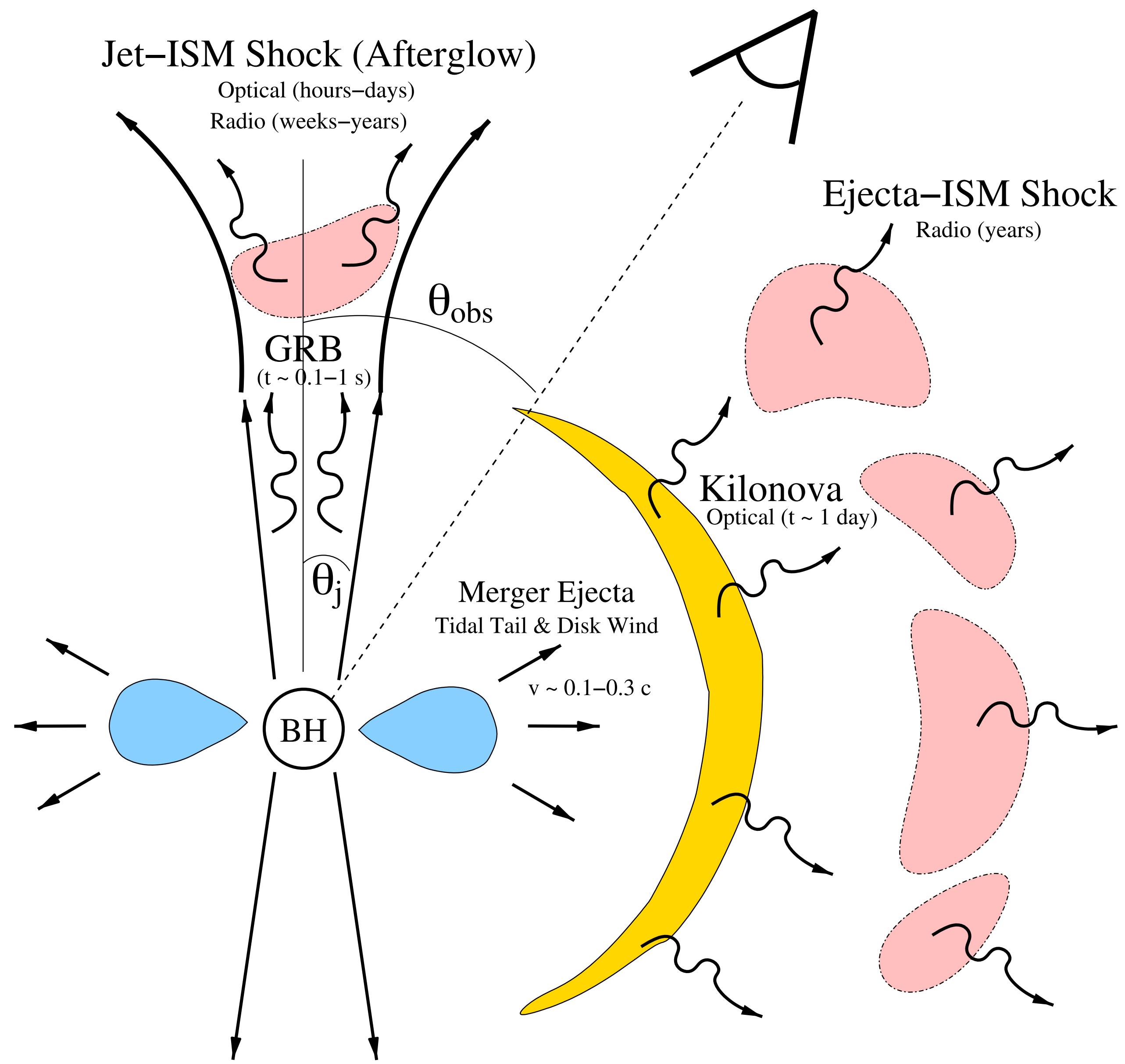
  Short GRB: strongly beamed

- Radio

  Delayed by years
  Low contamination rate

- Optical/NIR

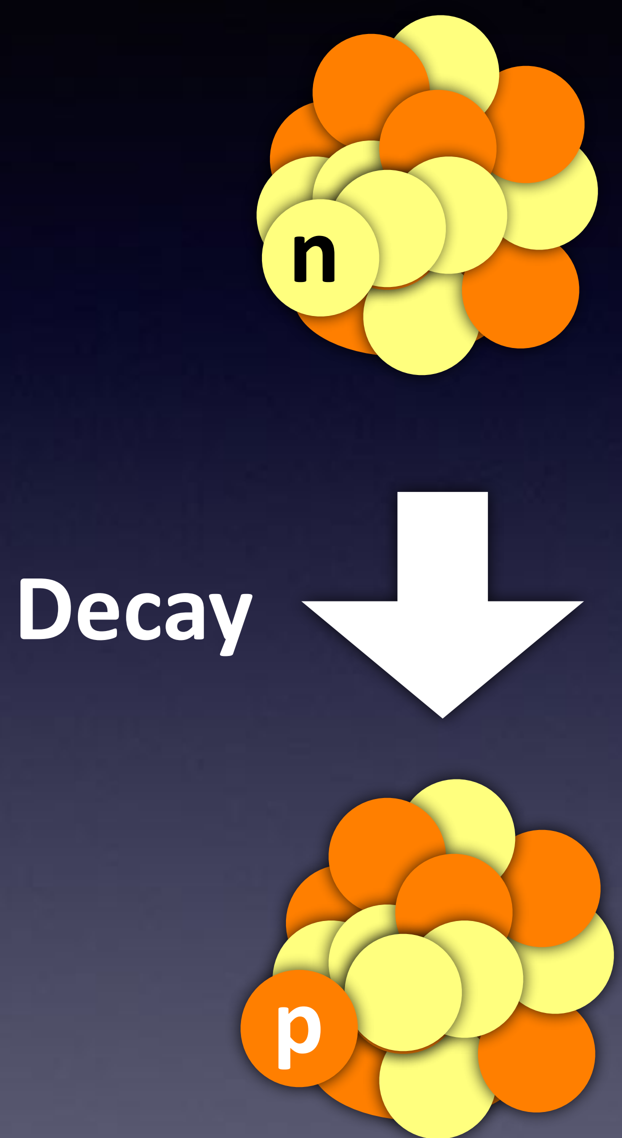
  Delayed by only ~ 1 week
  Isotropic



Metzger & Berger 2012, ApJ 746, 48

Neutron-capture nucleosynthesis

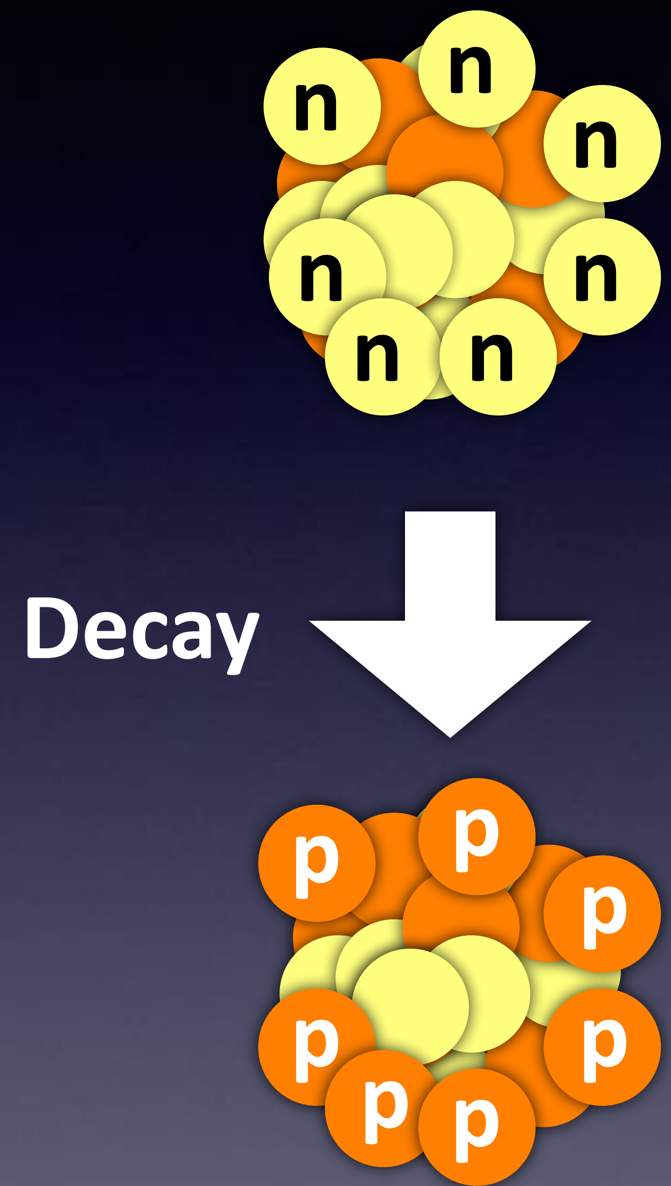
s (slow)-process



Ba, Pb, …

Inside of stars

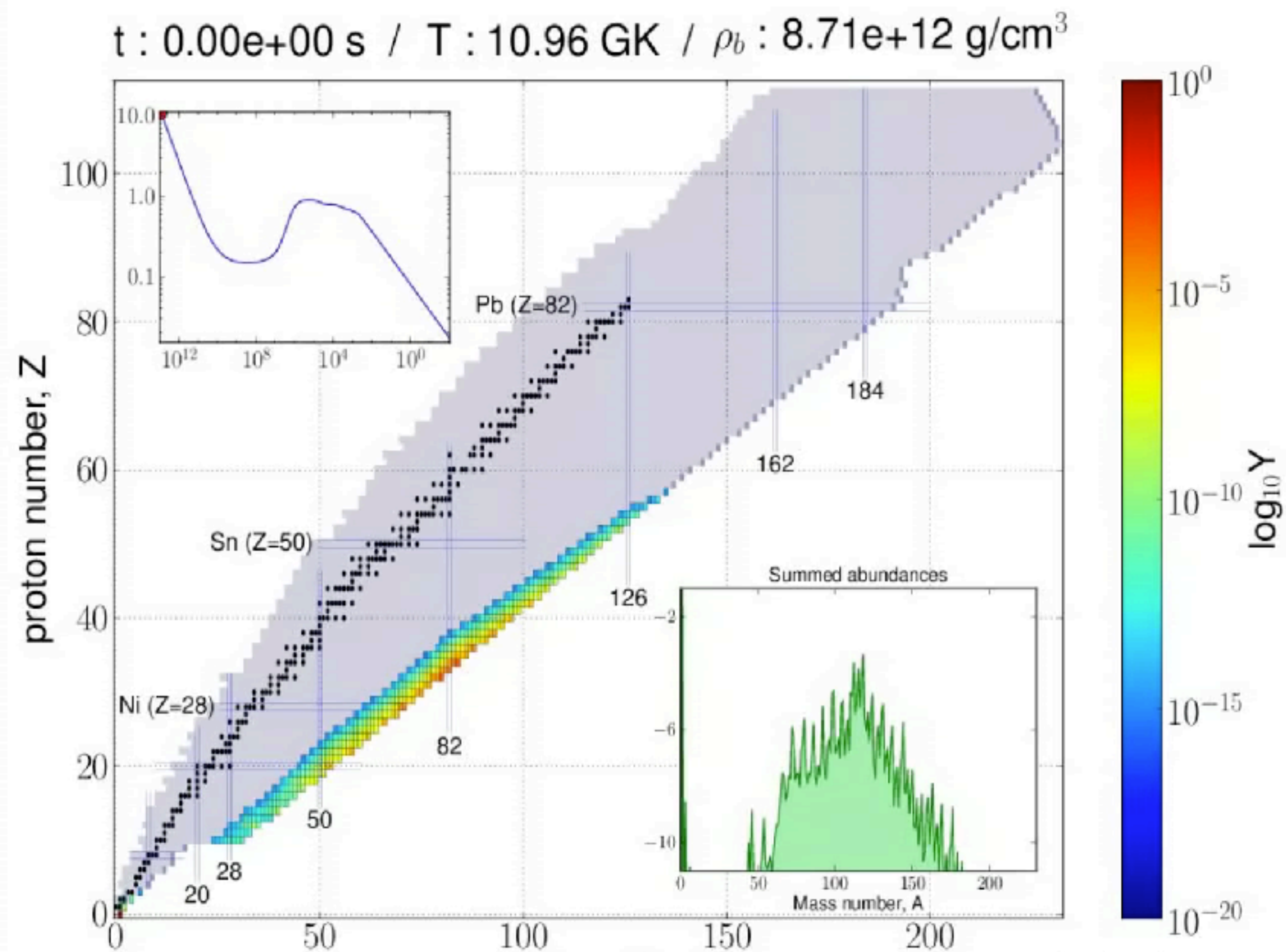
r (rapid)-process



Au, Pt, U, …

??

r-process nucleosynthesis

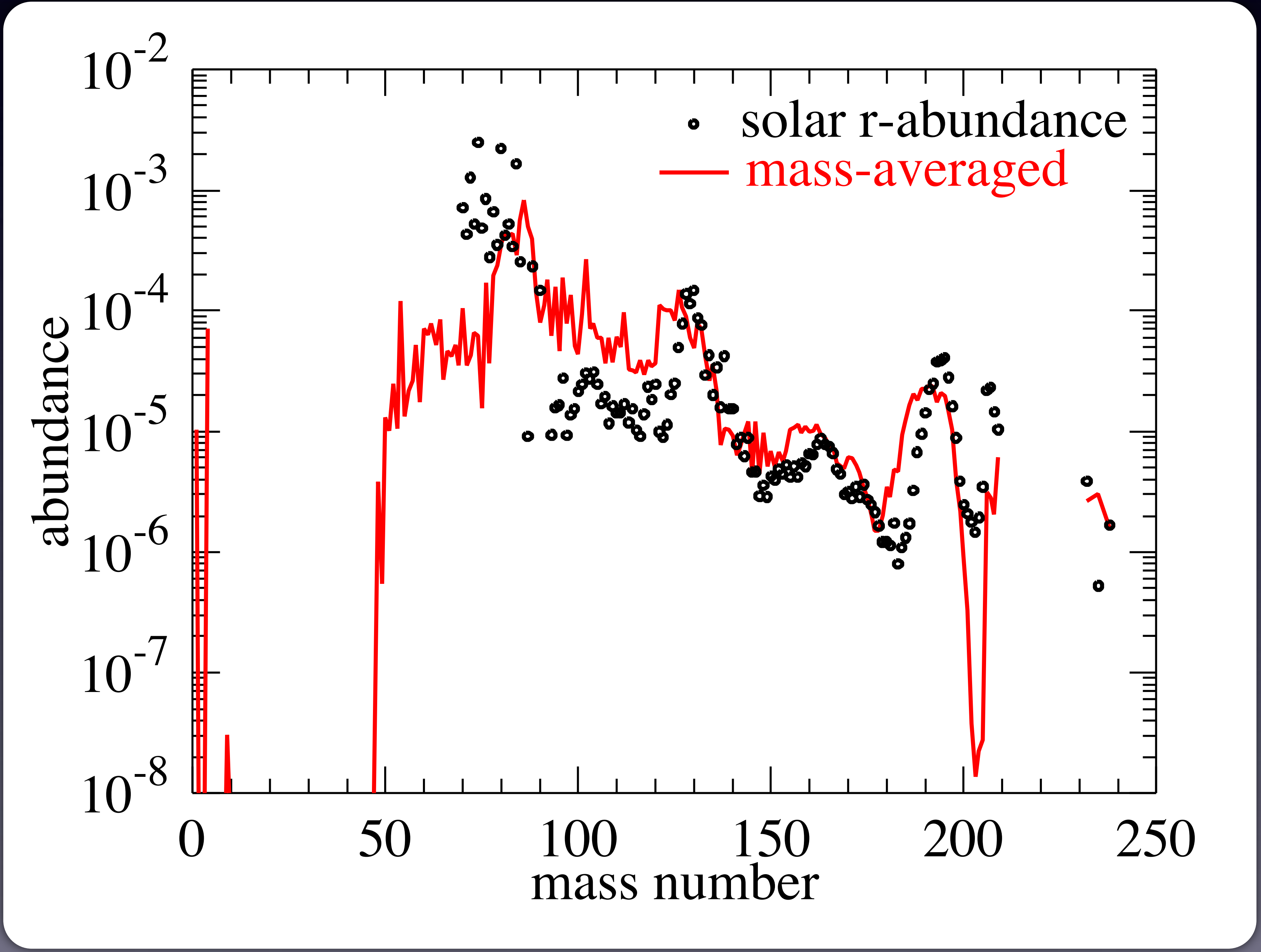


O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

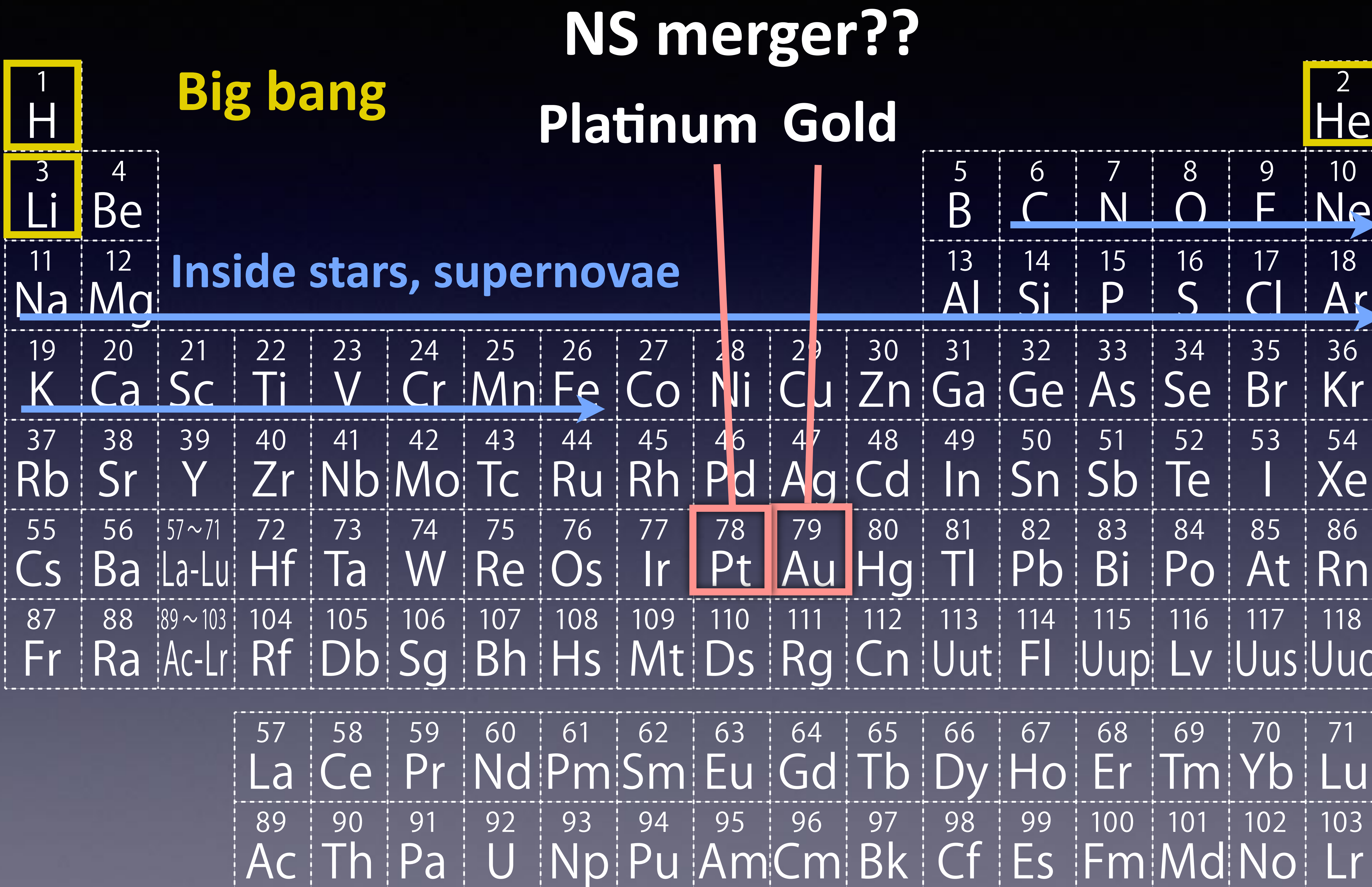
r-process nucleosynthesis in dynamical ejecta

~ solar abundance ratios

Dynamical ejecta: Wanajo+14, Radice+16, …
Post-merger ejecta: Just+14, Wu+16, …



The origin of elements

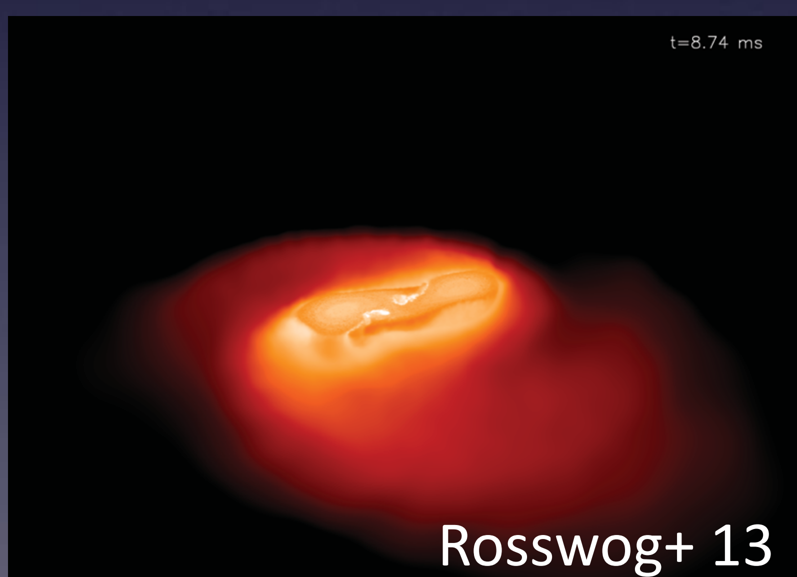


Merger → r-process nucleosynthesis → Radioactive decay => **kilonova**

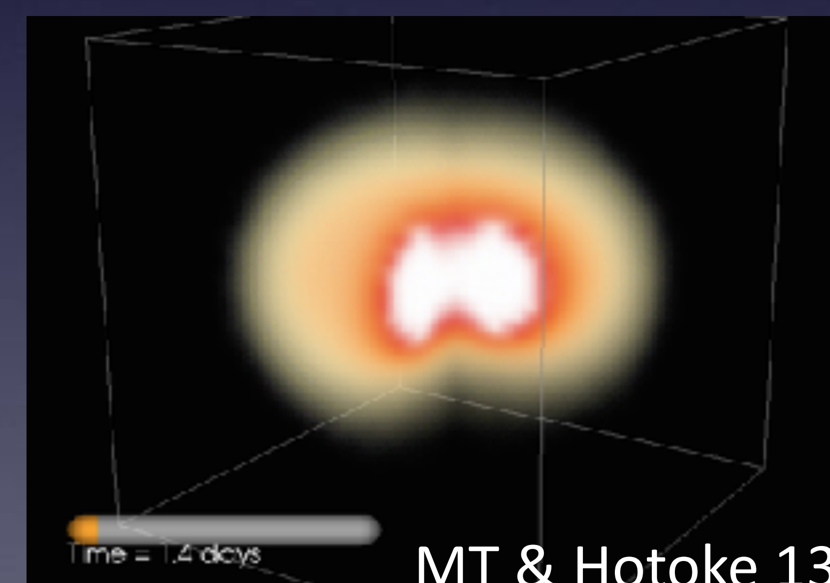
(1) Dynamical ejection

(2) Post-merger ejection

< 10 ms   ~< 100 ms   < 1 sec   ~> days



Rosswog+ 13


MT & Hotoke 13

Light curves of kilonova

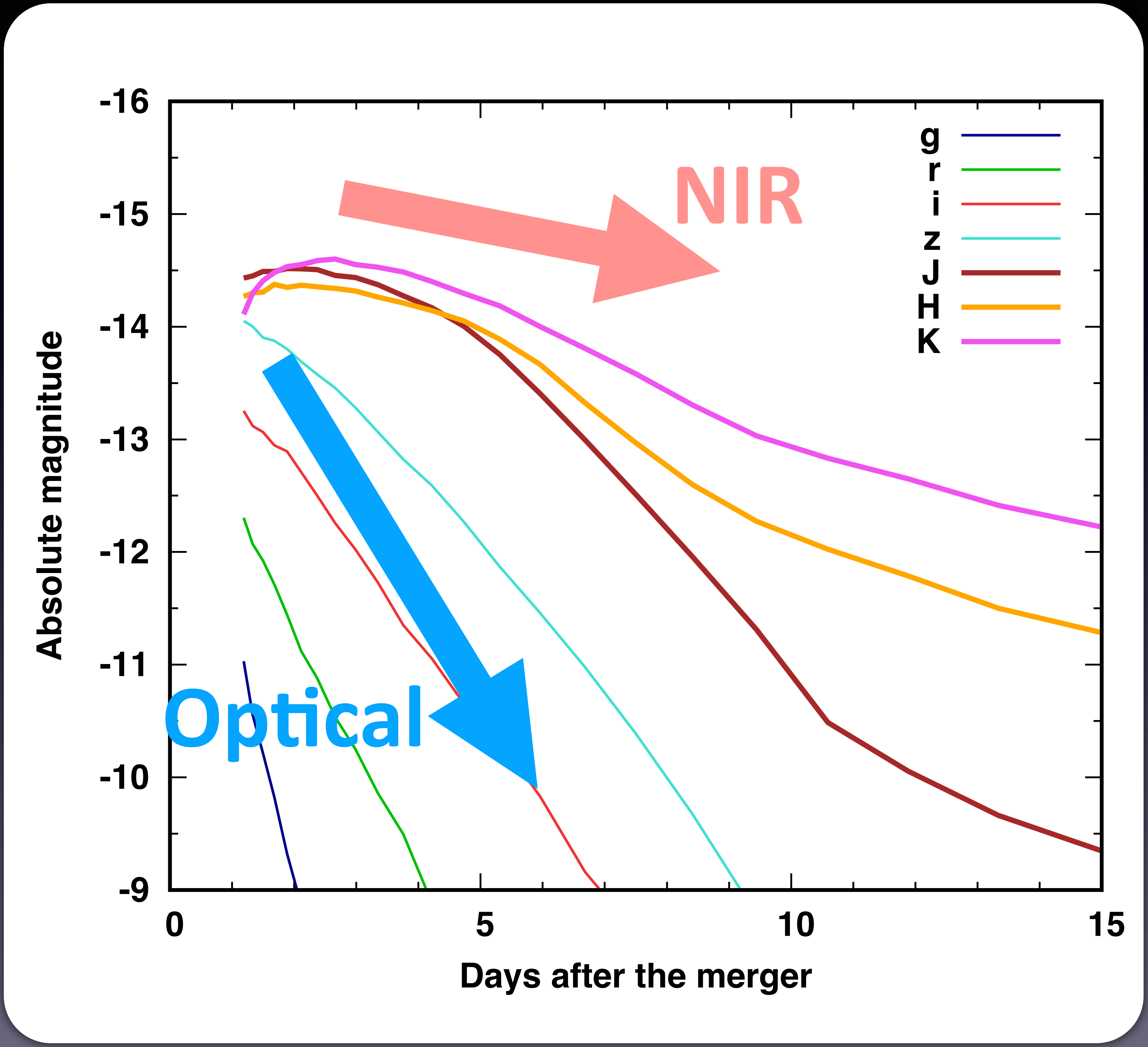
MT & Hotokezaka 13, MT+14,

L ~ 10^{40}-10^{41} erg s^{-1}

t ~ weeks

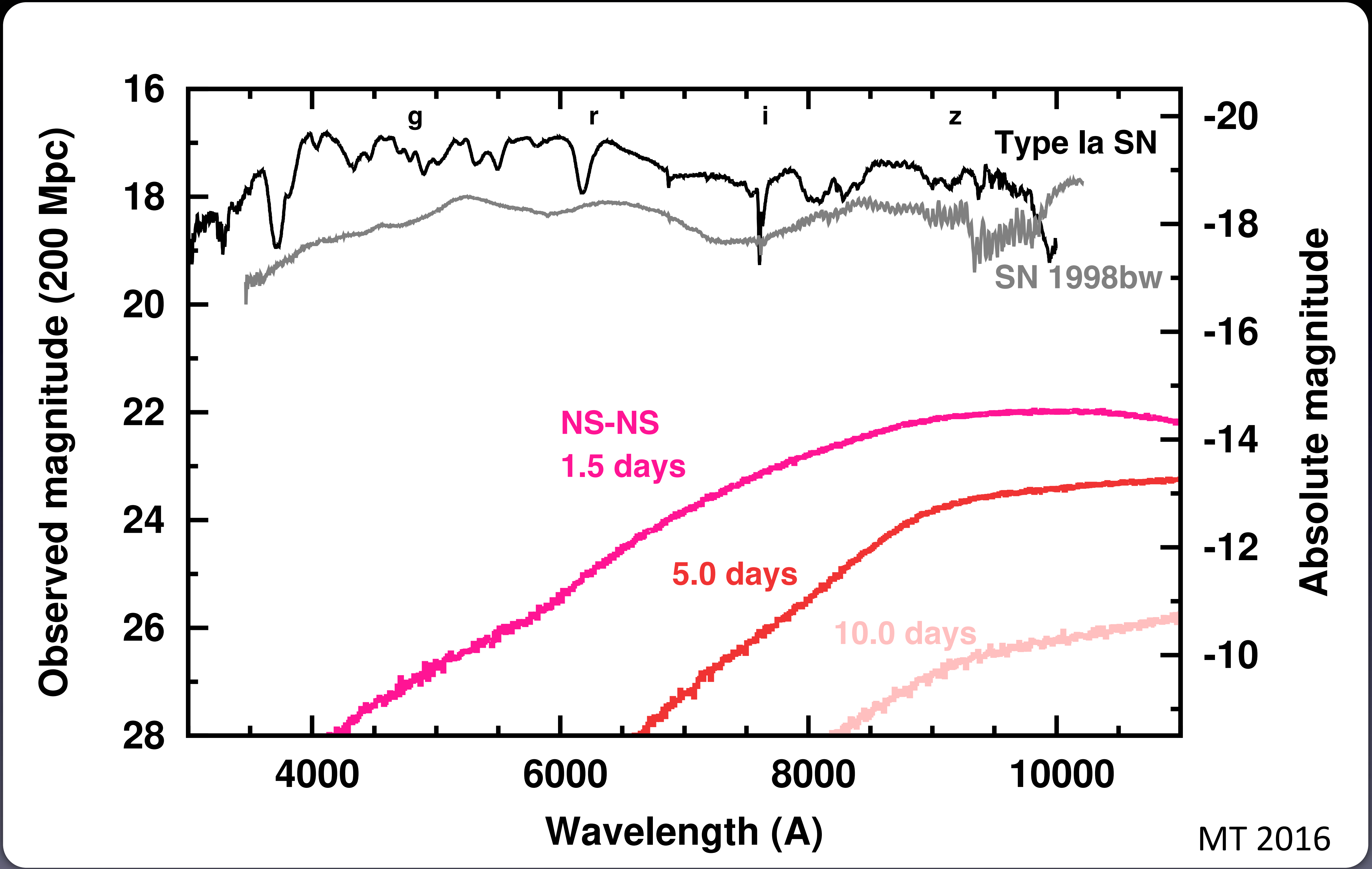
NIR > Optical

Smooth spectra

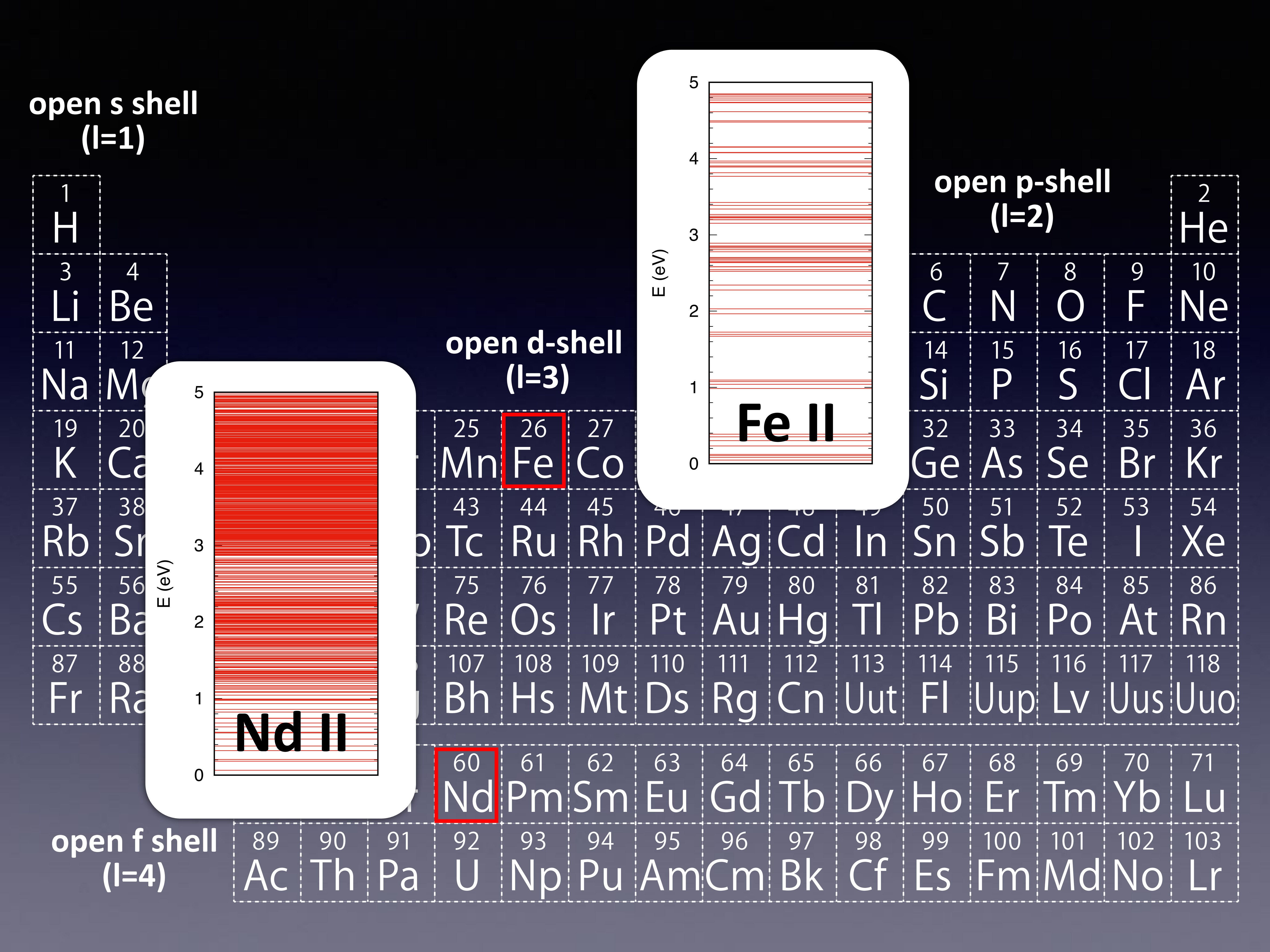


Model: MT+17a

Expected spectrum



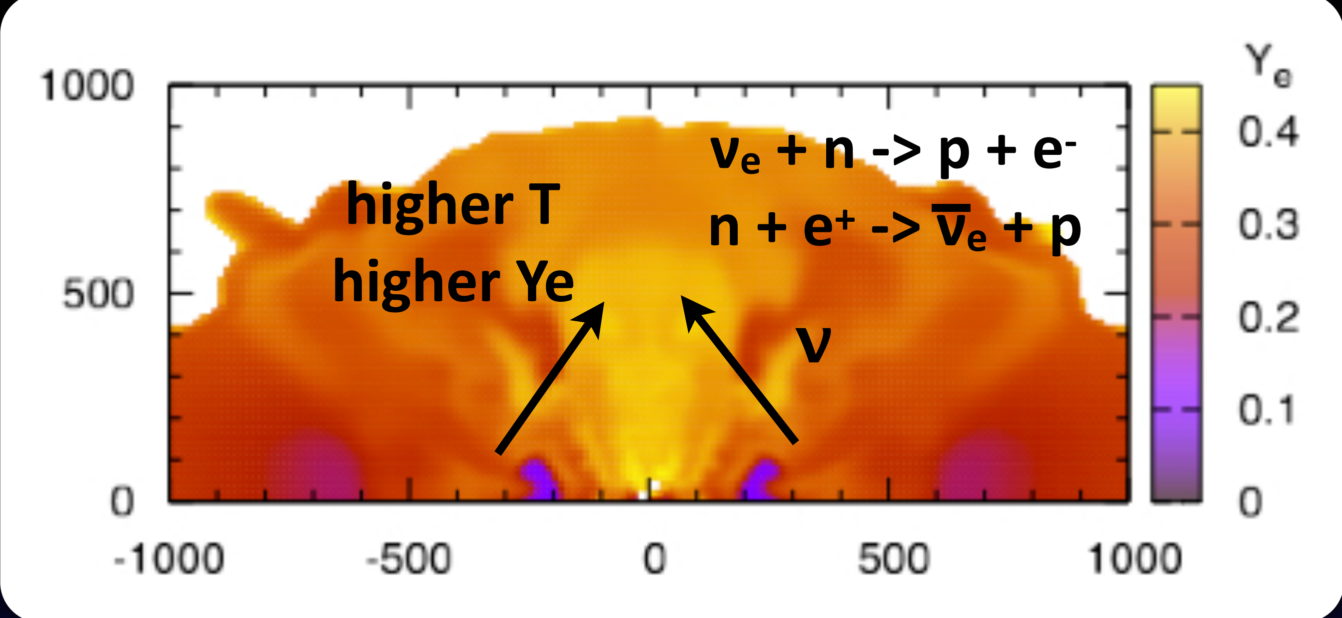
Extremely broad-line (feature-less) spectra

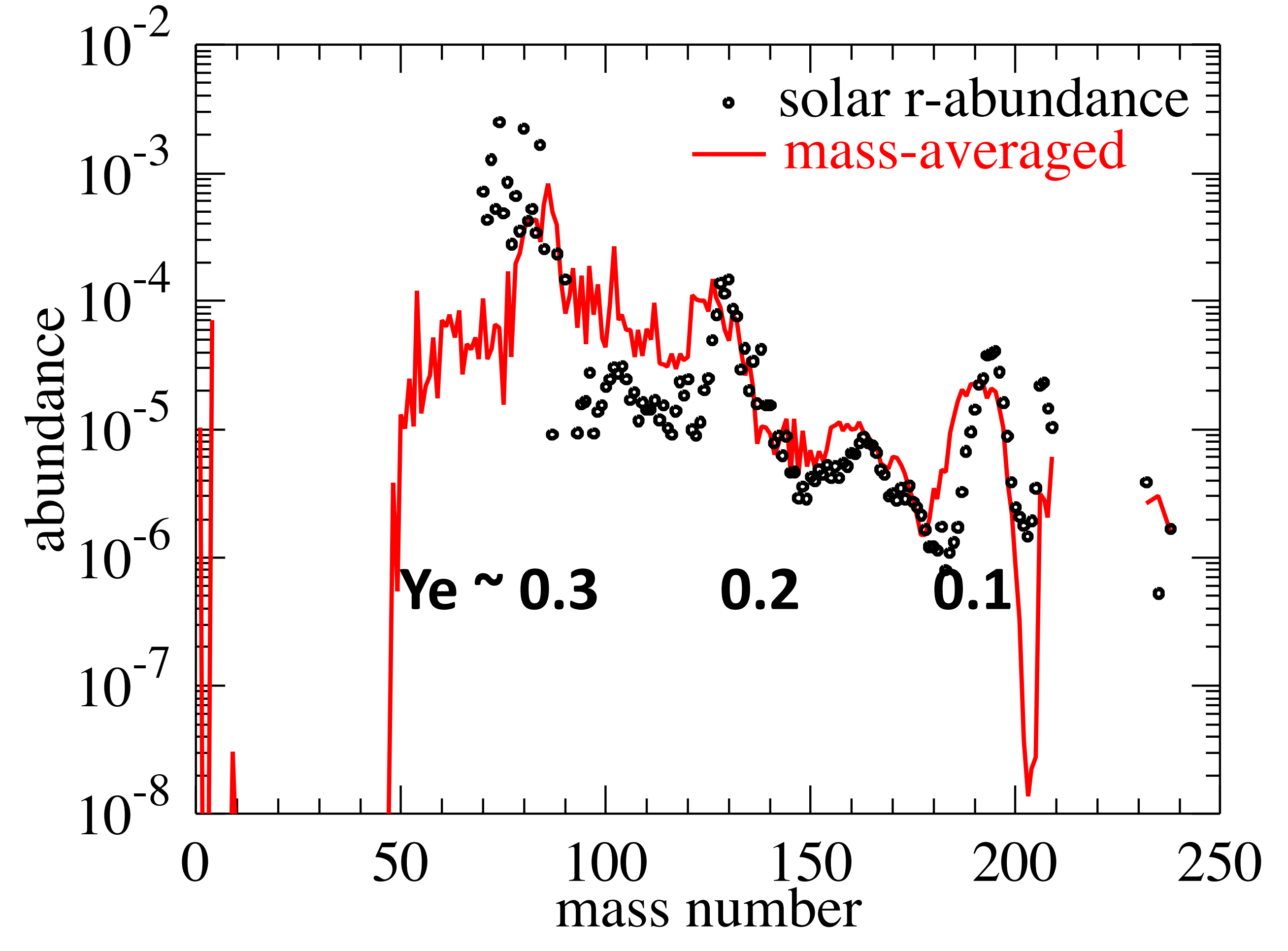

open s shell
(l=1)
open p-shell
(l=2)
open d-shell
(l=3)
open f shell
(l=4)
E (eV)
Fe II
E (eV)
Nd II
26
Fe
60
Nd

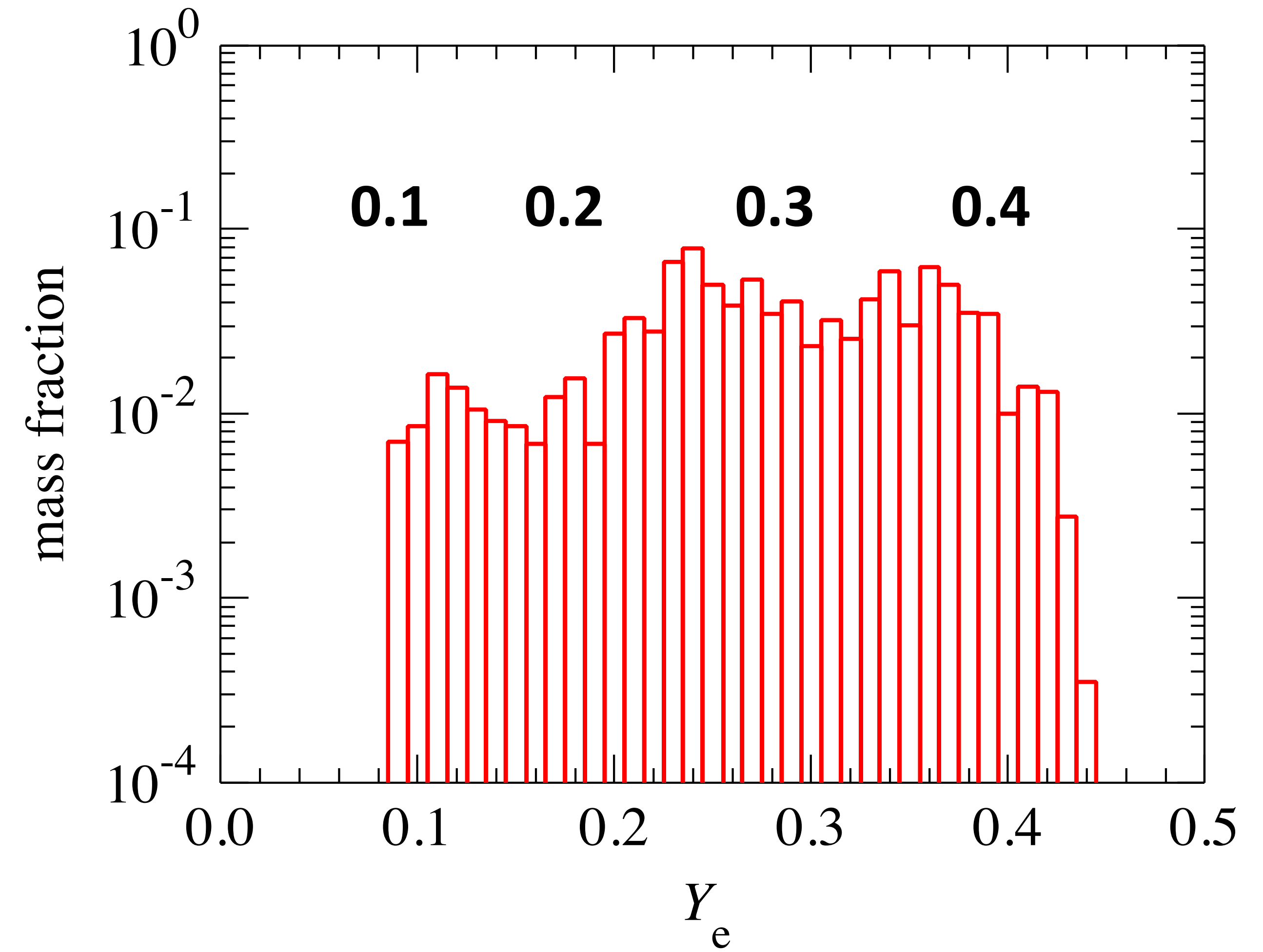
Distribution of elements

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

Low Ye => stronger r-process





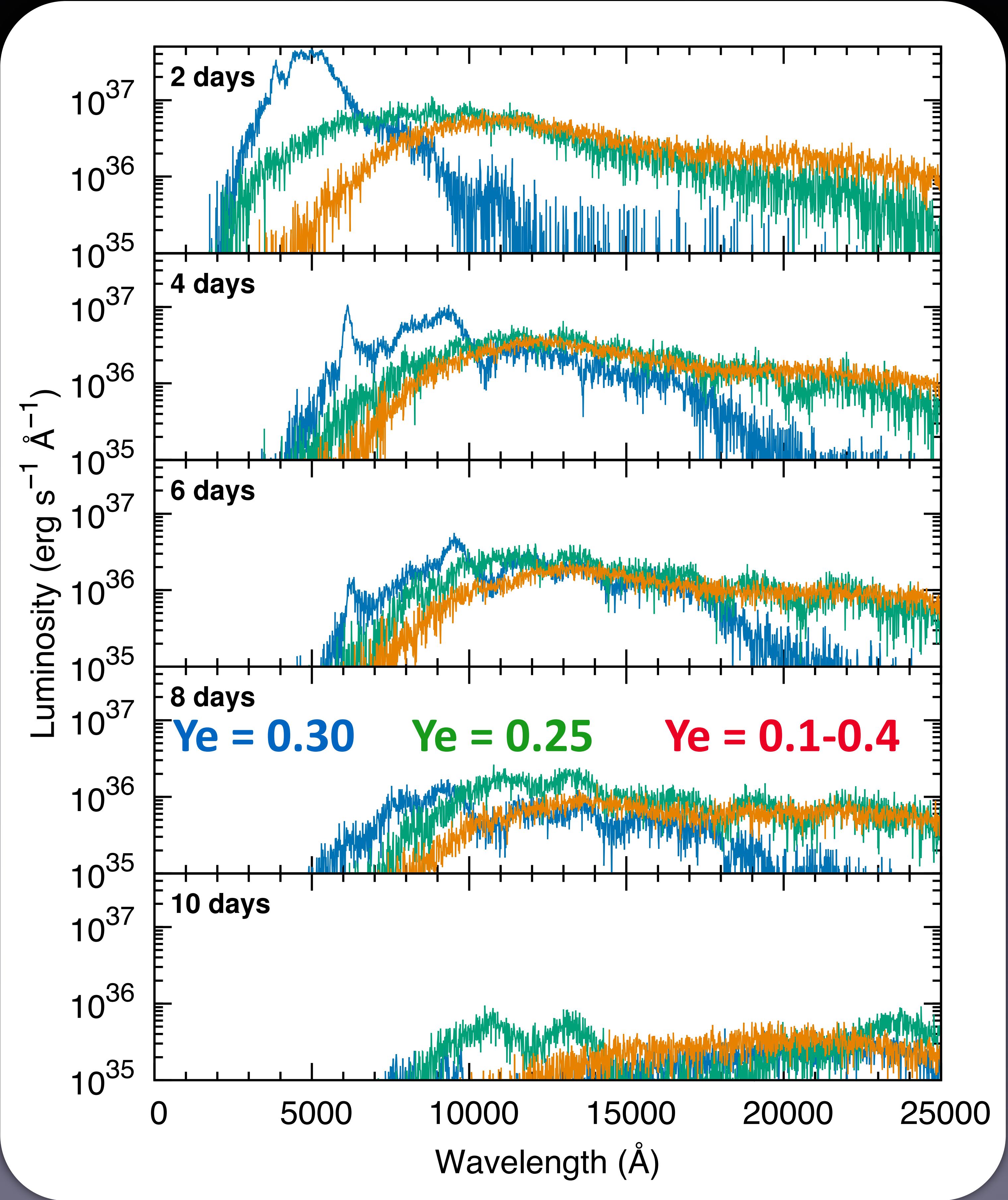


Wanajo+14, Sekiguchi+15,16, Radice+16, Foucart+16

Nucleosynthesis are imprinted in the spectra!!

"Red kilonova"
from low Ye ejecta

"Blue kilonova"
from high Ye ejecta



Metzger+14, Kasen+15

MT+17

NS merger as a possible origin of r-process elements

Event rate

$R_{NSM} \sim 10^3\ \mathrm{Gpc^{-3}\ yr^{-1}}$

$\sim 1 / 10^4$ yr in 1 galaxy

~ 30 GW events $\mathrm{yr^{-1}}$

(w/ Adv. detectors, < 200 Mpc)

Ejection per event

M_{ej}(r-process) $\sim 10^{-2}$ Msun

GW

LIGO O1 (arXiv:1607.07456)

$R_{NSM} < 10^4\ \mathrm{Gpc^{-3}\ yr^{-1}}$

EM

Enough to explain the r-process abundance in our Galaxy

M(Galaxy, r-process) $\sim M_{ej}(r) \times (R_{NSM} \times t_G)$

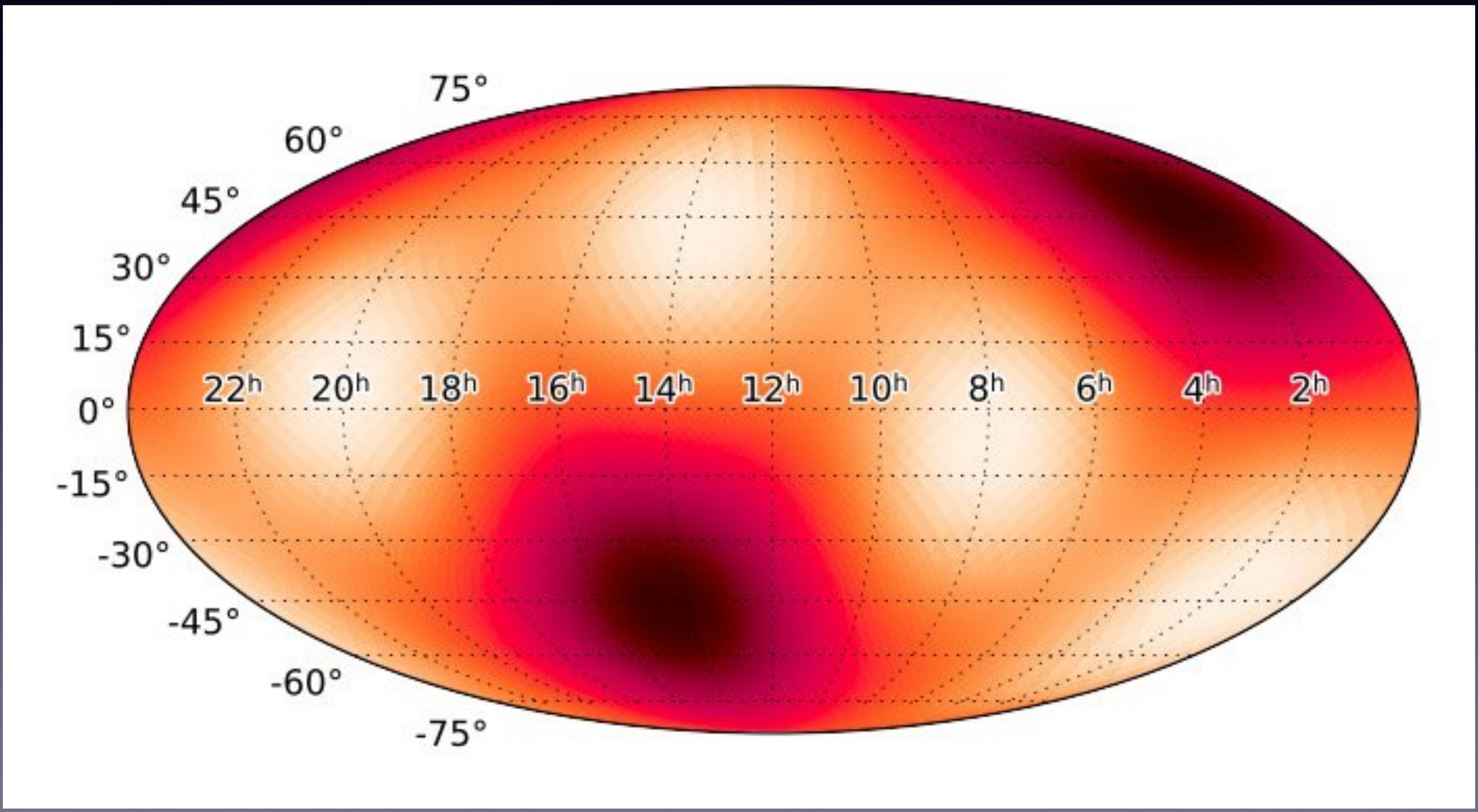
$\sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4$ Msun

GW170817: Electromagnetic Wave Observations

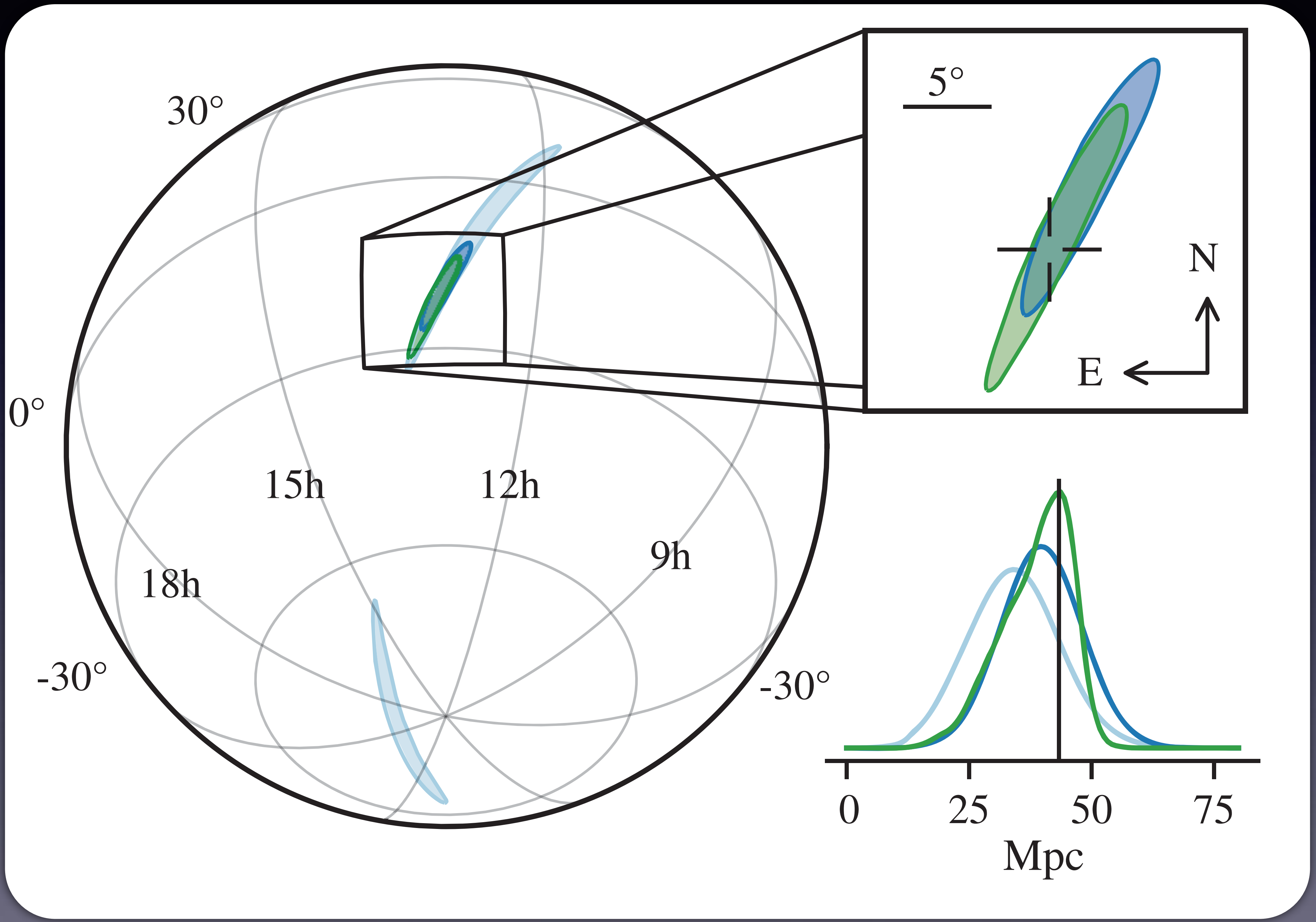
- What was expected
- What was observed

The initial skymap (only from LIGO/Hanford)

*LIGO/Livingstone data suffer from a glitch noise

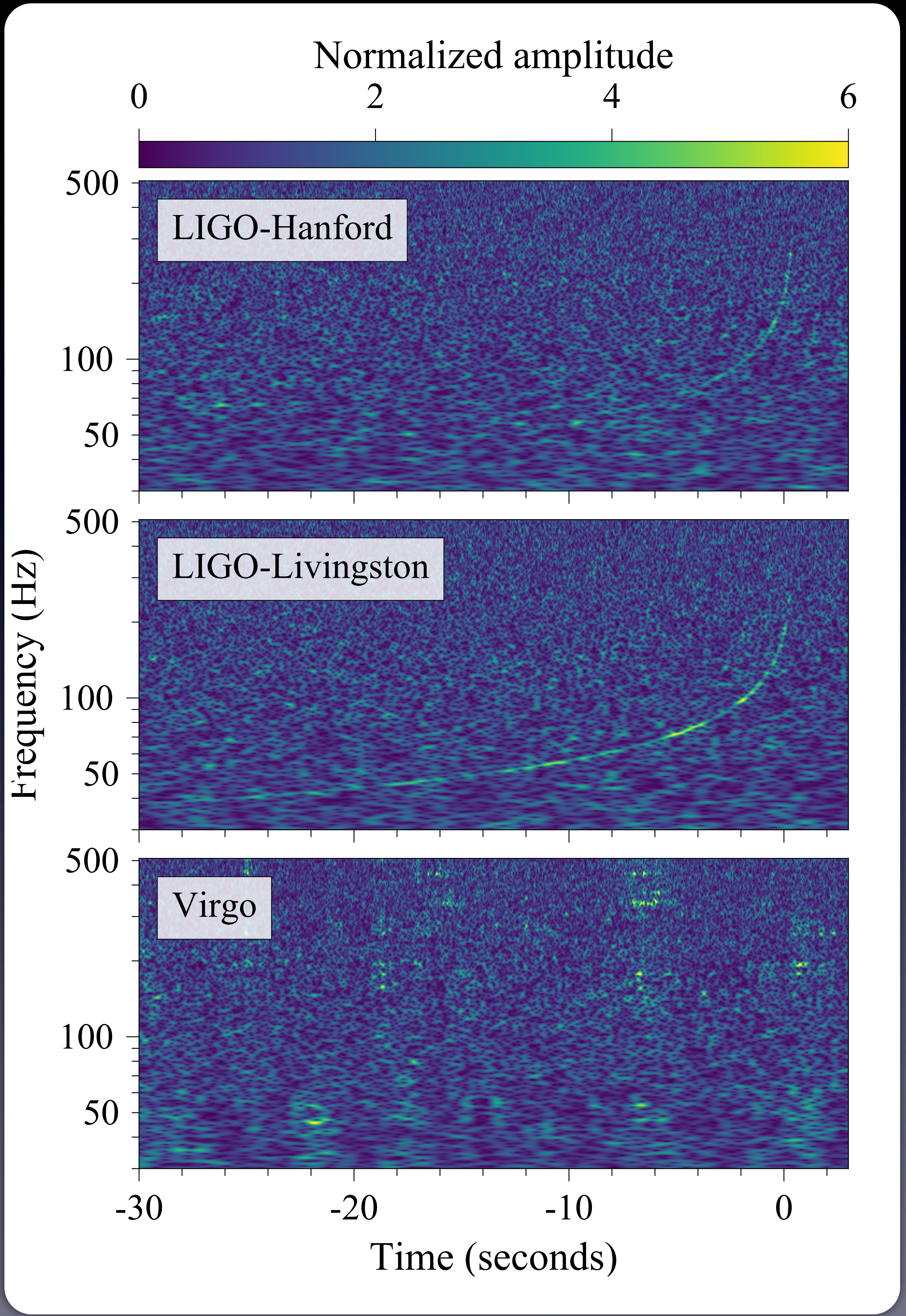


Skymap from 3 detectors (LIGO x 2 + Virgo)
==> 30 deg² (~40 Mpc)



LIGO Scientific Collaboration and Virgo Collaboration, 2017

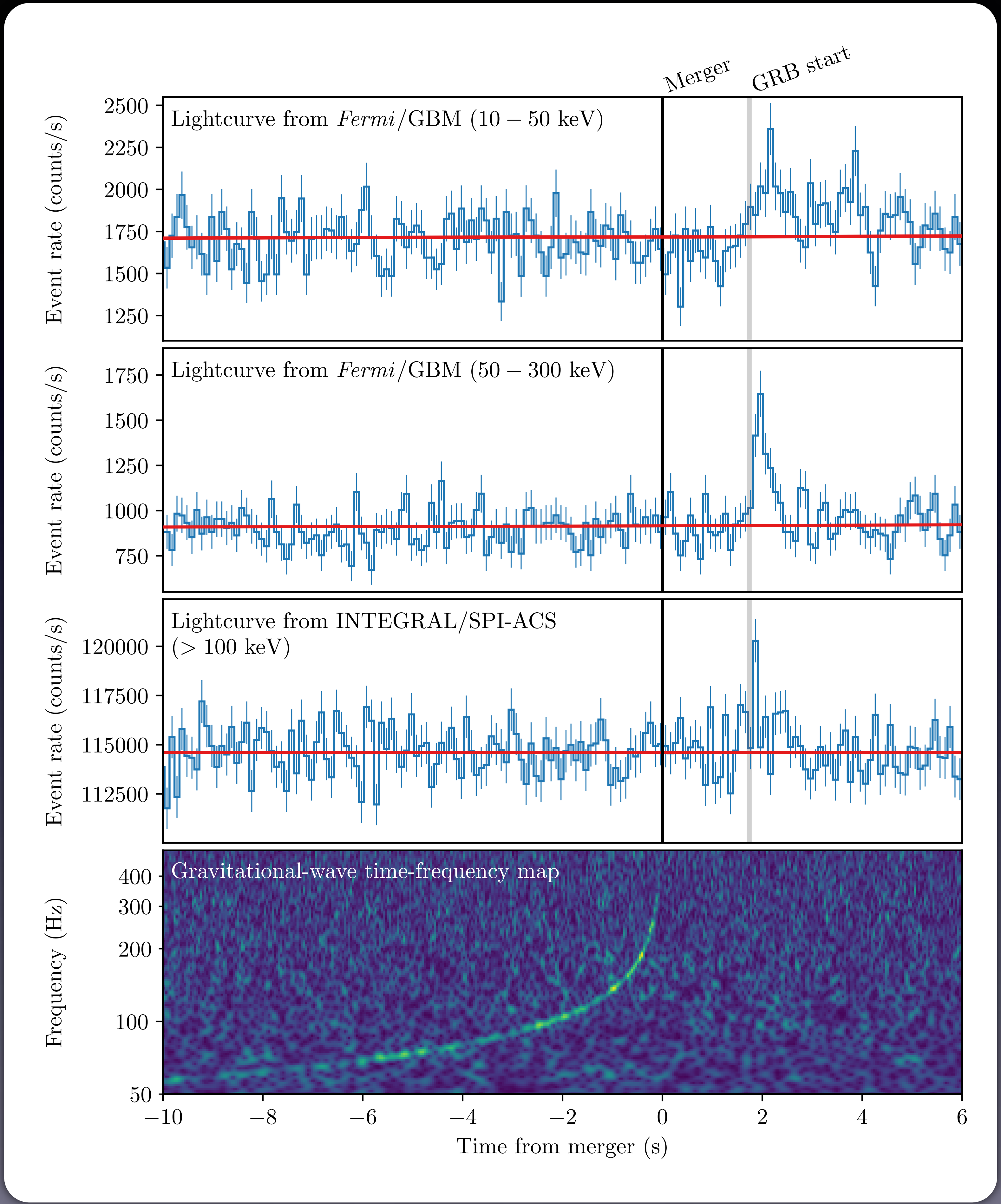
The first detection of GWs from neutron star merger (GW170817)



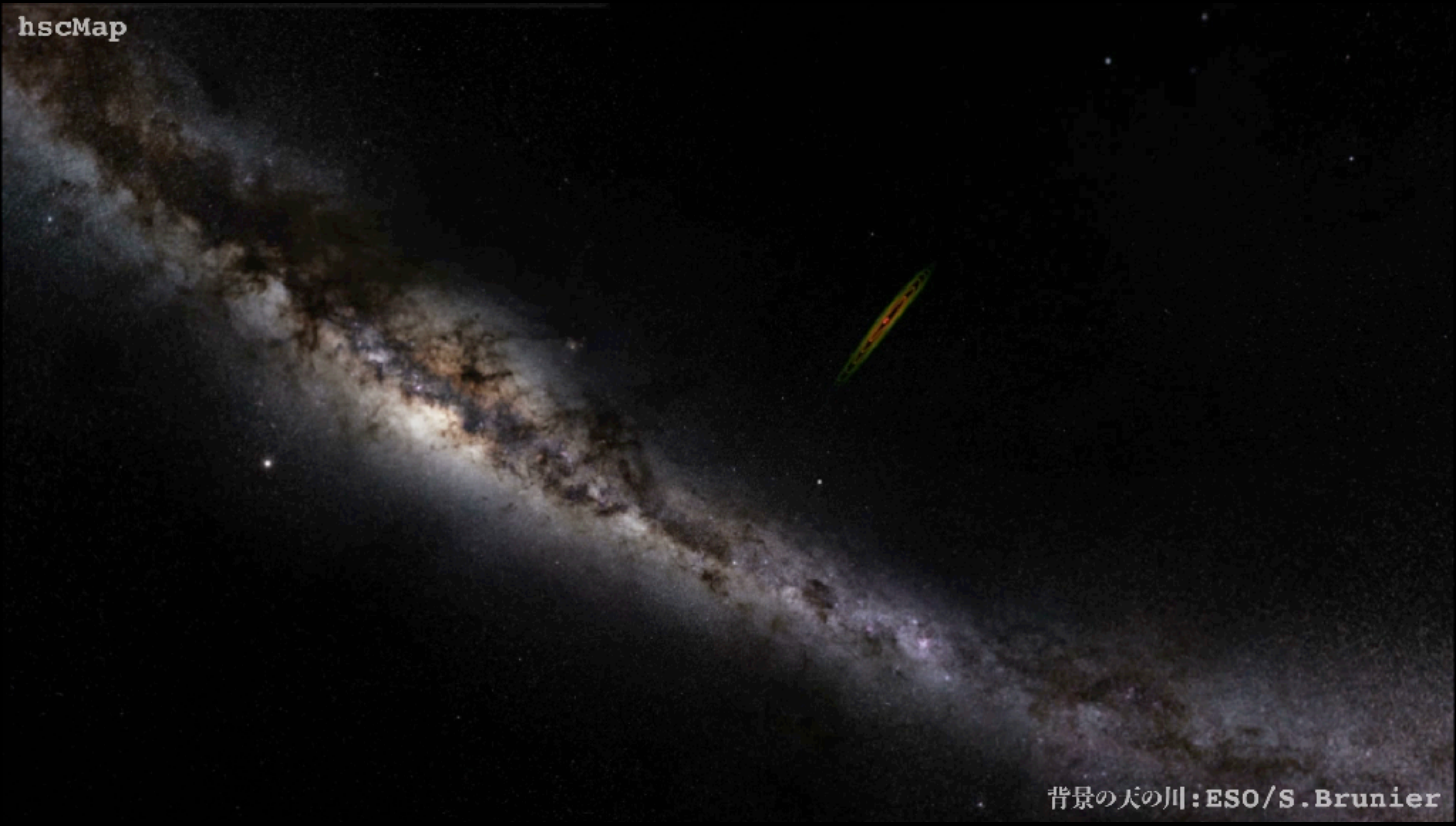
LIGO Scientific Collaboration and Virgo Collaboration, 2017, PRL

Gamma-ray
Fermi & INTEGRAL

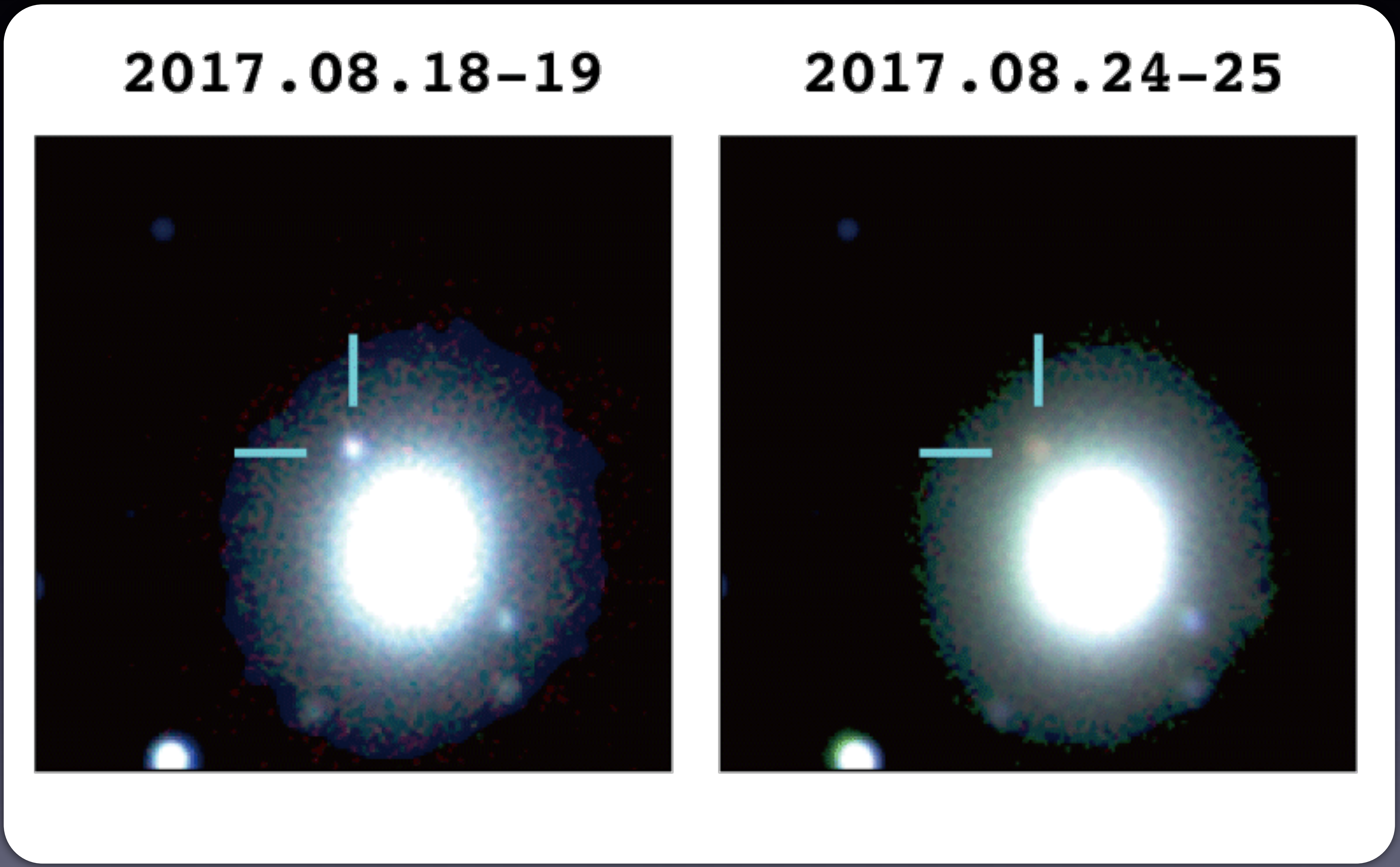
~2 sec after the merger



LIGO Scientific Collaboration
and Virgo Collaboration, 2017, ApJ


hscMap
背景の天の川：ESO/S.Brunier

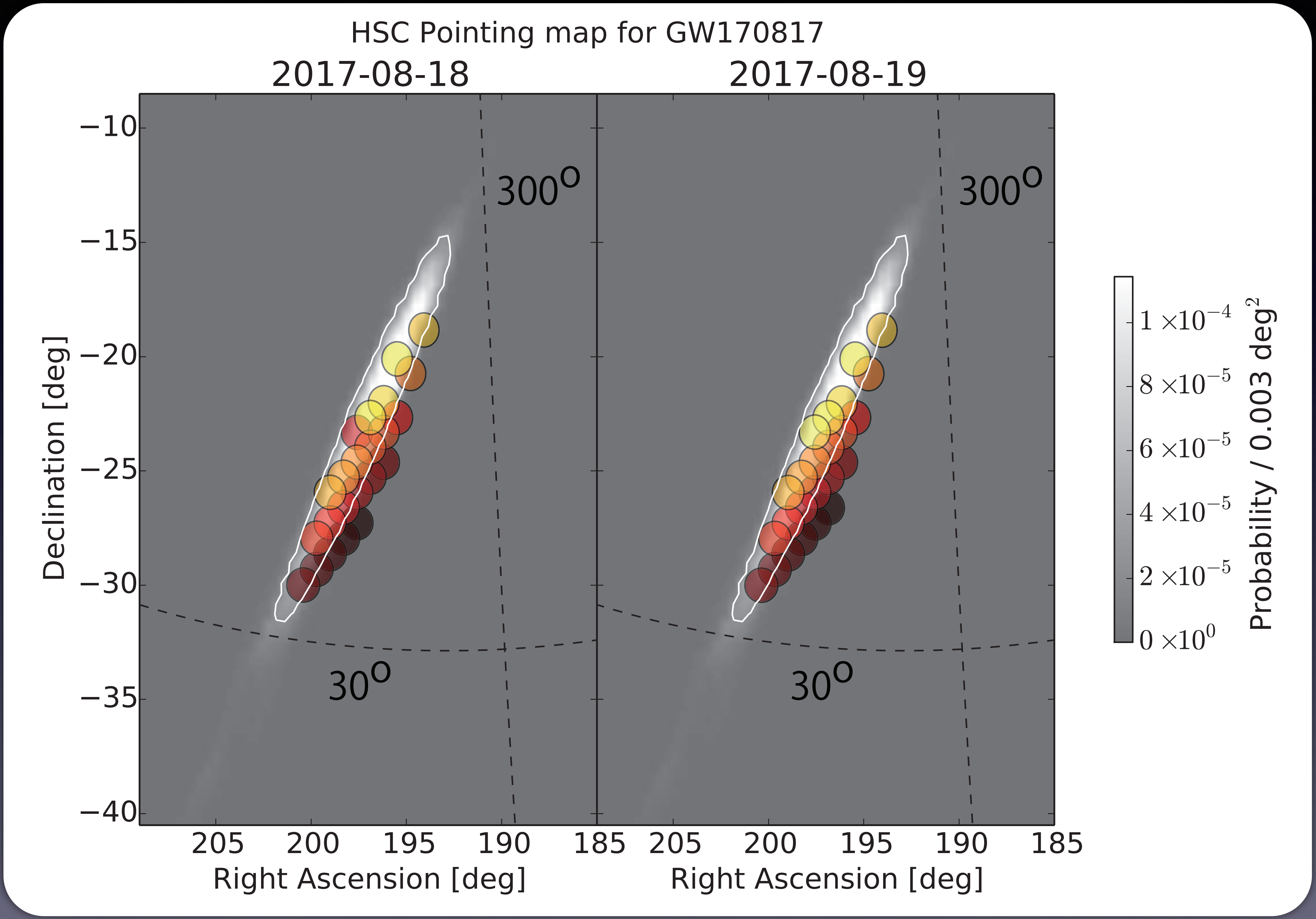
Electromagnetic counterpart of GW170817 @ 40 Mpc



Subaru/HSC z +IRSF/SIRIUS H, Ks

(Utsumi, MT et al. 2017, PASJ)

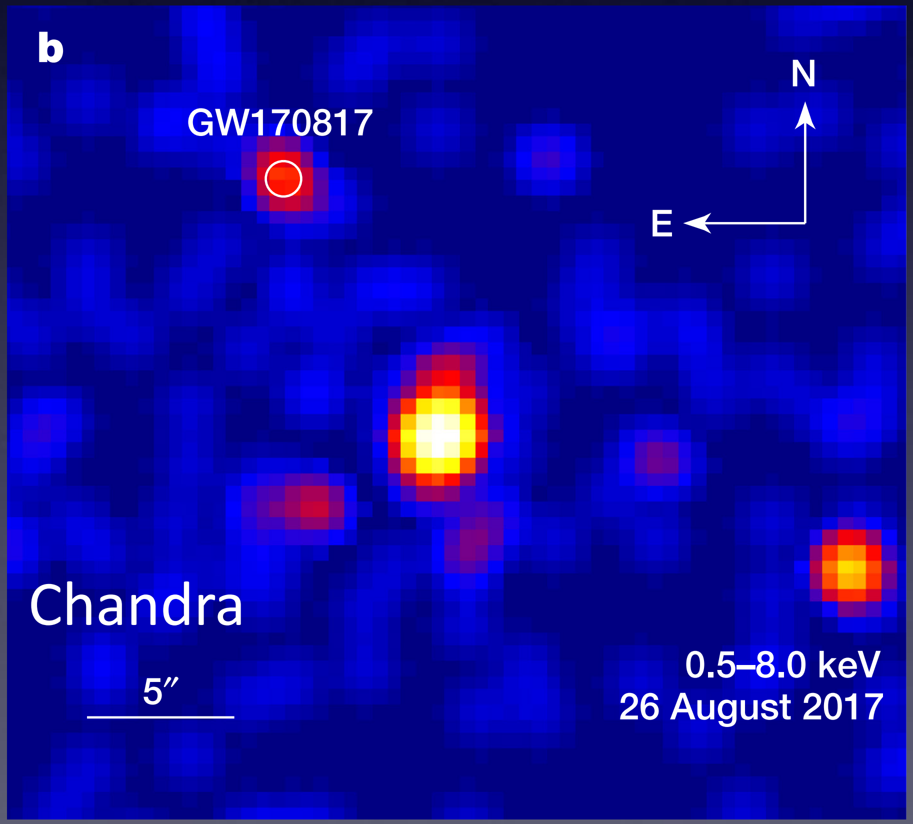
Survey with Subaru/HSC

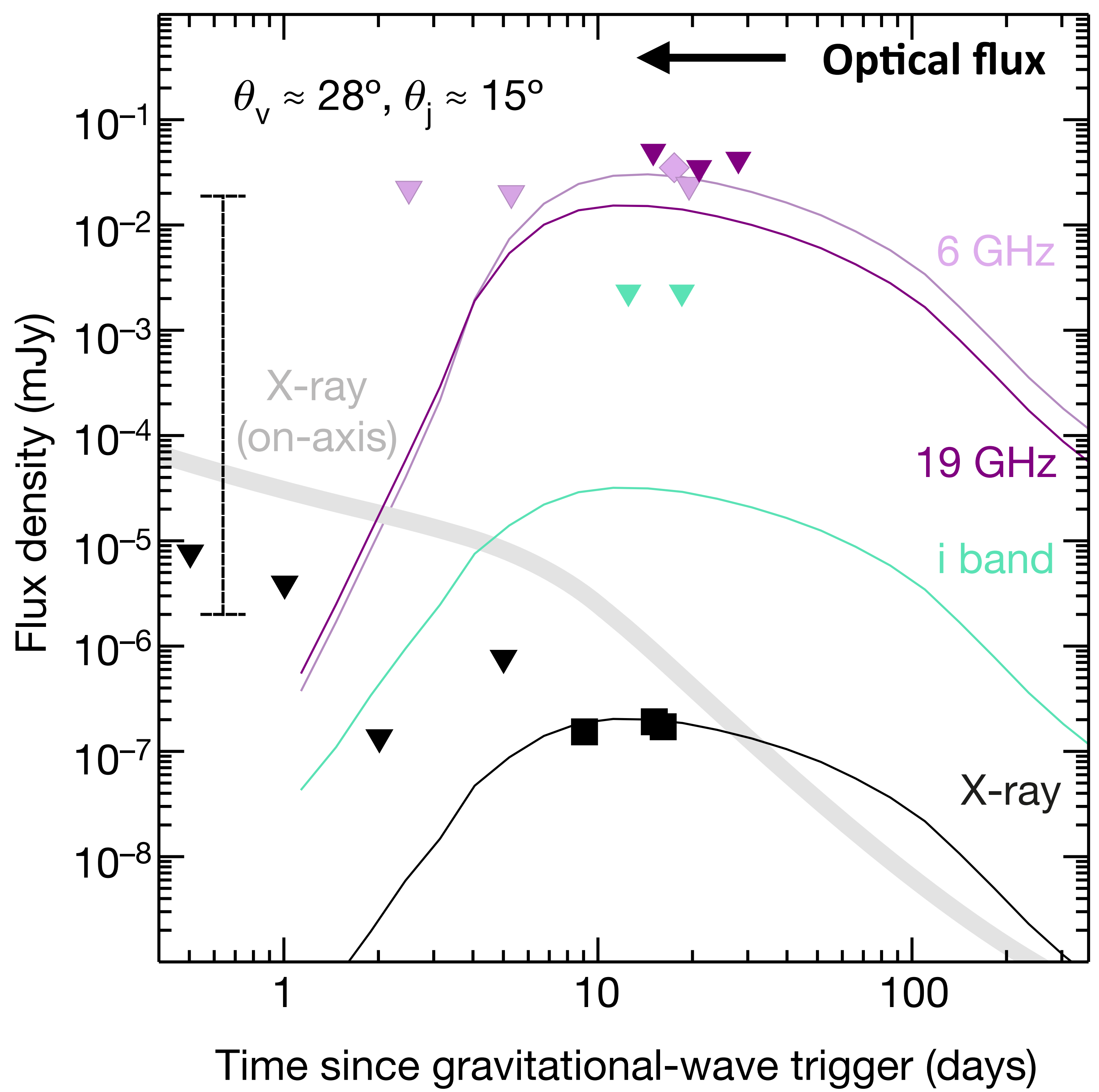


Tominaga, MT et al. 2017,
PASJ, arXiv:1710.05865

No other transient

X-ray and radio @ ~10 days





Troja+17

Summary of multi-messenger observations

Abbott+17

GRB

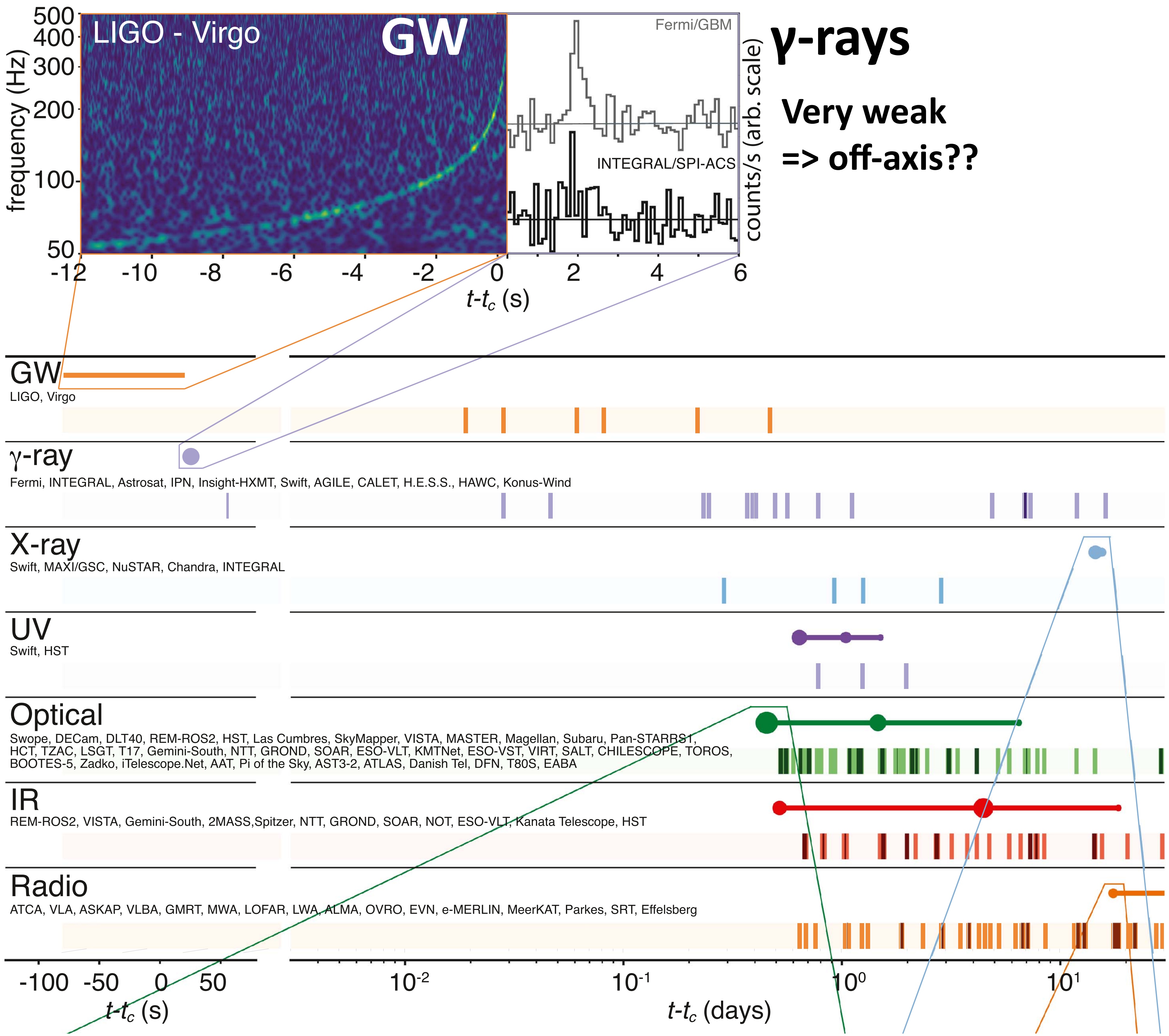
X-ray

Blue kilonova

Red kilonova

Radio

Everything!!



γ-rays

Very weak
=> off-axis??

What we learn from multi-messenger astronomy

- **Hubble constant**
  - GW => luminosity distance, EM => redshift
  - $H_0 = 70^{+12}_{-8}$ km s^{-1} Mpc^{-1}
- **Speed of GW**
  - Gamma-rays arrived 1.7 s after the merger (after 130 M light year race => 4 x 10^{15} s)
- **Jet formation in the merger**
  - ~2 sec?
- **Physics of neutron stars**
  - R ~< 14 km (for 1.4 Msun NS) <= GW phase
- **Origin of heavy elements!**

Light curves of kilonova

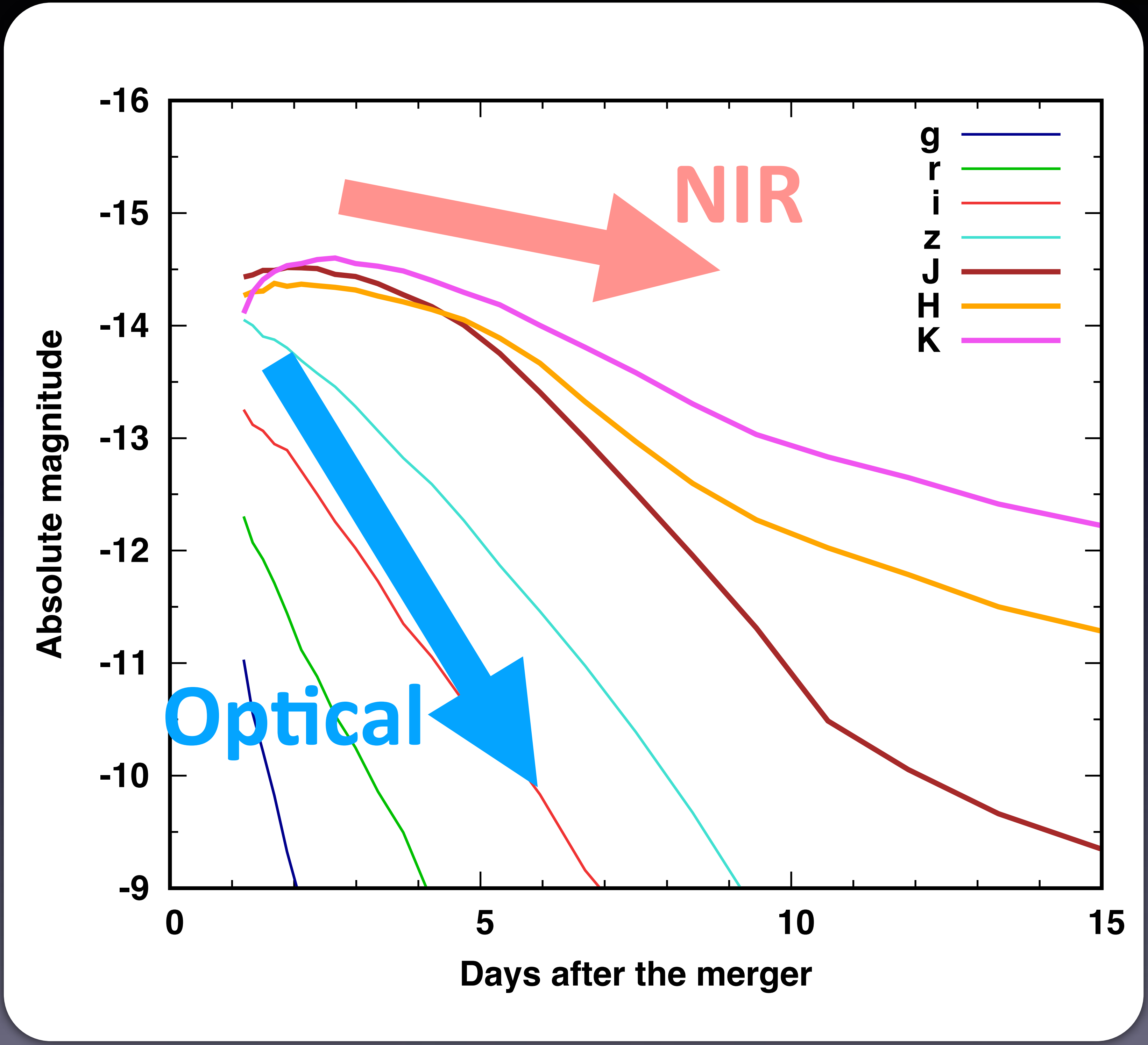
MT & Hotokezaka 13, MT+14,

$L \sim 10^{40}$-10^{41} erg s^{-1}

t ~ weeks

NIR > Optical

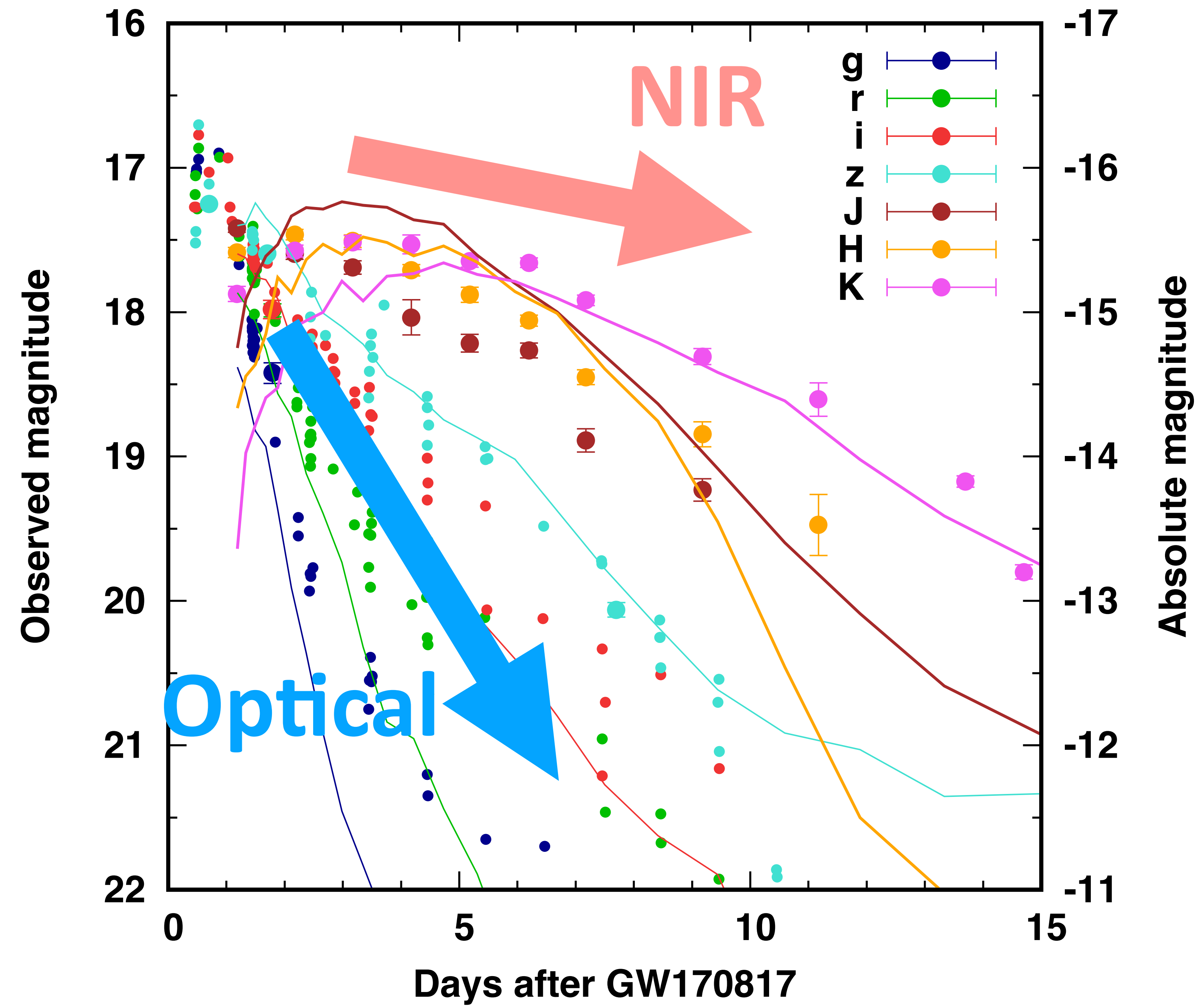
Smooth spectra



Model: MT+17a

GW170817: light curves

- Brightness
- Timescale
- SED



Model: MT+17b

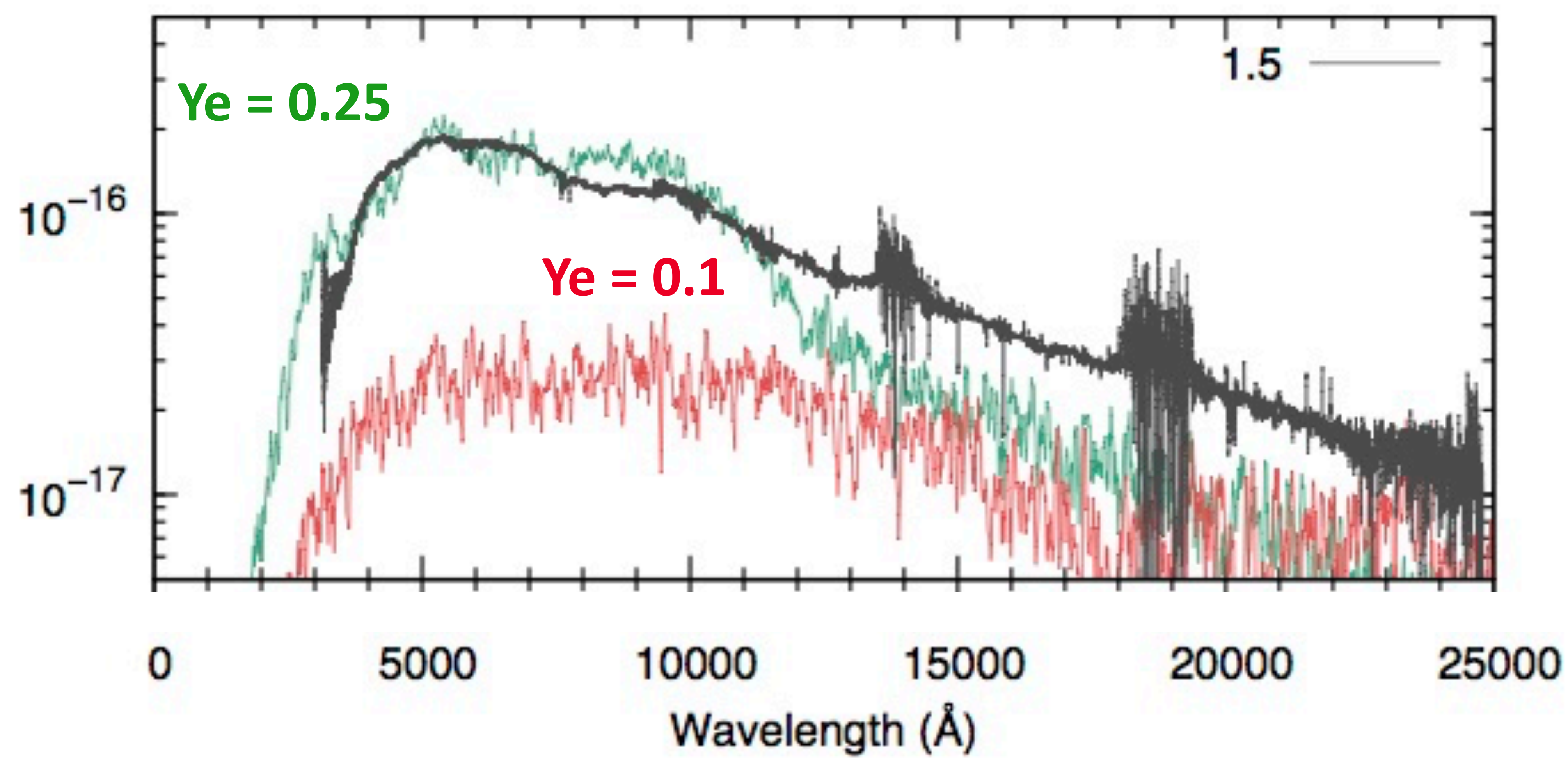
Data: Utsumi, MT+17, Drout+17, Pian+17, Arcavi+17, Evans+17, Smartt+17, Diaz+17, Valenti+17, Cowperthwaite+17, Tanvir+17, Troja+17, Kasliwal+17

Clear signature of kilonova!!
Ejecta mass ~0.03-0.05 Msun => post-merger ejecta!?

Presence of “blue” kilonova

=> wide range of r-process elements

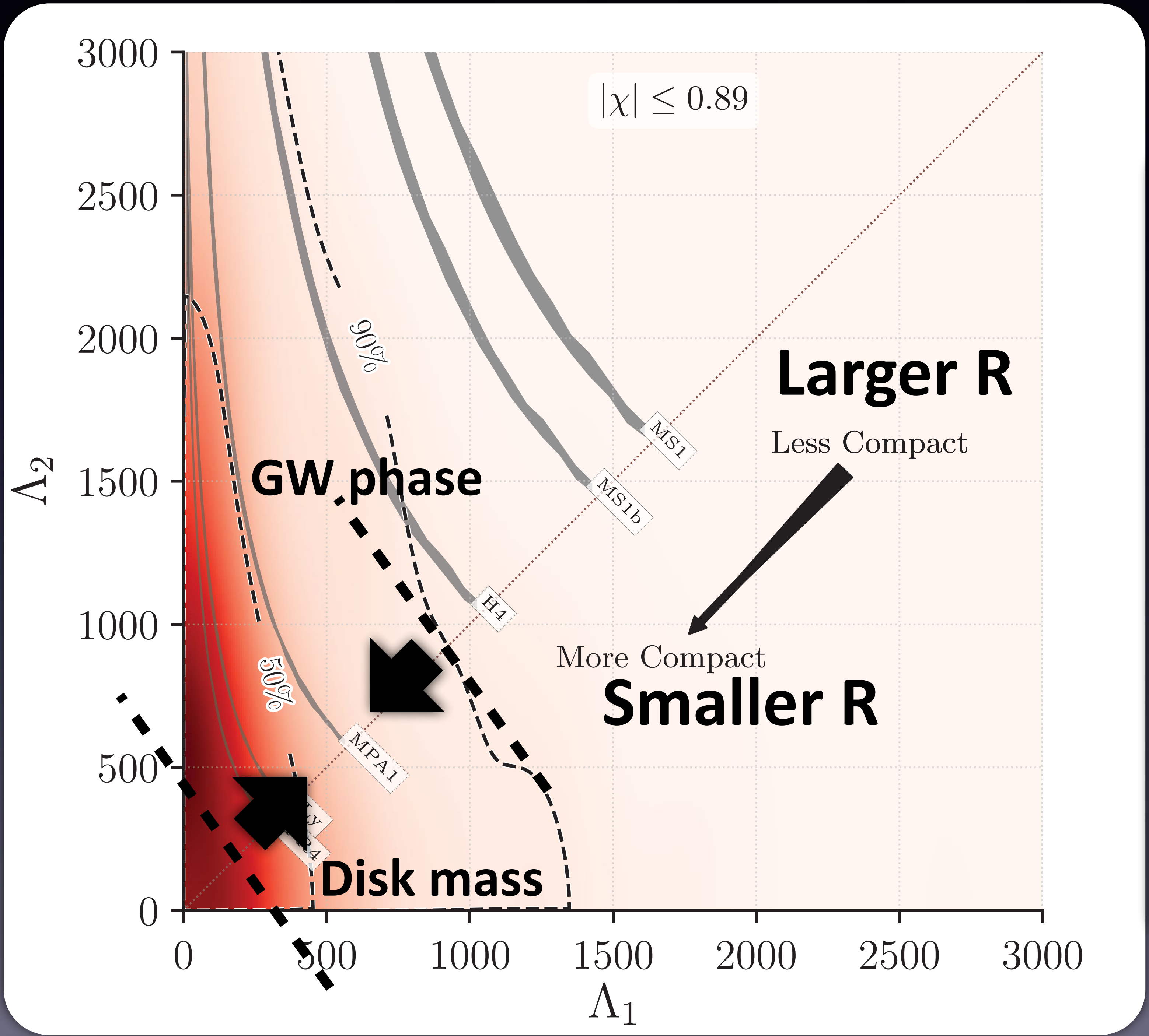
MT+2017



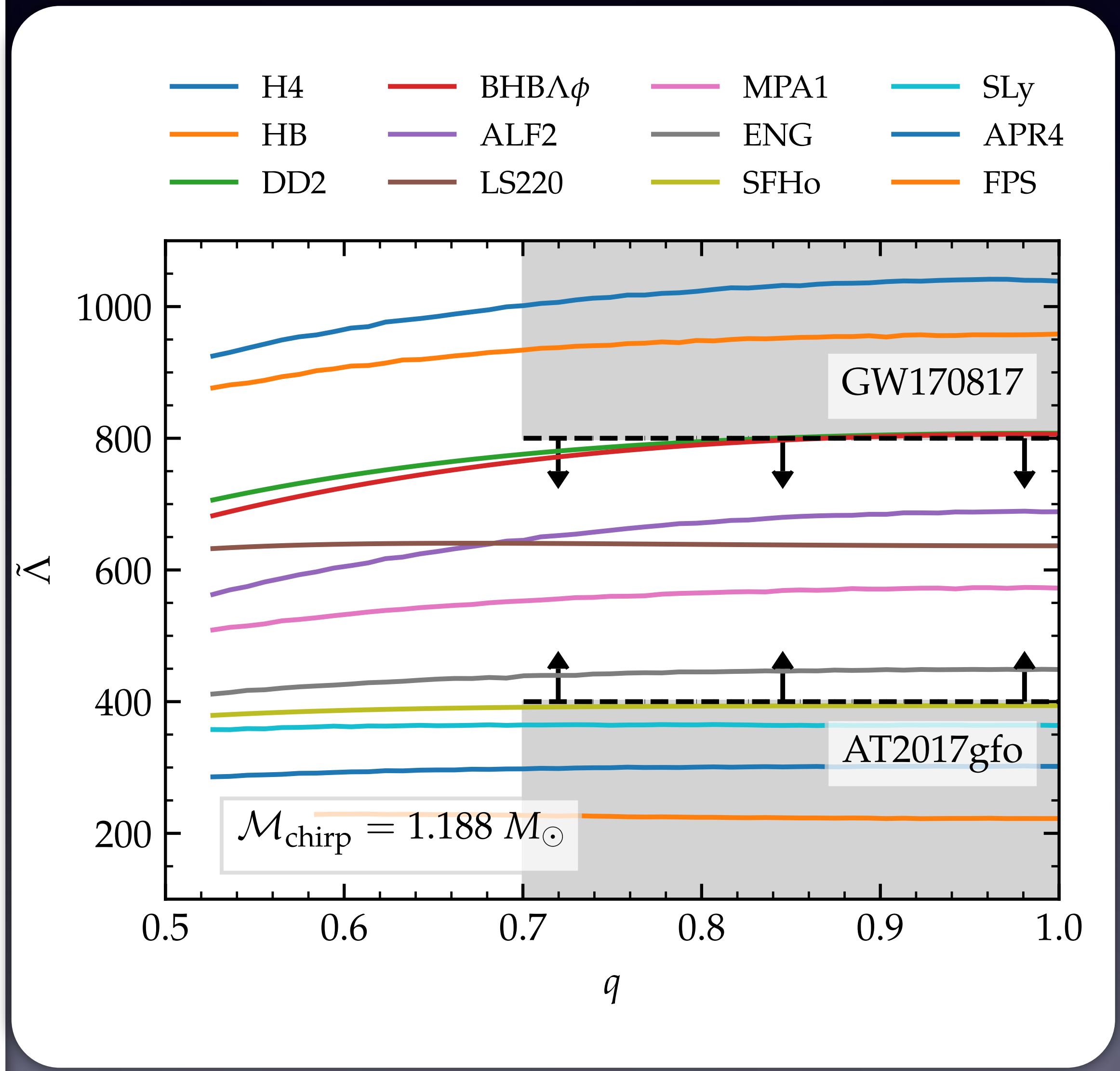
See also Cowperthwaite et al. 2017;
Drout et al. 2017; Nicholl et al. 2017; Villar et al. 2017

Neutron star physics <= GW + EM combination

Tidal deformability Λ ~ (R/M)⁵ (Tidal deformation accelerates GW phase)



LVC+17



Radice+17 (arXiv:1711.03647)

See also shibata+17

NS merger as an origin of r-process elements

Event rate

$R_{NSM} \sim 10^3\ Gpc^{-3}\ yr^{-1}$

$\sim 1 / 10^4$ yr in 1 galaxy

~ 30 GW events yr^{-1}

(w/ Adv. detectors, < 200 Mpc)

↑

GW170817

$R_{NSM} \sim 1500^{+3000}_{-1200}\ Gpc^{-3}\ yr^{-1}$

Ejection per event

M_{ej}(r-process) $\sim 10^{-2}$ Msun

↑

EM counterpart

~0.03 Msun

Enough to explain the r-process abundance in our Galaxy

$M(\text{Galaxy, r-process}) \sim M_{ej}(r) \times (R_{NSM} \times t_G)$

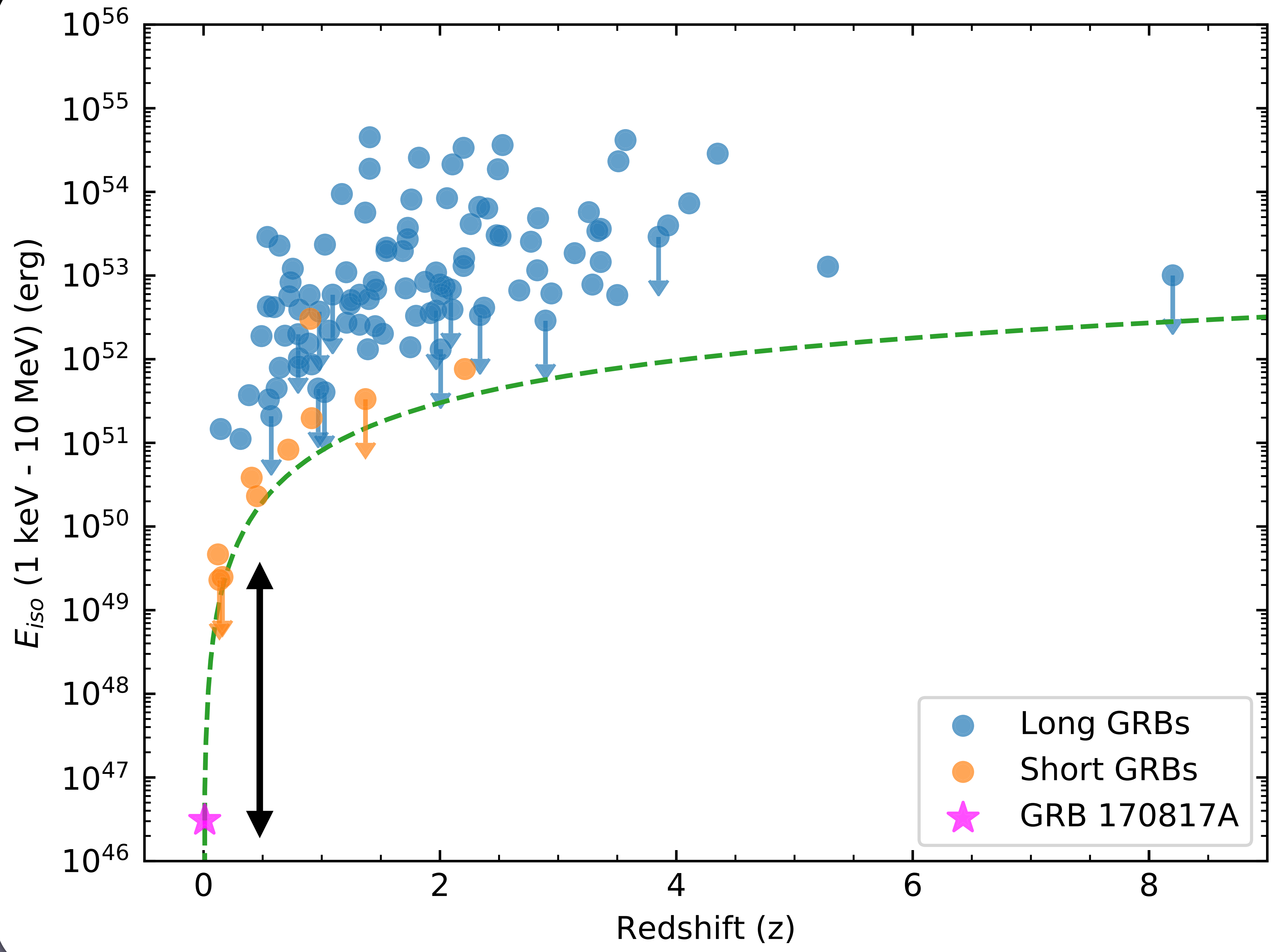
$\sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4$ Msun

Many open questions

- Why (weak) gamma-ray bursts?
- Why relatively early radio?
- Why relatively late X-ray?
- Why high ejecta mass (>0.03 Msun, not 0.01 Msun)?
- What is the abundance patterns?
  Is it consistent with solar abundances?
- What is a delay time?
- What happens for different total masses,
  mass ratios, and BH-NS merger?

Need more observations
with different masses and viewing angles

Extremely weak gamma-rays



An interpretation for gamma/X/radio

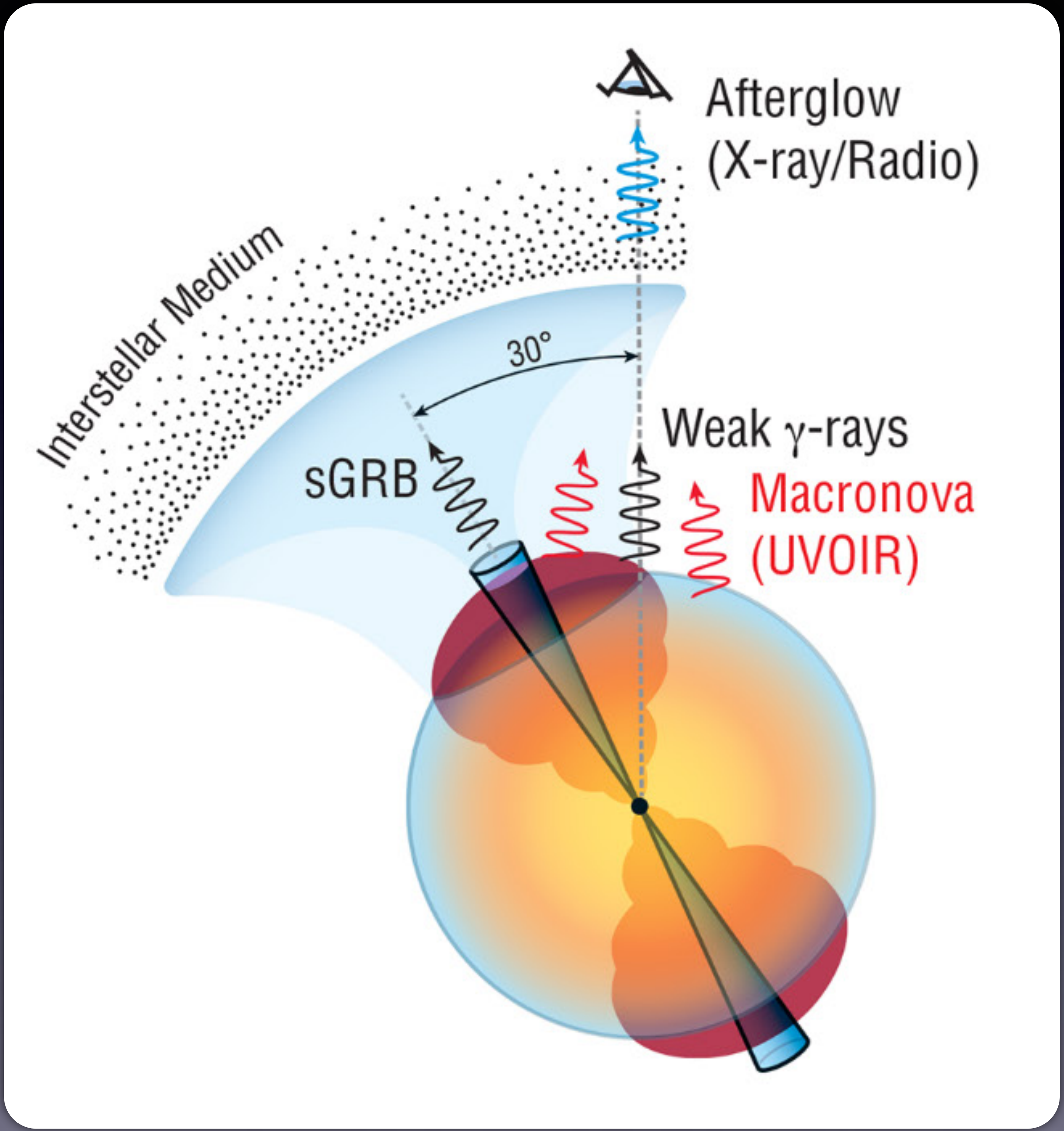
- Jet + cocoon
- Off-axis viewing angle

=>

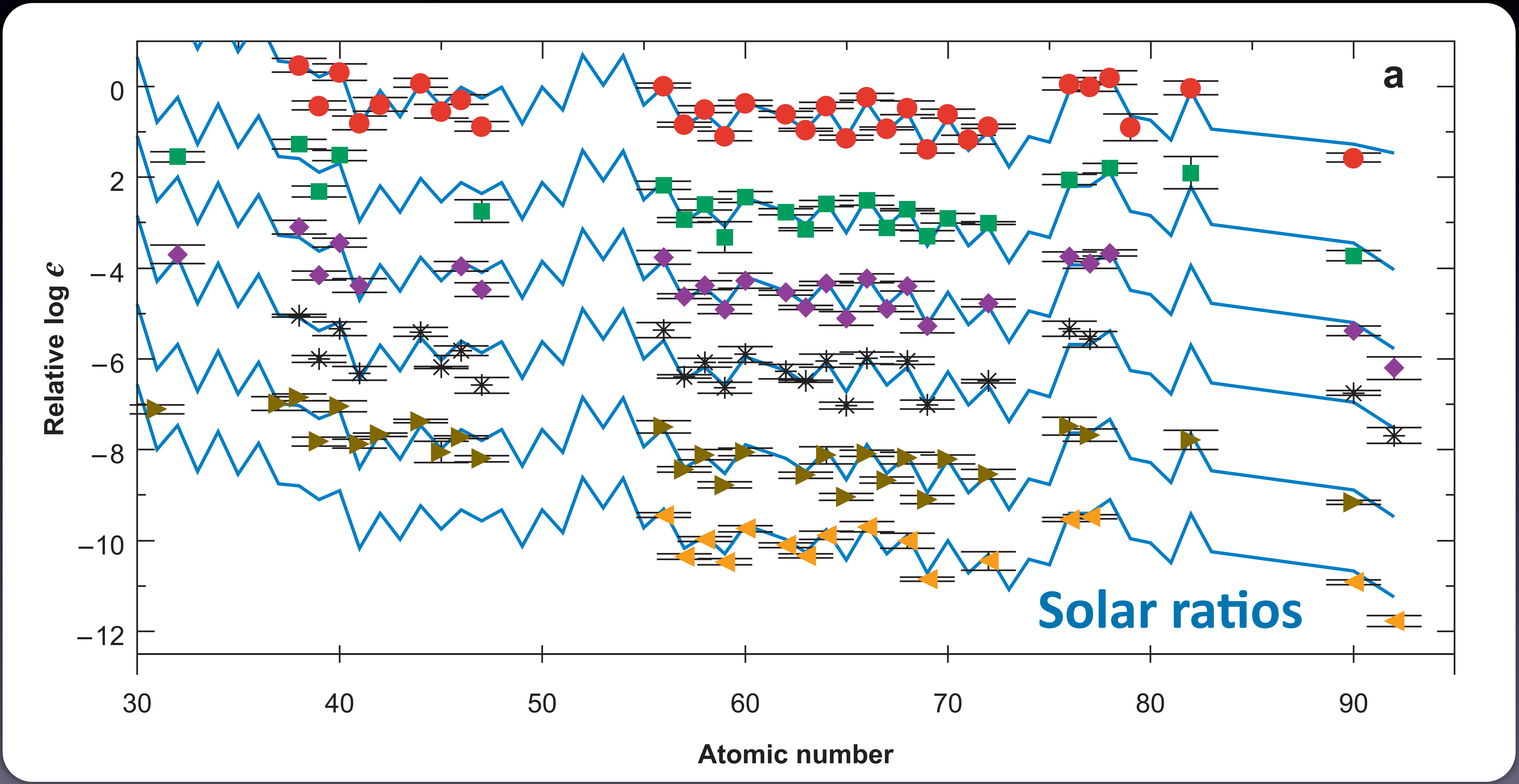
weak gamma-rays

X-ray & radio afterglow

Kasliwal+17

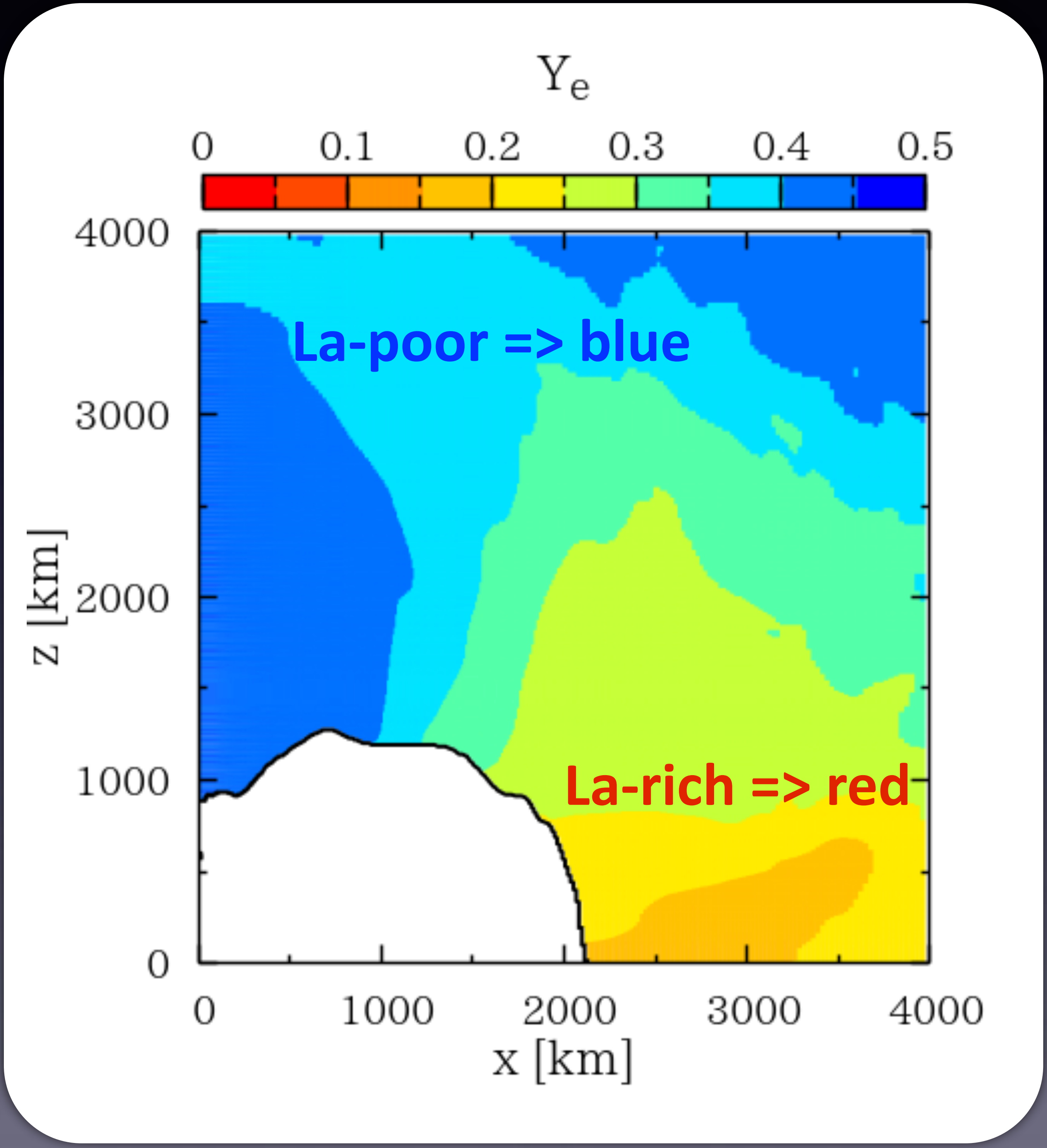


Galactic stars: “Universality” of r-process abundances



Sneden+2008

NS mergers reproduce solar abundances??
=> need a wide range of Ye



$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$

=> more events with different viewing angles!

Shibata+17

Summary

- **GW170817**
  - Wide range of EM signals
  - Opt/NIR emission consistent with (blue+red) kilonova
  - Confirmation of r-process in NS merger
- **Open questions and future prospects**
  - Origins of gamma-rays, X-rays, and radio emission
  - Mechanism of high mass ejection
  - Abundance patterns (solar parttern?)
  - More events with different masses, mass ratios, viewing angles
  - BH-NS mergers