EM counterparts of GW DNS mergers and Nuclear MeV gamma-rays

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Outline

- Overview of EM counterparts of neutron star mergers

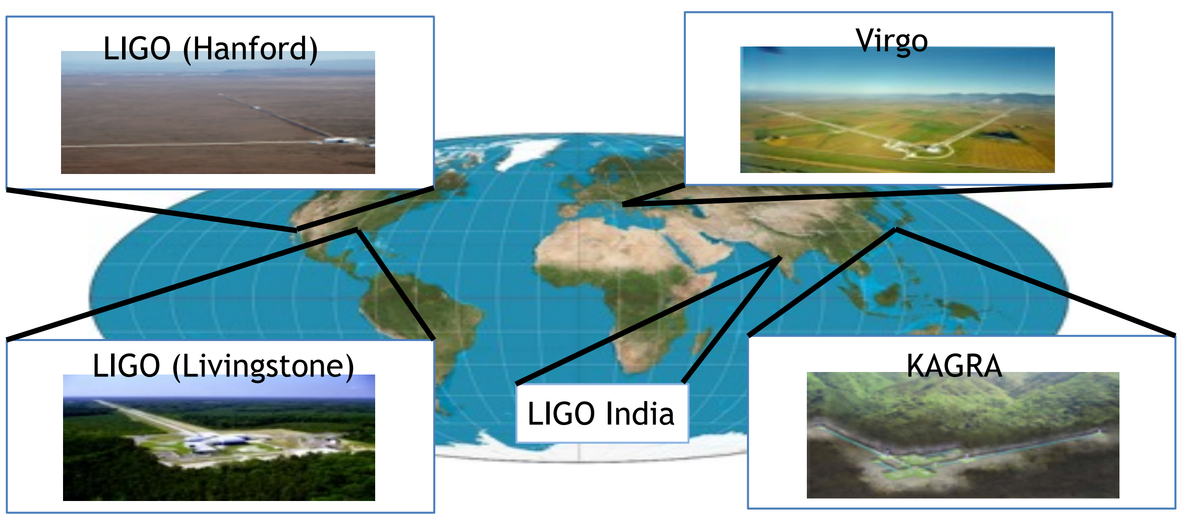
- R-process Kilonova/Macronova

- Nuclear gamma-rays from neutron star mergers:
  Important & Difficult

Gravitational-Wave Astronomy

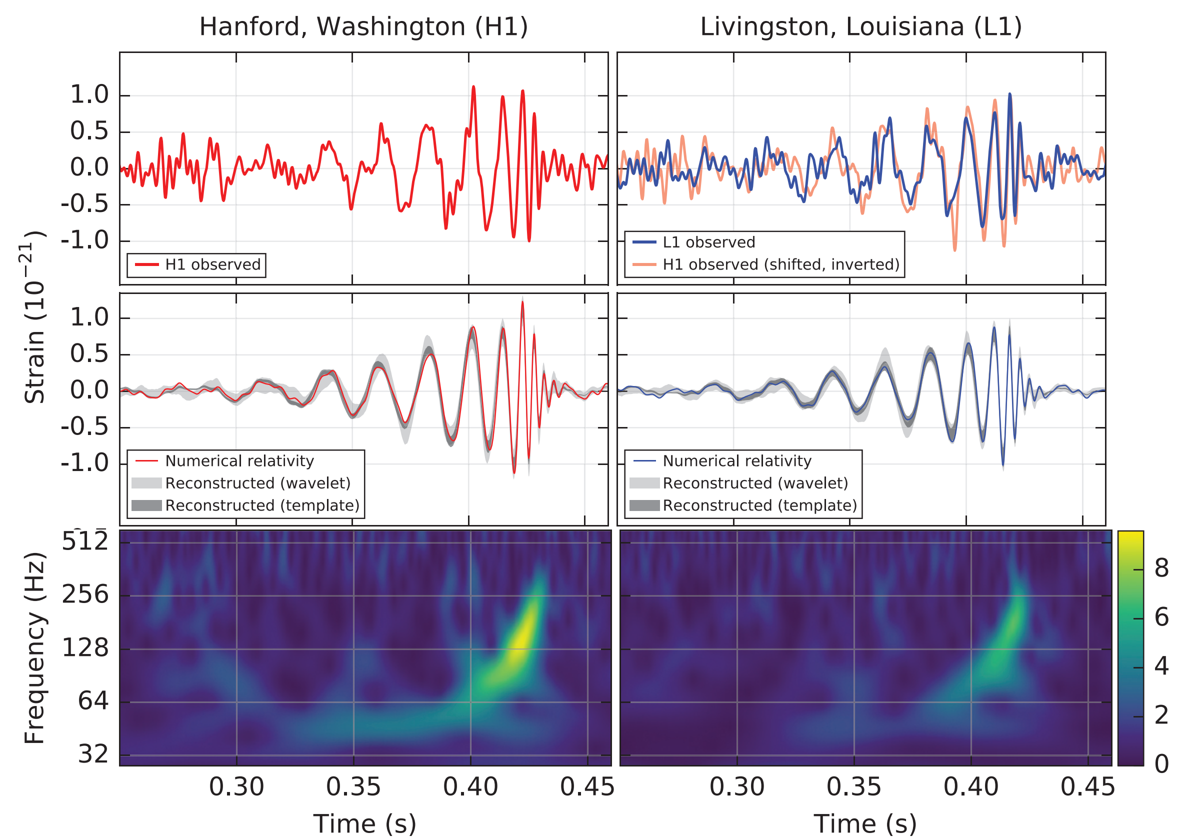
Two LIGO's detector discovered gravitational waves from binary black holes.

GW detector Netwok



The GW detector network is growing in the world.

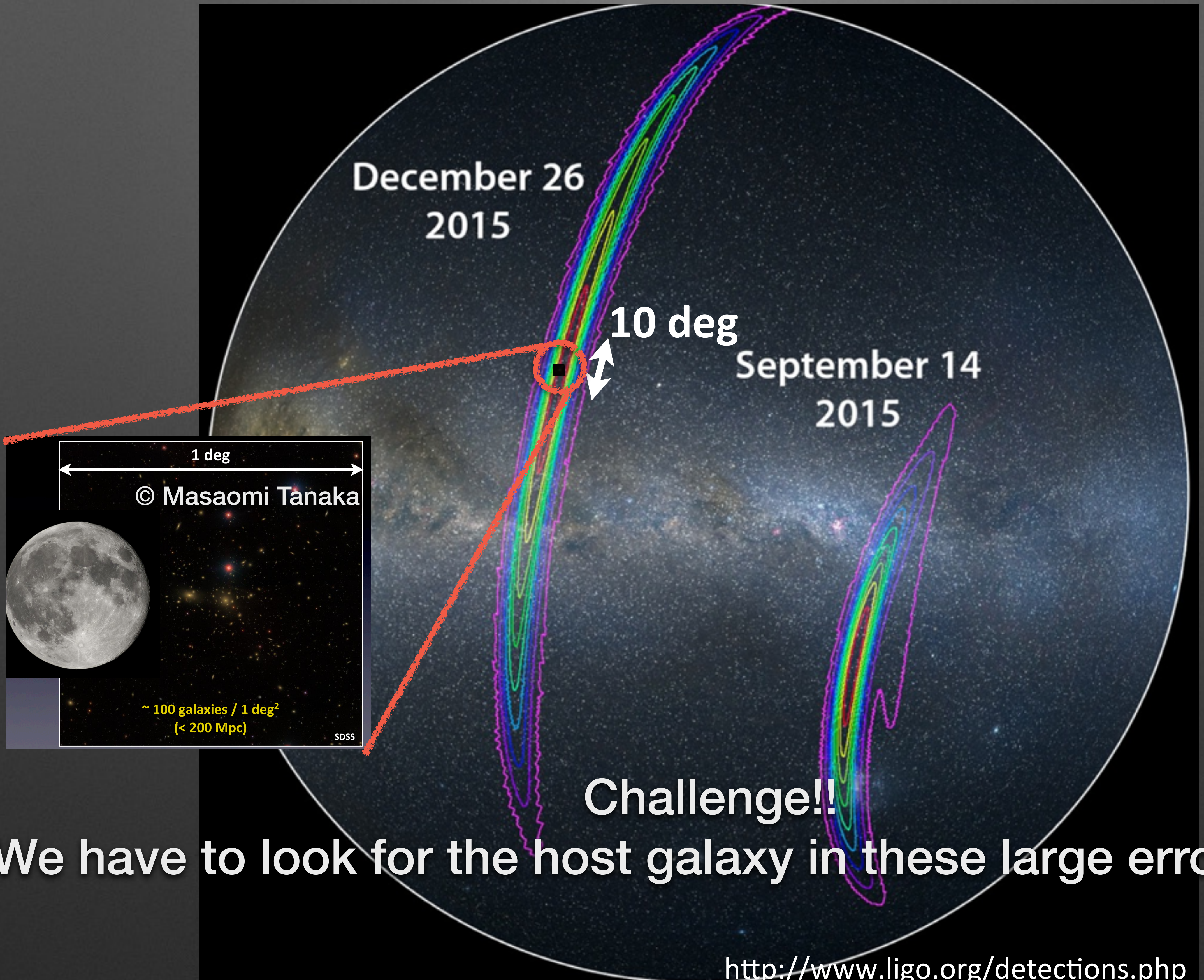
LIGO detected double black hole mergers



Abbott + 2016

The GW network tells us the location of GW events.
=> Challenge to discover electromagnetic counterparts.
e.g. A possible gamma-ray signal from GW150914 reported by Fermi GBM

Localization of the three LIGO's events



Challenge!!

We have to look for the host galaxy in these large error volume.

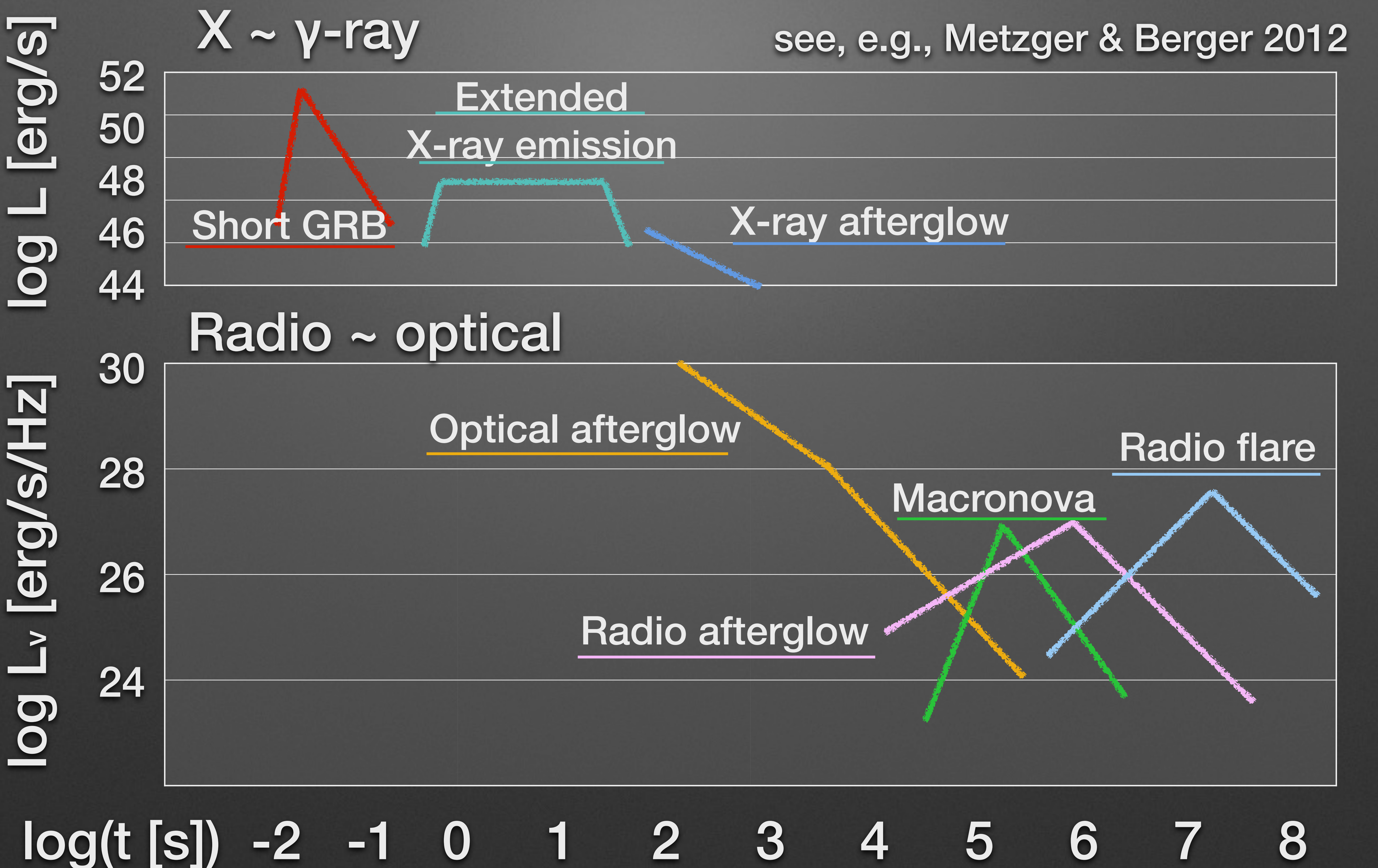
http://www.ligo.org/detections.php

The best strategy to search GW counterparts

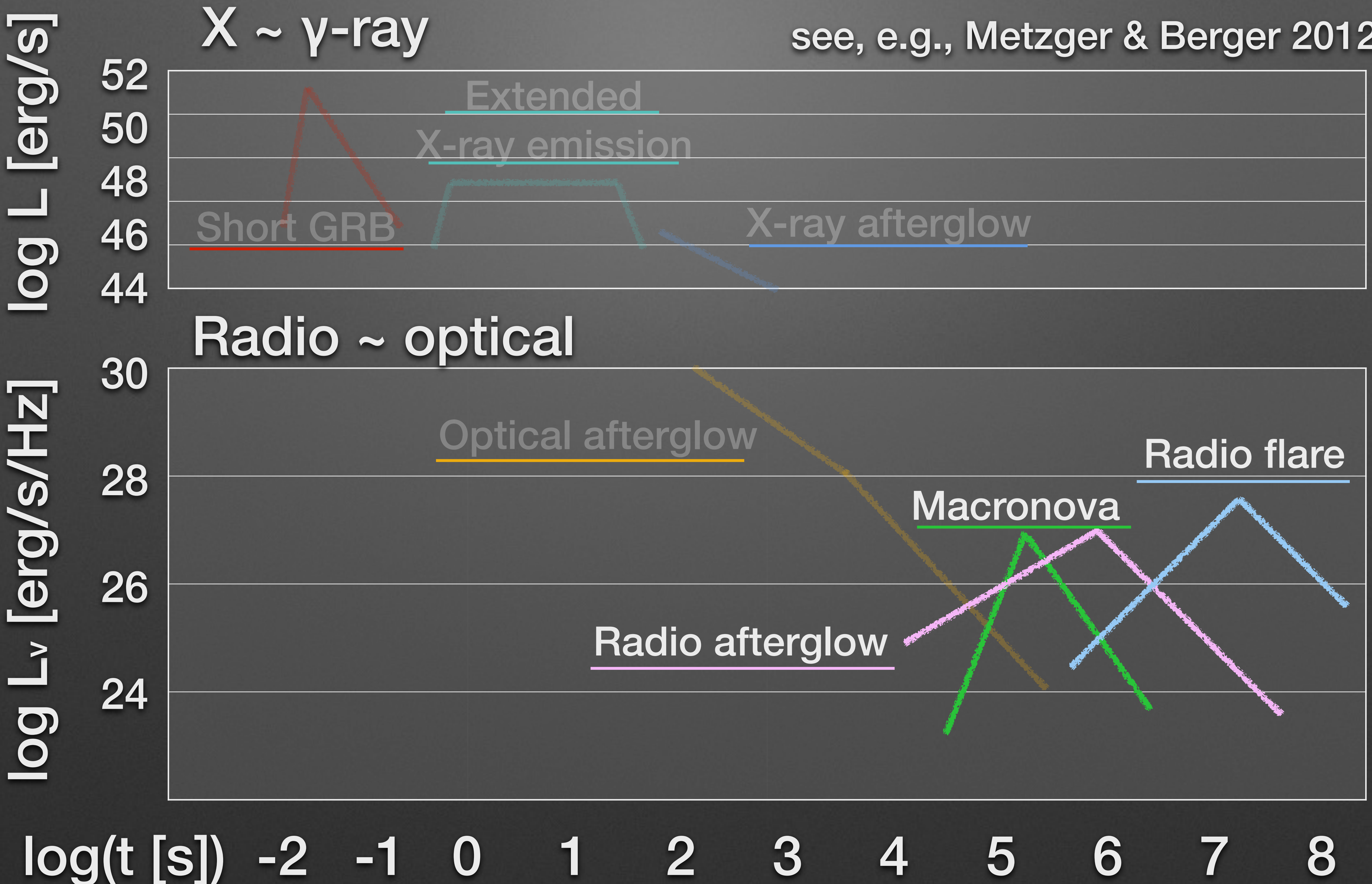
Use the telescope that can reach the largest survey volume on a given time scale and frequency.

i.e., the largest $\frac{d(\text{Survey Volume})}{dt}$

Electromagnetic counterparts of mergers

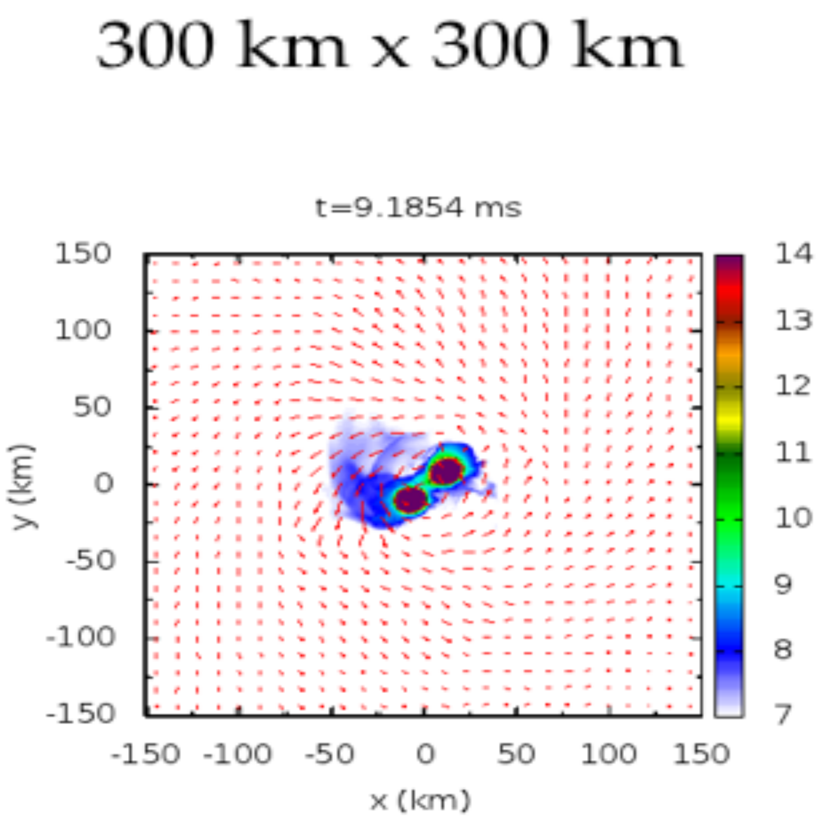


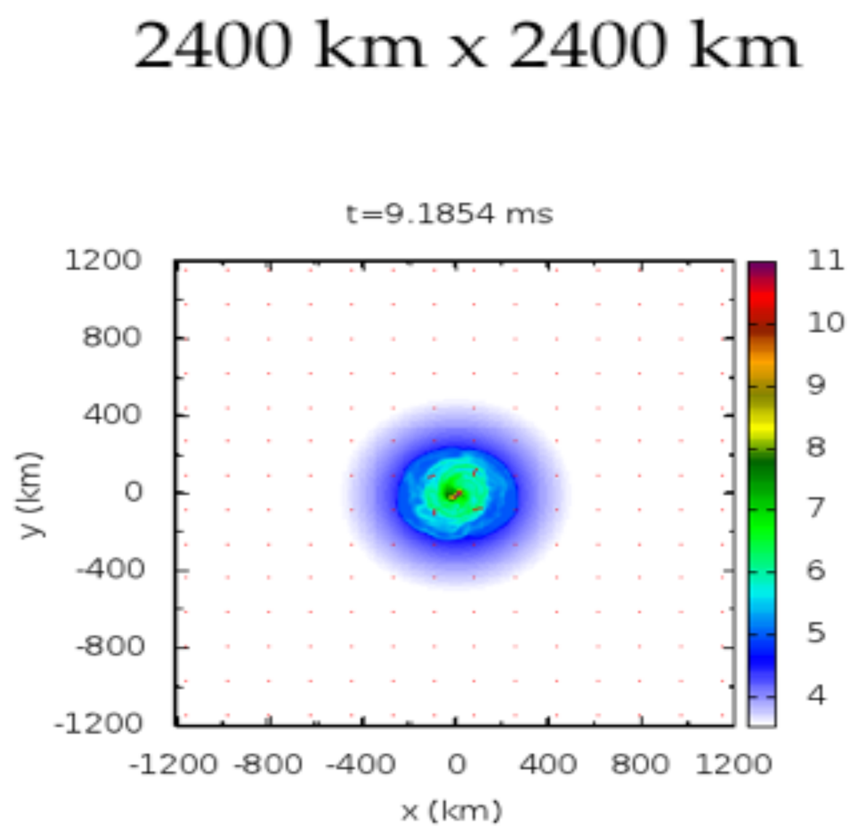
EM counterpart: Isotropic Emission



Dynamical Mass Ejection at Merger

Animation from KH+ 13

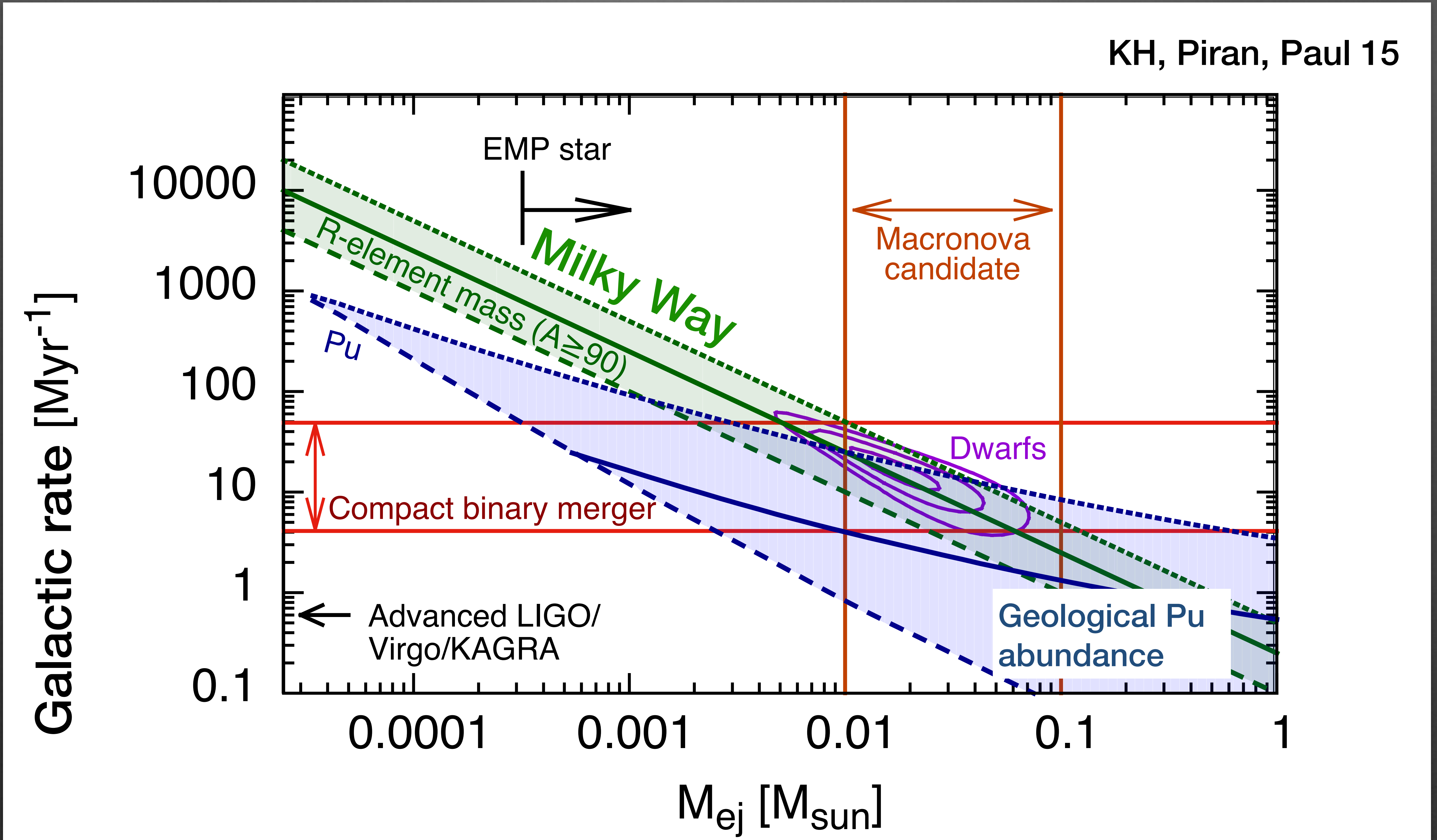




Baryonic outflow: ~ 0.001 - 0.01Msun with 0.1c - 0.3c.
Driven by gravity and hydrodynamics.
=> These ejecta produce electromagnetic signals.

also Davies+94, Freiburghaus+99, Rosswog+00, Ruffert & Janka 01,
Baustein + 13, Piran + 13, Rosswog 13, Kyutoku+15, Sekiguchi + 15, 16, East+16, Radice+16

Rate vs Mass/event of r-process

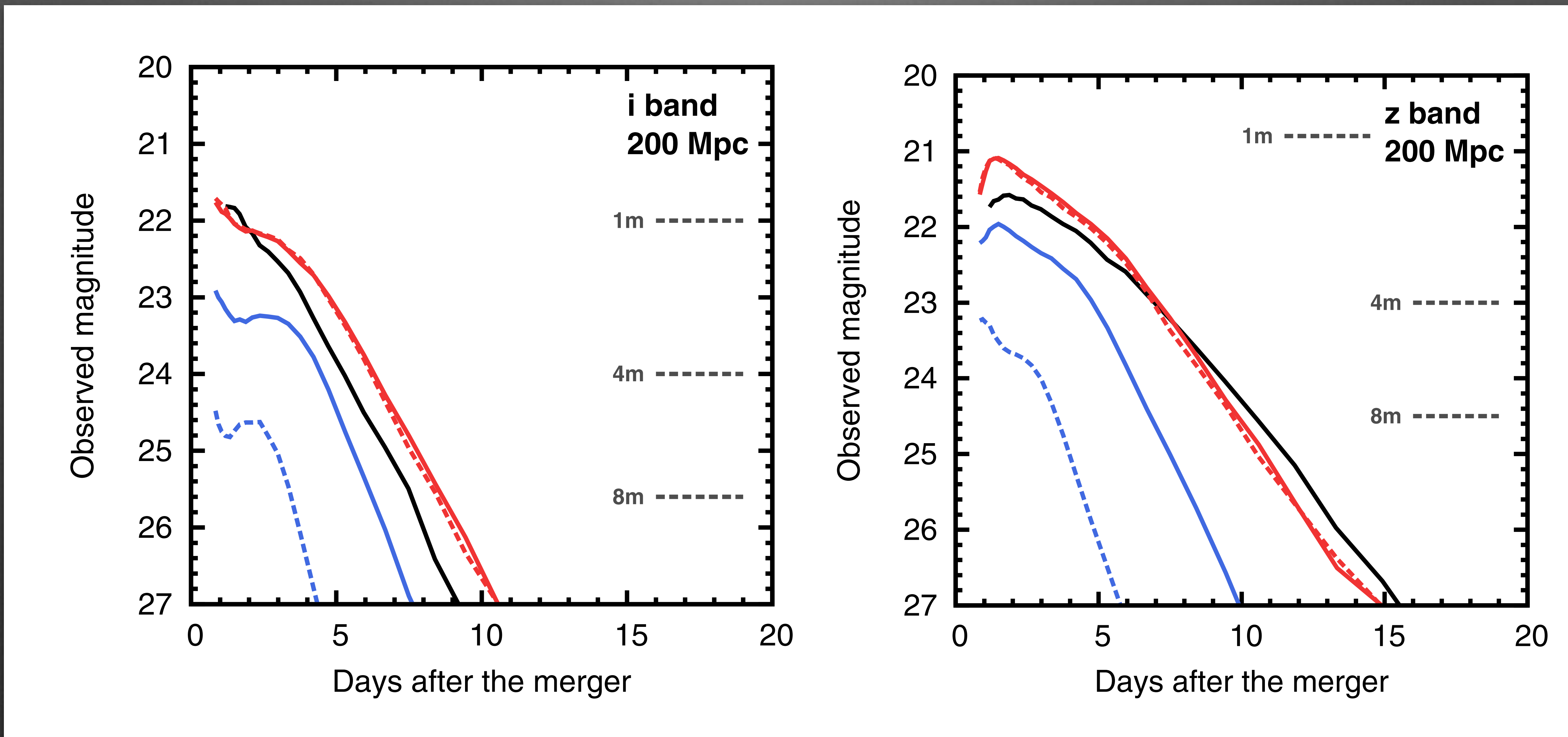


Ref: Battistini&Bensby 16 for the Milky Way, Macias & Ramirez-Ruiz 16 for Extremely Metal Poor Stars, Tuner+07, Wallner +15, KH+15 for geological Pu-244, Ji+16, Roederer+16, Bemiamini, KH, Piran 16 for Dwarf galaxies Tanvir+13, Berger+13, KH+13, Yang+15, Jin+16 for macronovae, Kim+15, Wanderman & Piran 15, Ghirlanda+16 for compact binary mergers

Macronova : Radiation transfer

Double Neutron Star Merger at 200 Mpc

Tanaka & KH 2013
also Barnes & Kasen 2013

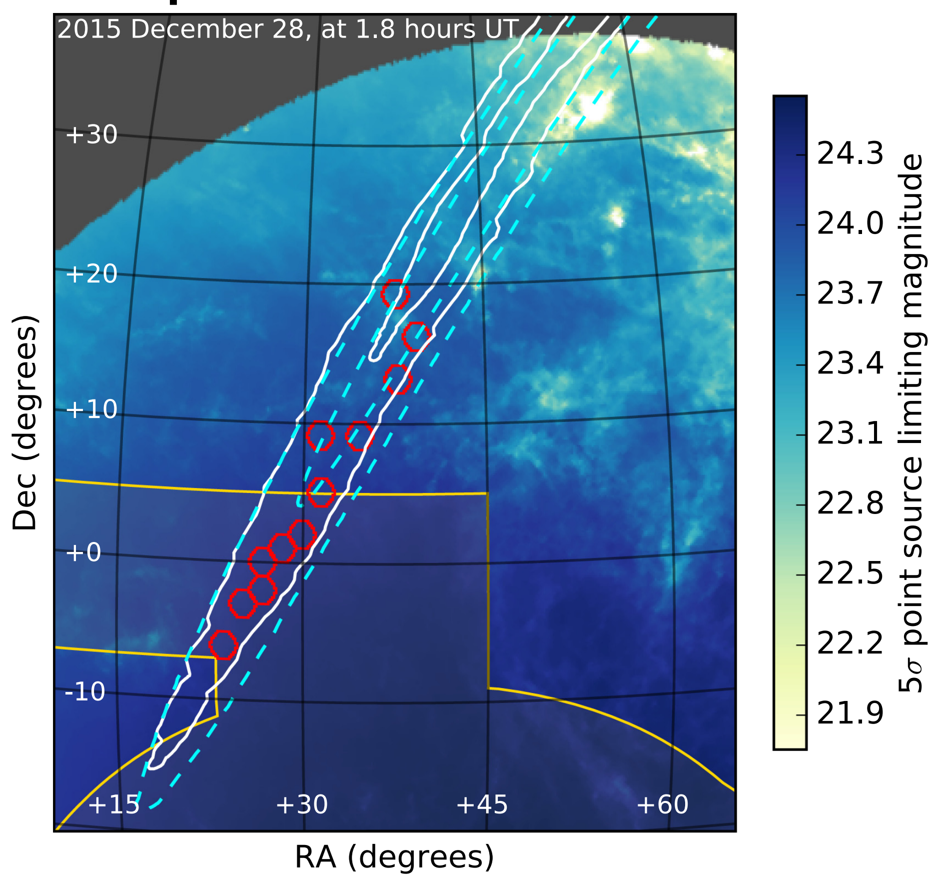


- It is red because of high opacity (Lanthanide) & rapid expansion.
- i & z-band mag ~ 21 - 24th mag within 5 days (optical).

DECam & Subaru follow up of LIGO's O1 Run

DECam: GW151226

Cowperthwaite et al 2017

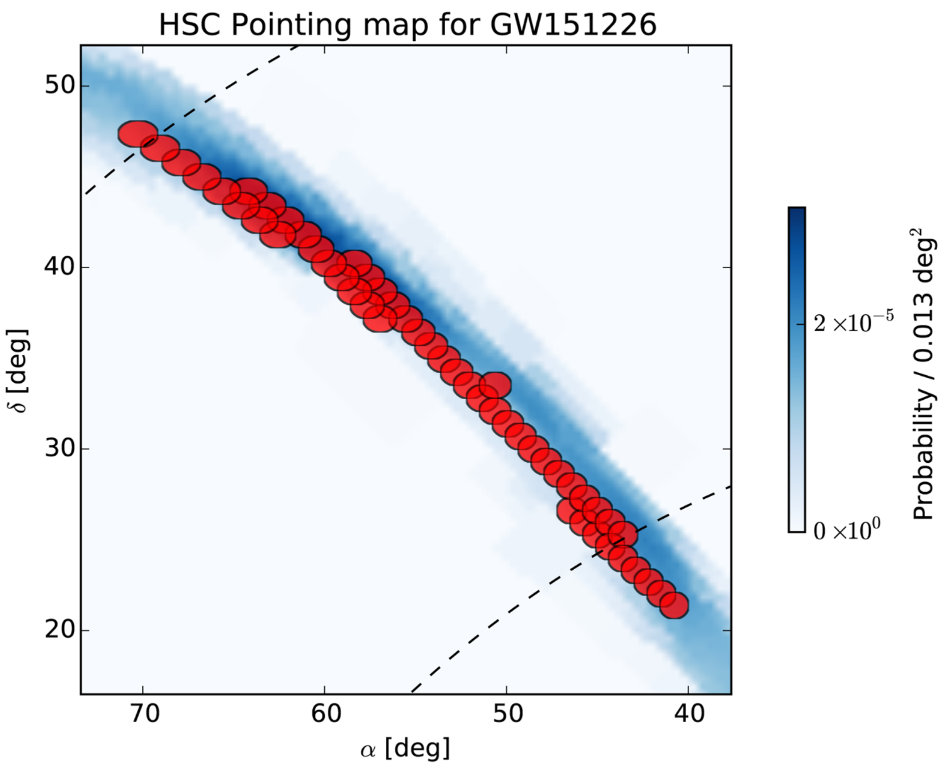


28.8 sq. degree

i, z < 21.7, 21.5 mag

HSC: GW151226

Yoshida et al 2017

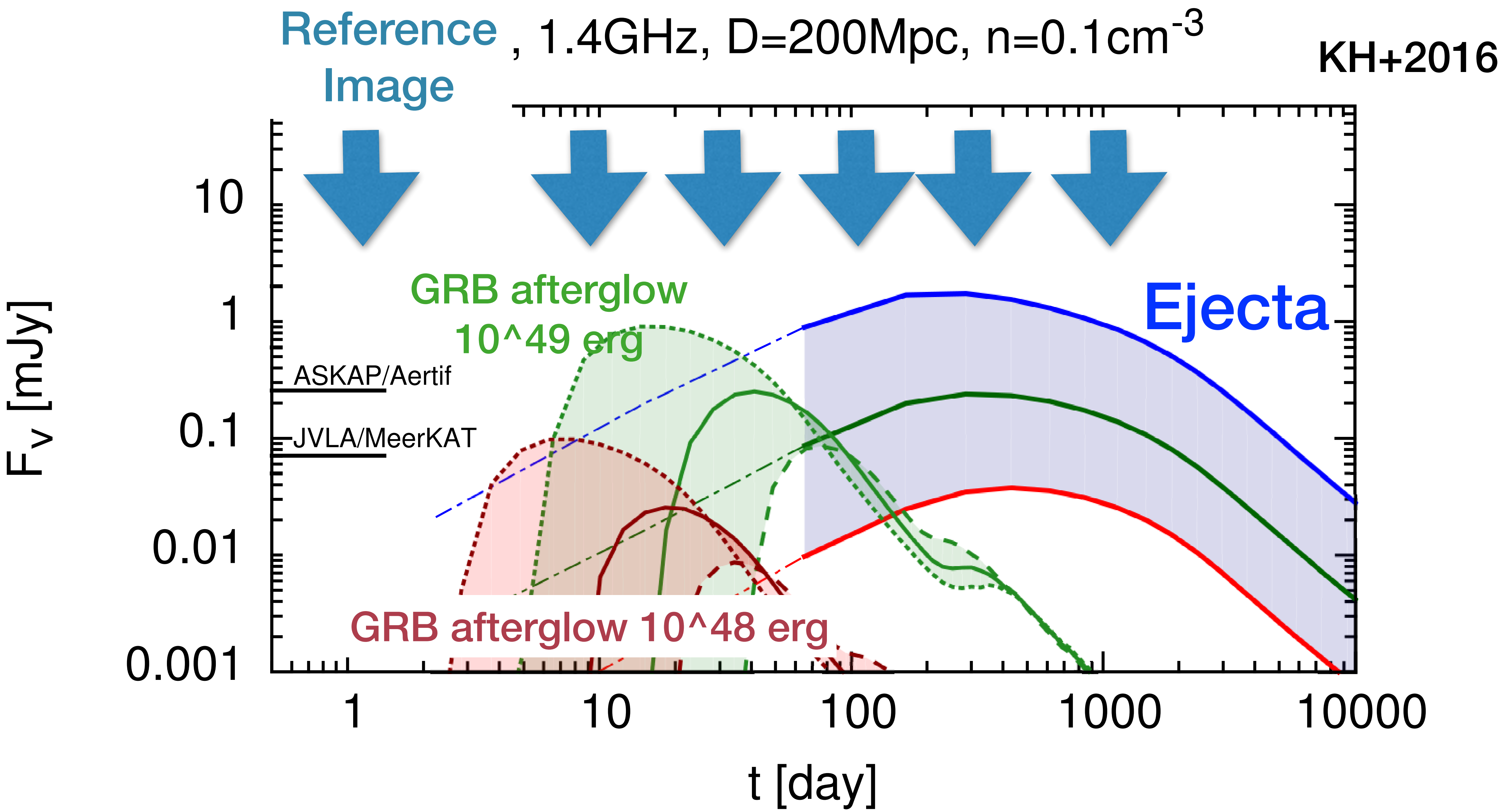


63.5 sq. degree

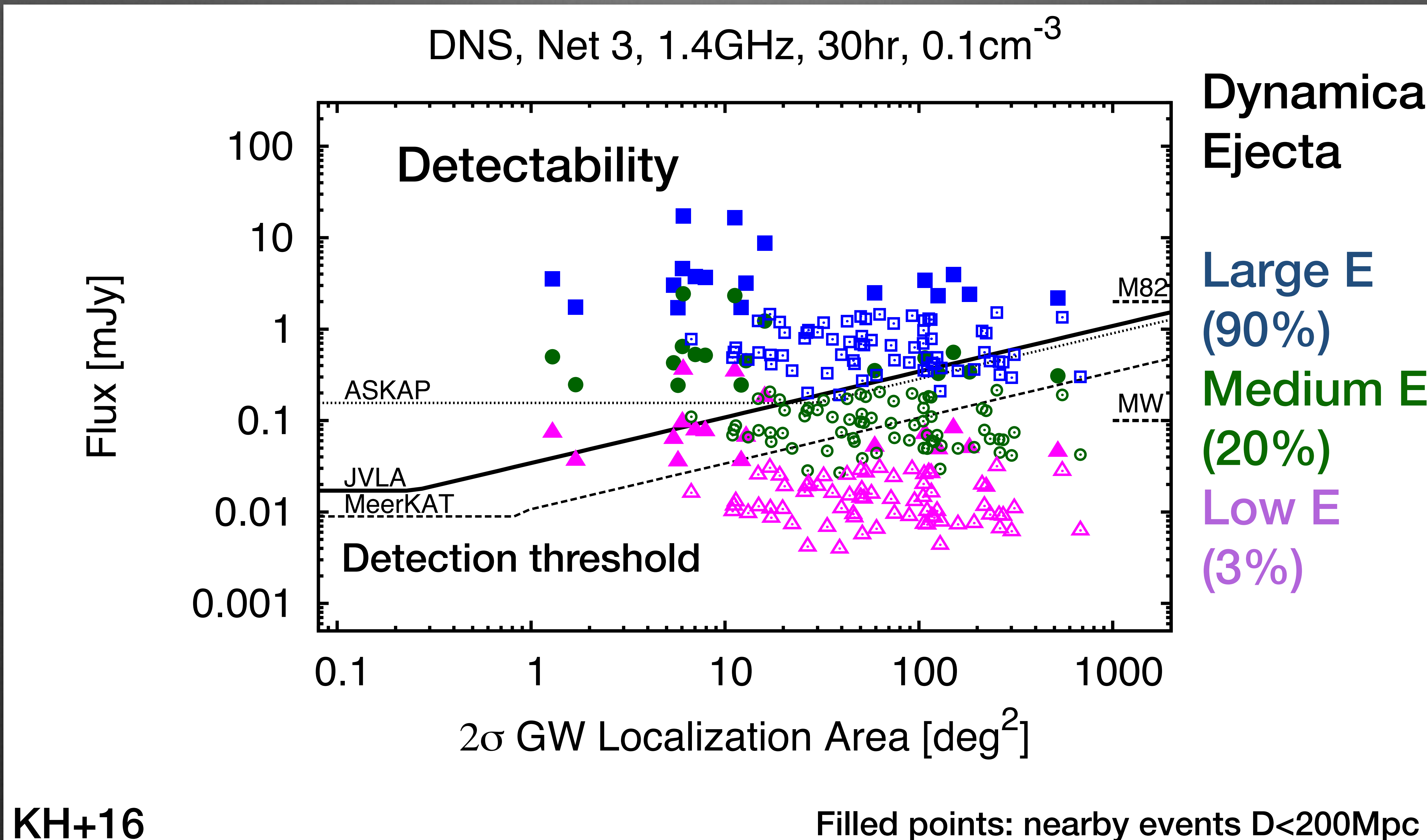
i, z < 24.6, 23.8 mag

No optical counterpart detection (note that this is a binary black hole). They demonstrated the deep and wide follow-up survey works.

Long-lasting Radio Remnant of neutron star mergers



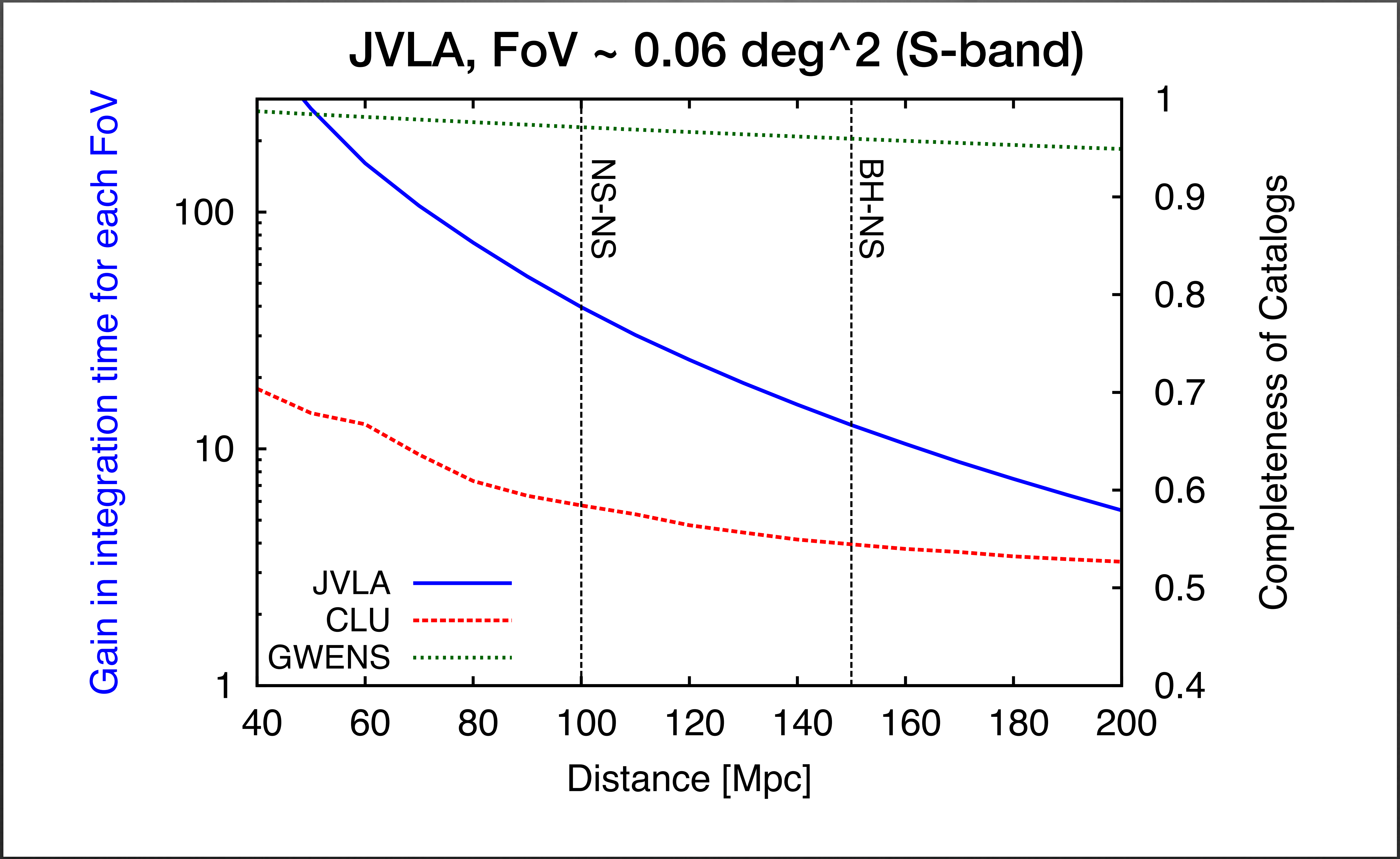
Radio Macronovae as GW counterparts



Point: radio false positives are quite rare, e.g., a few % of optical

Galaxy targeted search in the O2 run

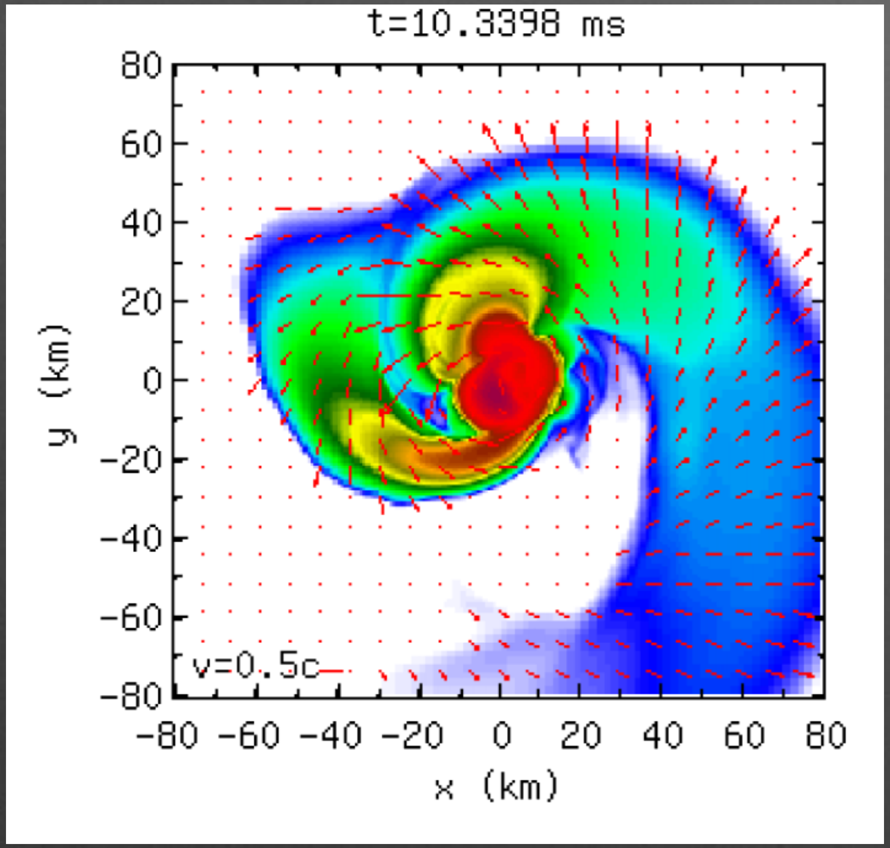
Small FoV => Use local galaxy catalogs



For DNSs, the sensitivity increases by a factor of ~7 when using the catalogs.

Macronova/Kilonova

Li & Paczynski 1998, Kulkarni 2005, Metzger+10

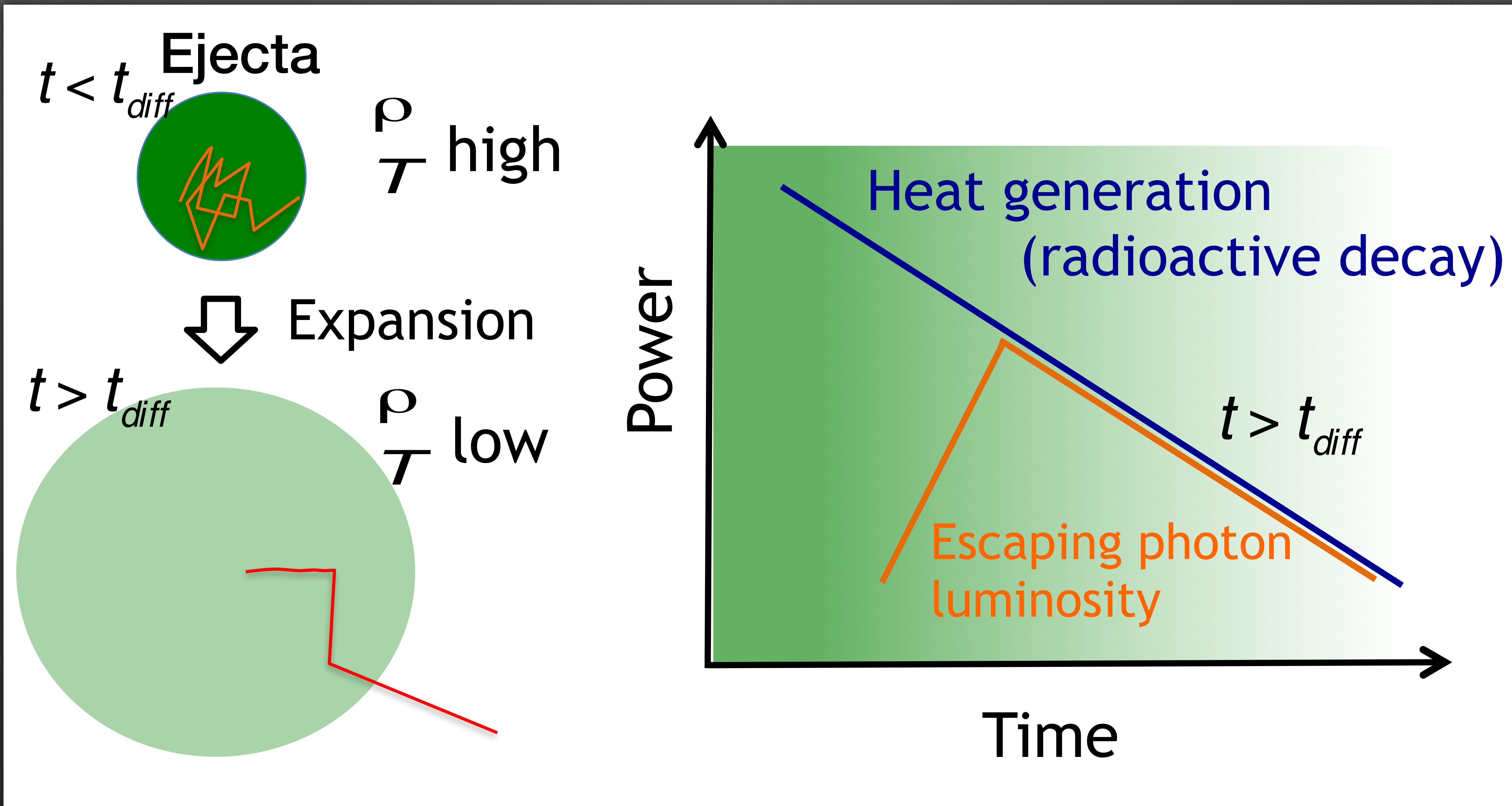


r-process
nucleosynthesis

Radioactivity of neutron rich nuclei heats up the ejecta
=> Bright emission: nova < macronova < supernova

Kilonova: Thermal emission from the merger ejecta

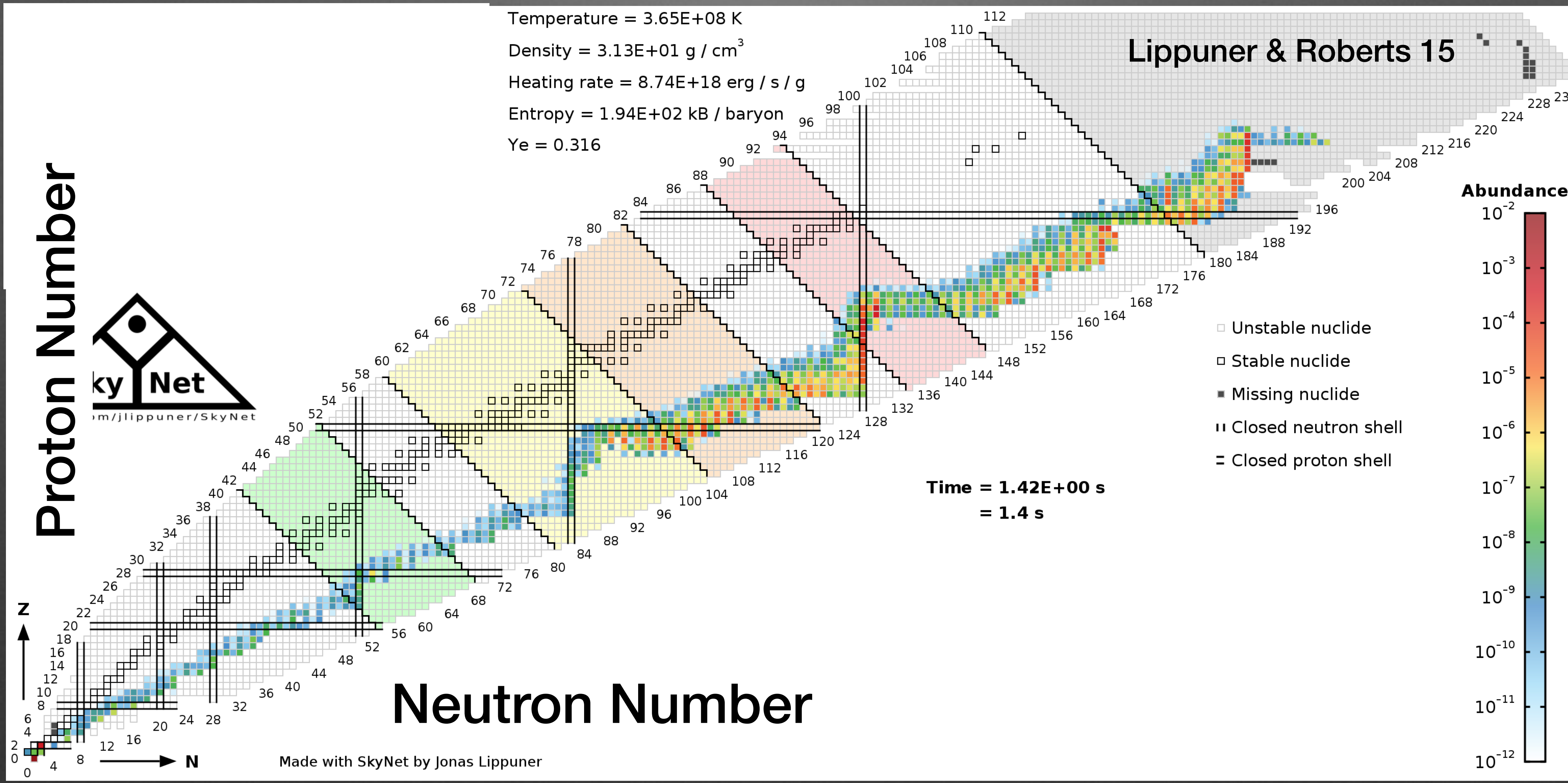
Li and Paczynski 1998, Kulkarni 2005 , Metzger+10, Tanvir+13, Berger+13



Important: The initial internal energy is practically negligible for macronova emission. Therefore, the light curve is determined by energy injection at late times.

R-process in Neutron Star Merger Ejecta

Lattimer & Schramm 74, Metzger+10, Goriely+11, Korobkin+12, Wanajo+14, Lippuner & Roberts 15, Wu+16

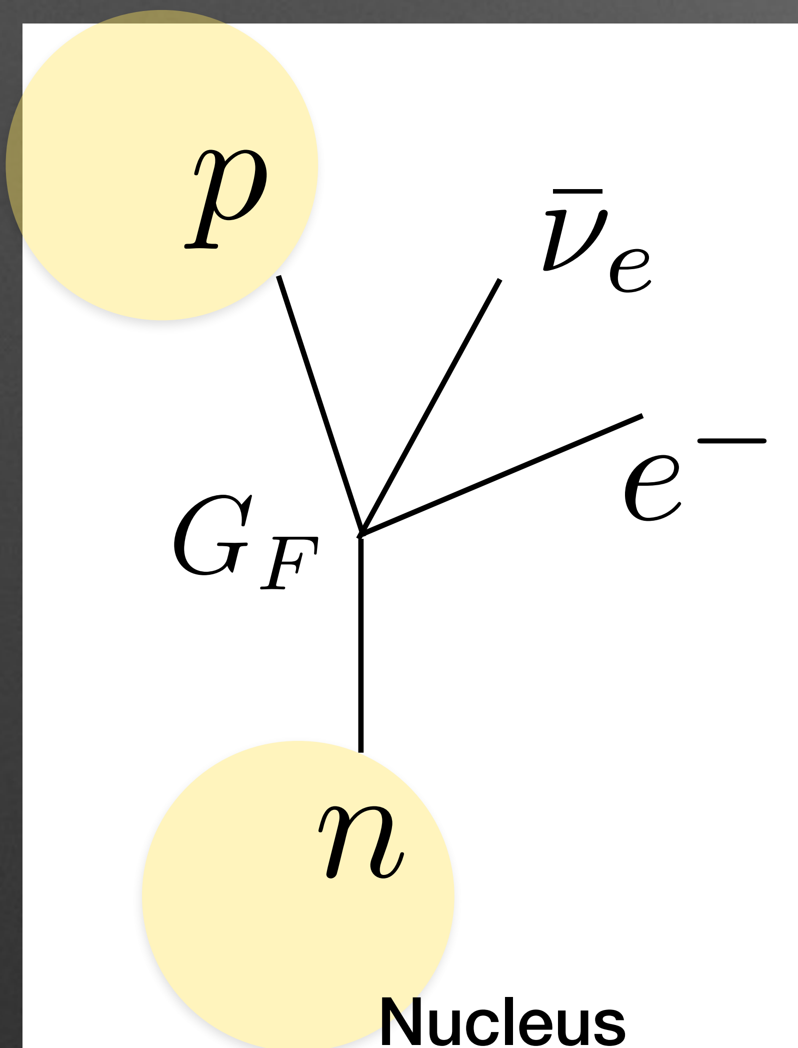


- ✓ Almost all material is synthesized in heavy r-process elements.
- ✓ Nuclei are initially far from the stability line.

Quick review of macronova heating

KH, Sari, Piran 2017

$(m_e,\ c,\ \hbar,\ G_F)$ in Fermi's theory of beta decay



The heating rate per nucleus (1st guess):

$$\dot{Q} \sim \frac{m_e c^2}{t_F}\frac{t_F}{t}$$

where Fermi time: $t_F \equiv \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 9000\ \mathrm{s}$

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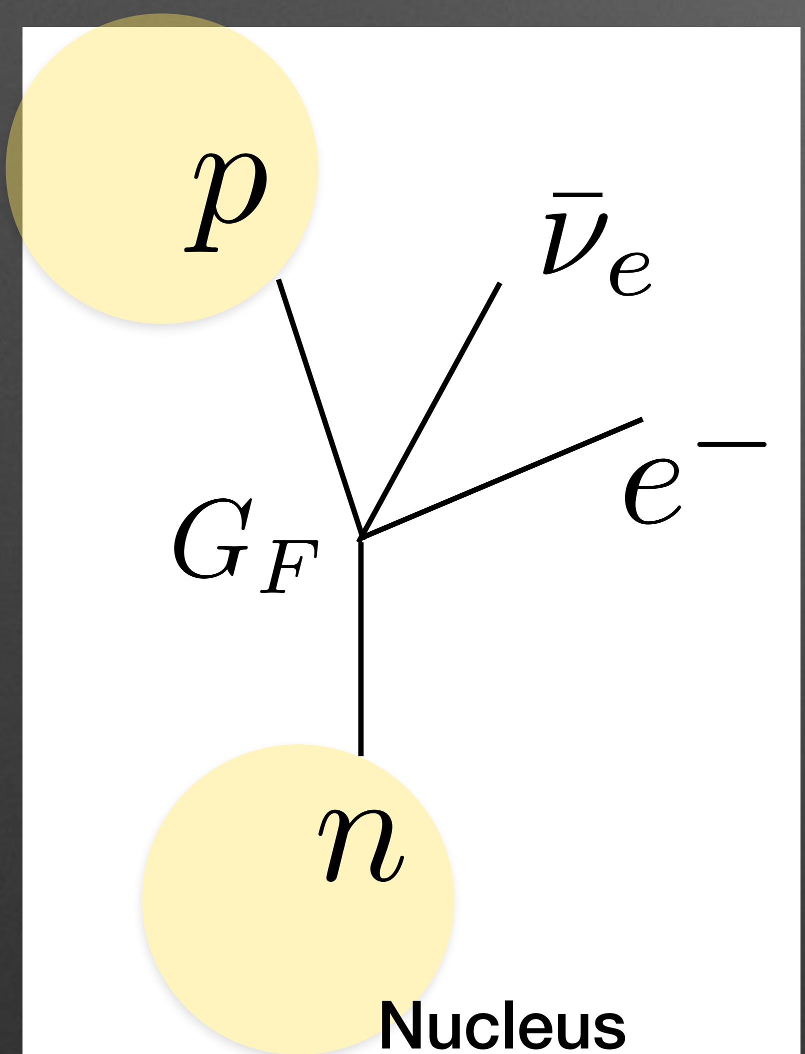

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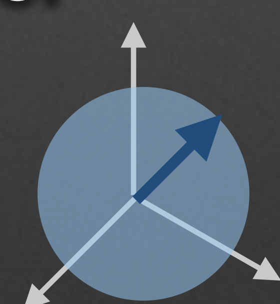
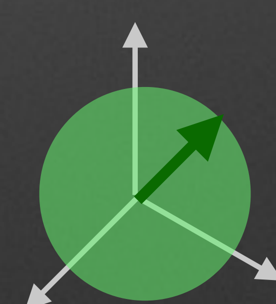
The lifetime:

$\frac{1}{\tau} \propto$  x  x $\delta(E - E_e - E_\nu)$

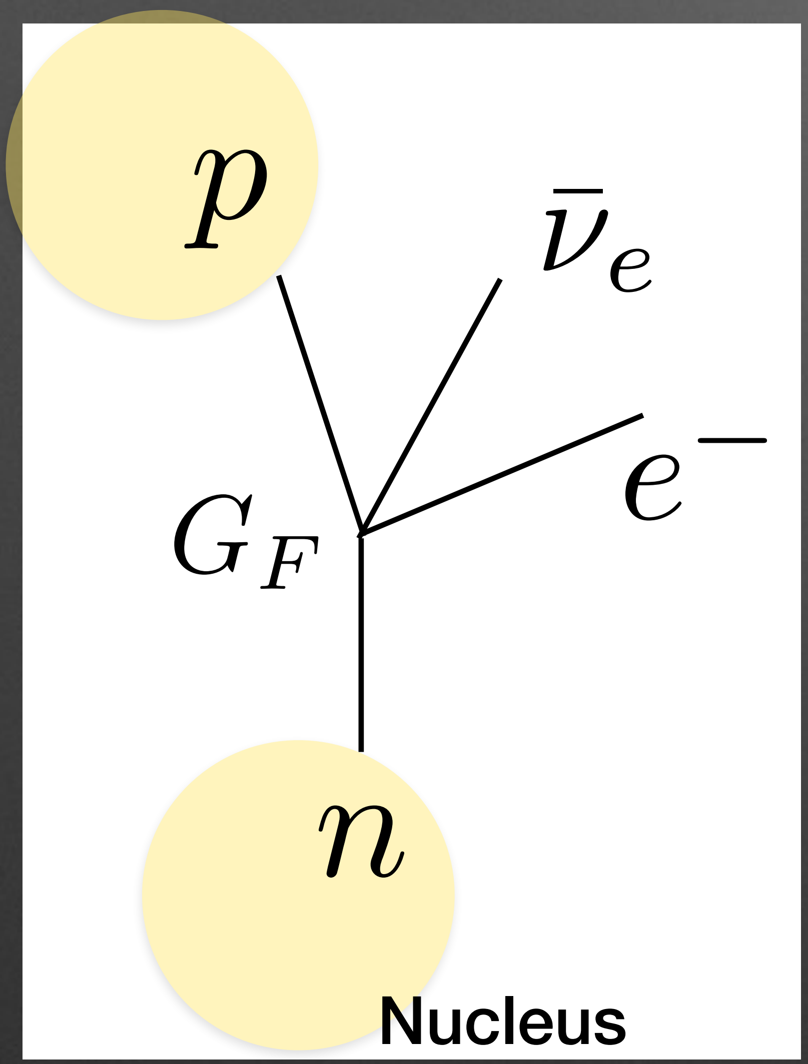
The phase space volume of e and nu

$\propto E^5$ for E>mec^2

Quick review of macronova heating

KH, Sari, Piran 2017

$(m_e,\ c,\ \hbar,\ G_F)$ in Fermi's theory of beta decay



The heating rate per nucleus:

$$\dot{Q}(t) \sim \frac{E(t)}{t} \sim \frac{m_e c^2}{t_F}\left(\frac{t}{t_F}\right)^{-1.2}$$

where Fermi time: $t_F \equiv \frac{2\pi^3}{G_F^2}\frac{\hbar^7}{m_e^5 c^4} \approx 9000\ \mathrm{s}$

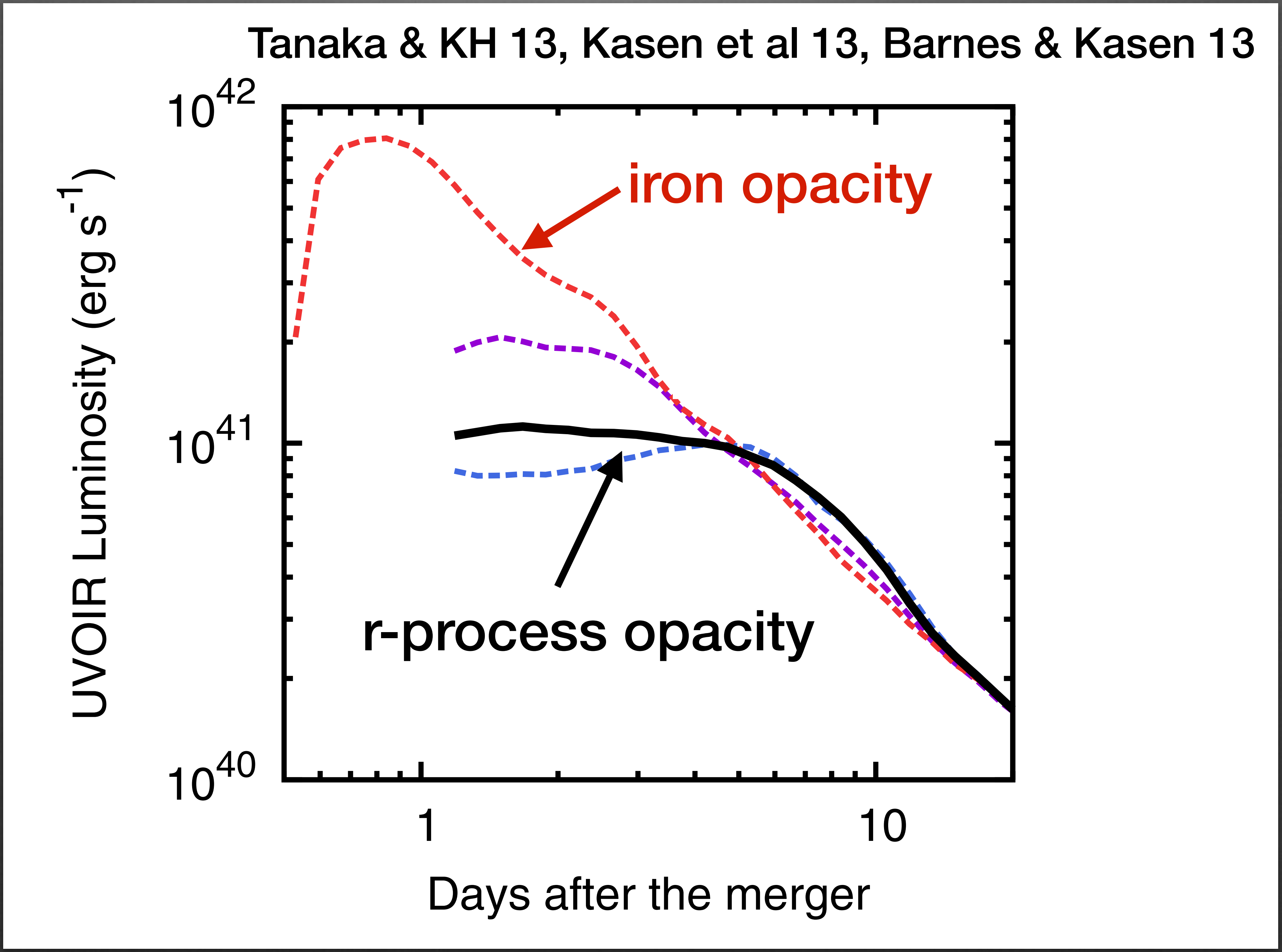
$$\dot{Q} \sim 10^{10}\ erg/s/g\left(\frac{t}{1\,\mathrm{day}}\right)^{-1.2}$$

For an ejecta mass of 0.01Msun,

=> 10^41 erg/s at 1 day

=> Kilonova

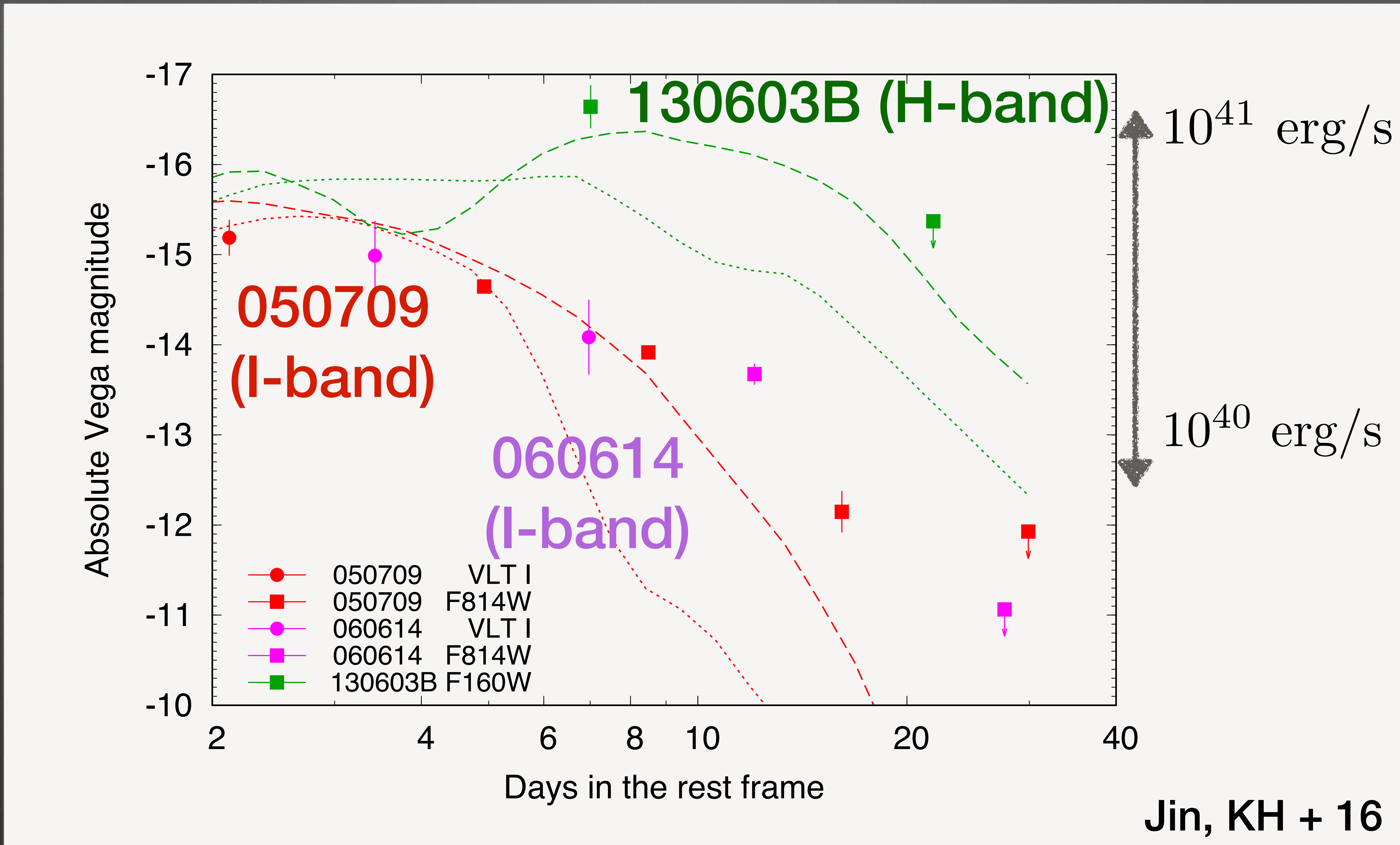
Light curve of kilonova/macronova



The atomic opacity of r-process elements is quite high.
~100 times the one of type Ia supernovae.

→ Fainter, Longer, Redder

Three macronova candidates after nearby short GRBs



- Peak luminosity ~ 10^41 erg/s.
- The I-band light curves of 050709 and 060614 are quite similar.

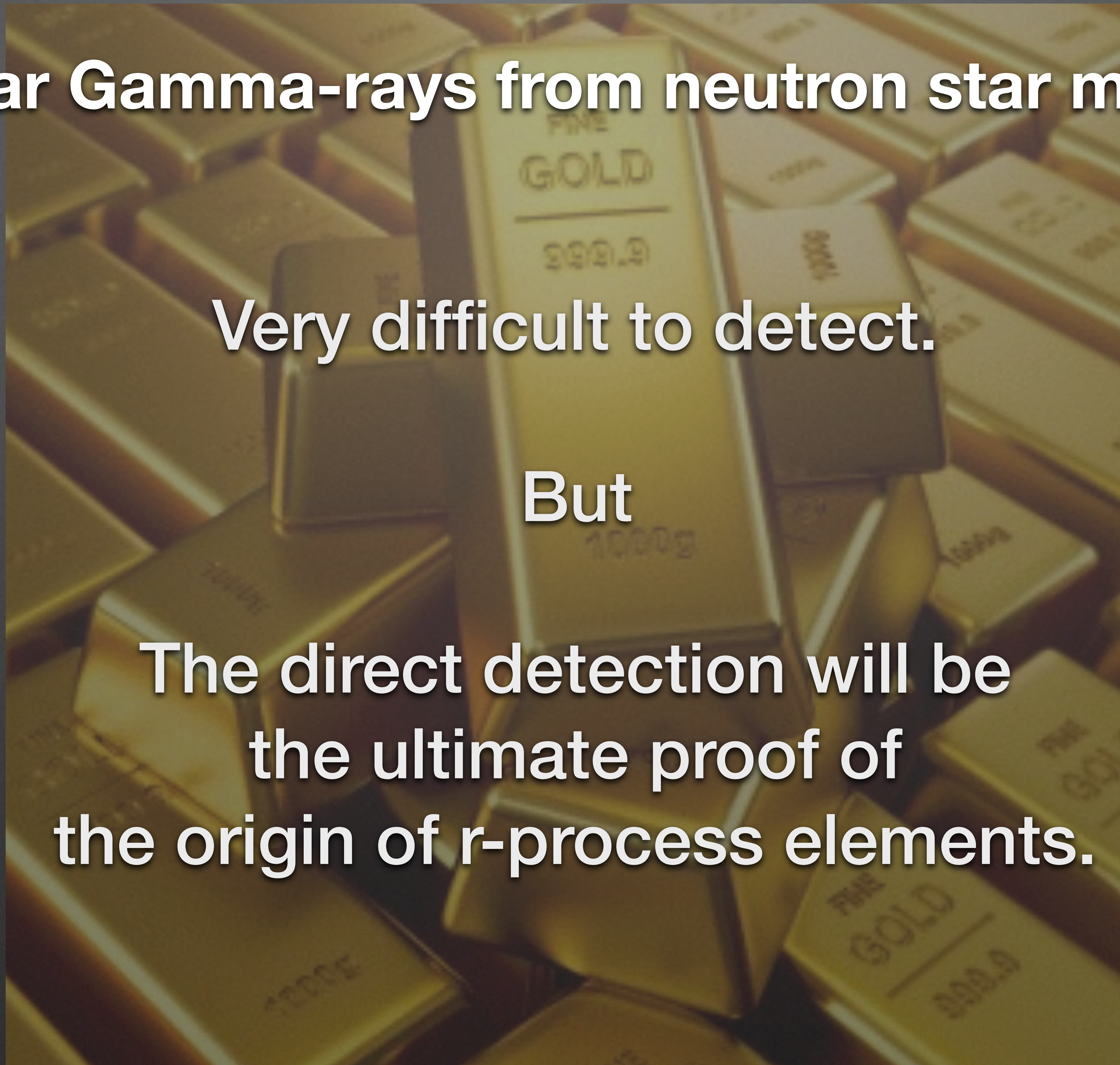
Kilonova/Macronova candidates

Jin, Hotokezaka et al 2016

	Redshift	T90 (s)	Eiso (10^51 erg)	Macronova (erg/s)	Note
GRB 050709	0.16	0.1 (+130)	0.07	10^41 (I-band)	very small host
GRB 060614	0.125	5 (+97)	2.5	10^41 (I-band)	not really a short burst
GRB 130603B	0.356	0.18	2.1	10^41 (H-band)	the first candidate
GRB 150101B no detection	0.134	0.012	0.013	<10^42 (H-band)	Early type host

We think a good fraction of sGRBs accompanying a macronova.

Nuclear Gamma-rays from neutron star mergers

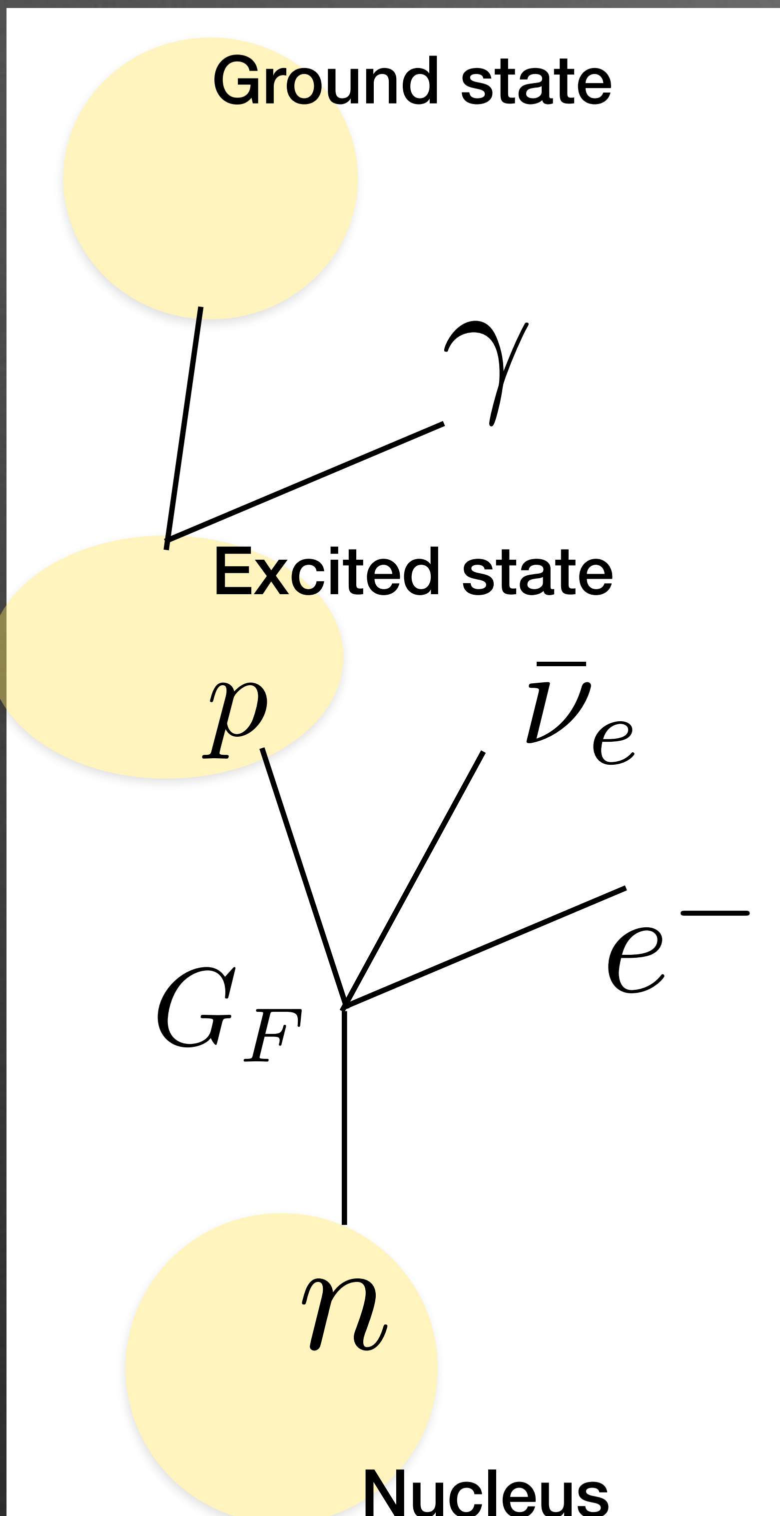


Very difficult to detect.

But

The direct detection will be
the ultimate proof of
the origin of r-process elements.

Gamma-rays from macronovae



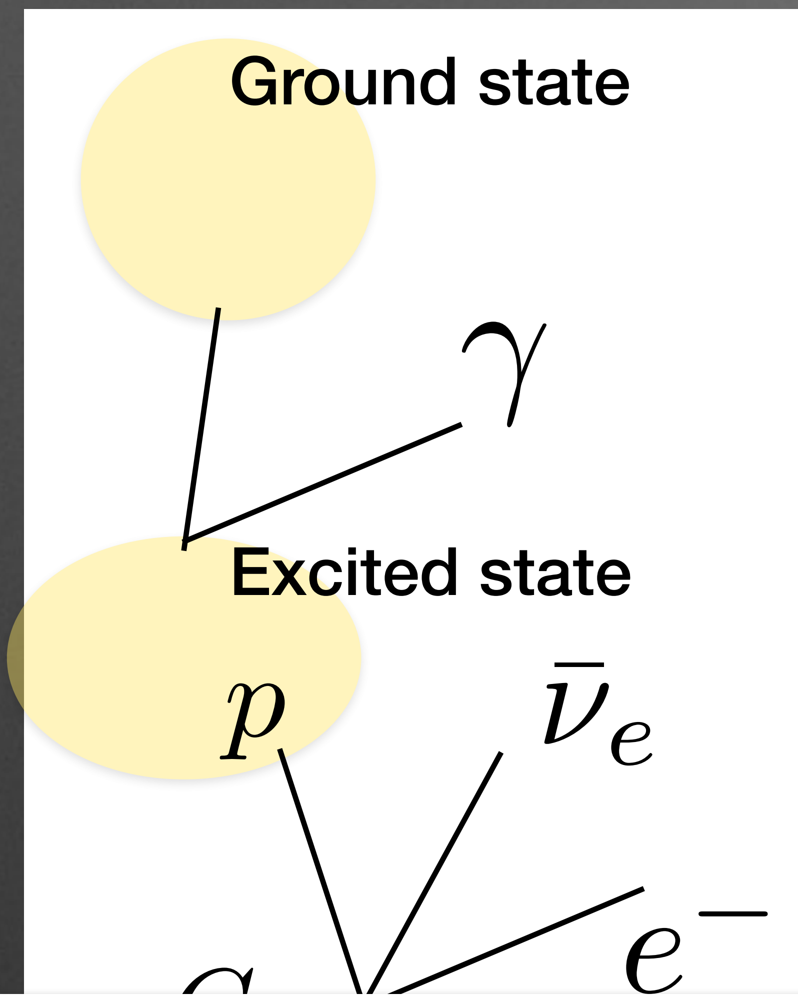
Specific heating rate of r-process material

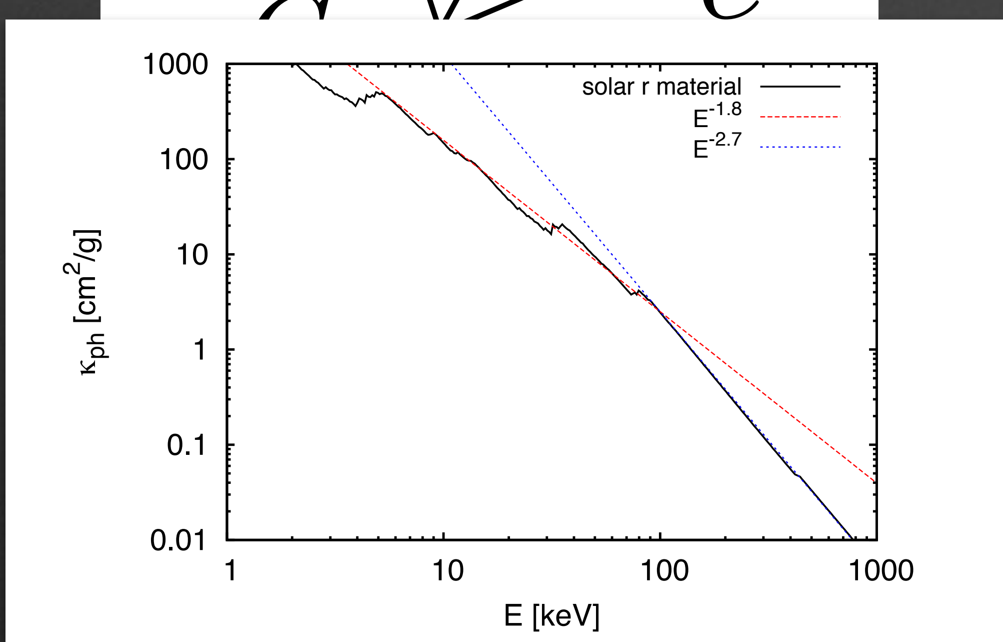
$$\dot{Q} \sim 10^{10}\ erg/s/g \left(\frac{t}{1\,\mathrm{day}}\right)^{-1.2}$$

Nuclear gamma-rays are produced immediately after beta-decay.

Gamma-ray luminosity
~ electron & neutrino luminosity

Quick review of macronova heating





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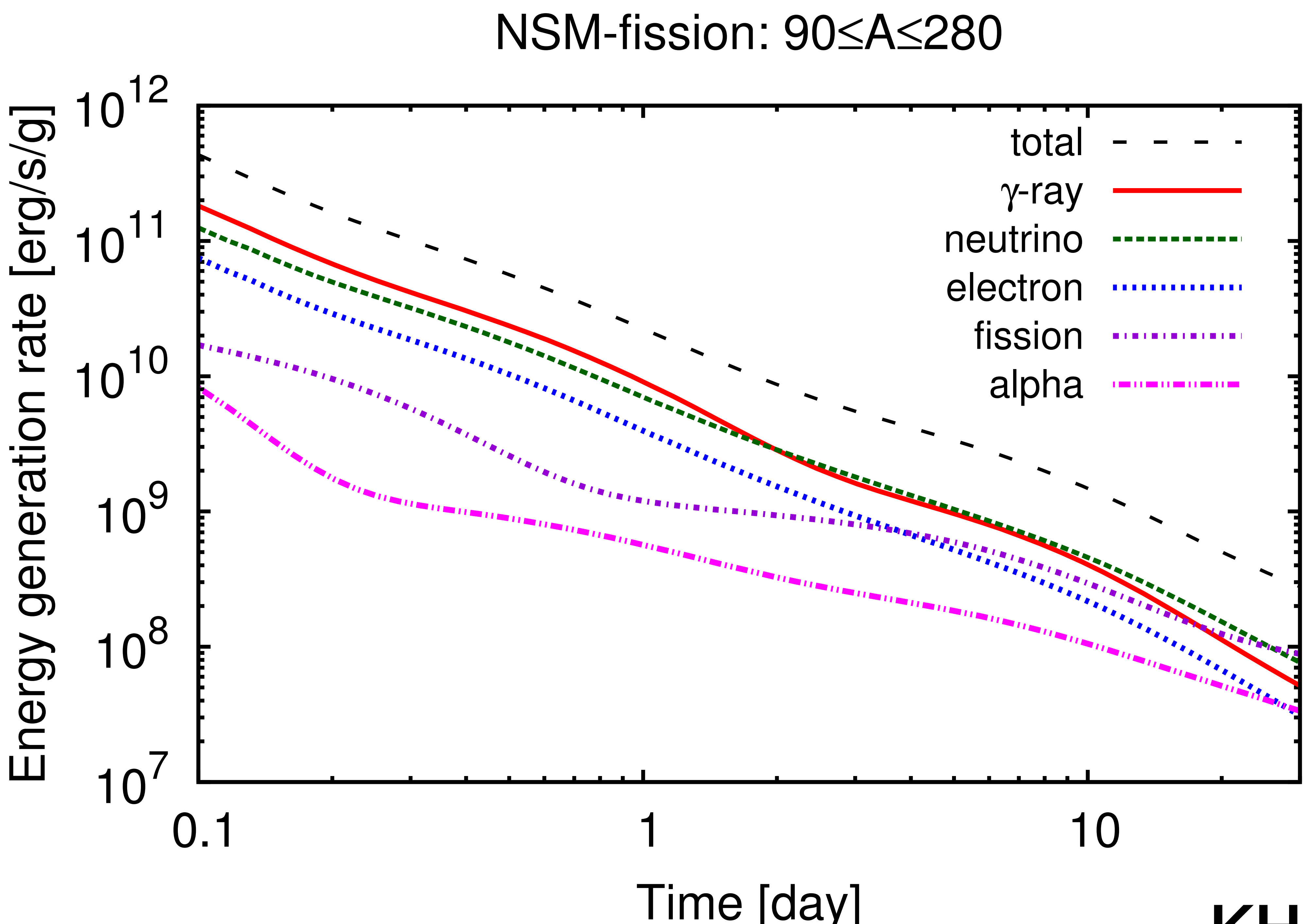
Nuclear Gamma-rays are produced immediately after beta-decay.

Gamma-ray luminosity
~ electron & neutrino luminosity

$$\begin{aligned}
\tau_\gamma(t) &\approx \frac{\kappa_\gamma}{\kappa_\mathrm{o}}\frac{c}{v}\left(\frac{t_{\mathrm{diff,o}}}{t}\right)^2, \\
&\approx 0.02\left(\frac{t_{\mathrm{diff,o}}}{t}\right)^2\left(\frac{\kappa_\gamma}{0.05\ \mathrm{cm^2/g}}\right) \\
&\qquad \times\left(\frac{\kappa_\mathrm{o}}{10\ \mathrm{cm^2/g}}\right)^{-1}\left(\frac{v}{0.3c}\right)^{-1},
\end{aligned}$$

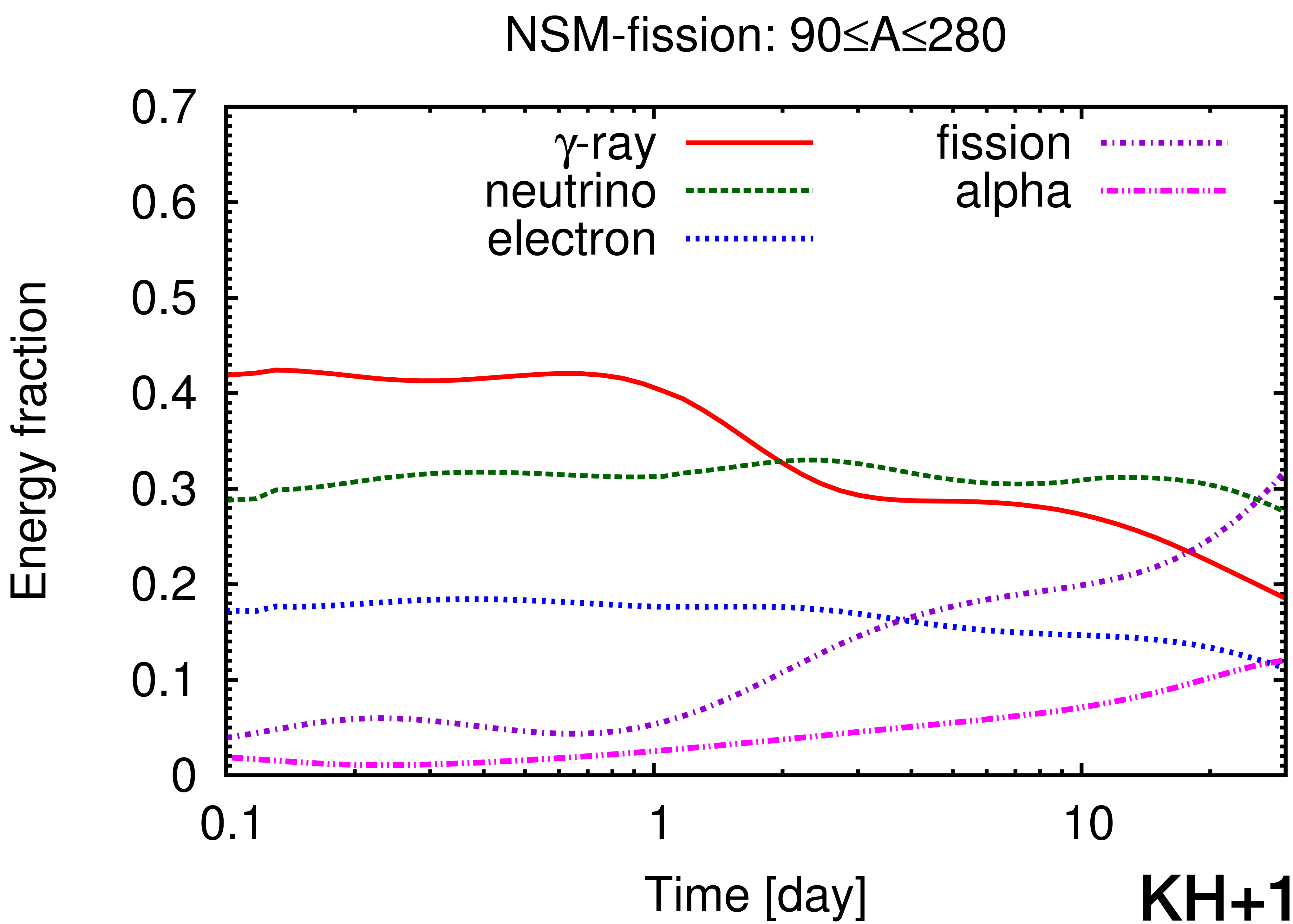
Thin to gamma-rays on the macronova timescale.

Energy partition to different products



KH+15

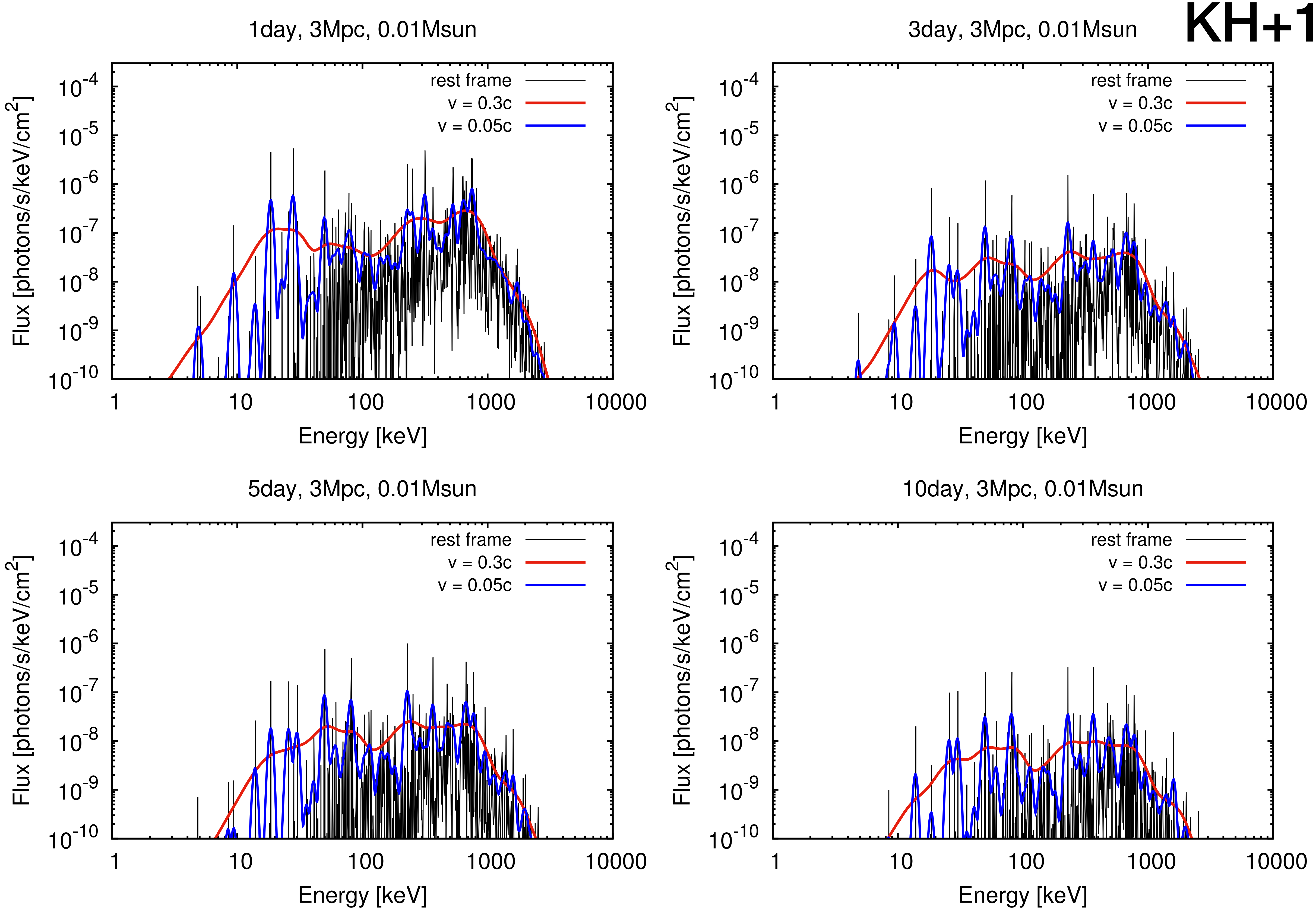
Energy partition to different products



KH+15

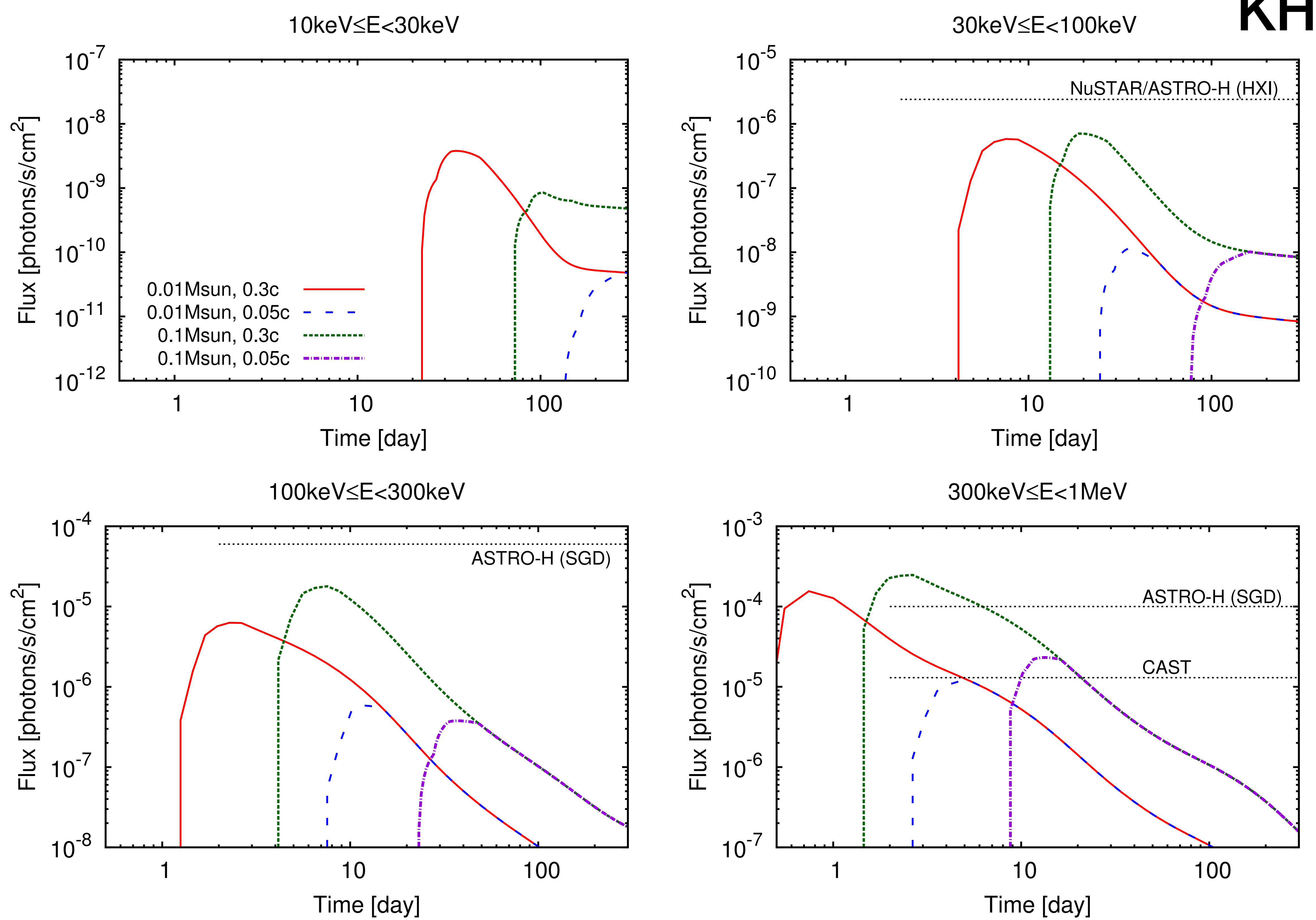
Gamma-ray spectra

KH+15



Gamma-ray light curves at 3Mpc

KH+15



Summary

Neutron star mergers are promising sources that are associated with electromagnetic signals.
=> Identifying the host galaxies and studying high energy astrophysics.

One of the expected counterparts is Kilonova/Macronova driven by the radioactivity of r-process elements.
=> The peak luminosity: 10^40 - 10^41 erg/s at 1 week in the red - infrared.

We have already seen three kilonova/macronova candidates after the nearby GRB 130603B, 060614, 050709.
=> Kilonovae/Macronovae may be ubiquitous phenomena.

The direct detection of MeV gamma-rays from neutron star mergers will be the ultimate proof of the origin of r-process elements.

The spectrum is flat from 100 keV - a few MeV. MeV is the best to see it.

They are detectable at 3 - 10 Mpc by CAST.