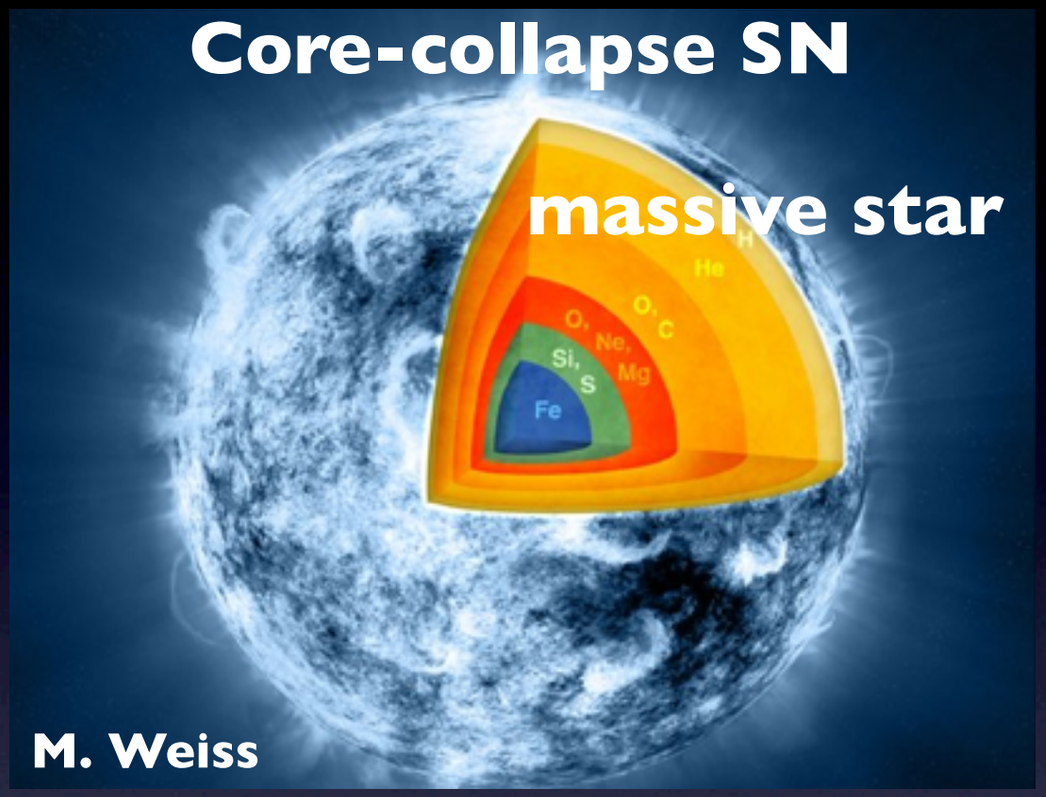
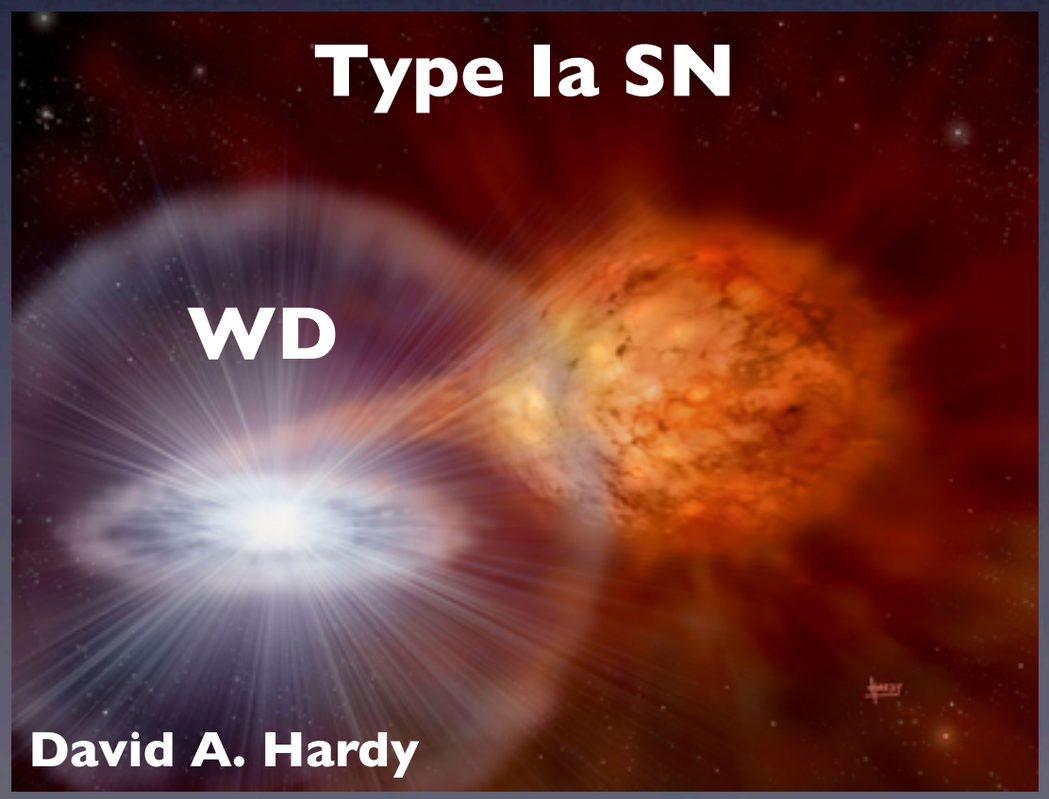
Optical/Infrared Emission from Supernova and "Kilonova"

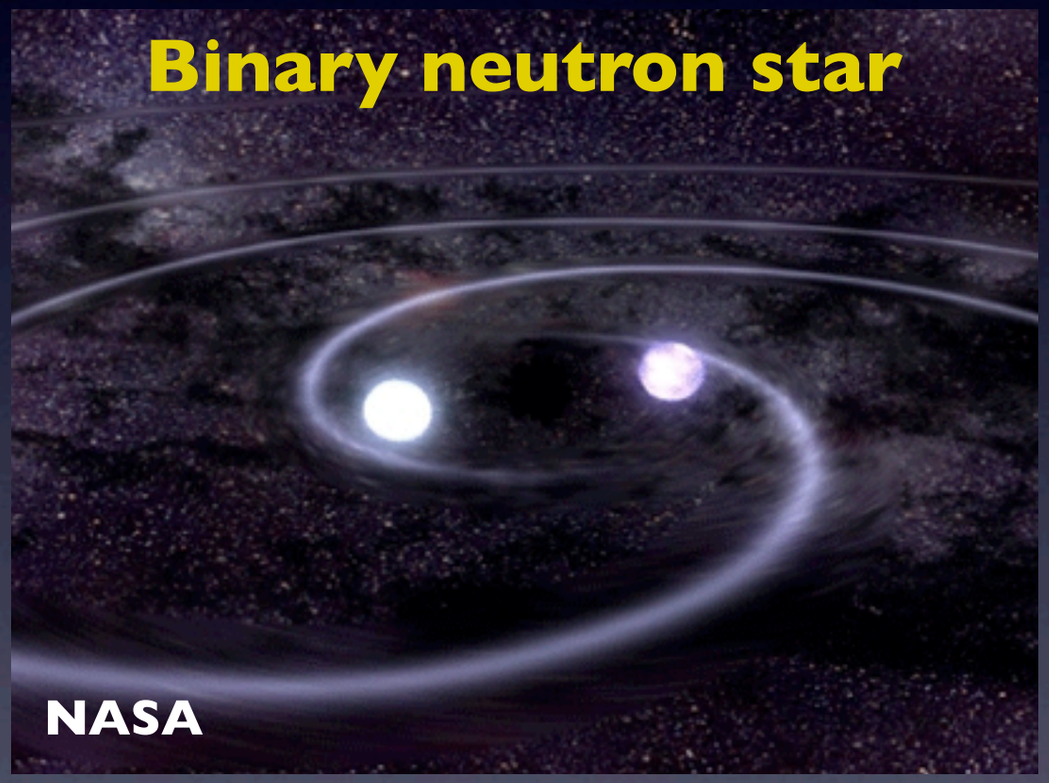
Masaomi Tanaka
(National Astronomical Observatory of Japan)

Supernova





“Kilonova”



Optical/Infrared Emission from Supernova and “Kilonova”

- Why “kilonova”?
- Opt/NIR emission from “kilonova”
- Prospects for observations

New astronomy with gravitational waves

Supernova

< 100 kpc
~1 event/100 yr

Merger of compact binary (neutron star/black hole)

< 200 Mpc
~10 events/ 1 yr

2017 -
- Advanced LIGO (US)
- Advanced Virgo (Europe)
- KAGRA (Japan)

==> Kanda-san's talk

2 deg

Kiso 1m
Schmidt telescope
(KWFC)

~ 200 galaxies / 4deg^2
(< 200 Mpc)

GW alert error box

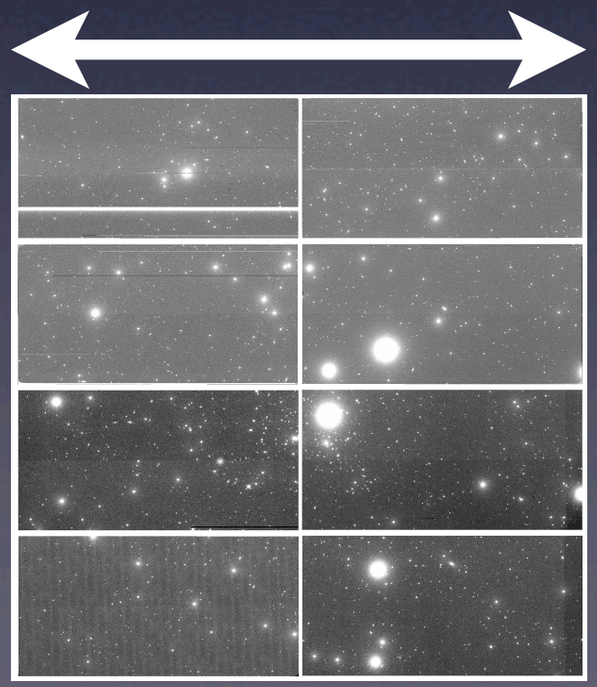
e.g. 6 deg x 6 deg

~ 2000 galaxies

(< 200 Mpc)

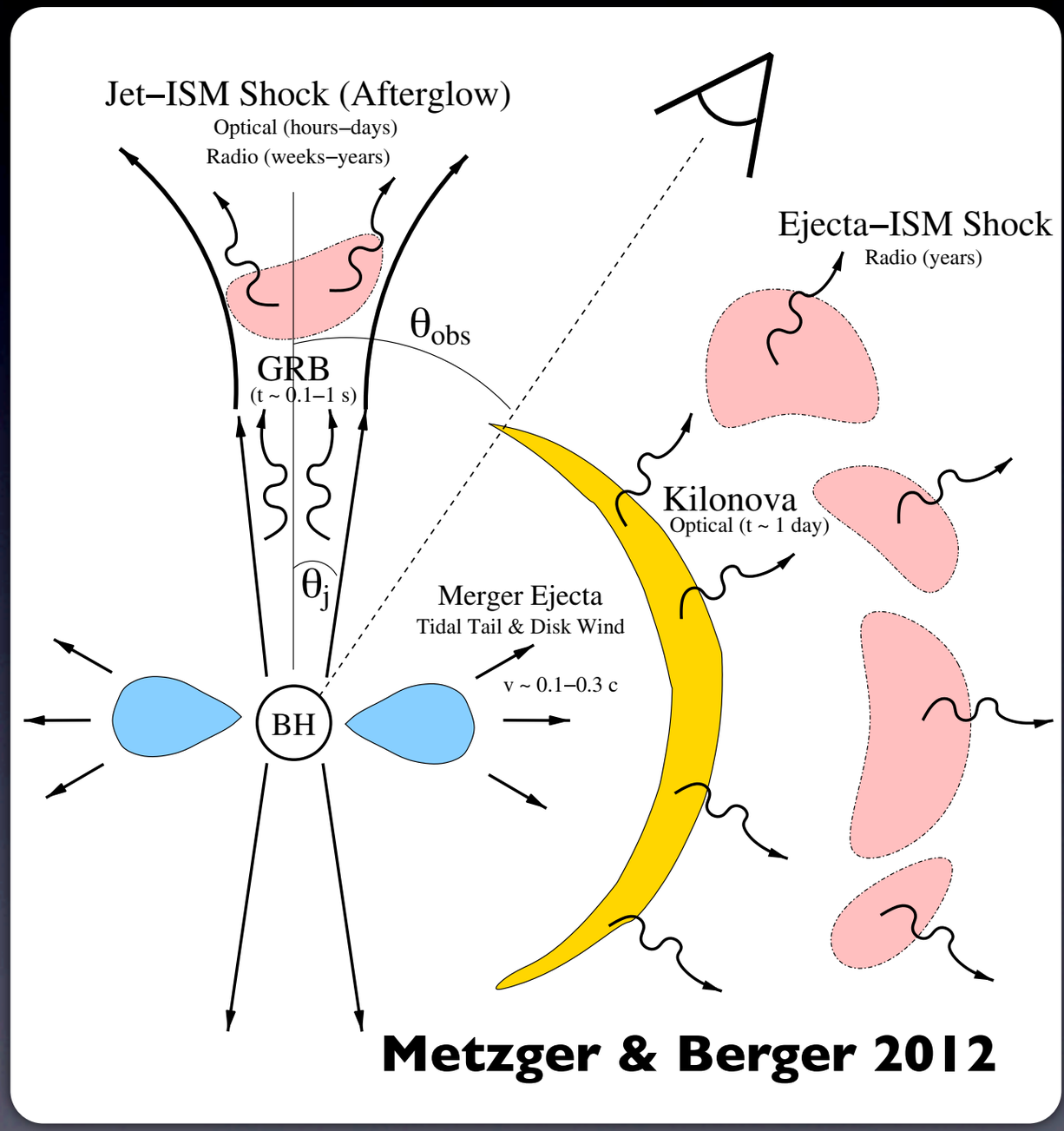
No electromagnetic counterpart
No gravitational wave astronomy

2 deg



EM signature from NS-NS merger

- **On-axis short GRB**
- **Off-axis radio/optical afterglow**
- **Radioactive emission r-process nuclei**
  - **kilonova**
  - **macronova**
  - **r-process nova**
  - **“gold” nova!**



Li & Paczynski 98, Kulkarni 05, Metzger et al. 2010

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- Why “kilonova”?
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Why supernova is so bright?

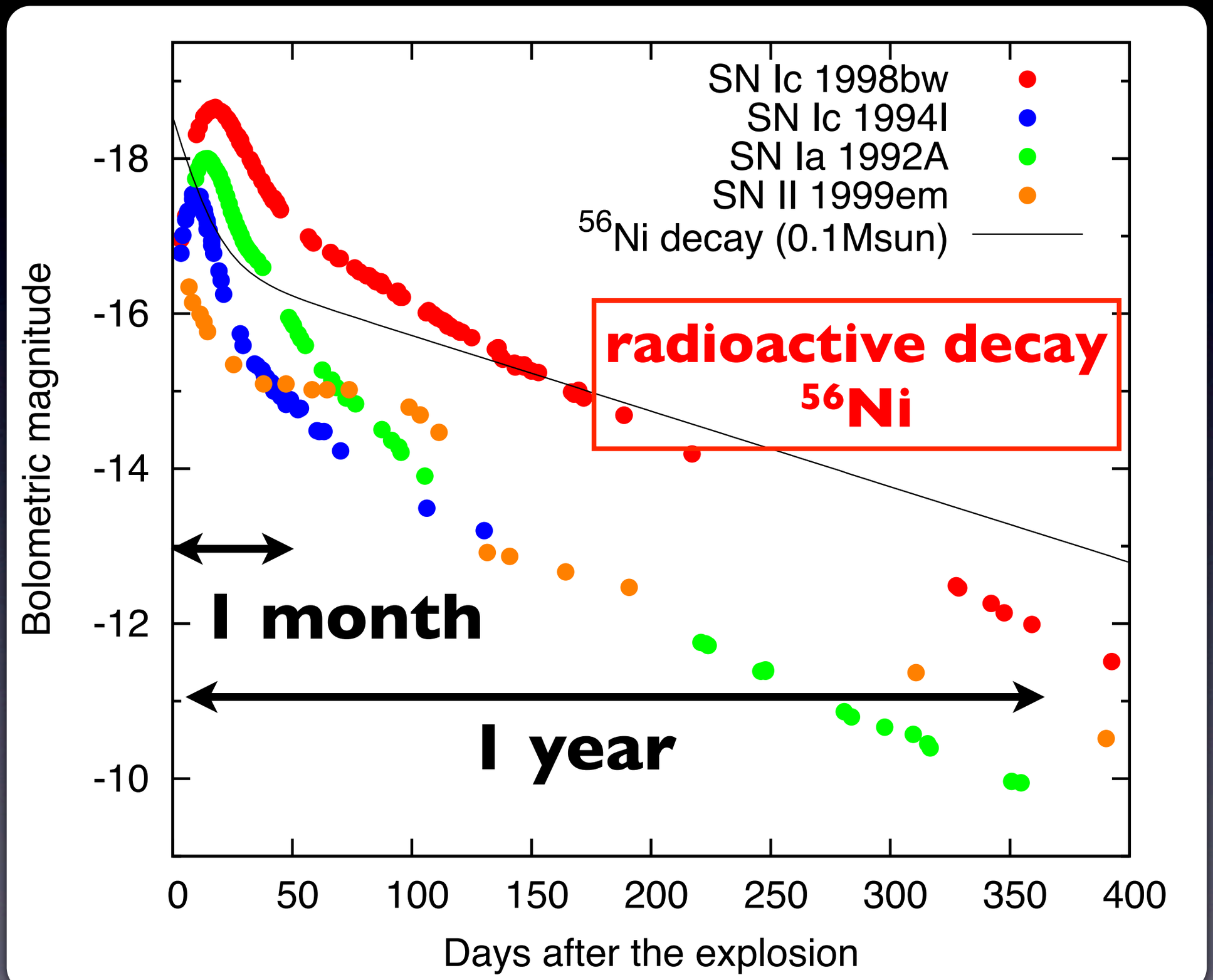
10^9 Lsun

10^8 Lsun

10^7 Lsun

γ-ray

optical



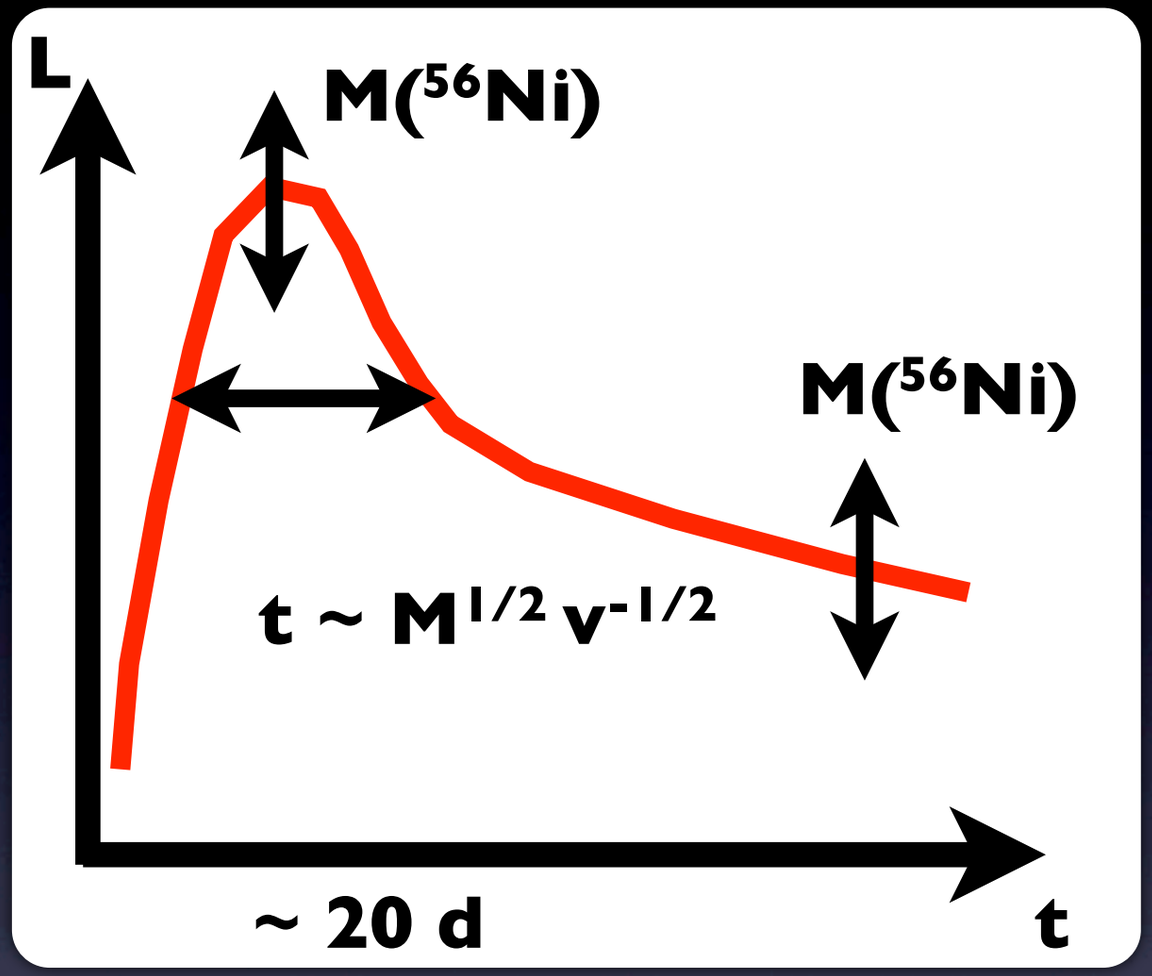
Heating source of supernova

$$^{56}\mathrm{Ni} \Longrightarrow {}^{56}\mathrm{Co} + \gamma + \nu_e$$

τ ~ 9 days

$$^{56}\mathrm{Co} \Longrightarrow \begin{cases} {}^{56}\mathrm{Fe} + \gamma + \nu_e \\ {}^{56}\mathrm{Fe} + e^+ + \gamma + \nu_e \end{cases}$$

τ ~ 100 days



Peak time

$$t_p \sim 20\ \mathrm{day} \left(\frac{M}{1M_\odot}\right)^{1/2} \left(\frac{v}{10,000\ \mathrm{km\ s^{-1}}}\right)^{-1/2} \left(\frac{\kappa}{0.1\ \mathrm{cm^2\ g^{-1}}}\right)^{1/2}$$

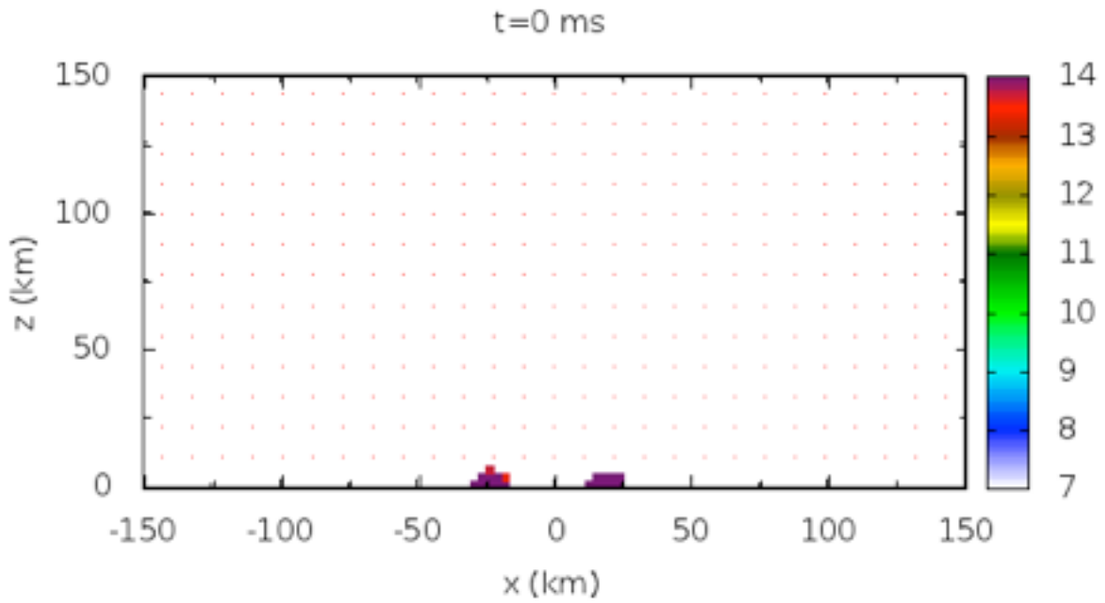
+ Shock heating (but negligible for compact progenitor)

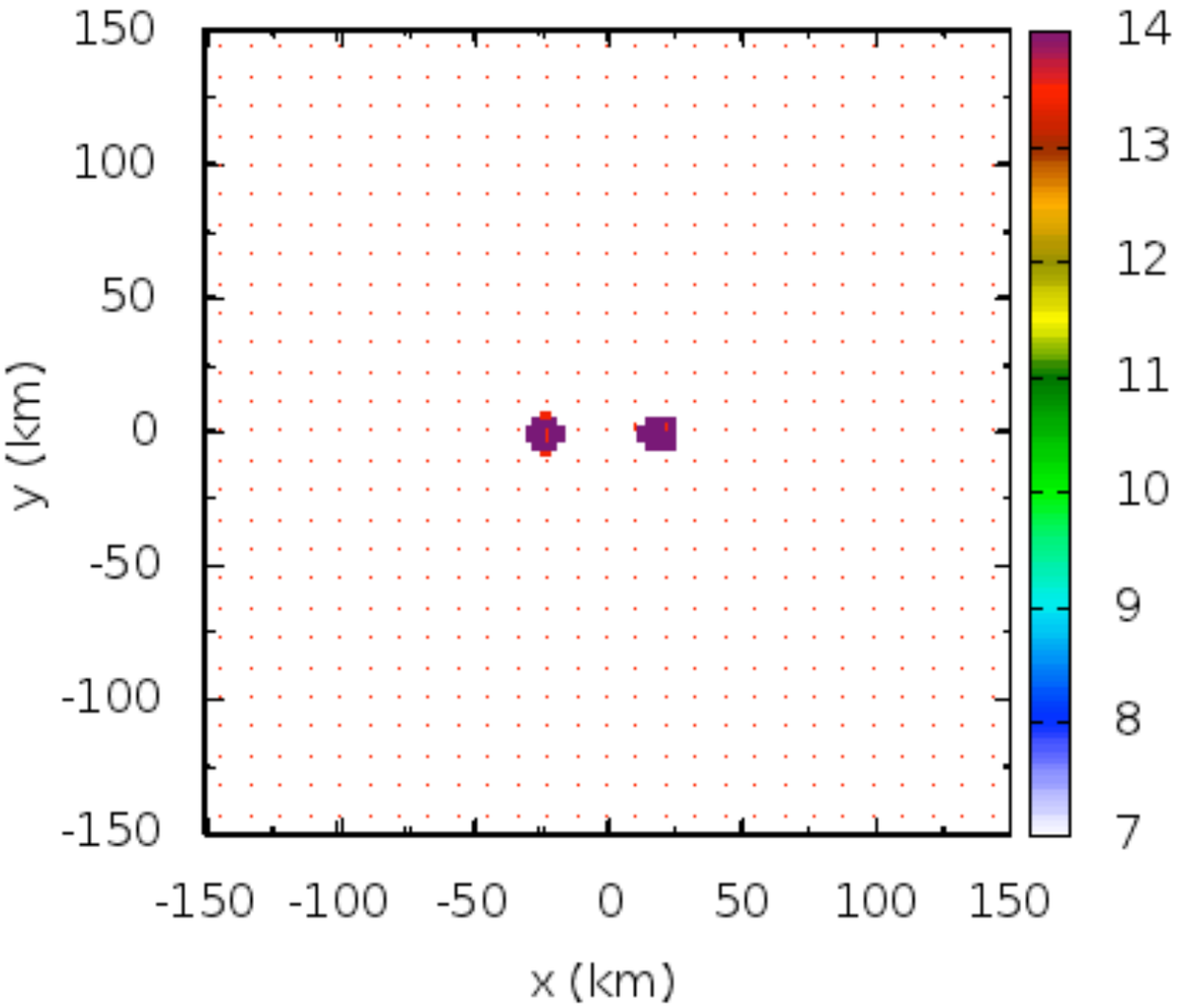
Keys for optical emission

1. Something should be ejected

2. Heating sources

3. Mass, velocity, and element abundance





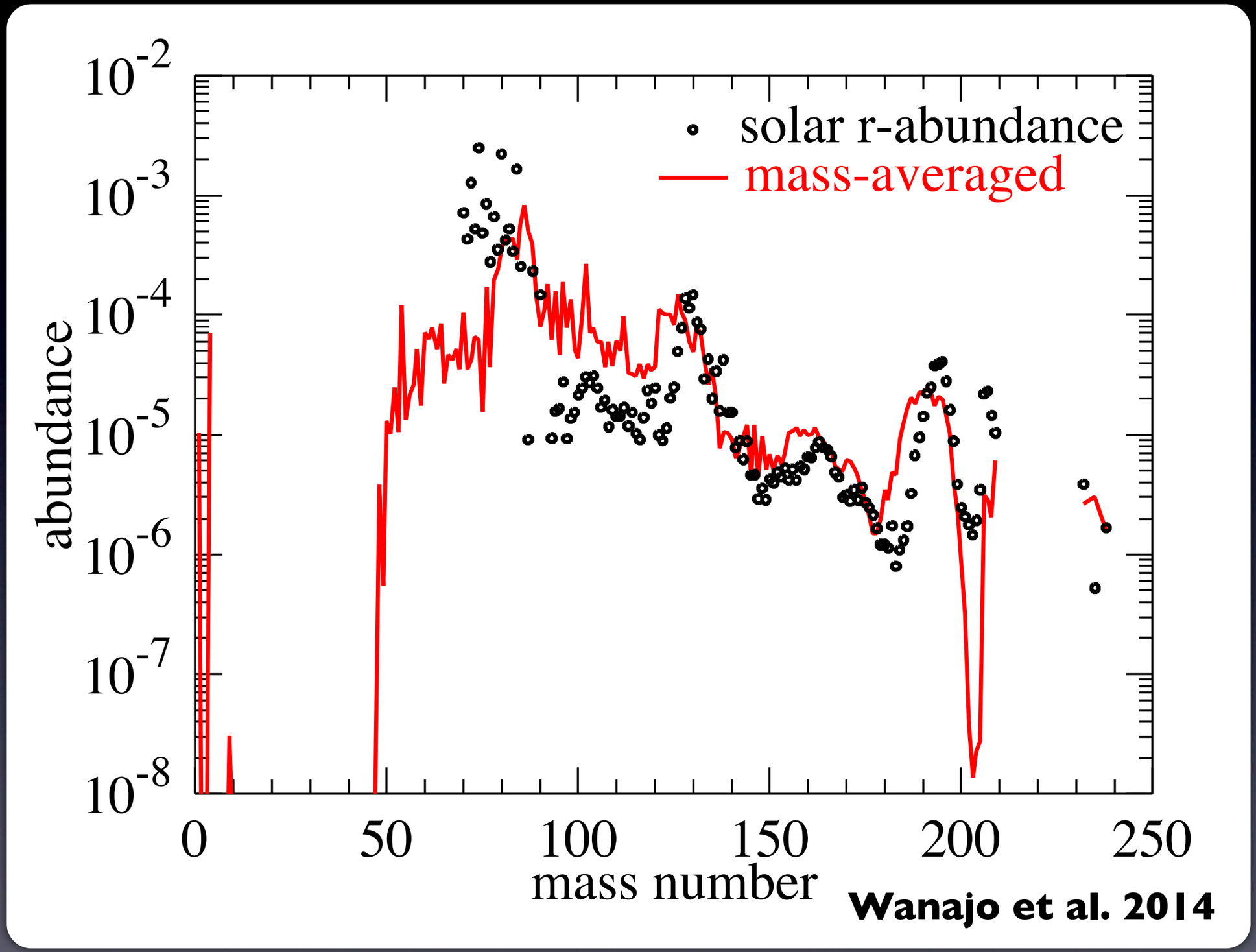
Mass ejection clearly occurs in NS mergers

==> Sekiguchi-san's talk

$M \sim 10^{-3} - 10^{-2}$ Msun
$v \sim 0.1 - 0.2$ c

Hotokezaka+13

r-process nucleosynthesis

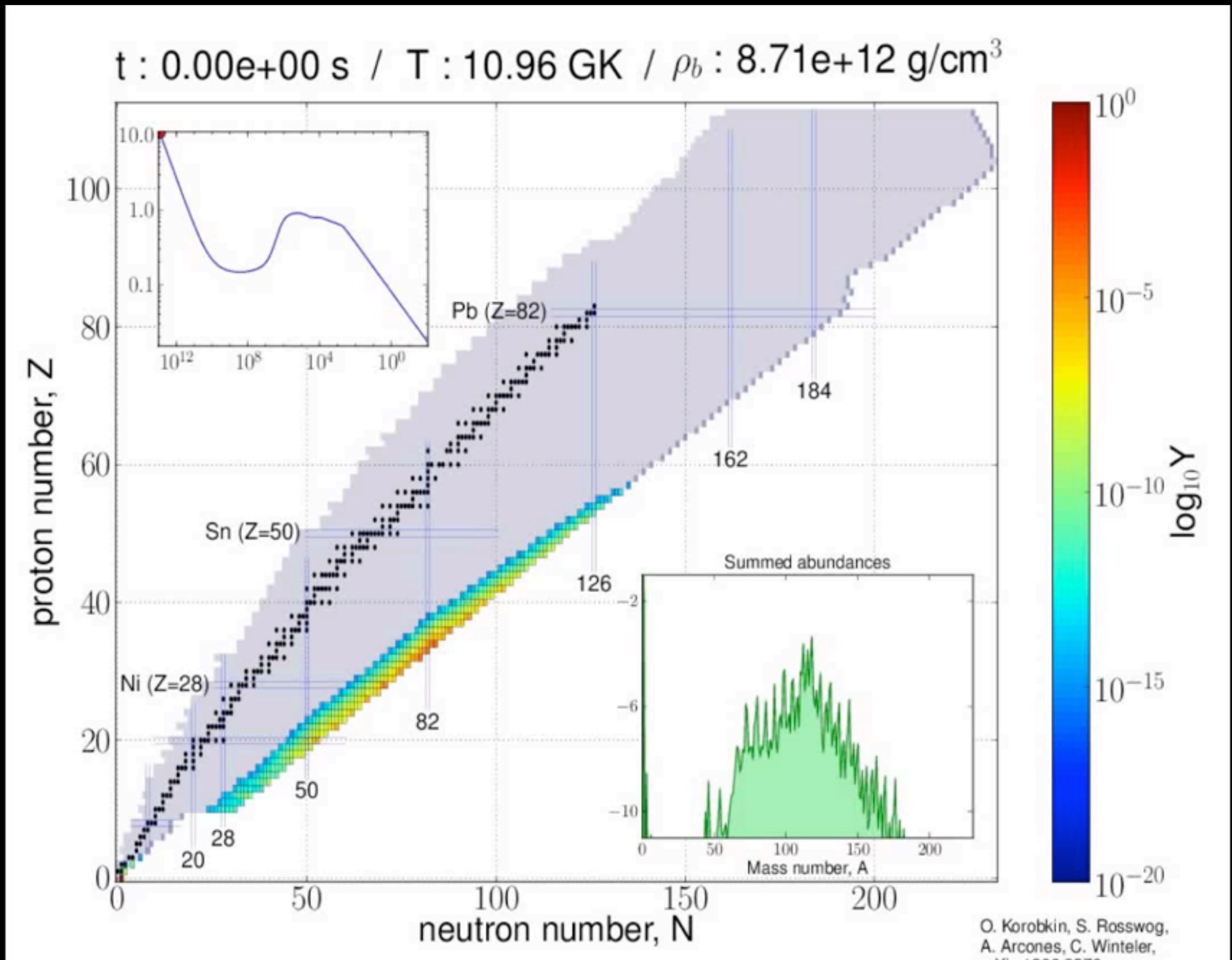


Wanajo et al. 2014

^{56}Ni is not major heating soruce

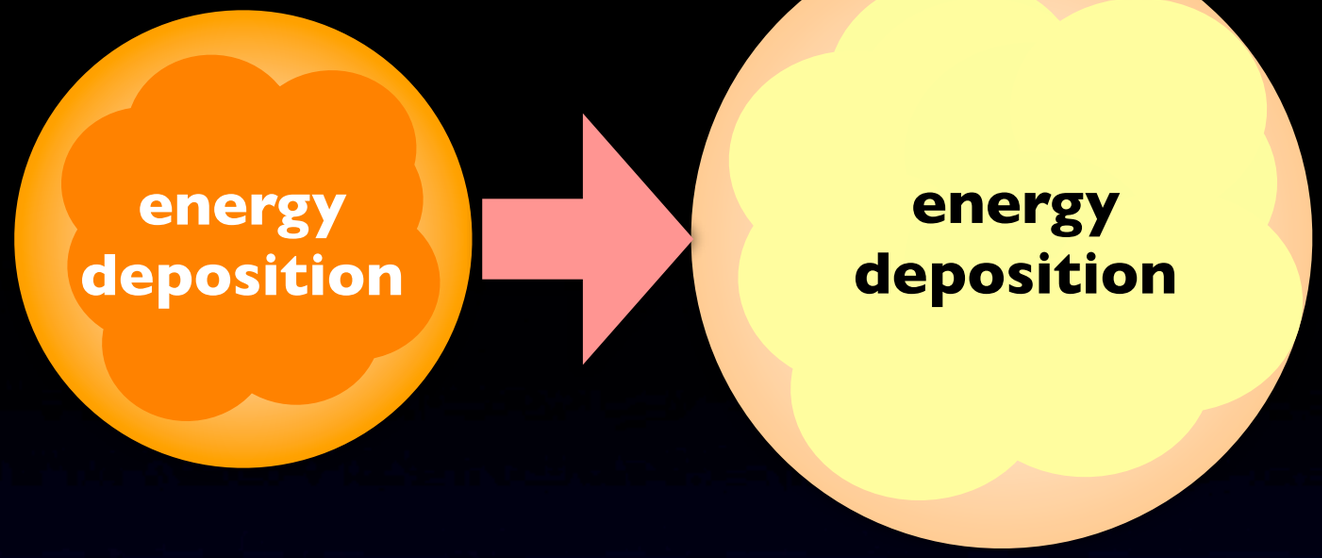
==> Wanajo-san's and Sekiguchi-san's talks

Heating source = r-process nuclei



“kilonova”

Li & Paczynski 98
Metzger+10



Timescale

$$t_p \sim 1 \text{ day} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{-1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{1/2}$$

Luminosity

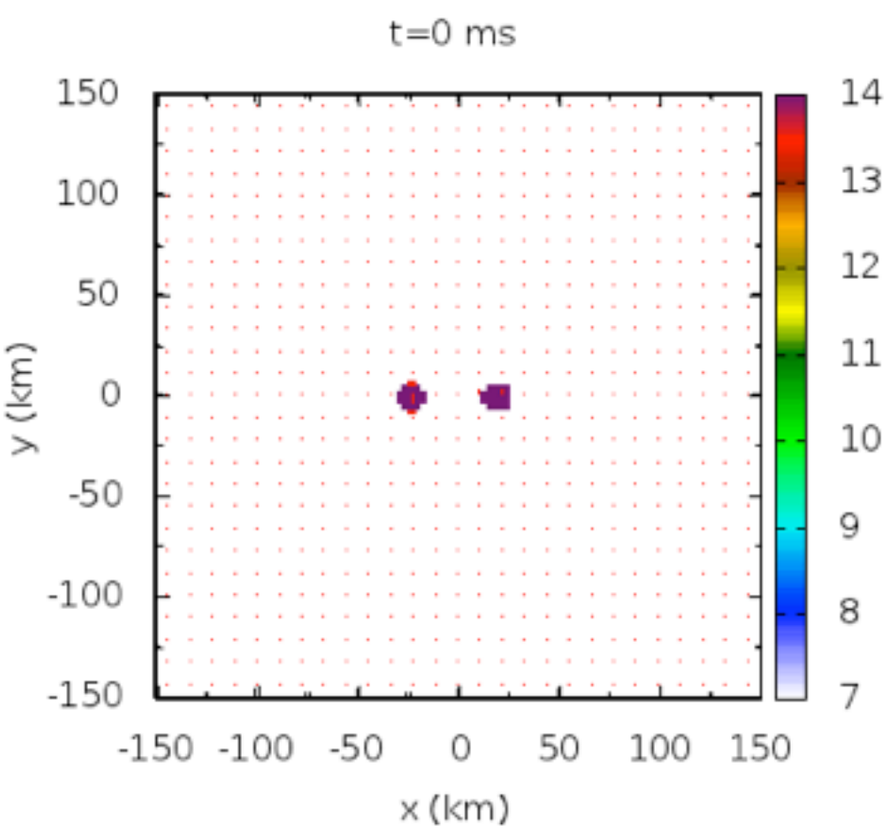
$$L \sim 10^{42} \text{ erg s}^{-1} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{-1/2}$$

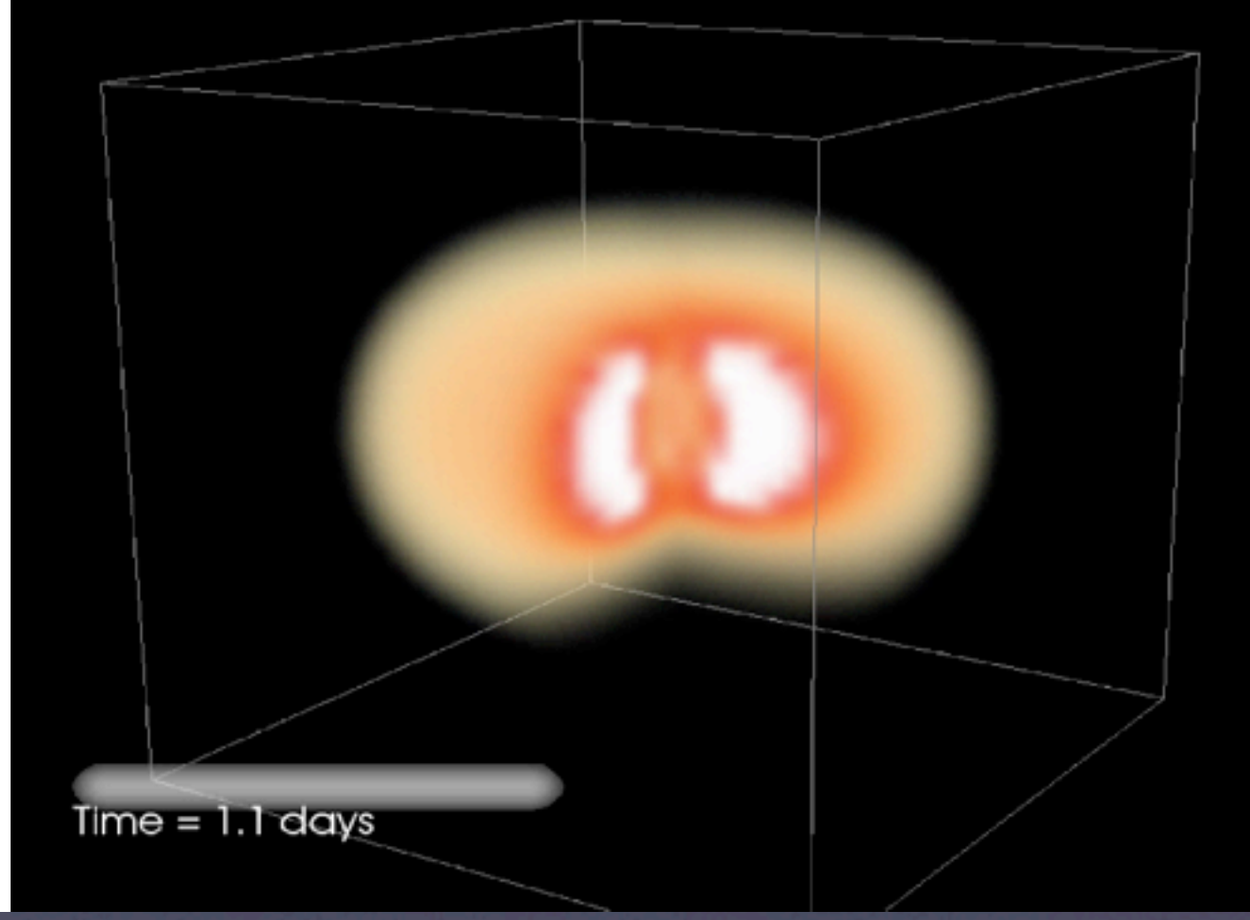
Opacity of Fe !

~ 20 mag at 200 Mpc
(1m-class telescopes)

Numerical relativity

3D, time-dependent, multi-frequency radiative transfer



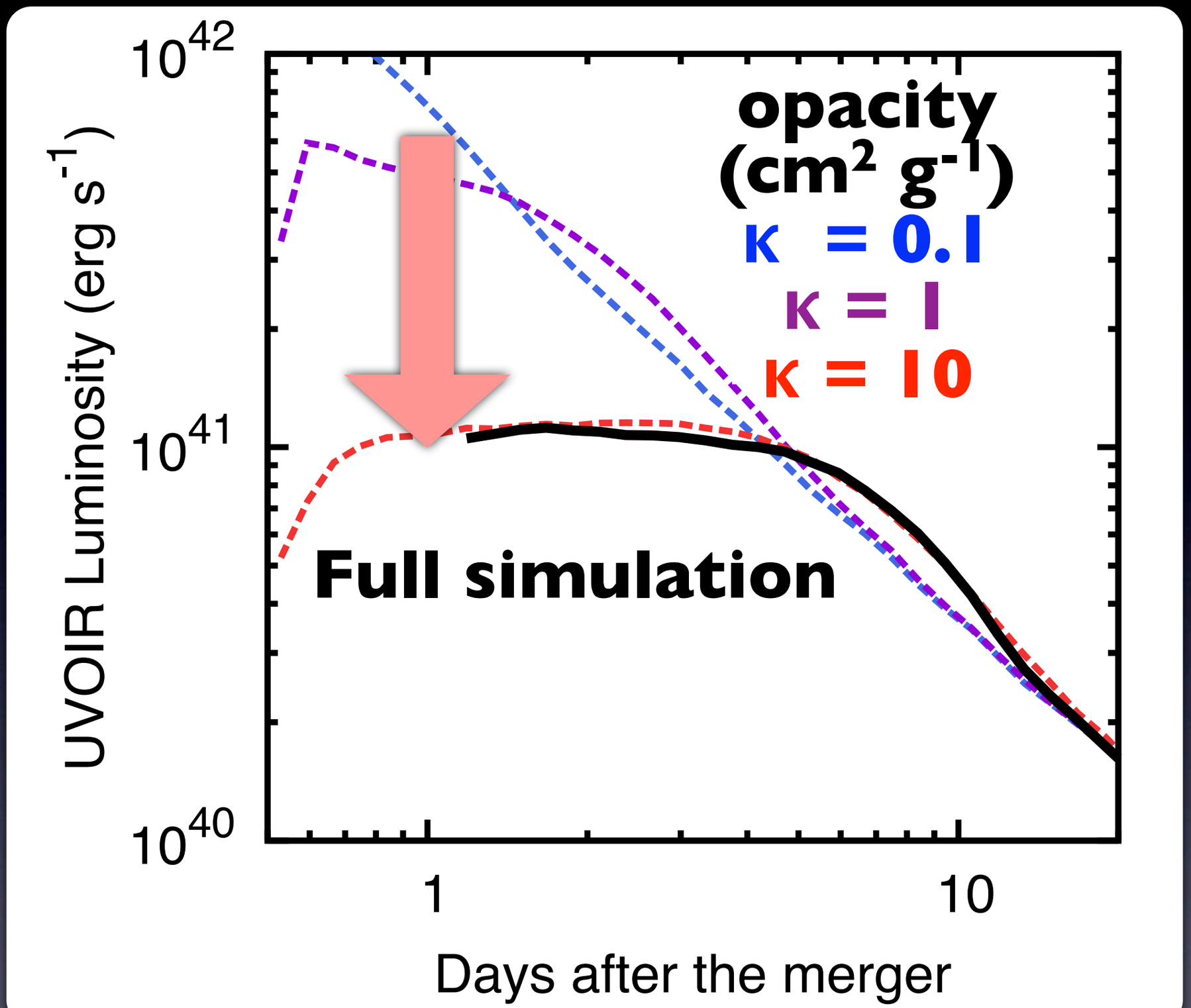


Hotokezaka et al. 2013

MT & Hotokezaka 2013, ApJ, 775, 113

1. Opacity of r-process-dominated ejecta?

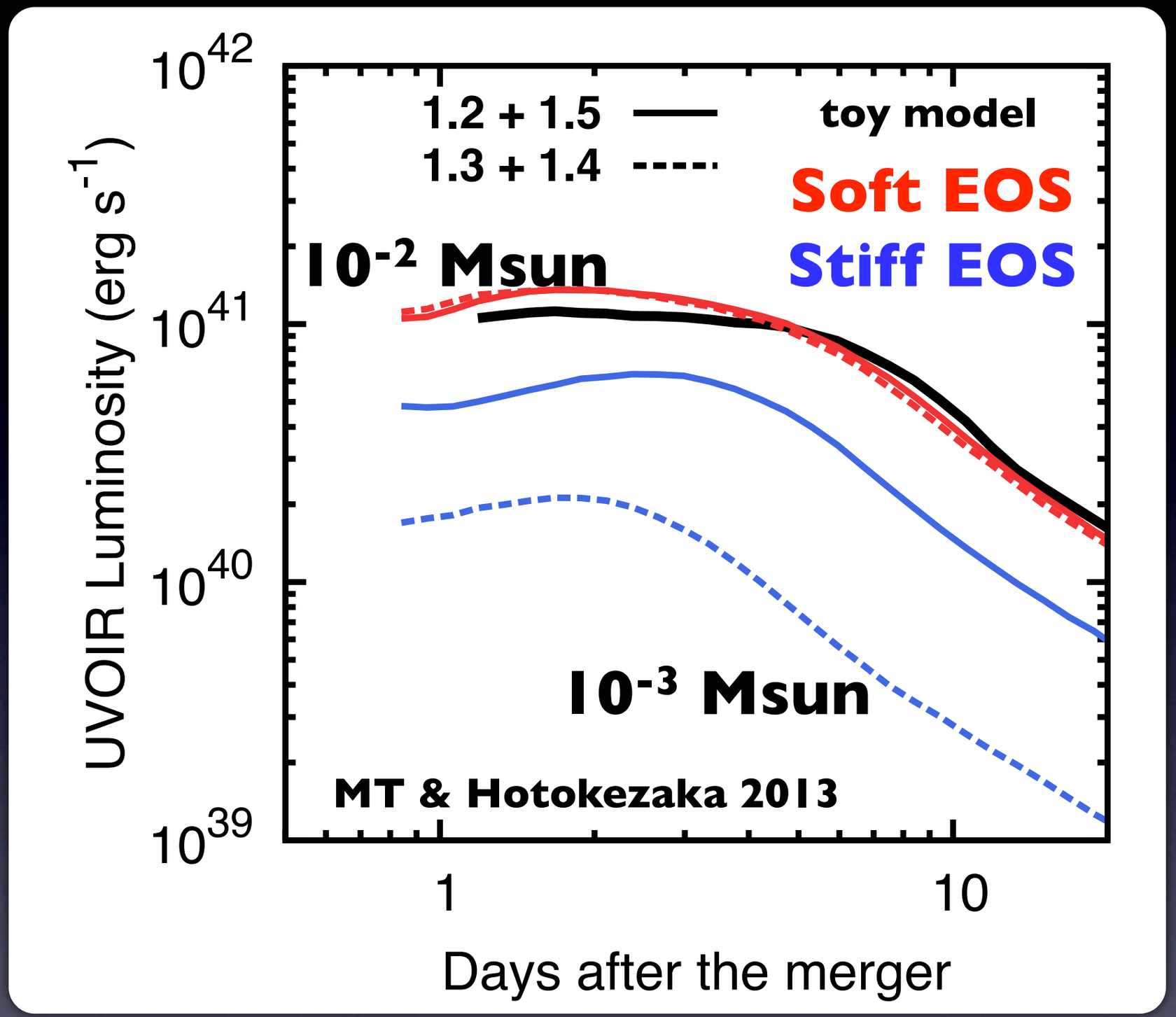
2. Characteristic feature of NS merger?



- Higher opacity by factor of 100

- Fainter than previously expected by a factor of 10

(see also Kasen+13, Barnes & Kasen 13)



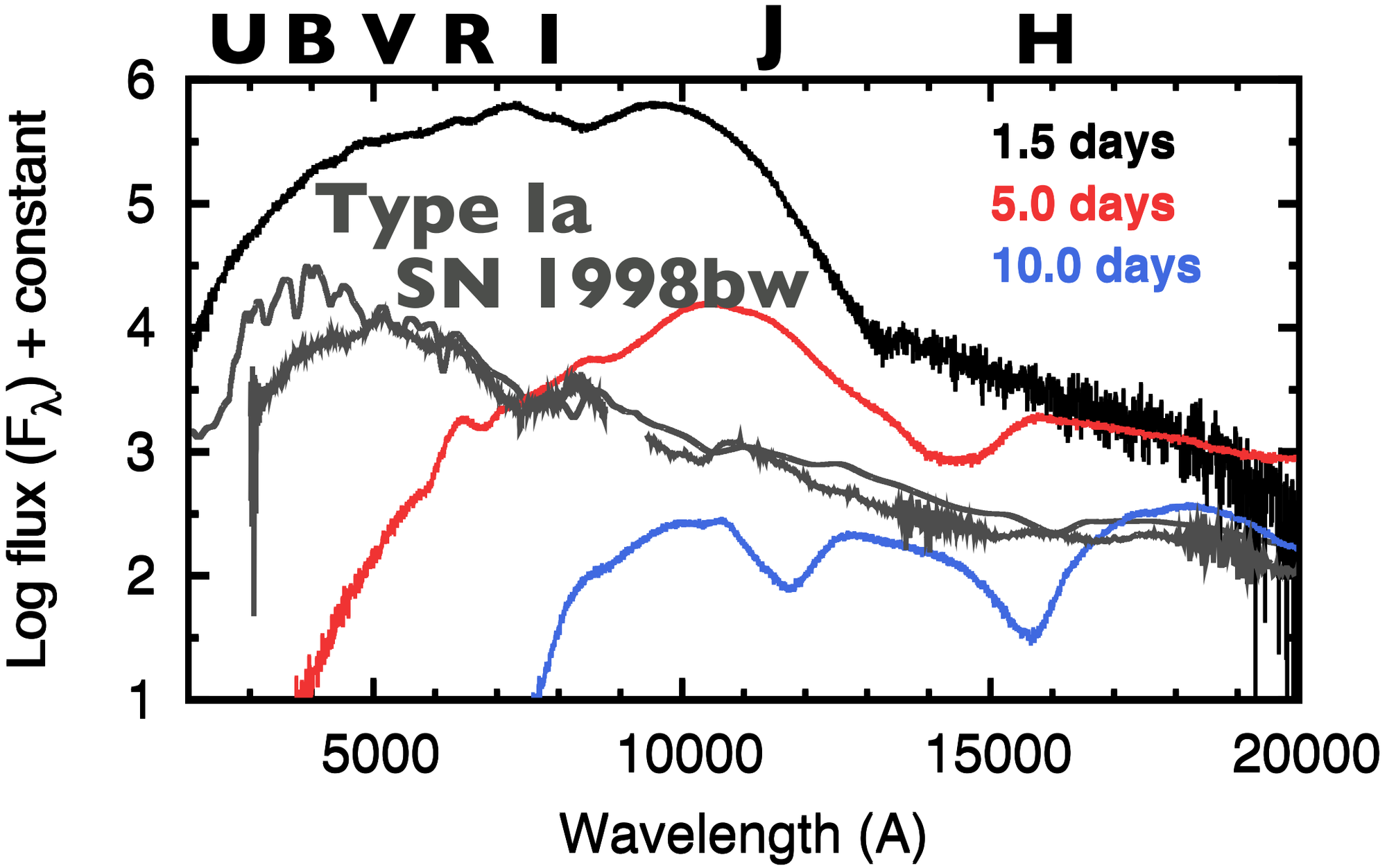
Radius of 1.35 Msun NS

R = 11.1 km
R = 13.6 km

Softer EOS/Higher NS mass ratio

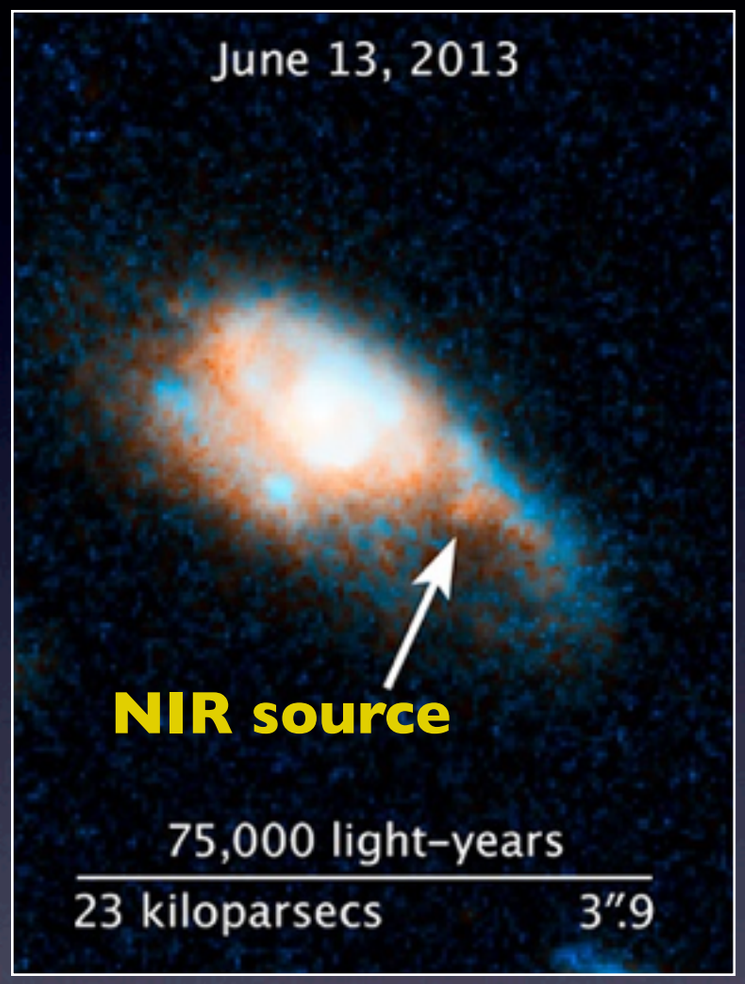
Brighter emission

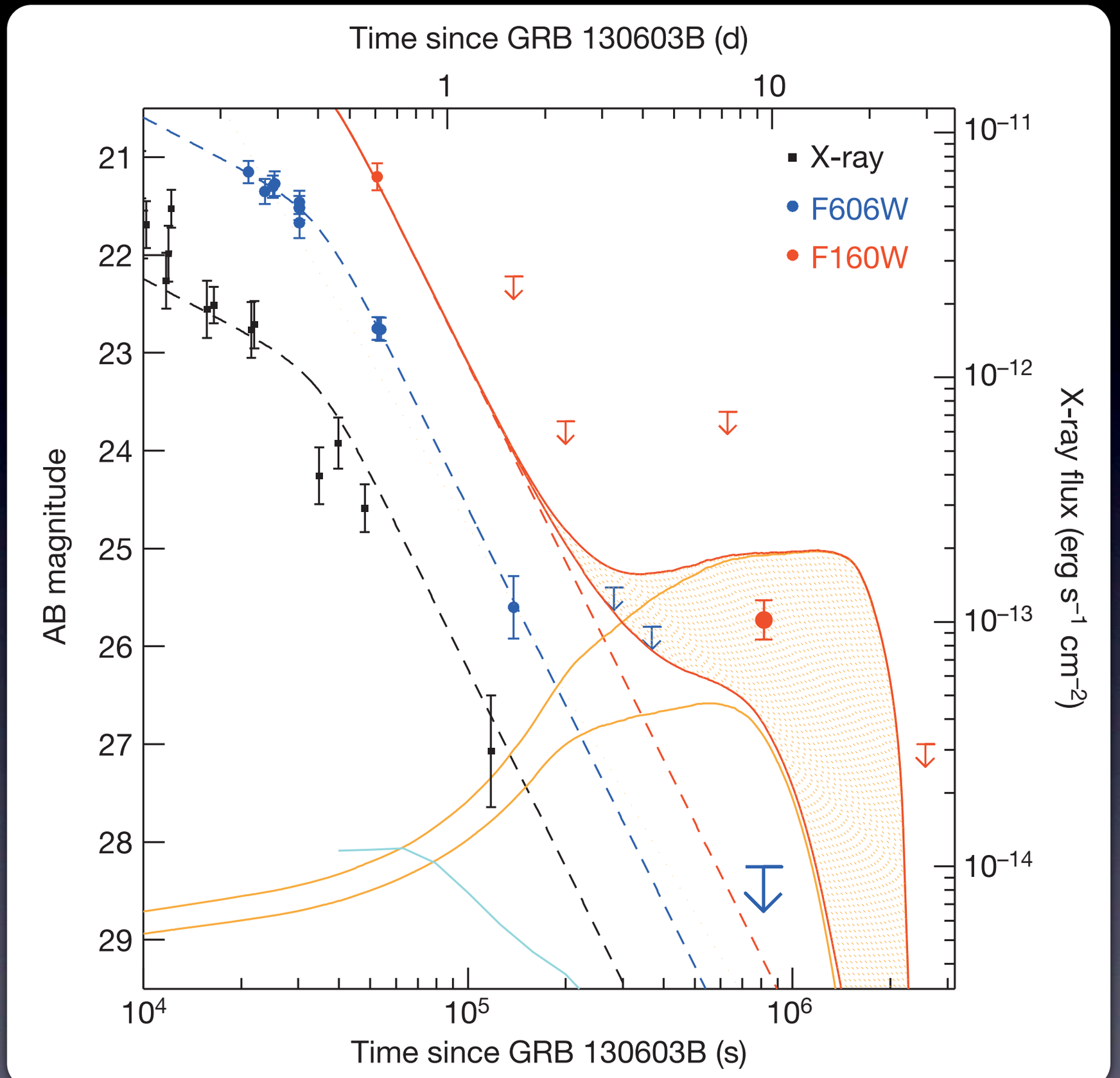
(see also Hotokezaka+13; Bauswein+13)



- Very red SED (peak at NIR)
- Extremely broad-line (feature-less) spectra
- Identification of r-process elements is difficult

GRB 130603B



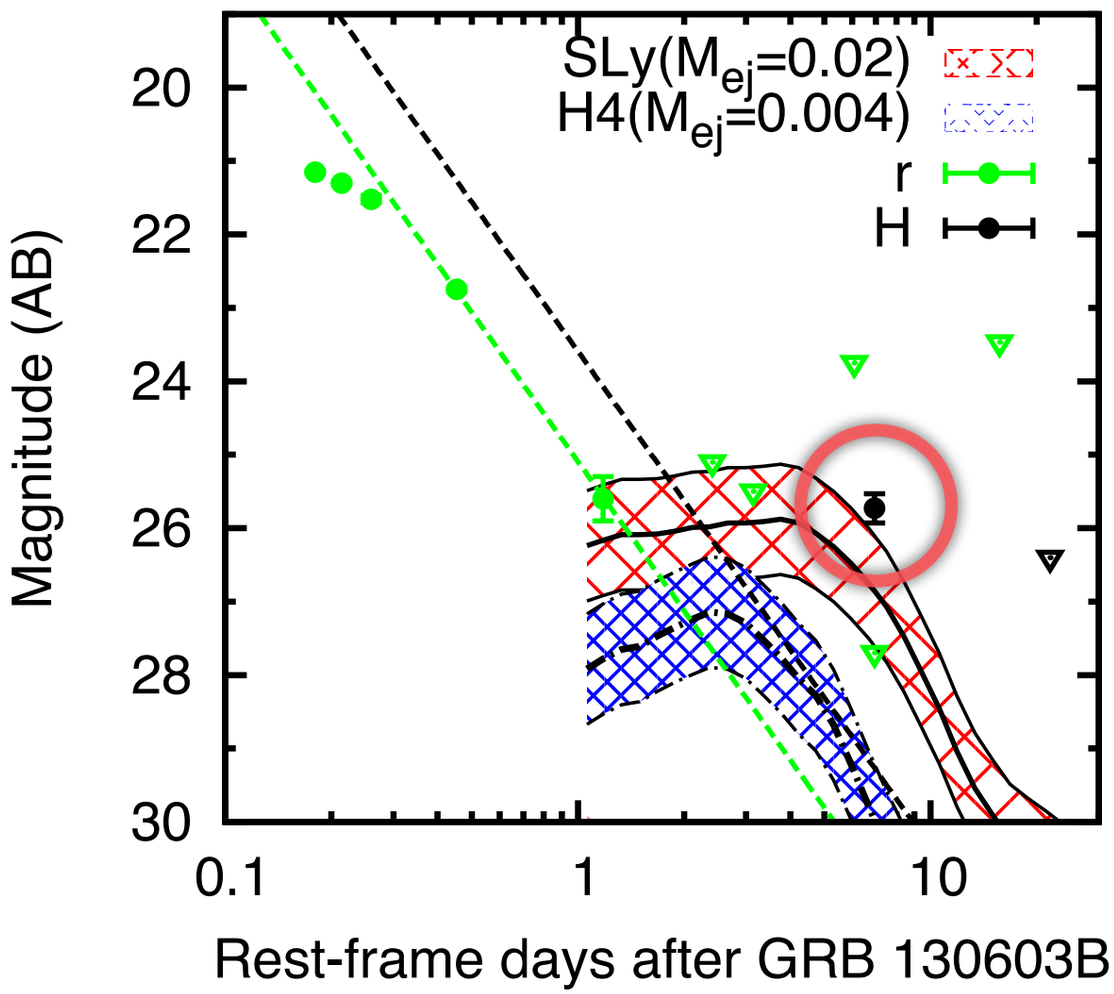


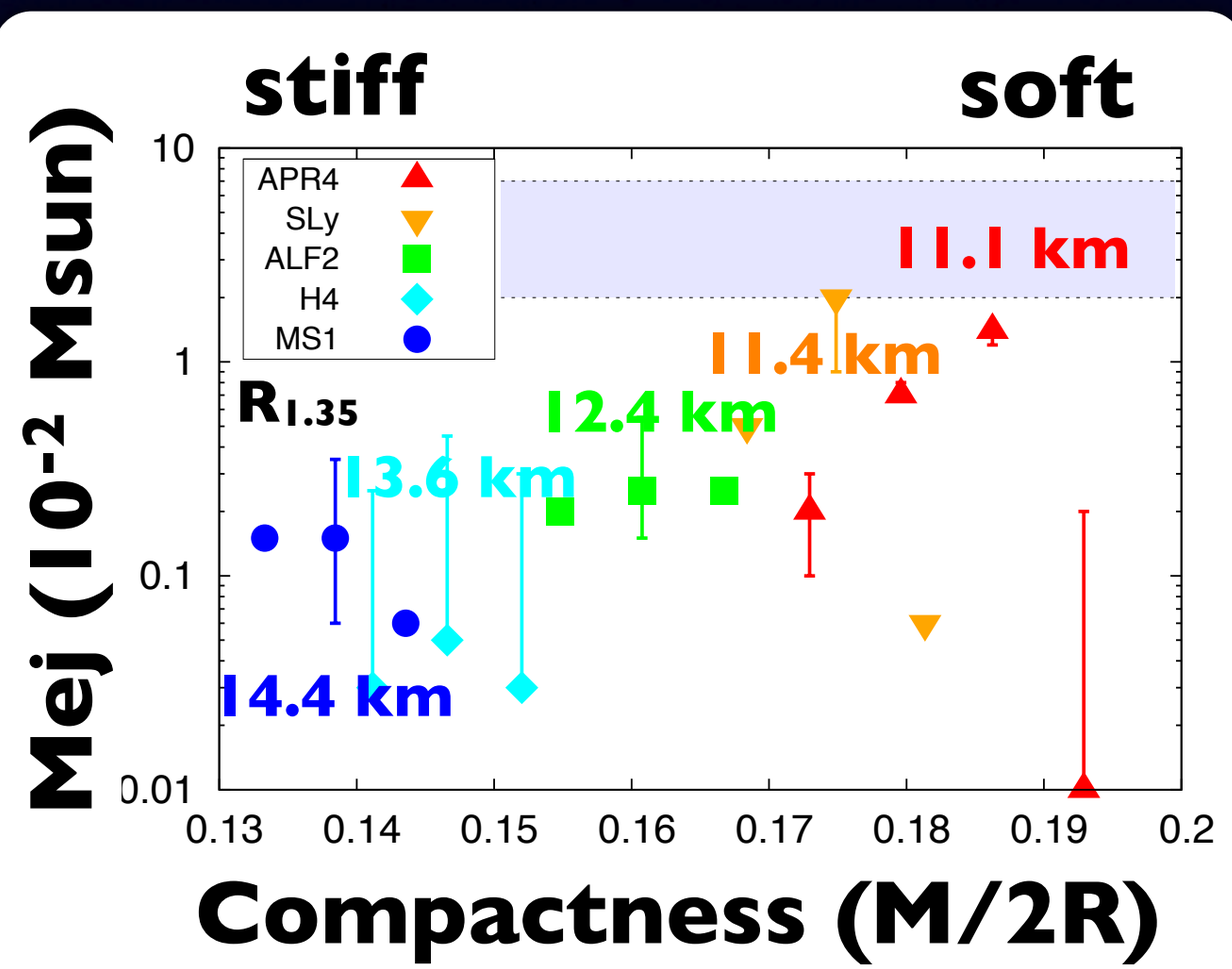
Tanvir+13
Berger+13

Very red (R-H > 2.5 mag)

Link between observations and theory

Mass ejection
Mej ~ 0.02 Msun





Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo
2013, ApJ, 778, L16

Origin of r-process elements

(==> Wanajo-san's and Sekiguchi-san's talks)

Galactic NS binary

R_{NSM} ~ 100 event/Myr/Galaxy

= 10^{-4} event/yr/Galaxy

→ NS-NS merger rate Within 200 Mpc ~ 30 events/yr (~0.3-300)

M_{ej}(r-process) ~ 10^{-2} Msun ← EM GW

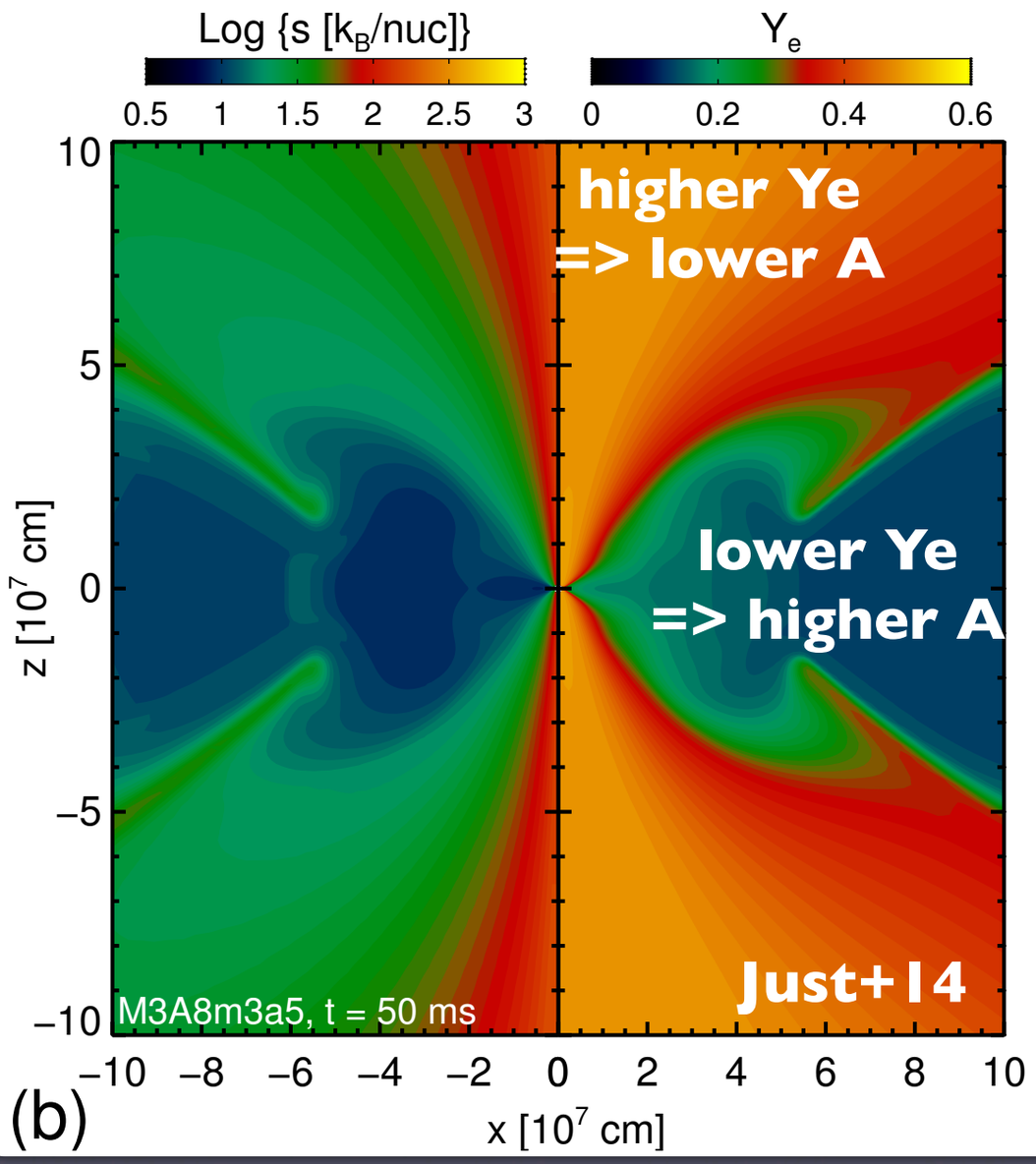
M(Galaxy, r-process) ~ $M_{ej}(r) \times (R_{NSM} \times t_G)$

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

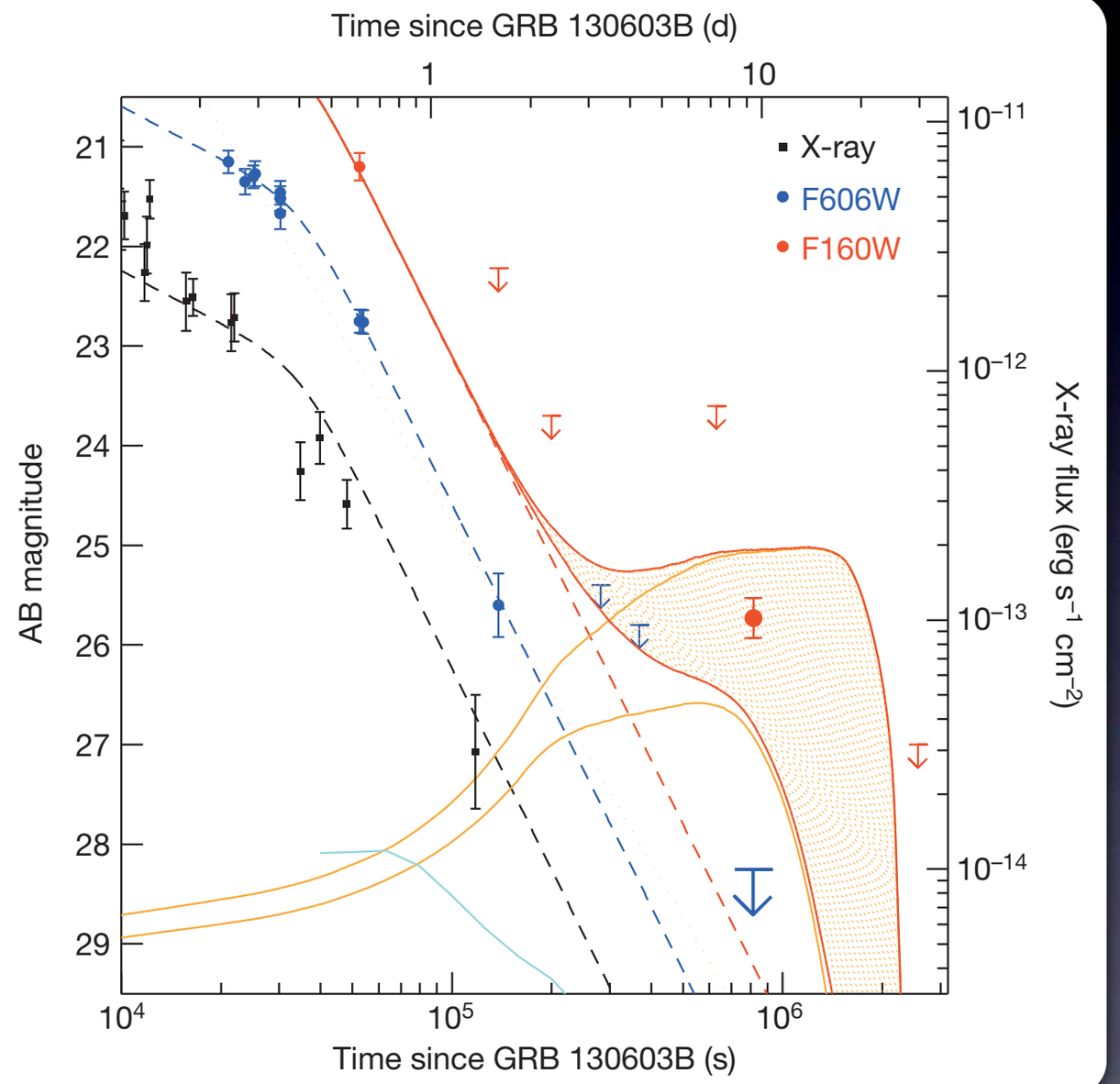
"Testable" scenario (EM+GW)

Caveats!!

Simulations



Observations



Two components
=> can be brighter/bluer

Photometry only
=> need spectroscopy

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- Why “kilonova”?
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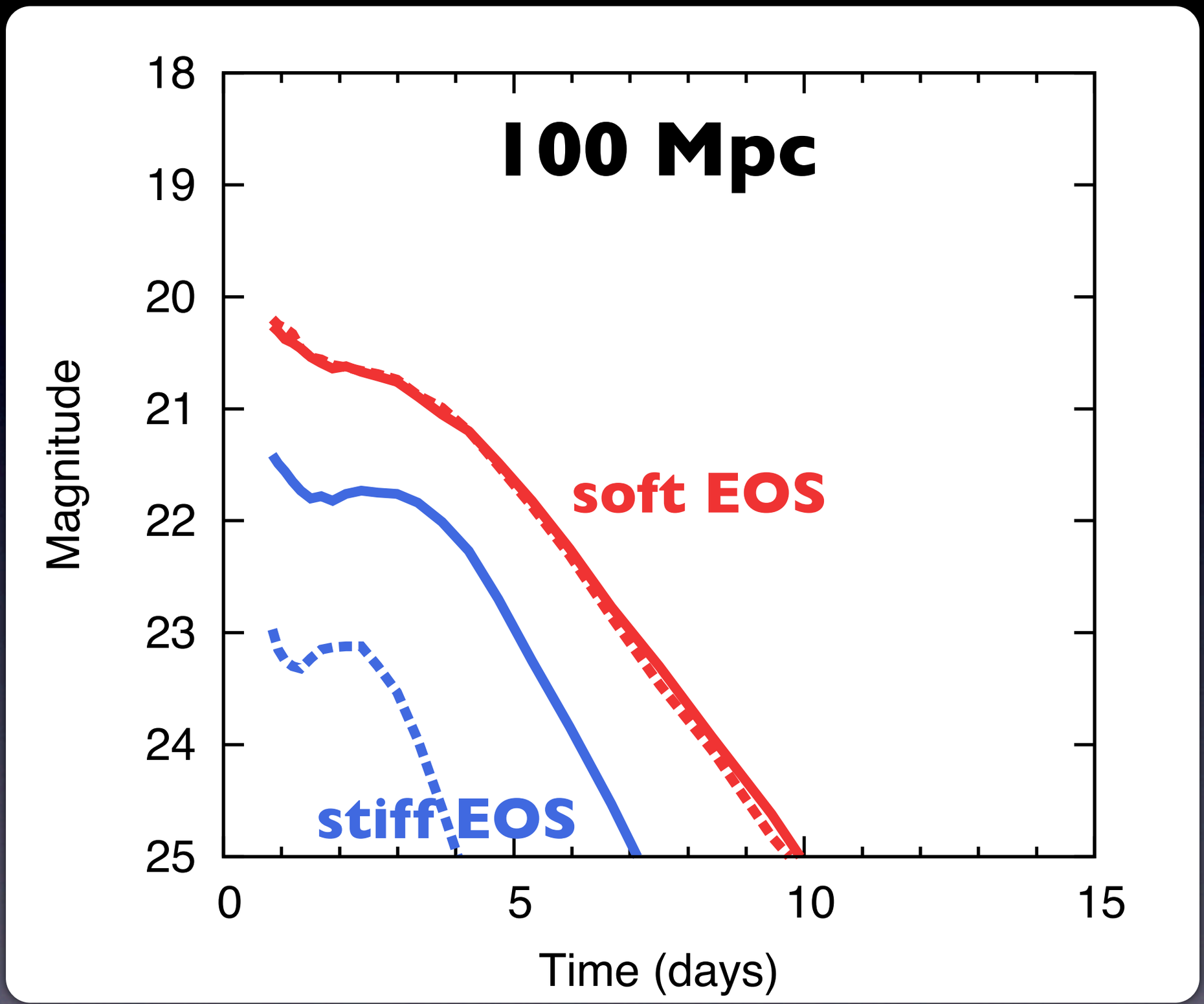
- Prospects for observations

GW early observing runs (2015-2016)



Im

KISS: KIso Supernova Survey

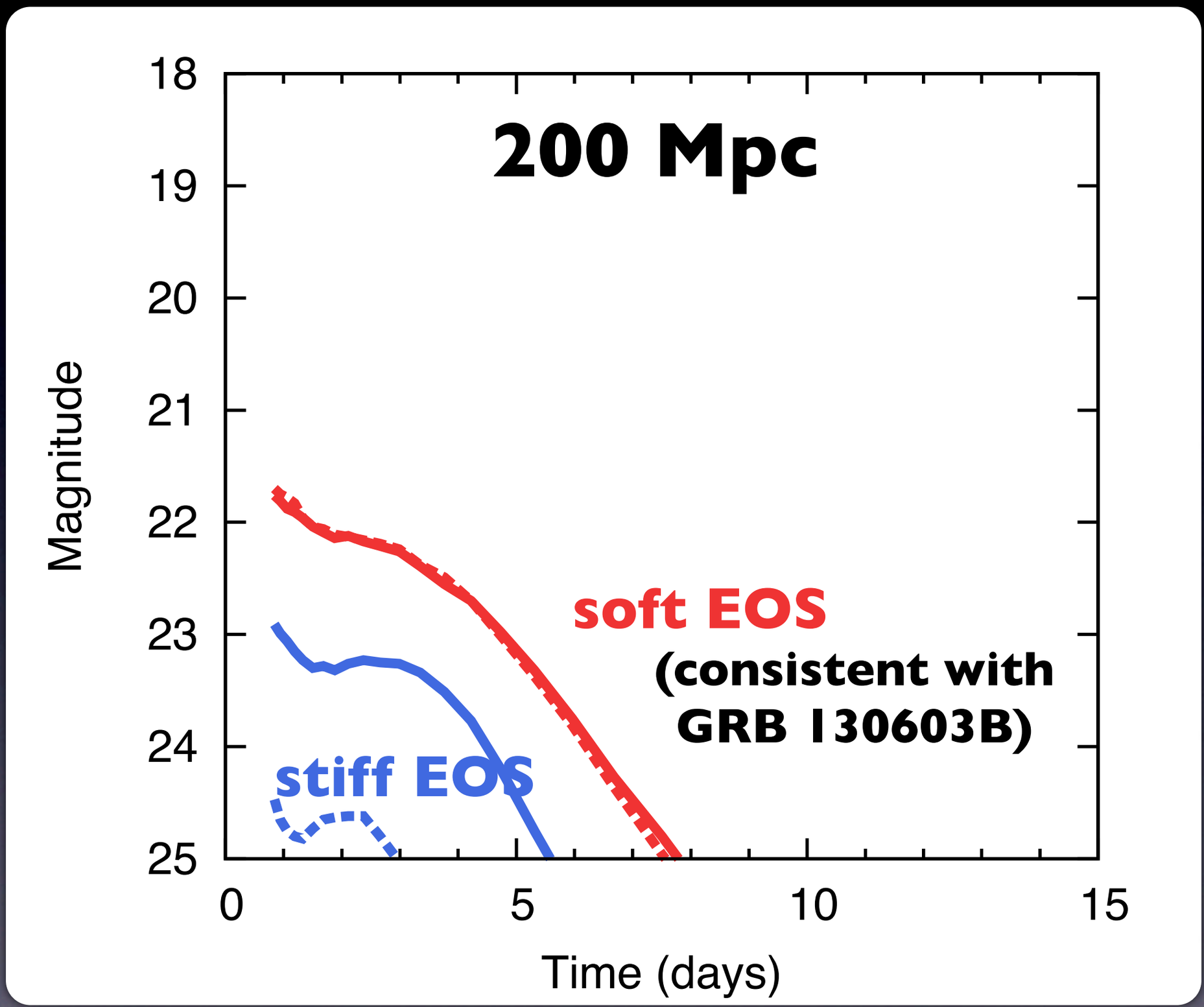
- High-cadence transient survey
  - 1-hr cadence <= 2-3 days
  - 4 deg^2 FOV KWFC
  - ~ 21 mag in g-band (3 min)
  - ~50-100 deg^2 /day
  - ~100 nights/yr (around new moon)


Kiso 1.05m Schmidt telescope

Primal goal: Detection of SN shock breakout

MOU between
Japanese collaboration for GW EM follow-up (J-GEM)
and LIGO/Virgo collaboration (LVC)

GW full observing run (2017 -)



1m

4m

8m

GW alert error box

e.g. 6 deg x 6 deg

Typical 8-10m telescope

0.3 deg

8m LSST (2020-)

3.5 deg

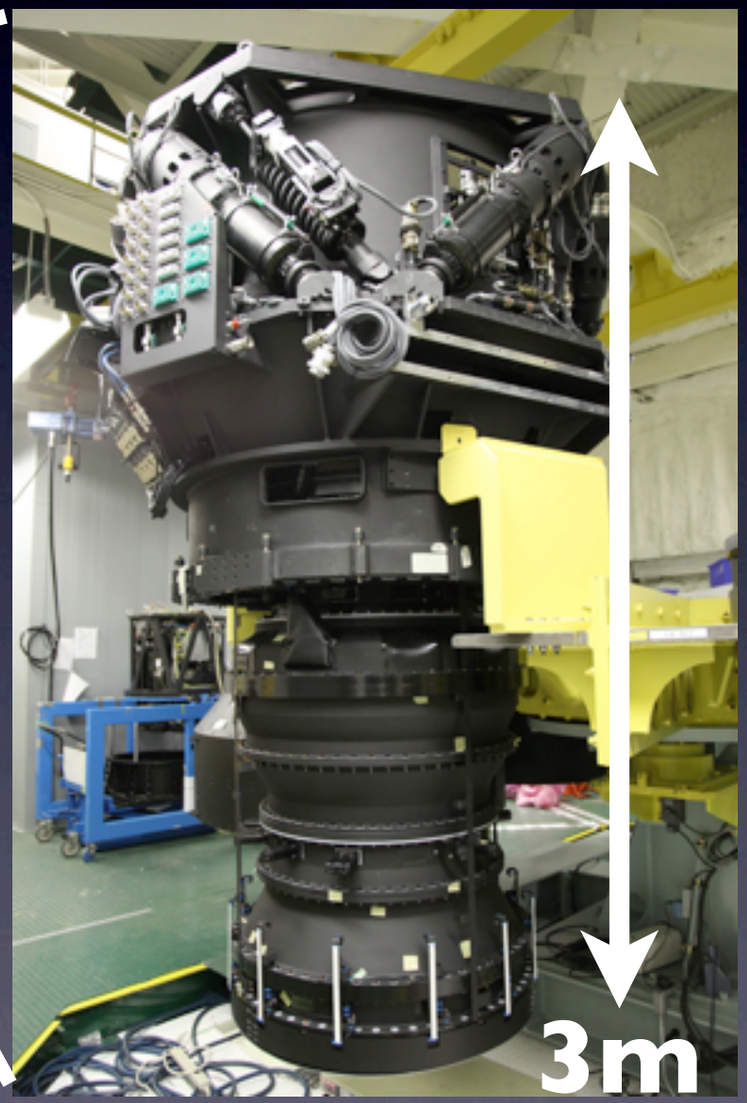
2 deg

8m Subaru

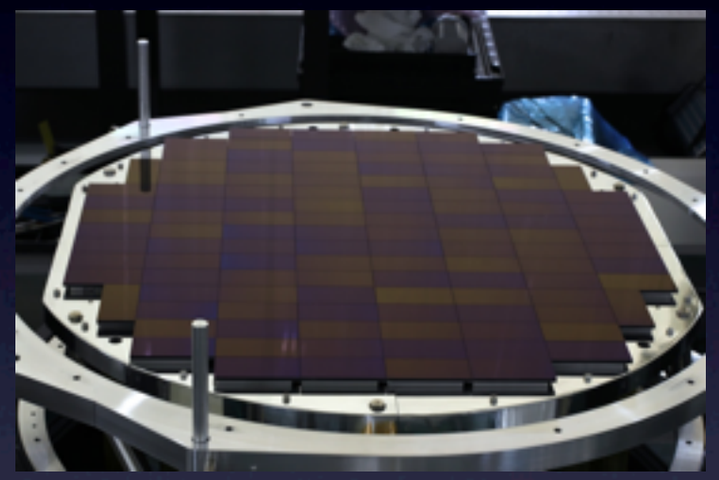
Hyper Suprime-Cam

1.5 deg

Subaru/ Hyper Suprime-Cam
2013 -



3t !



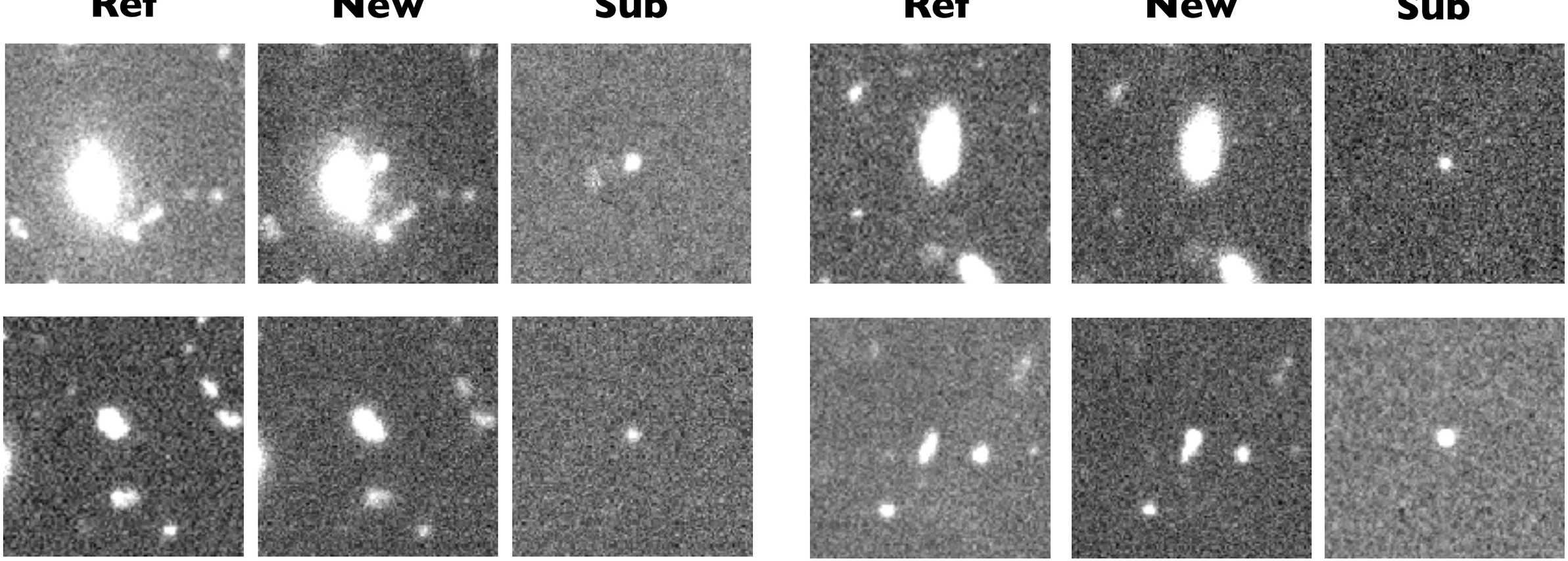
1.75 deg^2
116 CCDs

First transient survey with Subaru/HSC (2014 July 2-3 UT)

The Astronomer's Telegram

First supernova candidates discovered with Subaru/Hyper Suprime-Cam

ATel #6291; *Nozomu Tominaga (Konan U./Kavli IPMU, U. Tokyo), Tomoki Morokuma (U. Tokyo), Masaomi Tanaka (NAOJ), Naoki Yasuda (Kavli IPMU, U. Tokyo), Hisanori Furusawa (NAOJ), Jian Jiang (U. Tokyo), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*
on 4 Jul 2014; 15:51 UT



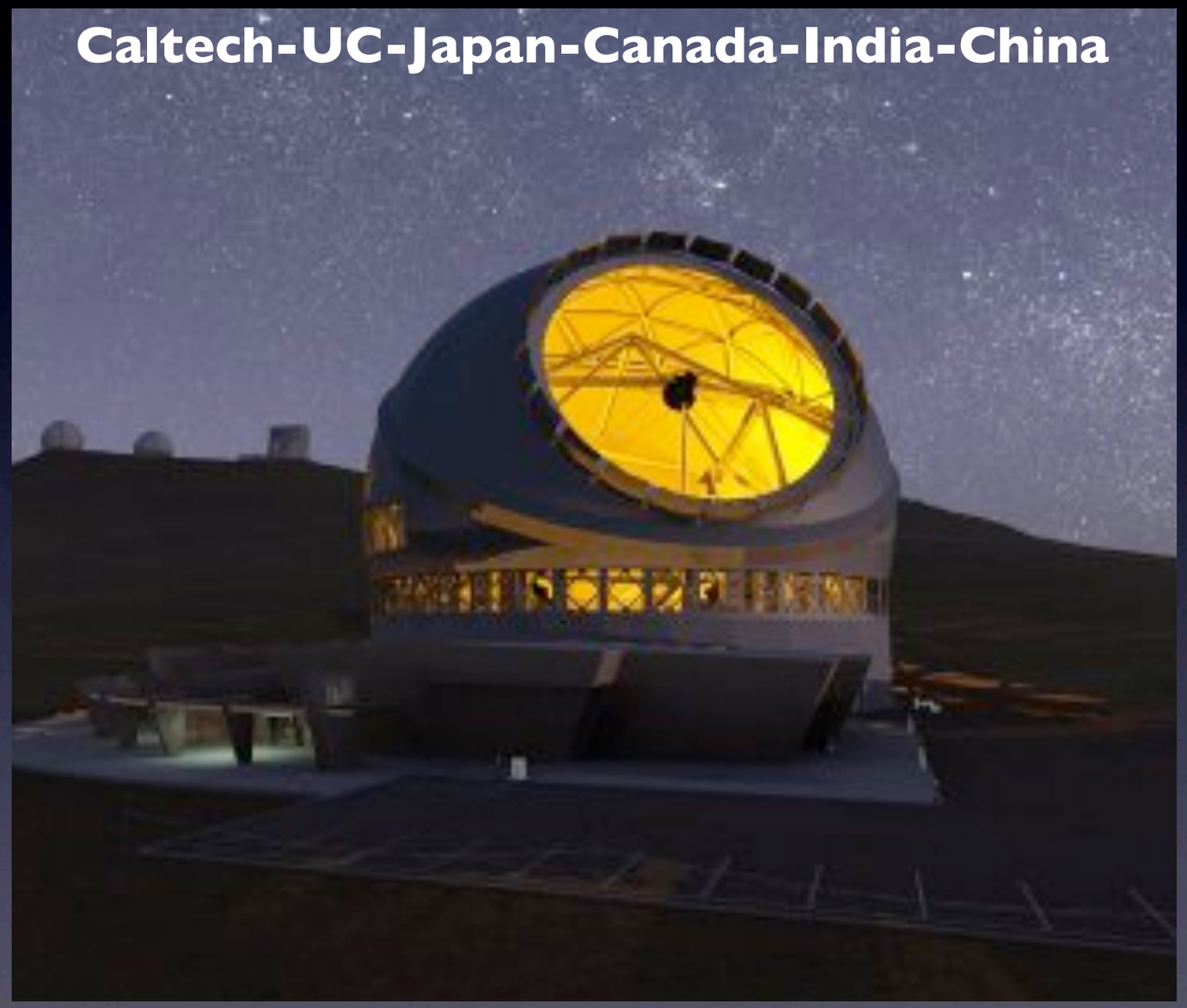
http://tpweb2.phys.konan-u.ac.jp/~tominaga/HSC-SN/

Future opportunity with TMT
Thirty Meter Telescope

Spectroscopy down to
- 28 mag (optical)
- 26 mag (NIR)

Instrument exchange within ~10 min

2014
Start construction
2022
First light



International Science Definition Team for Time-domain science (led by MT and G.C. Anupama) [K. Maeda and N. Tominaga from Japan]

Summary

- "Kilonova" EM emission from NS merger
  - Important as a counterpart of GW sources
  - Numerical relativity + full radiative transfer
  - Link between observations and progenitor/ properties of dense matter (GRB 130603B)
    - r-process nucleosyntheis
- Optical/IR observations for GW astronomy
  - ~20-21 mag @ 100 Mpc (2015-)
    ==> 1m class telescopes (e.g. KISS)
  - ~22-23 mag @ 200 Mpc (2017-)
    ==> 4-8m class telescopes (e.g. Subaru/HSC)

"Multi-messenger" astronomy is coming