Optical/Infrared Counterparts of Gravitational Wave Sources

- 重力波源の光学赤外線対応天体 -

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New astronomy with gravitational waves

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

NS merger within 200 Mpc
~ 30 events/yr

Talk by Hotokezaka-san

Supernovae in our Galaxy
~ 1 event/ 50 yr

Talks by Kotake-san and Koshio-san

2 deg

Kiso 1m
Schmidt telescope
(KWFC)

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

GW alert error box

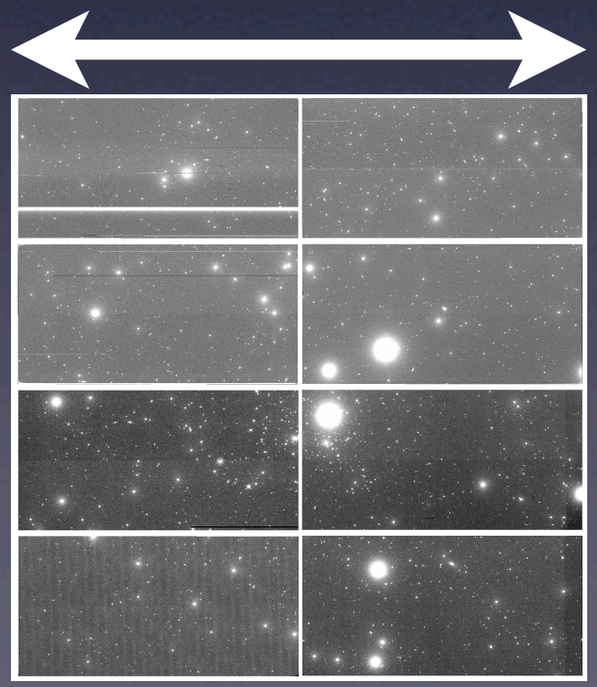
e.g. 6 deg x 6 deg

~ 2000 galaxies

(< 200 Mpc)

No electromagnetic counterpart
No gravitational wave astronomy

2 deg



Magnitude

$$m = -2.5 \log_{10}(F_\nu) - 48.6$$
$$= -2.5 \log_{10} \left(\frac{F_\nu}{3631 \times 10^{-23} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2}} \right)$$

Galactic SNe

SN 1987A @ 50 kpc

SN @ 200 Mpc

mag

0 5 10 15 20 25 30

eye 1m 4m 8m space

# of telescopes

2 - 3.5 m : many

3.5-6.5 m : 24

>8-10 m : 13

Need good observing strategy
Need good prediction

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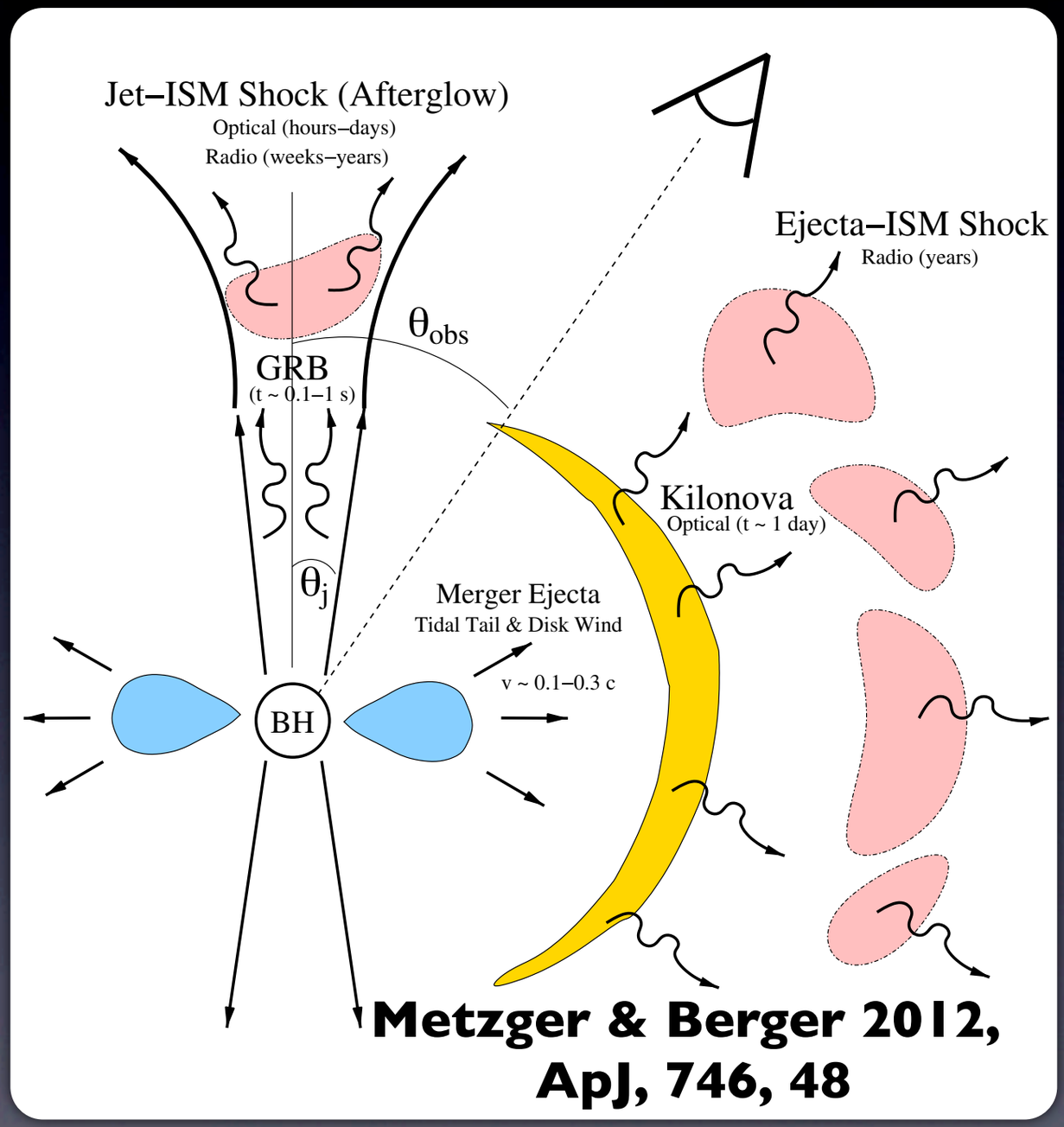
- 重力波源の光学赤外線対応天体 -

- 連星中性子星合体からの光学赤外線放射
- 光学赤外線突発天体サーベイ観測

EM signature from NS-NS merger

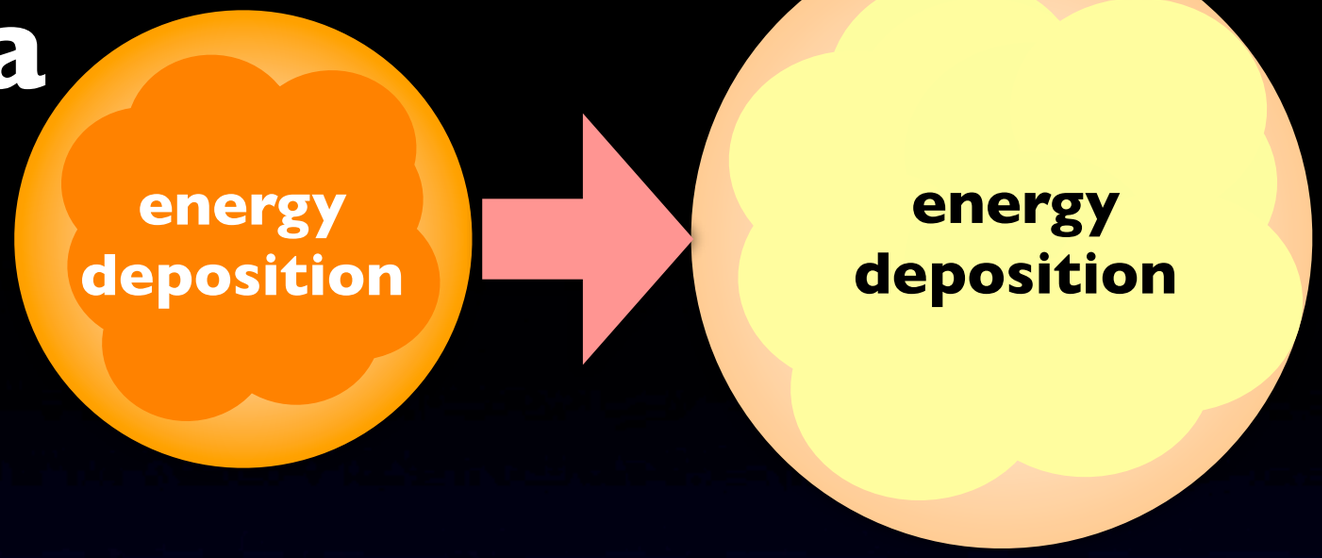
- On-axis short GRB
- Off-axis radio/optical afterglow
- X-ray extended emission
- Radioactive emission r-process nuclei
  - kilonova
  - macronova
  - r-process nova



Talks by Hotokezaka-san and Murase-san

kilonova/macronova
r-process nova

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

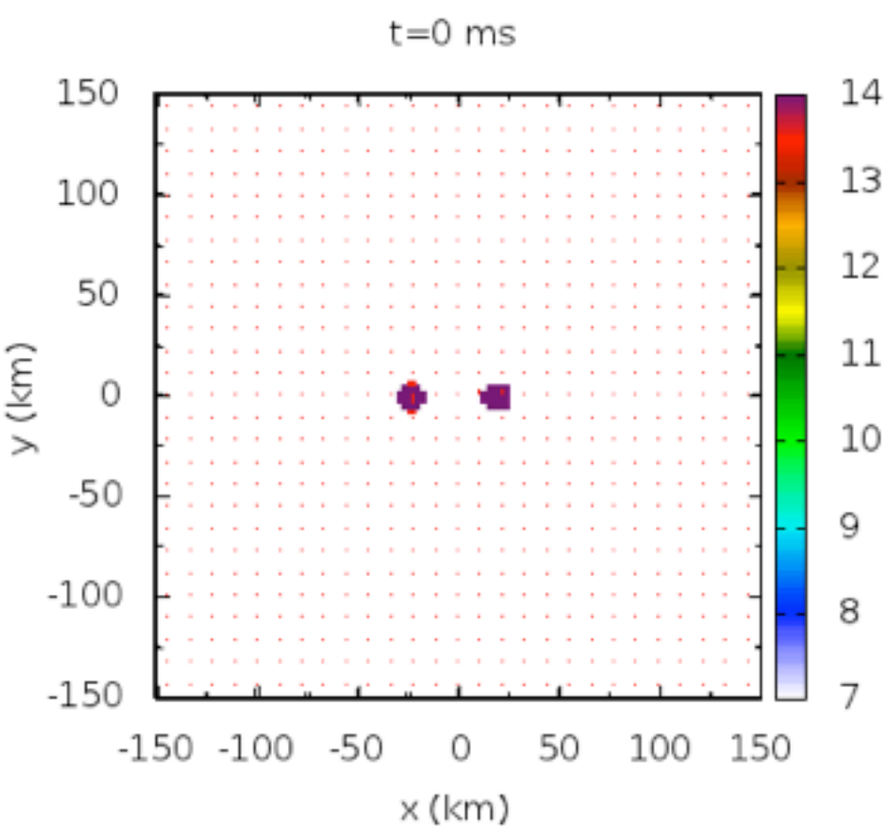
$$L \sim 10^{42} \text{ erg s}^{-1} \left(\frac{M}{0.01 M_\odot}\right)^{1/2} \left(\frac{v}{0.2c}\right)^{1/2} \left(\frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}}\right)^{-1/2}$$

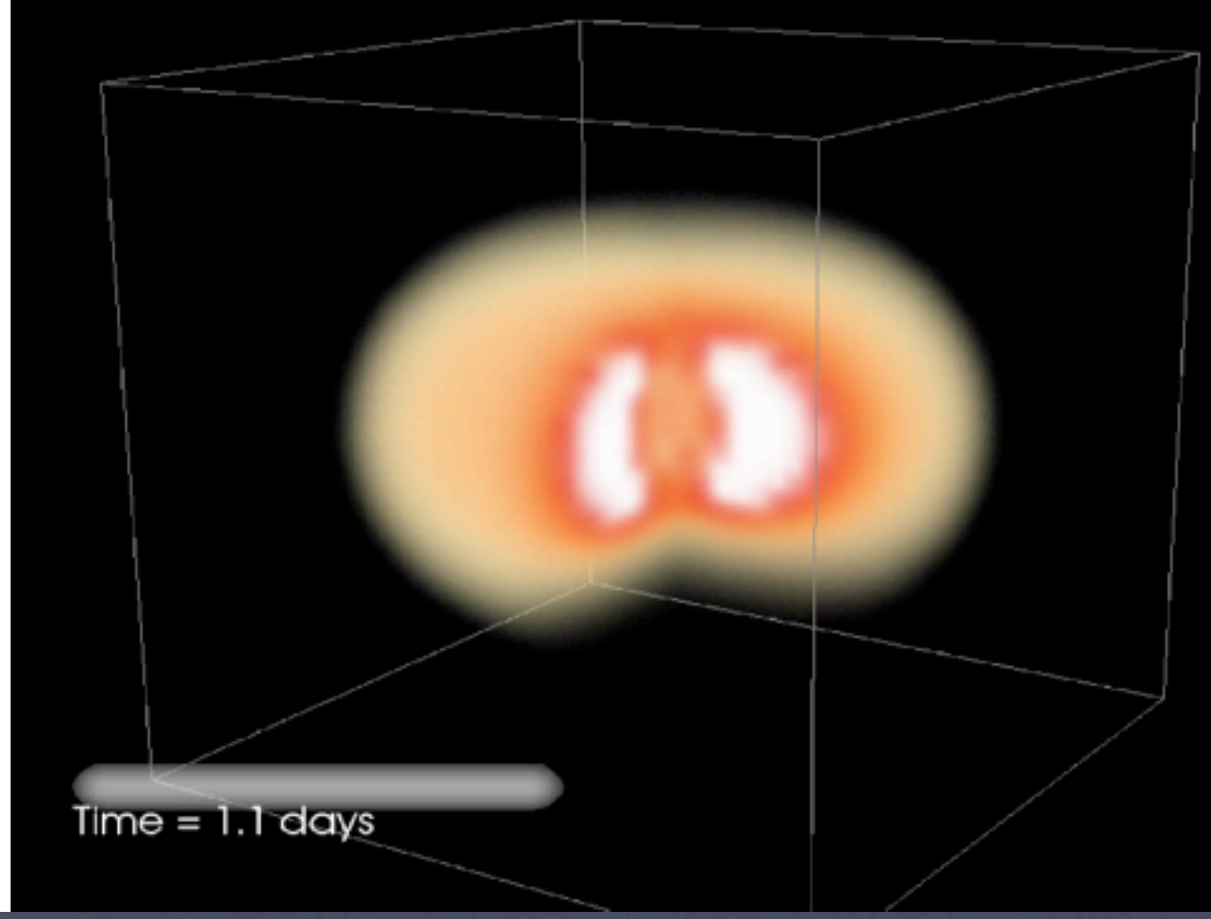
Opacity of Fe !

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

Numerical relativity

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



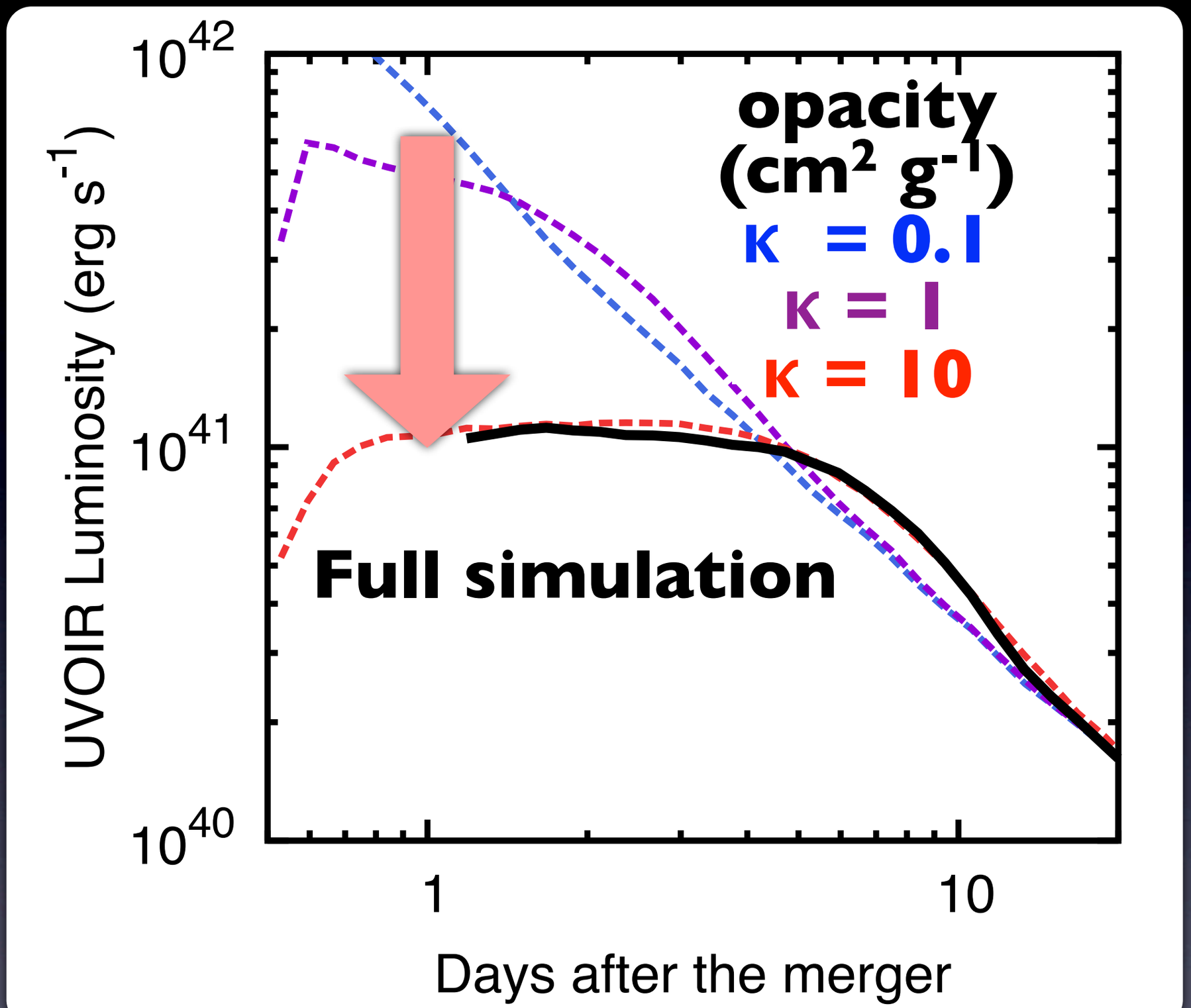


Hotokezaka et al. 2013

MT & Hotokezaka 2013

1. Opacity of r-process-dominated ejecta?

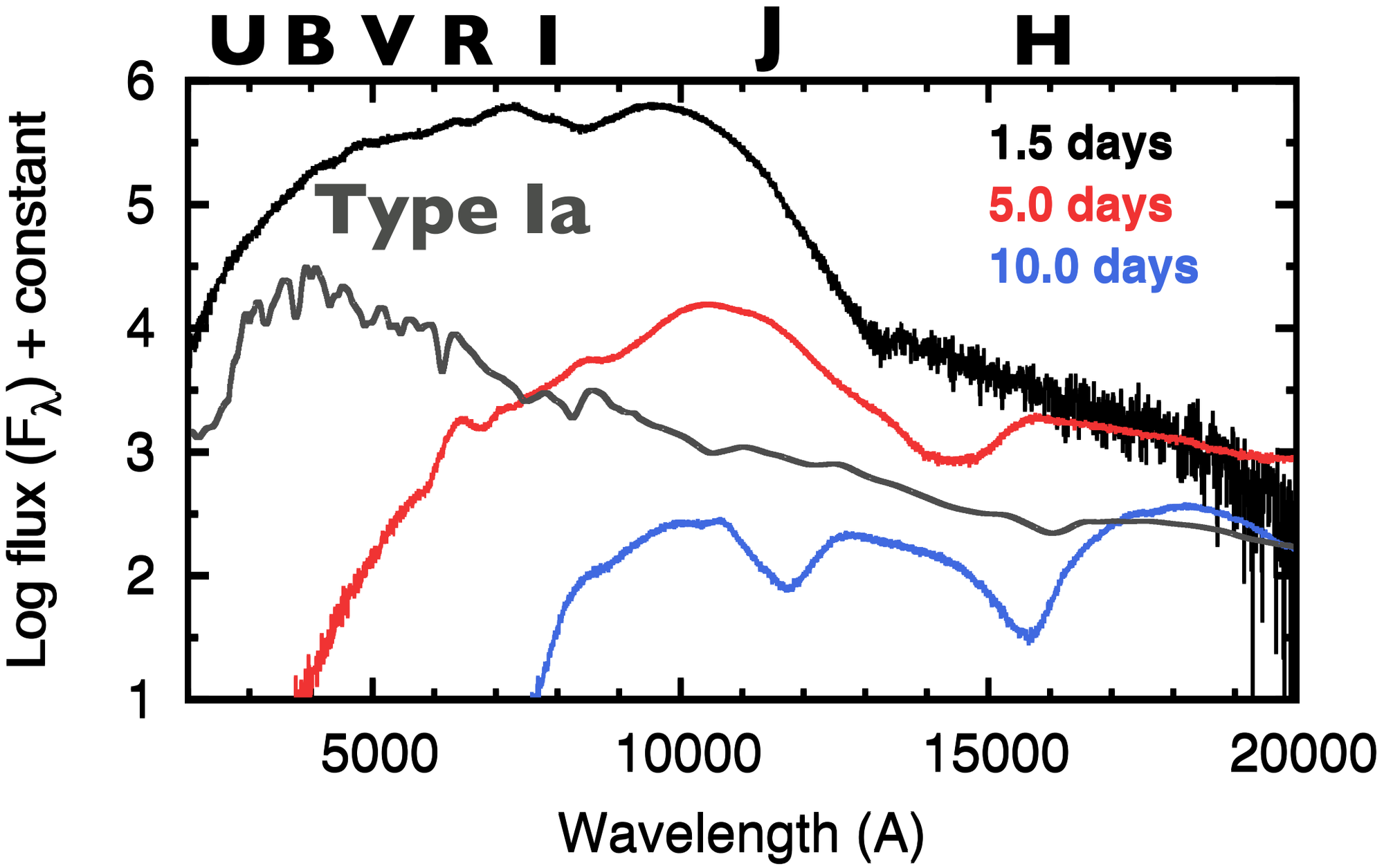
2. Characteristic feature of NS merger?



- Higher opacity by factor of 100

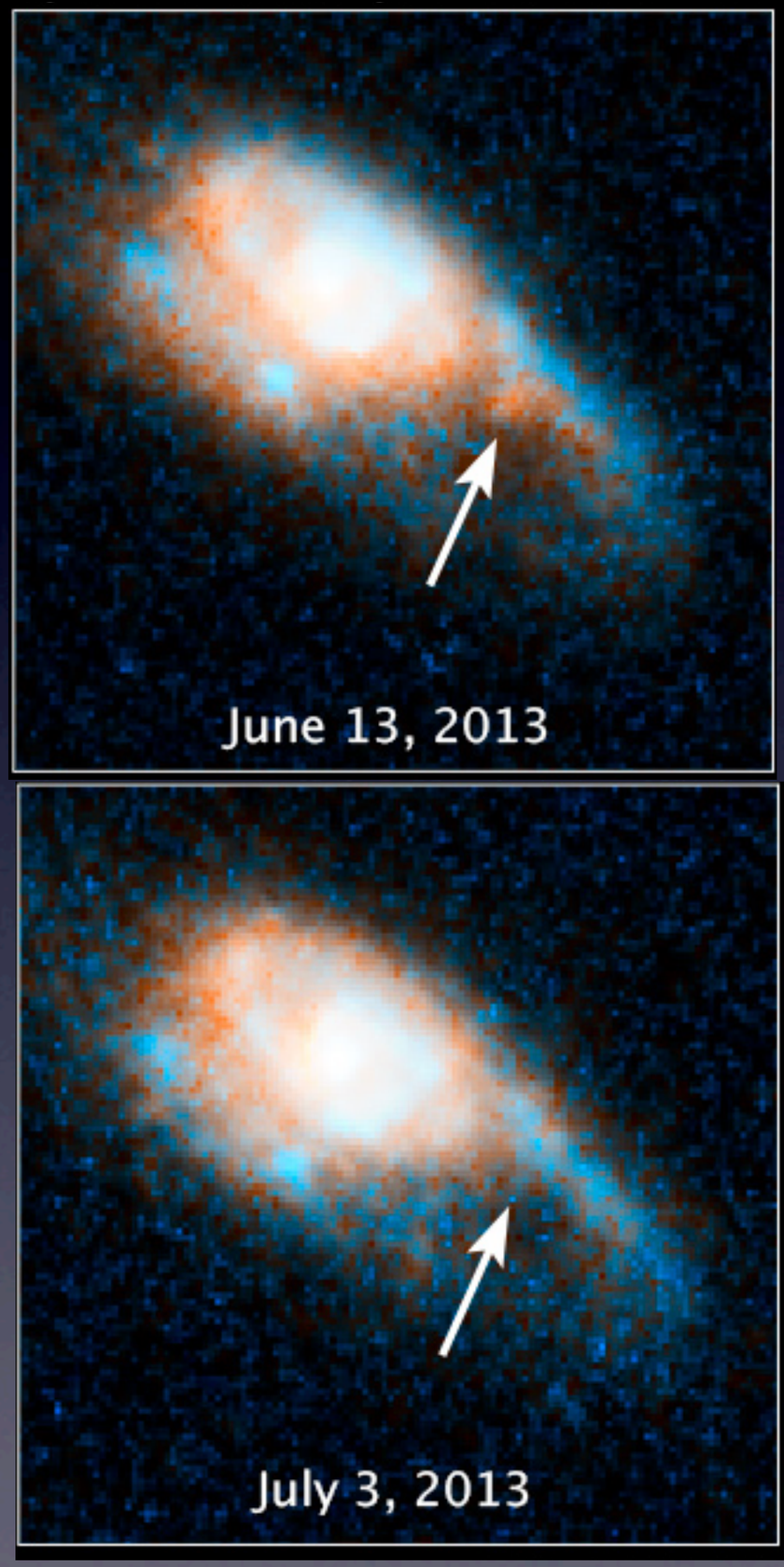
- Fainter than previously expected by a factor of 10

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

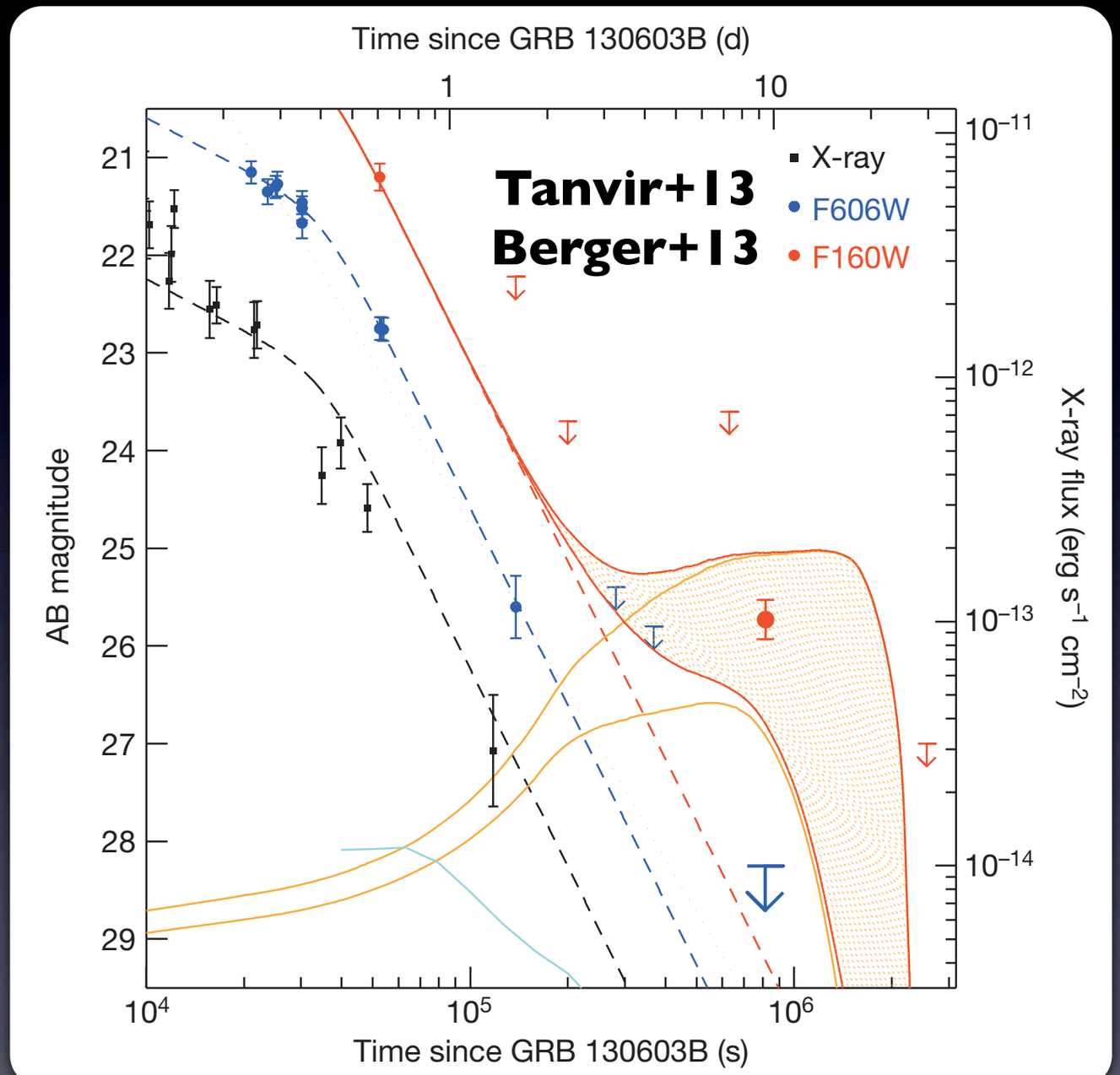


- **Very red SED (peak at NIR)**
- **Extremely broad-line (feature-less) spectra**
- **Identification of r-process elements is difficult**

GRB 130603B

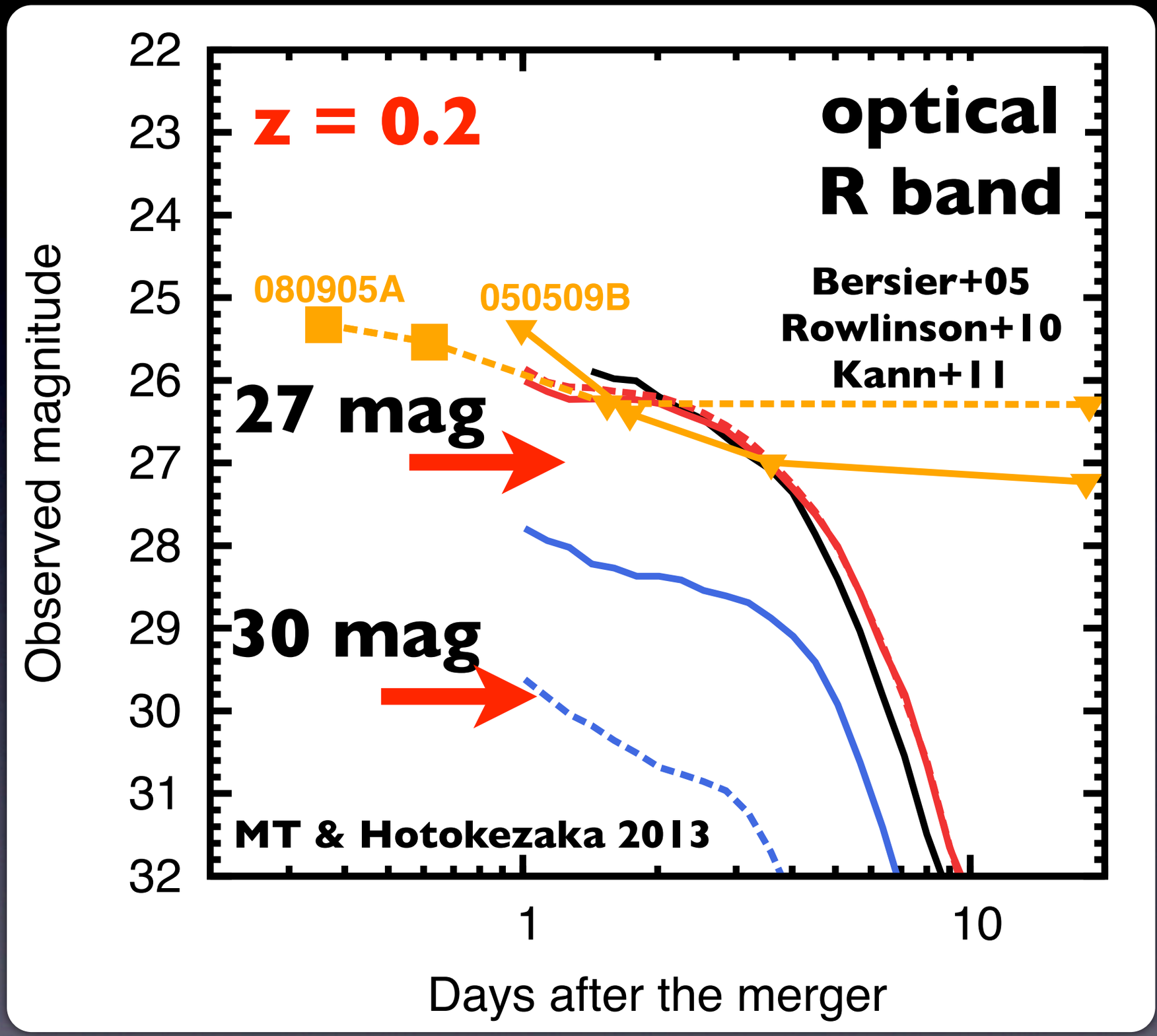


Very red (R-H > 2.5 mag)



Hotokezaka-san's talk

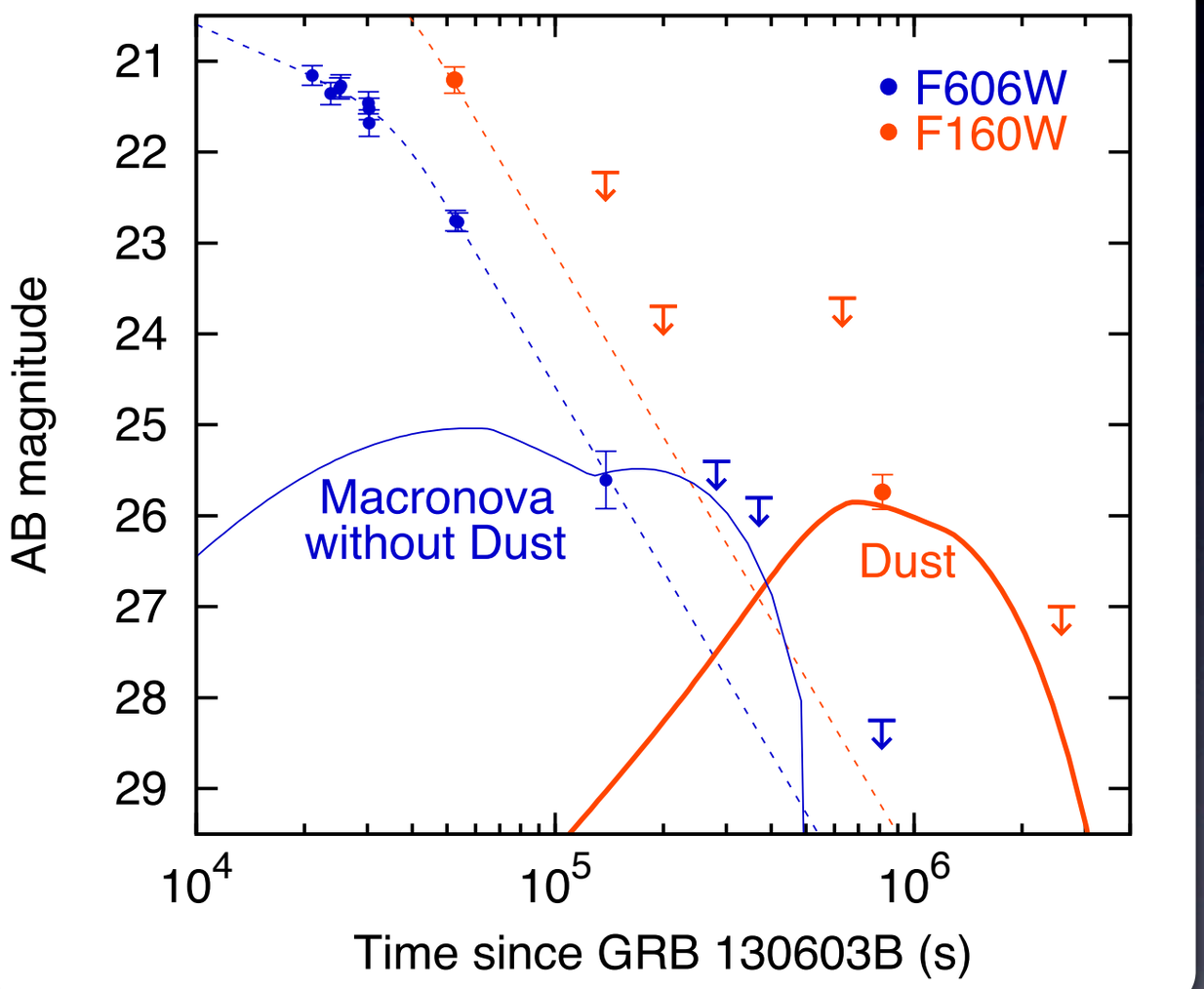
Previous search for “kilonova”



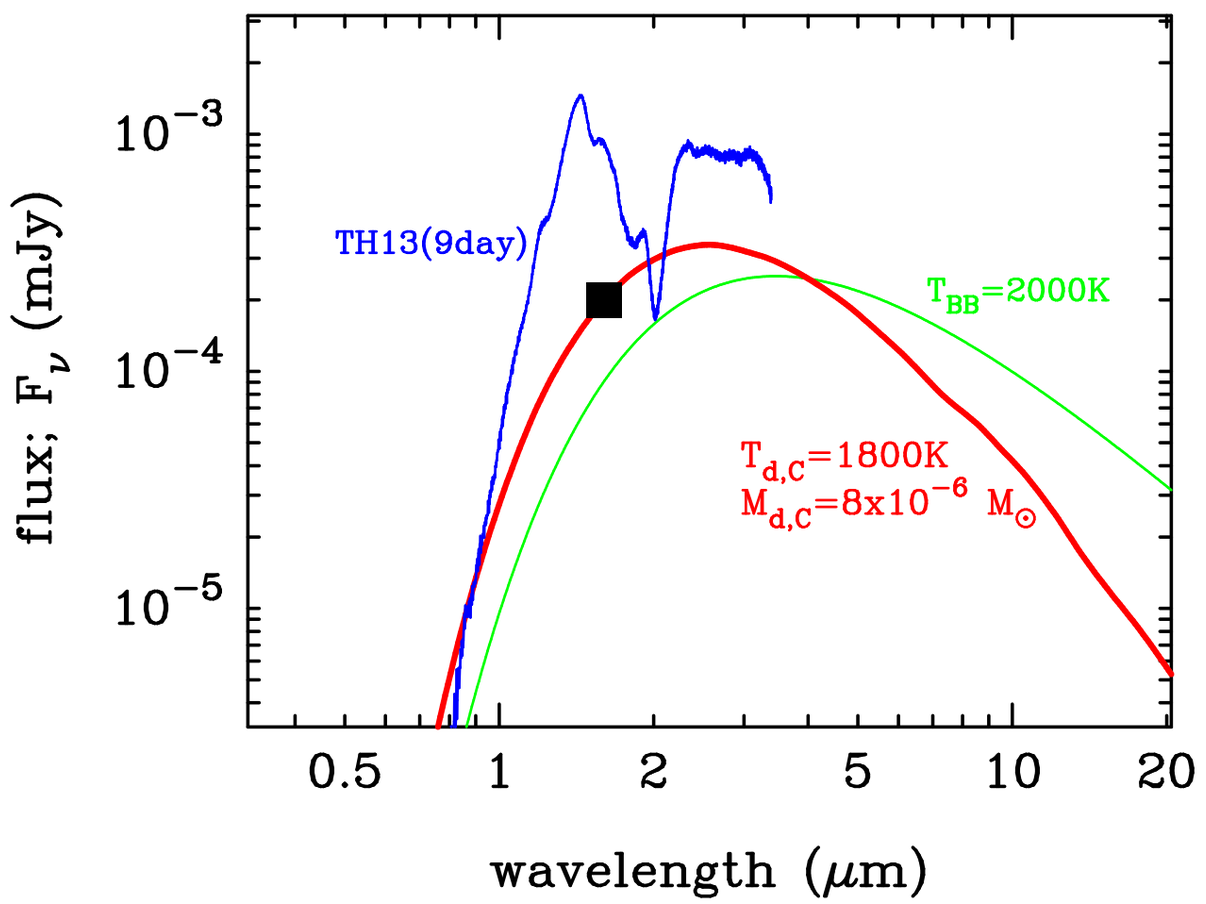
Observations were already inconsistent with “bright” models

Need spectroscopy

Light curve

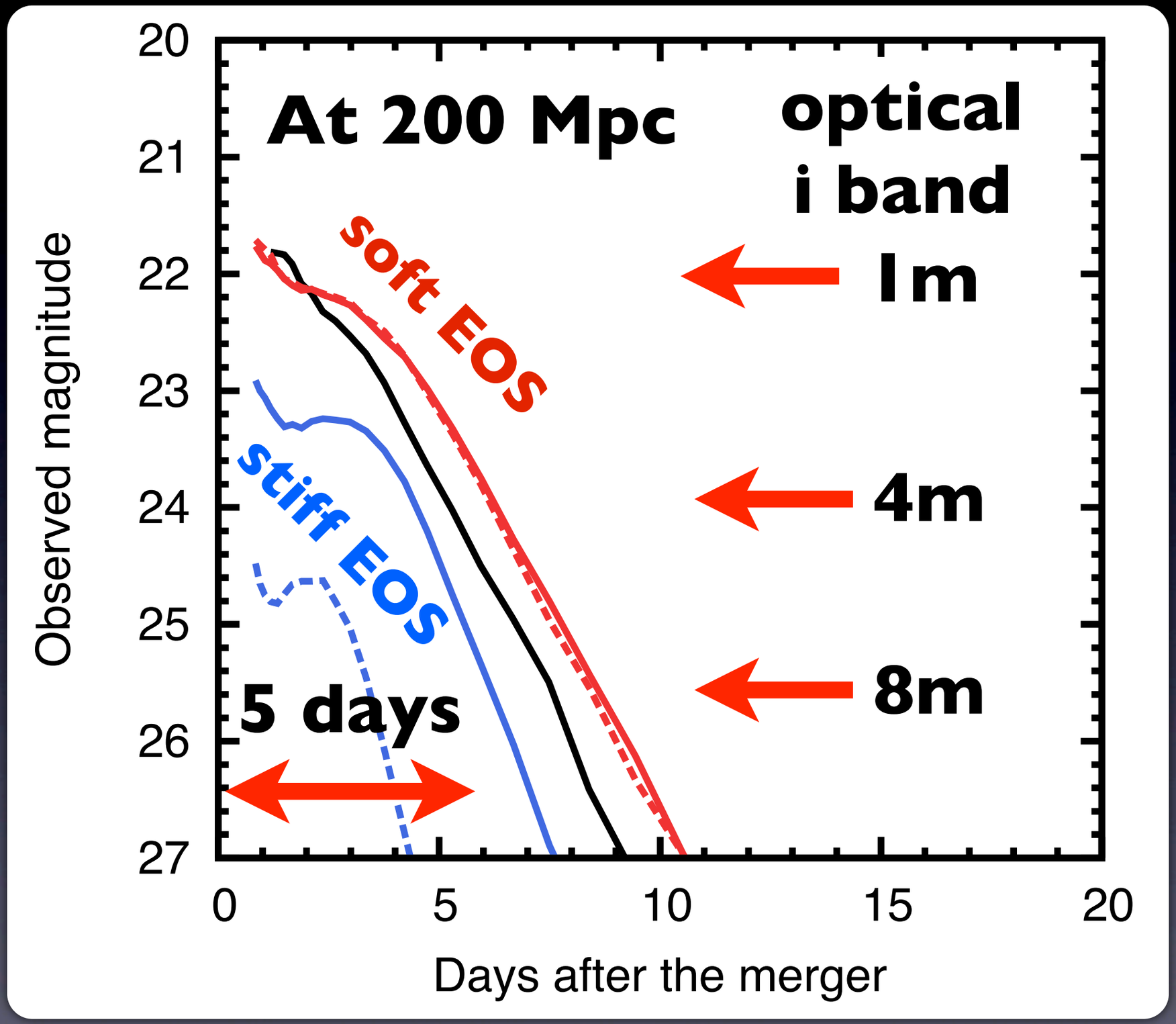


Spectrum



Dust model by
Takami, Nozawa, Ioka 2014 (arXiv:1403.5872)

Observing strategy for GW astronomy



10 min
5 sigma

Best with i band (0.8 um, red edge of optical)
1m-class telescopes for 100 Mpc events

Short summary

- kilonova/macronova/r-process nova
  - Accurate localization of GW sources
  - “Smoking gun” for r-process nucleosynthesis
- “Full” radiative transfer simulations
  - Higher opacity by a factor of 100
  - Fainter luminosity by a factor of 10
- Observing strategy
  - 22-25 mag (i band) @ 200 Mpc
    => 4-8m class telescopes
  - 1m class for 100 Mpc events
  - Extremely broad-line spectrum

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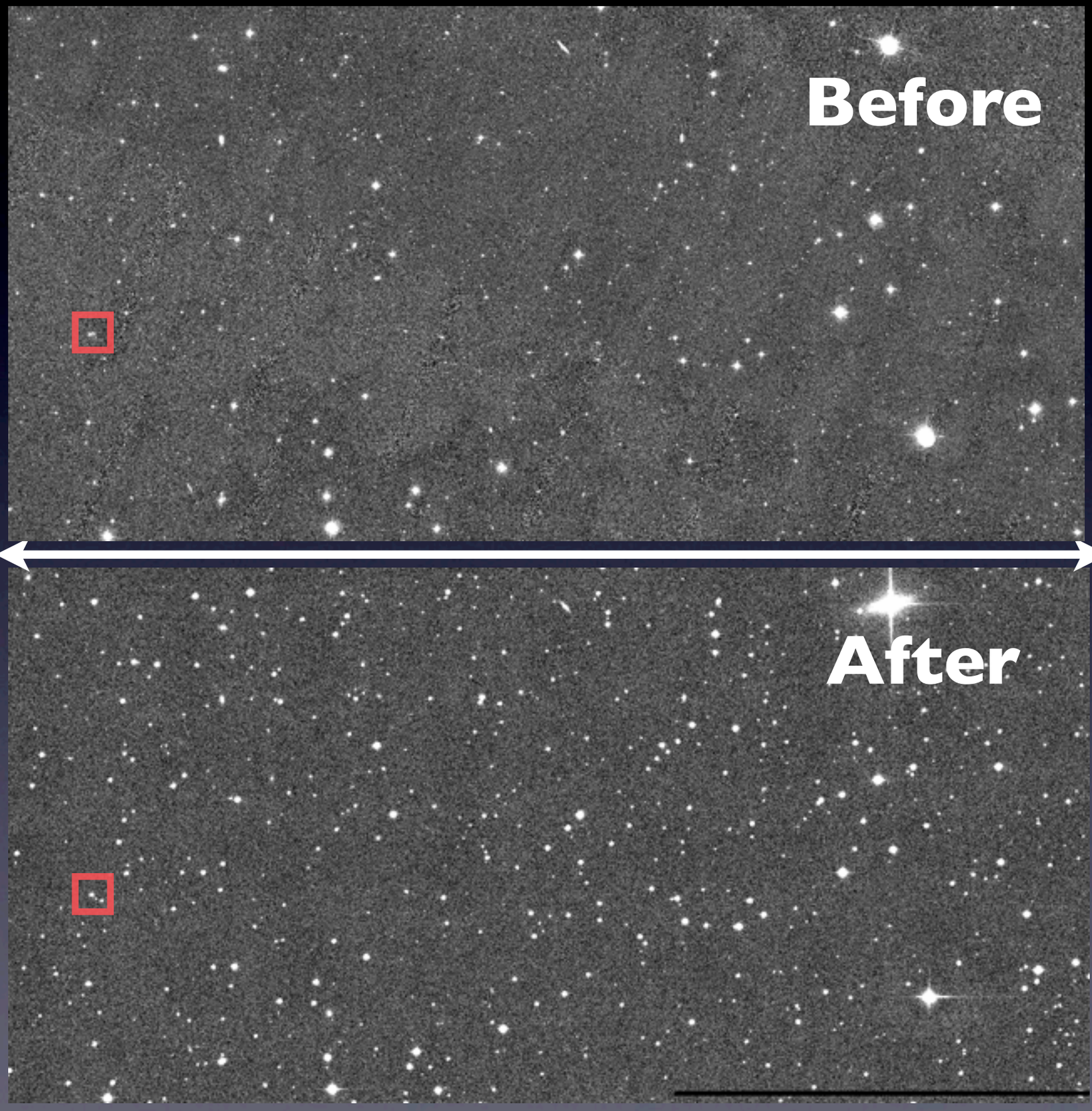
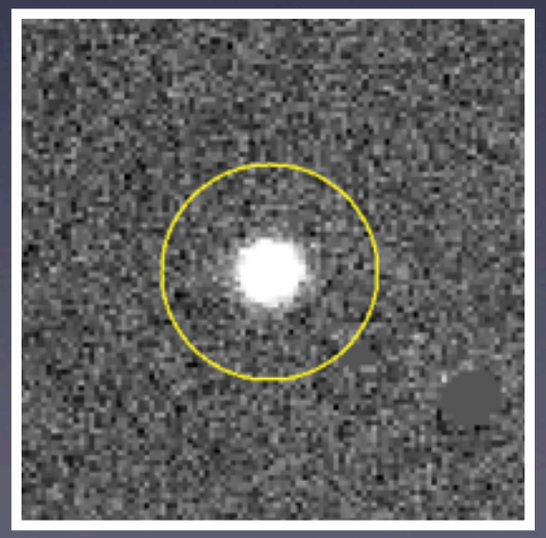
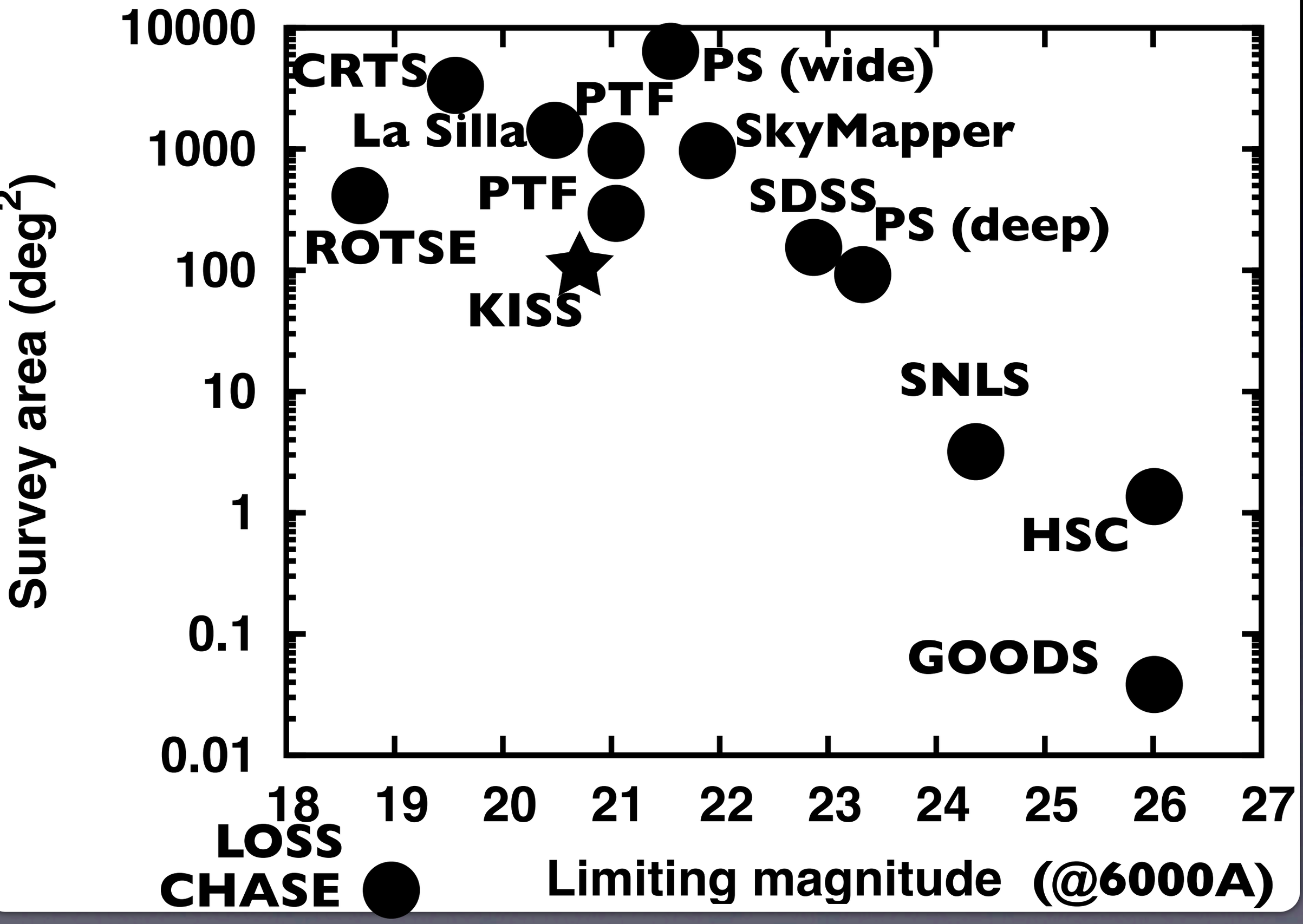
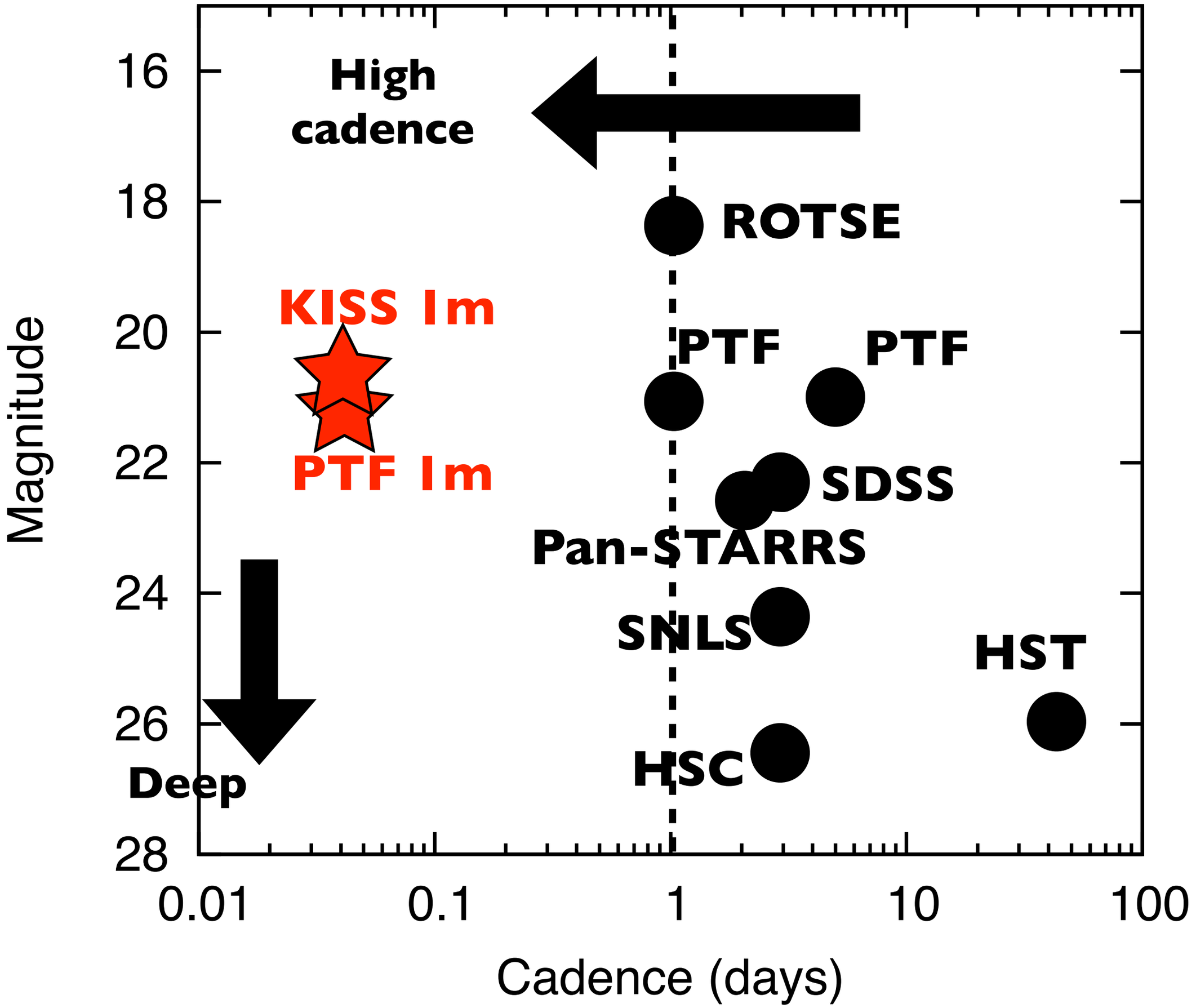
The most famous optical transient

Transient survey in optical

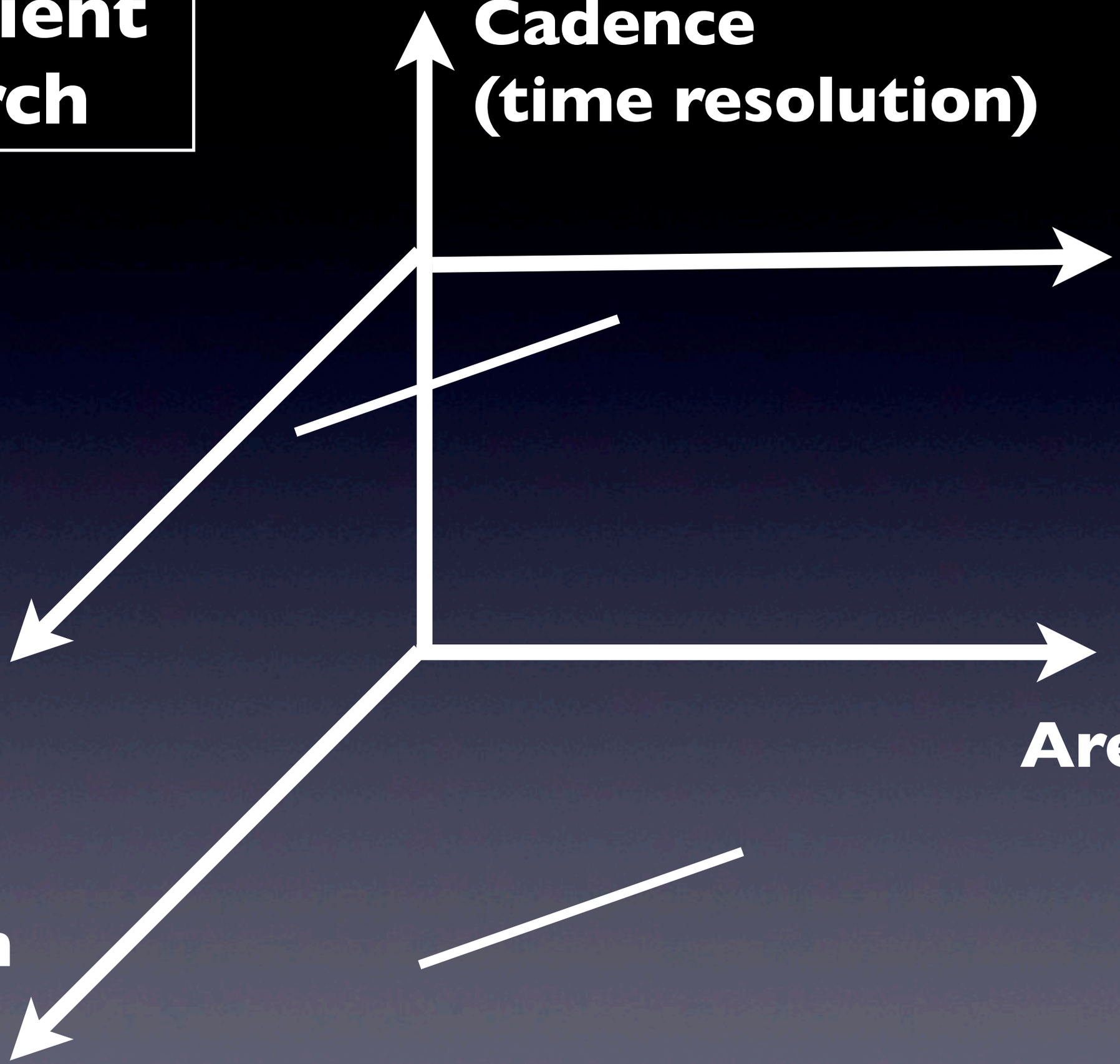





10000
1000
100
10
1
0.1
0.01
Survey area (deg^2)
CRTS
La Silla
ROTSE
PTF
PTF
KISS
PS (wide)
SkyMapper
SDSS
PS (deep)
SNLS
HSC
GOODS
LOSS
CHASE
18
19
20
21
22
23
24
25
26
27
Limiting magnitude (@6000A)


High cadence
Deep
KISS Im
PTF Im
ROTSE
PTF
PTF
SDSS
Pan-STARRS
SNLS
HST
HSC
16
18
20
22
24
26
28
Magnitude
0.01
0.1
1
10
100
Cadence (days)

Transient Search



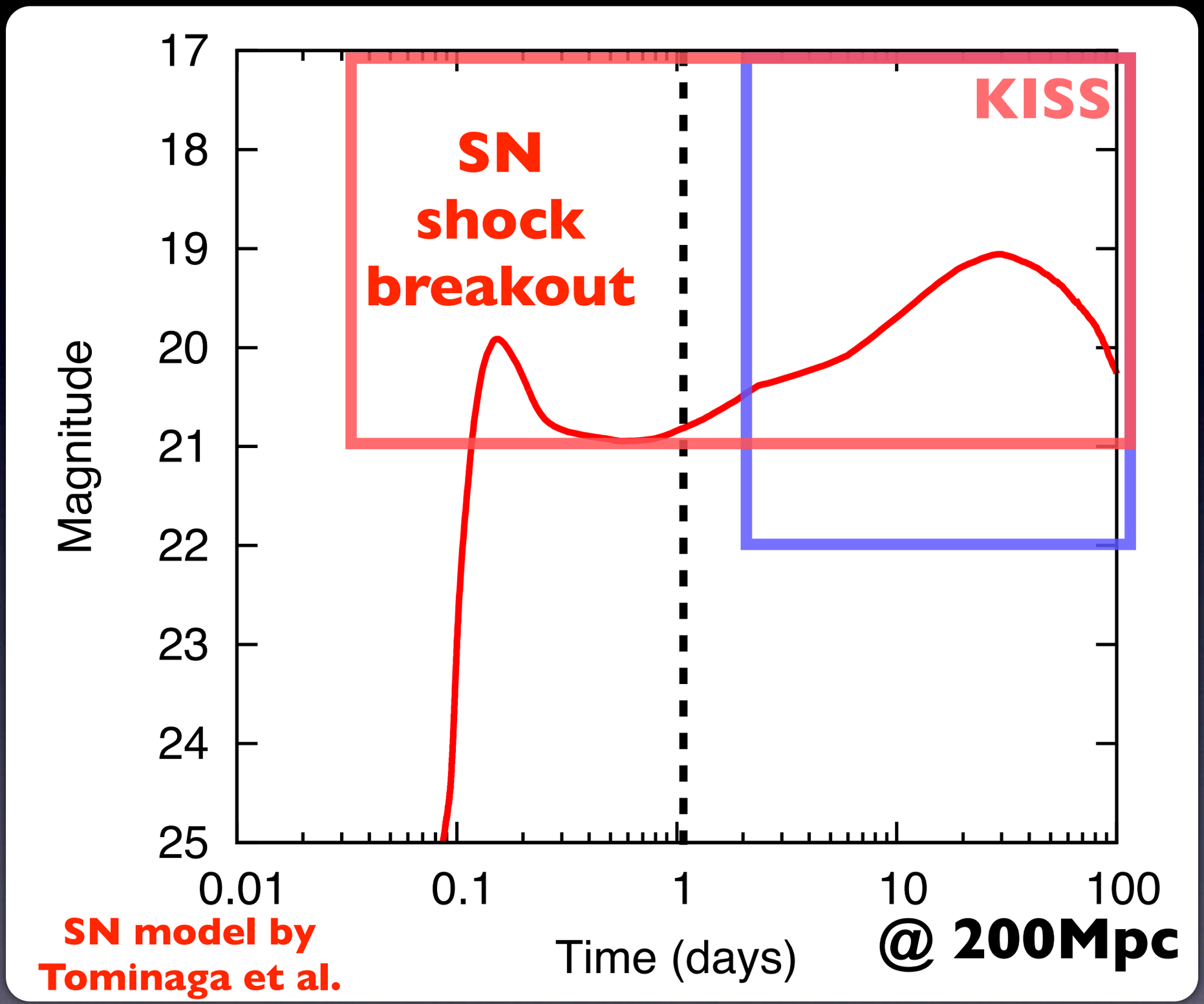
KISS: KIso Supernova Survey

2012 Apr: Dry run -
2012 Sep: Main survey -

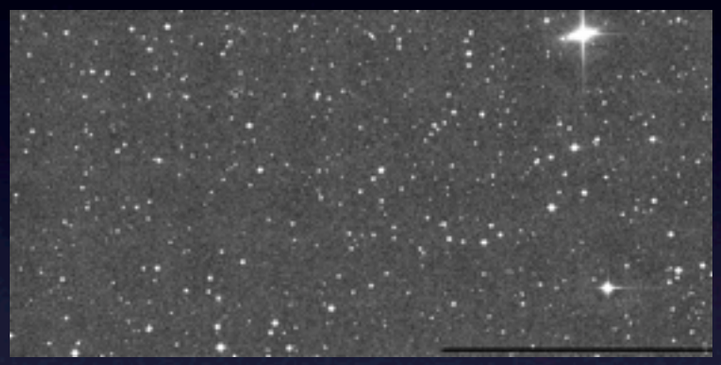
- Extremely high cadence
  - 1-hr cadence <= 2-3 days
  - 4 deg^2 FOV
  - ~ 21 mag in g-band (3 min)
  - ~50-100 deg^2 /day
- High SFR field (< 200 Mpc, 30-100 Msun/yr)
- ~100 nights/yr (around new moon)


Kiso 1.05m Schmidt telescope

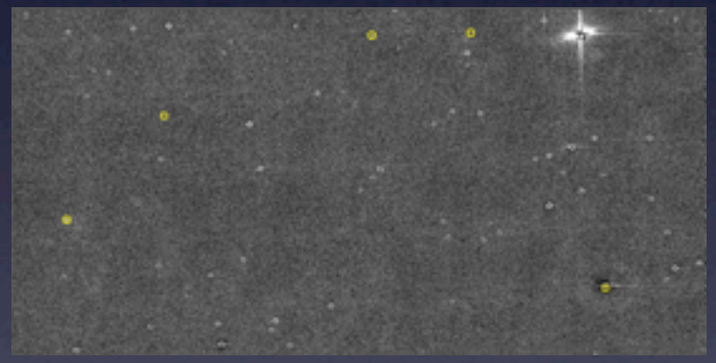
Goal: Detection of SN shock breakout


KISS
SN
shock
breakout
17
18
19
20
21
22
23
24
25
Magnitude
0.01
0.1
1
10
100
Time (days)
@ 200Mpc
SN model by
Tominaga et al.

Kiso observatory



Standard pipeline



Transient pipeline

< 10 min

~ 50GB/day

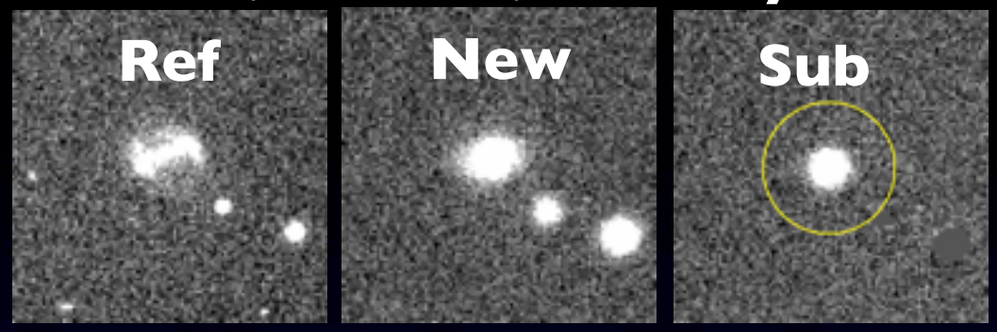
cut-out images (~1,000-10,000 /day)

KISS database

source info

Anywhere

cut-out images
1,000 - 10,000 /day



KISS database

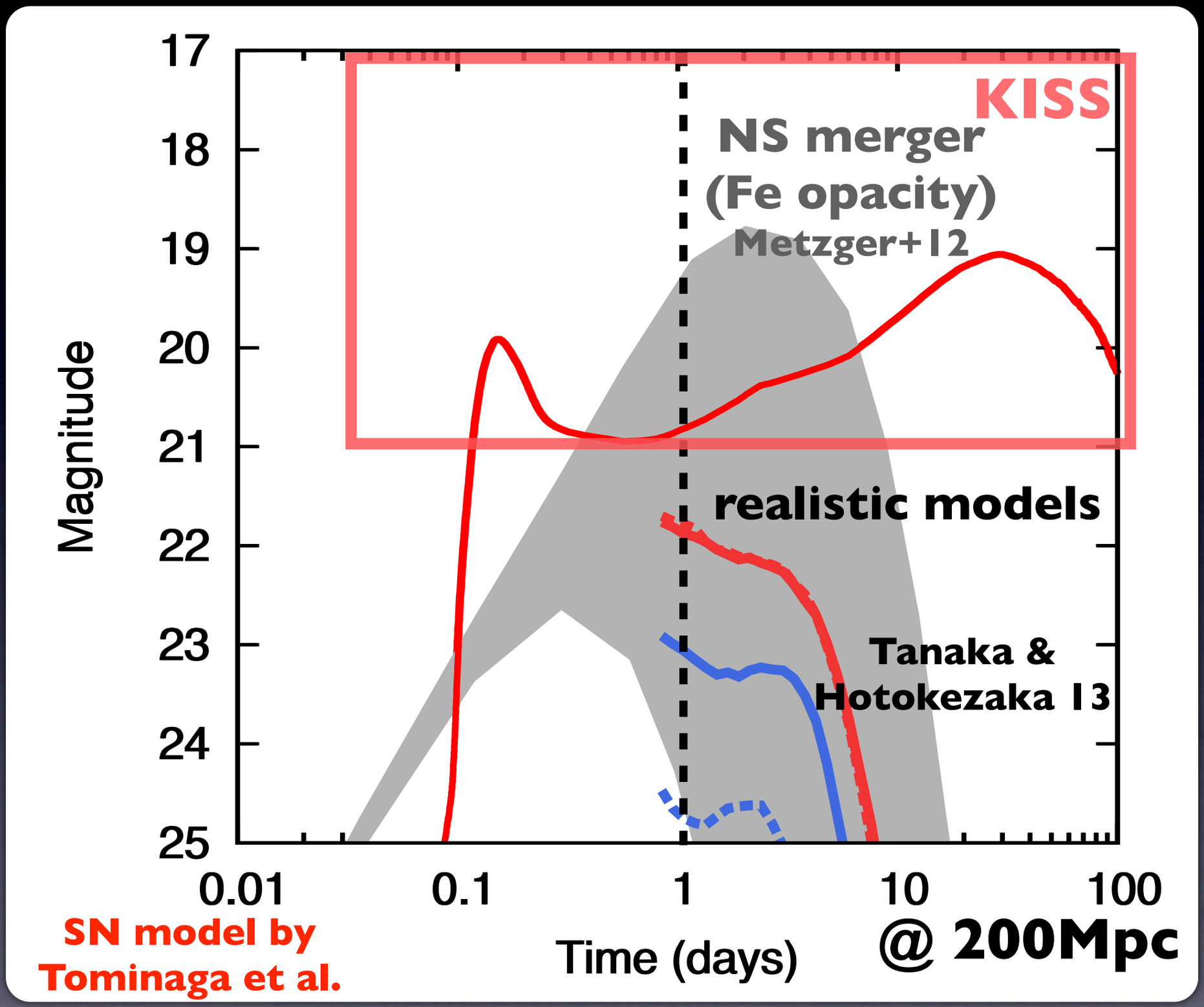
source info

KISS interface

~ 20 amateur astronomers

~60 SN candidates (as of 2014 Feb)

KISS12a
KISS12f
KISS12k
KISS13a
KISS12b
KISS12g
KISS12l
KISS13b
KISS12c
KISS12h
KISS12m
KISS13d
KISS12d
KISS12i
KISS12n
KISS13j
KISS12e
KISS12j
KISS12q
KISS13l


KISS
NS merger
(Fe opacity)
Metzger+12
realistic models
Tanaka &
Hotokezaka 13
SN model by
Tominaga et al.
Magnitude
Time (days)
17
18
19
20
21
22
23
24
25
0.01
0.1
1
10
100
@ 200Mpc
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

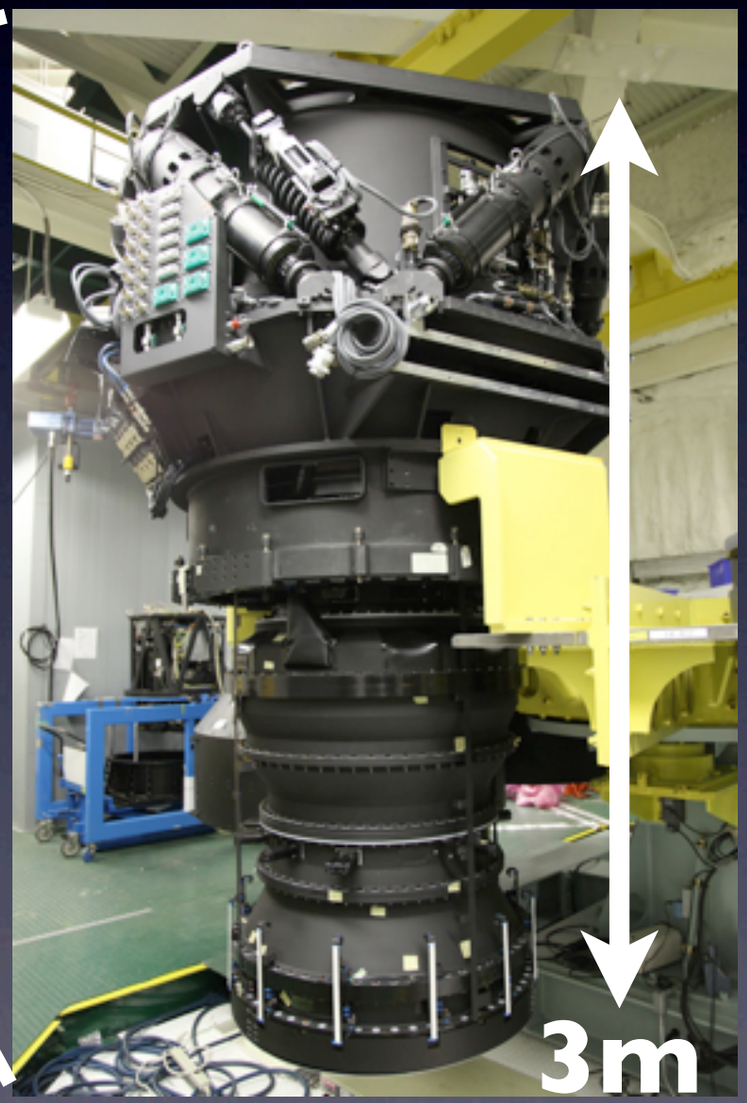
2 deg

8m Subaru

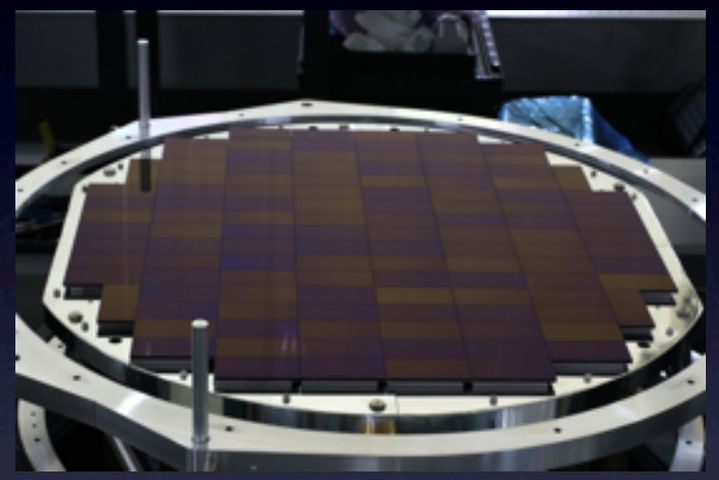
Hyper Suprime-Cam

1.5 deg

Subaru/ Hyper Suprime-Cam
2013 -



3t !



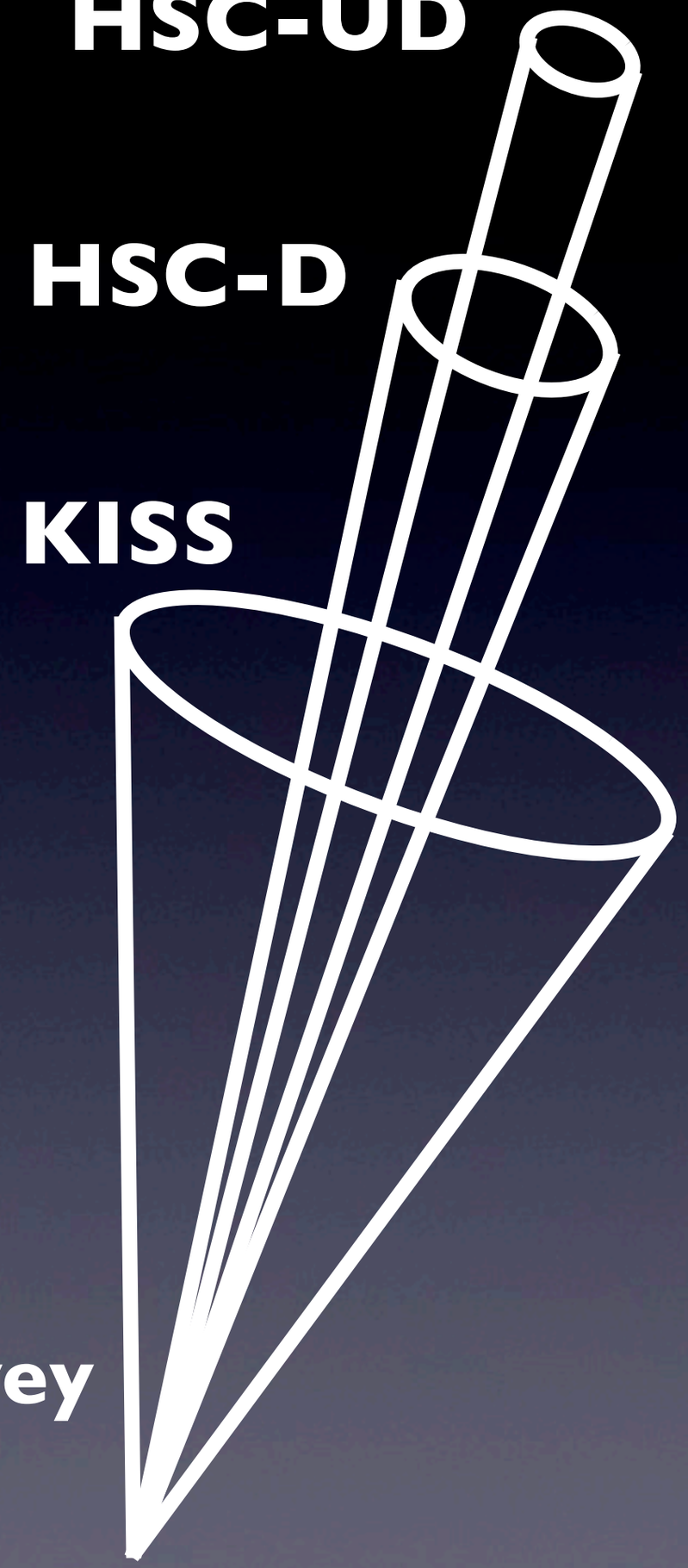
1.75 deg^2
116 CCDs

Survey with HSC 2014 - (THIS WEEK !)

- Ultra-Deep
  - 3.5 deg^2 - 26 mag - 3 days
- Deep
  - 30 deg^2 - 25 mag - 6 days

- c.f. KISS
  - 100 deg^2 - 21 mag - 1 hr

Excellent prior of deep transient survey for GW astronomy

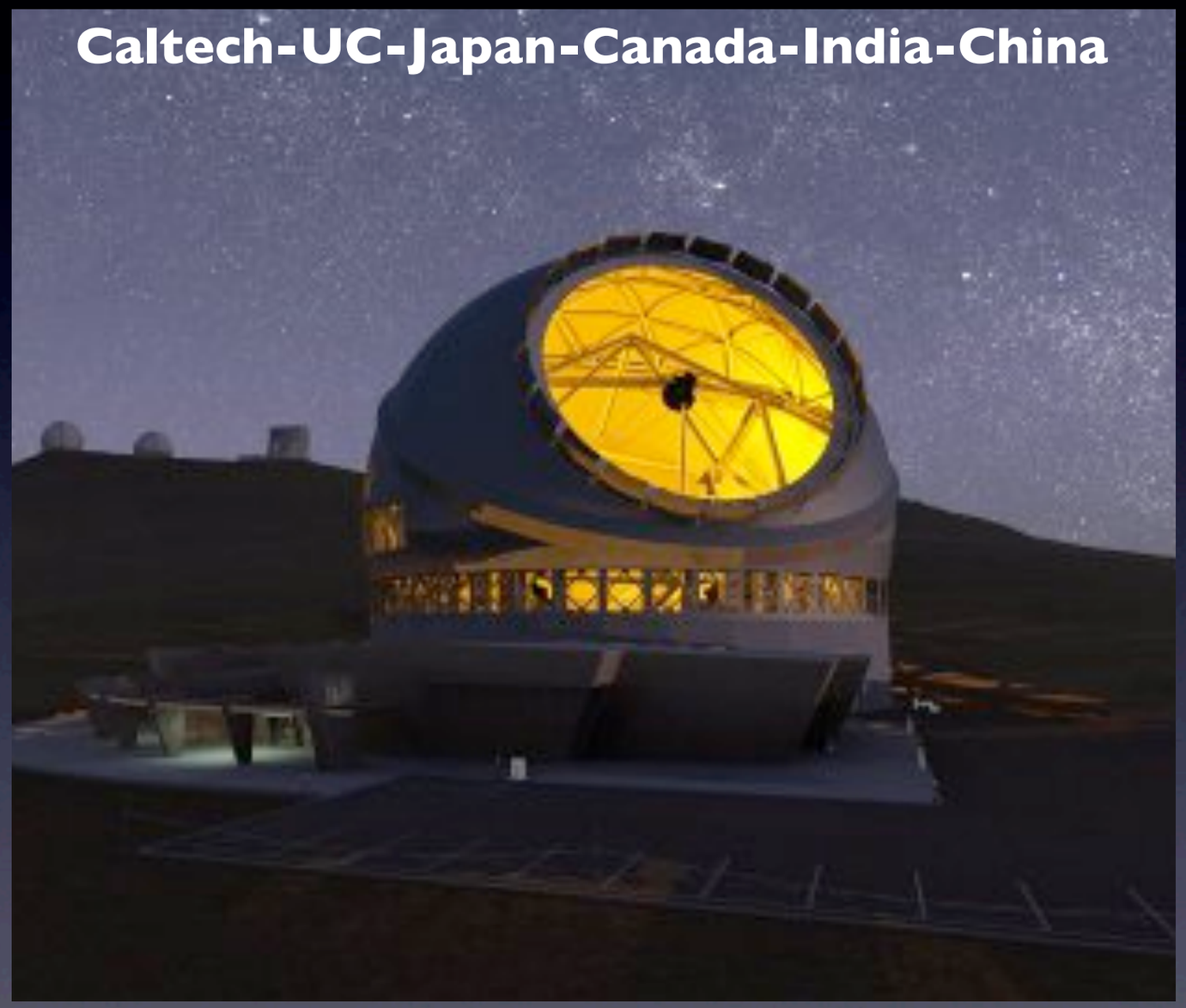


Future opportunity with TMT
Thirty Meter Telescope

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 G.C. Anupama and MT)

Summary

- kilonova/macronova/r-process nova
  - Accurate localization of GW sources
  - “Smoking gun” for r-process nucleosynthesis
- Status of theoretical prediction
  - Numerical relativity + full radiative transfer
- Status/future of optical/IR observations
  - Real-time transient survey with 1m telescopes
  - Coming transient survey with Subaru/HSC (2014-)
  - Spectroscopy with TMT (2022-)