

# Observations of optical transient

(重力波源の光学対応天体探査のための) 突発天体観測

**Masaomi Tanaka**

(National Astronomical Observatory of Japan)

1 deg

~ 100 galaxies / 1 deg<sup>2</sup>  
( < 200 Mpc )

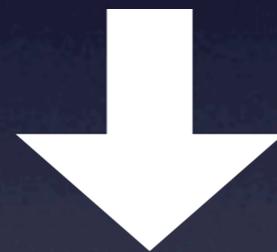


SDSS

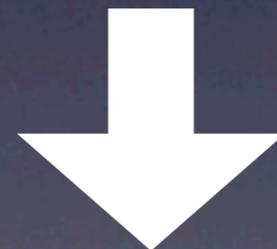
**GW alert error**  
e.g. 6 deg x 6 deg  
(not box shape in reality)

**No electromagnetic counterpart**  
**No gravitational wave astronomy**

**GW detection**



**EM search**



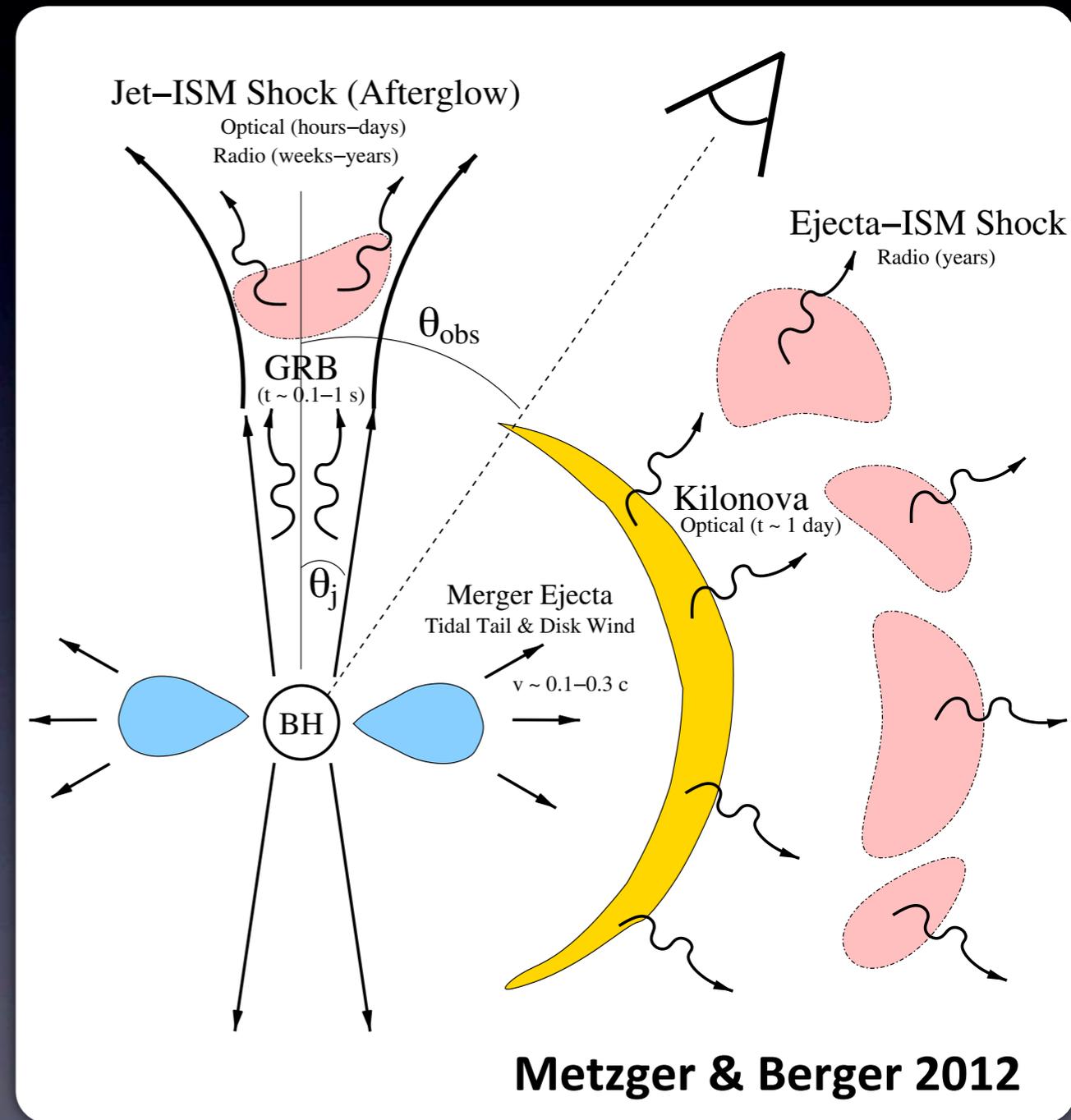
**Source identification**

**1 deg**



# EM signature from NS merger

- On-axis short GRB
- Extended emission (~25% of short GRB)
- Off-axis radio/optical afterglow
- Radioactive emission (kilonova, macronova)



Sekiguchi-san's talk

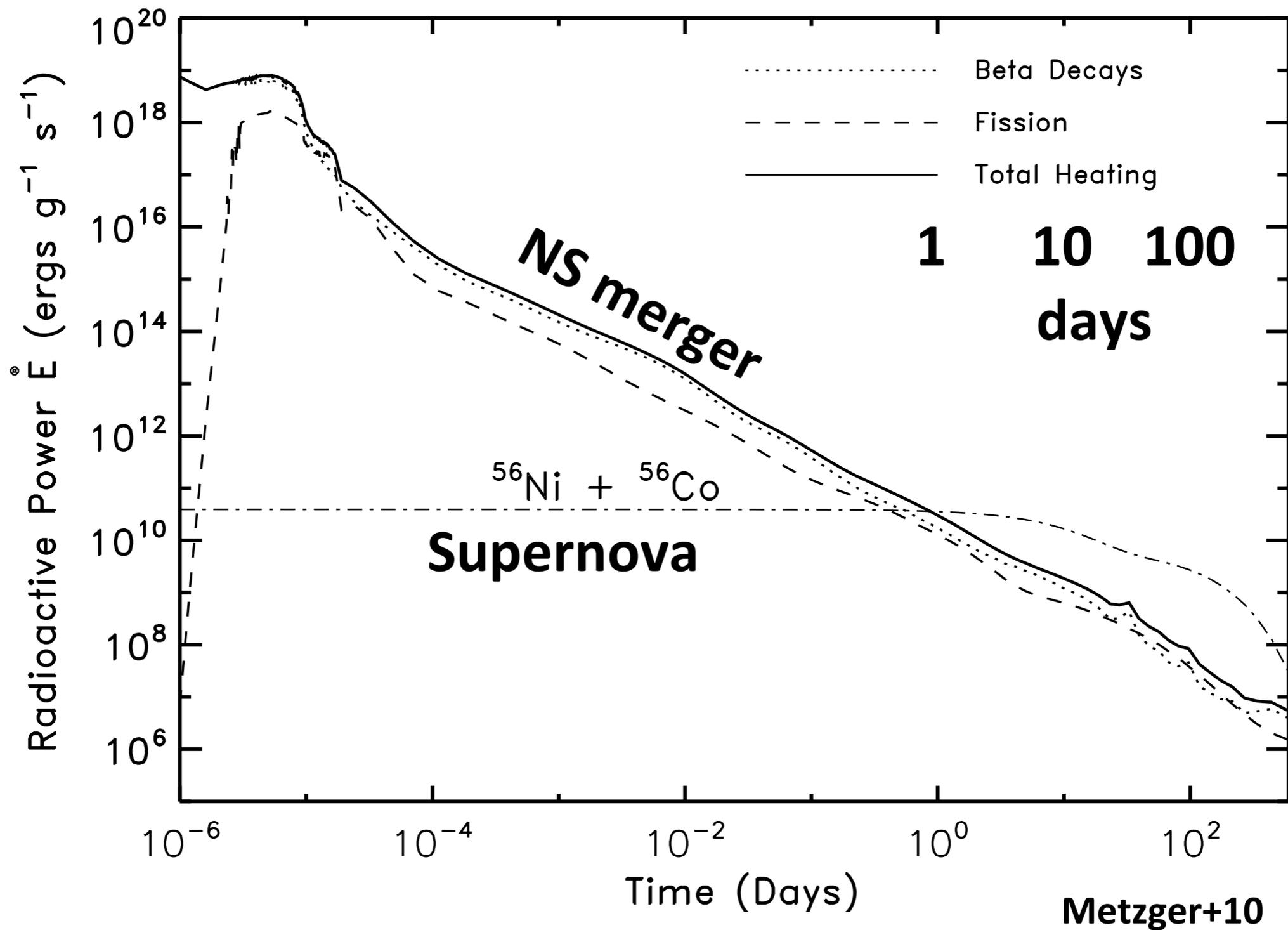
# Observations of optical transient

(重力波源の光学対応天体探査のための) 突発天体観測

- **Theoretical models for optical counterparts**
- **Status of observational effort**

Collaboration with

K. Hotokezaka, K. Kyutoku, Y. Sekiguchi, K. Kiuchi, M. Shibata, and S. Wanajo



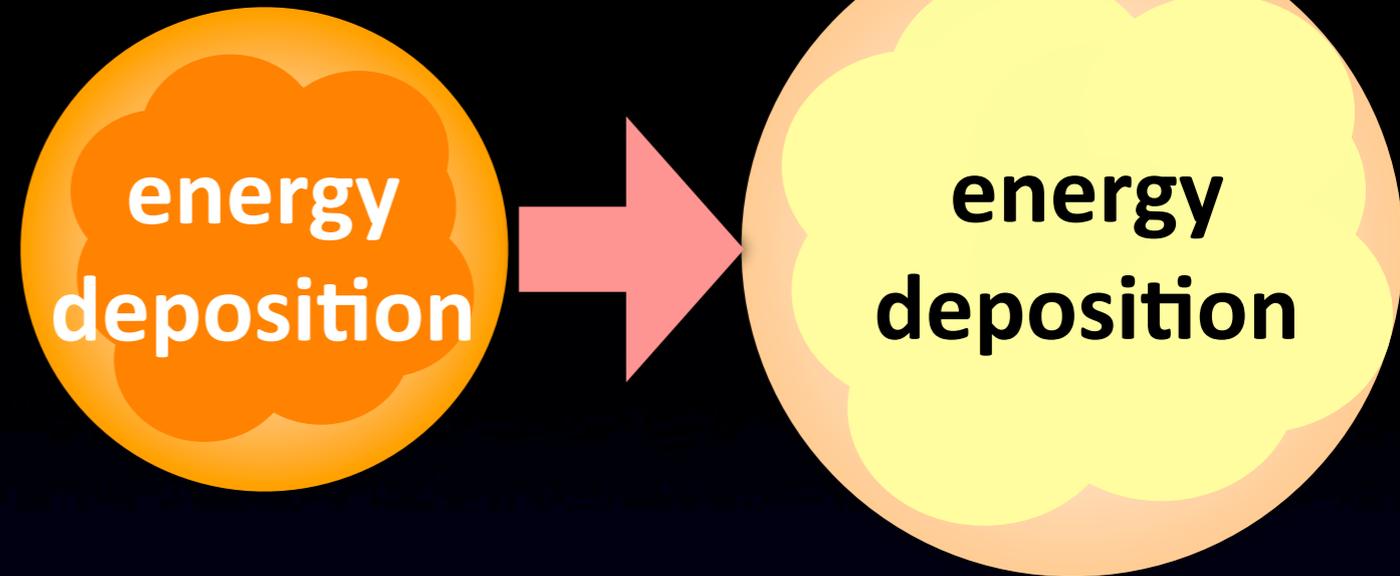
Thick against gamma-rays => optical emission

# “kilonova”

Li & Paczynski 98

Metzger+10

Sekiguchi-san’s talk



Timescale

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

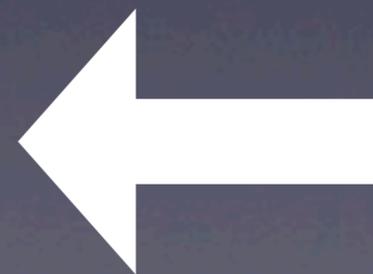
Luminosity

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

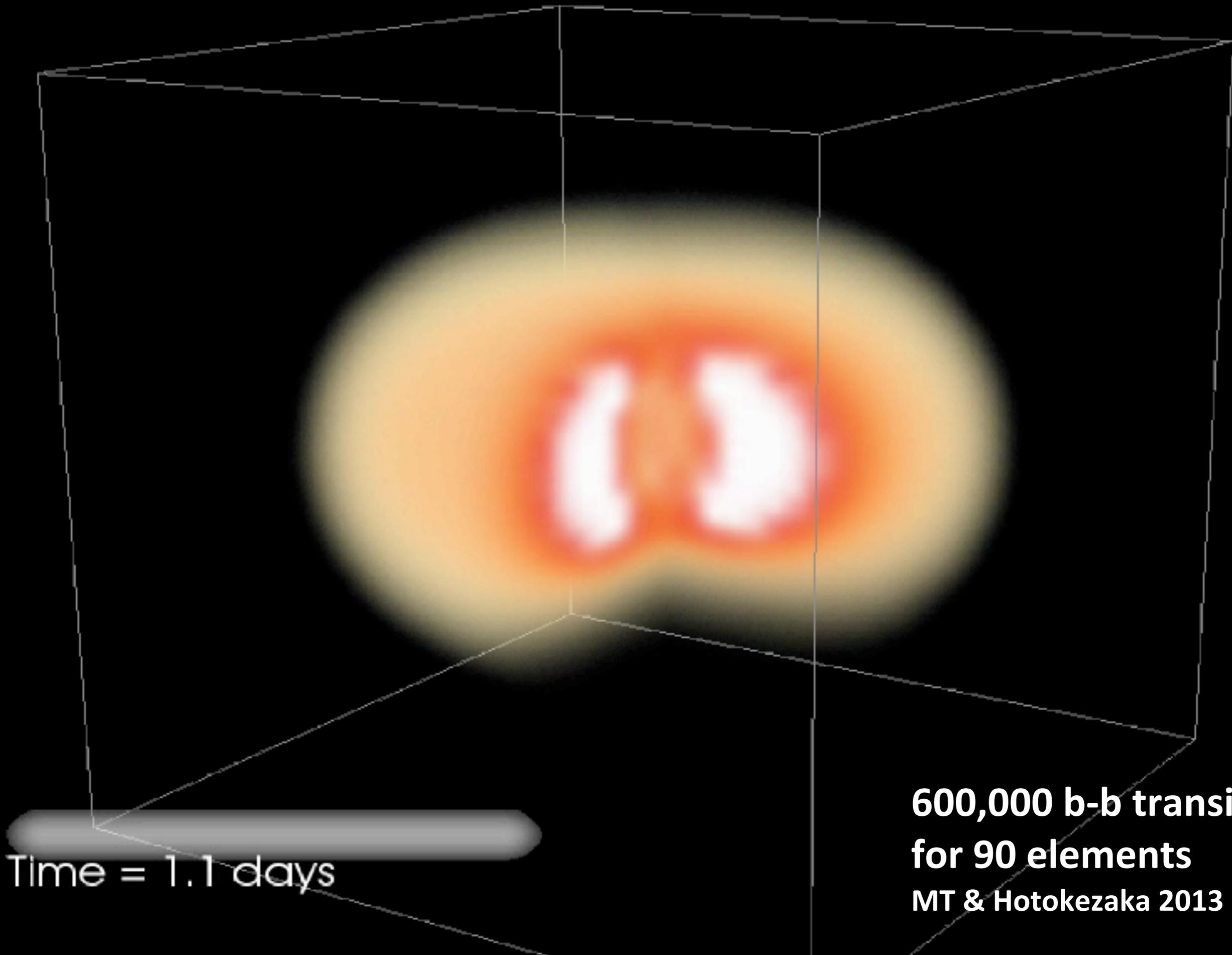
Opacity of r-process elements

$$\kappa \sim 10 \text{ cm}^2 \text{ g}^{-1}$$

(Kasen+13, MT & Hotokezaka 13)

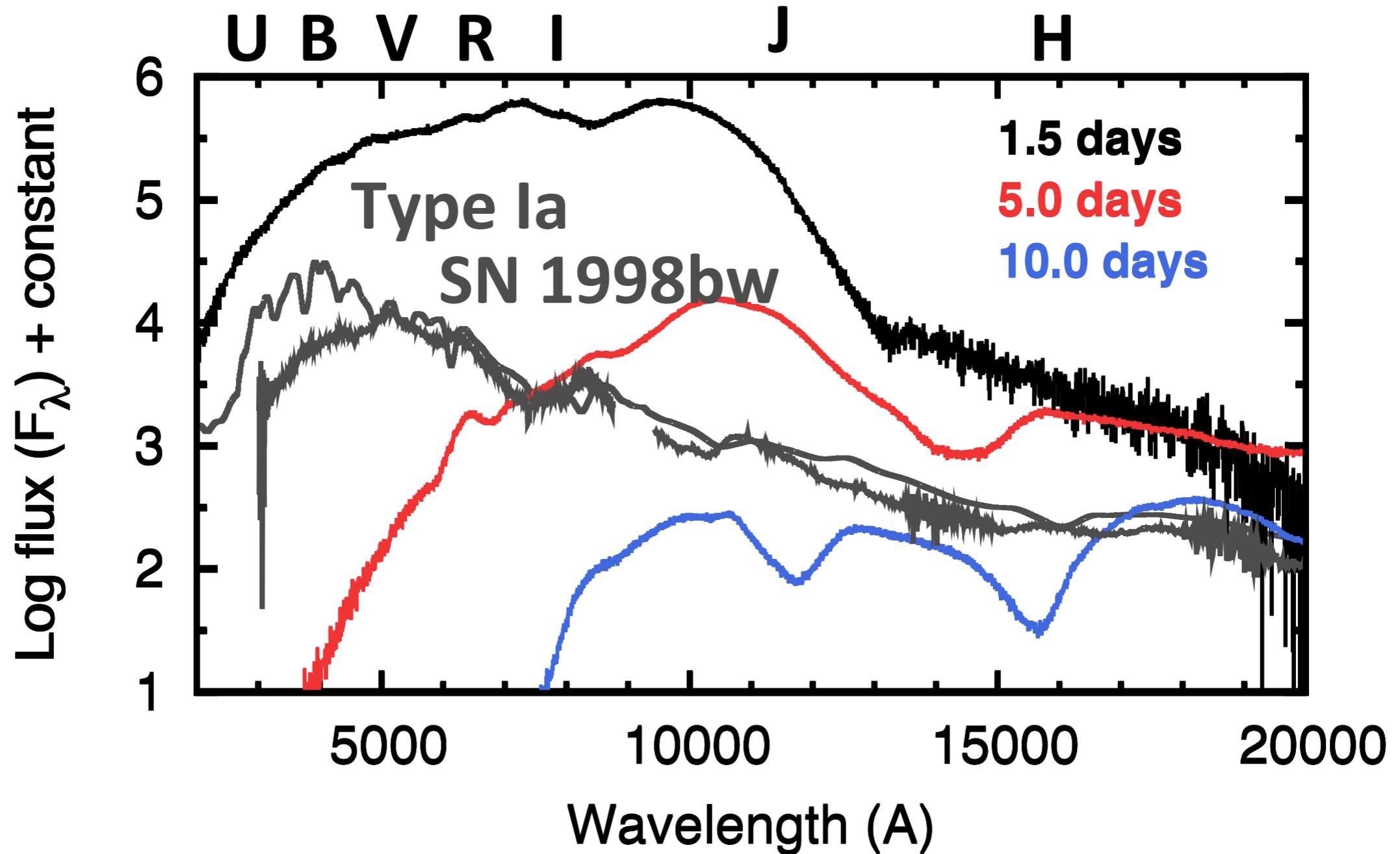


Bound-bound  
opacity of Fe



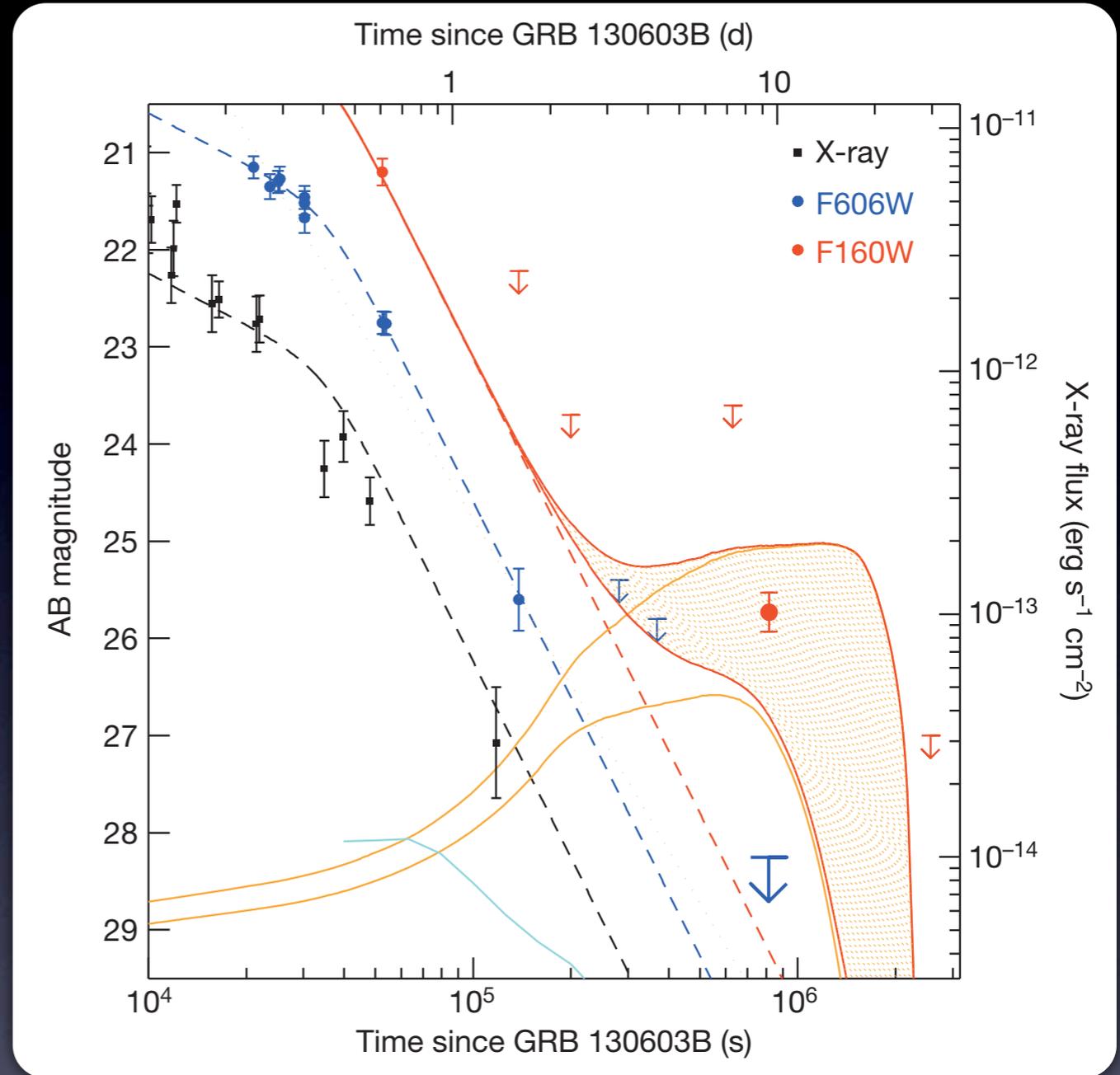
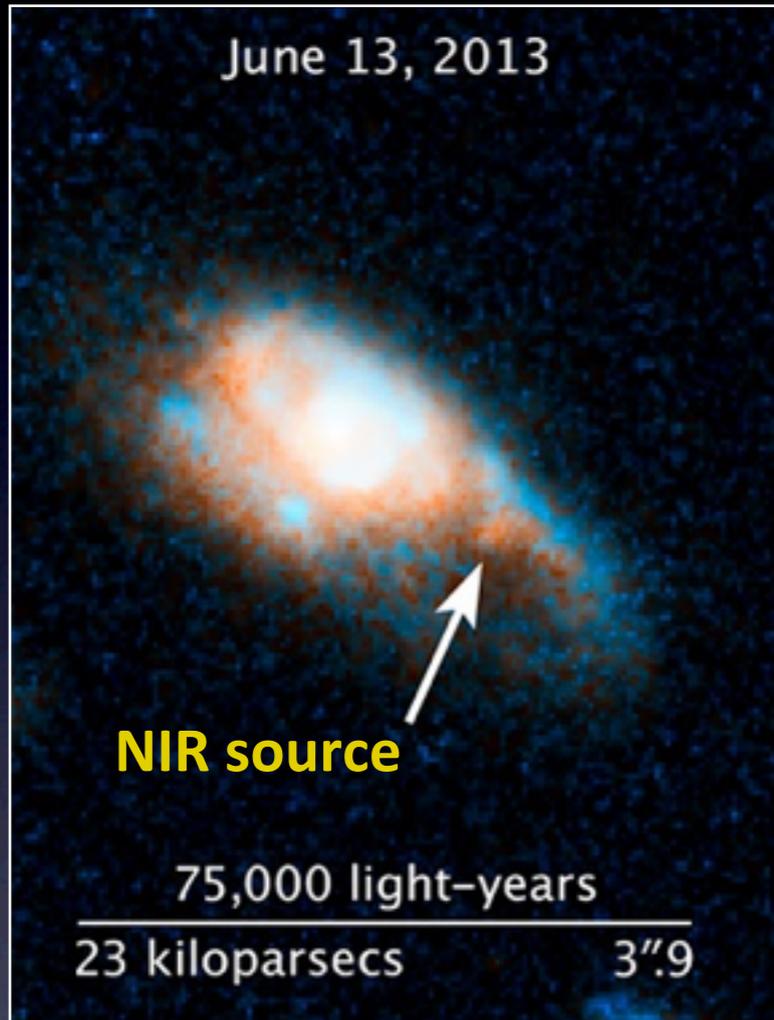
Time = 1.1 days

**600,000 b-b transitions  
for 90 elements  
MT & Hotokezaka 2013**



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

# Kilonova candidate in GRB 130603B



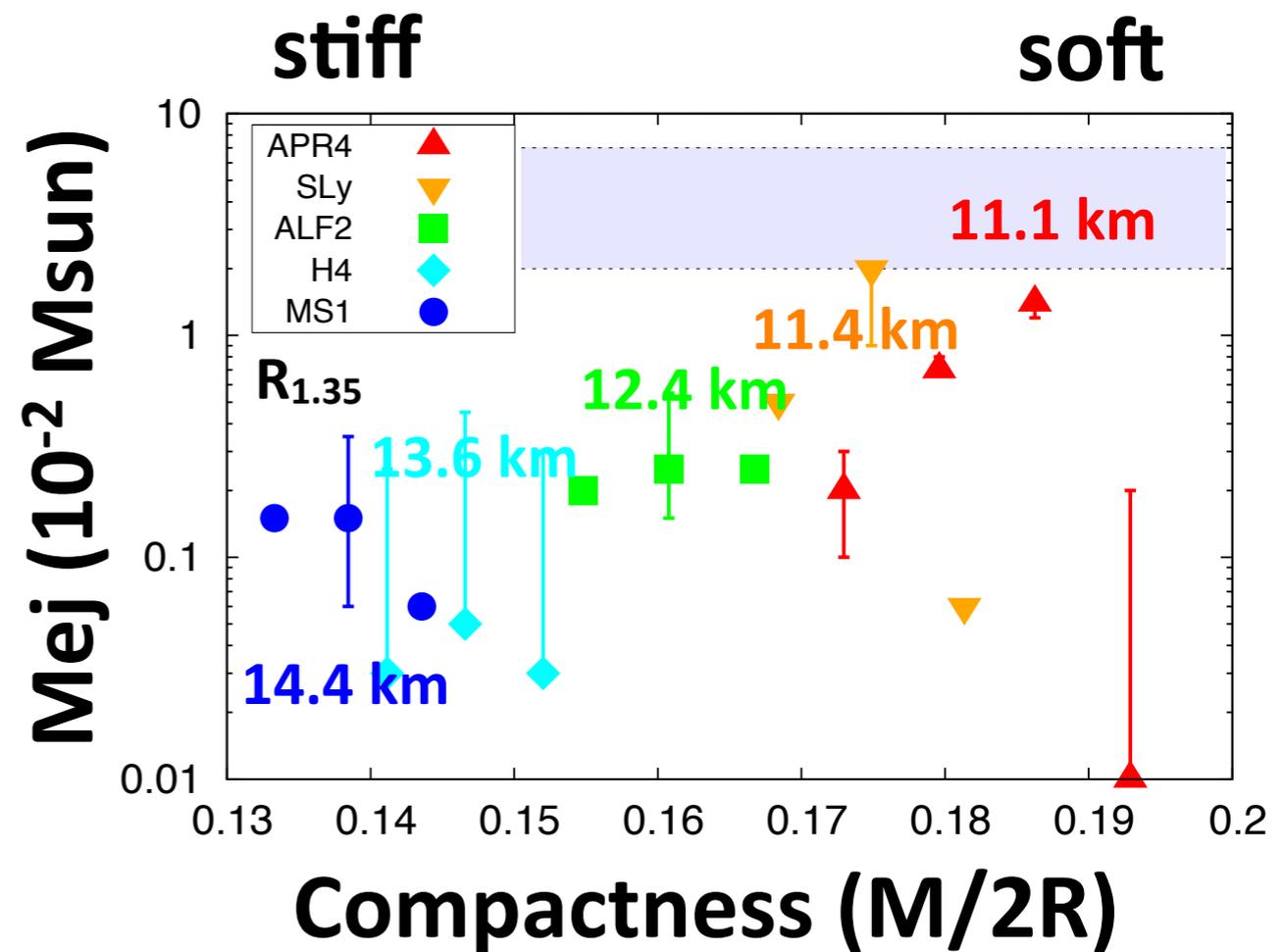
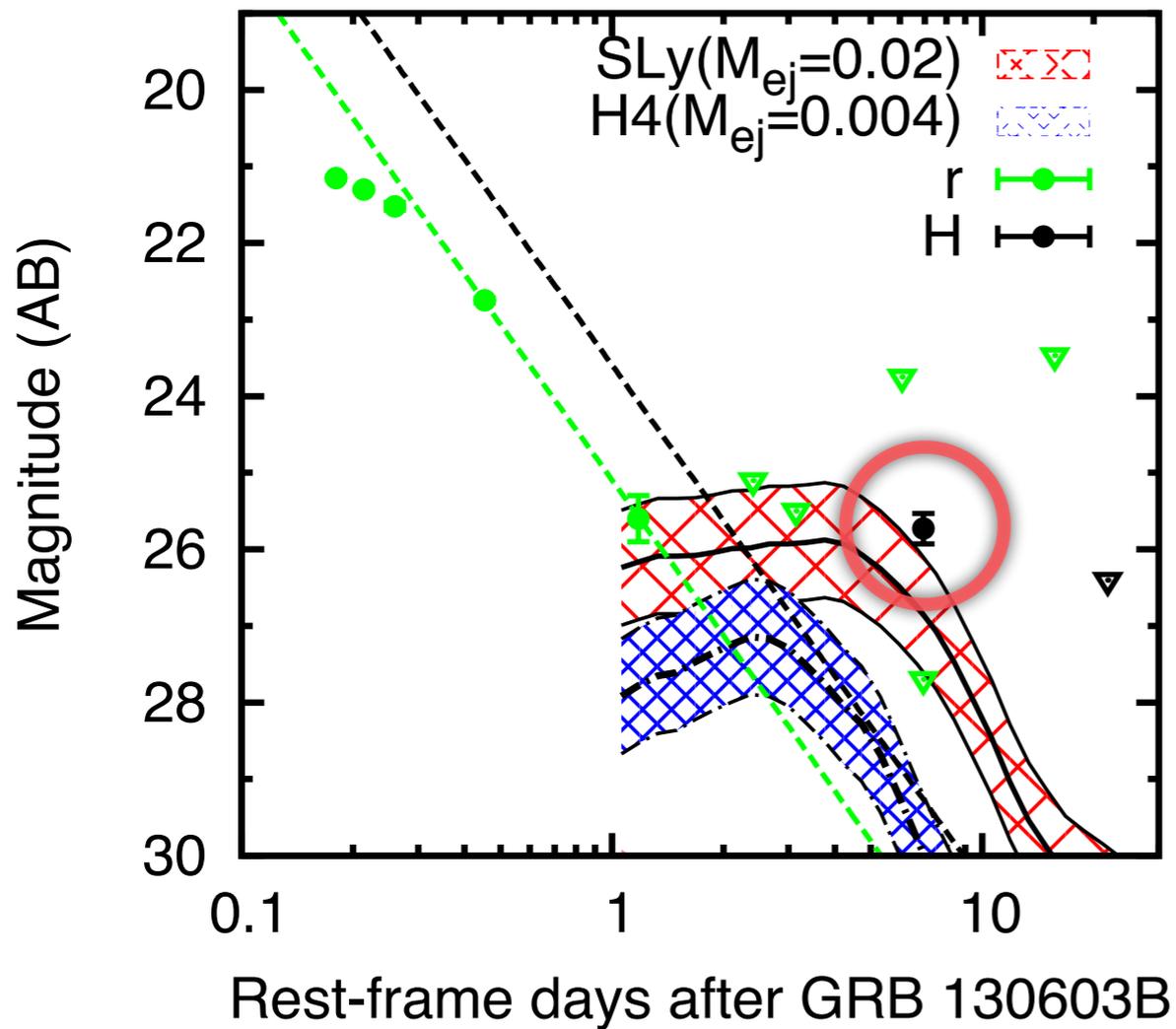
$M_{ej} \sim 0.02 M_{\text{sun}} \Rightarrow$  soft EOS (if NS merger)

Hotokezaka, Kyutoku, MT+2013

see also Takami, Nozawa, Ioka 2014

Kisaka, Ioka, Takami 2014

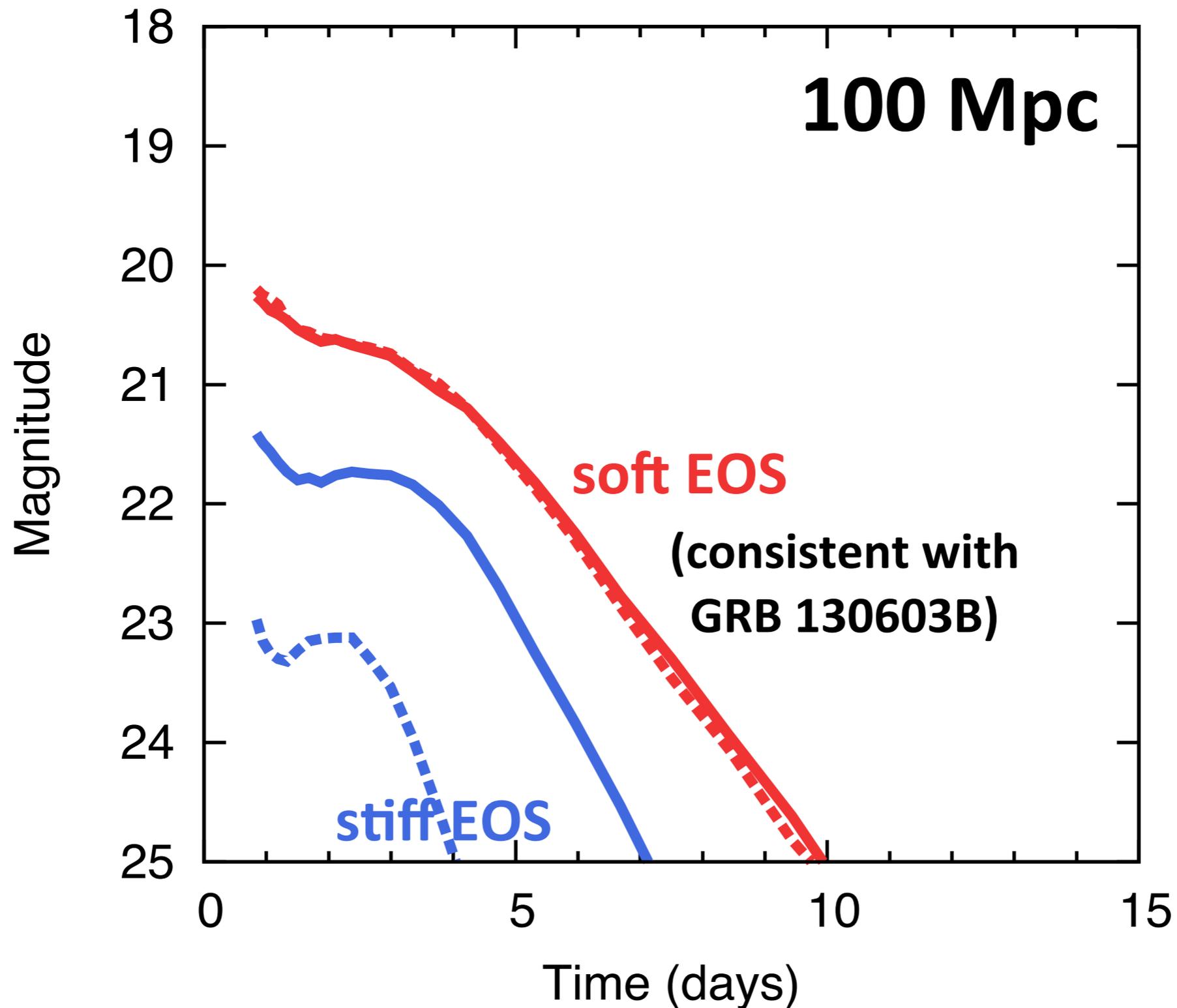
## Mass ejection $M_{ej} \sim 0.02 M_{sun}$



# GW early observing runs (2015-2016)

Horizon distance  $\sim$  50-100 Mpc

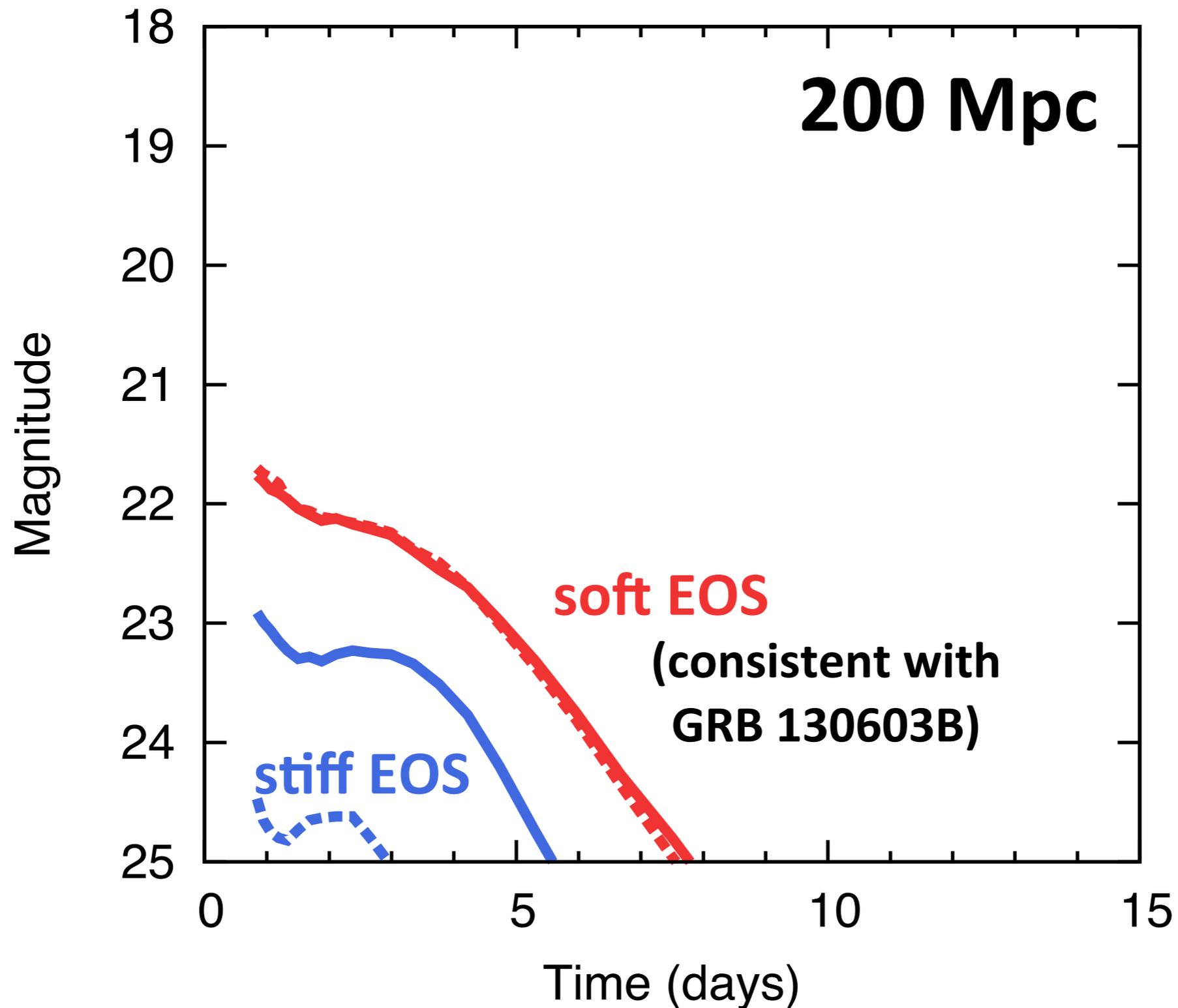
Localization  $>$  200 deg<sup>2</sup>



# GW early observing runs (2017-)

Horizon distance  $\sim 200$  Mpc

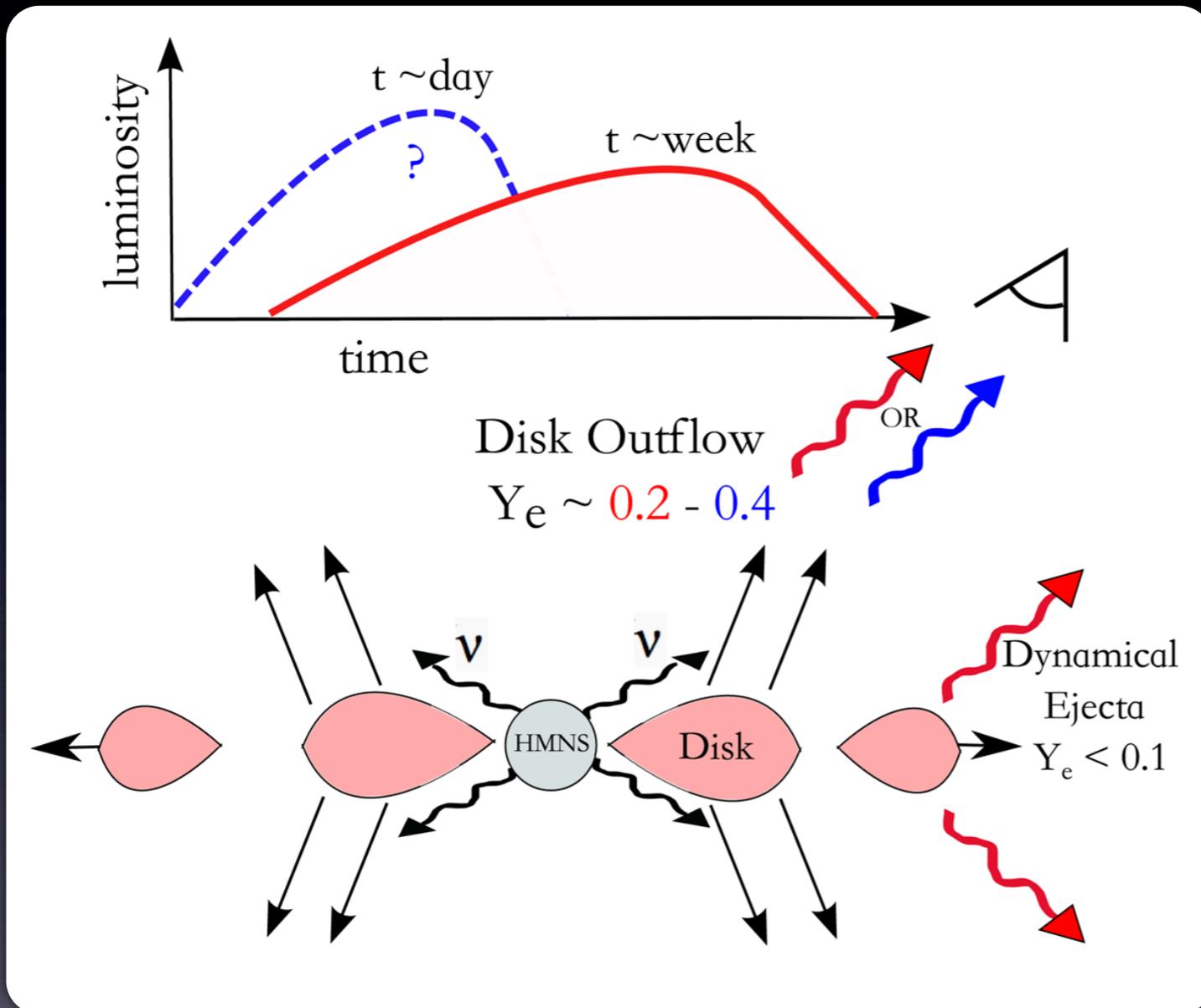
Localization  $\sim 50$  deg<sup>2</sup>



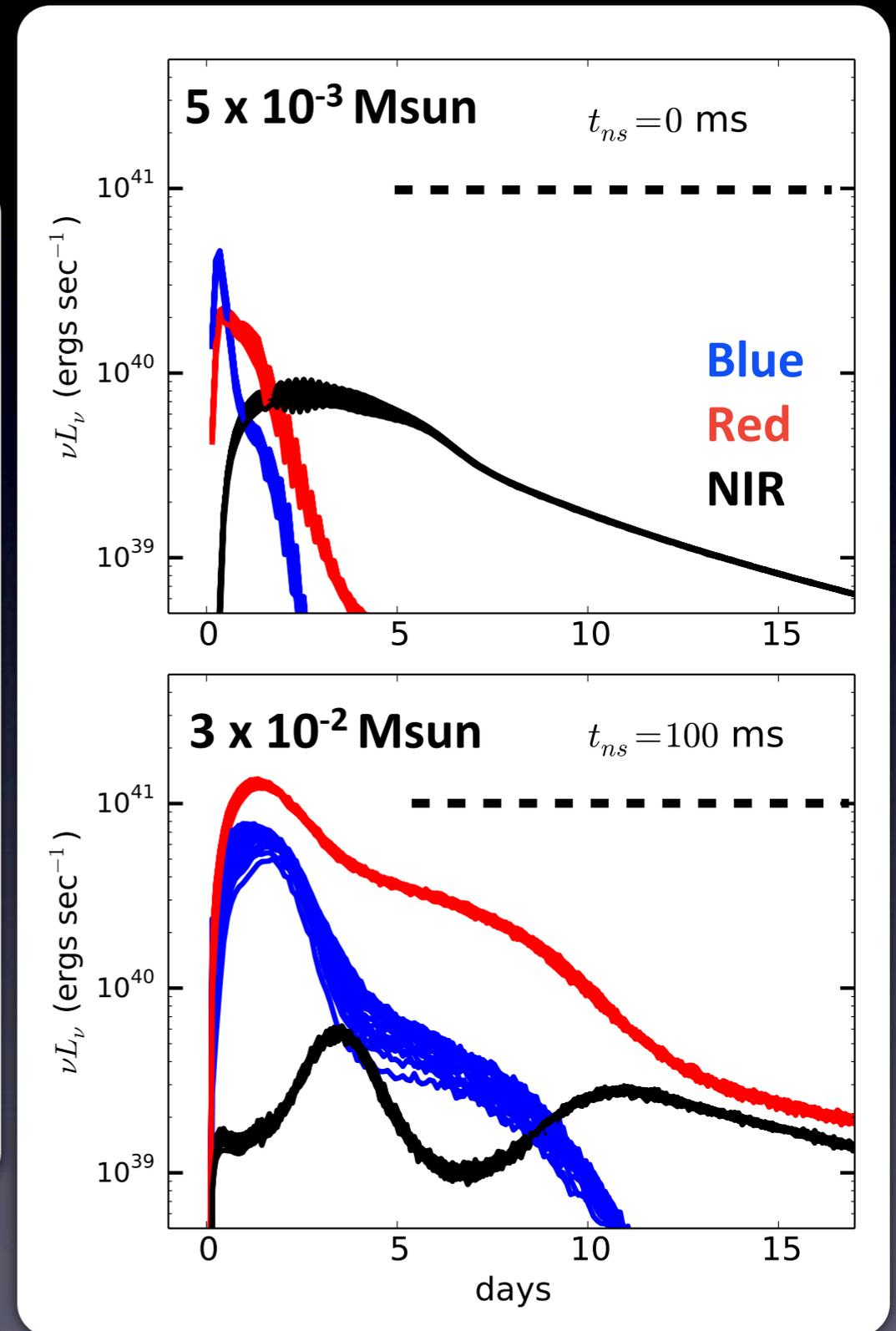
# Beyond dynamical ejecta/NS merger

1. Disk wind
2. Free neutron
3. BH-NS merger

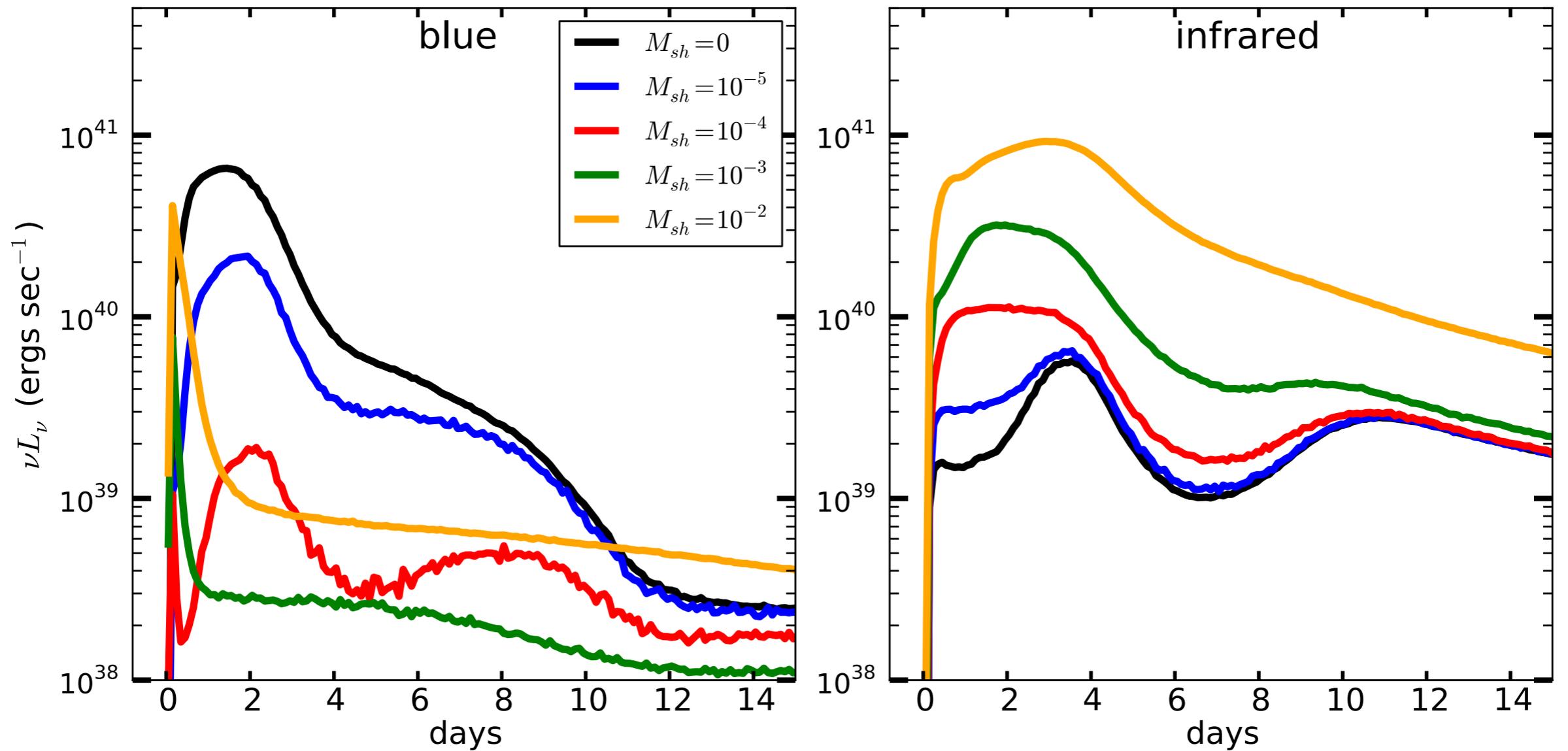
# 1. Disk wind



Metzger & Fernandez 2014



Kasen+2014

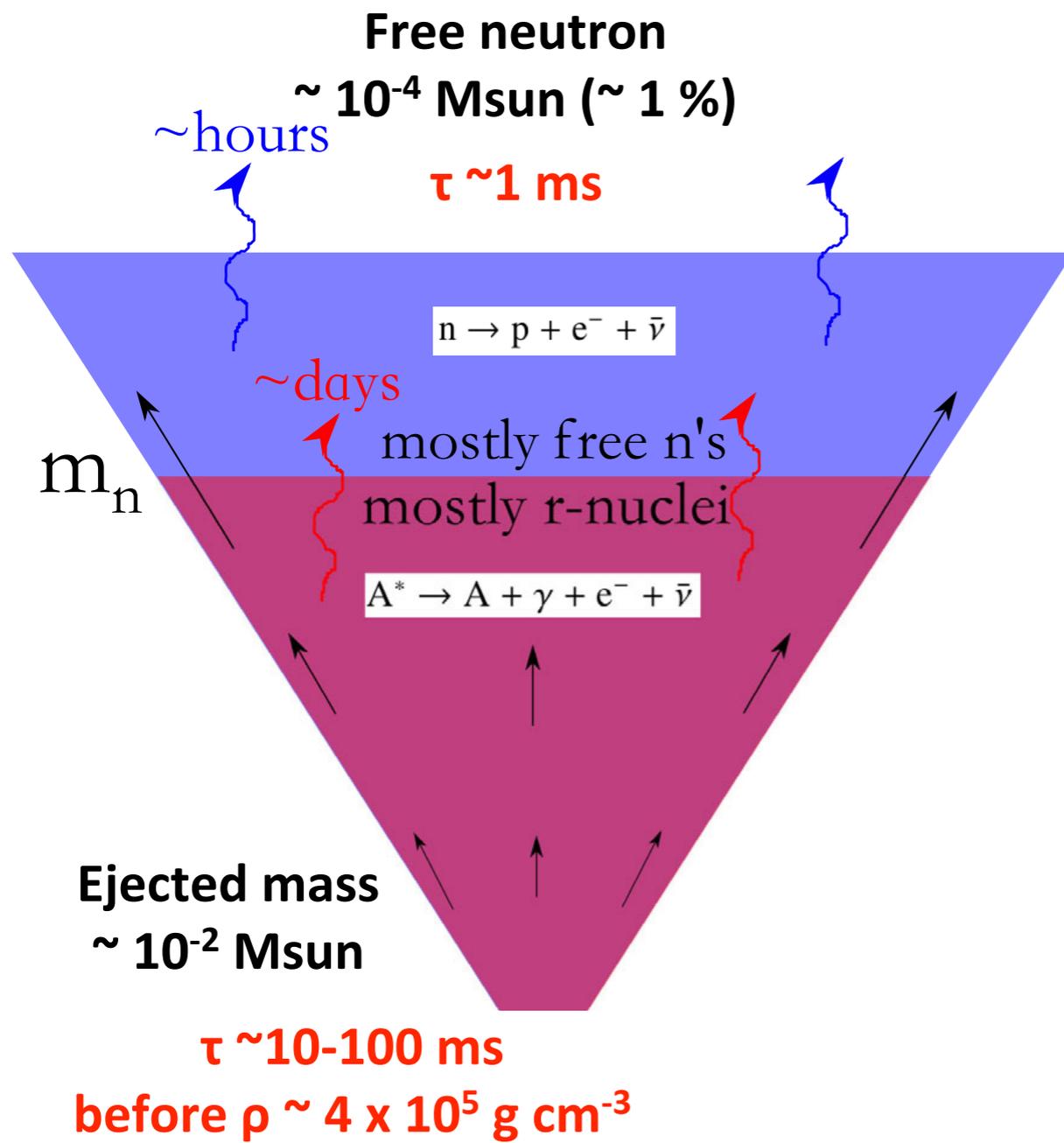


Might be hidden by dynamical ejecta (low Ye)

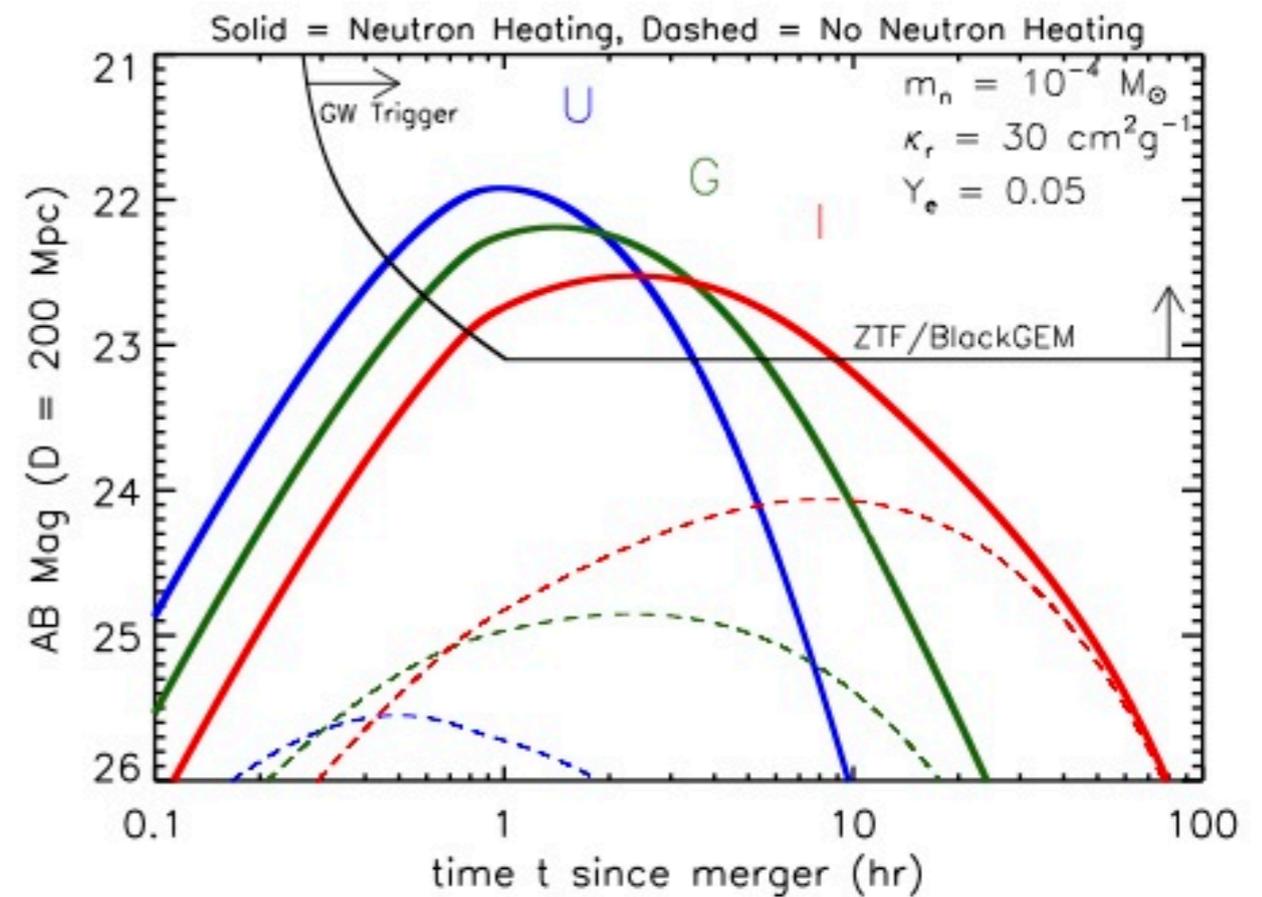
Kasen+2014

==> Visible in BH-NS case!? (Kiuchi-san's talk)

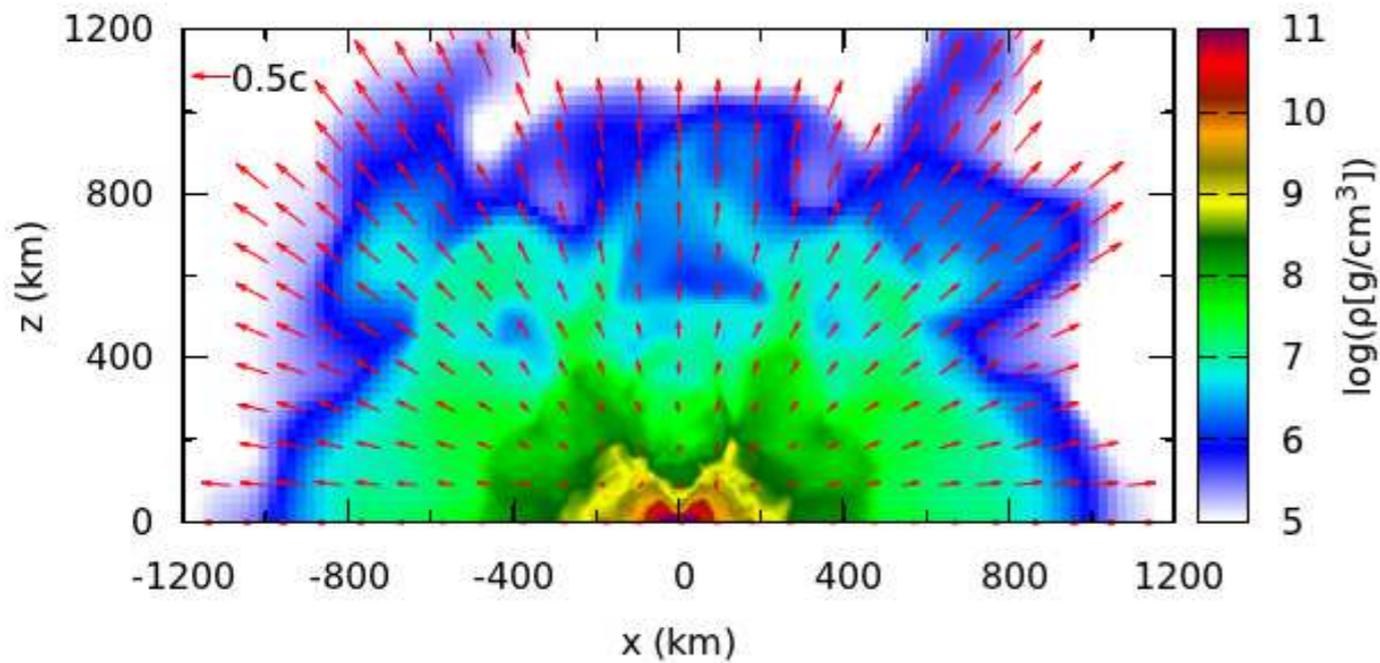
## 2. Free neutron



Metzger+2015



### 3. BH-NS mergers

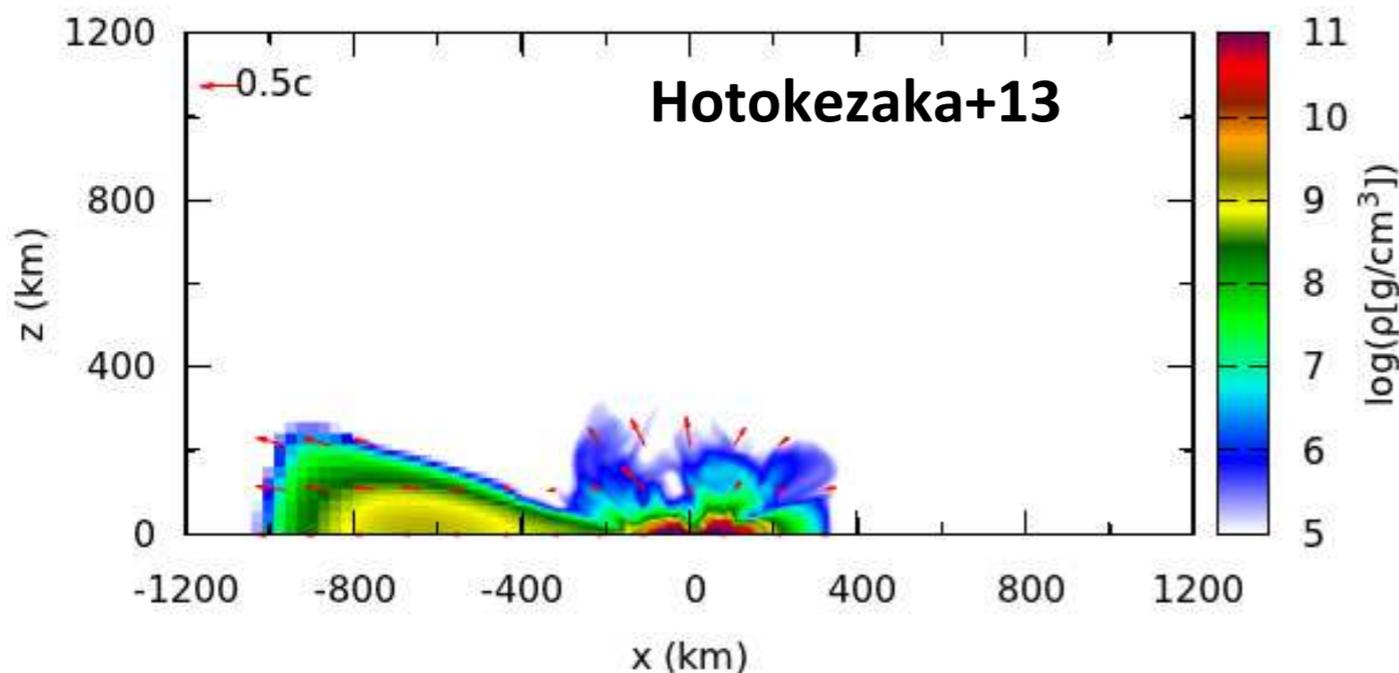


**NS-NS**

$M_{\text{ej}} \sim 10^{-4} - 10^{-2} M_{\text{sun}}$

$N \sim 40 (0.4-400) / \text{yr}$

(Abadie+10)



**BH-NS**

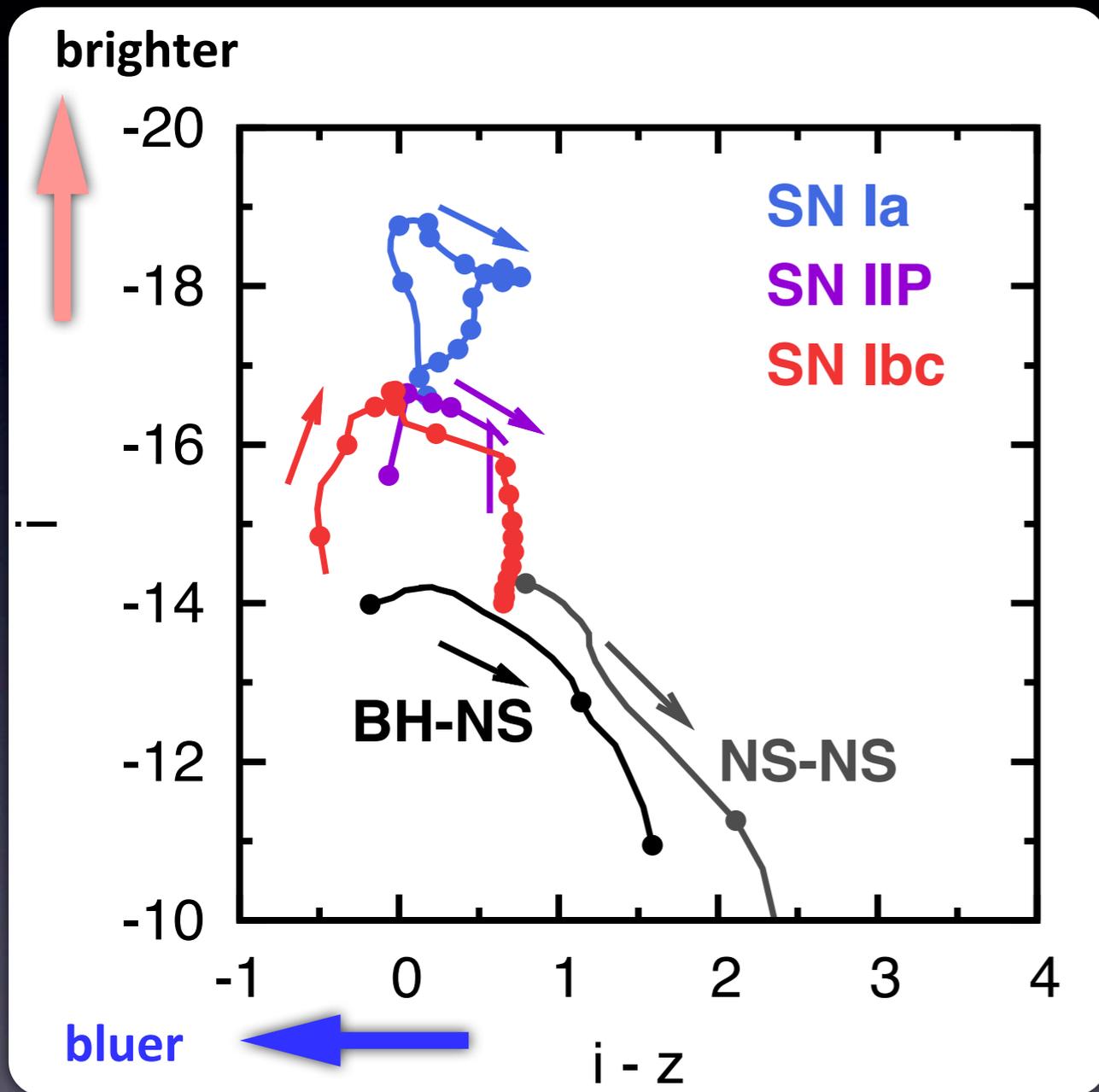
$M_{\text{ej}} \sim < 10^{-1} M_{\text{sun}}$

$N \sim 10 (0.2-300) / \text{yr}$

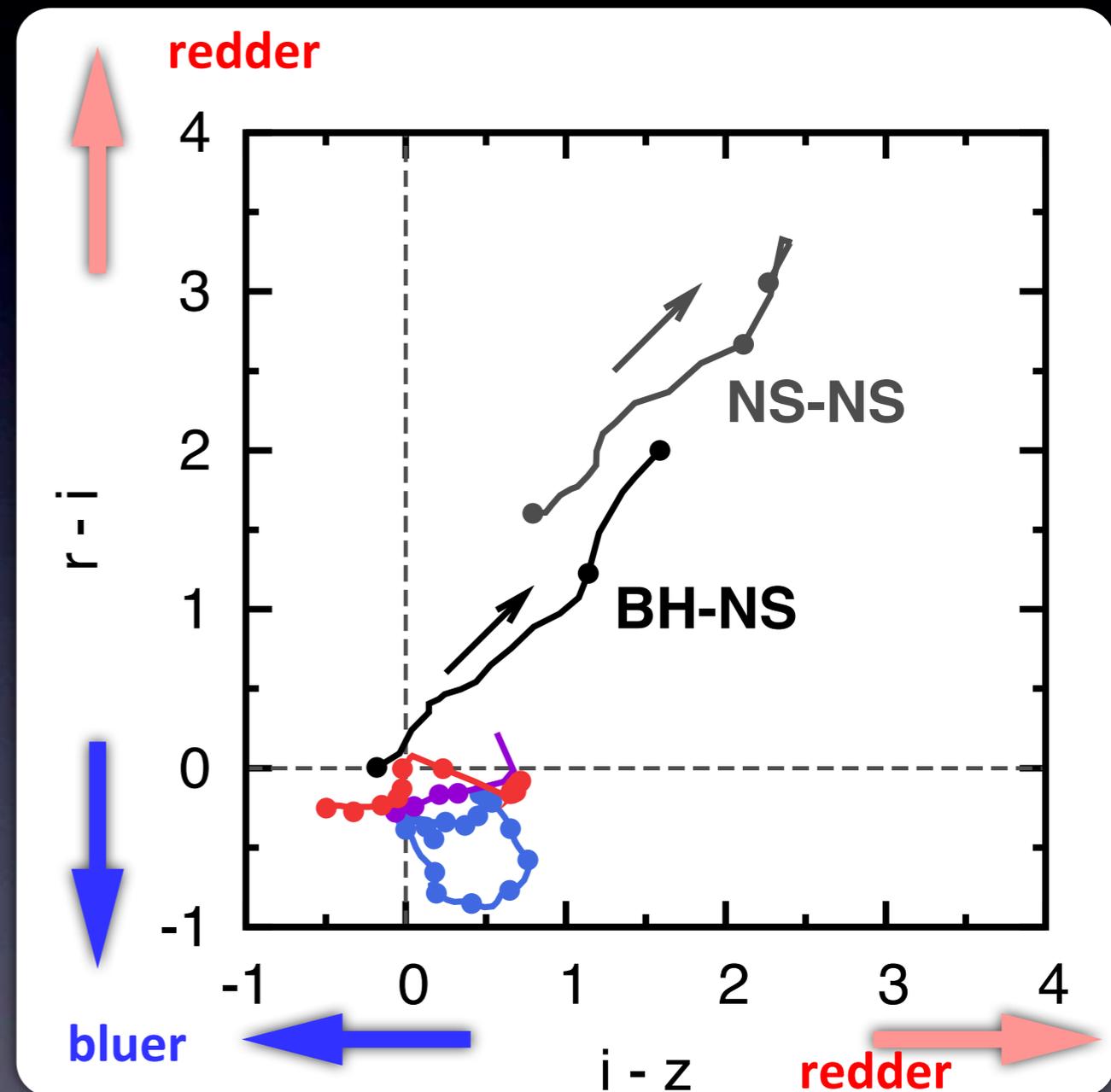
+disk wind

(Kiuchi-san's talk)

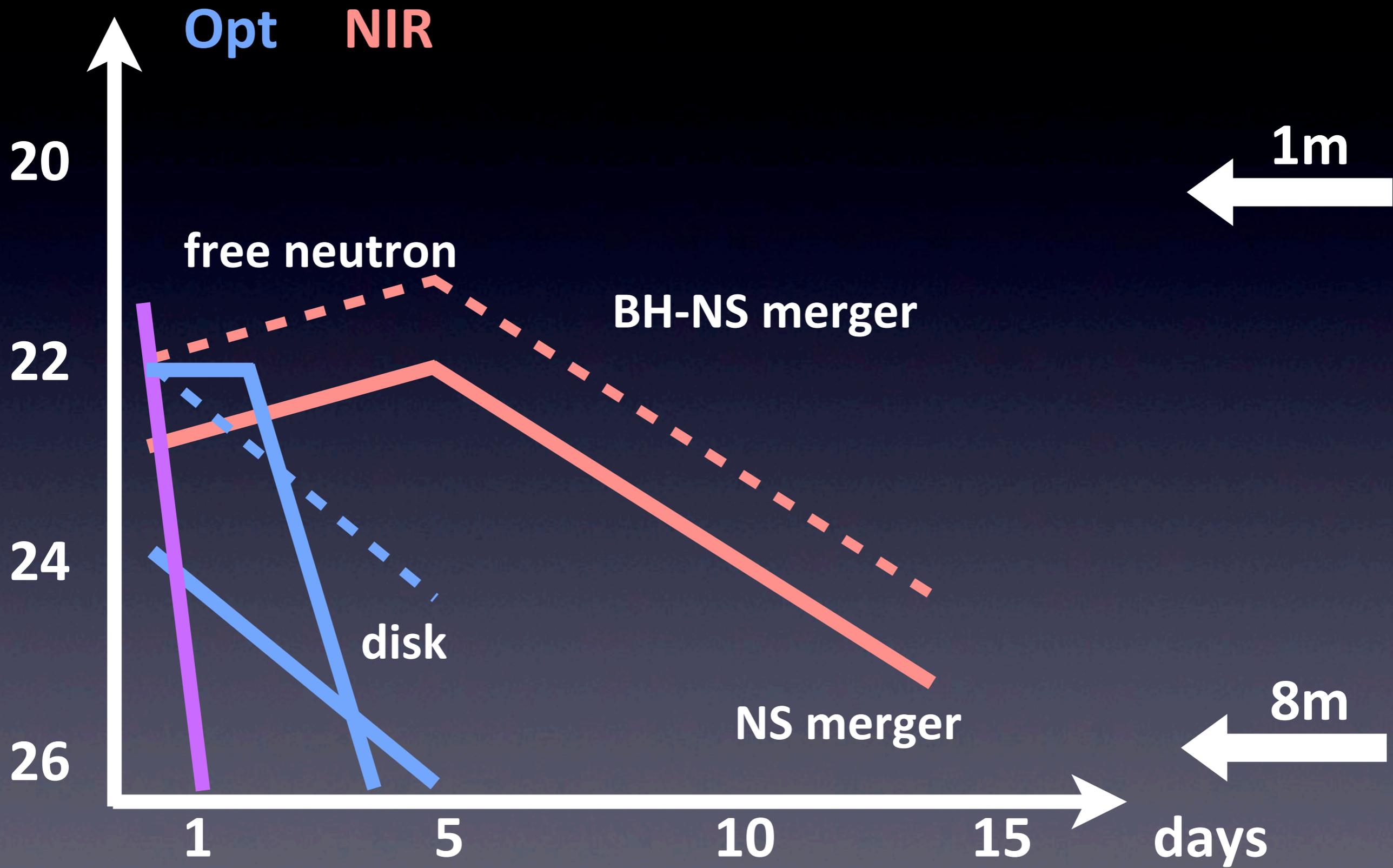
# Color-magnitude (HR diagram)



# Color-color



# Magnitude @ 200 Mpc



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- **Status of observational effort**

Collaboration with

T. Morokuma N. Tominaga, N. Yasuda, H. Furusawa, T. Shibata, E. Matsumoto  
(KISS team and HSC transient team)

# KISS: KIso Supernova Survey

- Extremely high cadence
  - 1-hr cadence  $\leq$  2-3 days
  - 4 deg<sup>2</sup> FOV KWFC
- $\sim$  21 mag in g-band (3 min)
- $\sim$ 50-100 deg<sup>2</sup> /day
- High SFR field ( $<$  200 Mpc, 30-100 Msun/yr)
- $\sim$ 100 nights/yr (around new moon)

Goal: Detection of SN shock breakout

2012: Main survey

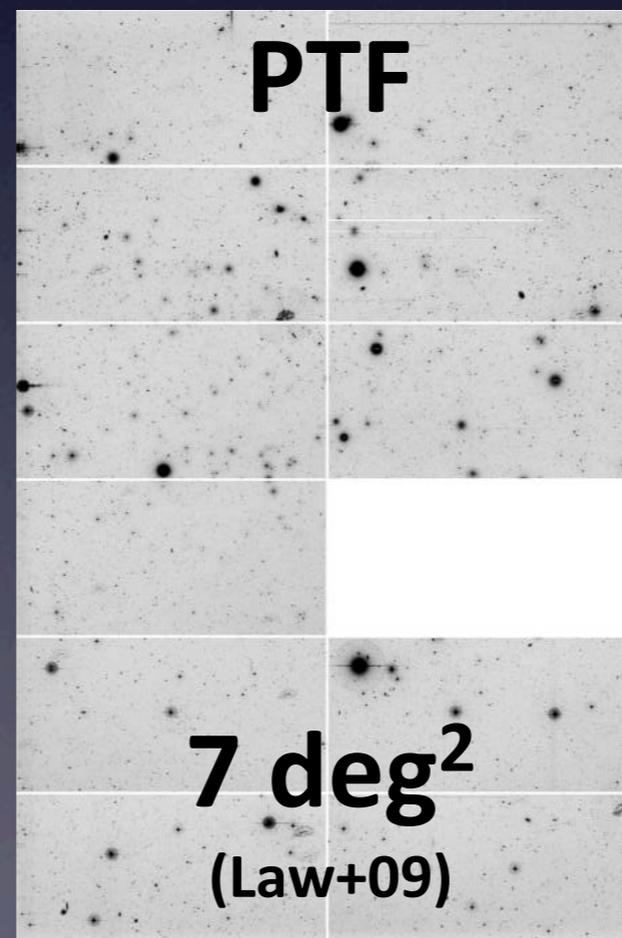
2014: MOU with LIGO/Virgo collaboration (as Japanese consortium)

2014: Fully automated operation



# GW alert error box

e.g. 6 deg x 6 deg

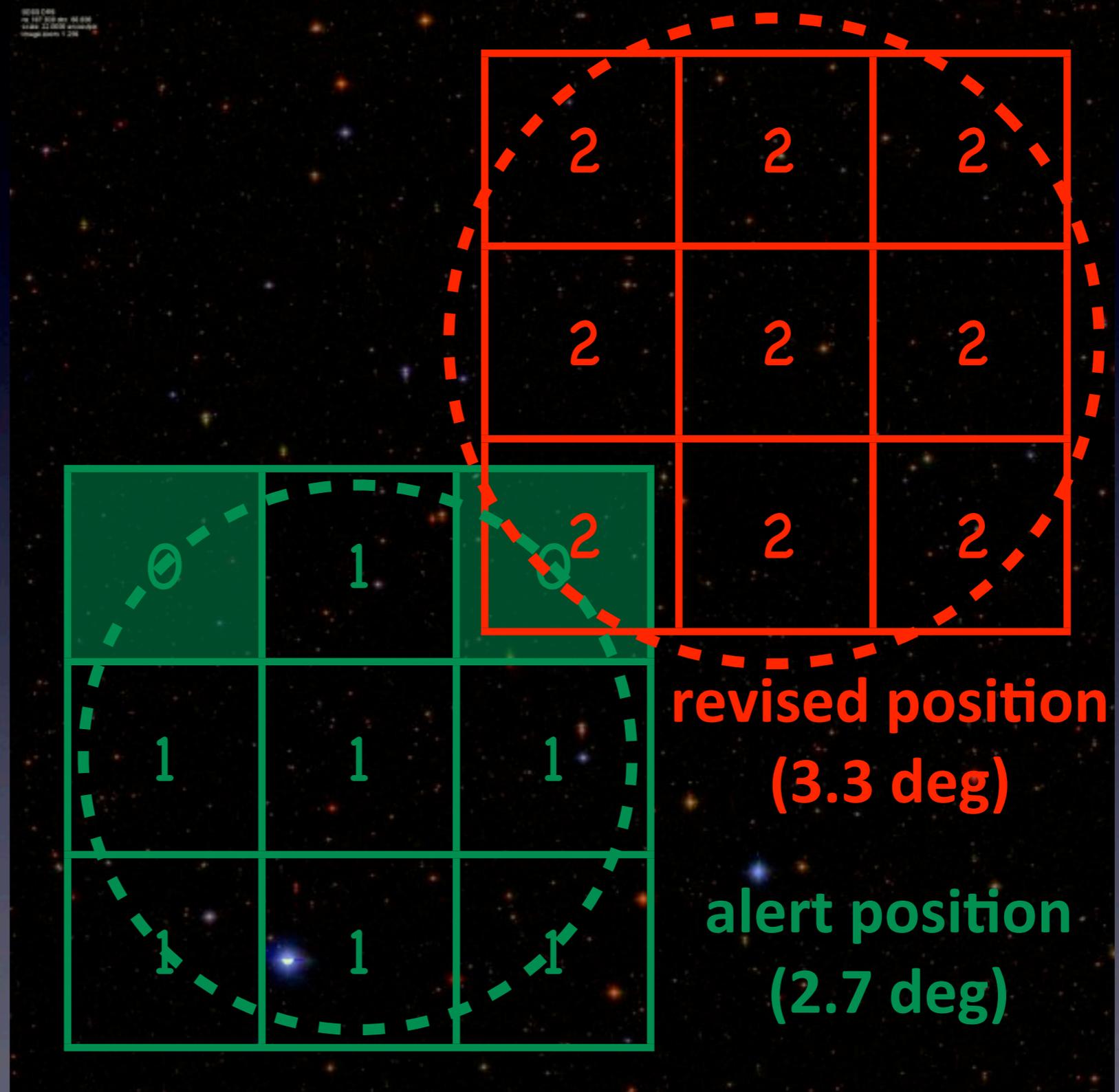


# “Drill” with Fermi/GBM alert



12.5 deg

< 3 hr after the alert



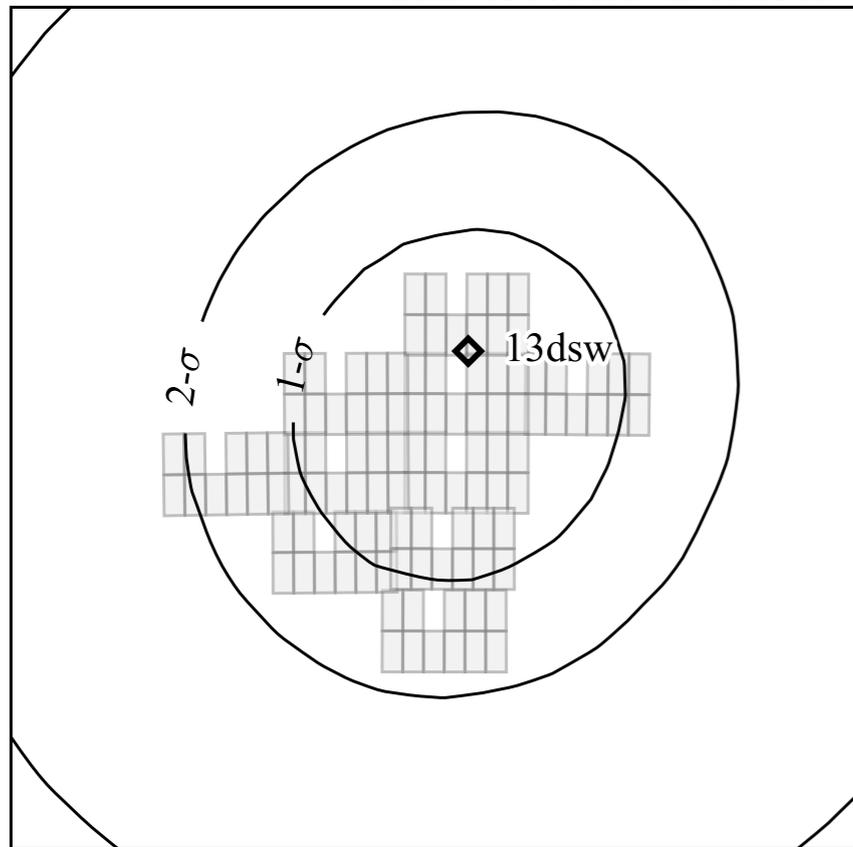
< 1 hr after the alert

by Tomoki Morokuma

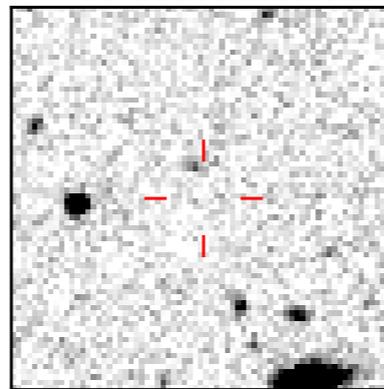
# PTF: Palomar Transient Factory

74 deg<sup>2</sup>

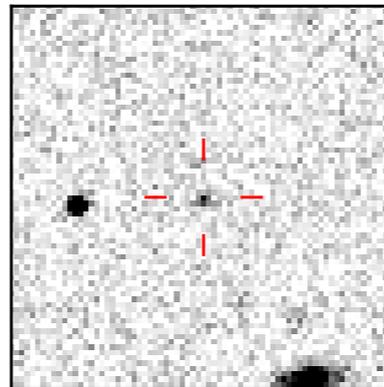
GRB 131011A / iPTF13dsw



co-added reference



2013-10-12 05:26



Singer+2013, 2015  
(arXiv:1501.00495)

GRB time <sup>a</sup>	GBM fluence <sup>b</sup>	$t_{p48} - t_{burst}^c$	P48 area <sup>d</sup>	Prob. <sup>e</sup>
2013-06-28 20:37:57	10 ±0.1	10.02	73	32%
→2013-07-02 00:05:20	57 ±1.2	4.20	74	38%
2013-08-28 07:19:56	372 ±0.6	20.28	74	64%
2013-09-24 06:06:45	37 ±0.6	23.24	74	28%
2013-10-06 20:09:48	18 ±0.6	15.26	74	18%
→2013-10-11 17:47:30	89 ±0.6	11.56	73	54%
2013-11-08 00:34:39	28 ±0.5	4.69	73	37%
2013-11-10 08:56:58	33 ±0.3	17.47	73	44%
2013-11-25 16:32:47	5.5±0.3	11.72	95	26%
2013-11-26 03:54:06	17 ±0.3	6.94	109	59%
2013-11-27 14:12:14	385 ±1.4	13.46	60	50%
2013-12-30 19:24:06	41 ±0.4	7.22	80	38%
→2013-12-31 04:45:12	1519 ±1.2	1.37	30	32%
2014-01-04 17:32:00	333 ±0.6	18.57	15	11%
2014-01-05 01:32:57	6.4±0.1	7.63	74	22%
2014-01-22 14:19:44	9.1±0.5	11.97	75	34%
2014-02-11 02:10:41	7.4±0.3	1.77	44	19%
2014-02-19 19:46:32	28 ±0.5	7.01	71	14%
2014-02-24 18:55:20	24 ±0.6	7.90	72	30%
2014-03-11 14:49:13	40 ±1.2	12.18	73	54%
2014-03-19 23:08:30	71 ±0.3	3.88	74	48%
2014-04-04 04:06:48	82 ±0.2	0.11	109	69%
2014-04-29 23:24:42	6.2±0.2	10.99	74	15%
→2014-05-08 03:03:55	614 ±1.2	6.68	73	67%
2014-05-17 19:31:18	45 ±0.4	8.60	95	69%
2014-05-19 01:01:45	39 ±0.5	4.42	73	41%
→2014-06-06 03:11:52	76 ±0.4	4.08	74	56%
2014-06-08 17:07:11	19 ±0.6	11.20	73	49%
→2014-06-20 05:15:28	61 ±0.6	0.17	147	59%
→2014-06-23 05:22:07	61 ±0.6	0.18	74	4%
2014-06-28 16:53:19	18 ±1.0	16.16	76	20%
2014-07-16 07:20:13	2.4±0.3	0.17	74	28%
2014-07-29 00:36:54	81 ±0.7	3.43	73	65%
2014-08-07 11:59:33	13 ±0.1	15.88	73	54%
→2014-08-08 00:54:01	32 ±0.3	3.25	95	69%

# Selection process

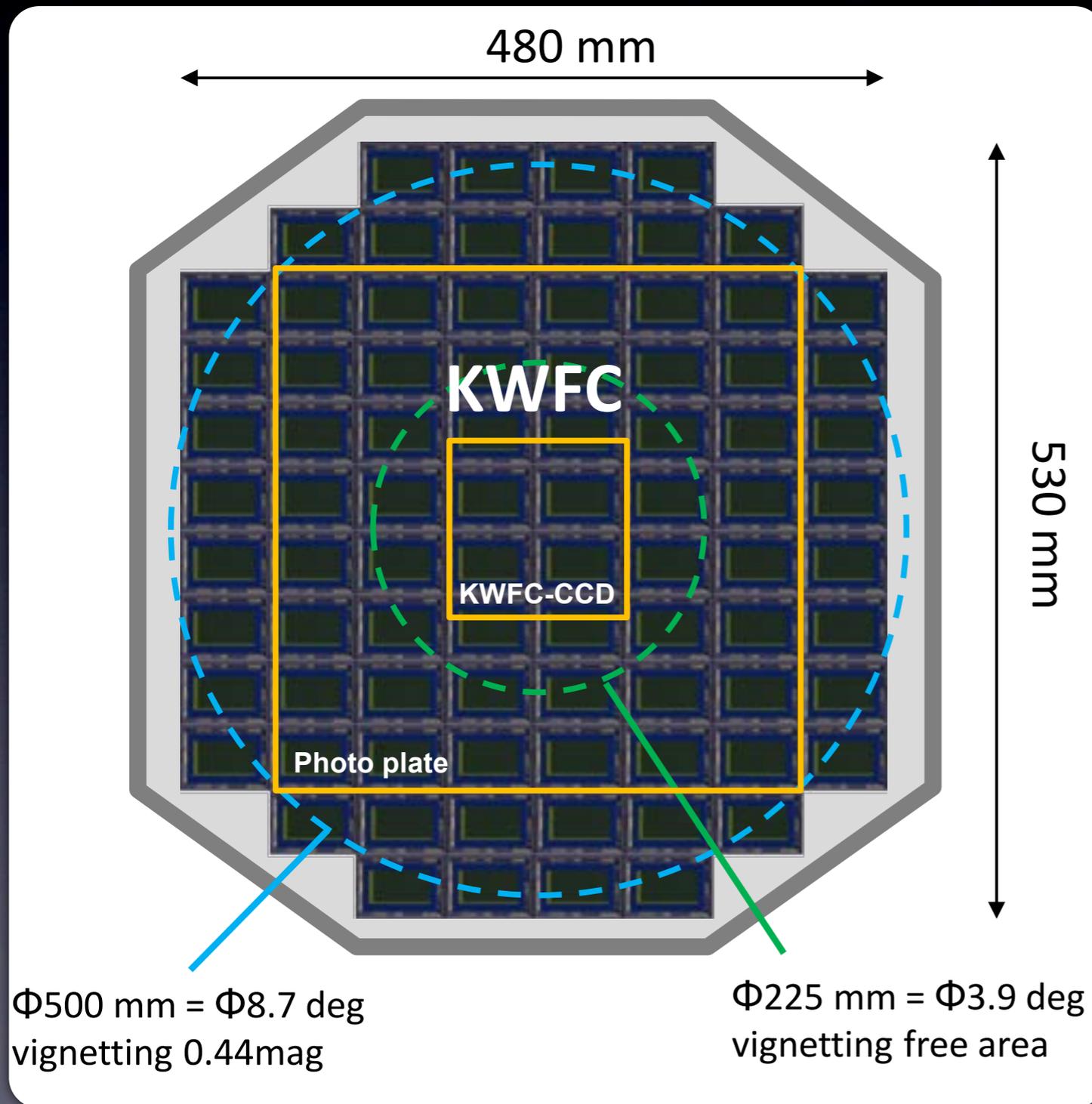
GRB	SNR > 5	RB2 > 0.1	not stellar	not in MPC <sup>a</sup>	detected twice	saved for follow-up
130702A	14 629	2 388	1 346	1 323	417	11
131011A	21 308	8 652	4 344	4 197	434	23
131231A	9 843	2 503	1 776	1 543	1 265	10
140508A	48 747	22 673	9 970	9 969	619	42
140606B	68 628	26 070	11 063	11 063	1 449	28
140620A	152 224	50 930	17 872	17 872	1 904	34
140623A	71 219	29 434	26 279	26 279	442	23
140808A	19 853	4 804	2 349	2 349	79	12
median reduction		36%	17%	16%	1.7%	0.068%

<sup>a</sup> Not in Minor Planet Center database

# Toward wider field of view: Tomo-e camera

<http://www.ioa.s.u-tokyo.ac.jp/tomoe/index.html>

PI: Shigeyuki Sako (U. Tokyo)



- Large FOV  $\Omega$  ( $20 \text{ deg}^2$ )
- Efficient observation  $f$

$$\text{Survey power} = fA\Omega$$

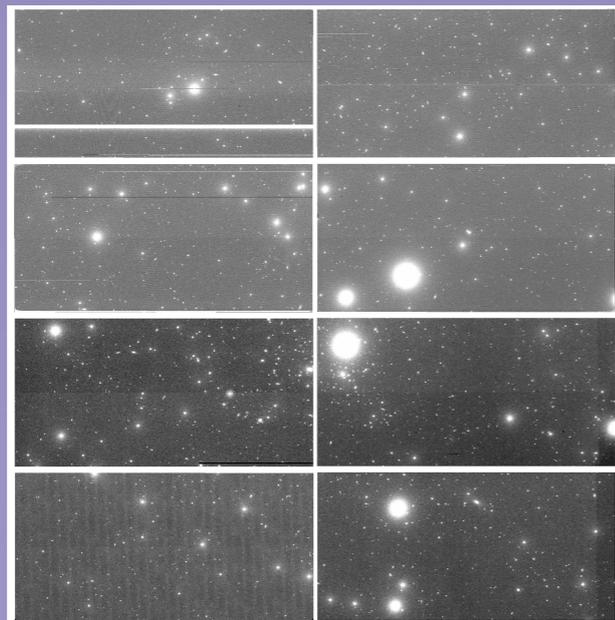
GW alert error box

e.g. 6 deg x 6 deg

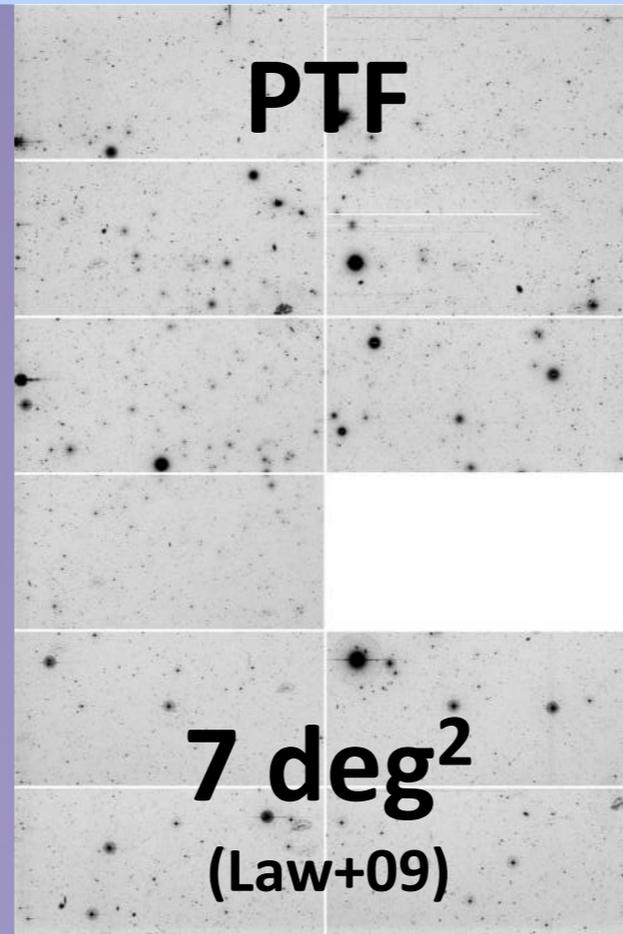
ZTF

Kiso/Tomo-e  
9 deg

Kiso/CCD  
2 deg

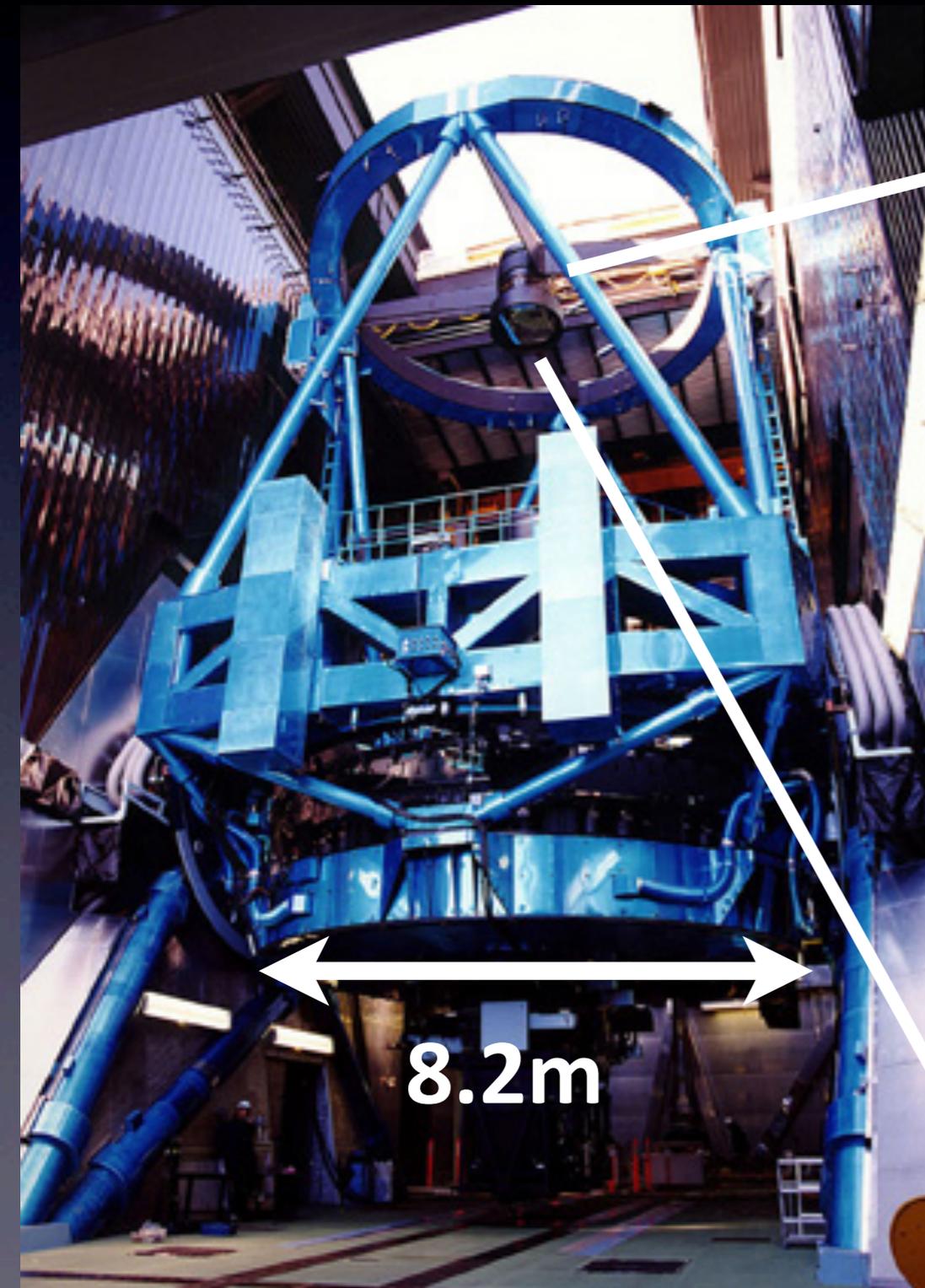


PTF



7 deg<sup>2</sup>  
(Law+09)

# Subaru/ Hyper Suprime-Cam

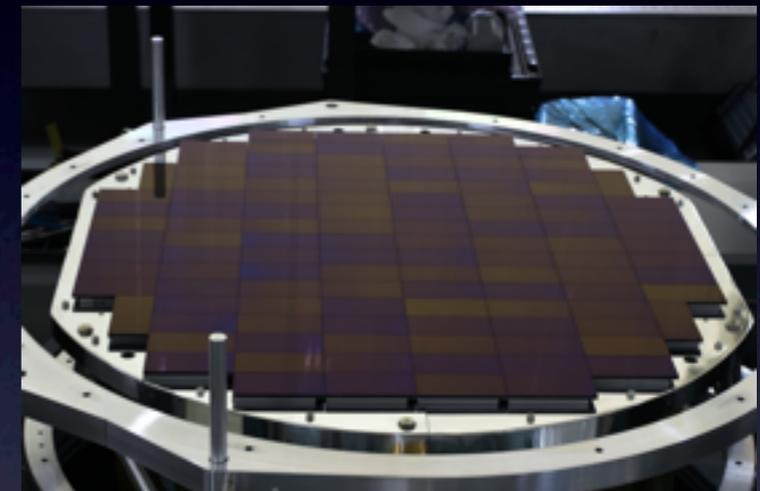


8.2m



3m

3t !



104 CCDs

~ 900 Megapixel

2 GB/image

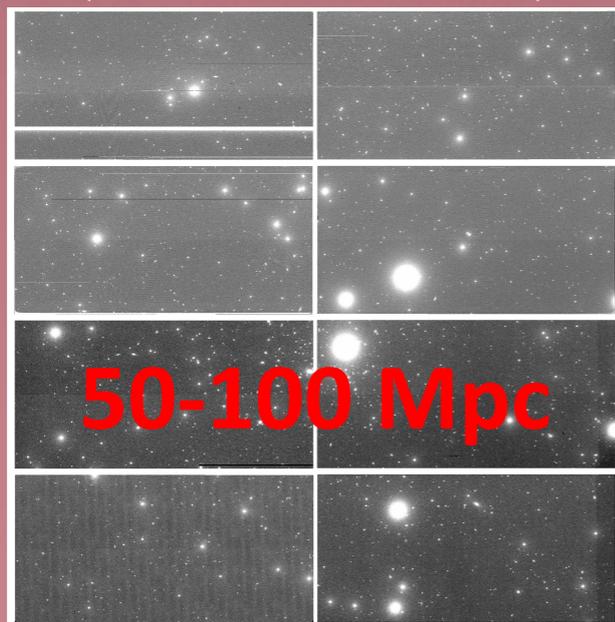
~300 GB/night

# GW alert error box

e.g. 6 deg x 6 deg

Kiso/Tomo-e  
9 deg

Kiso/CCD  
2 deg



50-100 Mpc

8m-class  
telescope



Subaru/HSC  
1.5 deg



400 Mpc

# Rapid alert: 2014 July 2 and 3

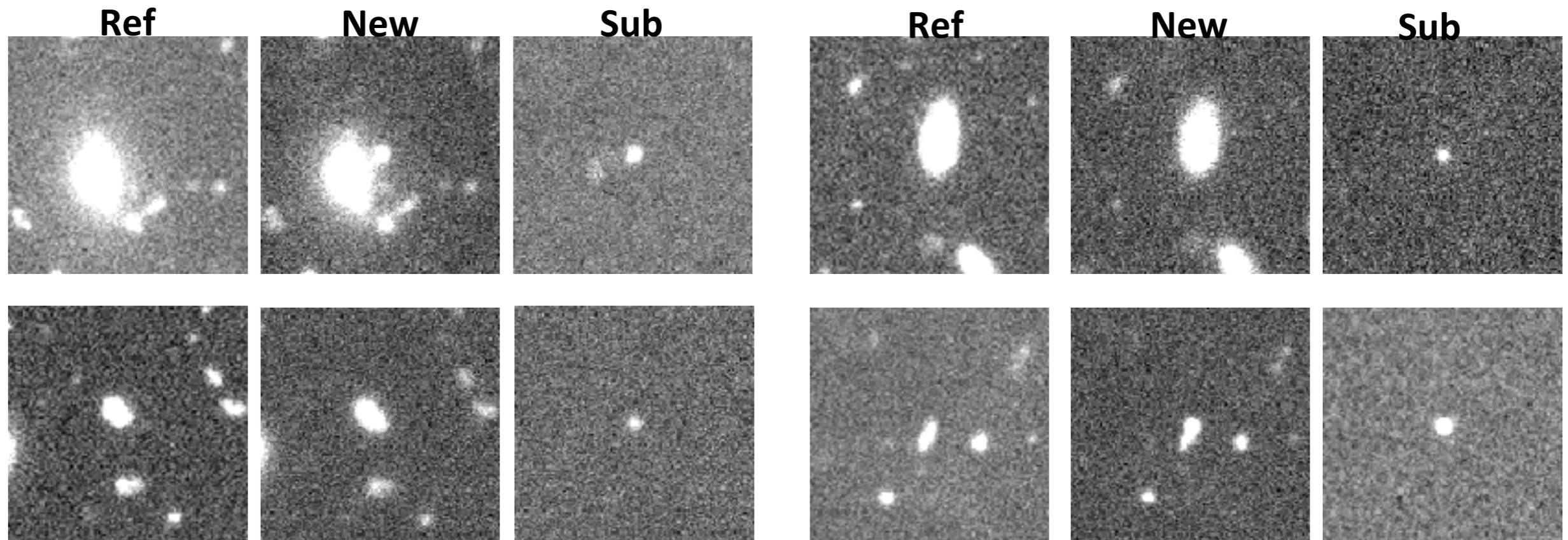
## The Astronomer's Telegram

### 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**

**10 hour after the end of observation**



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

# Rapid alert: 2014 Nov 26 and 27

## The Astronomer's Telegram

### Supernova candidates discovered with Subaru/Hyper Suprime-Cam

ATel #6763; *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), Nobuhiro Okabe (Kavli IPMU, U. Tokyo), Toshifumi Futamase (Tohoku Univ.), Satoshi Miyazaki (NAOJ), Takashi J. Moriya (AIfA, U. Bonn), Junichi Noumaru (NAOJ), Kiaina Schubert (NAOJ), and Tadafumi Takata (NAOJ)*

*on 27 Nov 2014; 18:03 UT*

*Credential Certification: Nozomu Tominaga (tominaga@konan-u.ac.jp)*

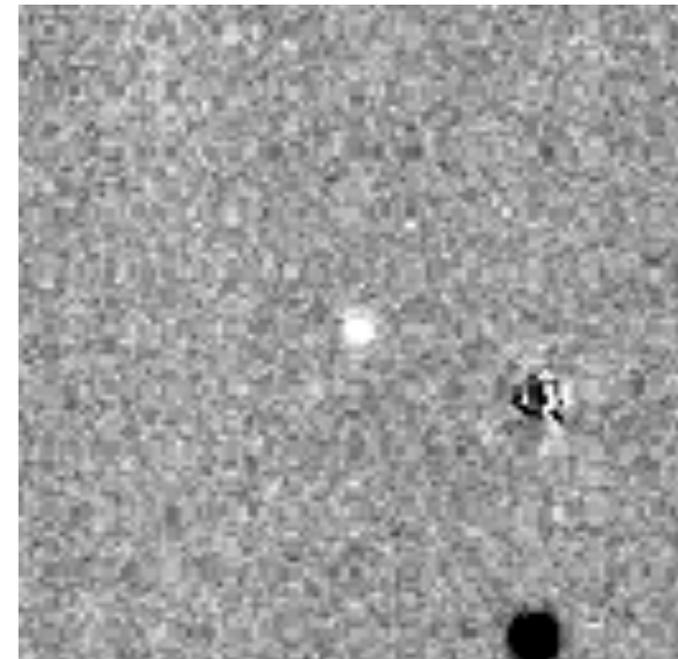
Ref



New



Sub



~35 deg<sup>2</sup> (20 pointing) with HSC

Detection	Selection	Multiple detection
137,222	20,625	1,787

(x 20 for 2 day observations)

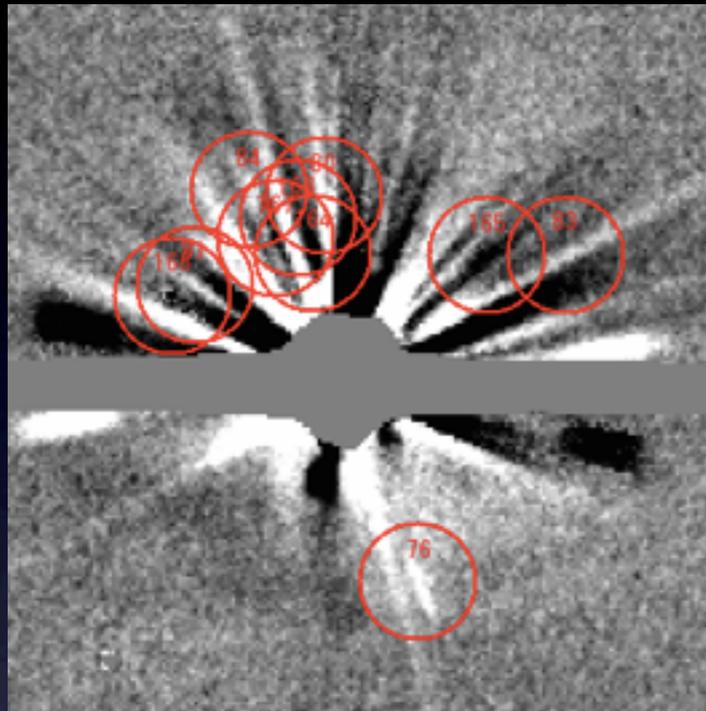
~100 deg<sup>2</sup> with PTF

Singer+2015

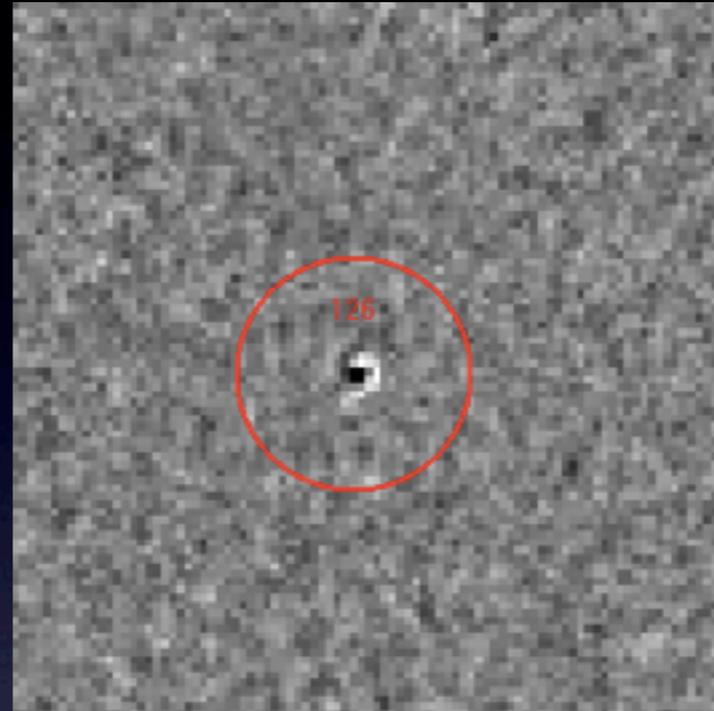
(arXiv:1501.00495)

GRB	SNR > 5	RB2 > 0.1	not stellar	not in MPC <sup>a</sup>	detected twice	saved for follow-up
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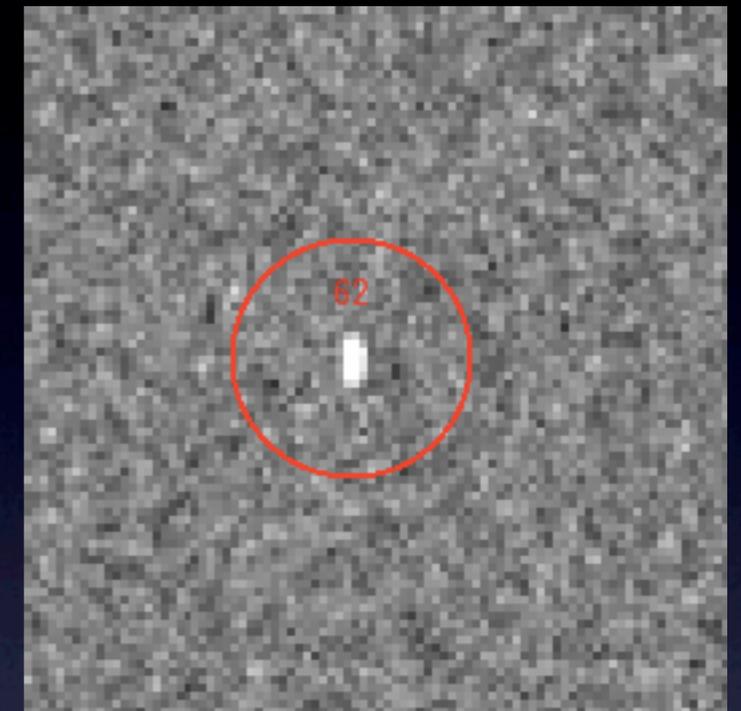
<sup>a</sup> Not in Minor Planet Center database



**artifacts around  
bright source**



**inaccurate  
convolution**

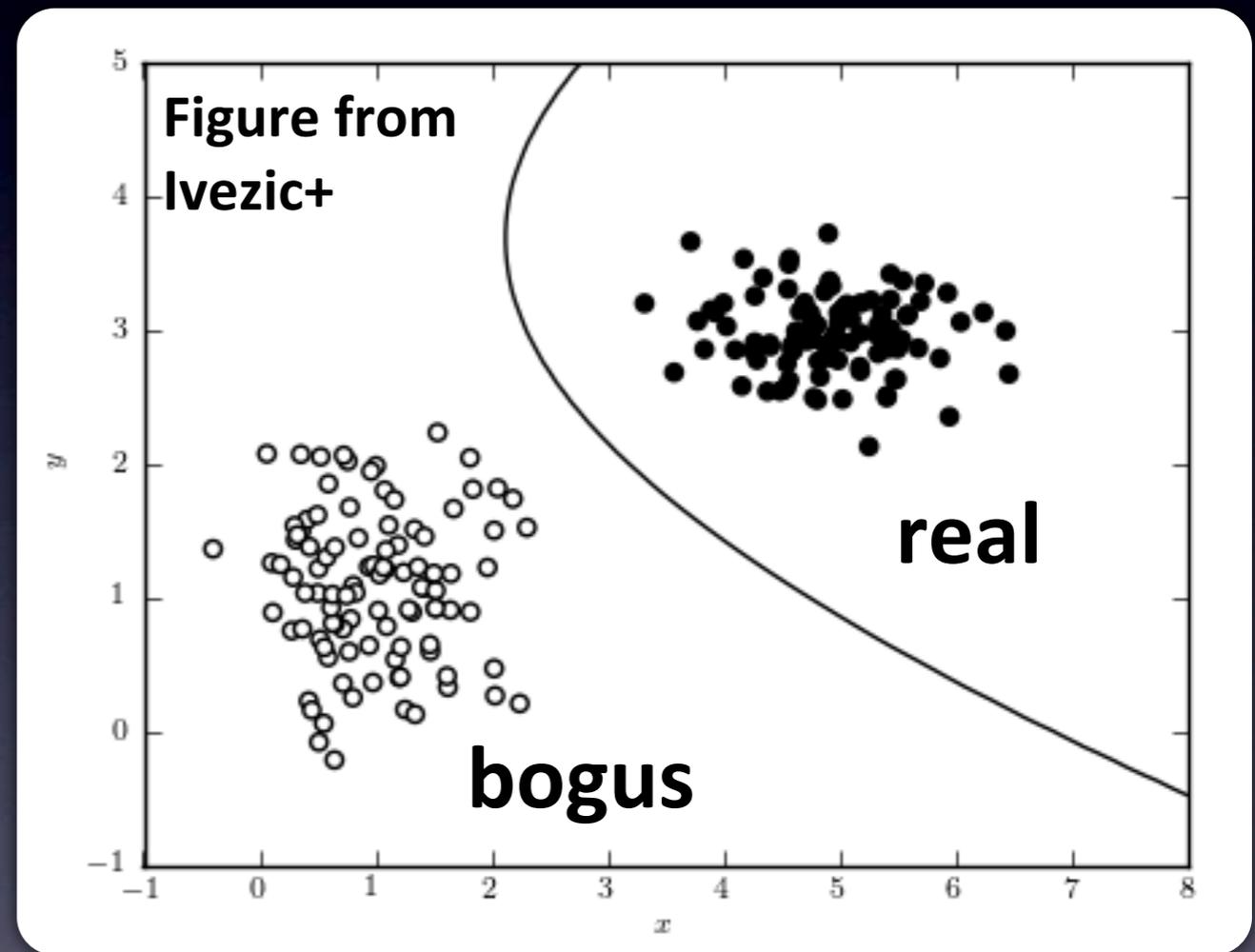
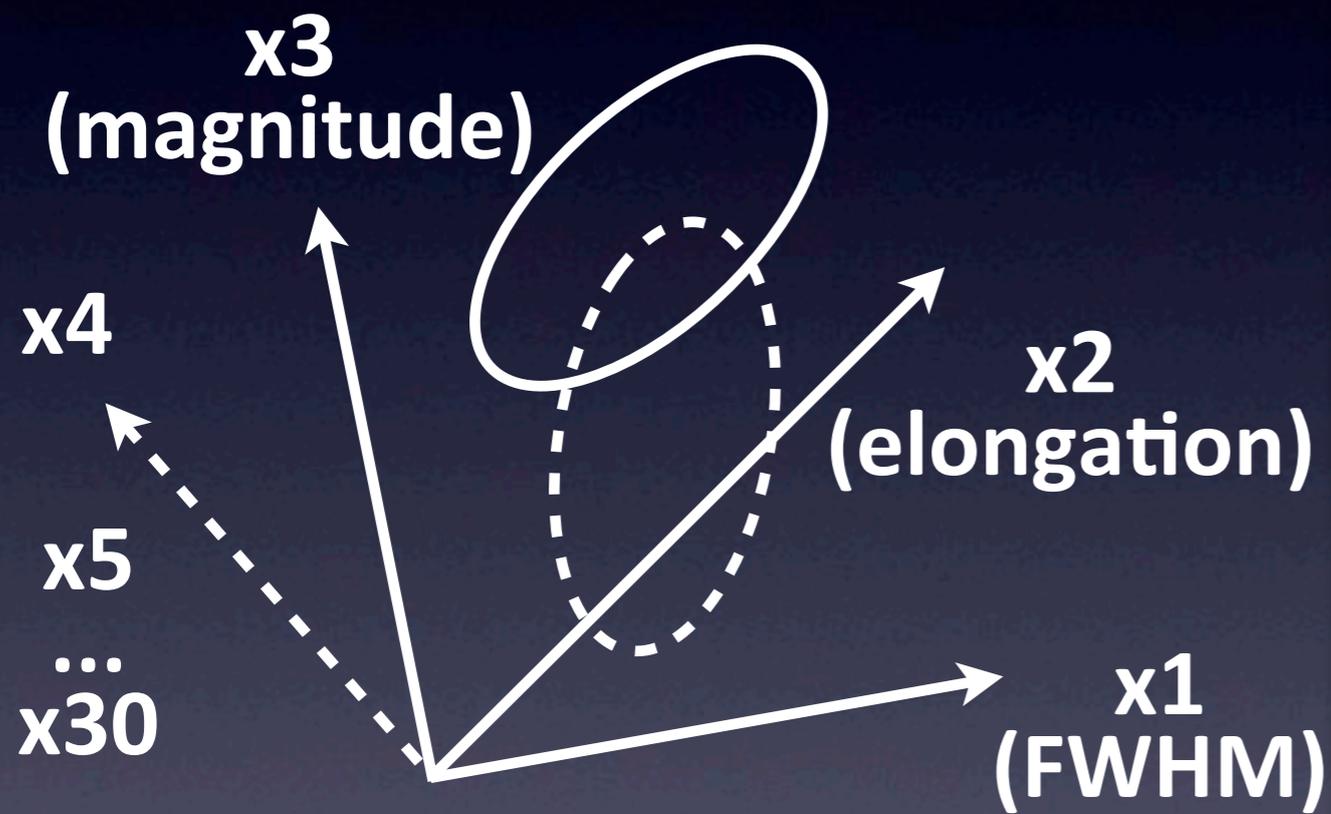
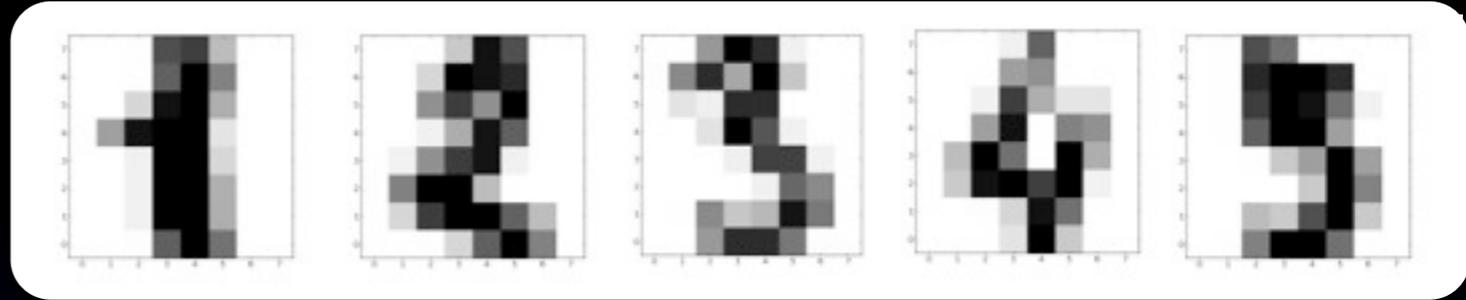


**cosmic ray  
event**

**real : bogus ~ 1 : 100-1000**

# Application of “Machine learning”

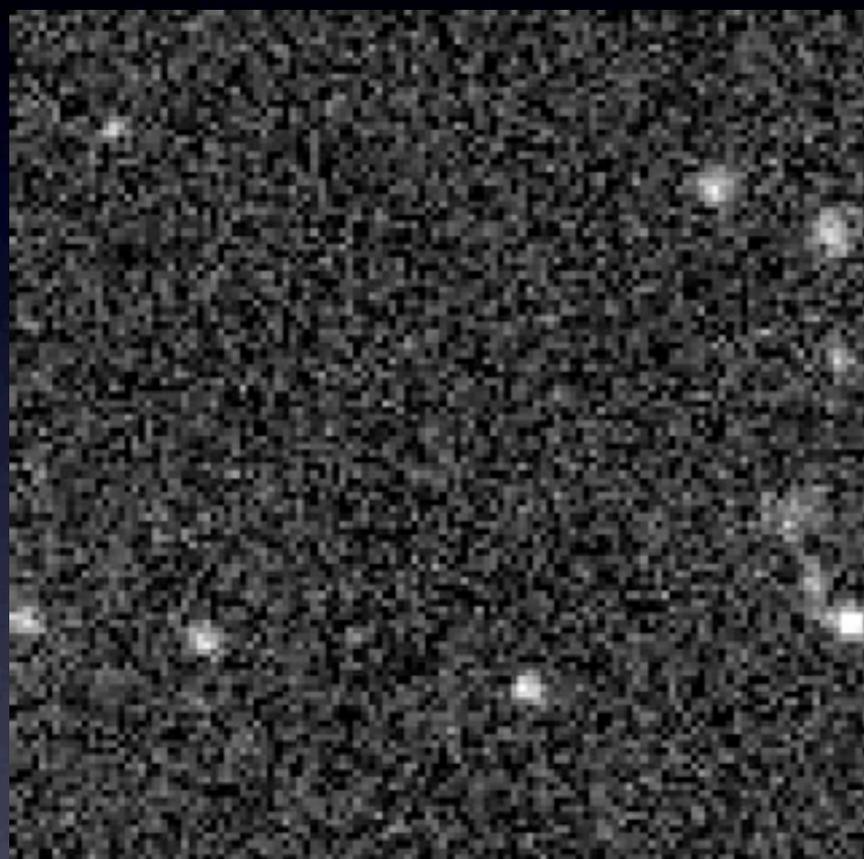
see e.g., Bloom+12, Brink+13, Wright+15



# Frontier of transient sky

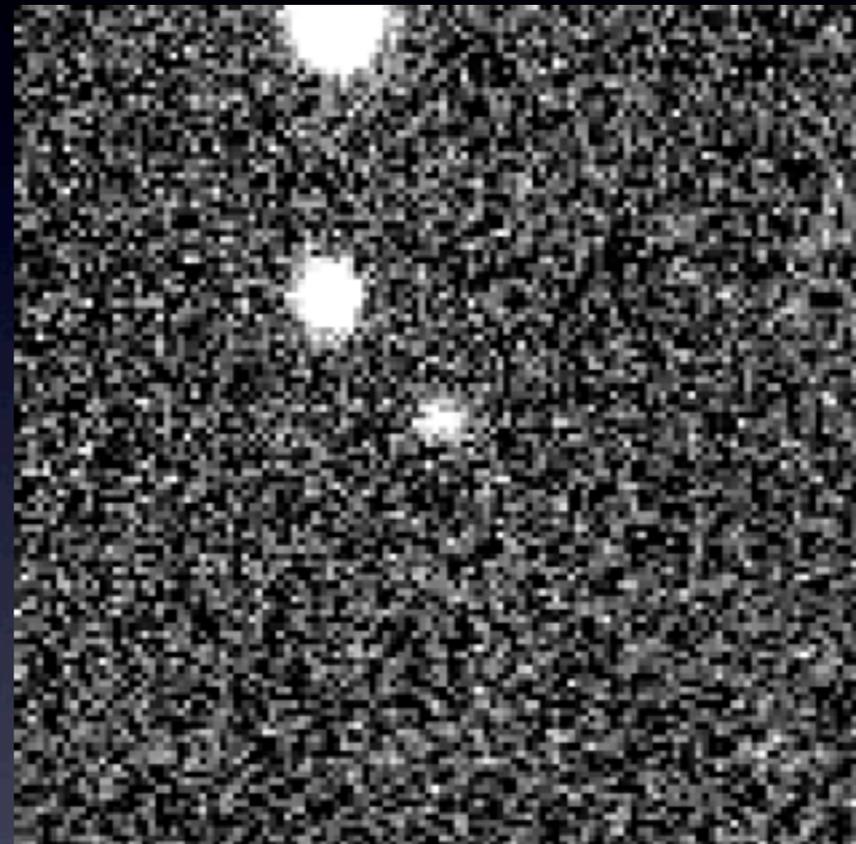
**25.5 mag depth,  $t < 10$  min**

20 arcsec (")



**moving object**  
(~25 mag, 2"/hr)

20 arcsec (")



**flare**  
(23.8 => 22.5 mag  
in 5min)

# Magnitude @ 200 Mpc

