Time-Domain Science with ULTIMATE-Subaru

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Time-domain science

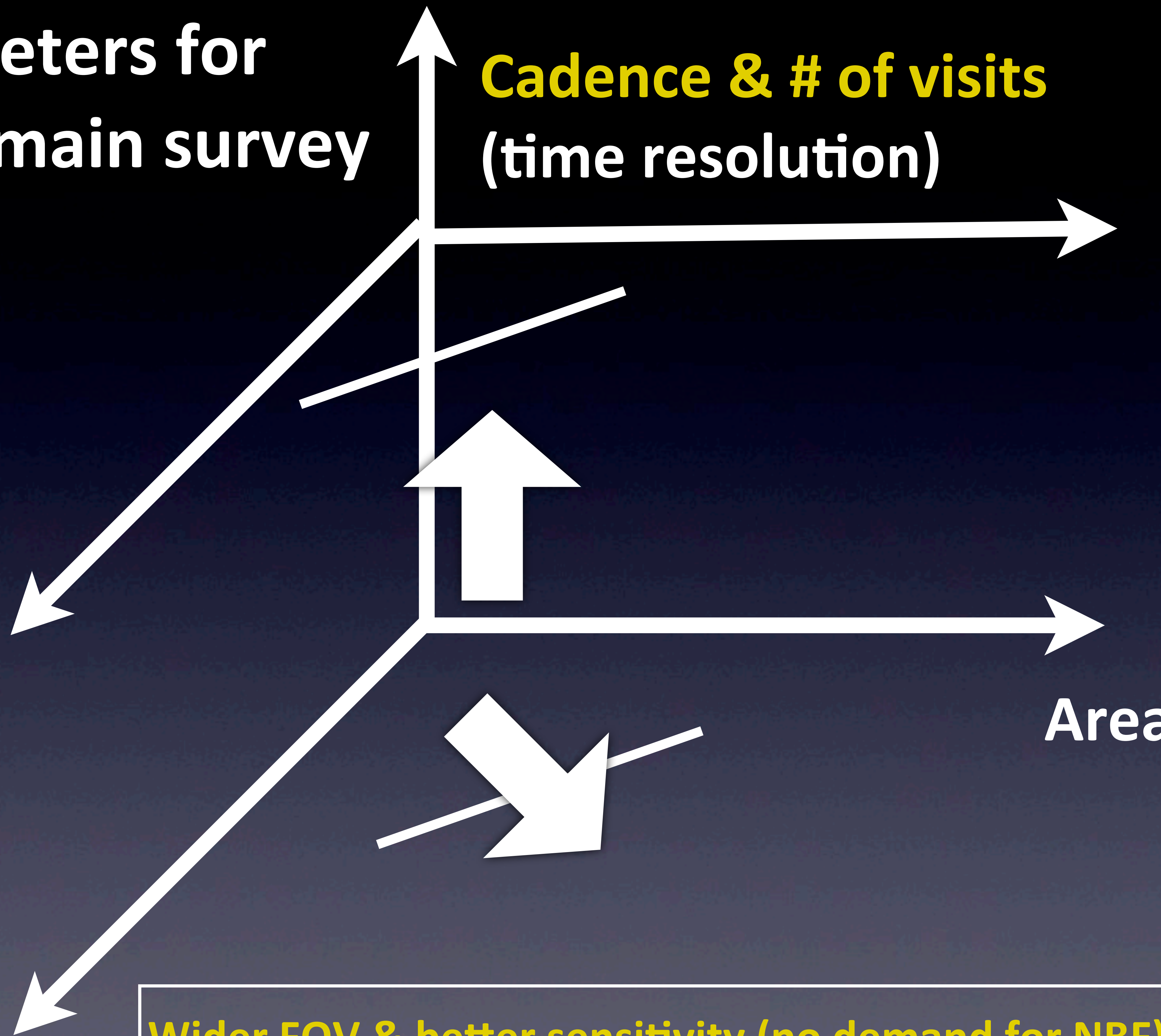
Image @ $t = t_1$

Image @ $t = t_2$

Subaru/HSC (Tominaga, Morokuma, MT+ 2015)

- Transients
  - supernova, gamma-ray bursts, GW sources, ...
- Variable stars

3 parameters for time-domain survey



Wider FOV & better sensitivity (no demand for NBF)
Most of transient surveys have been done in optical/BBF

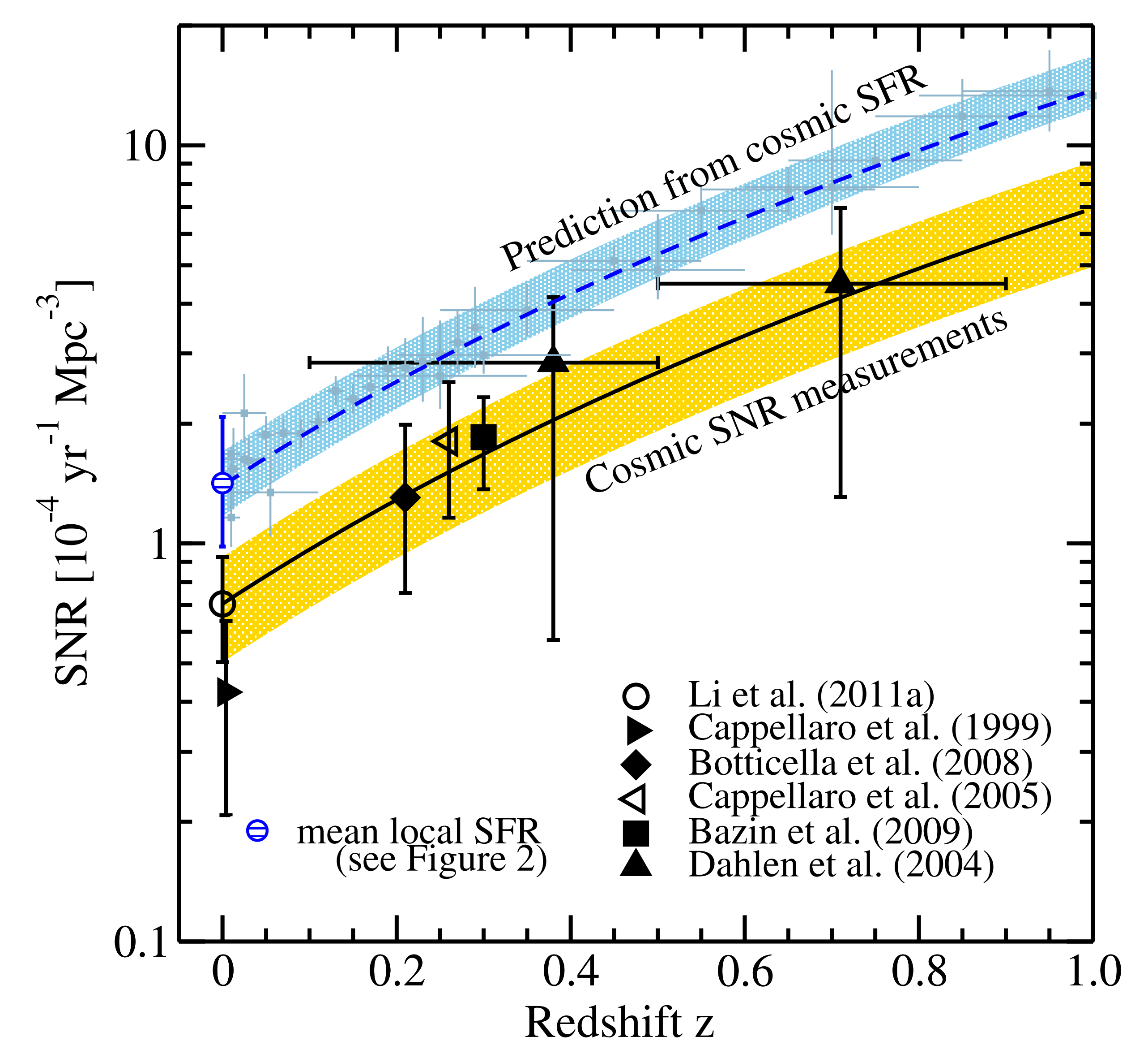
Why transient surveys in NIR?

- Nearby supernovae (reddened)
- High-redshift supernovae (redshifted)
- Gravitational wave sources (intrinsically red)

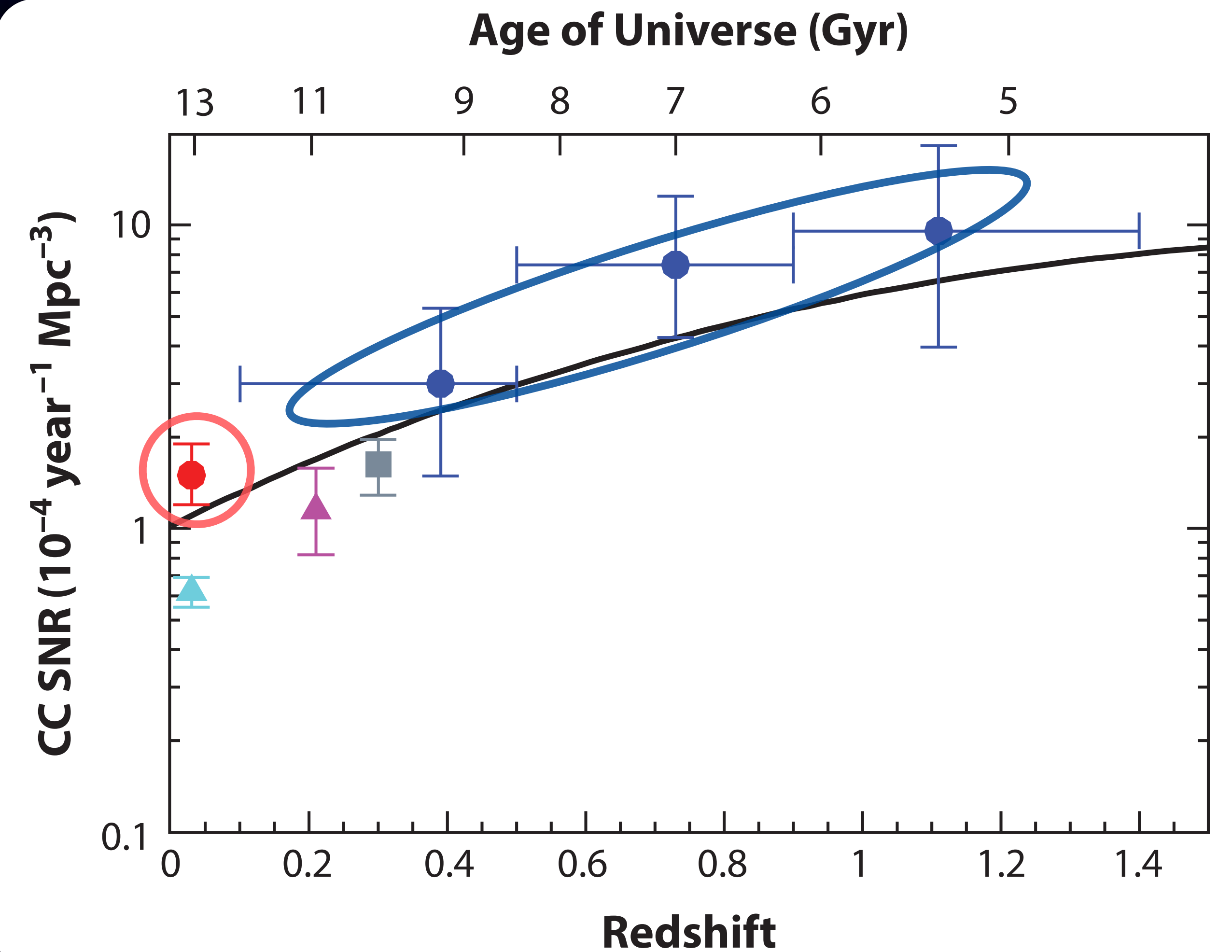
Missing supernovae?

star formation rate
=> supernova rate

$$R_{\rm SN}(z) = \dot{\rho}_*(z) \frac{\int_{M_{\rm min}}^{M_{\rm max}} \psi(M)\, dM}{\int_{0.1}^{100} M \psi(M)\, dM},$$



Horiuchi+11

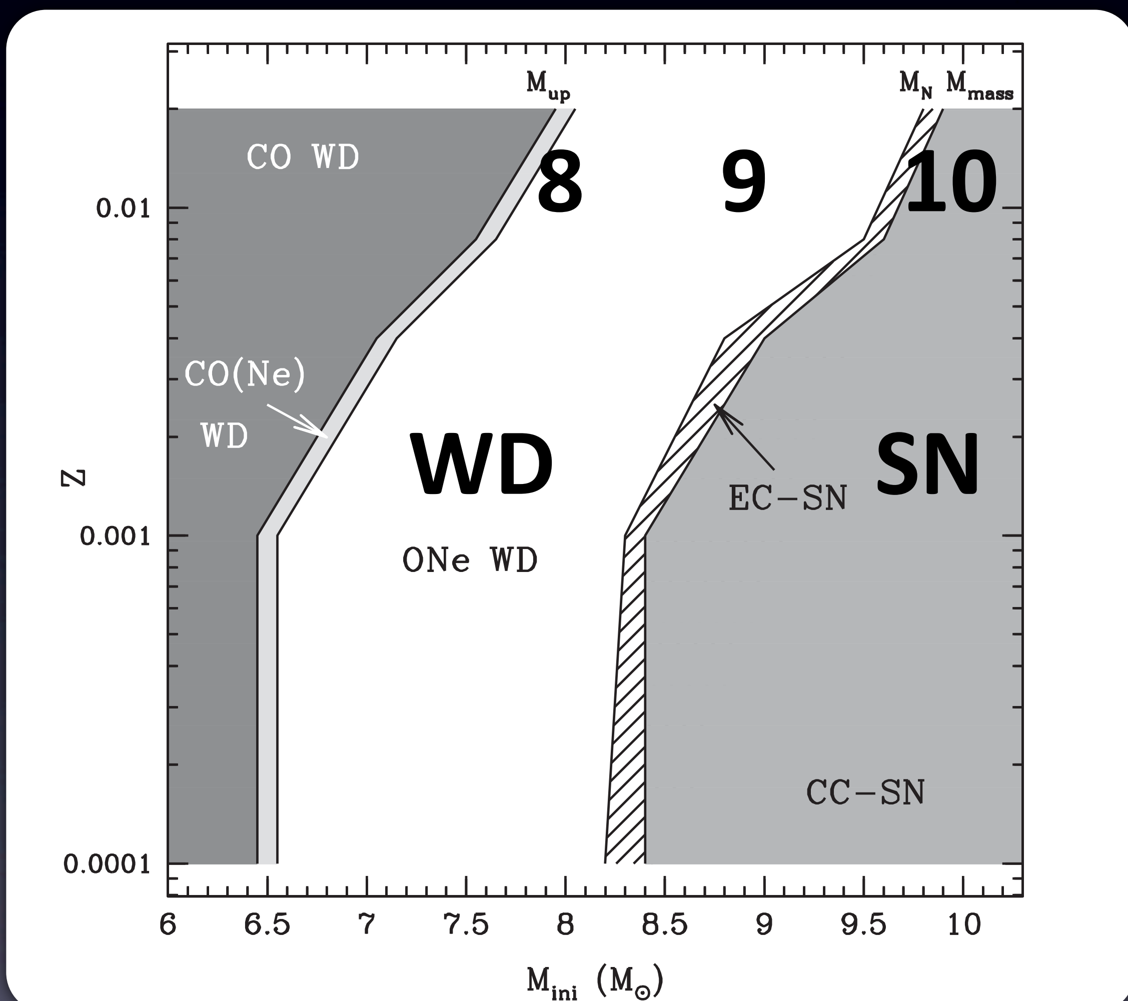


Madau & Dickinson 14

Fundamental questions in stellar astrophysics

Minimum mass of supernova?

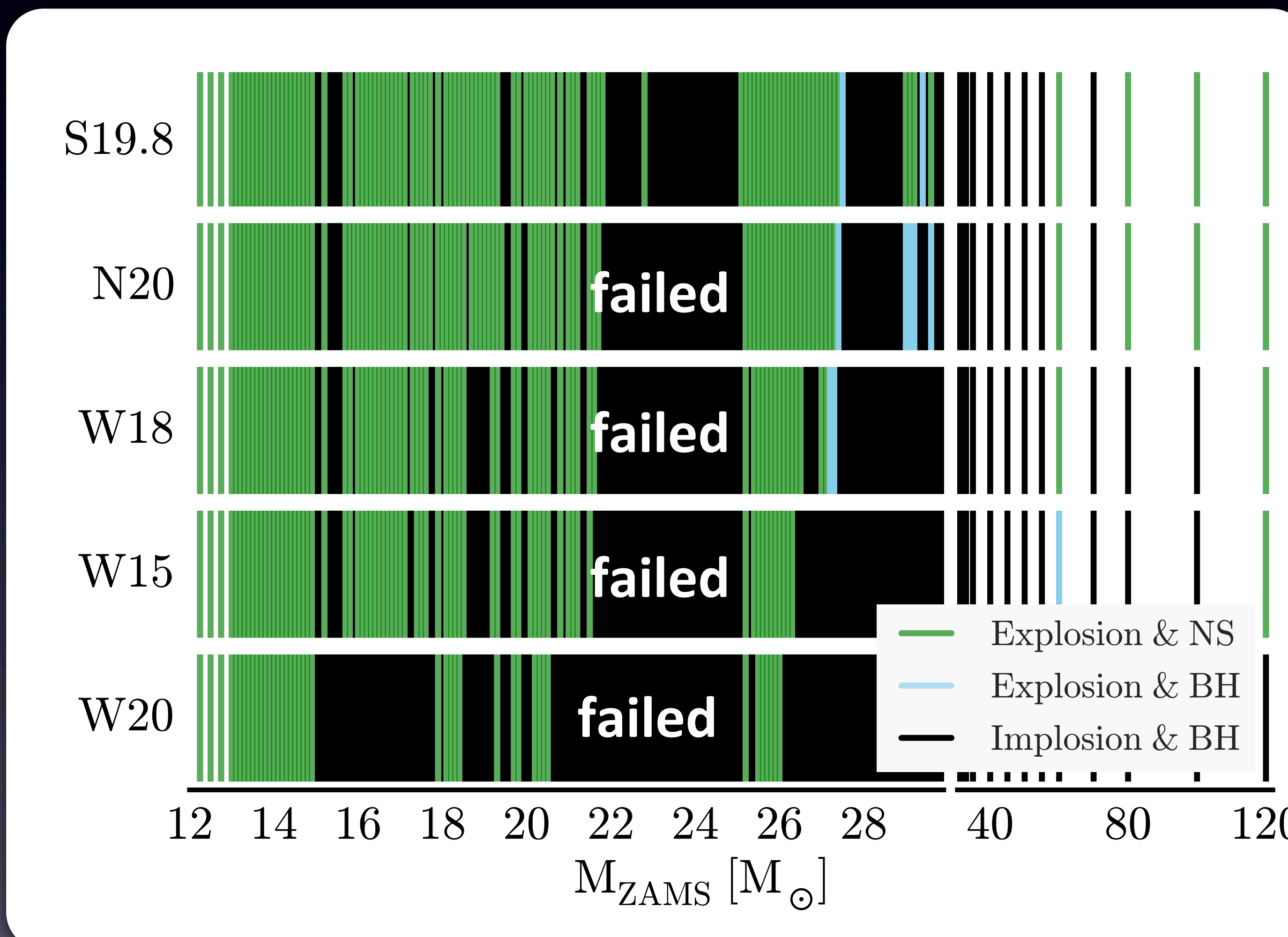
8 Msun? 10 Msun?



Doherty+15

Do all massive stars explode?

Not necessarily



Sukhbold+16

Population and mass function of BHs (=> GWs)

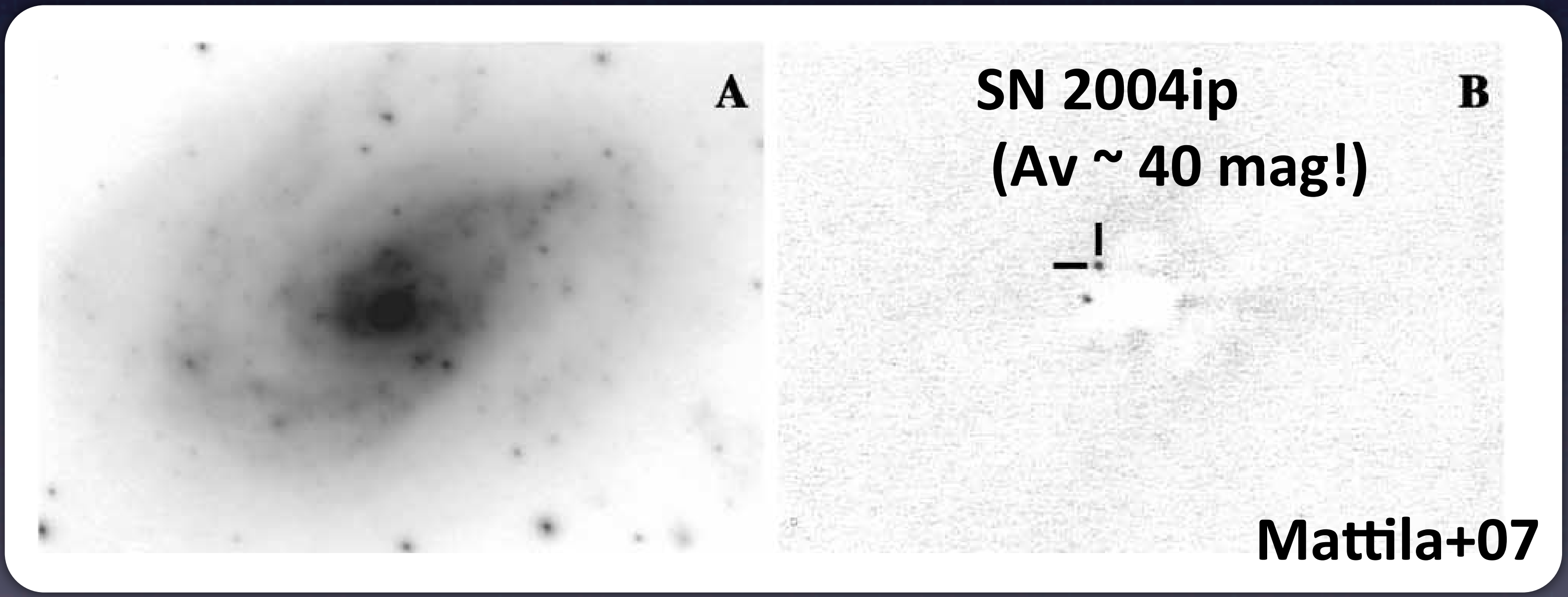
Observational uncertainty: dust extinction

Optical surveys miss ~> 20% of SNe?? Mattila+12

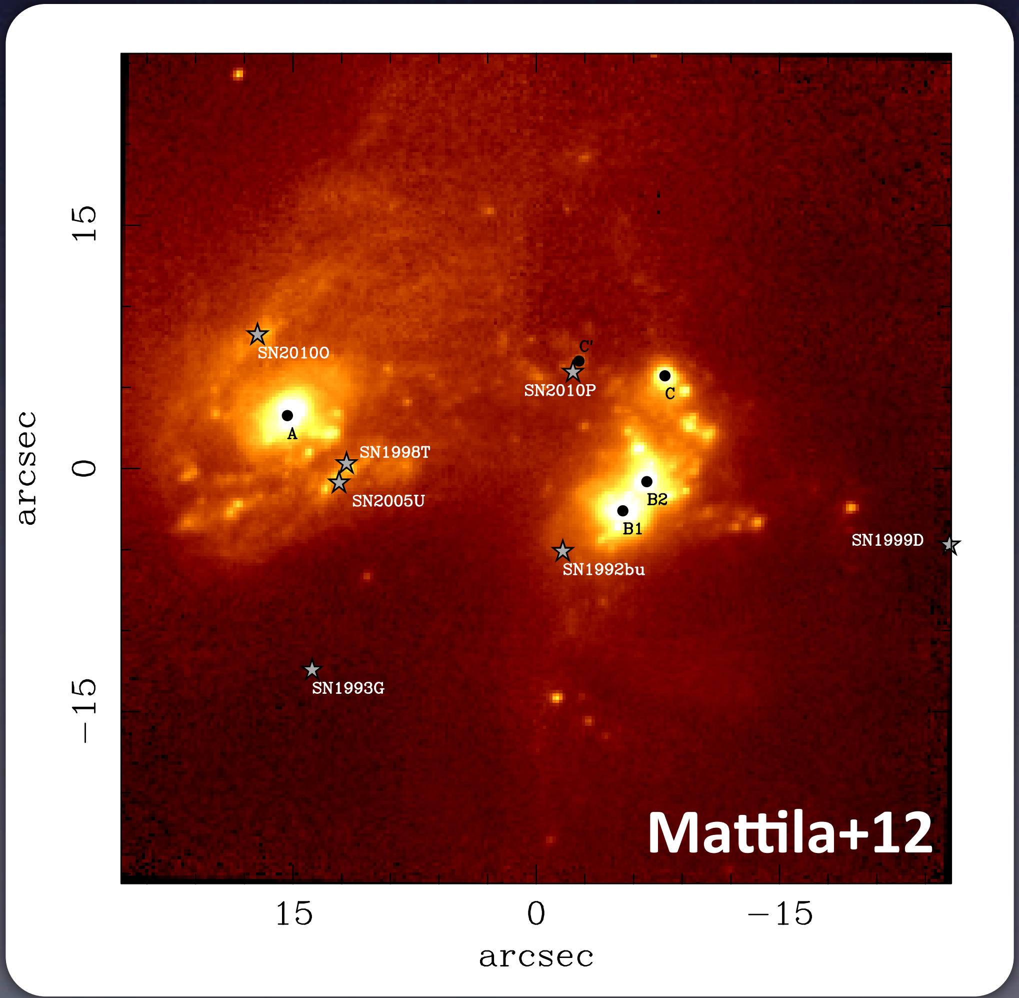
Demand for transient survey in NIR

Too small FOV => only LIRG and ULIRG (w/ AO)

LIRG IRAS 18293-3413
VLT/NACO (K-band)



Arp 299 (~2 SN / yr expected!)
HST/NICMOS (F164N)



ULTIMATE: Wide-field non-targeted transient survey

- “K-only” survey (survey design C)
  - 20 deg^2 over 5 yr, 5 hr (300 min) / FOV, 26.2 mag depth
    => ~23.5 mag x 100 epochs (3 min each)
  - Required time sampling ~ 5 day
    => 100 epochs over ~2 yr baseline
  - ~ 80 supernovae! (< 500 Mpc)
    The first systematic SN rate measurement in NIR

Pros: Good use of wide-field capability
Cons: WFIRST (0.3 deg^2) can do better
(wider surveys with better sampling/control)
* JH & K are not so different in terms of extinction

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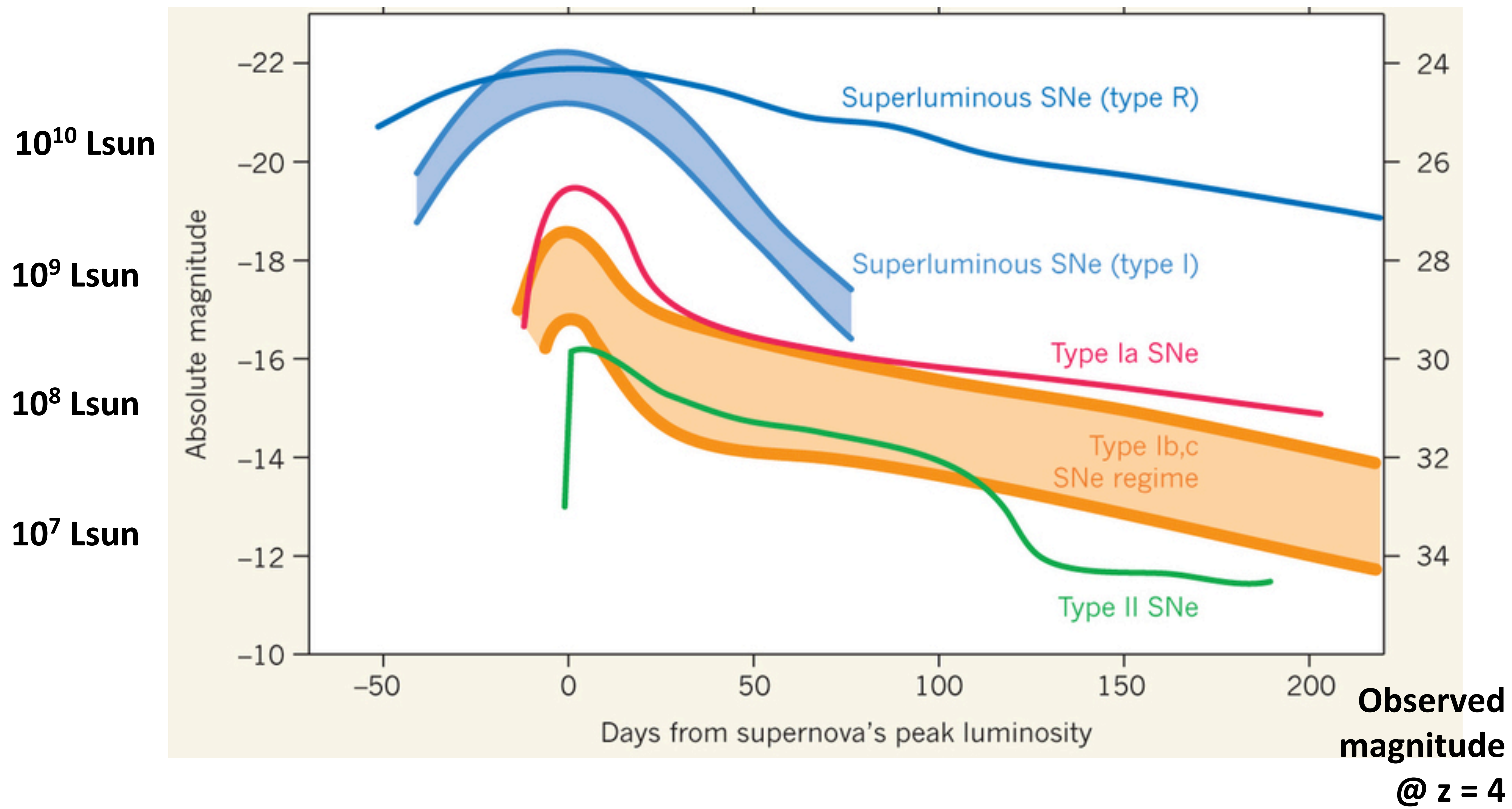
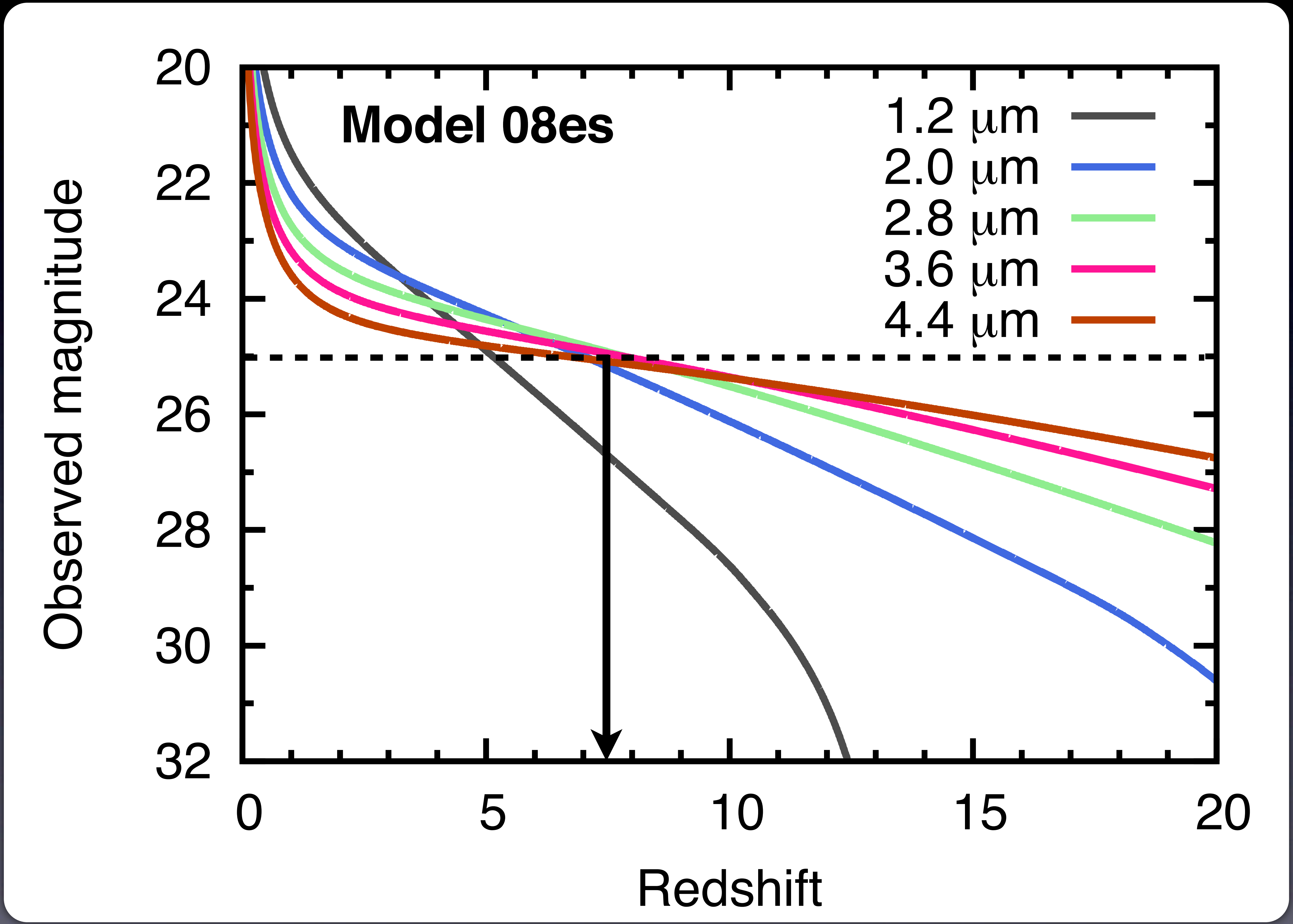
Supernova as tracers of high-z Universe

“Superluminous” SN: L ~ 10^{8-10} Lsun



Smartt 2012

Superluminous SNe are detectable @ z ~ 7



MT, Moriya, Yoshida+13

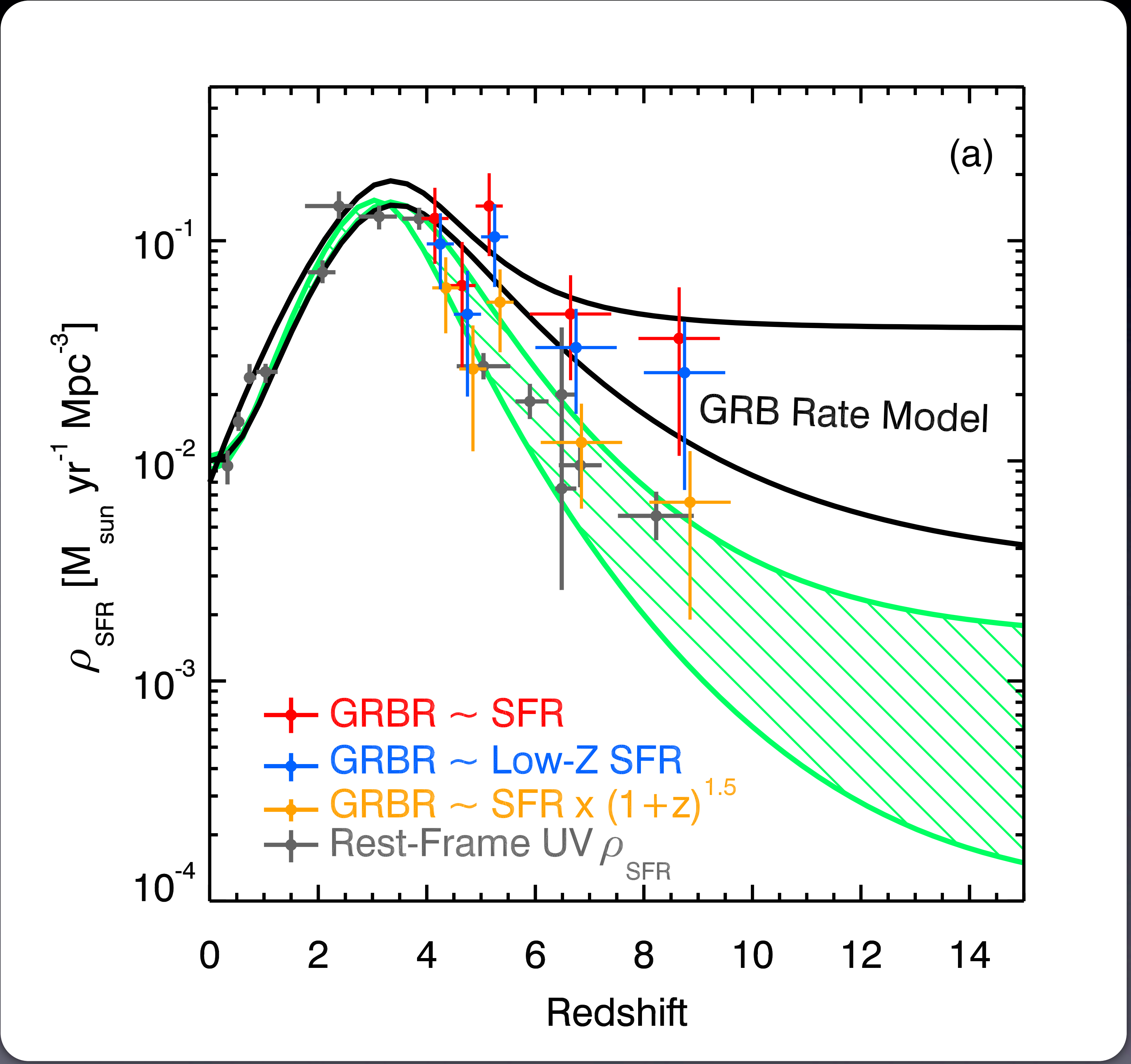
SN rate => # of massive stars
UV or dust emission => Star formation rate

IMF

GRB rate => SFR

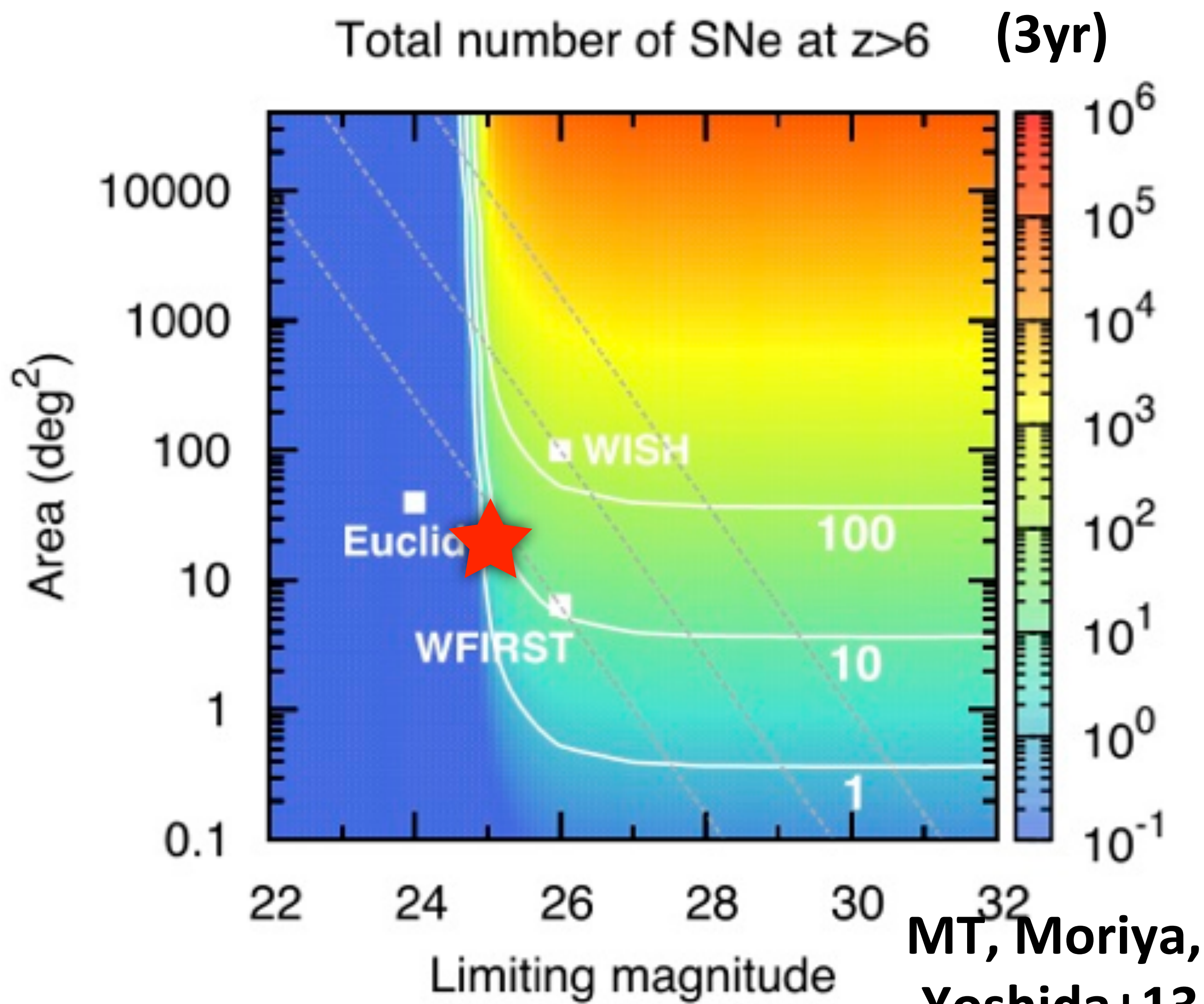
Robertson & Ellis 2012

Caveats:
Metallicity dependence of SN (GRB) progenitor



ULTIMATE: Deep IR transient survey?

- "K-only" survey (C)
  - 20 deg^2 over 5 yr, 26.2 mag depth
    => ~25 mag x 10 epochs over 3 yr
  - ~ 10 SNe @ z>6
    small number, but
    still among best in 2020s



MT, Moriya, Yoshida+13

Pros: K is slightly better than JH (Euclid/WFIRST) for z>7
Cons: WFIRST can go deeper

Coordinated survey with HSC/LSST + WFIRST?

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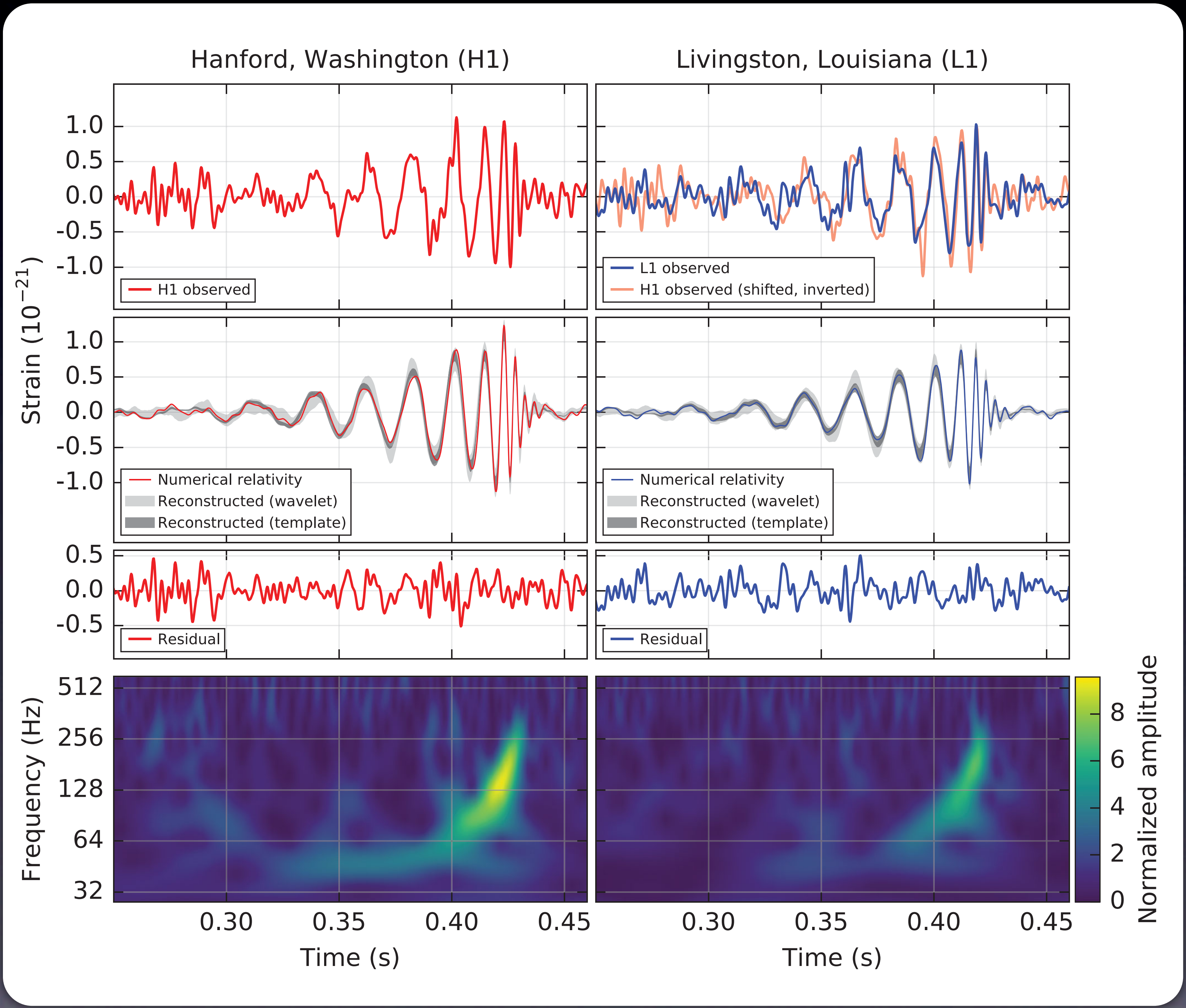
Dawn of GW astronomy



GW 150914
BH-BH merger
(~30 Msun) @ 400 Mpc

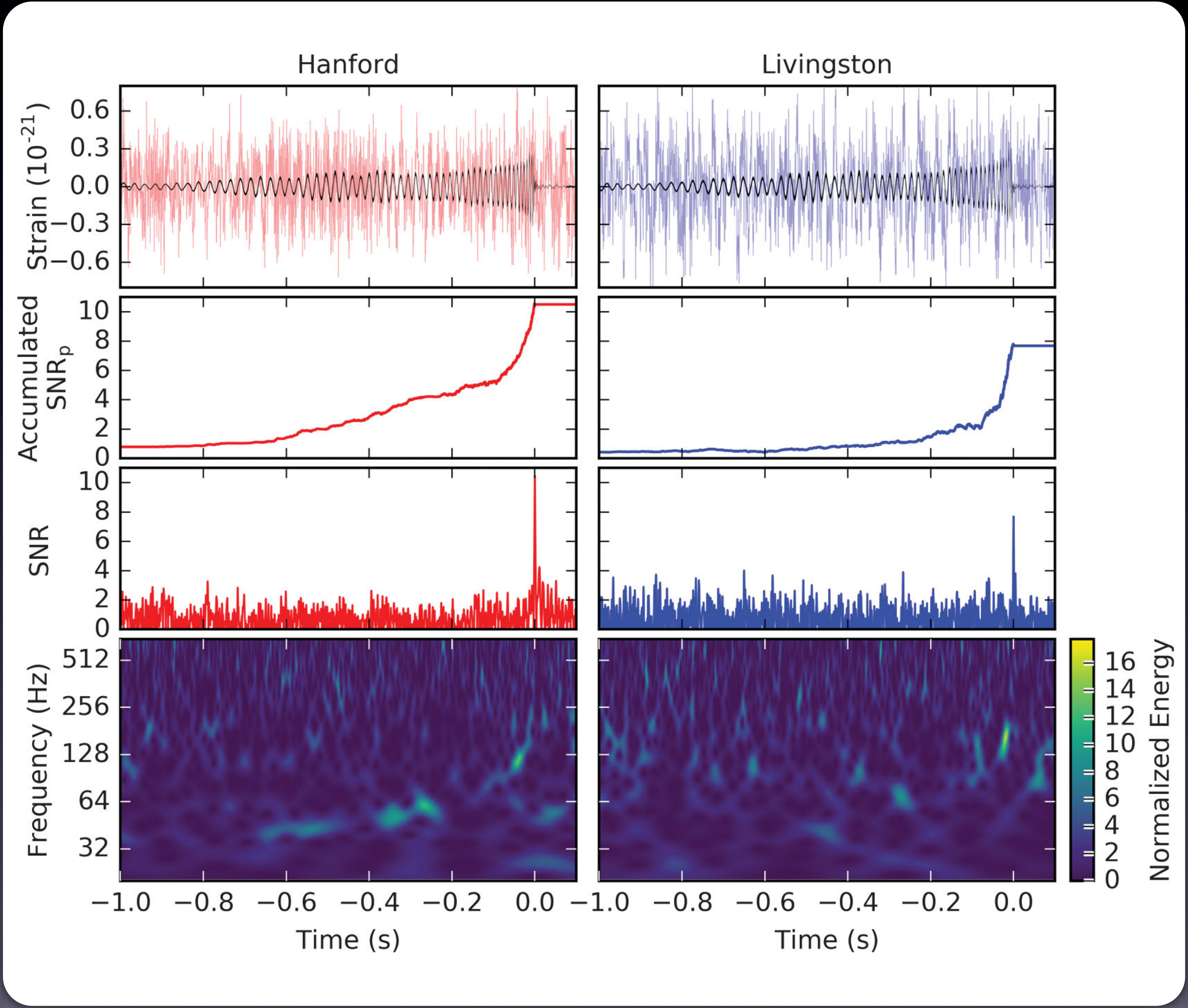
NEXT!
NS-NS merger (~< 200 Mpc)
or BH-NS merger (~< 800 Mpc)

N ~30 (0.3-300) events/ 1 yr

LIGO Scientific Collaboration and Virgo Collaboration, 2016, PRL, 061102

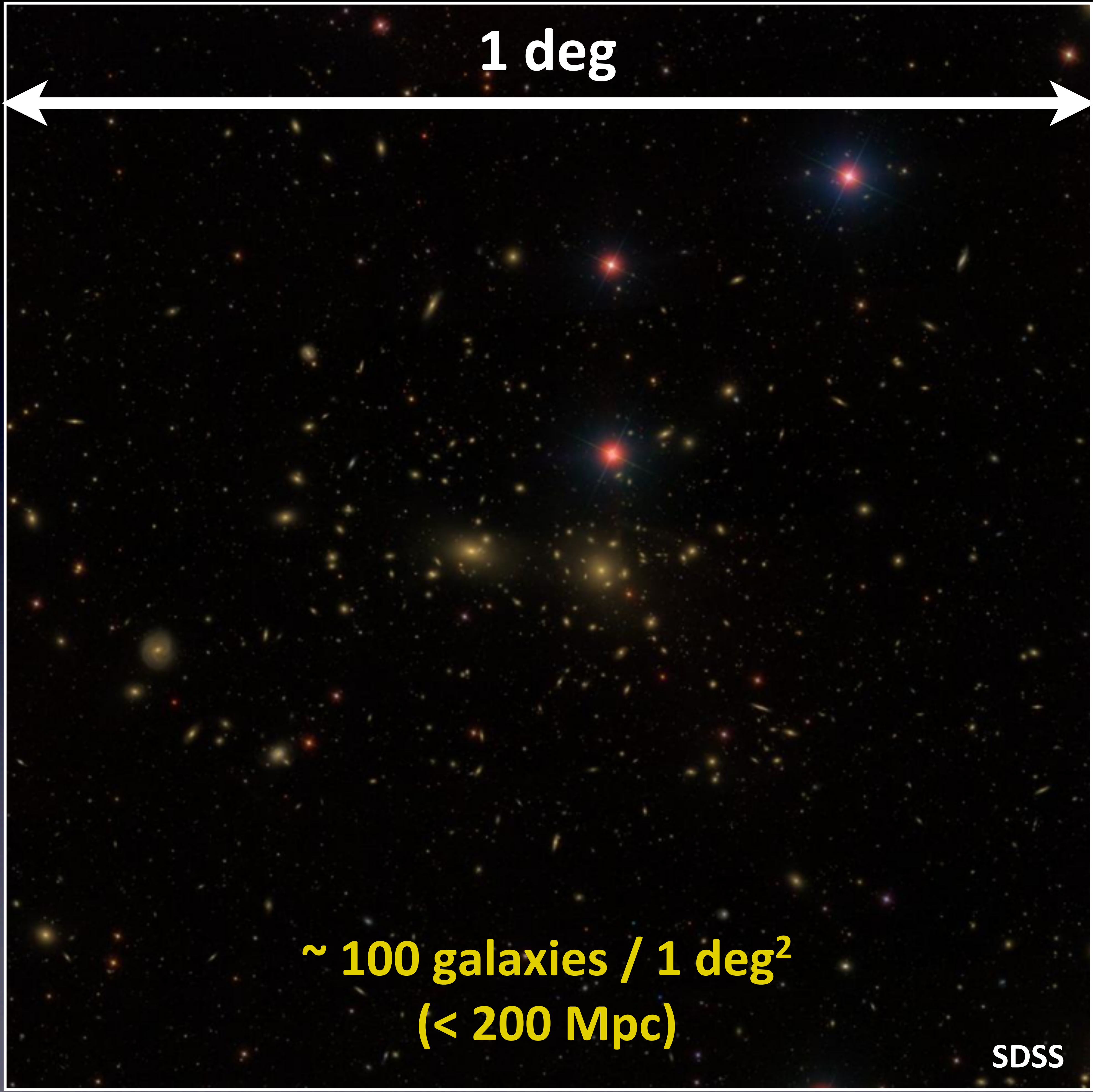
The 2nd is also BH-BH merger (released on this Wed)

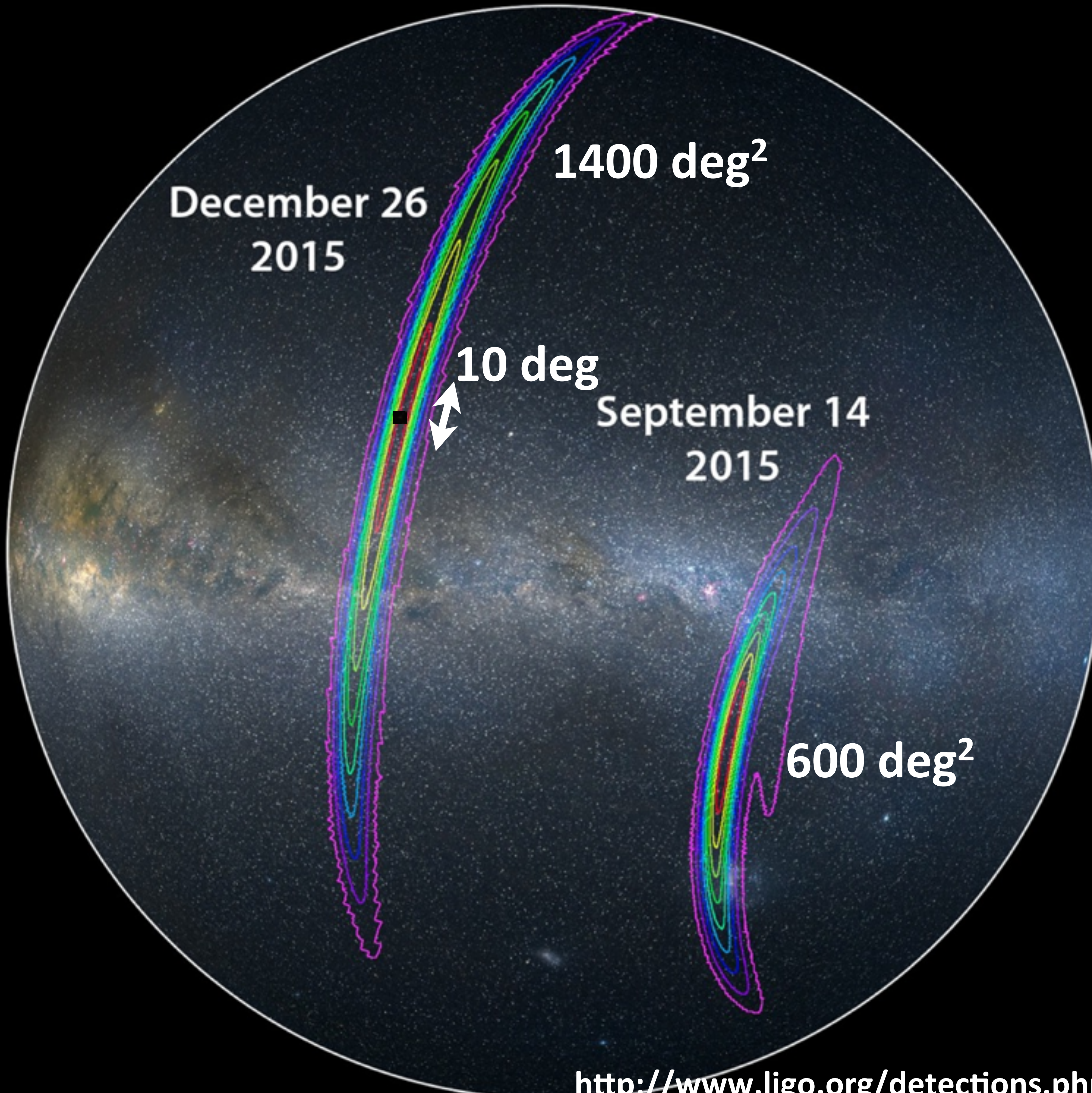
R. Flaminio's talk yesterday



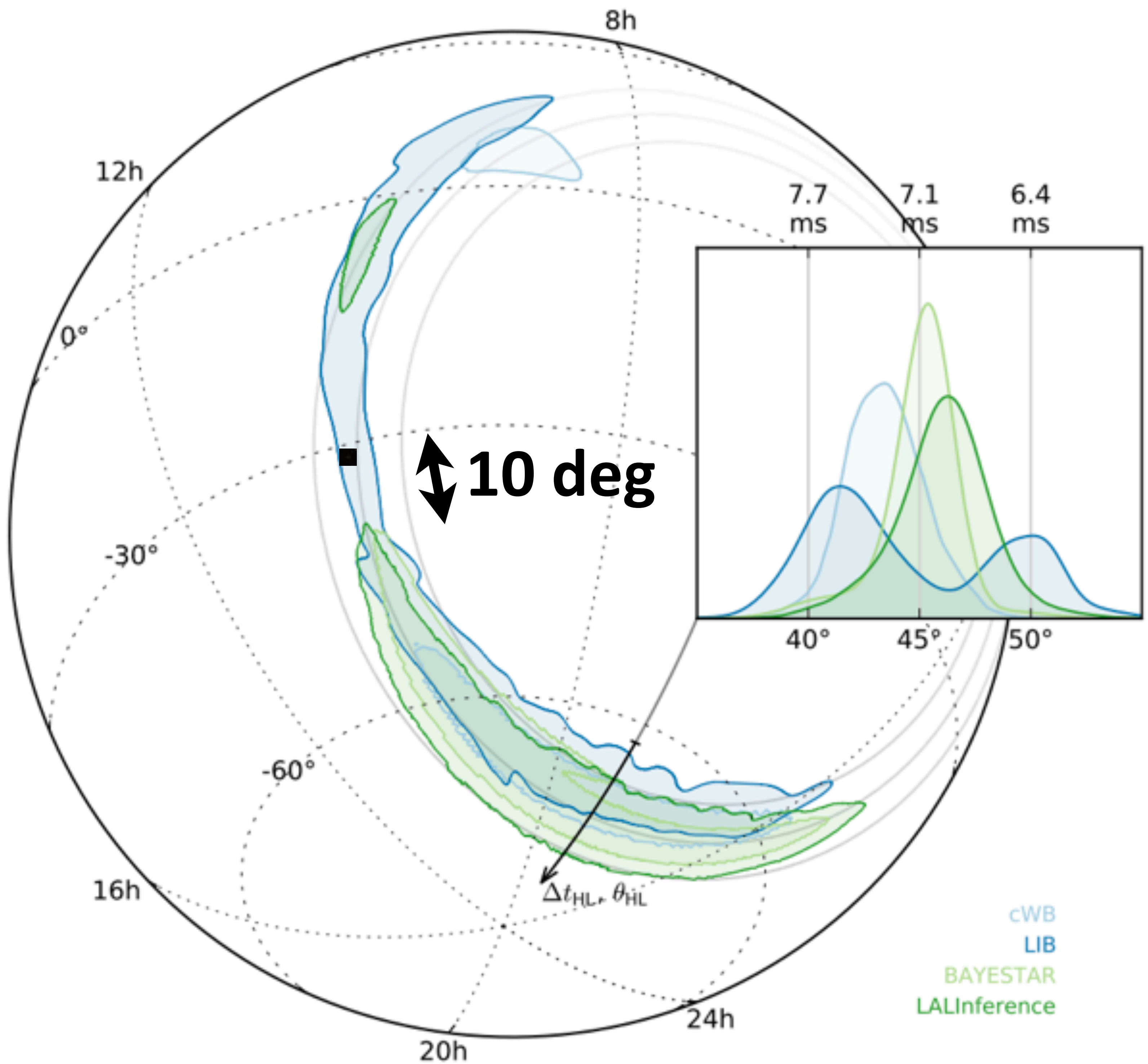
GW 151226
BH-BH merger
(~14+8 Msun) @ 440 Mpc

LIGO Scientific Collaboration and Virgo Collaboration, 2016, PRL, 241103


1 deg
~ 100 galaxies / 1 deg²
(< 200 Mpc)
SDSS



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



Abbott et al. 2016, ApJ, in press, arXiv:1602.08492

Localization

~ 600 deg^2 (GW150914)

~ 1400 deg2 (GW151226)

(~< 10 deg^2 with Advanced Virgo and KAGRA)

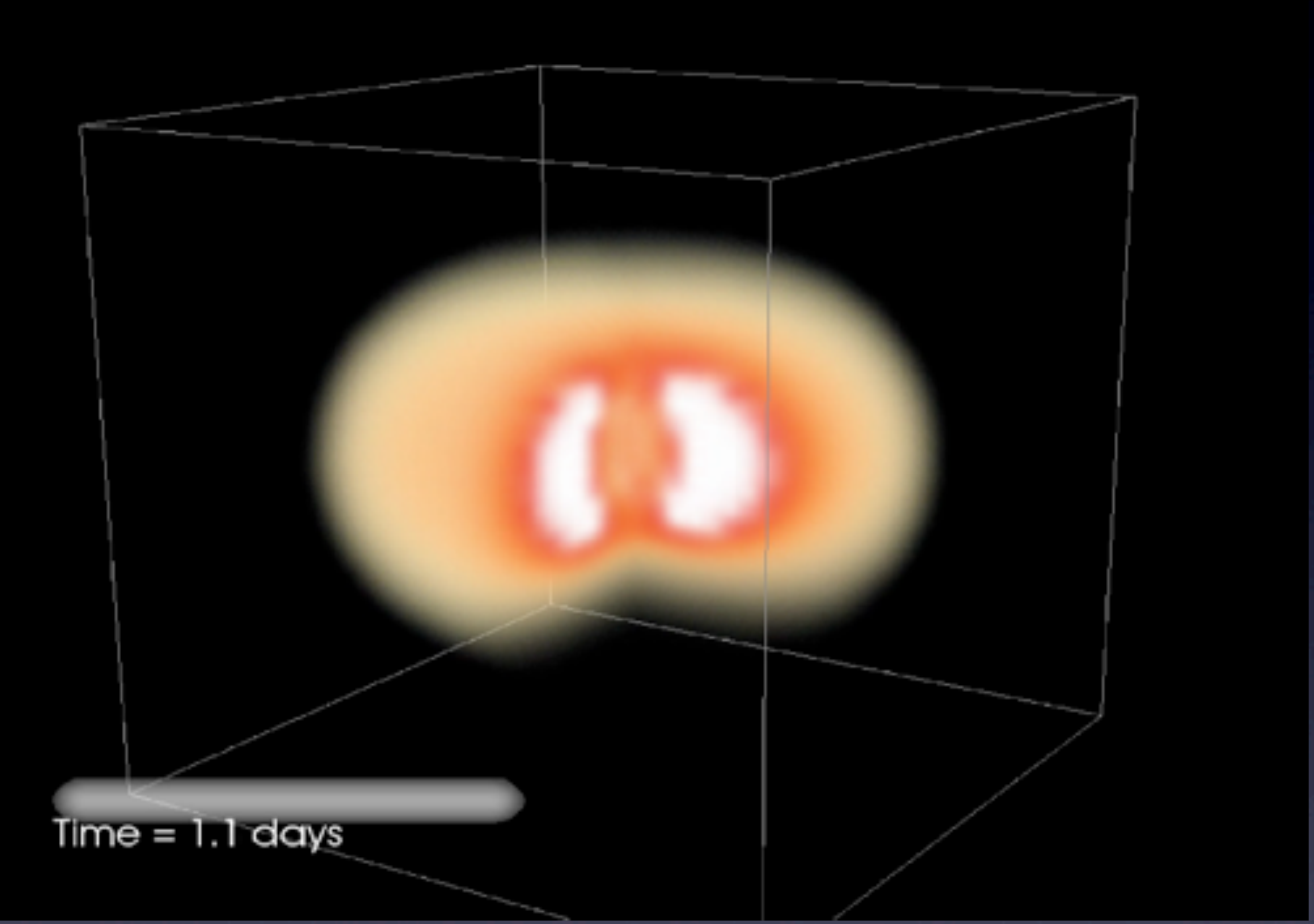
Detection of electromagnetic (EM) counterparts is essential

- Redshift (distance)
- Host galaxy
- Local environment

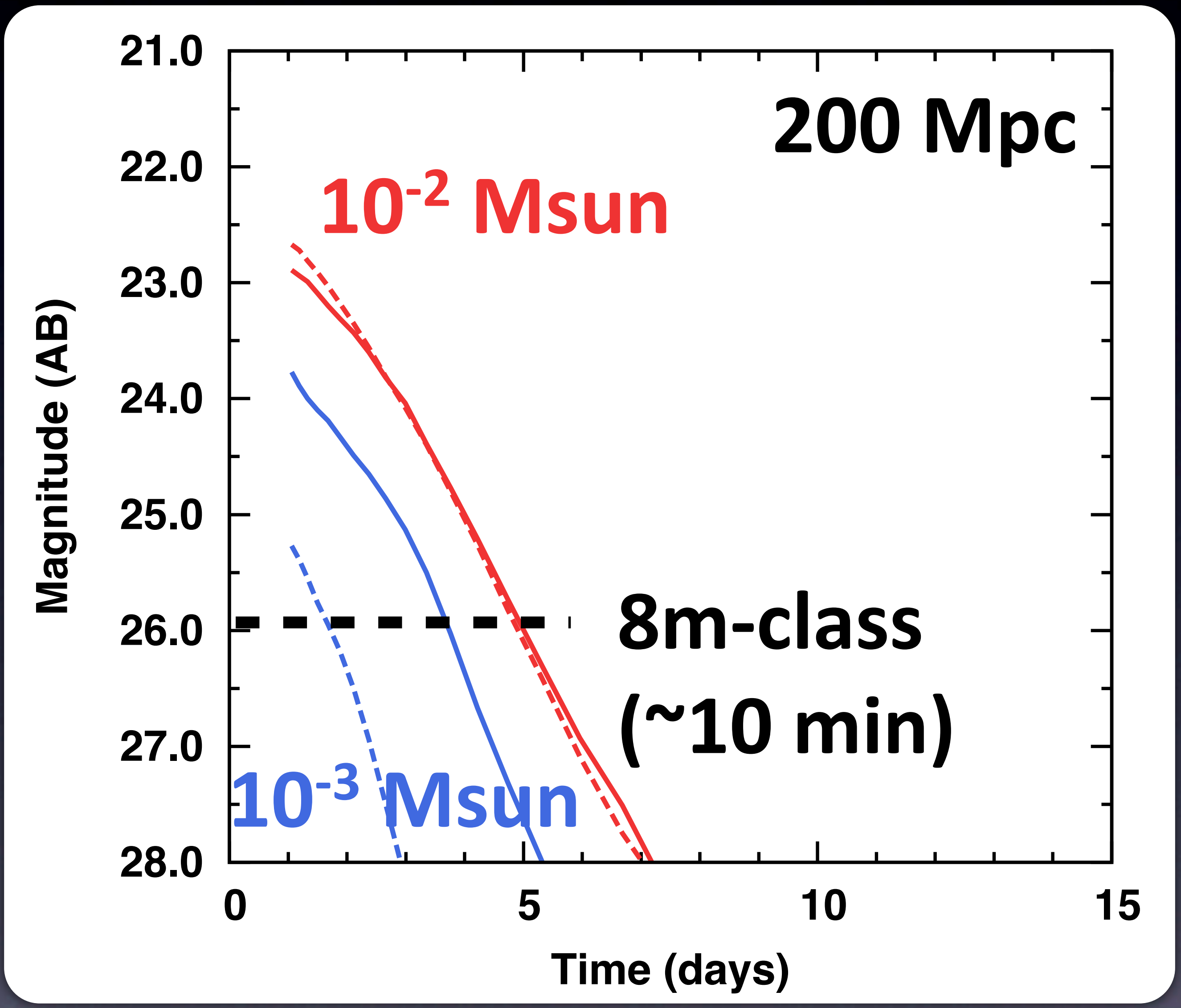
- No plausible EM counterpart was detected for GW150914 (neither for GW151226 so far)
- EM emission from BH-BH merger??

Electromagnetic signature from NS mergers (powered by radioactive r-process nuclei)

Optical (i)



MT & Hotokezaka 13, MT+14, MT 16



Subaru/HSC for GW151226 (50 deg^2)
(J-GEM, Yoshida et al. 2016, GCN 18840)

Brightness of the emission => Ejected mass of r-process elements

NS merger as a possible origin of r-process elements

Event rate ⇐ GW

R_{NSM} ~ 100 event/Myr/Galaxy
= 10^{-4} event/yr/Galaxy

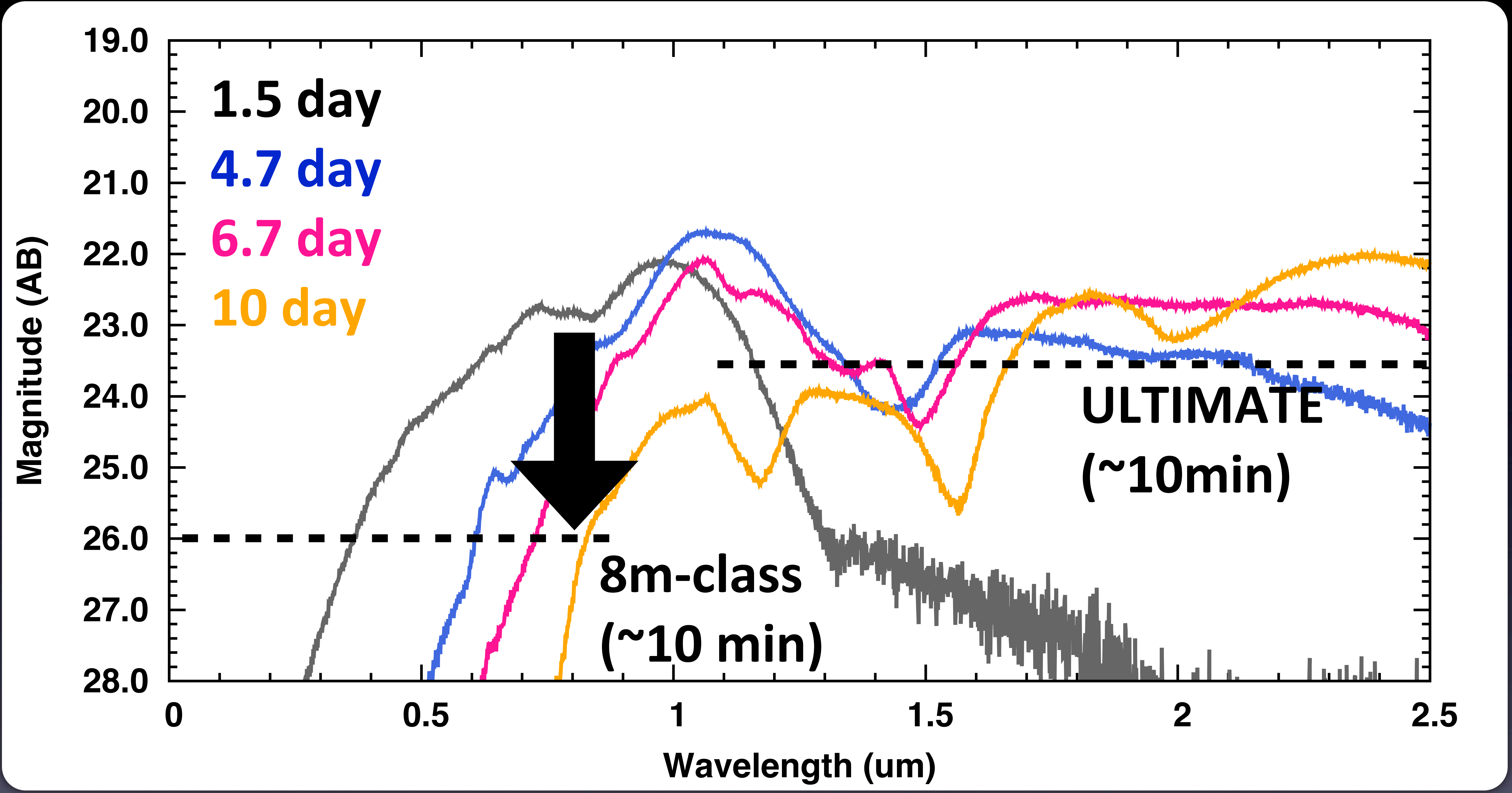
⇒ NS-NS merger rate
Within 200 Mpc
~ 30 GW events/yr
(~0.3-300)

Ejection per event ⇐ EM

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

M(Galaxy, r-process) ~ M_{ej}(r) x (R_{NSM} x t_G)
~ 10^{-2} x 10^{-4} x 10^{10} ~ 10^4 Msun

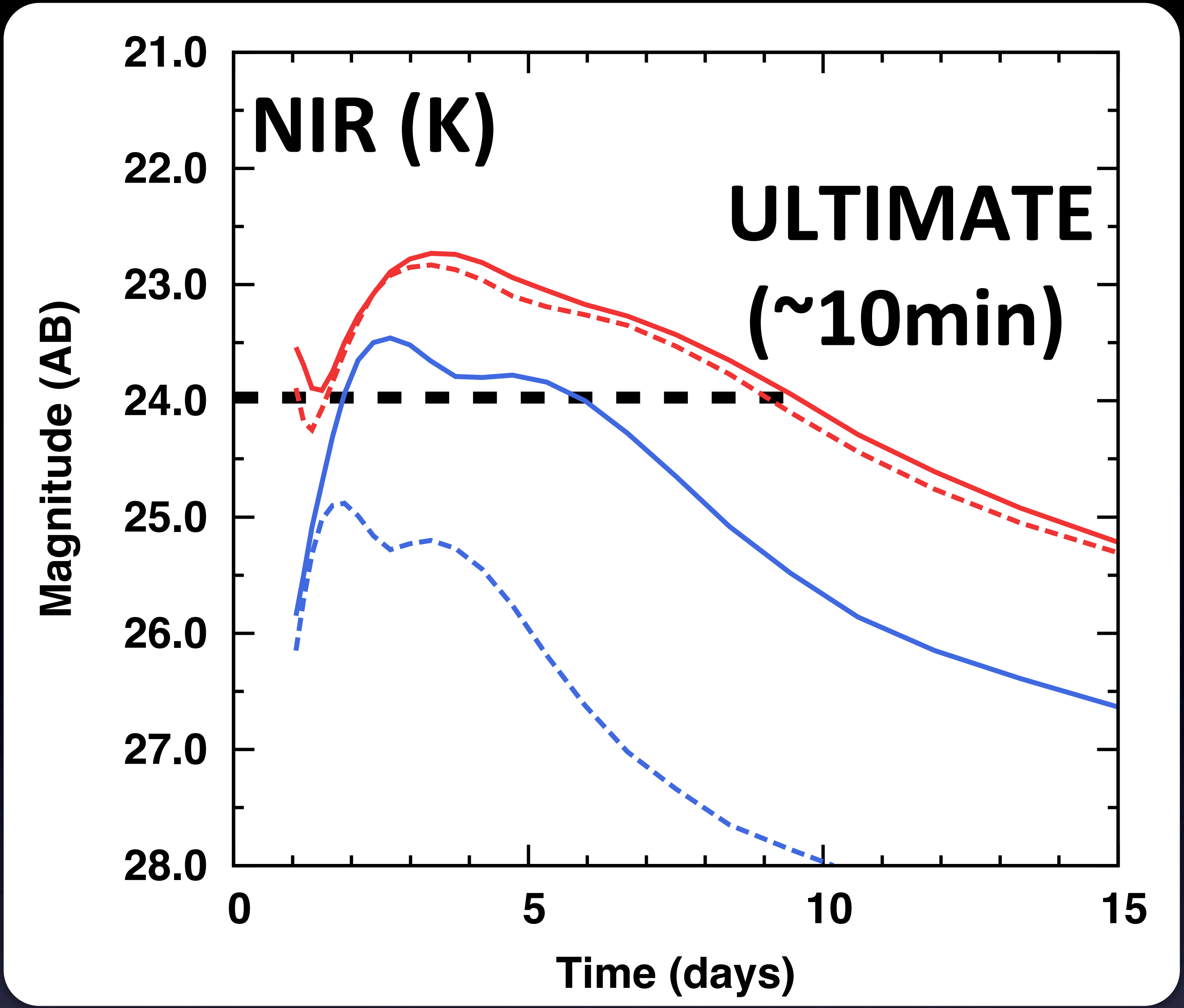
Importance of NIR: brighter/longer timescale



- L_{bol} ~ L_{IR} => Mass of ejected material
- Smoking gun: red and featureless spectrum
  (higher expansion velocity than supernovae)

ULTIMATE:
IR survey for GW sources

- Survey for ~10 deg^2
  - 24 mag depths (10 min)
  - 150 pointing (FOV 0.07 deg2)
    => 25 hr ~ 2.5 nights
- Spectroscopy w/ AO
  (multiplicity is not important)



Pros: Great use of wide-field capability
(would be great if even wider)

Cons: WFIRST can also do this
but ground telescopes are usually more flexible

Wider wavelength coverage is critical
to measure the total luminosity

Replies to the questions

1. Key science in the post-JWST/WFIRST era
   - Identification of GW sources (if not realized by 2020s) and mass measurement of r-process elements
2. 1st priority instrument
   - Wide-field imager for time-domain science
3. Science w/ GLAO + MOIRCS
   - ~1/7 of what I presented (proportional to FOV)
4. Which survey design
   - “K-only” survey (C) separated into many epochs
5. Options for wide-field imager
   - Wider field of view > pixel scale (in general)

Summary

- Transient science is blooming NOW!
  - PTF, PS1, DECam, HSC, ZTF, LSST, and WFIRST...
- Nearby supernovae
  - Do all massive stars explode?
  - IR blank-field transient survey
    ~ "K-band only" survey split into >50 epochs
- High-redshift supernovae
  - SN counting => IMF at high-z Universe
  - IR deep transient survey
    ~ "K-band only" survey split in to ~10 epochs
- Gravitational wave sources
  - NS merger as possible origin of r-process elements
  - ToO transient surveys & spectroscopy