Electromagnetic counterparts of neutron star mergers and the origin of heavy elements

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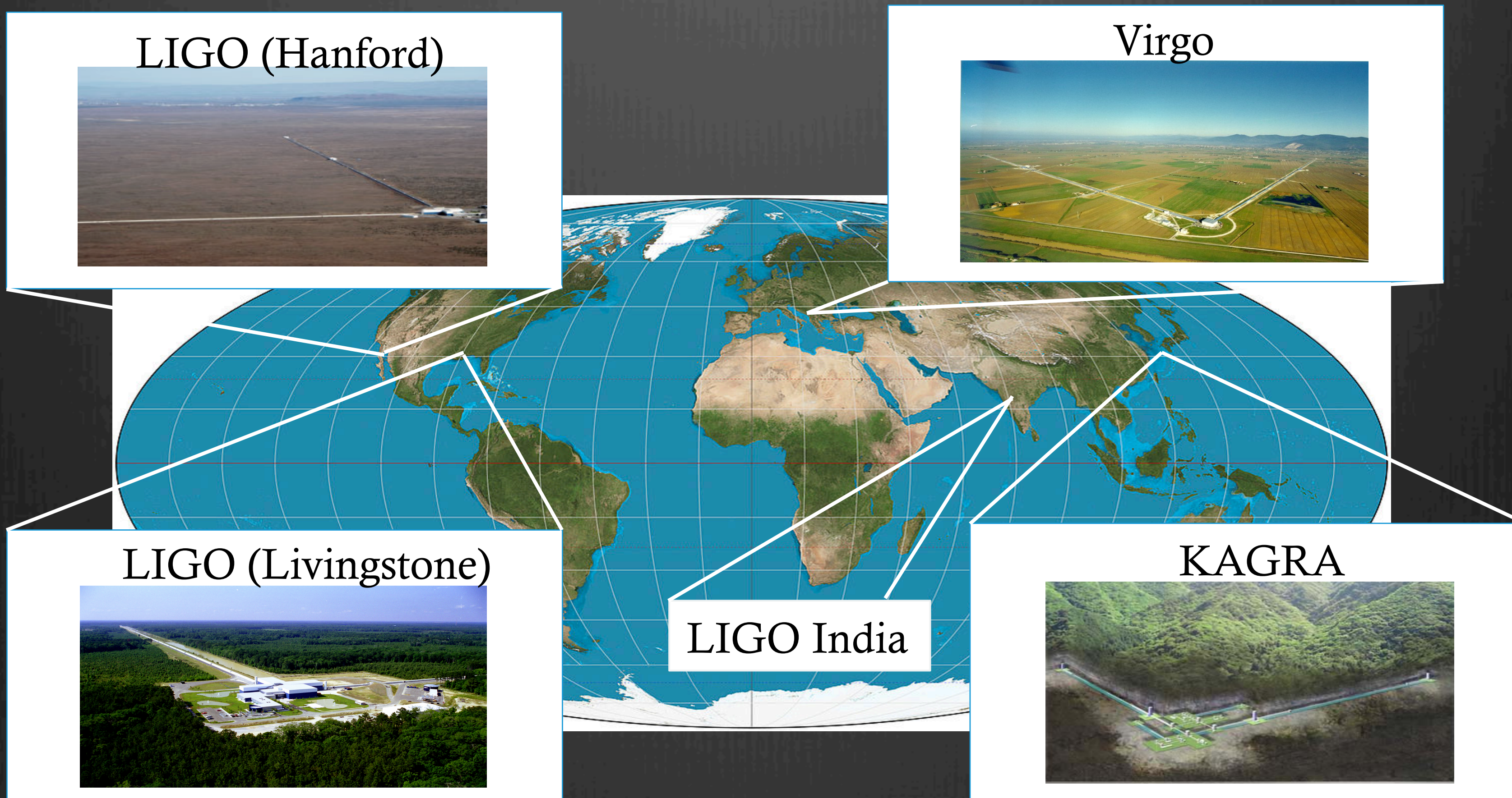
Advanced gravitational-wave detector network



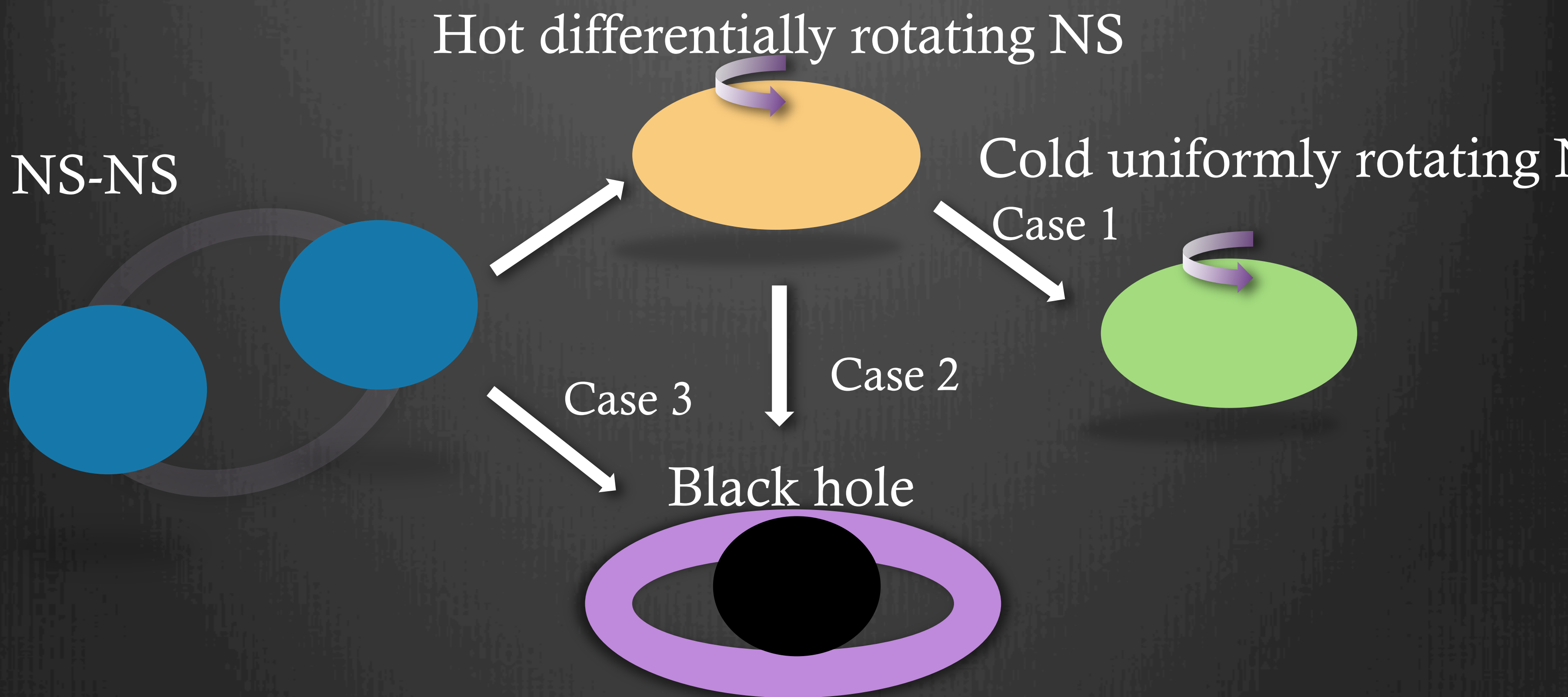
Compact binary Astrophysics

- **Variation in Neutron Star Mergers**

- **EM transients from Neutron Star mergers**
  - ✓ Mass ejection from a merger
  - ✓ What we can learn from macronova (kilonova) candidates

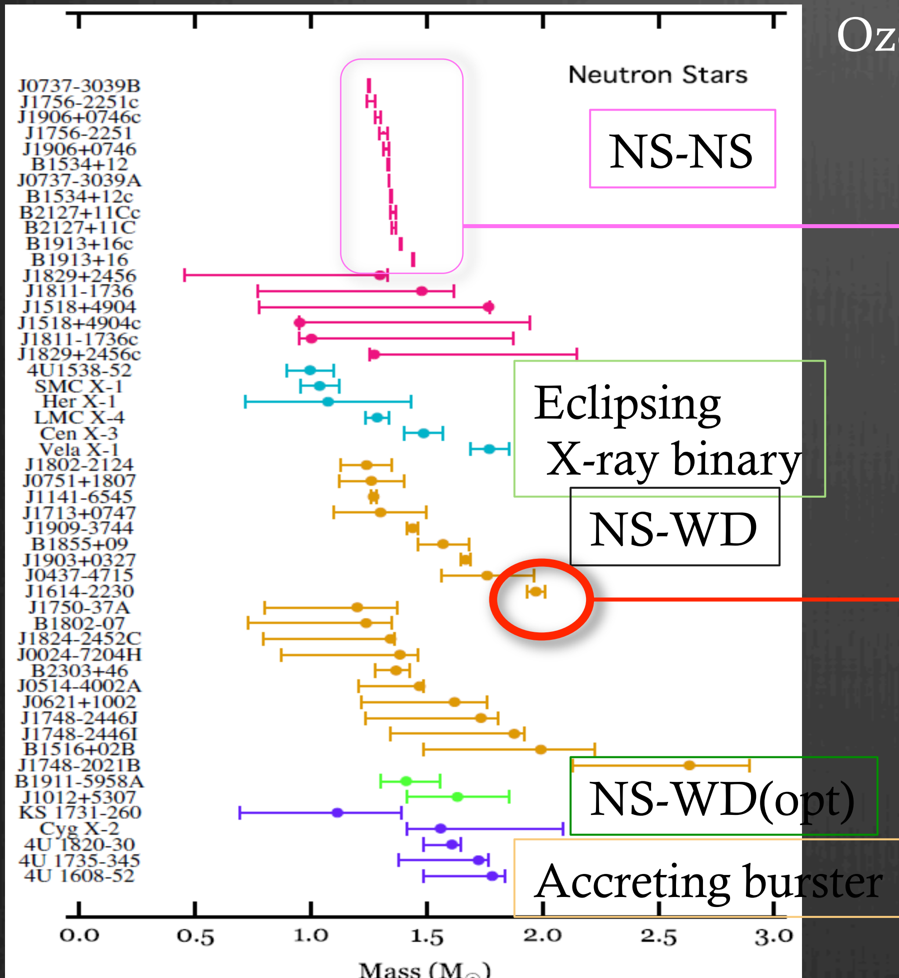
- **^{244}Pu and the origin of *r*-process elements**

Evolutionary path of NS-NS merger



Case 1 : Massive Neutron Star formation
Case 2 : Hypermassive Neutron Star formation
Case 3 : Prompt BH formation

Neutron Star Mass Observations



Ozel et al (2012)

Mass of Double NS system

$$1.33 \pm 0.05 M_{sun}$$

Clustering

PSR J1614+2230 (heavy pulsar)

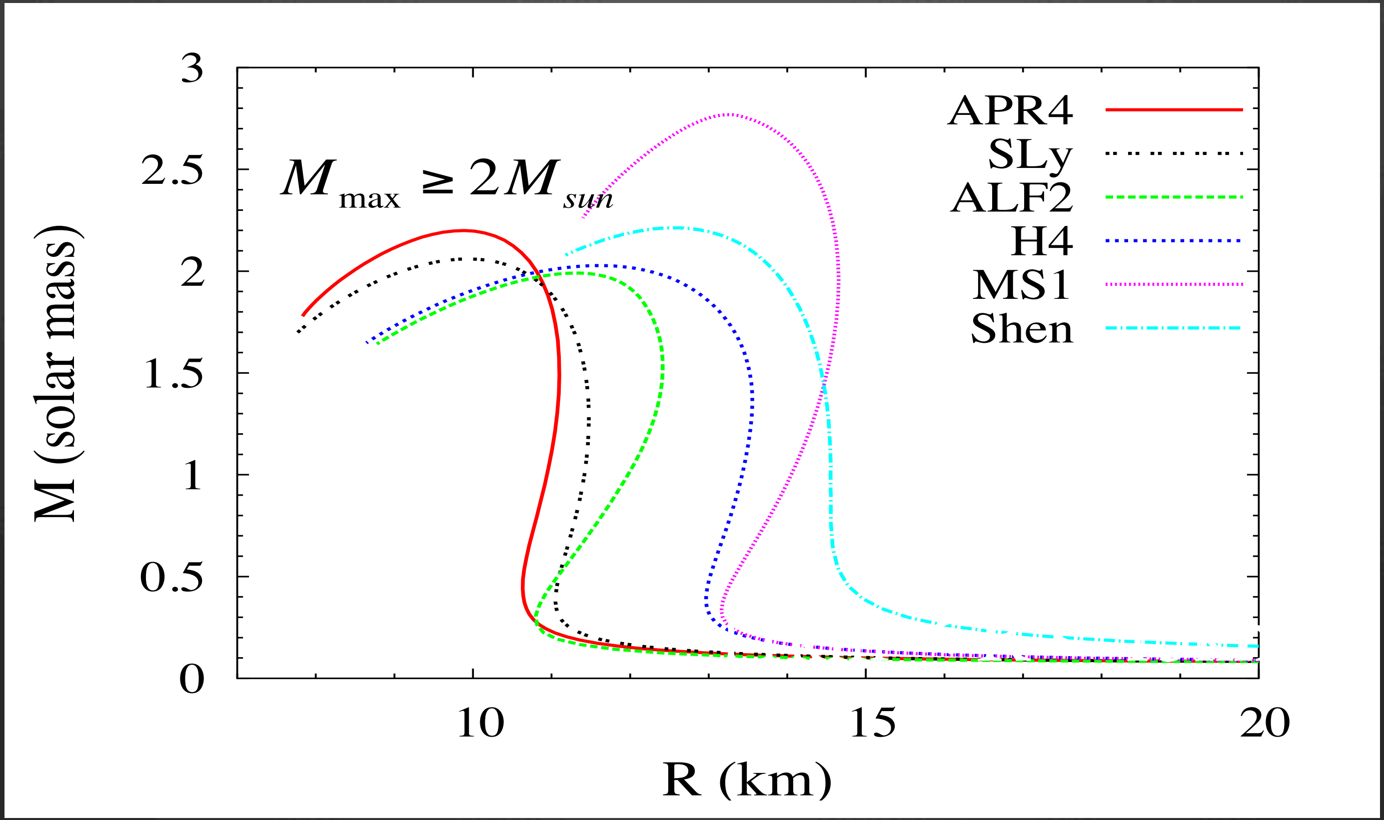
$$M_{NS} = 1.97 \pm 0.04 M_{sun}$$

Strong constraint on NS EOS.

Demorest et al (2010)

See also Antoniadis et al. (2013)

Systematic study: Dependence of NS-NS merger on NS EOS



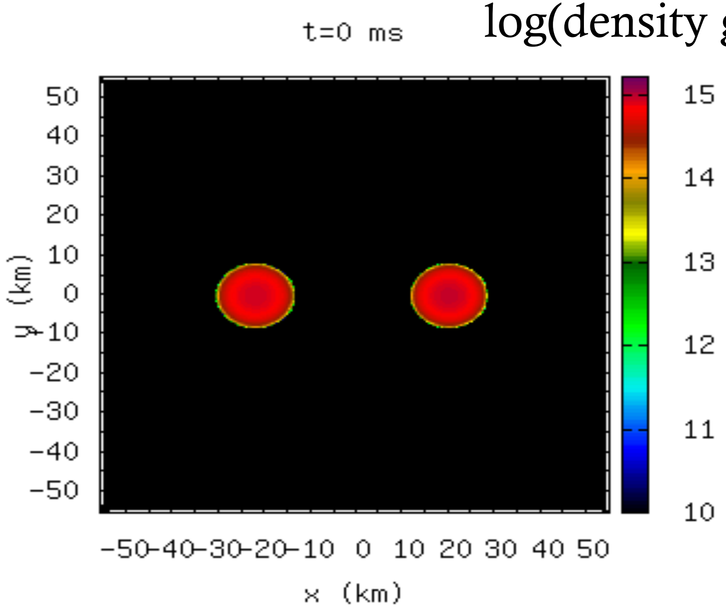
◆ Binary Mass

✓ Total Mass : 2.6〜2.9 Msun

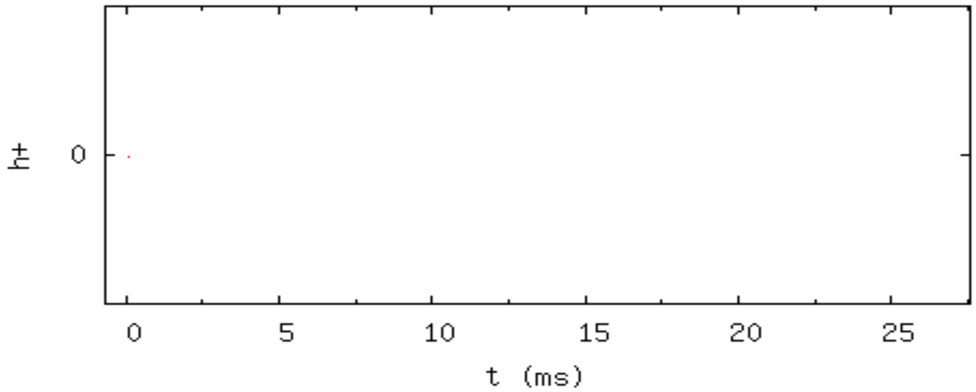
✓ Mass ratio : 0.8〜1.0

Numerical Relativity Simulation solving Einstein equation with fluid

log(density g/cc)

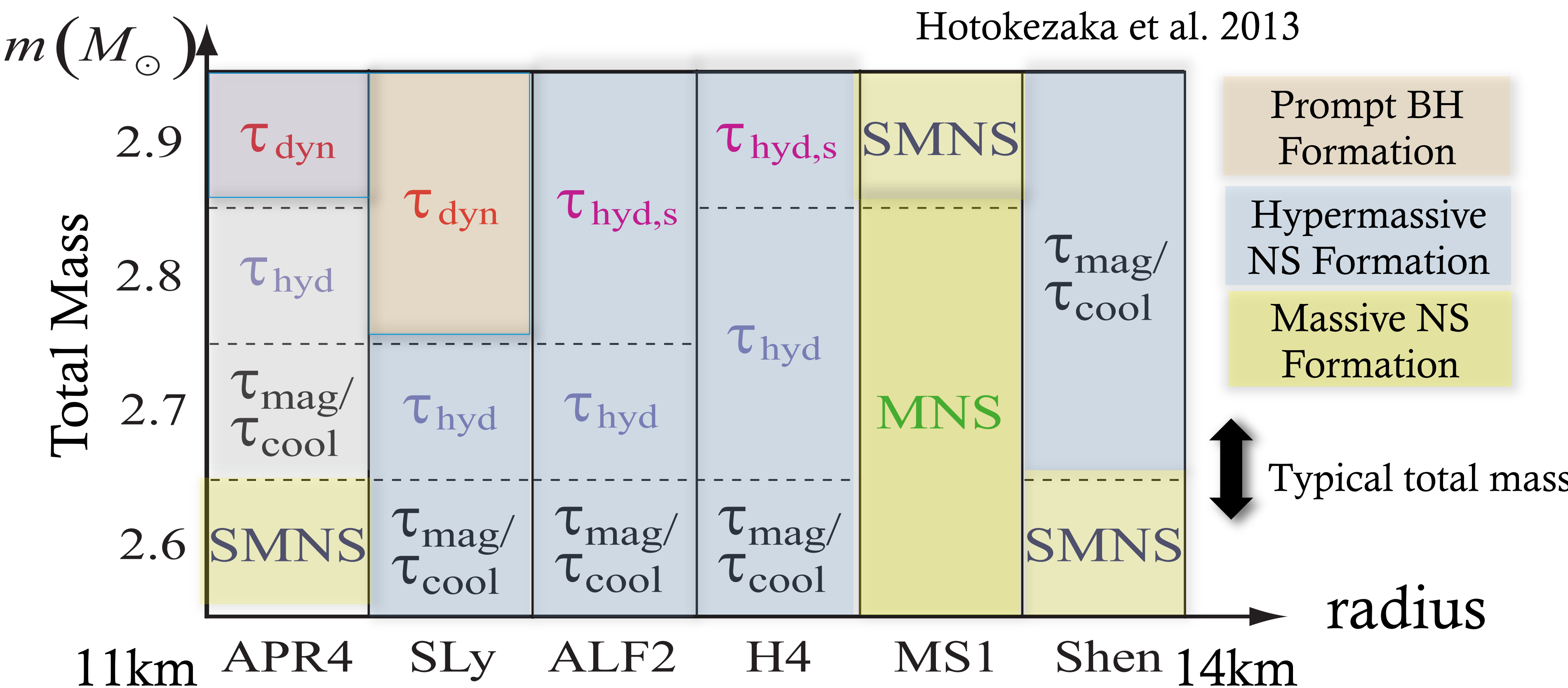


$M_1 = 1.4 M_{sun}$ $M_2 = 1.3 M_{sun}$



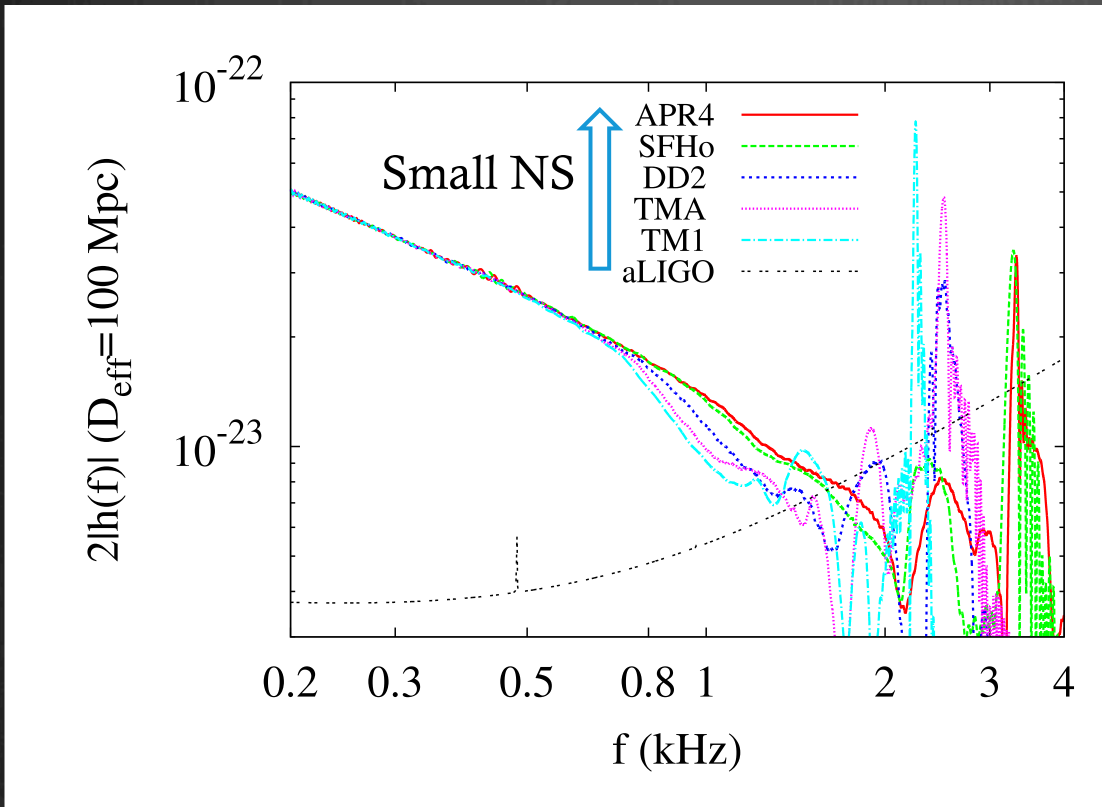
Hotokezaka et al. (2013)

First remnant of NS-NS mergers



A massive neutron star is likely to be formed after a merger for a NS-NS merger with typical total mass.

EOBNR hybrid waveforms



KH et al in prep

A numerical waveform
Is hybridized with an EOB waveform in the region from the first a few to 8 GW cycles.

We will probably be able to distinguish a neutron star with a radius of 13km and 14km for an event with SNR~17 (200Mpc).

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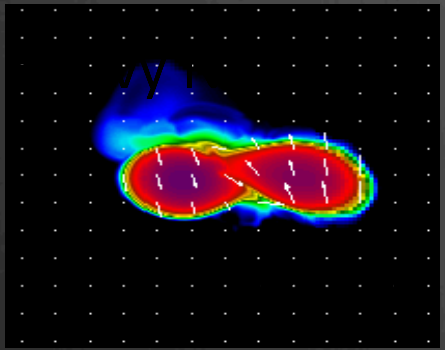
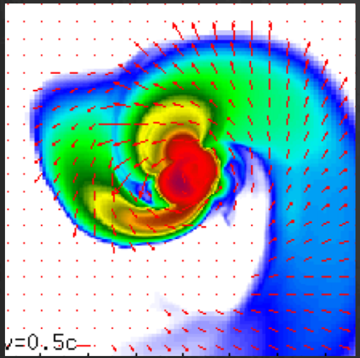
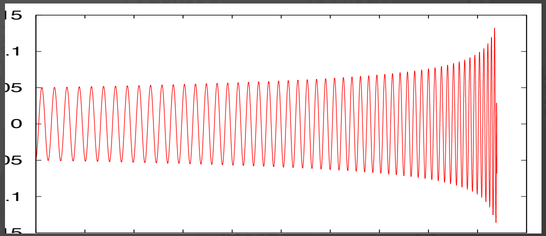
Neutron Star Merger





1. Gravitational waves
   LIGO's main target



2. Relativistic jet => short GRB

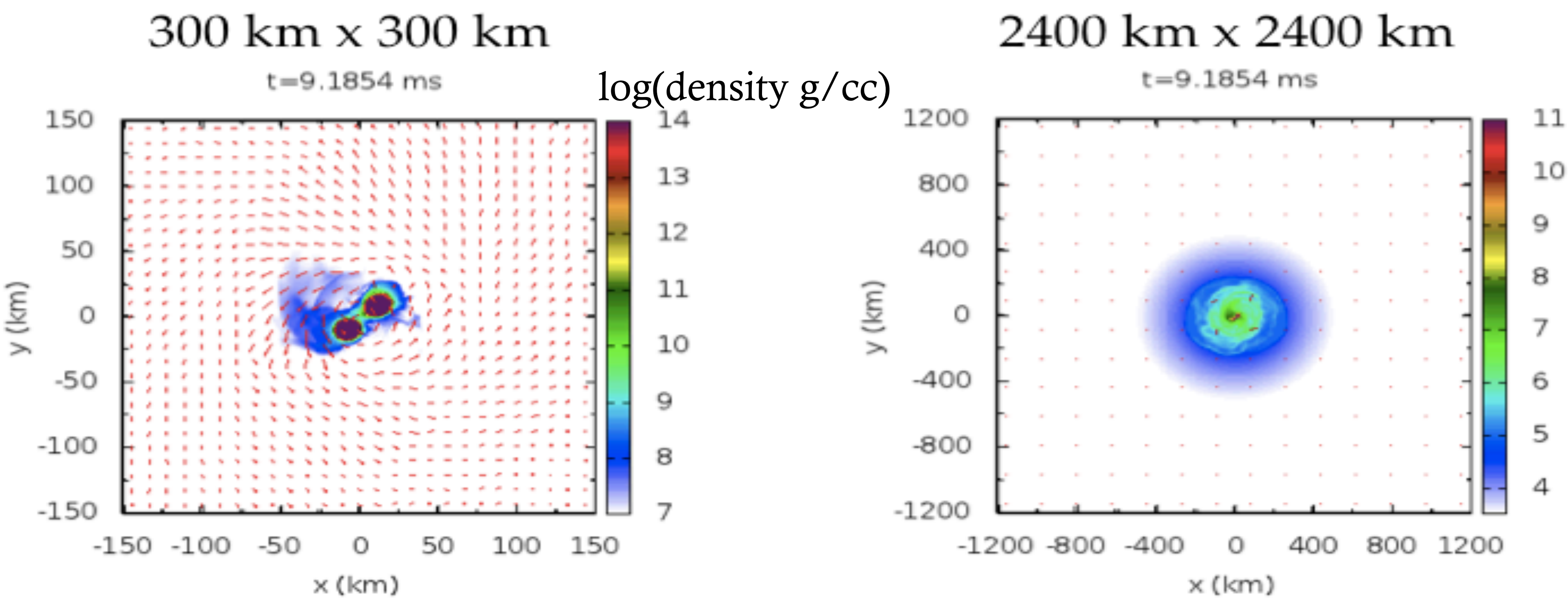
3. Mass ejection.
   (a) Isotropic electromagnetic signal
       EM counterpart of GWs

   (b) r-process nucleosynthesis
       The origin of heavy elements?

Mass ejection at merger

Model : 1.2Msun – 1.5Msun, APR4

Hotokezaka et al 2013

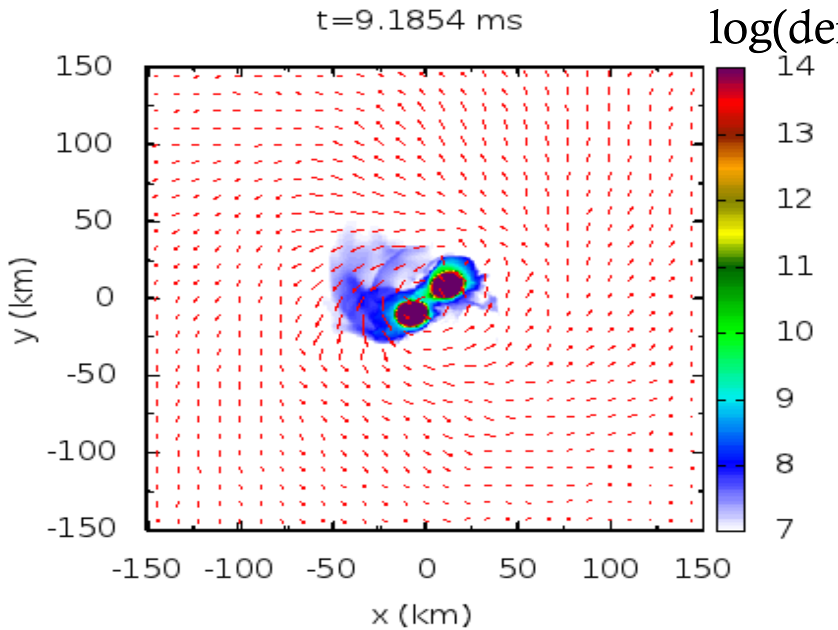


Mass ejection at merger

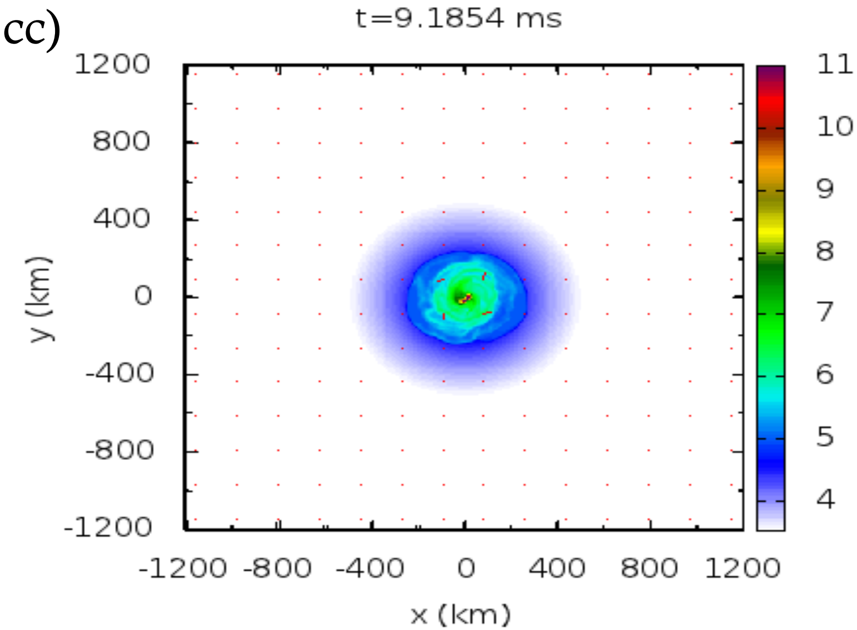
Model : 1.2Msun – 1.5Msun, APR4

300 km x 300 km

log(density g/cc)



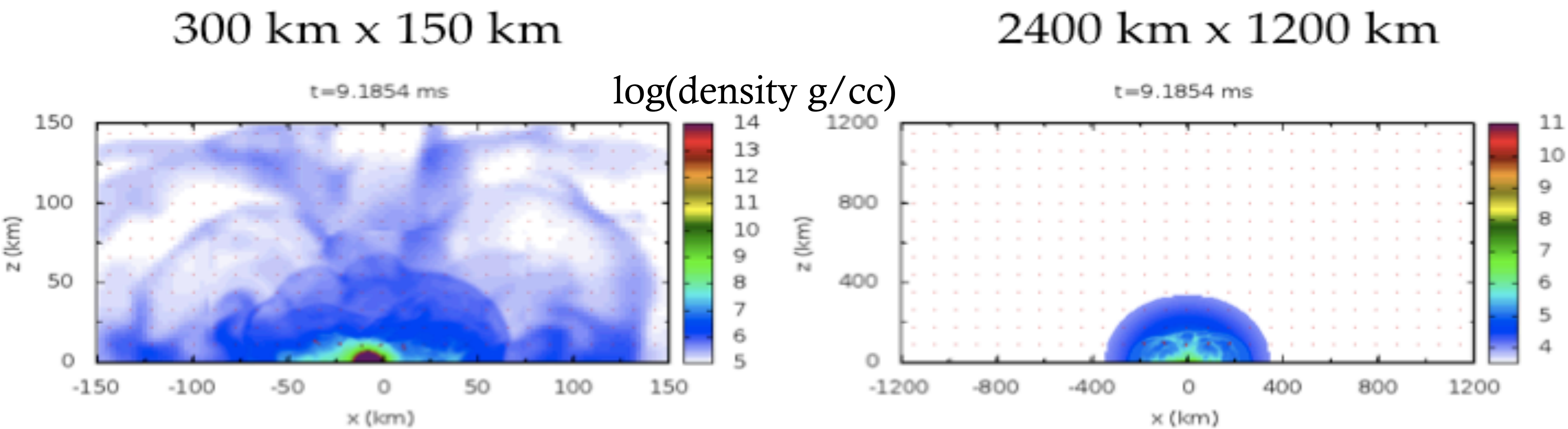
2400 km x 2400 km



Mass ejection : Mej ~ 0.01Msun, v ~ 0.2c

Mass ejection on the Meridional plane
(x-z plane)

Model : 1.2Msun – 1.5Msun, APR4



Mass ejection on the Meridional plane

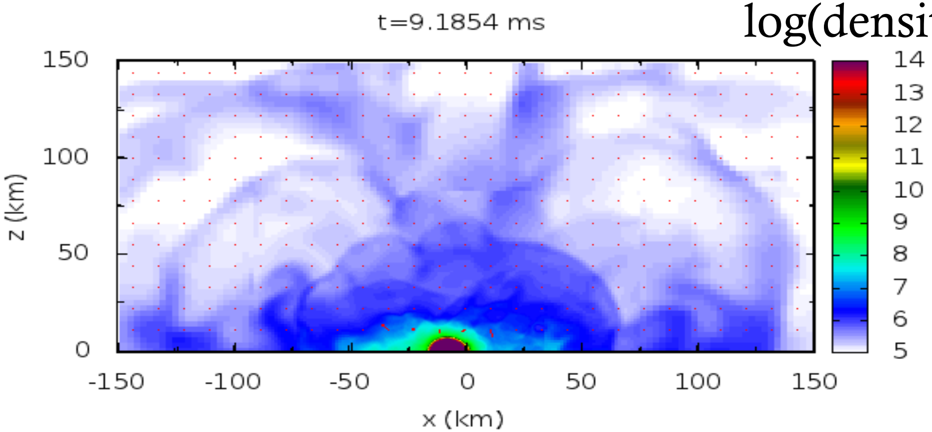
(x-z plane)

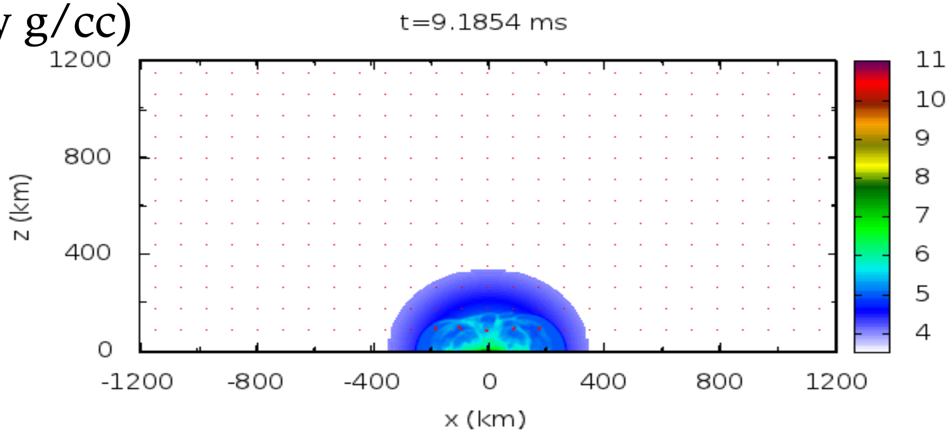
Model : 1.2Msun – 1.5Msun, APR4

300 km x 150 km

2400 km x 1200 km

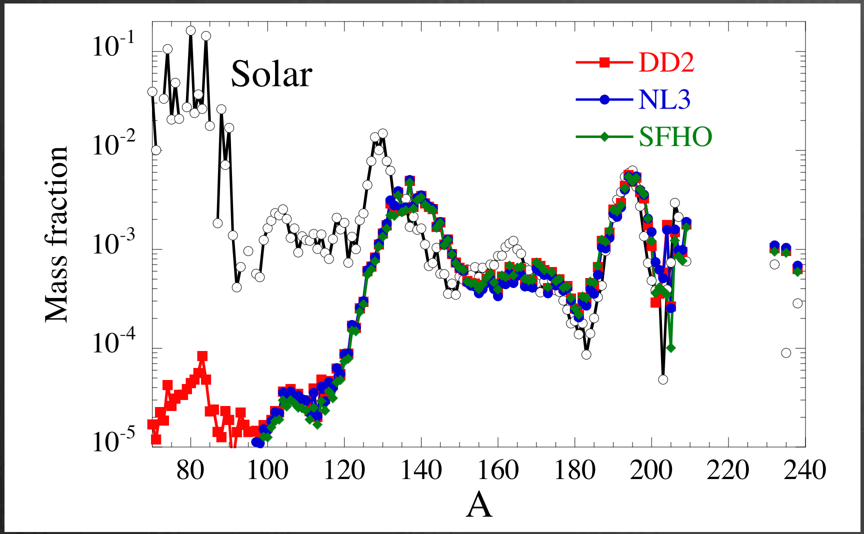
log(density g/cc)

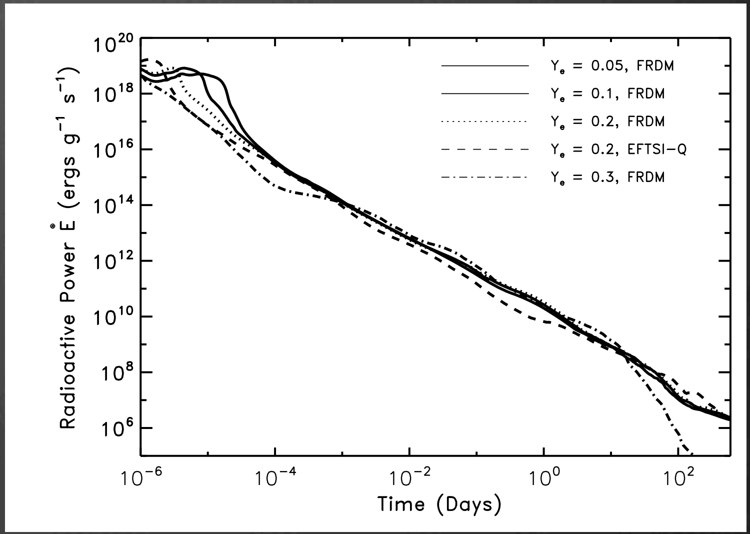




NS-NS Ejecta is spheroidal.

R-process and radioactive heating





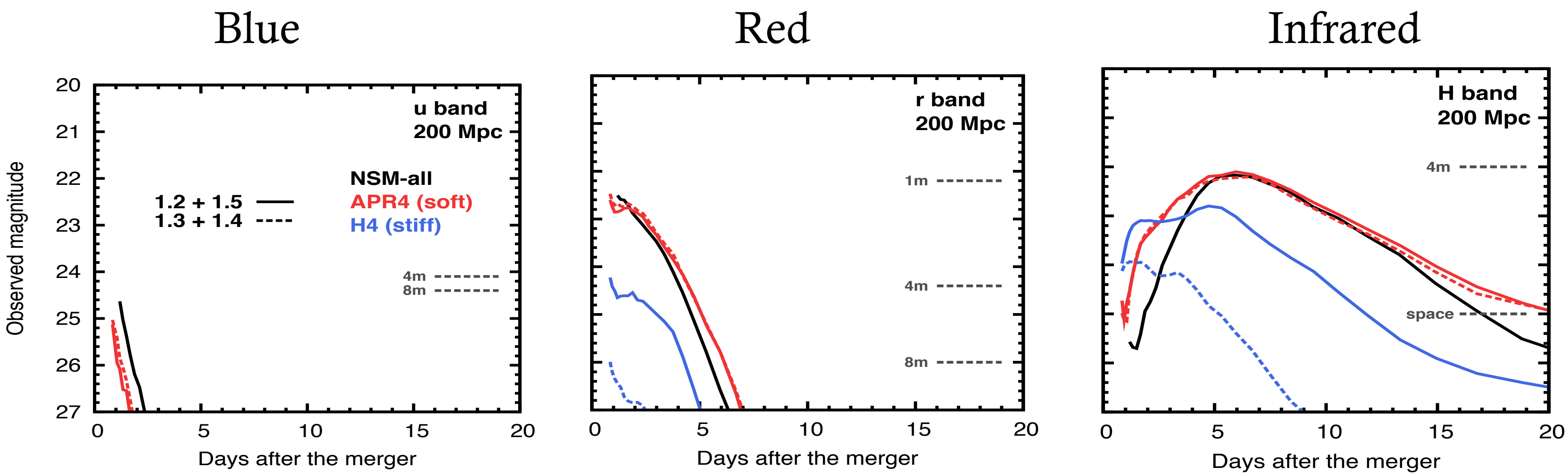
Bauswein et al 2013
see also Roberts et al 2011, Korobkin et al 2012, Wanajo 2014

Metzger et al 2010

✓ Almost all material is synthesized in heavy r-process elements.
1) Sum of many radioactive nuclides => power law heating rate.
2) A large absorption coefficient of atoms with high Z.

Macronova/Kilonova light curves

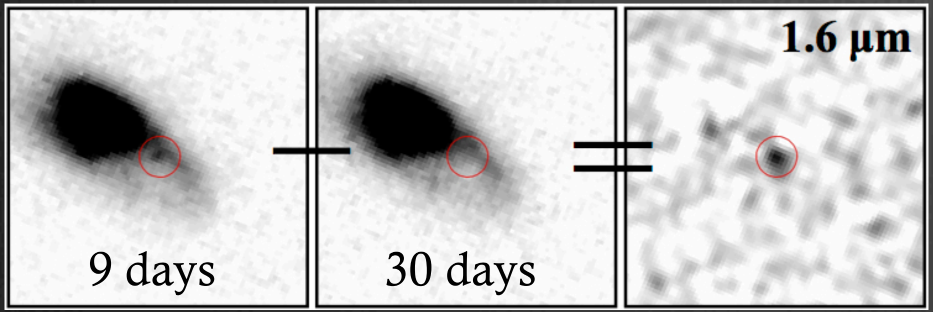
Tanaka & KH 2013 see also Barnes & Kasen 2013

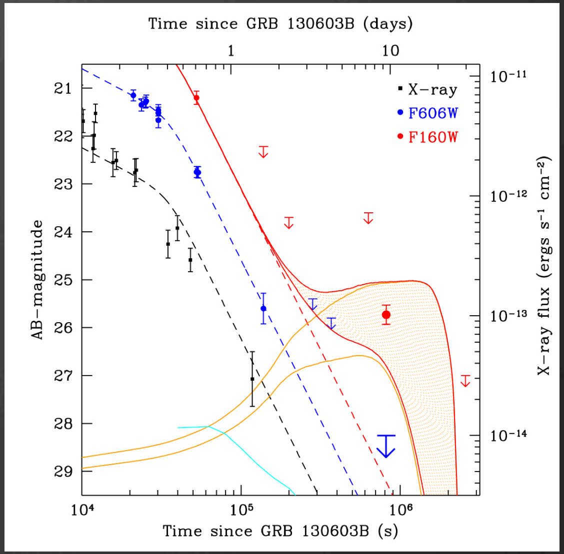


Red-IR bright transient with timescales of days ~ a few weeks

Discovery of Macronova (Kilonova)

- **A novel discovery of a possible macronova associated with the short GRB 130603B (Tanvir et al. 2013; Berger et al. 2013)**

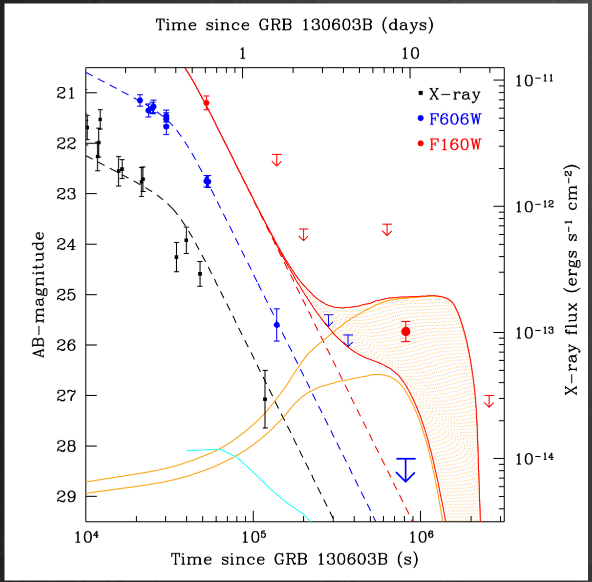




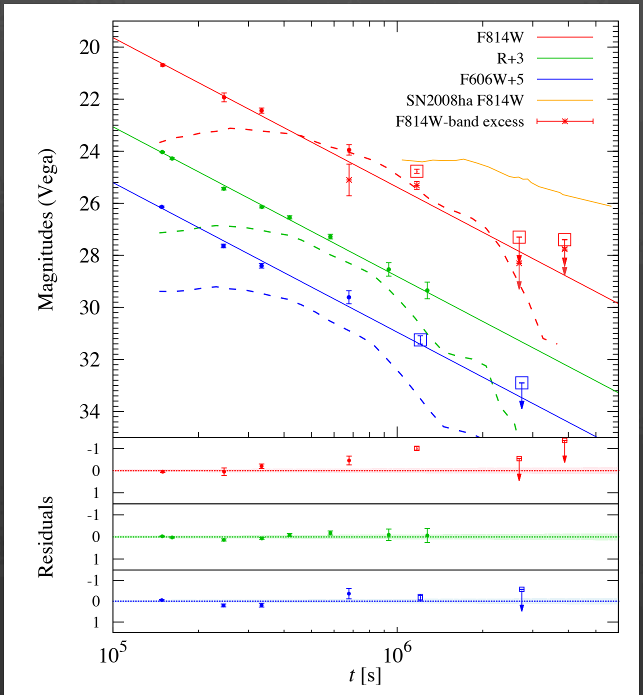
The observed data are consistent with the theoretical expectation.
The estimated ejecta r-mass is 0.01 ~ 0.1 Msun. (Hotokezaka et al 2013)

Three Macronova/Kilonova candidates?

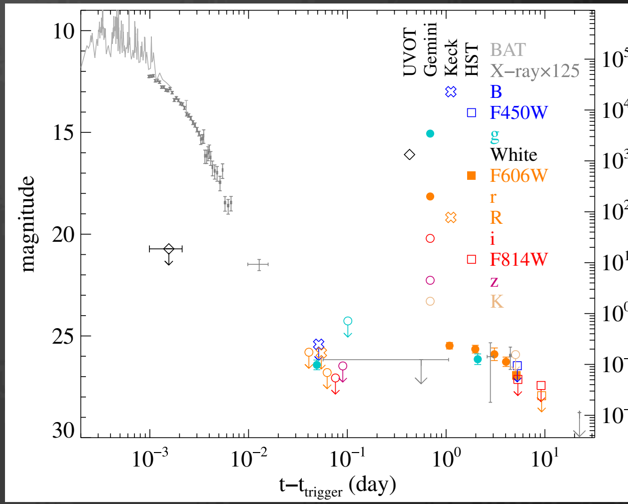
GRB 130603B (Tanvir et al 2013)



GRB 060614 (Yang et al 2015)



GRB 080503 (Perley et al 2009



Redshift is unknown

10^{41}erg/s at 7days

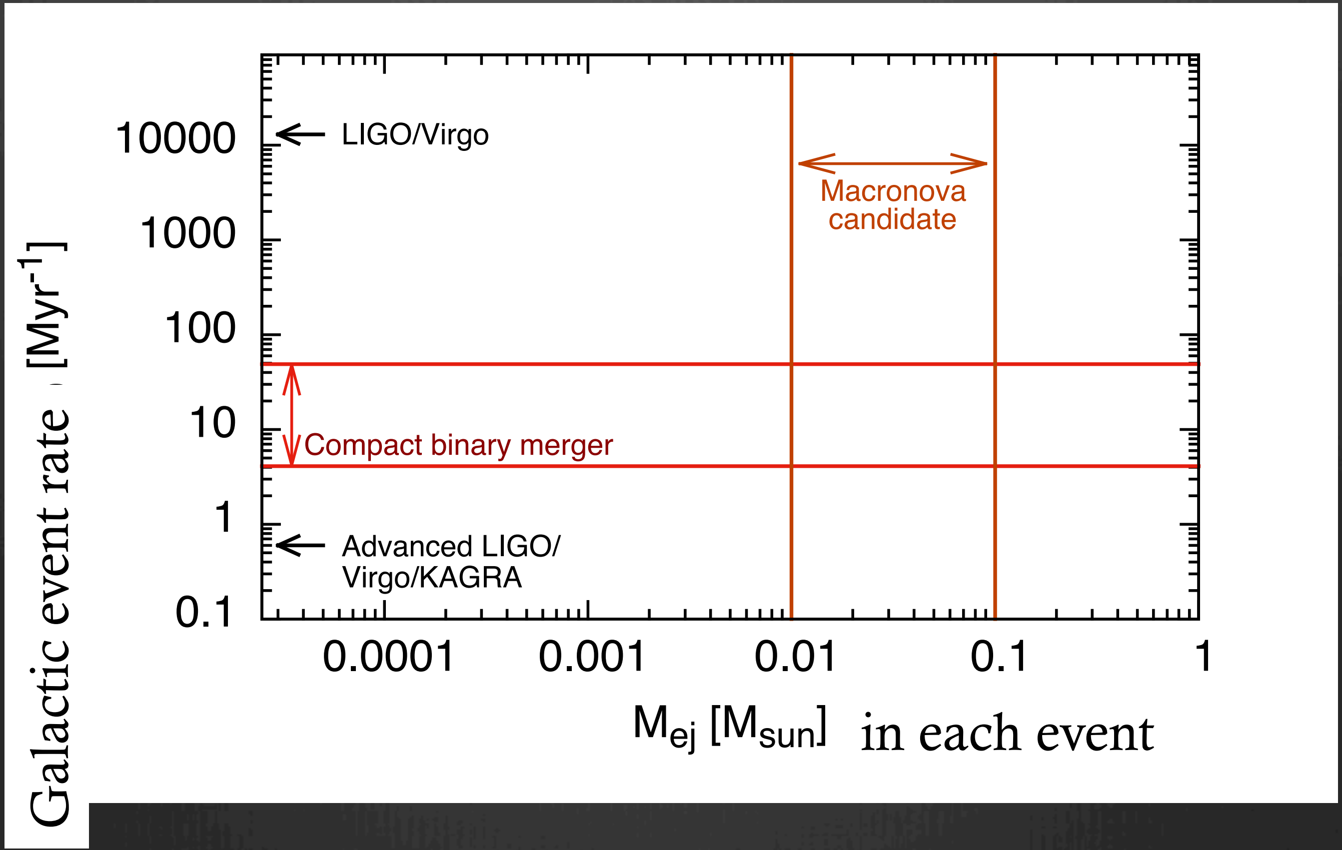
10^{41}erg/s at 13days

Macronova and Supernova

	Macronova (Neutron star merger)	**Supernova (Core collpase)**
Ejecta mass	$0.001-0.1M_{sun}$	$1-20M_{sun}$
Radioactive mass	$0.001-0.1M_{sun}$ (r-process)	$0.05-0.1M_{sun}$ (Ni56, Co56)
Electron fraction	0.01 – 0.4	0.5
Velocity	0.2c – 0.3c	0.01c – 0.1c
Peak luminosity	$10^{40}-10^{41}erg/s$	$10^{42}-10^{43}erg/s$
Peak time scale	~ week	~ month
Peak wavelength	Near Infrared	Optical
Spectral feature	Smooth, perhaps wide-absorption lines	Absorption & emission lines

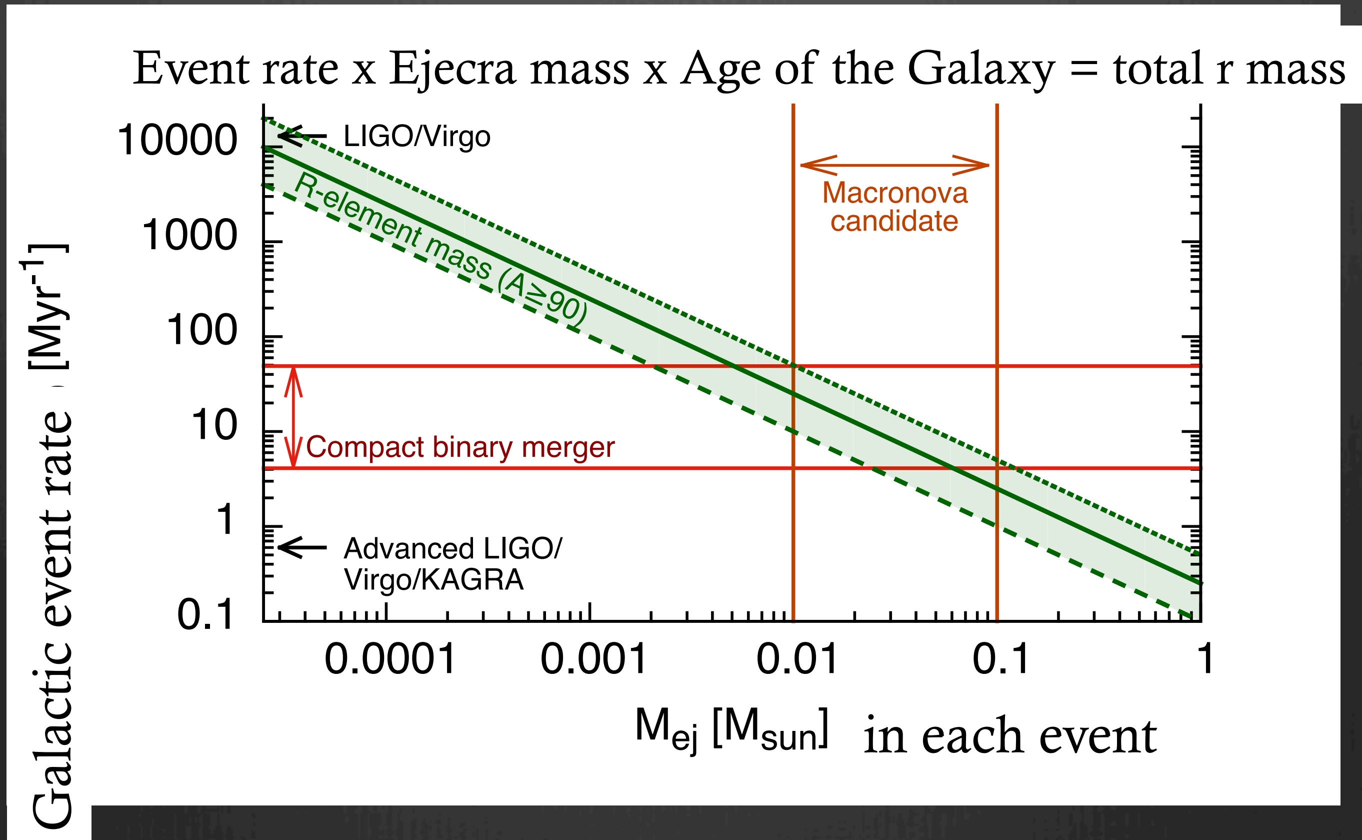
Mass ejection and the galactic rate

KH, Piran & Paul 2015



Comparison: the galactic r-element

KH, Piran & Paul 2015



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The origin of heavy r-process elements

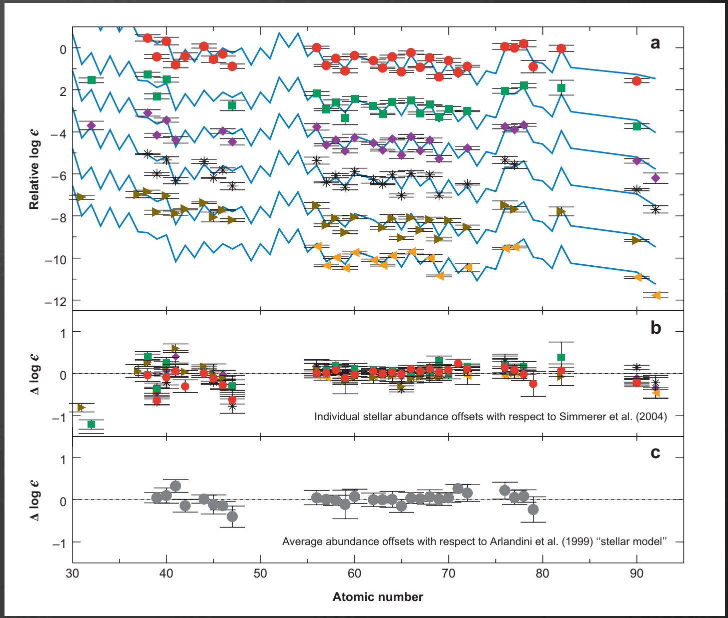
The origin is still a mystery.

R abundances (Z>50) of halo metal poor stars
⇒ Indistigushalble from the solar pattern
⇒ A single kind of phenomena may produce heavy elements.

Supernova vs NS merger

Supernova: High rate/Low yield
NS merger: Low rate/High yield

Sneden et al 2008



Short-lived ^{244}Pu & the origin

- ^{244}Pu :

  1) Produced only through the r-process,

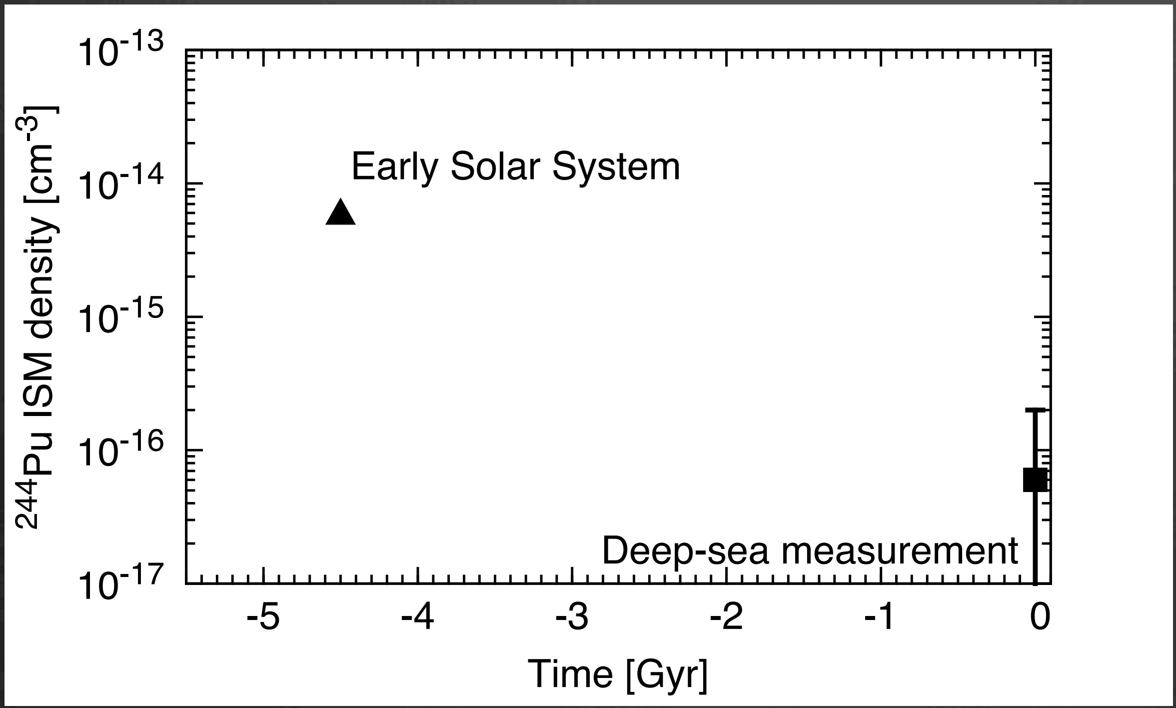
  2) the half-life is 81Myr,

✓ short enough compared to the Earth's age 4.6Gyr,

✓ long enough to accrete on Earth from ISM.

  3) the abundances at the present and Early Solar System are measured.

Estimated ^{244}Pu density

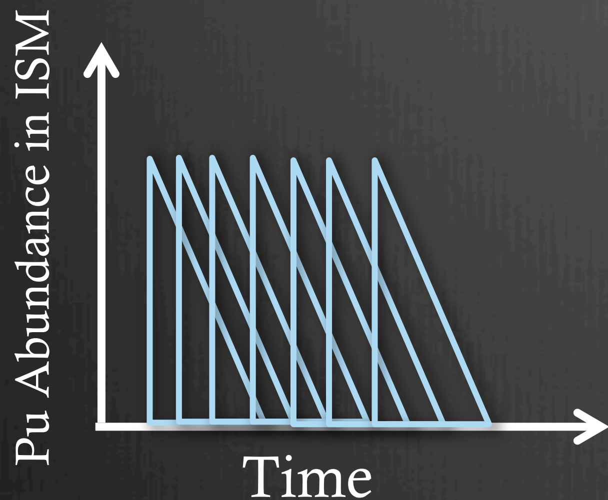


1. Early Solar data
Turner et al 2007
(ancient rock)
Lodders et al 2007
(meteorite)

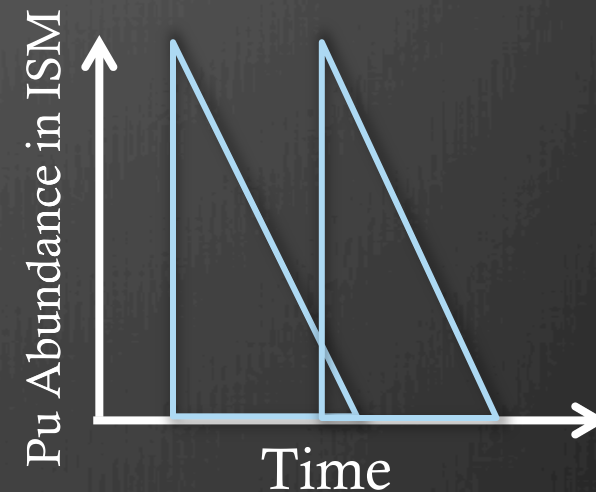
2. Deep-sea data
Wallner et al 2015
sea crust & sediment
for the last 25 Myr.

Supernova vs Neutron Star merger

Normal core-collapse SNe
=> High rate/low yield



Neutron Star Mergers
=> Low rate/high yield



$$\tau_{\rm mix} \approx 300~{\rm Myr}~(R/10~{\rm Myr})^{-2/5}(\alpha/0.1)^{-3/5} (v_t/7~{\rm km/s})^{-3/5}(H/0.2~{\rm kpc})^{-3/5}.$$

Turbulent mixing

$$\langle n_i \rangle_m \approx n_{{\rm eq},i} \exp\left(-\frac{\tau_{\rm mix}}{2\tau_i}\right) \quad \text{where } n_{{\rm eq},i} \approx N_i \mathcal{R} \tau_i$$

Chemical evolution of ^{244}Pu around the solar circle

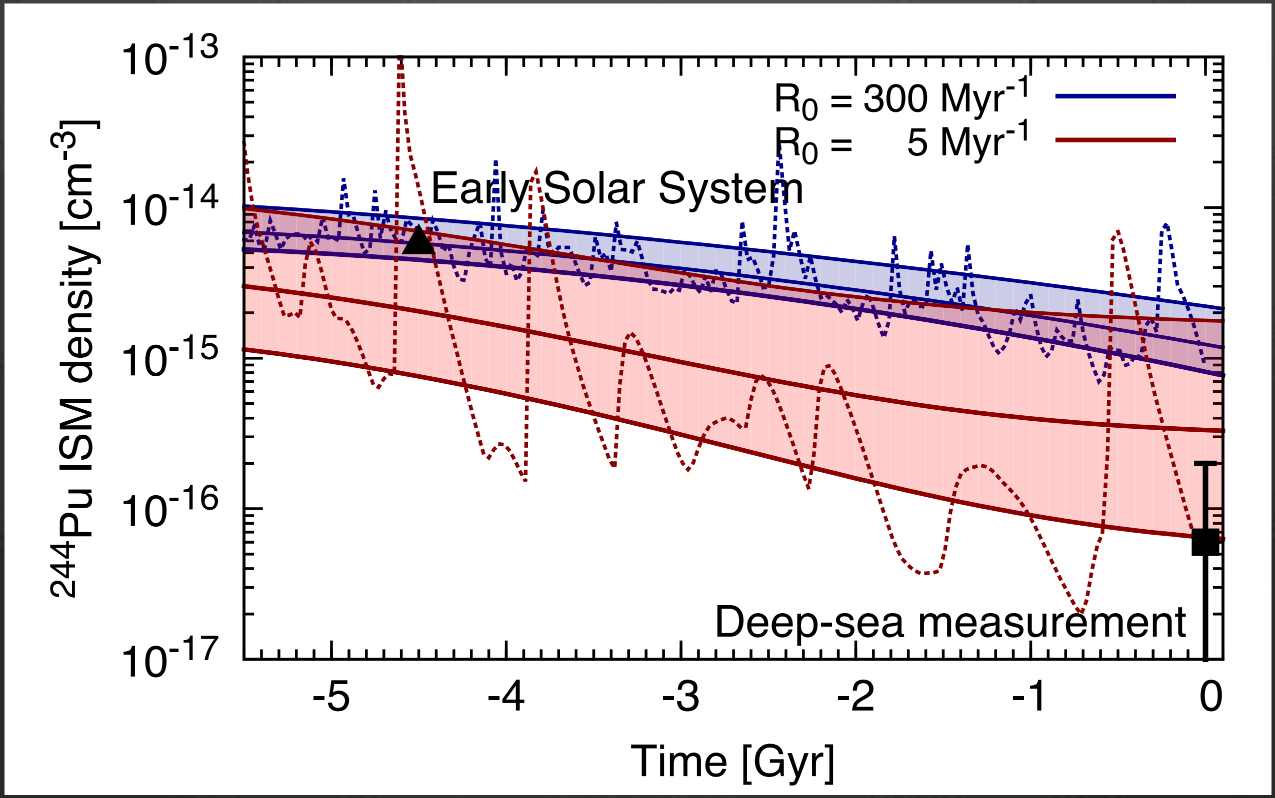
We perform a Monte-Carlo simulation of Pu abundance taking

(1)Turbulent diffusion process of the ISM,
(2)The event rate evolution follows:
(a) short GRBs and (b) star formation history,
(3) ^{244}Pu decays with the half-life of 81Myr,

into account.

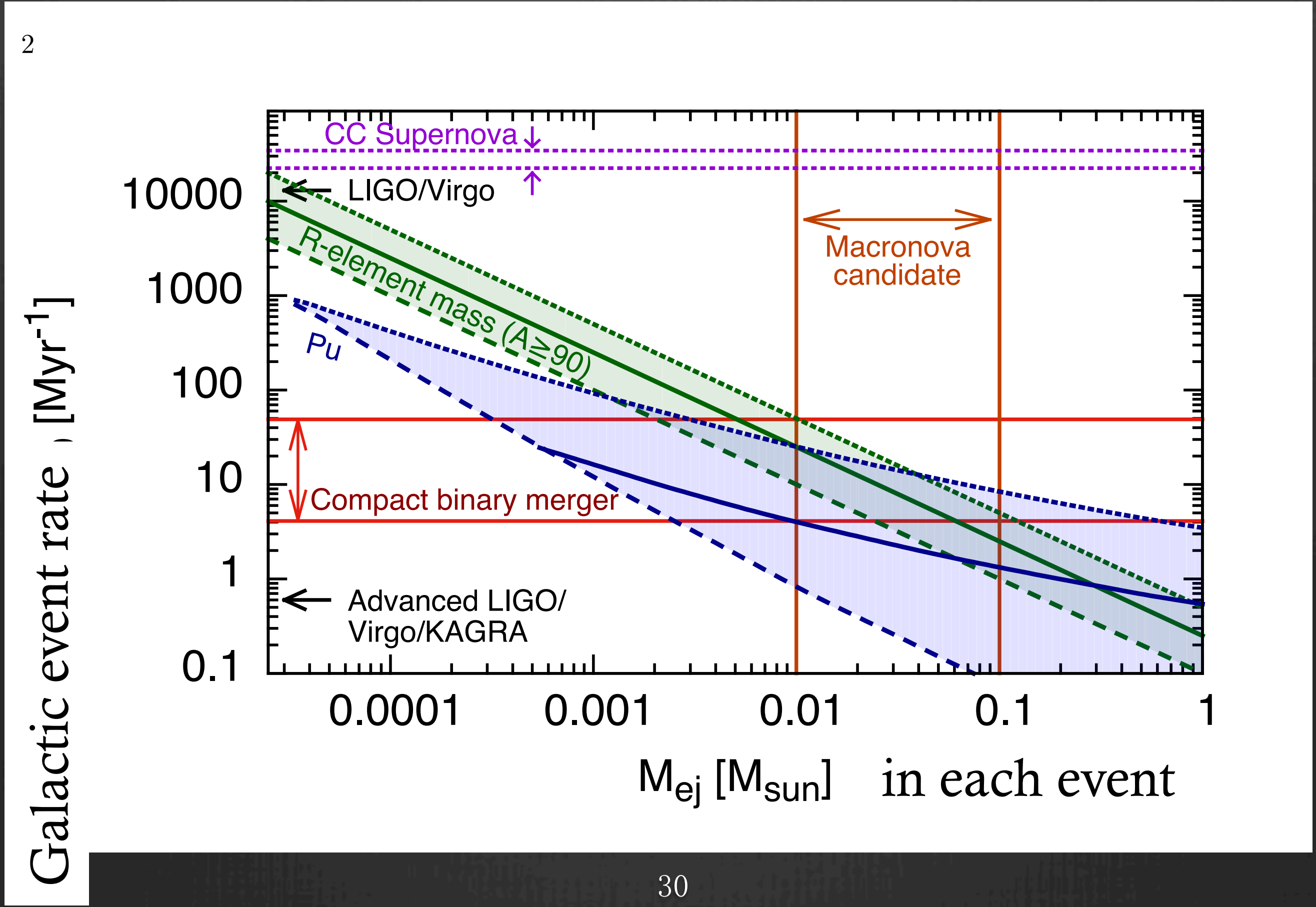
History of Abundance of ^{244}Pu

KH, Piran & Paul 2015



Comparison: Astronomical observations

KH, Piran & Paul 2015



Summary & Conclusion

- A neutron star merger ejects a significant amount of mass.
- Macronova (Kilonova) candidates are discovered and the estimated ejecta mass is ~ $0.01M_{sun}$ ~ $0.1M_{sun}$
- We test high rate/low yield and low rate/high yield scenarios (Sne vs NS mergers) using the measured ^{244}Pu data
- The estimated rate and yield are $R < 100\ Myr^{-1}$ & $M_{ej} > 0.001\ M_{sun}$.
- These are consistent with other astronomical observations of NS mergers.