Multi-Messenger Studies of Compact Binary Merger

- コンパクト連星合体のマルチメッセンジャー研究 -

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田中 雅臣

in collaboration with
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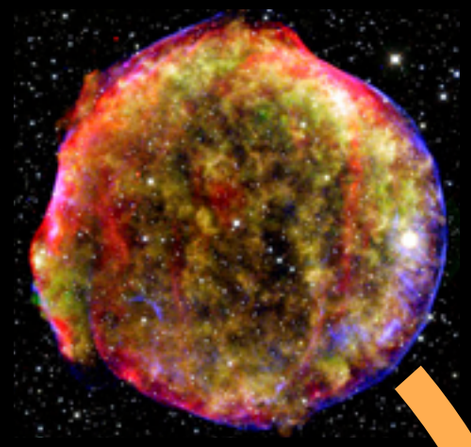
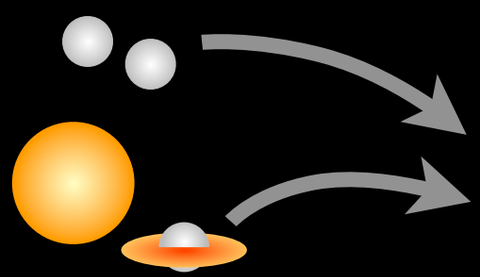
The Elements
H 1
He 2
Li 3
Be 4
B 5
C 6
N 7
O 8
F 9
Ne 10
Na 11
Mg 12
Al 13
Si 14
P 15
S 16
Cl 17
Ar 18
K 19
Ca 20
Sc 21
Ti 22
V 23
Cr 24
Mn 25
Fe 26
Co 27
Ni 28
Cu 29
Zn 30
Ga 31
Ge 32
As 33
Se 34
Br 35
Kr 36
Rb 37
Sr 38
Y 39
Zr 40
Nb 41
Mo 42
Tc 43
Ru 44
Rh 45
Pd 46
Ag 47
Cd 48
In 49
Sn 50
Sb 51
Te 52
I 53
Xe 54
Cs 55
Ba 56
Hf 72
Ta 73
W 74
Re 75
Os 76
Ir 77
Pt 78
Au 79
Hg 80
Tl 81
Pb 82
Bi 83
Po 84
At 85
Rn 86
Fr 87
Ra 88
Rf 104
Db 105
Sg 106
Bh 107
Hs 108
Mt 109
Ds 110
Rg 111
Uub 112
Uut 113
Uuq 114
Uup 115
Uuh 116
Uus 117
Uuo 118
Radioactive elements
La 57
Ce 58
Pr 59
Nd 60
Pm 61
Sm 62
Eu 63
Gd 64
Tb 65
Dy 66
Ho 67
Er 68
Tm 69
Yb 70
Lu 71
Ac 89
Th 90
Pa 91
U 92
Np 93
Pu 94
Am 95
Cm 96
Bk 97
Cf 98
Es 99
Fm 100
Md 101
No 102
Lr 103

supernova

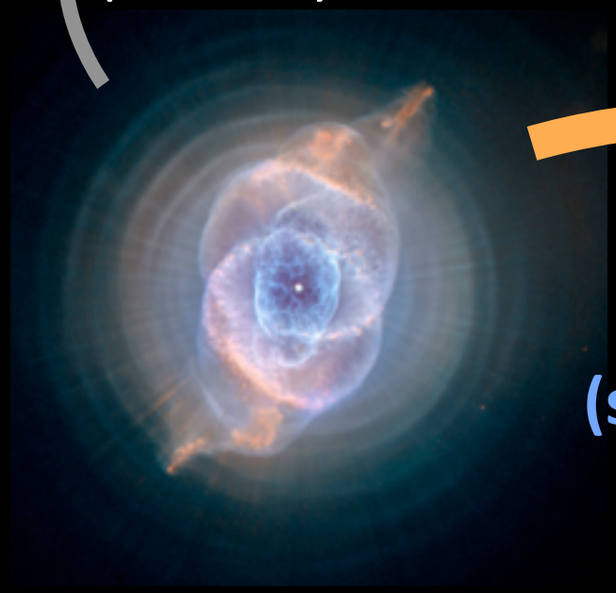




binary

white dwarf

planetary nebula



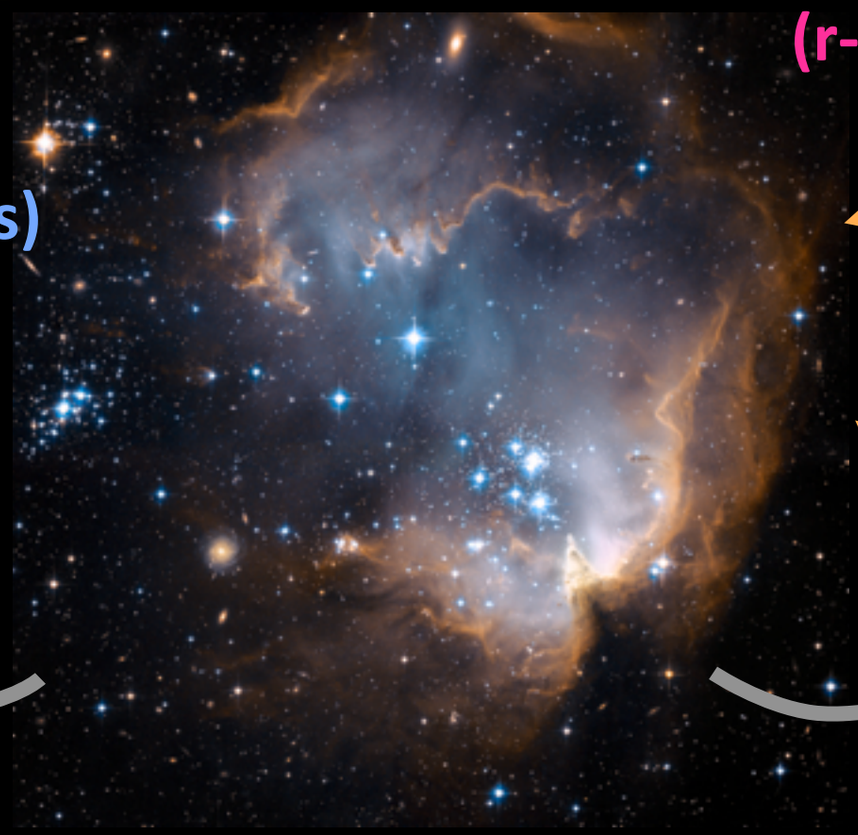
asymptotic
giant branch

H

low mass star

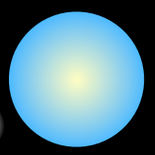
H, C, N
Ba, Pb
(s-process)

Si, Fe



Interstellar medium

binary



neutron star

neutron star merger

black hole

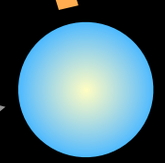
supernova

Au, Ag?
(r-process)

O, Mg, Ca
Au, Ag?
(r-process)

H

H



red supergiant

high mass star

Images: NASA, ESA, JPL-Caltech, CXC

Multi-Messenger Studies of Compact Binary Merger

- **Mass ejection and nucleosynthesis**
- **Electromagnetic wave signals**
- **Toward multi-messenger astronomy**

New astronomy with gravitational waves

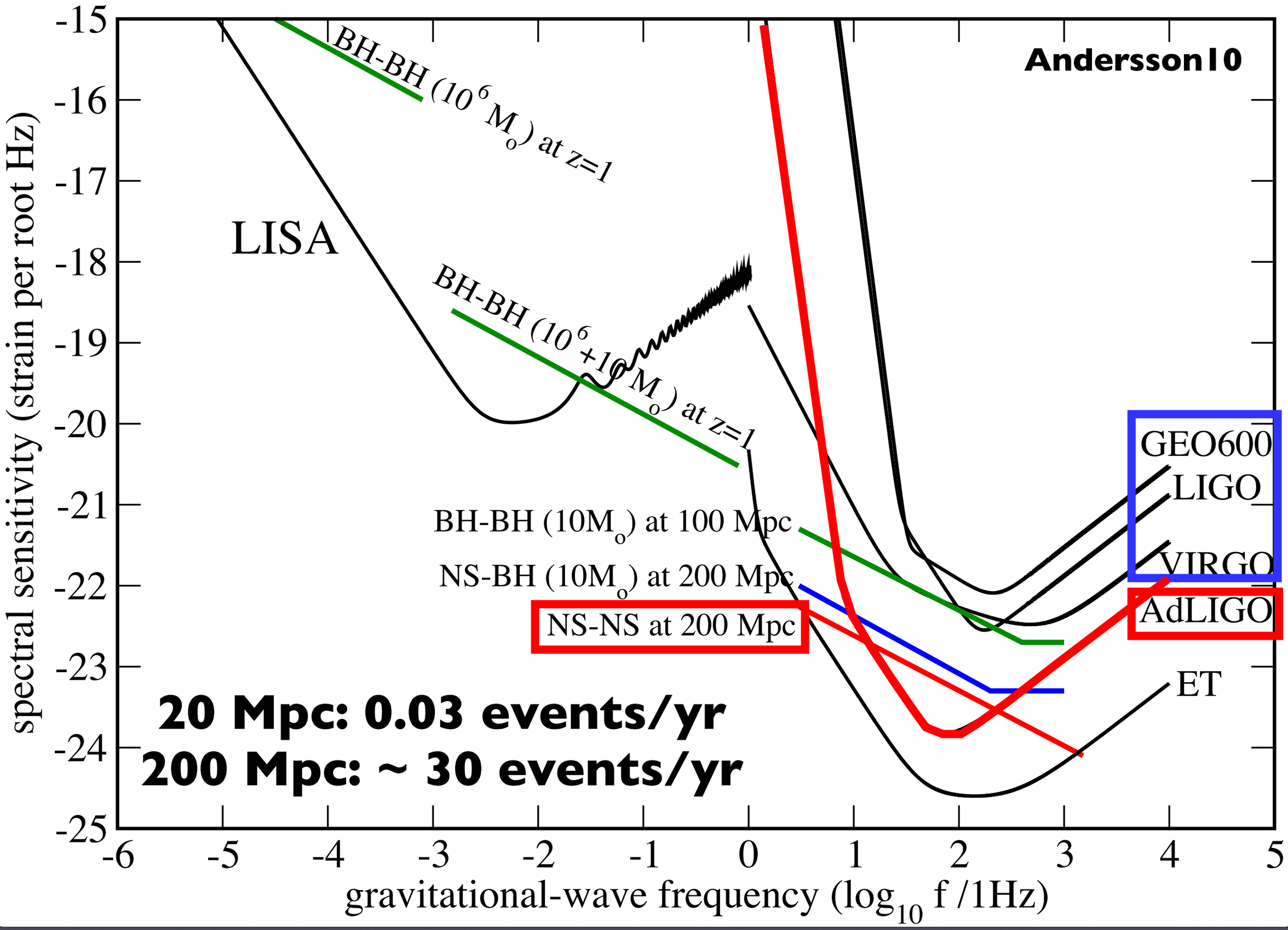
Supernova

< 10-100 kpc
~0.01 event/ 1 yr

Compact binary merger (neutron star/black hole)

< 200 Mpc
~30 (0.3-300) events/ 1 yr

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


Andersson10
LISA
BH-BH ($10^6 M_o$) at z=1
BH-BH (10^6+$10^6 M_o$) at z=1
BH-BH ($10M_o$) at 100 Mpc
NS-BH ($10M_o$) at 200 Mpc
NS-NS at 200 Mpc
GEO600
LIGO
VIRGO
AdLIGO
ET
20 Mpc: 0.03 events/yr
200 Mpc: ~ 30 events/yr
spectral sensitivity (strain per root Hz)
gravitational-wave frequency ($\log_{10}$ f /1Hz)
-15
-16
-17
-18
-19
-20
-21
-22
-23
-24
-25
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5

1 deg

~ 100 galaxies / 1 deg^2
(< 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

1 deg

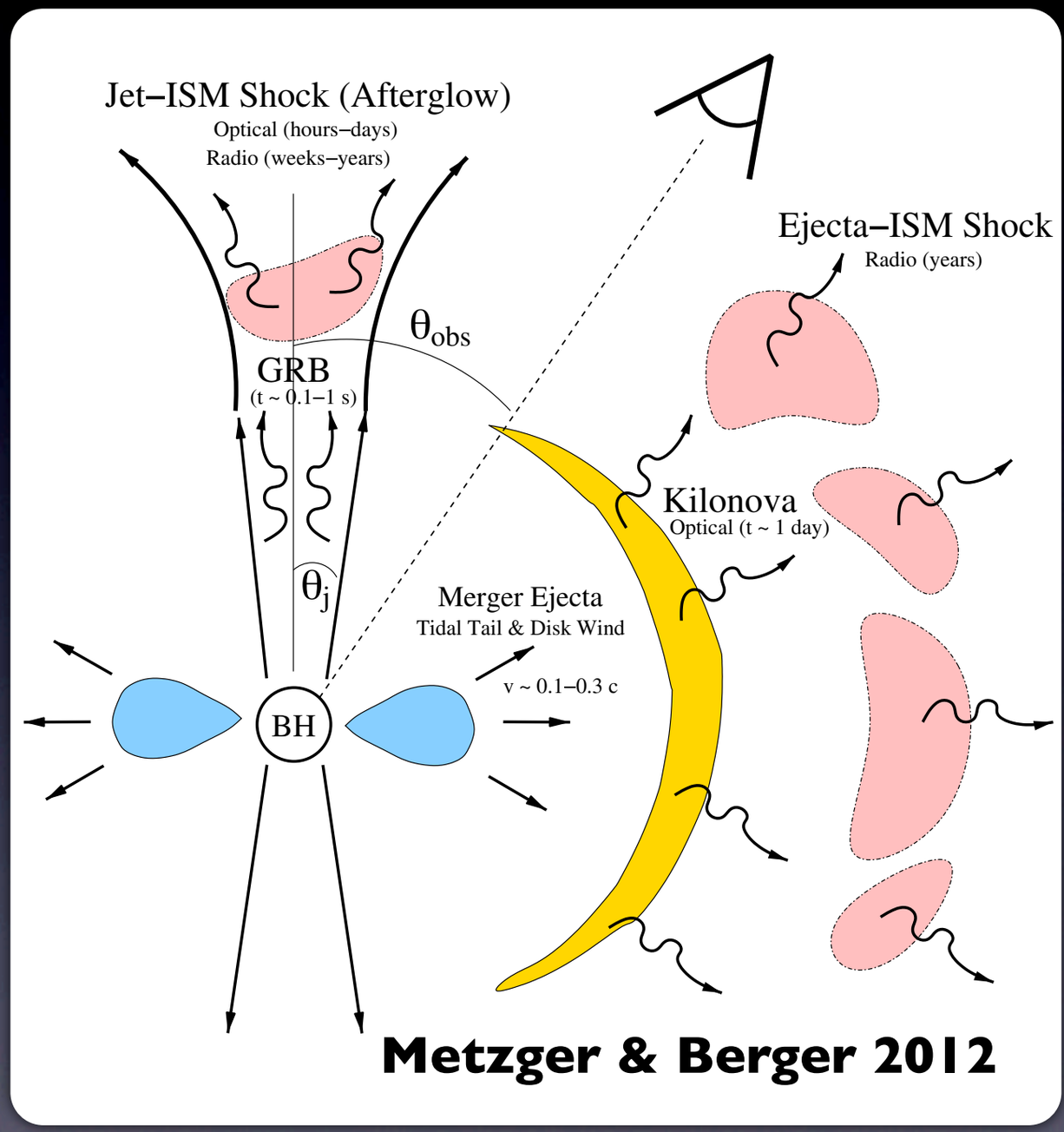
Source identification

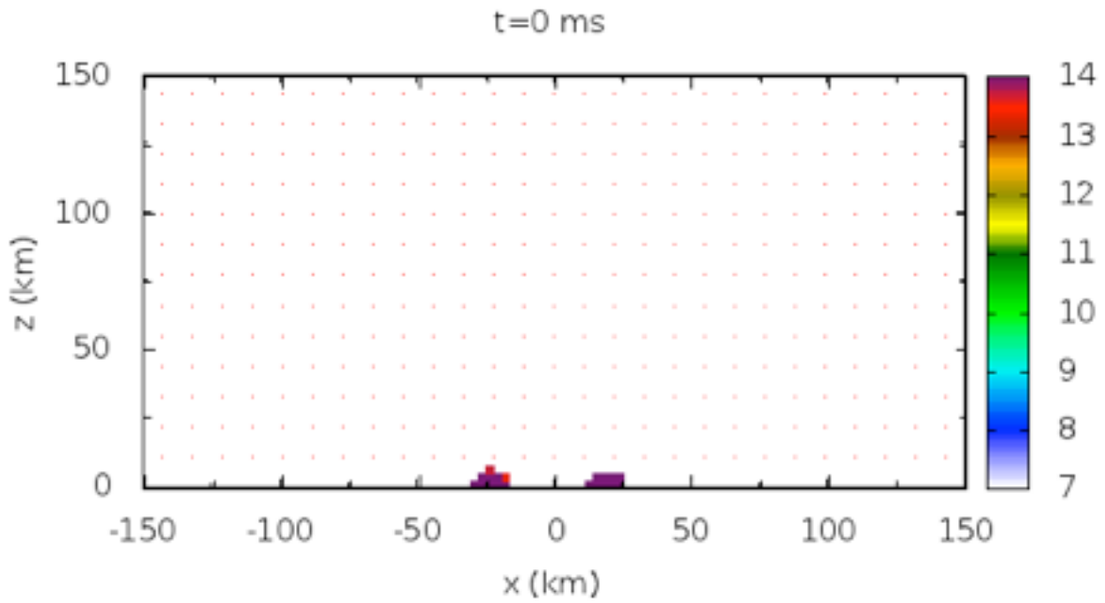
“Multi-messenger” astronomy

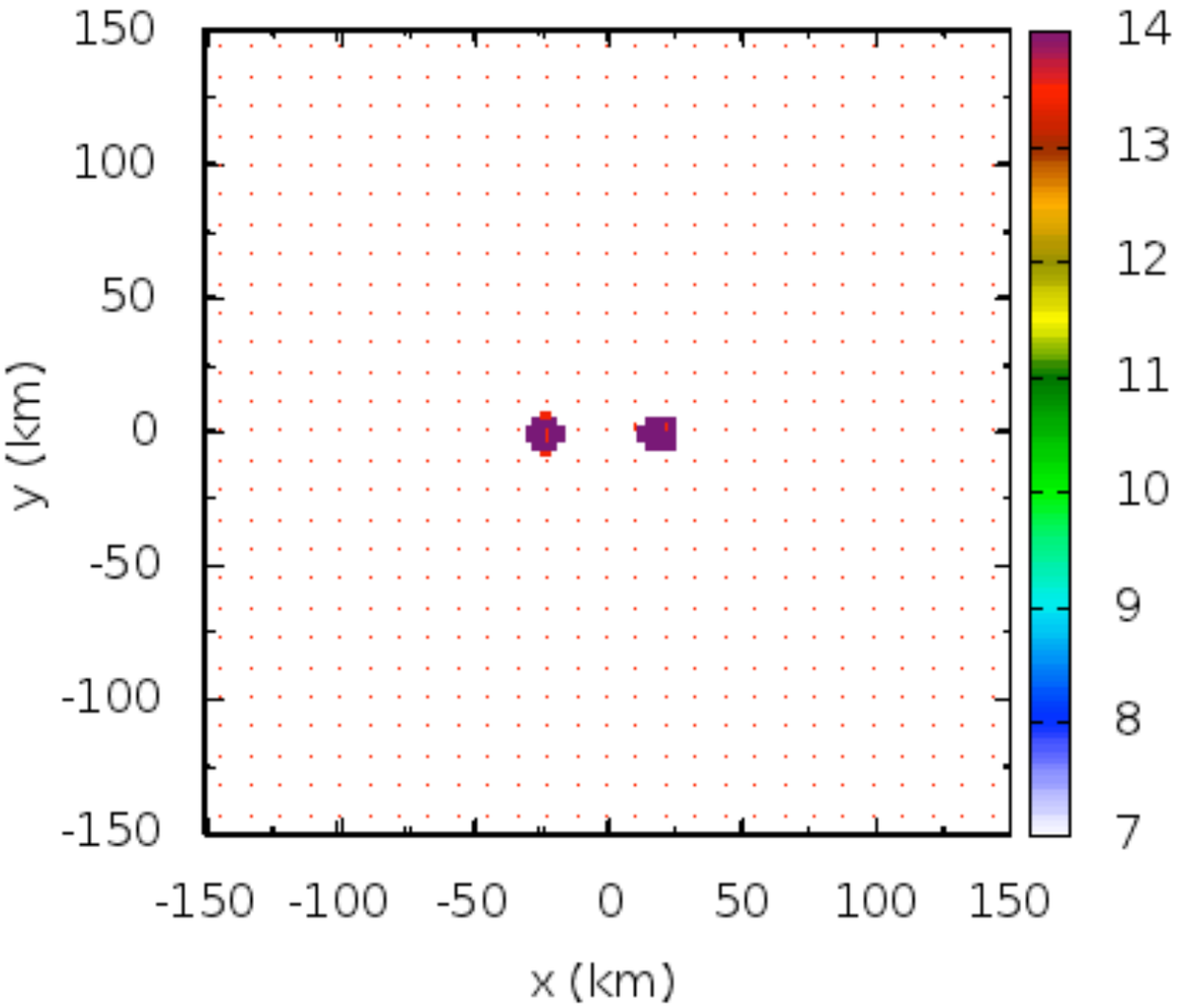
EM signature from NS merger

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

Need mass ejection







Mass ejection from NS mergers

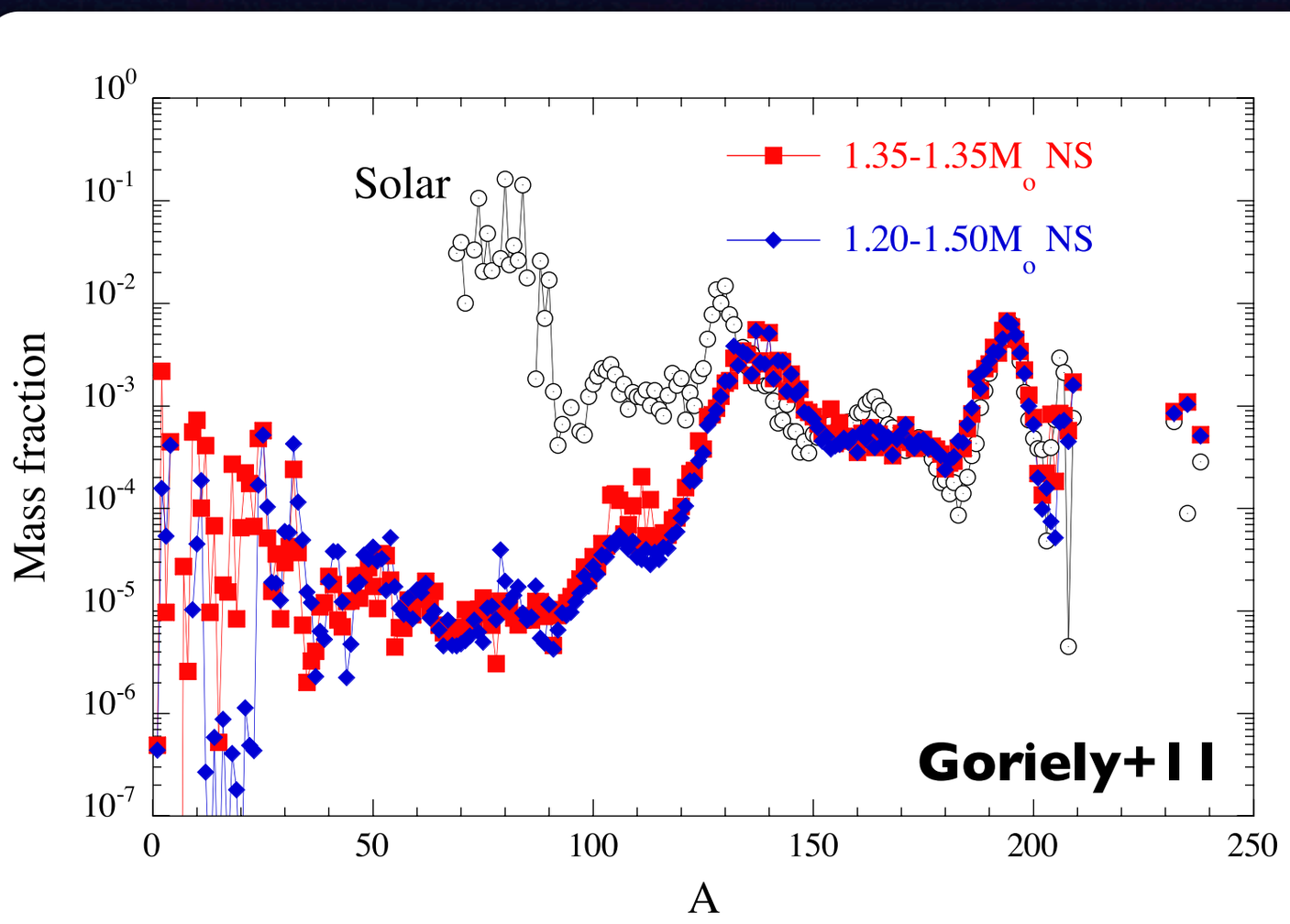
M ~ 10^{-3} - 10^{-2} Msun

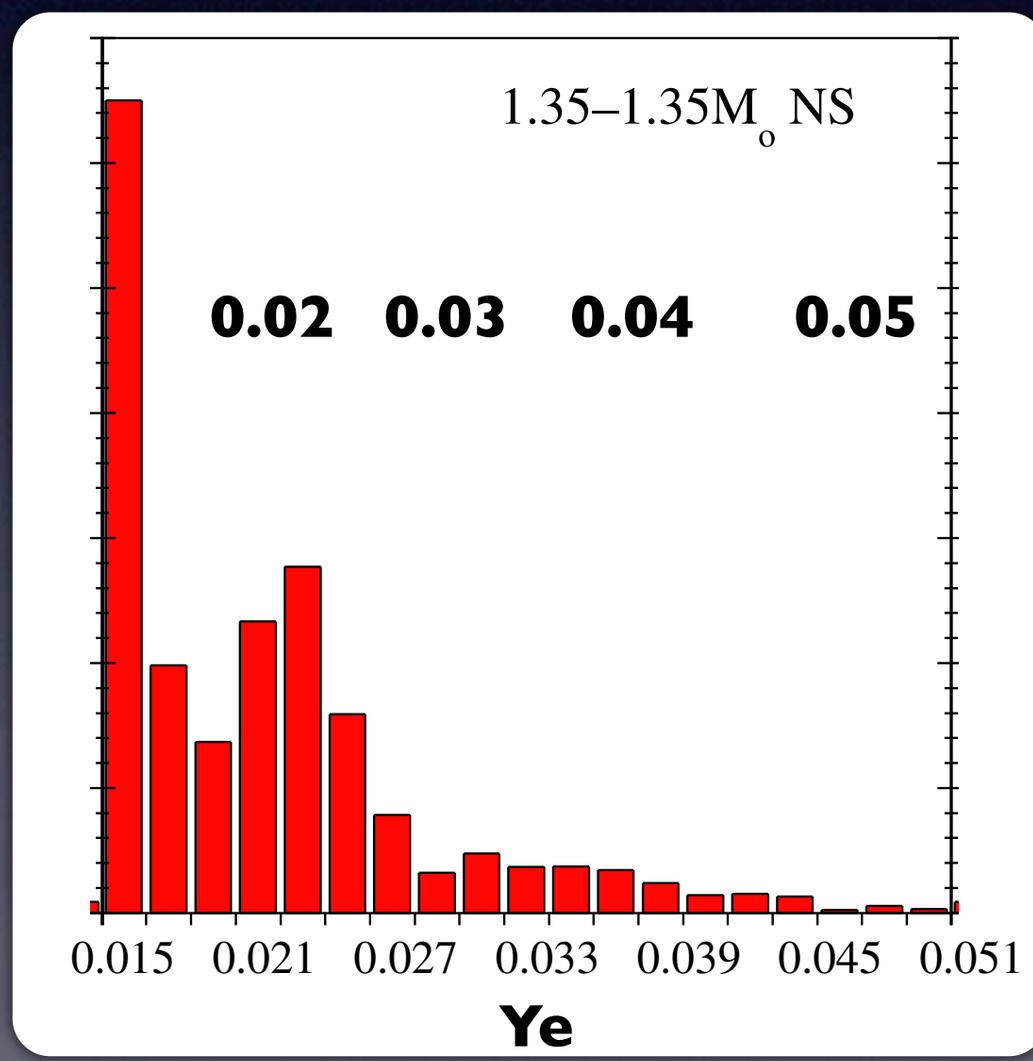
Hotokezaka+13

see Kiuchi-san's talk

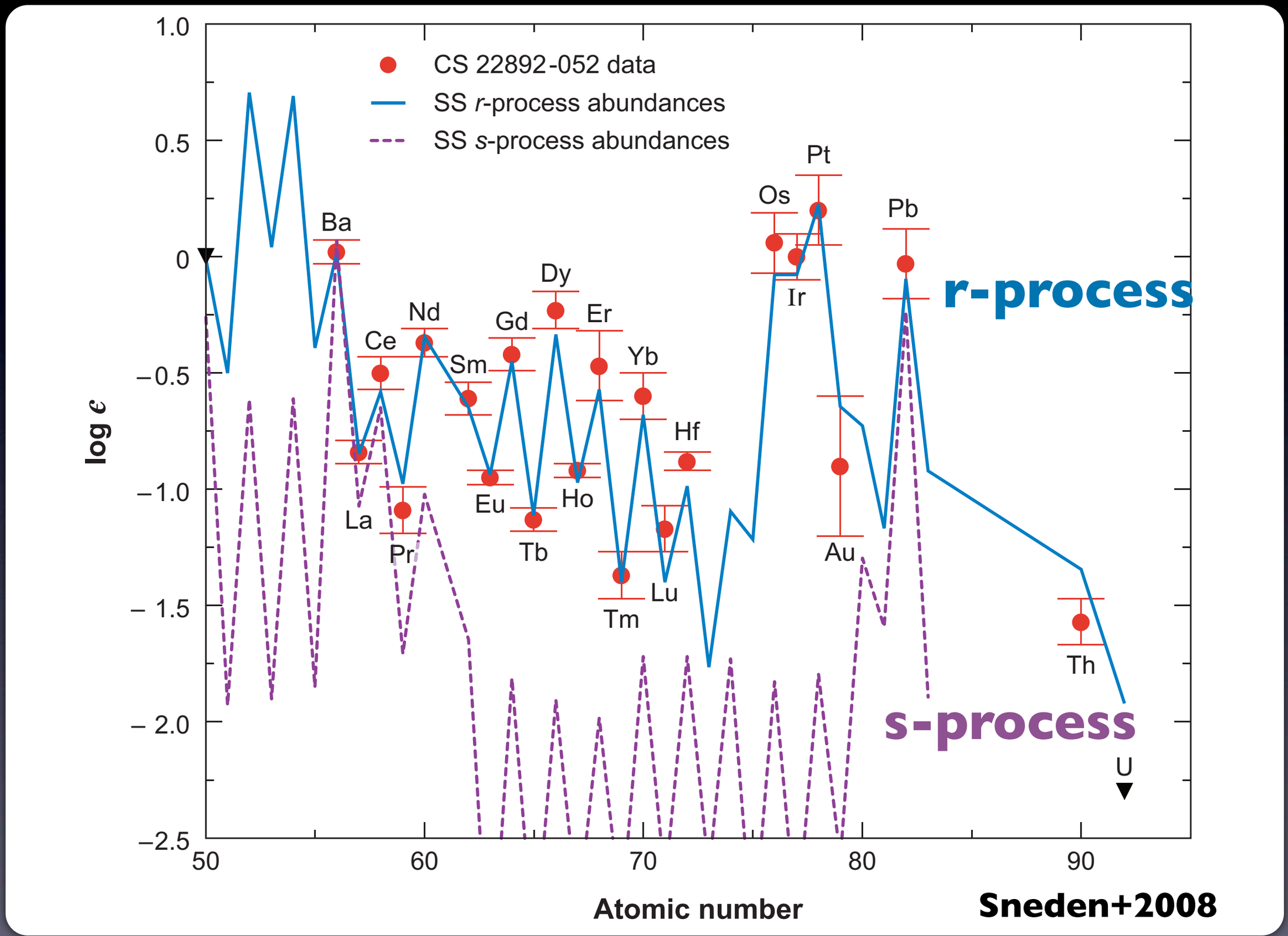
Nucleosynthesis in NS merger

$$Y_e = \frac{n_e}{n_p + n_n} = \frac{n_p}{n_p + n_n}$$





r-process elements in stars

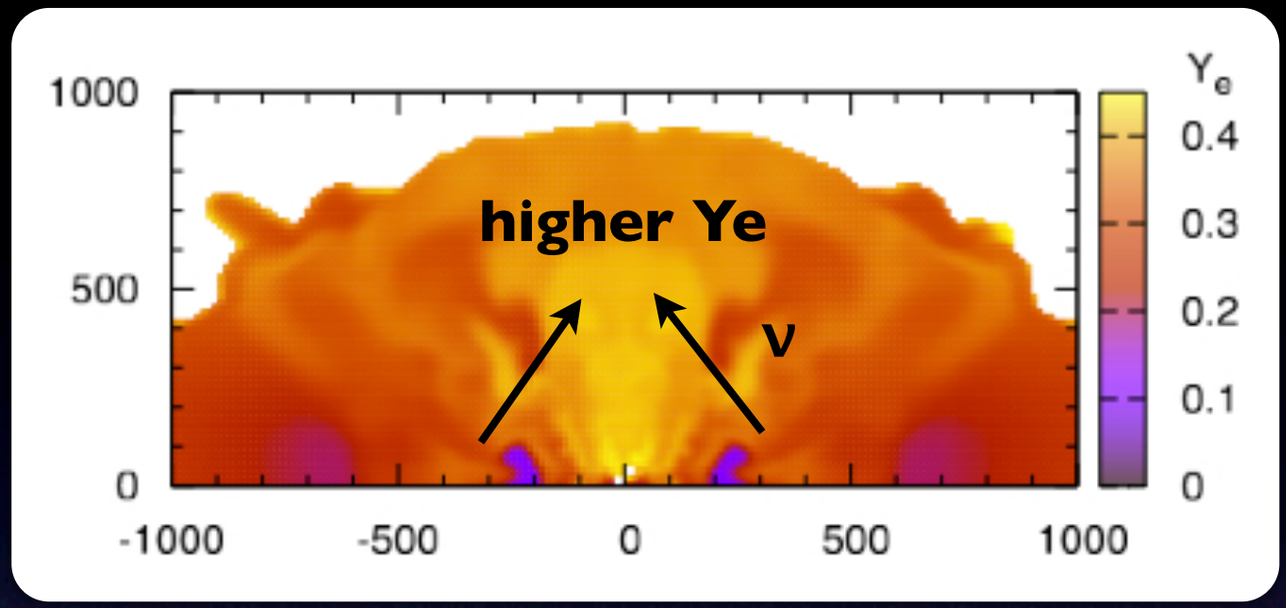


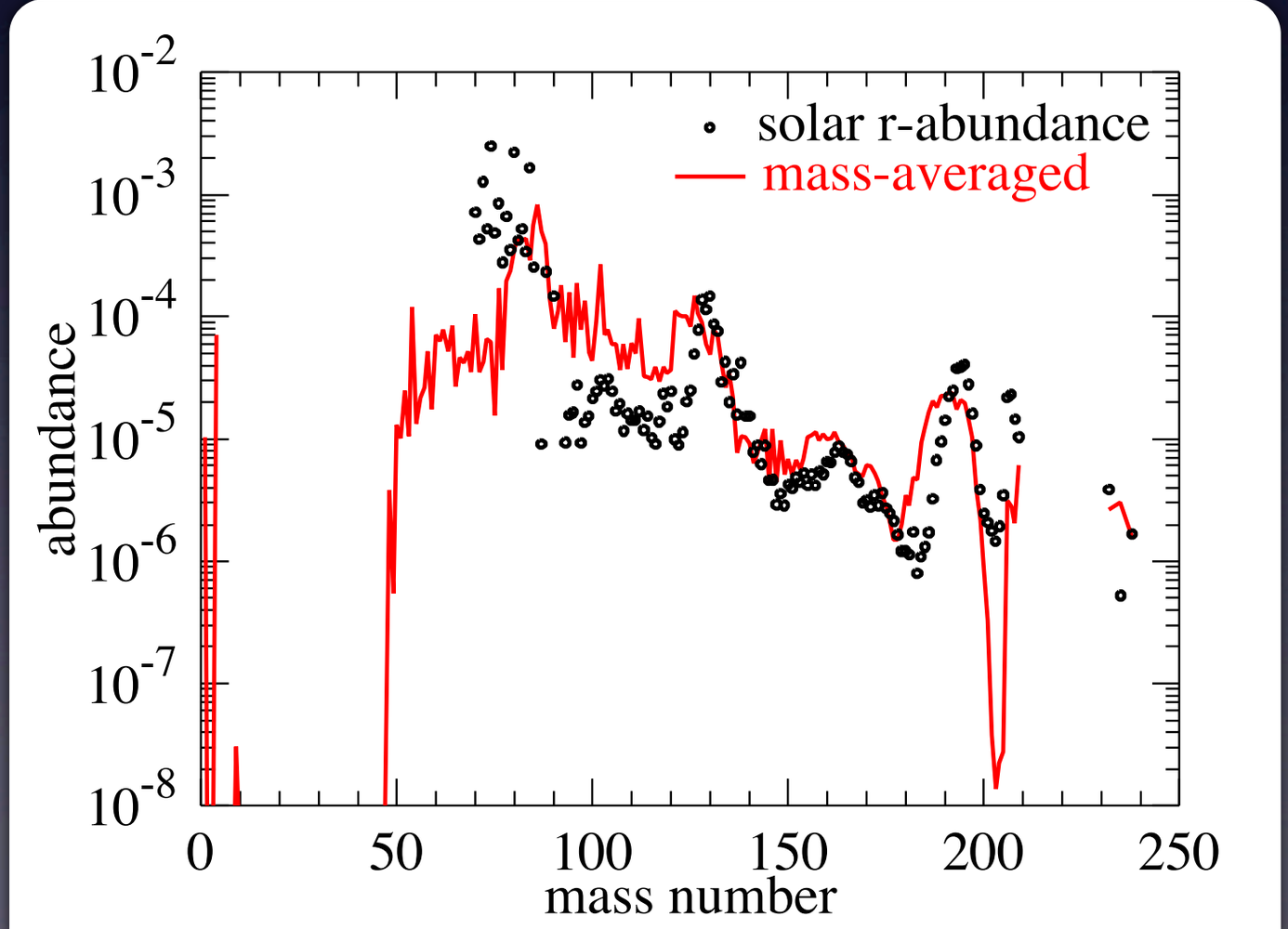
Sneden+2008

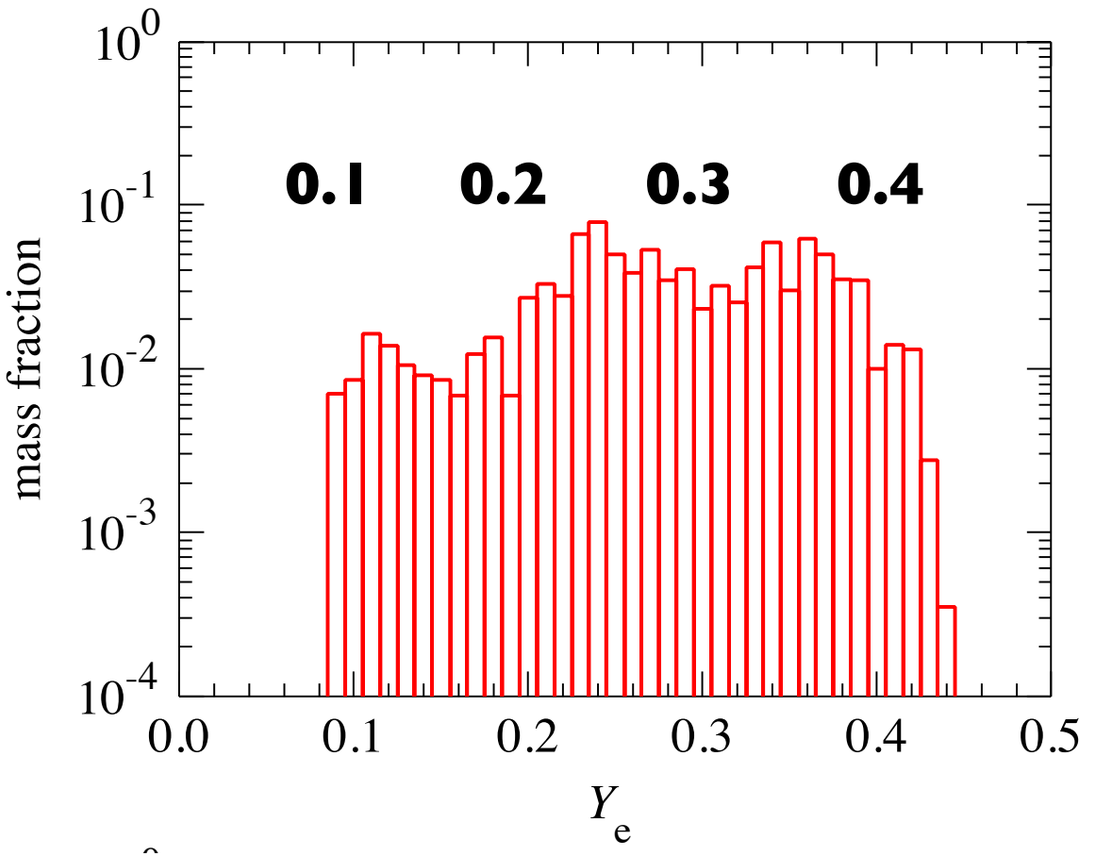
Recent progress

General relativity with neutrino transfer

See Sekiguchi-san's poster (No 37)







Wanajo, Sekiguchi+2014

Amount 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 events/yr

(~0.3-300)

⇓

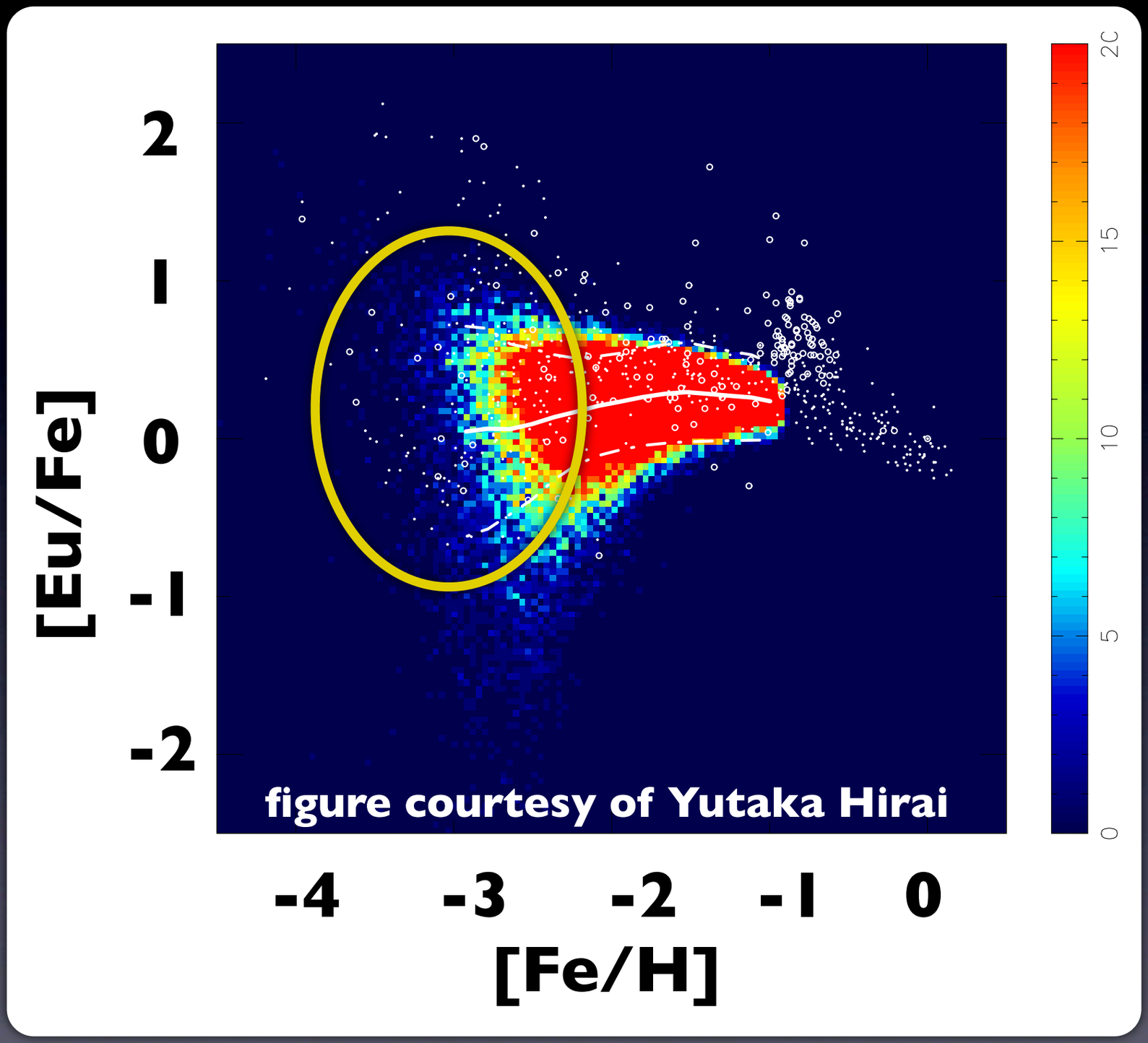
Ejection per event

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

r-process elements in the early Universe



Data from Suda+08,14

- Milkyway
- Dwarf galaxy

see Hirai-san's poster (No 65)

(e.g., Argast+04, Matteucci+14, Tsujimoto & Shigayema 2014)

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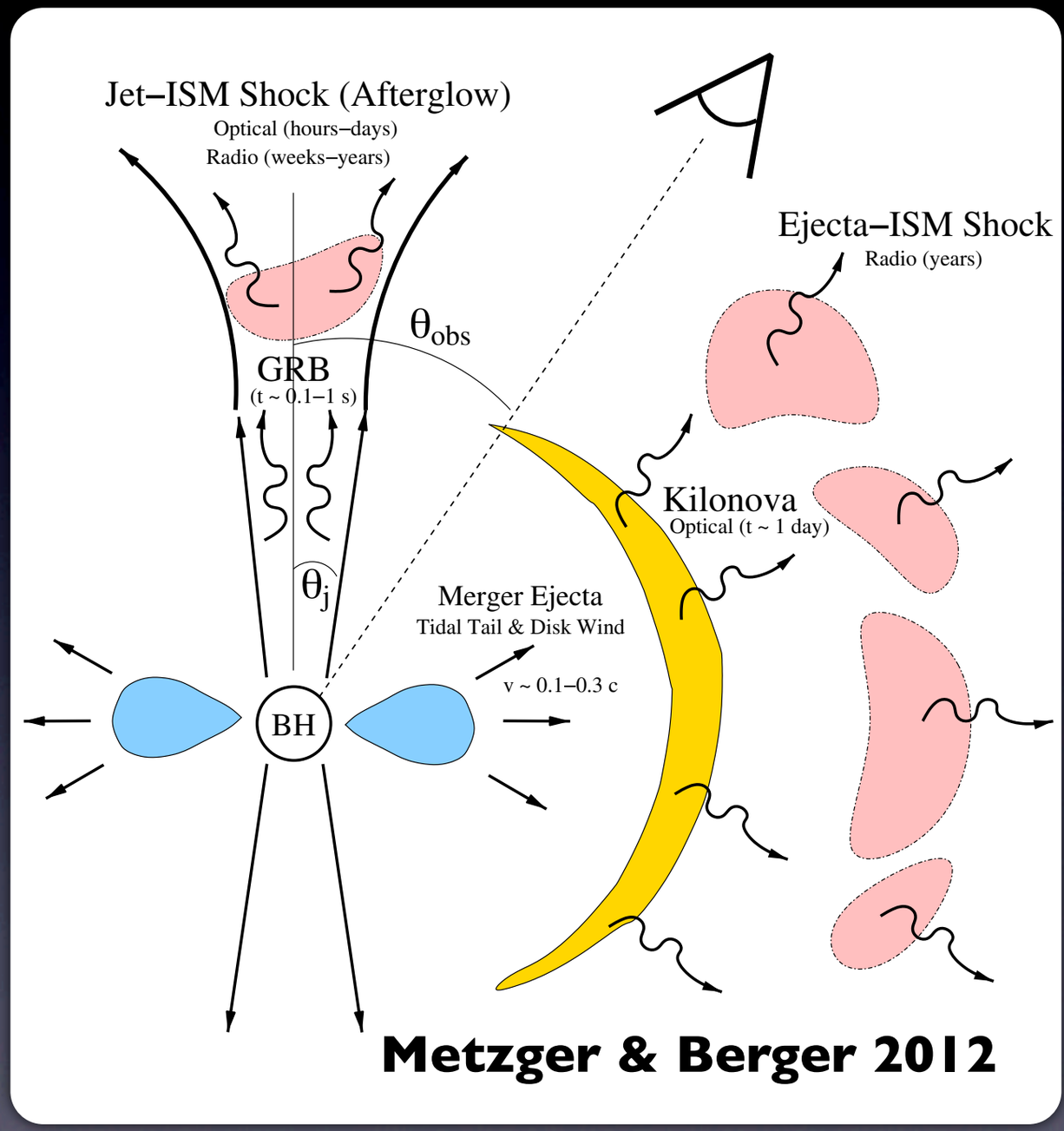
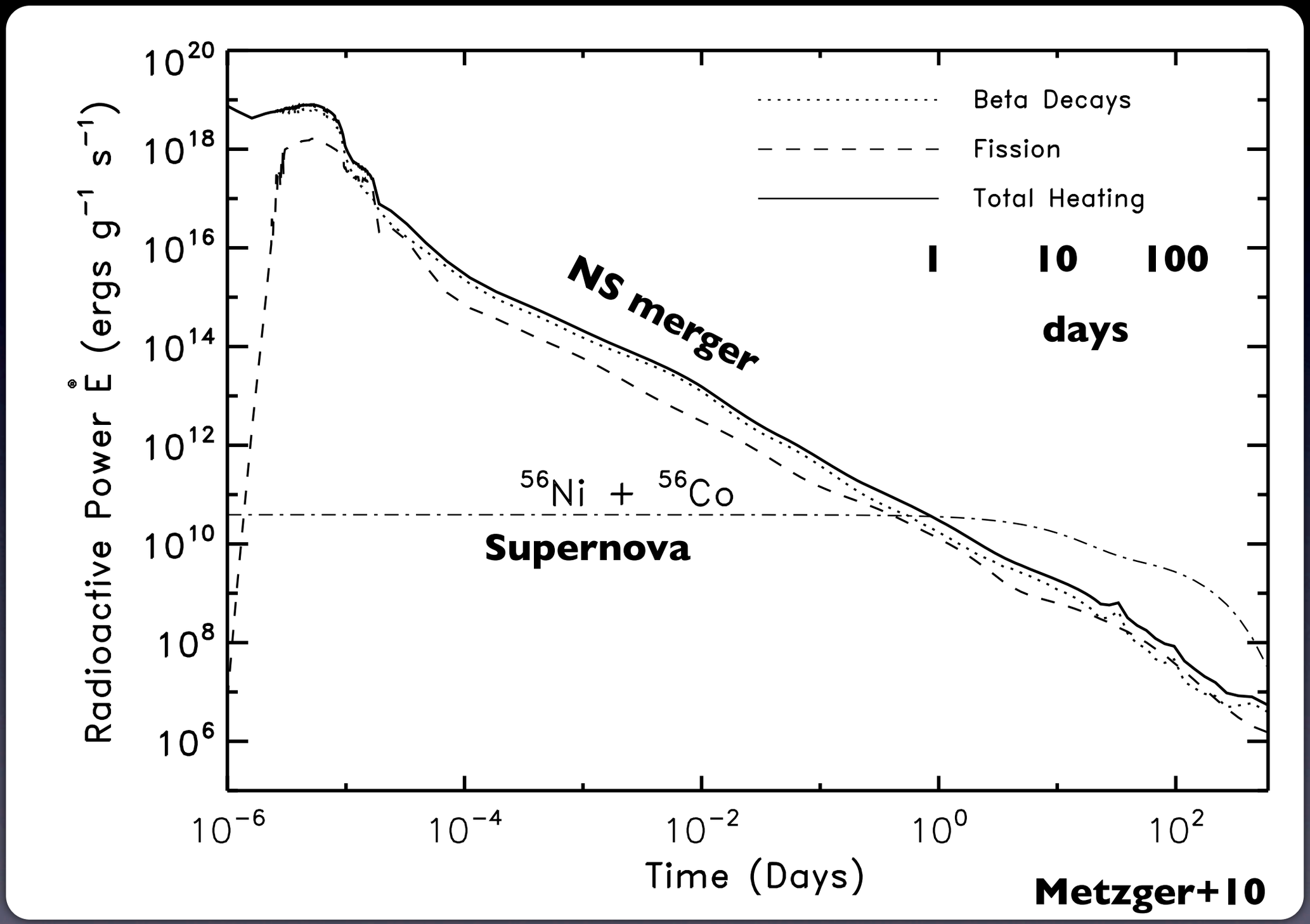
EM signature from NS merger

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



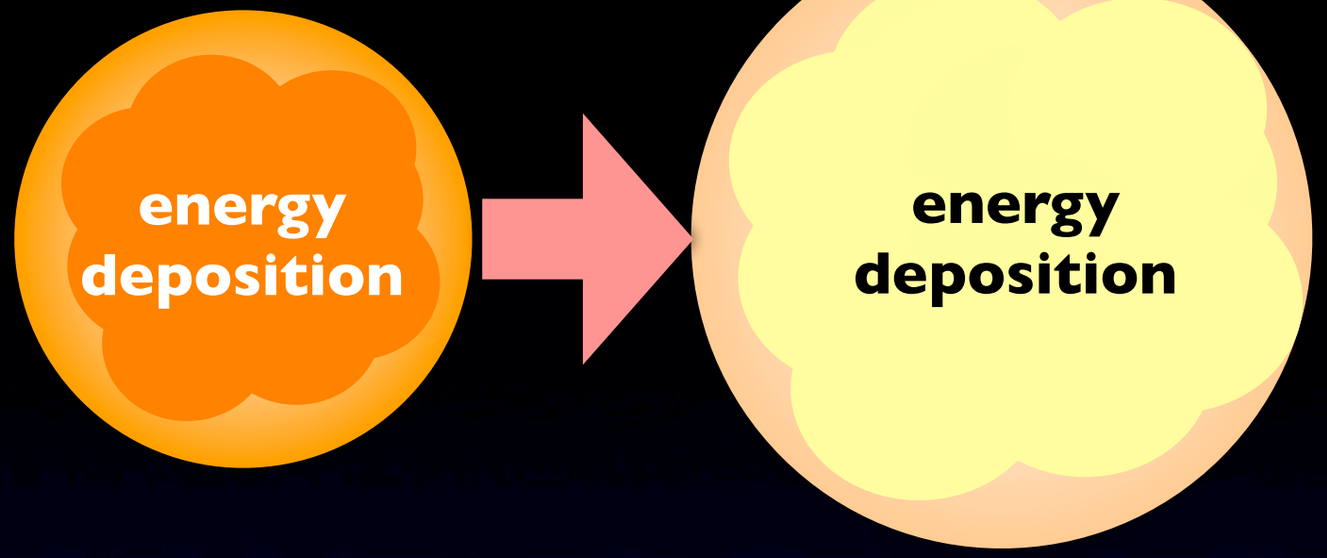
Radioactive-powered emission



Thick against gamma-rays => optical emission

"kilonova"

Li & Paczynski 98
Metzger+10



Timescale

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

Luminosity

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

Opacity of r-process elements

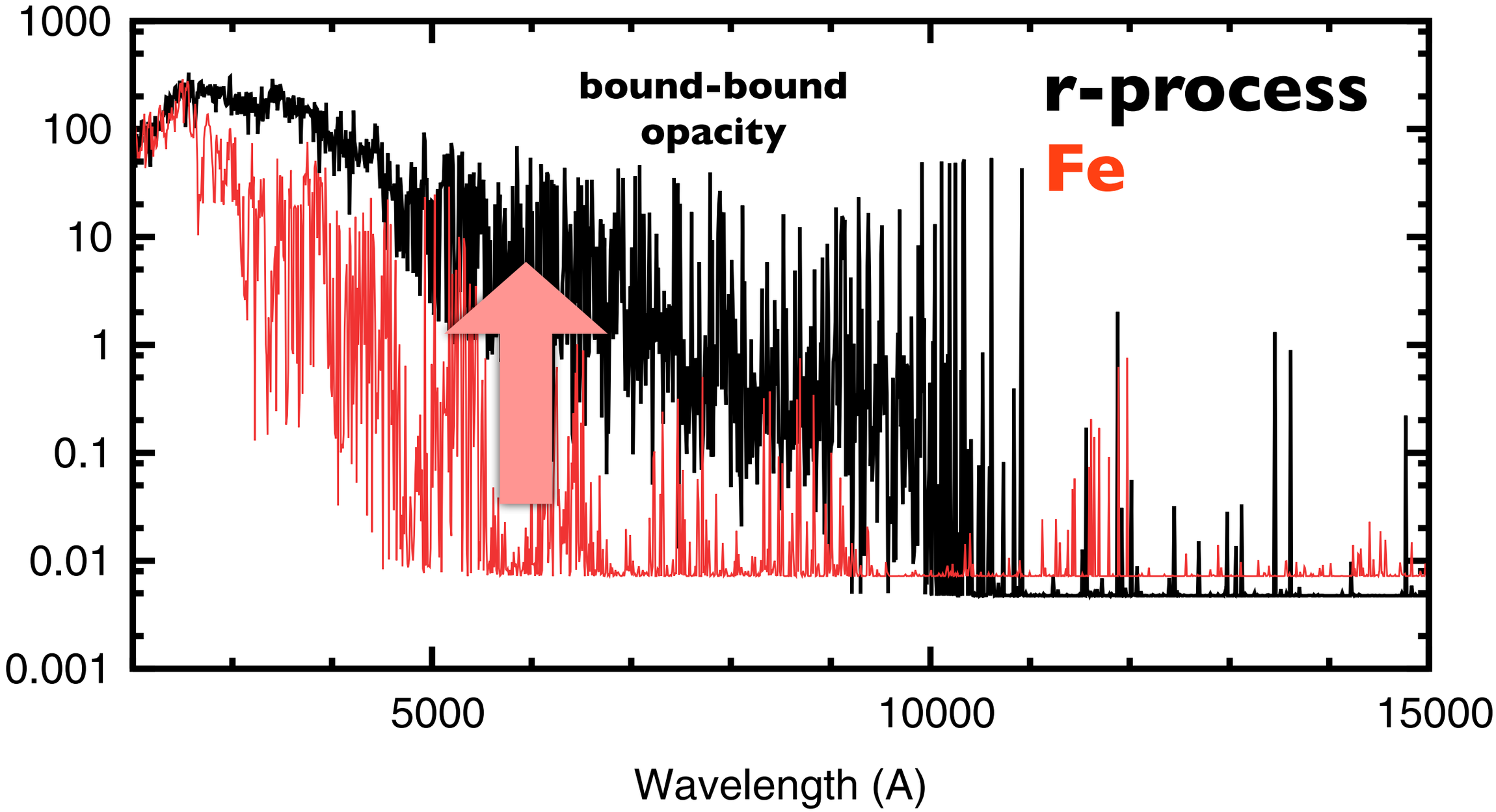
$\kappa \sim 10\ \mathrm{cm^2\ g^{-1}}$

(Kasen+13, MT & Hotokezaka 13)

Bound-bound opacity of Fe

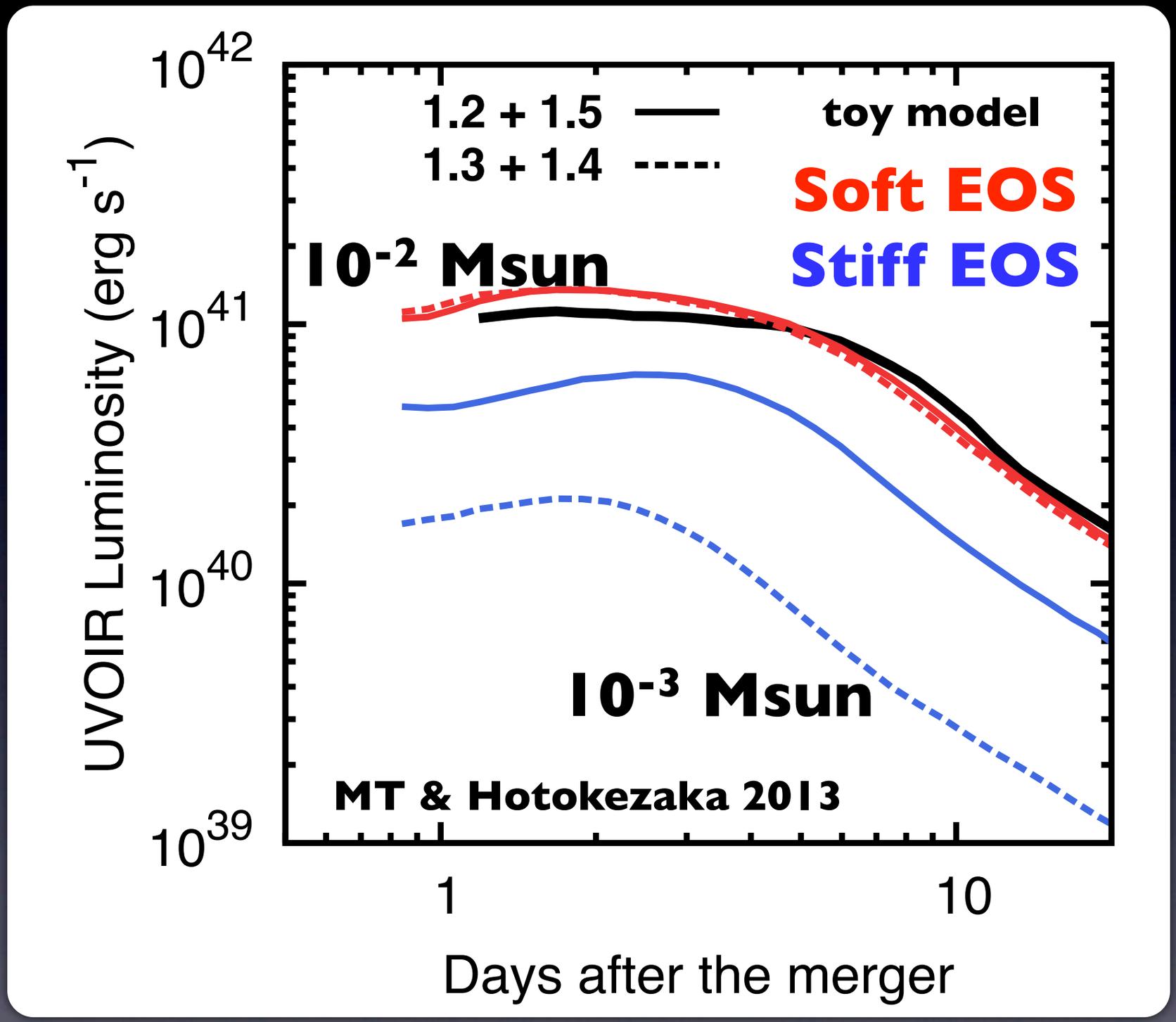
Time = 1.1 days

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



Higher opacity by factor of 100!

Equation of state => EM emission



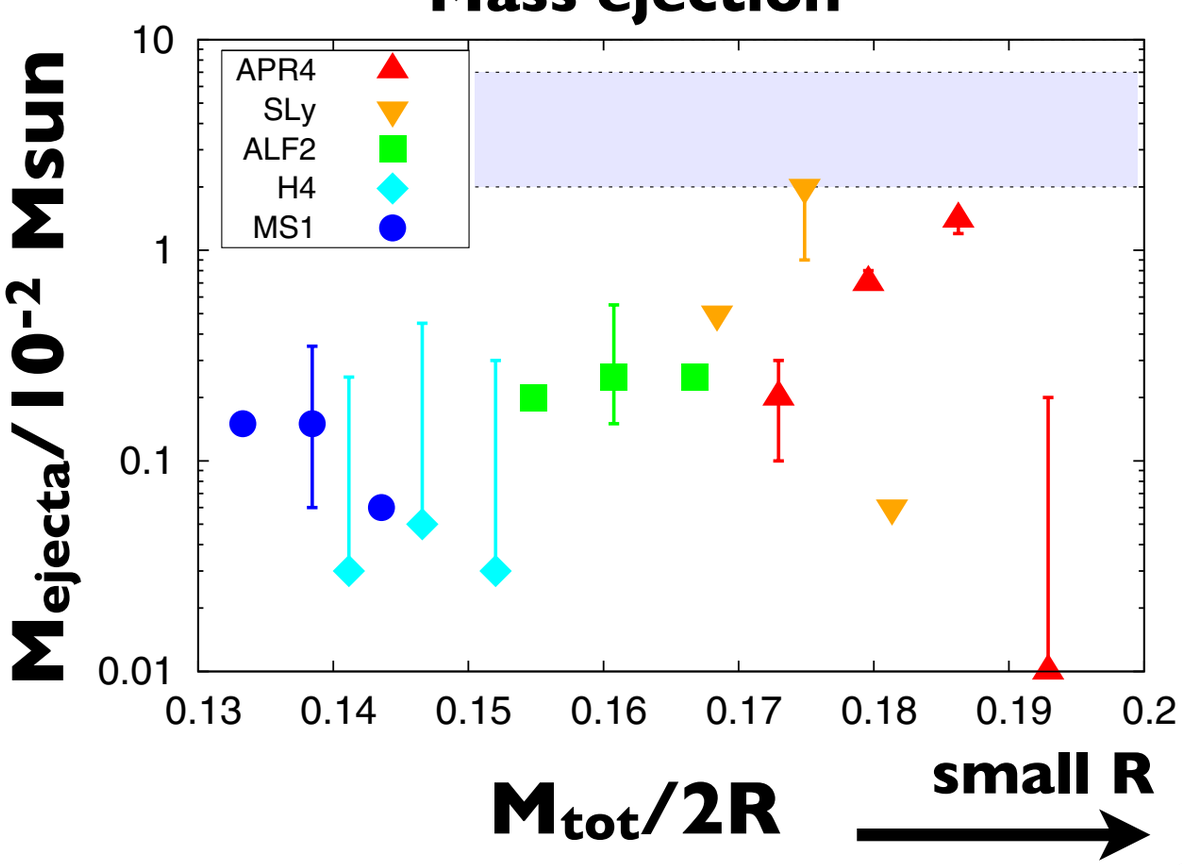
Radius of
1.35 Msun NS

R = 11.1 km
R = 13.6 km

Softer EOS (smaller NS radius) => brighter emission

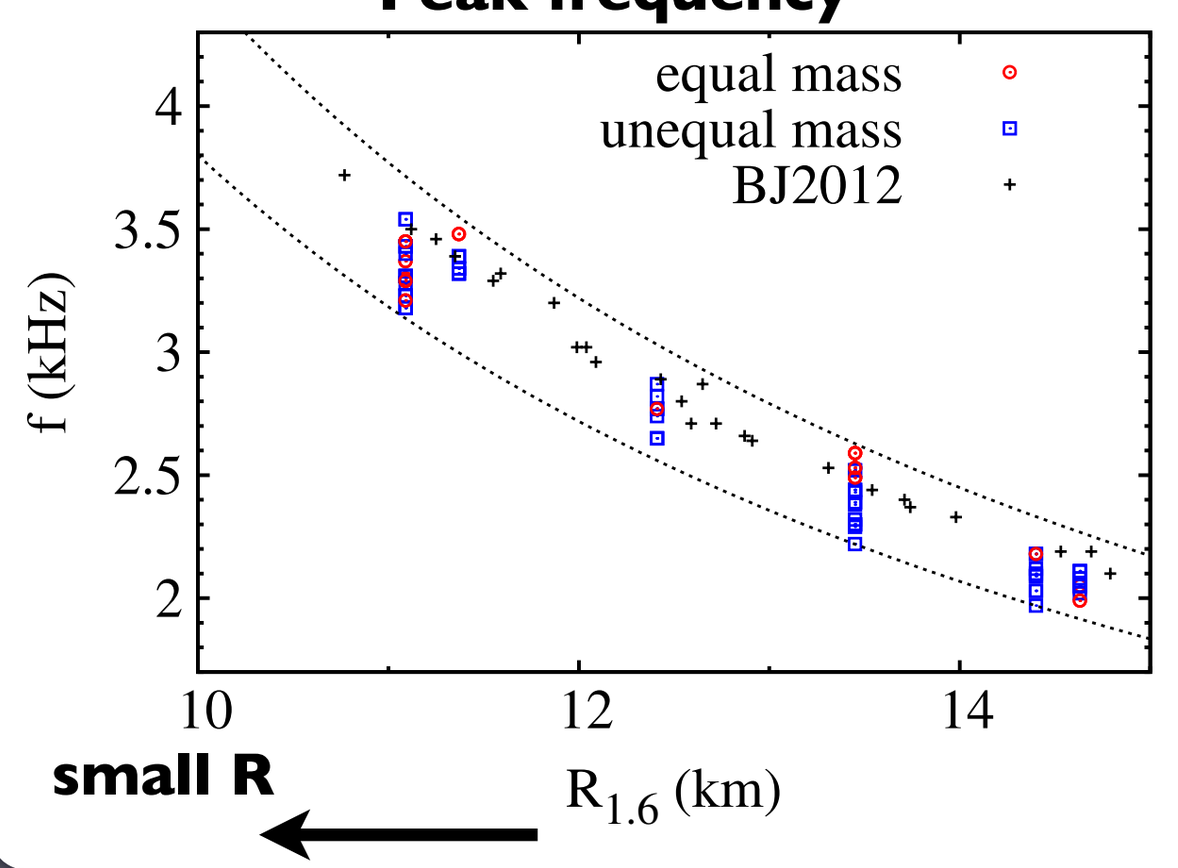
Observational constraints on EOS

EM signal



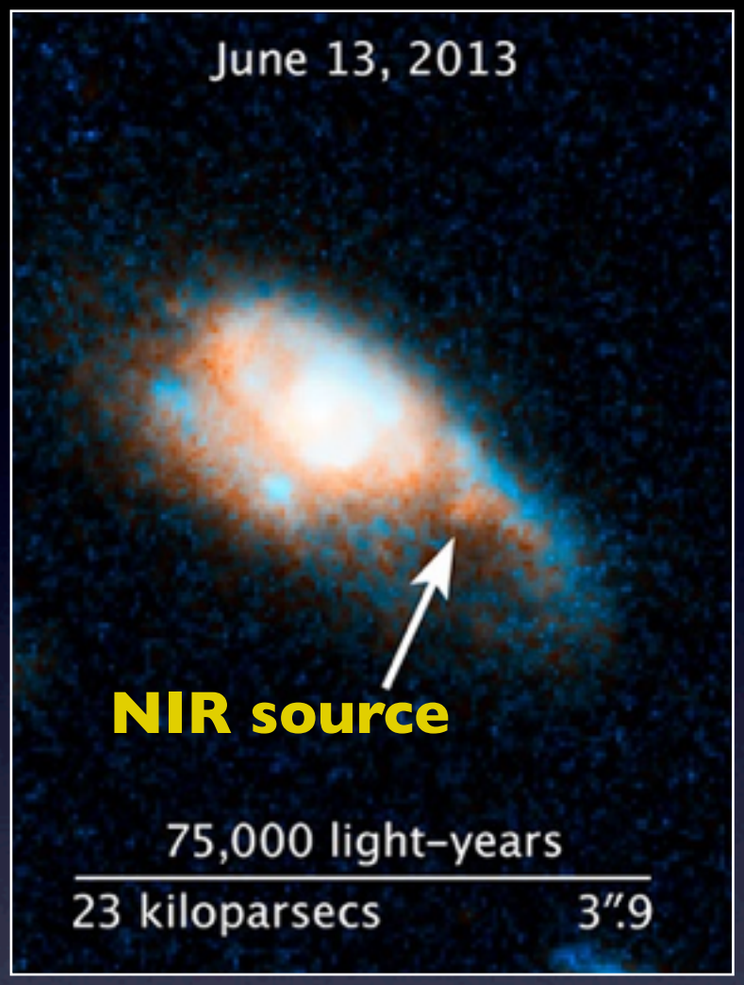
Hotokezaka, Kyutoku, MT+ 2013

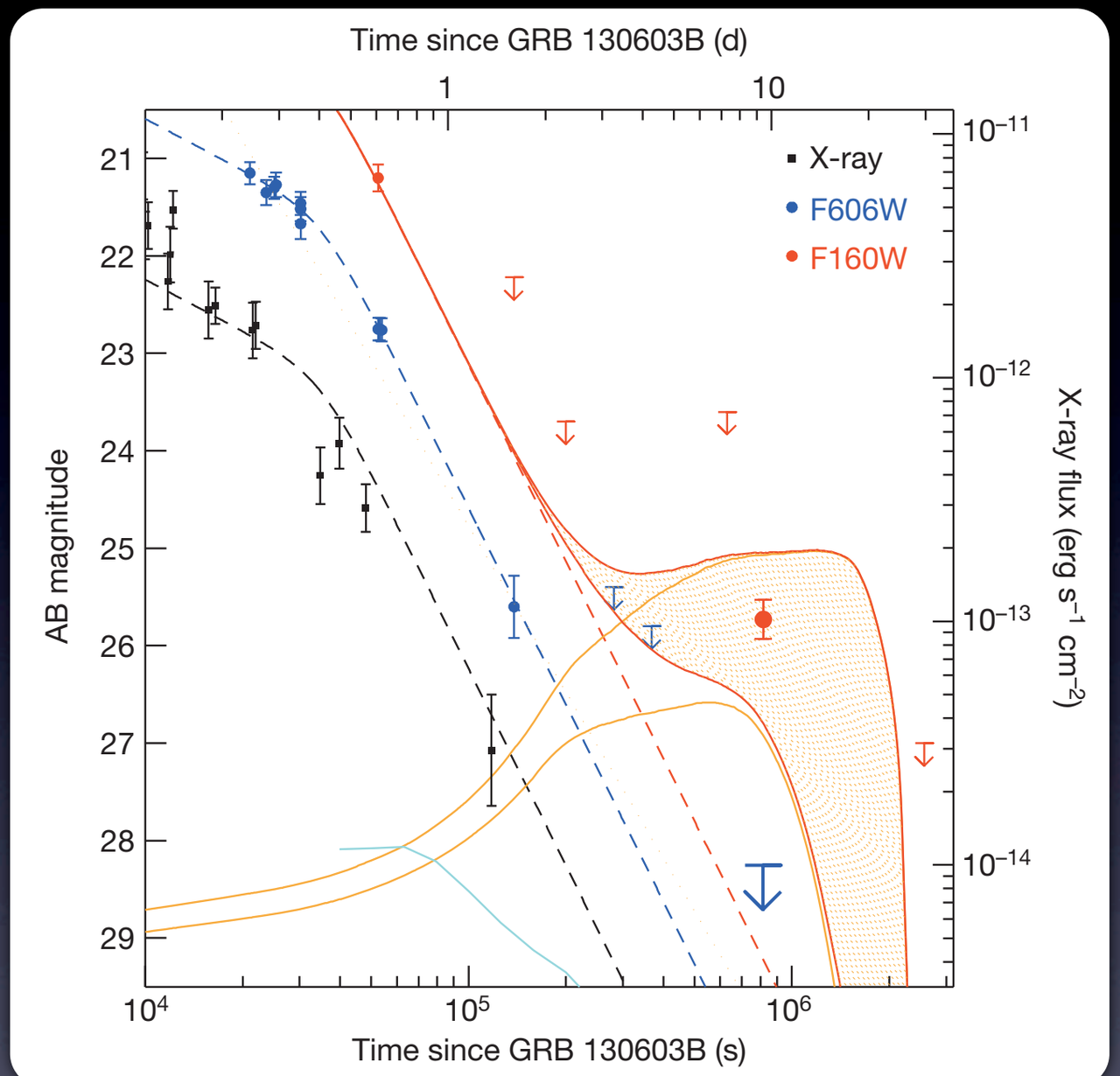
GW signal



Bauswein & Janka 2012
Hotokezaka, Kiuchi, Kyutoku 2013

Kilonova candidate in GRB 130603B





Mej ~ 0.02 Msun => soft EOS (if NS merger)

Hotokezaka, Kyutoku, MT+2013

see also Takami, Nozawa, Ioka 2014
Kisaka, Ioka, Takami 2014 (Kisaka-san's poster No 23)

Amount 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 events/yr

(~0.3-300)

↓

Ejection per event

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

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

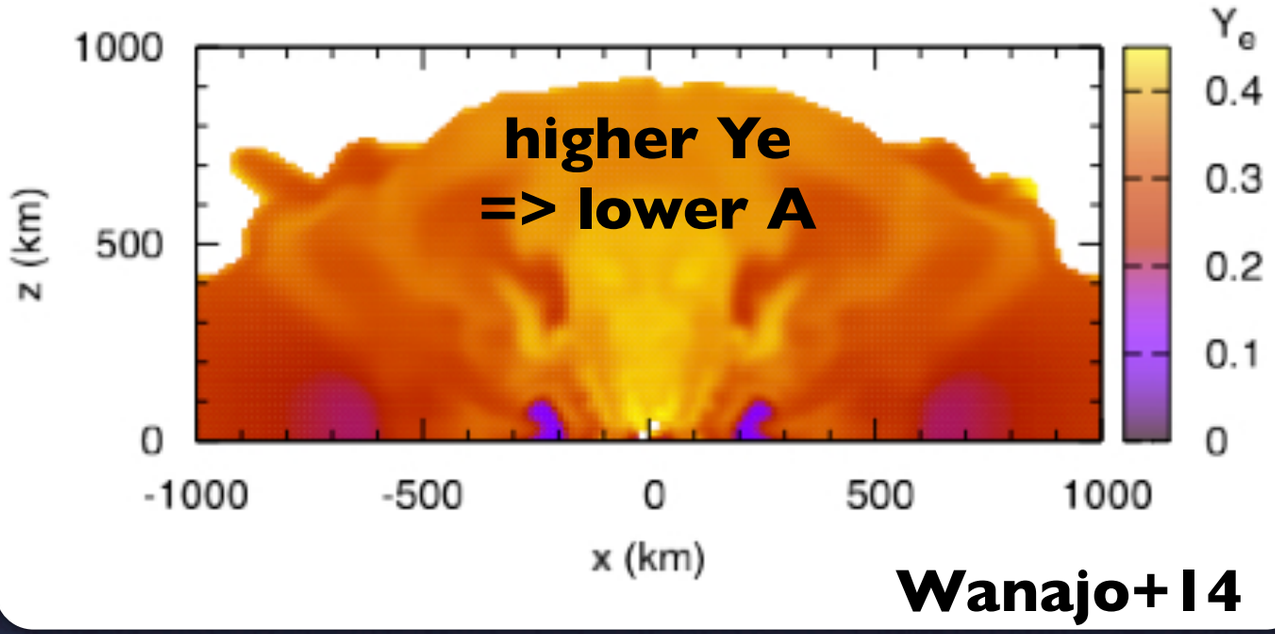
~ 10^{-2} x 10^{-4} x 10^{10} ~ 10^4 Msun

"Testable" scenario for r-process nucleosynthesis

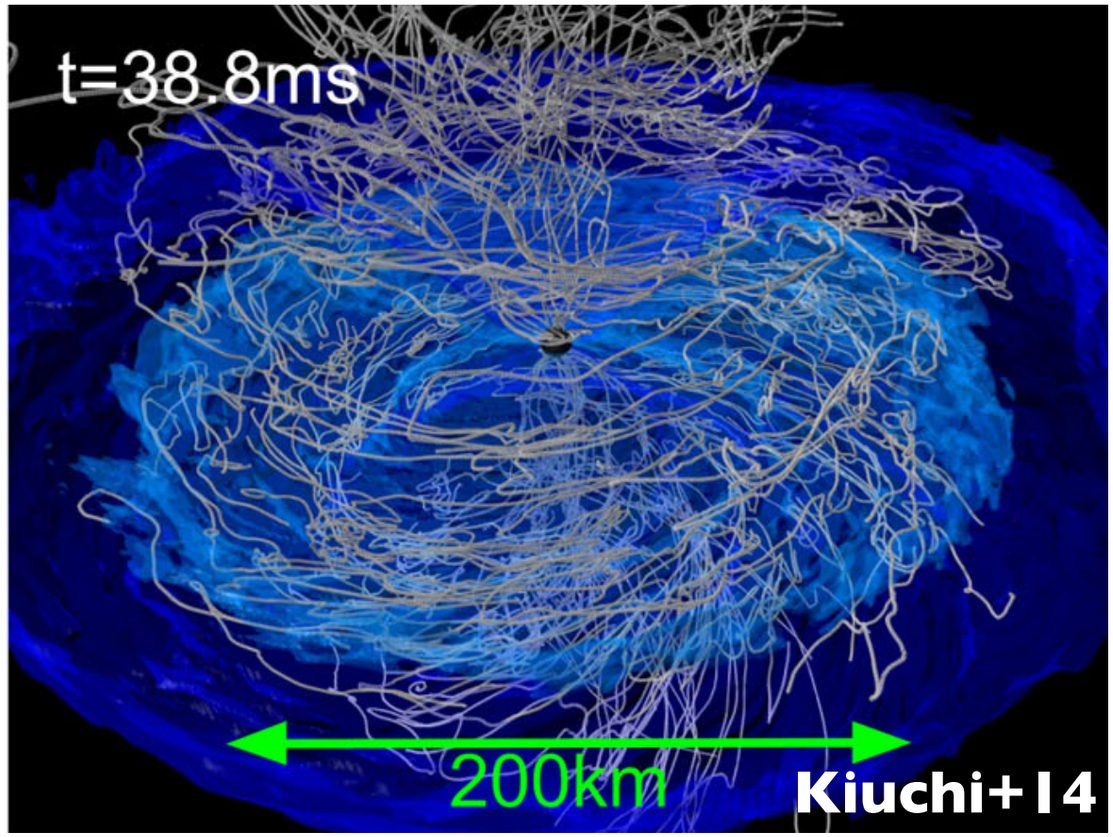
Multi-Messenger Studies of Compact Binary Merger

- Mass ejection and nucleosynthesis
- Electromagnetic wave signals
- Toward multi-messenger astronomy

I. Numerical simulations



Wanajo+14



Kiuchi+14

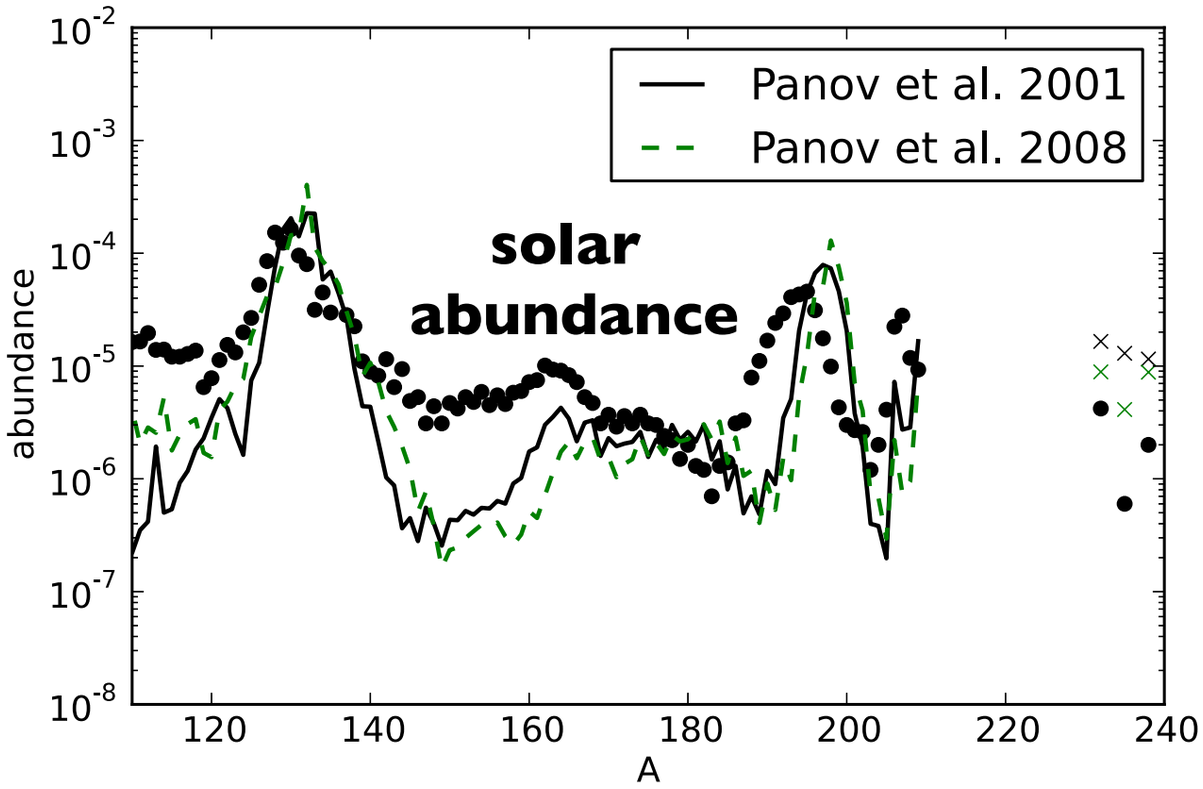
Effect of neutrino
=> EM emission can be brighter/bluer

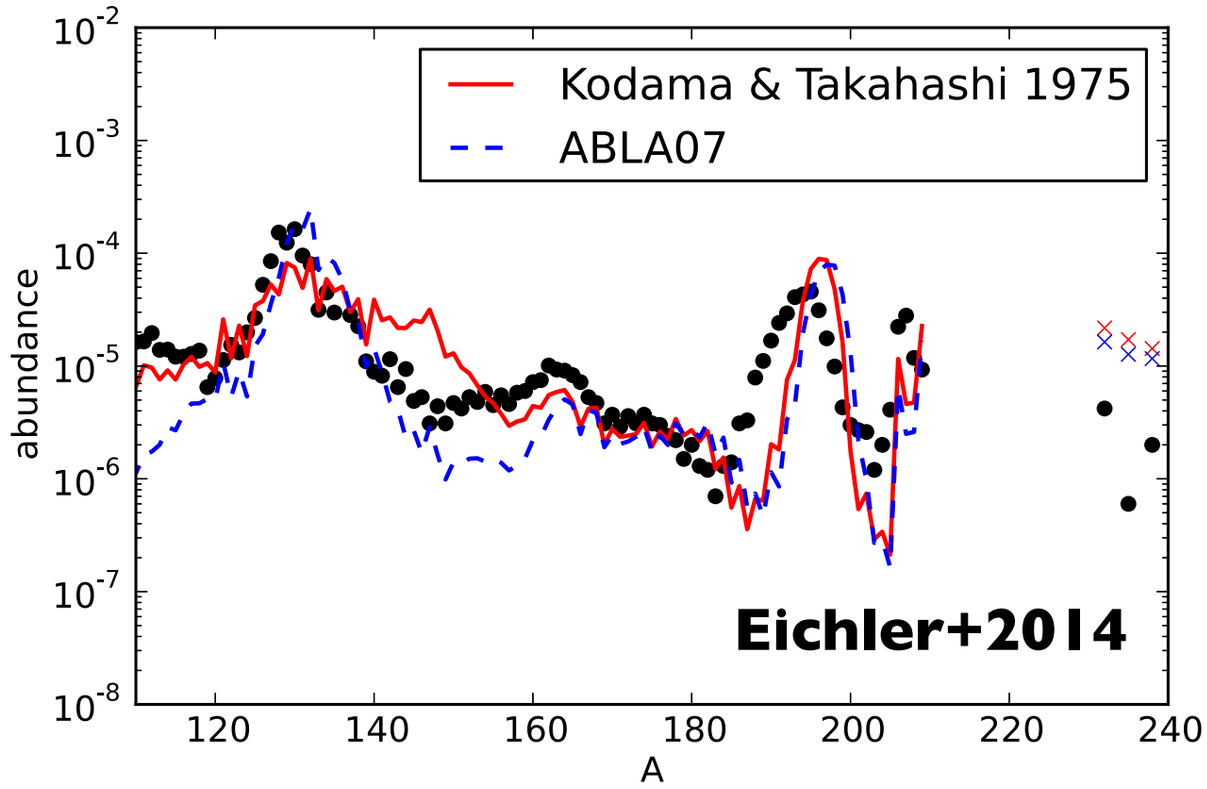
(e.g., Just+14, Metzger+14, Kasen+14)

Magnetized NS
=> Additional mass ejection?
(Kiuchi-san's talk)

Numerical relativity + radiative transfer (ν+EM)

2. Nuclear physics

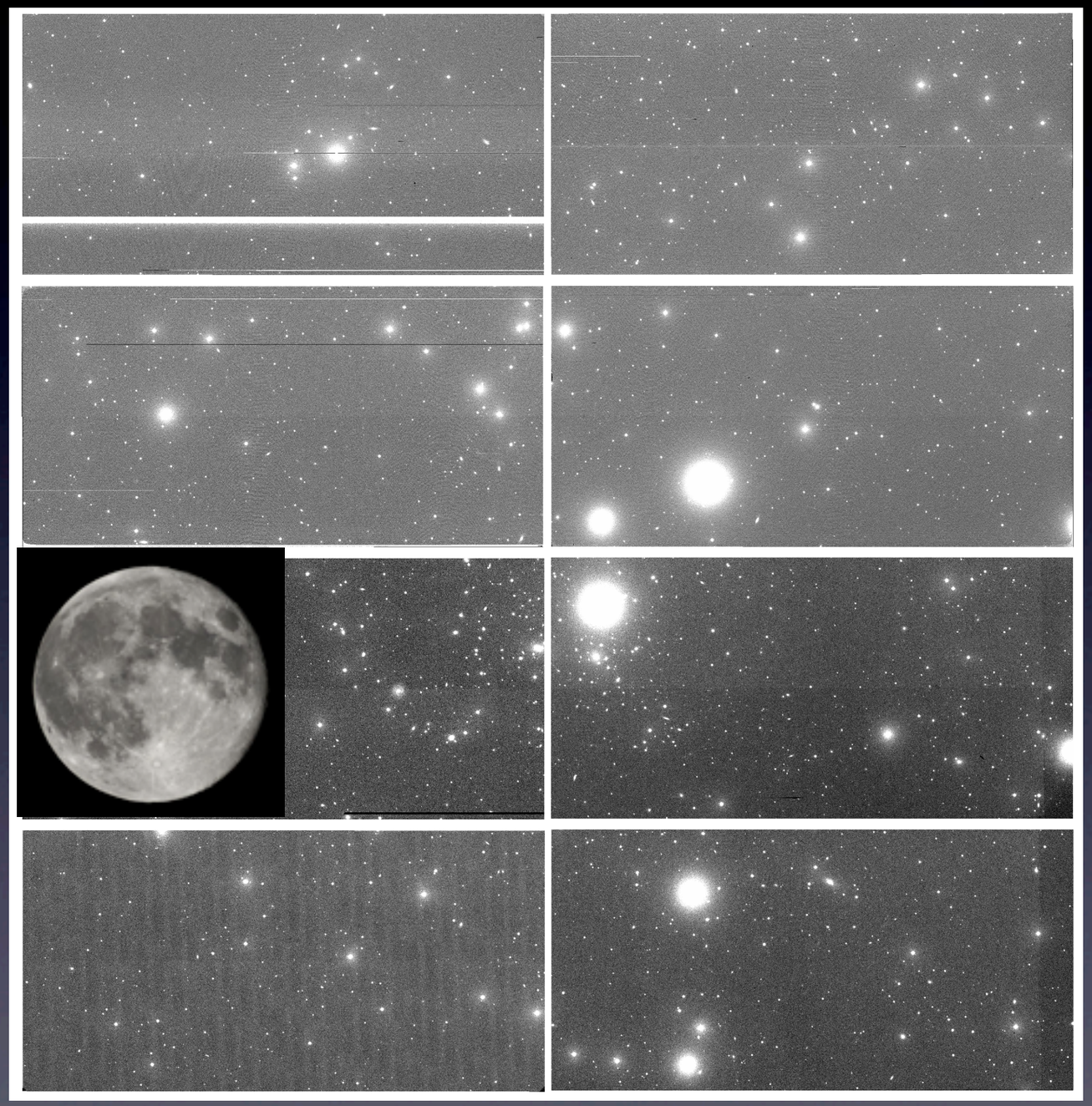




Same NS merger model
with different fission fragment distribution

see Shibagaki-san's poster (No 31)

3. EM counterpart search



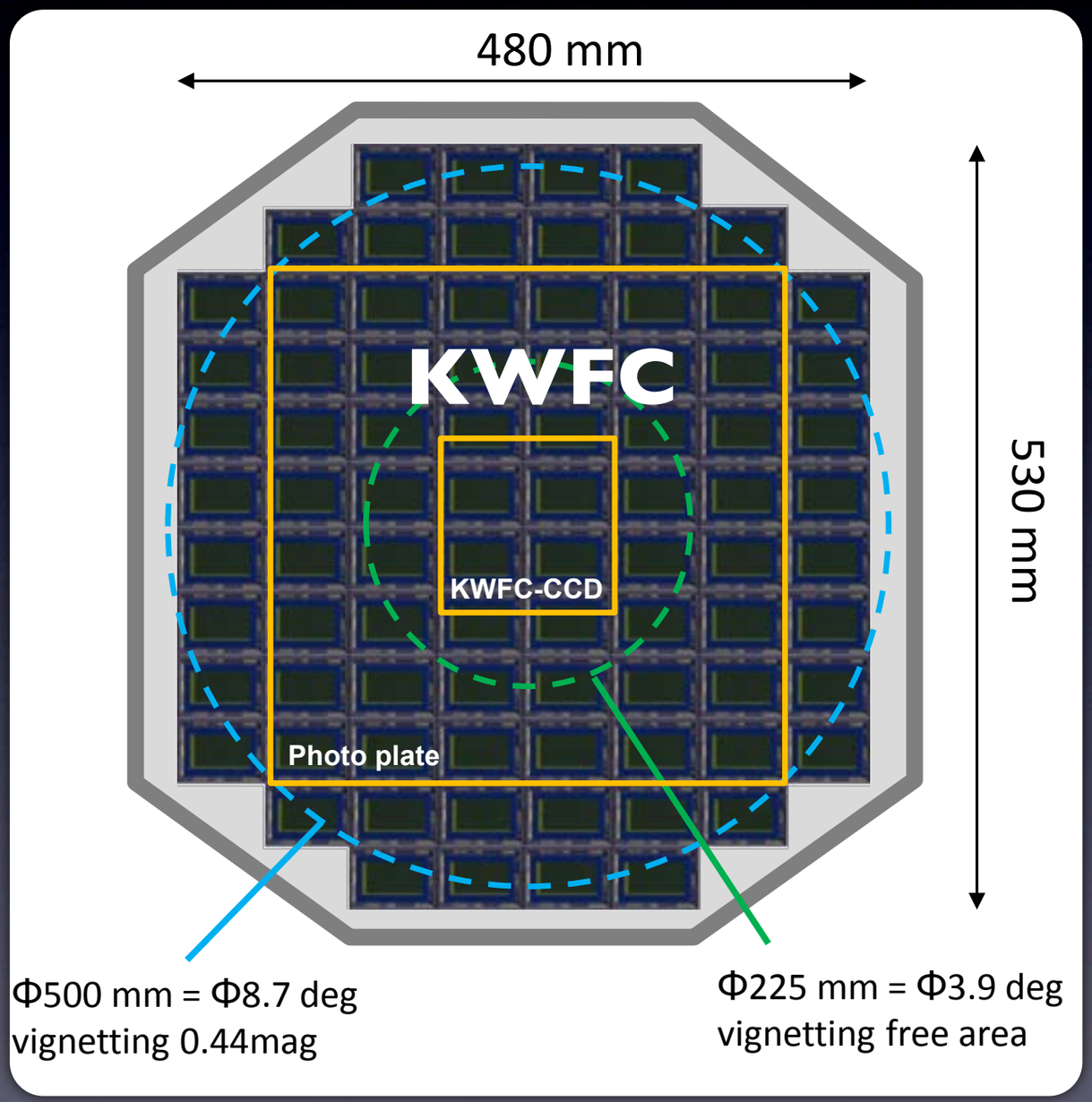
2 deg

Kiso 1.05m Schmidt telescope

MOU between
Japanese Opt/IR group
and
LIGO/Virgo collaboration

Toward wider field of view
- Tomo-e camera -

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



(PI: Shigeyuki Sako)

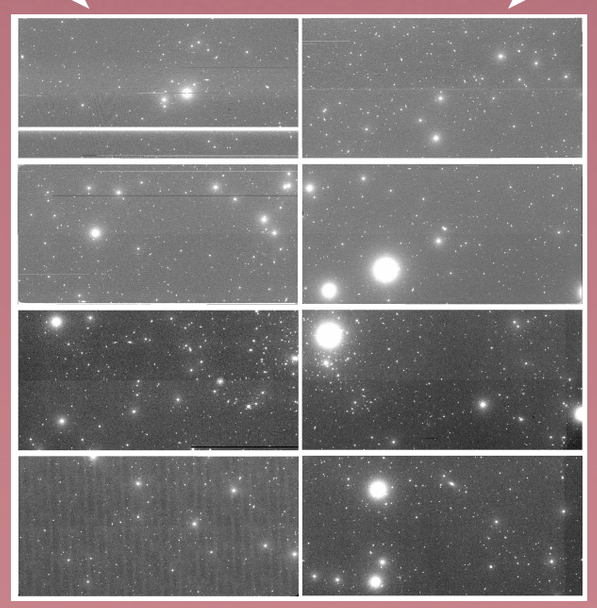
- **Large FOV Ω (20 deg²)**
- **Efficient observation f**

Survey power = fAΩ

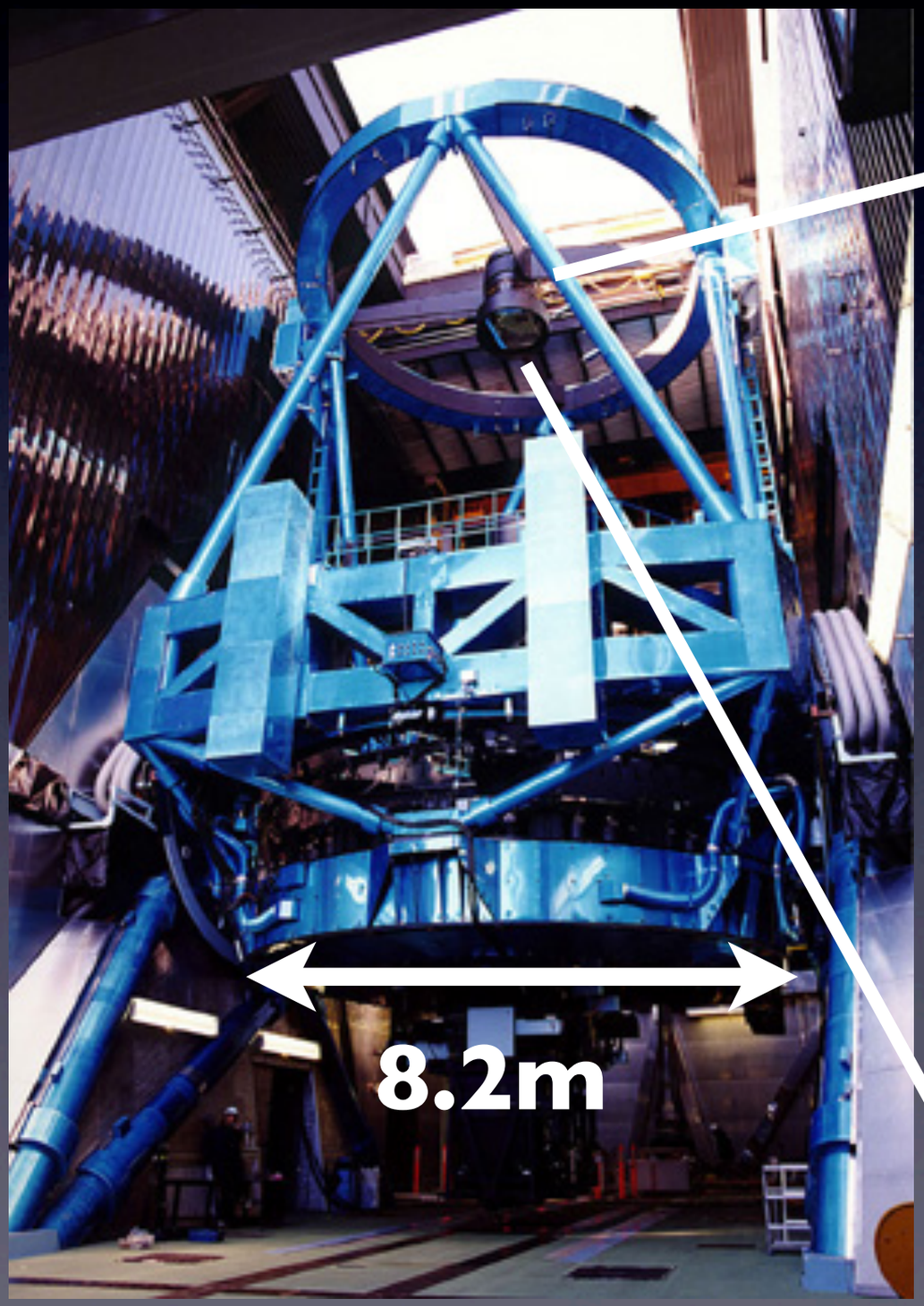
GW alert error box
e.g. 6 deg x 6 deg

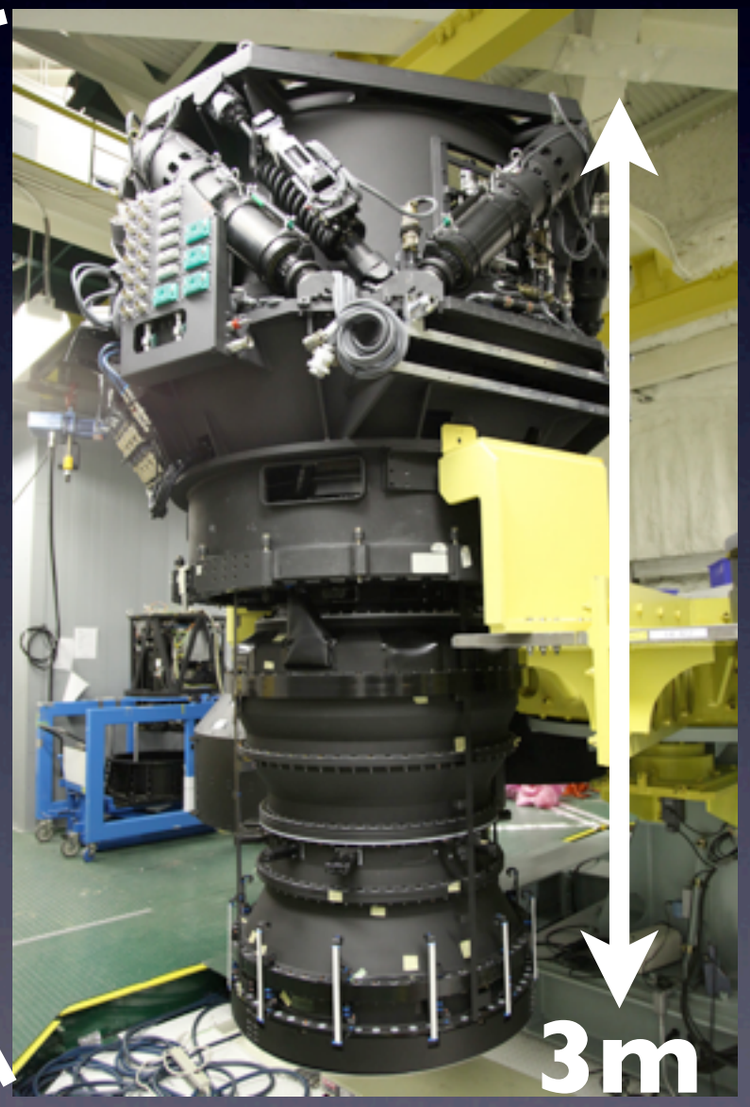
Kiso/Tomo-e
9 deg

Kiso/CCD
2 deg

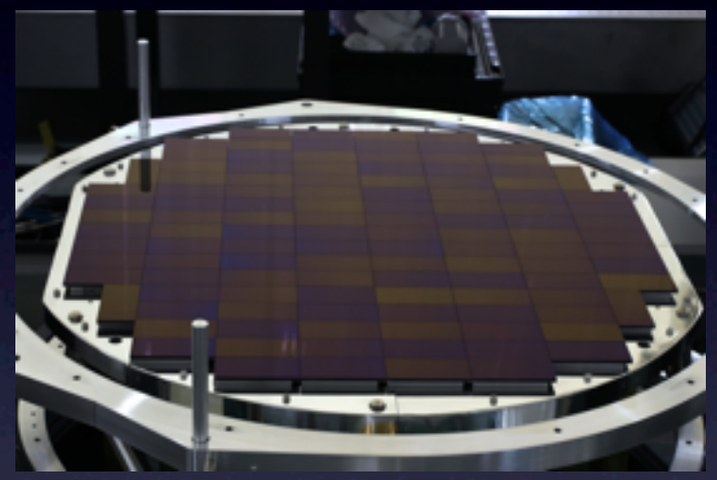


Subaru/ Hyper Suprime-Cam





3t !



104 CCDs

~ 900 Megapixel

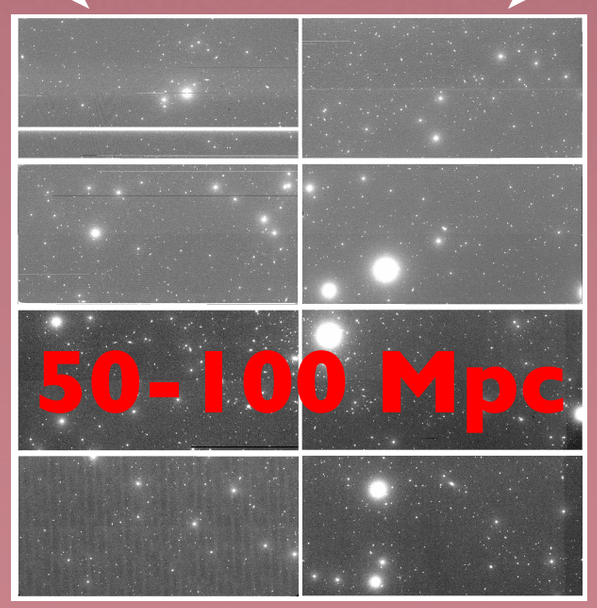
2 GB/image

~300 GB/night

GW alert error box
e.g. 6 deg x 6 deg

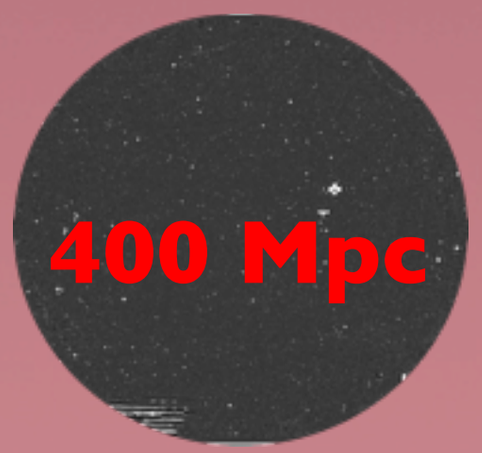
Kiso/Tomo-e
9 deg

Kiso/CCD
2 deg

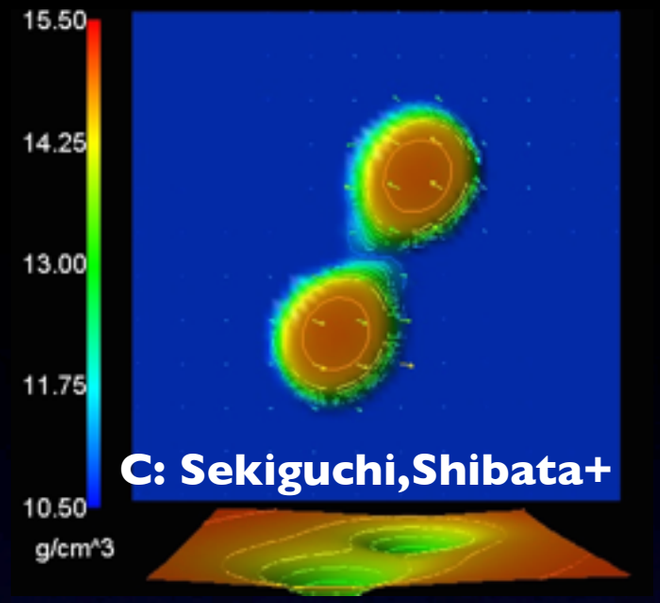


Subaru/HSC
1.5 deg

8m-class telescope



Numerical simulation



EM astronomy

GW astronomy

“Multi-messenger” astronomy

+Nuclear physics

+Galaxy evolution

Origin of r-process elements
Neutron star radius (High-density EOS)