Supernova as Sources of Multi-messenger Signals

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KN+, submitted to MNRAS, arXiv:1602.03028

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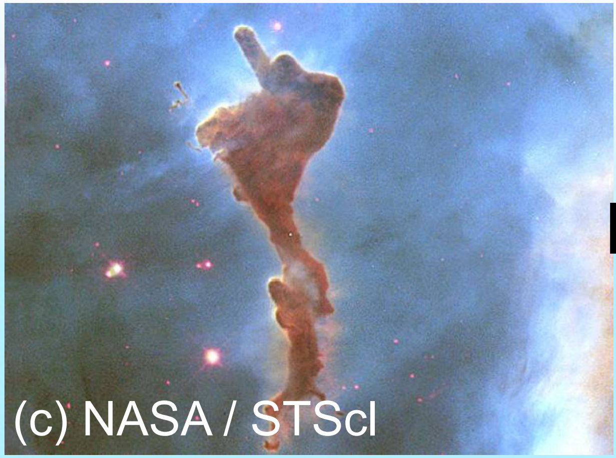
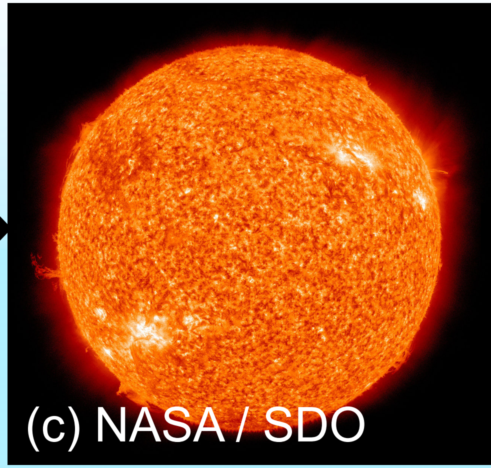
May 11-13, 2016

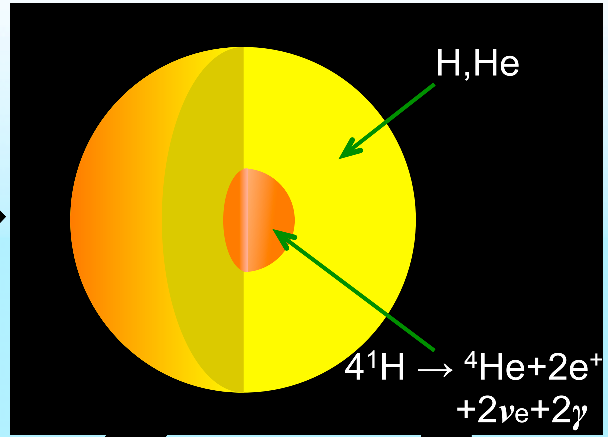
Stellar formation, evolution, and explosion



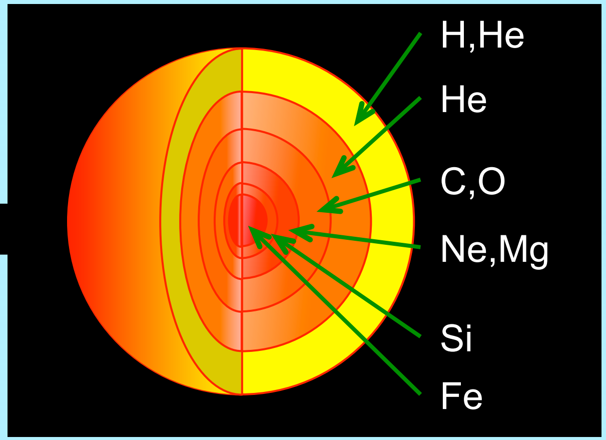
(η Carina Nebula)



(Far-UV image of the Sun)

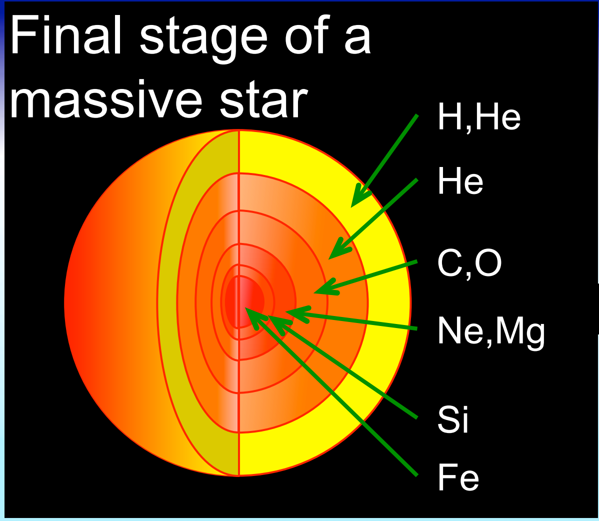


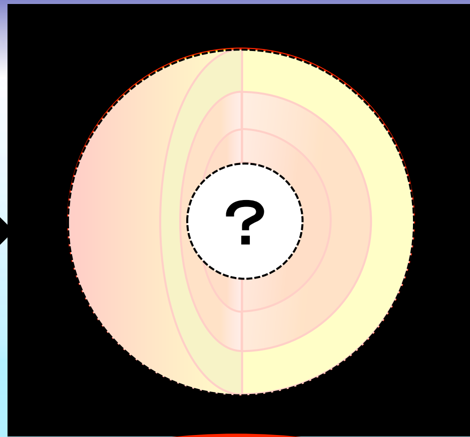
$M > \sim 10 M_o$



White Dwarf

How to create a Core-collapse SN (CCSN)





Basic equations:

$$\frac{d\rho}{dt} + \rho \nabla \cdot \mathbf{v} = 0$$

$$\rho \frac{d\mathbf{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

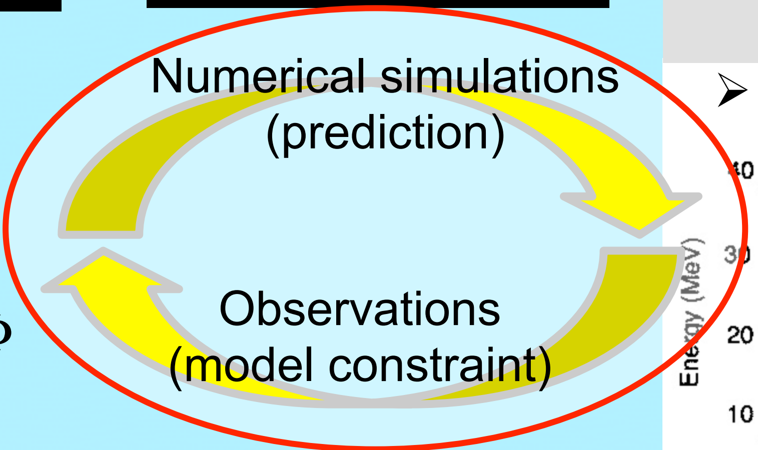
$$\frac{\partial e^*}{\partial t} + \nabla \cdot [(e^* + P)\mathbf{v}] = -\rho \mathbf{v} \cdot \nabla \Phi + Q_E$$

$$\frac{dY_e}{dt} = \Gamma_N$$

$$\triangle \Phi = 4\pi G \rho$$

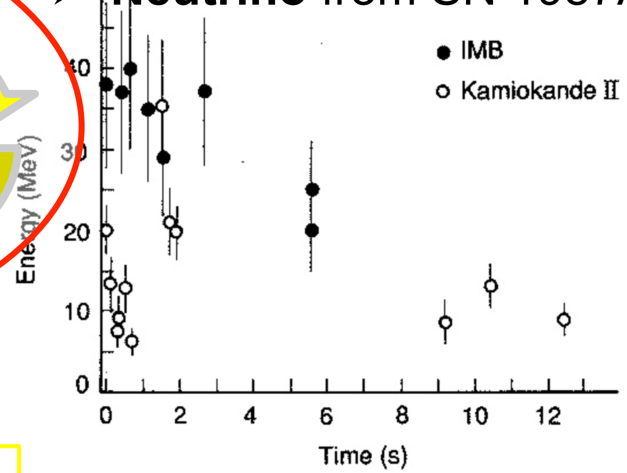
+ EOS.

Energy and electron fraction change due to neutrino interactions.



Multi-messenger signals from CCSNe

- **Neutrino** from SN 1987A



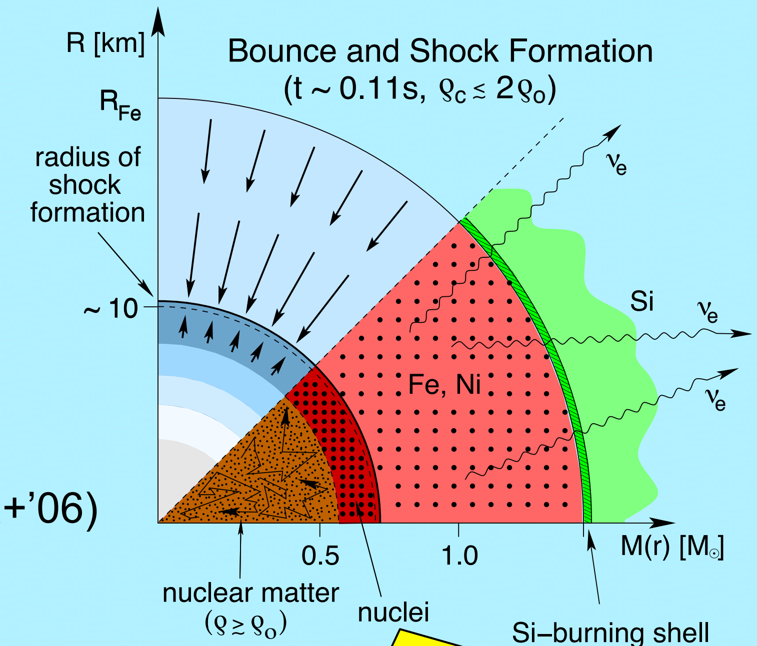
- **Gravitational wave**
- **Electromagnetic wave**

Outline

- Introduction
- Core-collapse supernova (CCSN) model
  - numerical simulation and results
  - multi-messenger signals
- Observation strategy
  - neutrino, GW, & EM signals / detectors
- Summary & Discussion

Explosion mechanism of CCSN

- Core-collapse supernova
  - Final fate of massive stars（>~10Mo）
  - Unclear mechanism of explosion
  - **Neutrino heating mechanism**
  - Convection, SASI



(Janka+'06)

$\nu_e + n \rightarrow p + e^-$,
$\bar{\nu}_e + p \rightarrow n + e^+$, etc.

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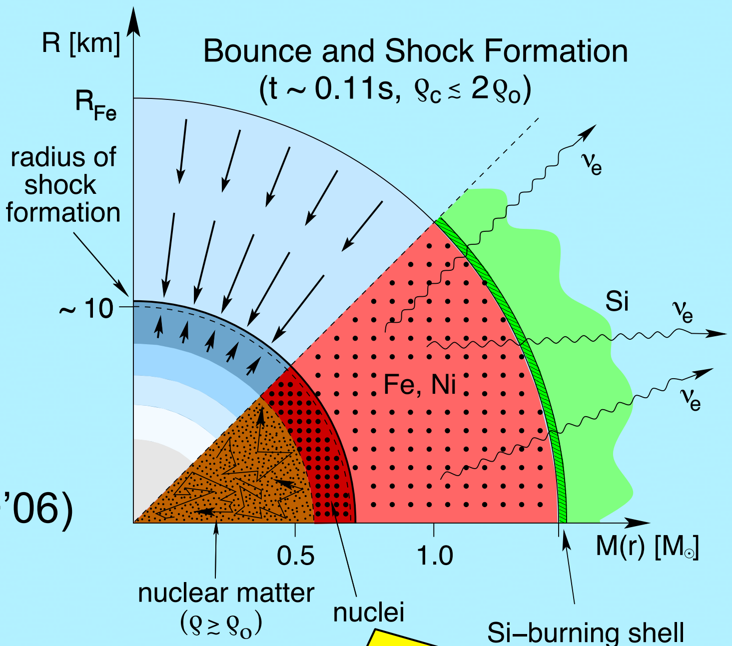

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$\nu_e + n \rightarrow p + e^-$,
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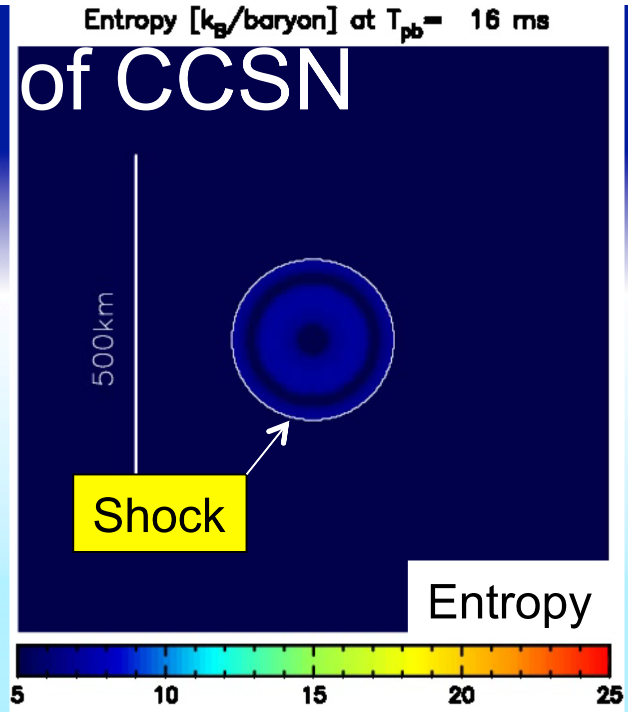
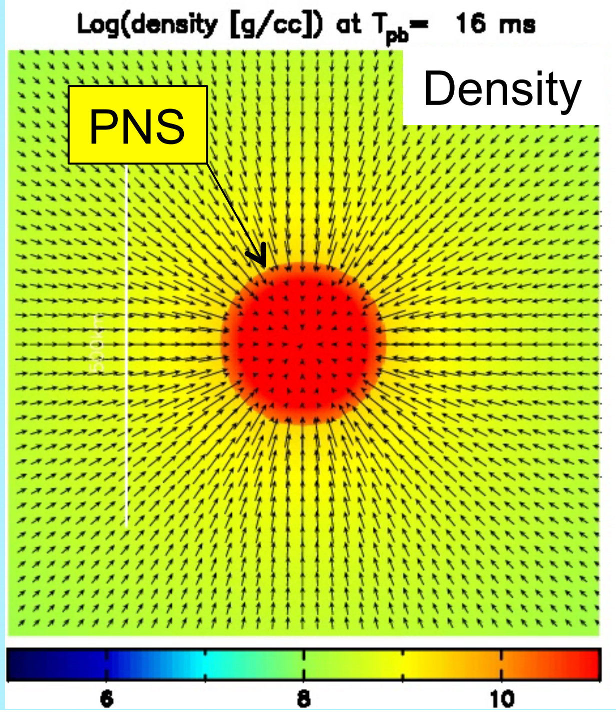
ex.)
M = 17 Mo
Z = Zo





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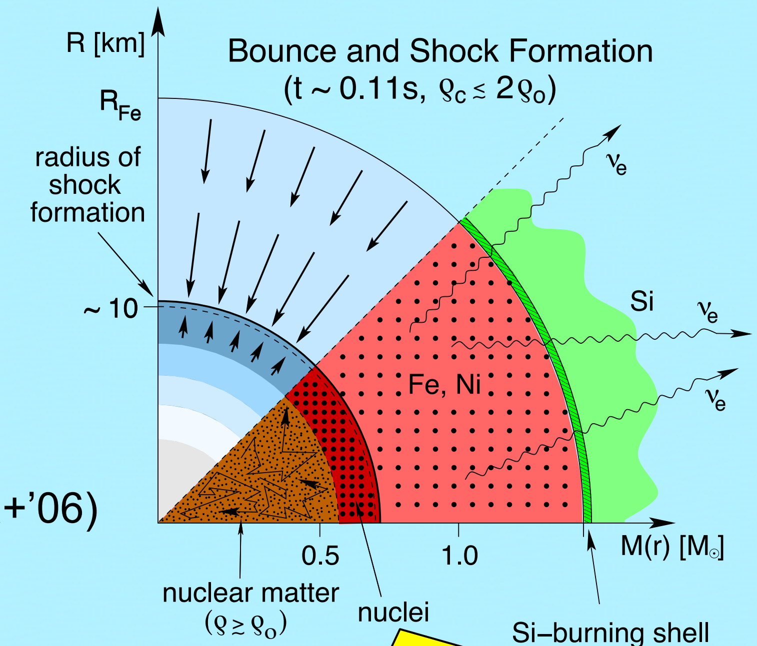

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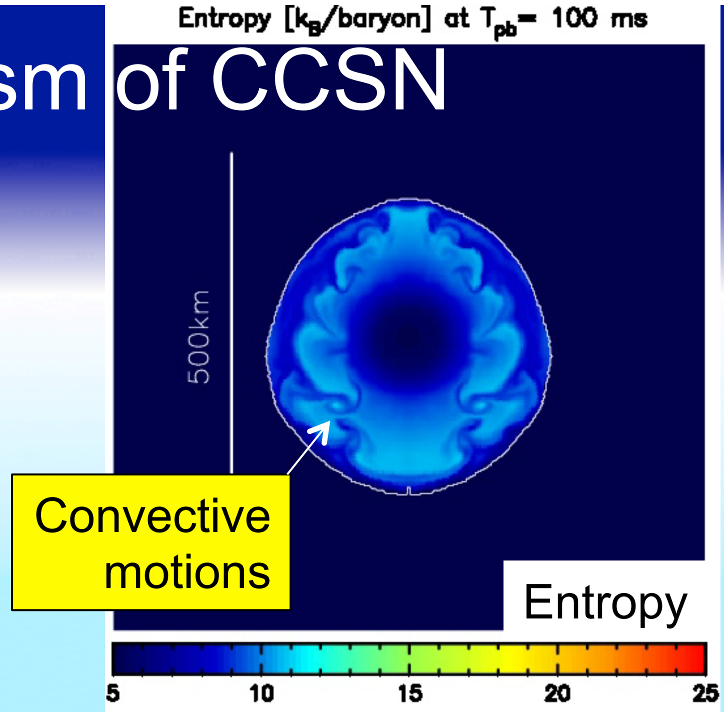
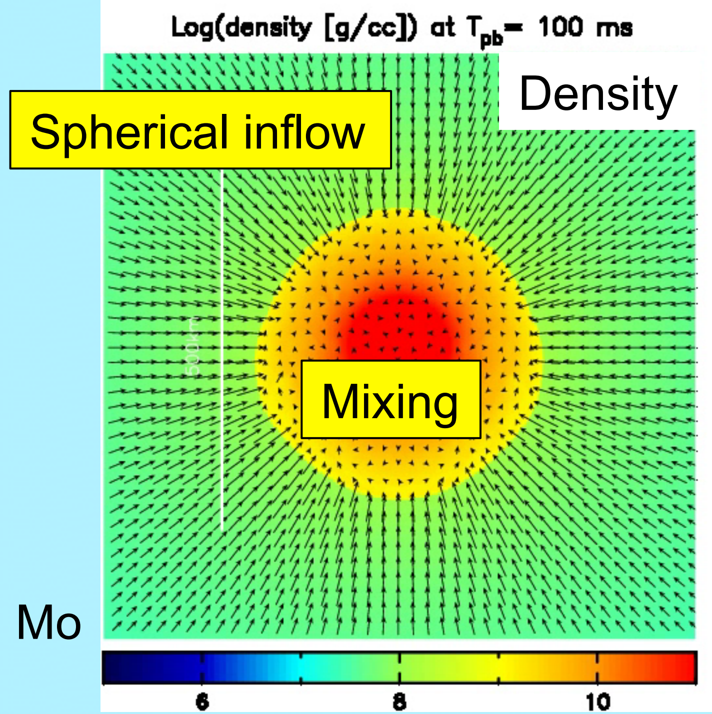


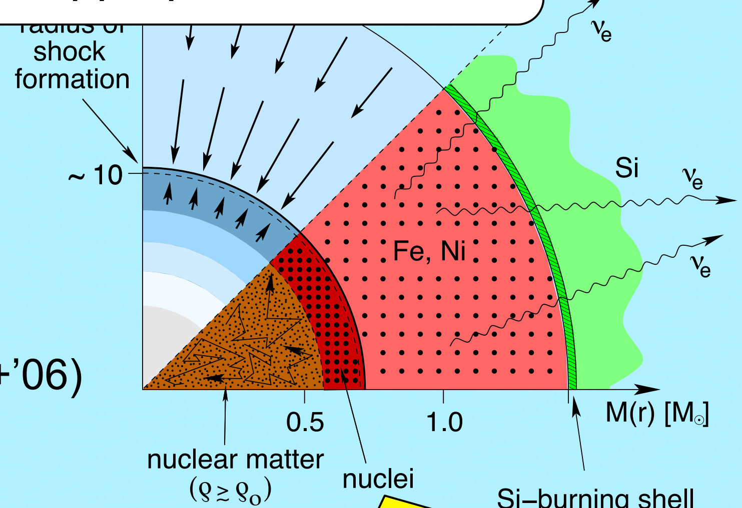


Explosion mechanism of CCSN

Neutrino transport
from interior of PNS to outside of the shock
Energy distribution
to solve energy-dependent reactions

– **Neutrino heating mechanism**
– Convection, SASI

~~1D~~/**2D**/3D
with appropriate resolution



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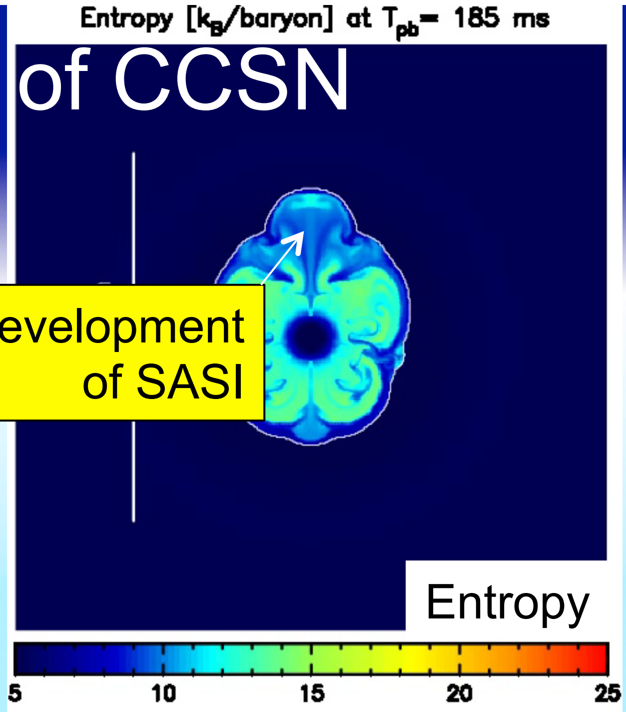
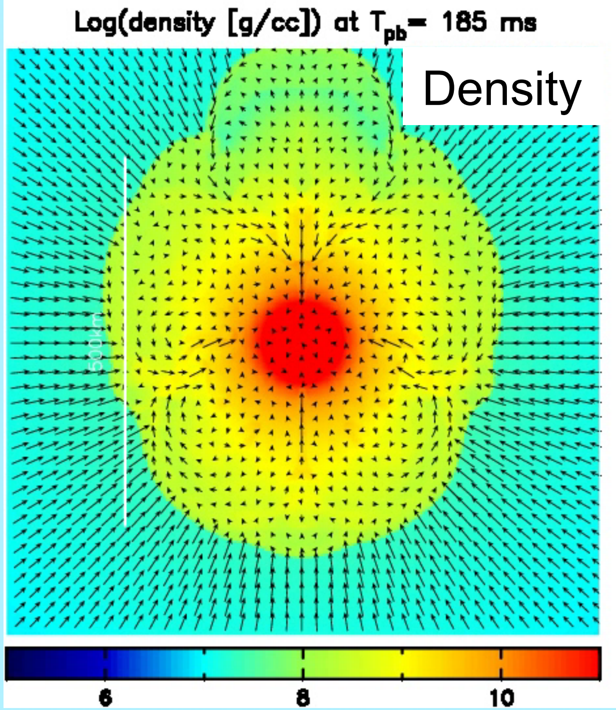
Development of SASI



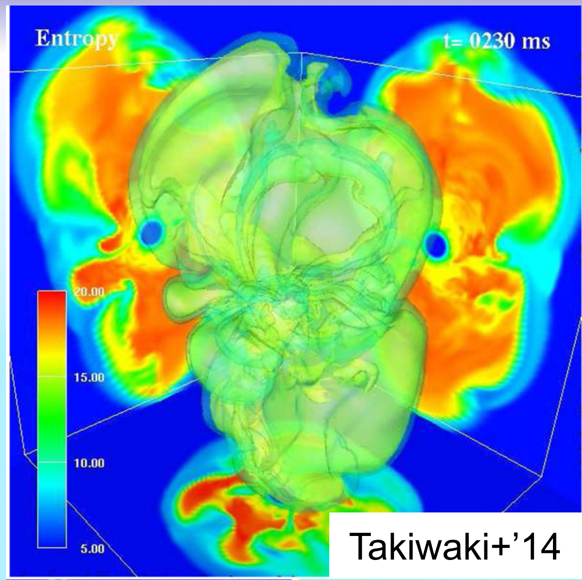


Numerical simulations of CCSNe

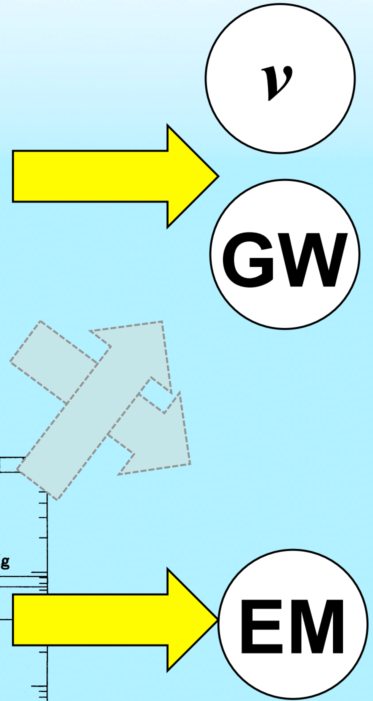
➢ **Detailed simulations**

R<5000km, t<1s
(small & short)

2D／3D simulations
taking account of ν transport.
Comp. cost is very high.



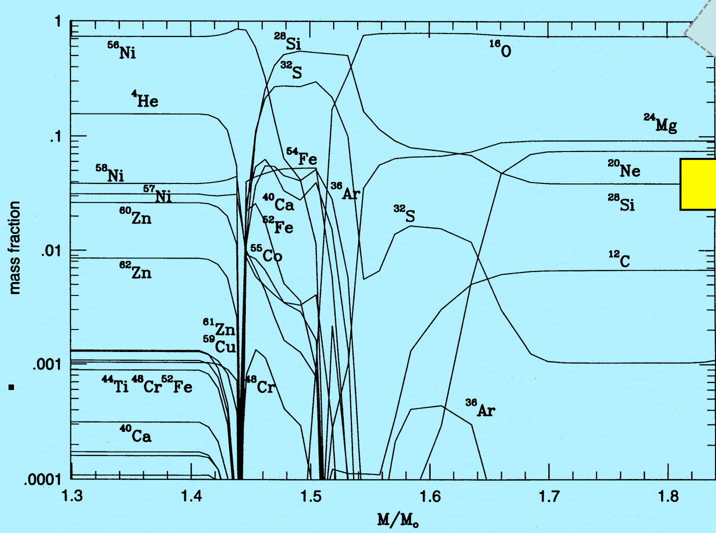
Takiwaki+'14



➢ **Simplified models**

R>~10^{13}cm, t>~10^4s
(large & long)

1D／2D simulations by
thermal bomb／piston model.
→ nucleosynthesis

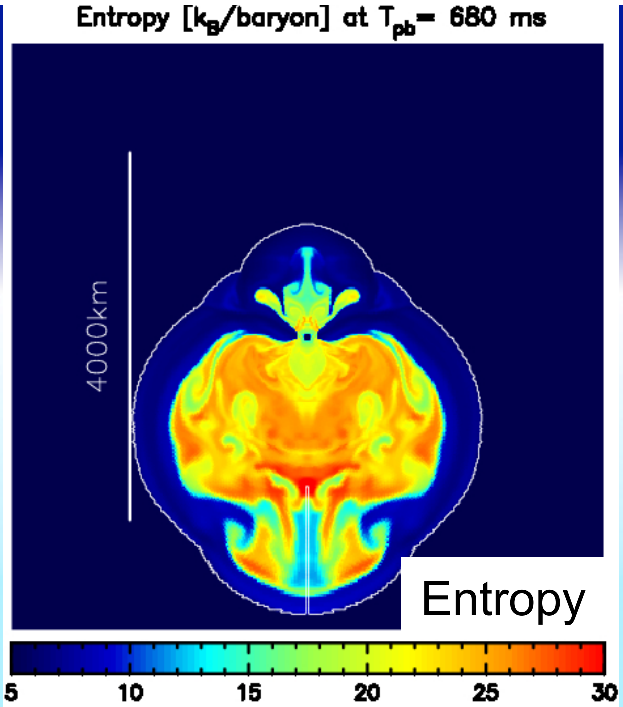


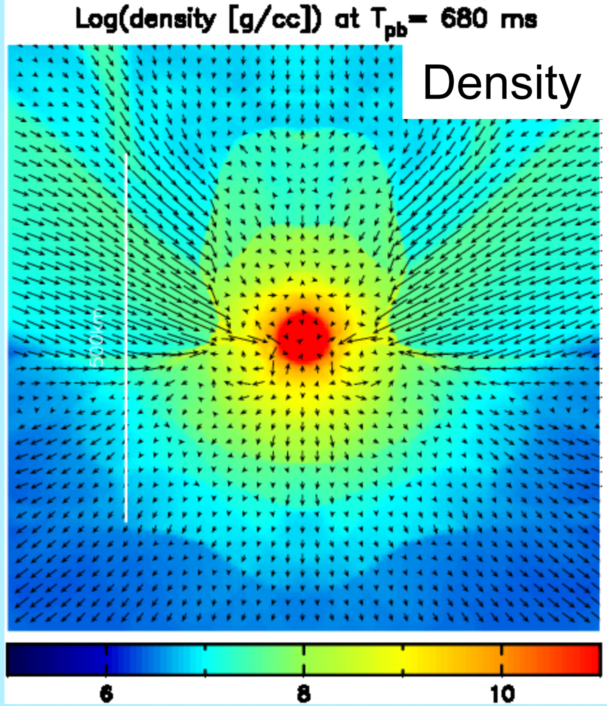
Thielemann+'96

Long-term CCSN simulation

- **Numerical code**
  - **2D**, n(r)*n(θ) = 1008*128
    r=0-**100,000 km**, θ=0-π
  - Neutrino transport
    $\nu e, \overline{\nu e}$: **IDSA spectral transport** (Liebendoerfer+09)
    νx : **leakage scheme**
    with 20 energy bins (< 300 MeV)
- **EoS**
  - LS220 (Lattimer & Swesty '91) + Si gas
- **Nuclear reactions**
  - 13α (He-Ni) network
- **Progenitor model**
  - **M = 11.2, 17, 27 Mo**, Z = Zo, w/o rotation & B-field
  (Woosley, Heger, & Weaver '02)

- Numerical computations were carried out on Cray XC30（576 cores × 20 days / model）





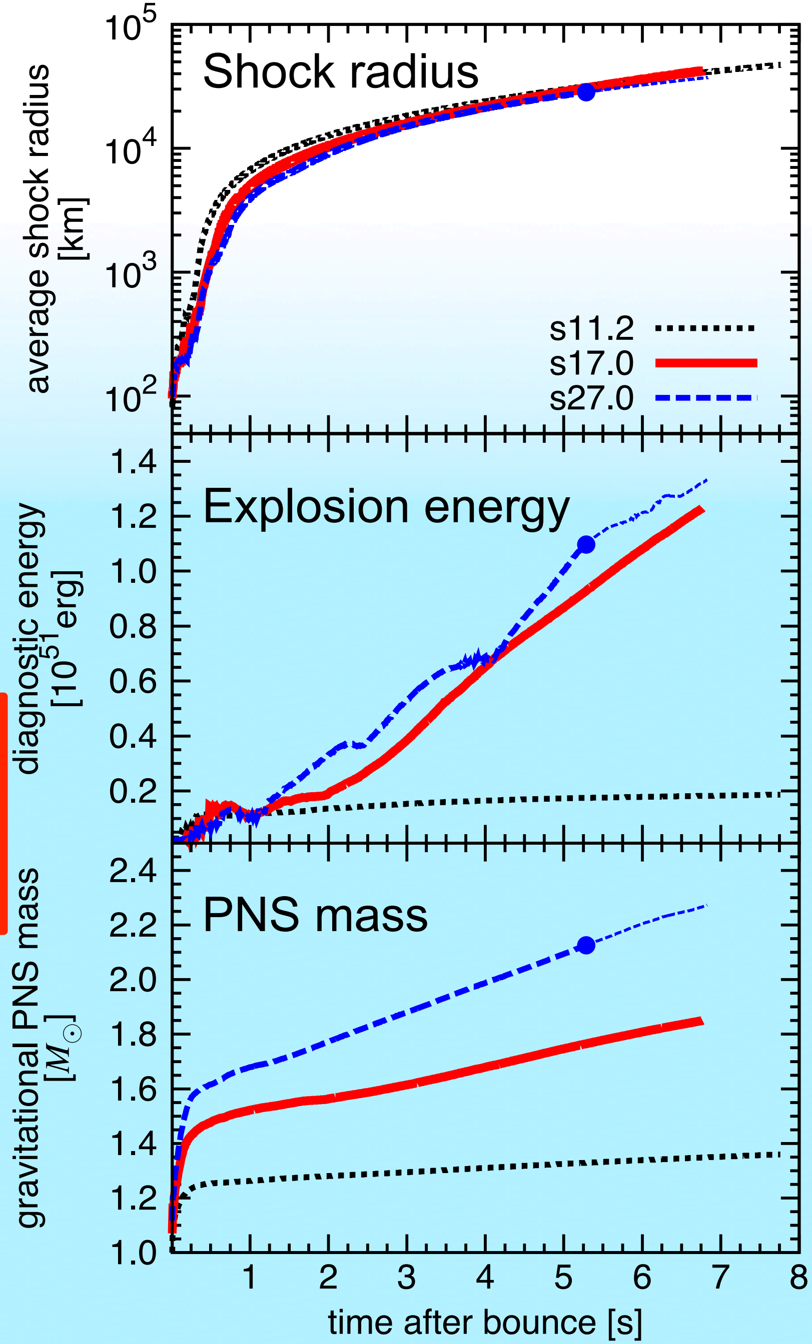
Long-term CCSN simulati

- ✓ All models exhibit shock revival.
  The shock reaches at r = 100,000 km
  (nearly the bottom of He layer)
  within t = 7-8 s.

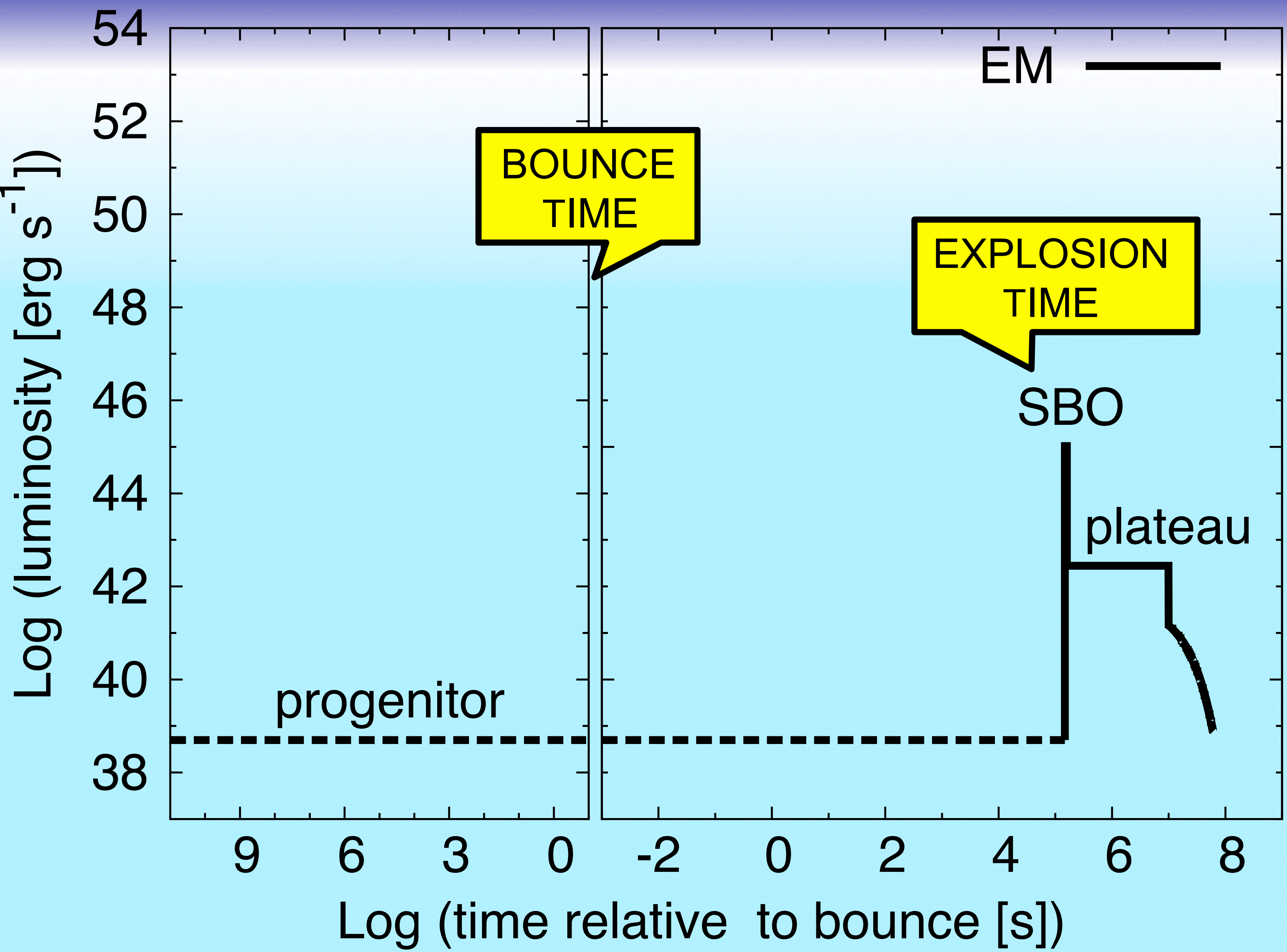
- ✓ **s11.2 model**
  shows almost converged E_{exp} & M_{PNS}.
  E_{exp} = 0.19 foe, M_{PNS} = 1.36 Mo

- ✓ **s17.0 model**
  shows still growing E_{exp} & M_{PNS} at t ~ 7s.
  E_{exp} = = 1.23 foe, M_{PNS} = 1.85 Mo

- ✓ **s27.0 model**
  is similar to s17.0 models, but the PNS
  mass reaches the limit（M_{PNS} = 2.13 Mo）
  predicted by 1D GR simulation.
  (O'Connor & Ott '11; KN+'15)



Multi-messenger signals from 17$M_\odot$ CCSN



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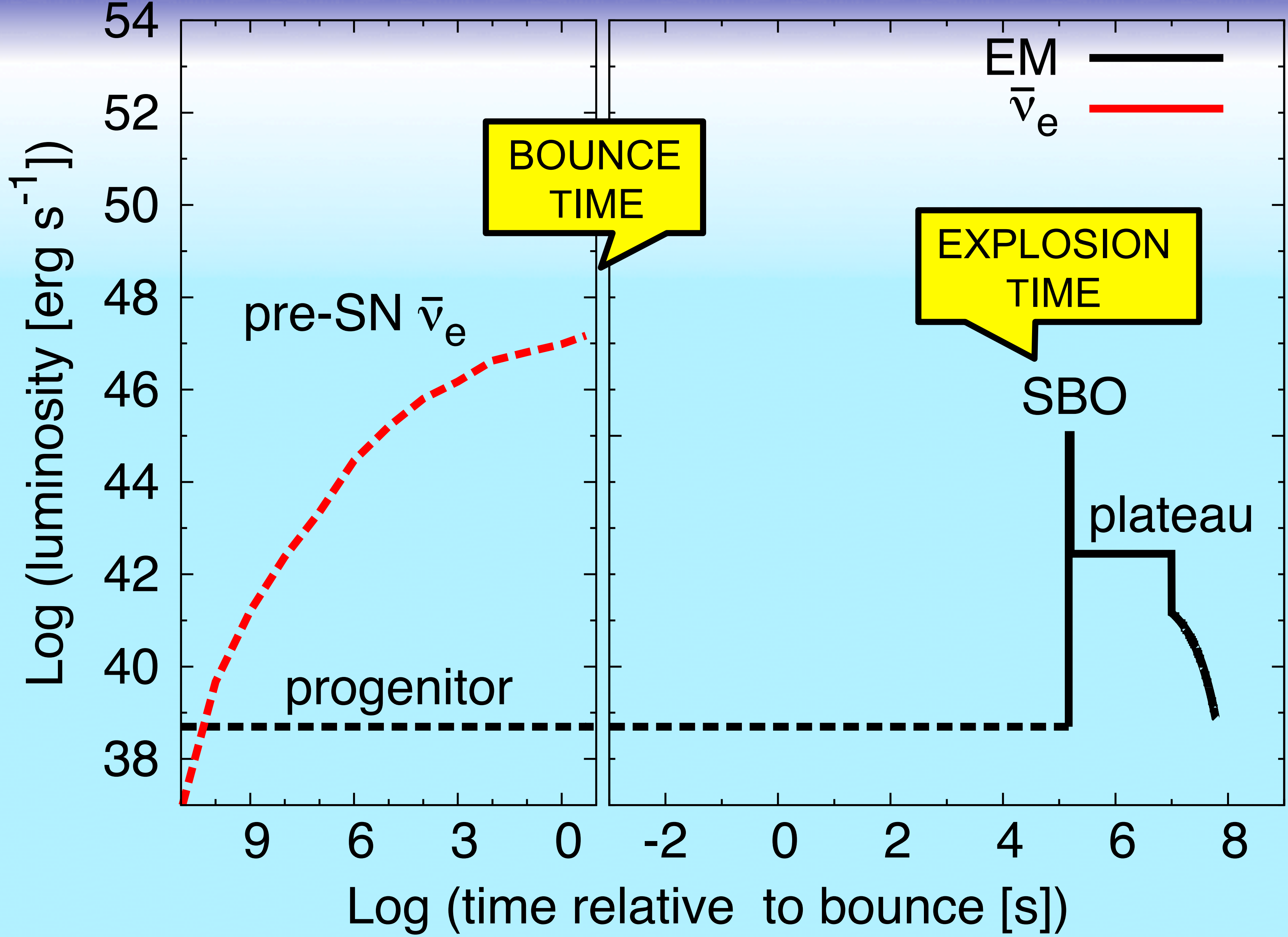

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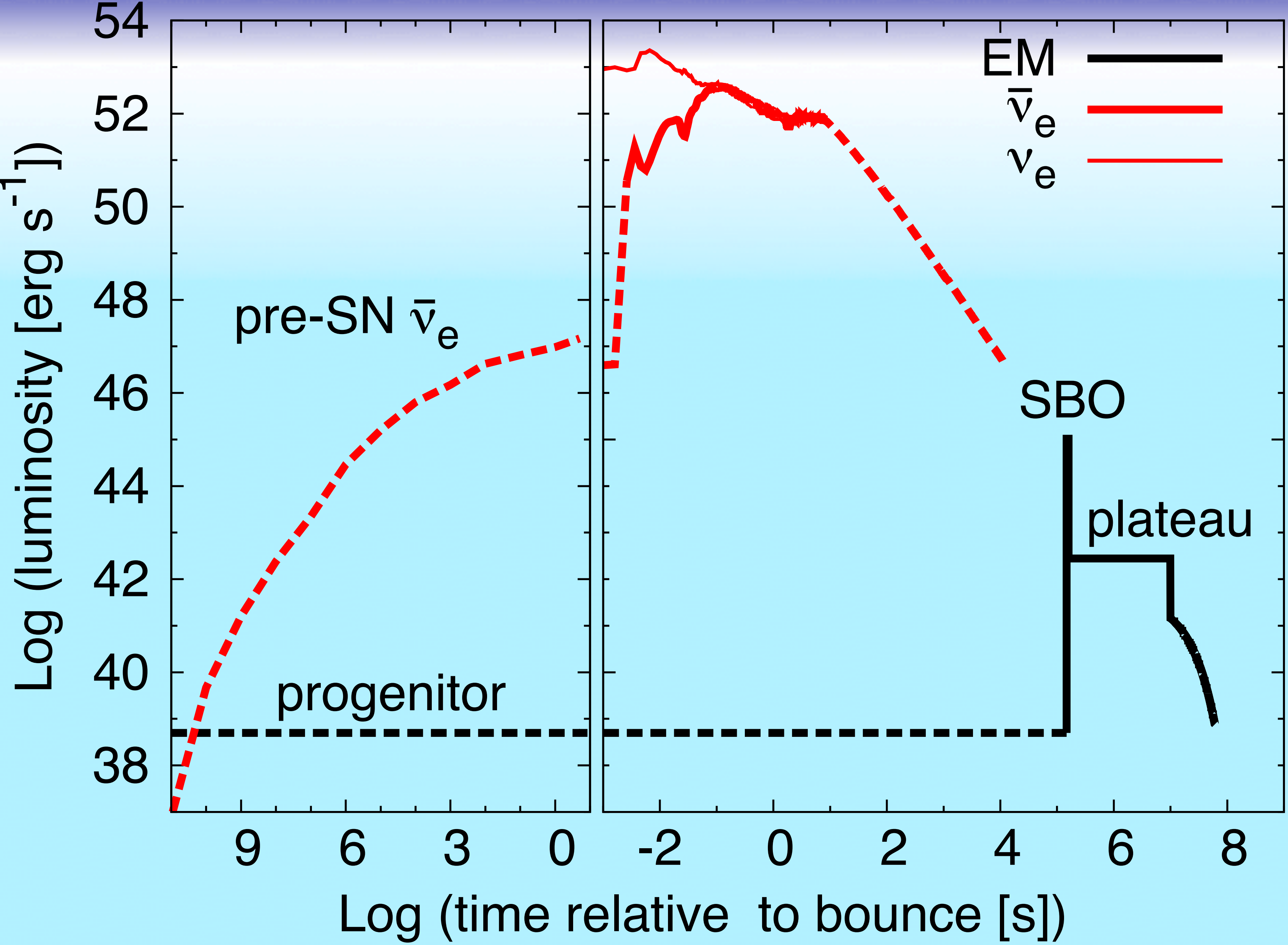
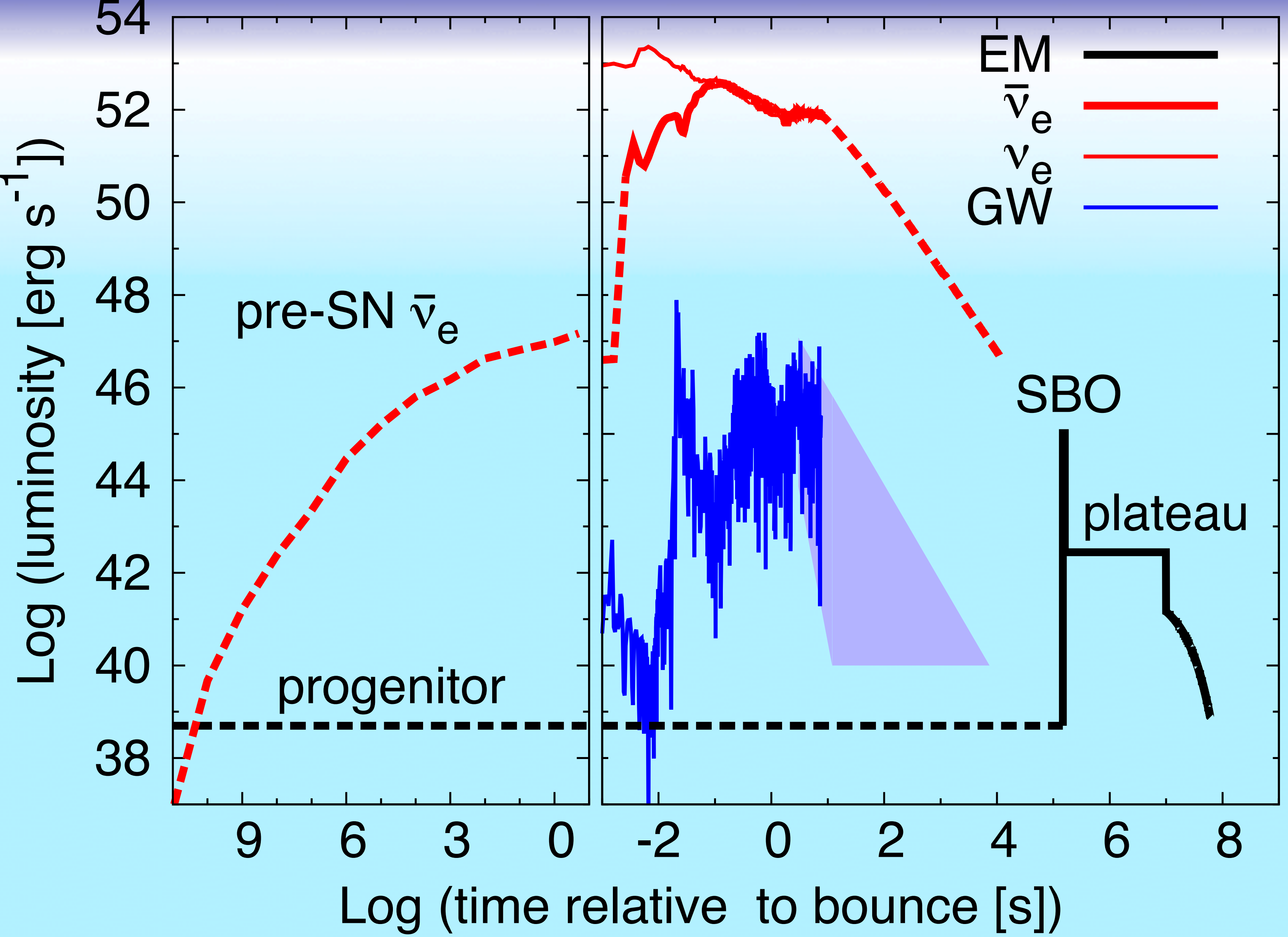
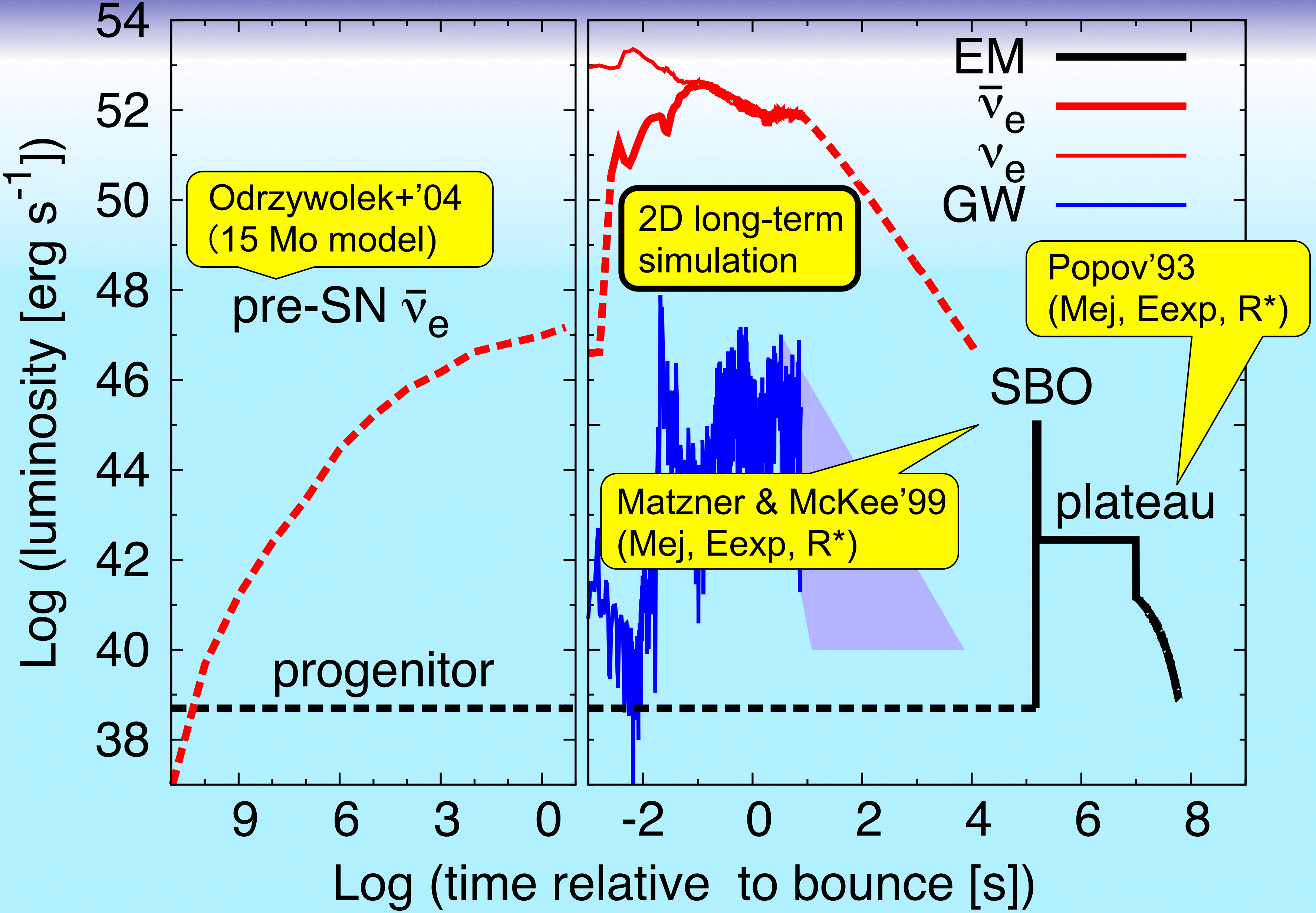


Multi-messenger signals from 17*M*o CCSN



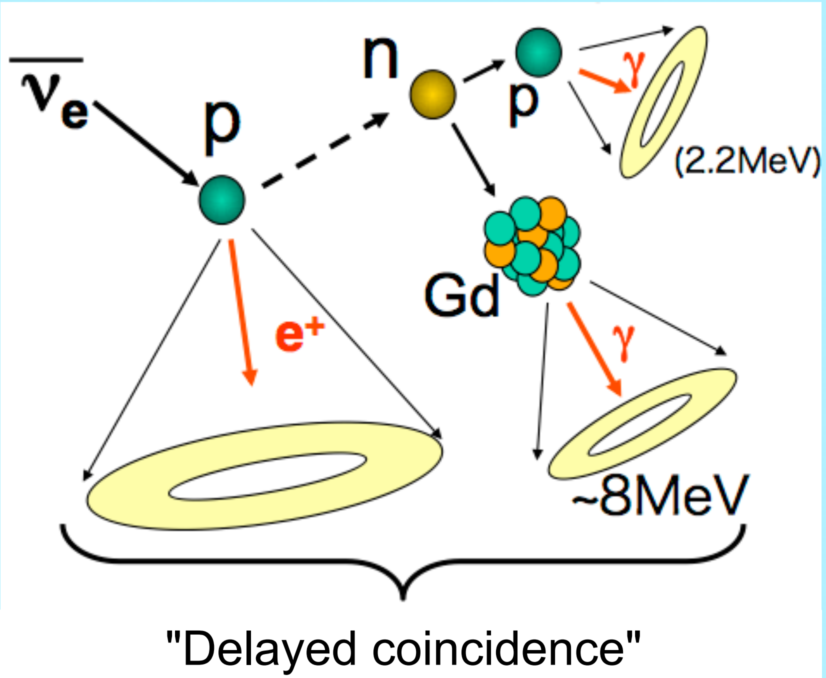
Multi-messenger signals from 17$M_\odot$ CCSN

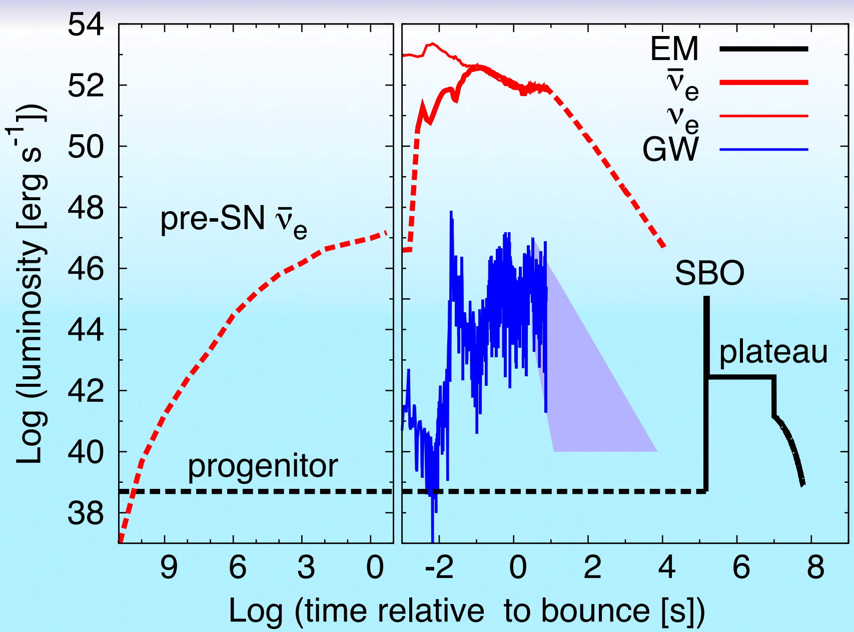


Neutrino - signals & detectors

✓ Water-Cherenkov detector
  - Super Kamiokande (33 kton)
  - Hyper Kamiokande (740 kton)

✓ Reaction channels
  - electron scattering
  - inverse beta decay





Gd-doped SK/HK can drastically suppress the background noise (Beacom & Vagins '04).

← ***Nakahata-san's talk***

Neutrino - Galactic event @ 8.5 kpc

✓ Water-Cherenkov detector
  - Super Kamiokande (33 kto
  - Hyper Kamiokande (740 kt

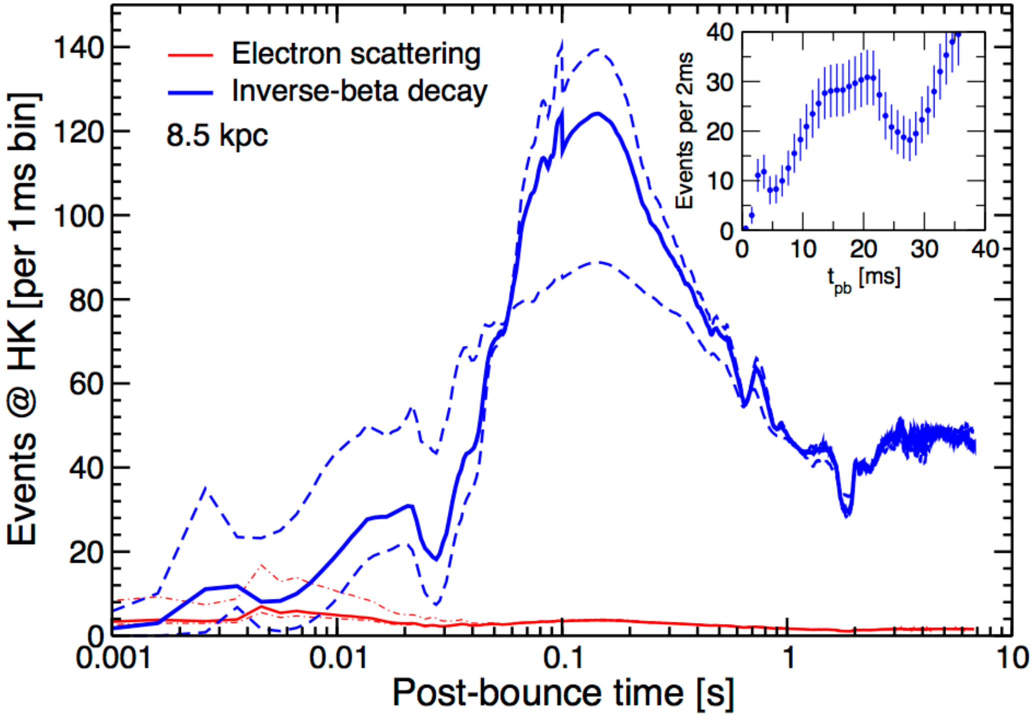
✓ Reaction channels
  - electron scattering
  - inverse beta decay

✓ Observed event rate:

$$\frac{dN_e}{dT_e} = N_t \int_{E_{\min}}^{\infty} dE_\nu \frac{dF_\nu}{dE_\nu}(E_\nu) \frac{d\sigma}{dT_e}(E_\nu, T_e)$$

Number of targets

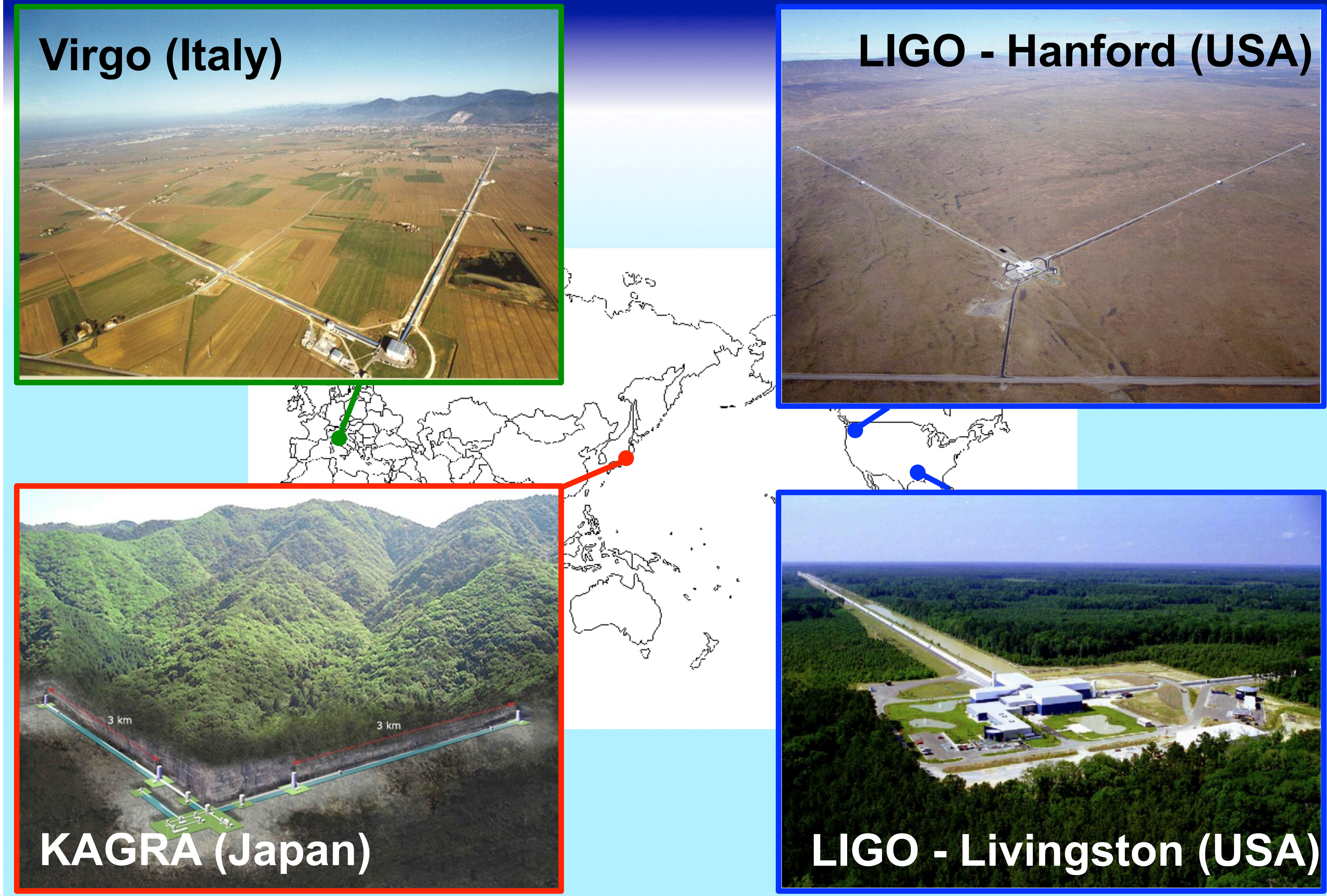
$$\frac{dF_\nu}{dE_\nu}(E_\nu) = \frac{L_\nu}{4\pi d^2 \langle E_\nu \rangle} f(E_\nu)$$



✓ Timing information (via IBD):
the bounce time within ± 3.0 ms (HK)
at 95% confidence level.

✓ Pointing information (via e^- scattering):
~ 6° (SK), ~ 3° (Gd-SK),
~ 0.6° (Gd-HK), ~ 0.3° (DUNE)

Gravitational wave detectors



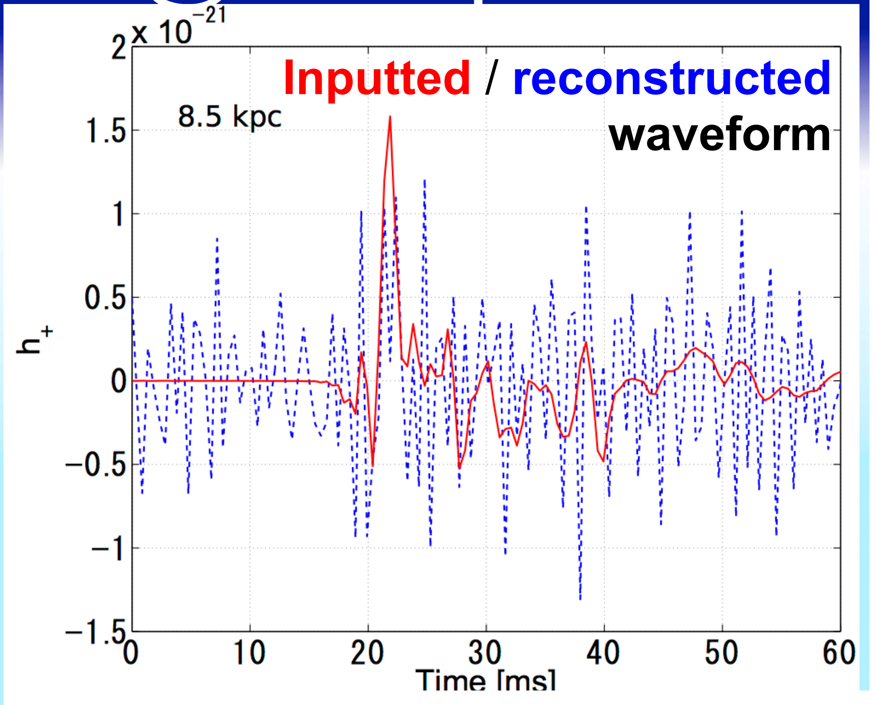
GW - Galactic event @ 8.5 kpc

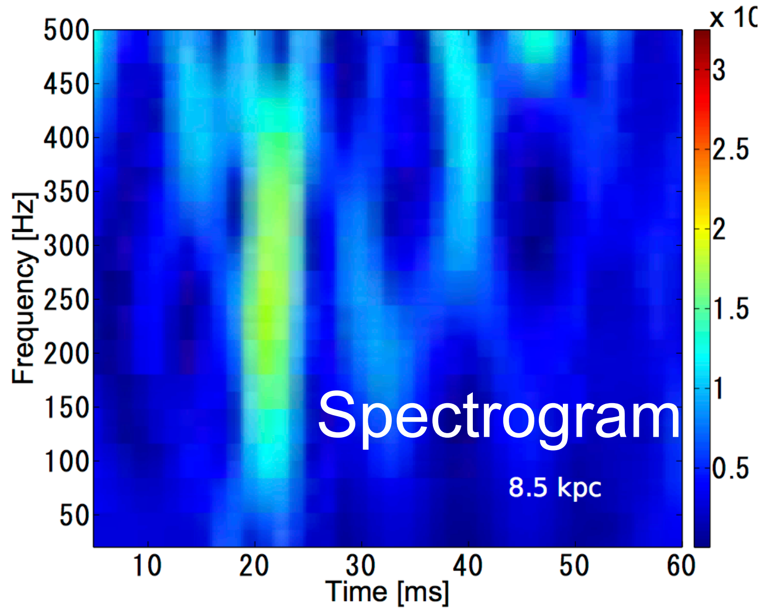
- ✓ Coherent network analysis
  (Hayama et al. 2015)
  → hard to see time-dependent
  waveform structure...

- ✓ With the aid of the **timing information**
  → small time window [0, 60] ms.

- ✓ Prompt convection
  → small frequency window
  [50, 500] Hz.

- ✓ The maximum S/N ratio ~ 7.5
  → **CCSN-GW is detectable!**
  → Core rotation (Yokozawa+'15)





Electromagnetic wave

✓ Shock breakout (Matzner & McKee '99)

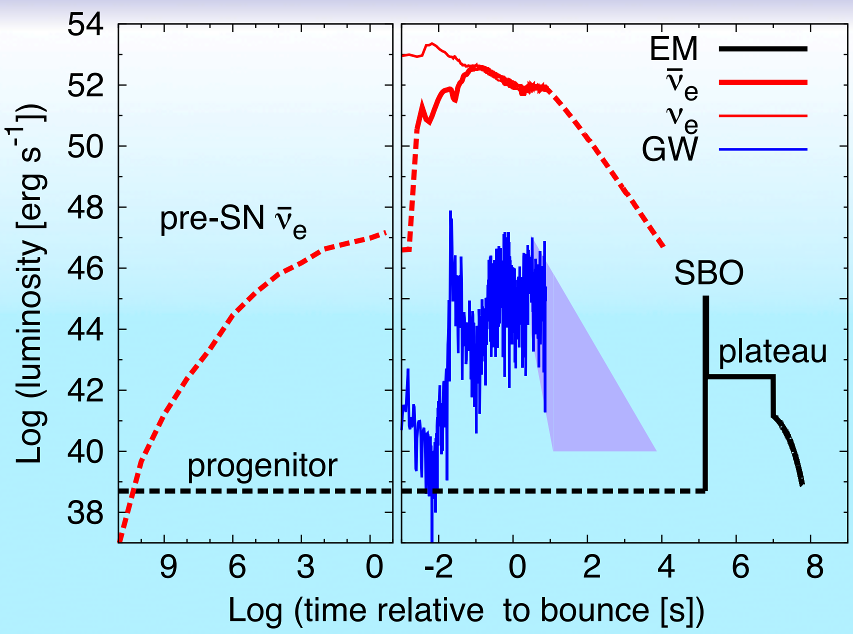
$$L_{\rm SBO} \sim 2.2 \times 10^{45}\ {\rm ergs\ s^{-1}} \left(\frac{\kappa}{0.34\ {\rm cm^2\ g}}\right)^{-0.29} \times \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-0.65} \left(\frac{E_{\rm exp}}{10^{51}\ {\rm erg}}\right)^{1.35} \left(\frac{R_0}{500\ R_\odot}\right)^{-0.42}$$

$$t_{\rm SBO} \sim 790\ {\rm s} \left(\frac{\kappa}{0.34\ {\rm cm^2\ g}}\right)^{-0.58} \times \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{0.21} \left(\frac{E_{\rm exp}}{10^{51}\ {\rm erg}}\right)^{-0.79} \left(\frac{R_0}{500\ R_\odot}\right)^{2.16}$$

✓ Plateau phase (Popov '93)

$$L_{\rm plateau} \sim 1.6 \times 10^{42}\ {\rm ergs\,s^{-1}} \left(\frac{\kappa}{0.34\,{\rm cm^2\,g^{-1}}}\right)^{-1/3} \times \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{-1/2} \left(\frac{E_{\rm exp}}{10^{51}\ {\rm erg}}\right)^{5/6} \times \left(\frac{R_0}{500\ R_\odot}\right)^{2/3} \left(\frac{T}{5000\,{\rm K}}\right)^{4/3},$$

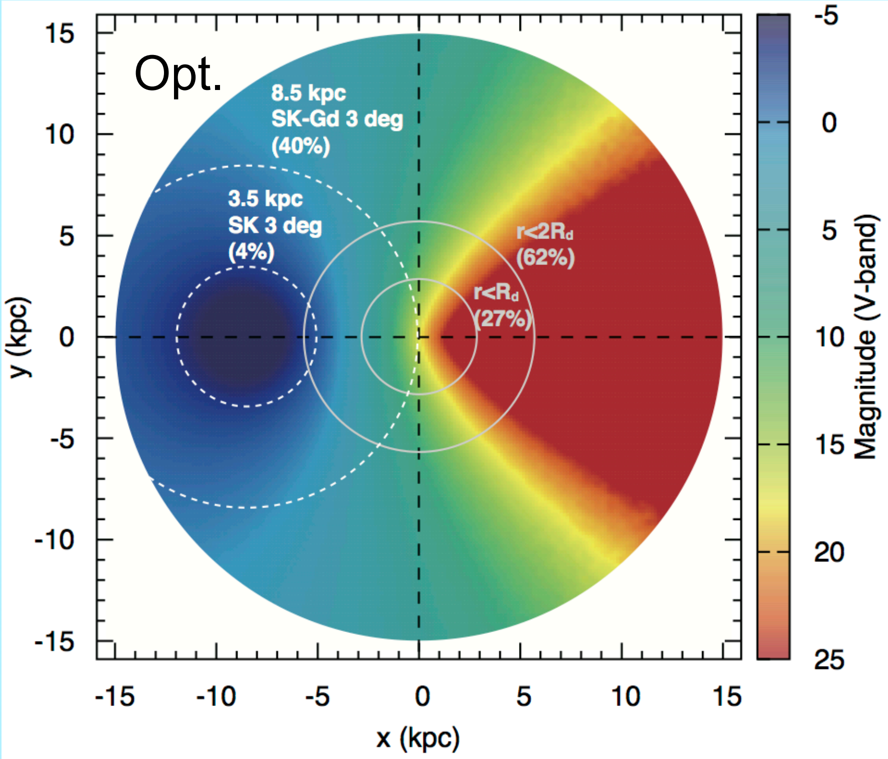
$$t_{\rm plateau} \sim 99\,{\rm d} \left(\frac{\kappa}{0.34\,{\rm cm^2\,g^{-1}}}\right)^{1/6} \times \left(\frac{M_{\rm ej}}{10\ M_\odot}\right)^{1/2} \left(\frac{E_{\rm exp}}{10^{51}\ {\rm erg}}\right)^{-1/6} \times \left(\frac{R_0}{500\ R_\odot}\right)^{1/6} \left(\frac{T}{5000\,{\rm K}}\right)^{-2/3}.$$

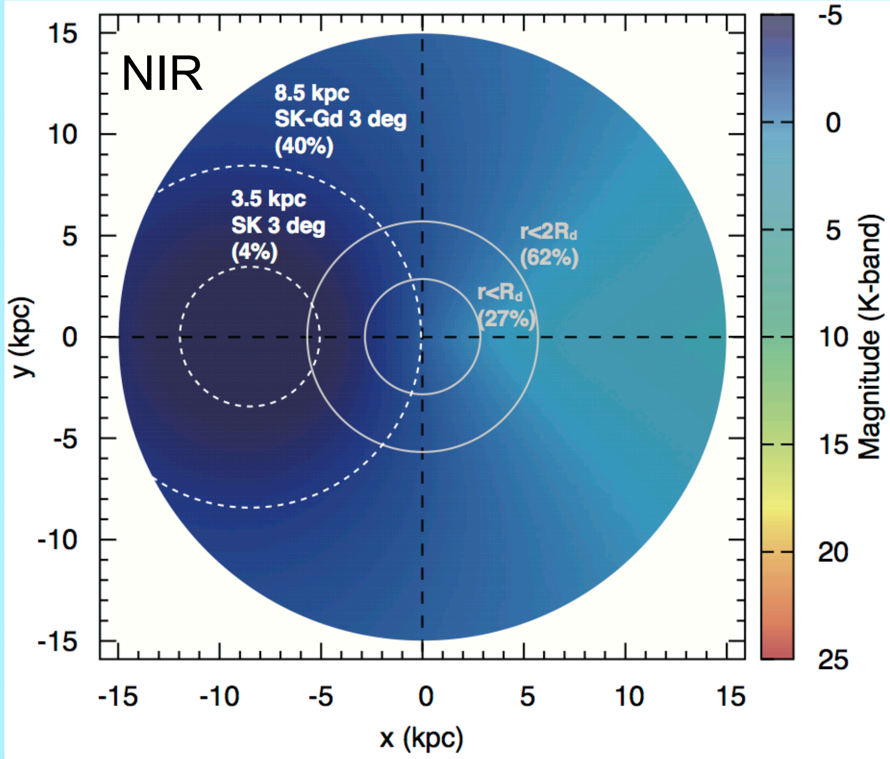


✓ Tail phase (Nadyozhin '94)
powered by radioactive decay

Galactic event - EM

- ✓ To find SBO and/or early light curve signals
  in a error circle identified by SK (**~6 deg. = ~ 28 deg^2.**),
- ✓ we have to take
  20 images by Subaru-HSC,
  within a typical SBO duration time **30 minutes.**
- ✓ Integral time a for each image is
  $(a+0.5)*20=30 \rightarrow a=1$ min. → **24-25 mag**.





Time sequence of observations:
MM signals from a future Galactic CCSN event

(pre-SN neutrino)

Red Supergiant (RSG) progenitor
→ **Type II SN**

Wolf-Rayet (WR) progenitor
→ **Type Ib/c SN**

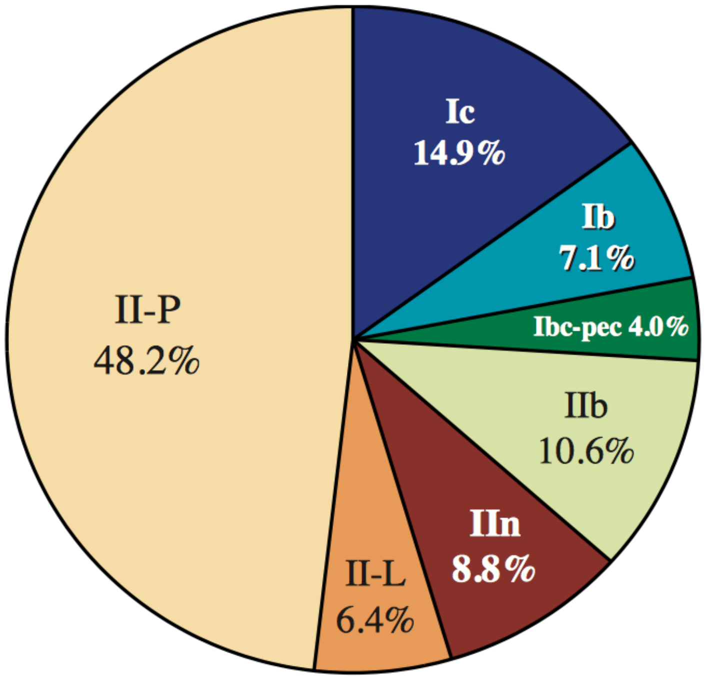
neutrino burst

$R^* \sim 10^{13\text{-}14}$ cm, shock velocity $\sim 10^9$ cm/s
→ $\Delta t \sim R^*/v \sim 10^{4\text{-}5}$ s **(a few hours - a day)**

$R^* \sim 10^{11}$ cm
→ $\Delta t \sim R^*/v \sim 100$ s **(a few minutes) !**

Distribute ALERT !

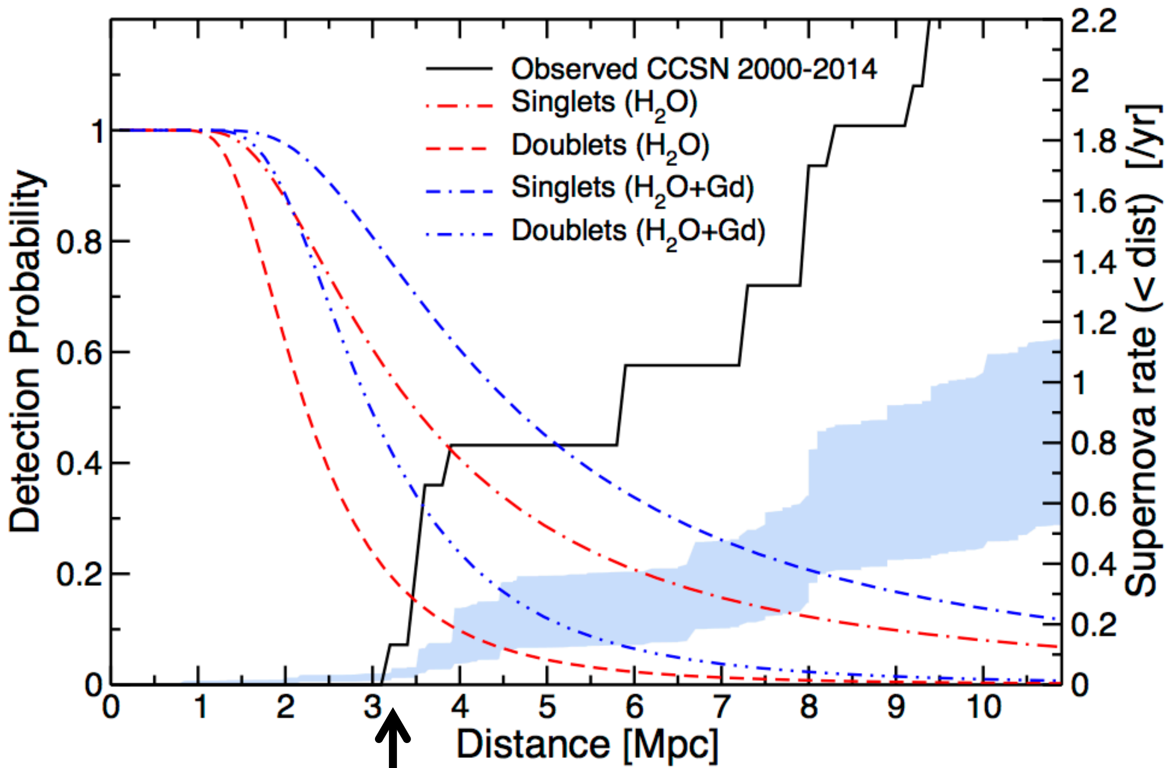
SBO



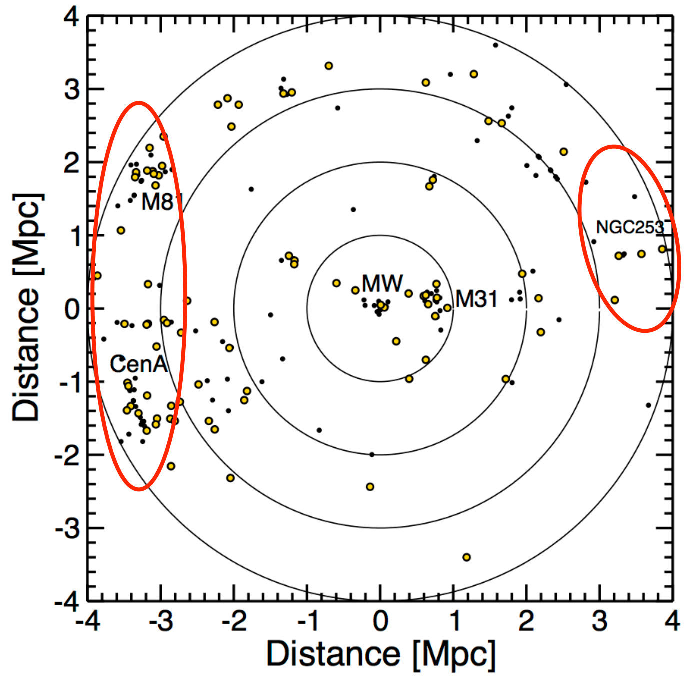
Core-Collapse SN Fractions

Neutrino from extragalactic events

Probability of neutrino detection
& cumulative CCSN rate as a function of D.
HK is assumed.



Nearby galaxies within 4 Mpc.



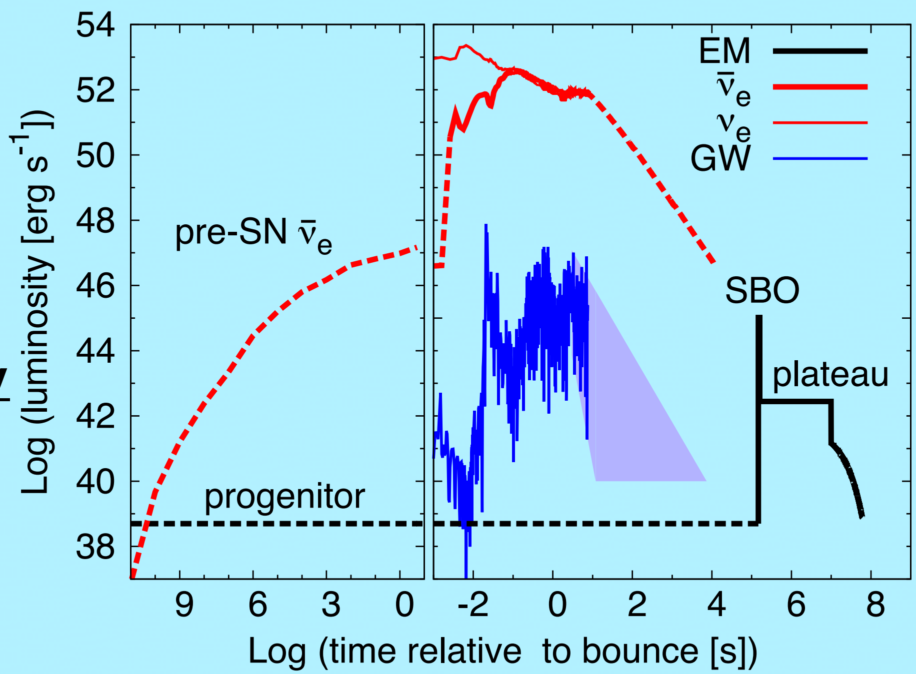
SN rate jumps at D ~ 3 Mpc.

Summary

KN+ (2015), arXiv:1406.2415
KN+, submitted to MNRAS, arXiv:1602.03028

The next Galactic supernova is expected to bring great opportunities for the direct detection of multi-messenger signals.

- **Long-term simulations for representative models.**
  Selected progenitors with small/middle/high compactness ξ
  (M = 11.2, 17.0, 27.0 Mo).
  → multi-messenger signals
  - neutrino: $L\nu$, $f(E\nu)$
  - GW: h, E_{GW}
  - EM: L



- **Toward multi-messenger astronomy**
  Trigger = neutrino detection.
  → timing & pointing information
  → GW detection.
  → EM counterpart search.