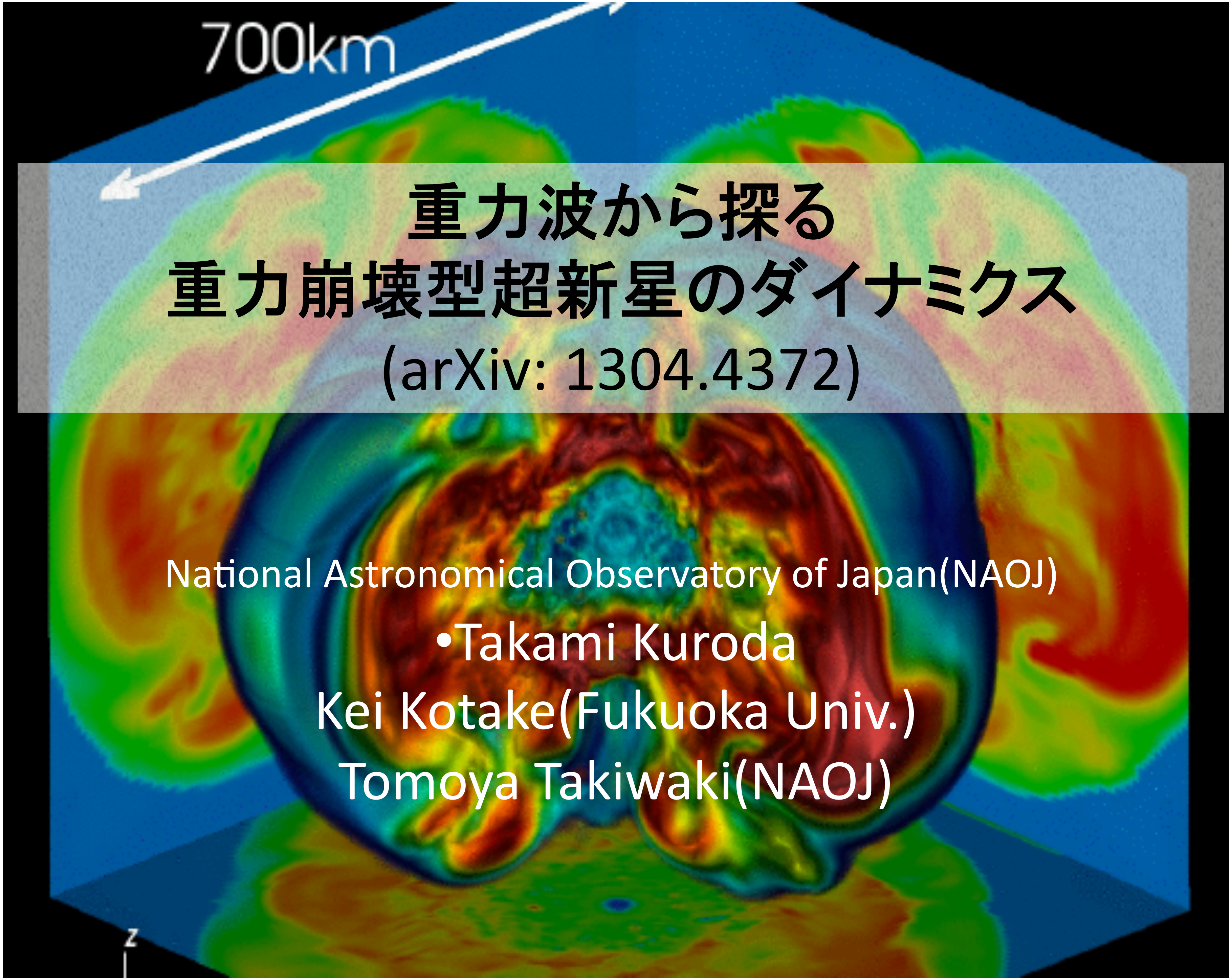
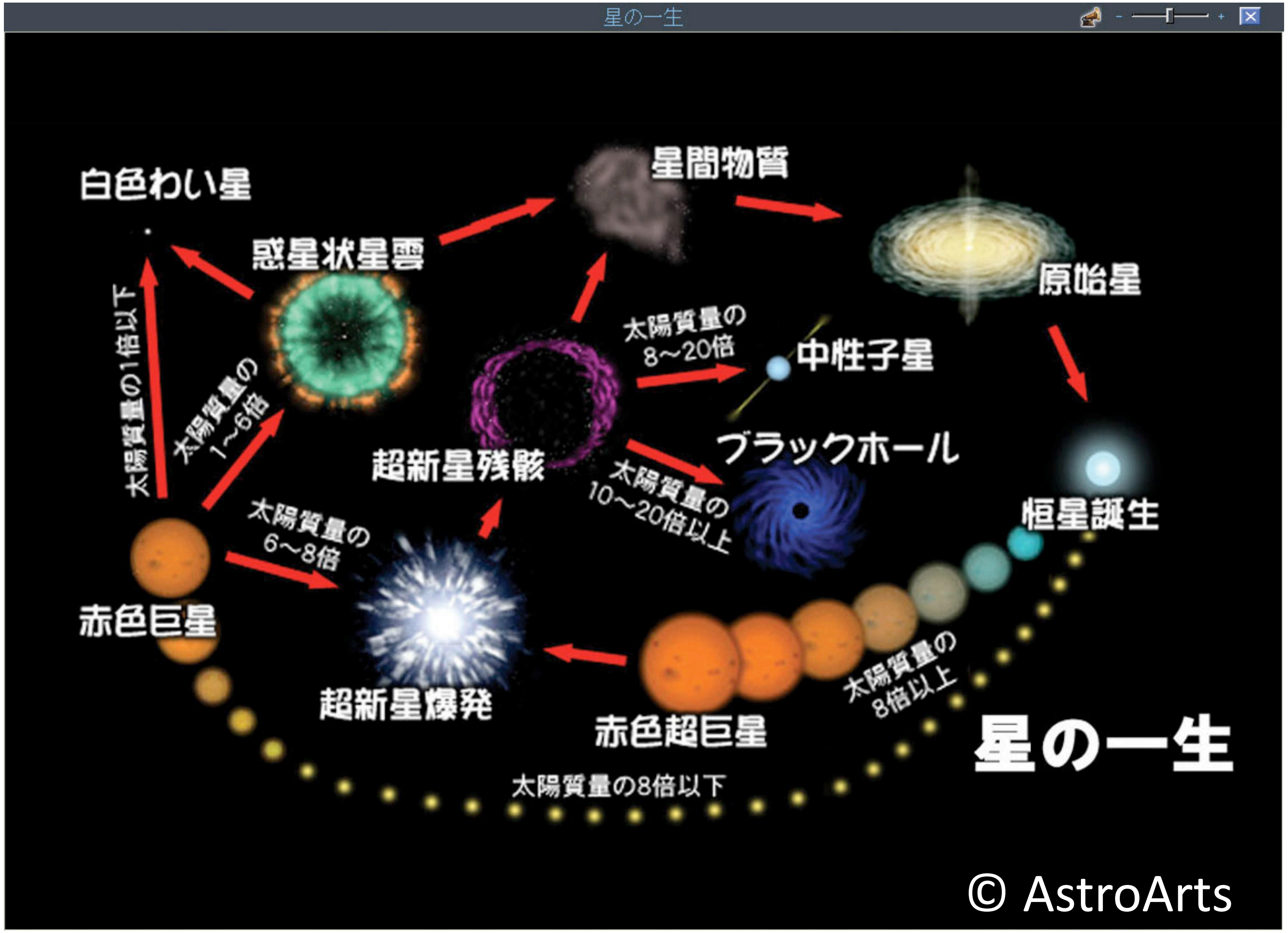


重力波から探る
重力崩壊型超新星のダイナミクス
(arXiv: 1304.4372)

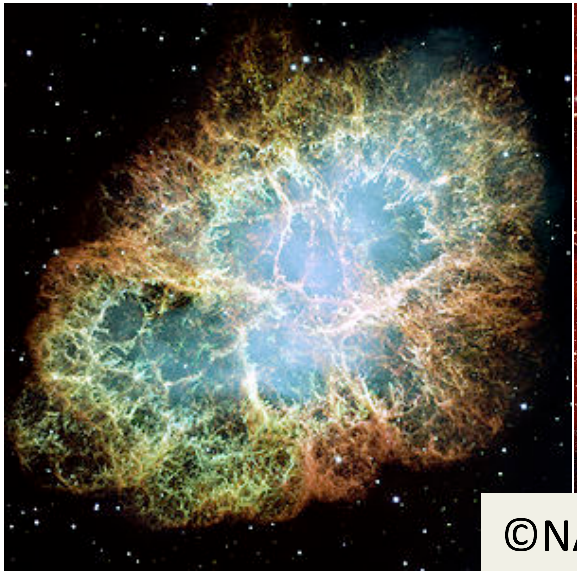
National Astronomical Observatory of Japan(NAOJ)
•Takami Kuroda
Kei Kotake(Fukuoka Univ.)
Tomoya Takiwaki(NAOJ)

1. 重力崩壊型超新星爆発(CCSN)とは？

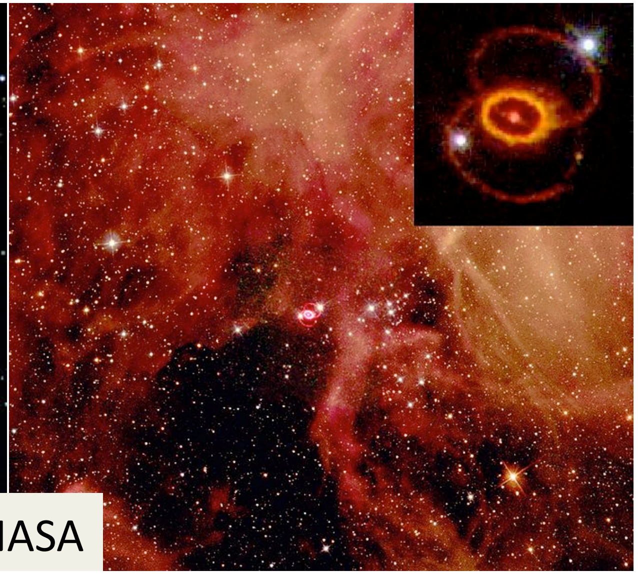


1. 重力崩壊型超新星爆発(CCSN)とは？

SN1054



SN1987A



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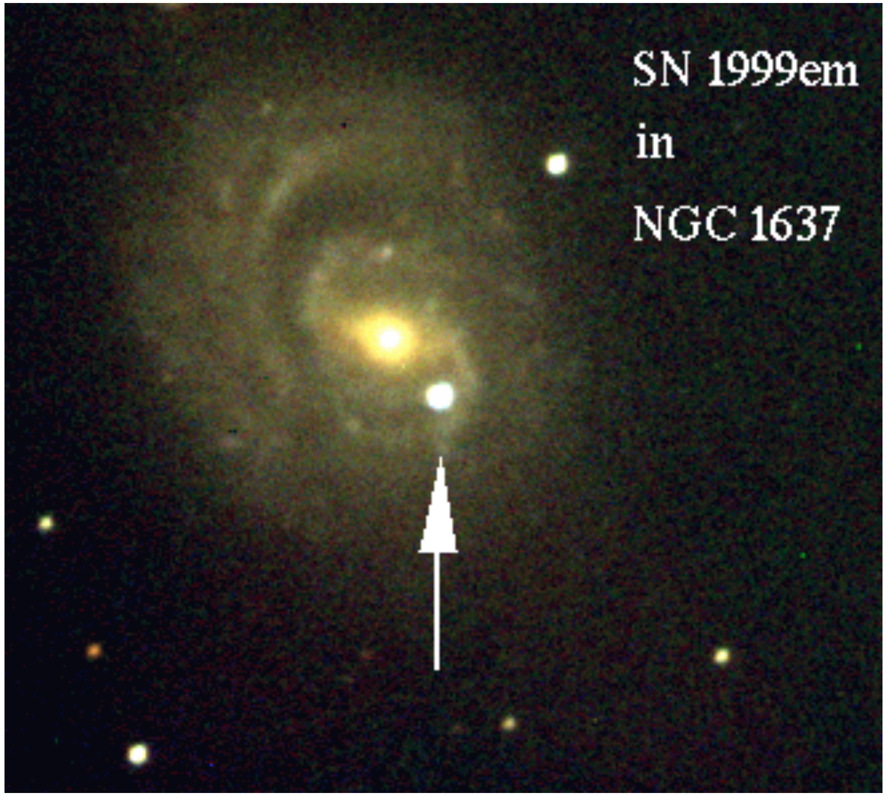
Core Collapse Supernovae (CCSNe) are
one of the most energetic events in the universe

1. 重力崩壊型超新星爆発(CCSN)とは？

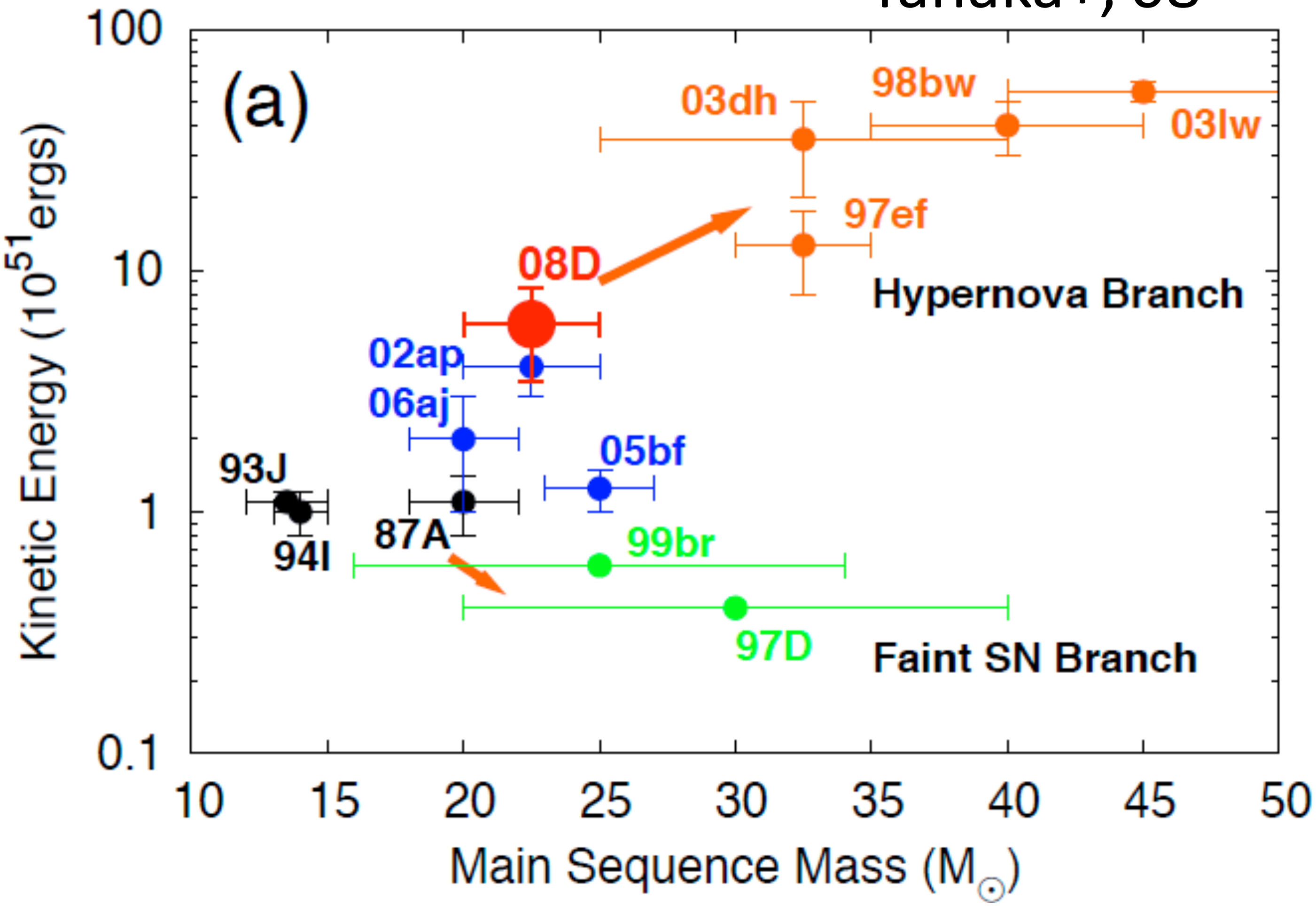


- They are so bright comparable to a galaxy.
- They affect on galactic evolution in both dynamically and chemically

e.g. Kobayashi+'11

1. 重力崩壊型超新星爆発(CCSN)とは？

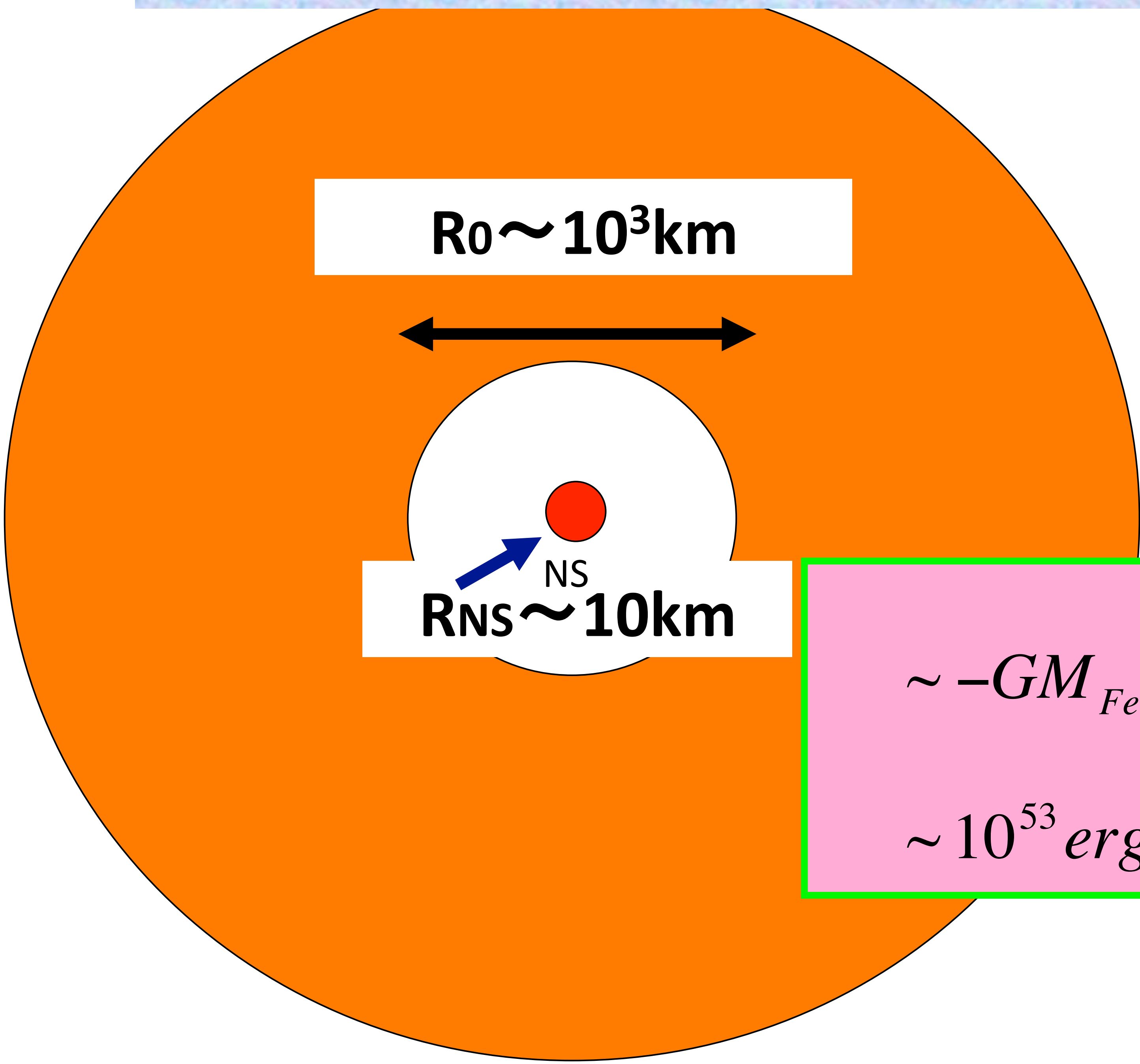
Tanaka+,’08



Typical explosion energy → E_{kin}~10^{51}ergs

~M_{sun}x (10^4km/s)^2

1．重力崩壊型超新星爆発(CCSN)とは？

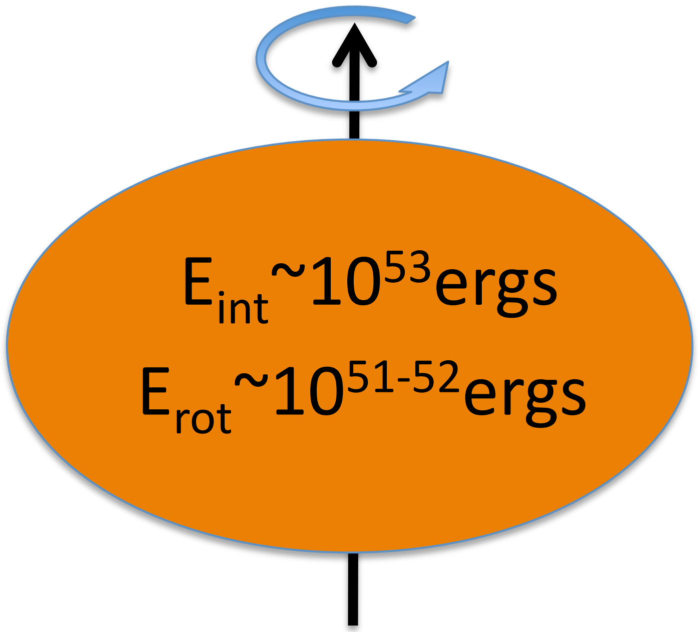


$$\sim -GM_{Fe}^{\ 2}\left(\frac{1}{R_0}-\frac{1}{R_{NS}}\right)$$

$$\sim 10^{53}\, ergs$$

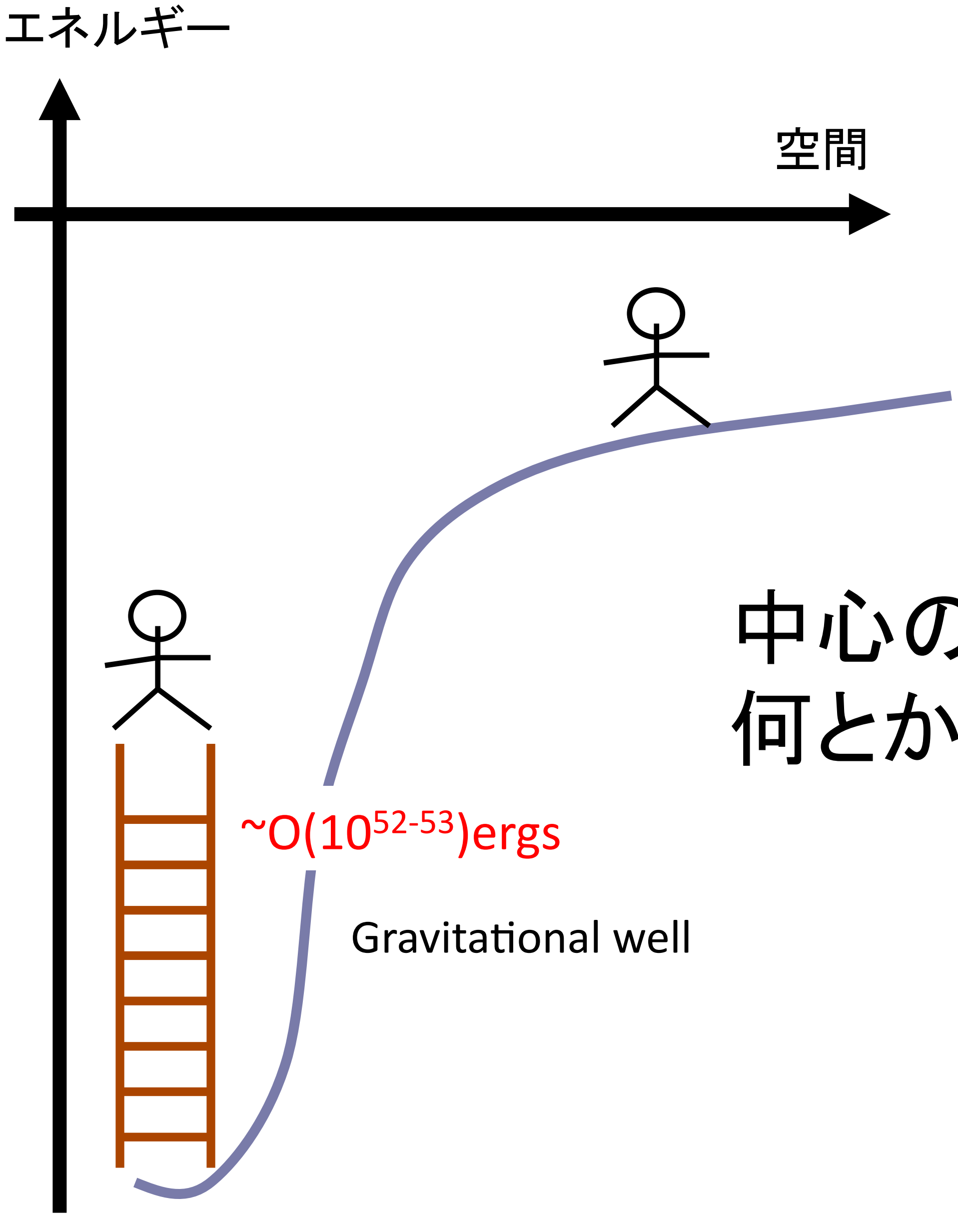
1. 重力崩壊型超新星爆発(CCSN)とは？

Liberated gravitational energy ~10^{53}ergs
is stored in the proto-neutron star (PNS)



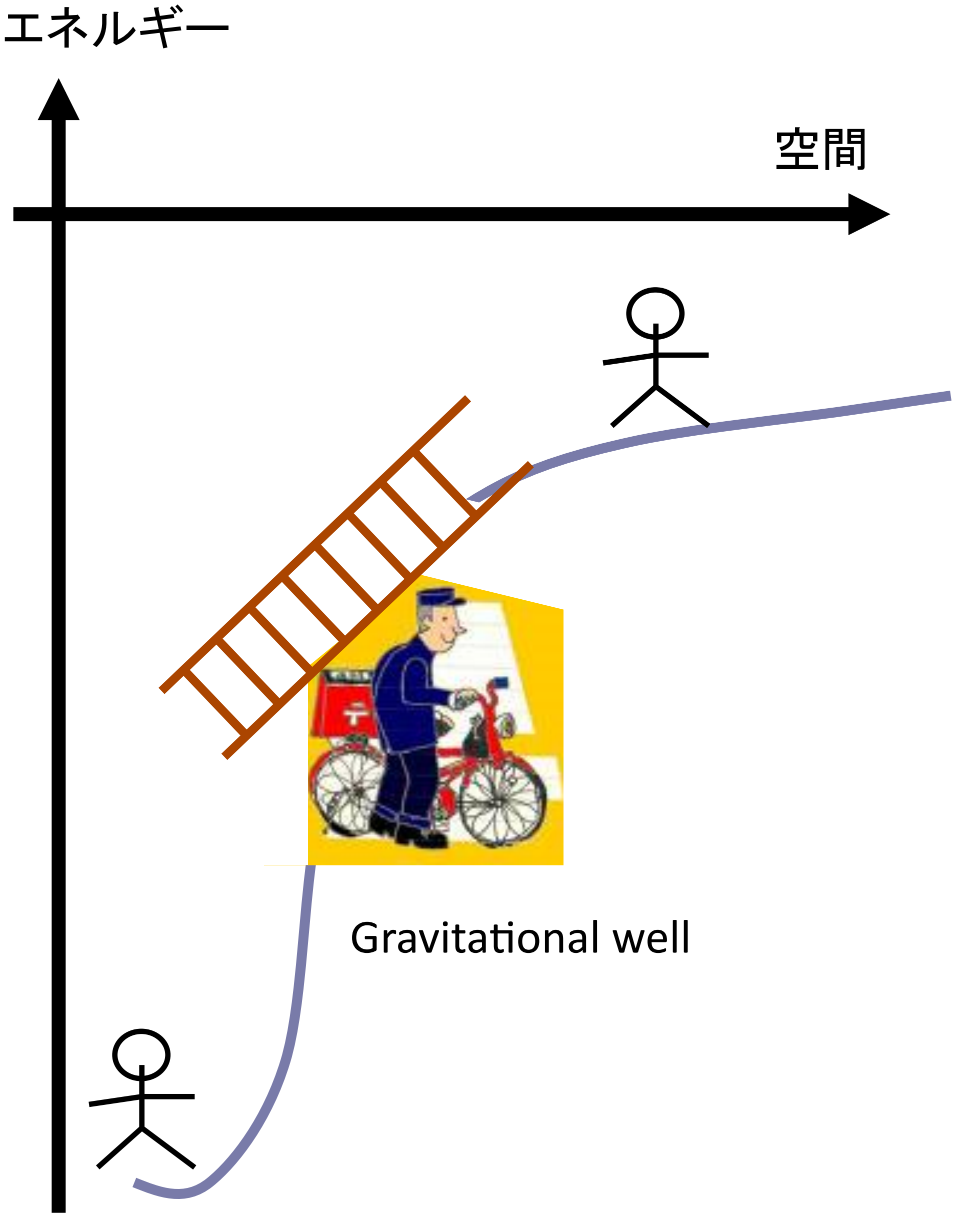
1. 重力崩壊型超新星爆発(CCSN)とは？

典型的な爆発運動エネルギー ~O(10^{51}) ergs

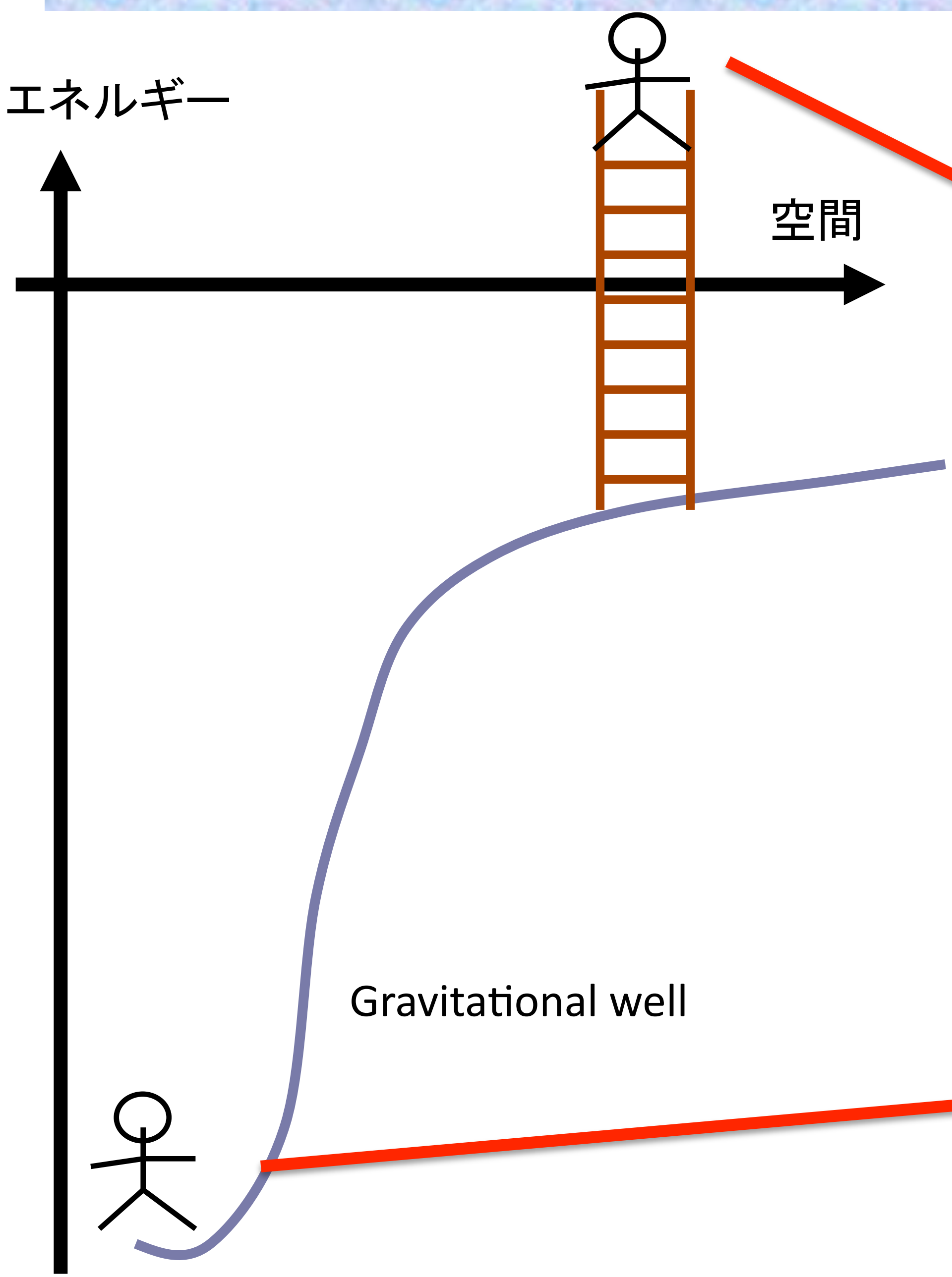


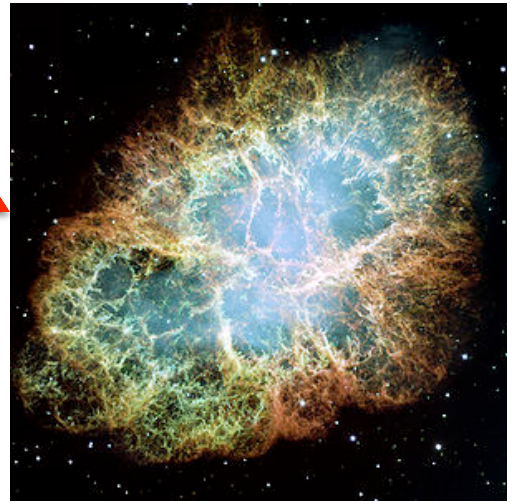
中心の莫大なエネルギーを
何とかして外層へと渡したい

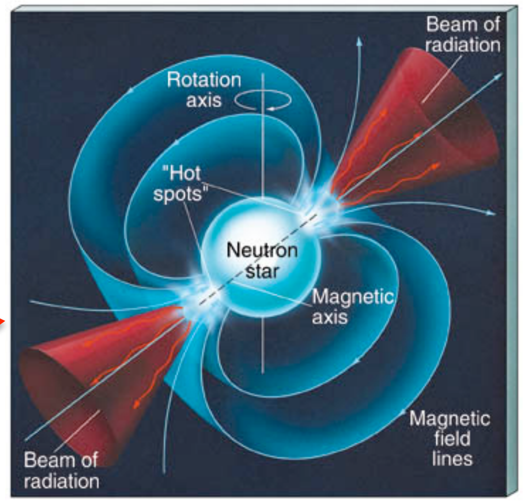
1. 重力崩壊型超新星爆発(CCSN)とは？



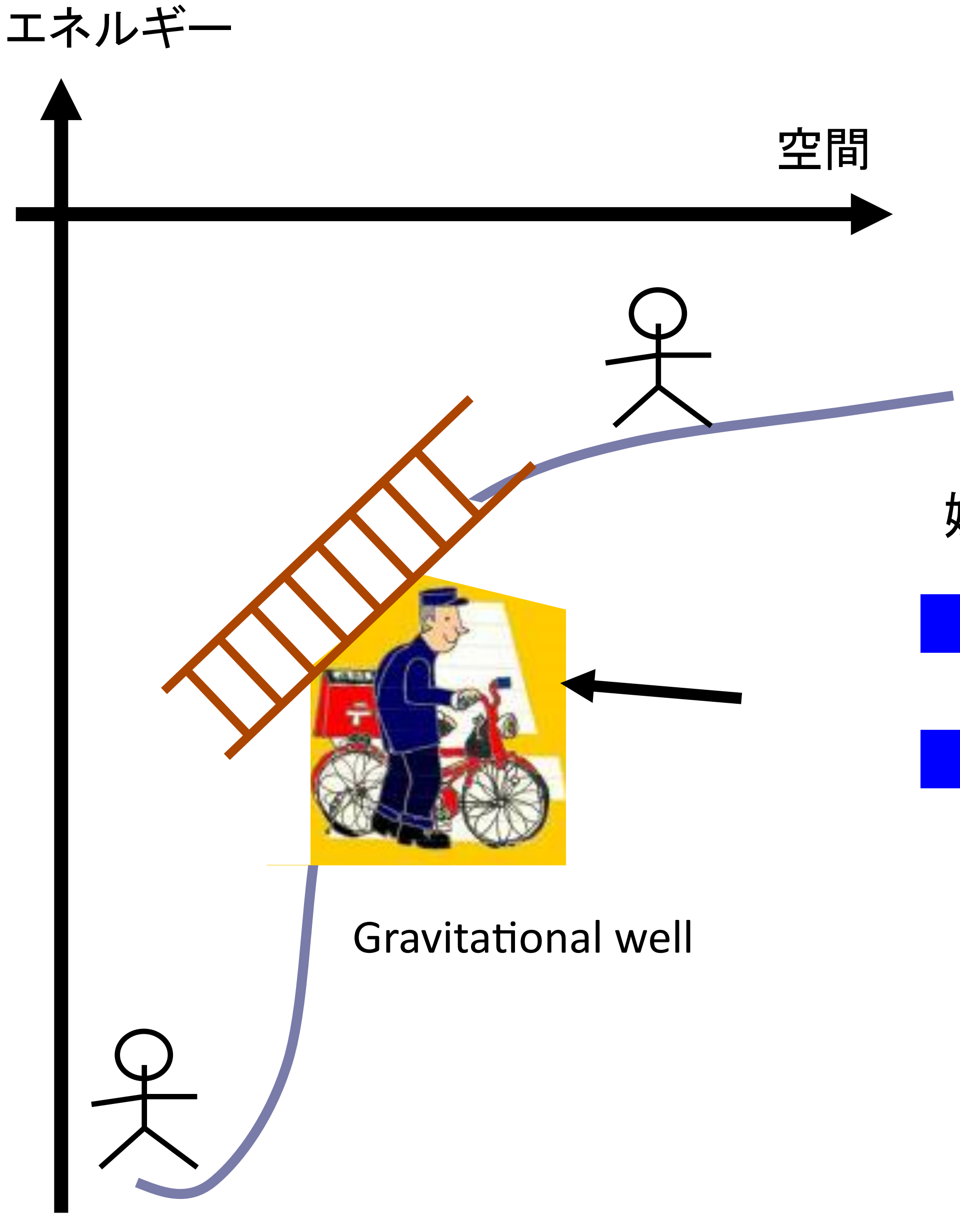
1. 重力崩壊型超新星爆発(CCSN)とは？







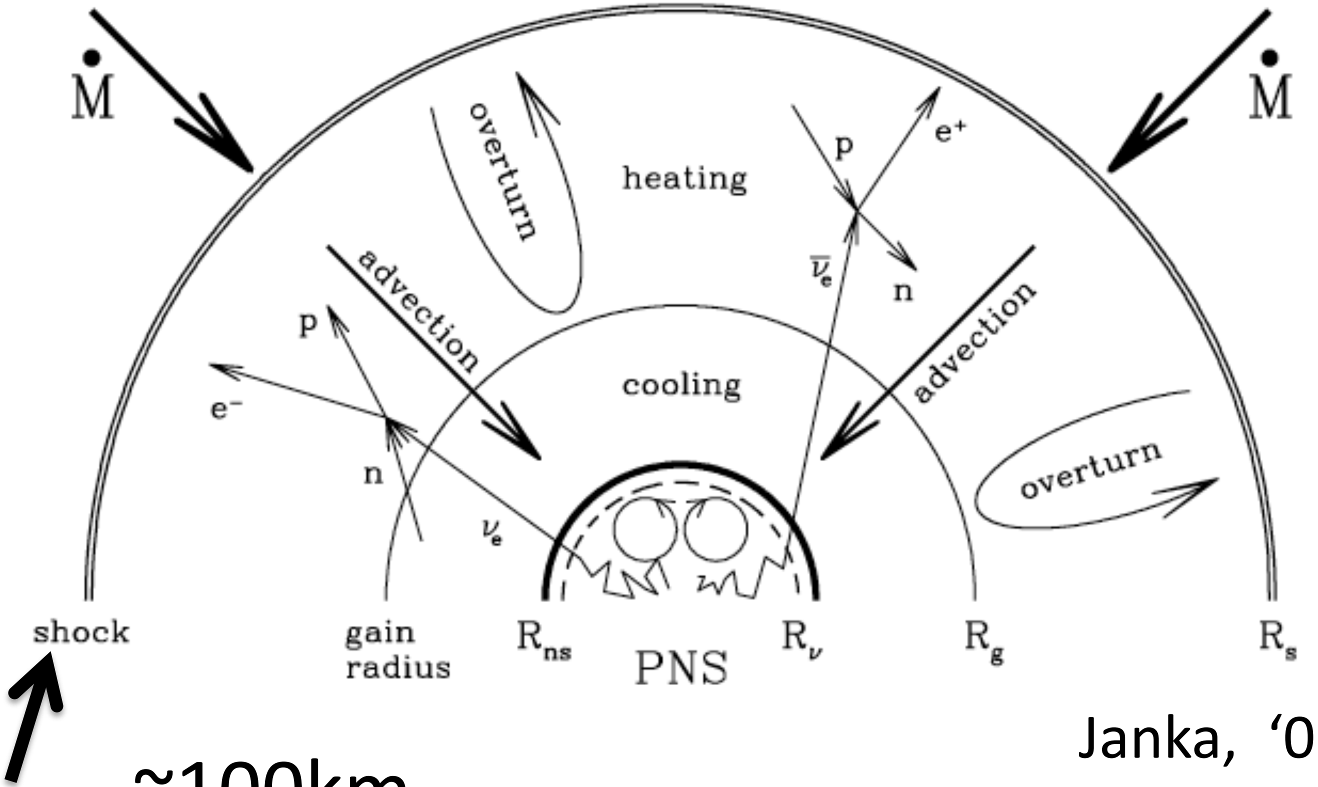
1.　重力崩壊型超新星爆発(CCSN)とは？



媒体物	媒体対象
ν	内部エネルギー
磁場	角運動量

2. CCSNにおける数値計算

1)ν-driven scenario



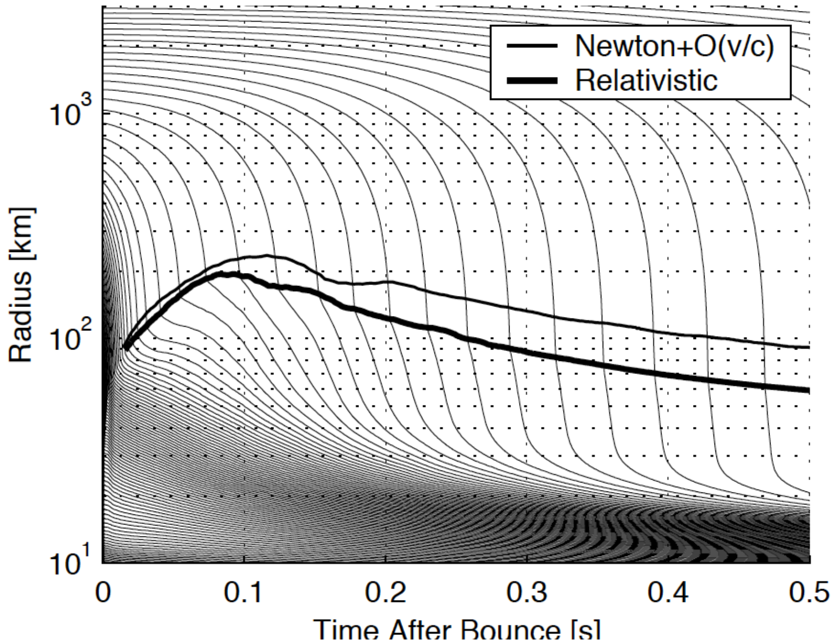
$R_{stalled\_shock}$~100km

Janka, ‘01

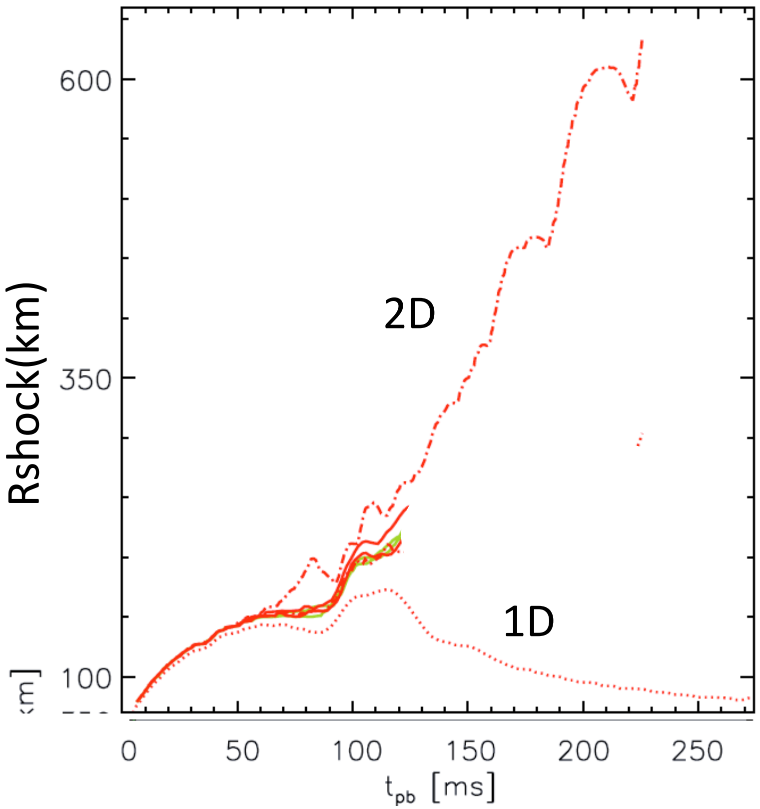
2. CCSNにおける数値計算

1)ν-driven scenario (no-explosion under spherical symmetry)

$13M_{sun}$ Liebendorfer+,'01



Buras+,'06

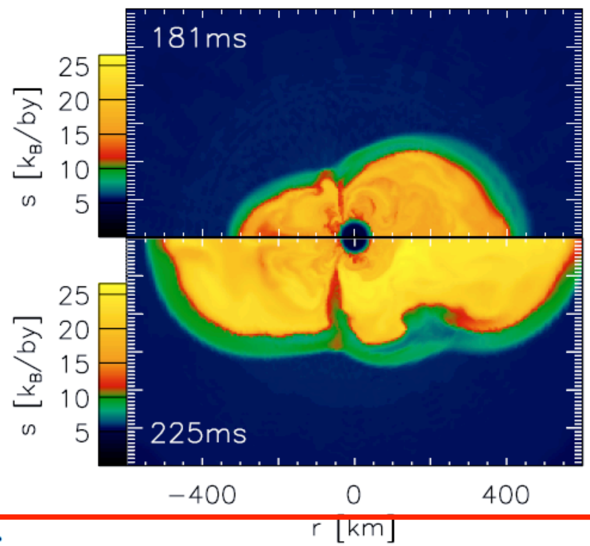


2. CCSNにおける数値計算

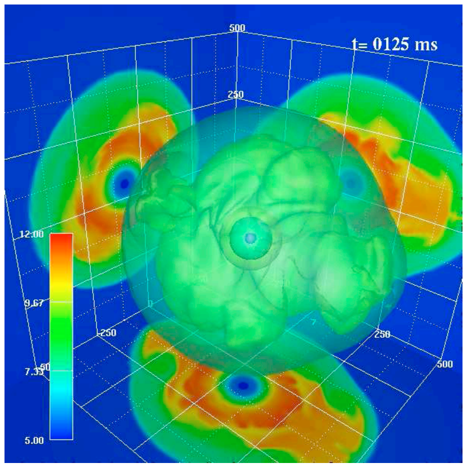
1)ν-driven scenario　(successful explosions in multi-D)

11.2M_{sun}

Buras+,'06

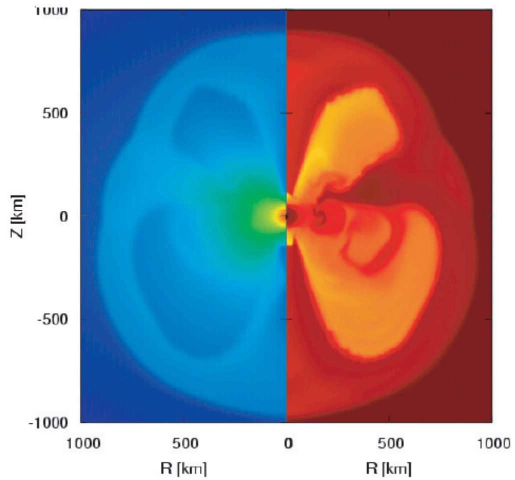


Takiwaki+,'11



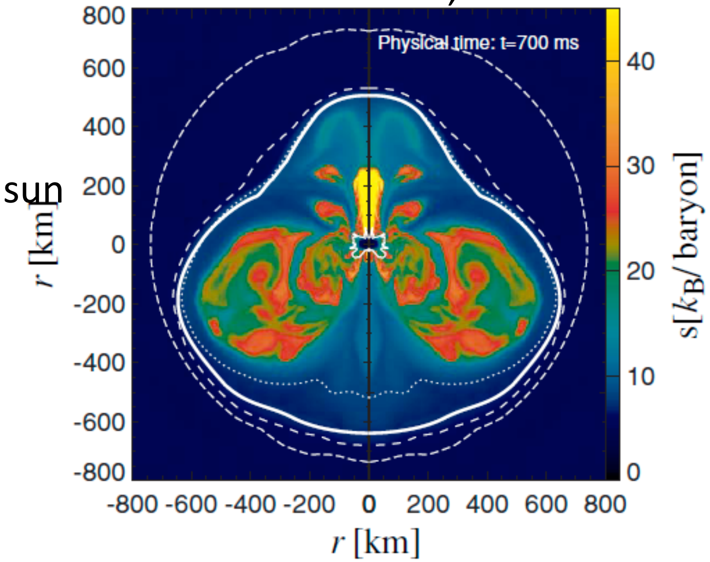
13M_{sun}

Suwa+,'10



15M_{sun}

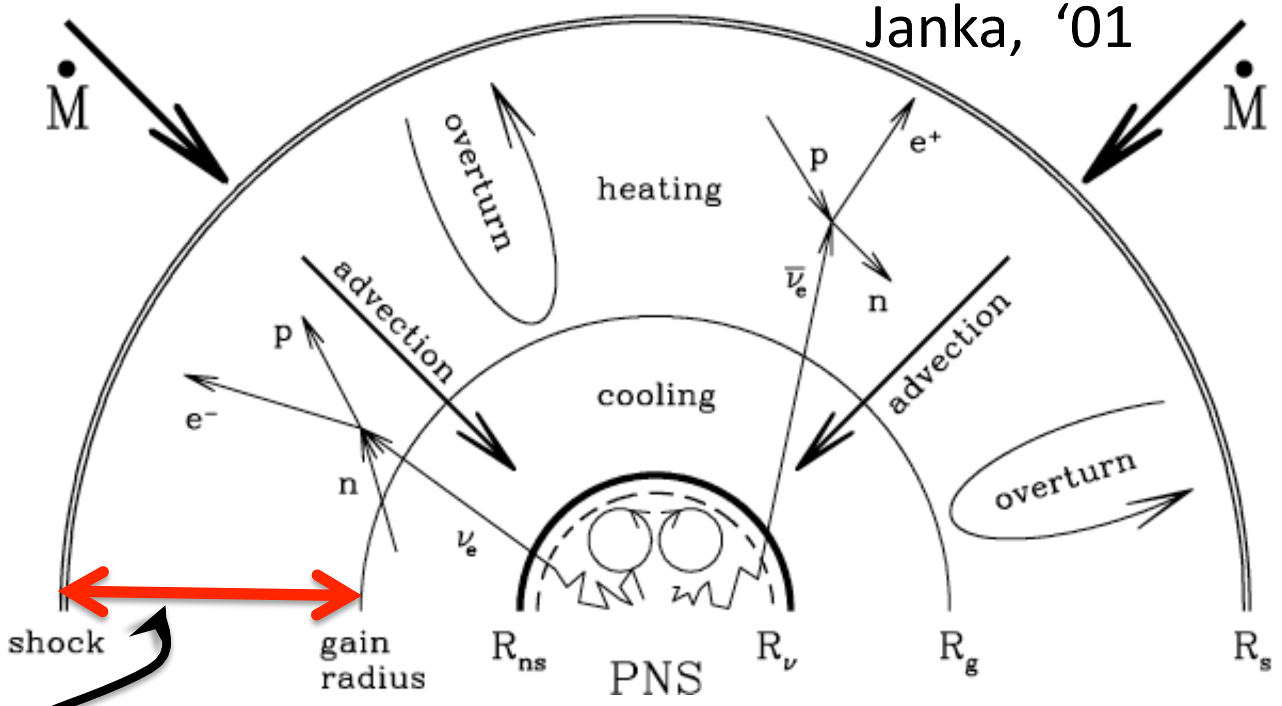
Marek&Janka,'09



2. CCSNにおける数値計算

1)ν-driven scenario

Janka, ‘01



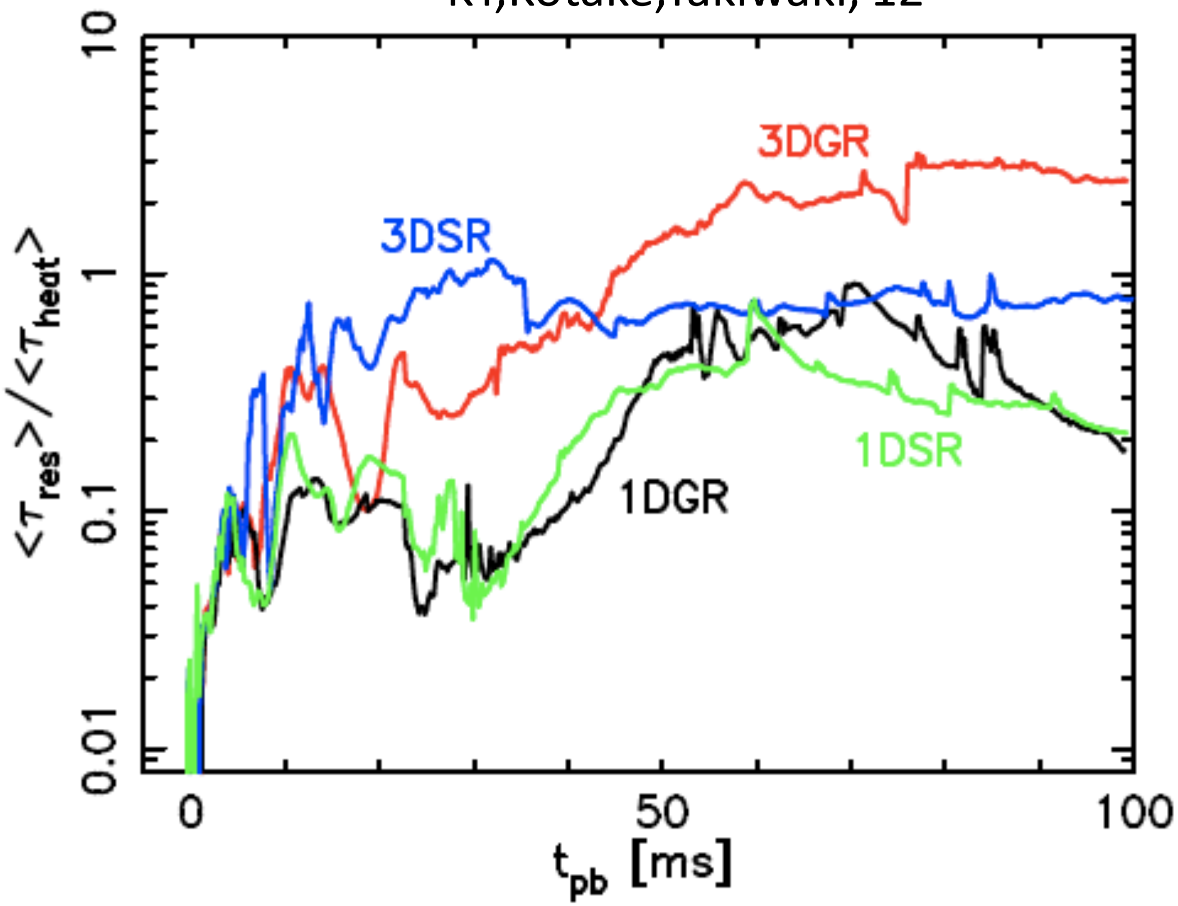
$$\tau_{\rm res} \equiv \begin{cases} \frac{r_{\rm gain}(\theta,\phi)-r}{v^r} & \text{for} \quad v^r < 0 \\ \frac{r_{\rm shock}(\theta,\phi)-r}{v^r} & \text{for} \quad v^r > 0 \end{cases}$$

$$\tau_{heat} \equiv \frac{-e_{bind}}{\dot{Q}}$$ Time scale of binding energy to be 0 (unbound)

2. CCSNにおける数値計算

1)ν-driven scenario (successful explosions in multi-D)

KT,Kotake,Takiwaki,'12

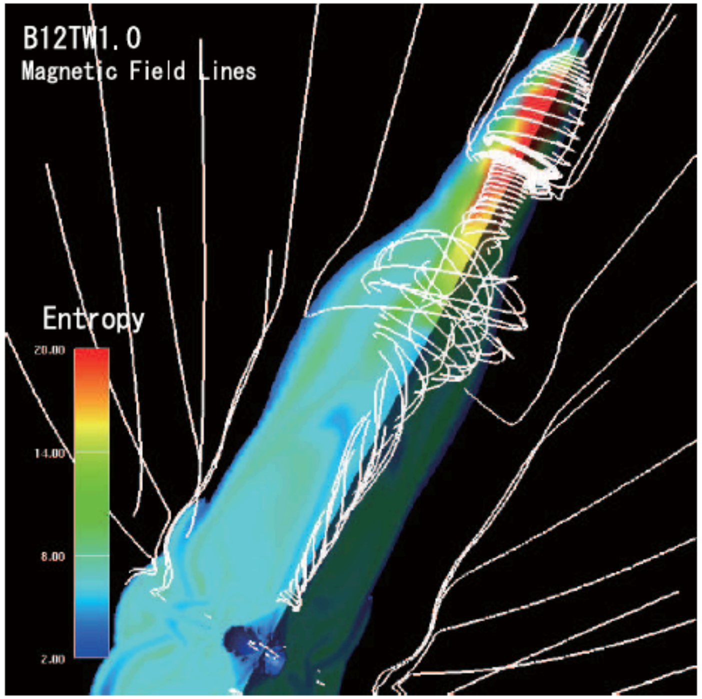


Multi-D effects are key to successful explosion

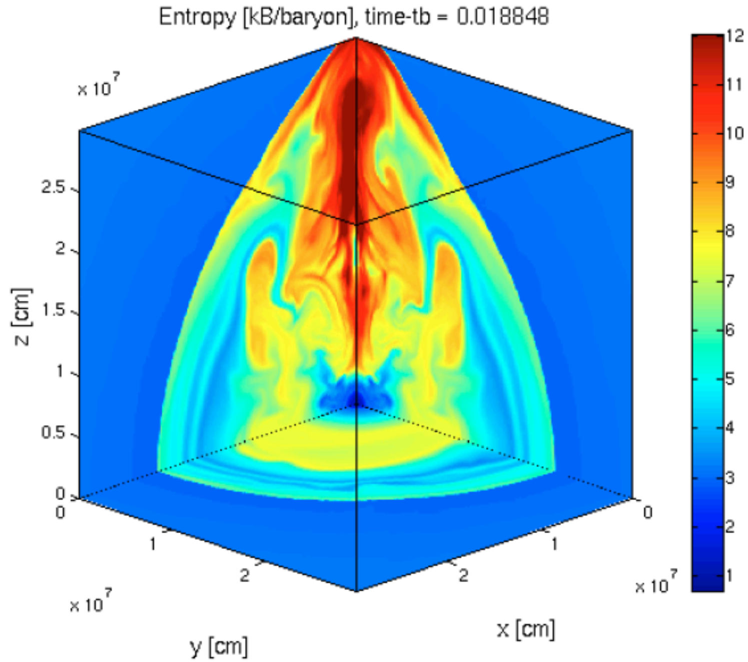
2. CCSNにおける数値計算

2)magneto-rotational explosion (MRE)

Takiwaki+,'08 (2D-axisymmetry)



Scheidegger+,'10 (3D)



Possible amplification mechanisms are

1) winding effect

2) magneto rotational instability(MRI)

2. CCSNにおける数値計算

✓Microphysics

- EOS of baryonic matters above nuclear density (ρ>~2x10^{14}g/cc)
- Neutrino transfer (Burrows+ '06, Marek&Janka,'09, Suwa+,'10,Takiwaki+,'11)

✓一般相対論 (e.g., Obergaulinger+'06,Shibata+'06)

✓３次元の効果 (e.g., Mikami+'08,Scheidegger+'09,Iwakami+'09)

✓磁場の影響 （e.g., Yamada&Sawai,04,Kotake+'05, Burrows+'07 ,Takiwaki+'09,Kuroda&Umeda'10)

Numerical scheme (code)

$$G^{\alpha\beta} = 8\pi T^{\alpha\beta}$$

$$\equiv 8\pi\left(T^{\alpha\beta}_{fluid} + T^{\alpha\beta}_{radiation}\right)$$

Features of our code (see, KT, Kotake & Takiwaki, ApJ, '12)

- BSSN formalism (metric)
- Relativistic (M)HD
- 3D-Nested grid (or AMR)

(BSSN formalism, Relativistic (M)HD, 3D-Nested grid: KT & Umeda,'10)

- Neutrino radiation (gray energy)
  1) cooling (leakage) Roswog&Liebendorfer'03, Sekiguchi,'10
  2) heating (truncated (M1) method) Thorne'81, Shibata+'11

BSSN equations (17 variables) + Gauge conditions

$$
\begin{aligned}
(\partial_t - \mathcal{L}_\beta)\tilde{\gamma}_{ij} &= -2\alpha\tilde{A}_{ij} \\
(\partial_t - \mathcal{L}_\beta)\phi &= -\alpha K/6 \\
(\partial_t - \mathcal{L}_\beta)\tilde{A}_{ij} &= e^{-4\phi}\left[\alpha(R_{ij} - 8\pi(S_{ij} + P_{ij})) - D_i D_j \alpha\right]^{\mathrm{trf}} + \alpha(K\tilde{A}_{ij} - 2\tilde{A}_{ik}\tilde{\gamma}^{kl}\tilde{A}_{jl}) \\
(\partial_t - \mathcal{L}_\beta)K &= -\Delta\alpha + \alpha(\tilde{A}_{ij}\tilde{A}^{ij} + K^2/3) + 4\pi\alpha(S_0 e^{-6\phi} + E + \gamma^{ij}(S_{ij} + P_{ij})) \\
(\partial_t - \beta^k\partial_k)\Gamma^i &= -16\pi\tilde{\gamma}^{ij}(S_j e^{-6\phi} + F_j) \\
&\quad -2\alpha(\frac{2}{3}\tilde{\gamma}^{ij}K_{,j} - 6\tilde{A}^{ij}\phi_{,j} - \tilde{\Gamma}^i_{jk}\tilde{A}^{jk}) \\
&\quad +\tilde{\gamma}^{jk}\beta^i_{,jk} + \frac{1}{3}\tilde{\gamma}^{ij}\beta^k_{,kj} - \tilde{\Gamma}^j\beta^i_{,j} + \frac{2}{3}\tilde{\Gamma}^i\beta^j_{,j} + \beta^j\tilde{\Gamma}^i_{,j} - 2\tilde{A}^{ij}\alpha_{,j}
\end{aligned}
$$

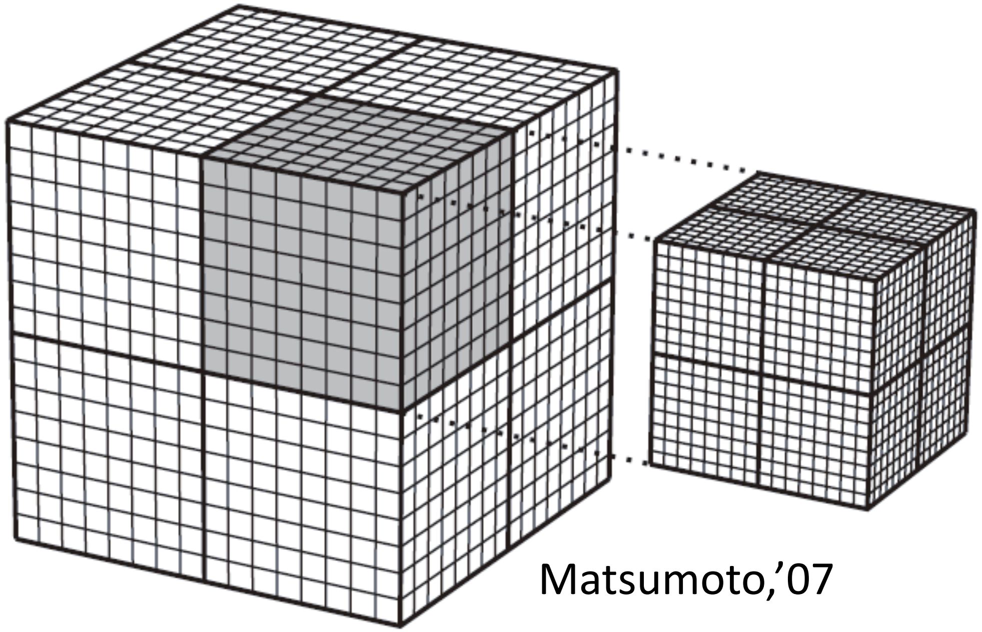
Hydrodynamic equations (10+3 variables)

$$
\begin{aligned}
\partial_t\rho_* + \partial_i(\rho_* v^i) &= 0 \\
\partial_t S_i + \partial_j(S_i v^j + \alpha e^{6\phi}P_{\mathrm{tot}}\delta^j_i) &= -S_0\partial_i\alpha + S_k\partial_i\beta^k + 2\alpha e^{6\phi}S^k_k\partial_i\phi \\
&\quad -\alpha e^{2\phi}(S_{jk} - P_{\mathrm{tot}}\gamma_{jk})\partial_i\tilde{\gamma}^{jk}/2 - e^{6\phi}\alpha Q^\mu\gamma_{i\mu} \\
\partial_t\tau + \partial_i(S_0 v^i + e^{6\phi}P_{\mathrm{tot}}(v^i + \beta^i) - \rho_* v^i) &= \alpha e^{6\phi}KS^k_k/3 + \alpha e^{2\phi}(S_{ij} - P_{\mathrm{tot}}\gamma_{ij})\tilde{A}^{ij} - S_i D^i\alpha \\
&\quad + e^{6\phi}\alpha Q^\mu n_\mu \\
\partial_t(\rho_* Y_l) + \partial_i(\rho_* Y_l v^i) &= \rho_*\Gamma_l
\end{aligned}
$$

Neutrino Radiation equations (12xNene variables)

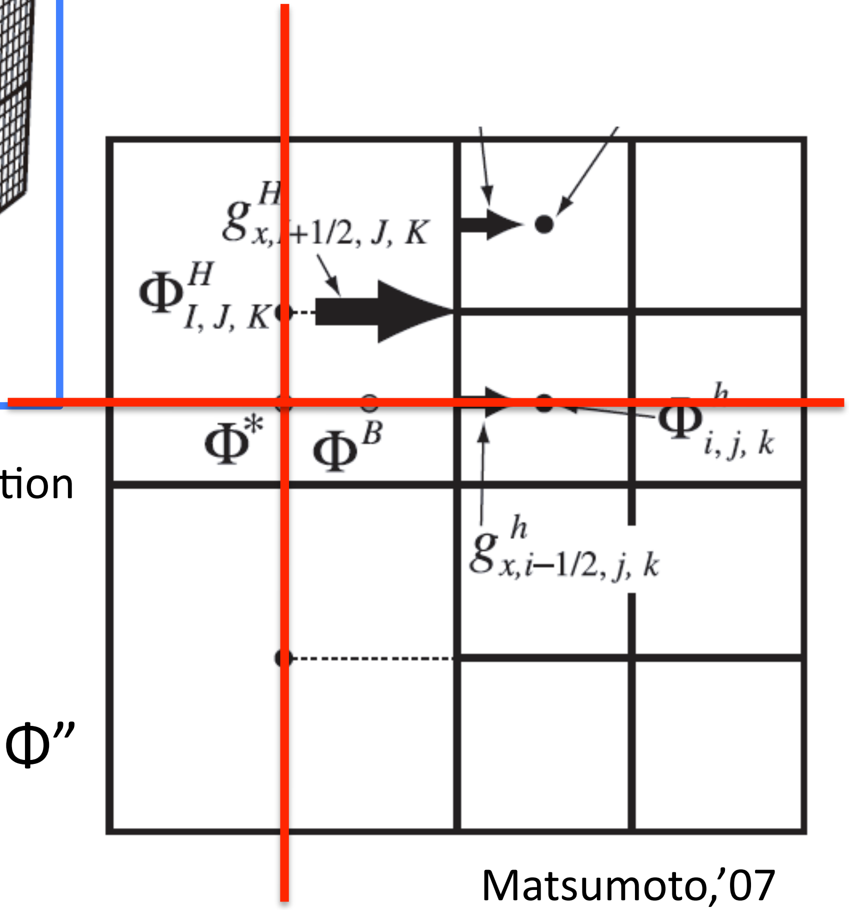
$$
\begin{aligned}
\partial_t(e^{6\phi}F_i) + \partial_j[e^{6\phi}(\alpha P^j_i - \beta^j F_i)] &= e^{6\phi}[-E\partial_i\alpha + F_j\partial_i\beta^j + (\alpha/2)P^{jk}\partial_i\gamma_{jk} + \alpha Q^\mu\gamma_{i\mu}] \\
\partial_t(e^{6\phi}E) + \partial_i[e^{6\phi}(\alpha F^i - \beta^i E)] &= e^{6\phi}(\alpha P^{ij}K_{ij} - F^i\partial_i\alpha - \alpha Q^\mu n_\mu)
\end{aligned}
$$

Numerical scheme (code)



Matsumoto,'07

(1) 2D interpolation



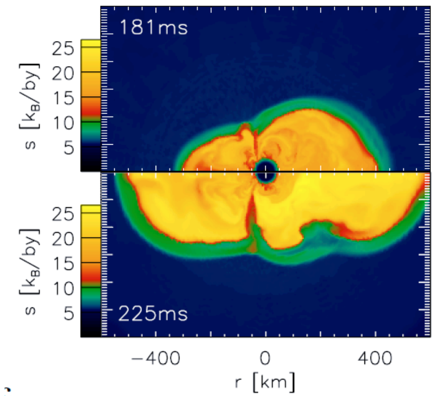
(2) 1D interpolation

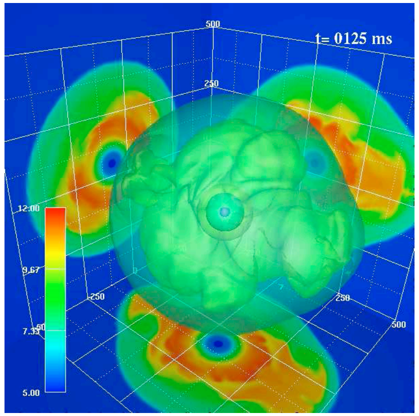
To obtain continuous "$\nabla\Phi$"

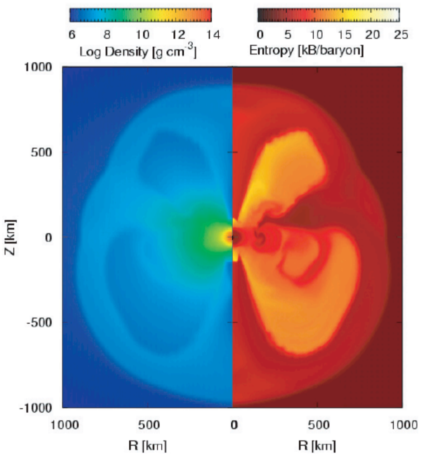
Matsumoto,'07

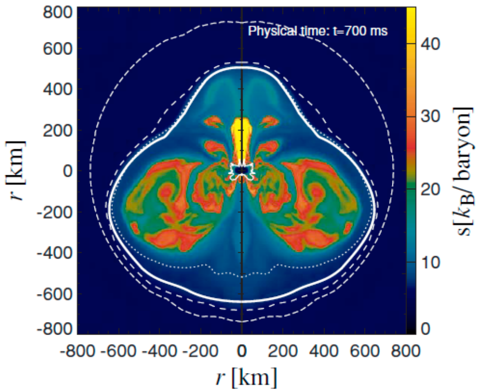
GW emission from rotating star

1)ν-driven explosion



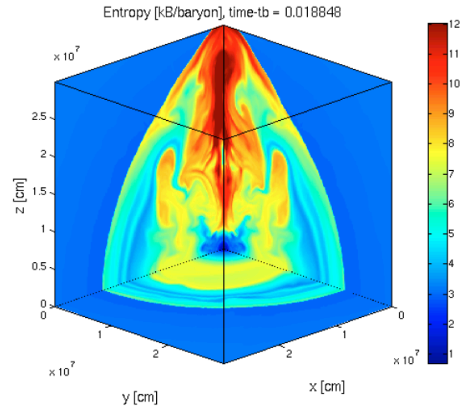


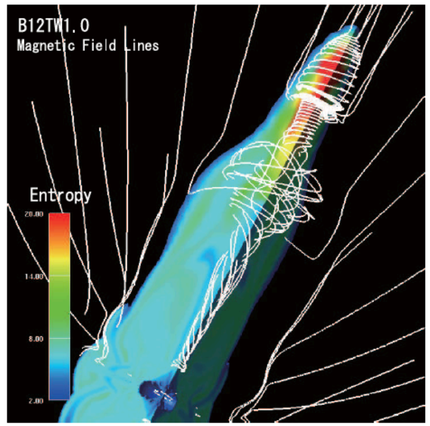




“Spherical” explosion

2)MRE





“Oriented” explosion

GW emission from rotating star

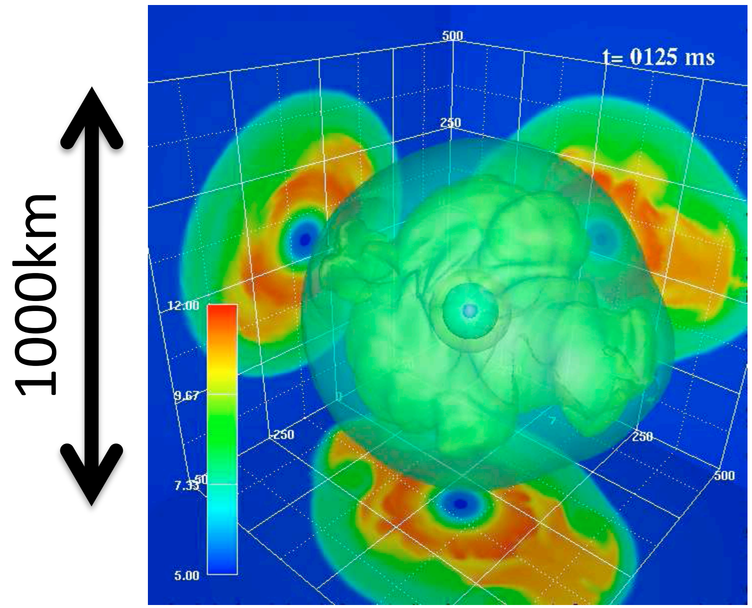
But there are several problems…

✓Usually CCSNe occur very far from us!

$\theta \sim (10^{8}\mathrm{cm}/10^{22}\mathrm{cm}) = 10^{-14}$

✓Explosion occurs deep down the star!

optically thick



GW emission from rotating star

Then, how can we decipher which mechanism affects mostly on the explosion?

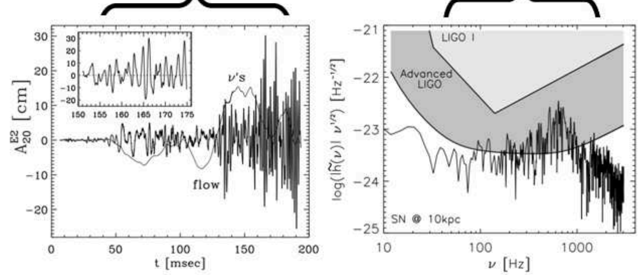
Model Dim. | **Candidate Explosion Mechanism**

- Neutrino-driven mechanism (slow/no rotation)
- MHD mechanism (rapid rotation/large B fields)

2D

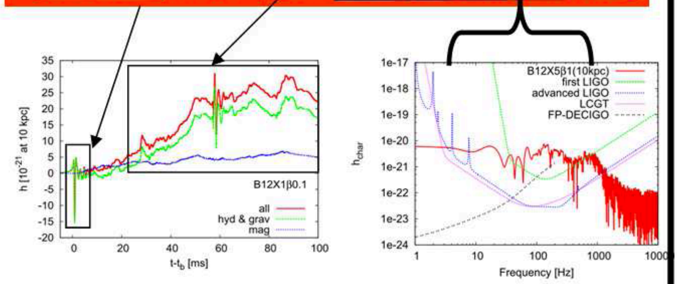
Neutrino-driven mechanism: SASI & Convection

"stochastic" and broad-band signal



MHD mechanism: Bounce & MHD Outflows

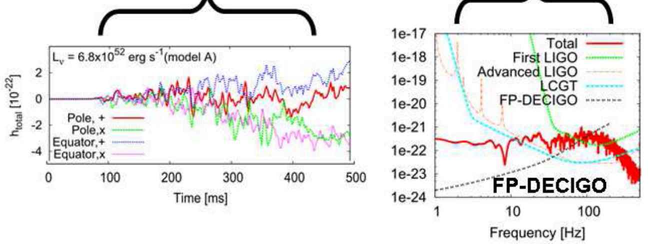
"Bounce with "tail" broad-band signal



3D

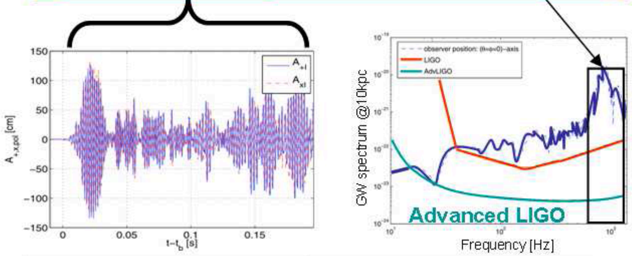
Neutrino-driven mechanism: SASI & Convection

"stochastic" and broad-band signal



MHD mechanism: Non-axisymmetric Instabilities

"Long-lasting" narrow-band signal

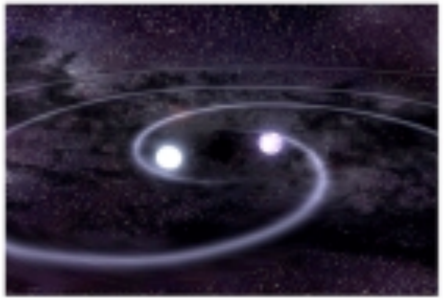


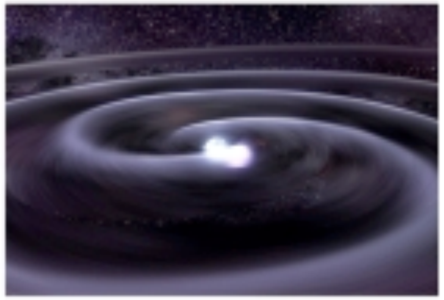
Kotake,'11, "Gravitational Waves (from detectors to astrophysics)"

GW emission from rotating star

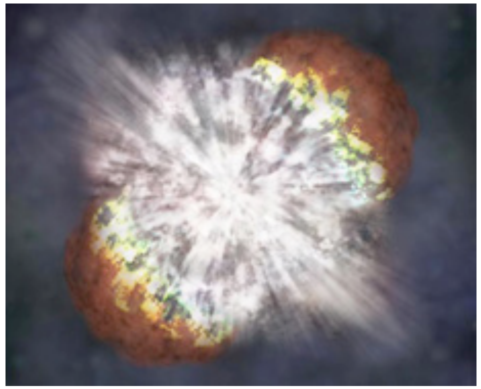
As candidates of strong GW emitters

mergers of compact stars
(NSNS,NSBH,BHBH)





Core Collapse Supernovae
(CCSNe)



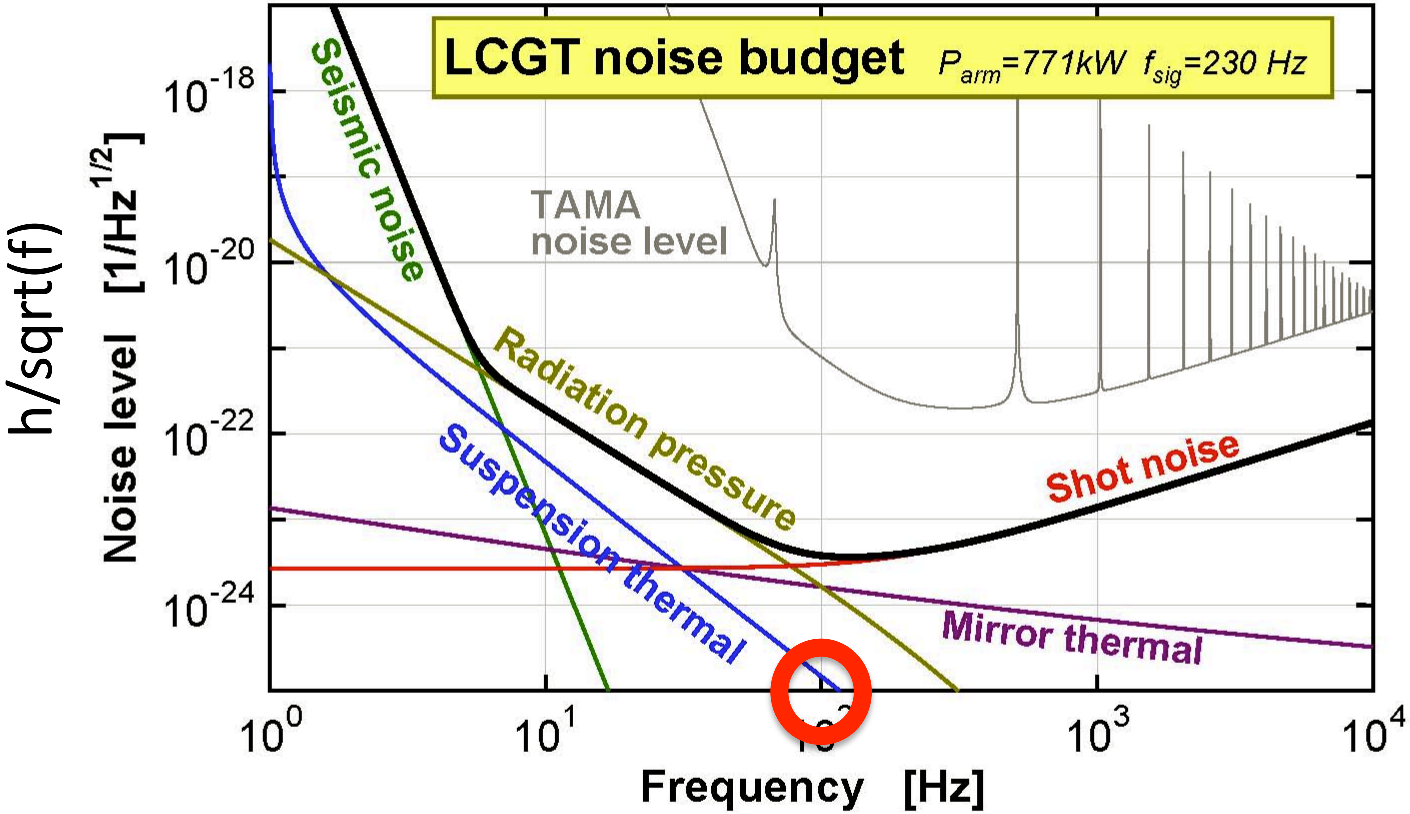
	mergers of compact stars	CCSNe
occurrence frequency	~1/y/(200Mpc)^3 Phinney+,'91	~1/y/(20Mpc)^3 Mannucci+,'07
GW Amp@src	~km (Shibata+,'03)	~m
h=A/D	~10^-22 (D~200Mpc)	~10^-24 (D~20Mpc)

GW emission from rotating star

$h = A_{GW}/D$ ~10^-24 (with D=10Mpc)

(h/sqrt(100Hz)~10^-25)

Can we detect such extraordinary small signals?



GW emission from rotating star

What we have to do is to predict
gravitational waveforms and neutrino luminosities
as precisely as possible in advance.

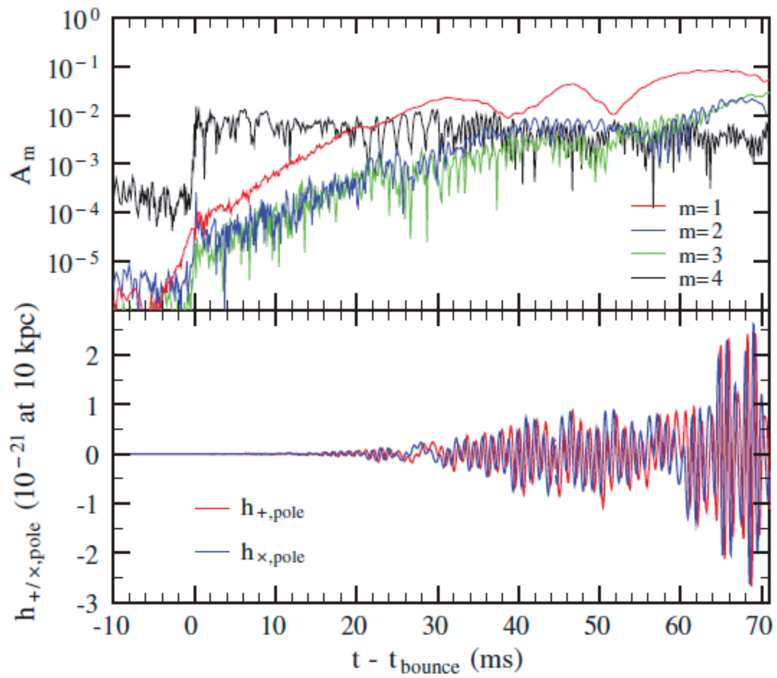
- Full general relativistic
- Multi-energy & multi flavor neutrino radiation
- 3-D
- (Magneto-hydrodynamical)

simulations are indispensable.

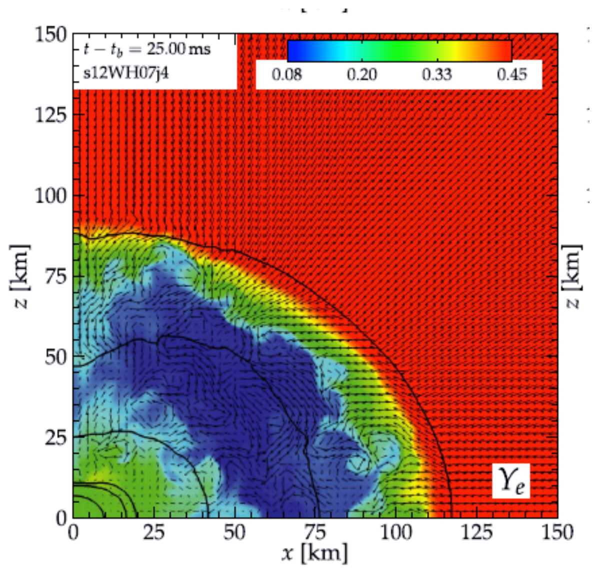
Aim

- By using full 3DGR-Rad. hyd. code, we investigate rotational effects on GW emission

In Ott+,'07, they neglect ν-cooling



In Ott+,'12, the computational domain is only one quadrant.



Numerical scheme (initial condition)

Progenitor: 15Msun (WW95)

EOS: Shen eos (Shen+,'98)+e^-e^++photon(+neutrino)

Initial rotational profile

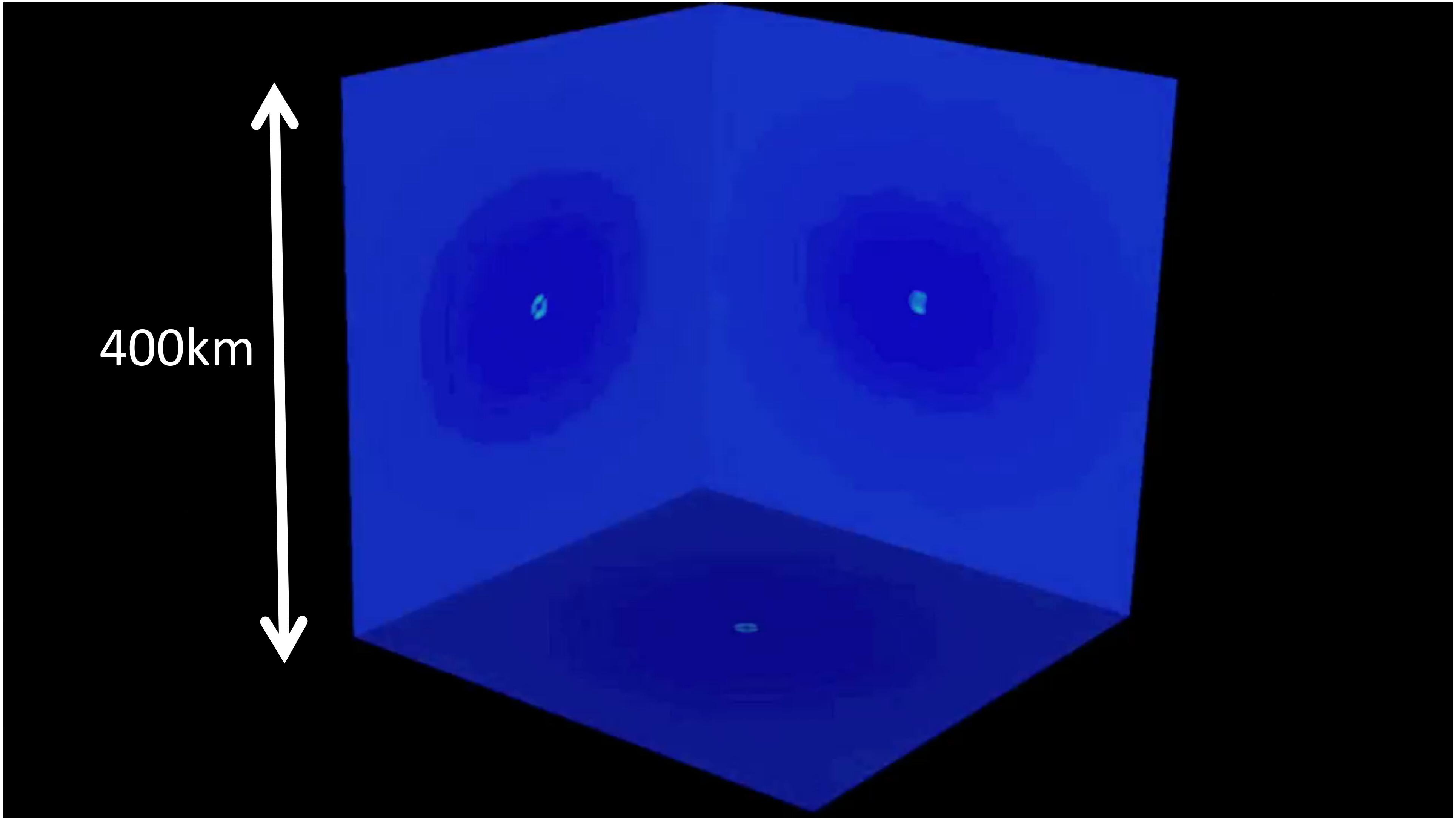
$$\begin{cases} \Omega(\varpi) = \Omega_0 \dfrac{{\varpi_0}^2}{{\varpi_0}^2 + \varpi^2} \\ \varpi_0 = 1000km \end{cases}$$

We calculated 4 models with varying Ω_0

$$\Omega_0 = 0, \frac{\pi}{6}, \frac{\pi}{2}, \pi(rad/s)$$

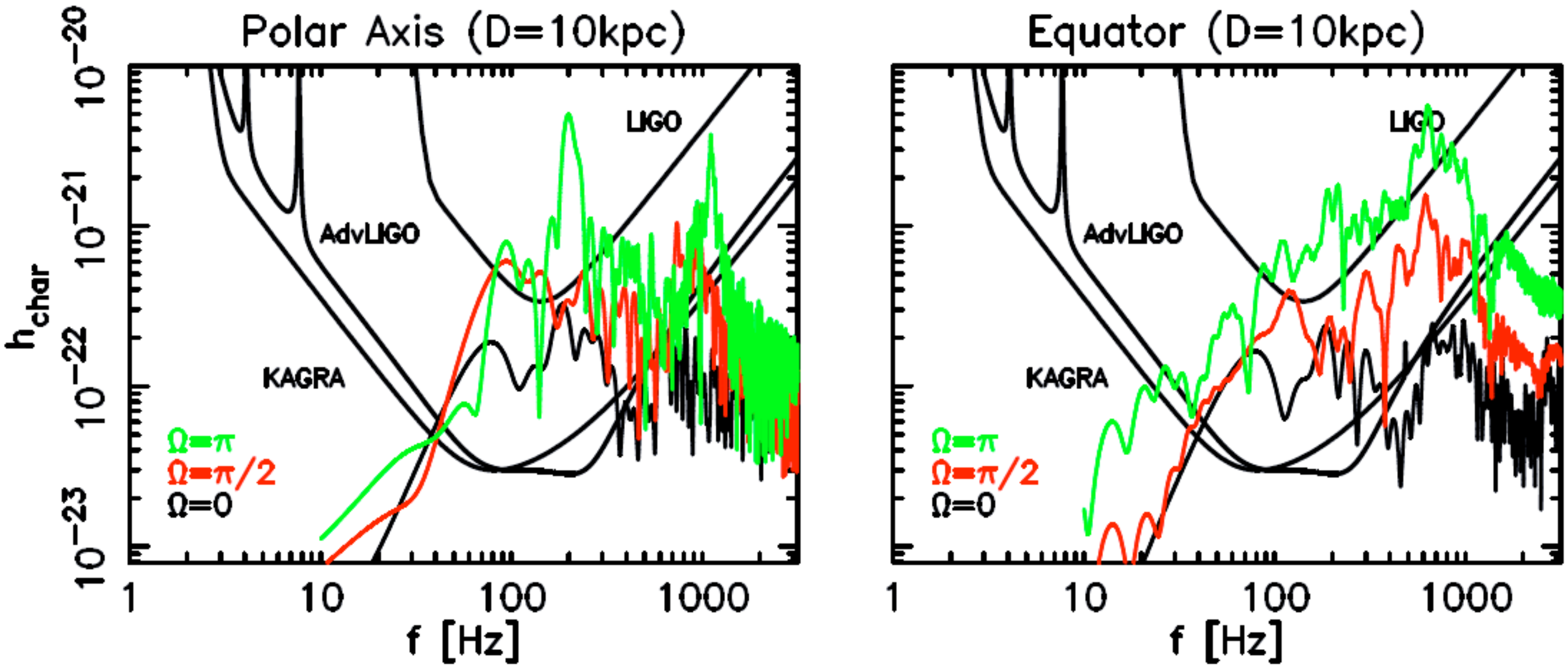
According to Hegar, '05,
Ω_0～1 (rad/s) at maximum.

- 128^3cells * 9 Level nested structure (dx$_{min}$~450m)
- Random perturbation（1%）in density was added at initial
- Cray XT4 (512core) @ NAOJ, ~1.3ms/1day



0<T_{pb}<50ms

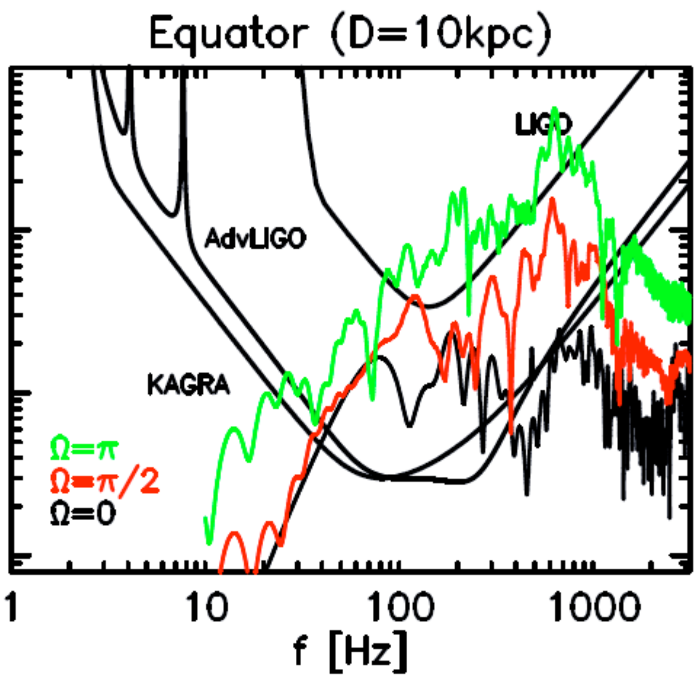
Results (GW spectra)

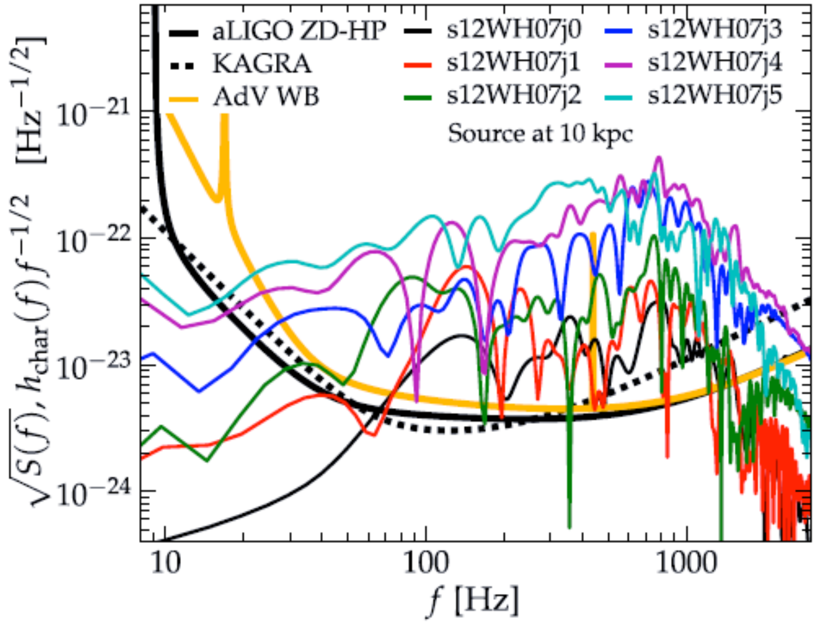


- If CCSN occurs within our galaxy (D<10kpc) and progenitor rotates sufficiently fast（Ω>pi/2）, (S/N)>10 can be achieved.
- Observation along polar axis also gives us possibility of detection.

Results (GW spectra)

Comparison with Ott+,'12





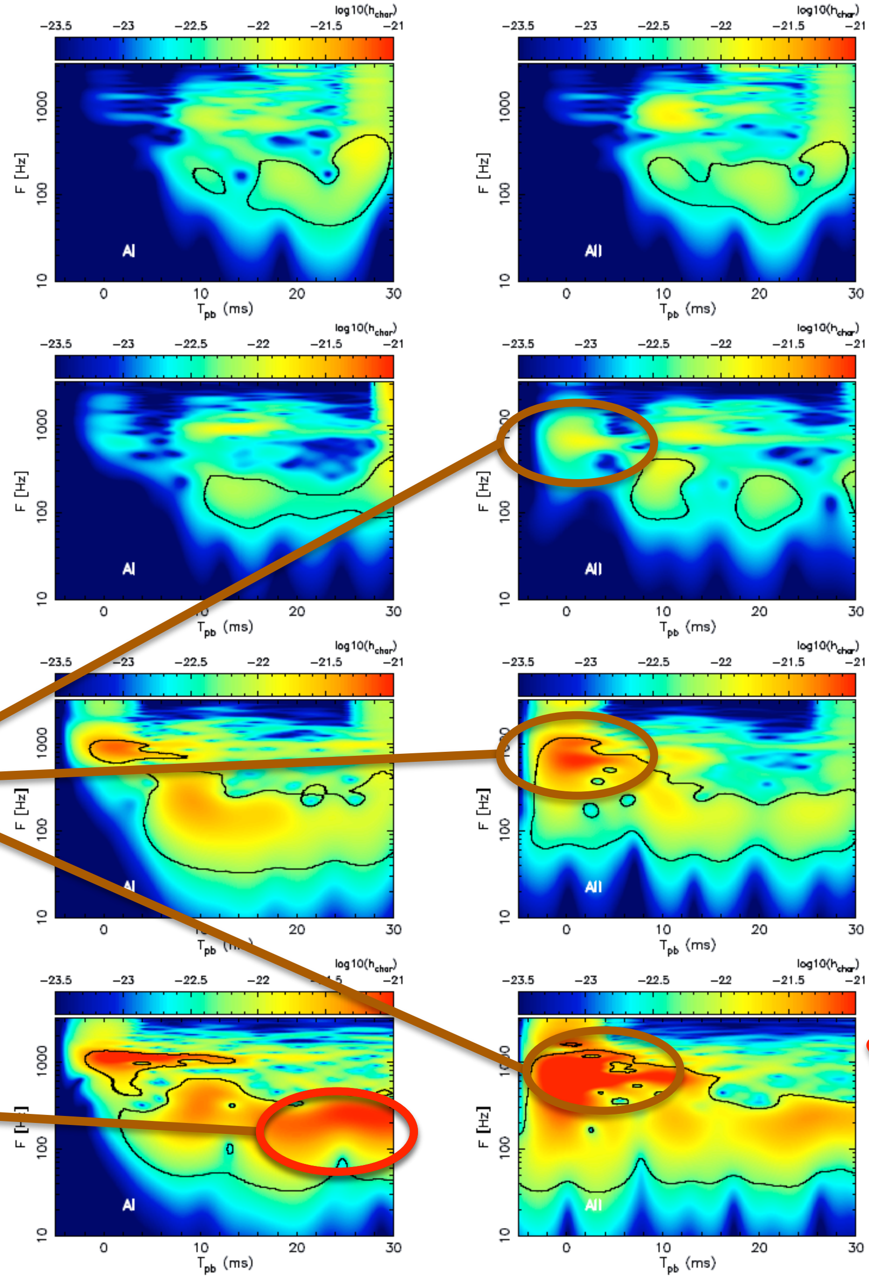
Spectral peak appears at similar value ~670Hz(ours)

~700Hz(Ott+'12)

Rotational signatures in GW spectra

rotational axis

equator



immediately after the bounce	late phase
equator	polar axis
～700Hz	～200Hz

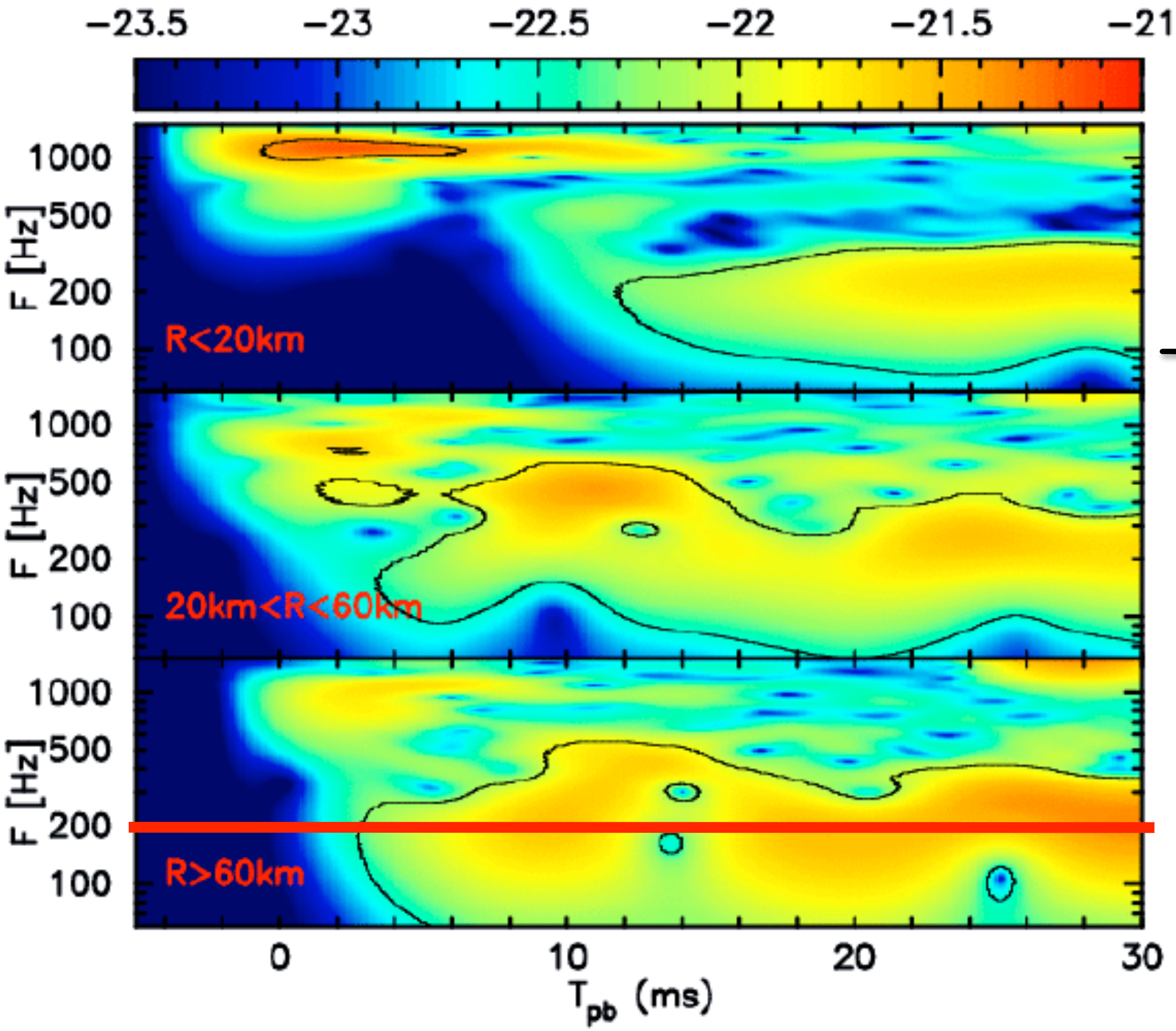
l=2 mode

Rotation

Where do these signals come from ?

Rotational signatures in GW spectra

Spatial distribution of GW source toward polar axis



GW extraction by quadrupole formulae

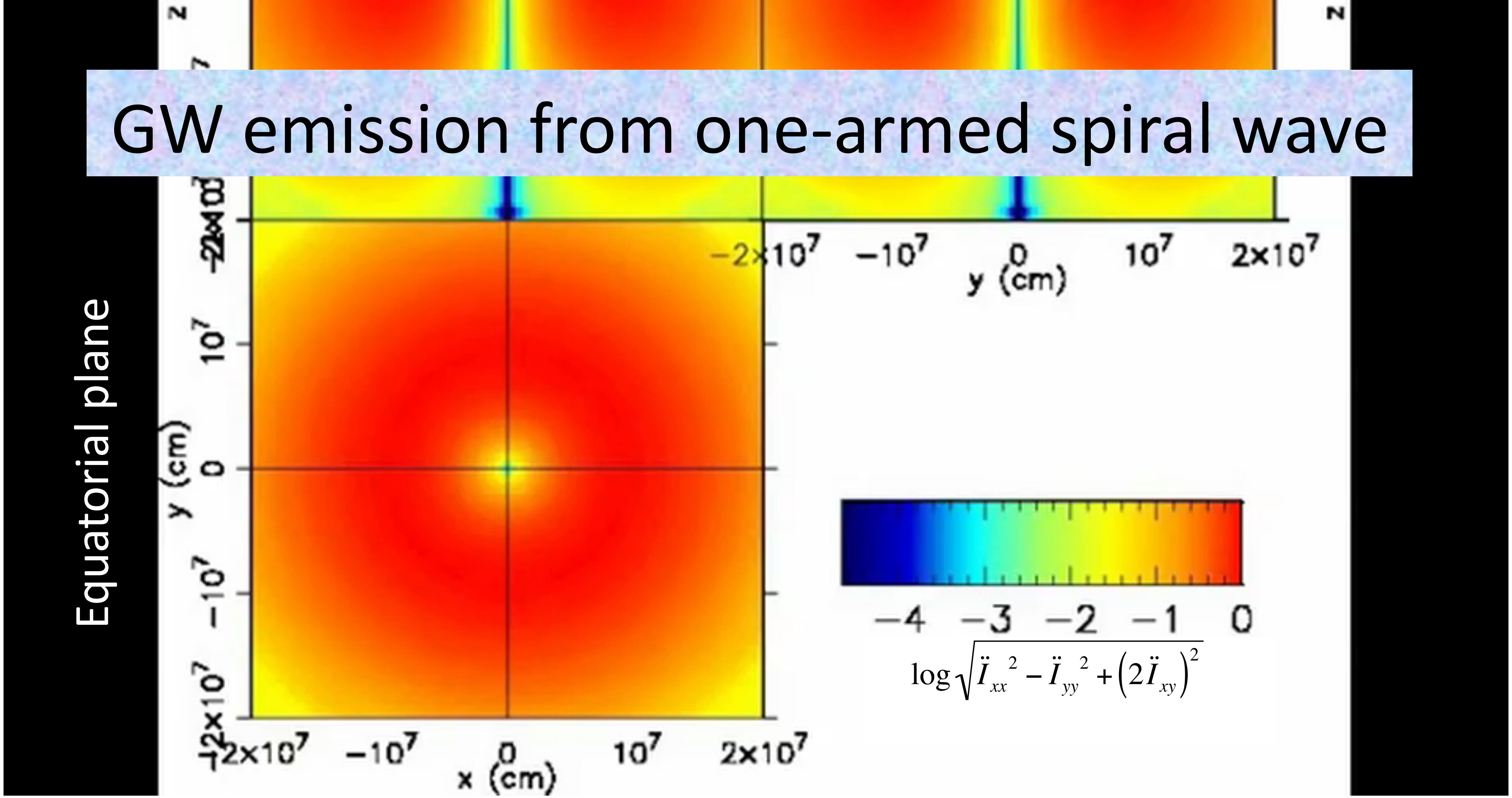
$$
\begin{cases} A_+(\theta,\phi) = \ddot{I}^{TT}_{\theta\theta} - \ddot{I}^{TT}_{\phi\phi} \\ A_\times(\theta,\phi) = 2\ddot{I}^{TT}_{\theta\phi} \end{cases}
$$

where

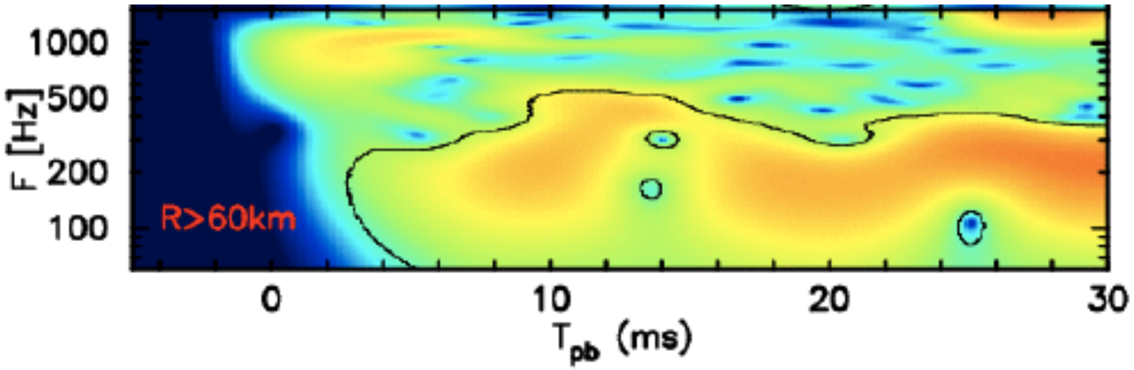
$$
\dot{I}_{ij} = \frac{G}{c^4}\int \rho_*(v^i x^j + x^i v^j) d^3x.
$$

Ω=pi

GW emission from one-armed spiral wave

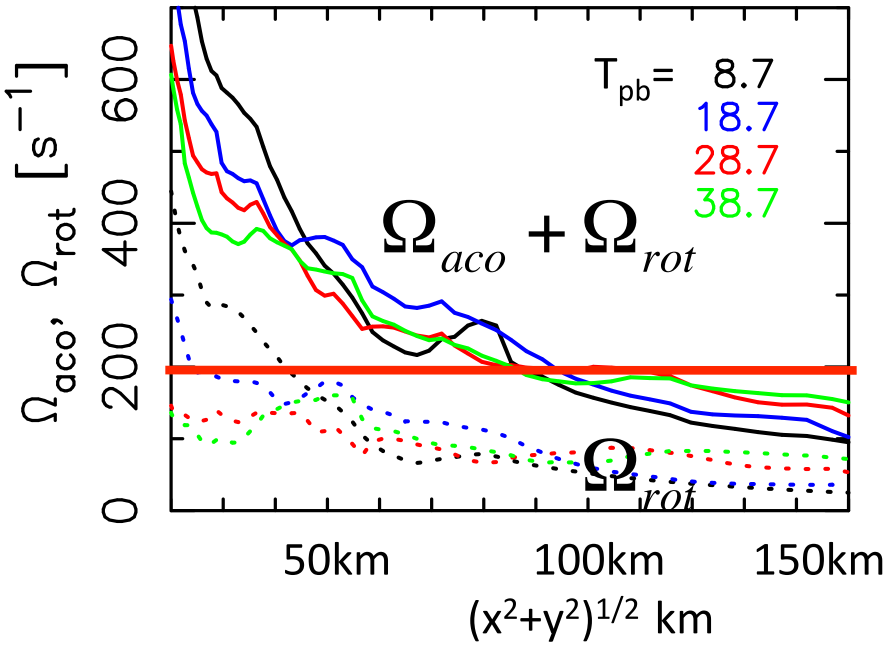


One-armed Spiral wave is the GW (@~200 Hz) emitter



GW emission from one-armed spiral wave

What determines emission @~200Hz?



$$\Omega_{\rm rot} \equiv 2\frac{V_\phi}{2\pi\sqrt{x^2+y^2}},$$

$$\Omega_{\rm aco} \equiv 2\frac{C_s}{2\pi\sqrt{x^2+y^2}},$$

- ~200Hz is determined from Doppler shift (rot. + sound velocity)
- Since Ω_{aco} (~100Hz) is hardly changed by progenitor rotation

  → "F_{peak}-100Hz" reflects rotational time scale above the PNS(?)

Conclusions

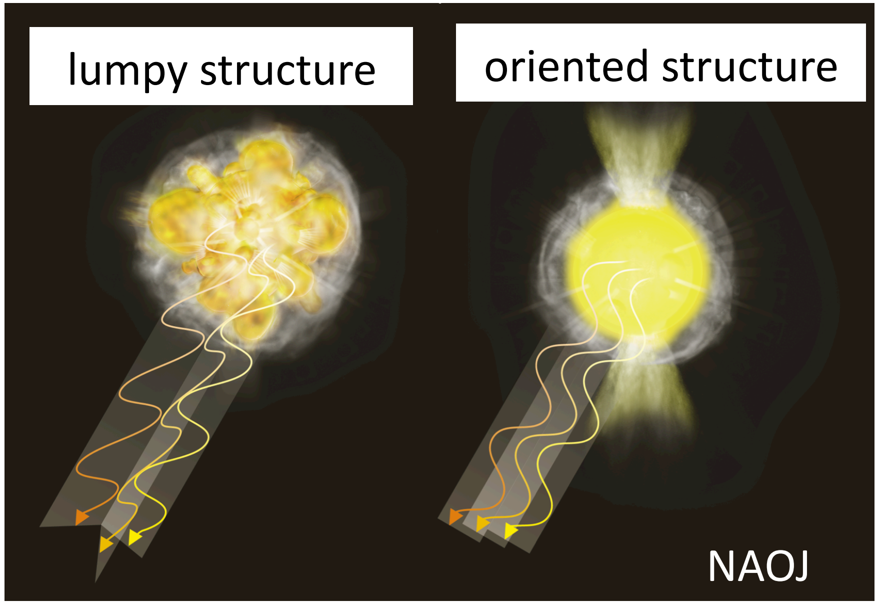
① Combination of low-T/W instability and spiral SASI can leave its message in GW emission.

② Its emission frequency can be determined from Doppler shift.

Toward future analysis

Usually CCSNe occur far from us and it is very difficult to resolve angular dependence of asymmetry.

Resolve explosion morphology by polarized EM wave



c.f., Tanaka+,'12

Resolve explosion morphology by polarized gravitational wave