Workshop on the progenitor-supernova-remnant connection
@Ringberg Castle, Germany
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Rotation aided Neutrino-driven Explosion of Core-Collapse Supernovae

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Collaborators:

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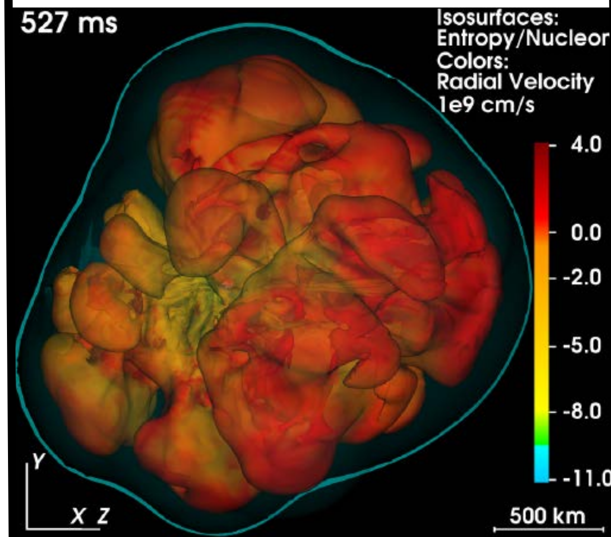
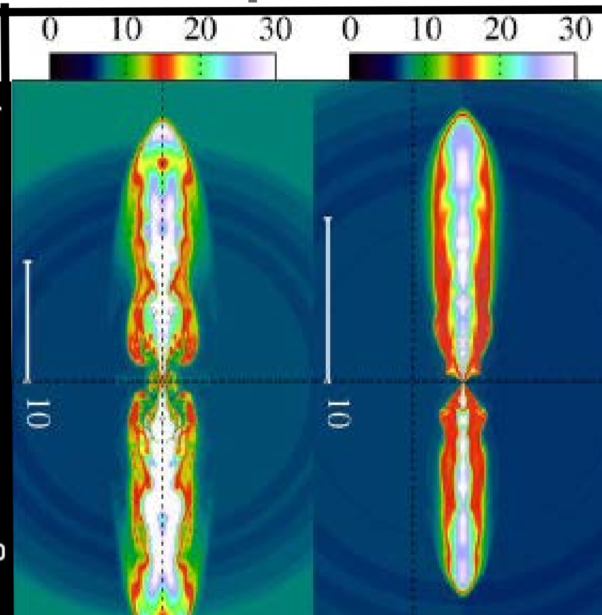
Explosion Mechanism of Core-Collapse Supernovae



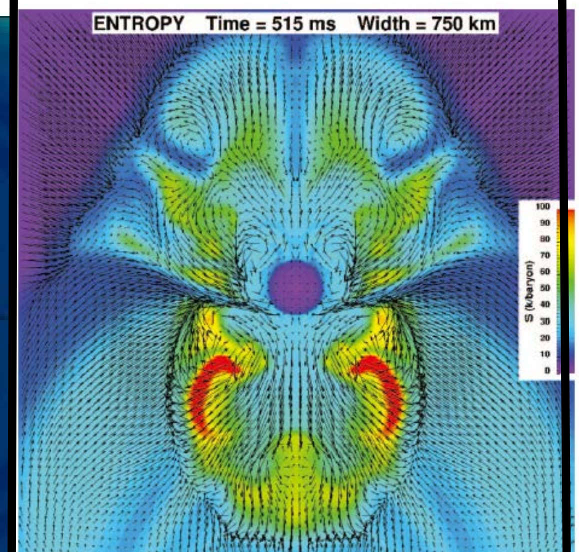
Melson+15

Neutrino Driven Mechanism



Obergaulinger+17

MHD Mechanism



Burrows+06

Acoustic Mechanism

I'll introduce a NEW mechanism.

That appears in a 3D simulation.

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Method in this presentation (now updated)

Hydro: 3DnSNe

- Geometry: Spherical coordinate, PWL interp.
- HLL scheme

Neutrino Radiation Transport: IDSA+Leakage

- For ν_e and $\bar{\nu}_e$, flux-IDSA (Takiwaki+2014)
- For ν_X, Leakage Scheme (Rosswog & Liebendoerfer 2003)
- Minimum set of the reactions considered (Takiwaki+14)

Gravity:

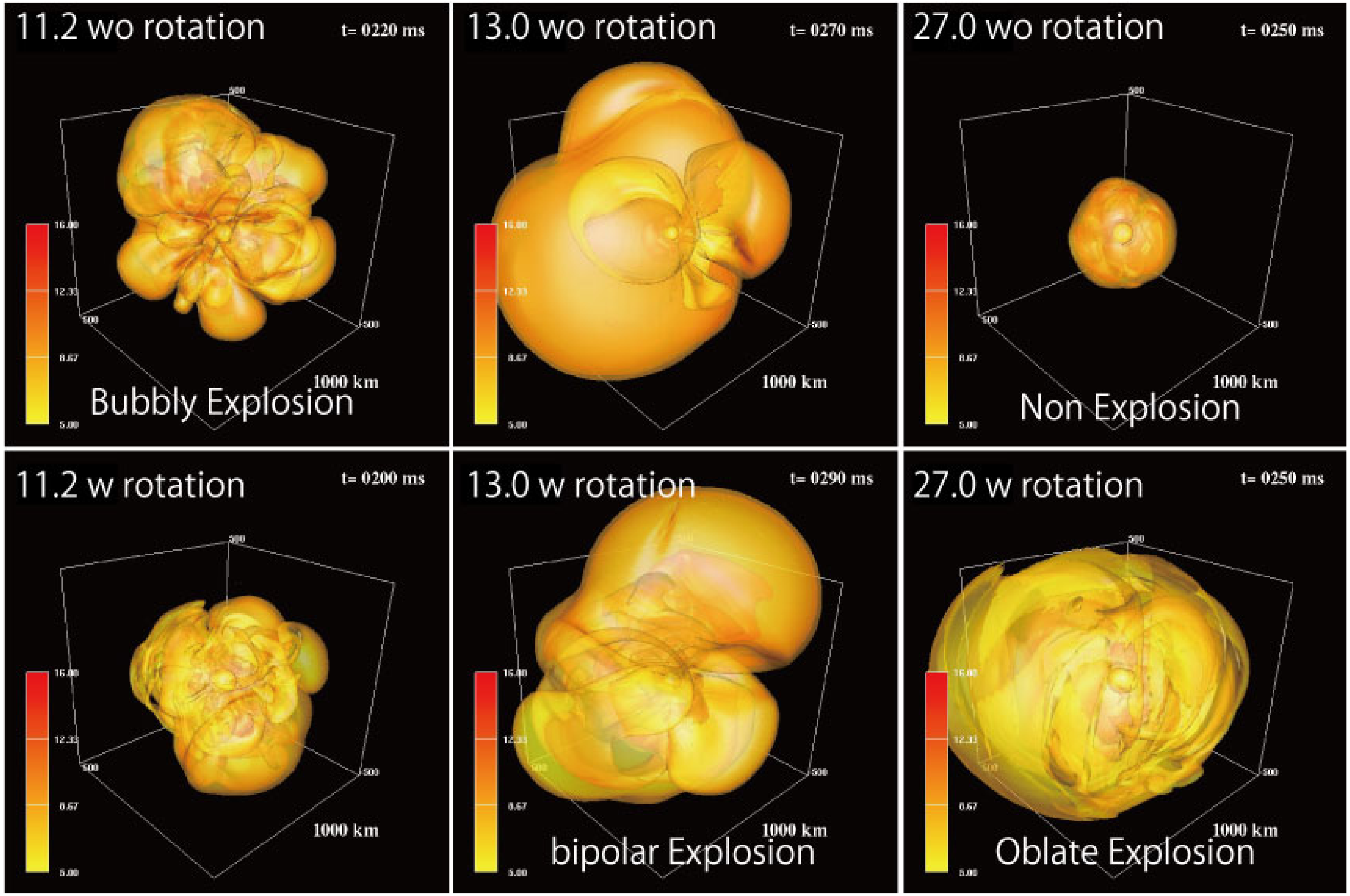
- Newtonian Monopole approximation

While our method is not state-of-the art,

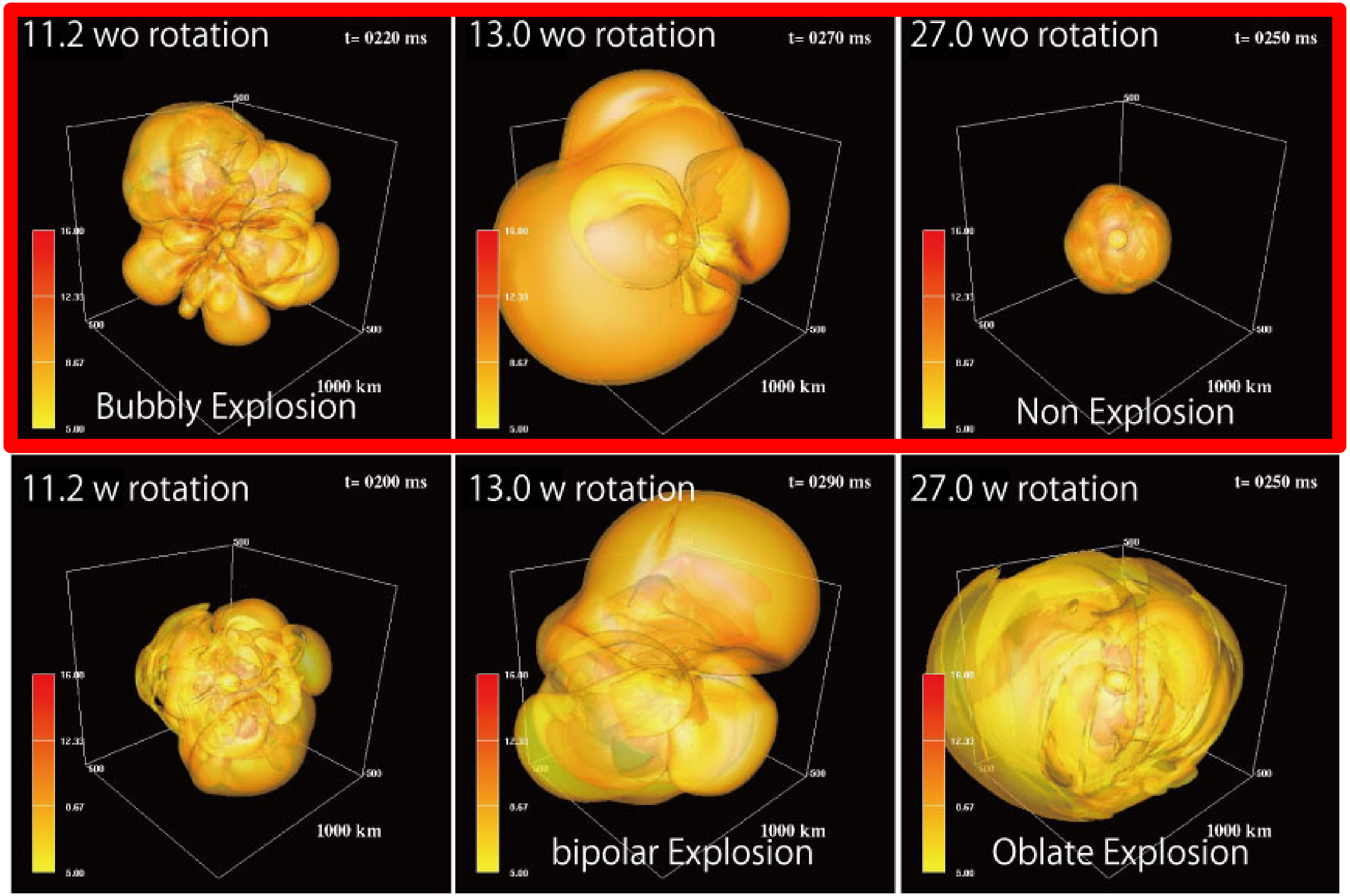
that does NOT require high CPU resources.

We can perform many models.

Initial setups and Results

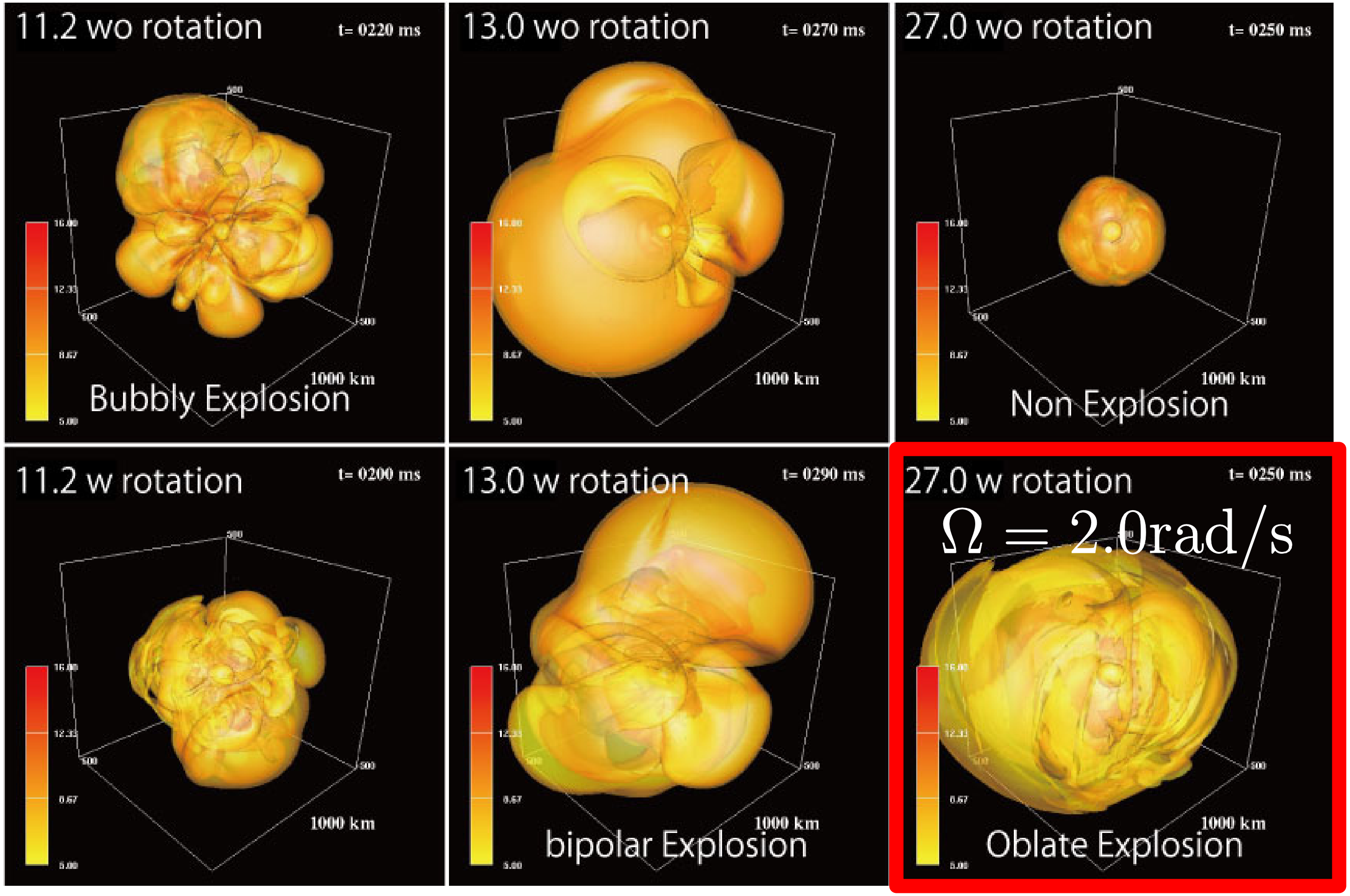


Initial setups and Results



- For non-rotating 3D simulations, Bernhard Mueller will talk. I'll skip it.

Initial setups and Results



- I focus on most interesting models. Rotation plays an essential role in the explosion.

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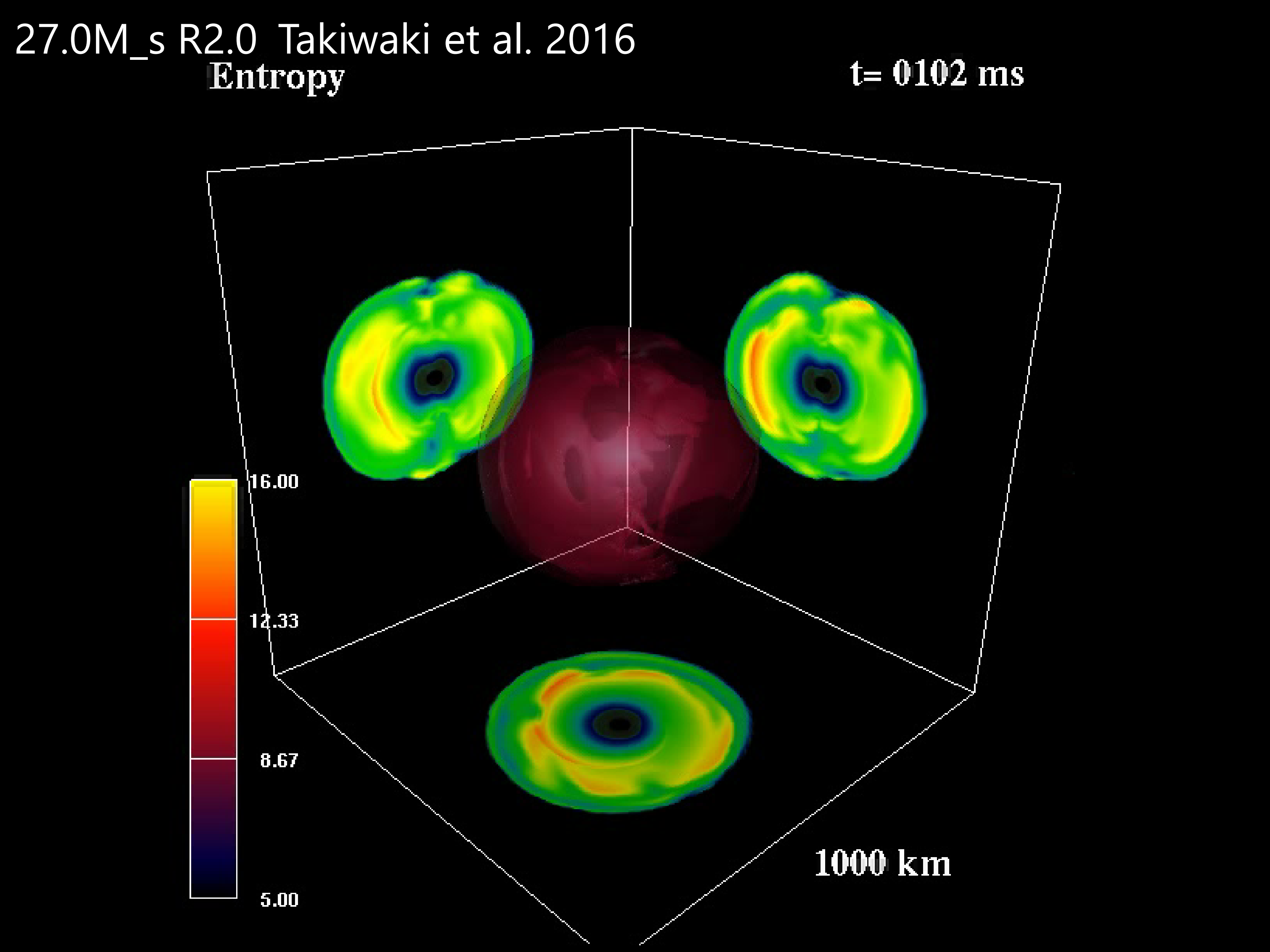
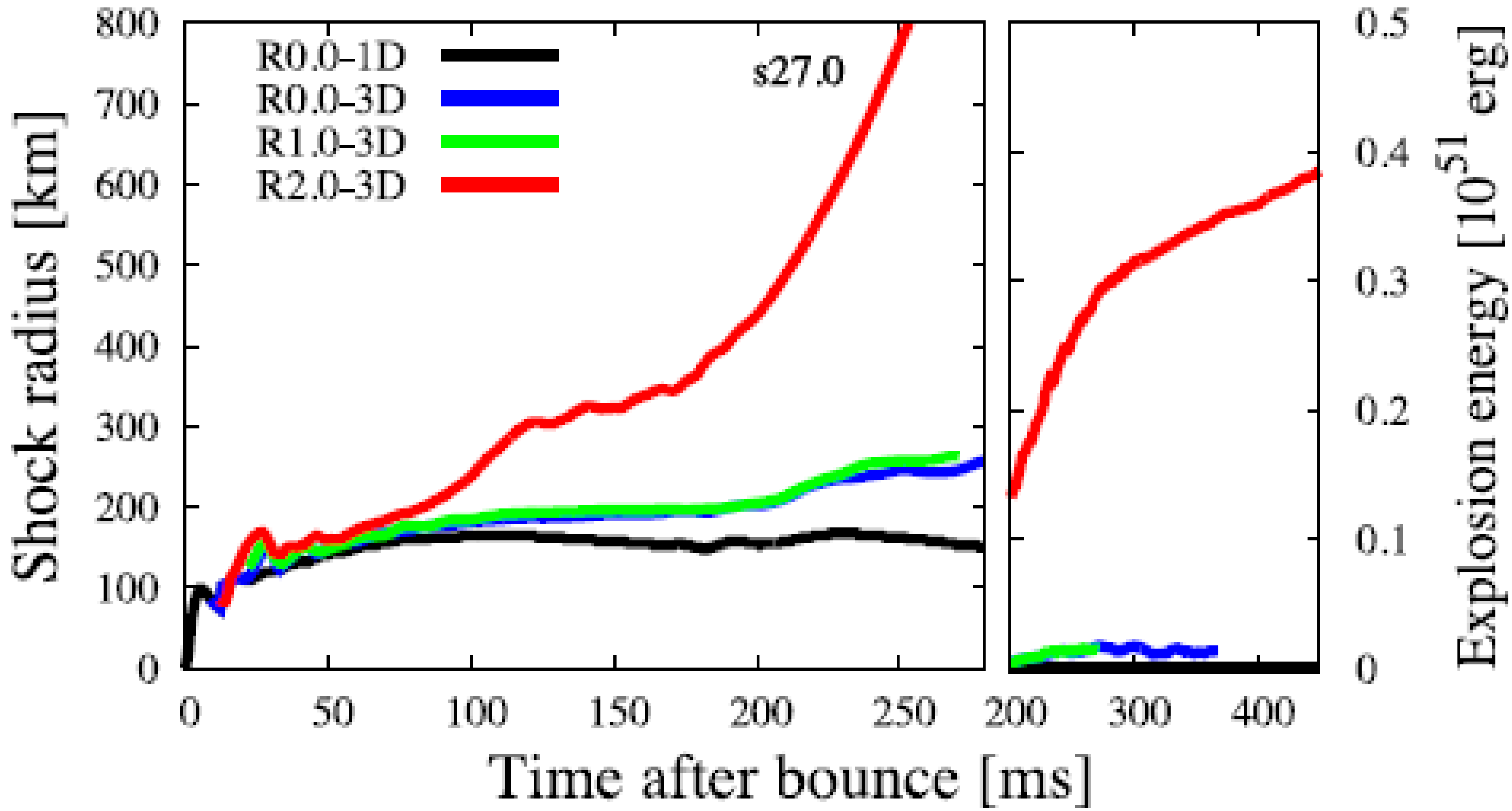

27.0M_s R2.0 Takiwaki et al. 2016
Entropy
t= 0102 ms
16.00
12.33
8.67
5.00
1000 km

Evolution of the Shock and Explosion Energy



This progenitor does not explode without the rapid rotation.

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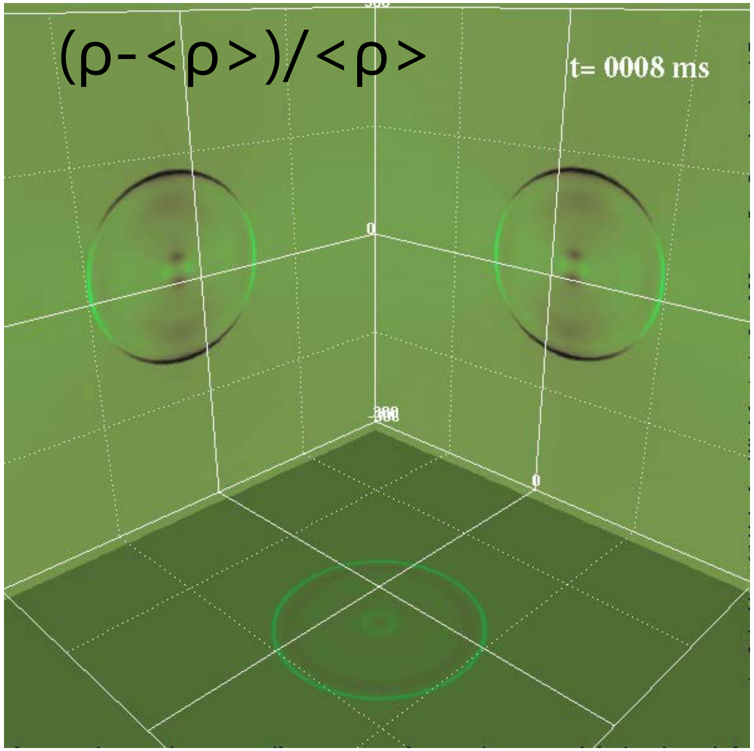
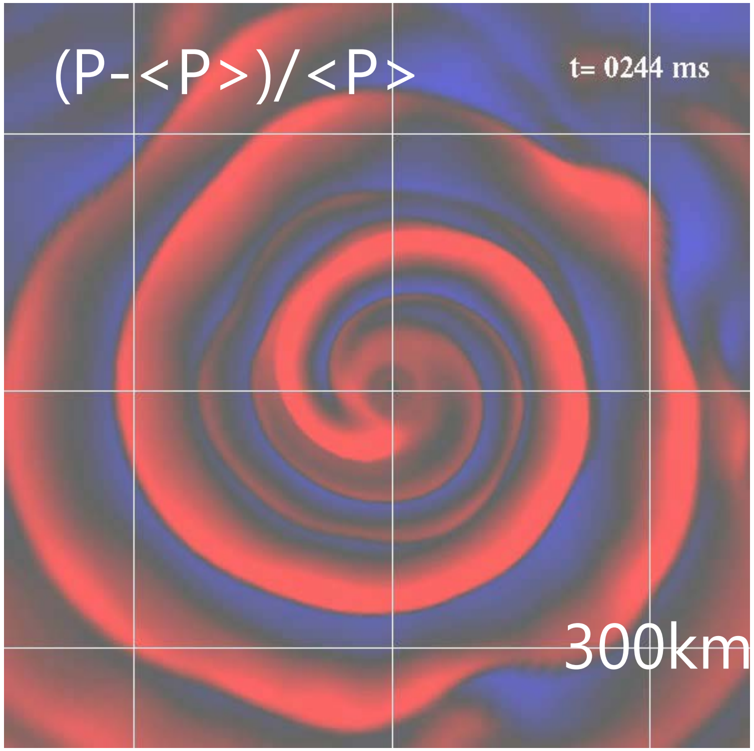
Growth of Spiral Mode





Rotational energy(T)/gravitational energy(W) reach some criteria => Spiral mode arises

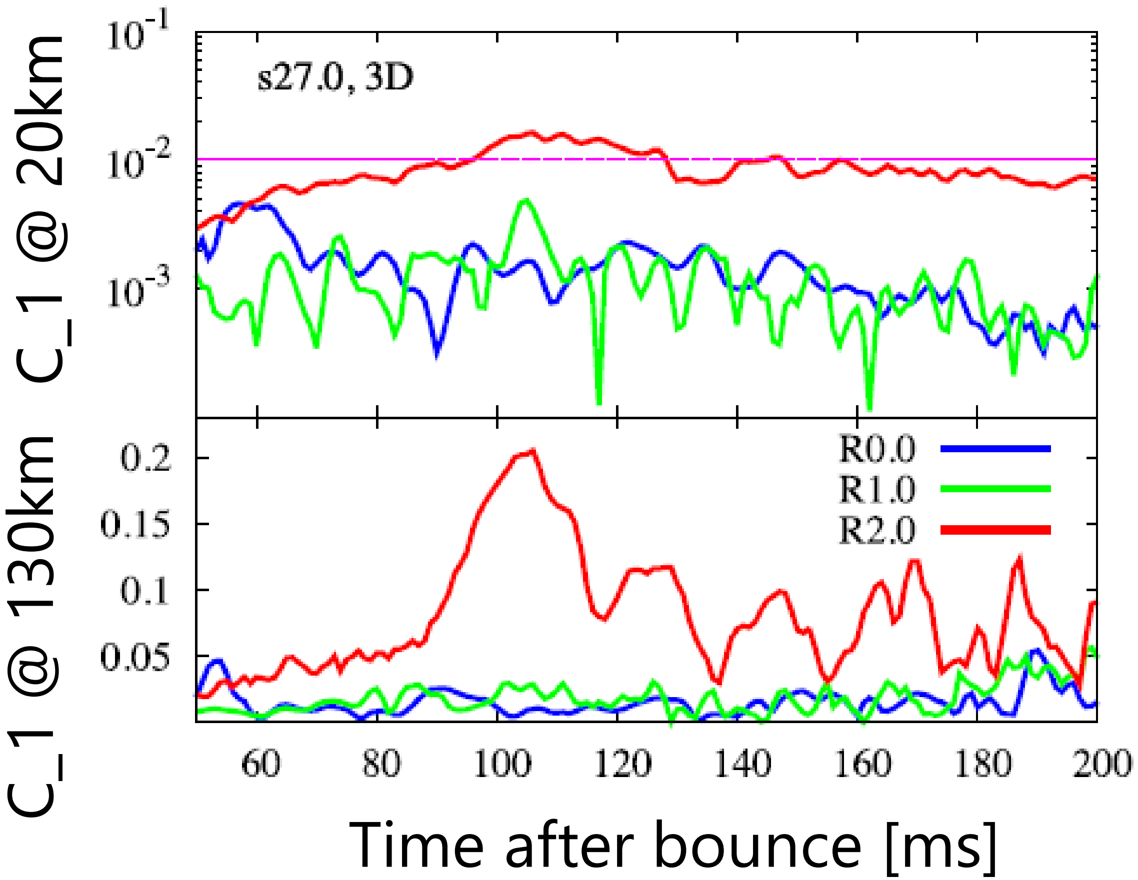
In the rigid ball: 14%

Ott+ 2005

In SNe case: ~ 6% (Called low-T/W instability)

Growth of Spiral Mode

$$C_1(r) = \int_0^{2\pi} \rho Y_{1,1} \mathrm{d}\phi / \int_0^{2\pi} \rho Y_{0,0} \mathrm{d}\phi,$$



Rapidly rotating model is unstable and spiral density structure grows.

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    1. Shock revival helped by a rotational instability
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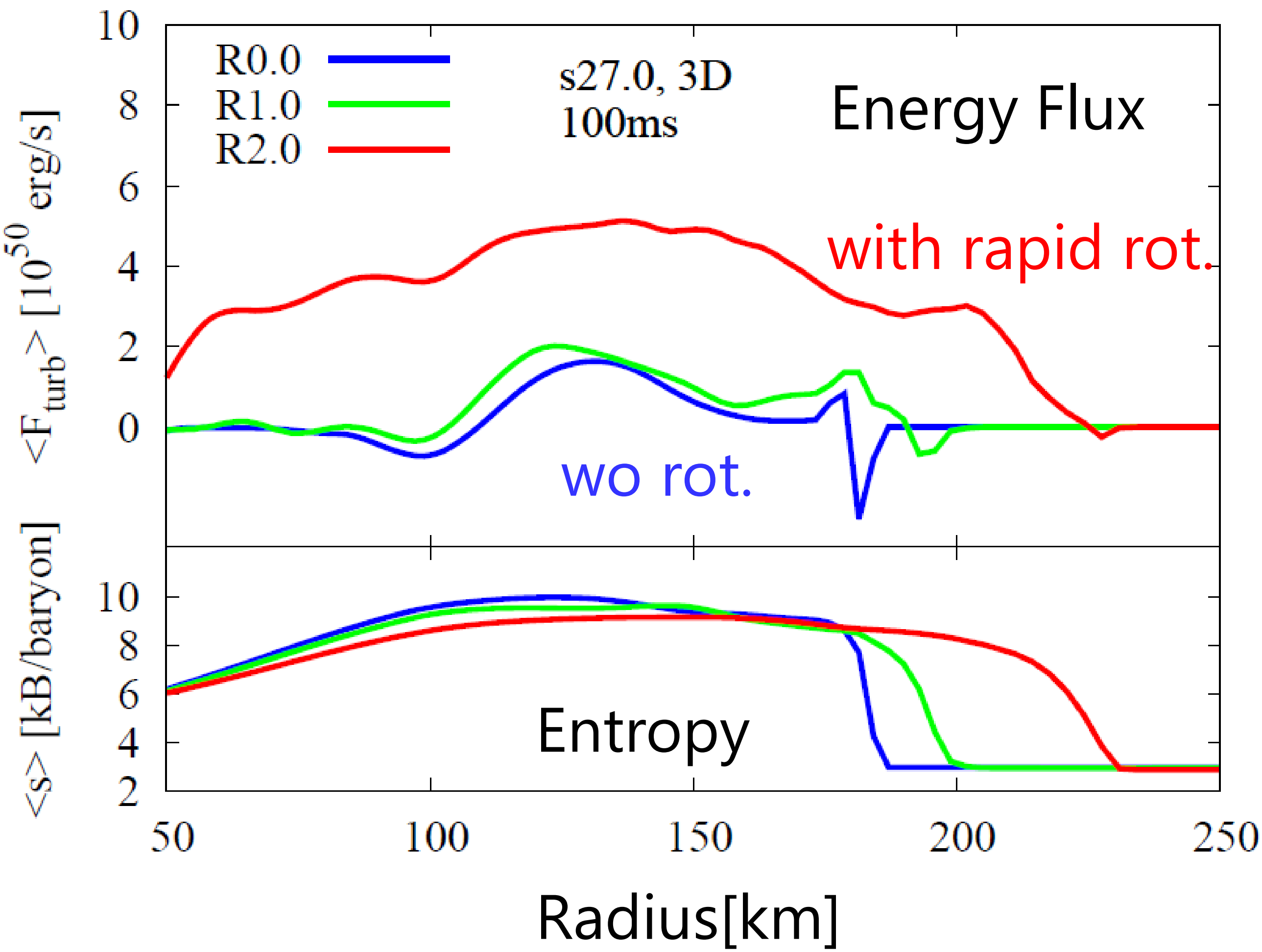
Energy Transport by spiral mode

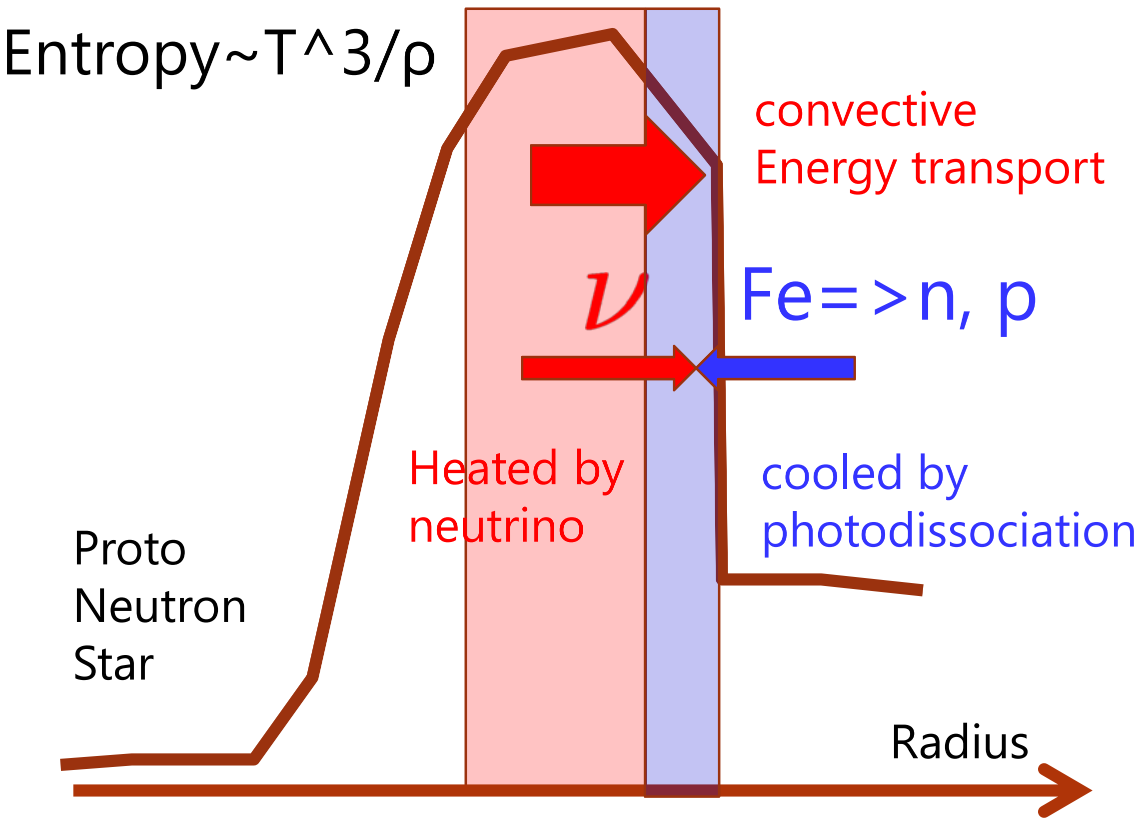


Power of νheating = 10^52 erg/s

Power of Spiral mode = 0.5 x 10^52 erg/s

Spiral mode transport energy from center to outer region and helps explosion.

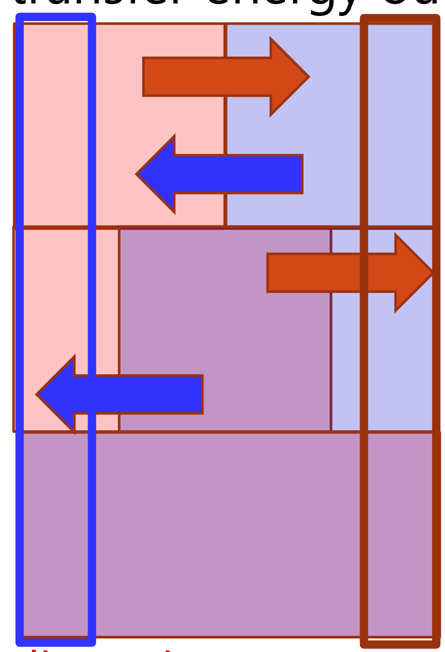
Key aspects of Neutrino Mechanism



Negative entropy gradient leads Rayleigh-Taylor instability

(Cold heavy matter is put over Hot light matter)

Rayleigh-Taylor convection transfer energy outward.

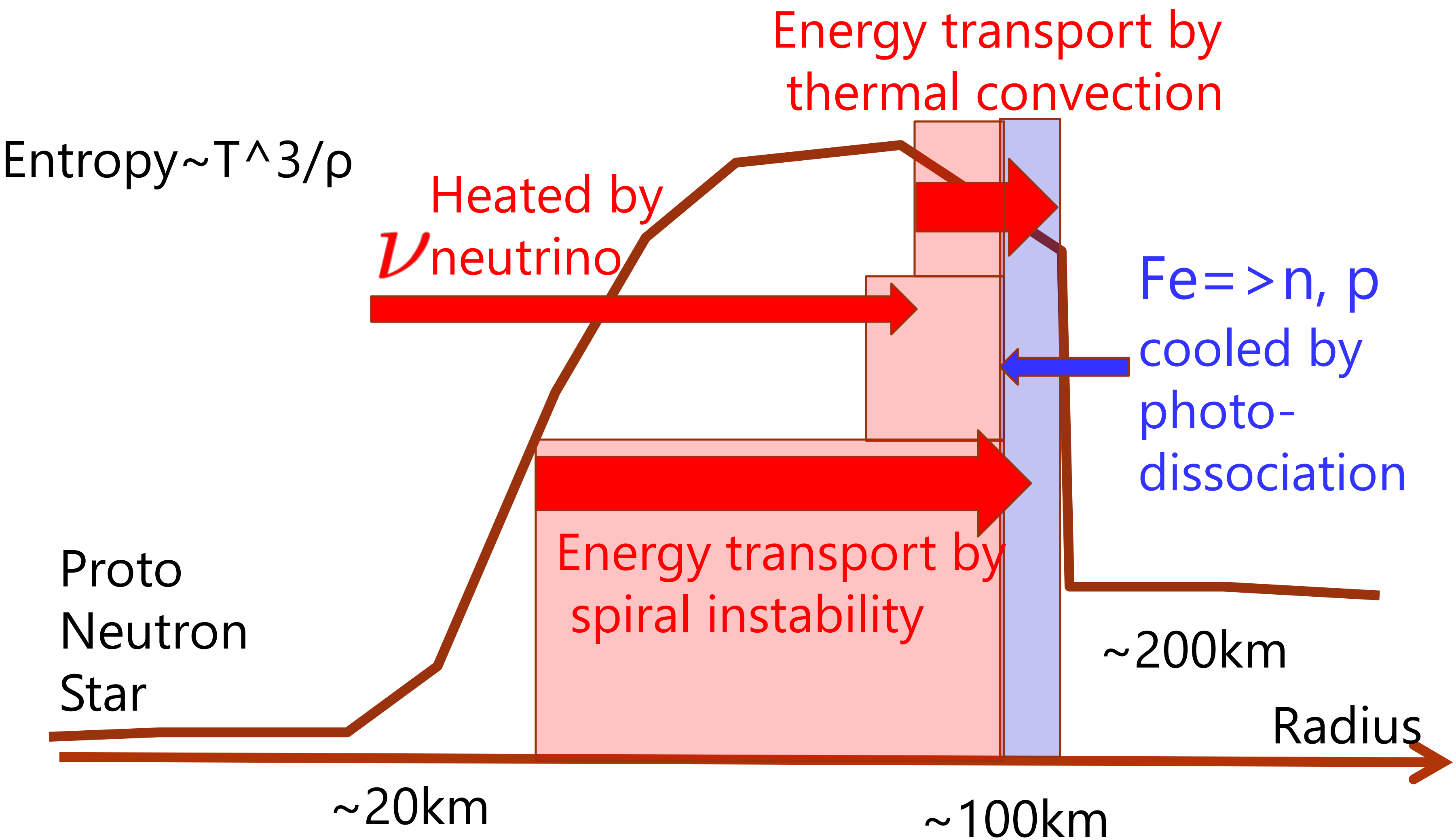


Cooler than the initial state but ν heat is active

Hotter than the initial state

See next three presentations for more complete discussion

Convective Effects by the spiral mode



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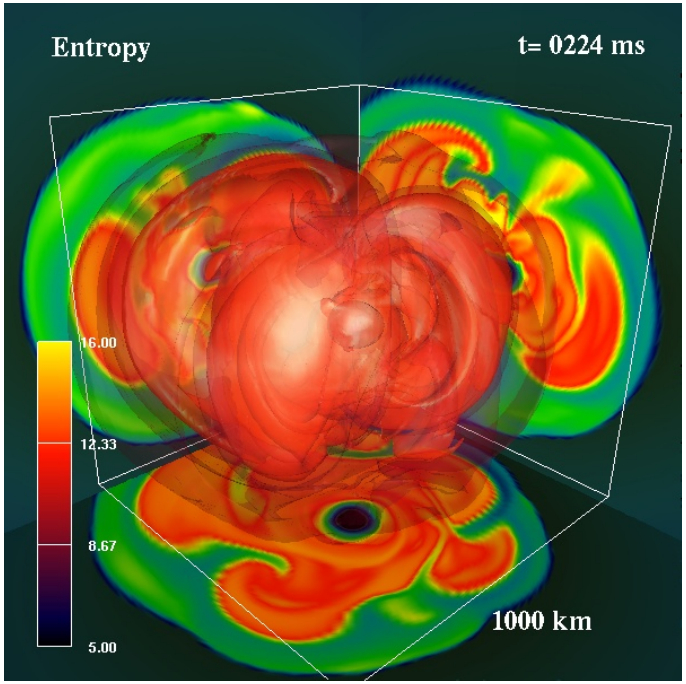
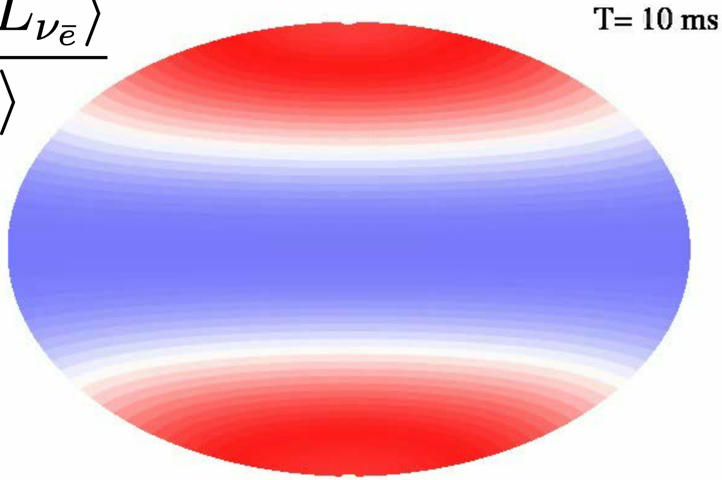
Neutrino signals from rotating model



Anisotropy of neutrino emission:

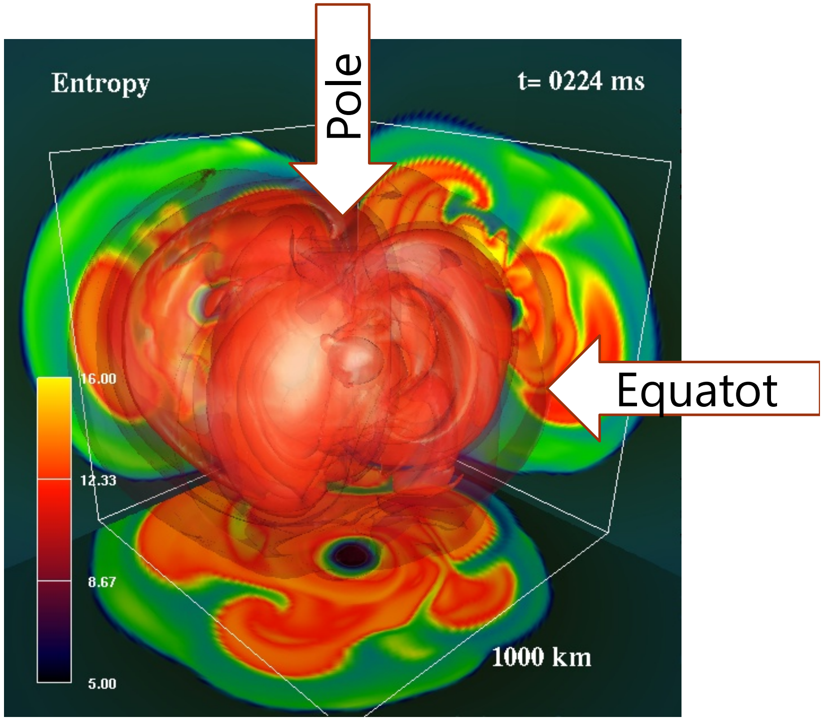
$$\frac{L_{\nu_{\bar{e}}} - \langle L_{\nu_{\bar{e}}} \rangle}{\langle L_{\nu_{\bar{e}}} \rangle}$$

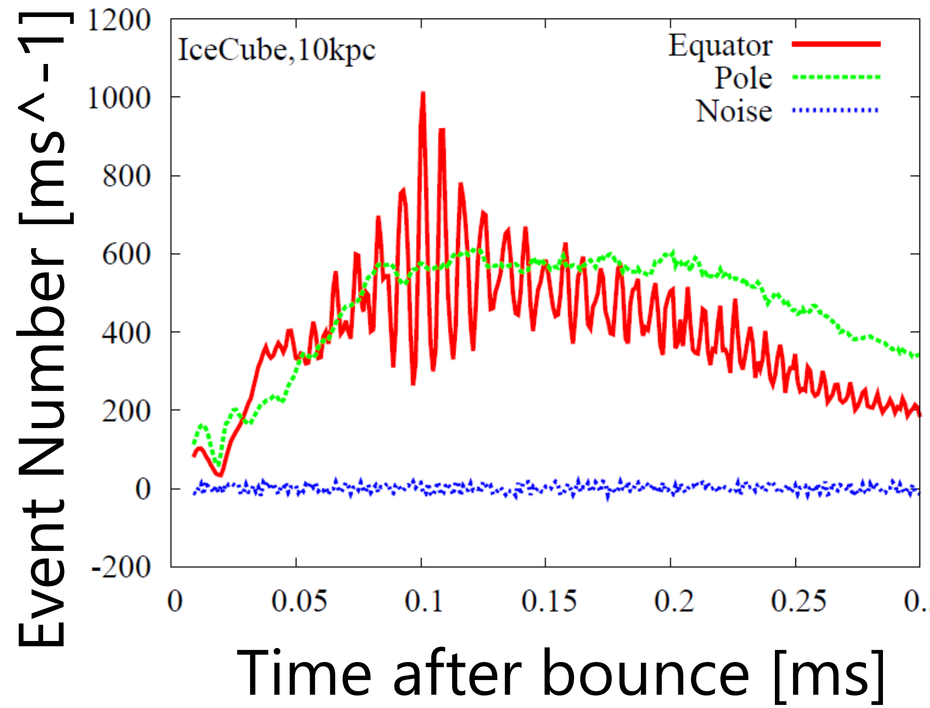


Takiwaki+ in prep

Like Light house, periodic signal of the neutrino will come to an observer.

Neutrino signals from rotating model

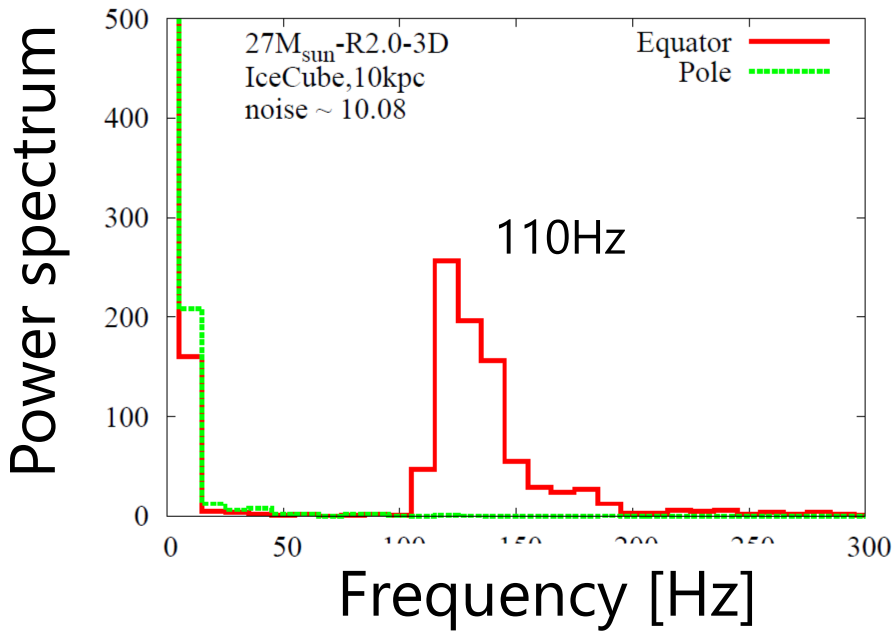


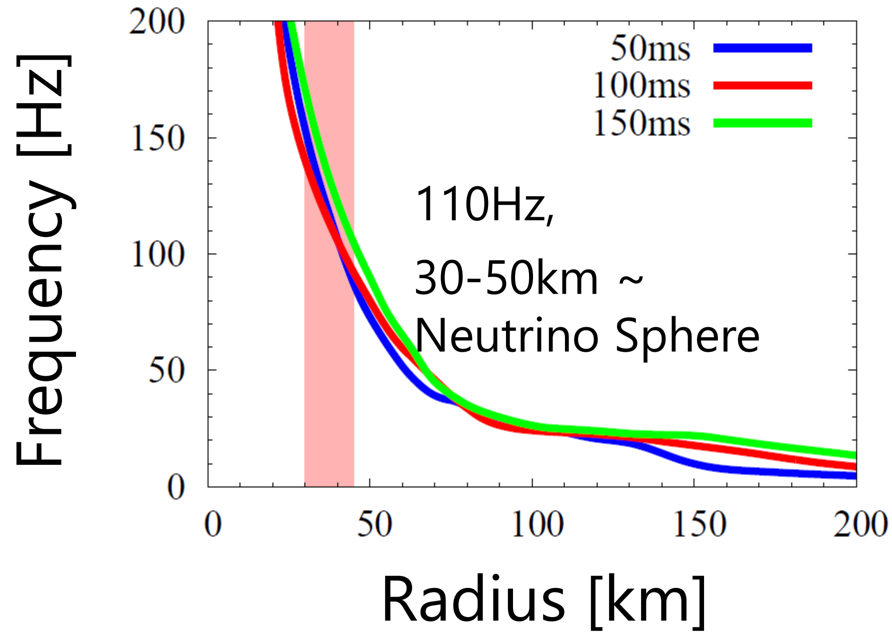


Takiwaki+ in prep

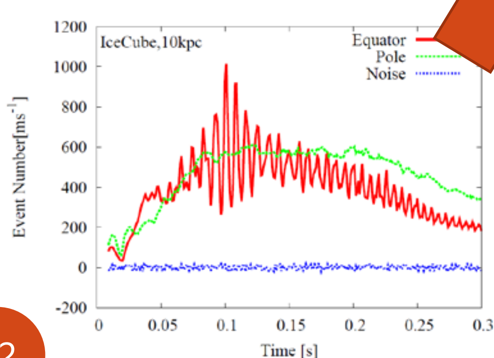
The time variability is visible at the direction of equator by the observation of IceCube (as well as Hyper Kamiokande). From the pole, the variability disappers.

Neutrino signals from rotating model





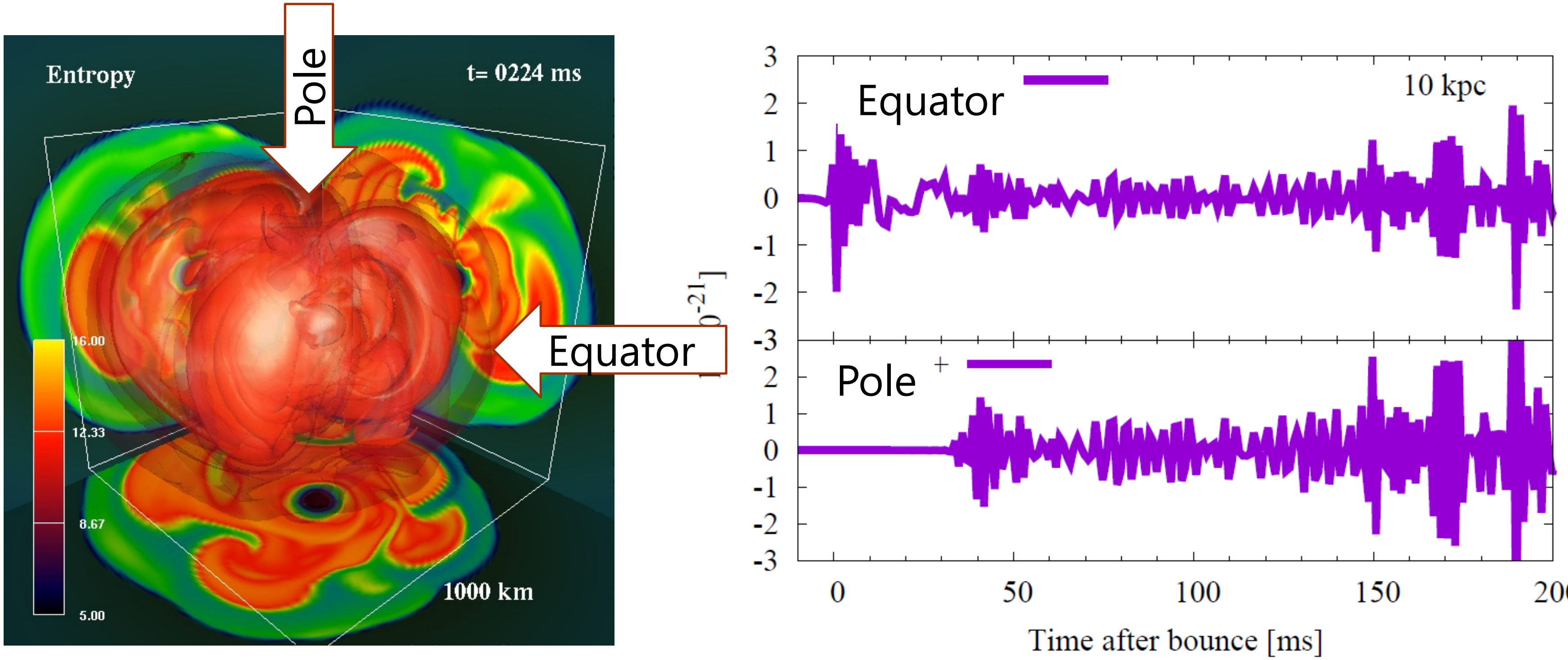
Fourier Transformation



From Frequency of the observed neutrino event, we can extract how high the core rotates at the radius of neutrino sphere.

Takiwaki+ in prep

GW signals from rotating model



Takiwaki+ in prep

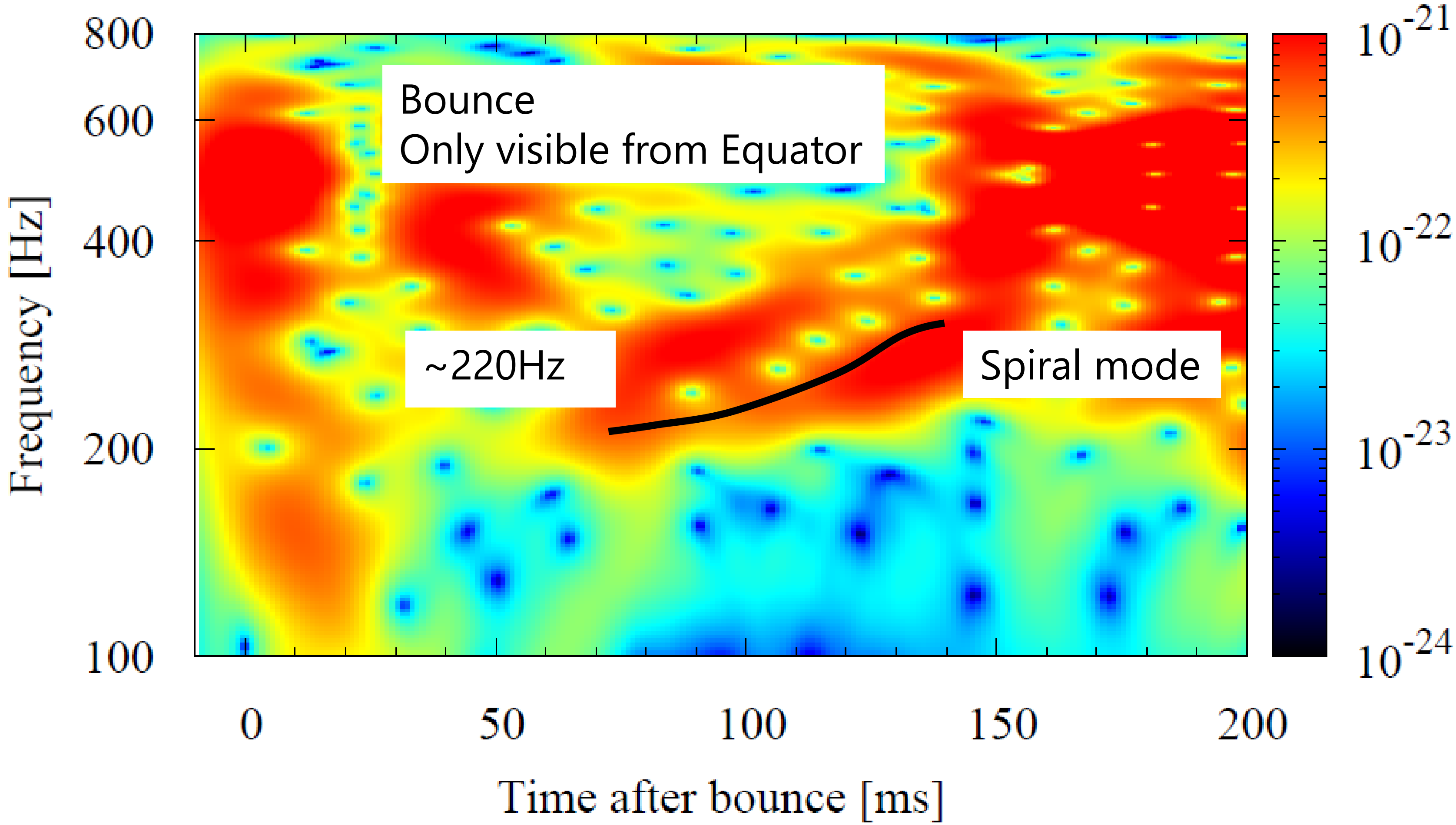
Bounce signal can be observed from side view.

Non-axisymmetric motion emits GWs at later phase.

Feature of GWs from Rotational Explosion

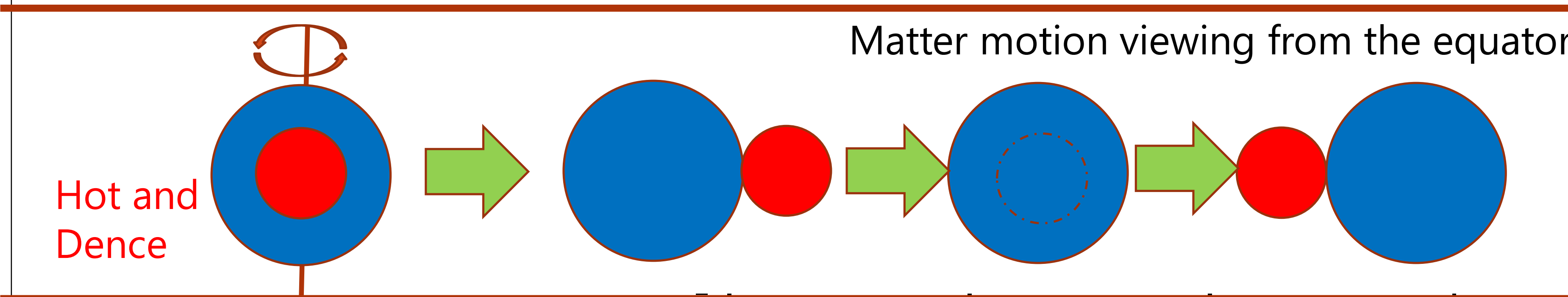
Viewing from side direction

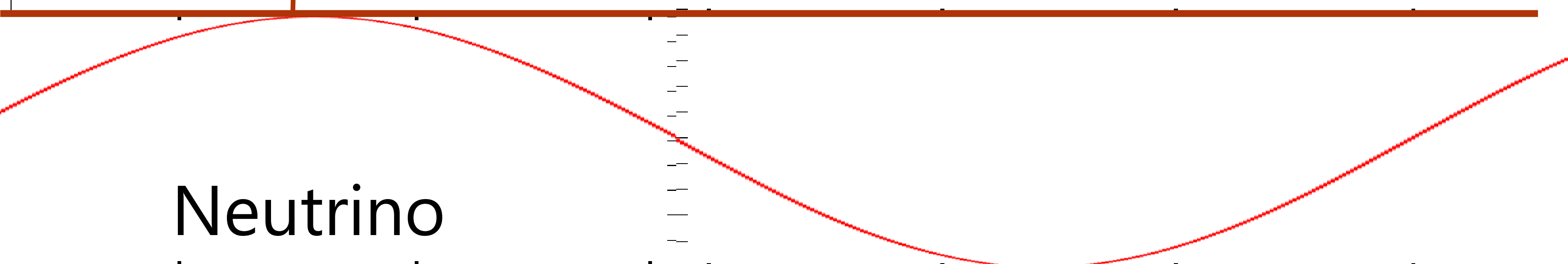
Takiwaki+ in prep

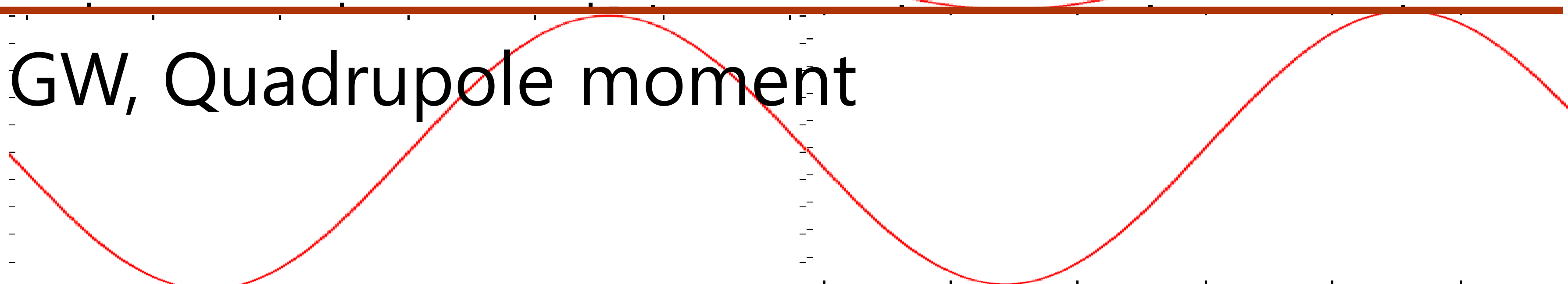


In addition to g-mode signal, GW from spiral mode arises and spin period of PNS surface can be extracted.

Why GW has twice high frequency







The high frequency would originate from rapid motion of quadrupole

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Progenitor?

- Rapid rotation of $\Omega = 2.0\mathrm{rad/s}$ is assumed in our model.
- In solar metallicity, such a rotation is difficult due to large mass loss and large angular momentum transfer via magnetic fields.
- If the metallicity become lower, Chemically homogeneous evolution might be possible and large angular momentum could remain in the core.
- In that sense, we expect the star like our model would live in LMC and SMC (however, a few such progenitors are found in our Galaxy. Martins 2013).

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Summary

1. We found a new model of ν-driven explosion that is helped by the rotation.
2. The rotation induced low-T/|W| instability that makes a spiral mode.
3. Pushed by the spiral mode, the shock expands oblately.
4. The neutrino and GW signal oscillate with their characteristic frequency that are related to the angular velocity of the neutrino sphere.

Method in the latest version

Hydro: 3DnSNe

- Geometry: Spherical coordinate, PWL interp. (Mignone 2014)
- HLL scheme

Neutrino Radiation Transport: IDSA+Leakage

- flux-IDSA for all flavor (Takiwaki+2014)
- Standard set of the reactions considered (Liebendoerfer+ 2005)

Gravity:

- Effective GR Monopole approximation(Marek+ 2006)