Gravitational-wave and Neutrino Signal from Accretion-induced Collapse (AIC) of White Dwarfs

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Plan of this talk

Stellar Evolution Overview

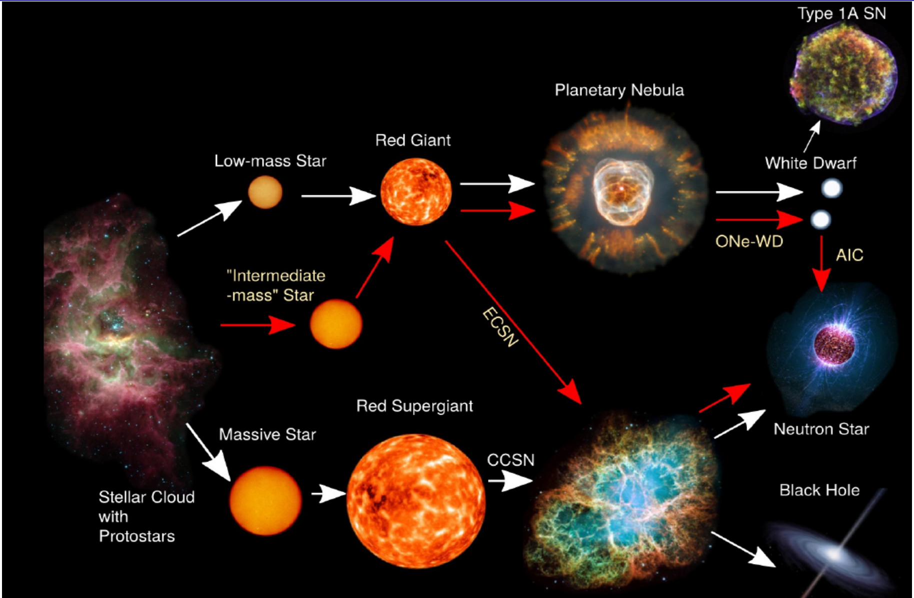
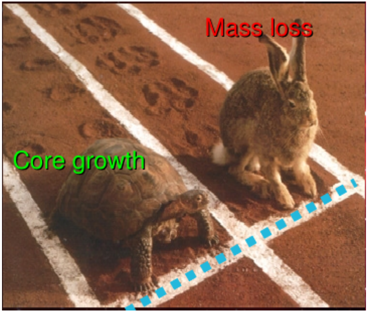
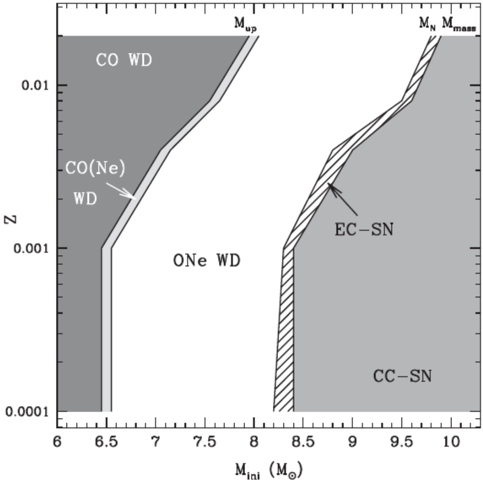


Image credit: Unknown/Jones/Möller

AIC or ECSN?



If $M_{\rm core}$ reaches $\simeq 1.375 M_\odot$, ECSN will occur; otherwise an ONe WD is left, perhaps producing an AIC.

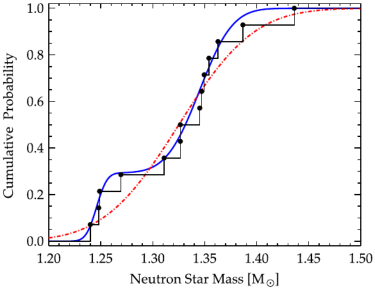


Doherty+ 2015

Why study AIC?

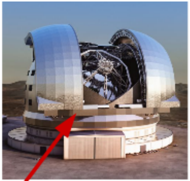
Less well-studied case of stellar death, with potential importances:

- Nucleosynthesis:
  - Production of Ag and Pd (Hansen+ 2012)
  - Possible r-process (Au, Eu) site (Fryer+ 1999)
- 'Bimodal' NS mass distibution, low-mass pulsars

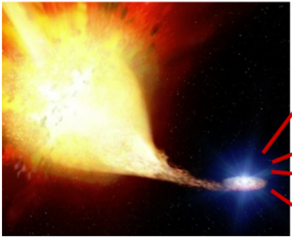


NS mass distribution(Schwab+ 2010)

AIC as a multi-messenger candidate



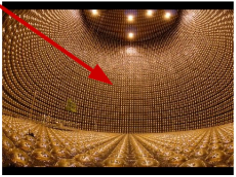
AIC event



ligo.caltech.edu

Feeble interaction →

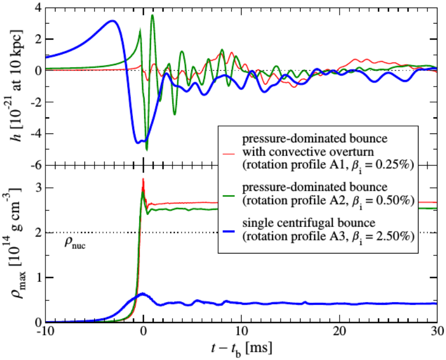
- Direct information
- Early warning



SuperK

G-wave as a probe of the rotating SN core

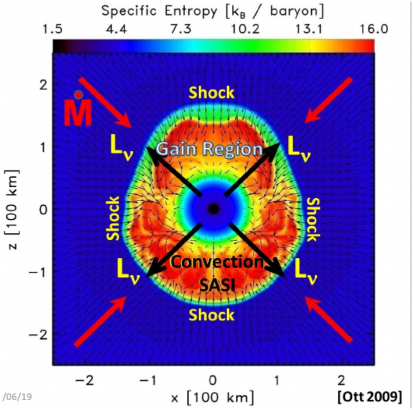
G-wave from collapse of rotating iron core:



Dimmelmeier+ 2007

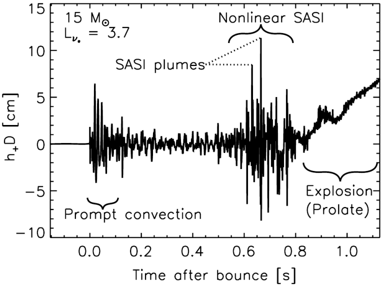
Measuring the angular momentum of the SN core (Abdikamalov+ 2014).

G-wave as a probe of the explosion mechanism



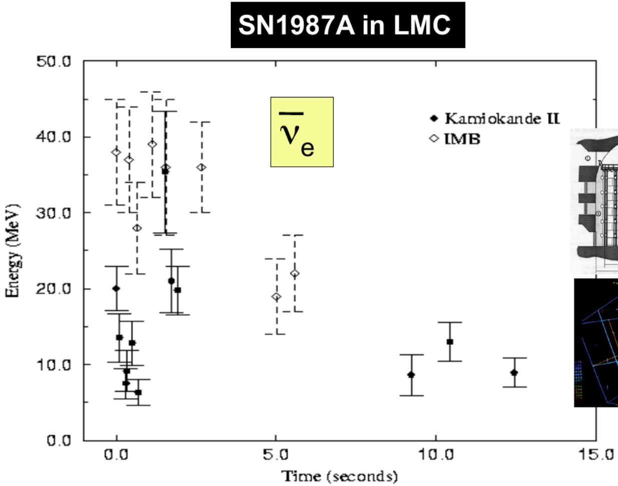
Neutrino heating failed to explode the star in spherically symmetric simulations. Multi-dimensional instabilities required.

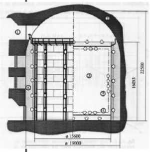
G-wave from the convection, SASI and explosion.

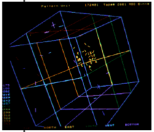


Murphy+ 2009

Neutrinos: direct probe of the SN core







Confirmed baseline model... and limits on ν properties
....but still many questions

Method: radiative-hydrodynamic simulation

Ideal compressible hydrodynamics (Leung+ 2015):

- A 5th-order shock capturing scheme.

G-wave extraction:

$$\text{quadrupole formula } h_+ = \frac{G}{c^4}\frac{1}{D}\frac{3}{2}\ddot{I}_{zz}$$

Neutrino transport:

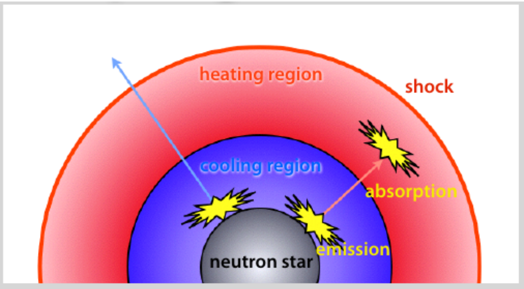
- Isotropic diffusion source approximation (IDSA) (Liebendöfer+ 2009, Suwa+ 2011, Pan+ 2015)
- Ray-by-ray plus scheme for multi-dimension

Neutrino transport

Various methods for solveing Boltzmann neutrino transport:

S_N > VE > M_1 > FLD, IDSA > leakage

← **ab initio**	→ **approximate**
higher cost	**lower cost**



Two limiting cases:

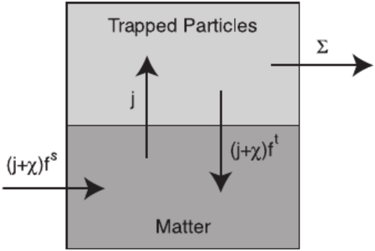
1. Diffusion (inside NS/ν-sphere)
2. Free streaming (outside shock)

Spirit of FLD/IDSA is to interpolate in-between with some flux-factor treatment.

Credit: Y. Suwa

IDSA

f^t: trapped particle
f^s: streaming particle
j, χ: emissivity and absorption



Σ reproduce diffusion limit in the ν-optically thick region.

Reduced Boltzmann eq.

$$D(f^t) = j - (j+\chi)f^t - \Sigma$$
$$D(f^s) = -(j+\chi)f^s + \Sigma$$

Neutrino-matter interaction

Emission & absorption:

$$n + \nu_e \rightleftharpoons p + e^-$$
$$p + \bar{\nu}_e \rightleftharpoons n + e^+$$

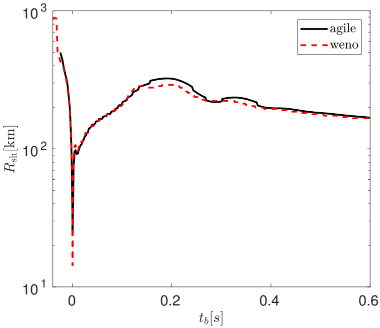
Scattering:

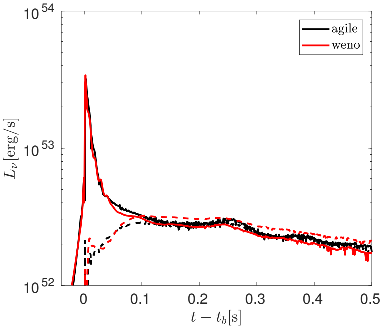
$$N/\alpha/A + \nu \to N/\alpha/A + \nu$$

Bruenn (1985)

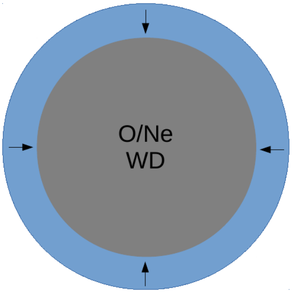
Code performance

Spherically-symmetric simulation of $11 M_{\odot}$ solar-metallicity progenitor from Woosley et al. (2002).
Left: time evolution of shock radius;
Right: luminosity curve for electron (anti-)neutrino.

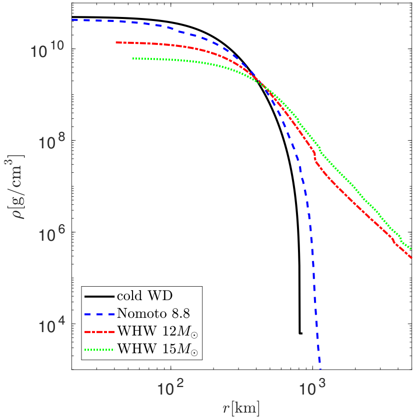




AIC progenitor structure (initial condition)



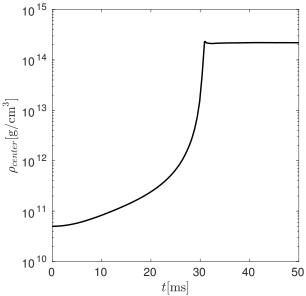
$$M \to M_{\mathrm{Ch}} \sim 1.44 M_\odot$$

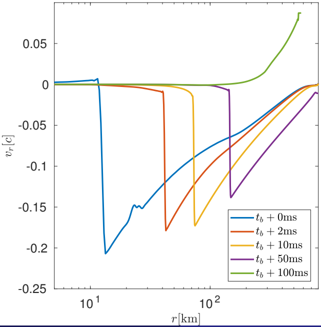


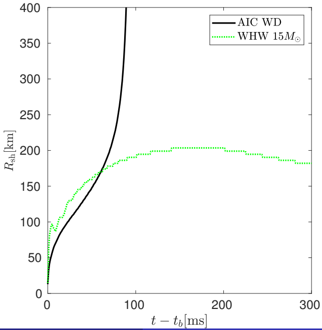
- Higher central density and no extended envelop.
- Electron capture process reduces pressure and collapse ensues.

Collapse and post-bounce dynamics

- Reaches nuclear density $\rho_{\rm nuc} \sim 2.3 \times 10^{14}{\rm g/cm}^3$ in $\sim$ 30ms.
- EOS stiffens at $\rho_{\rm nuc}$, core rebounds ('bounce'), launches a bounce shock.
- Turns to accretion shock quickly, breaks out the star surface at $\sim$ 90ms after bounce.
- Ejecta $\sim 0.02 M_\odot$, $E_{\rm exp} \sim 10^{50}$erg





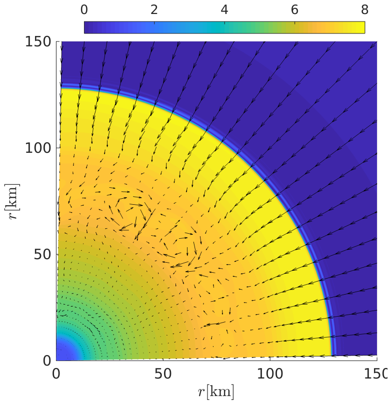


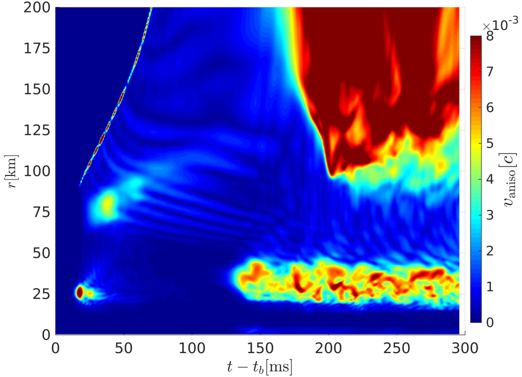
Convective motion in 2D simulation

Anisotropic velocity:

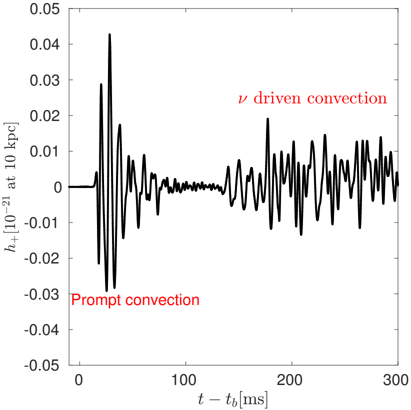
$$v_{\mathrm{aniso}} = \sqrt{\frac{\langle \rho[(v_r - \langle v_r \rangle)^2 + v_\theta^2] \rangle}{\langle \rho \rangle}}$$

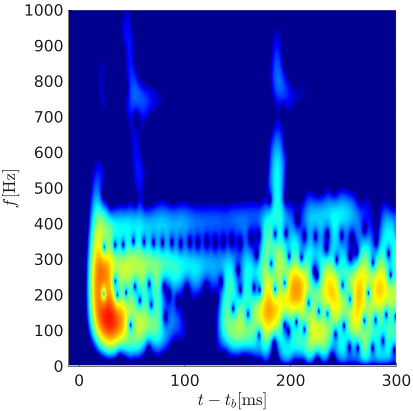
Entropy&velocity at $t_b + 40$ ms





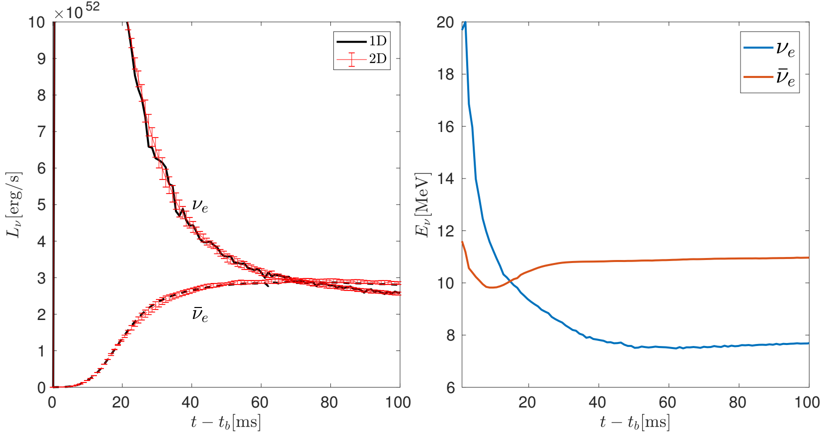
G-wave for non-rotating case





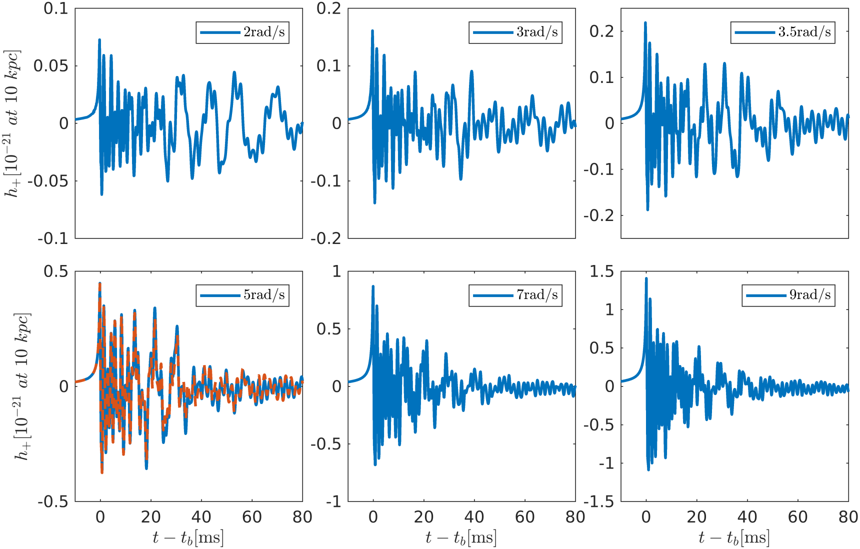
- Time is relative to core bounce time t_b.
- Shock break out surface at $\sim t_b + 90\mathrm{ms}$.

Neutrino signal for non-rotating case

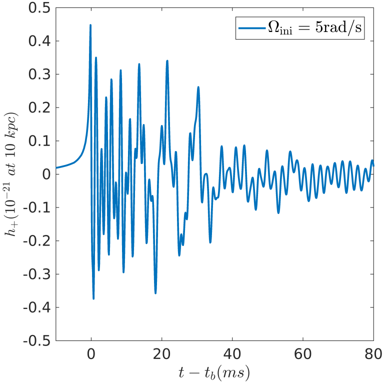


- Luminosity curve similar as those from CCSNe.
- No strong variations in 2D due to the mild convective motion.

G-wave waveforms of uniform rotating models



Time-frequency informations



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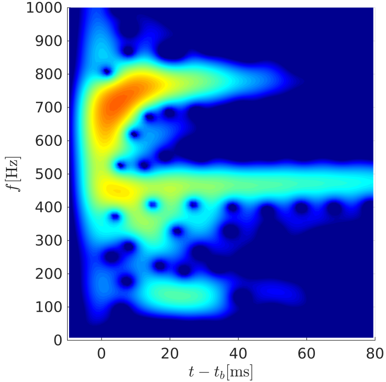
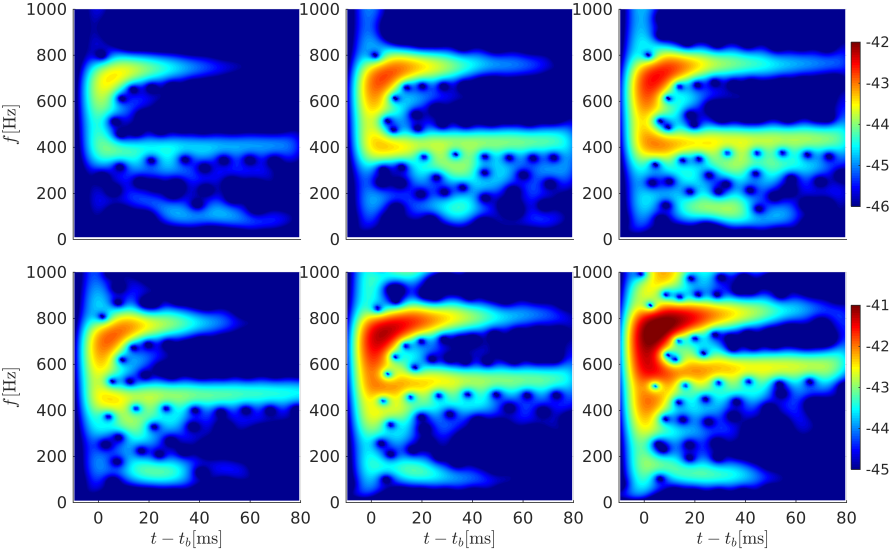


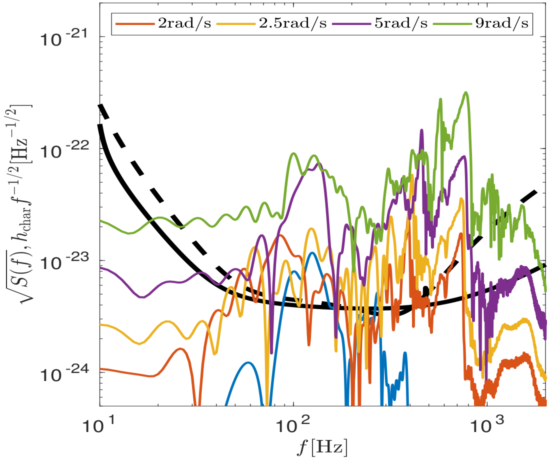
- 600∼800Hz, $\sim t_b \rightarrow t_b + 20$ms, hydrodynamic ringdown of PNS,
- 400∼500Hz, long-term signal, PNS convection
- 100∼200Hz, $\sim t_b + 10\text{ms} \rightarrow t_b + 40$ms, prompt post-shock convection

Generic features in the g-wave signal



Detectability

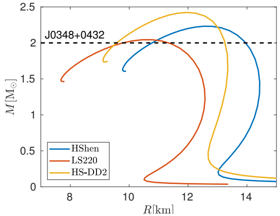
Assume source at 10 kpc;
compared with Adv-LIGO/Adv-Virgo noise spectrum.

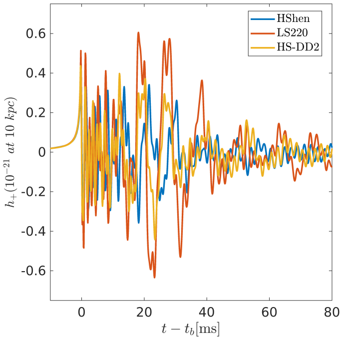


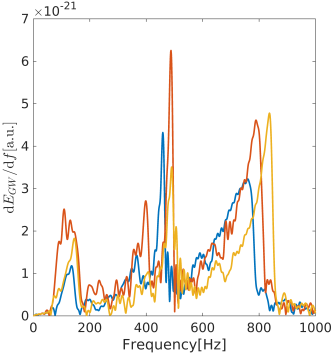
Just for illustration.

Effect of EOSs (preliminary)

HShen, HS-DD2; LS220
All consistent with current NS mass-radius constraints, while the softer LS220 shows easier explosion in some CCSNe simulations.

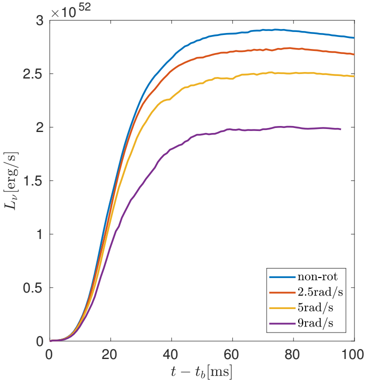


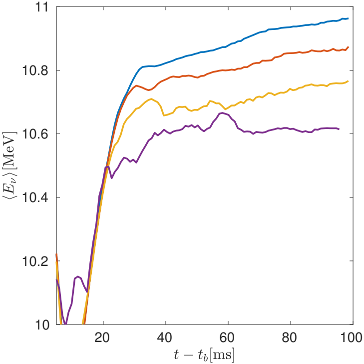




Effect of rotation on neutrino signals

Less luminous (50% drop at most) and less stiff

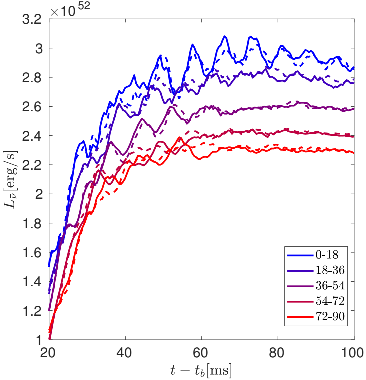




Left: angular averaged anti-neutrino light curve ;
Right: mean neutrino energy

Variation of L_ν along rotation axis (preliminary)

$\sim$5% and 8ms quasi-periodic variation in $\bar{\nu}_e$ luminosity along the rotation axis.



- - high resolution run

Angles are with respect to rotation axis.

Differential rotation

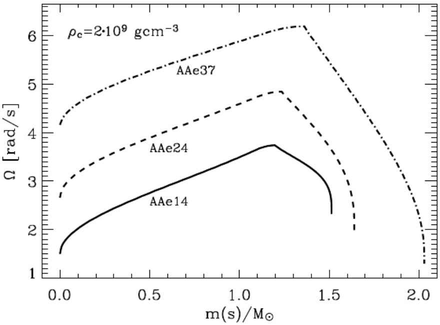
Differentially rotational law presented in Yoon and Langer (2004)

Assuming cylindrical rotation, the core is controlled by dynamical shear instability:

$$\Omega(s) = \Omega_c + \int_0^s \frac{f_{\mathrm{sh}}\sigma_{\mathrm{DSI,crit}}}{s'} \mathrm{d}s'$$

outer part assumes an anlytical law:

$$\Omega(s)/\Omega_K(s) = \Omega(s_p)/\Omega_K(s_p) + C(s - s_p)^a$$

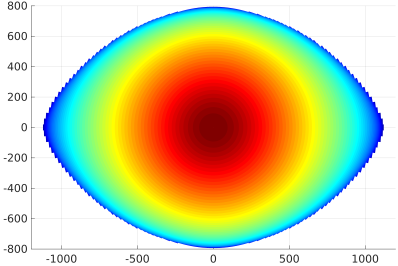


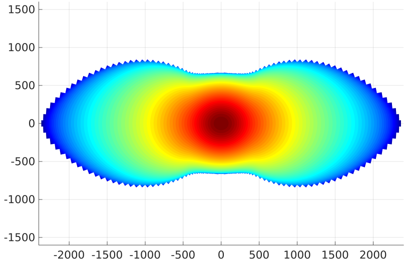
The core can rotate much faster while the surface doesn't exceed its Kepler angular velocity.

Deformation of the initial WD

For uniform rotating WD with $\Omega_{\rm ini} \sim \Omega_{\rm Kepler}$, $\beta = \frac{E_{\rm rot}}{|E_{\rm grav}|} \simeq 1\%$.

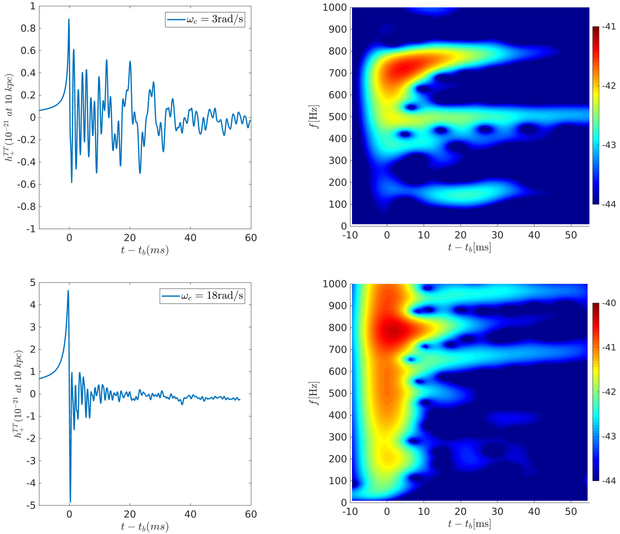
$\Omega_c = 3$rad/s & $\beta_{\rm ini} = 1.0\%$ | $\Omega_c = 18$rad/s & $\beta_{\rm ini} = 8.5\%$





Initial density distributions.

G-wave from differential rotating models (preliminary)



Summary & outlook

- A suite of rotating AIC models shows quite generic features of g-wave, radiated from ring-down, prompt convection and PNS convection.
- Faster rotating models radiate less in neutrino luminosity. At rotational axis, the luminosity shows some temporal variability.
- Can perturbation analysis reproduce these g-wave radiation modes? Can we parametrize the waveforms for GW search?
- More comprehensive studies on the effects of EOSs and neutrino physics are needed.

Thank you!!