Neutrino Signatures of *Tumbling* Supernova Cores :
From 3D radiation-hydro simulations

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Flavor observations with SN Neutrinos
INT, August, 2016

Quiz: Depending on (a), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

(a SN shock can *dance* because of (a).)

3D full General Relativistic (GR) simulations (BSSN) with 3 flavor neutrino transport (gray, M1 scheme)

(Kuroda, KK, and Takiwaki 2012, ApJ, 2014, PRD)

see **multi-energy version available !**

in Kuroda,Takiwaki, & KK. ApJS (2016))

Choice (1) Progenitor mass / compactness

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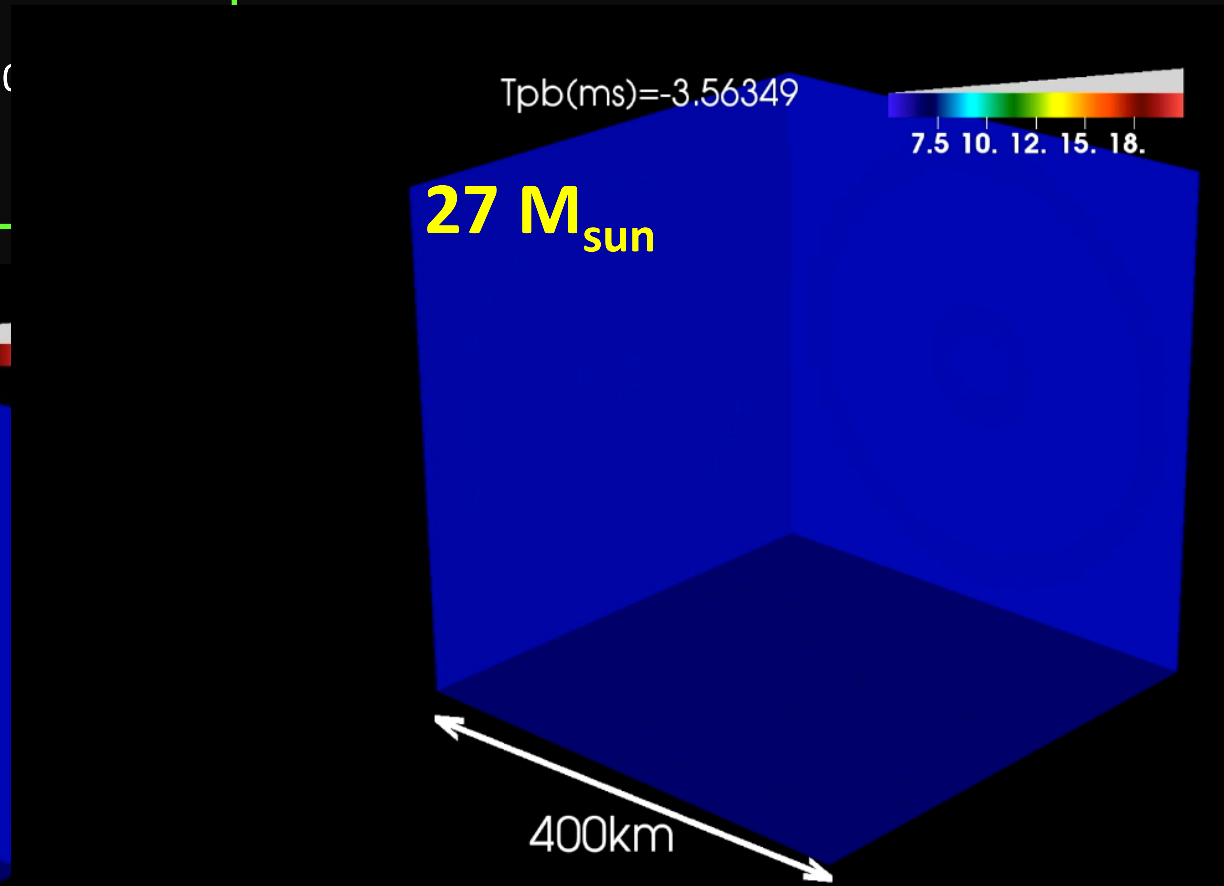
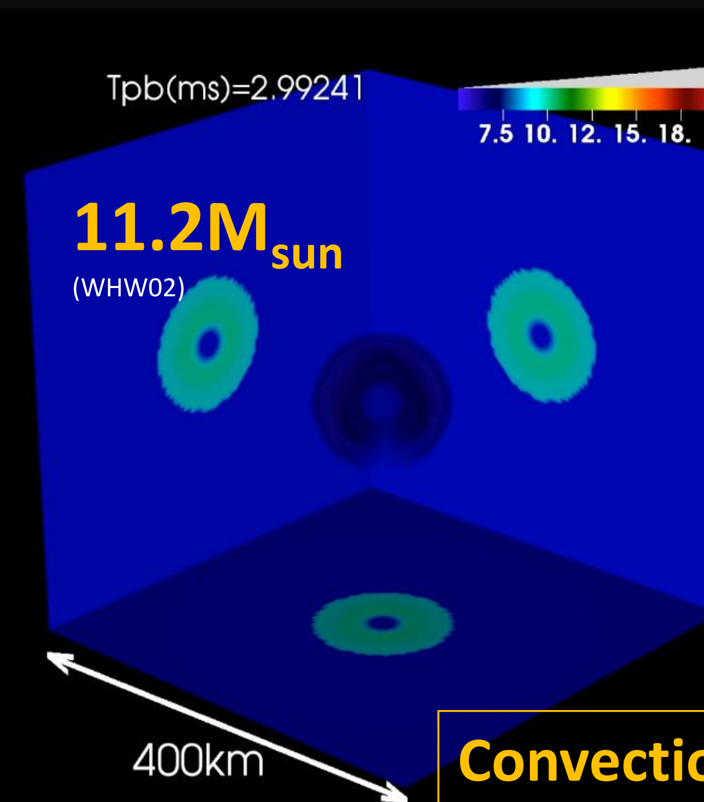
Choice (1) Progenitor mass / compactness

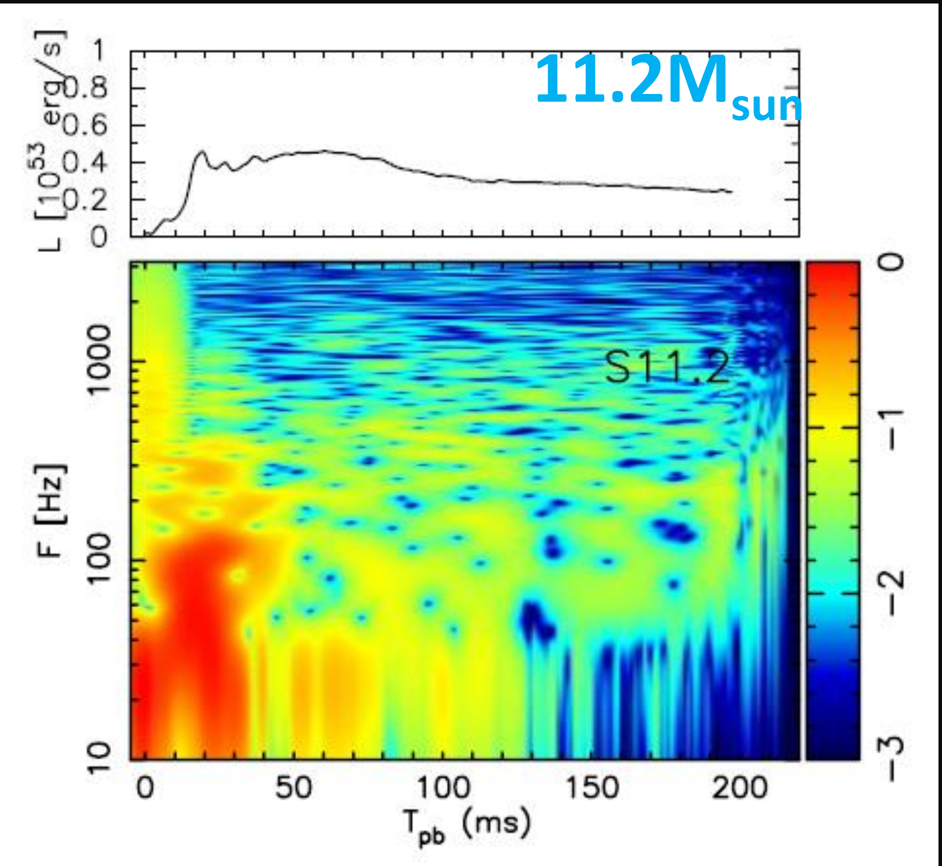


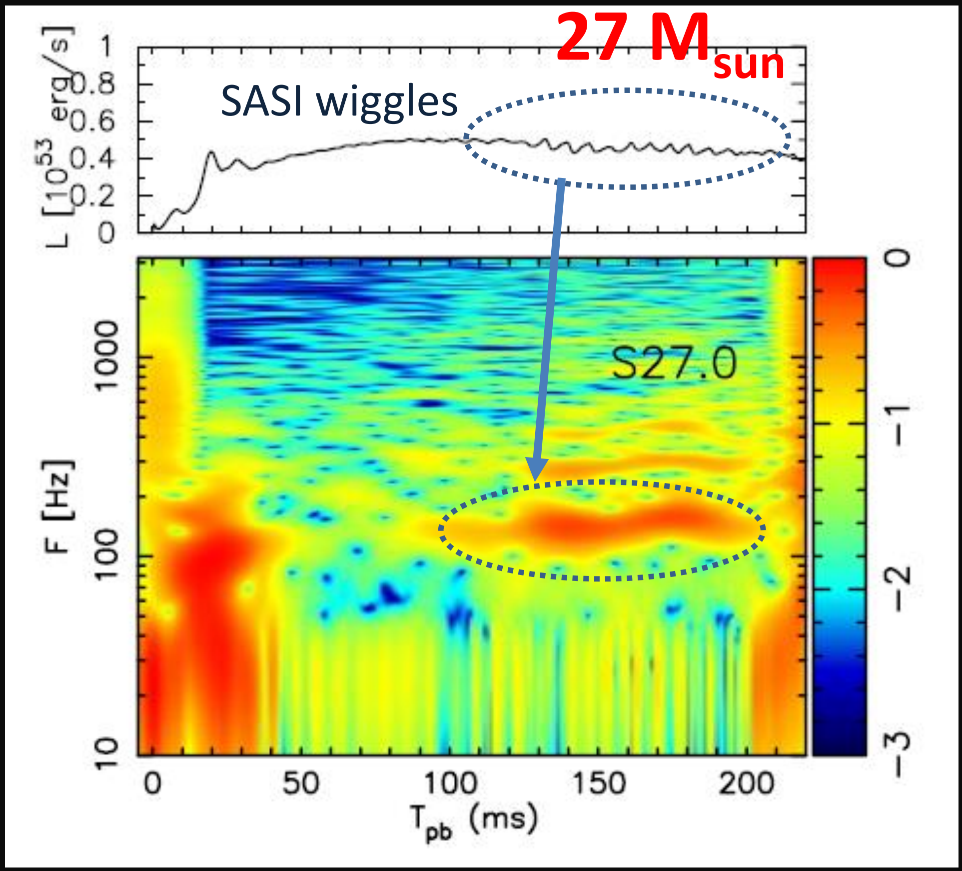
SASI-dominant



Convection-dominant

Neutrino luminosity ($\bar{\nu}_e$) and Spectrogram Analysis





⇒ **SASI-induced modulation is visible in the luminosity.**

⇒ **Confirmation of** Tamborra, Hanka, Mueller, Janka, Raffelt (2013,2014)) by 3D-GR simulations (Kuroda et al. in prep.)

⇒ Detectable by IceCube and Hyper-K out to Galactic events.

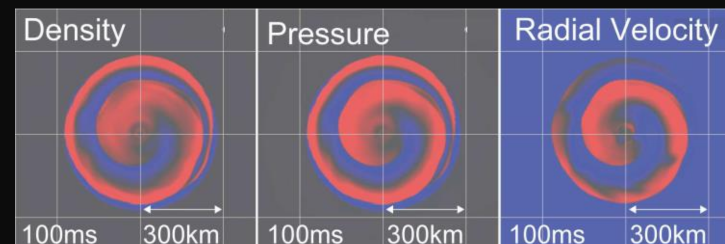
Quiz: Depending on (a) , non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

(a SN shock can *dance* because of (a) .)

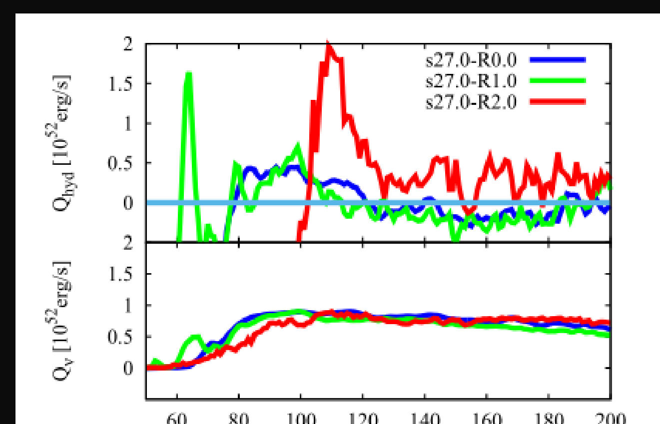
Choice (2) Precollapse rotation rate

3D rotating core-collapse of 27 M_{sun} star (Ω_0 = 2 rad/s) with IDSA transport.
(Takiwaki, KK, and Suwa, MNRAS Letters, (2016))

✓ One-armed (low T/|W|) instability



✓ Spiral waves enhance energy transport from PNS to gain region !

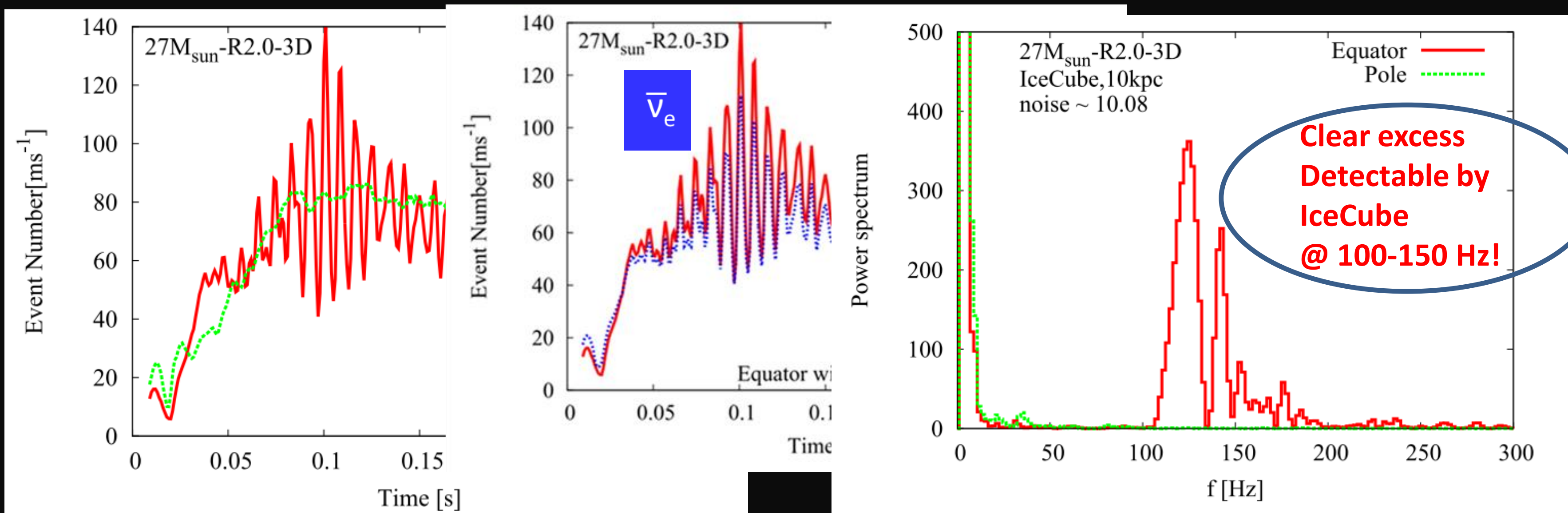


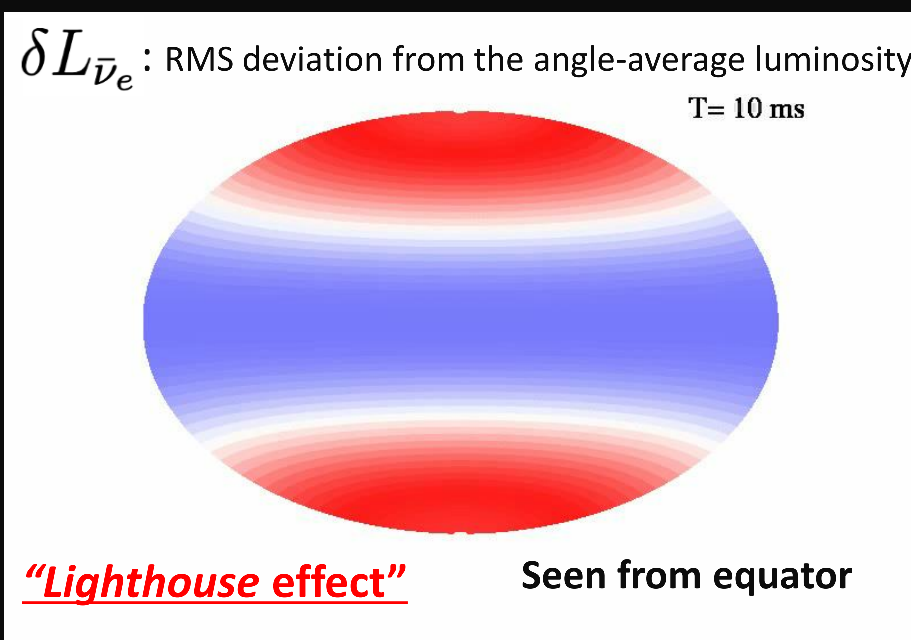
Rotation-assisted explosion !

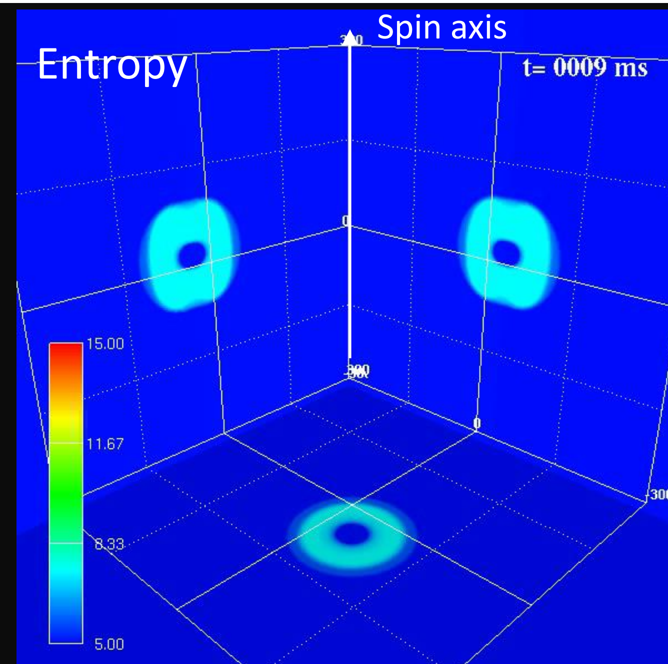
Neutrino signatures from rapidly rotating explosion of 27 M_{sun} star

Takiwaki and KK in prep

Quasi-periodic variation ! May survive with coll. oscillation







Quiz: Depending on (a) , non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

(or, a SN core can be a dancing queen because of (a) .)

Choice (1) Progenitor mass / compactness

Answer(1): Yes. (More progenitors needed !)

Choice (2) Precollapse rotation rate

Answer(2): Yes.
The rotational frequency of the spiral arm is marked in the neutrino signals.
← The "***lighthouse*** effect".

Choice (3) Equation of State

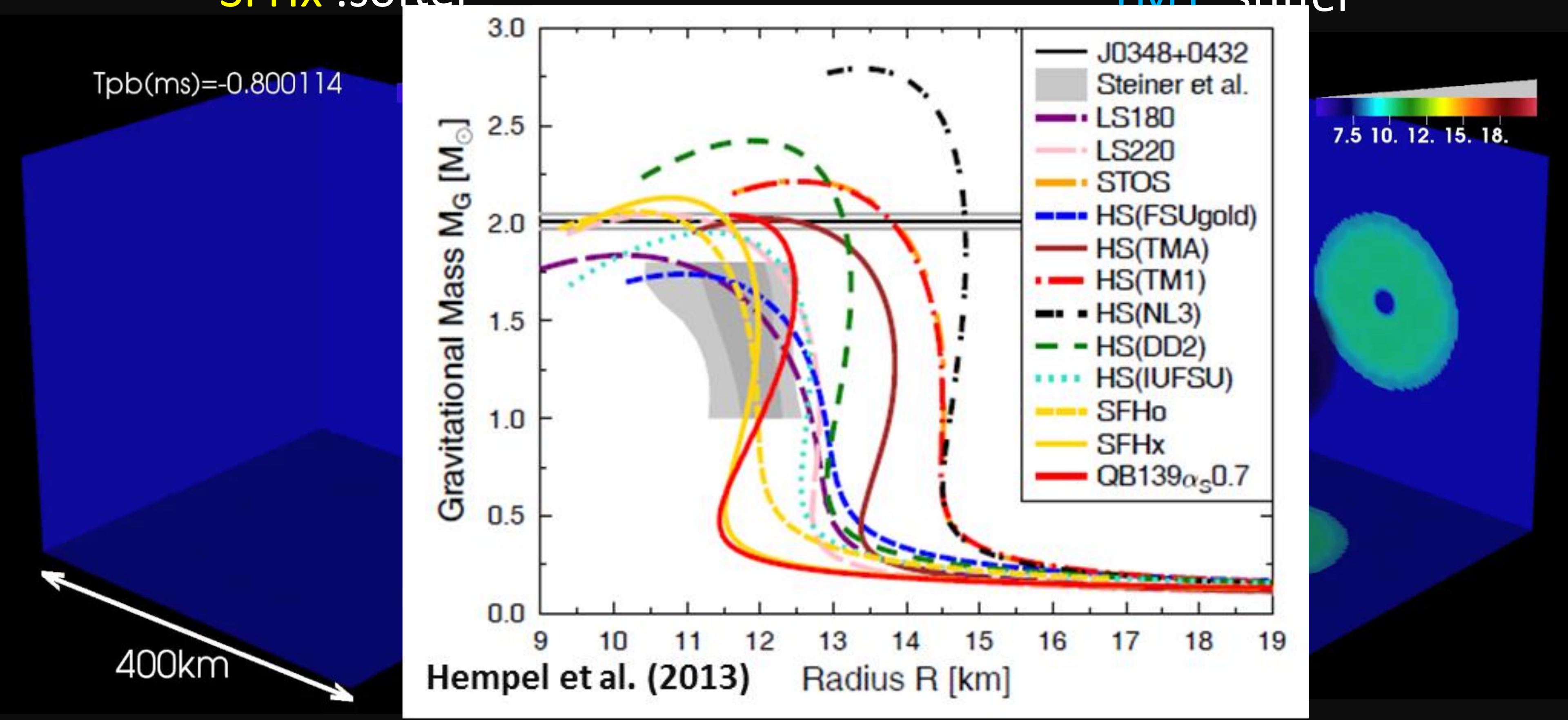
Neutrino signals from 3D-GR models with different EOSs (1/2)

✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)),
HS(TM1) (Shen et al. (1998), Hempel & Schaffner-Bielich (2010)).

✓ 15 M_{sun} star (Woosley & Weaver (1995))

SFHx :softer

TM1 :stiffer



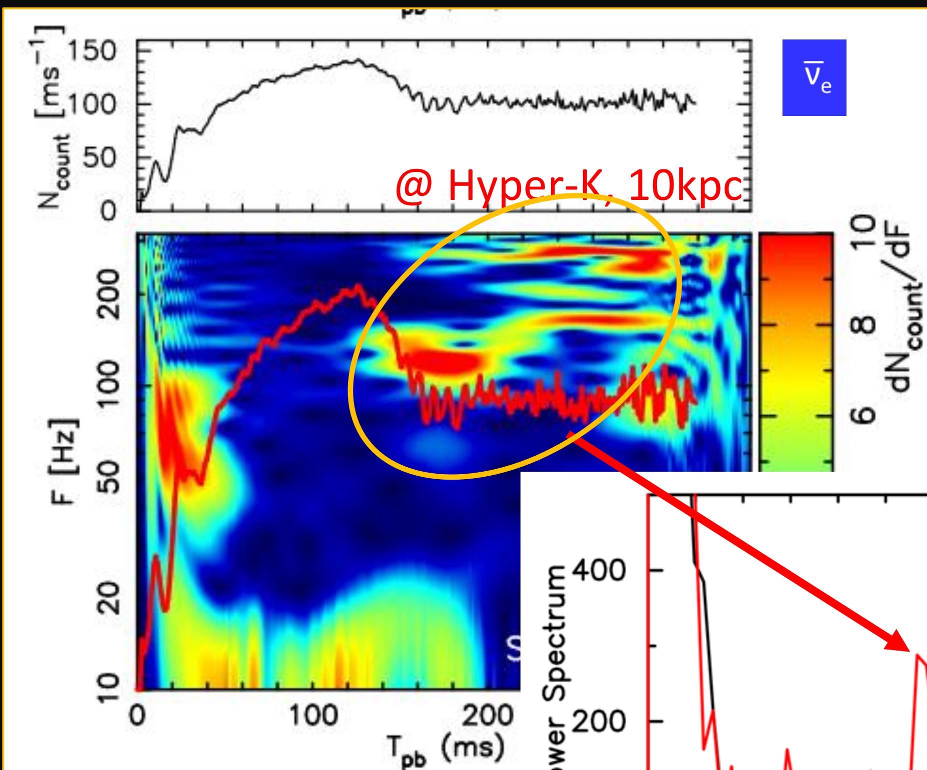
✓ **SASI activity higher for softer EOS** (due to shorter growth rate, e.g., Foglizzo et al. ('06)).

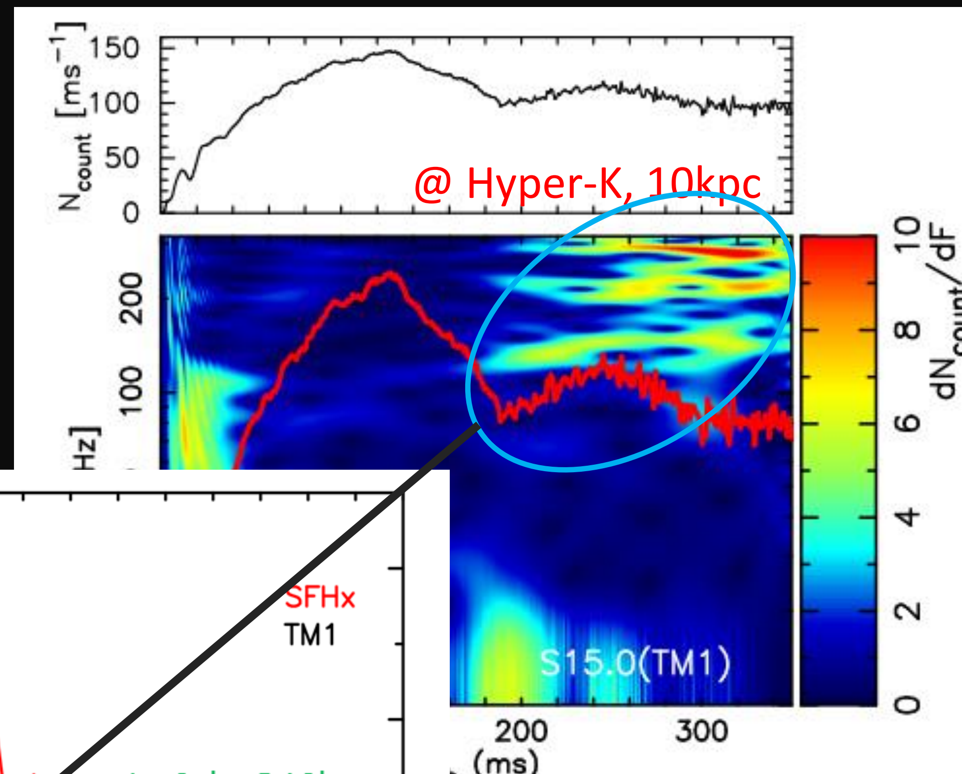
Neutrino signals from 3D-GR models with different EOSs (2/2)

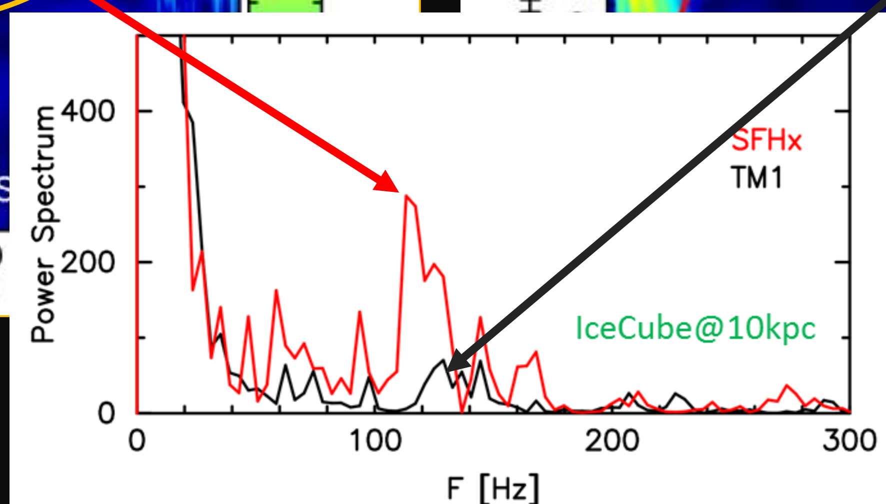
Kuroda, KK, Takiwaki in prep

SFHx :softer

TM1 :stiffer







$$T_{\rm SASI} = \tau_{\rm adv} + \tau_{\rm ac} = \int_{r_\nu}^{r_{\rm sh}} \frac{dr}{|v_r|} + \int_{r_\nu}^{r_{\rm sh}} \frac{dr}{c_s - |v_r|}$$

☺ The **SASI modulation appears more clearly in 3D-GR model with best EOS available !**

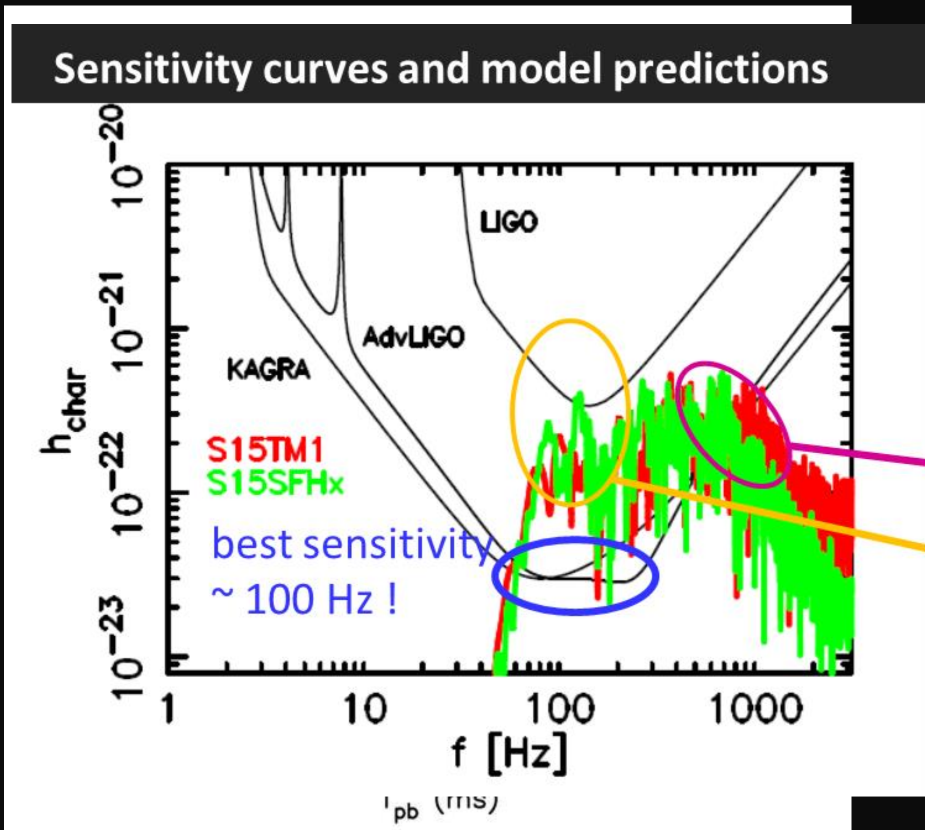
☹ **The modulation freq. from the SASI and rapid rotation: in the range (100 – 200 Hz).**

So… how to tell the difference ?

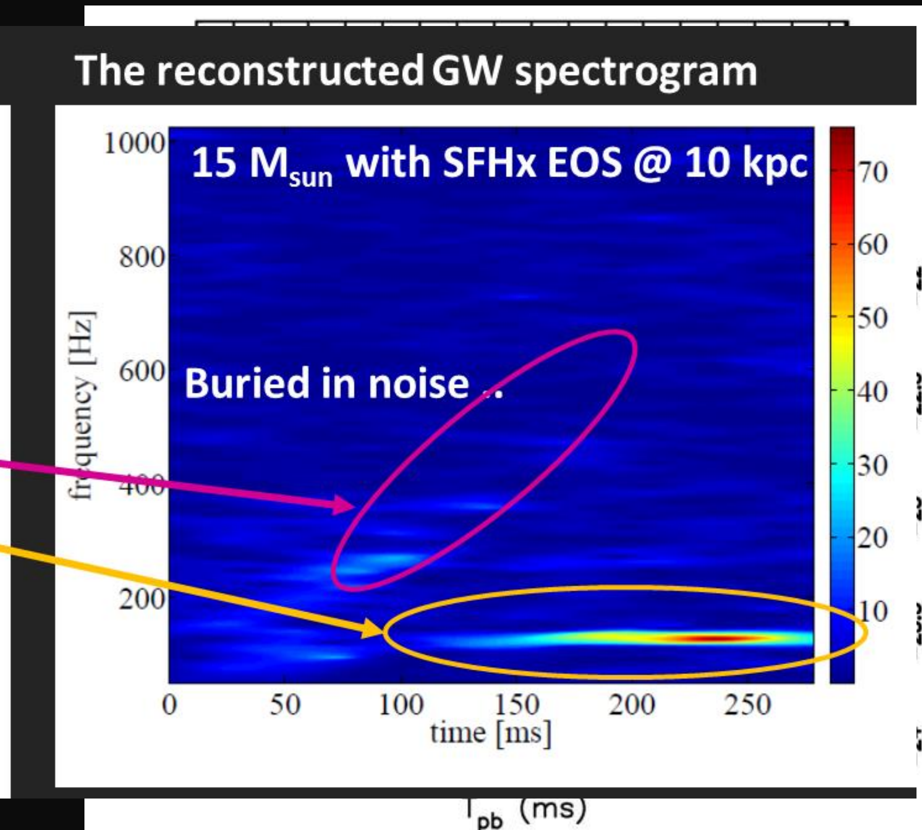
Gravitational Wave (GW) : the key !

(Kuroda, KK, & Takiwaki submitted, see also Andresen et al.)

SFHx :softer



TM1 :stiffer



✓ **The quasi-periodic modulation is associated with SASI, clearly visible with soft EOS.**

✓ By **coherent network analysis** of LIGOx2, VIRGO, and KAGRA, the signal detectable out to the LMC (50 kpc, Hayama, Kuroda, KK et al. (2015, PRD)).

✓ The SASI activity, if very high, results in characteristic signatures in both GWs and neutrino signals (even for non-rotating progenitors !).

Summary

Quiz: Depending on (a), non-axisymmetric instabilities (incl. the SASI) can develop vigorously in CCSN cores.

Choice (1) Progenitor mass / compactness

Ans: Yes !
⇒ the SASI modulation is a smoking gun of the dancing shock.

Choice (2) Precollapse rotation rate

Answer(2): Yes !
The rotational frequency of the spiral arm is imprinted in the neutrino signals.
← The "***lighthouse*** effect".

Choice (3) Equation of State

Answer(3): Yes !
The SASI modulation is **more clearly visible in 3D-GR model with soft EOS**.

Choice (4) More important ingredients ?

Answer(4): Keep it secret !

Our proposal :
Break the degeneracy of the neutrino signals from between non-rotating and rapidly rotating case,
detection of GW is the key !
(albeit not easy).

Thanks!