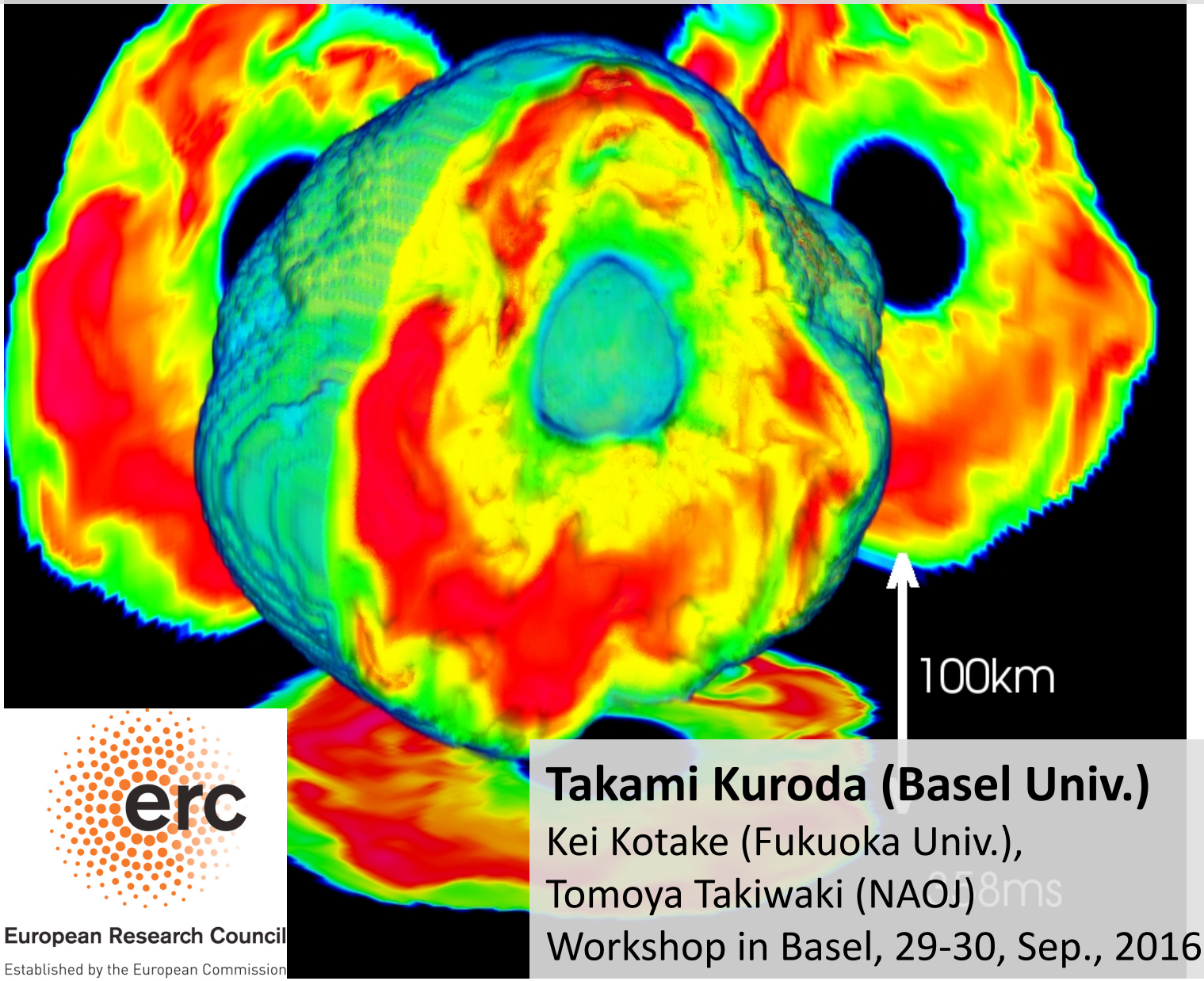
What can we decipher multi messages delivered from CCSNe?



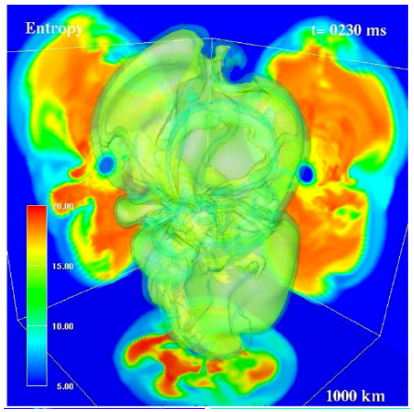
Takami Kuroda (Basel Univ.)
Kei Kotake (Fukuoka Univ.),
Tomoya Takiwaki (NAOJ)
Workshop in Basel, 29-30, Sep., 2016

UNI BASEL

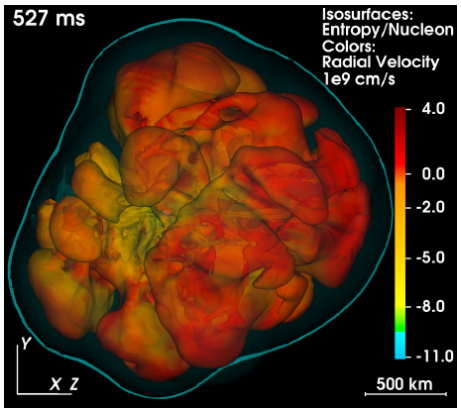
European Research Council
Established by the European Commission

Background

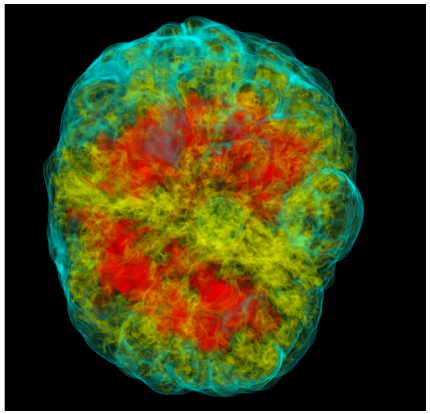
Recent self consistent numerical simulations report "*successful*" SN explosion



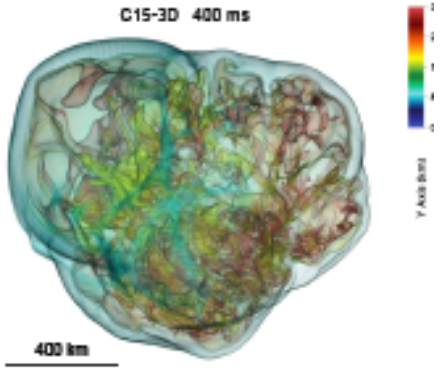
Takiwaki+, '14



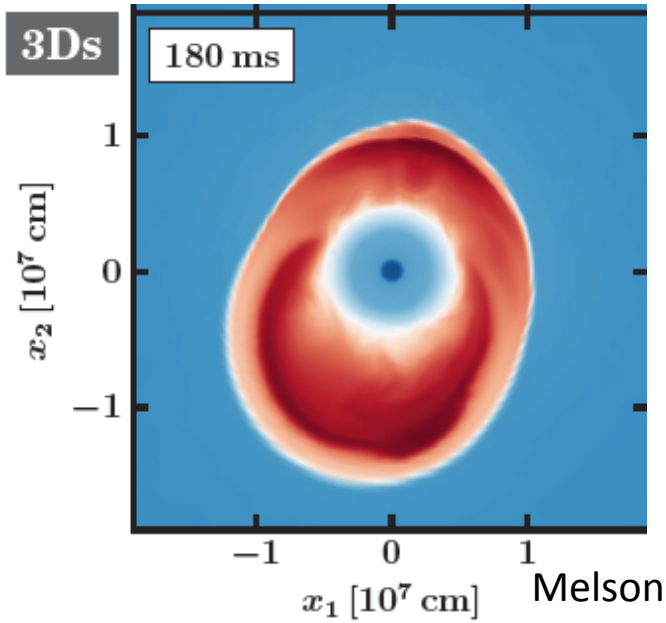
Melson+, '15



Roberts+, '16



Yakunin+, '15



Melson+, '15

Especially in heavier progenitor models (>15-20Msun(?)), the SASI activities are considered to play important roles, sometimes to aid the explosion.

Numerical Setups

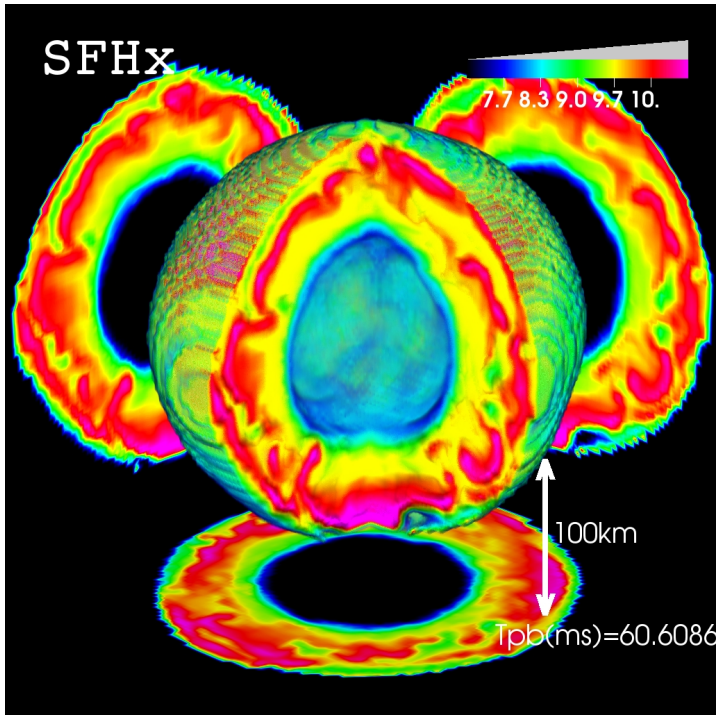
We performed 3D full GR gray-neutrino transport simulations

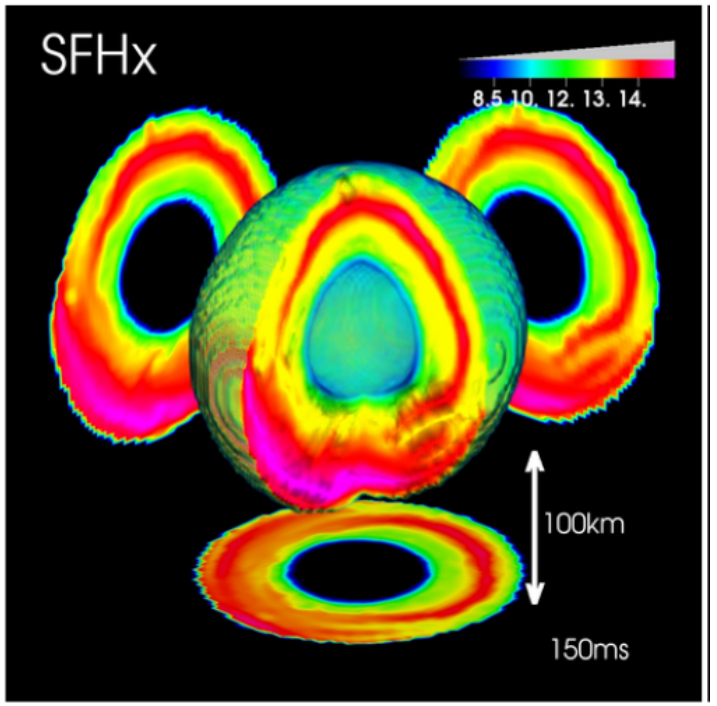
$$\begin{cases} G^{\mu\nu} = 8\pi T^{\mu\nu} \\ \nabla_\alpha T^{\alpha\beta}_{(\mathrm{total})} = \nabla_\alpha T^{\alpha\beta}_{(\mathrm{fluid})} + \nabla_\alpha T^{\alpha\beta}_{(\nu)} = 0 \end{cases}$$

KT+,'12, arXiv:1605.09215

- ✓ Progenitor: 15.0$M_\odot$ (WW95)
- ✓ 128^3cells*9 Level nested structure
  ($\{x,y,z\} \in [-7500,7500]$km, dx_{min}~450m)
- ✓ EOS : HS(SFHx, DD2 & TM1) (Hempel+,'12 & Steiner+,'13)

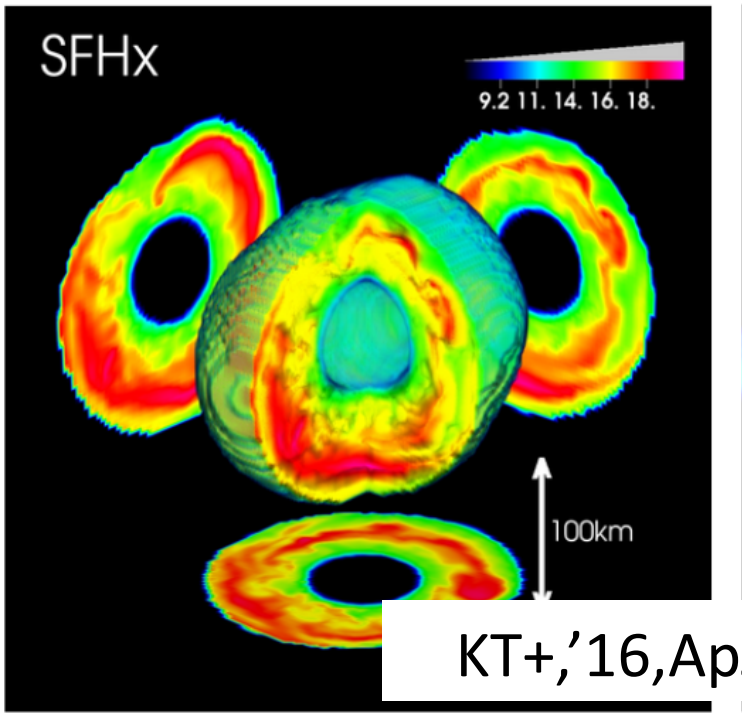
Prompt convection
T_{pb}<60ms

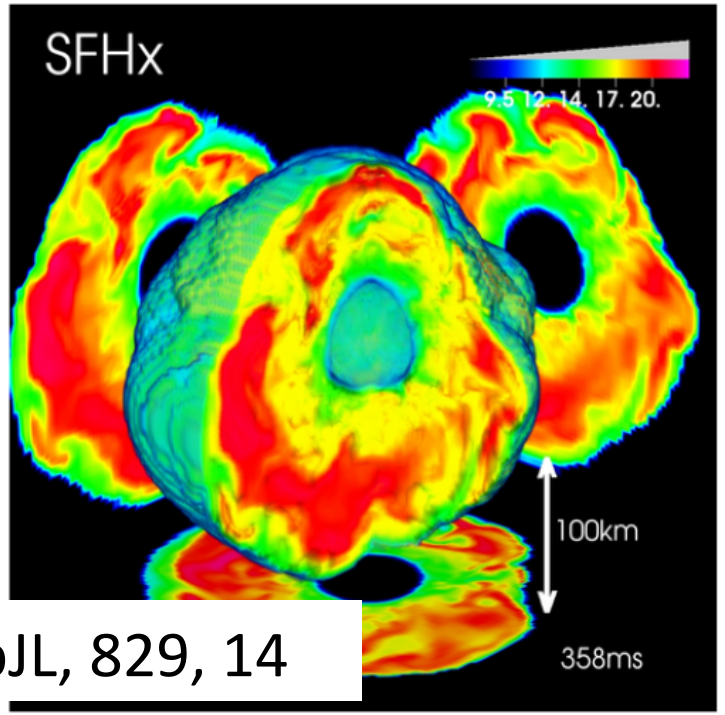




Sloshing
SASI
T_{pb}<180ms

Spiral
SASI
T_{pb}<300ms

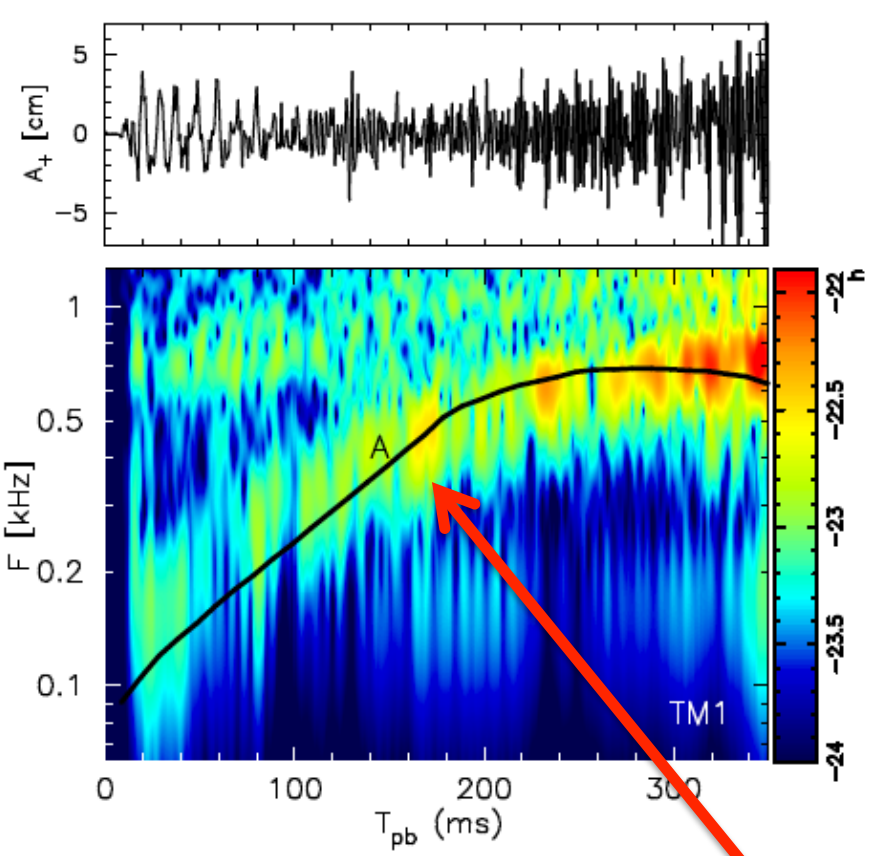


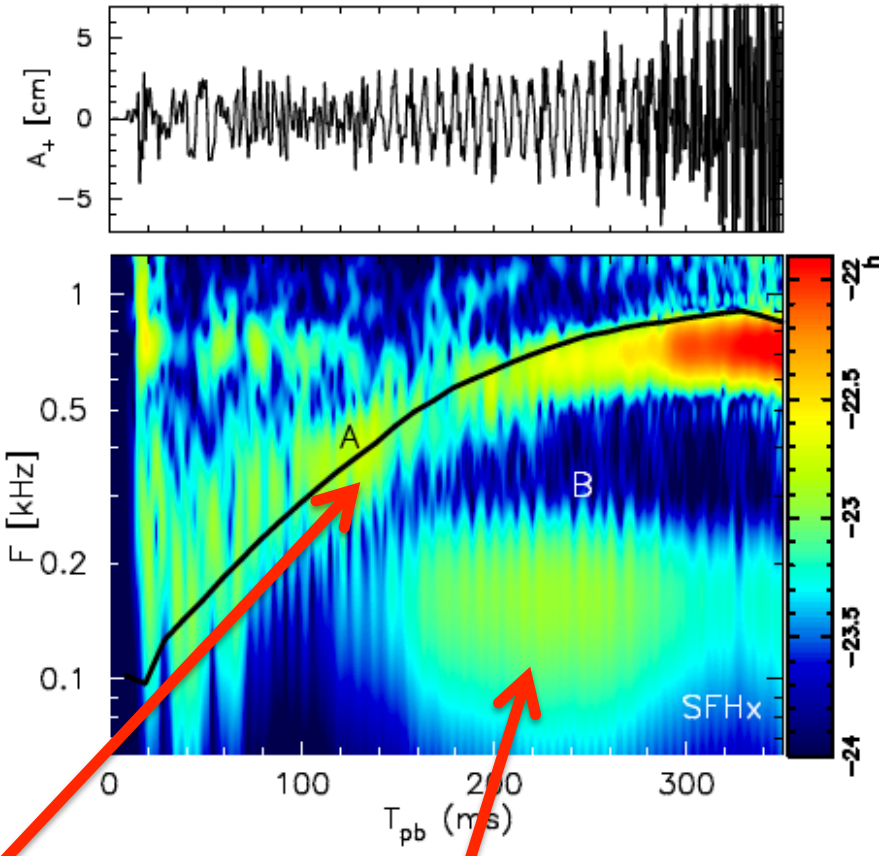


Neutrino
driven
convection
T_{pb}>300ms

KT+,'16,ApJL, 829, 14

Gravitational wave emission





TM1 (stiff eos)

SFHx (soft eos)

$$F_{\rm peak} = \frac{1}{2\pi}\sqrt{\frac{1.1 m_{\rm n}}{\langle \varepsilon_{\bar{\nu}_e} \rangle}}\frac{GM}{R^2}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

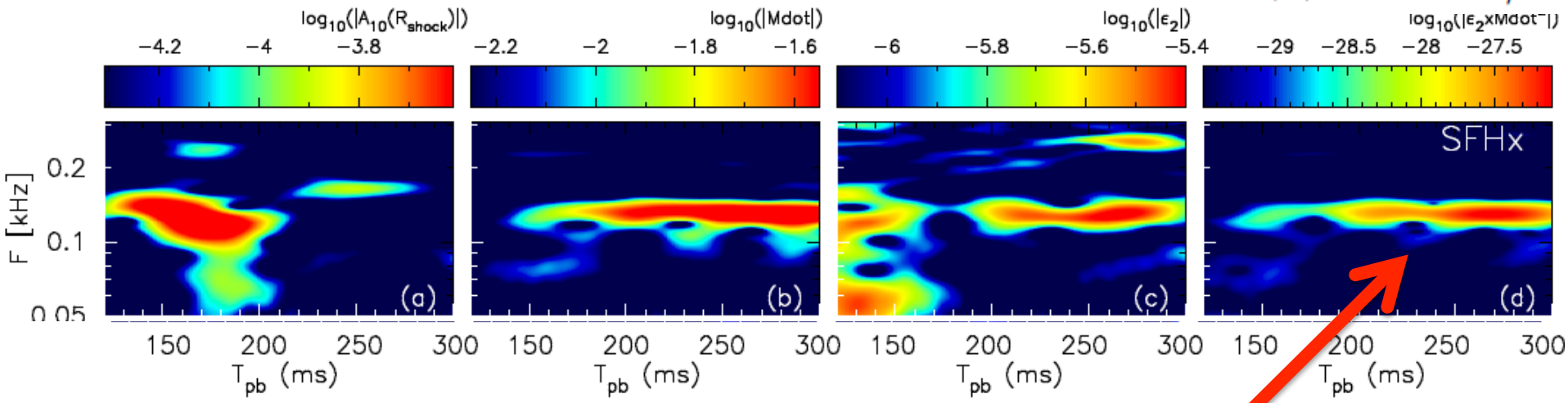
Mueller,'13

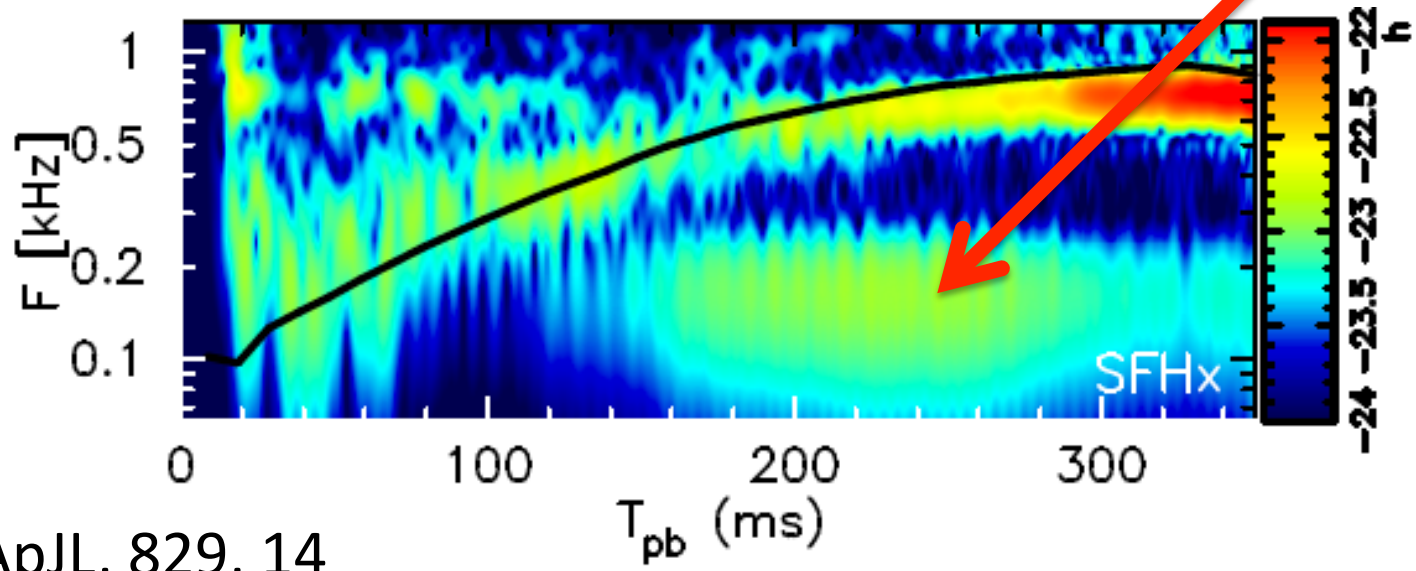
KT+,'16,ApJL, 829, 14

This emission is localized at 10<R<20km

Mechanism of low frequency GW emission

$\dot{M}(R = 20km)$ L=2 core deformation $D|h| \sim 2\epsilon R^2 \dot{M}^2 / M$

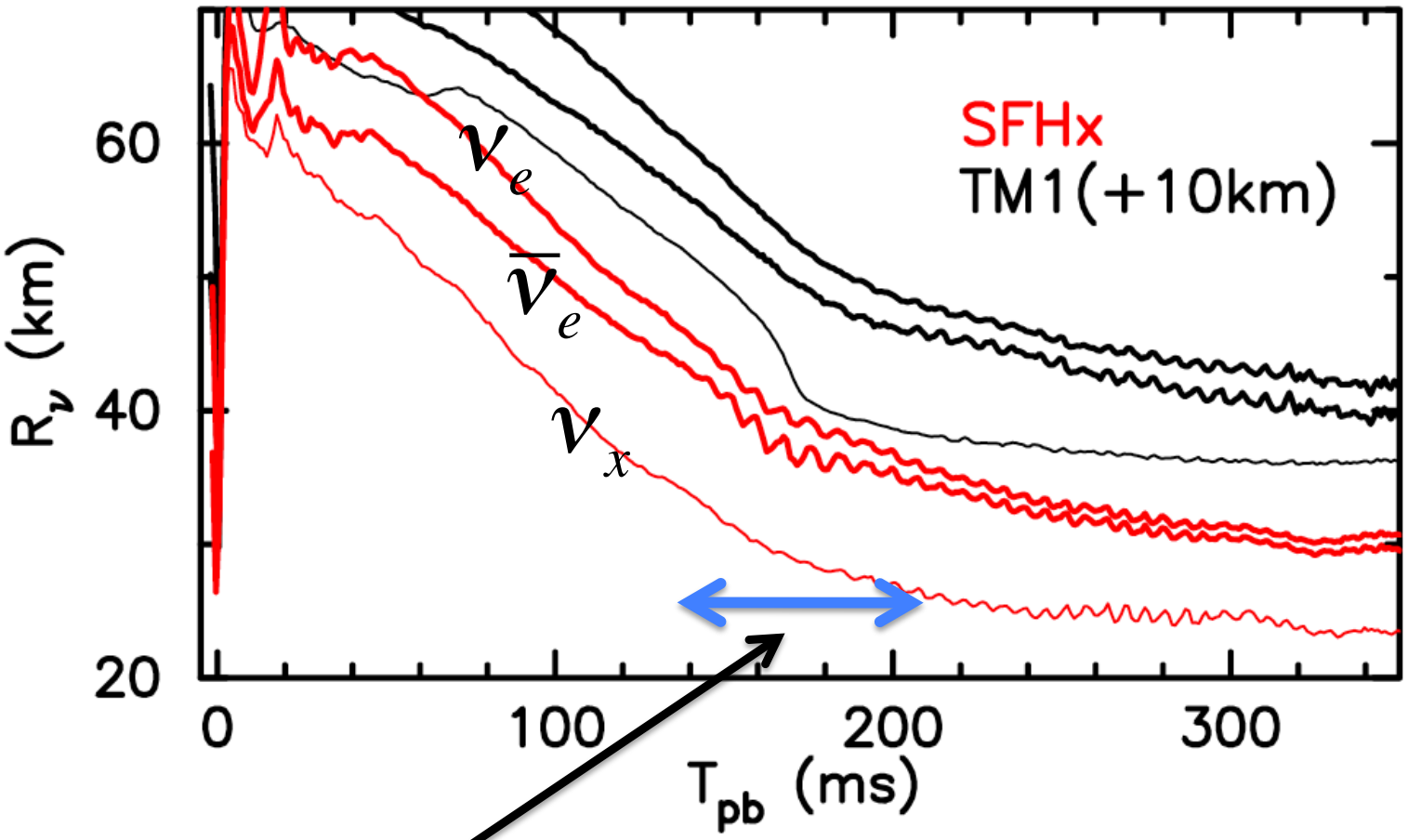




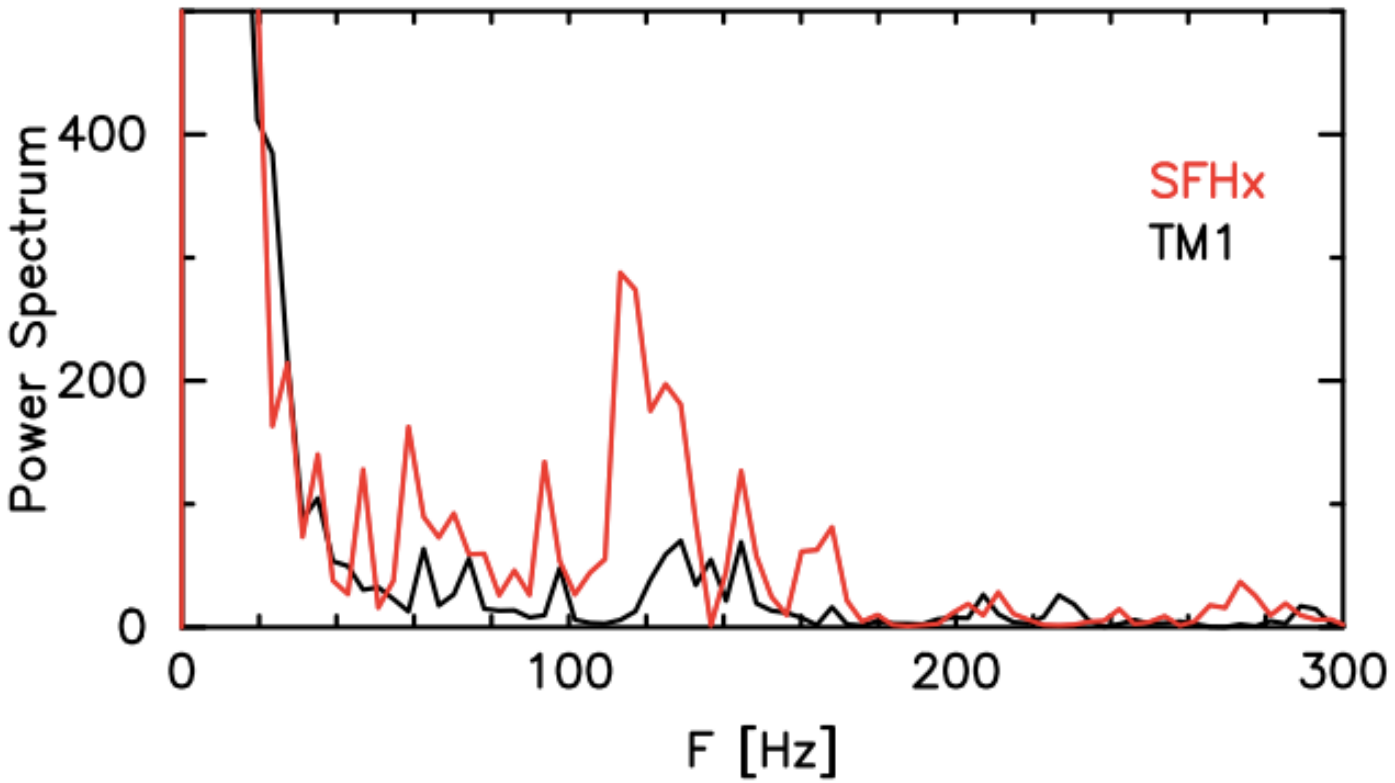
KT+,'16,ApJL, 829, 14

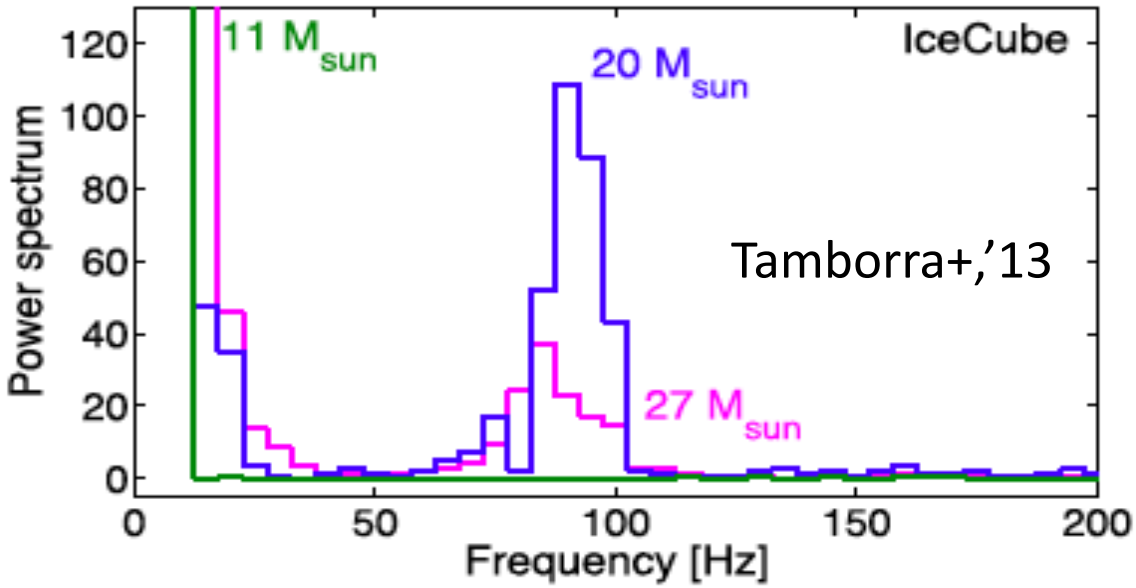
For more basic GW emission mechanisms,
Kotake & Kuroda, "Handbook of supernovae", in press

Coherence of GWs and Neutrinos due to the SASI downflows



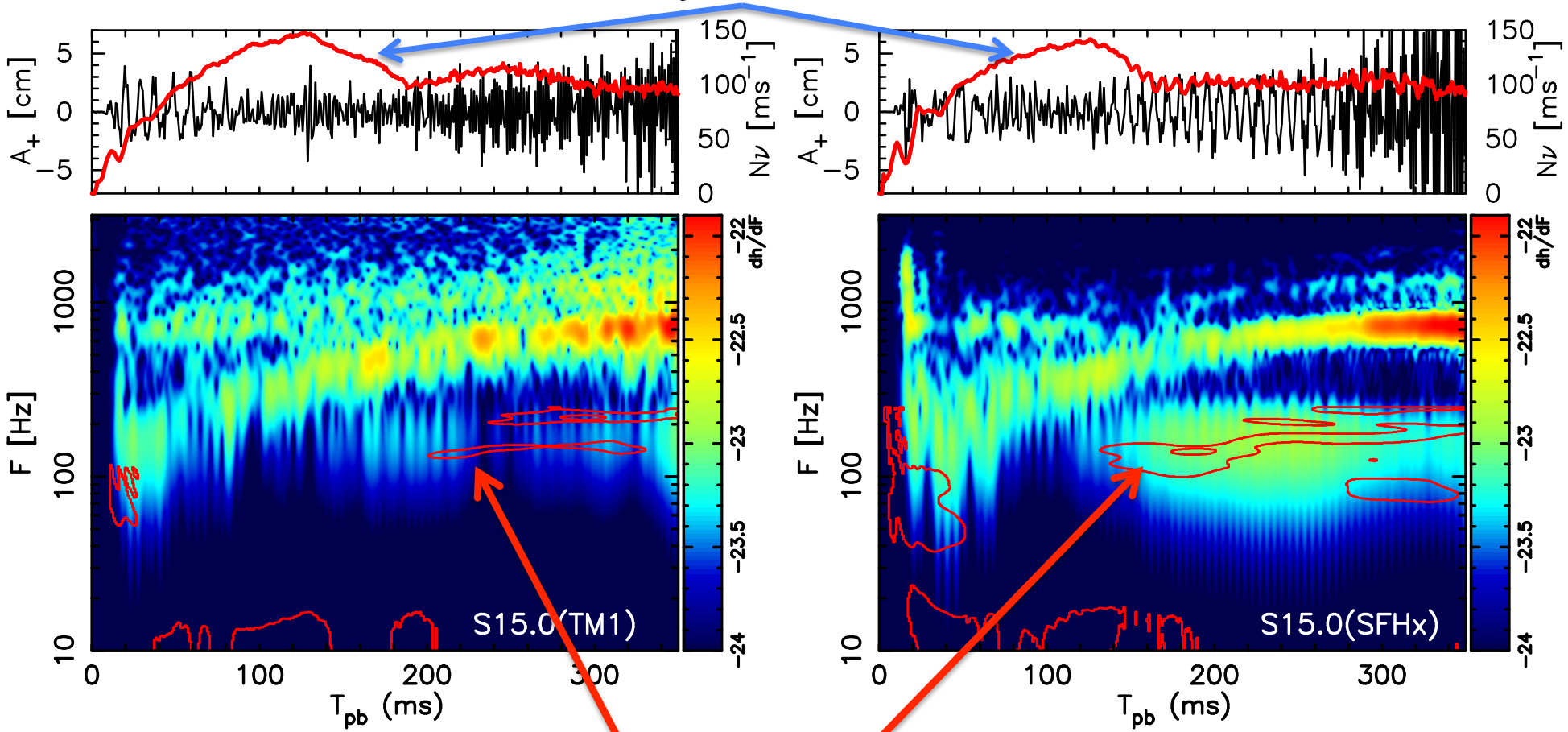
Due to the violent SASI downflows, R_ν oscillates.


Power Spectrum
400
200
0
0
100
200
300
F [Hz]
SFHx
TM1


Power spectrum
120
100
80
60
40
20
0
0
50
100
150
200
Frequency [Hz]
11 M sun
20 M sun
27 M sun
IceCube
Tamborra+,'13

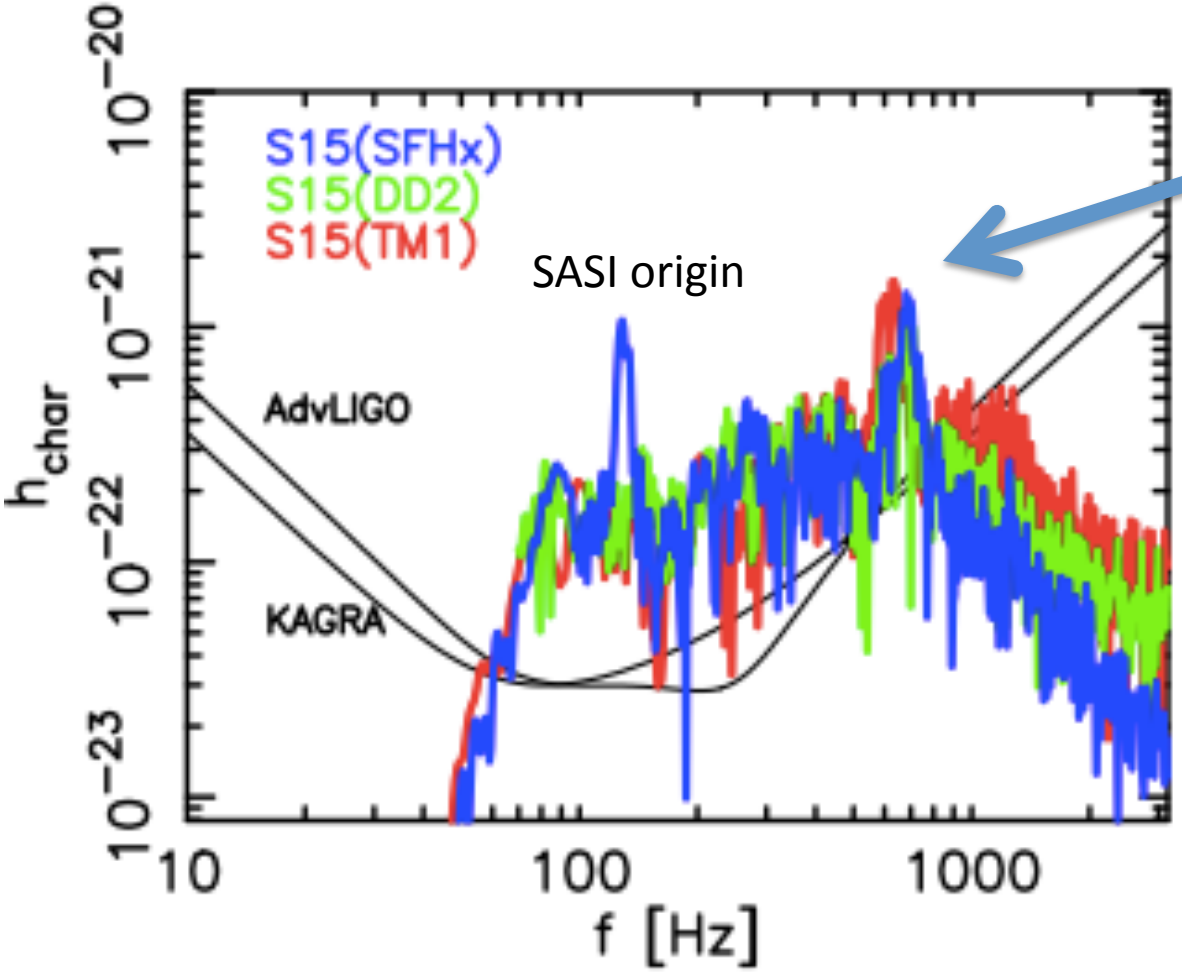
Coherence of GWs and Neutrinos due to the SASI downflows

Detection rate of $\bar{\nu}_e$ by Hyper-K (red curve) with D=10kpc



$$N_\nu(F) = 5$$

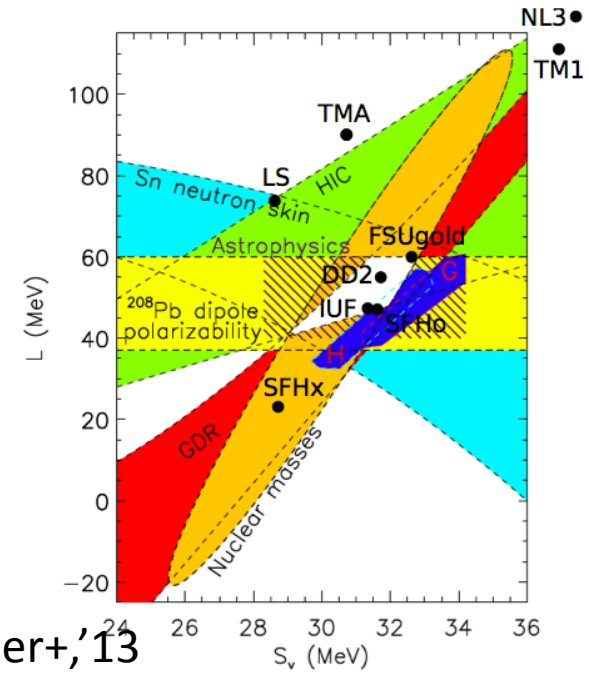
To link GW spectrogram with EOSs



635Hz -- TM1
671Hz -- DD2
681Hz -- SFHx

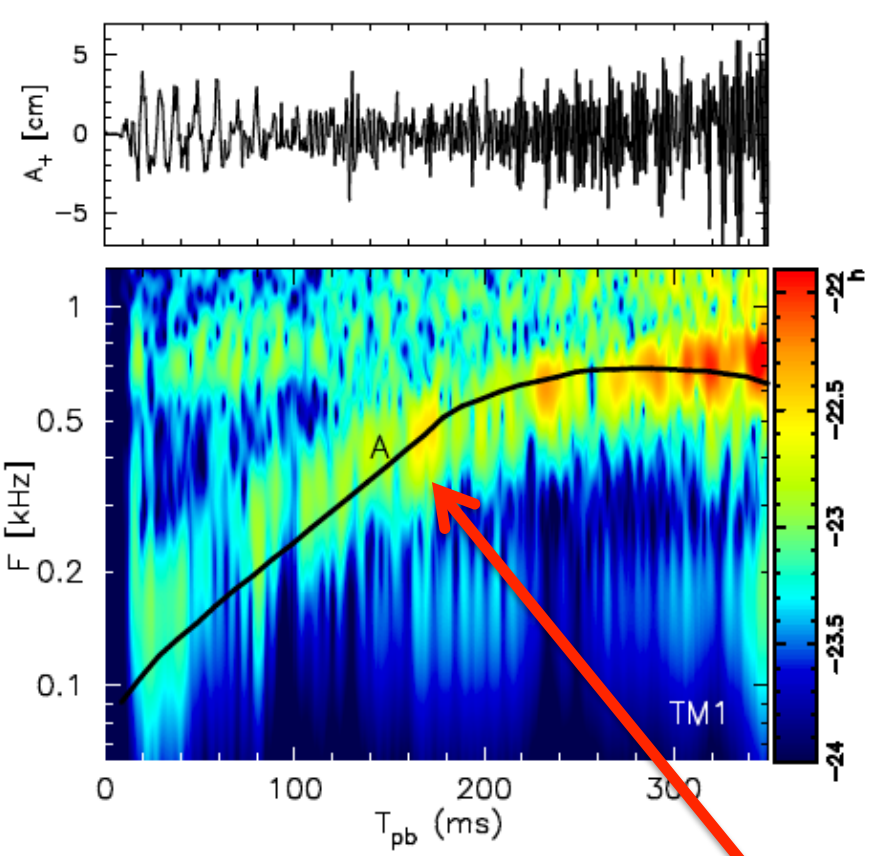
stiff

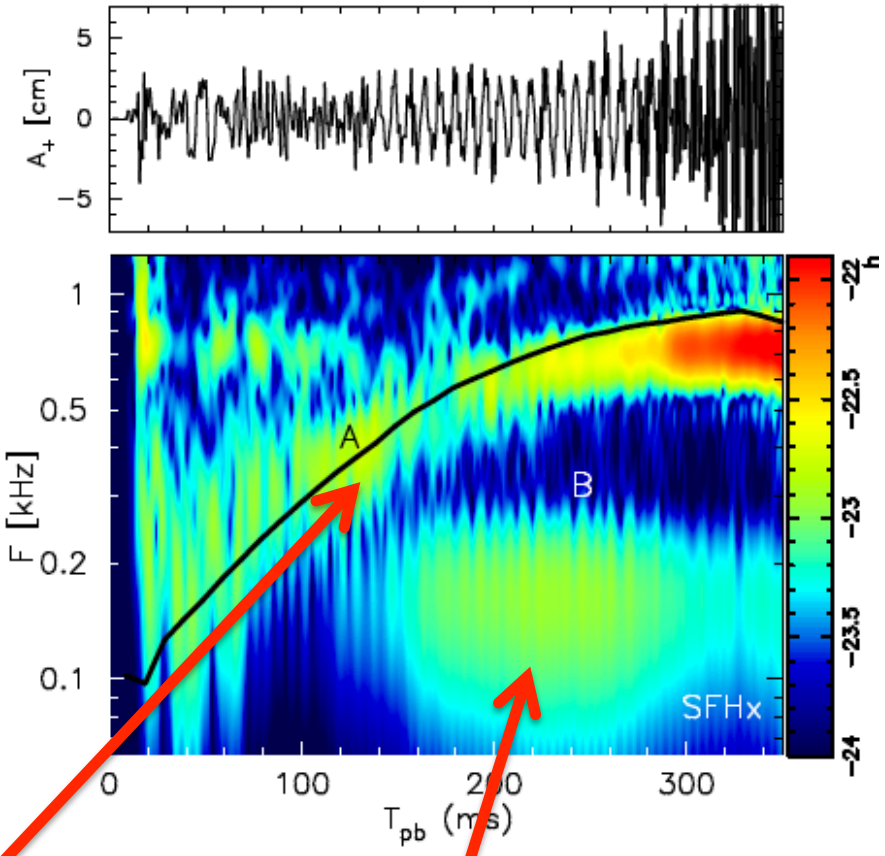
soft



Lattimer+,'13

Gravitational wave emission





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Mueller,'13

KT+,'16,ApJL, 829, 14

This emission is localized at 10<R<20km

Summary & Open questions

- Numerical prediction tells that we may decipher SN evolution (in some phases) through GW and Neutrino observations.
- To put some constraints on EoS, we should focus on late phase Tpb>~300ms till explosion phase (from our limited number of models), but it still requires systematic study with various progenitor models.