Status of GW Predictions of Core Collapse Supernovae

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Consented by Core-Collapse Supernova Model Panels

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Gravitational Waves (GWs) from Stellar Collapse

(see reviews in Ott (2009), Fryer & New (2011), Kotake (2013), Kotake and Kuroda (2016) in "Handbook of Supernovae")

GW amplitude from the quadrupole formula

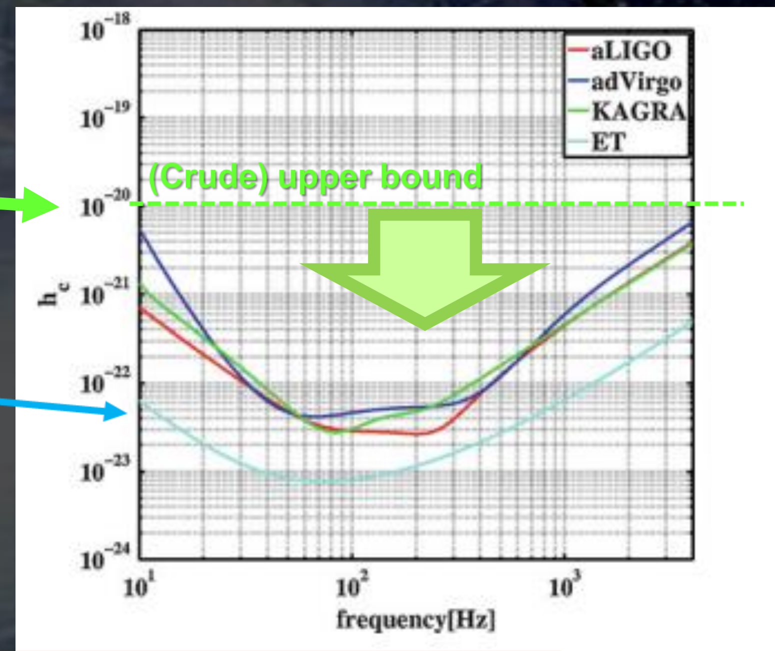
$$h_{ij} = \frac{2G}{c^4 R}\frac{\partial^2}{\partial t^2} Q_{ij} \sim \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

Quadrupole moment

Typical values at the formation of Neutron Star (NS)

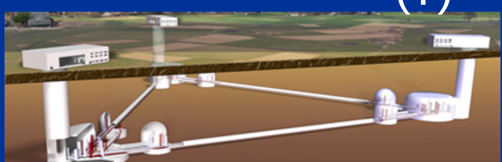
$$R_s = 3\ \mathrm{km}\left(\frac{M}{M_\odot}\right) \quad v/c = 0.1 \quad R = 10\ \mathrm{kpc}$$

$$h \sim 10^{-20}$$



Good news ! (Future)

10 km long:
Einstein Telescope (ET)
could start ~2025(?)



40 km long:
Cosmic Explore (CE)
could operate ~2035.(?)

✓CCSN event in our galaxy (several/century) is primary target !

More correctly..

$$h_{ij} = \epsilon \frac{R_s}{R}\left(\frac{v}{c}\right)^2$$

ϵ : the degree of anisotropy.

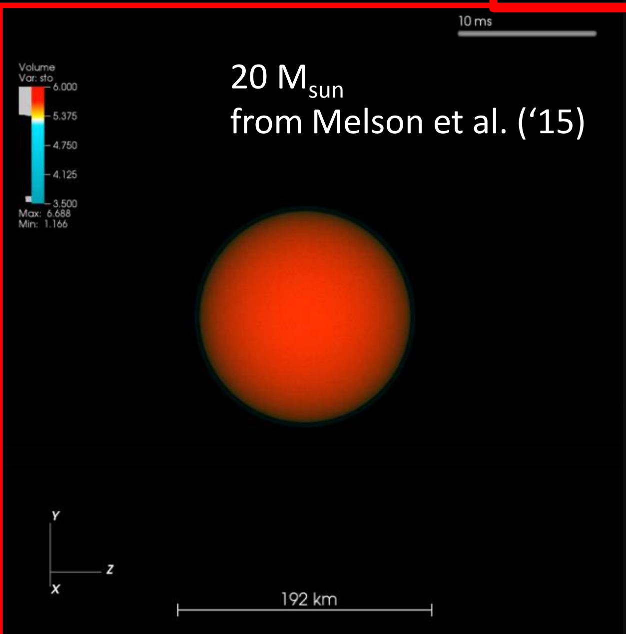
If collapse proceeds spherically, $\epsilon = 0$ no GWs !

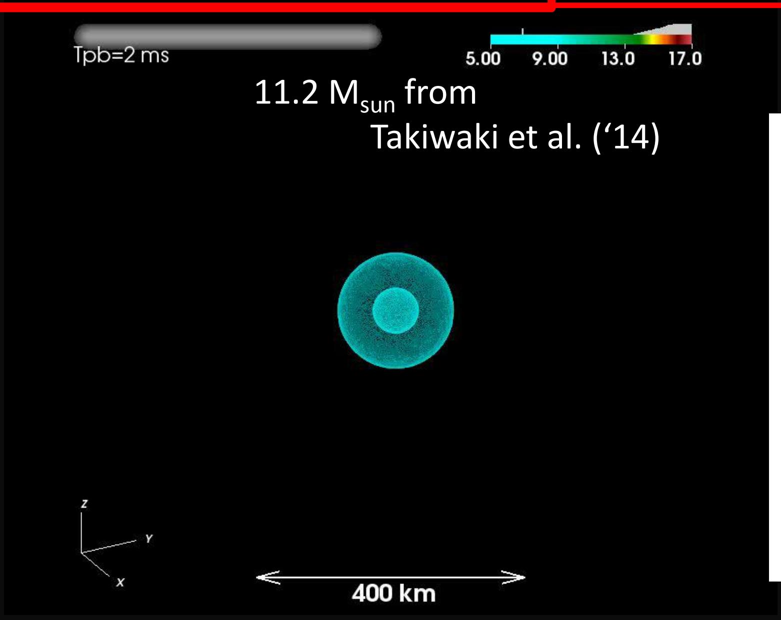
What makes the SN-dynamics deviate from spherical symmetry is essential for the GW emission mechanism !

Two candidates : **The key** is "initial rotation rate" (Ω_0) of the iron core

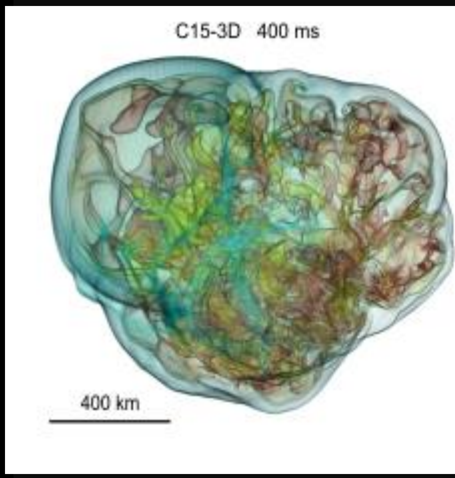
(See reviews in Janka ('17), Mezzacappa et al. ('15), Foglizzo et al. ('15), Burrows ('13), Kotake et al. ('12))

	Neutrino mechanism	**MHD mechanism**
Progenitor	Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s)	Rapidly rotating star with strong B fields ($\Omega_0 > \sim\pi$ rad/s, $B_0 > \sim 10^{11}$ G)
Main origin of GW emission	Turbulent Convection and SASI	Rotating bounce and Non-axisymmetric instabilities
Progenitor fraction	~99% : Main players	~1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)





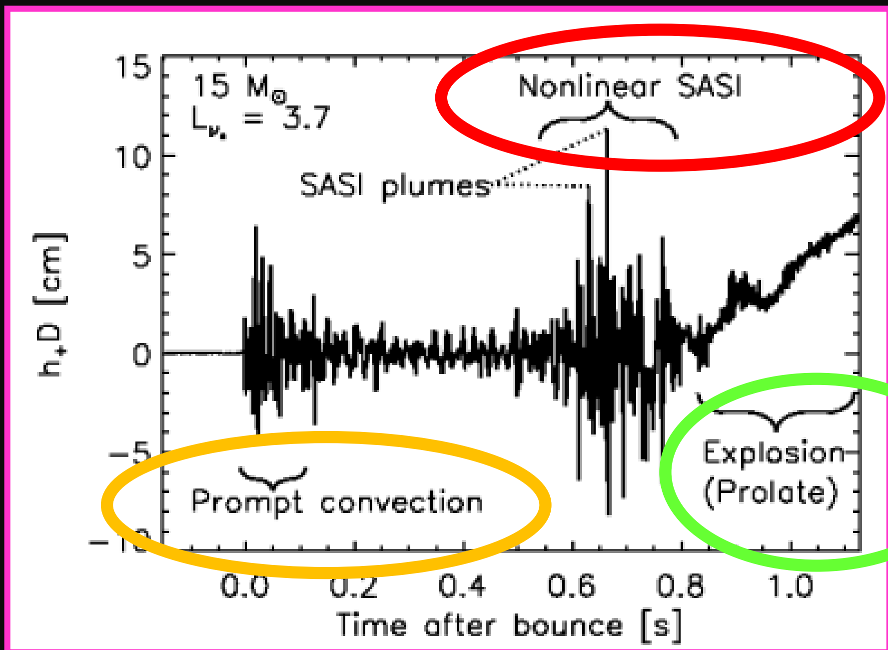
15 M_{sun} star
from Lentz et al. ('15)



(see also, Burrows et al. ('17), Melson et al. ('15), Lentz et al. ('15), Roberts et al. ('16), B. Mueller ('15), Takiwaki et al. ('16))

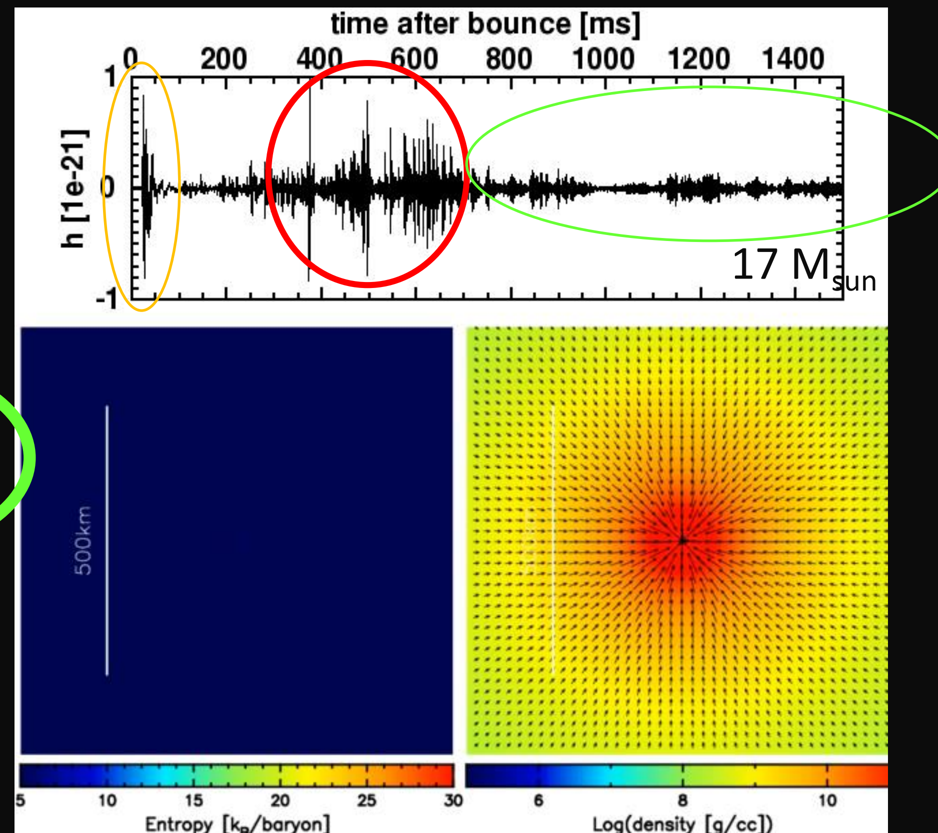
GW signatures from 2D neutrino-driven explosion (1/3)

Waveform from Murphy et al. (2009) ApJ



(Later confirmed by B. Mueller et al. ('13), ApJ, Yakunin et al. (2015), PRD)

Waveform from Nakamura et al. ('16) MNRAS



✓ Three generic phases in neutrino-driven models:

1. Prompt-convection phase : within ~50 ms post-bounce
2. Non-linear phase (Convection/SASI) : Downflows hit the PNS surface
3. Explosion phase : Long-lasting signal but terminates if BH forms

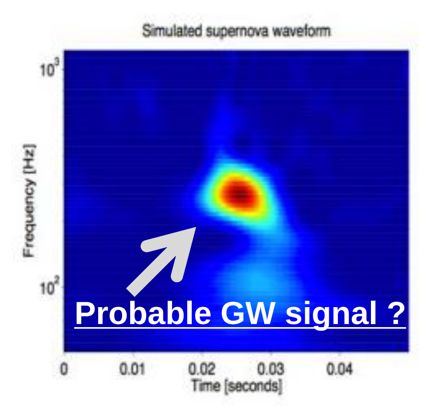
(Müller et al. (2004, ApJ), Cerda-Duran et al. (2013, ApJ))

✓ Waveforms have no template character: stochastic explosion processes.

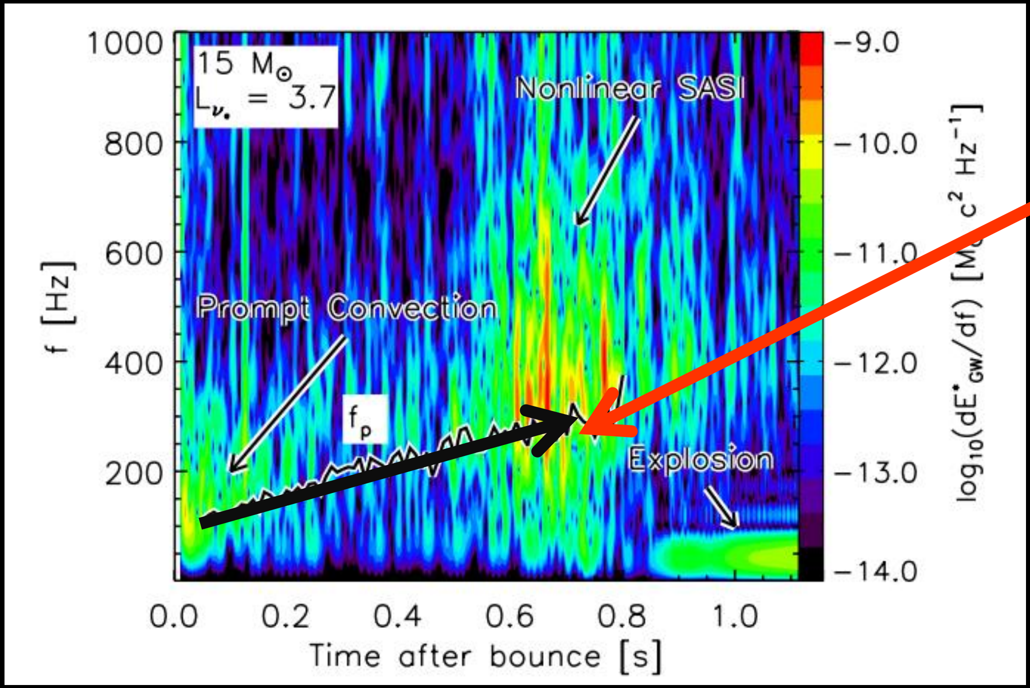
How to detect GWs with no-template features…

✓ **Excess power method**: Flanagan & Hugh (1998)

⇒ Decompose data-stream into time-frequency domains
⇒ Search for "hot" regions with excess power in the spectrogram !



✓ GW spectrogram from Murphy et al. ('09) ApJ.



☆ **Increase of typical frequency**
⇒ the g-mode frequency of PNS

$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1-\frac{GM}{Rc^2}\right)^{3/2}$$

M, R, T : mass, radius & temperature of PNS, Γ : stiffness of EOS

Due to mass accretion, M ↗ , R ↘

⇒ f_p ↗

(see complete derivation in B. Mueller et al. ('13), ApJ)

- ✓ **(With no template character…) Three generic phases are in the spectrogram !**
- ✓ Secular increase of typical GW frequency (f_p) **reflects the PNS evolution**.
- ✓ On top of f_p , the high frequency component comes from strong downflows to PNS.
- ✓ **These qualitative features are common to more recent 2D and 3D models**.
- ✓ More detailed analysis needed if we claim the detection only from the spectrogram.

Recent GW predictions from 3D CCSN models with neutrino transport

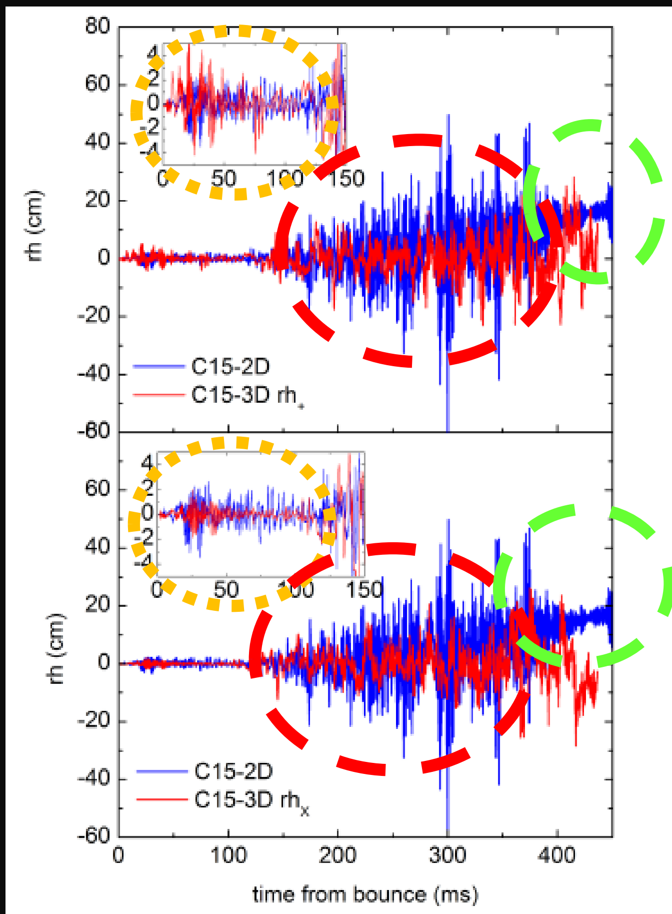
- **Yakunin, Mezzacappa et al. (2017)**

✓ **"Three generic phases" also seen in 3D**

✓ **2D overestimates GW amp. relative to 3D**

+ mode

× mode

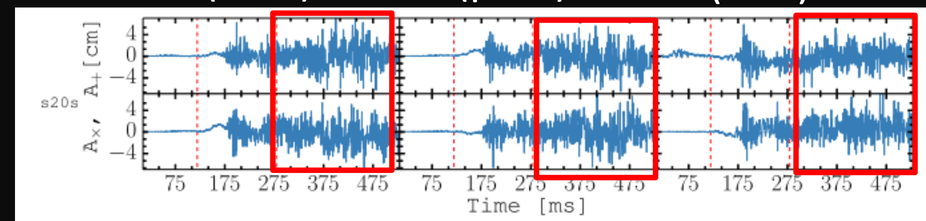


Based on 15 M_{sun} model
from Lentz et al. (2015), ApJL

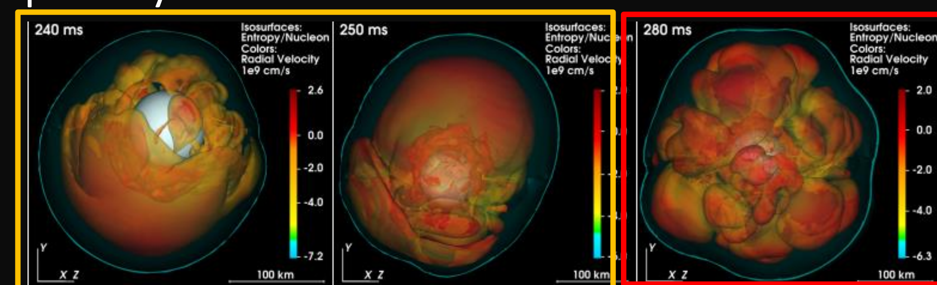
- **Andresen, B & E Müller and Janka (2016)**

✓ Wave amplitudes; **rather insensitive** to direction (to the observer).

(max) (pole) (min)



especially when convection dominates over SASI.



✓ The horizon of LIGO is limited to nearby events.
Third generation detectors (ET) could detect any Galactic event !

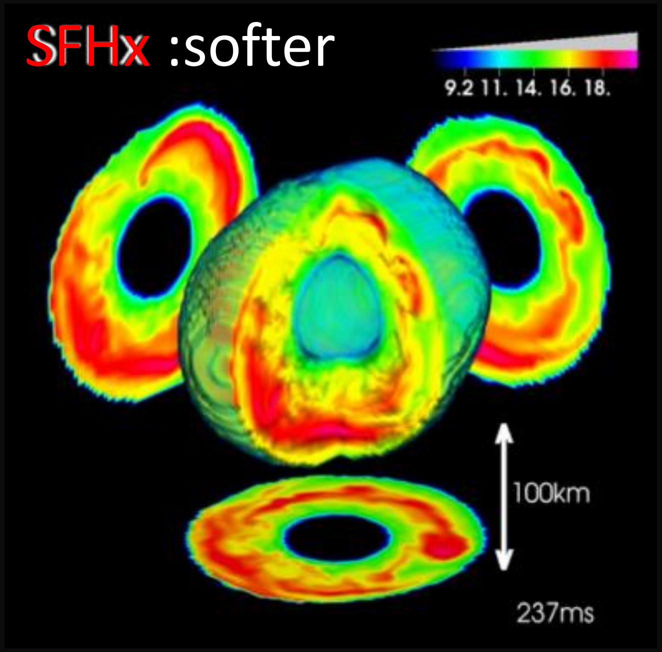
	s27				s20			
	Low	High	Total	Low/High	Low	High	Total	Low
AdvLIGO	3.7	4.5	8.8	0.82	5.3	7.7	9.4	0.82
ET-C	50.0	64.0	81.3	0.78	73.9	109.3	131.9	0.83
ET-B	78.5	73.7	107.7	1.07	113.9	127.0	170.6	0.74

GW Spectrograms from 3D-GR models with strong SASI vs. weak SASI activity

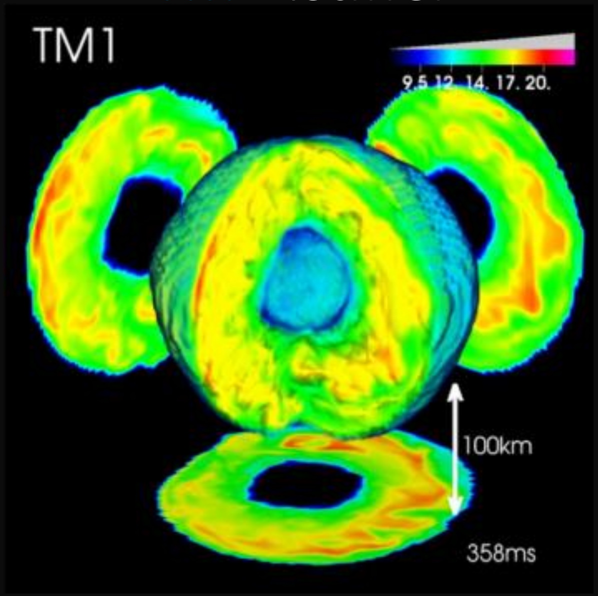
(from **Kuroda, KK, & Takiwaki ApJL (2016),** see also Andresen et al. (2016))

✓ Two EOSs → SFHx (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)), HS(TM1) (Shen et al. (1998)).

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



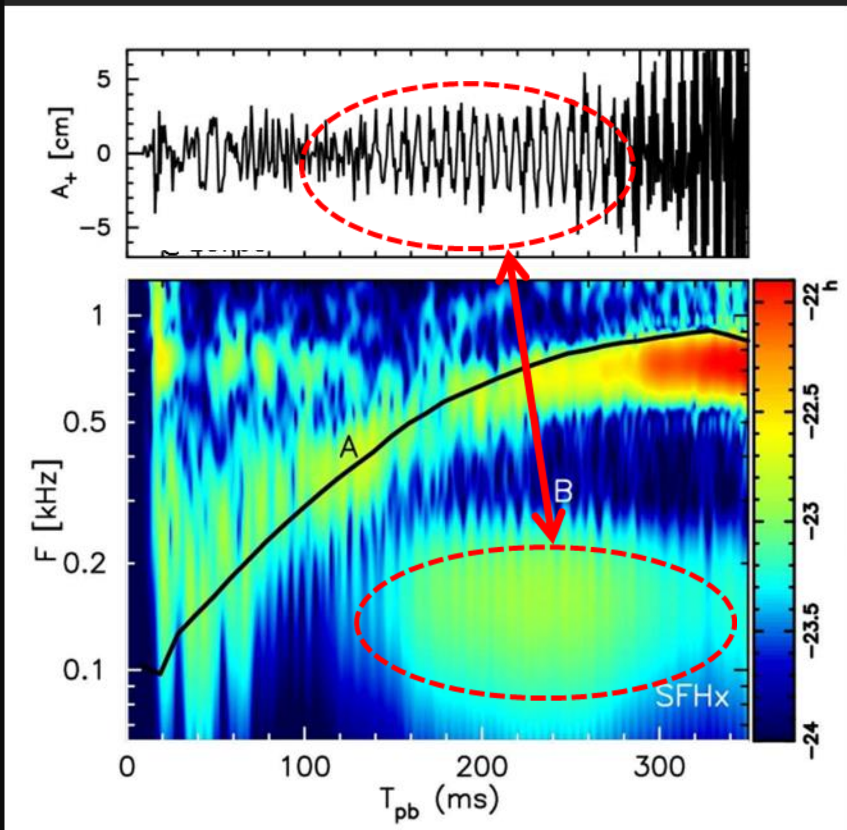
TM1 :stiffer



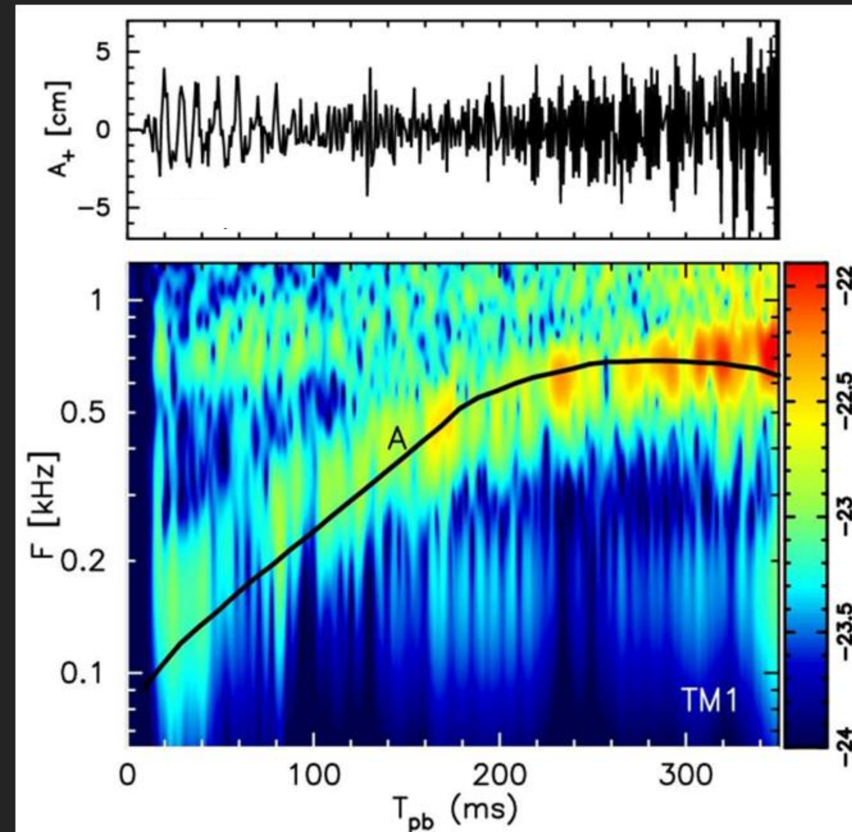
- ✓ **The quasi-periodic modulation is associated with SASI, clearly visible with realistic EOS.**
- ✓ By coherent network analysis of LIGO, VIRGO, and KAGRA, the detection horizon is only 2~3 kpc, but could extend out to 100 kpc when **ET and CE are on-line (>2035).**
- ✓ **Detection of neutrinos (Super-K, IceCube) important to get timestamp of GW detection.**
- ✓ **The SASI activity, if very high, results in characteristic signatures** in both **GWs and neutrino signals** (e.g., Tamborra et al. (2012) for SASI-induced neutrino signals).

GW Spectrograms from 3D-GR models with strong SASI vs. weak SASI activity

SFHx :softer



TM1 :stiffer



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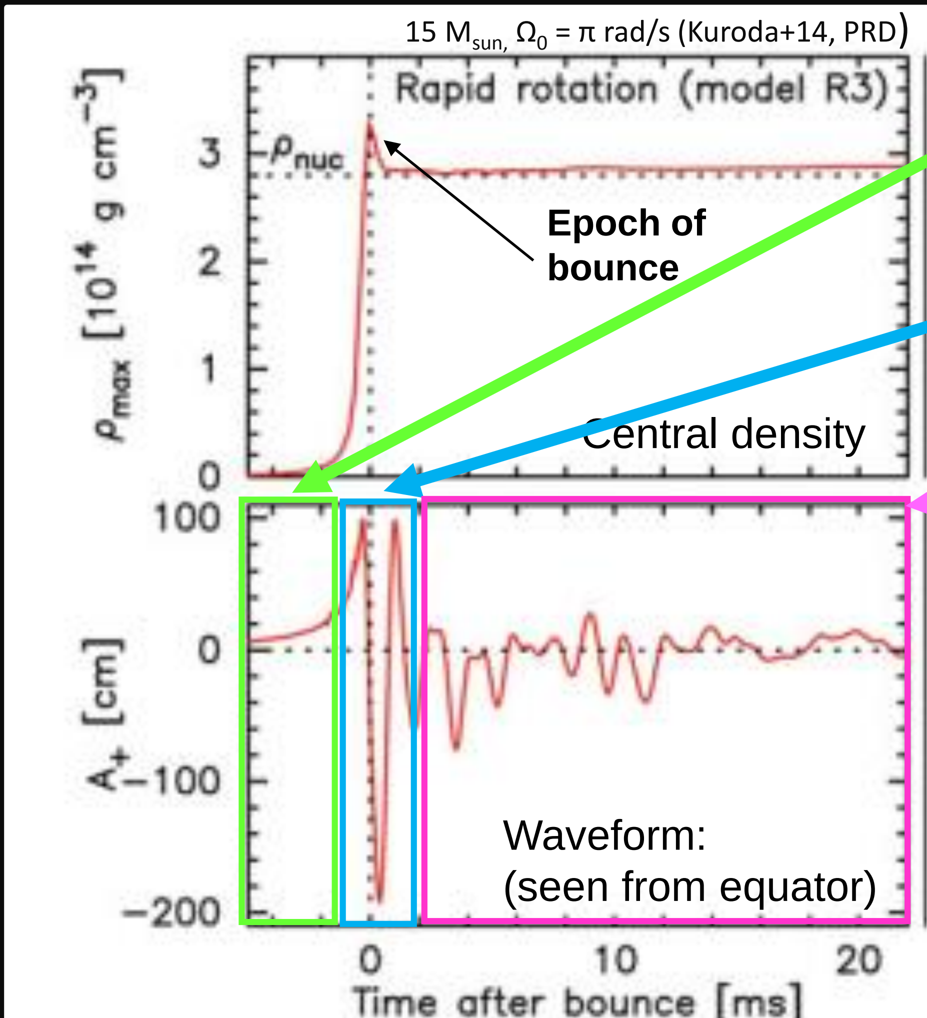
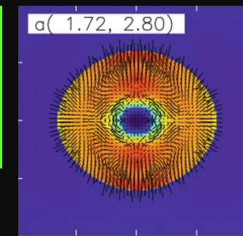
Switching gears to MHD mechanism (rapid rotation required !!)

GW from Rapidly Rotating Core-Collapse and Bounce

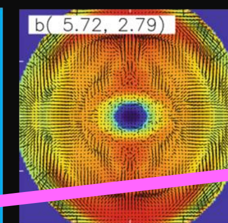
(Dimmelmeier et al. (07, PRL), Scheidegger et al. (10, A&A) Ott et al. (12, ApJ), Abdikamalov+(14, PRD), Kuroda+(14,PRD))



✓ **Infall phase:** Rotational flattening of the core



✓ **Core bounce:** stiffening of nuclear EOS, making big change in the mass quadrupole

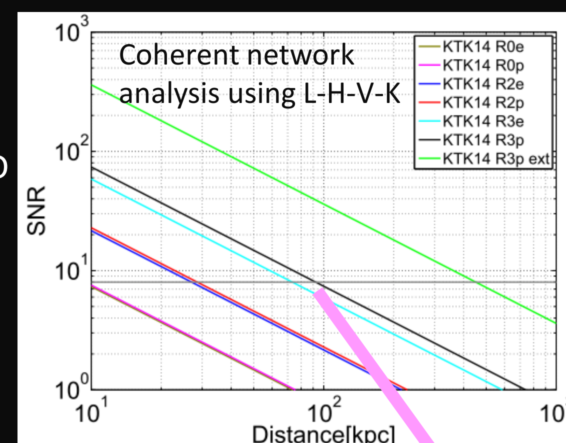


✓ Ring-down phase: settles down to stationary state, with amplitudes decreasing with time.

✓"Optimal" detection horizon using matched filtering

$$\mathrm{SNR} = \frac{h_c}{\sqrt{f_c S_n(f_c)}}$$

Hayama +(15), PRD (see collective references in Gossan +(16), Powell +(16), PRD)



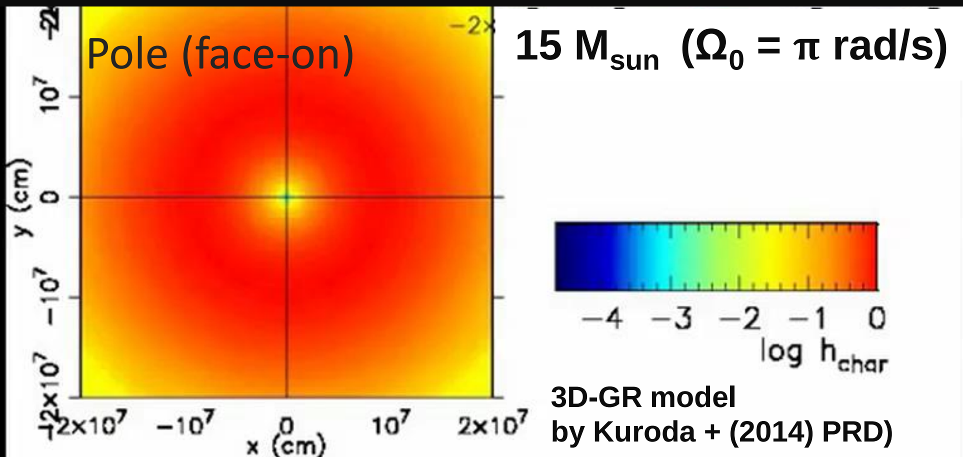
Bounce GW signal (in the context of rapidly rotating collapse and bounce):
✓Characterized by big spike at bounce followed by smaller peaks.
✓Matched filtering (or PCA) likely applicable.✓Horizon distance can reach beyond LMC (50kpc)

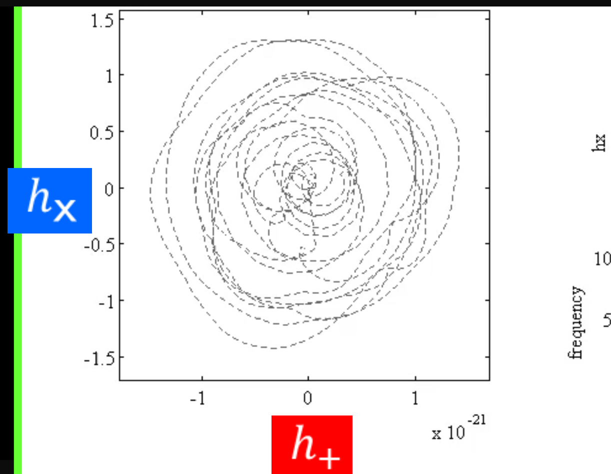
GWs from (Rotation-induced) Non-Axisymmetric Instabilities

✓ **Low T/|W| instability** is most likely to develop (Ott + (05, ApJL), Scheidegger + (10, A&A))

GW emissivity: $\psi \equiv (A_{+}\mathrm{I})^2 + (A_{\times}\mathrm{I})^2 = (\ddot{I}_{xx} - \ddot{I}_{yy})^2 + (2\ddot{I}_{xy})^2$

Circular polarization of h_{+} and $h_{\times}$





Strong emission from one-armed spiral wave

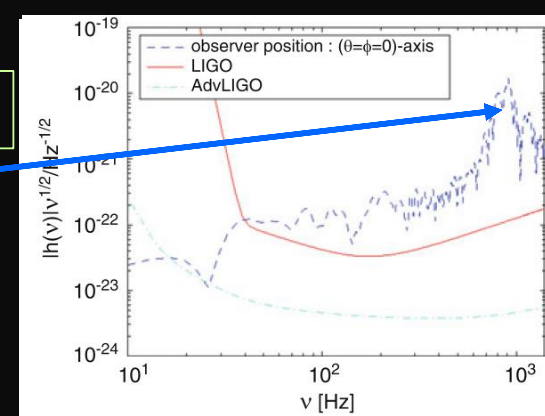
Hayama et al. (2016), PRL
(see also Klimenko et al. (2015) PRD)

✓ **GW from non-axisym. instabilities (incl. low T/|W|, spiral SASI) : Quasi-Periodicity**

(Ott + (07, PRL), Scheidegger + (10, A&A), Kuroda + (14, PRD))

⇒ The effective amplitude scales as the # of GW cycles as

$$h_{\mathrm{eff}} \propto h\sqrt{N}$$



✓ **Circular polarization can be evidence of "rapid rotation".**
✓ **"Quasi-periodicity" enhances the chance of detection.**

Summary

	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star $(\Omega_0 < \sim 0.1\ \mathrm{rad/s})$	Rapidly rotating star with strong B fields $(\Omega_0 > \sim\pi\ \mathrm{rad/s}, B_0 > \sim 10^{11}\ \mathrm{G})$
Main GW signatures	**Three generic phases: Prompt convection, neutrino-driven convection & SASI, and explosion**	**Rotating bounce (< 20 ms p.b.) and non-axisymmetric instabilities (< ? ms)**
Detection Prospect	✓ **Requires 3rd generation detector to see every Galactic event (with high SNR).** ✓ **Closeby events (2~3kpc) detectable by LIGO-class detectors.** ✓ **If detected, critical information about SN engine (convection-dominant vs. SASI dominant) can be obtained.**	✓ **Bounce GW signal: detection horizon of LIGO, depending on Ω_0, can cover our Milky way and beyond.** ✓ **GWs from non-axisymmetric instabilities: "quasi-periodicity" of the signal enhances the chance of detection.** ✓ **Detection of circular polarization: important probe of core rotation.**