1st . General Introduction

✓ Why multi-messengers (inc. GW)?

✓ Basics of GW Physics and Detection

✓ First detection of GW150914

2nd . Core-collapse supernova theory: how to solve "*numerically*" the space-time evolution of dying stars (40 min)

3rd . GW signatures from core-collapse supernovae: what we can learn from future GW observation ? (40 min)

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

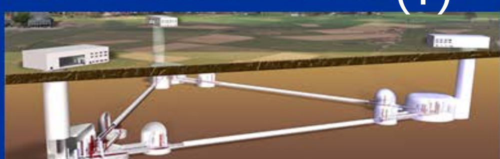
Typical values at the formation of Neutron Star (NS)

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

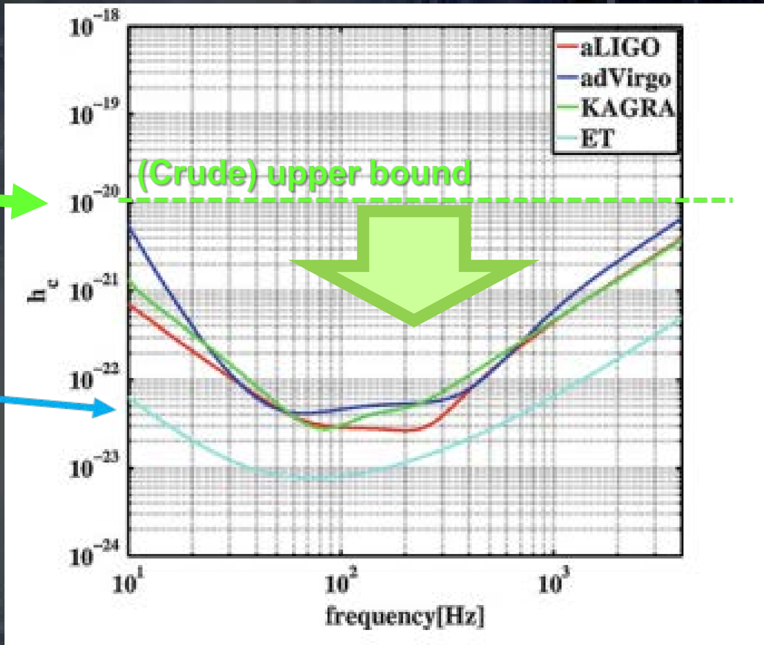
$$h \sim 10^{-20}$$

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.

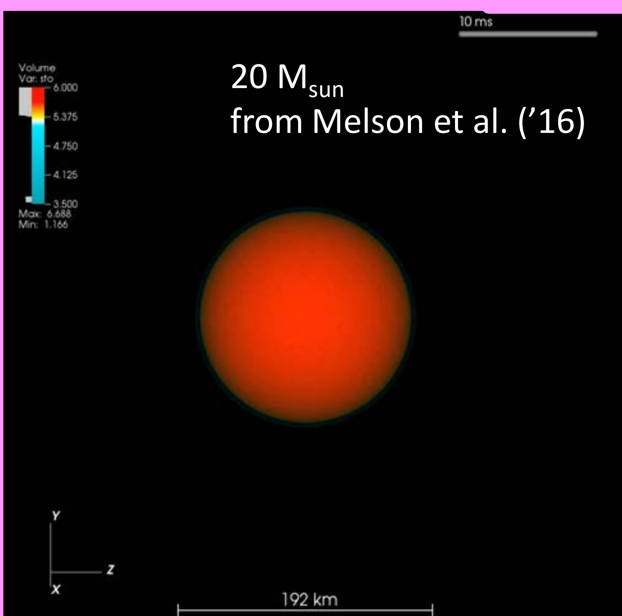
If collapse proceeds spherically, $\epsilon = 0$ no GWs !

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

Two candidate mechanisms of core-collapse supernovae

(Lecture by T. Foglizzo, reviews in Janka ('17), Müller ('16), Foglizzo+('15), Burrows('13), Kotake+ ('12))

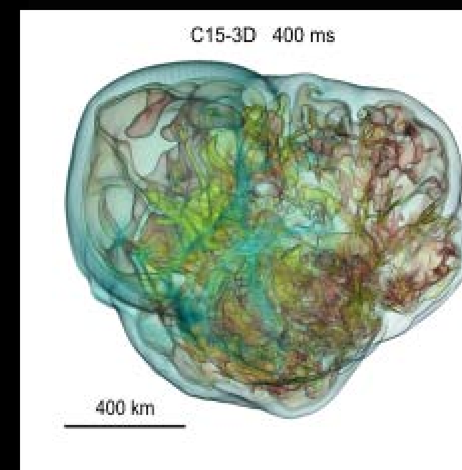
	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s)	Rapidly rotation with strong B ($\Omega_0 > \sim\pi$ rad/s, $B_0 > \sim 10^{11}$ G)
Key ingredients	✓ **Turbulent Convection and SASI** (e.g., Kazeroni, Guilet, Foglizzo, (2017)) ✓ **Precollapse Inhomogenities/structures** (e.g., B.Mueller et al. (17), Suwa & Mueller (16)) ✓ **Novel microphysics:** Bollig+(17), Fischer+(18)	✓ **Field winding and the MRI** (e.g., Obergaulinger & Aloy (2017), Rembiasz et al. (2016), Moesta et al. (2016), Masada + (2015)) ✓ **Non-Axisymmetric instabilities** (e.g., Takiwaki, et al. (2016), Summa et al. (2017))
Progenitor fraction	Main players	~<1% (Woosley & Heger (07), ApJ): (hypothetical link to magnetar, collapsar)



20 M_{sun} from Melson et al. ('16)

11.2 M_{sun} from Nakamura et al. in prep.

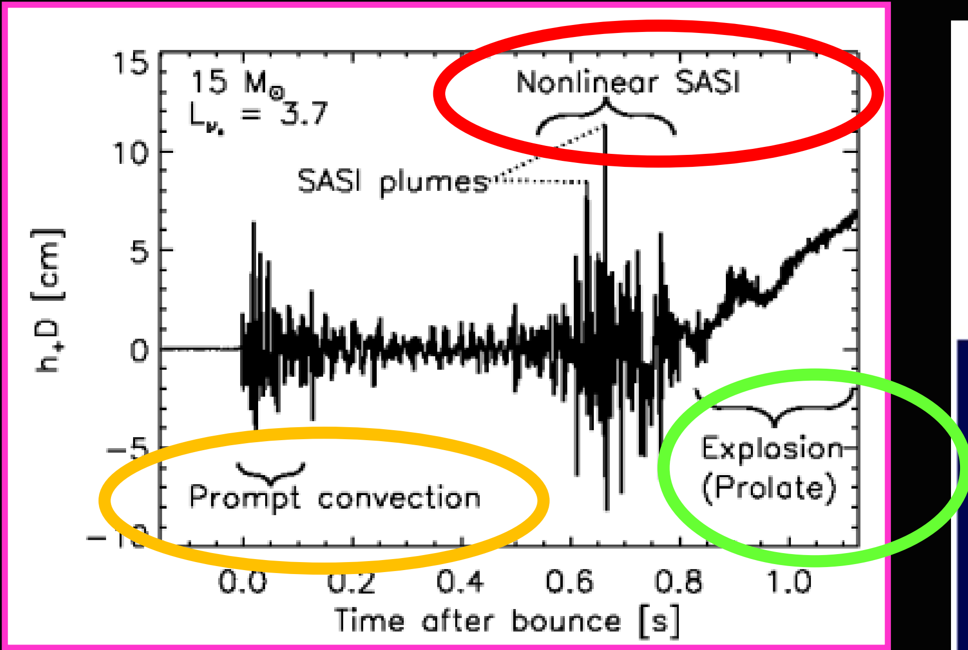
15 M_{sun} star from Lentz et al. ('15)



(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))

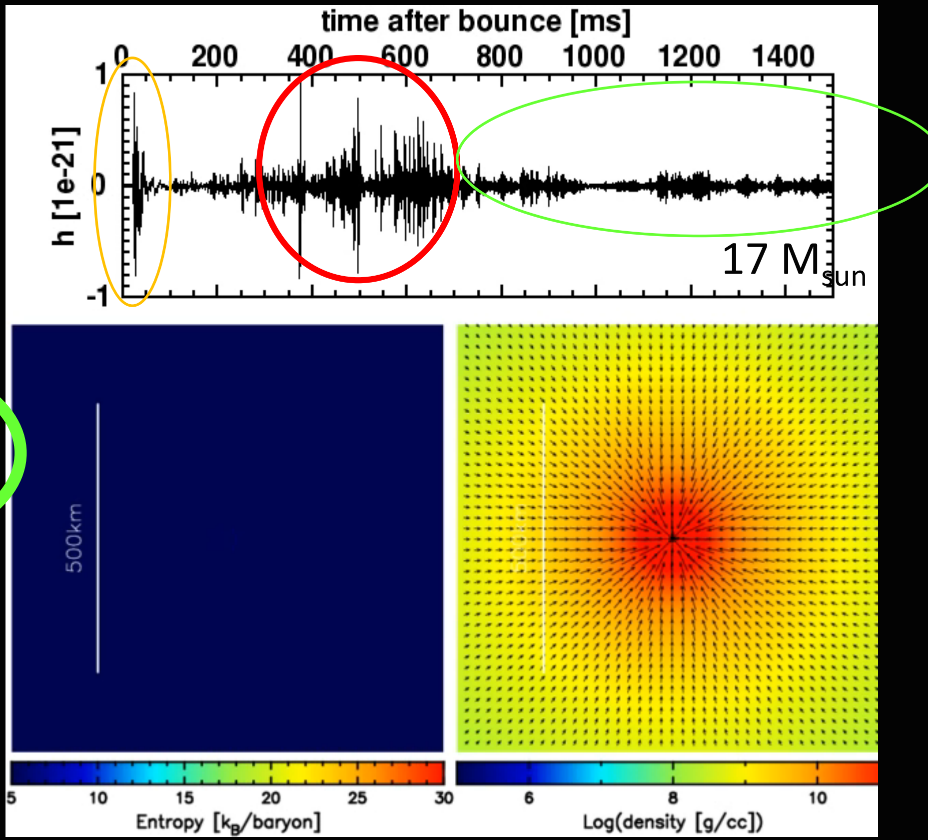
GW signatures from 2D neutrino-driven explosion (1/2)

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



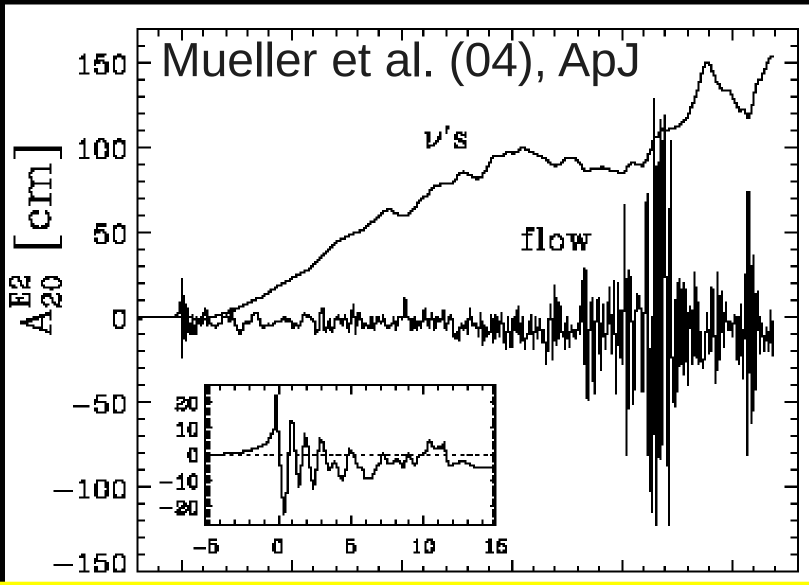
✓ Three generic phases in neutrino-driven models:

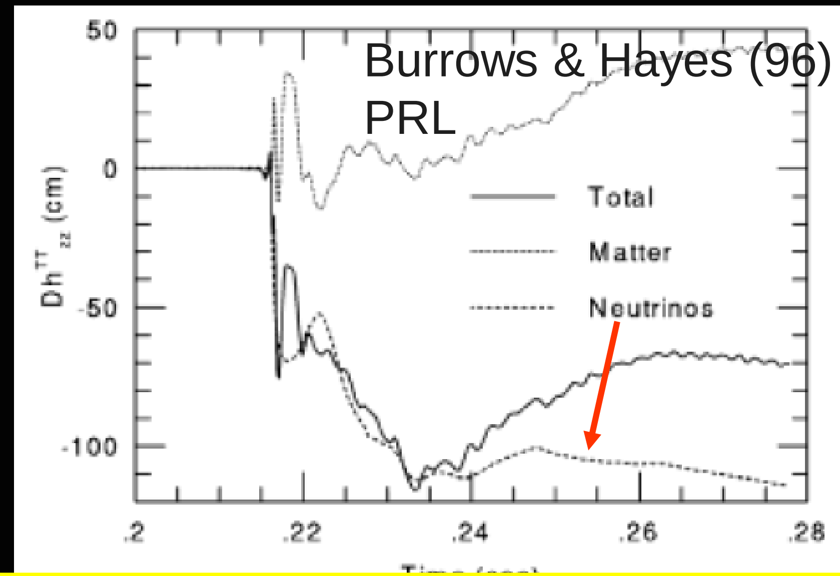
1. Prompt-convection phase : within ~50 ms post-bounce
2. Non-linear phase (Convection/SASI) : Downflows hit the PNS surface
3. Explosion phase : Long-lasting signal but terminates if BH forms

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

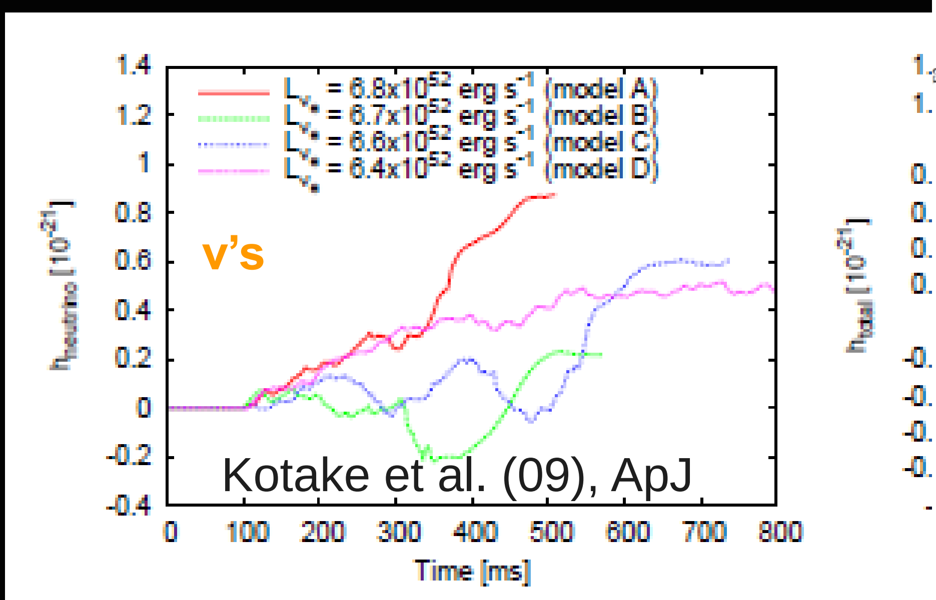
✓ Waveforms have no template character: stochastic explosion processes.

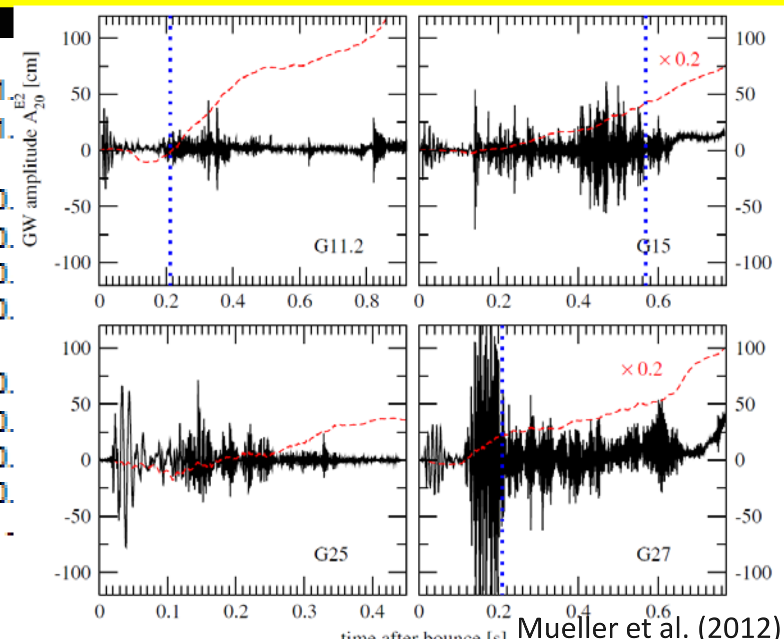
GW signatures from 2D neutrino-driven explosion (2/2)





✓ **GWs by anisotropic neutrino emission** ~ bigger than the matter contribution !





Mueller et al. (2012)

GWs from anisotropic neutrino emission

$$h^{\mu\nu}(t, \boldsymbol{x}) = 4 \int \frac{T^{\mu\nu}(t - |\boldsymbol{x} - \boldsymbol{x}'|, \boldsymbol{x}')}{|\boldsymbol{x} - \boldsymbol{x}'|} d^3x'$$

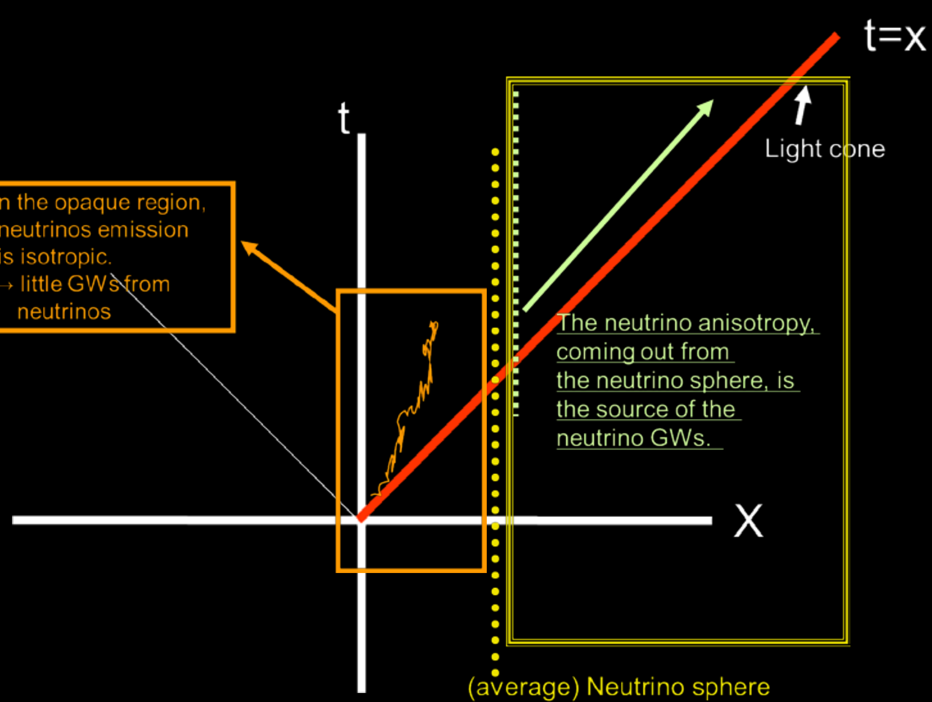
$$T^{\mu\nu} = T^{\mu\nu}_{\mathrm{matter}} + T^{\mu\nu}_{\mathrm{neutrino}}$$

Epstein(78), Mueller & Janka (97)

$$h_\nu(t) = \frac{2G}{c^4 R} \int_0^t dt L_\nu(t') \alpha(t')$$

Neutrino anisotropy: degree of anisotropic neutrino emission (zero if spherical)

In 2D, $\alpha(t) = \frac{1}{L_\nu(t)} \int_{4\pi} d\Omega' \Phi(\theta') \frac{dl_\nu(\Omega', t')}{d\Omega'}$



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t=x

n the c
neutrin
is isotr
→ little
neut

Typical amplitude :

$$|h_\nu| \sim 10^{-21}\left(\frac{\alpha}{0.01}\right)\left(\frac{L_\nu}{10^{52}\mathrm{erg/s}}\right)\left(\frac{\delta t}{1\ \mathrm{sec}}\right)\left(\frac{R}{10\ \mathrm{kpc}}\right)^{-1}$$

$$|h_\nu| \sim h_{\mathrm{bounce}} \sim 10^{-21} \quad (10\mathrm{kpc})$$

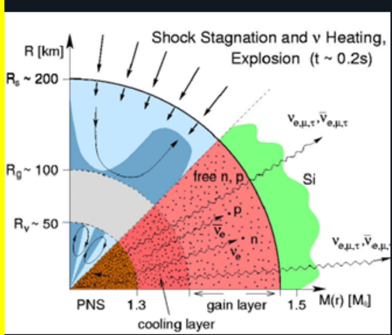
~ as large as the matter GW

Typical frequency :

$$t_\nu \sim \frac{1}{\sqrt{G\rho}} \geq 10\ \mathrm{msec}\left(\frac{\rho_{\mathrm{trap}}}{10^{11}\ \mathrm{gcm}^{-3}}\right)^{-1/2}$$

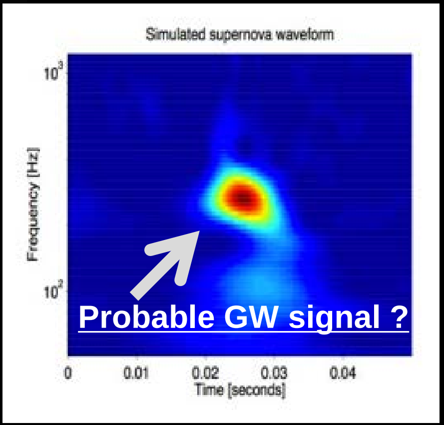
, longer than the matter GW signal because the dynamical time scale is determined at the position of neutrino sphere, where forms further out from the center.

$$\nu_\nu \sim \frac{1}{t_\nu} \leq 100\ \mathrm{Hz}$$



Frequencies of GWs from neutrinos are typically lower than ~ 100 Hz.

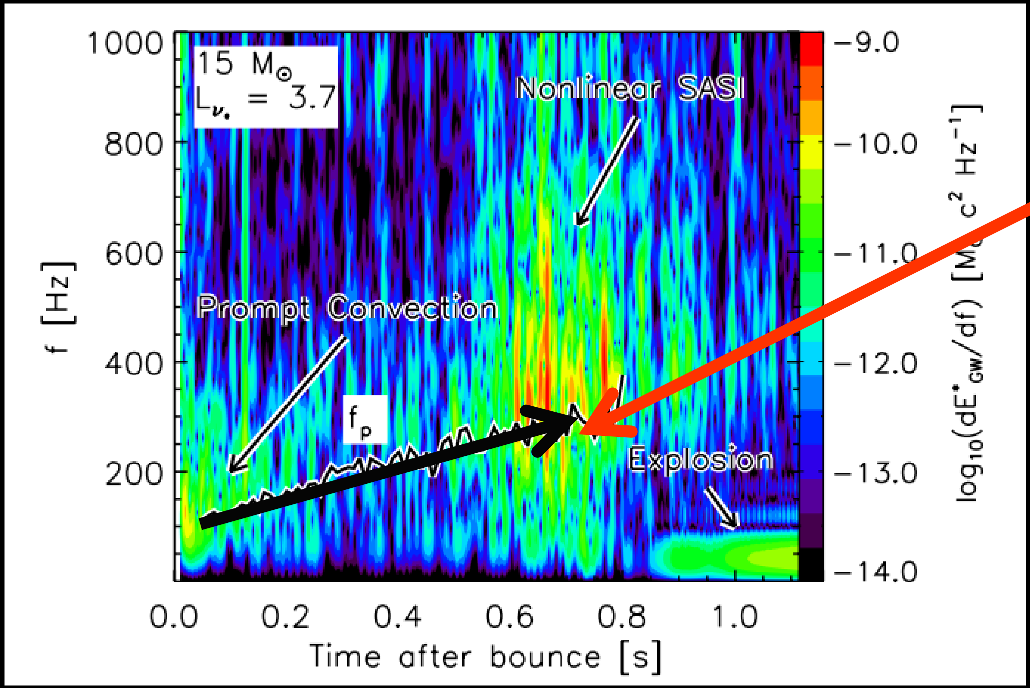
How to detect GWs with no-template features…



✓ **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 ↗

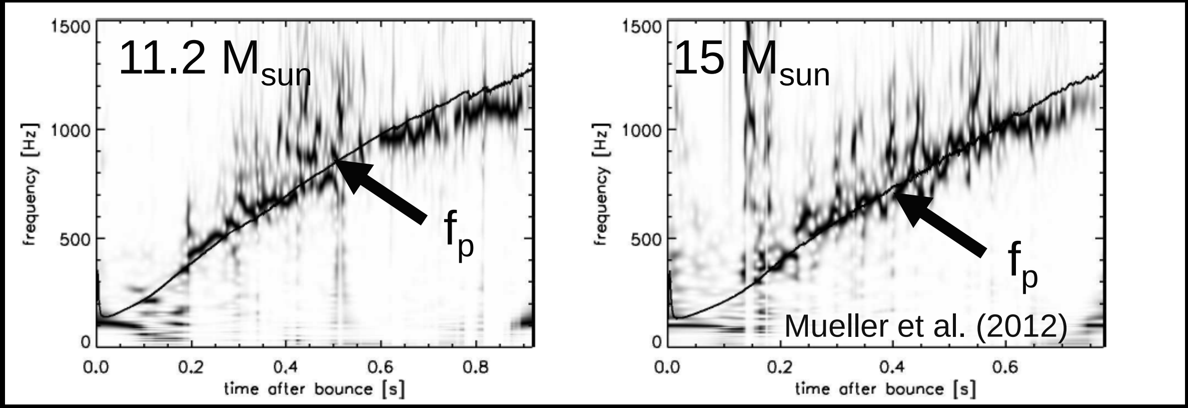
(see complete derivation in B. Mueller et al. ('13), ApJ)

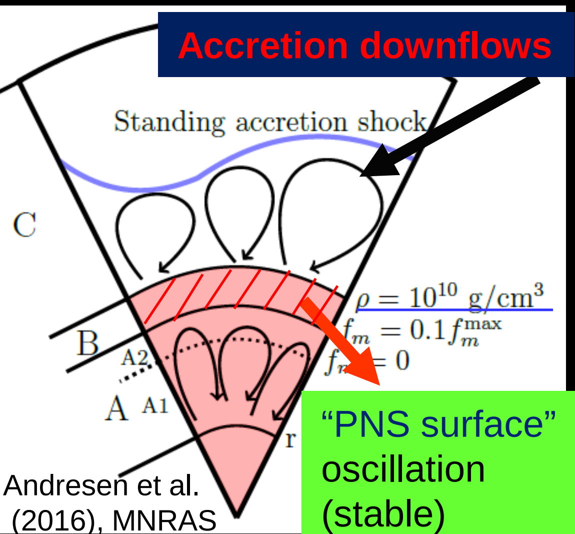
✓ **(With no template character…) Three generic phases are in the spectrogram !**
✓ Secular increase of typical GW frequency (f_p) **reflects the PNS evolution**.
✓ On top of f_p , the high frequency component comes from strong downflows to PNS.
✓ **These qualitative features : Common to more recent 2D and 3D models** !

"PNS" asteroseismology

: How to derive f_p ?

Knock a "watermelon" the best time to eat





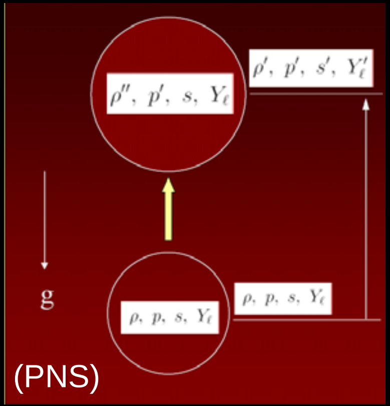
"PNS surface" oscillation (stable)

✓Buoyancy frequency (Brunt-Vaisälä (BV) frequency, or **g-mode**)

$$N^2 = \frac{1}{\rho}\frac{\partial \Phi}{\partial r}\left[\frac{1}{c_s^2}\frac{\partial P}{\partial r} - \frac{\partial \rho}{\partial r}\right]$$

[check the unit !] $\Phi \sim \frac{\mathrm{cm}^2}{\mathrm{s}^2}, N^2 \sim \frac{\Phi}{r^2} \sim \frac{1}{s^2}, \boldsymbol{f_p = \frac{N}{2\pi}}$ **[Hz]**

(characteristic frequency)



✓Relativistic Extension of f_p

$$N^2 = \frac{\partial \alpha c^2}{\partial r}\frac{\alpha}{\rho h \phi^4}\left(\frac{1}{c_s^2}\frac{\partial P}{\partial r} - \frac{\partial \rho(1+\epsilon/c^2)}{\partial r}\right)$$

$$h = 1 + \epsilon/c^2 + P/(\rho c^2)$$

$P = \rho k_B T / m_n$ (non-relativistic baryon)

$$\frac{d\rho}{dr} = \frac{m_n}{k_B T}\frac{dP}{dr}$$

$$c_s^2 = \Gamma k_B T / m_u$$

PNS in hydrostatic equilibrium

: "1PN" ToV equation

$$\frac{dP}{dr} = -\frac{\rho G M}{R^2 \alpha}$$

$$\alpha = 1 - \frac{GM}{R}, \phi = \alpha^{-2}$$

3+1 decomposition

$$g_{\mu\nu} = \left(\begin{array}{c|ccc} -\alpha^2 + \beta_i\beta^i & \beta_1 & \beta_2 & \beta_3 \\ \hline \beta_1 & & & \\ \beta_2 & & \gamma_{ij} & \\ \beta_3 & & & \end{array}\right)$$

$$\gamma_{ij} = \phi^4 \hat{\gamma}_{ij},$$

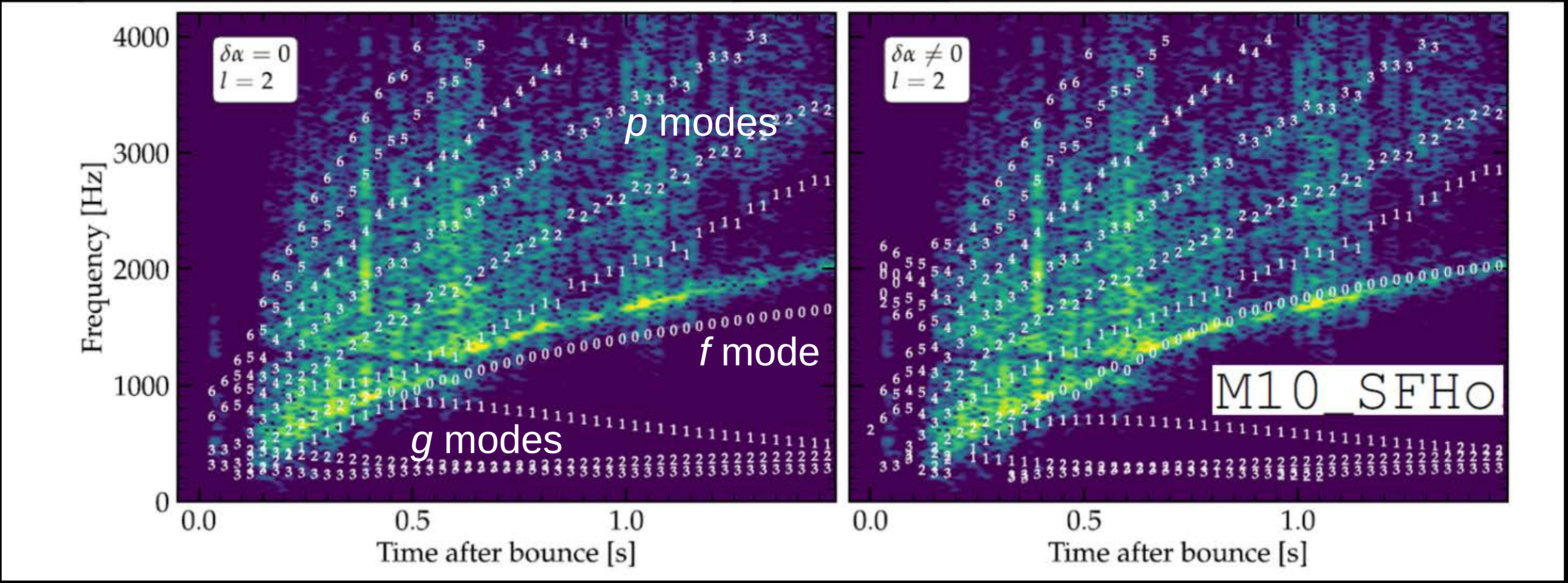
$$f_p = \frac{N}{2\pi} = \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}\left(1 - \frac{GM}{Rc^2}\right)^{3/2}$$

Gravitational redshift

“PNS” asteroseismology (2/2)

✓ GR (1PN) correction important !

Morozova et al. (2018), MNRAS



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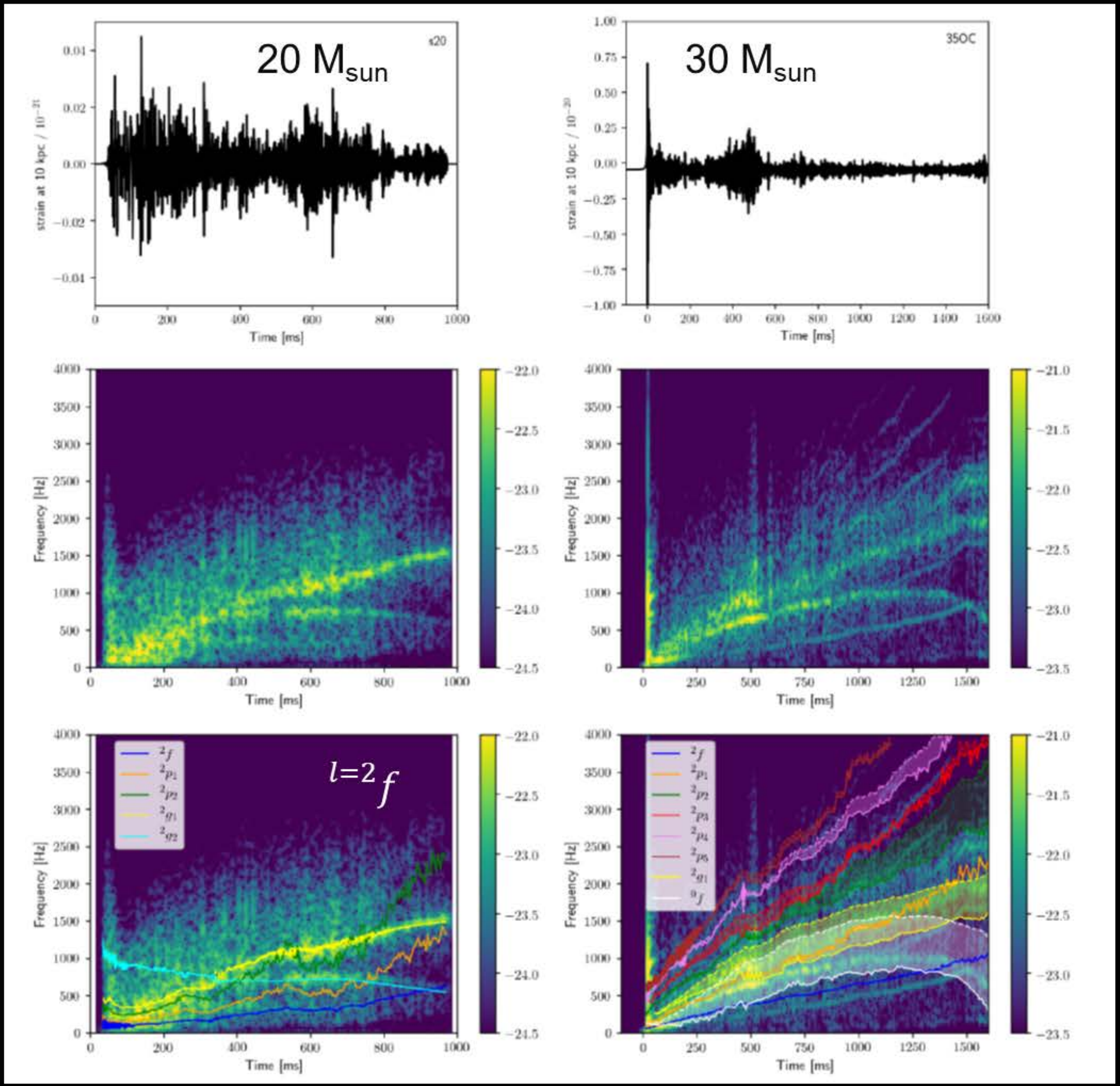
Morozova et al. (2018), MNRAS

Torres-Forné et al. (2017, 2018), MNRAS



✓ Important:
Toward
“template-based”
GW search !

✓ Just started !
(e.g., Sotani et al. (2017). PRD)
Detectability :
yet to be understood.

How to detect GWs with no-template features…

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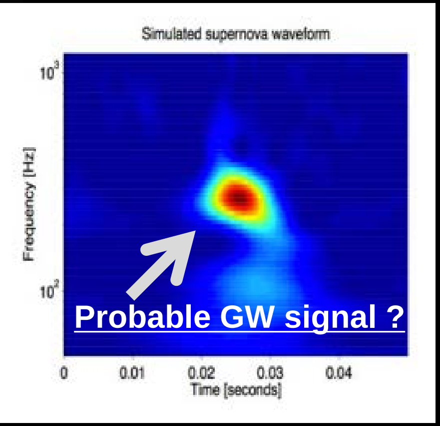

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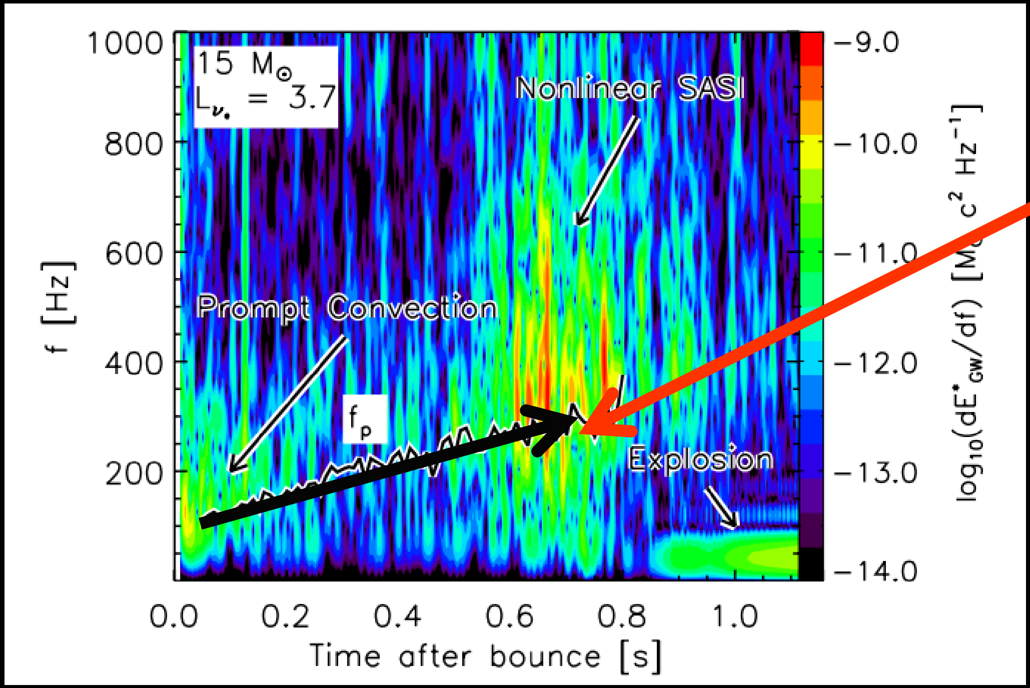

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Recent GW predictions from 3D CCSN models with neutrino transport

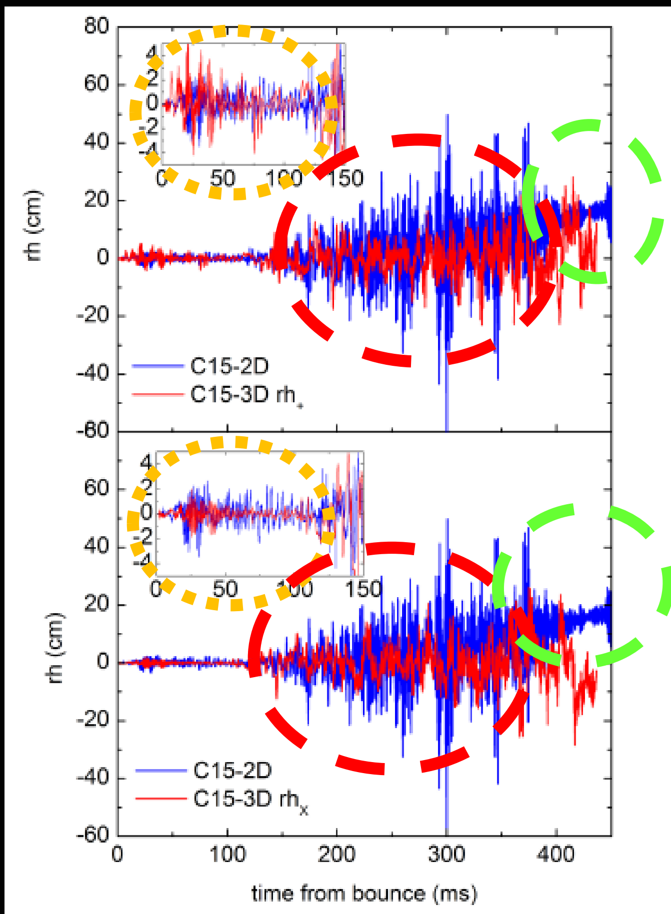
▪ **Yakunin, Mezzacappa et al. (2017)**

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

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

+ mode

× mode

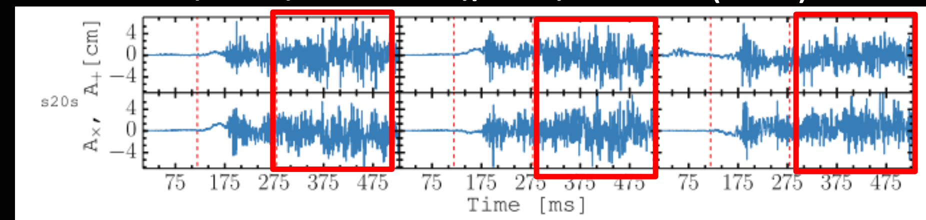


Based on 15 M_{sun} model from Lentz et al. (2015), ApJL

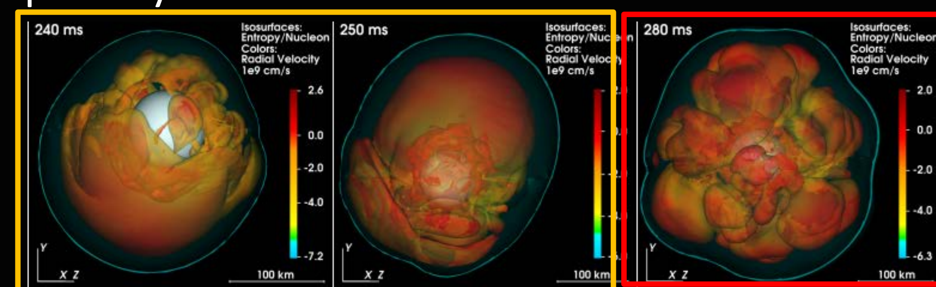
▪ **Andresen, B & E Müller and Janka (2017) MNRAS**

✓ 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 events !

	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

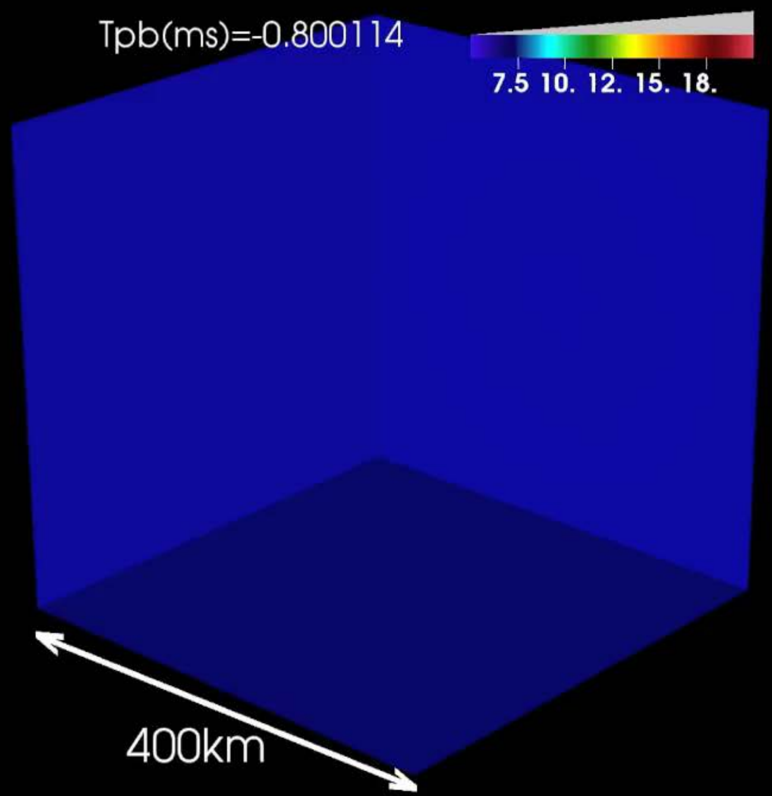
GW signautures from 3D-GR models with strong SASI vs. weak SASI activity

(from **Kuroda, KK, & Takiwaki ApJL (2016), see also Andresen, B, E Müller and Janka (2017))**

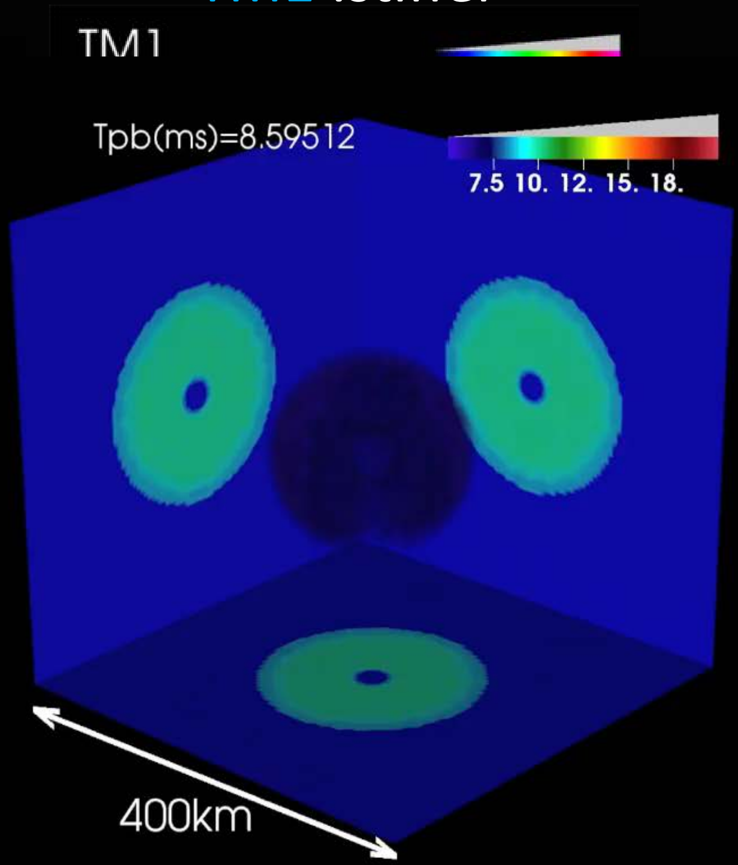
✓ Two EOSs → **SFHx** (Steiner et al. (2013), fits well with experiment/NS radius,Steiner+(2011)), **HS(TM1)** (Shen et al. (1998)).

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

SFHx :softer



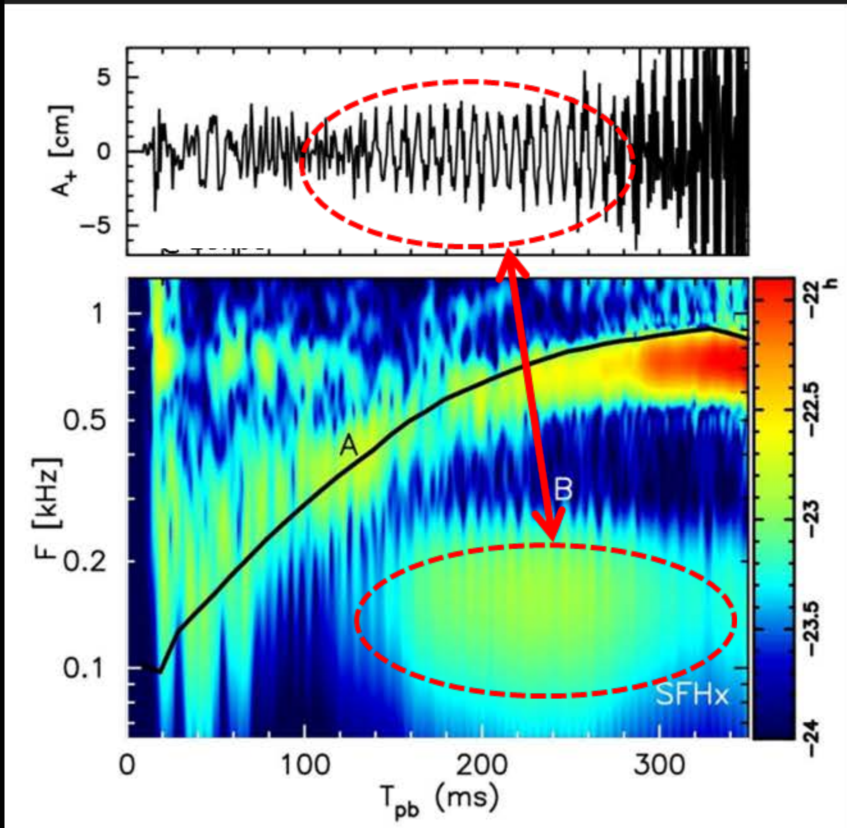
TM1 :stiffer



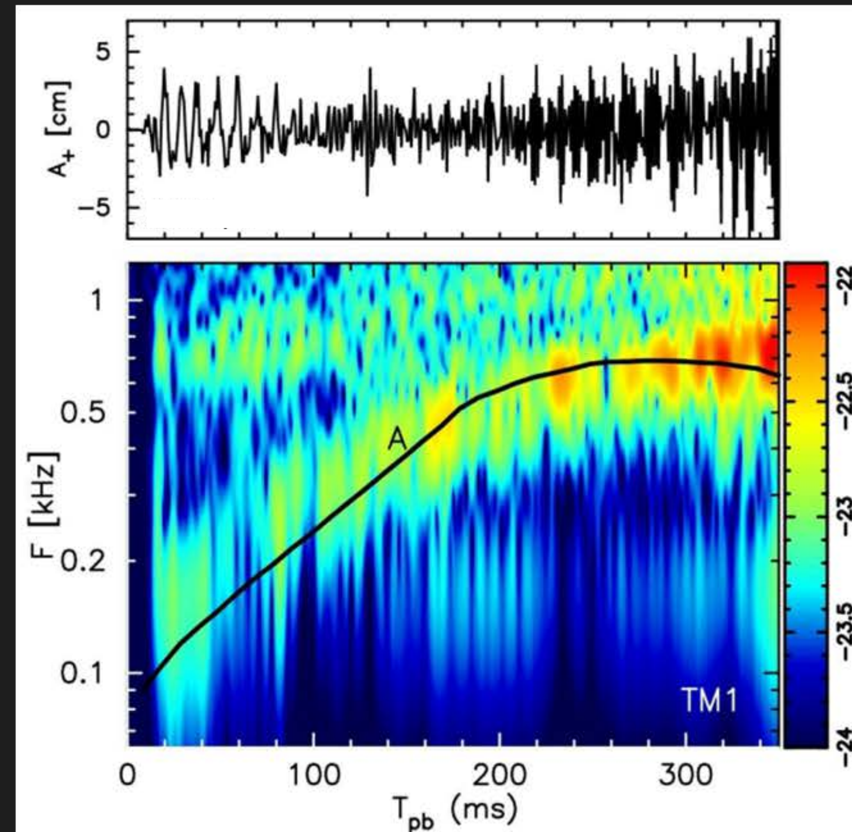
✓ **SASI activity higher for softer EOS** (due to high growth rate, e.g., Foglizzo et al. ('06)).

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

SFHx :softer

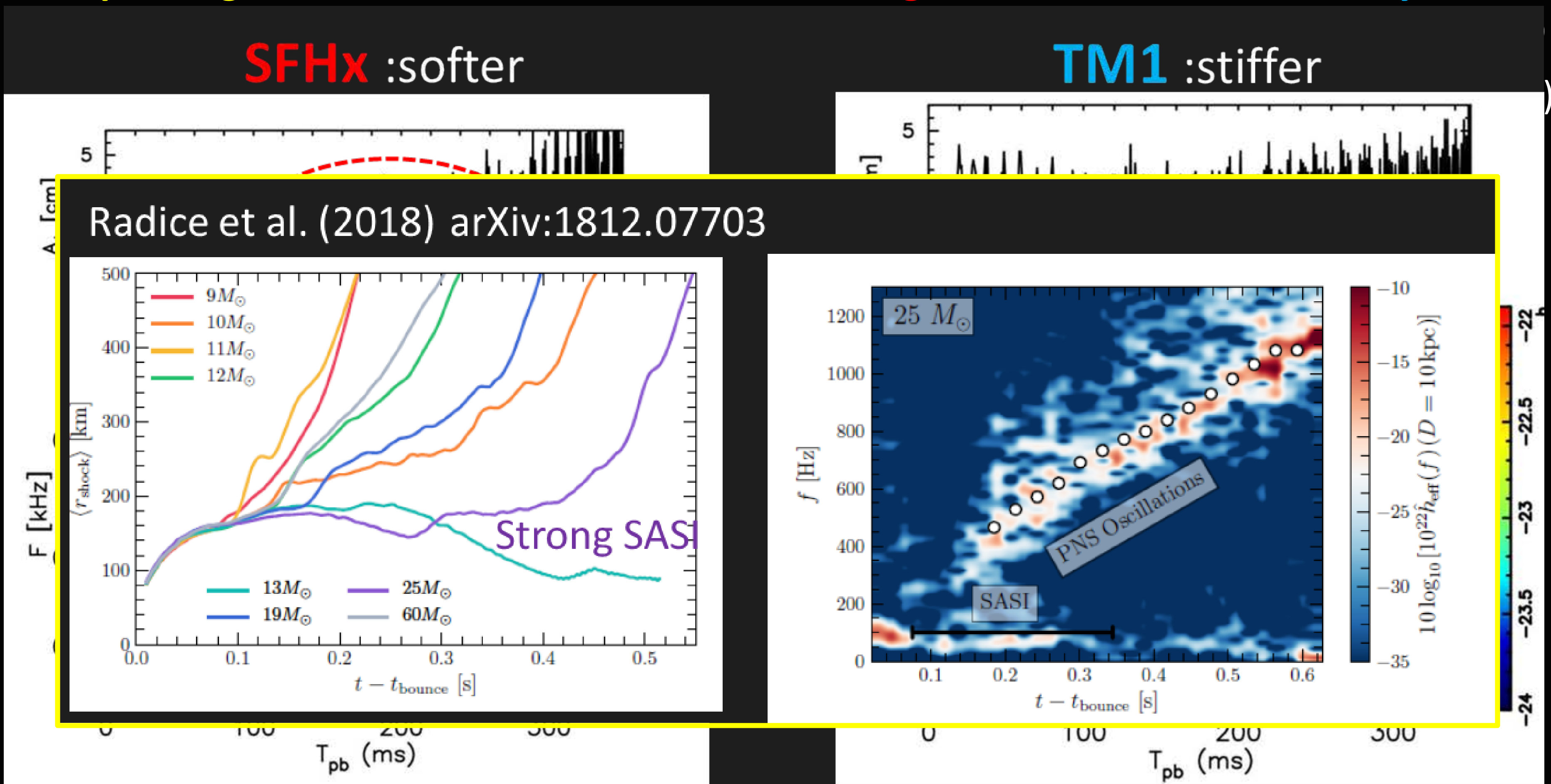


TM1 :stiffer



- ✓ **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



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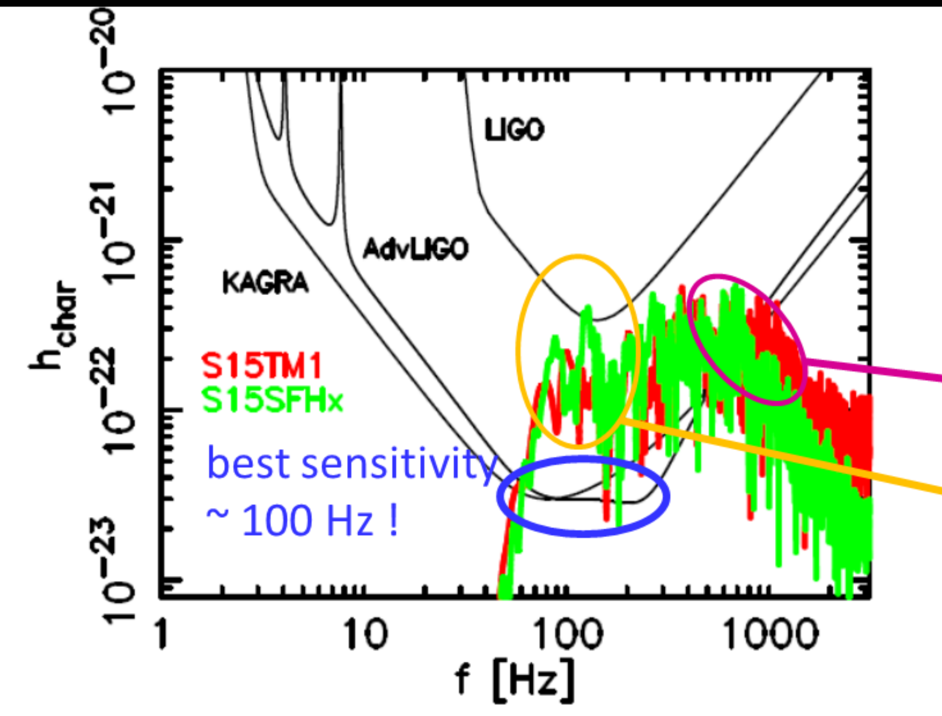
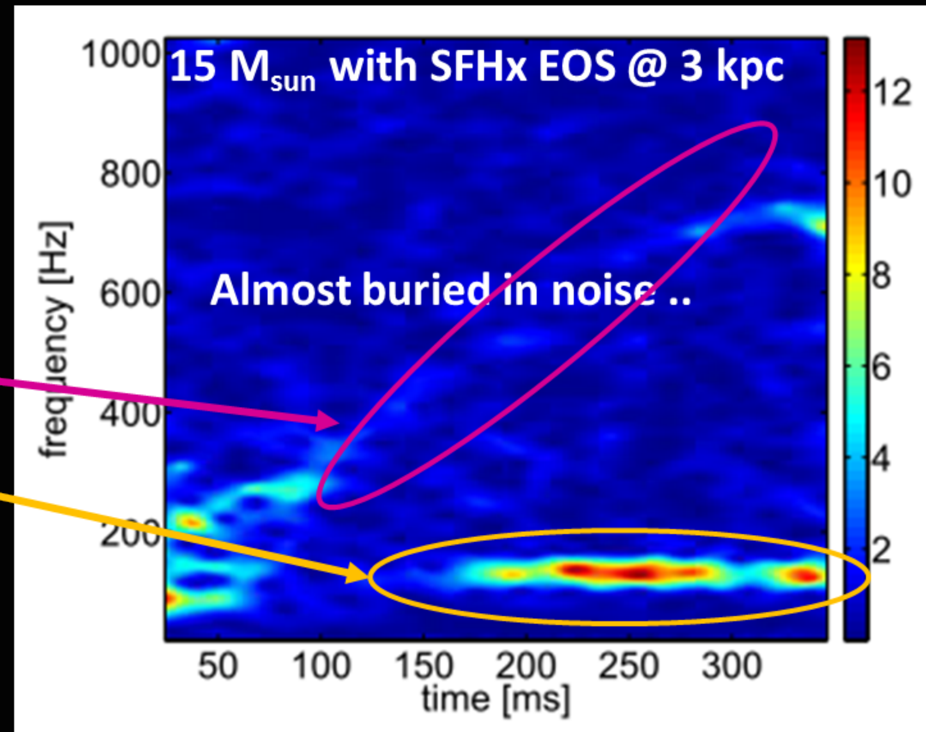
GW Spectrograms from 3D-GR models with strong SASI vs. weak SASI activity

SFHx :softer   **TM1** :stiffer

Sensitivity curves and model predictions



The reconstructed GW spectrogram



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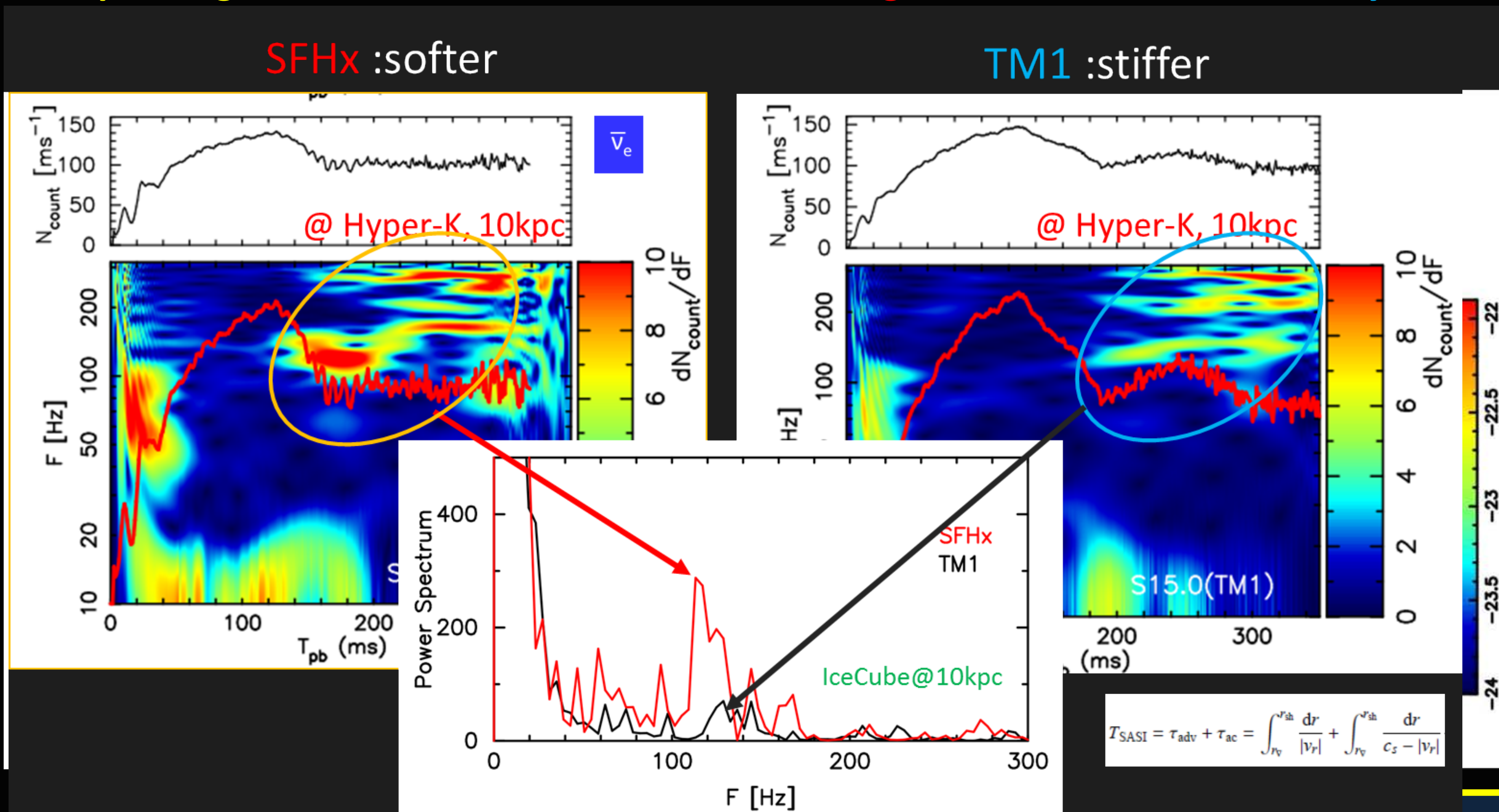

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"New" GW messenger is Circular Polarization of GW :Non-axisymmetric instabilities (incl. low T/|W|, spiral SASI)

Stokes Parameters:

$$\begin{pmatrix} \langle h_R(f,\hat{n}) h_R(f',\hat{n}')^* \rangle & \langle h_L(f,\hat{n}) h_R(f',\hat{n}')^* \rangle \\ \langle h_R(f,\hat{n}) h_L(f',\hat{n}')^* \rangle & \langle h_L(f,\hat{n}) h_L(f',\hat{n}')^* \rangle \end{pmatrix} = \frac{1}{4\pi} \delta_D^2(\hat{n}-\hat{n}') \delta_D(f-f') \times \begin{pmatrix} I(f,\hat{n}) + V(f,\hat{n}) & Q(f,\hat{n}) - iU(f,\hat{n}) \\ Q(f,\hat{n}) + iU(f,\hat{n}) & I(f,\hat{n}) - V(f,\hat{n}) \end{pmatrix}$$

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

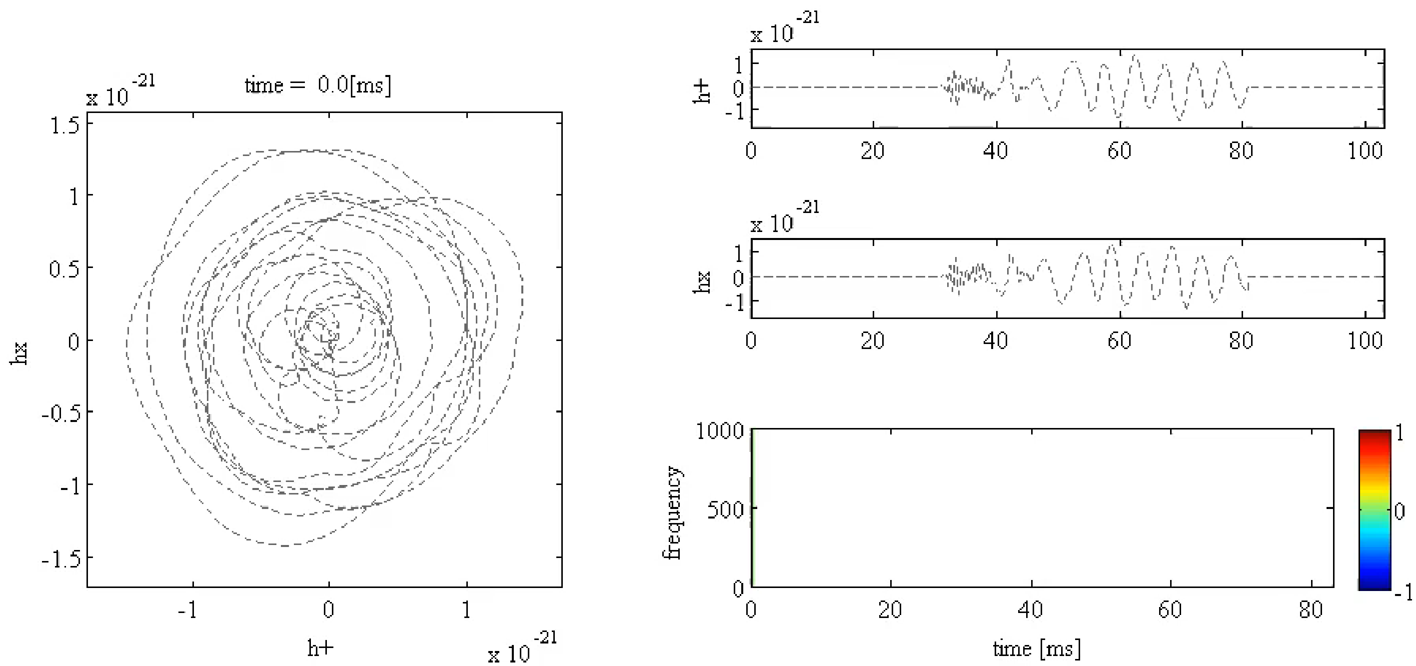
V parameter = Asymmetry of right and left modes

$h_R := (h_+ - ih_\times)/\sqrt{2}$ $h_L := (h_+ + ih_\times)/\sqrt{2}$

(See definitions in Seto and Taruya (2007), PRL)

Rapidly rotating 15 M_{sun} (early postbounce phase) from Kuroda, Takiwaki, KK (2014) PRD)

@10kpc



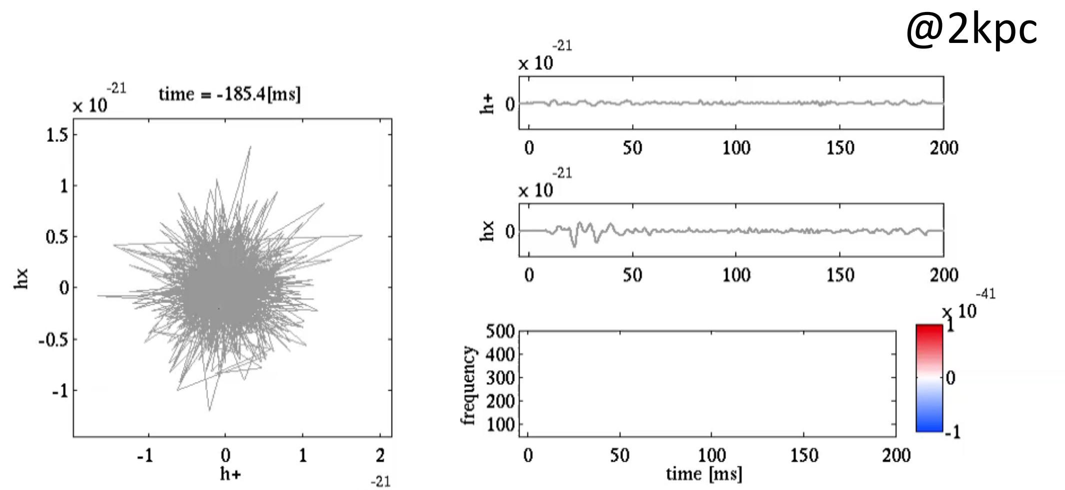
CP (if seen from the spin axis) :evidence of "rapid rotation".

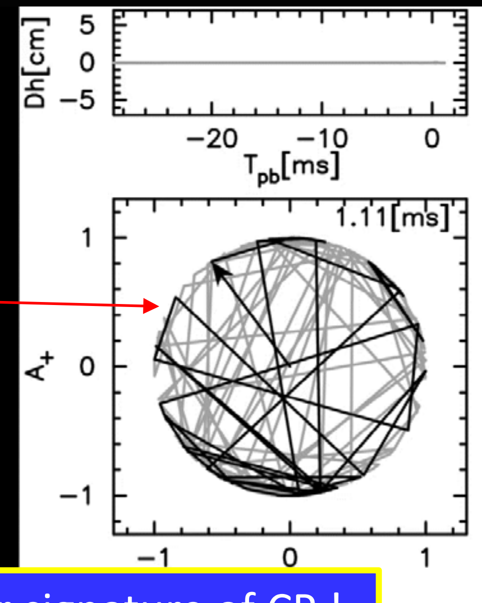
What about Circular GW polarization in “Non-rotating” progenitors ?

Hayama, KK et al. (2018)

Non-rotating 11.2 M_{sun} star ; Convection dominant

@2kpc



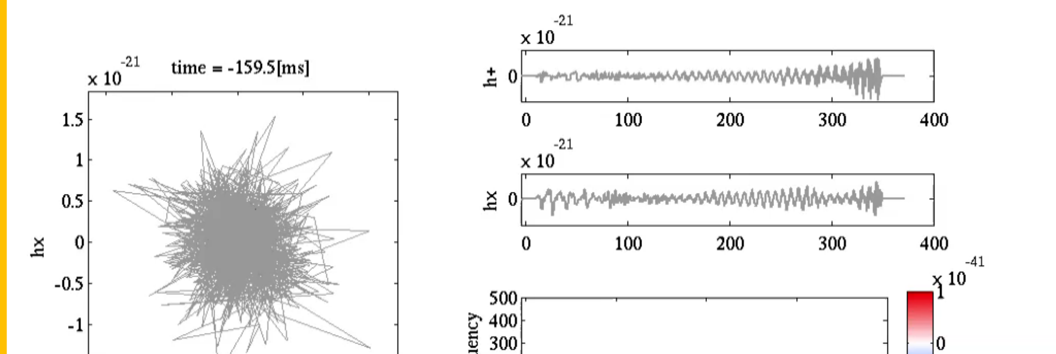


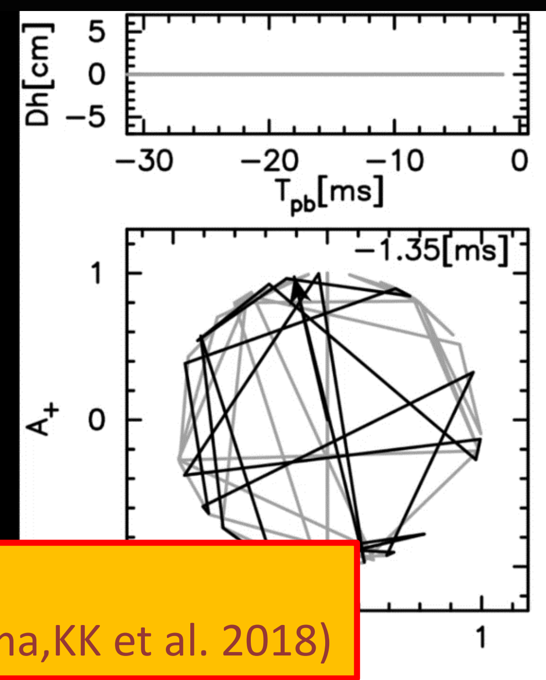
Normalized polarization (e.g., $\frac{x}{\sqrt{x^2+y^2}}$, $x = h_+, h_\times$)

If the core is convection-dominant (likely for low ξ stars), no clear signature of CP !

Non-rotating 15 M_{sun} star (SFHx EOS); SASI dominant

@5kpc

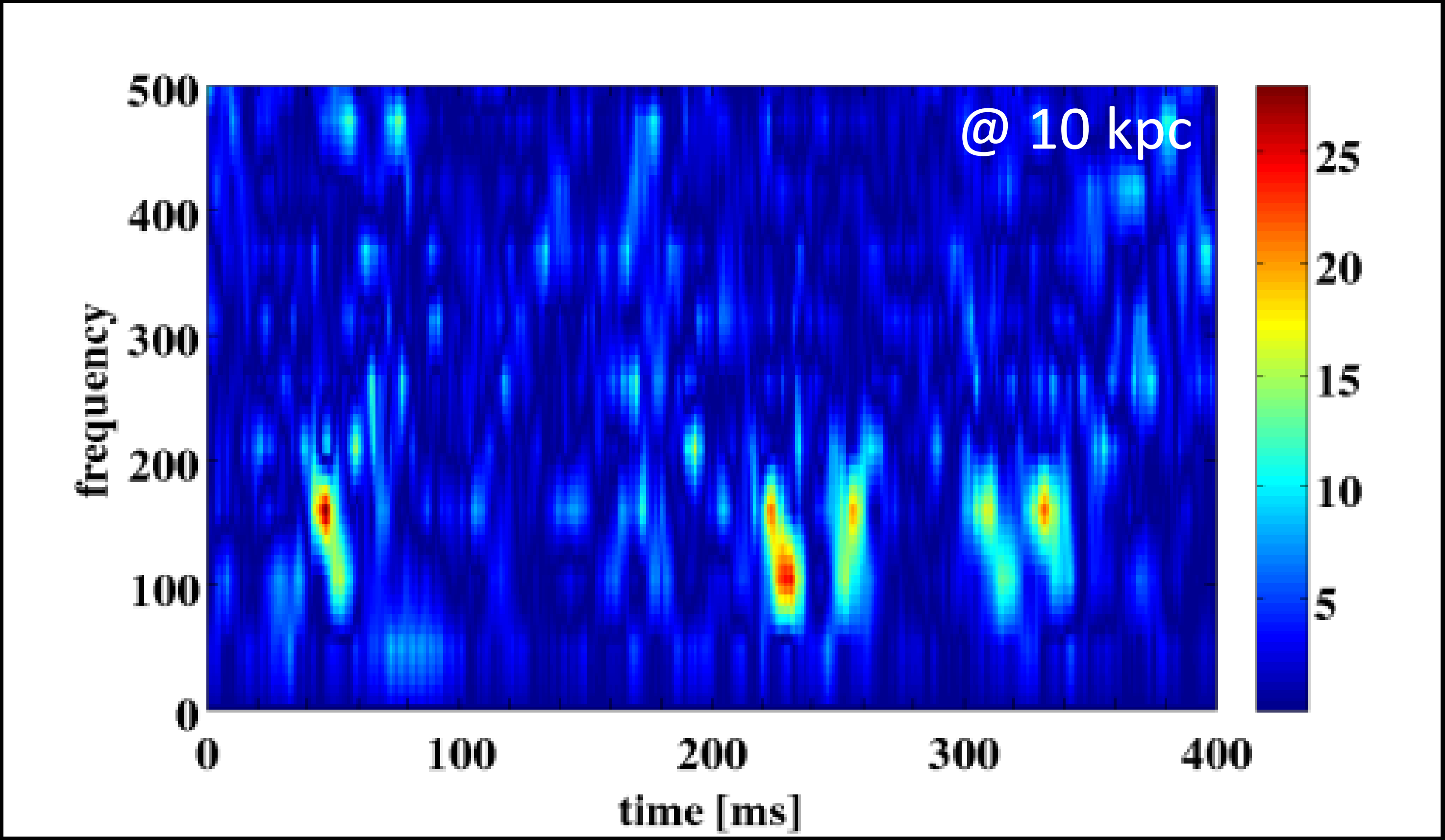




If the SASI dominant (likely for high ξ stars), clear signature of CP !

⇒ indication of SASI motions non-spherical mass accretion (Hayama,KK et al. 2018)

SNR of Circular Polarization of GW relative to background



- ✓ The detection of GW amplitude is within several kpc using LIGO (e.g.,Andresen et al. (2017))
- ✓ The detection of CP could extend (far) beyond the detection horizon of GW waveform !
- ✓ The CP would provide new window to detect GW signals !

(Hayama, Takiwaki, KK, Kuroda, MNRAS Letters, (2018))

The Origin of the Nobel-Prize-awarded BHs (7 ~40 M_{sun}) ?

The Nobel Prize in Physics 2017
Rainer Weiss, Barry C. Barish, Kip S. Thorne

Share this: 1.3K

The Nobel Prize in Physics 2017

Rainer Weiss
Prize share: 1/2

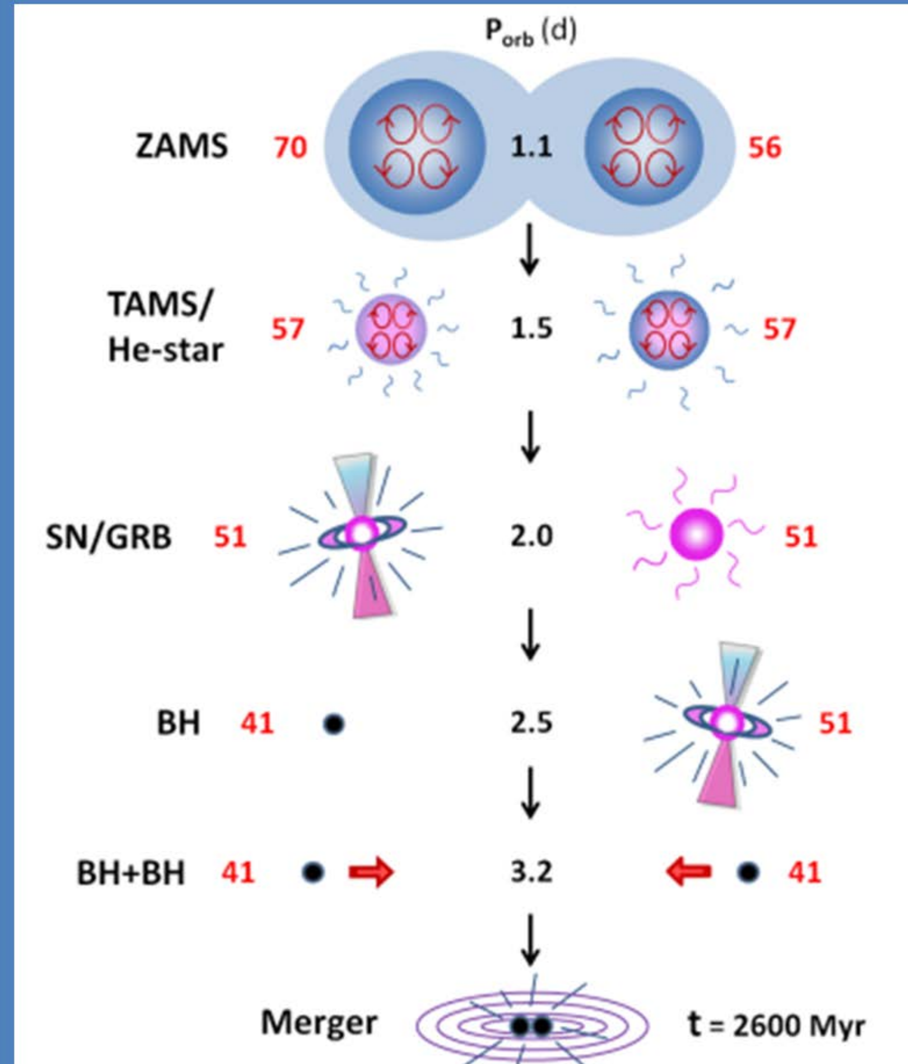
Barry C. Barish
Prize share: 1/4

Kip S. Thorne
Prize share: 1/4

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

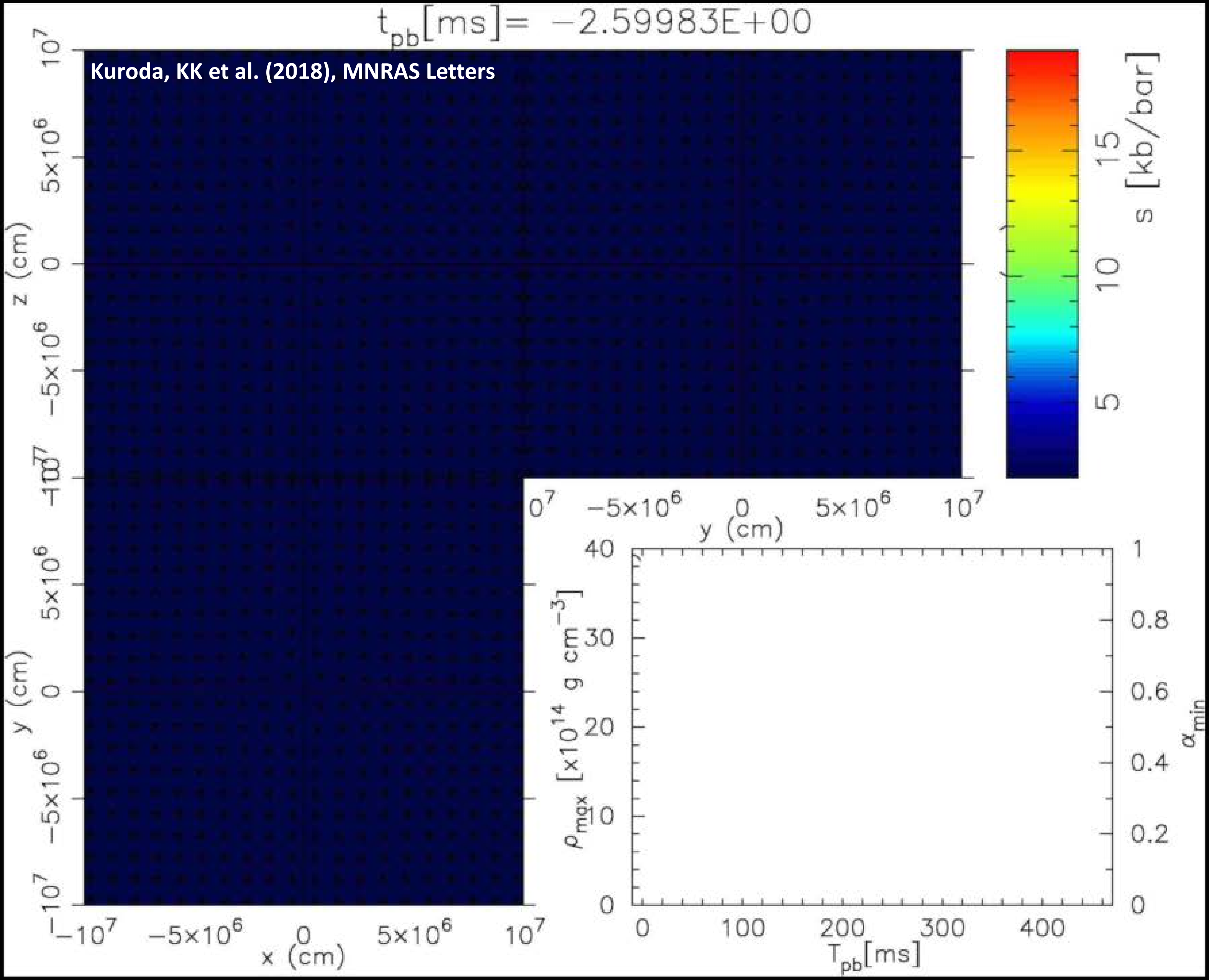
✓ **Low metallicity** environment needed for large stellar mass BH formation.
(e.g., Kinugawa et al .(2014,2016))

✓ One of them.. "Isolated binaries"



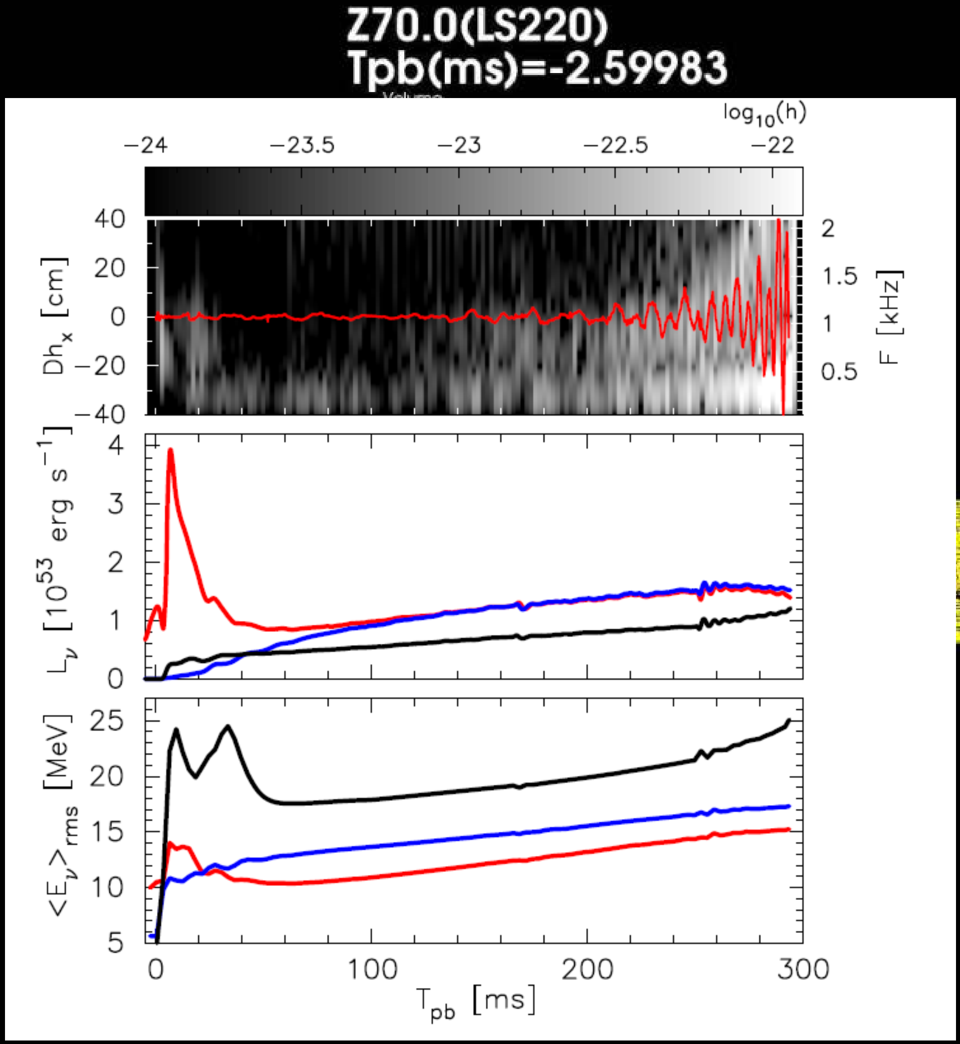
Marchant, Langer, Podsiadlowski et al. (2006)

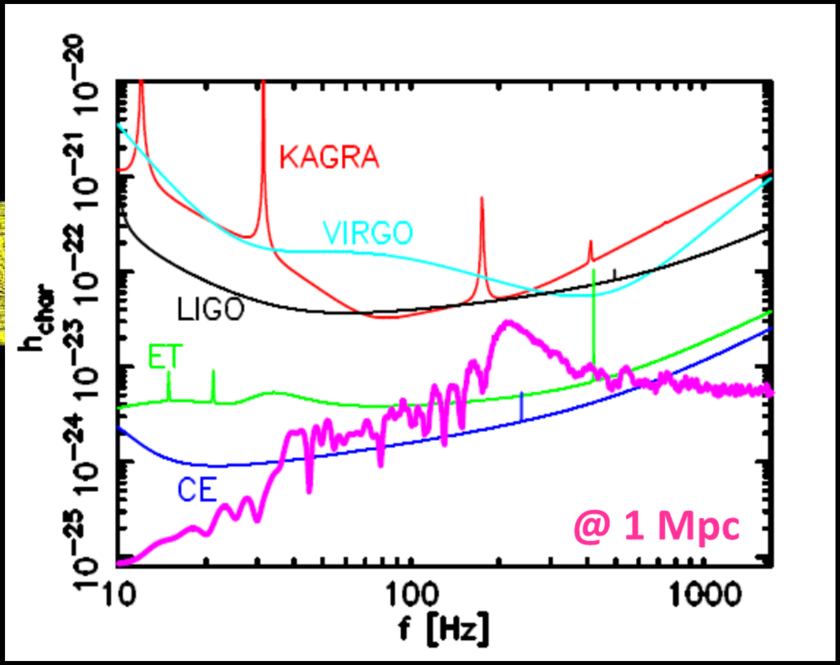
✓3D-GR results of 70 M_{sun} (M_{CO} ~ 28.5 M_{sun}) (progenitor from Takahashi et al. (2014))



✓3D-GR results of 70 M_{sun} (M_{CO} ~ 28.5 M_{sun})

Kuroda, KK et al. (2018), MNRAS Letters

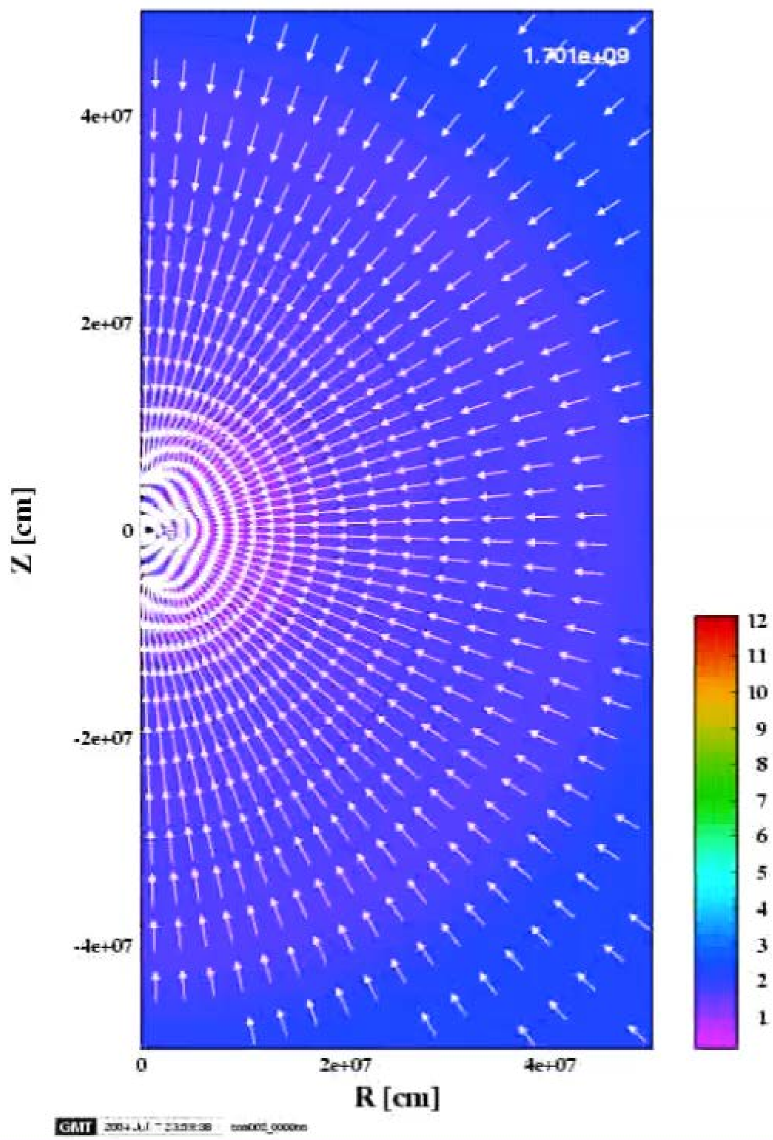




- ✓ **The first BH forming simulation** in 3D !
- ✓ Before the BH formation, **monotonic increase** of neutrino luminosity and rms energy. (**consistent with** 1D, e.g., Sumiyoshi+ (2006), Fischer+ (2009), Huedepohl+(2016))
- ✓ Strong GW emission is visible to 1 Mpc, **but not** O(100) Mpc…

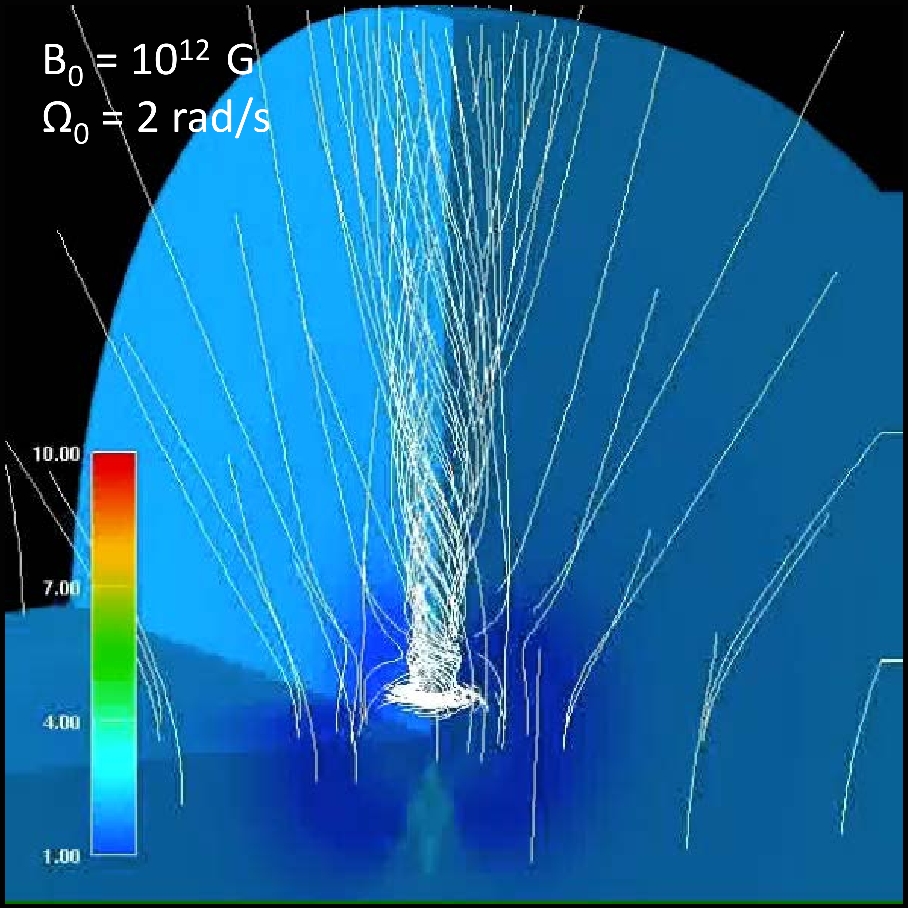
Switching gears to MHD mechanism (rapid rotation required !!) My research life….

Kotake, Yamada, Sato (2003) ApJ



Magnetohydodynamics Simulations

Kotake et al. (2004), (2006)

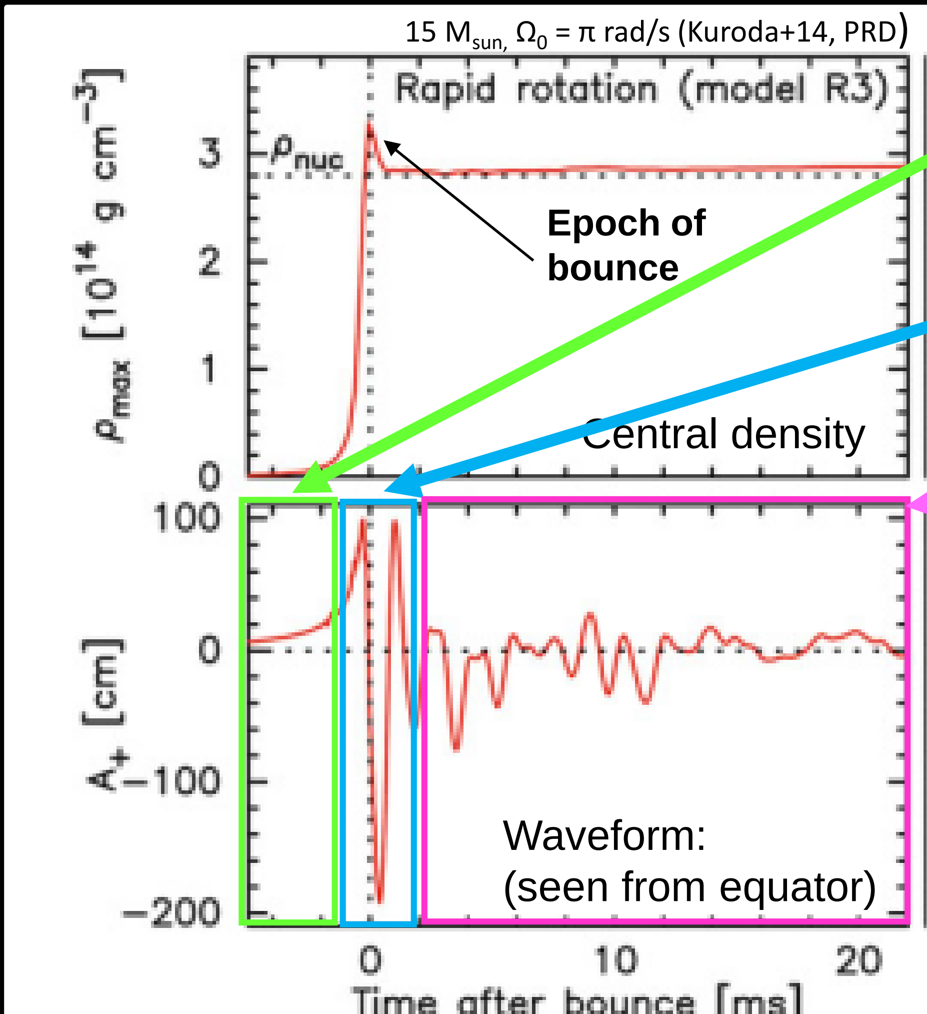


See recent developments in Moesta et al.(2015) Masada et al. (2015), Ramirez et al. (2016), Sawai et al. (2014)

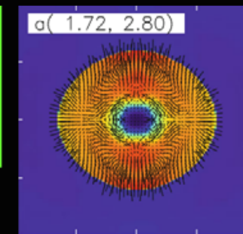
Switching gears to MHD mechanism (rapid rotation required !!)

GW from Rapidly Rotating Core-Collapse and Bounce

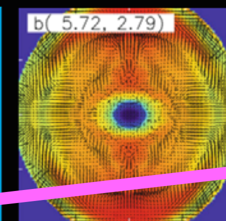
(Dimmelmeier et al. (07, PRL), Scheidegger et al. (10, A&A) Ott et al. (12, ApJ), Abdikamalov+(14, PRD), Kuroda+(14,PRD))



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



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

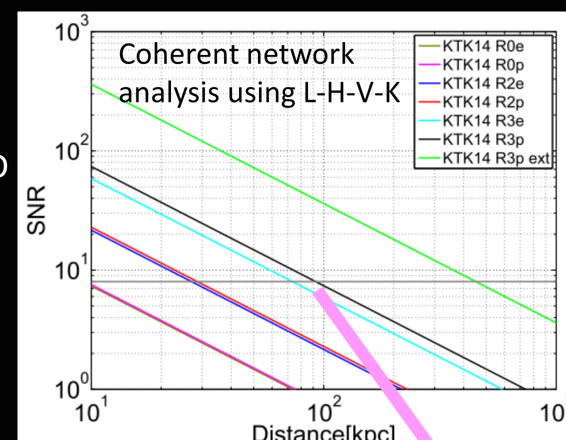


✓ Ring-down phase: settles down to stationary state, with amplitudes decreasing with time.

✓ "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 "one" big spike at bounce followed by smaller peaks: "type I" signal

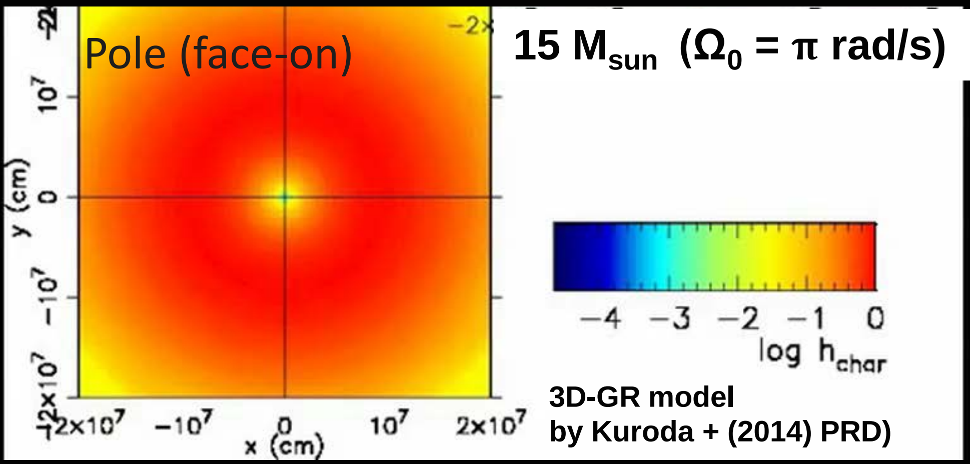
✓Matched filtering (or PCA) likely applicable.✓Horizon distance can reach beyond LMC (50kpc)

GWs from (Rotation-induced) Non-Axisymmetric Instabilities

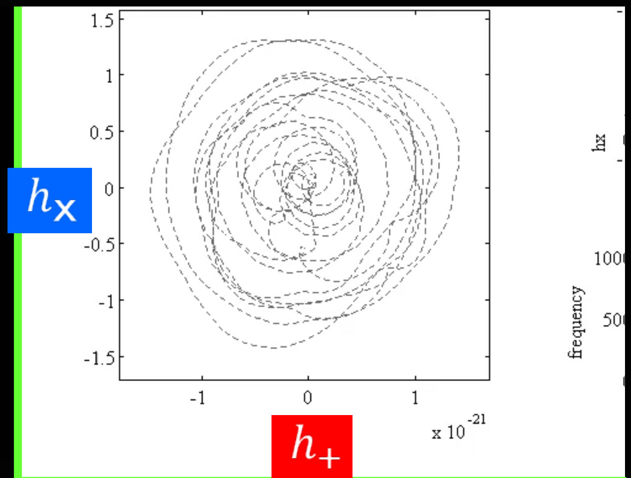
✓ **Low T/|W| instability** is most likely to develop (Ott + (05, ApJL), Scheidegger + (10, A&A))

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

Circular polarization of h_+ and $h_\times$



Strong emission from one-armed spiral wave



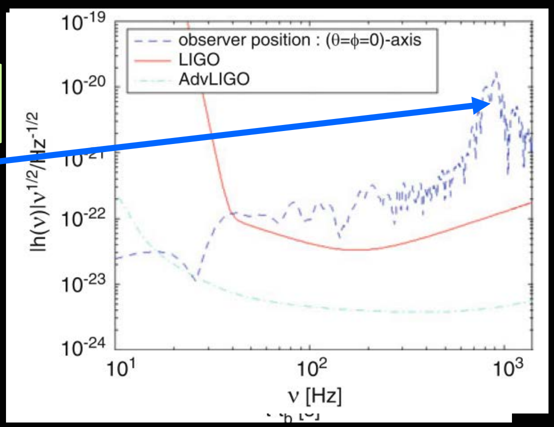
Hayama et al. (2016), PRL
(see also Klimenko et al. (2015) PRD)

✓ **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

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



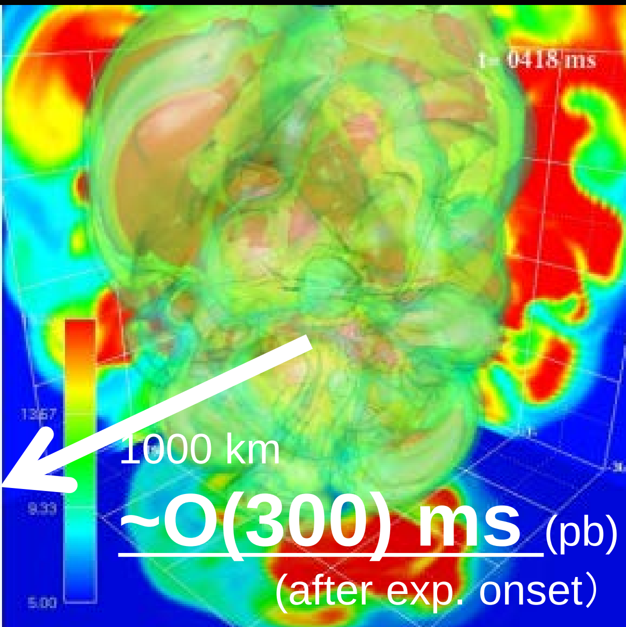
✓ **Circular polarization can be evidence of "rapid rotation".**
✓ **"Quasi-periodicity" enhances the chance of detection.**

Summary

	Neutrino mechanism	MHD mechanism
Progenitor	Non- or slowing- rotating star ($\Omega_0 < \sim 0.1$ rad/s)	Rapidly rotating star with strong B fields ($\Omega_0 > \sim\pi$ rad/s, $B_0 > \sim 10^{11}$ 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, LIGO/Virgo/KAGRA** ✓ **If detected, critical information about SN engine (convection-dominant vs. SASI dominant) can be obtained.** ✓ **Detection of circular polarization: important probe of SASI.**	✓ **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" enhances chance of detection.** ✓ **Detection of circular polarization: important probe of core rotation.**

Next 10 years: Where are we and are we going ?

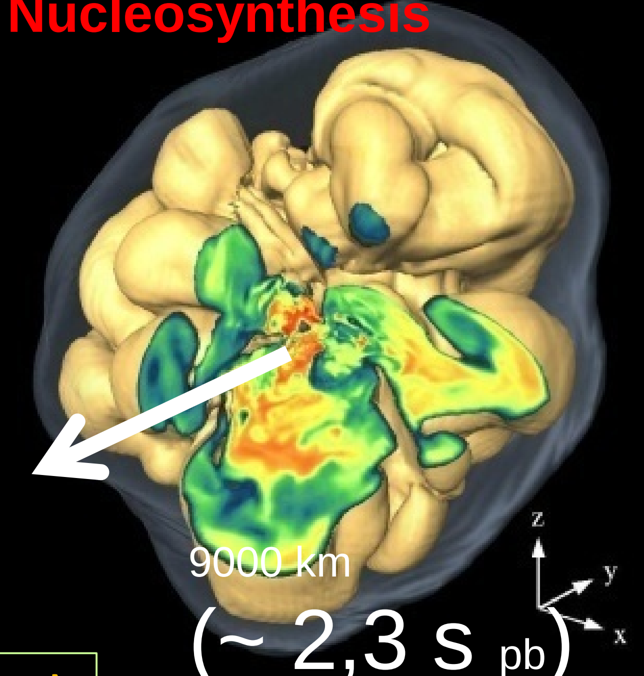
“A” self-consistent 3D model



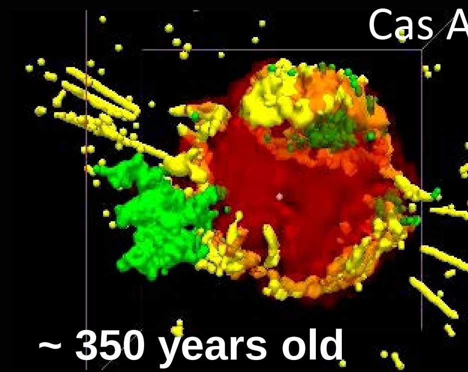
Melson+15, Takiwaki+16, Ott+18

Gray-transport simulation

Nucleosynthesis

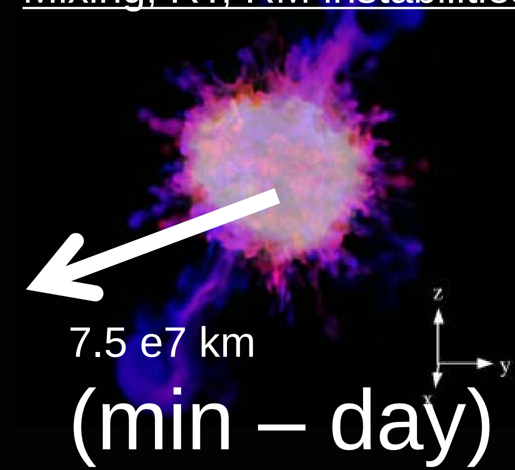


Wongwathanarat et al. (2015)



DeLaney et al. (2010)

Hydrodynamic model:
Mixing, RT, RM instabilities



Wongwathanarat et al. (2016)

For progenitors (11.2,15,20,27 M_{sun}), the stalled shock revived !
(5D/4D with approximate transport)

To-do-1: Long-term evolution in self-consistent 3D (GR) models
⇒ confront CCSN theory with observation ⇒ Pragmatism

To-do-2 : Full GR and Boltzmann project :
⇒ ultimately test whether the stalled shock would revive. ⇒ Perfectionism

SN 20xx ! in the Galactic center: End-to-End Bridging Simulations

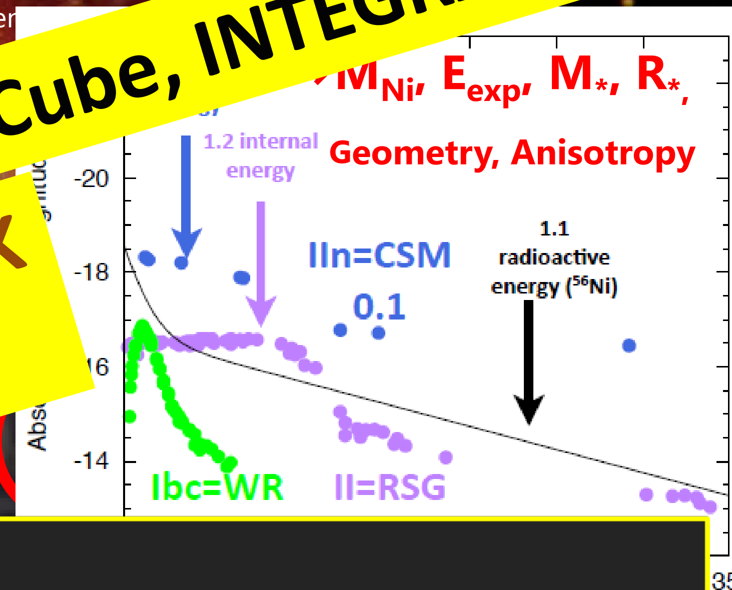
sec	min		hours	day		years
- 4	- 3	- 2	- 1	0	2	>3

log (day)

SK detects ~ 10,000 neutrinos

< 15min SURGE meeting (Supernova Urgen…

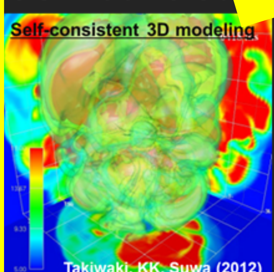
< 1 hour SK provide alert: Astrono…
(onset of neutri…



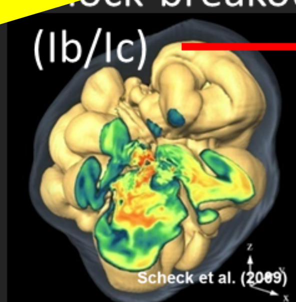
LIGO, Virgo, SK, KamLAND, K, IceCube, INTEGRAL
KAGRA, Hyper-K, and Post-K
ET, CE, DUNE…..

Self-Consis…

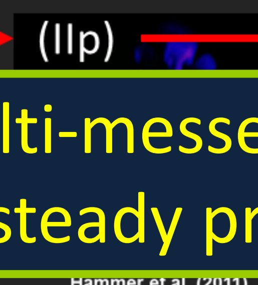
Self-consist… …ock-breakout



(Ib/Ic)



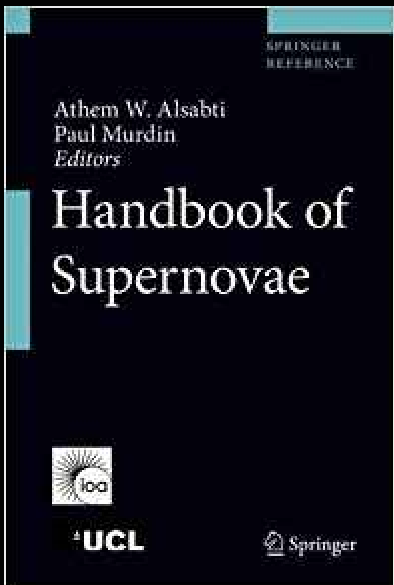
(IIp)



Multi-messenger research
in steady progress !

Useful references

1. Review on GW signatures from CCSNe



~1000 $!

Chapter 7
"Gravitational waves From Core-Collapse Supernovae"
By Kotake and Kuroda

C. R. Physique 14 (2013) 318–351

Contents lists available at SciVerse ScienceDirect

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www.sciencedirect.com

Gravitational waves / Ondes gravitationnelles

Multiple physical elements to determine the gravitational-wave signatures of core-collapse supernovae

Éléments physiques multiples déterminant les signatures des ondes gravitationnelles de supernovas à effondrement de cœur

Kei Kotake[a,b,*]

TOPICAL REVIEW

The gravitational-wave signature of core-collapse supernovae

Christian D Ott

Published 23 February 2009 • 2009 IOP Publishing Ltd

Classical and Quantum Gravity, Volume 26, Number 6

2. Recent publications on CCSN GWs

Summary of publication lists (by Ewald Mueller):

https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

Asteroseismology:

Morozova et al. (2018), ApJ

Torres-Forne et al. (2019), MNRAS

Sotani et al. (2017), PRD