Formation of the central engine of Long GRBs

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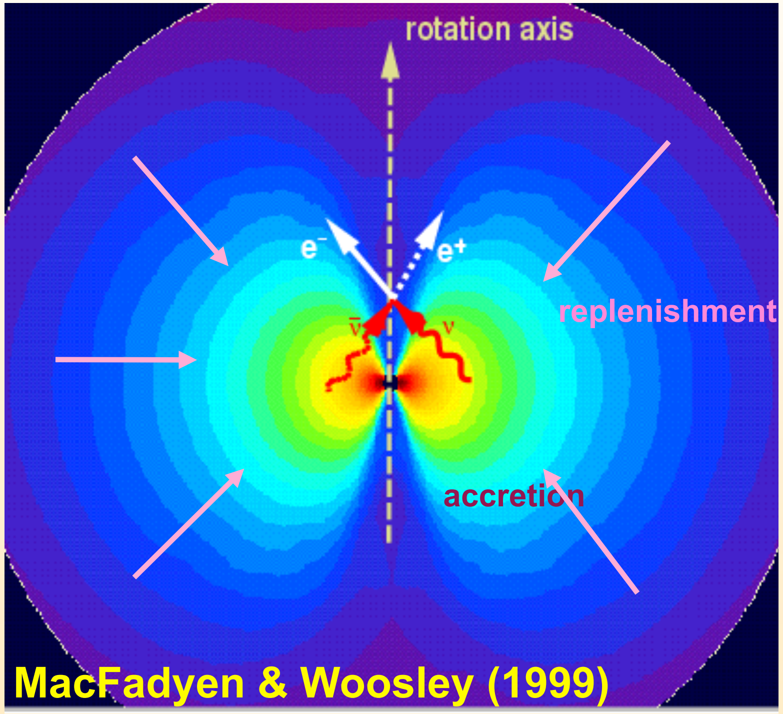
(Cerdá-Durán+’13, arXiv:1310.8290)

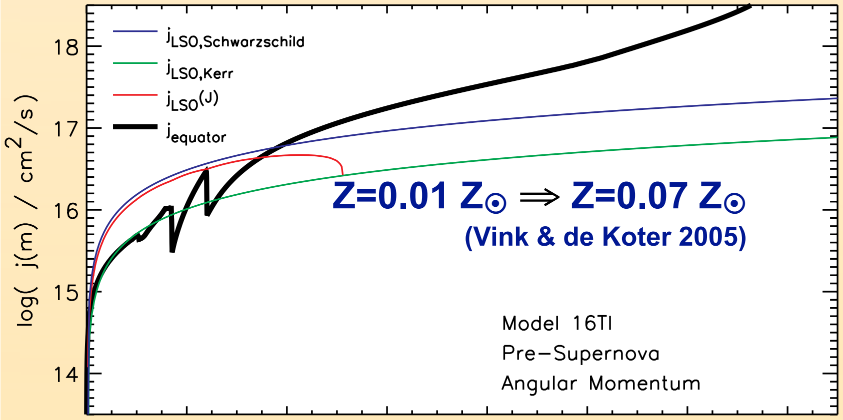
Supernovae and GRBs in Kyoto

Kyoto, 12 – 11 - 2013

LGRB Progenitors: Collapsars



MacFadyen & Woosley (1999)



$Z=0.01\ Z_\odot \Rightarrow Z=0.07\ Z_\odot$

(Vink & de Koter 2005)

Woosley & Heger (2006)

Woosley (1993):

- Collapse of a massive ($M_* \sim 30M_\odot$, WR) rotating star that does not form a successful SN but collapses to a BH ($M_{BH} \sim 3M_\odot$) surrounded by a thick accretion disk. The hydrogen envelope is lost by stellar winds, interaction with a companion, etc.

Caveats:

- Rapidly spinning stars produce low rotating cores due to magnetic torques (Spruit'02, Heger+'05)

Solutions:

- Low metallicity + strong rotation ⇒ chemically homogeneous evolution ⇒ cores retain high spin (Yoon& Langer'05, Woosley & Heger'06, Yoon+'06)
- Interacting binaries

Outcomes:

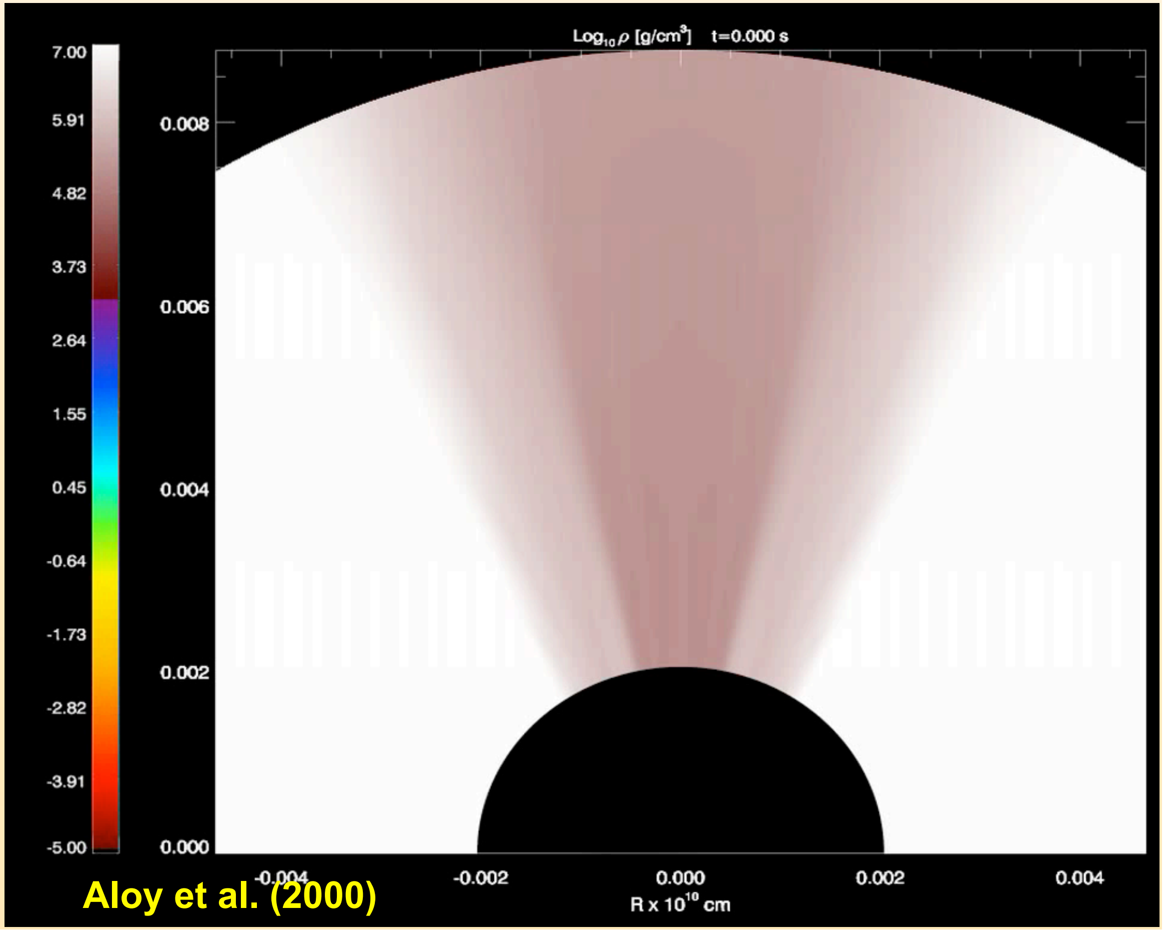
- LGRB?
- SNe / *Unnovae*?
- BH or proto-magnetar?

LGRB Progenitors: Collapsars

If the progenitor forms a collapsar:

- The viscous accretion onto the BH ⇒ strong heating ⇒ thermal νν-annihilating preferentially around the axis ⇒ formation of a relativistic jet (Γ>10)?.
- Numerical models: ultrarelativistic outflow can form *if luminosity* > ***L_{th} ~10^{49} erg***
- Numerical simulations: core-collapse, rapid rotation, computing GW and other aspects of the problem:

  Shibata'00,'03, Dimmelmeier'02,'07,'08, Fryer'04, Cerdá-Durán'05,'07, Dessart'08, Kiuchi'09, Kotake'09,'11, Scheideger'10, Sekiguchi'11, O'Connor'10,'11, Ott'11,'13...



Aloy et al. (2000)

Formation of the central engine.
the code

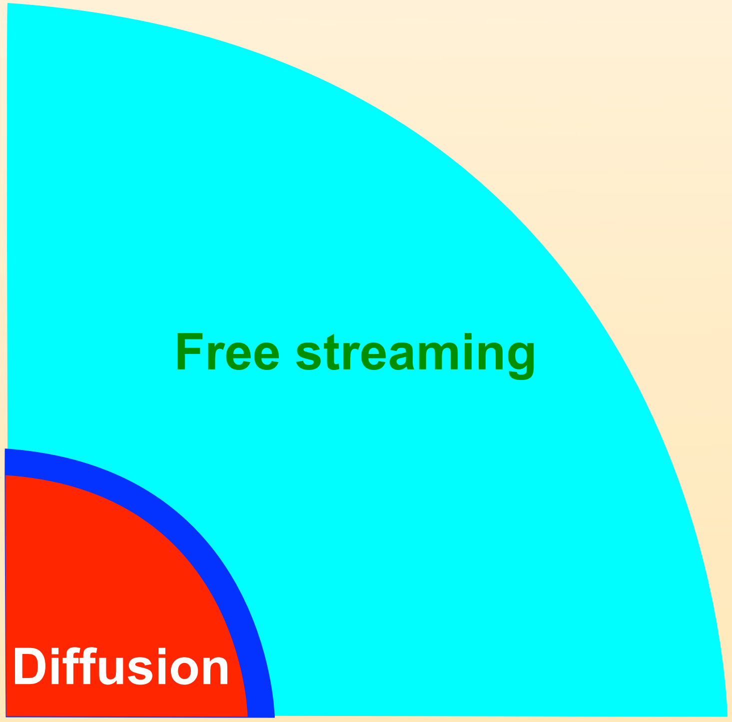
- General relativity:
  - XCFC approximation (Isenberg 2008, Wilson et al 1996, Cordero-Carrión et al 2009)
  - spectral methods (LORENE library)
- Godunov-type schemes for hydrodynamics.
- Spherical polar coordinates:
  - Δr = 200 m (innermost 20 km)
  - logarithmic grid for r>20 km -> $\Delta r \sim$ 800 m at 100 km
  - outer boundary 30000 km
  - $\Delta\theta = 1.4^\circ$
- Axisymmetry (2D) + equatorial symmetry
- EOS: Lattimer & Swesty'91 + Timmes & Arnett'99 (table by O'connor & Ott 2010, LS220 in this work)
- GW: quadrupole formula (good approx. in PNS: Reisswig et al 2010)
- Neutrino leakage scheme (De Brye et al in prep)

CoCoNuT

Formation of the central engine.
neutrino treatment: leakage

Ruffert et al 1996, Rosswod & Liebendörfer 2003, ***O'connor & Ott 2010***

Leakage simplified scheme



Neutrinosphere

(for mean neutrino energy)

Life is actually harder...

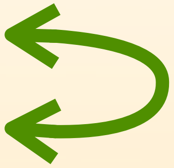
The main focus of our models is not an accurate determination of whether a particular star develops an explosion due to neutrino heating, but specifically an exploration of the consequences of a fSN, ***in which neutrino heating does not stop the mass accretion and thereby prevent the collapse of the inner core to a BH***.

Thus, ***very high accuracy in the neutrino physics is only of secondary relevance here*** and we can employ ***simple***, ***fast*** approximations for the neutrino physics.

Formation of the central engine.
neutrino treatment: leakage

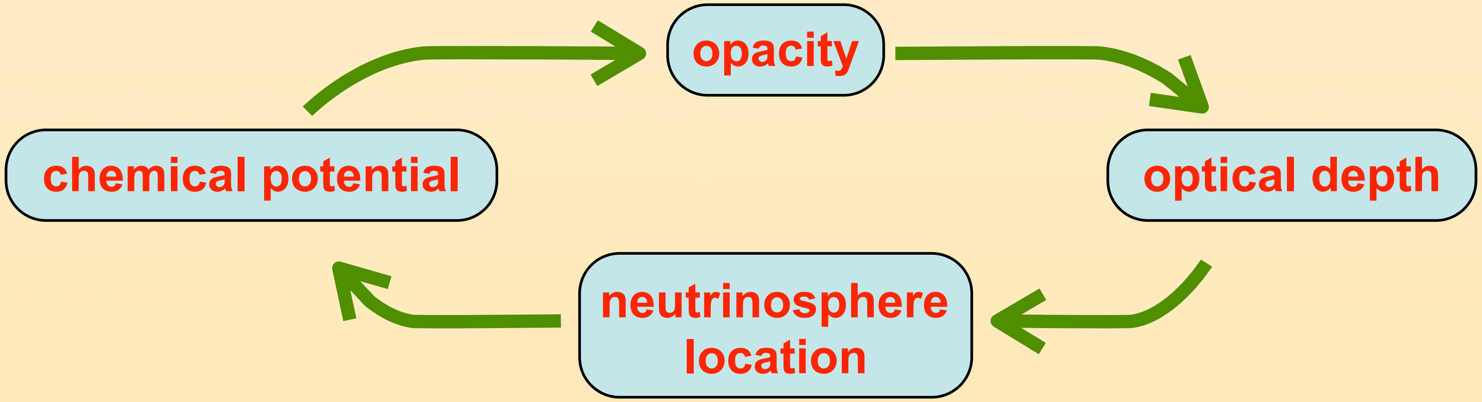
– Energy averaged: Fermi distribution

- inside ⇒ thermal + beta eq. ⇒ $\eta = \eta_{\mathrm{eq}}$, $T_\nu = T_{\mathrm{fluid}}$
- outside ⇒ neutrinos scape ⇒ $\eta = 0$, $T_\nu = T_{\nu\text{-sphere}}$


Matching

– Neutrinosphere = τ threshold ⇒ ray-by-ray in radial direction

– Neutrinosphere-opacity loop (computationally expensive):


opacity

chemical potential

optical depth

neutrinosphere location

NOTE: loop can be avoided by fixing beta-equilibrium everywhere (e.g. Sekiguchi'11)

Formation of the central engine.
neutrino treatment: leakage

– Diffusion region: rates based on optical depth

$$Q_{\nu_i}^{\mathrm{diff}} \propto \frac{1}{t_{\nu_i}^{\mathrm{diff}}}; \qquad t_{\nu_i}^{\mathrm{diff}} \propto k\tau_{\nu_i}^{\mathrm{diff}}$$

Includes a *free* parameter

k=0.5 ⟹ Ruffert, Janka & Schaffer'96
Rosswog & Liebendörfer'03
Cerdá-Durán et al.'13

k=1.0 ⟹ O'Connor & Ott (2011)

– Effective rates: ***Harmonic mean*** of diffusion and free streaming rates

$$E_{\nu_i}^{\mathrm{diff}} = \frac{Q_{\nu_i}^{\mathrm{diff}}}{R_{\nu_i}^{\mathrm{diff}}} \qquad E_{\nu_i}^{\mathrm{free}} = \frac{Q_{\nu_i}^{\mathrm{free}}}{R_{\nu_i}^{\mathrm{free}}}$$

$$\Rightarrow \quad \frac{1}{E_{\nu_i}^{\mathrm{eff}}} = \frac{1}{E_{\nu_i}^{\mathrm{diff}}} + \frac{1}{E_{\nu_i}^{\mathrm{free}}} \qquad \frac{1}{R_{\nu_i}^{\mathrm{eff}}} = \frac{1}{R_{\nu_i}^{\mathrm{diff}}} + \frac{1}{R_{\nu_i}^{\mathrm{free}}}$$

$$\Rightarrow \quad Q_{\nu_i}^{\mathrm{eff}} = R_{\nu_i}^{\mathrm{eff}} E_{\nu_i}^{\mathrm{eff}}$$

Formation of the central engine.
neutrino treatment: leakage

– Three neutrino species: ν_e, $\bar{\nu}_e$ and ν_X

– Neutrino emission:

- β-processes: $e^- + p \rightarrow n + \nu_e$; $e^+ + n \rightarrow p + \bar{\nu}_e$
- thermal pair annihilation: $e^- + e^+ \rightarrow \nu_i + \bar{\nu}_i$
- plasmon decay: $\gamma \rightarrow \nu_i + \bar{\nu}_i$

– Neutrinos diffusion:

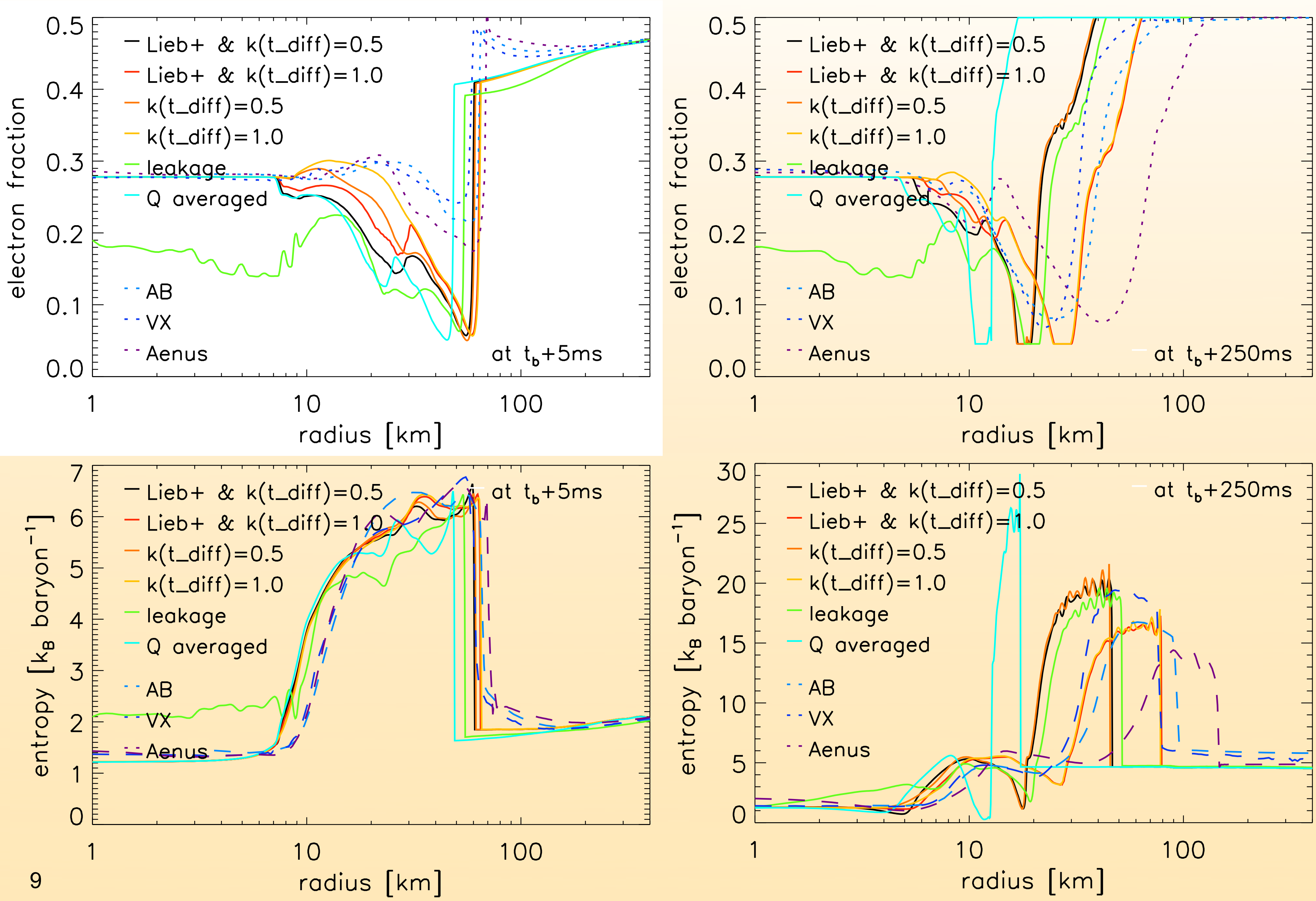
- absorption: $n + \nu_e \rightarrow e^- + p$; $p + \bar{\nu}_e \rightarrow e^+ + n$
- scattering: $\nu_i + N \rightarrow \nu_i + N$; $N \in \{p, n, A\}$

– Inelastic scattering: cannot be implemented in a leakage scheme (relevant before bounce). Alternatives:

- Simple deleptonization scheme (Liebendörfer 2005)
- **Own deleptonization tables:** 1D Simulations, multi-energy, hyperbolic 2-momentum eqs. for $\nu-$transport (Obergaulinger & Janka 2013; Obergaulinger et al. 2013)

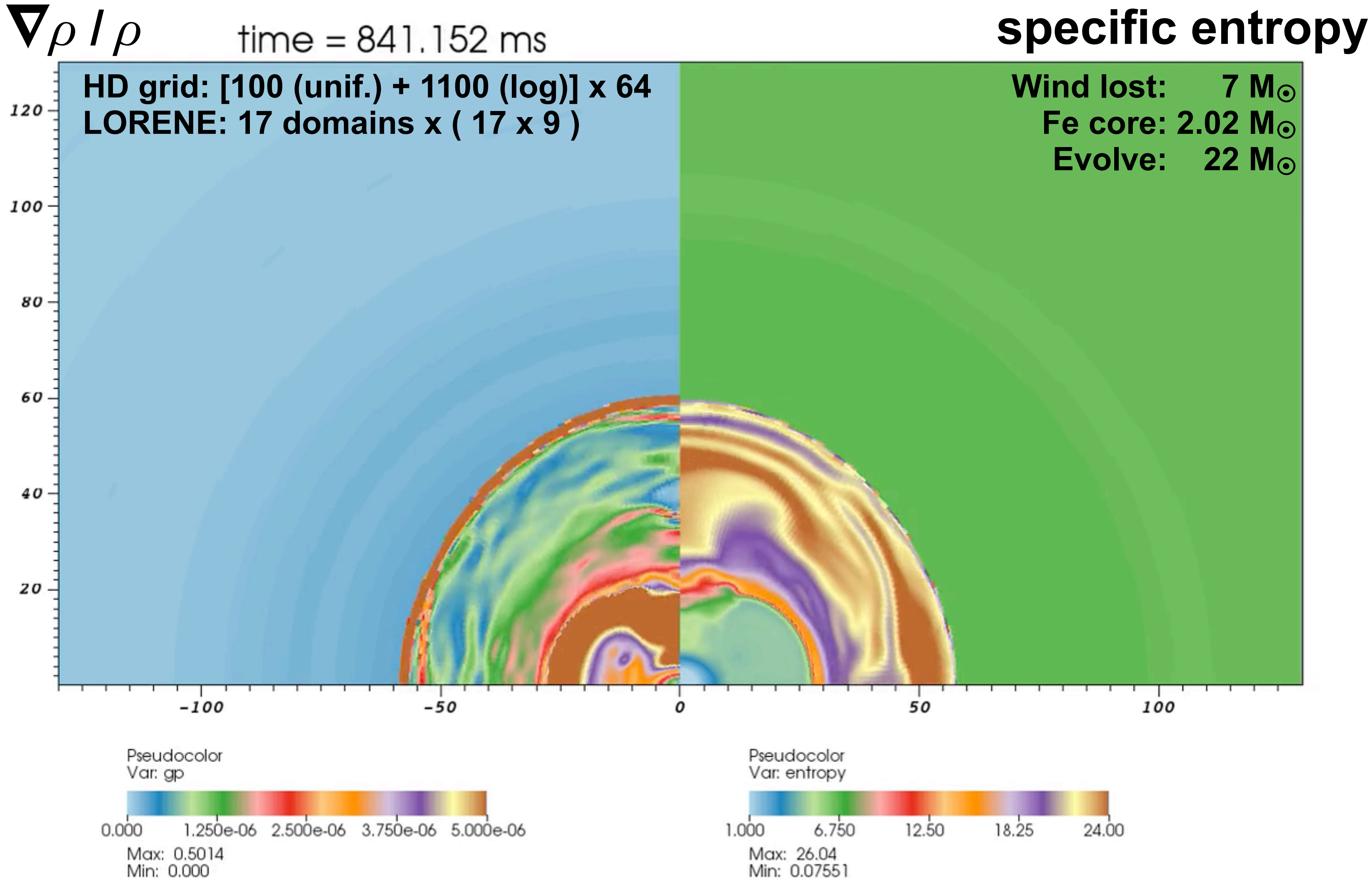
(see talk by O. Just on Friday)

Comparison with Liebendörfer et al 2005 (G15 model)



Model: 35OC of Woosley & Heger 2005

(Wolf-Rayet star, $\Omega_c \sim 2\ \mathrm{rad\ s^{-1}}$), EOS: LS220



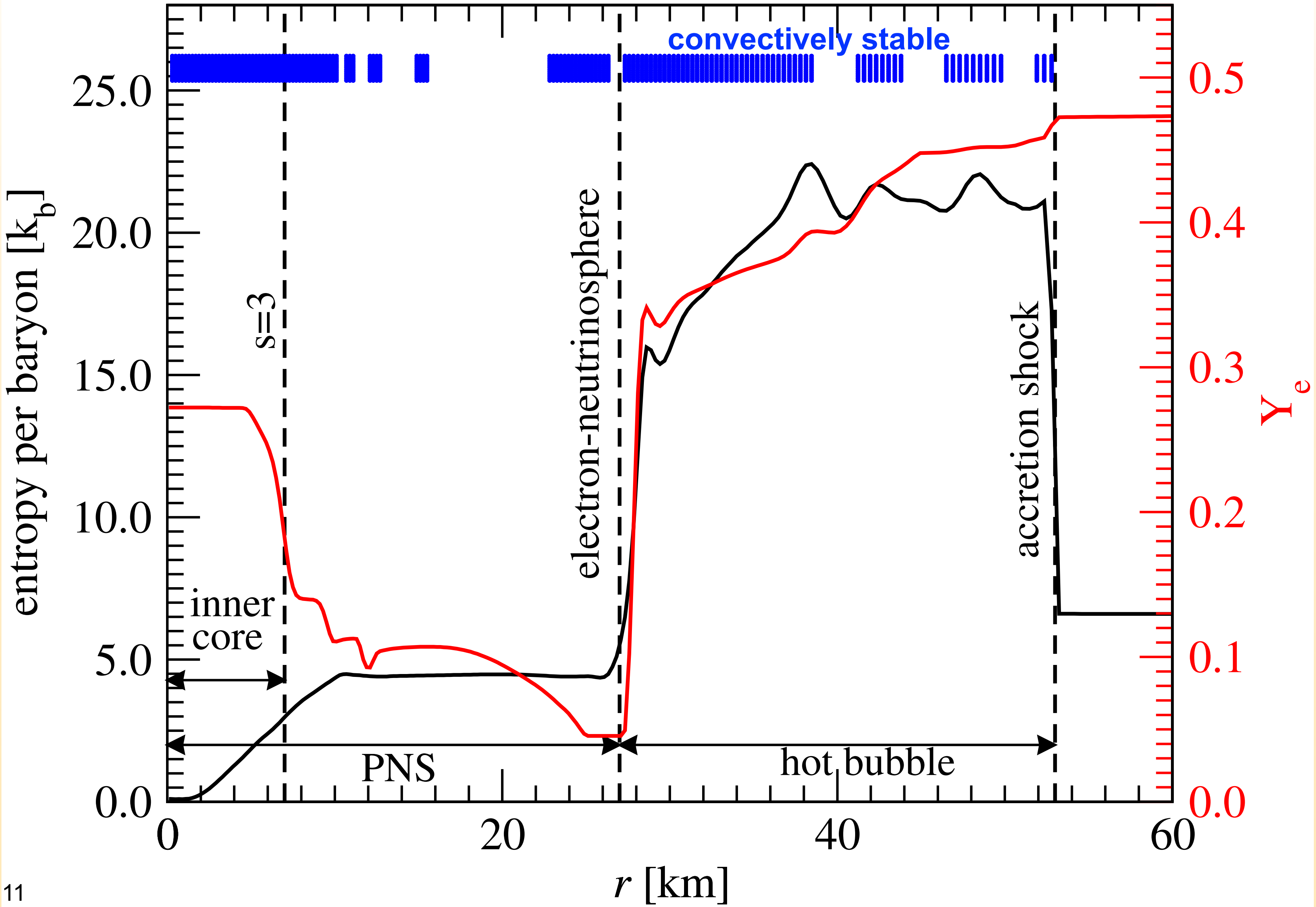
$\nabla\rho\ /\ \rho$

specific entropy

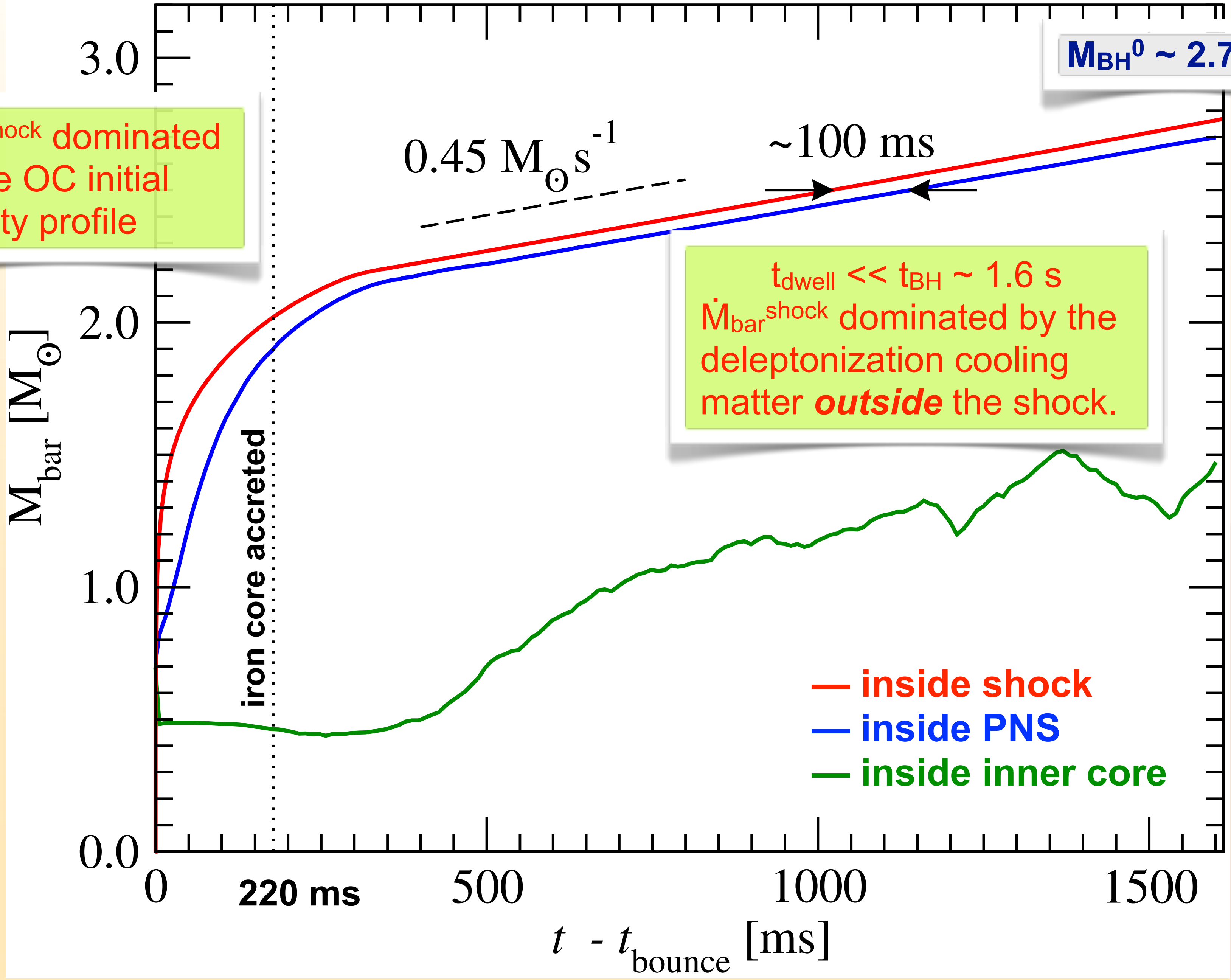
HD grid: [100 (unif.) + 1100 (log)] x 64
LORENE: 17 domains x (17 x 9)

Wind lost: 7 $M_\odot$
Fe core: 2.02 $M_\odot$
Evolve: 22 $M_\odot$

Typical conditions after bounce inside the shock: t - t_b ~ 0.5 s, equatorial profile



Time evolution of the baryonic mass



$\dot{M}_{bar}^{shock}$ dominated by the OC initial density profile

$M_{BH}^0 \sim 2.7\ M_\odot$

$t_{dwell} \ll t_{BH} \sim 1.6$ s
$\dot{M}_{bar}^{shock}$ dominated by the deleptonization cooling matter ***outside*** the shock.

Formation of the central engine.

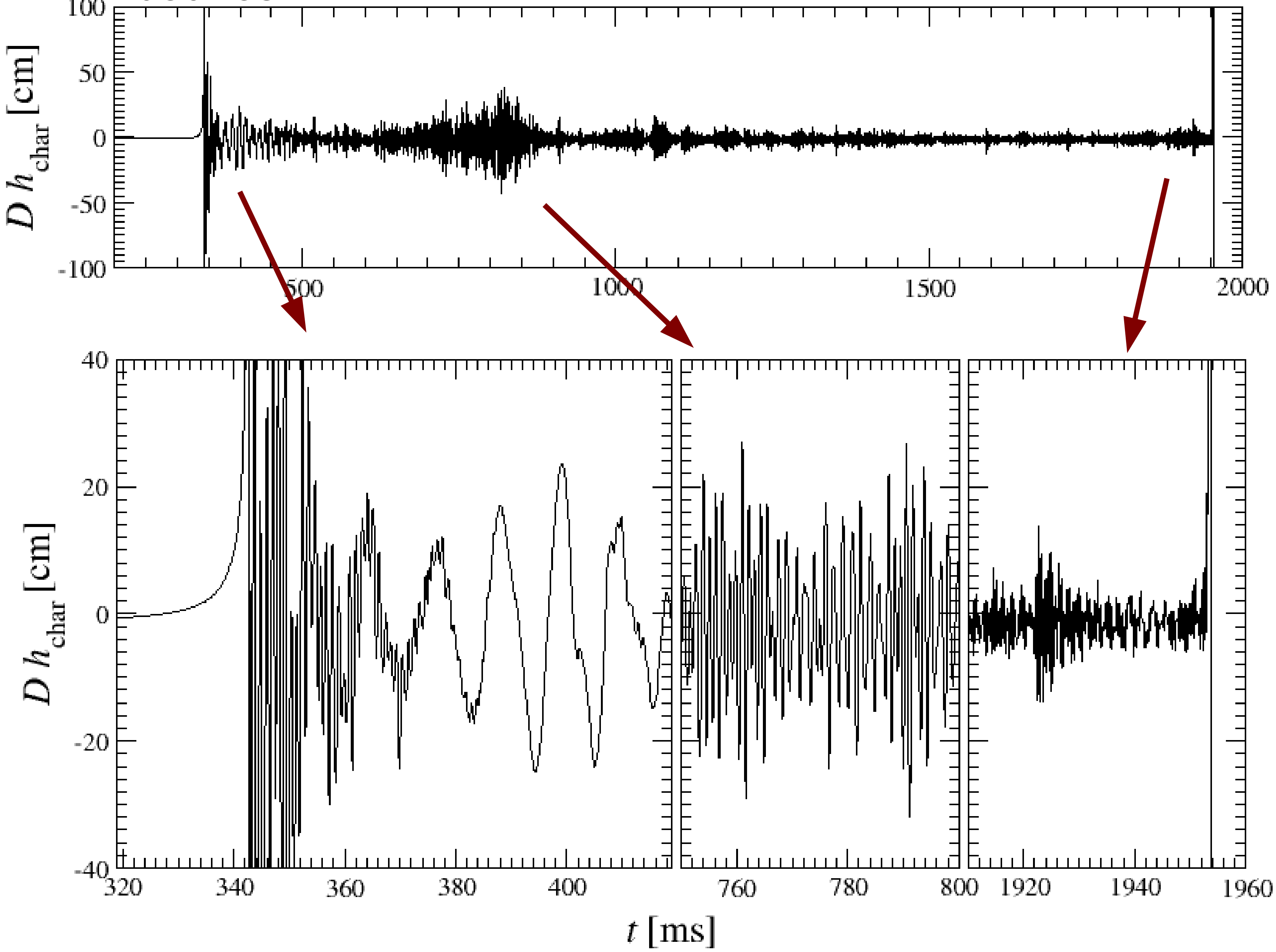
limitations of our treatment

– The thermal structure and the rotation profile of the PNS evolves from the t_b to t_{BH}

⇒ M_{BH}^0 and t_{BH} depend on the evolution of the PNS, including the cooling by neutrinos diffusing out of the PNS and the angular momentum redistribution.

- The presence of strong B-fields, due to the MRI, or non-axisymmetric instabilities will probably enhance the transport of angular momentum, decreasing the M_{BH}^0 and t_{BH}.
- ***Non-magnetized axisymmetric simulations provide an upper limit to the t_{BH}.***
- Lower limit estimate for t_{BH}: time at which 2.41 $M_\odot$ have accreted through the shock, **$t_{BH}^{min} - t_b \sim 820$ ms**.
- Using a stiffer EoS would allow for larger maximum masses and hence longer collapse times.

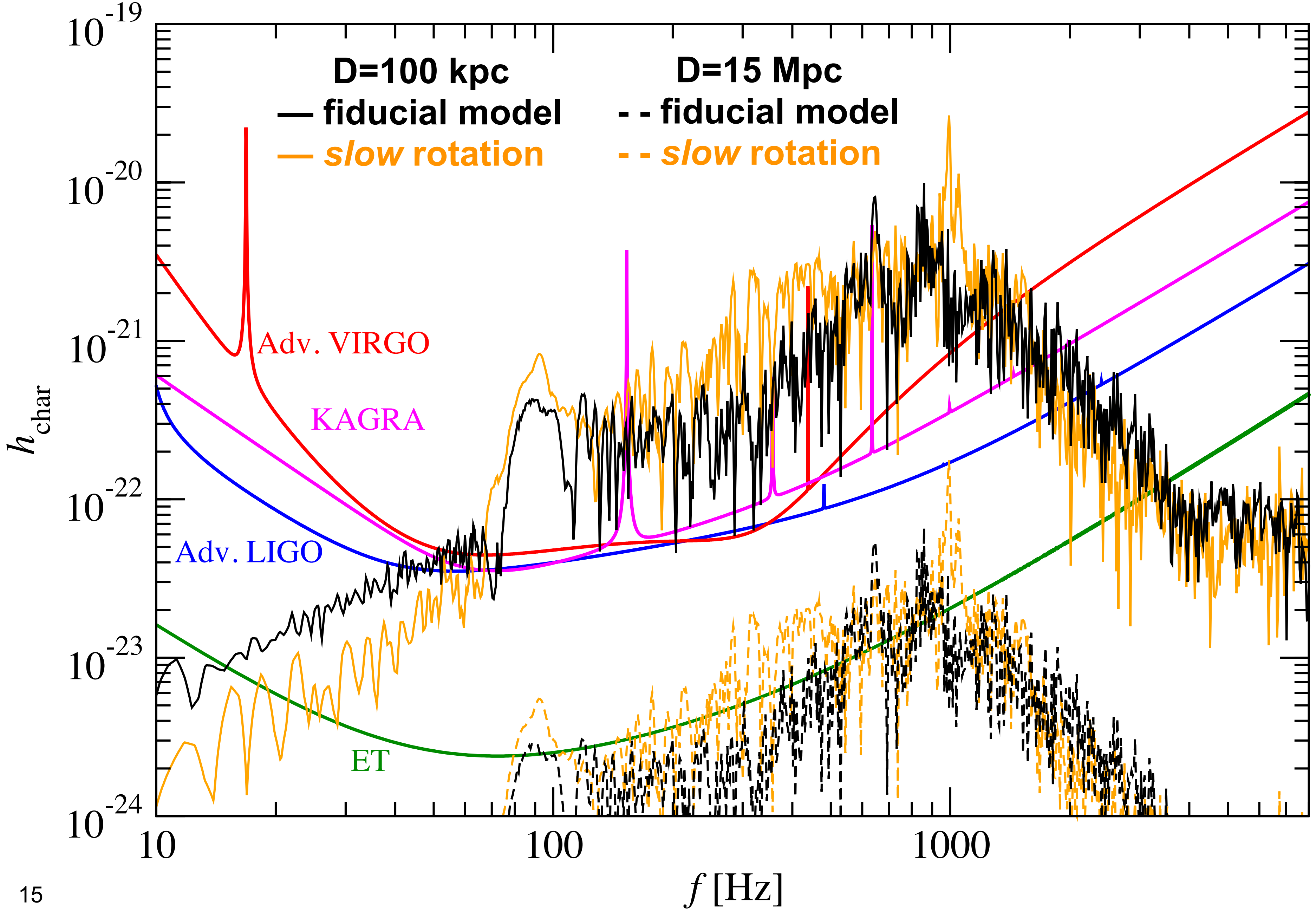
Gravitational waves - waveform



bounce

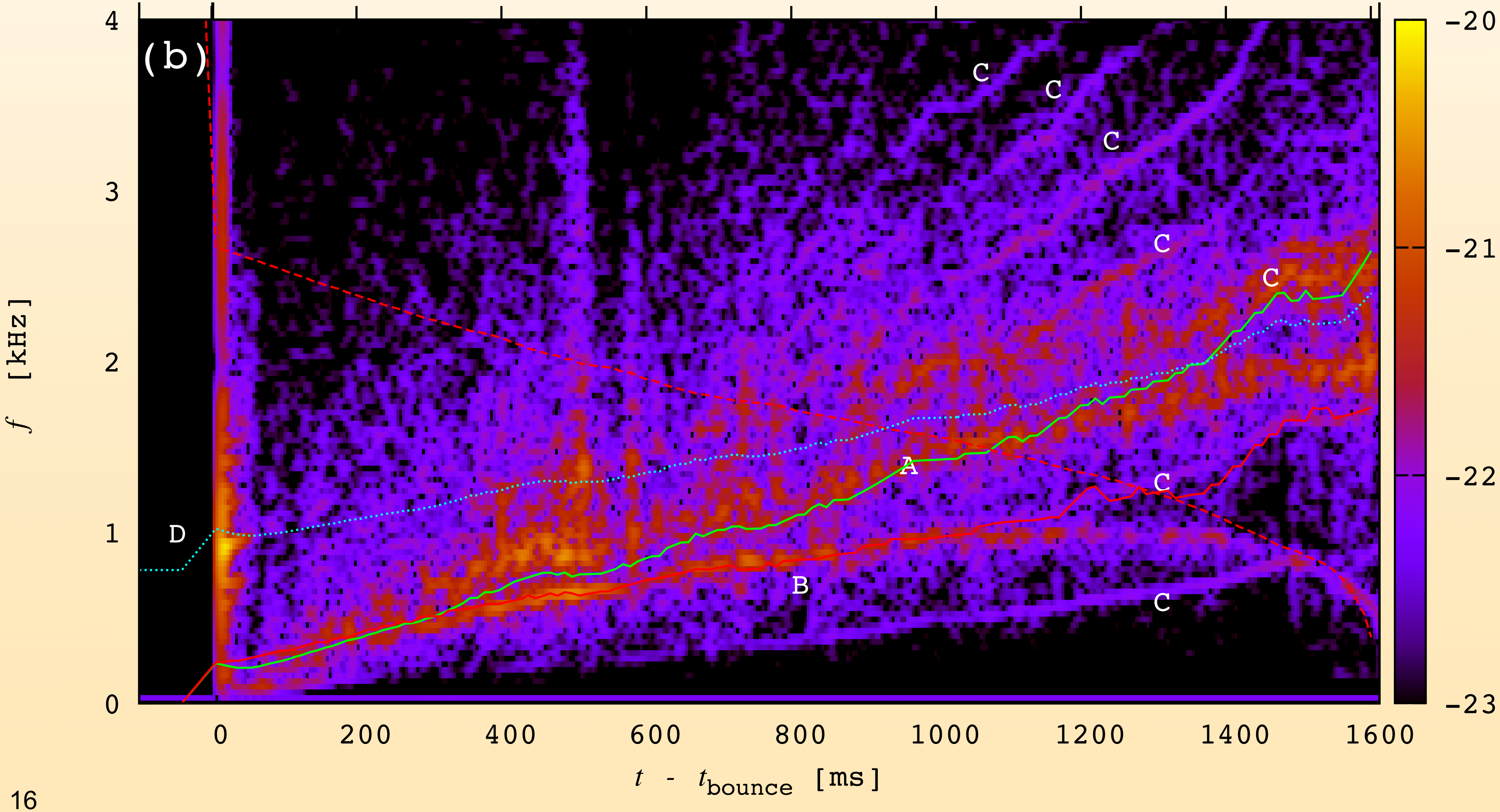
BH formation

Gravitational wave spectrum

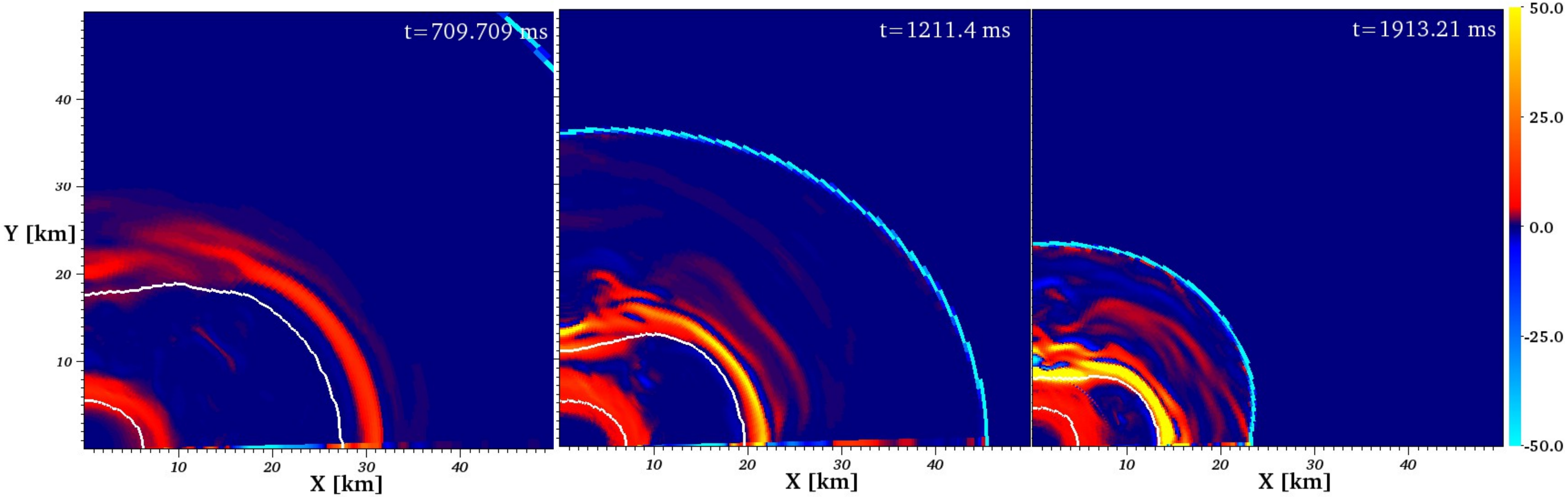


Spectrogram analysis

Complex spectrogram, whose analysis is done by identifying frequencies and regions where this frequencies are produced (i.e., with the help of other spectrograms of, e.g., density, shock position, etc.)



Buoyancy frequency



- Local linear stability analysis (non-rotating, non-relativistic)

$$N^2 = \left(\frac{\nabla \rho}{\rho} - \frac{\nabla P}{\Gamma_1 P} \right) \cdot \boldsymbol{g}$$ Brunt-Väisälä frequency

$$N^2 > 0$$ Convectively stable (Ledoux criterion)

- Caveats:
  - Rotating star: Solberg-Høiland criteria (work in progress...)
  - General relativity (Müller et al 2013)

Spectrogram analysis.
Buoyancy frequency

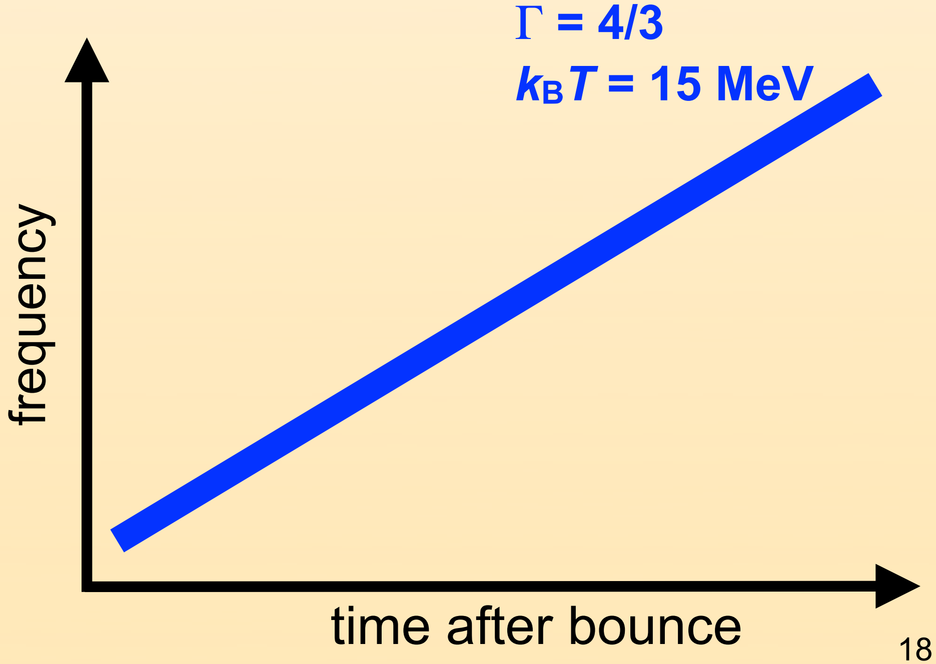
Postshock/PNS convection excites g-modes at the lower boundaries of the unstable regions.

$$f_{\mathrm{g,PNS}} \sim \frac{\sqrt{N_{\mathrm{turn}}^2}}{2\pi} \sim \frac{1}{2\pi}\frac{GM_{\mathrm{PNS}}}{R_{\mathrm{PNS}}^2}\sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_{\mathrm{B}}T}}\left(1+\frac{GM_{\mathrm{PNS}}}{2c^2R_{\mathrm{PNS}}}\right)^{-4}$$

(Murphy et al 2009, Müller et al 2013)

Outer stable layer:

- ~ 100 Hz after bounce
- monotonically increasing frequency to a few kHz
- contraction+ν-cooling



Avoided crossing of modes

During the rise: quadrupolar velocity patterns.

During the drop: quasi-radial velocity pattern. Since $f_{\mathrm{qr}} \rightarrow 0 \Longrightarrow$ unstable mode $\Longrightarrow$ BH formation (Chandrasekhar'64)

Change in behaviour of this feature likely due to an ***avoided crossing of two modes***:

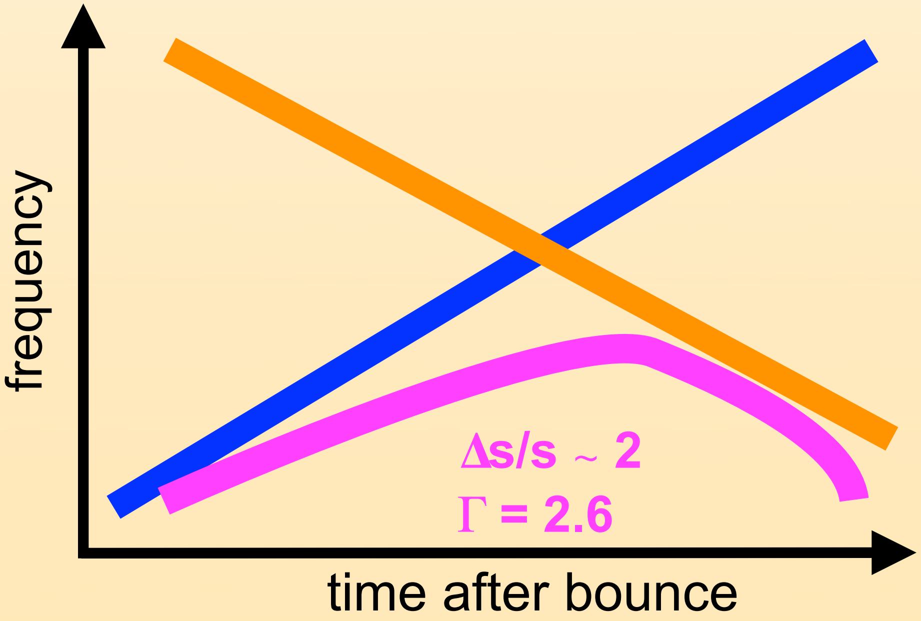
i. **g-mode (inner convectively stable layer)** $f_{\mathrm{g,c}} \sim \frac{1}{2\pi}\frac{GM_{\mathrm{IC}}}{R_{\mathrm{IC}}^2}\sqrt{\frac{1}{\Gamma}\frac{\Delta s}{s}}\left(1+\frac{GM_{\mathrm{IC}}}{2c^2R_{\mathrm{IC}}}\right)^{-4}$ kHz

ii. **qr-mode with decreasing frequency** $f_{\mathrm{qr}} \sim 3.3\left(\log\frac{\rho_{\mathrm{c,BH}}}{\rho_{\mathrm{c}}}\right)^{1/2}$ kHz

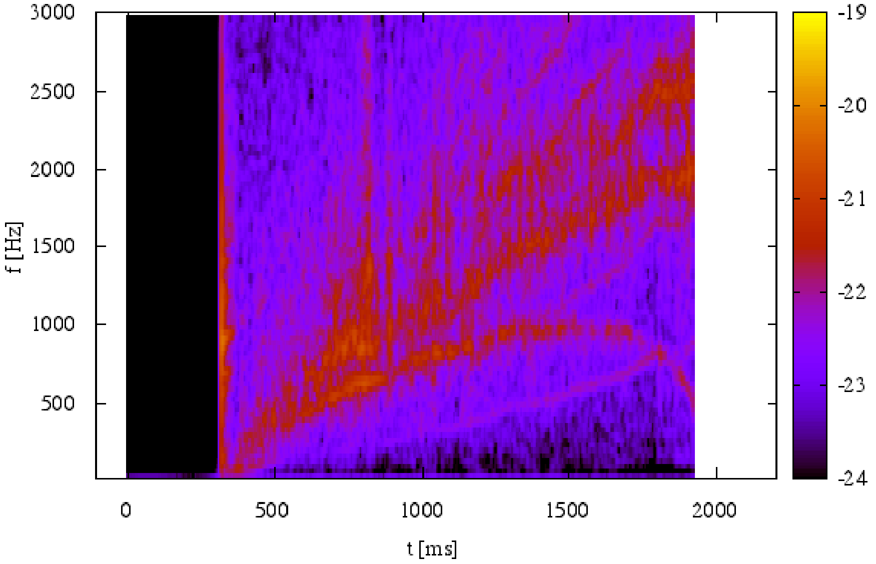
(Gondek et al. 1997)

Avoided crossings have been observed:

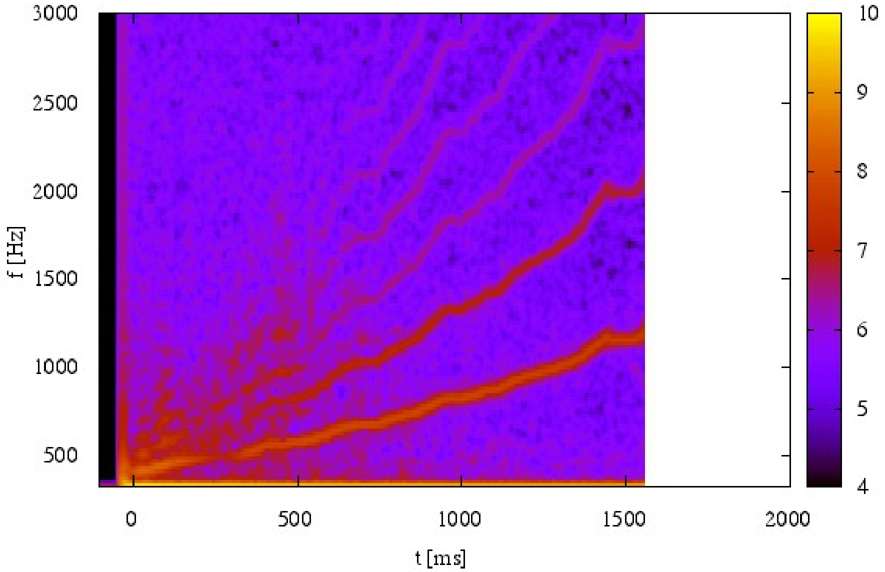
- Numerically: in NSs around its maximum mass (Gourgoulhon et al. 1995; Galeazzi et al. 2013).
- Perturbation analysis: radial- and f-modes(Gondek et al. 1997; Kokkotas & Ruoff 2001) and crustal-modes(Gondek & Zdunik 1999).



GW



Shock radius at equator



Signature of SASI on the gravitational waves

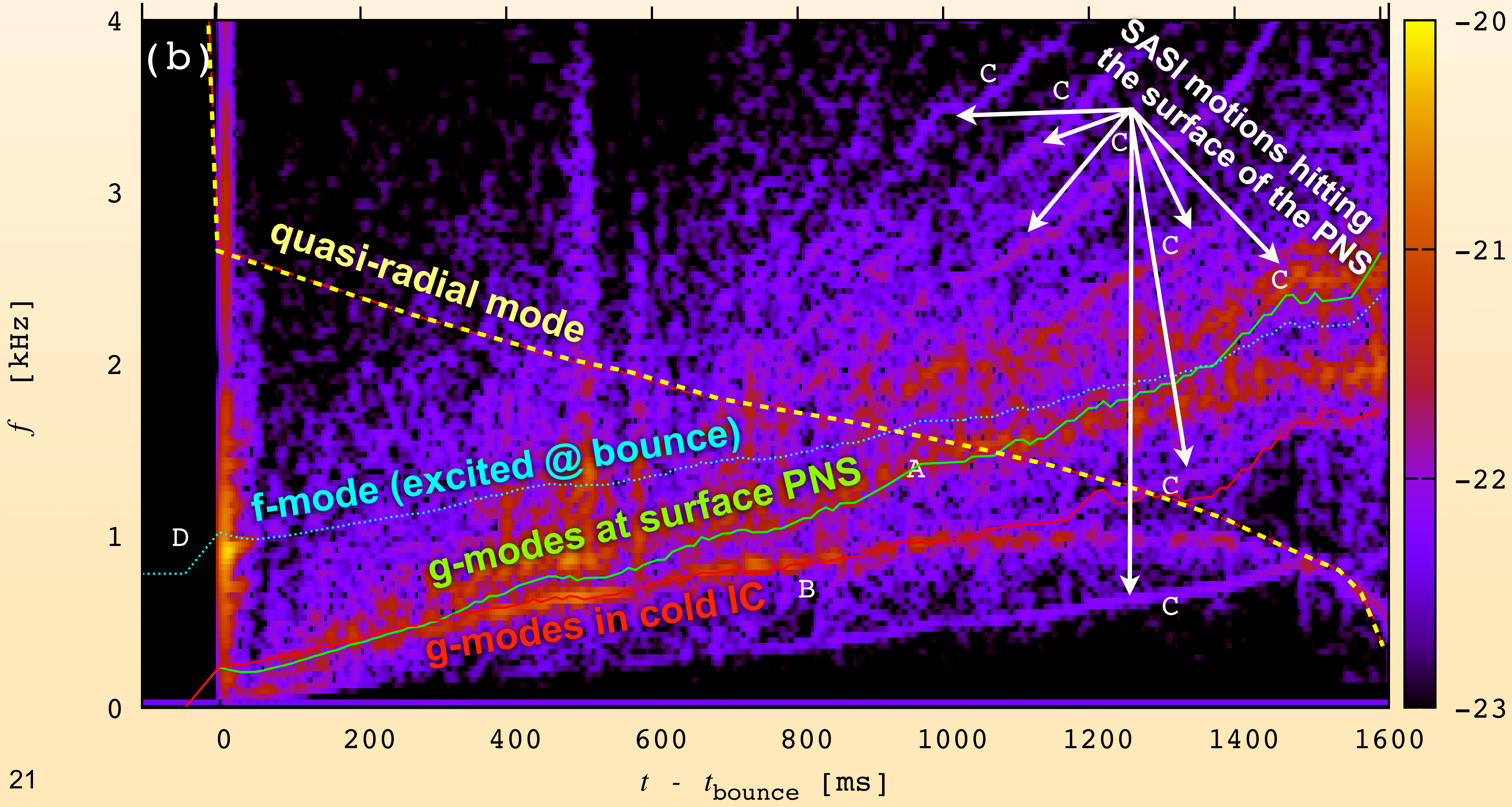
- Observed from the neutrino-sphere to the shock location
- Sound waves confined in a cavity
- Multiple overtones

Spectrogram analysis

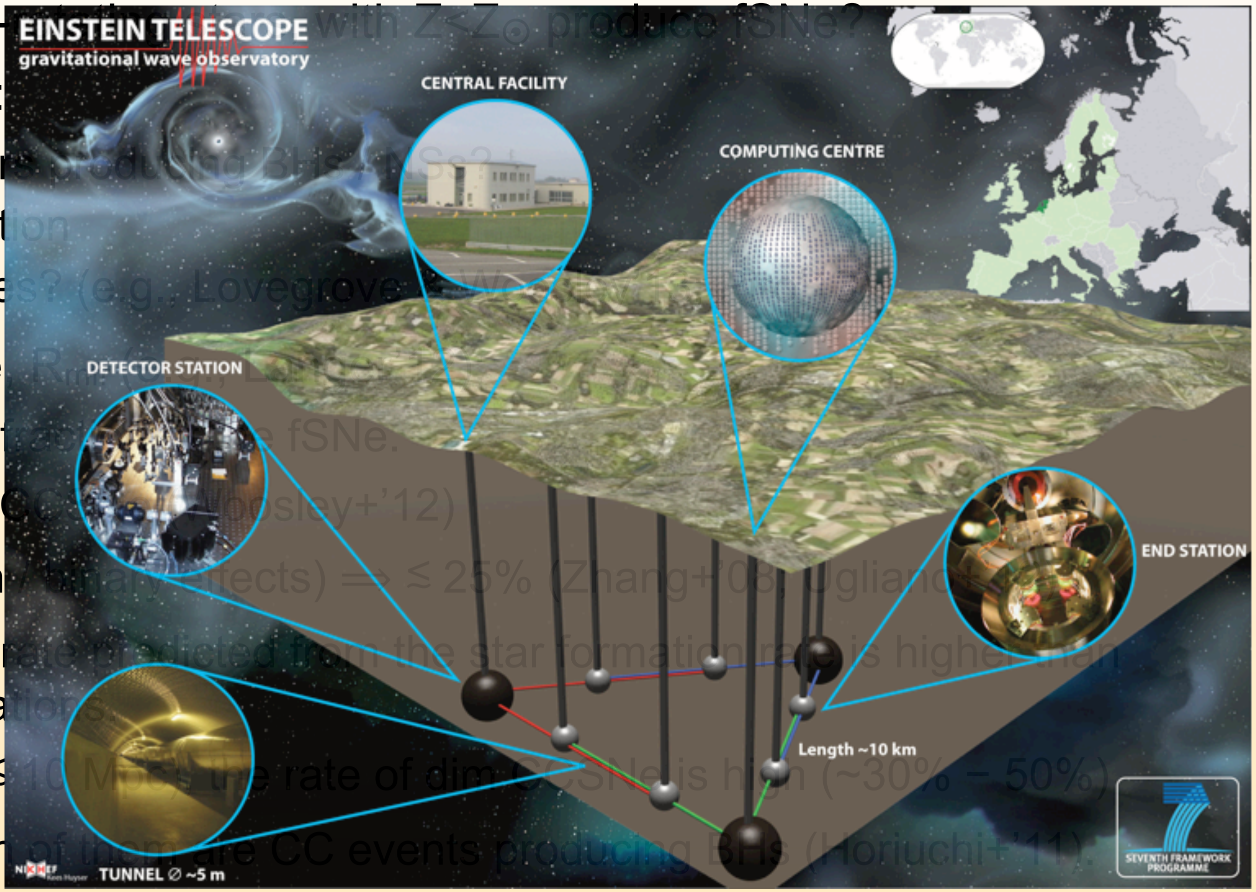
D: f-mode excited at bounce. Highly damped by sound waves in the hot bubble

$$f_\mathrm{f} \sim 0.78 + 1.635\sqrt{\frac{M_\mathrm{PNS}}{1.4\,M_\odot}\left(\frac{10\,\mathrm{km}}{R_\mathrm{PNS}}\right)^3}\,\mathrm{kHz}$$

(Andersson & Kokkotas'98)



Detectability

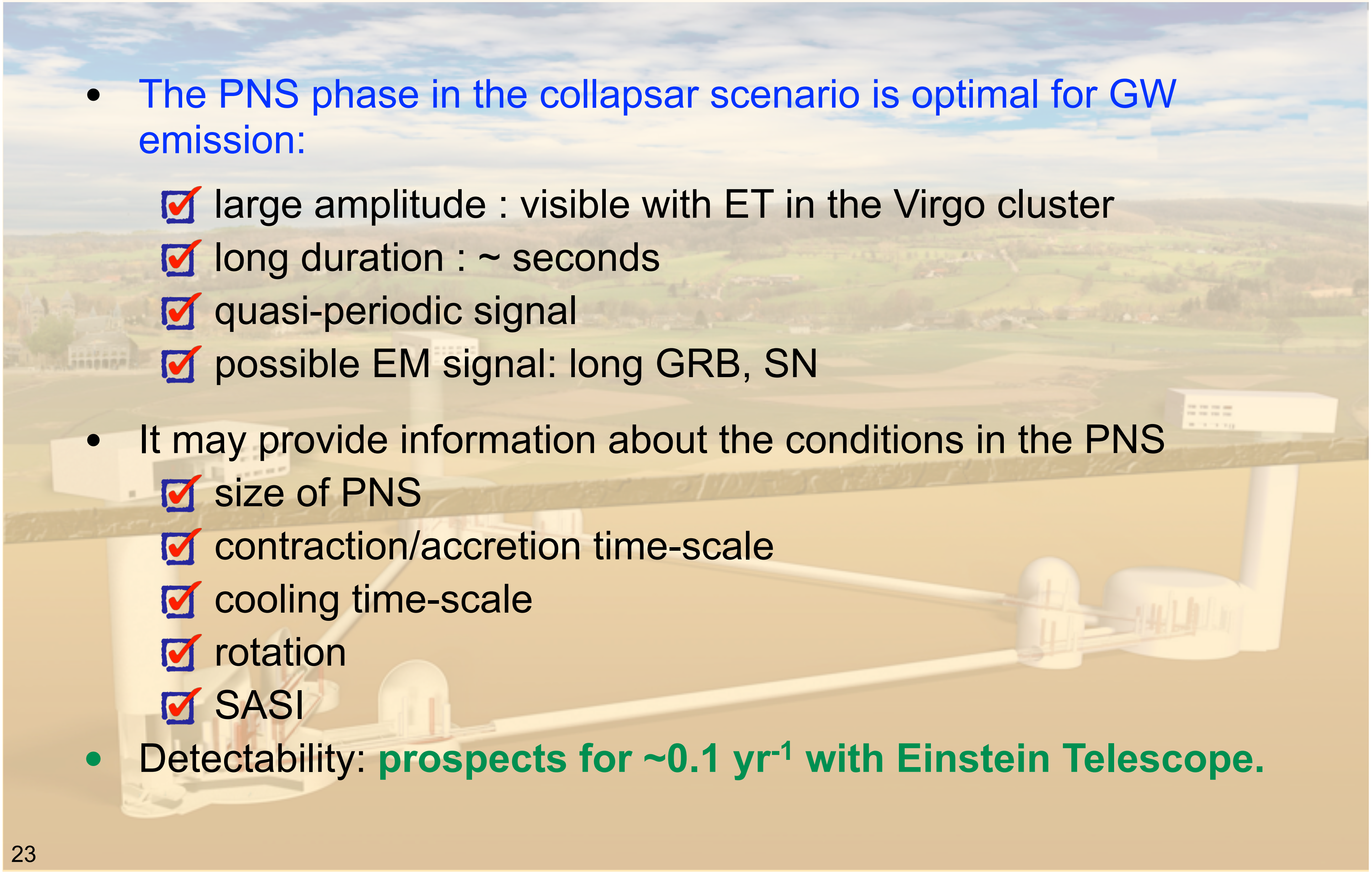


- How many massive, fast-[illegible] with $Z<Z_\odot$ produce fSNe?
- Active matters of debate:
    - fraction of massive stars producing BHs / NSs?
    - channels for BH formation
    - observational signatures? (e.g., Lovegrove [illegible]
- Hard to estimate the rate, $R_{\rm m}$ (e.g., L[illegible]
    - They can be a sizable fraction of the fSNe.
    - Rate of fSNe ~10% of CCSNe (Woosley+'12)
    - 1D-pistons (no rotation / binary effects) ⟹ ≲ 25% (Zhang+'08; Ugliano+
    - ***SN rate problem***: SN rate predicted from the star formation rate is higher than the SN rate by observations.
        - In local Universe (≲ 10 Mpc), the rate of dim CCSNe is high (~30% − 50%)

          ⟹ a fraction of them are CC events producing BHs (Horiuchi+'11).
        - Paucity of observed high mass RSGs in $16.5M_\odot \lesssim M \lesssim 25M_\odot$ can be explained if they are fSNe. ***fSNe rate ≲ 20% of CCSN ⟹ ~ 0.2 y^{-1}*** (Kochanek'13).
    - 10% − 50% of massive MS stars are fast rotators (≲ 200 km s^{-1}; Mink+'13).

➡ **Fast spinning, moderate-Z, massive stars happening in nearby galaxies, might bring detectable GW signals for the Einstein Telescope at rates of ≲ 0.1y^{-1}.**

Conclusions



- The PNS phase in the collapsar scenario is optimal for GW emission:
  - ☑ large amplitude : visible with ET in the Virgo cluster
  - ☑ long duration : ~ seconds
  - ☑ quasi-periodic signal
  - ☑ possible EM signal: long GRB, SN
- It may provide information about the conditions in the PNS
  - ☑ size of PNS
  - ☑ contraction/accretion time-scale
  - ☑ cooling time-scale
  - ☑ rotation
  - ☑ SASI
- Detectability: **prospects for ~0.1 yr^{-1} with Einstein Telescope.**