# Gravitational Waves from the innermost parts of Core-Collapse Supernovae

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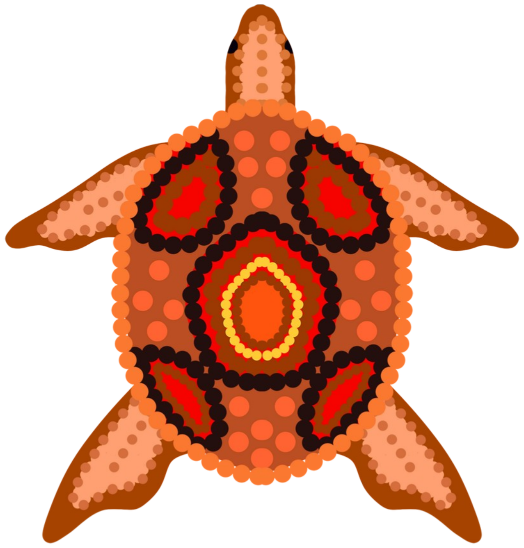
MONASH University

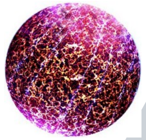
Dr. Pia Jakobus
University of Hamburg

By Maria Pereira

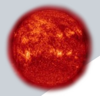


XVIth Quark Confinement and the Hadron Spectrum Conference 2024

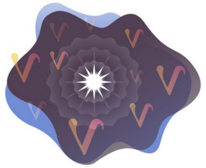

- Since 1932, more than 160.000 papers have been written (key words "Supernova" or "Neutron star")
- Since 2014 ~7000 Supernovae discovered



1934 Zwicky & Baade



1966 Colgate & White



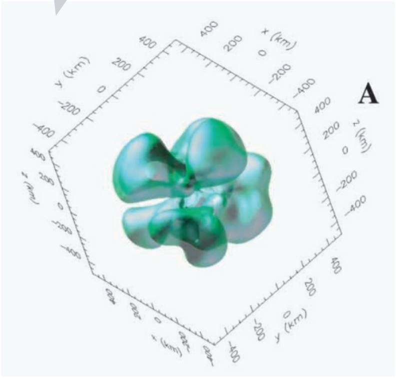
1985 Bethe & Wilson

SN1987A

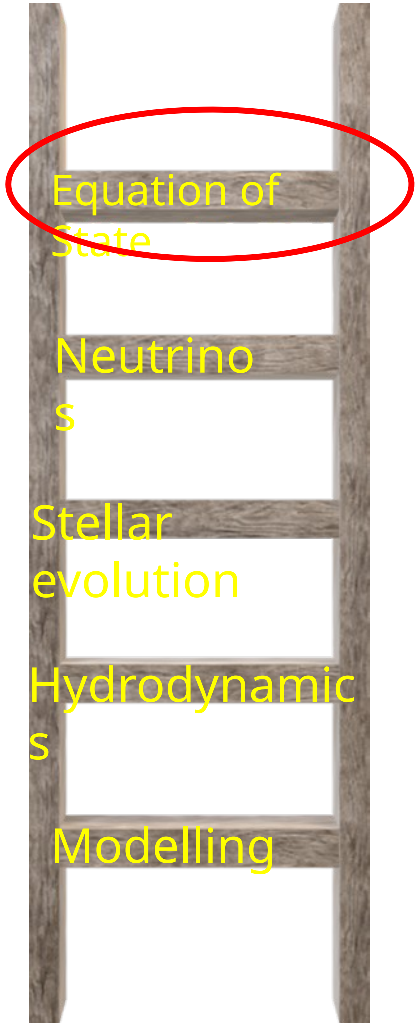
Early 2000s (first 3D simulation)

In addition, the new problem of developing a more detailed picture of the happenings in a super-nova now confronts us. With all reserve we advance the view that a super-nova represents the transition of an ordinary star into a *neutron star*, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the


Cover of TIME magazine



3D by Fryer & Warren (2002)

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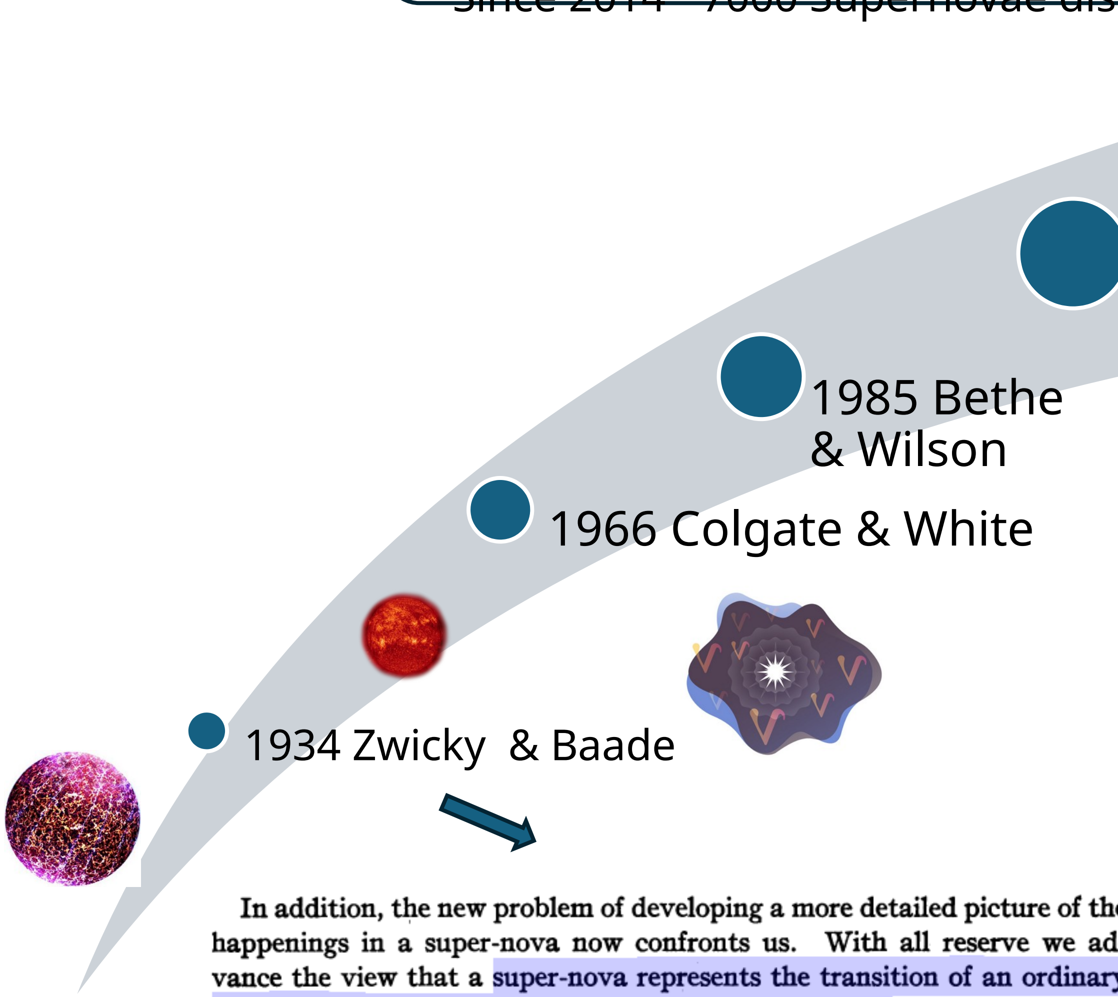
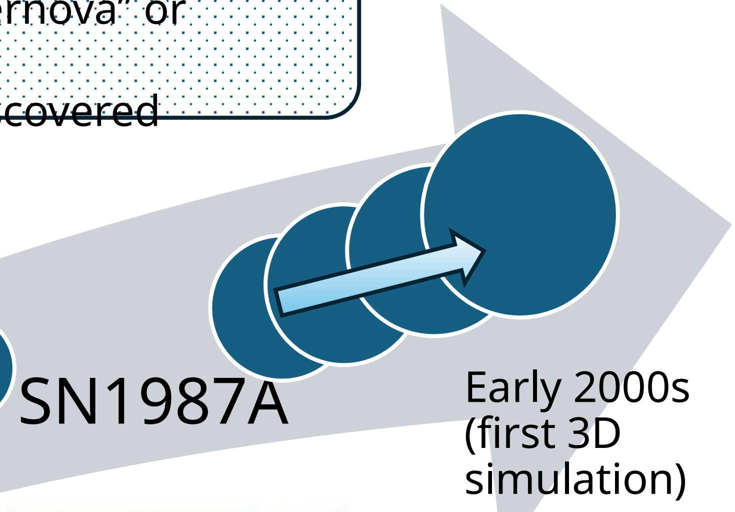
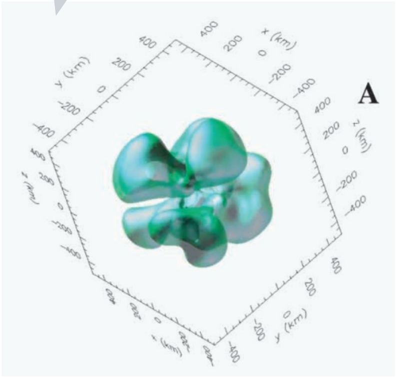




Cover of TIME magazine

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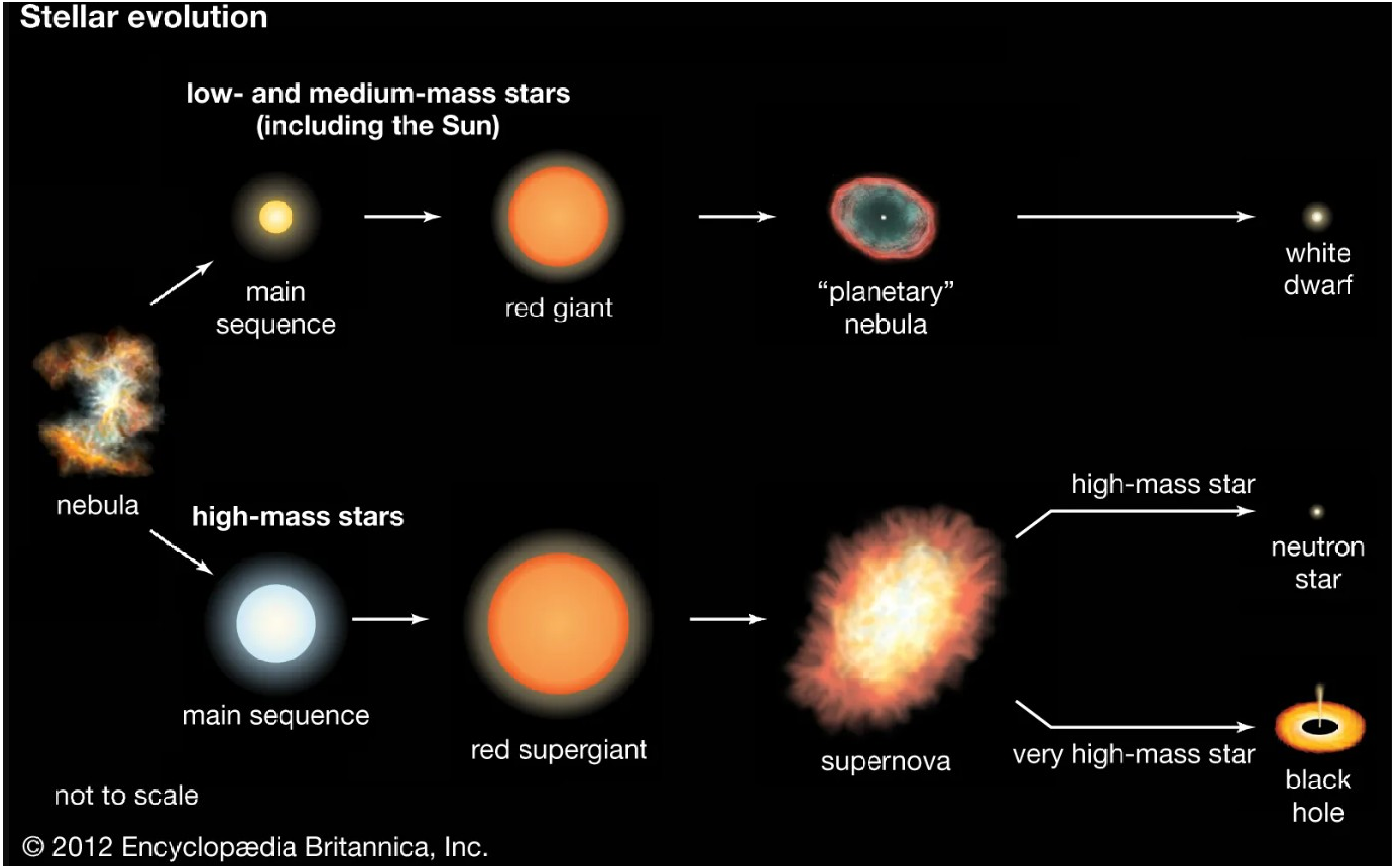
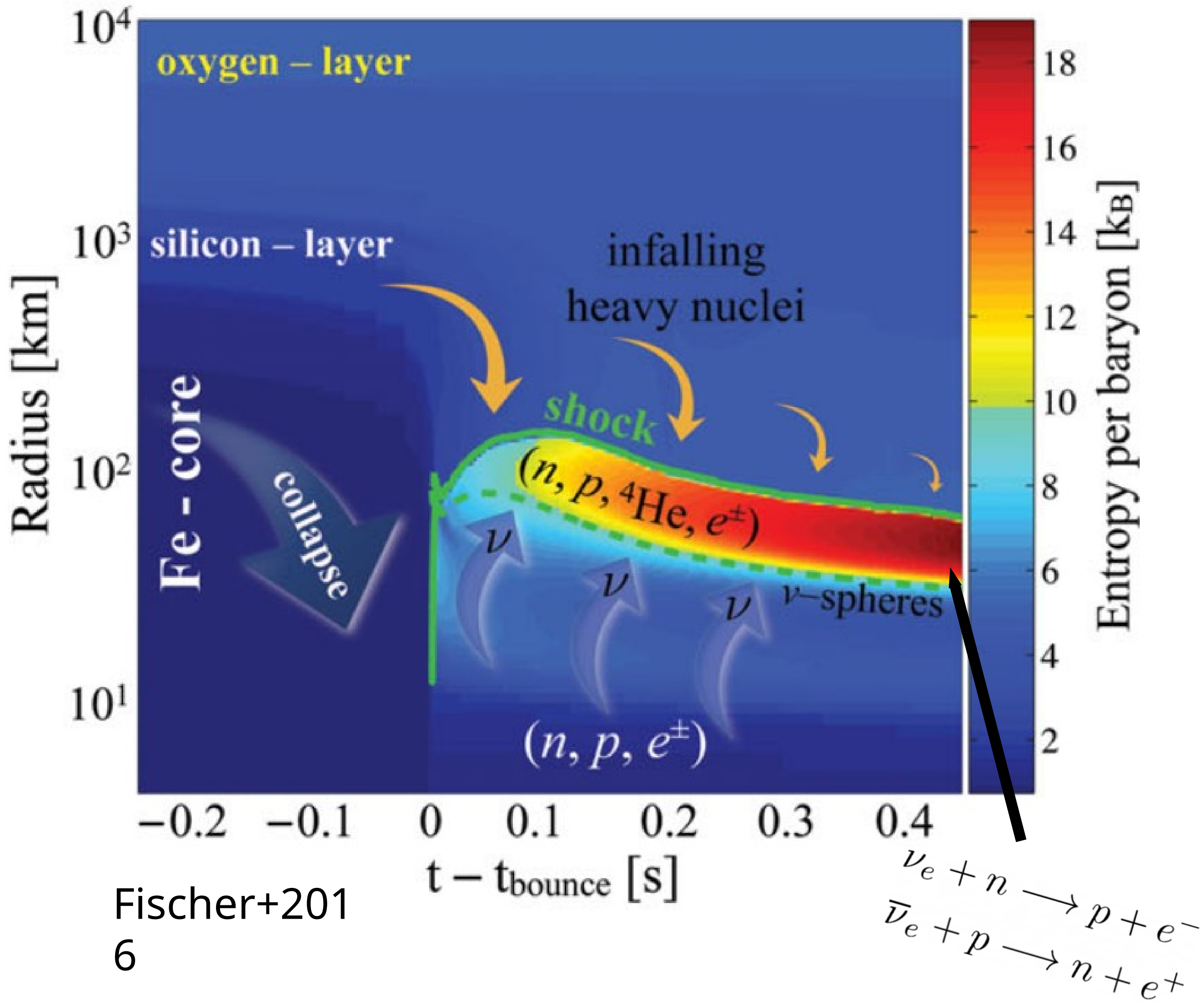

Stellar evolution
low- and medium-mass stars
(including the Sun)
main
sequence
red giant
"planetary"
nebula
white
dwarf
nebula
high-mass stars
main sequence
red supergiant
supernova
high-mass star
neutron
star
very high-mass star
black
hole
not to scale
© 2012 Encyclopædia Britannica, Inc.

# I: Collapse phase

- Iron core: No exotherm reaction possible
  - Iron core accreting material from Silicon shell burning
  - Exceeds Chandrasekhar mass limit
  - “Time zero” of what (can) be called a CCSN
  - Core collapses

Collapse further accelerated by electron captures on Iron peak nuclei




Fischer+2016

# II: Core-bounce

## Around <u>nuclear saturation density</u>:

Neutrinos become trapped

à Iron core can either form a BH or a NS

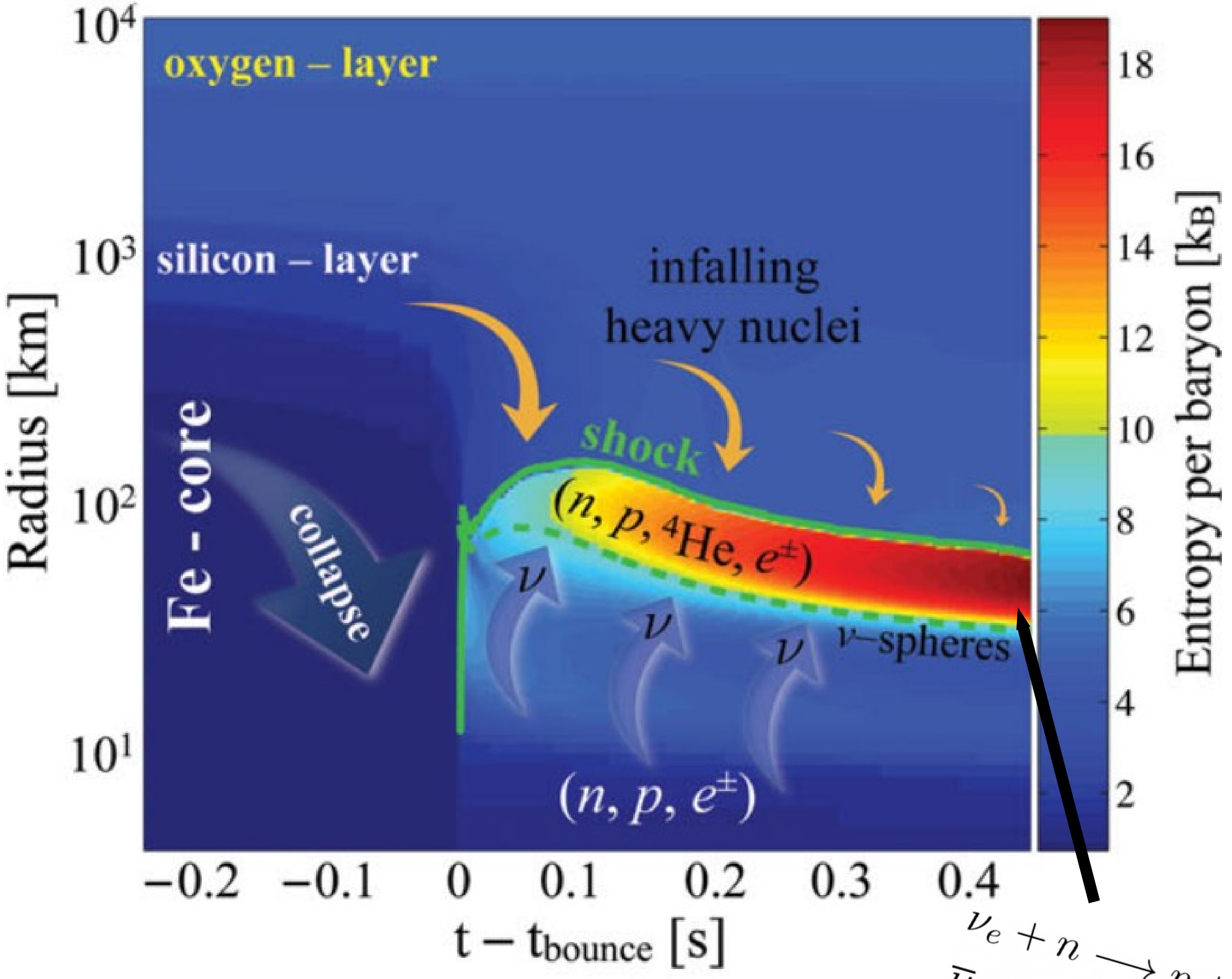
à Core decelerates and bounces

à Shock wave forms ~1e51 erg

# III: Explosion phase

Shock wave stalls…

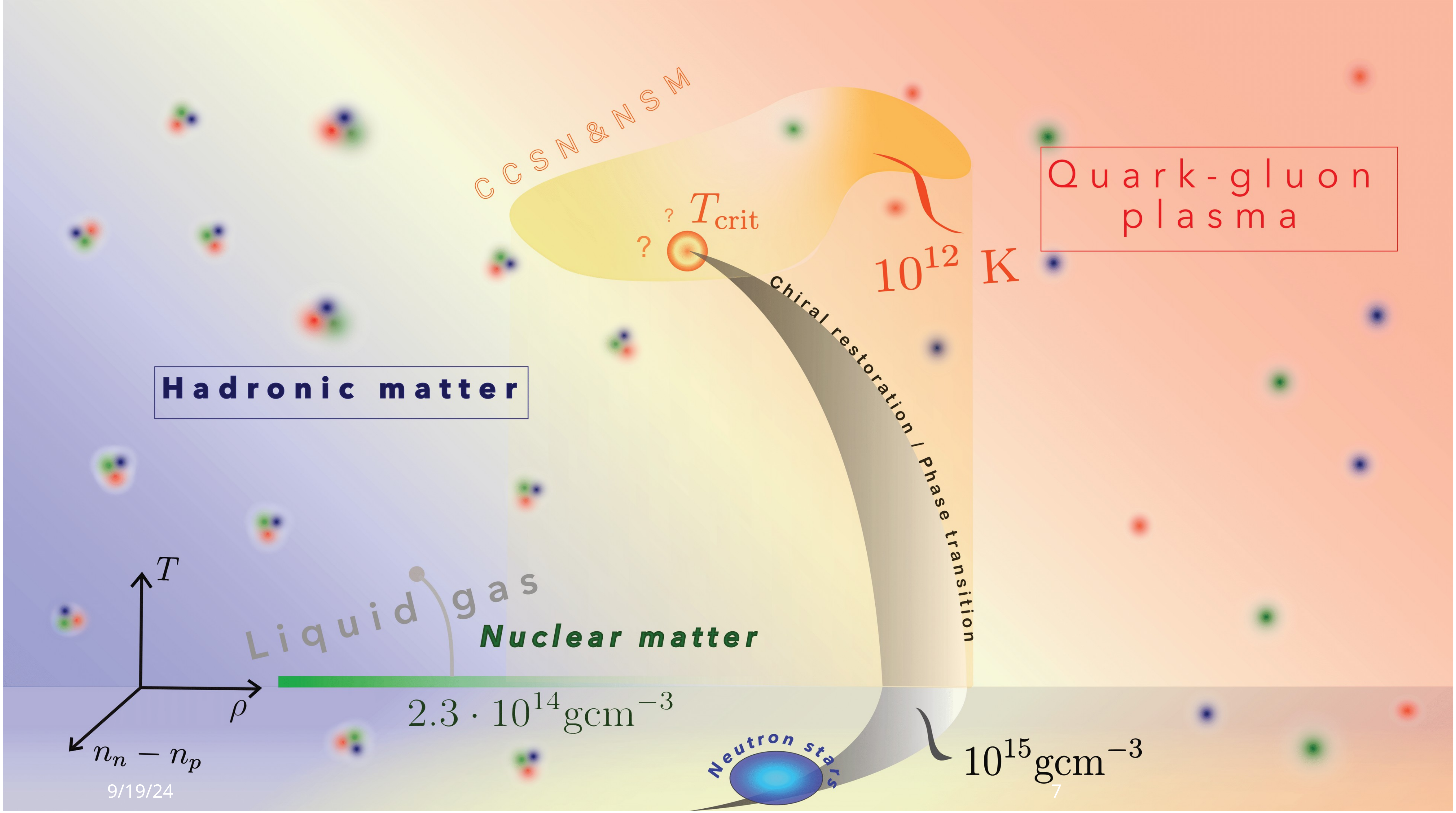
- “real explosion” sets in 100-200ms post-bounce
- Driven by neutrino heating behind the shock
- Explosion can outshine entire galaxy!
- Asymmetric effects pivotal



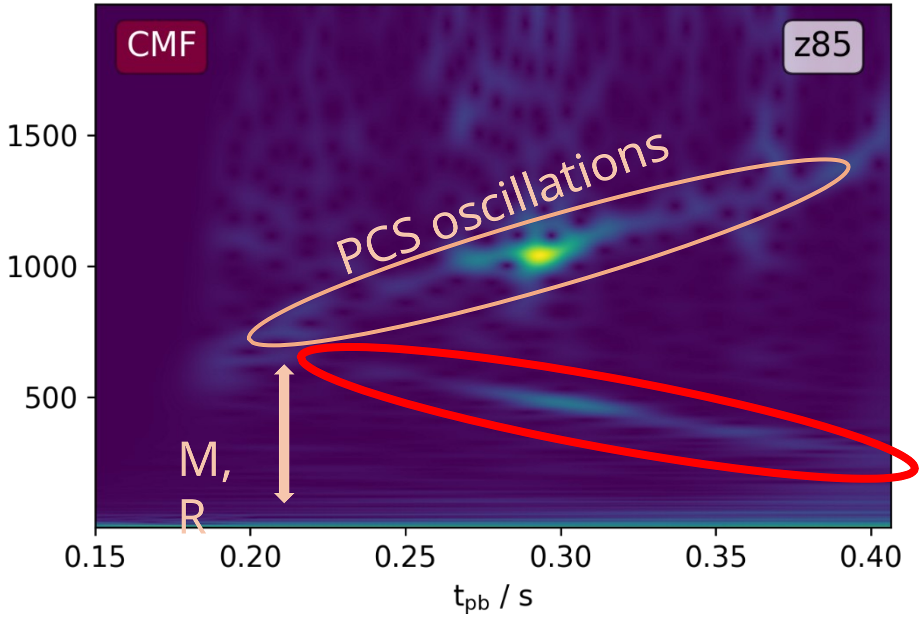

Fischer+2016

$$\nu_e + n \longrightarrow p + e^-$$

$$\bar{\nu}_e + p \longrightarrow n + e^+$$

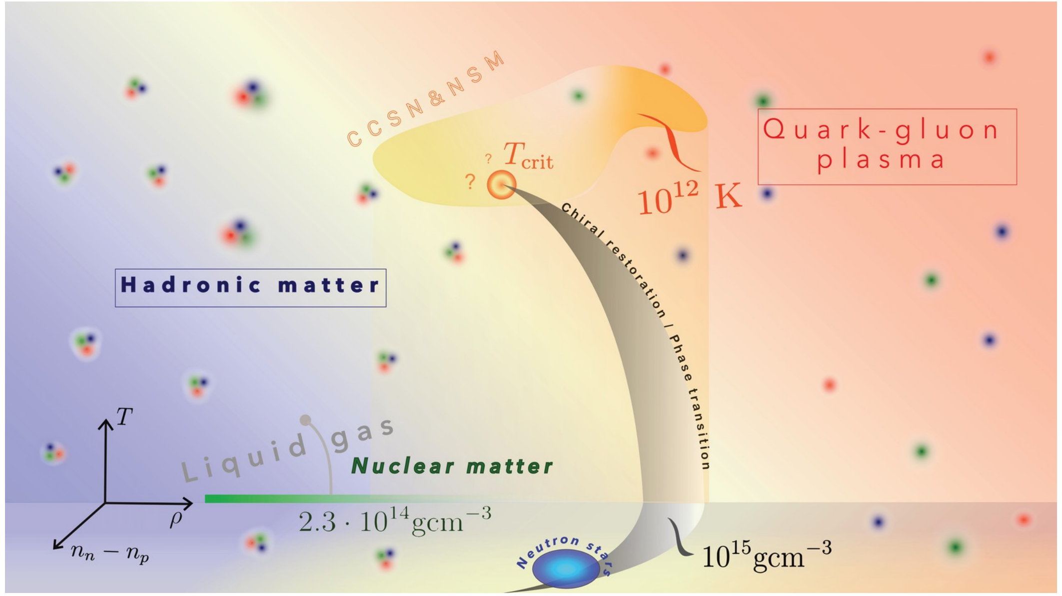


CCSN & NSM
? $T_{\rm crit}$
?
$10^{12}$ K
Quark-gluon plasma
Chiral restoration / Phase transition
Hadronic matter
$T$
$\rho$
$n_n - n_p$
Liquid
gas
Nuclear matter
$2.3 \cdot 10^{14} \mathrm{gcm}^{-3}$
Neutron stars
$10^{15} \mathrm{gcm}^{-3}$



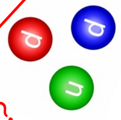

PCS evolution

Constrain EoS

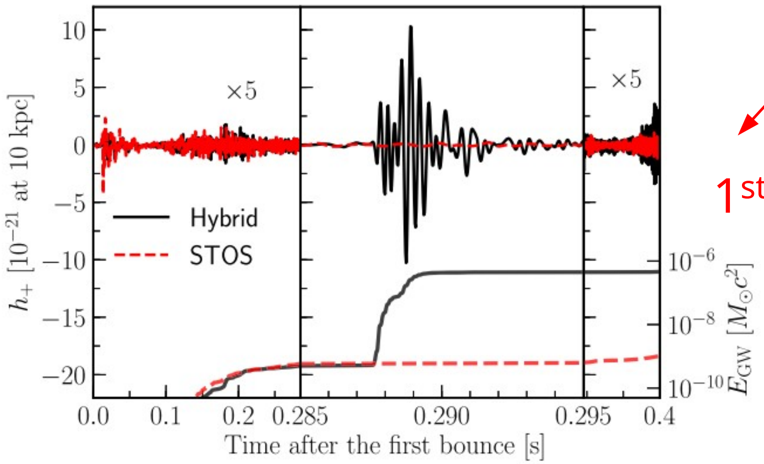



$$f_{\text{peak}} \approx \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{1.1\frac{m_n}{<E_\nu>}}\left(1-\frac{GM}{Rc^2}\right)^2$$

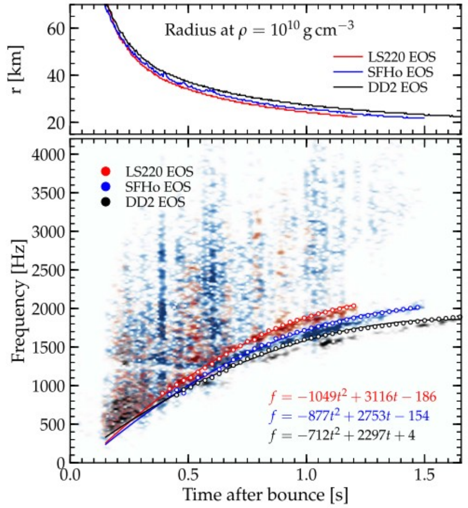
Free quarks?



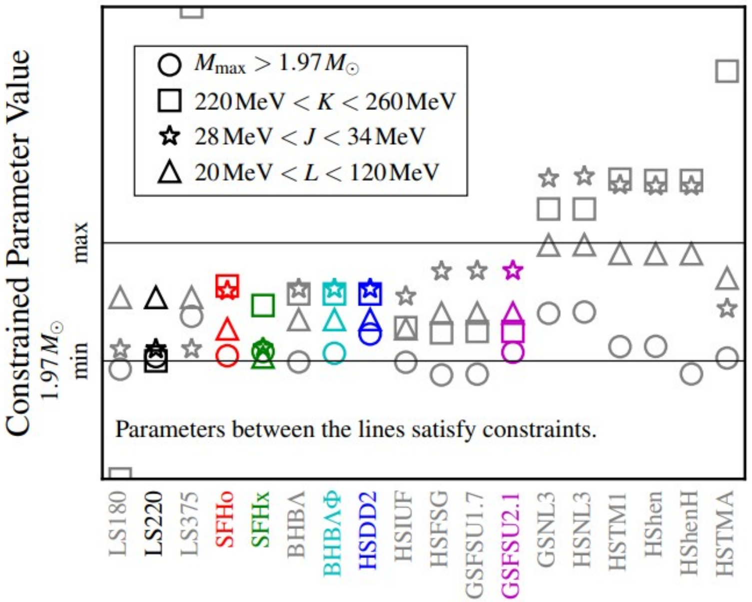

$1^{st}$ order PT




(Zha et al., 2020)




(Morozova et al., 2018)

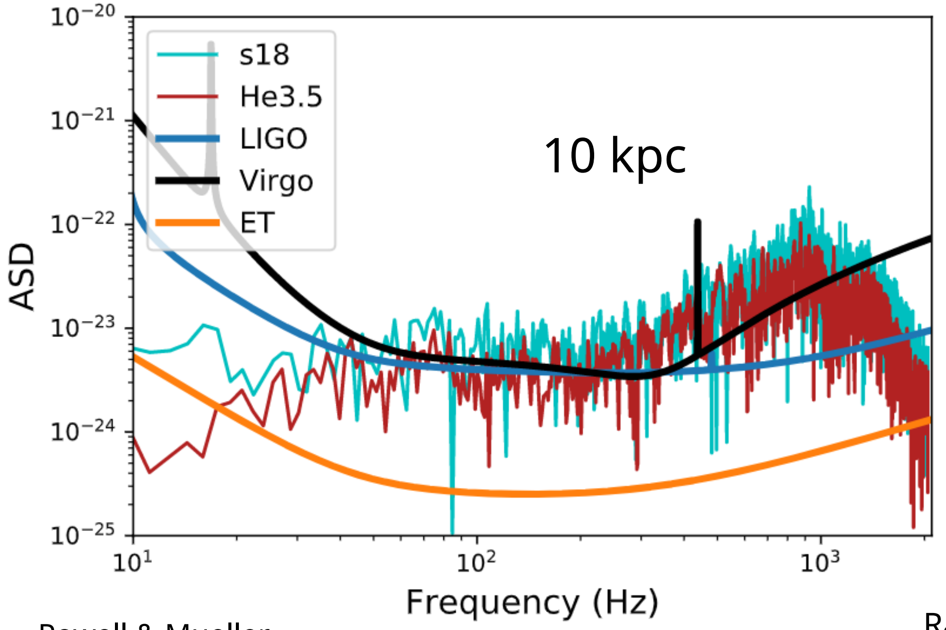





(Richers et al., 2017)

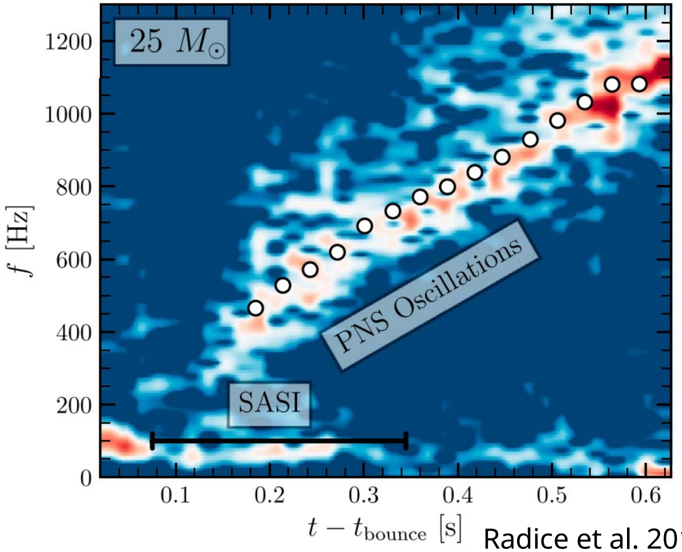
# Gravitational Waves from Core-Collapse Super

- CCSNe ~3 event per century in our Galaxy
- Observable distance ~10-20 kpc
- Time changing mass quadrupole moment
- GWs provide access to compact inner core

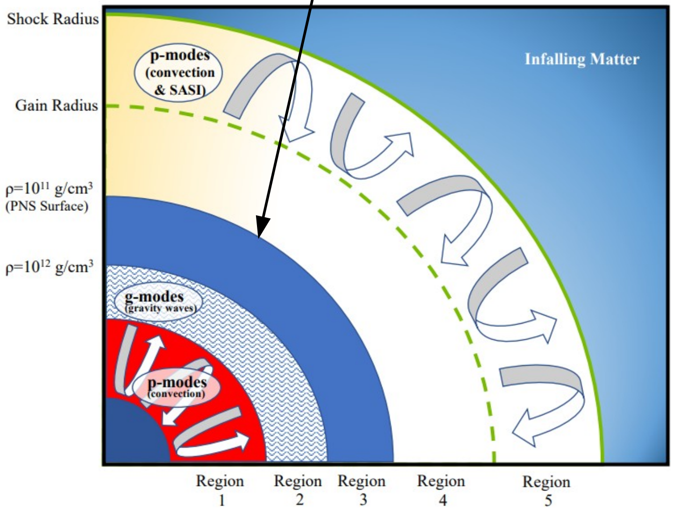



Powell & Mueller (2018)

Radius of Proto-Compact Stars ~40km to ~10km
Mass accretion on PCS: ~1.4-2$M_\odot$




Radice et al. 2019




Mezzacappa et al. 2020

- Different regions susceptible to different mode oscillations (p-,g- f-modes)
- Positive entropy gradient: g-mode oscillations
- Characteristic frequency of g-modes: Brunt Väisälä frequency:

$$\omega_{\rm BV}^2 = \frac{d\alpha}{dr}\frac{\alpha}{\rho h \Phi^4}\cdot\left(\frac{1}{c_s^2}\frac{dP}{dr} - \frac{d\rho}{dr}\right)$$

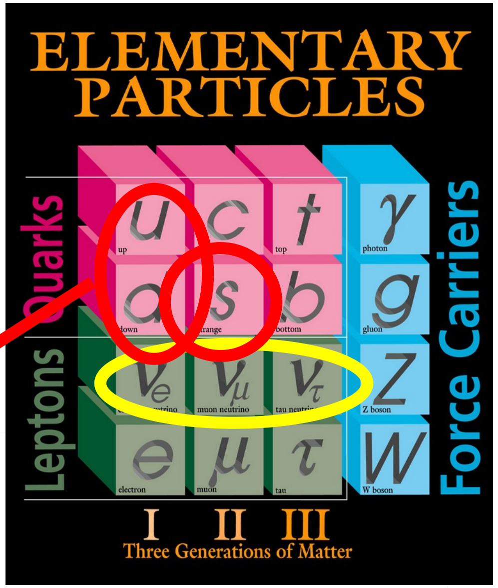
Stripy clouds

# Setup

**CoCoNut-FMT**

**Kepler**

Feed-in (1D)




Incorporated hadron-quark EoS into CoCoNuT-FMT

neutrinos.fnal.gov

- **Godunov-based** finite-volume solver (Dimmelmeier et al. 2002; Müller et al. 2013)
- 3+1 splitting formalism; **CFC approximation**
- Three flavour **Fast Multigroup Transport** (FMT)

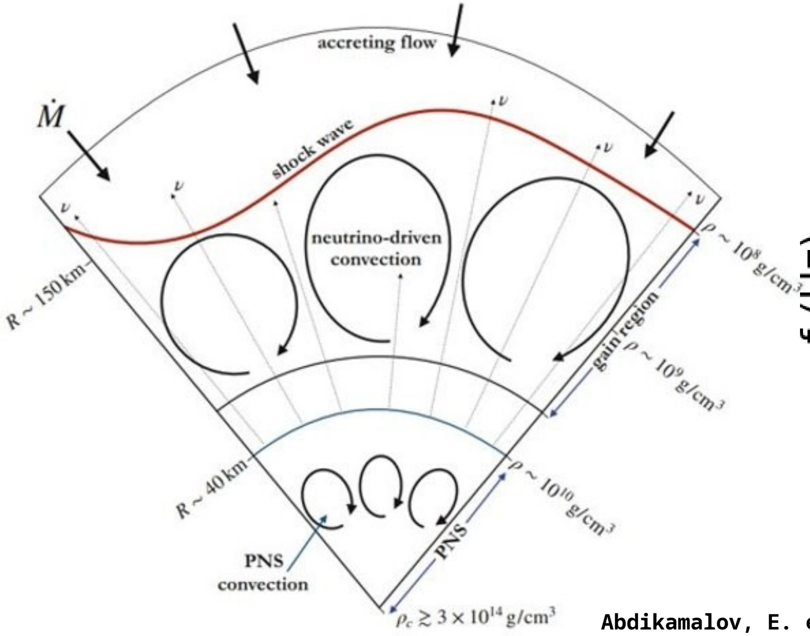
**Up to 50 million core hours ☺**

Image: NCI

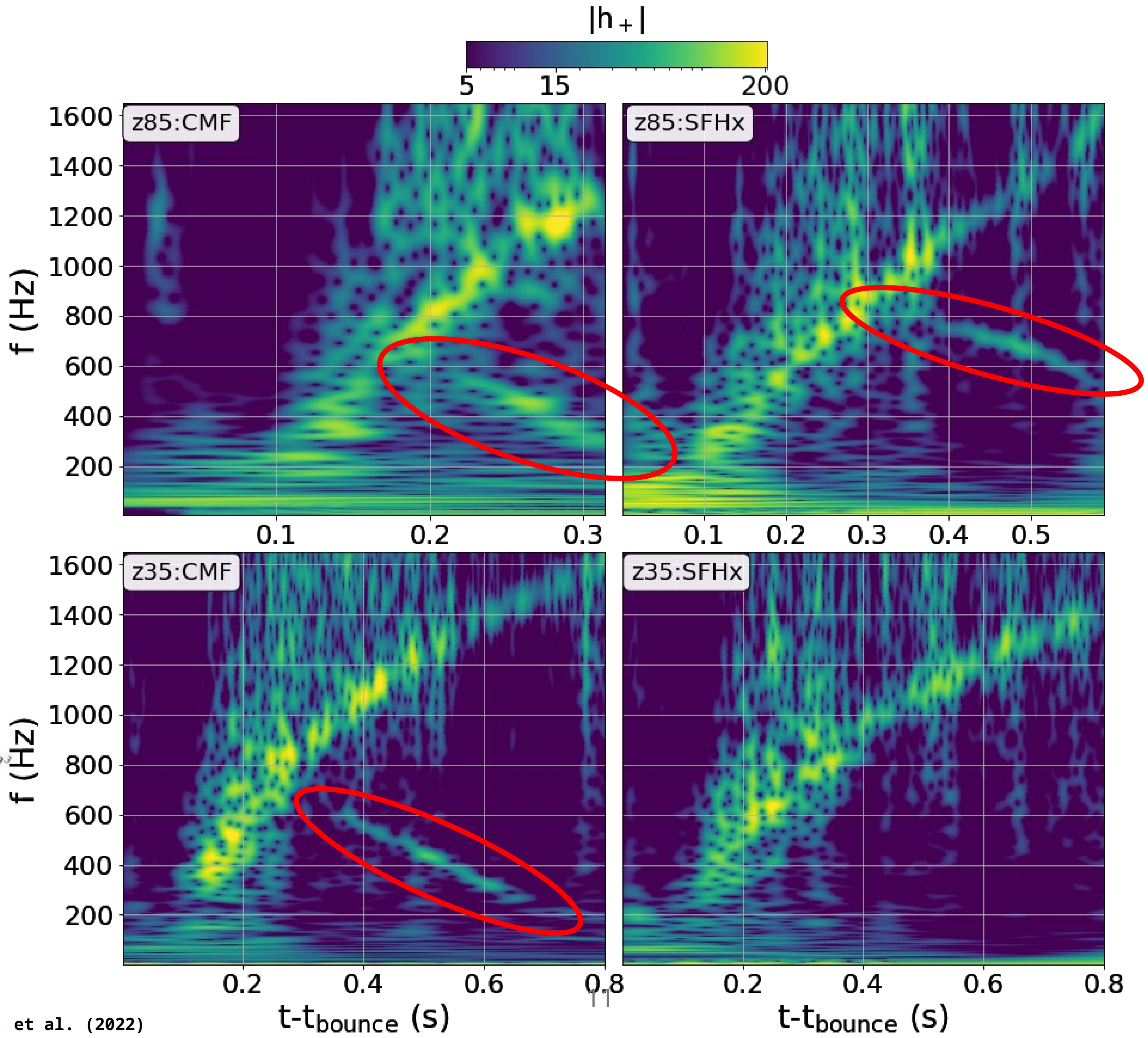
*CoCoNuT-FMT: Müller et al. (2010), Müller & Janka (2015)*
*Kepler: Weaver et al. (1978), Heger & Woosley (2010)*

- Gravitational wave signals show lower frequency g-modes
- Frequency depends on Equation of State
    1. Where is signal originating from?
    2. No signal in z35:SFhx?
    3. Lower frequencies in CMF?

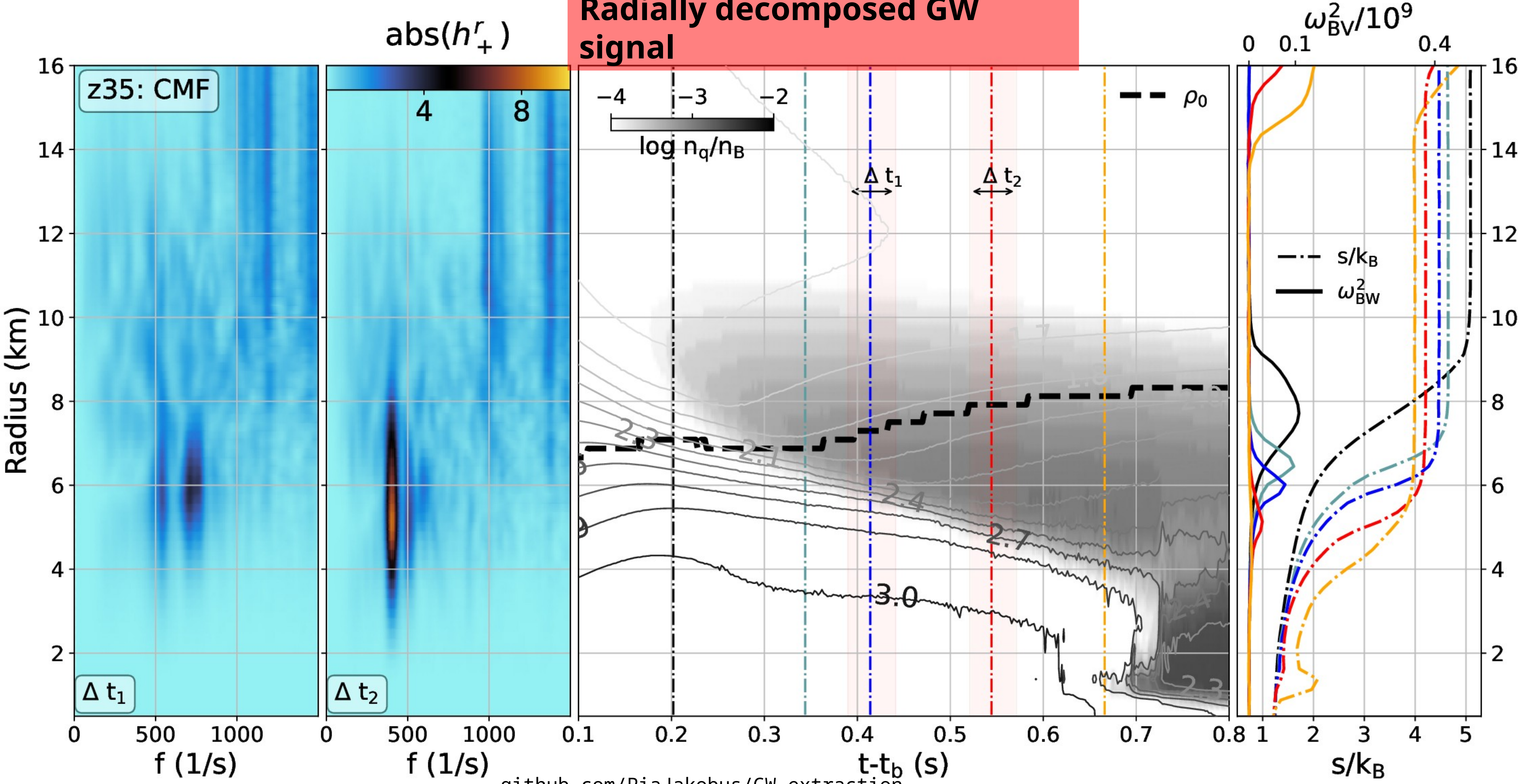
1) Where is the signal originating from?



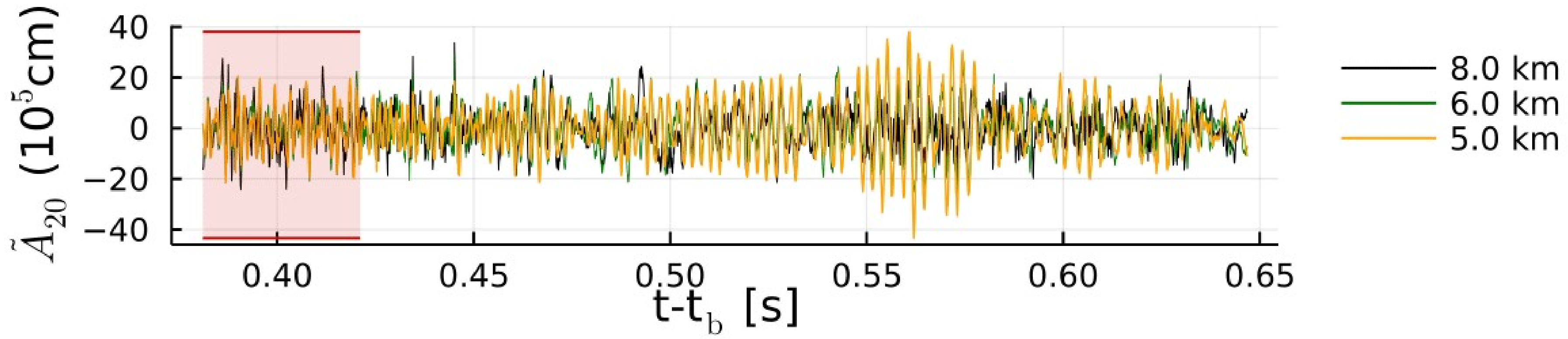

Abdikamalov, E. et al. (2022)

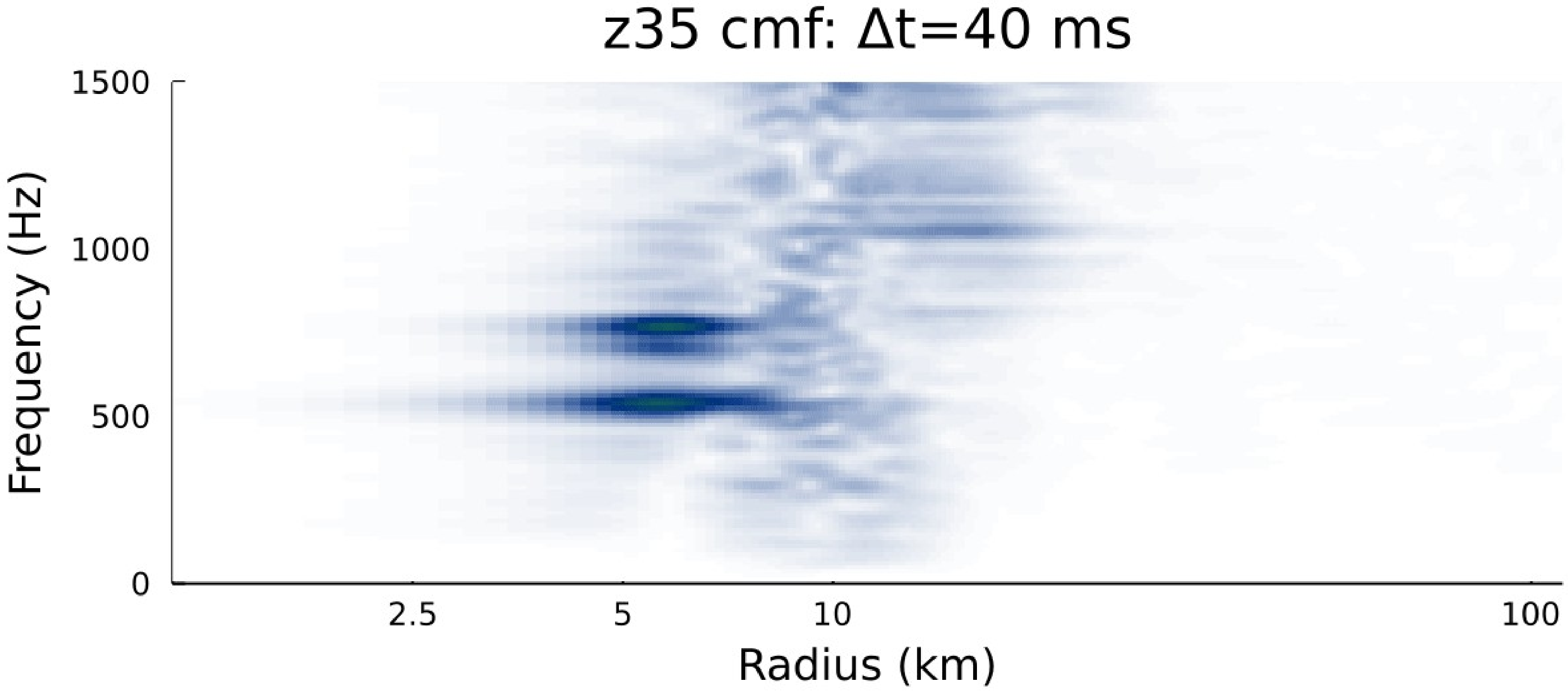


# Radially decomposed GW signal




github.com/PiaJakobus/GW_extraction

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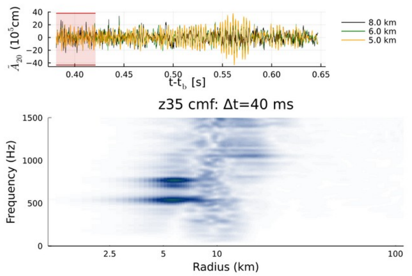
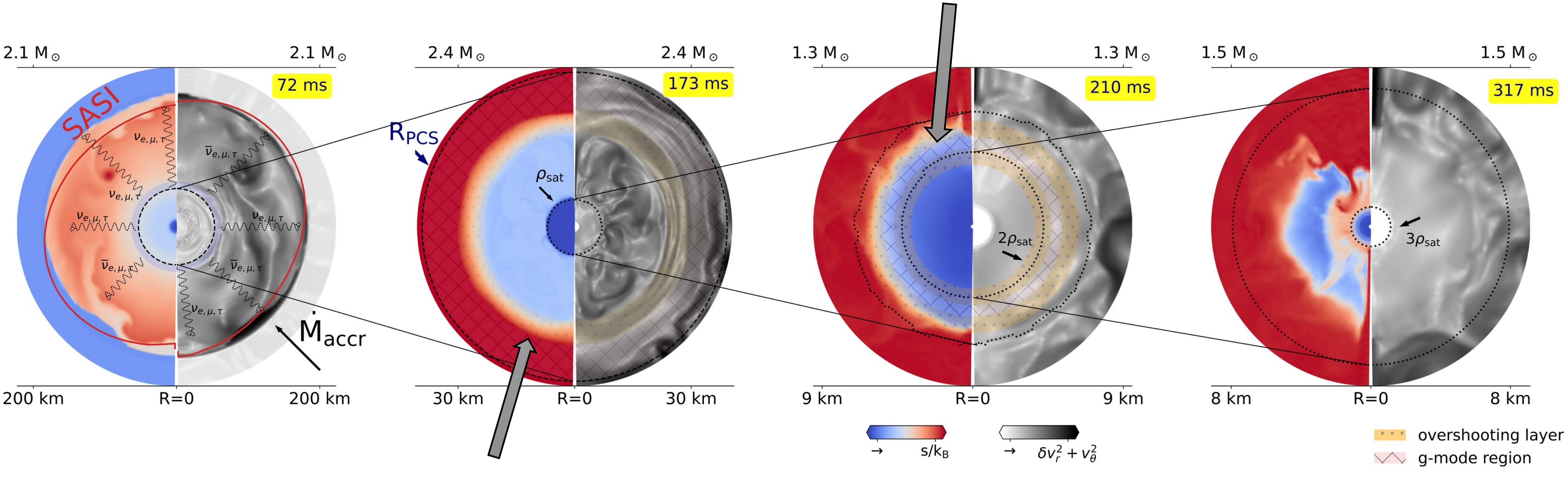
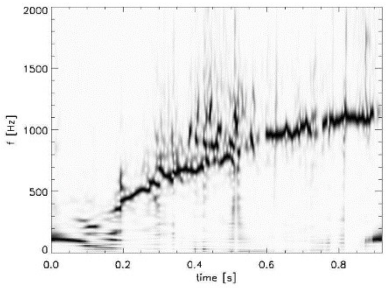
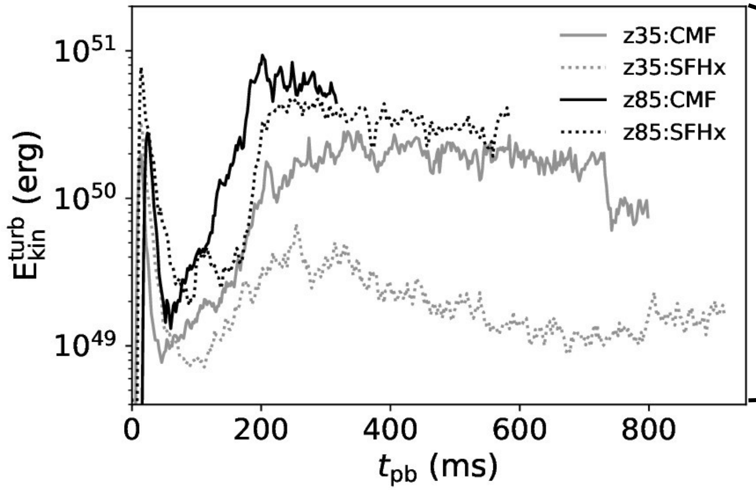

8.0 km
6.0 km
5.0 km
t-t_b [s]
z35 cmf: Δt=40 ms
Frequency (Hz)
Radius (km)


2.1 M⊙
2.1 M⊙
72 ms
SASI
Ṁaccr
200 km
R=0
200 km
2.4 M⊙
2.4 M⊙
173 ms
R_PCS
ρ_sat
30 km
R=0
30 km
1.3 M⊙
1.3 M⊙
210 ms
2ρ_sat
9 km
R=0
9 km
1.5 M⊙
1.5 M⊙
317 ms
3ρ_sat
8 km
R=0
8 km
s/k_B
δv_r^2 + v_θ^2
overshooting layer
g-mode region

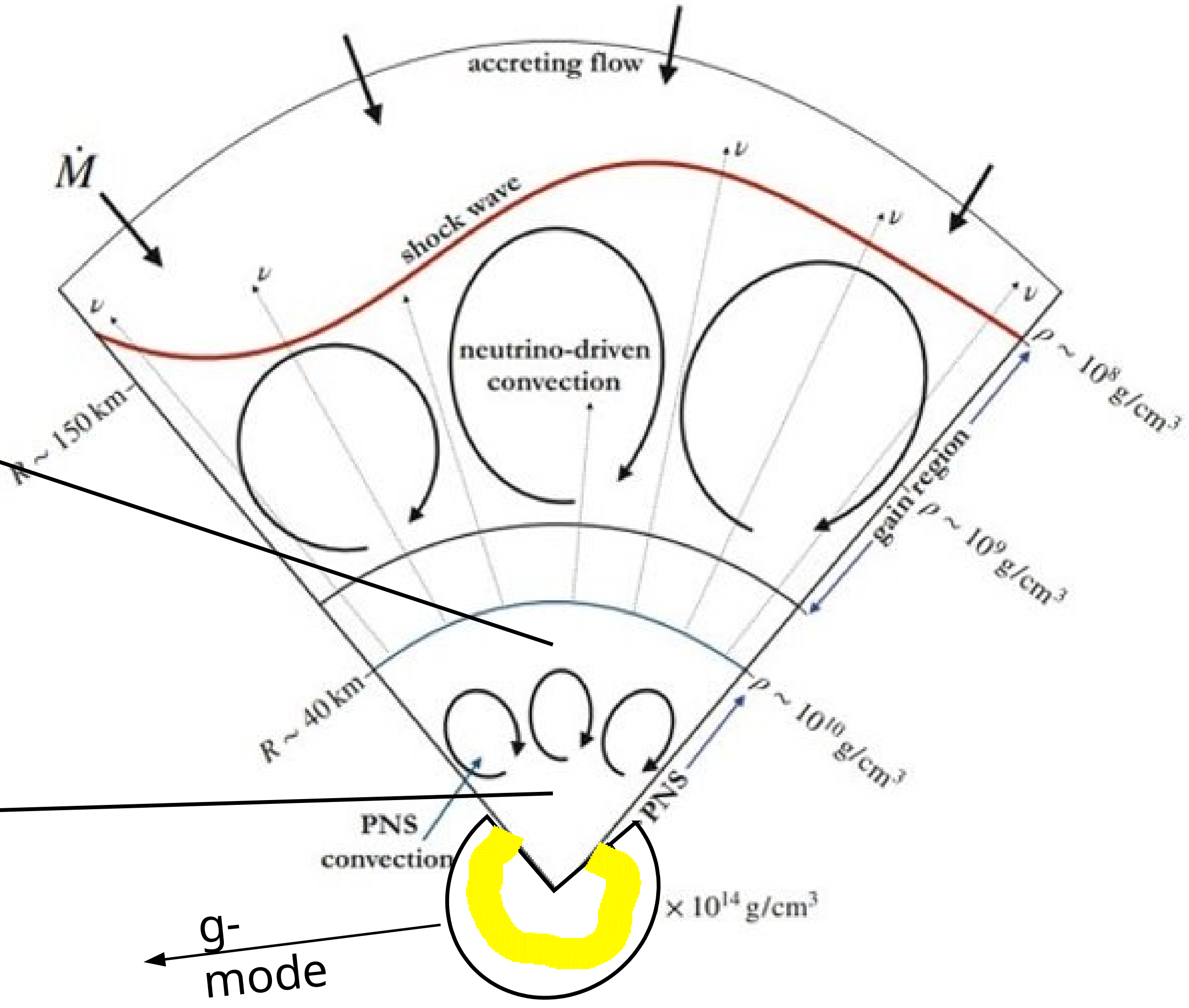

f [Hz]
time [s]

## Where is signal originating from?

1. g-mode “lives” in convectively stable PCS region beneath the PCS convection zone
2. Higher turbulent convective energies seen in CMF, particularly z35




$$E_{\rm kin}^{\rm turb} = \frac{1}{2}\int_{\rm PCS} \delta v^2 \rho r^2 {\rm d}V$$




(Abdikamalov et al. 2022)

No signal in z35:SFhx?

1.

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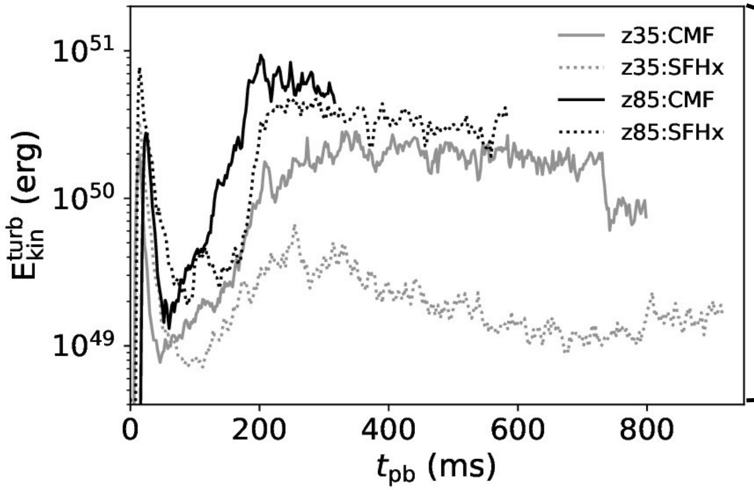


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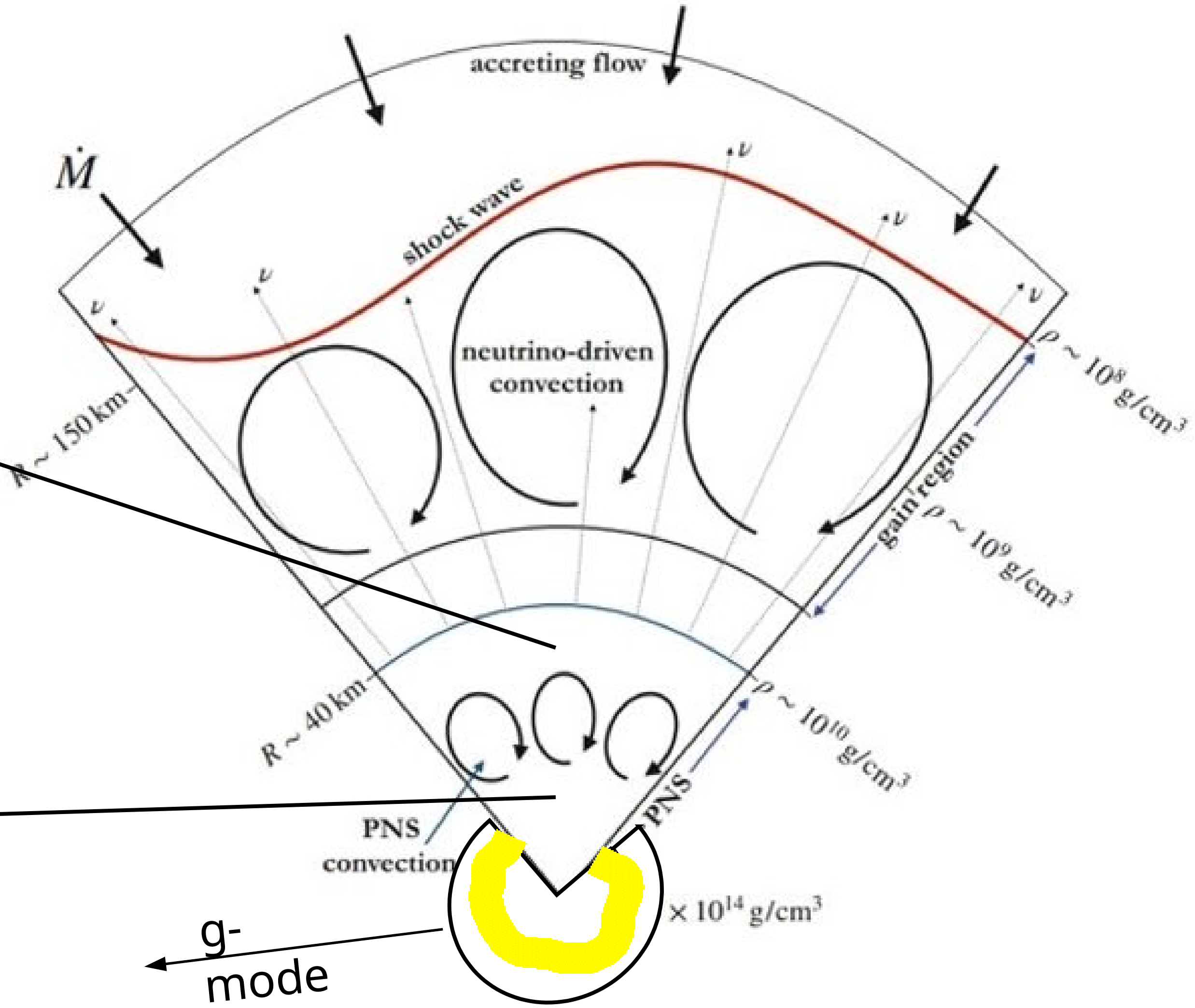
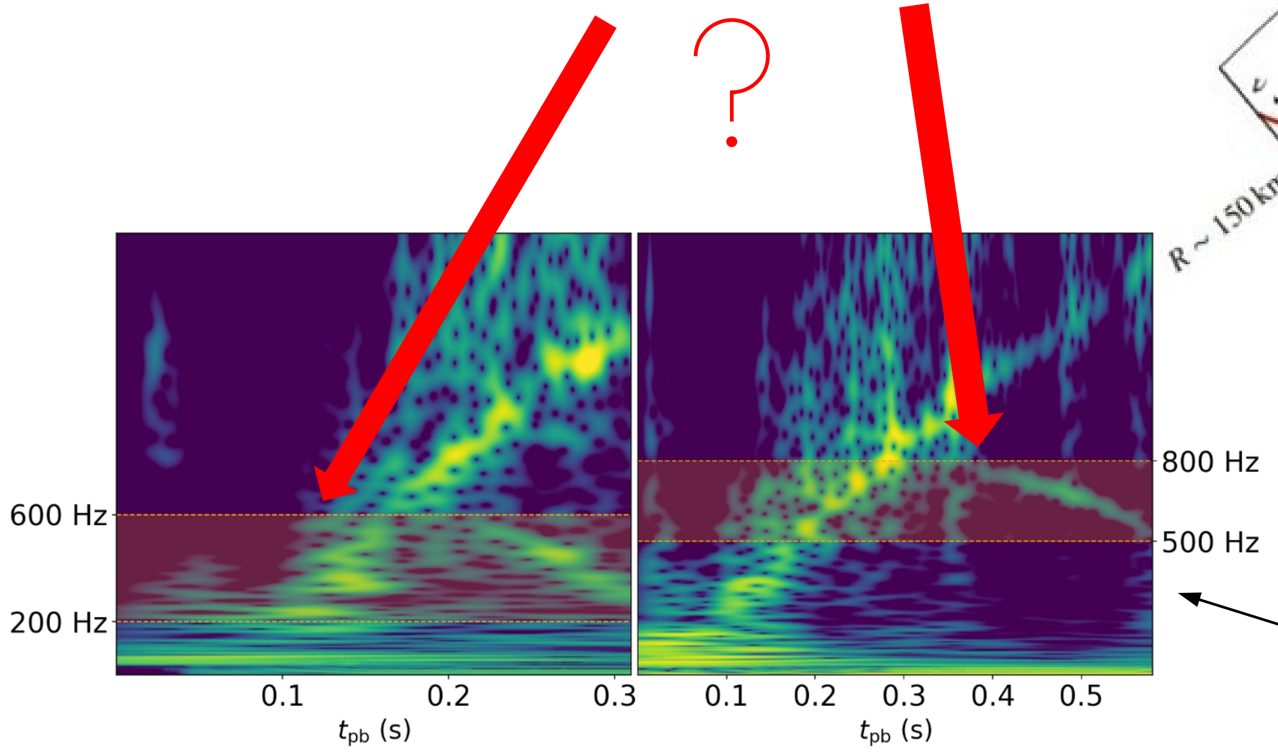
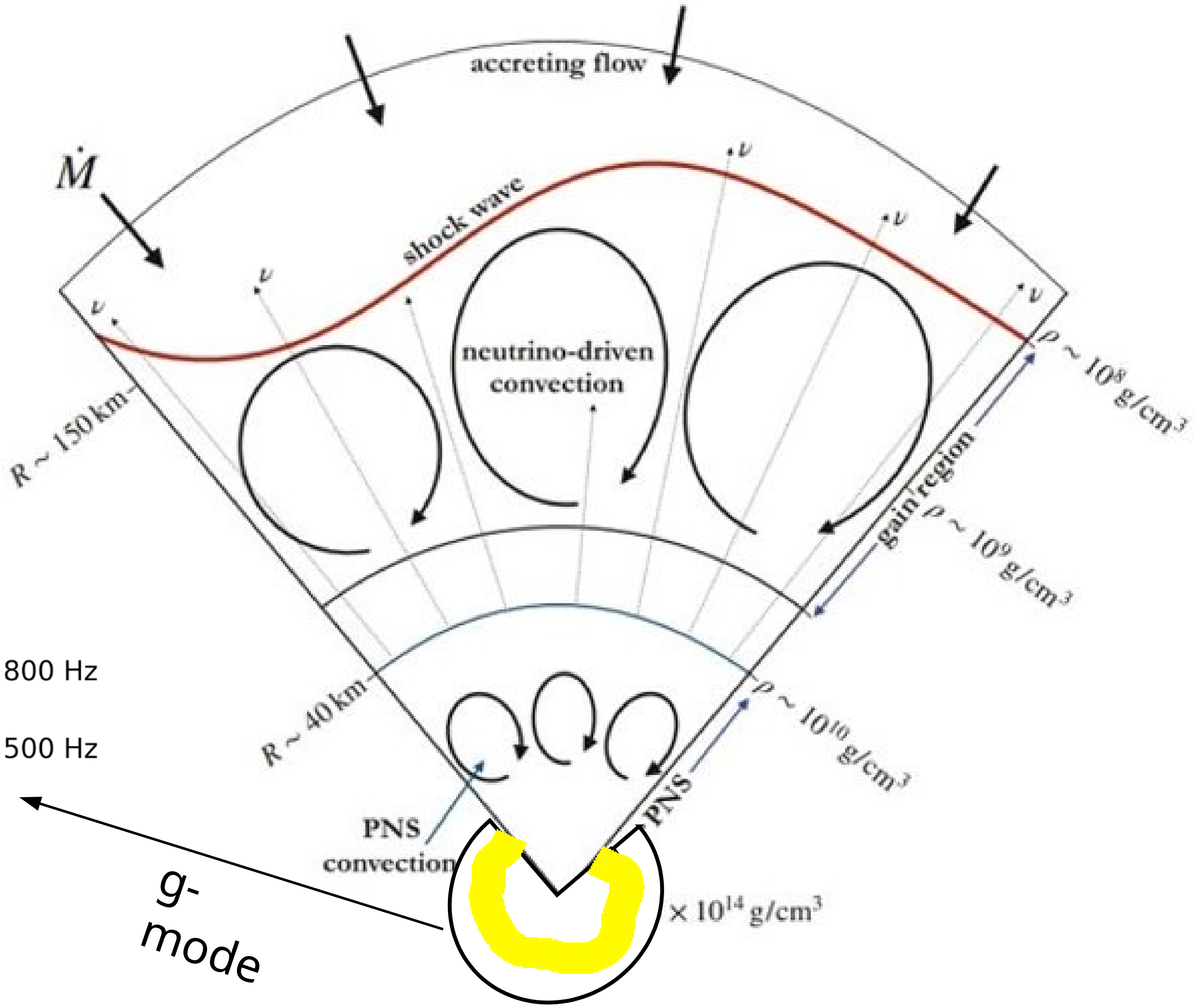



(Abdikamalov et al. 2022)

3. What EoS properties cause ~20% lower g-mode frequencies in CMF?



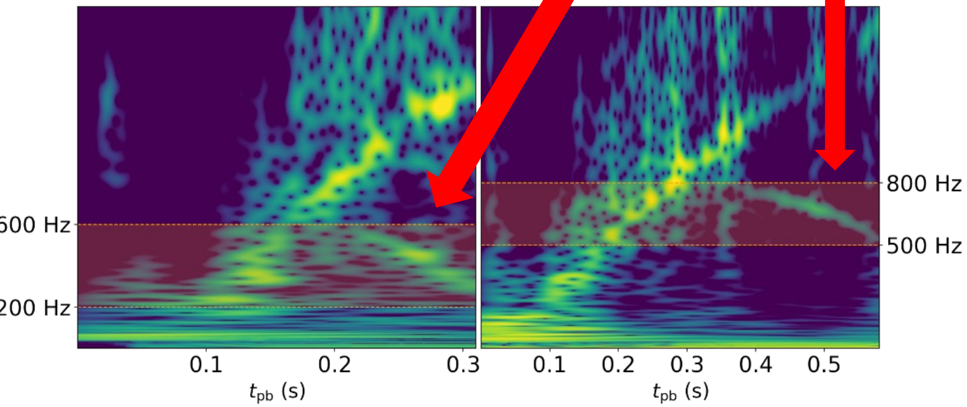



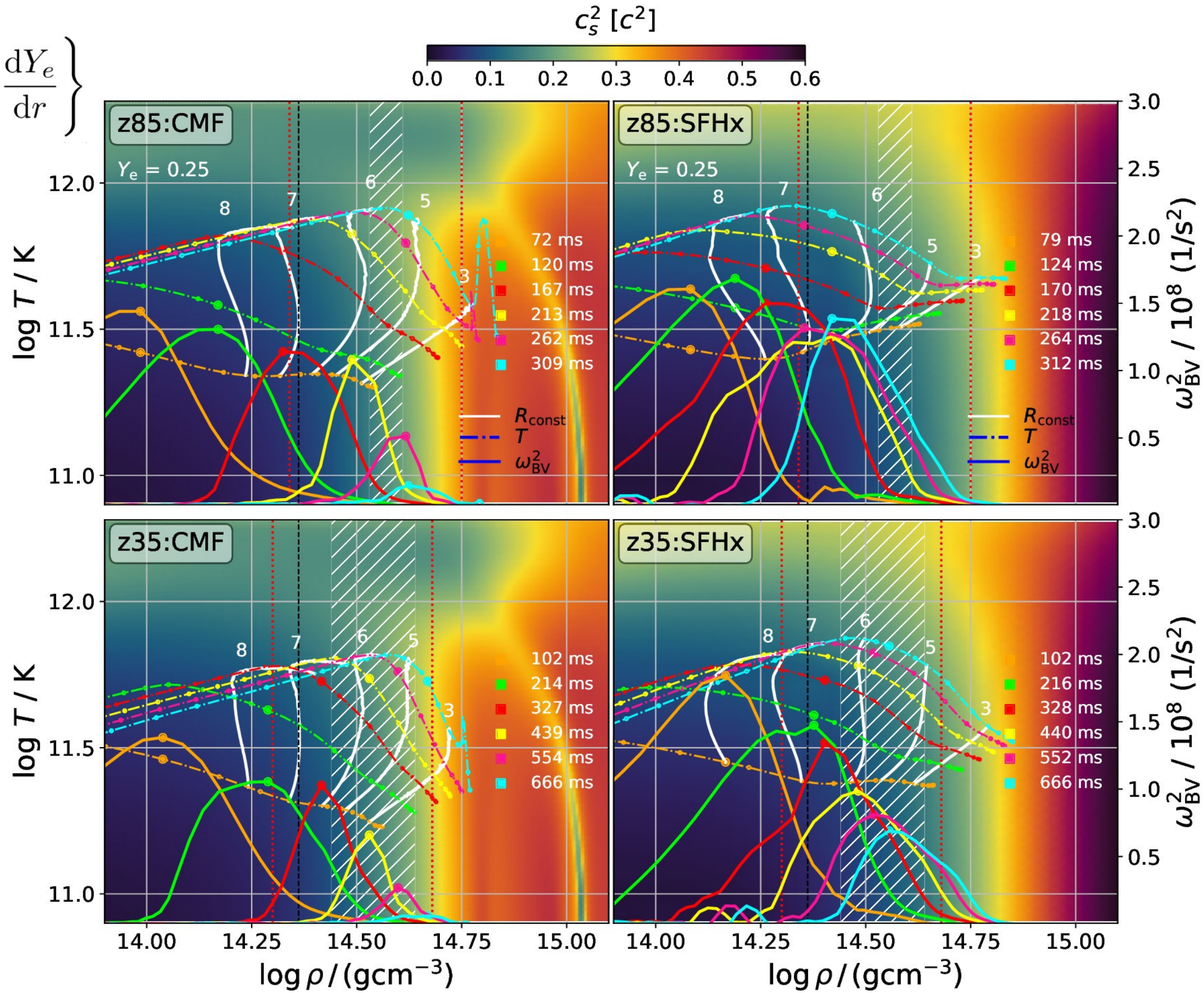

(Abdikamalov et al. 2022)

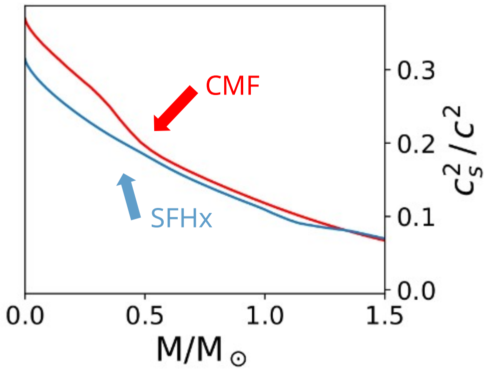
$$\omega_{\rm BV}^2 = \frac{d\alpha}{dr}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde\rho, Y_e}\frac{ds}{dr} + \left(\frac{\partial P}{\partial Y_e}\right)_{\tilde\rho, s}\frac{dY_e}{dr}\right\}$$

What EoS properties cause a ~20% lower g-mode frequency in CMF?

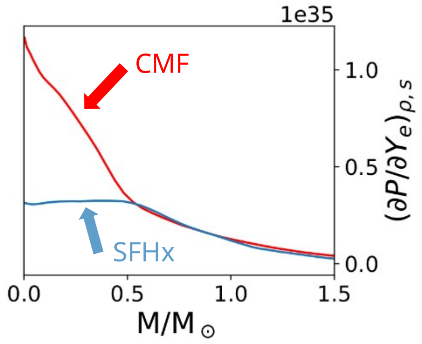
?



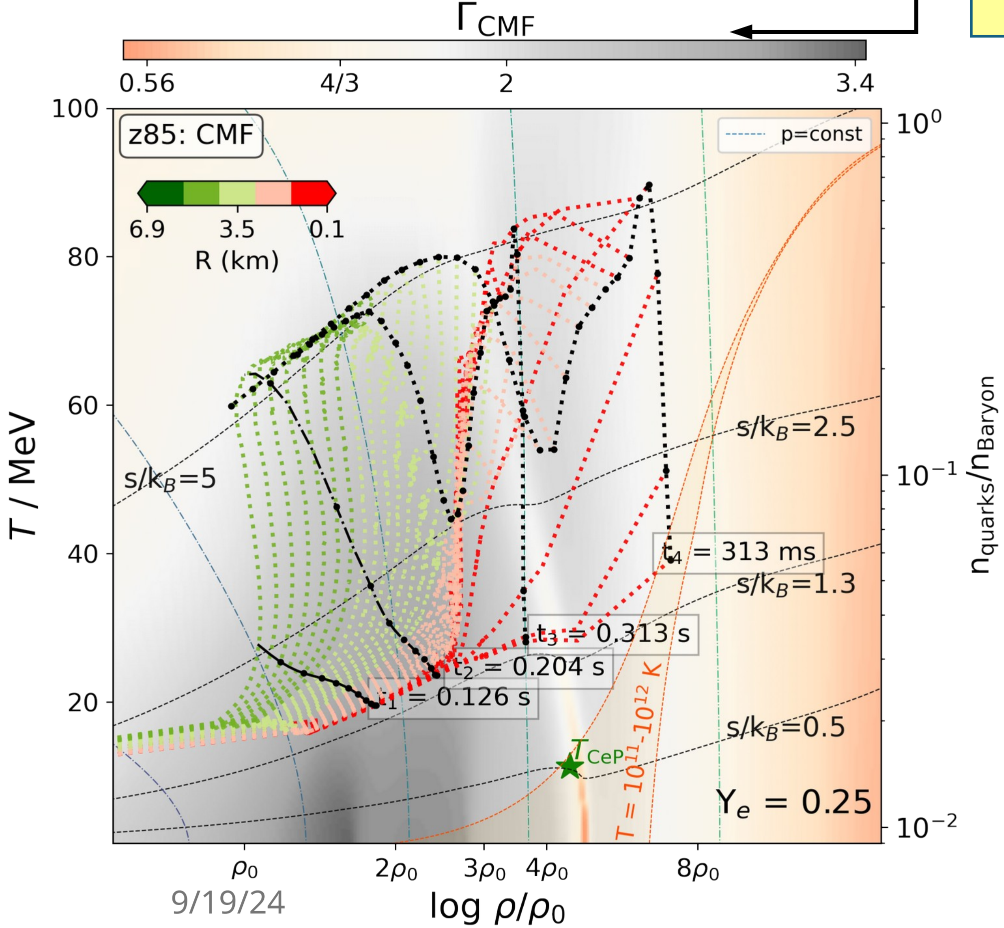



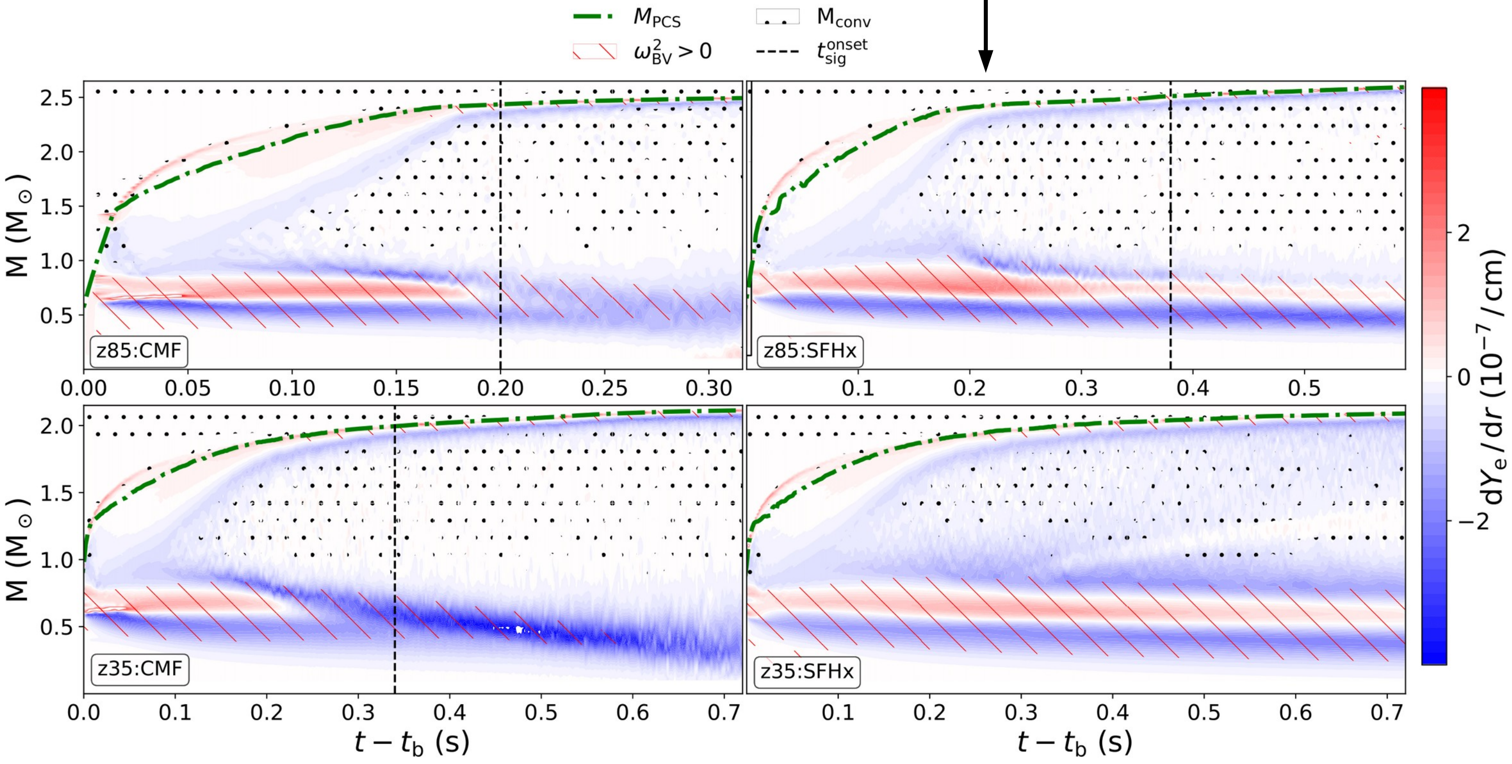


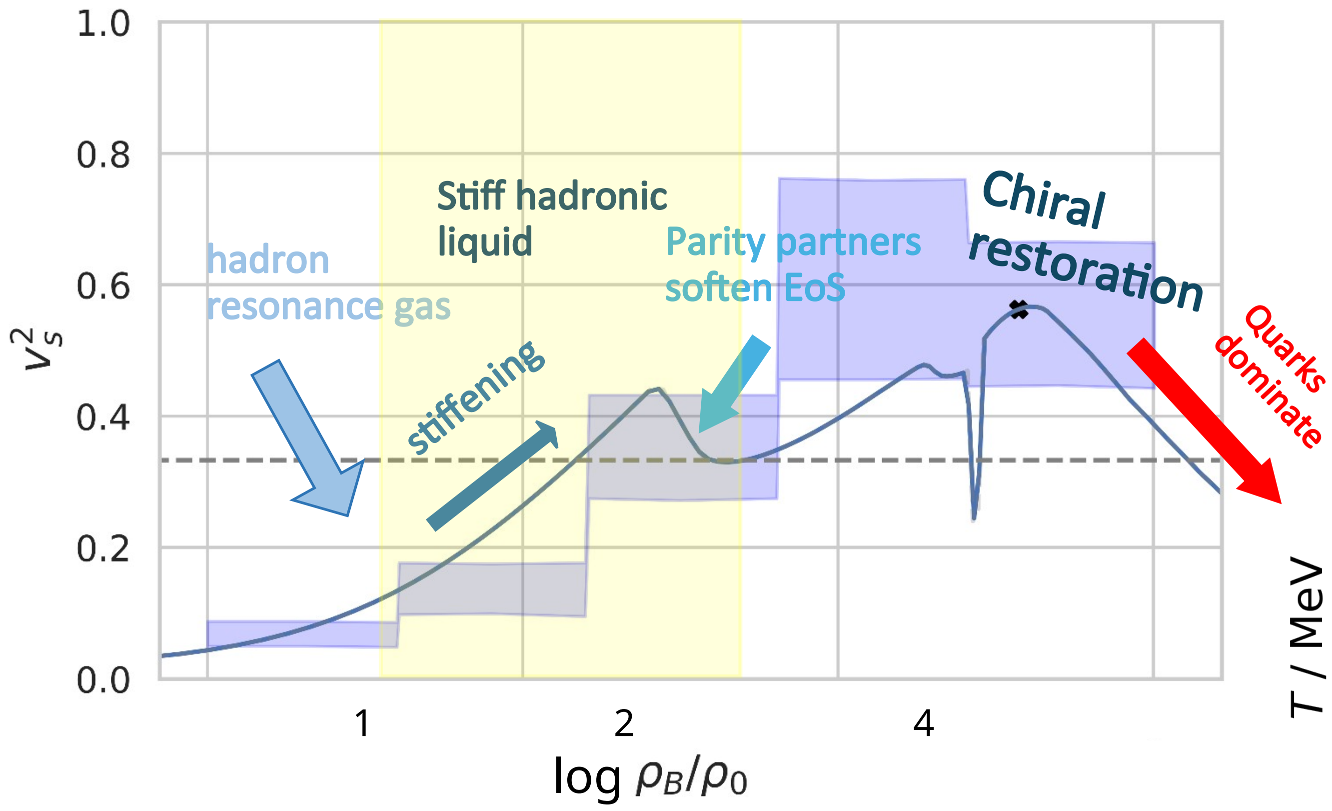

$$\omega_{\rm BV}^2 = \frac{\mathrm{d}\alpha}{\mathrm{d}r}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{\mathrm{d}s}{\mathrm{d}r}+\left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right\}$$

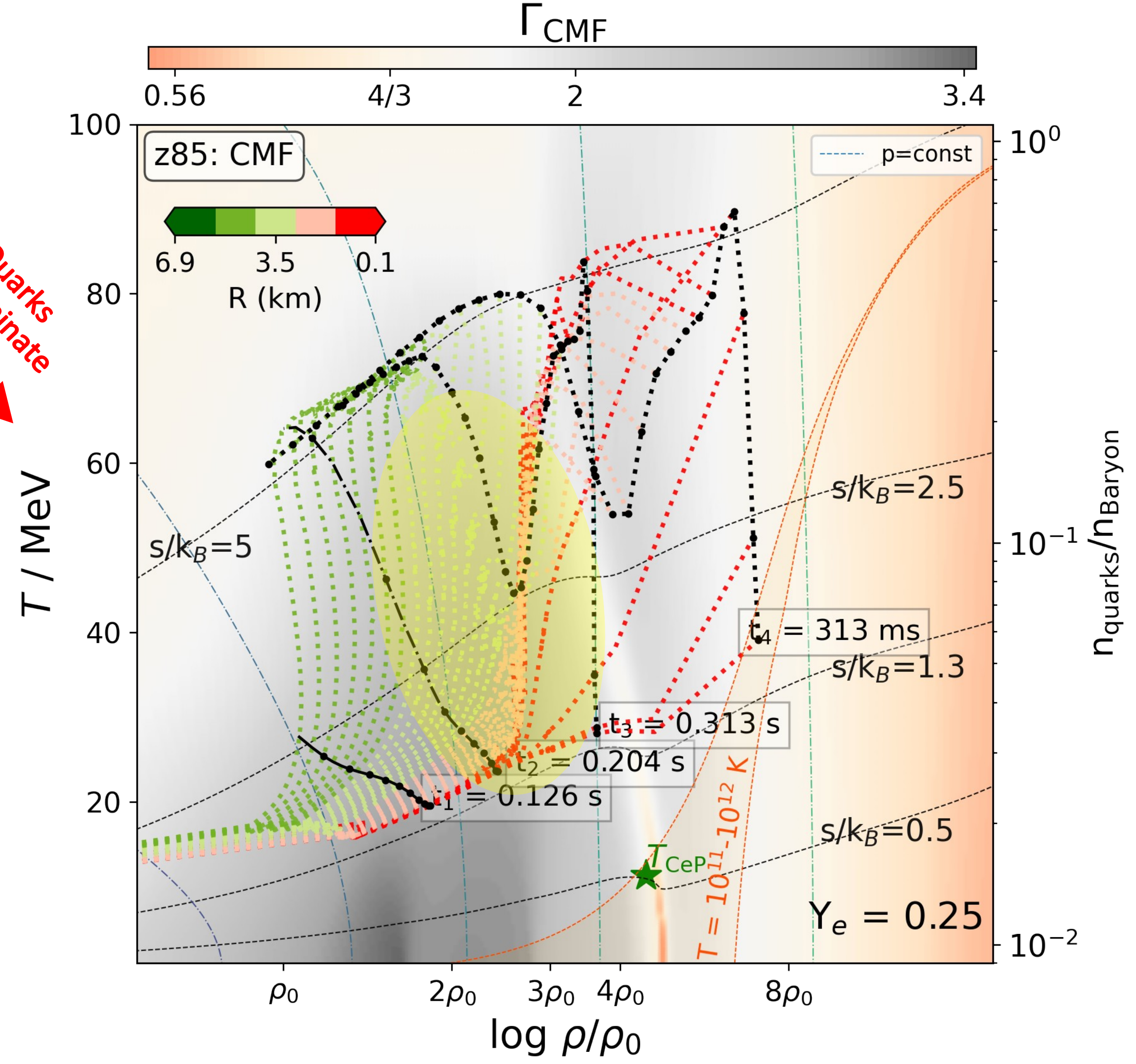



What EoS properties cause ~20% lower g-mode frequencies in CMF?

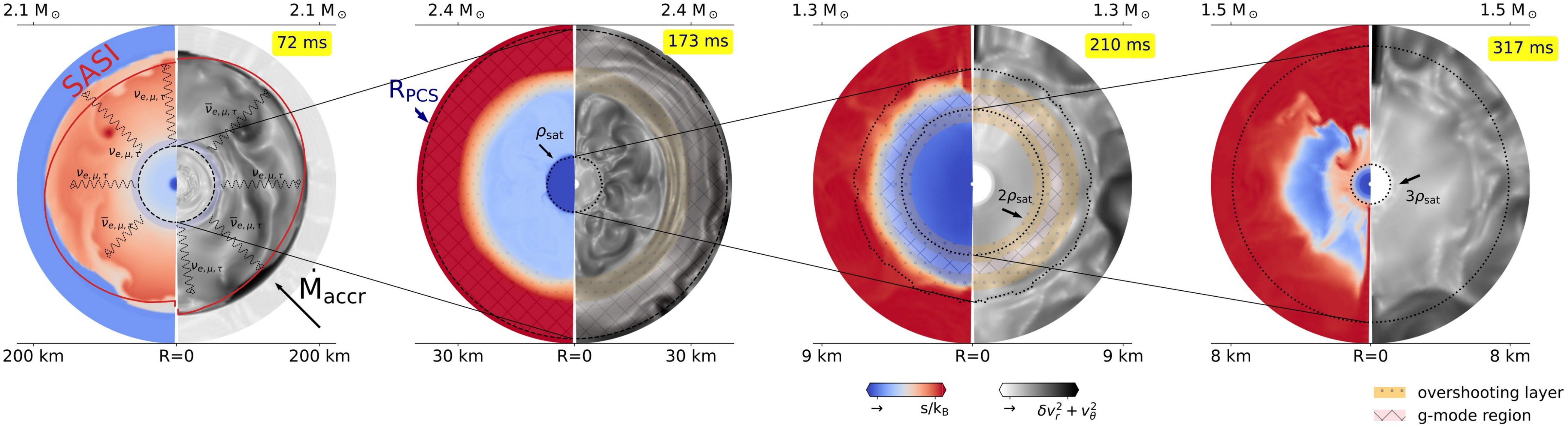




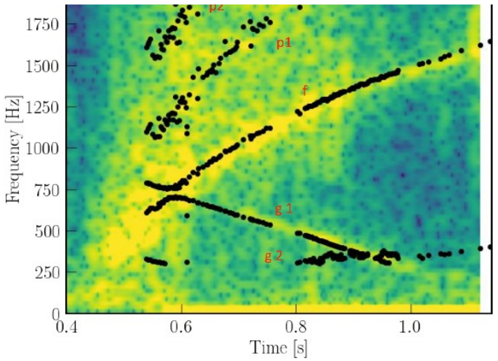




- Quarks are abundant in very low numbers
- Matter dominated by Nucleons / Quarks
- Interplay of electron gradient in combination with a large $(\partial P/\partial Y_e)_{\rho,s}$ drives down B.V.f.




# Summary

- Signal corresponds to g-mode oscillations in the PCS
  - ~5-10 km (200-500 ms post-bounce)
  - l-mode [Zha et al., paper in prep]



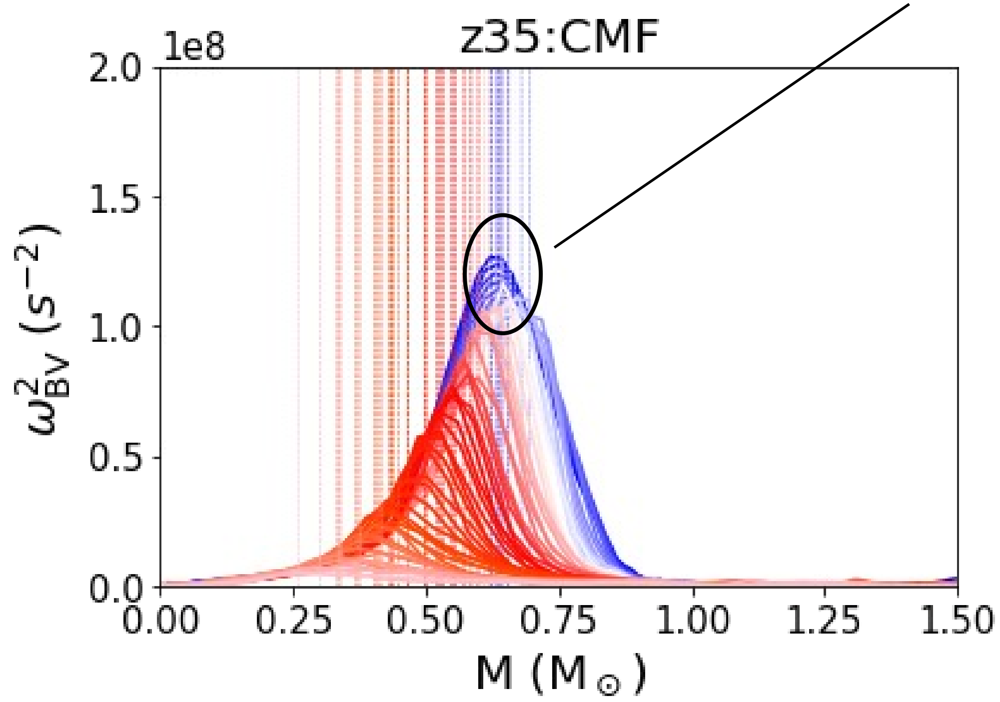

- Mode frequency very sensitive to speed of sound at around twice saturation density
- Low frequency feature of mode lies within the sensitivity range of current GW detectors

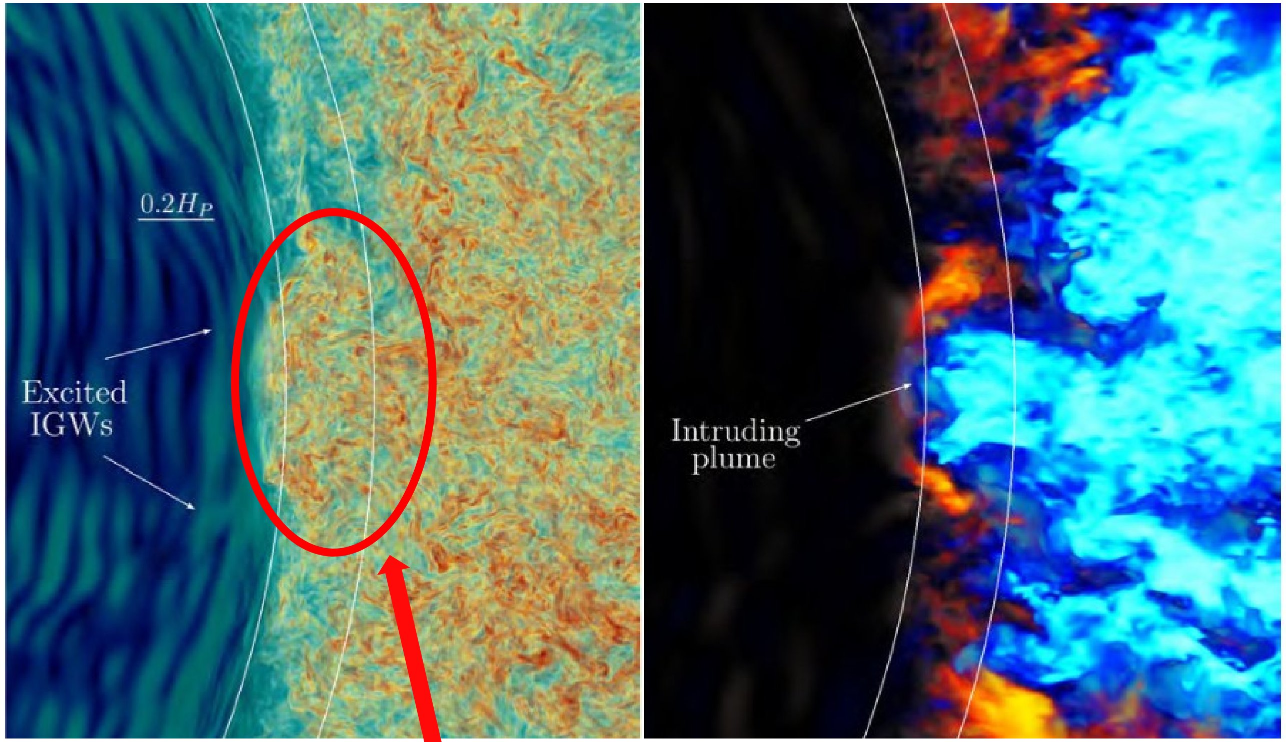
**2D versus 3D: Jakobus et al. 2024**

# If a fluid parcel is perturbed- will it settle back into its equilibrium position?


Oscillation of a displaced fluid element →

Higher frequencies give rise to larger 2nd order time-derivatives of the mass quadrupole moment




**Blouin+23**

Based on the Ledoux criterion:

$$\omega^2_{\rm BV} = \frac{{\rm d}\alpha}{{\rm d}r}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{{\rm d}s}{{\rm d}r}+\left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{{\rm d}Y_e}{{\rm d}r}\right\}$$

Overshoot into convectively stable region

Buoyancy force back toward convective region

**z35 progenitor 550 ms**

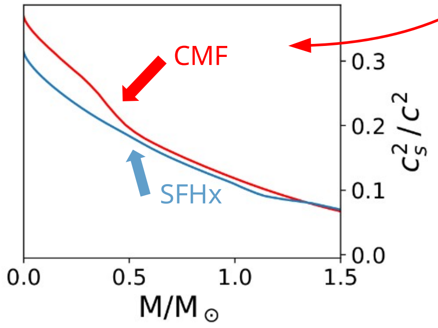
$$\omega_{\mathrm{BV}}^2 = \frac{\mathrm{d}\alpha}{\mathrm{d}r}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde\rho,Y_e}\frac{\mathrm{d}s}{\mathrm{d}r}+\left(\frac{\partial P}{\partial Y_e}\right)_{\tilde\rho,s}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right\}$$

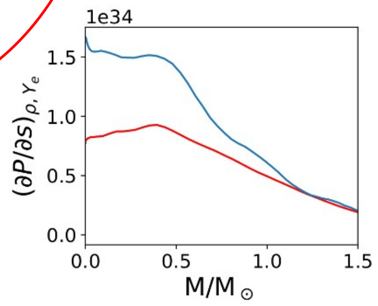
Speed of sound larger (CMF)

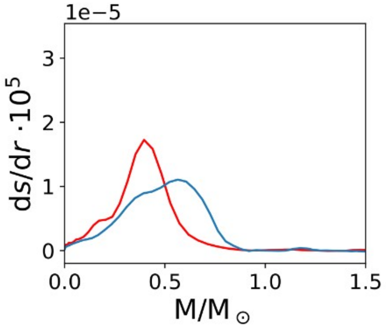
Increases over time (CMF)

Changes sign
Absolute becomes larger (CMF)

1

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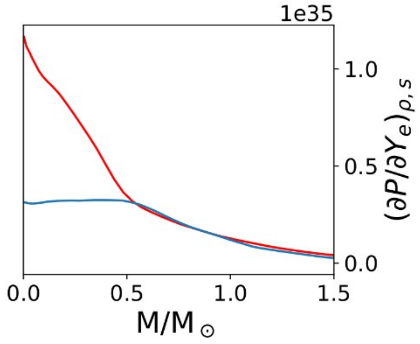
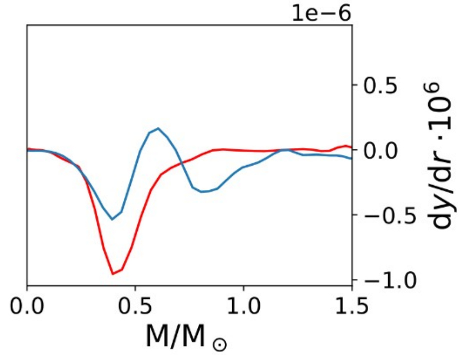
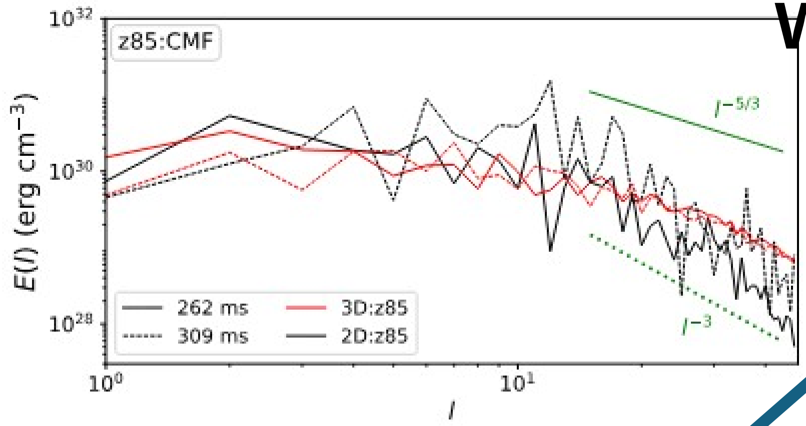
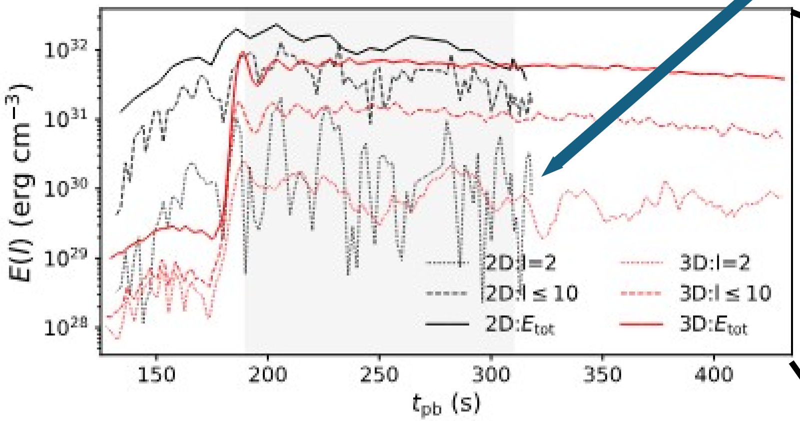
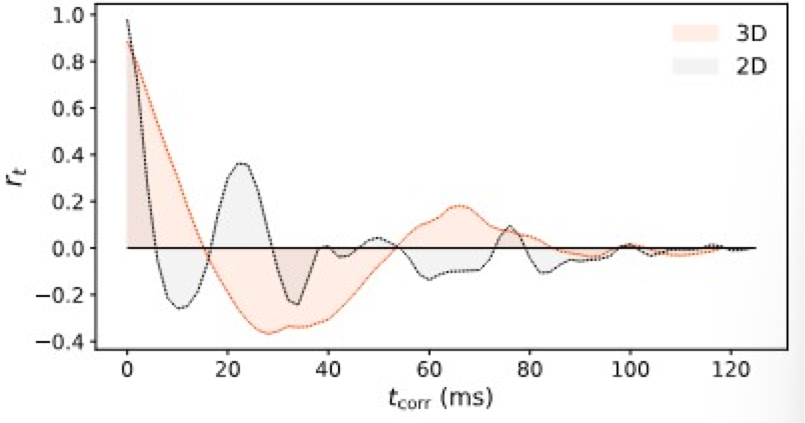


# Why is the GW signal absent in 3D?

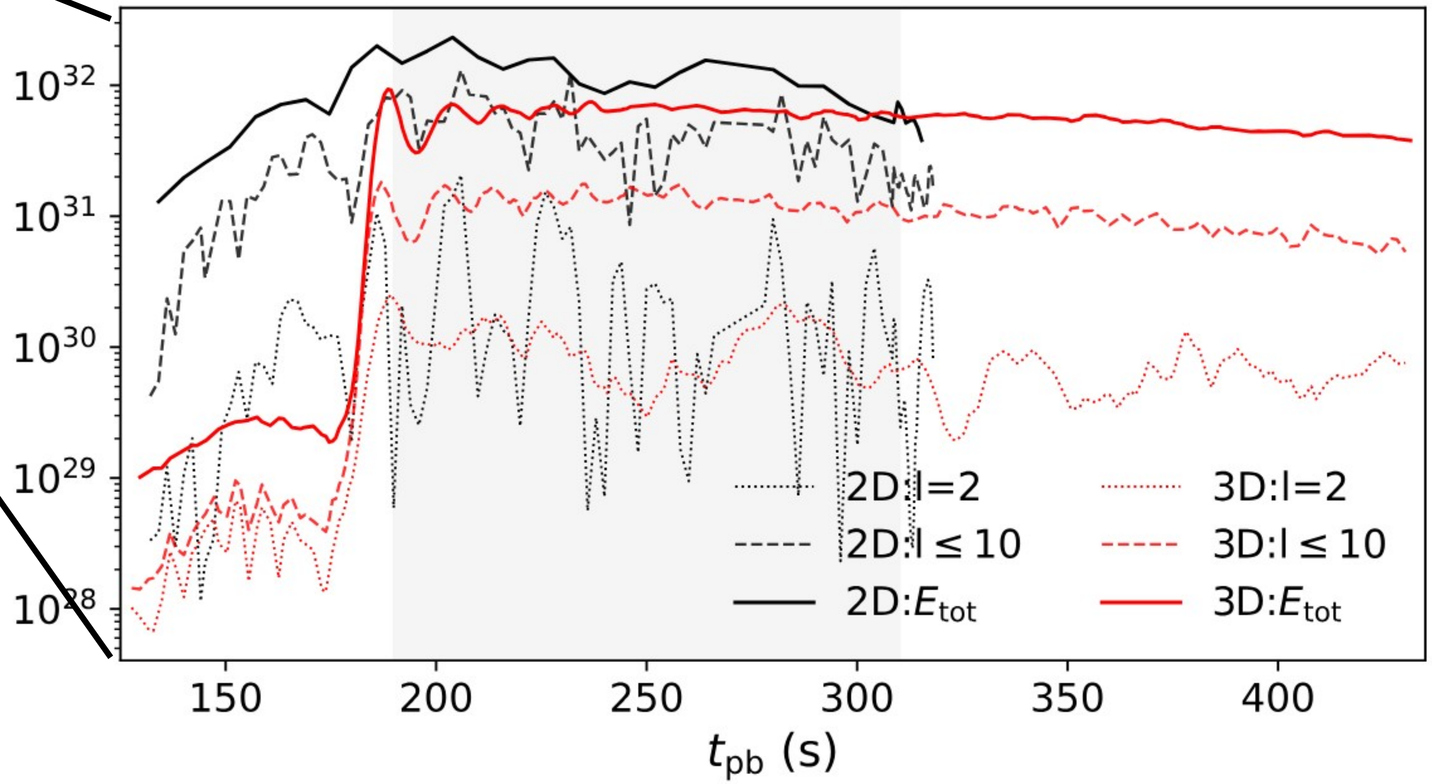



- 1st guess: Inverse cascade leads to more quadrupolar turbulent motion in 2D and more resonant excitation?

Absolute strength very similar...

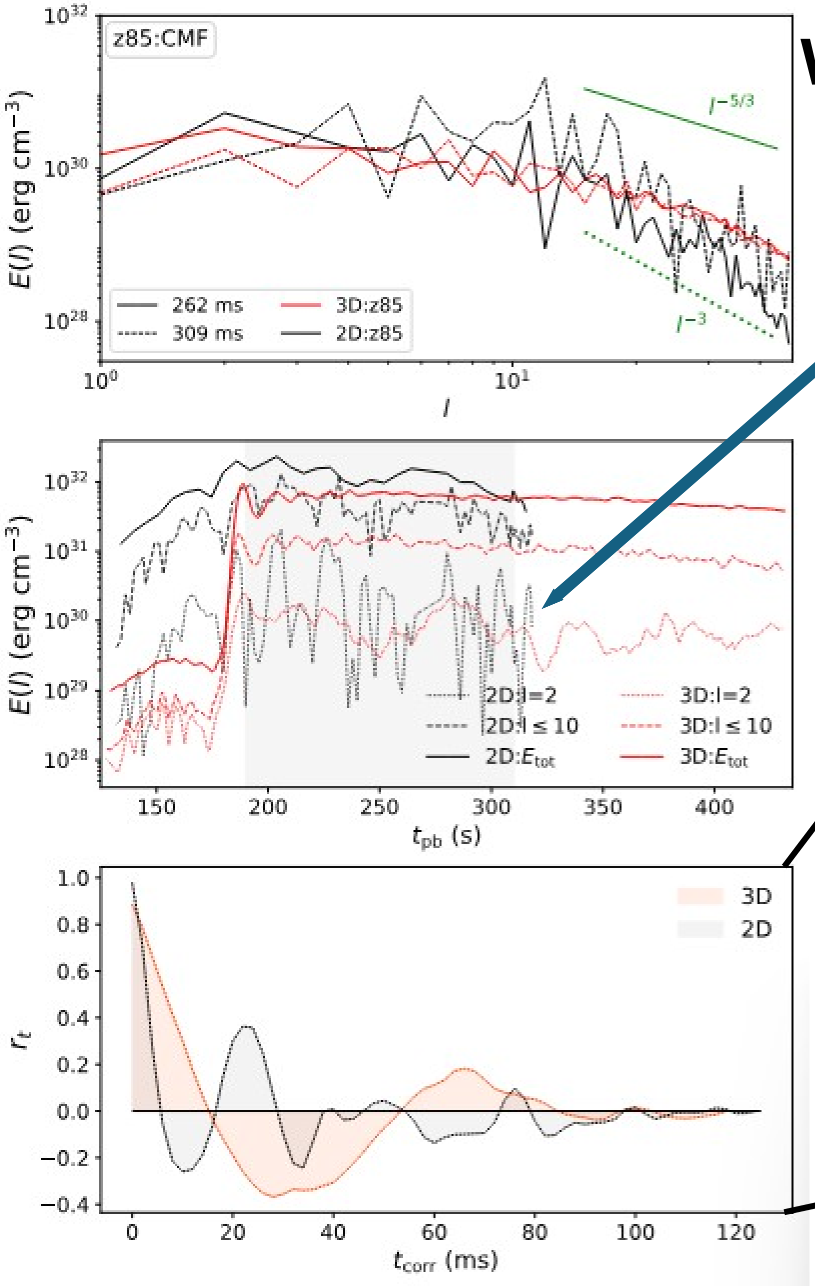


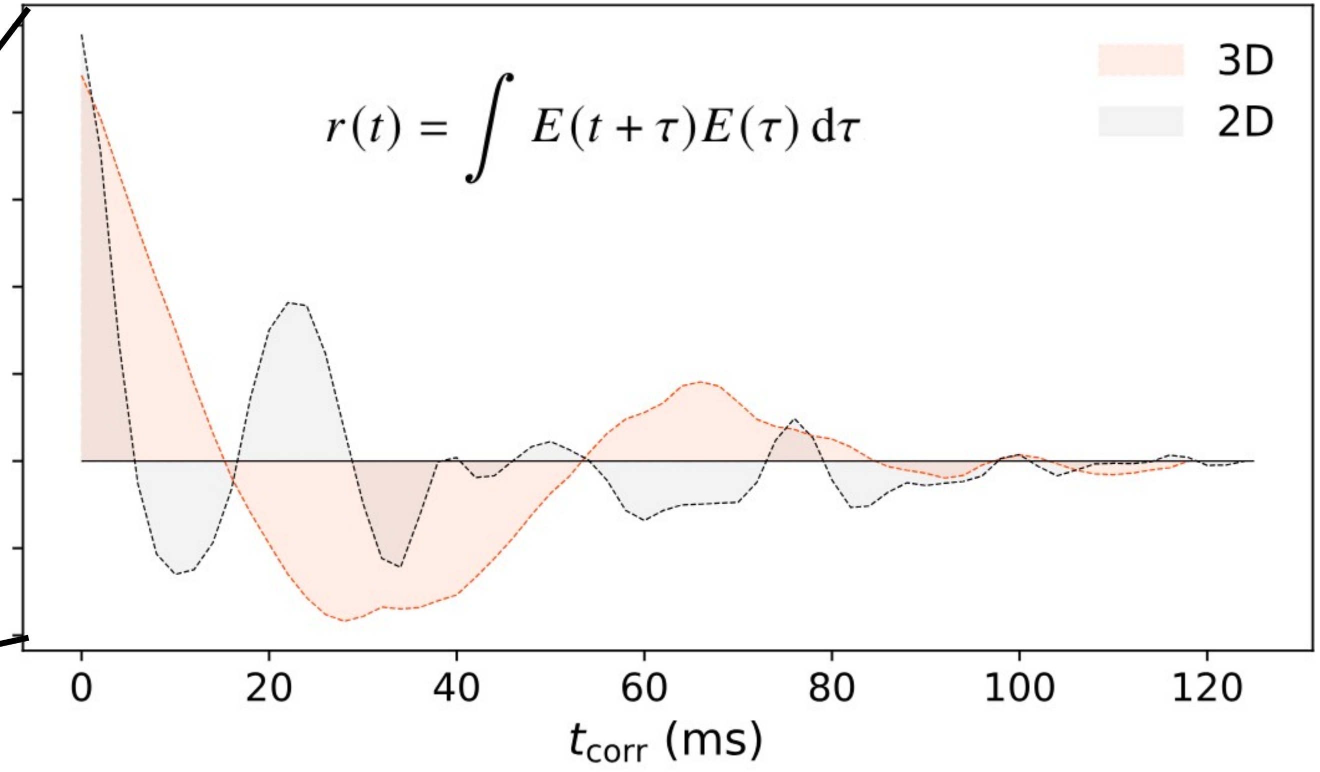
# Why is the GW signal absent in 3D?

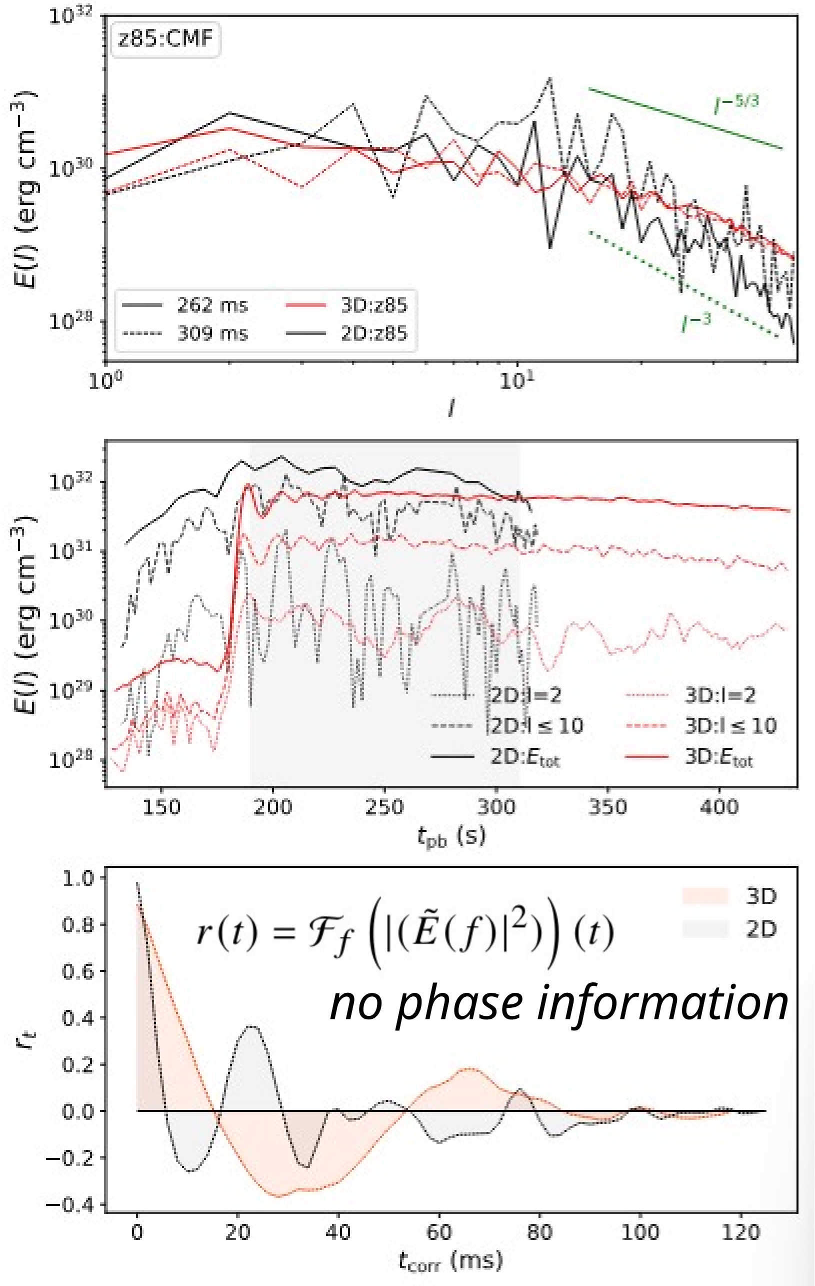
$2^{nd}$ guess : Larger temporal variability:

- Reflected in shorter auto-correlation time of E(2)
- Increased power at higher frequencies in the Fourier spectra

Physical meaning: faster decay rates of eddies in 2D greater velocity dispersion



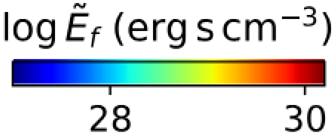



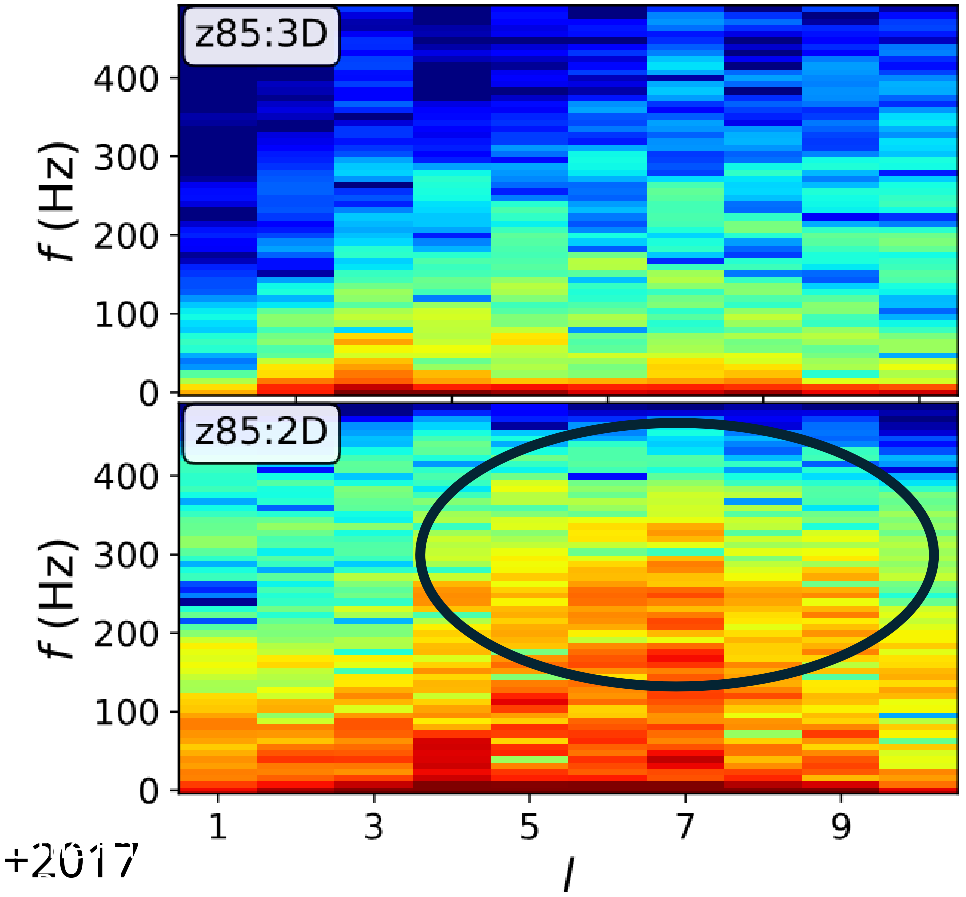



# Why is the GW signal absent in 3D?

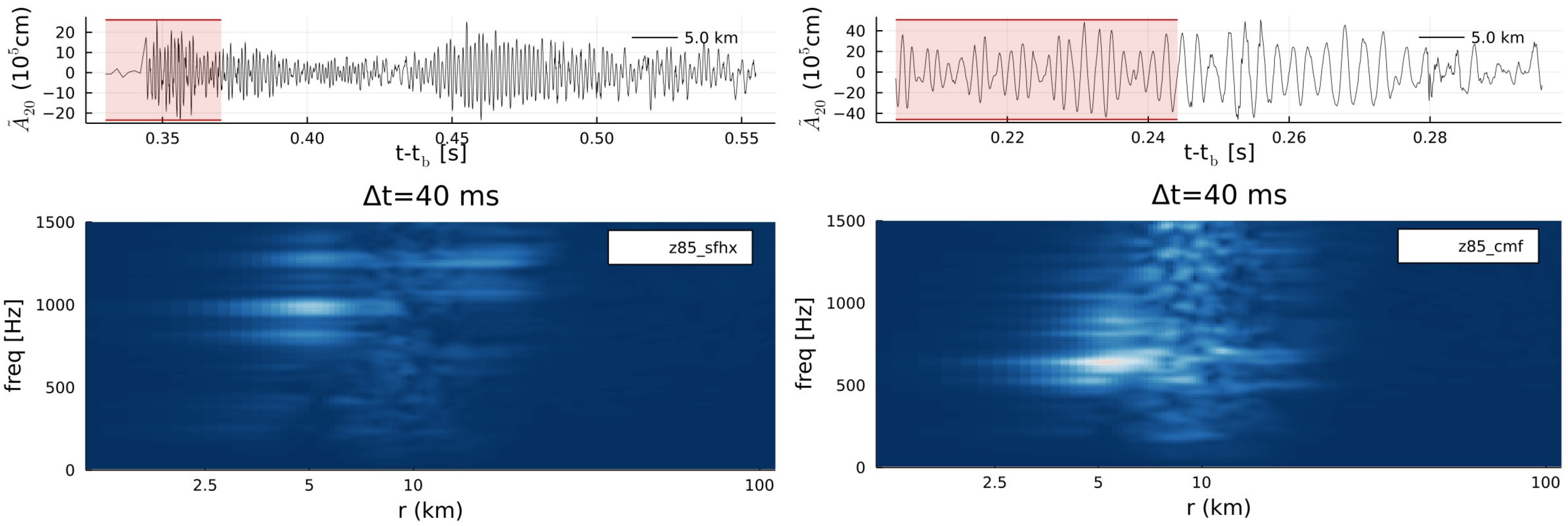
Autocorrelation function and Fourier transform look very different!

$$\tilde{E}(f) = 1/\sqrt{2\pi} \int E(t) e^{-2\pi i f t} \mathrm{d}t$$




See also Andresen+2017




github.com/PiaJakobus/GW_extraction