Gravitational Wave signature from QCD matter in Proto-Compact Stars

Workshop on the QCD Equation of State 2023

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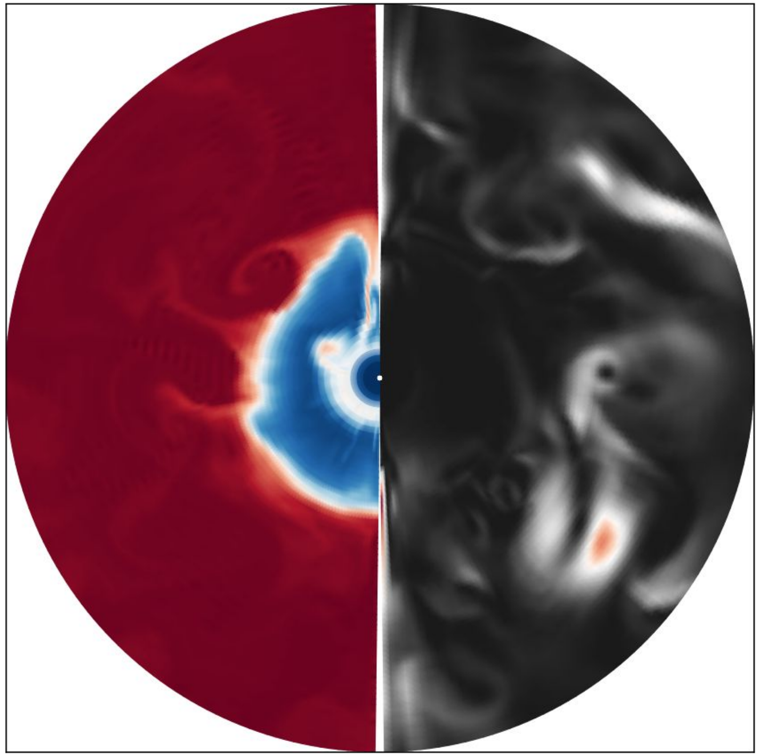
ASTRO 3D



Overview I: Core-Collapse Supernovae

- Stars with M > 8 M_s (H,He,C,Ne,O,Si)
- Iron final product of nuclear fusion
- Silicon shell burning accreting on PCS; M > 1.44 M_s

⟶ Core collapses

⇓

- Core bounces
- Formation of shock
- Neutrinos become trapped
- Photodissociation of heavy nuclei into nucleons

⟶ Accretion shock at ~100-200km

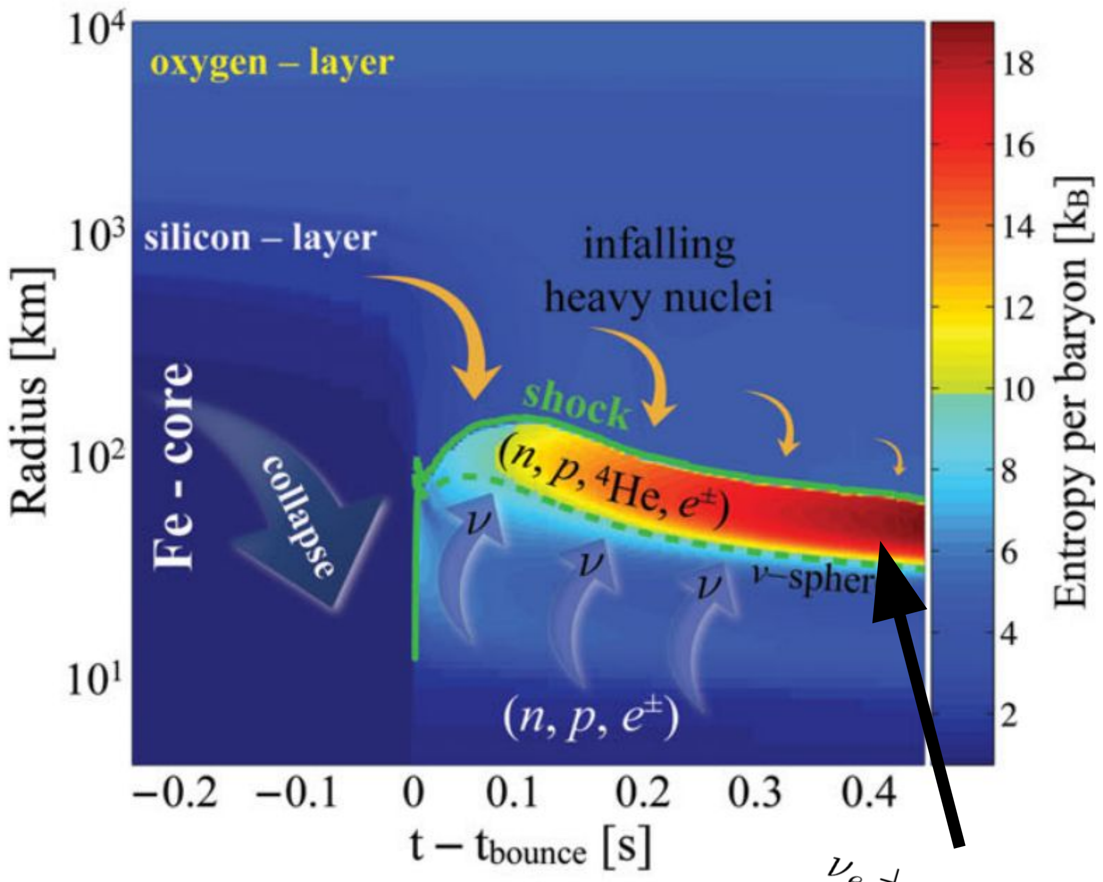
⇓

- Hot Proto-Compact Star in interior accreting material
- Neutrinos decouple from Neutrinosphere
- Transport energy into “hot bubble region

⟶ Shock revival?

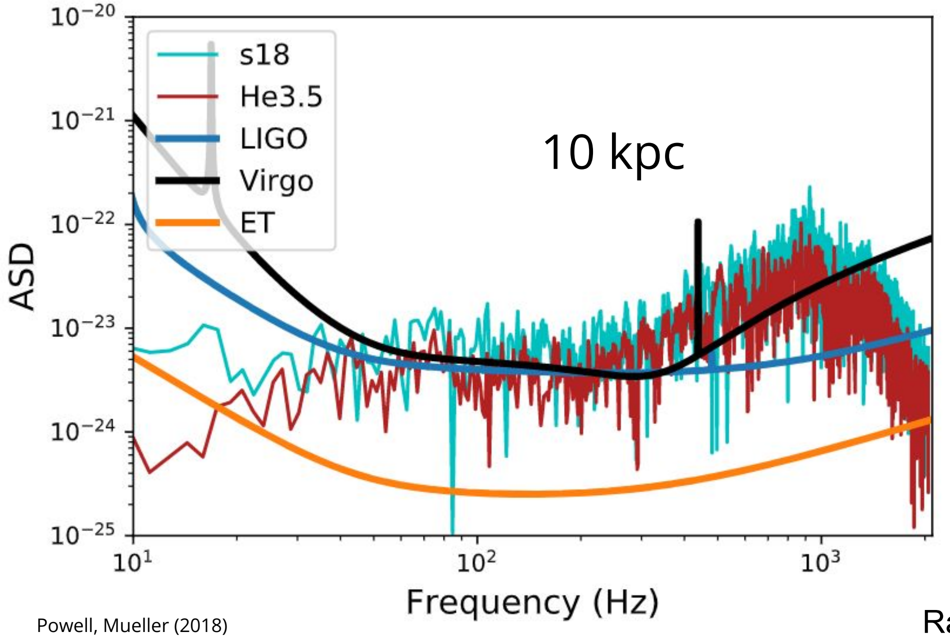
⇓

- Late Proto-Compact Star fully transparent to neutrinos



$$\nu_e + n \longrightarrow p + e^-$$
$$\overline{\nu}_e + p \longrightarrow n + e^+$$

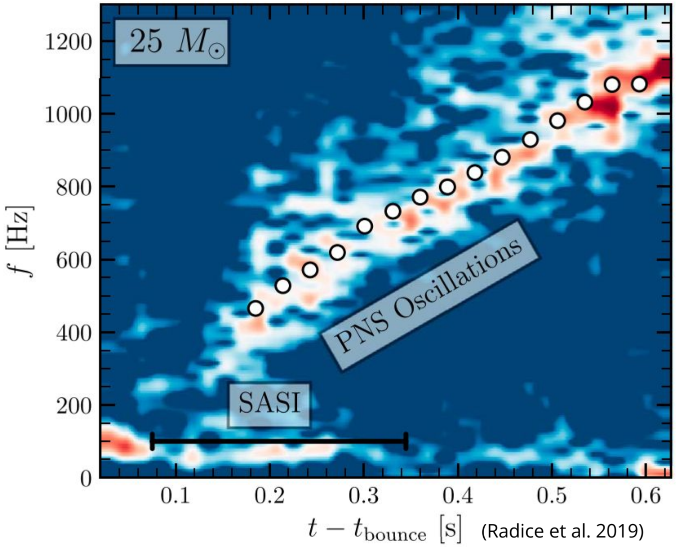
Gravitational Waves from Core-Collapse Superno



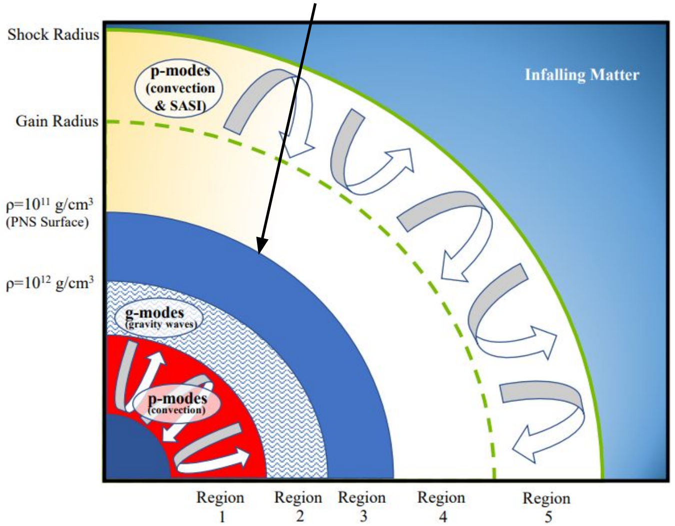
Powell, Mueller (2018)

- 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

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:

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

Stripy clouds

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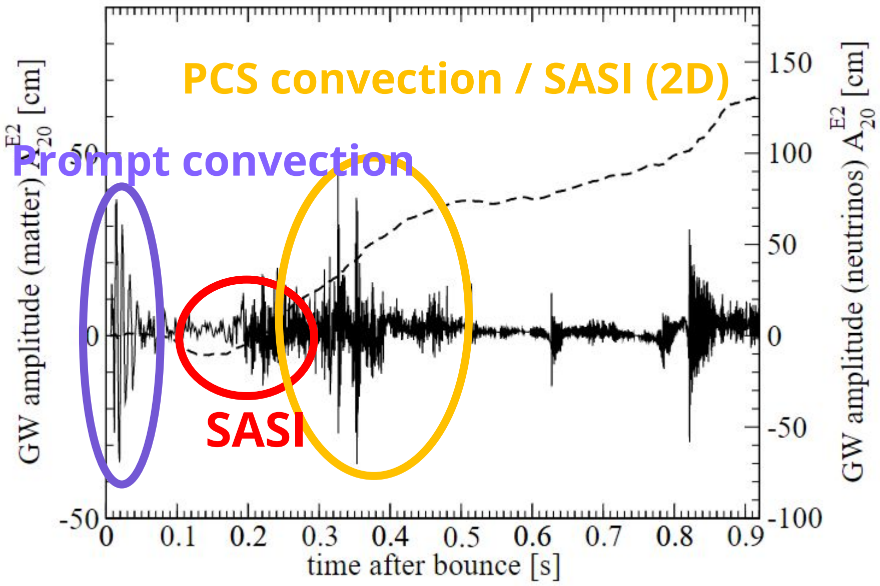
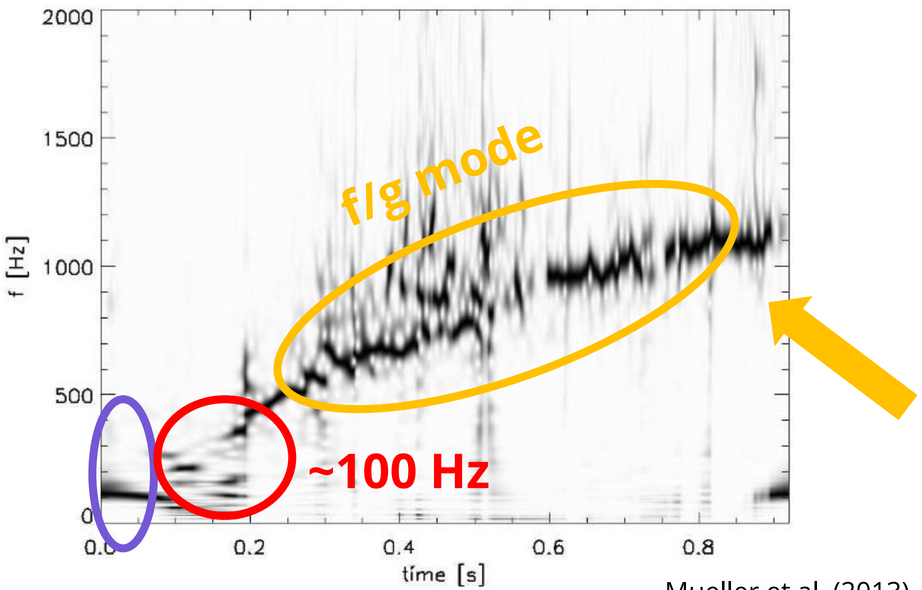


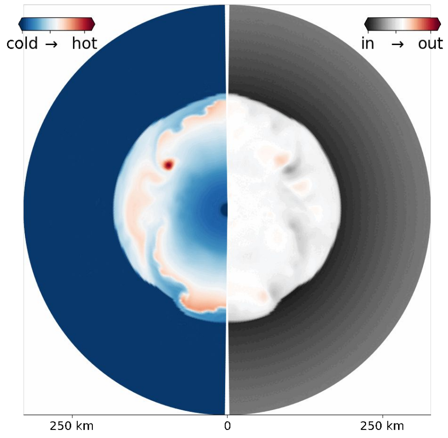


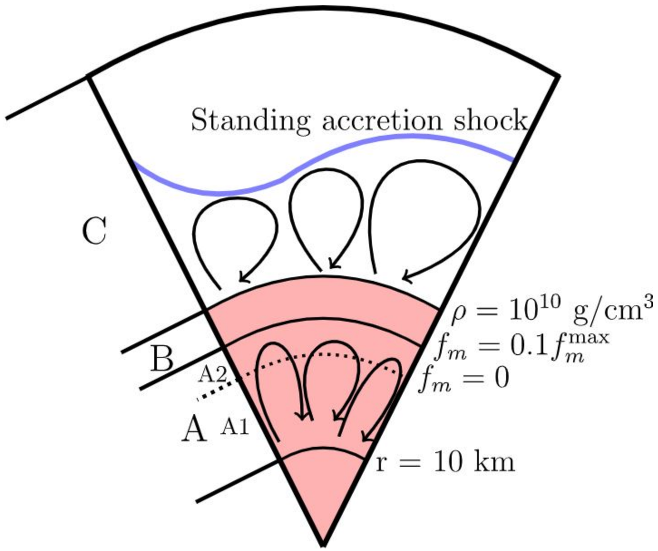
Mueller et al. (2013)

2D GW output for 15 solar mass progenitor

Common features of the GW signal

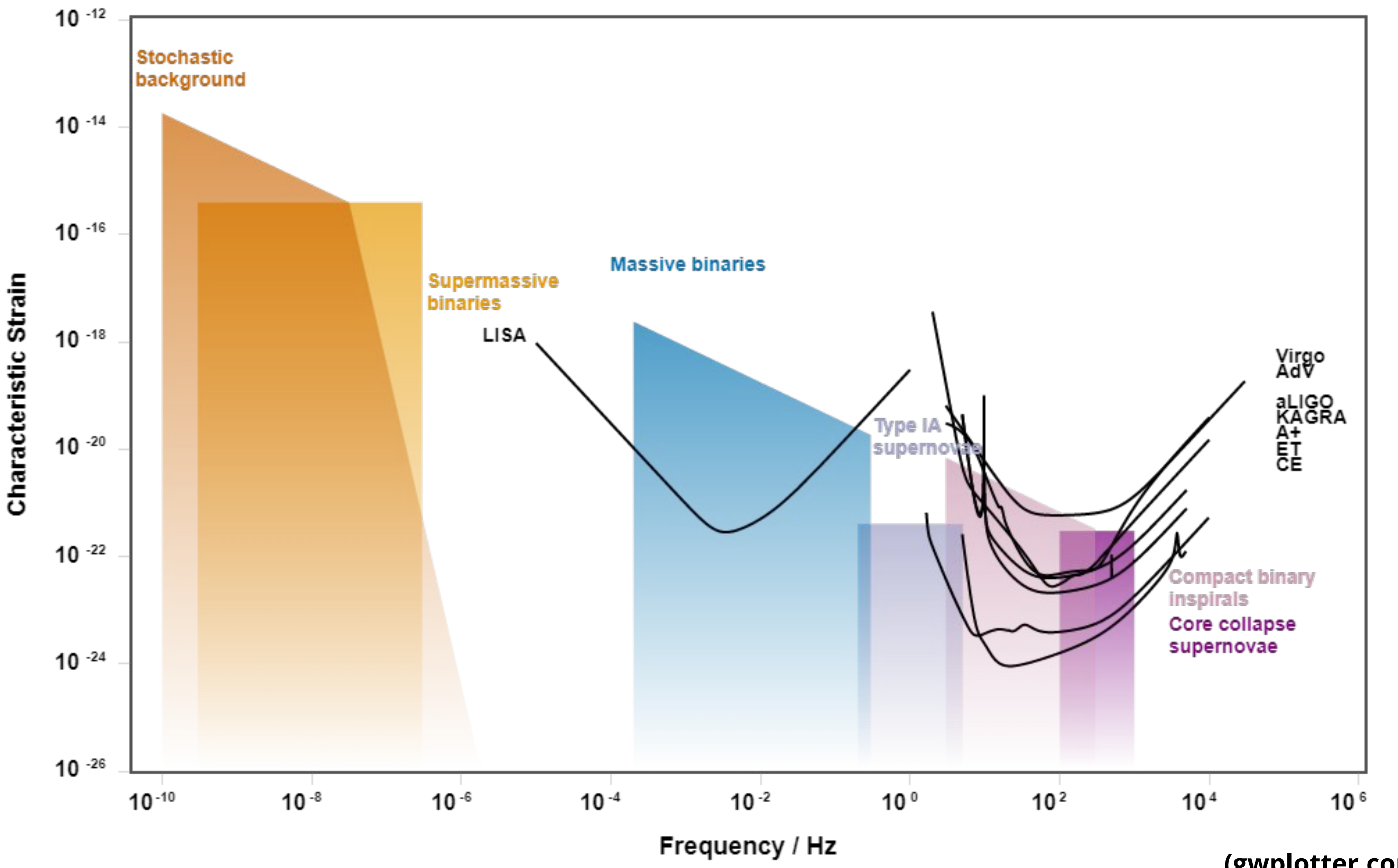
- Turbulent structure by convective downflows stronger in 2D
- Frequency spectrum of SASI *narrower* in 3D
- Amplitudes in 2D overestimated (PCS amplitudes ~10x)



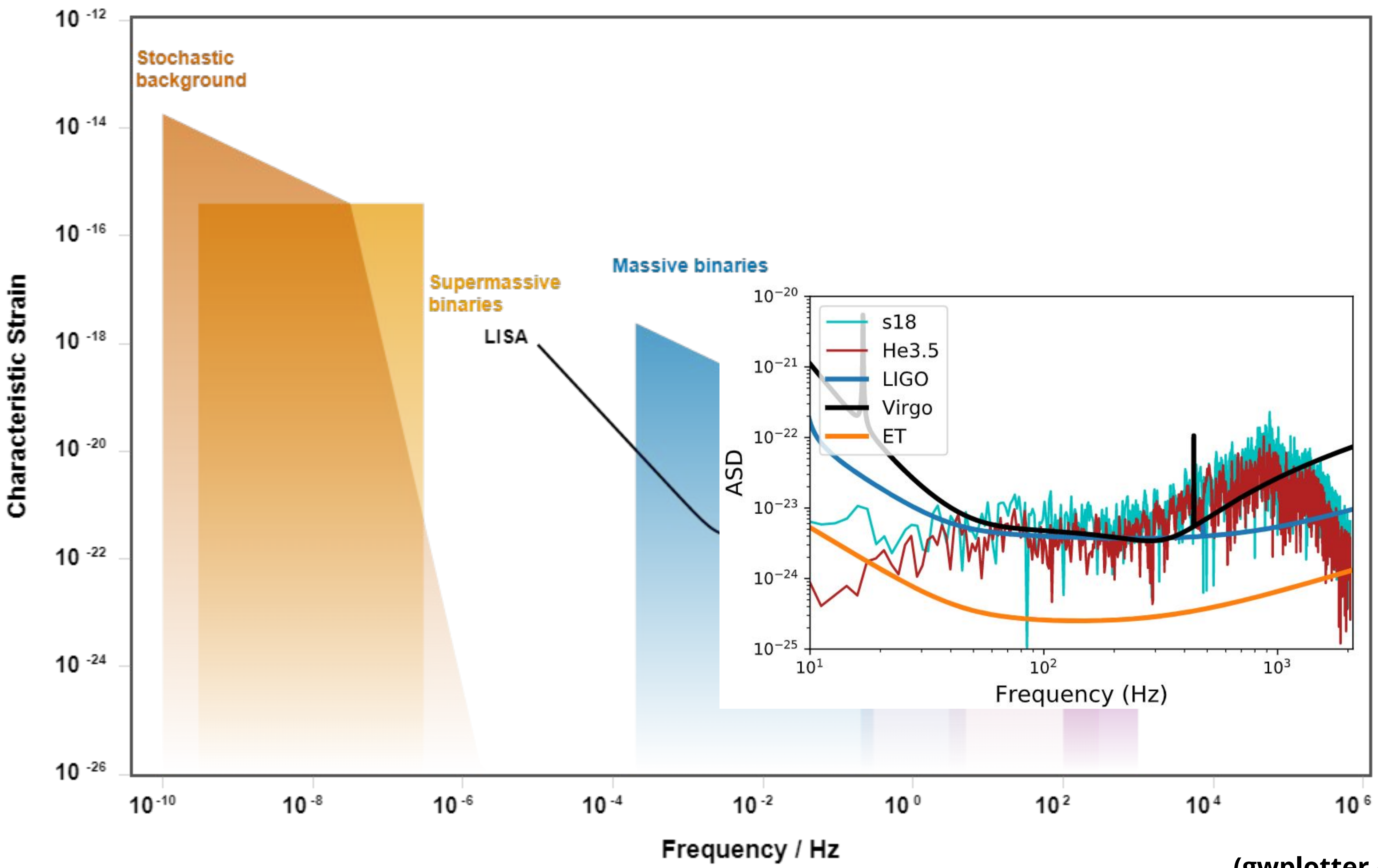


$$f_{\rm peak} \approx \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{1.1\frac{m_n}{<E_\nu>}}\left(1-\frac{GM}{Rc^2}\right)^2$$

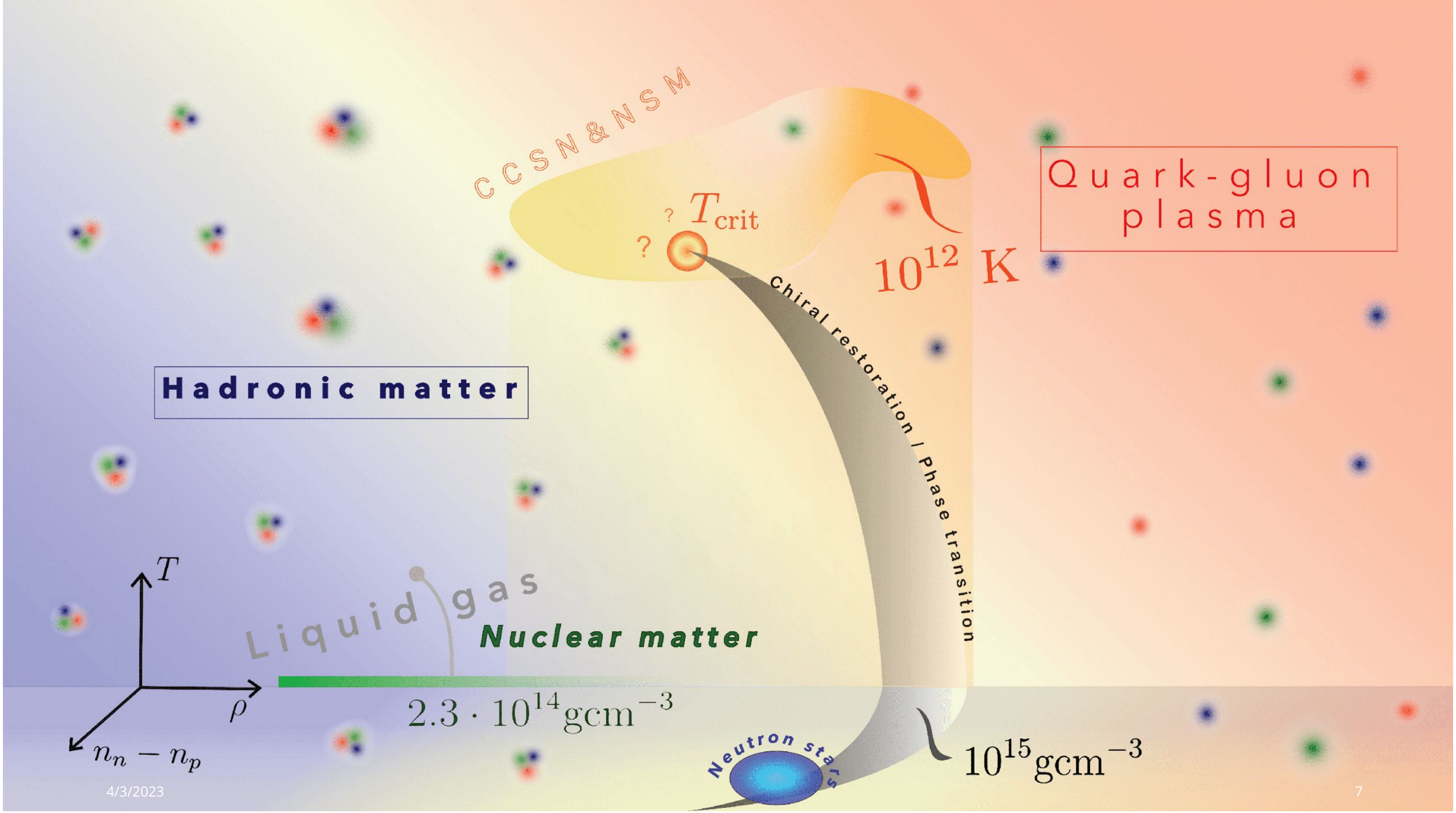
Electron antineutrino mean energy



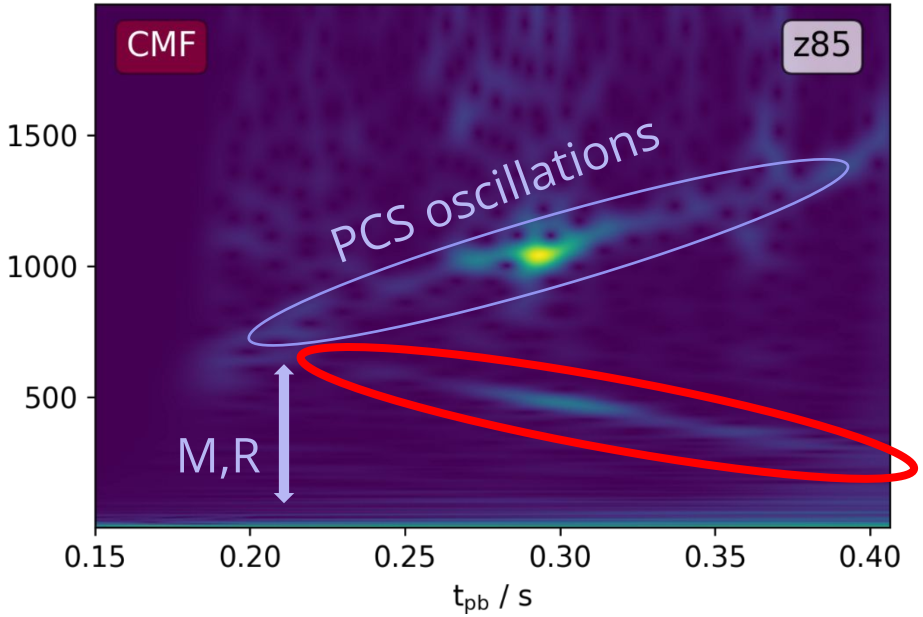
(gwplotter.com)



(gwplotter.com)

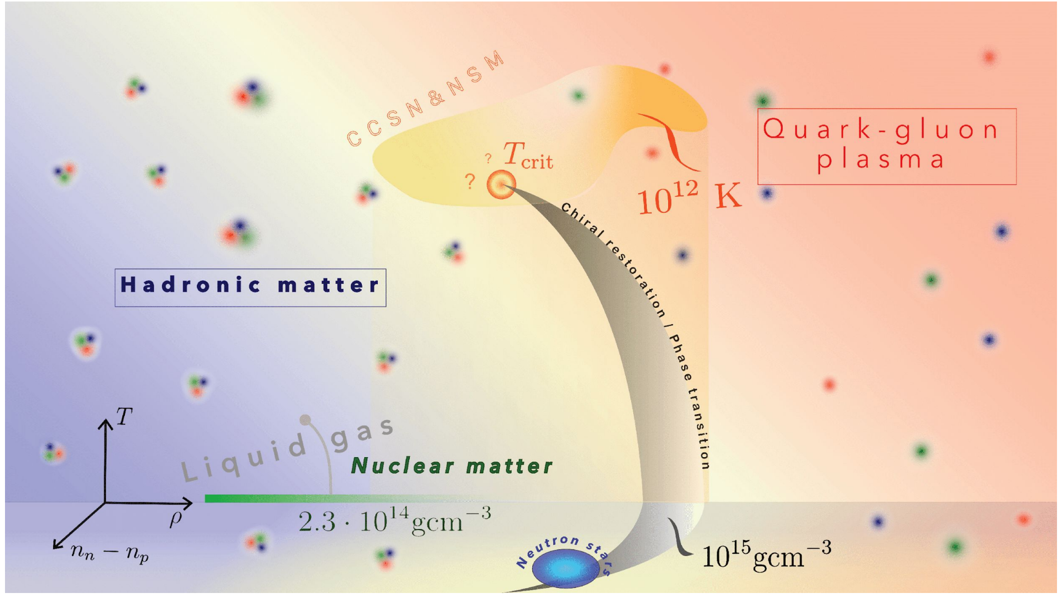


CCSN&NSM
? T_{crit}
?
10^{12} K
Quark-gluon plasma
Chiral restoration / Phase transition
Hadronic matter
T
Liquid gas
Nuclear matter
ρ
$2.3 \cdot 10^{14} \mathrm{gcm}^{-3}$
$n_n - n_p$
Neutron stars
$10^{15} \mathrm{gcm}^{-3}$

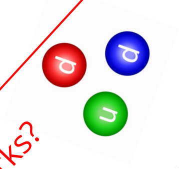


PCS evolution

Constrain EoS

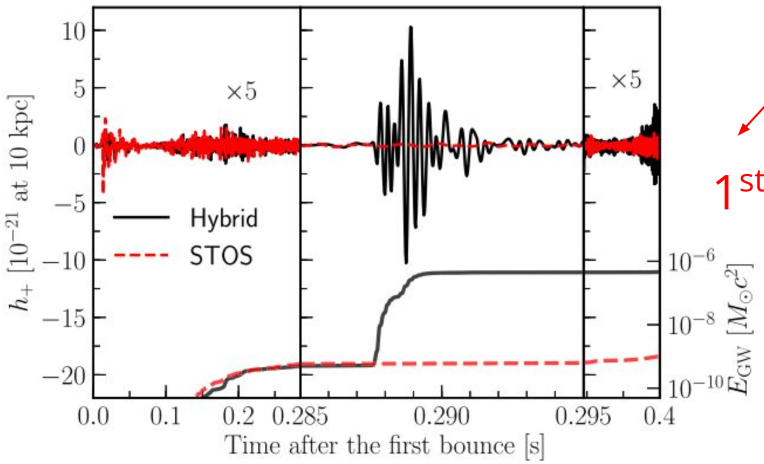


$$f_{\mathrm{peak}} \approx \frac{1}{2\pi}\frac{GM}{R^2}\sqrt{1.1\frac{m_n}{<E_\nu>}}\left(1-\frac{GM}{Rc^2}\right)^2$$

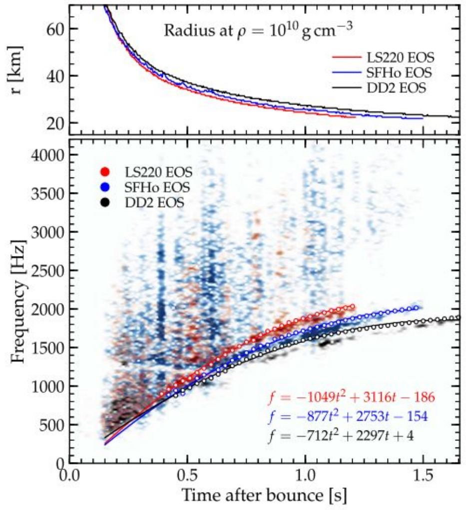


Free quarks?

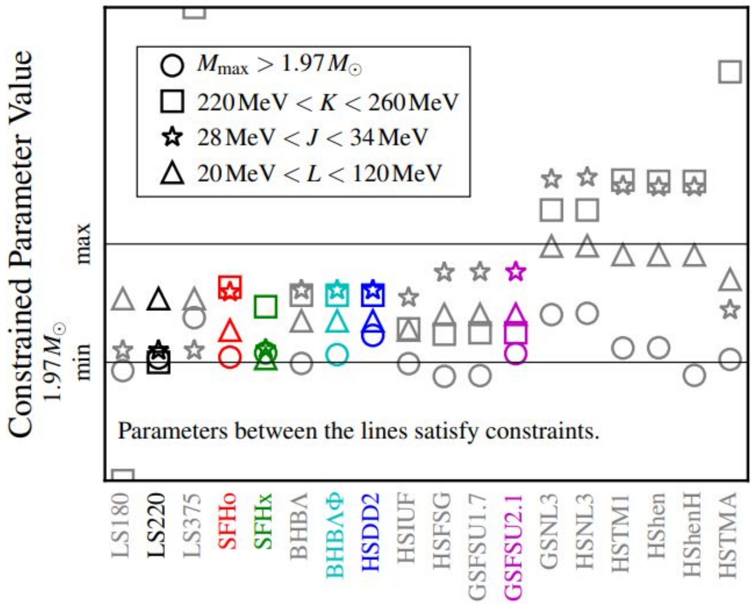
1st order PT



(Zha et al., 2020)



(Morozova et al., 2018)



(Richers et al., 2017)

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EOS	n_0 [fm^{-3}]	E_0 [MeV]	K [MeV]	S [MeV]	L [MeV]	$R_{1.4}$ [km]	M_{max} [$M_\odot$]
SFHo	0.1583	16.19	245	31.57	47.10	11.89	2.06
SFHx	0.1602	16.16	238	28.67	23.18	11.99	2.13
HS(TM1)	0.1455	16.31	281	36.95	110.99	14.47	2.21
HS(TMA)	0.1472	16.03	318	30.66	90.14	13.85	2.02
HS(FSUgold)	0.1482	16.27	229	32.56	60.43	12.55	1.74
HS(DD2)	0.1491	16.02	243	31.67	55.04	13.22	2.42
HS(IUFSU)	0.1546	16.39	231	31.29	47.20	12.68	1.95
HS(NL3)	0.1482	16.24	272	37.39	118.49	14.77	2.79
STOS(TM1)	0.1452	16.26	281	36.89	110.79	14.50	2.22
LS (180)	0.1550	16.00	180	28.61	73.82	12.16	1.84
LS (220)	0.1550	16.00	220	28.61	73.82	12.67	2.05
Exp.	~ 0.15	~ 16	240 ± 10[1]	$29.0 - 32.7$[2]	$40.5 - 61.9$[2]	$10.4 - 12.9$[3]	$\gtrsim 2.0$[4,5]

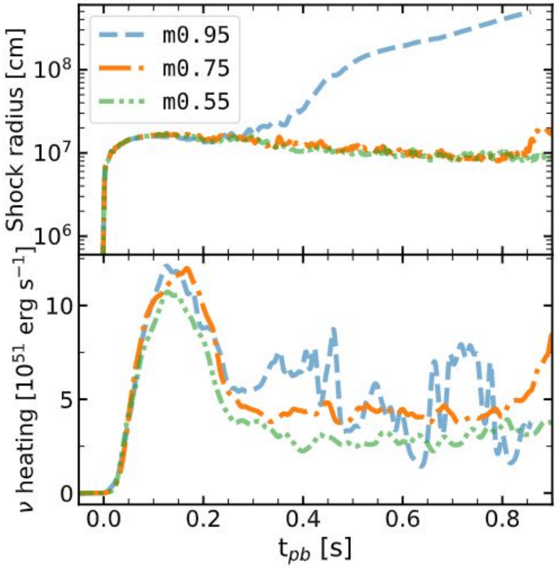
1. Lattimer-Swetsy EoS (1991)
2. Shen EoS (1998)

Lattimer, Swetsy: A generalized equation of state for hot, dense matter; 1991

Shen, Toki, Oyamatsu & Sumiyoshi: Relativistic equation of state of nuclear matter for supernova and neutron star; 1998

EoS effects in CCSNe

- Pressure
  - Structure, core-bounce,..
- Entropy
  - neutrino energy
- Composition
  - Weak interactions



Andersen et al. 2021

- **Radius**: If PCS contracts faster an explosion can set in more easily (Janka, 2012,Suwa et al. (2013)); earlier (smaller BH mass)
- **Stiffness:** Neutrino luminosities increased; more efficient heating behind the shock
- **Symmetry energy**: impacts PCS convection, lower symmetry energy S leads to lower core Y_e (Fischer et al. 2014)
- **Effective nucleon masses:** larger m* decrease thermal pressure in core (Schneider et al. 2019, Andresen et al. 2021)

Review: Equations of state for supernovae and compact stars (Oertel, 2017)

Equation of state in CCSNe

SFHx EoS (Steiner et al., 2013) ($\rho > 10^{11}\ gcm^{-3}$)

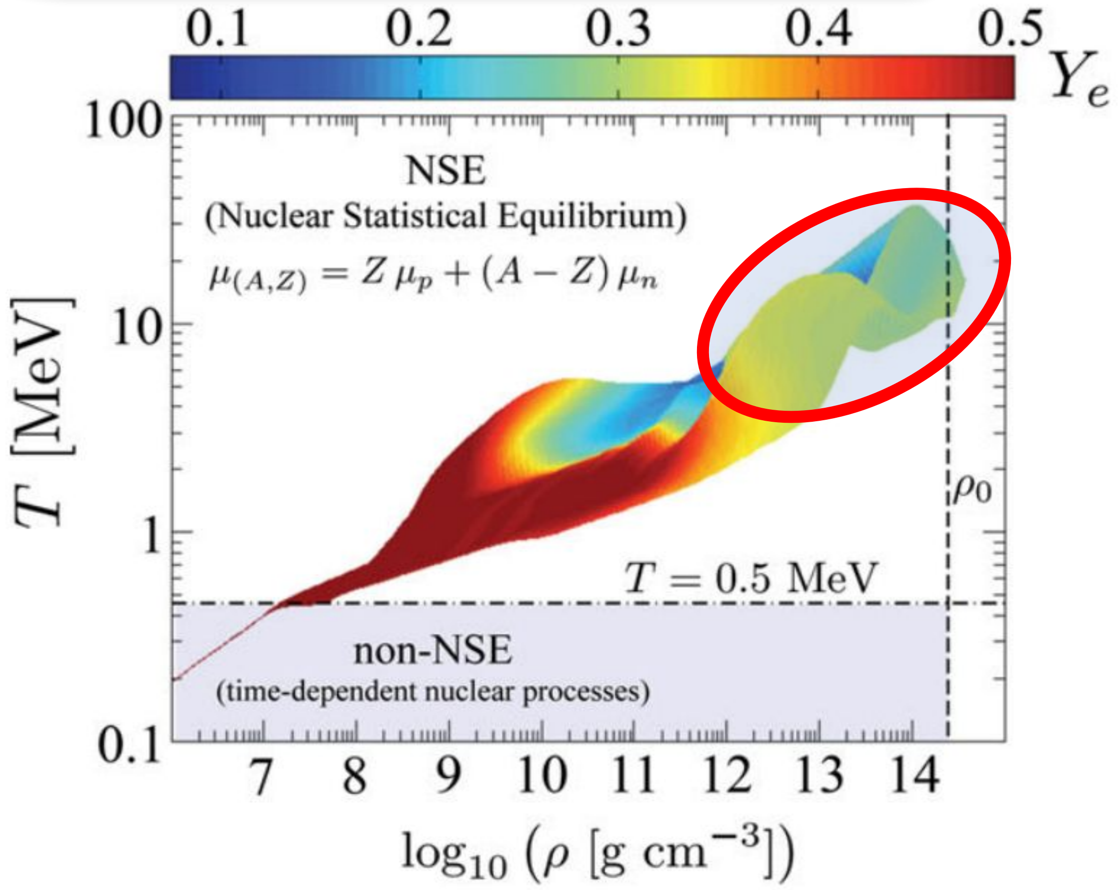
- **Purely hadronic**
- Class of 'HS' (Hempel & Schaffner-Bielich)
- Nuclei (several 1000) are treated as Boltzmann particles
- Nucleons described in **RMF approach (non-linear Walecka model)**
- Fitted to NS properties **(2.13 M_s**)
- Rather low slope parameter 23.2 MeV

CMF EoS (Motornenko et al., 2020) ($\rho > 10^{11}\ gcm^{-3}$)

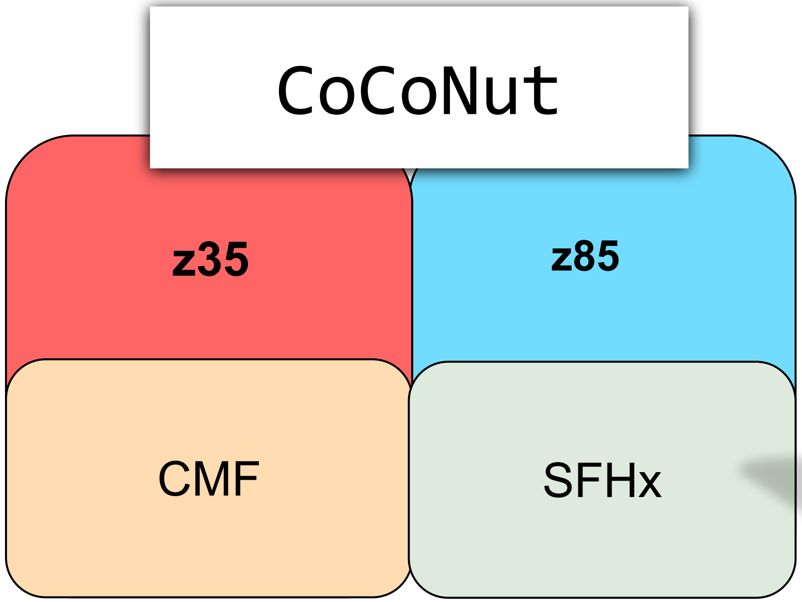
- **Hadron-Quark** Chiral mean field model (**CMF**)
- Fitted to lattice QCD data
- Excluded volume effects supress Baryons at high μ_B
- **1st order nuclear liquid vapor phase transition**
- Weak **1st order chiral phase transition** at about 4 x ρ_{sat}
- **Smooth deconfinement** to quarks (Polyakov-loop as order parameter)
- Maximum TOV **Mass 2.10 M_s**

Low density regime

- ideal gas EoS of iron group nuclei; e, e^+, γ
- 5 GK < NSE with 470 different nuclei
- Nuclear reaction network below 5 GK

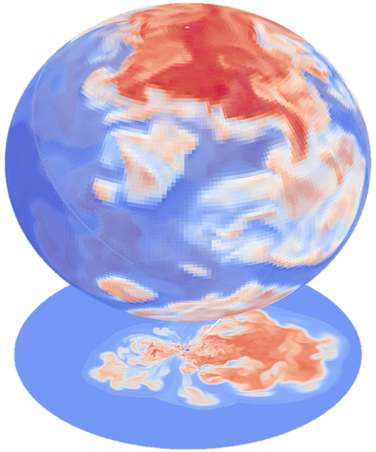


Simulation CCSNe explosions

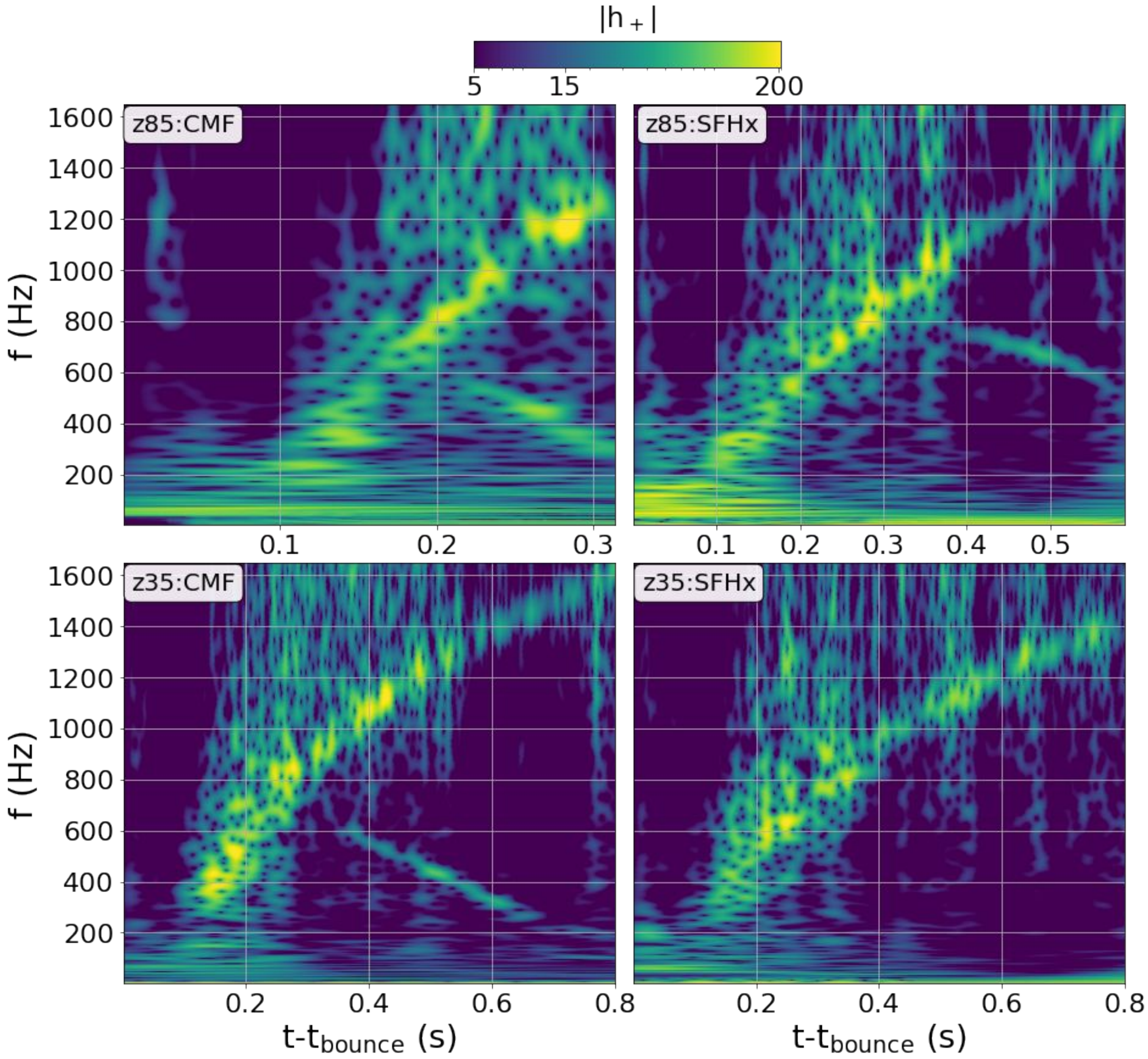


- GR neutrino hydrodynamic code (Dimmelmeier et al. 2002; Mueller et al. 2013)
- Fast three flavor multigroup transport (FMT) for neutrinos (Mueller et al.,2010; Mueller and Janka 2015)
- Inner 1.4 km calculated in spherical symmetry

- 4 simulations in axisymmetry



<u>Neutrinos in CCSNe:</u>
Physical, numerical, and computational challenges of modeling neutrino transport in core-collapse supernovae (Mezzacappa et al. 2020)



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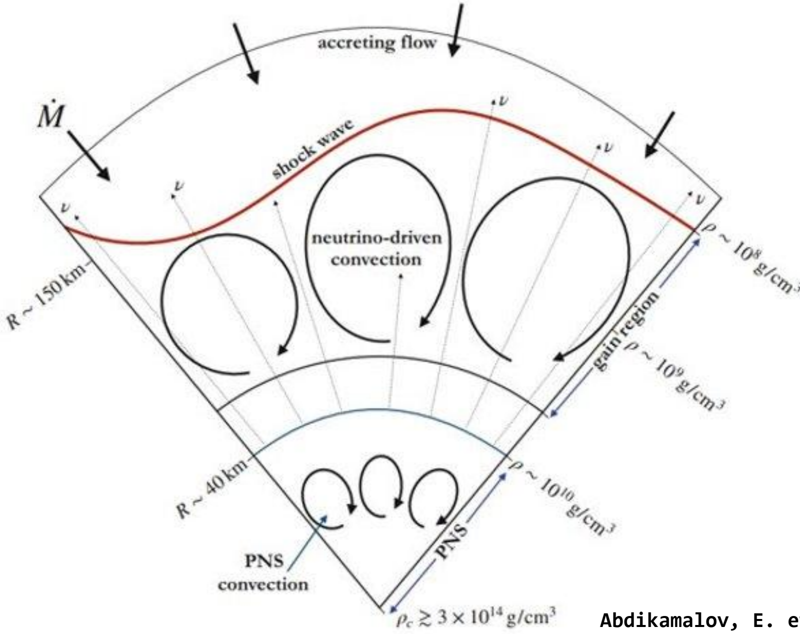
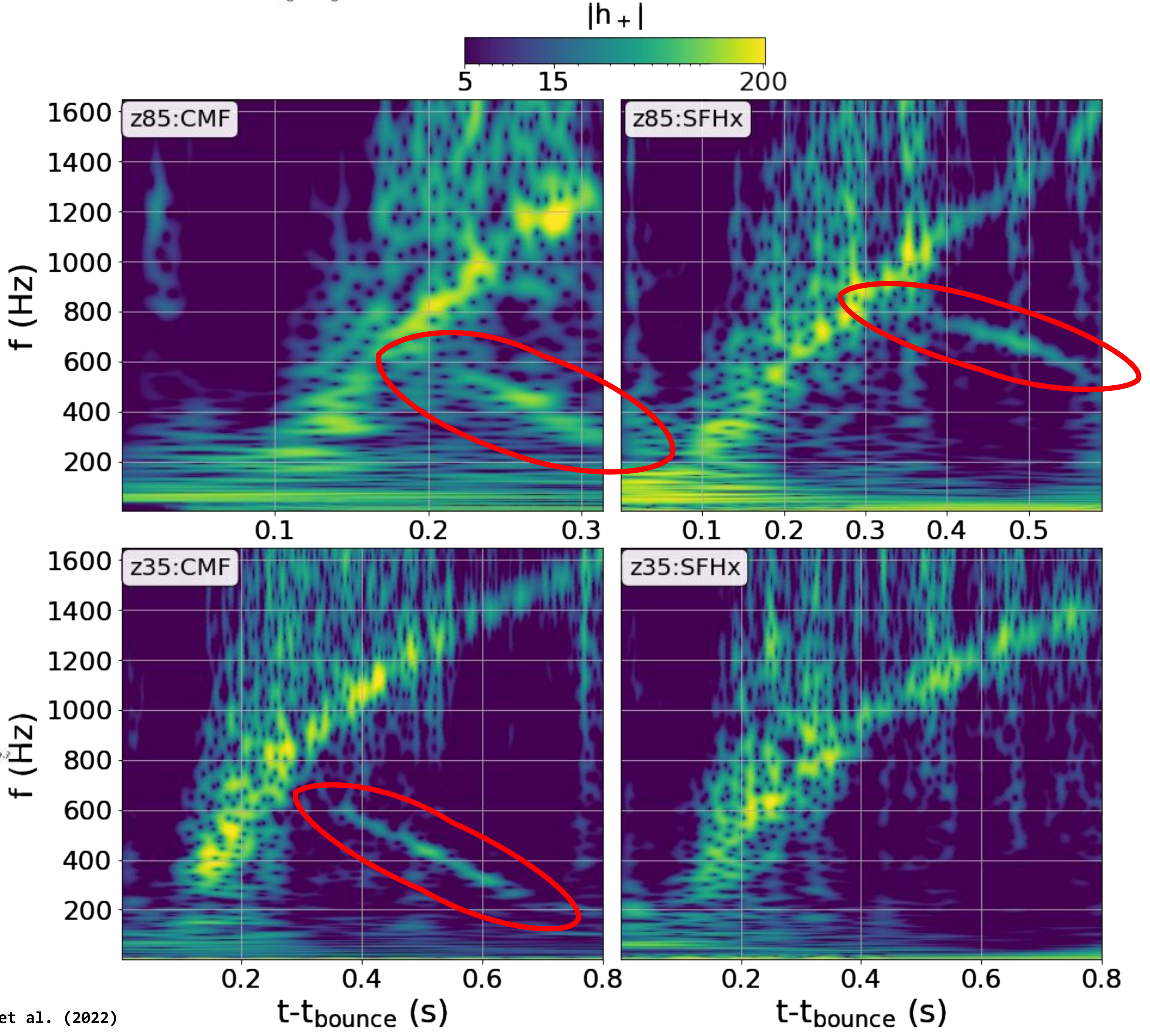
$$A_{20}^{\mathrm{E2}} = \frac{32\pi^{3/2}G}{\sqrt{15}\,c^4}\int_0^r\int_0^\pi \mathrm{d}r\,\mathrm{d}\theta\,\Phi^6 r^3 \sin\theta \times \left\{\frac{\partial}{\partial t}\left(S_r(3\cos^2\theta - 1)\right) + \frac{3}{r}S_\theta \sin\theta\cos\theta\right\}$$

- 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)

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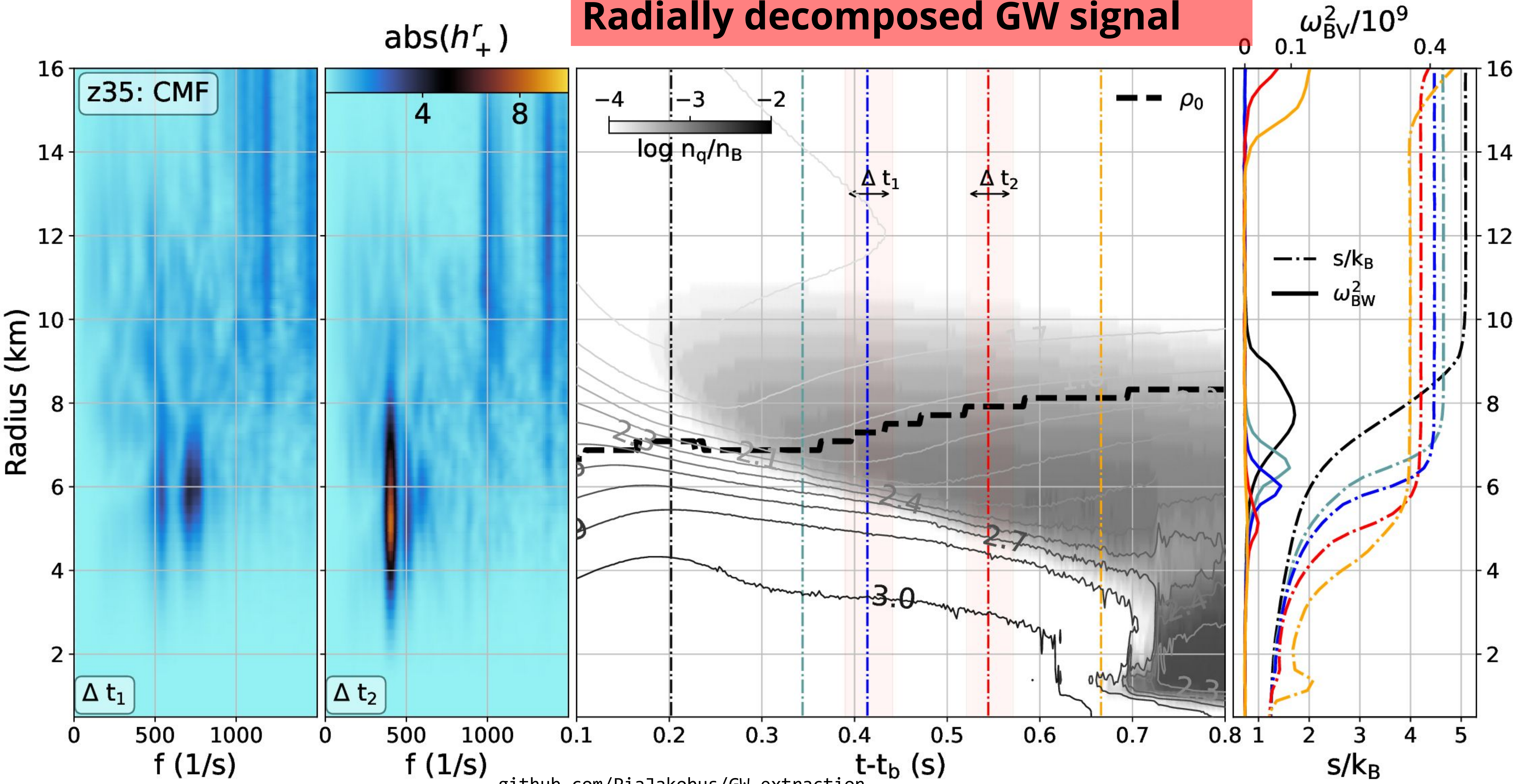
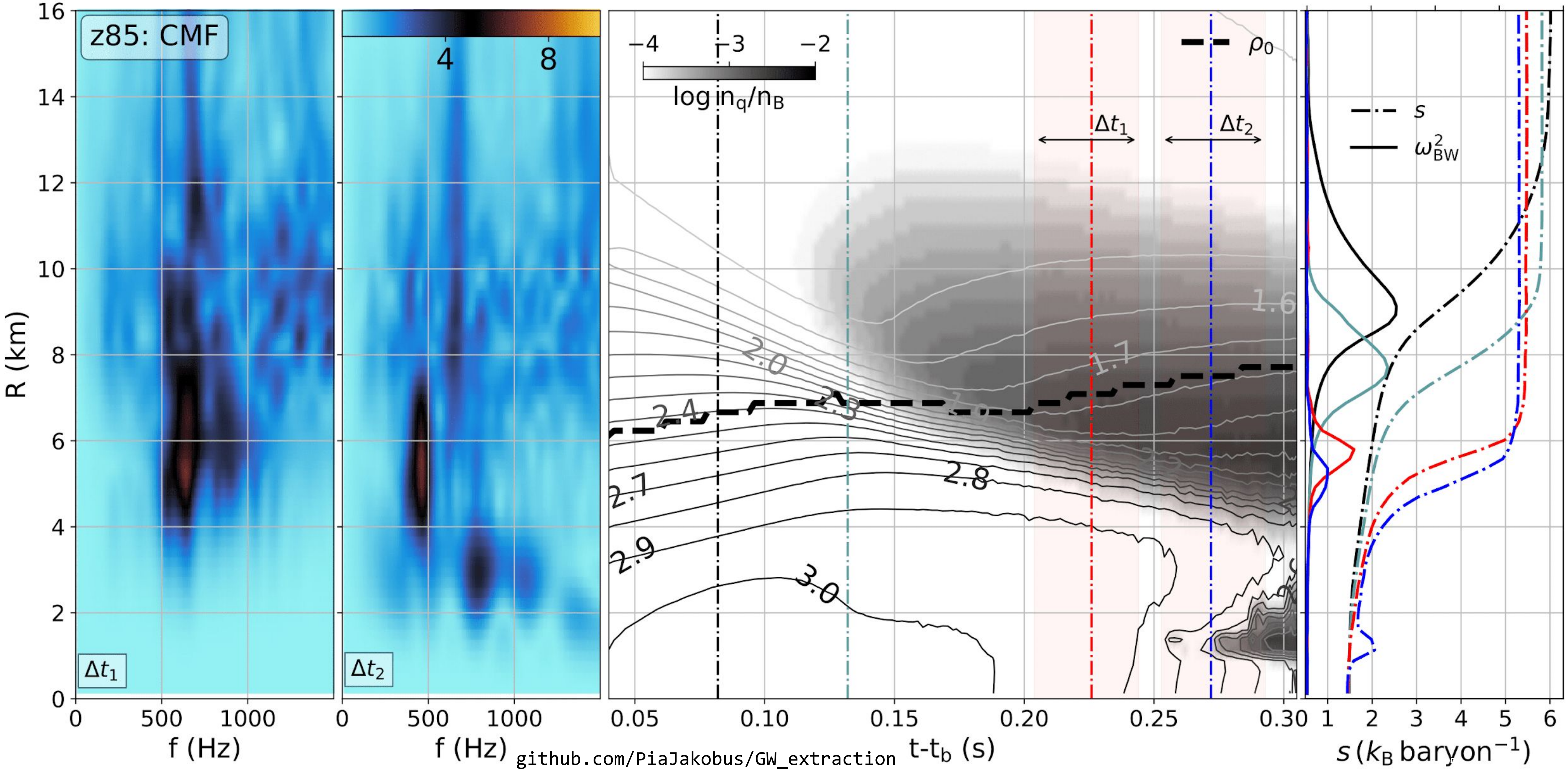
Radially decomposed GW signal



github.com/PiaJakobus/GW_extraction

Radially decomposed GW signal



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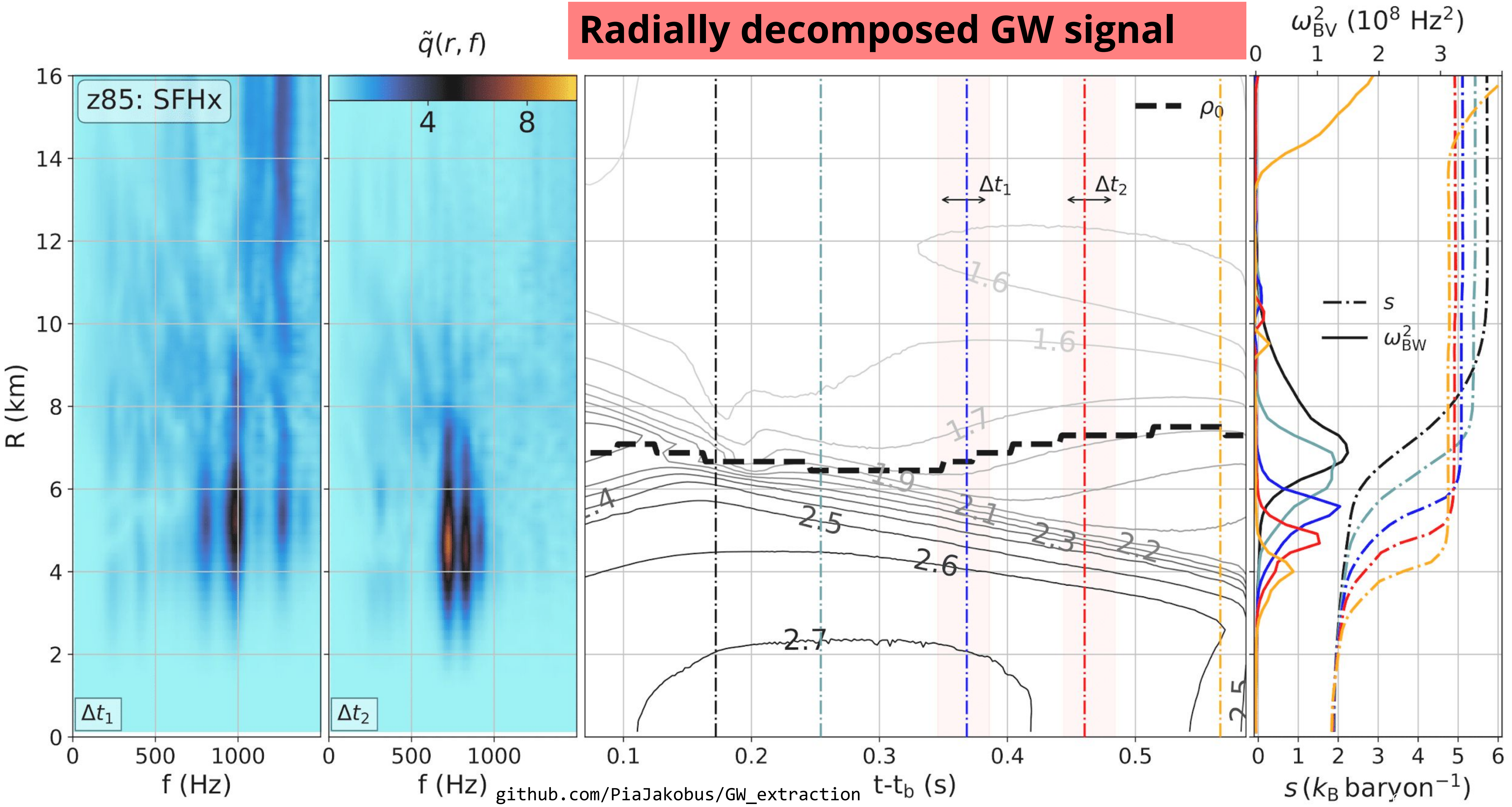

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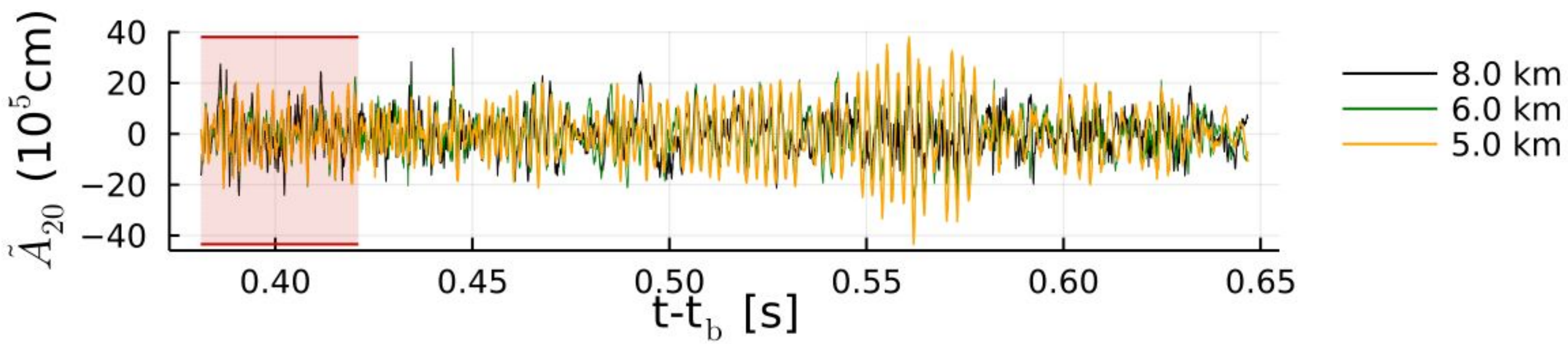

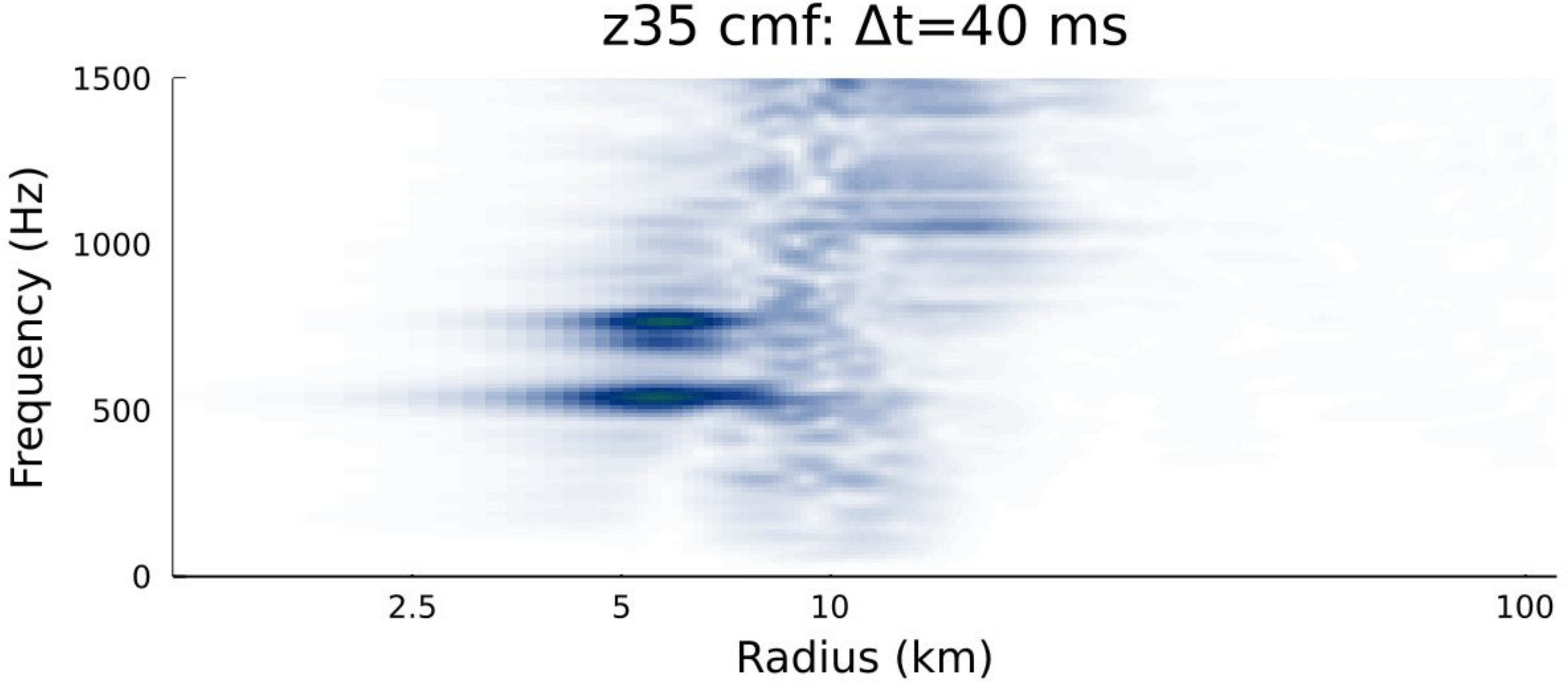

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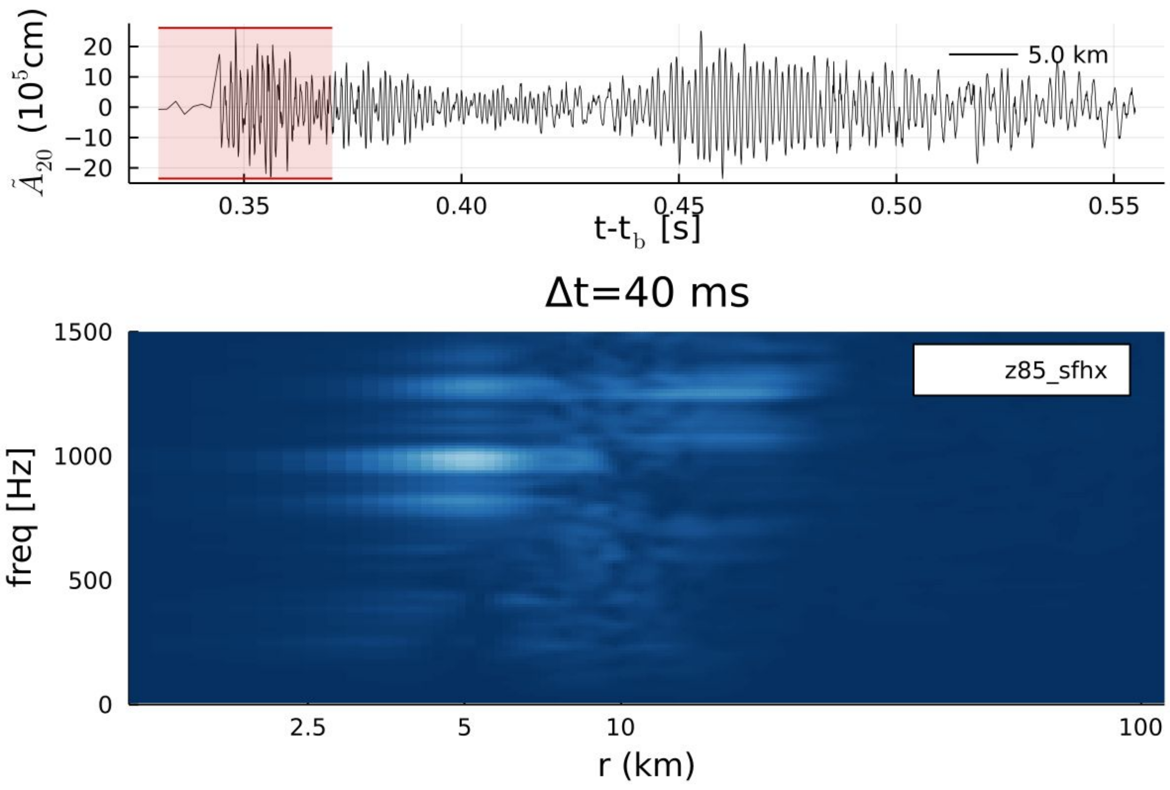

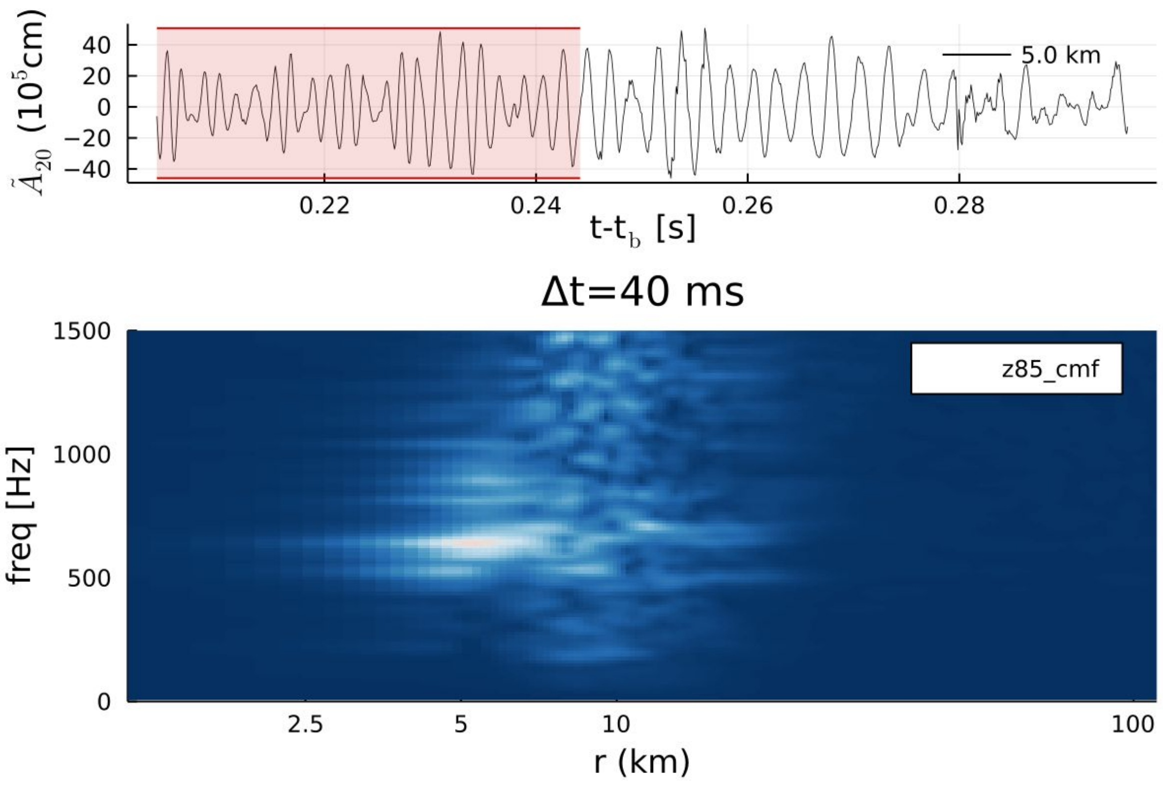

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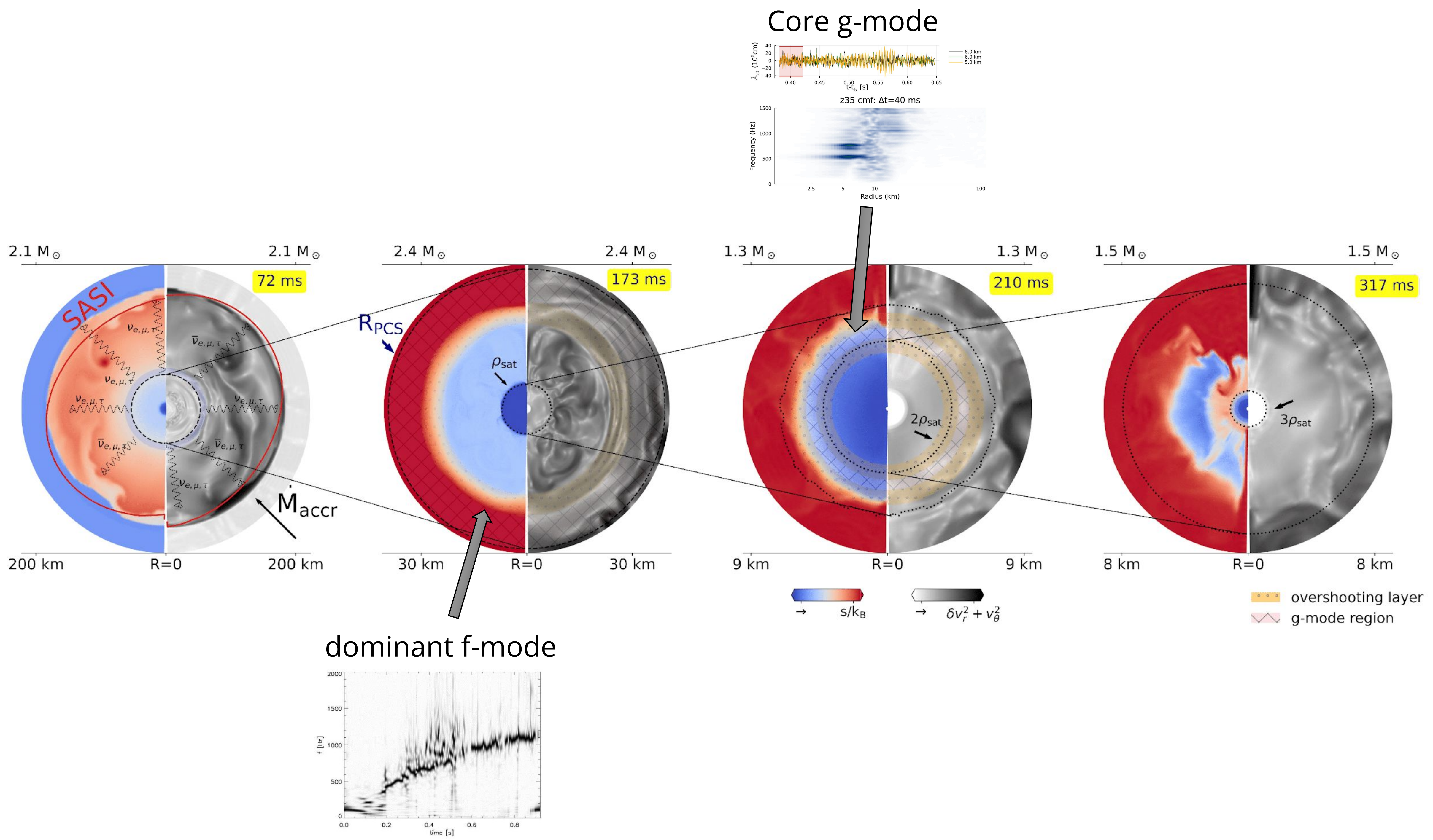
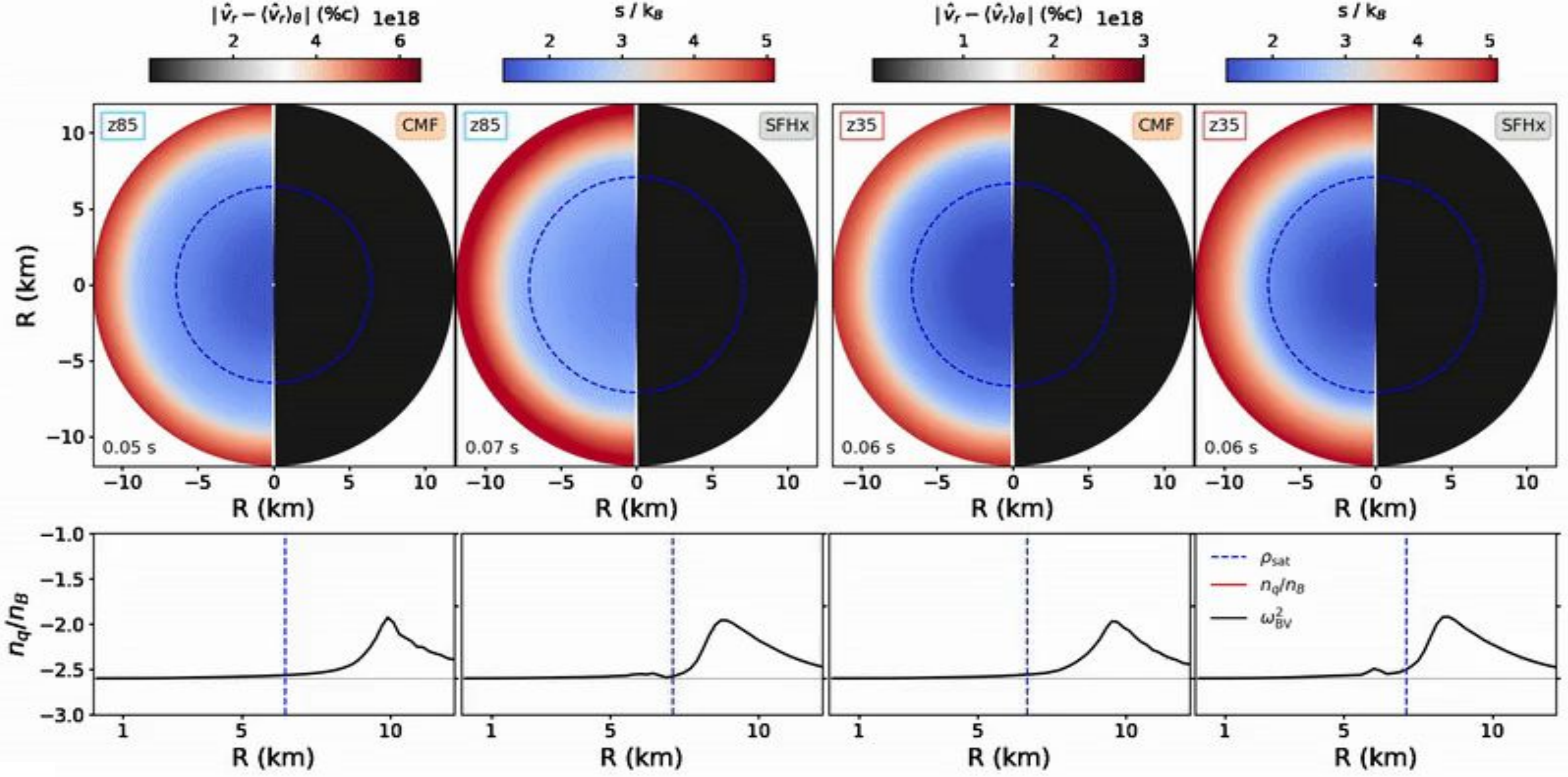
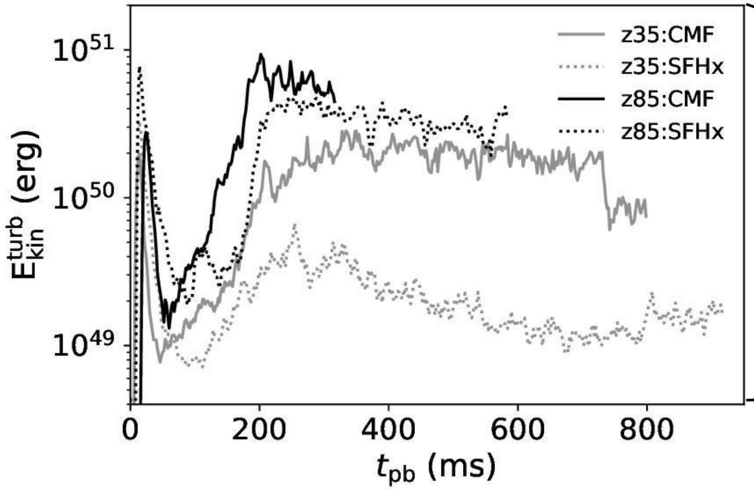

Core g-mode
z35 cmf: Δt=40 ms
Frequency (Hz)
Radius (km)
8.0 km
6.0 km
5.0 km
2.1 M⊙
2.4 M⊙
1.3 M⊙
1.5 M⊙
72 ms
173 ms
210 ms
317 ms
SASI
R_PCS
ρ_sat
2ρ_sat
3ρ_sat
Ṁ_accr
200 km
R=0
30 km
9 km
8 km
s/k_B
δv_r^2 + v_θ^2
overshooting layer
g-mode region
dominant f-mode
f [Hz]
time [s]

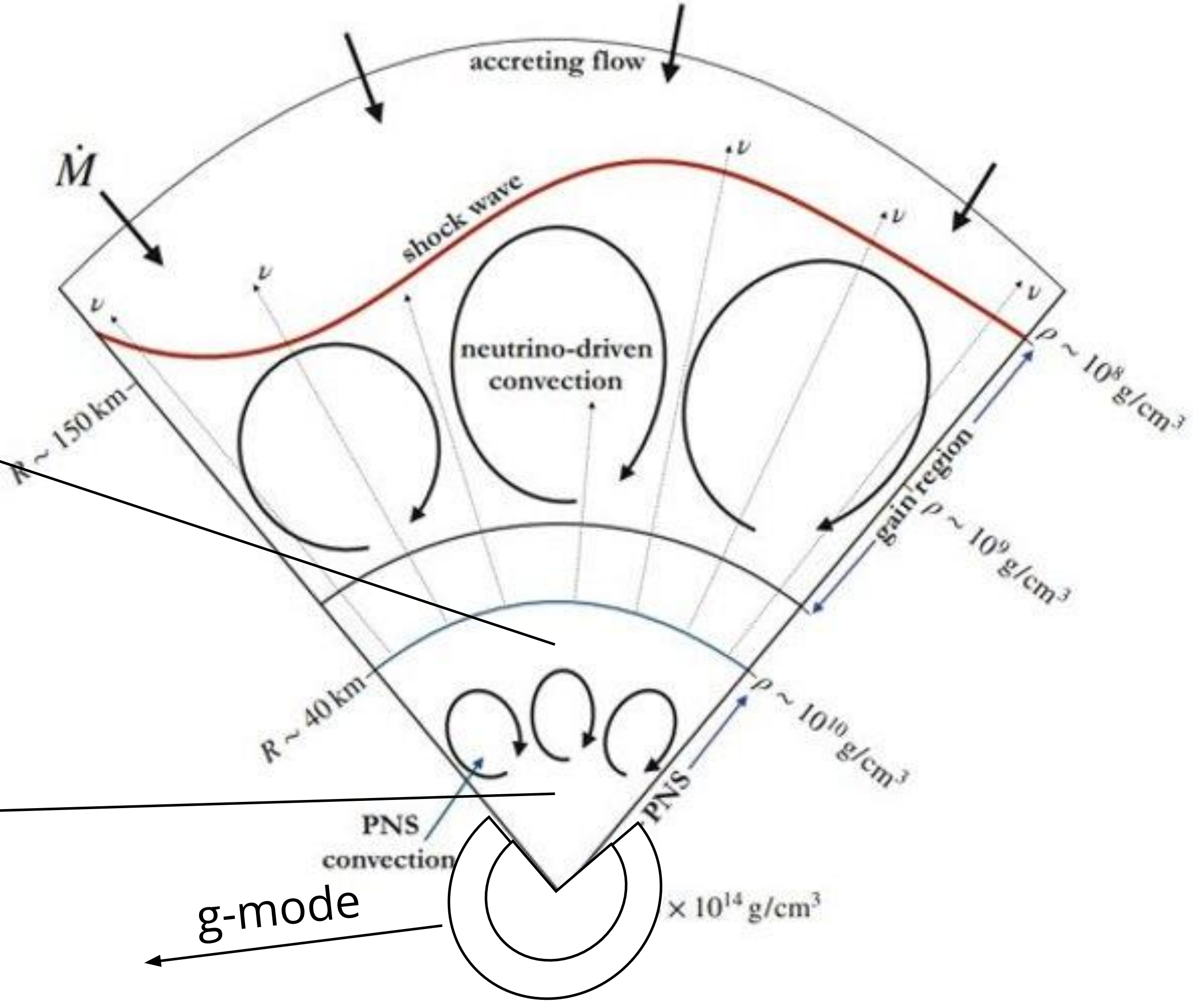


$|\hat{v}_r - \langle\hat{v}_r\rangle_\theta|$ (%c) 1e18
s / k_B
z85
CMF
0.05 s
z85
SFHx
0.07 s
z35
CMF
0.06 s
z35
SFHx
0.06 s
R (km)
n_q/n_B
ρ_{sat}
n_q/n_B
ω^2_{BV}

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)

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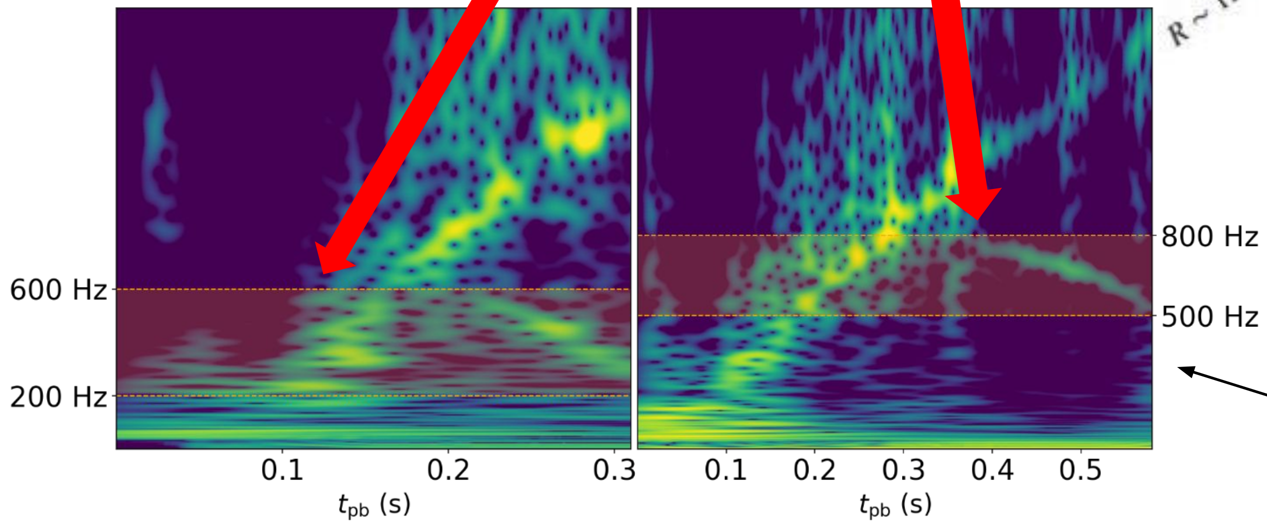
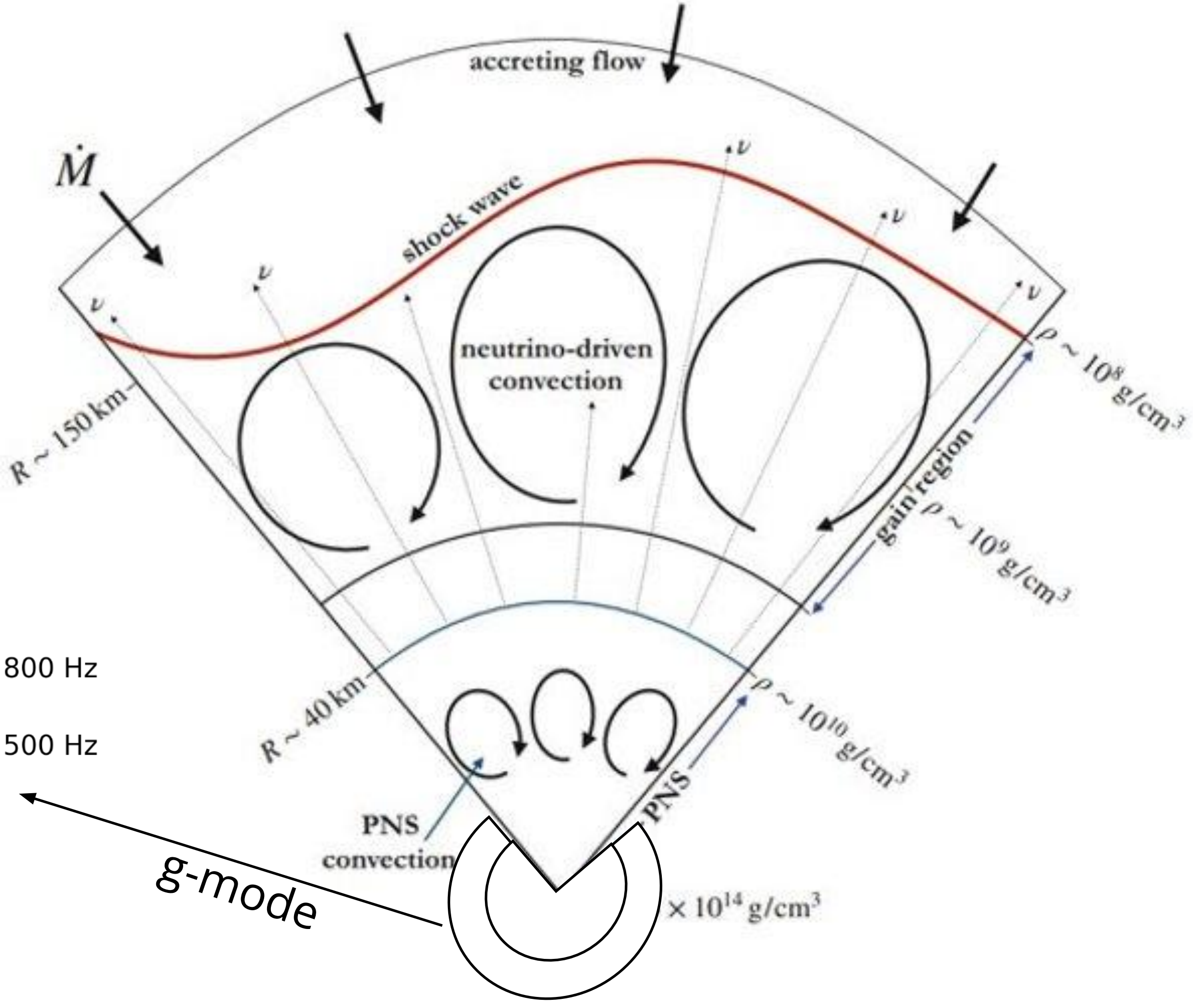
3. What EoS properties cause ~20% lower g-mode frequencies in CMF?

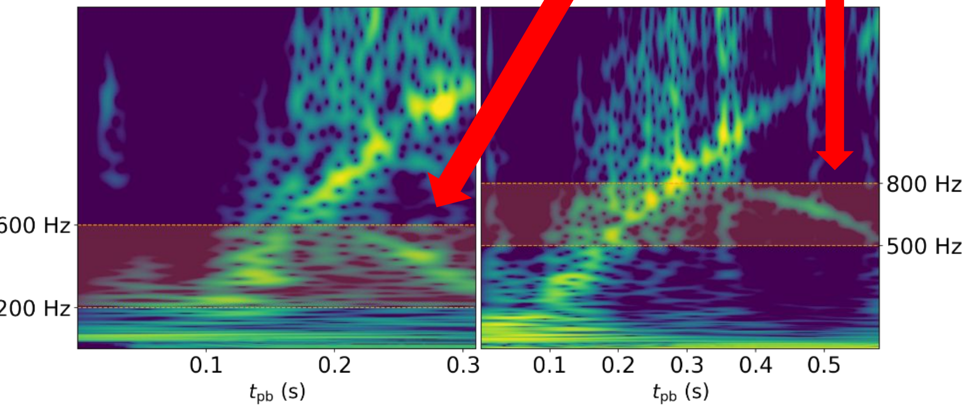


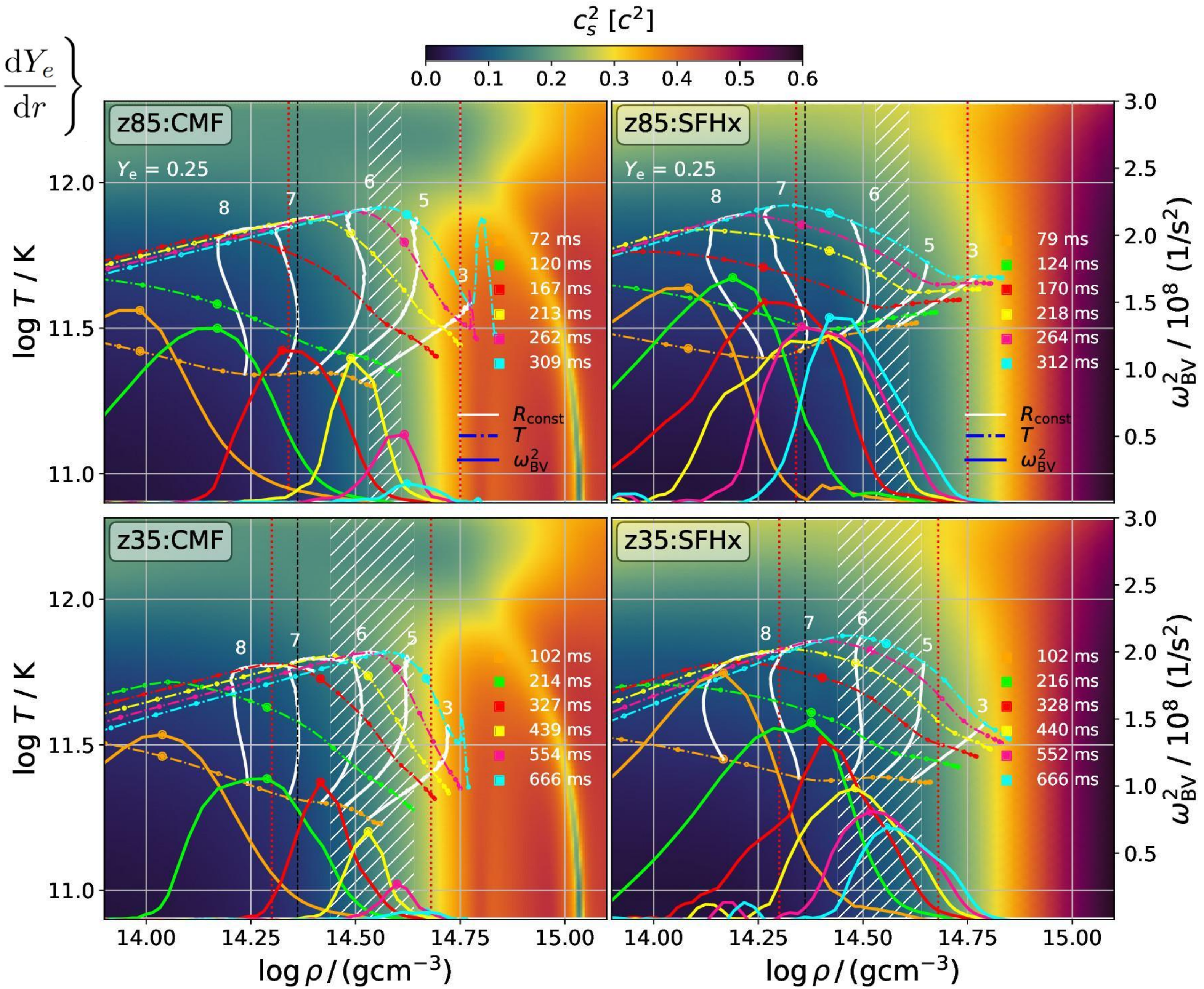


(Abdikamalov et al. 2022)

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

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

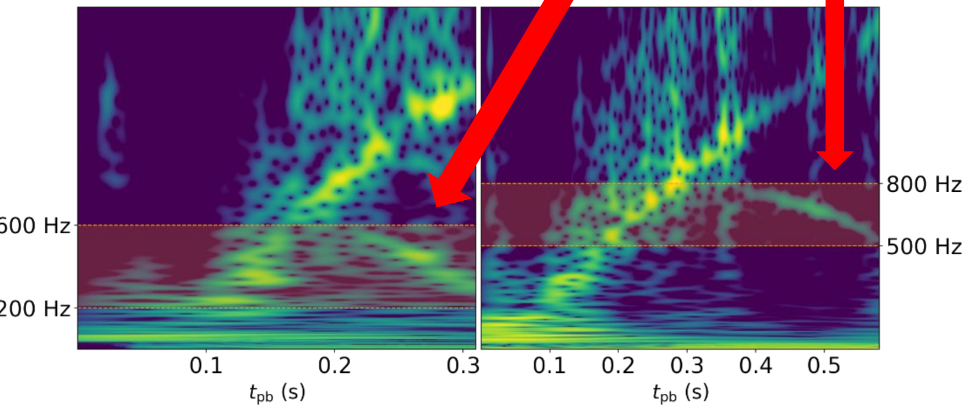


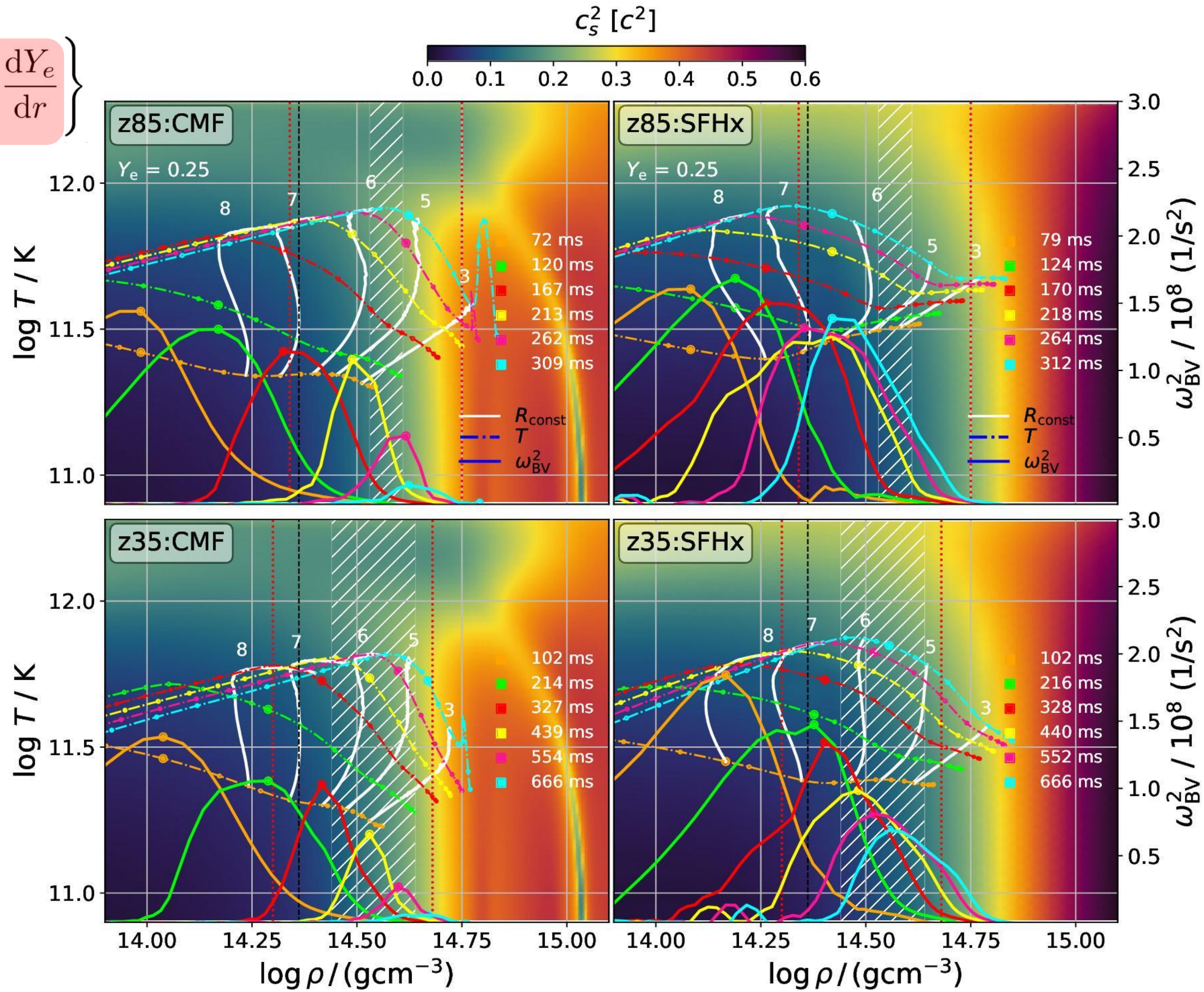


$$\omega_{\rm BV}^2 = \frac{{\rm d}\alpha}{{\rm d}r}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{{\rm d}s}{{\rm d}r} + \left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{{\rm d}Y_e}{{\rm d}r}\right\}$$

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

?





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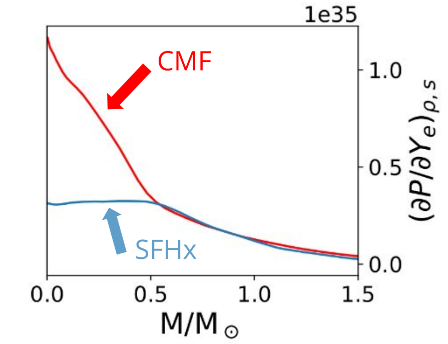
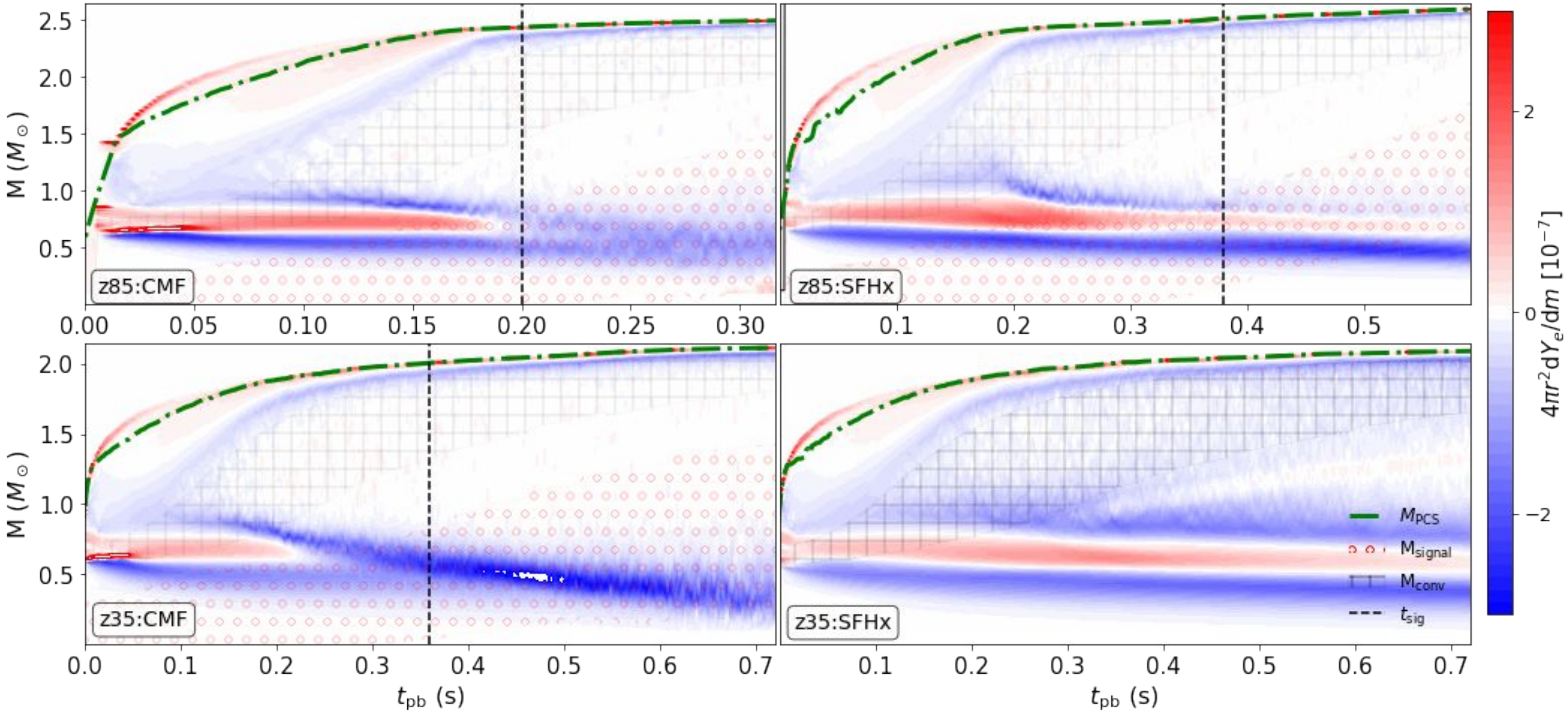
$$\omega_{\mathrm{BV}}^2 = \frac{\mathrm{d}\alpha}{\mathrm{d}r}\,\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{\mathrm{d}s}{\mathrm{d}r} + \left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right\}$$





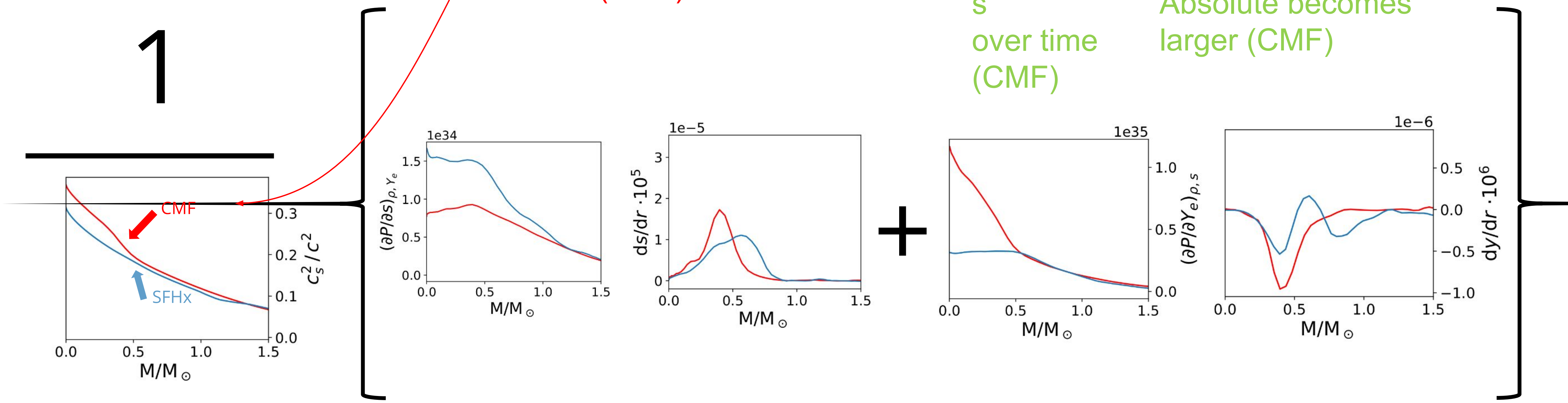
z35 progenitor
550 ms

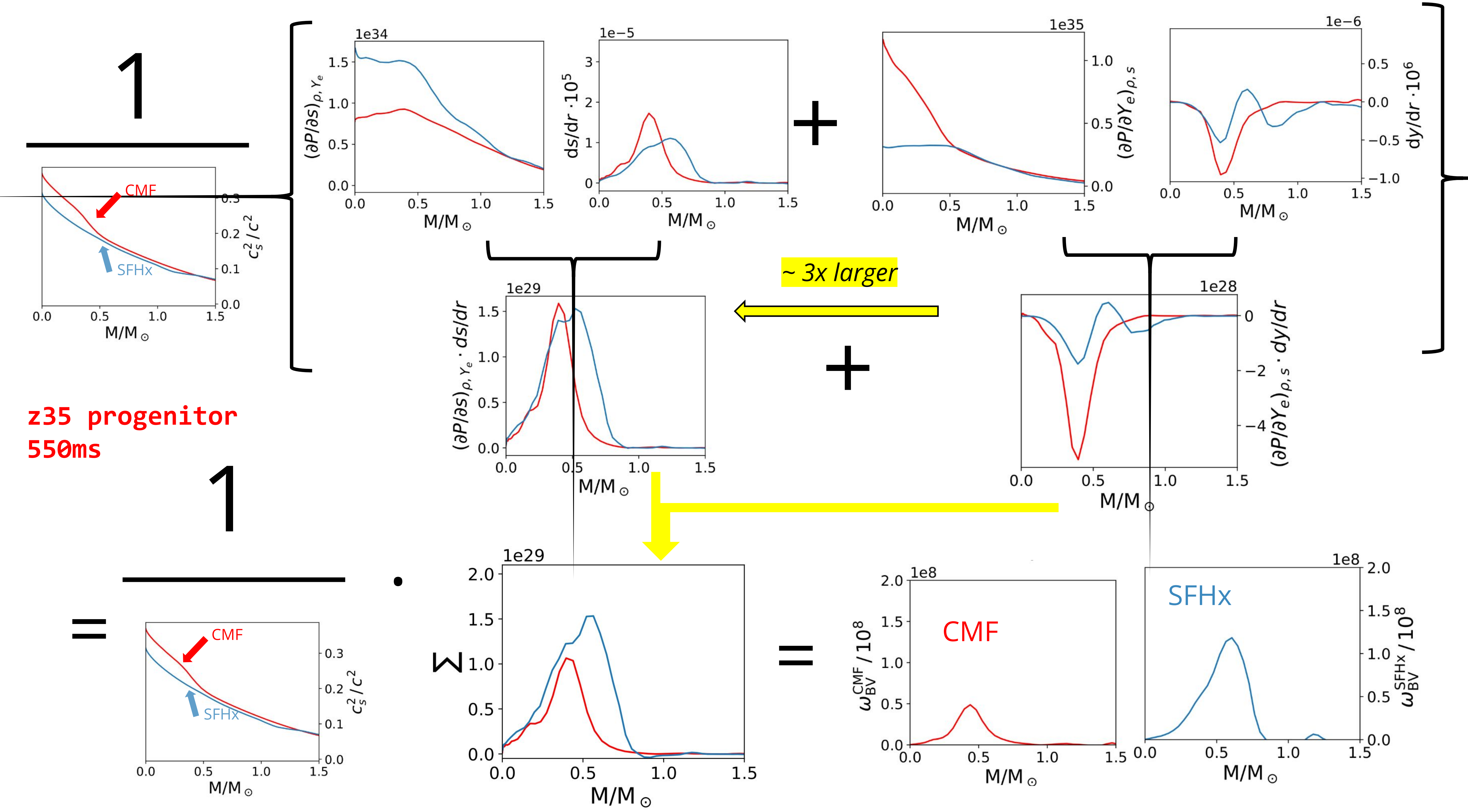
$$\omega_{\mathrm{BV}}^2 = \frac{\mathrm{d}\alpha}{\mathrm{d}r}\frac{\alpha}{\rho h \Phi^4} \cdot \frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{\mathrm{d}s}{\mathrm{d}r} + \left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right\}$$

Speed of sound larger (CMF)

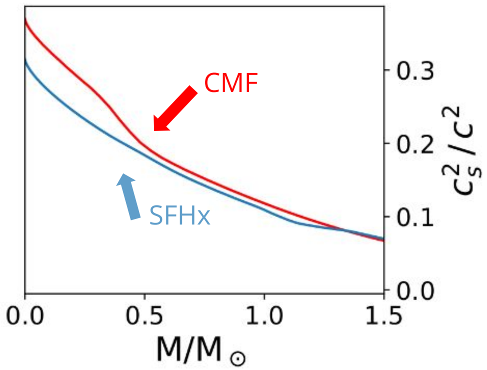
Increase s over time (CMF)

Changes sign Absolute becomes larger (CMF)

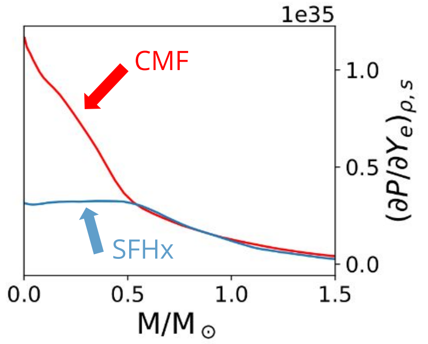




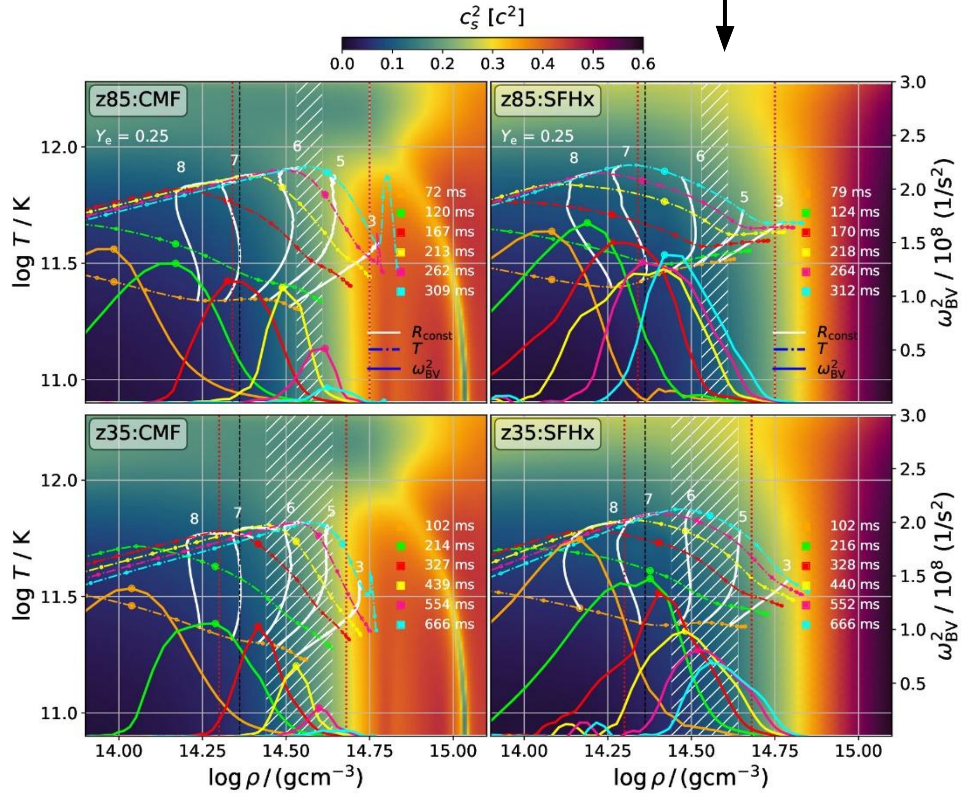
1
CMF
SFHx
c_s^2/c^2
M/M$_\odot$
1e34
$(\partial P/\partial s)_{\rho, Y_e}$
1e−5
$ds/dr \cdot 10^5$
+
1e35
$(\partial P/\partial Y_e)_{\rho, s}$
1e−6
$dy/dr \cdot 10^6$
~ 3x larger
1e29
$(\partial P/\partial s)_{\rho, Y_e} \cdot ds/dr$
1e28
$(\partial P/\partial Y_e)_{\rho, s} \cdot dy/dr$
z35 progenitor
550ms
=
·
Σ
$\omega_{BV}^{CMF} / 10^8$
$\omega_{BV}^{SFHx} / 10^8$
1e8

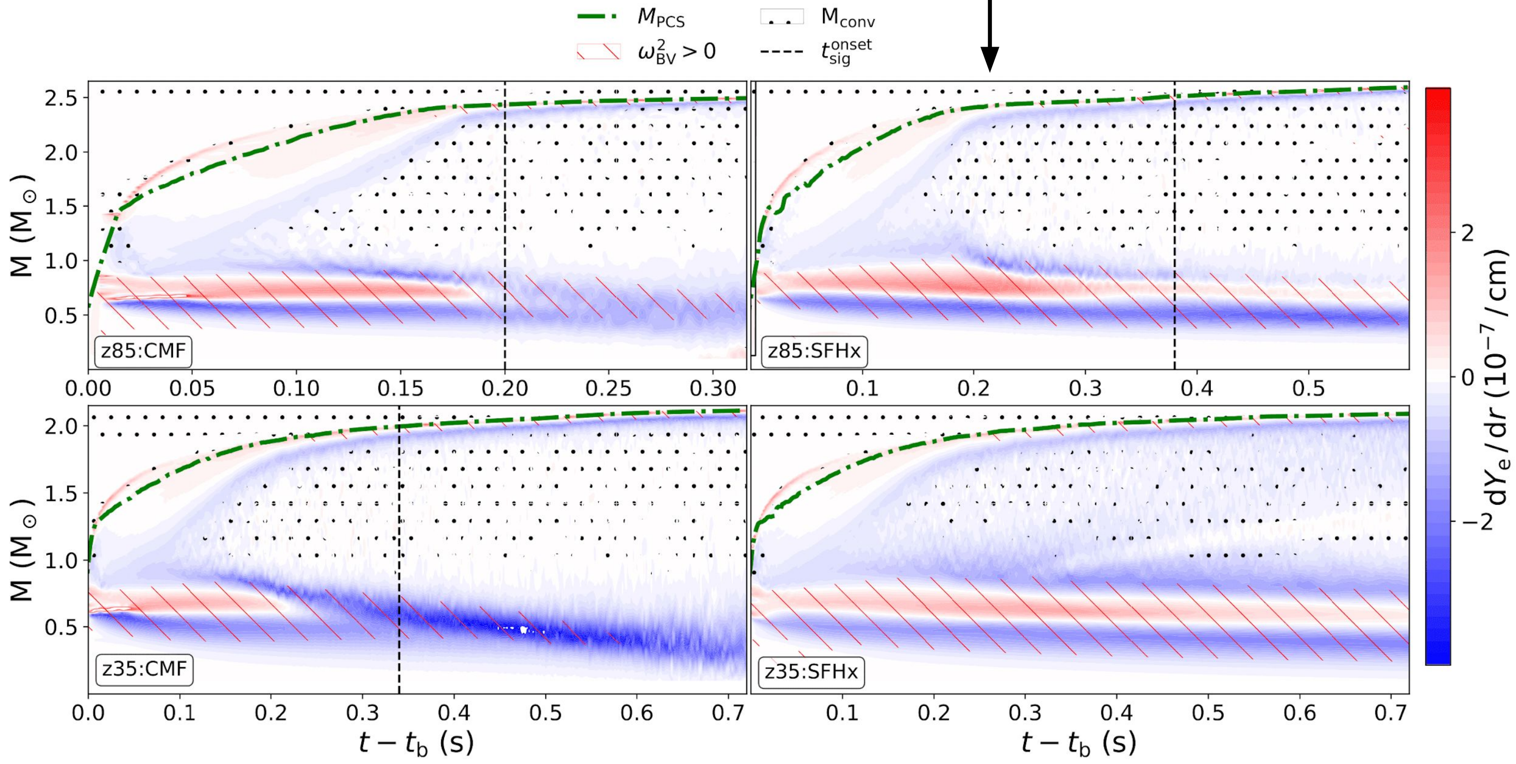


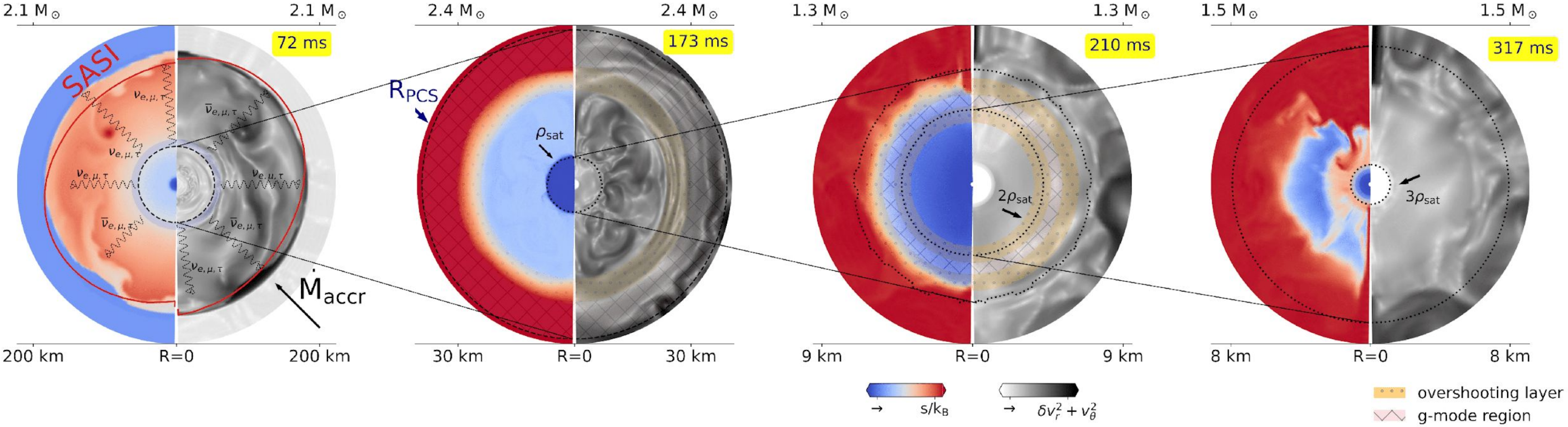
$$\omega_{\mathrm{BV}}^2 = \frac{\mathrm{d}\alpha}{\mathrm{d}r}\frac{\alpha}{\rho h \Phi^4}\cdot\frac{1}{c_s^2}\left\{\left(\frac{\partial P}{\partial s}\right)_{\tilde{\rho},Y_e}\frac{\mathrm{d}s}{\mathrm{d}r} + \left(\frac{\partial P}{\partial Y_e}\right)_{\tilde{\rho},s}\frac{\mathrm{d}Y_e}{\mathrm{d}r}\right\}$$



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





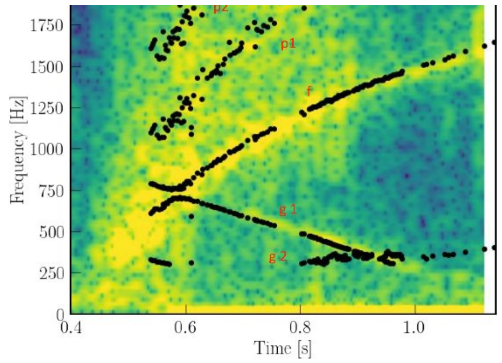


Summary

❖ Signal corresponds to g-mode oscillations in the PCS

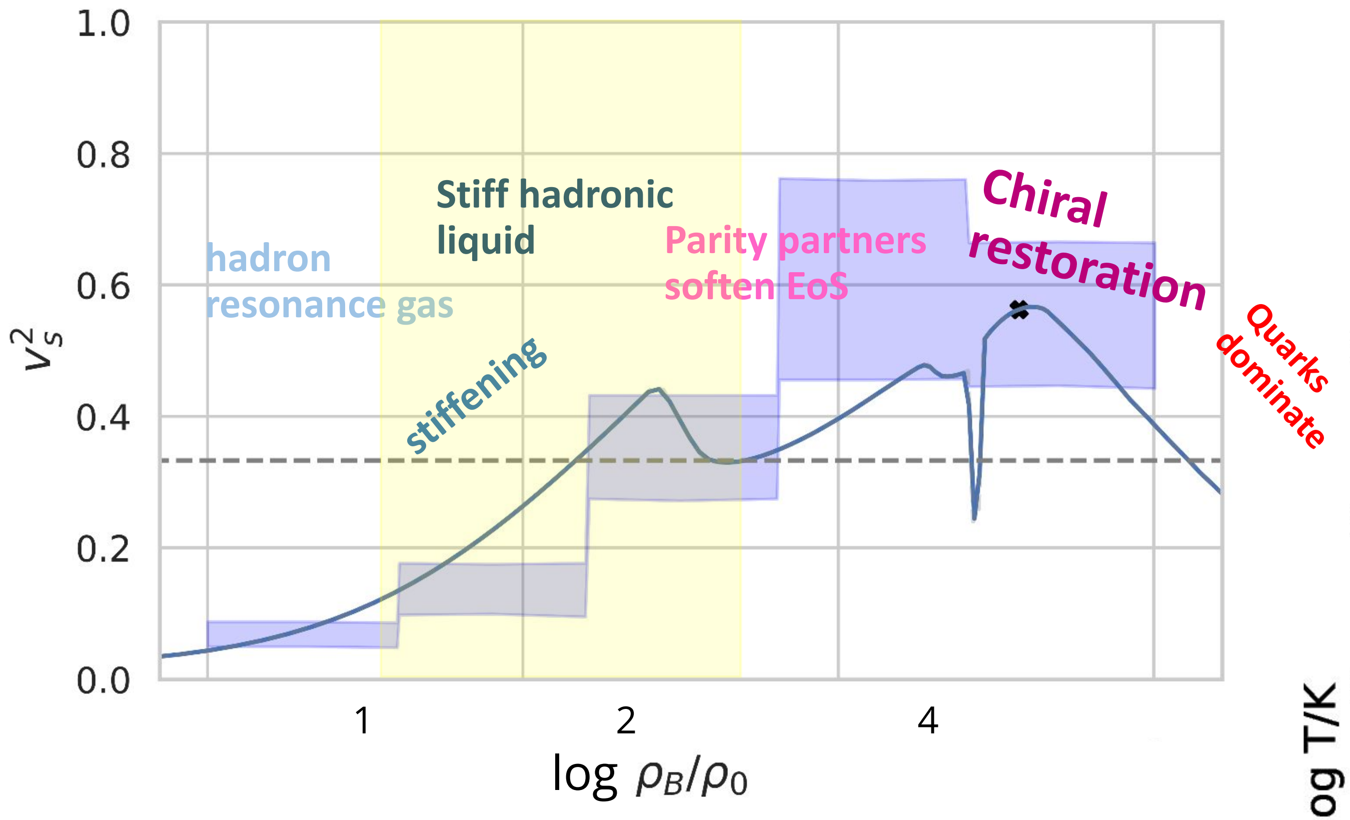
→ ~5-10 km (200-500 ms post-bounce)

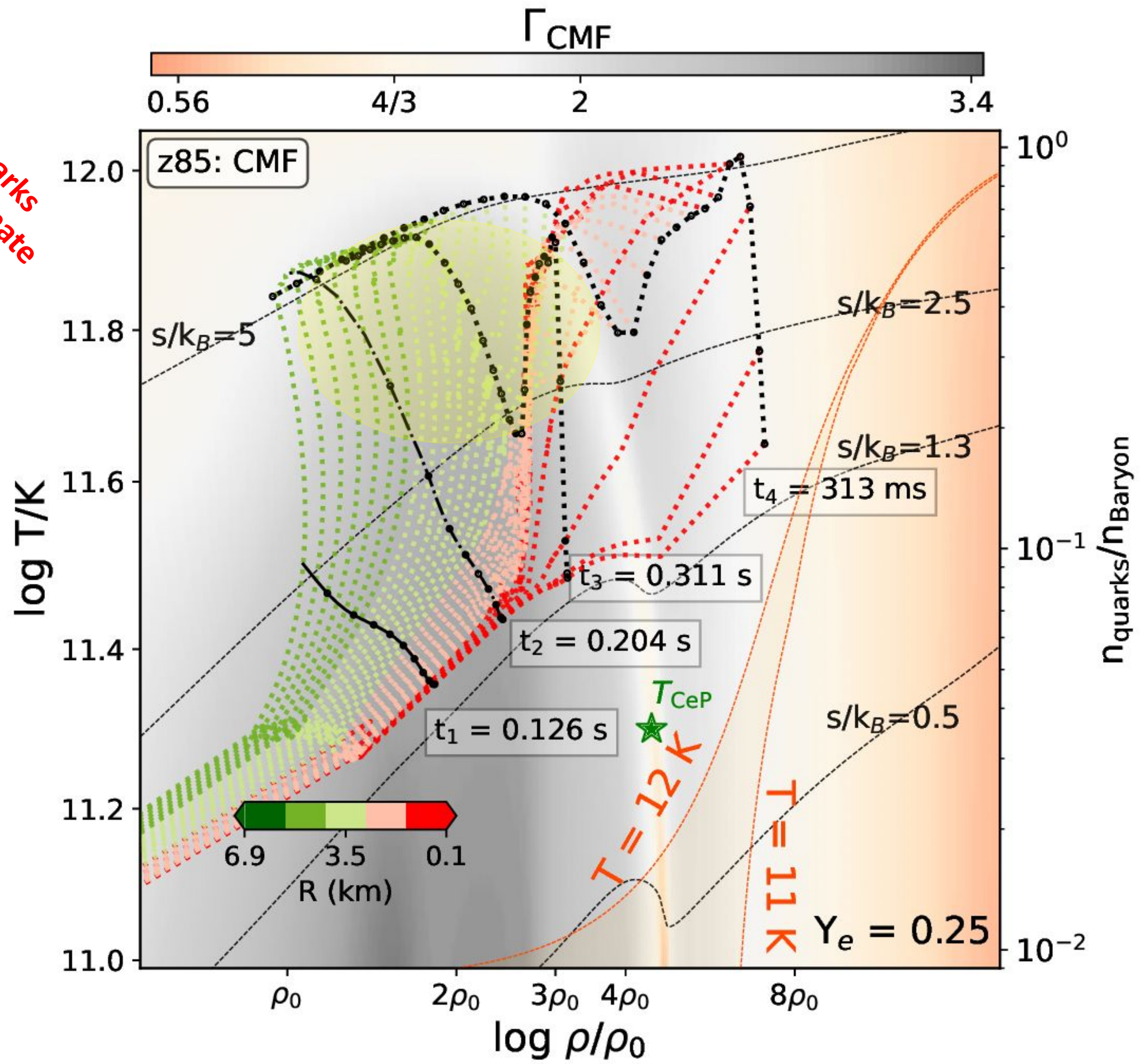
→ l= 2 g_1-mode [Zha et al., paper in prep]



❖ Mode frequency very sensitive to speed of sound at around twice saturation density

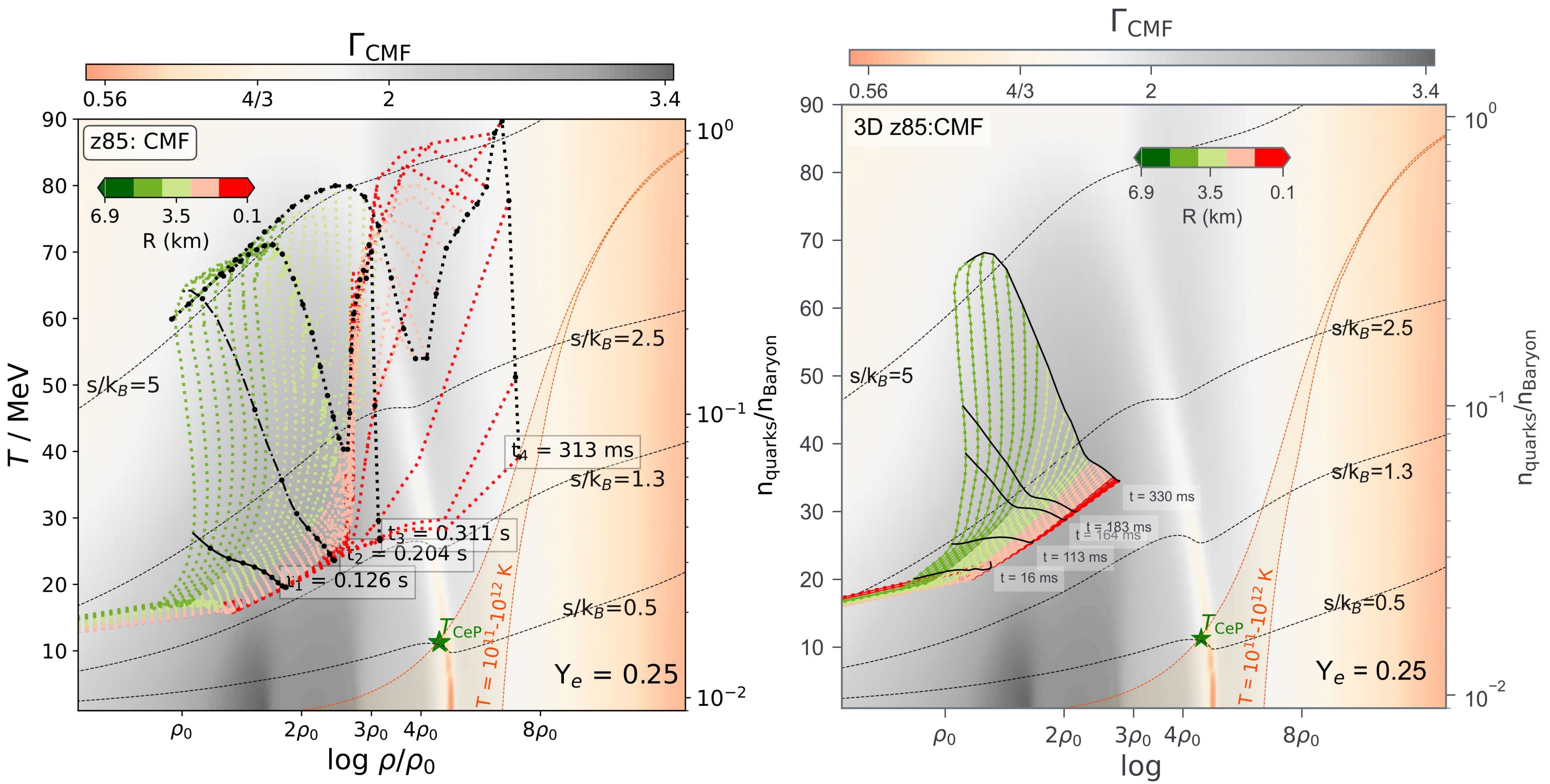
❖ Low frequency feature of mode lies within the sensitivity range of current GW detectors





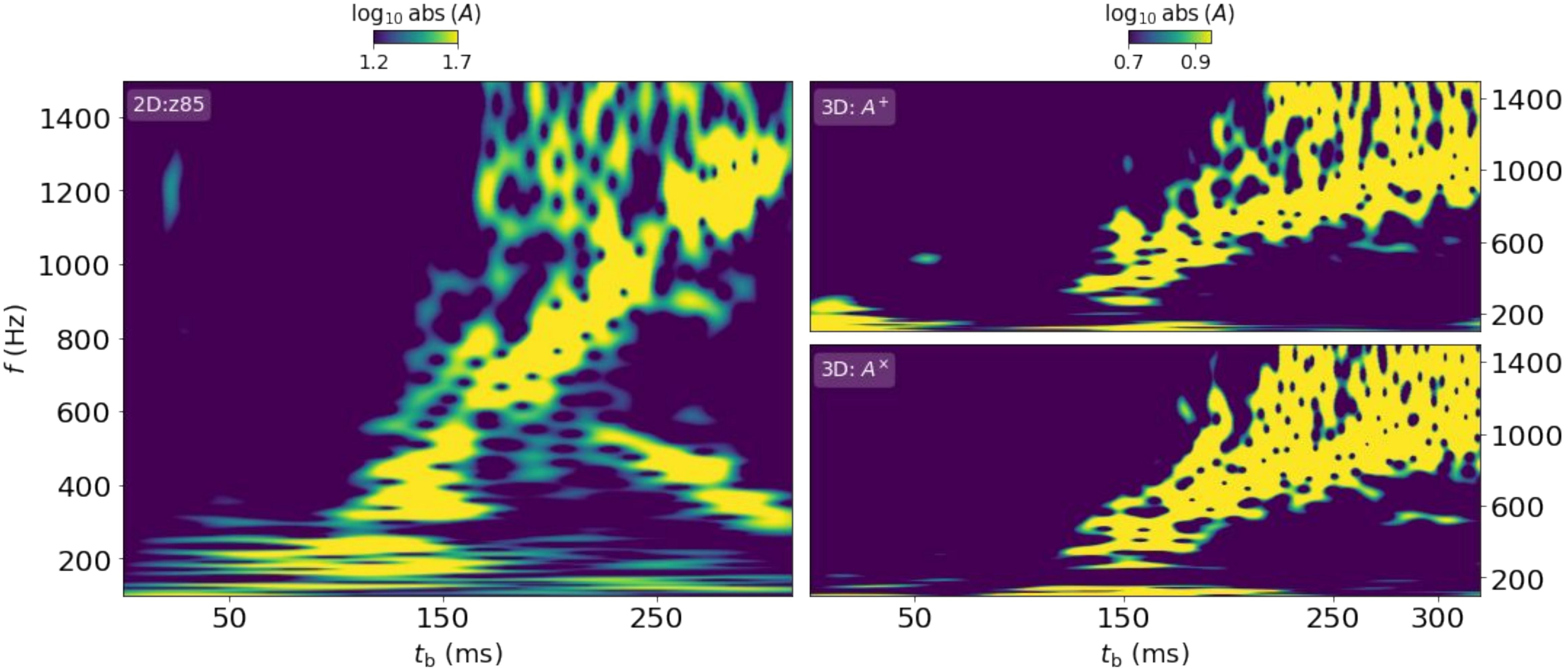
- Quarks are abundant in very low numbers
- Nucleon-nucleon interactions make EoS stiff
- Interplay of electron gradient in combination with a large $(\partial P/\partial Y_e)_{\rho,s}$ drives down B.V.f.

Motornenko et al:
10.1103/PhysRevC.101.034904 [Mar 2020]
10.1016/j.nuclphysa.2020.121836 [Jan 2021]

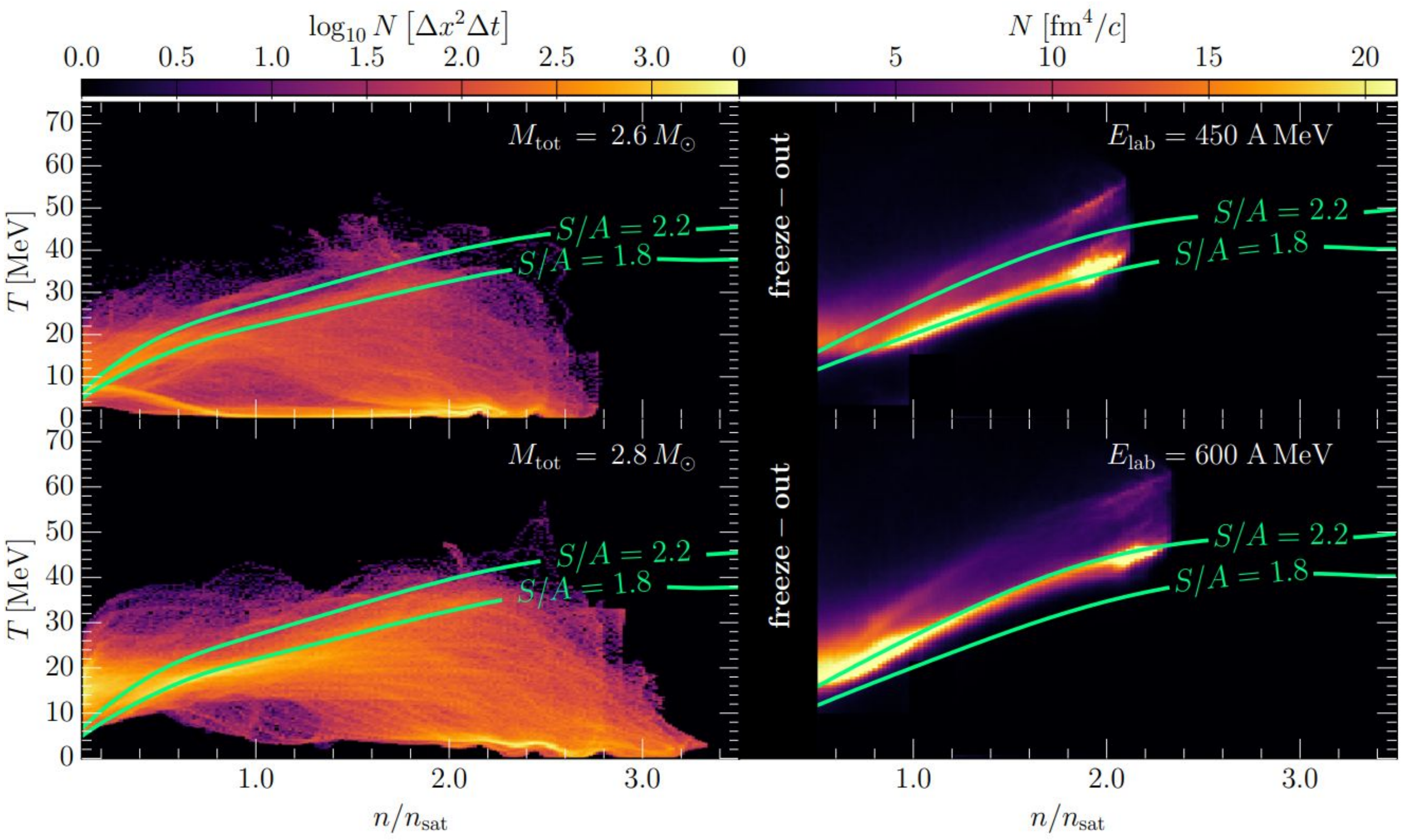


Γ_CMF
0.56
4/3
2
3.4
z85: CMF
6.9
3.5
0.1
R (km)
s/k_B=5
s/k_B=2.5
s/k_B=1.3
s/k_B=0.5
t_4 = 313 ms
t_3 = 0.311 s
t_2 = 0.204 s
t_1 = 0.126 s
T_CeP
T = 10^11-10^12 K
Y_e = 0.25
T / MeV
log ρ/ρ_0
n_quarks/n_Baryon
3D z85:CMF
t = 330 ms
t = 183 ms
t = 164 ms
t = 113 ms
t = 16 ms
log

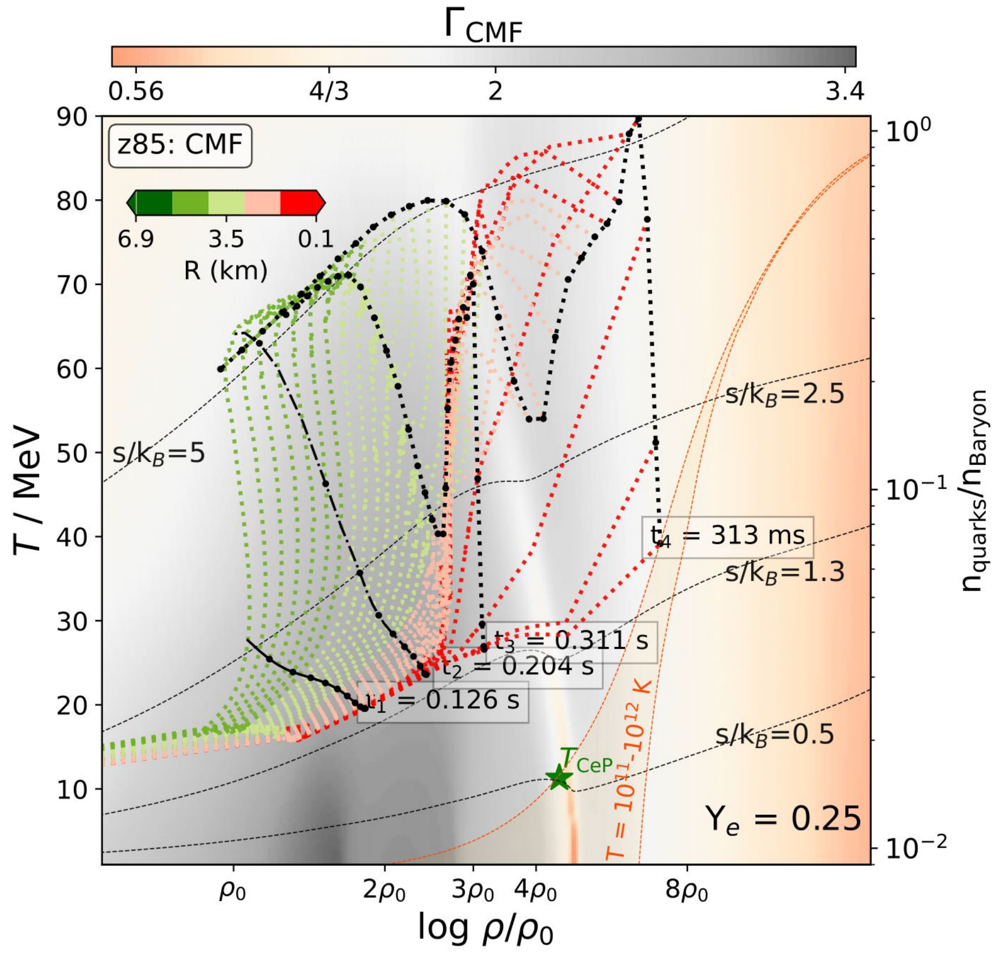
How do 2D and 3D compare?



Temperature and density comparison to NS-merger



(Most et al. 2022:arXiv-2201)



Thank you for your attention!