MODELING CORE-COLLAPSE SUPERNOVAE AND REMNANTS OF NEUTRON-STAR MERGERS

OLIVER JUST
RIKEN

"PHYSICS OF CORE-COLLAPSE SUPERNOVAE AND COMPACT STAR FORMATIONS"

WITH: H.-TH.-JANKA, R. BOLLIG, M. OBERGAULINGER, R. GLAS, S. NAGATAKI, A. BAUSWEIN, R. ARDEVOL, S. GORIELY, M. WU, I. TAMBORRA AND OTHERS

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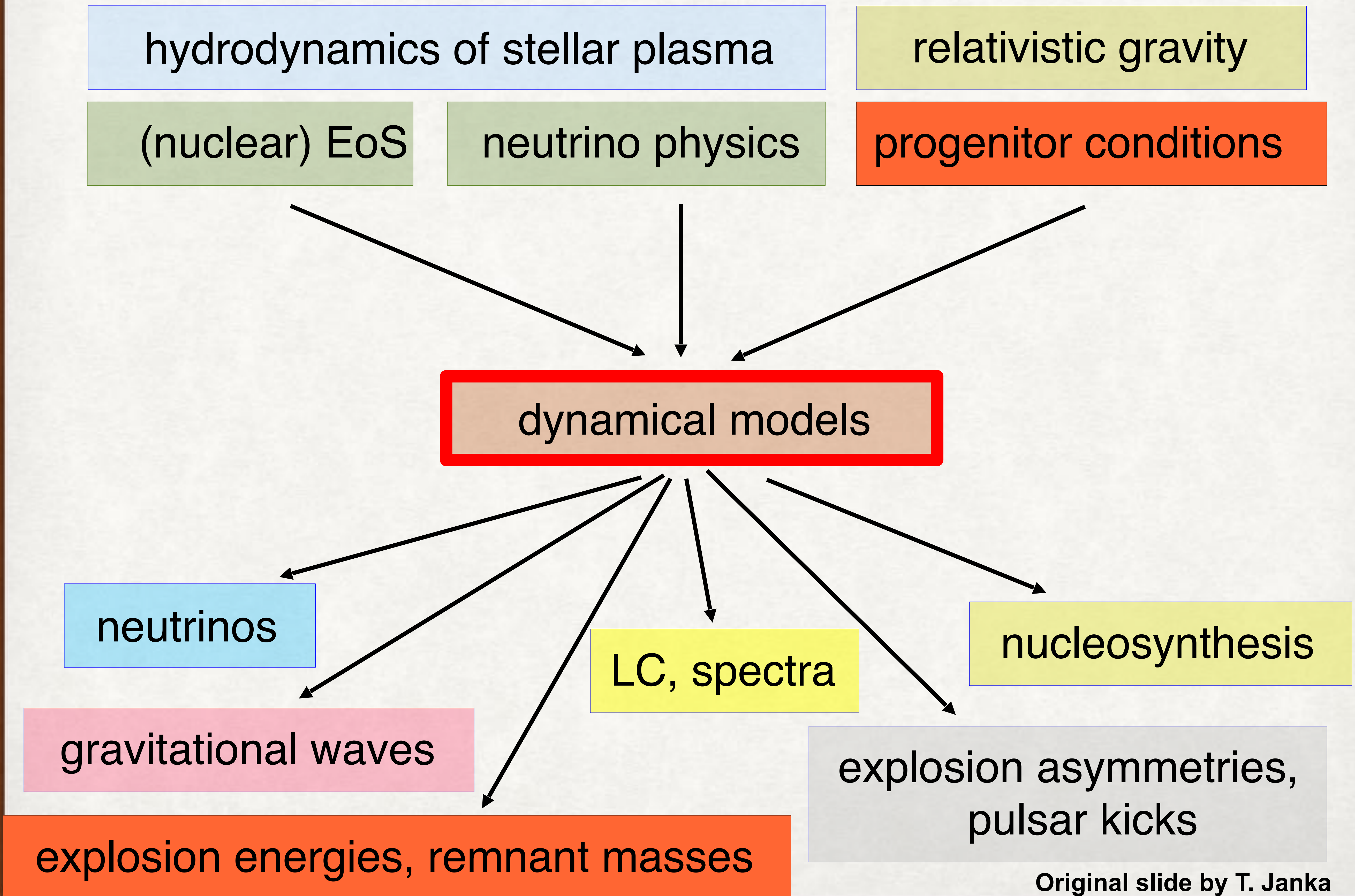
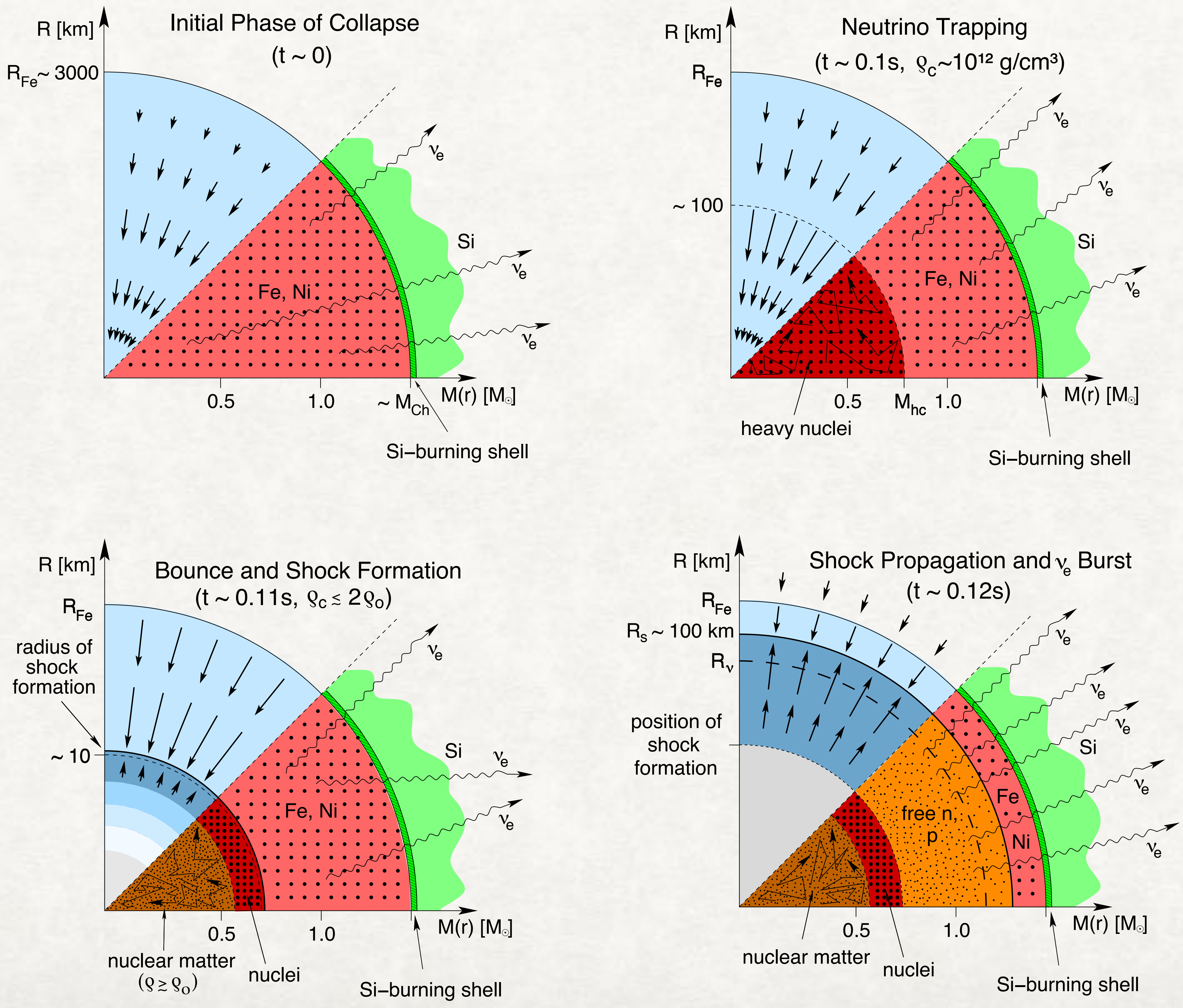
PART 1:
CORE-COLLAPSE SUPERNOVA SIMULATIONS

Predictions of Signals from SNe & NSs



Original slide by T. Janka

THE NU-DRIVEN CCSN MECHANISM



Figures from Janka '07

THE NU-DRIVEN CCSN MECHANISM

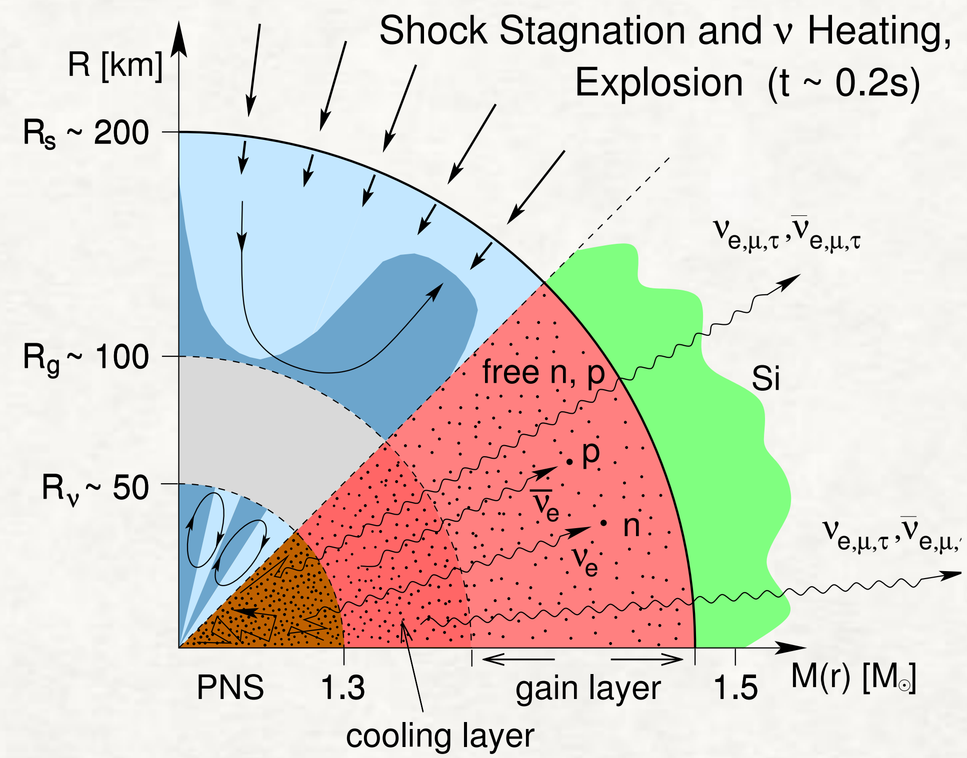
Successful revival of the shock depends ***sensitively*** on:

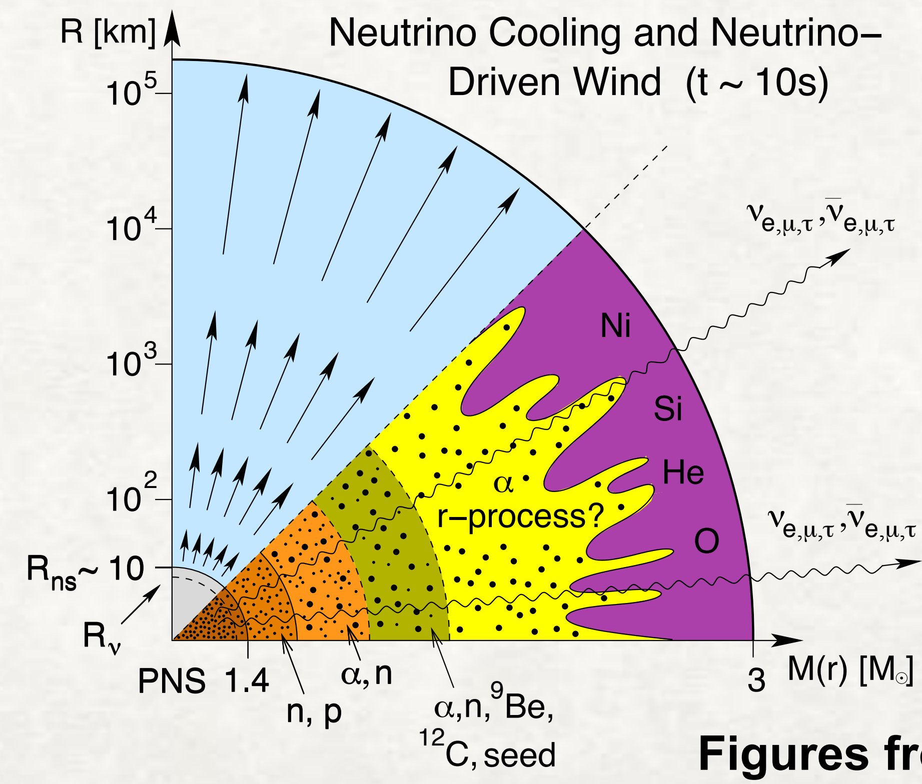
- neutrino emission and contraction of neutron star
- neutrino heating
- multidimensional hydro-dynamic instabilities (SASI, convection)

=> need multidimensional simulations with accurate neutrino transport

=> but: simulations need to remain computationally feasible

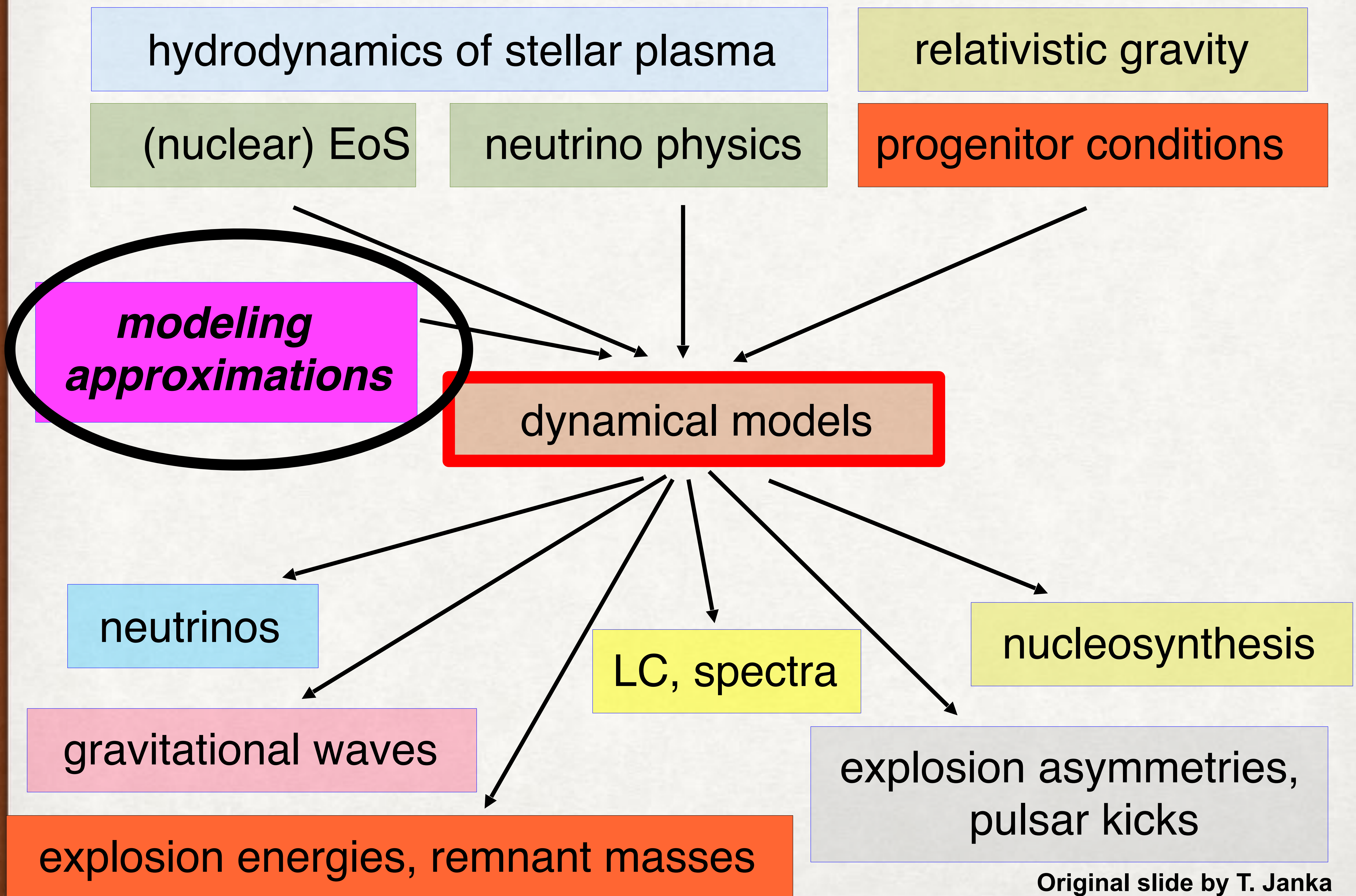
—> ***approximations inevitable***





Figures from Janka '07

Predictions of Signals from SNe & NSs



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CCSN MODELS: CURRENT STATUS

- multi-D needed for explosions!
- only very few 3D models with detailed neutrino transport (computational cost ~ O(10 million core-h, Hanke+12, Lentz+15, Roberts+16)
- exploding 2D-axisymmetric models obtained by various groups (Bruenn+, Burrows+, Couch+, Janka+, Kotake+, Nakamura+, Obergaulinger+, OConnor+, Roberts+, Sumiyoshi+, Suwa+...)

  using vastly different approximations concerning microphysics, general relativity and numerical schemes

- **BUT:** poor agreement of explosion behavior between models by different groups and codes
- demand for code comparisons and tests of approximations
- **additional challenges in multi-D:** high computational costs per simulation, turbulence, resolution, stochasticity

"ALCAR" NEUTRINO TRANSPORT MODULE

(OJ, OBERGAULINGER, JANKA '15, MNRAS, 453, 3386)

TWO-MOMENT TRANSPORT WITH ALGEBRAIC EDDINGTON FACTOR (*AEF OR M1 SCHEME*)

$$E = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)$$ ← **energy density, 0th-angular moment**

$$F^i = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i$$ ← **momentum density, 1st-angular moment**

$$P^{ij} = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j$$ ← **pressure, 2nd-angular moment**

$$Q^{ijk} = \int d\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k$$

evolution equations

$$\begin{cases} \partial_t E + \nabla_j \left(\alpha F^j + v^j E\right) + P^{ij}\nabla_i v_j + F^i \nabla_i \alpha \\ \quad - \partial_\epsilon \left[\epsilon \left(P^{ij}\nabla_i v_j + F^i \nabla_i \alpha\right)\right] = \alpha S^{(0)}, \\ \partial_t F^i + \nabla_j \left(\alpha c^2 P^{ij} + v^j F^i\right) + F^j \nabla_j v^i + c^2 E \nabla^i \alpha \\ \quad - \partial_\epsilon \left[\epsilon \left(Q^{ijk}\nabla_j v_k + c^2 P^{ij}\nabla_j \alpha\right)\right] = \alpha S^{(1),i} \end{cases}$$

$$\left.\begin{aligned} P^{ij} &= P^{ij}(E, F^i) \\ Q^{ijk} &= Q^{ijk}(E, F^i) \end{aligned}\right\}$$

central approximation of M1:
local closure relation for higher moments
(e.g. "M1 closure")

=> removes two degrees of freedom of nu-phase space
=> large gain of computational efficiency
=> trade-off: potential loss accuracy
(at least in optically thin regions)

(SEE ALSO: KURODA, ROBERTS, OCONNOR, RADICE FOR OTHER M1 CODES)

“VERTEX” NEUTRINO TRANSPORT MODULE

(RAMPP+’02, BURAS+’05, HANKE+’12)

TWO-MOMENT TRANSPORT WITH VARIABLE EDDINGTON FACTOR AND RAY-BY-RAY-PLUS APPROXIMATION

$$E = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)$$ ← **energy density, 0th-angular moment**

$$F^i = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i$$ ← **momentum density, 1st-angular moment**

$$P^{ij} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j$$ ← **pressure, 2nd-angular moment**

$$Q^{ijk} = \int \mathrm{d}\Omega\, \mathcal{I}(\boldsymbol{x}, \boldsymbol{n}, \epsilon, t)\, n^i n^j n^k$$

evolution equations

$$\begin{cases} \partial_t E + \nabla_j \left(\alpha F^j + v^j E\right) + P^{ij}\nabla_i v_j + F^i \nabla_i \alpha \\ \qquad - \partial_\epsilon \left[\epsilon \left(P^{ij}\nabla_i v_j + F^i \nabla_i \alpha\right)\right] = \alpha S^{(0)}\,, \\ \partial_t F^i + \nabla_j \left(\alpha c^2 P^{ij} + v^j F^i\right) + F^j \nabla_j v^i + c^2 E \nabla^i \alpha \\ \qquad - \partial_\epsilon \left[\epsilon \left(Q^{ijk}\nabla_j v_k + c^2 P^{ij}\nabla_j \alpha\right)\right] = \alpha S^{(1),i} \end{cases}$$

P^{ij}, Q^{ijk} ***accurate*** } **higher moments obtained from from additional evolution of spherically symmetric Boltzmann equation**

F_theta = F_phi = 0 } **solve quasi-independent 1D radiative transfer problems but include lateral advection and pressure effects (“Ray-by-Ray-plus” approximation)**

OFTEN USED APPROXIMATIONS

- two-moment M1 scheme closure

  => systematically tested so far only in 1D

  (e.g. O'Connor '15, Kuroda+16, Just+16Sumiyoshi '15, Dolence '15)

- "Ray-by-ray-plus": ignore non-radial flux-densities

  => claimed to enhance explodability (e.g. Skinner+ '16, Sumiyoshi '15, Dolence '15)

- ignoring/simplifying reactions which couple energy bins, e.g. neutrino-electron scattering, pair-annihilation

- ignoring/simplifying frame-dependent effects, e.g. Doppler- and gravitational energy-shift

COMPARISON STUDY

(OJ, BOLLIG, JANKA, OBERGAULINGER, GLAS, NAGASAKI, TO BE SUBMITTED)

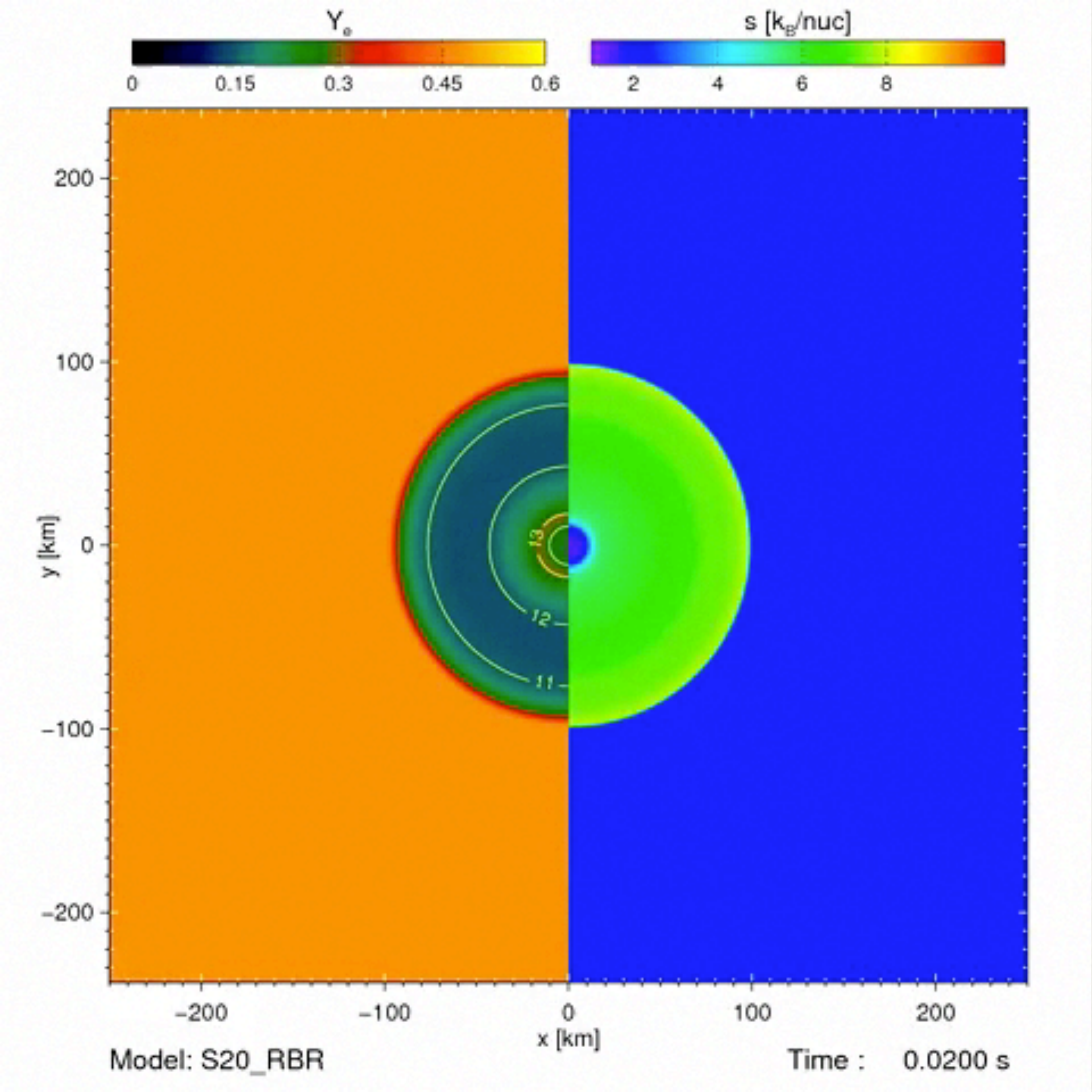
- SFHO nuclear equation of state by Steiner, Hempel
- Progenitor models: “S20” of Woosley & Heger 2007 and “S9”
- Newtonian evolution with effective GR potential
- neutrino interaction rates by Bruenn (+ NN-Bremsstrahlung)
- RBR switched on/off
- velocity-dependent terms switched on/off
- neutrino-electron scattering switched on/off
- pair-processes: using either full description or simplified scheme suggested by O’Connor ’15
- for comparison: switch on/off strange-quark corrections and many-body corrections
- direct comparison to VERTEX in 1D and 2D for 2 models

20 Msun progenitor model ‘S20’

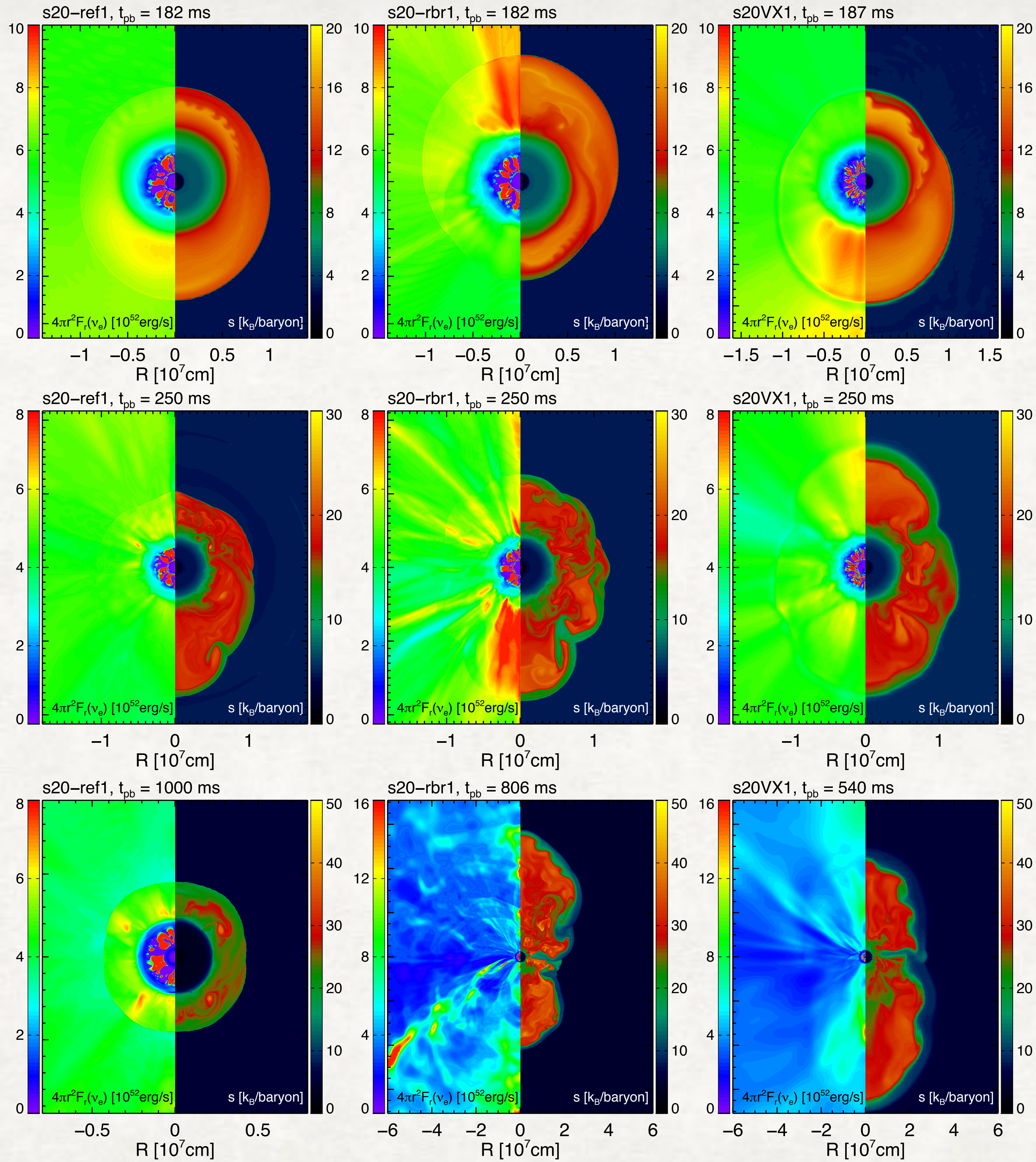
- high progenitor mass causes high mass-accretion rate

=> short advection timescales

=> good (bad) conditions for SASI (convection)



(ALCAR, with ray-by-ray+)

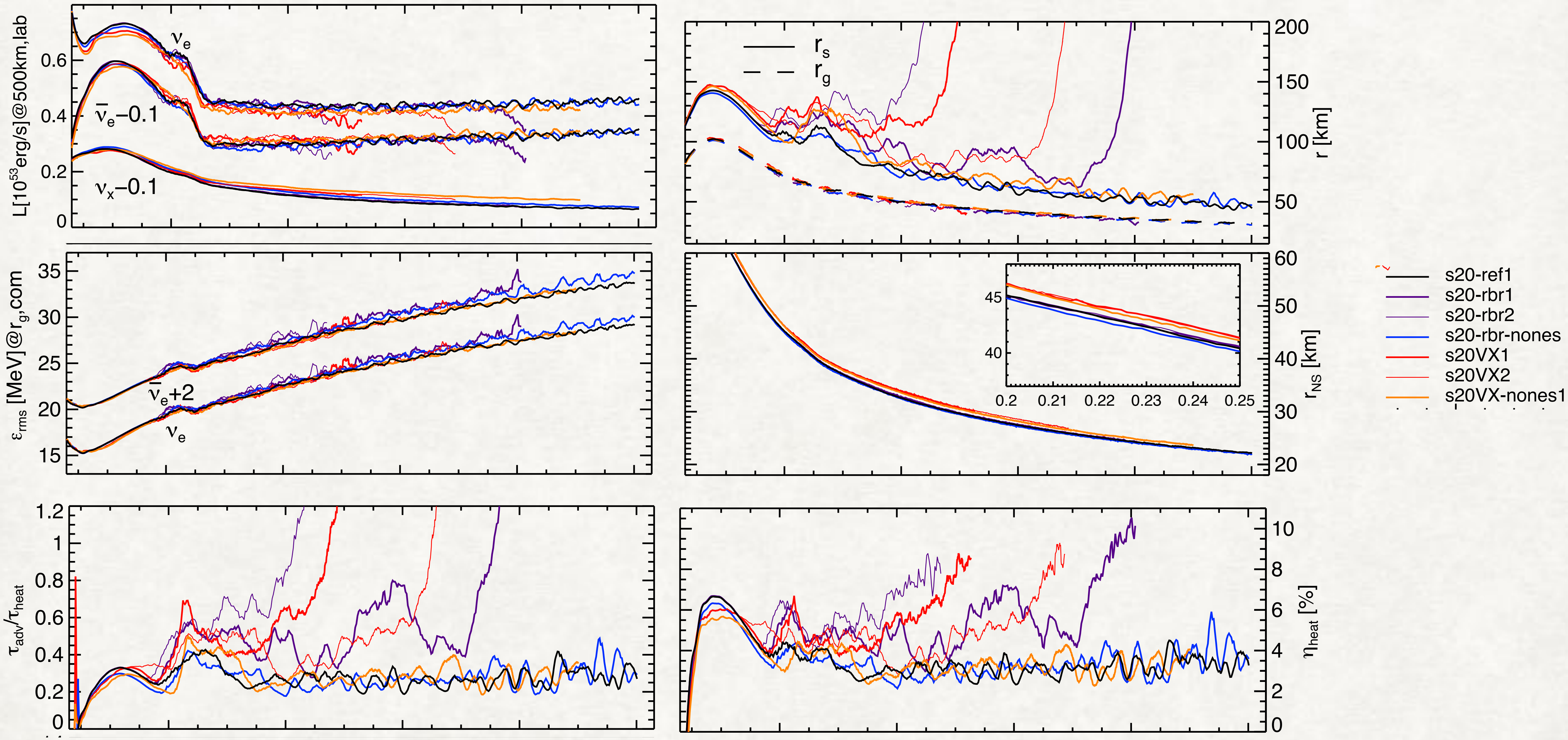


(ALCAR)

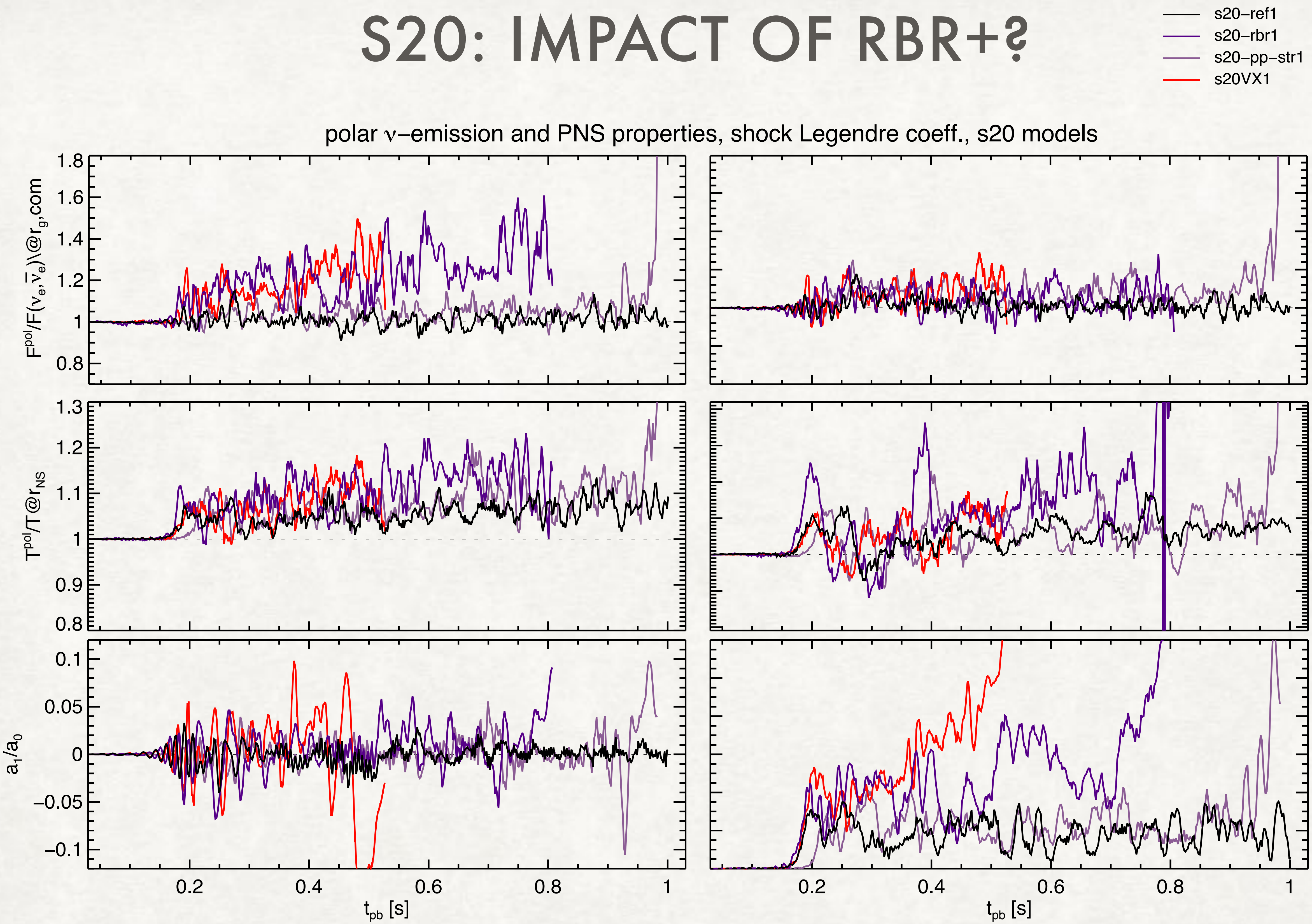
(ALCAR
\w RbR+)

(VERTEX
\w RbR+)

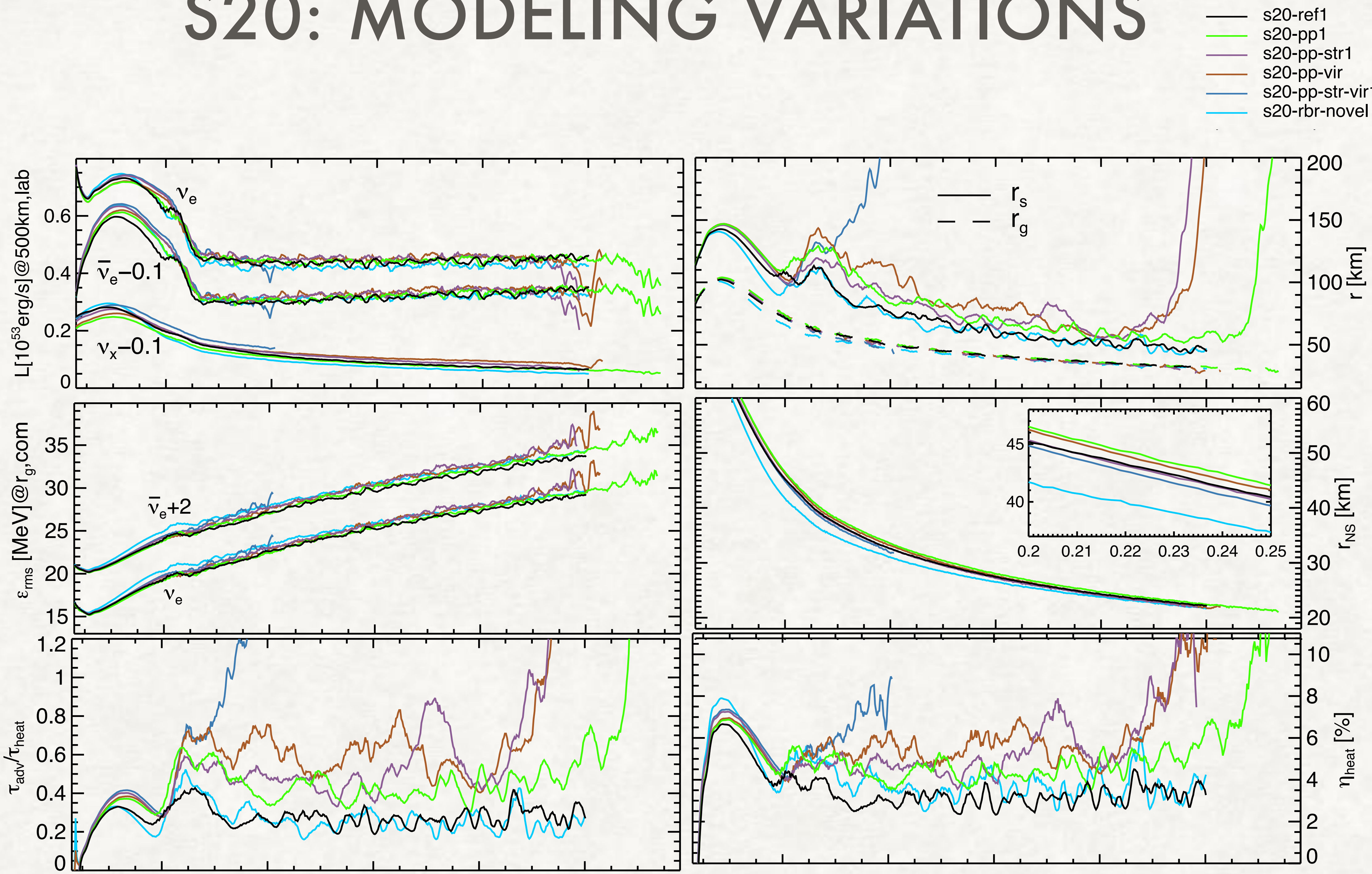
S20: ALCAR VS VERTEX VS RBR+



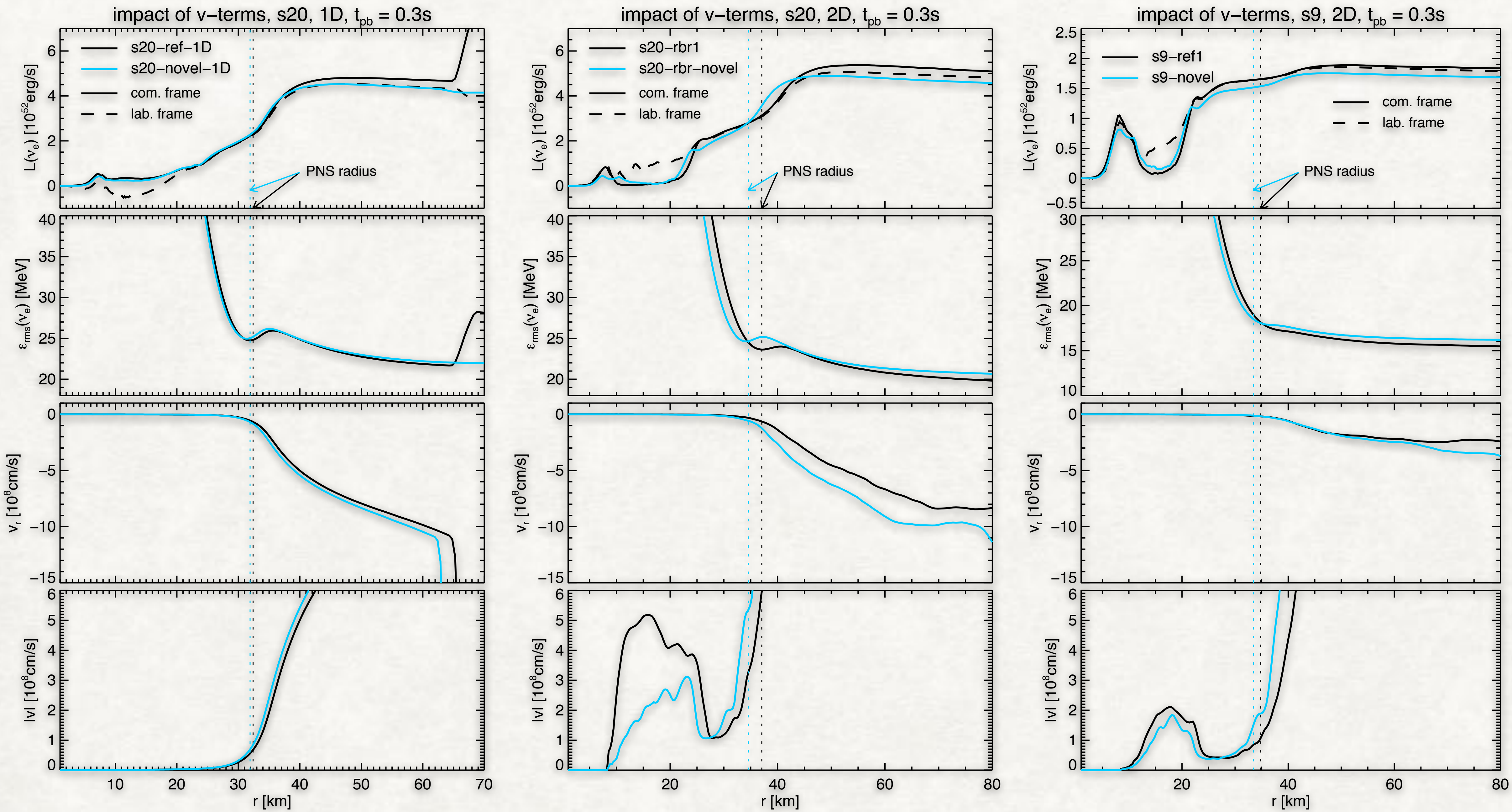
S20: IMPACT OF RBR+?



S20: MODELING VARIATIONS



IMPACT OF NEGLECTING V-TERMS



=> assuring similarities in all quantities

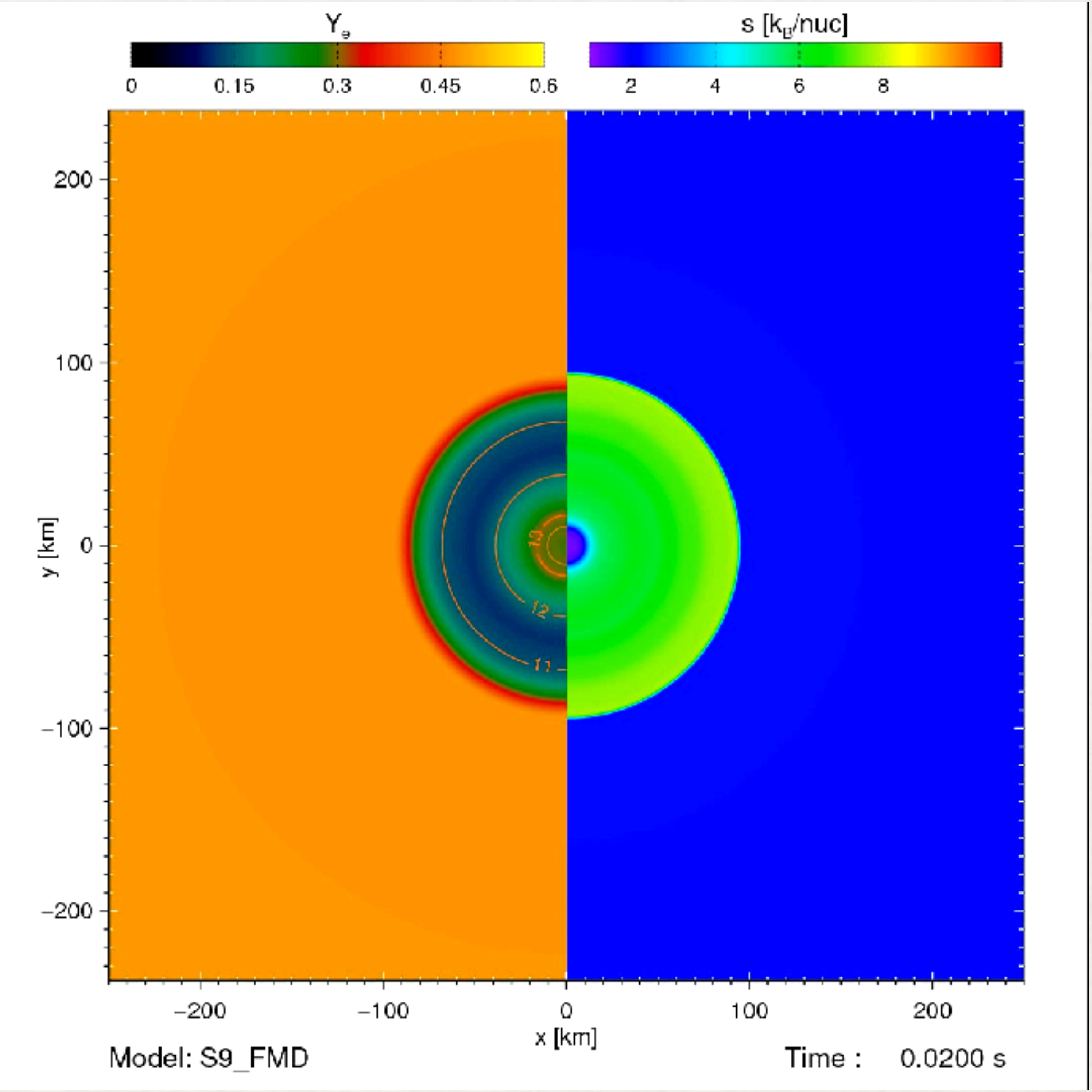
relevant for the neutrino emission (except 1 model)

9 Msun progenitor model ‘S9’

- low progenitor mass causes low mass-accretion rate

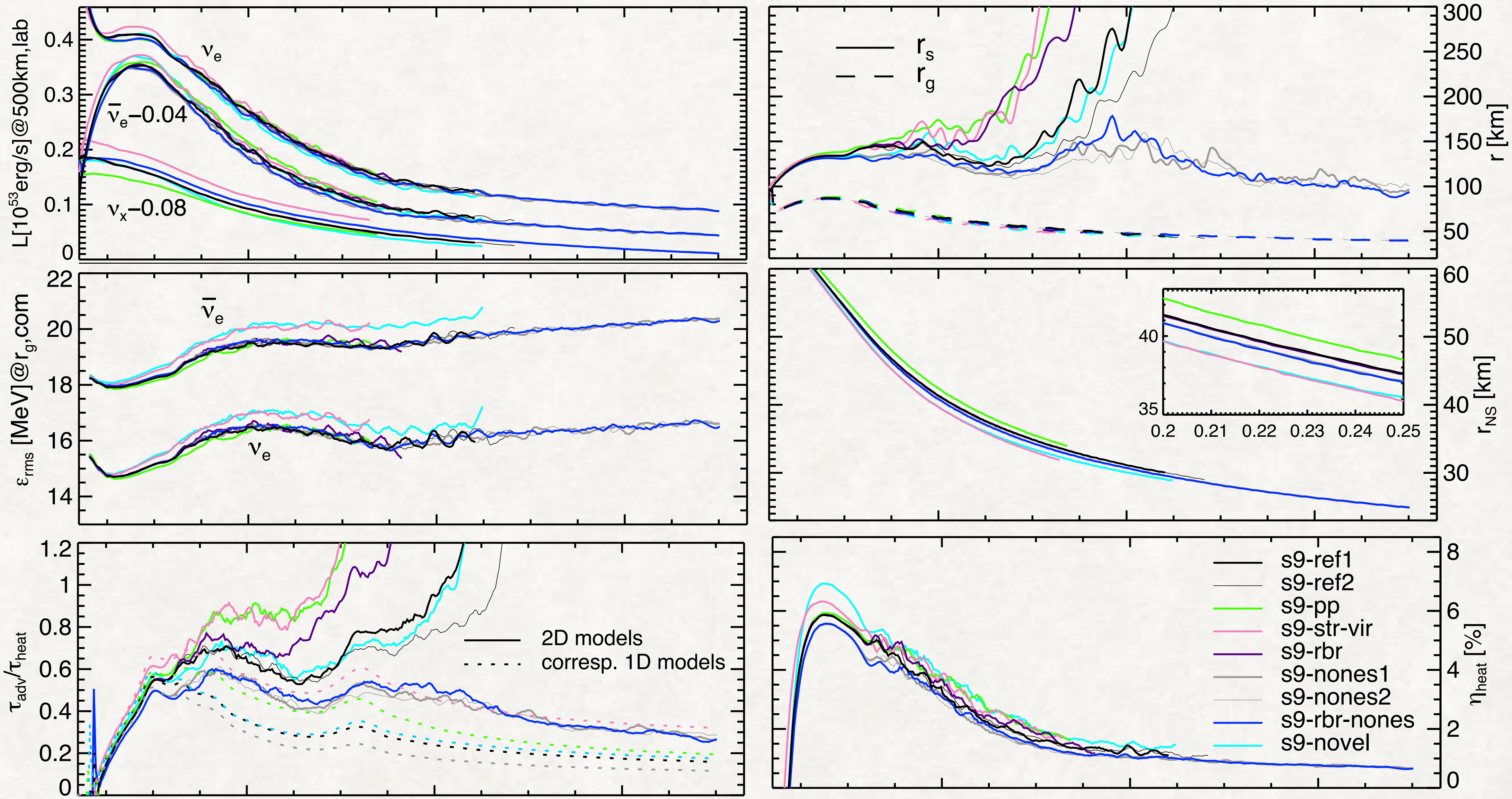
=> long advection timescales

=> good (bad) conditions for convection (SASI)

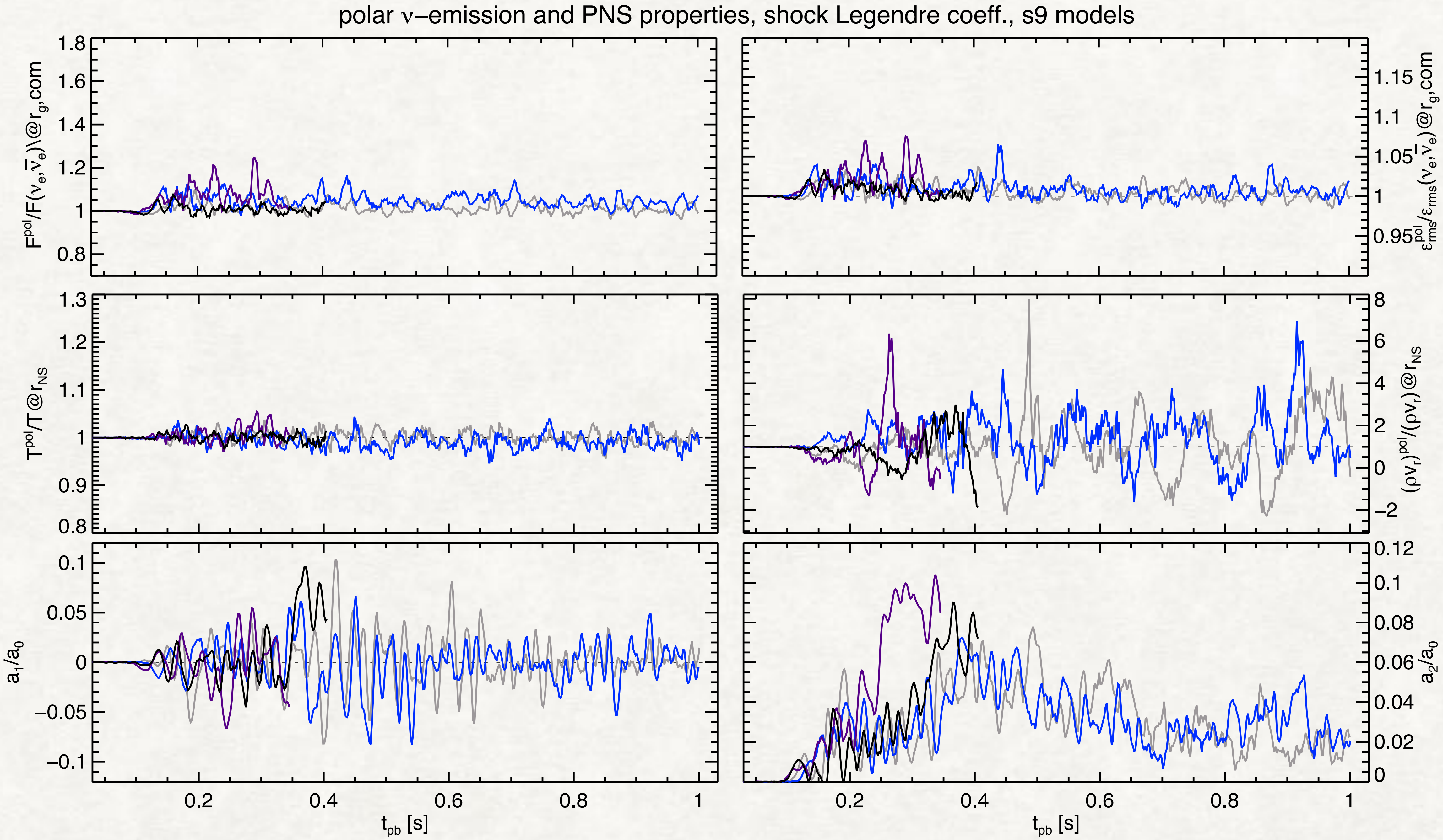


(ALCAR, without ray-by-ray+)

S9: MODELING VARIATIONS



S9: IMPACT OF RBR+?

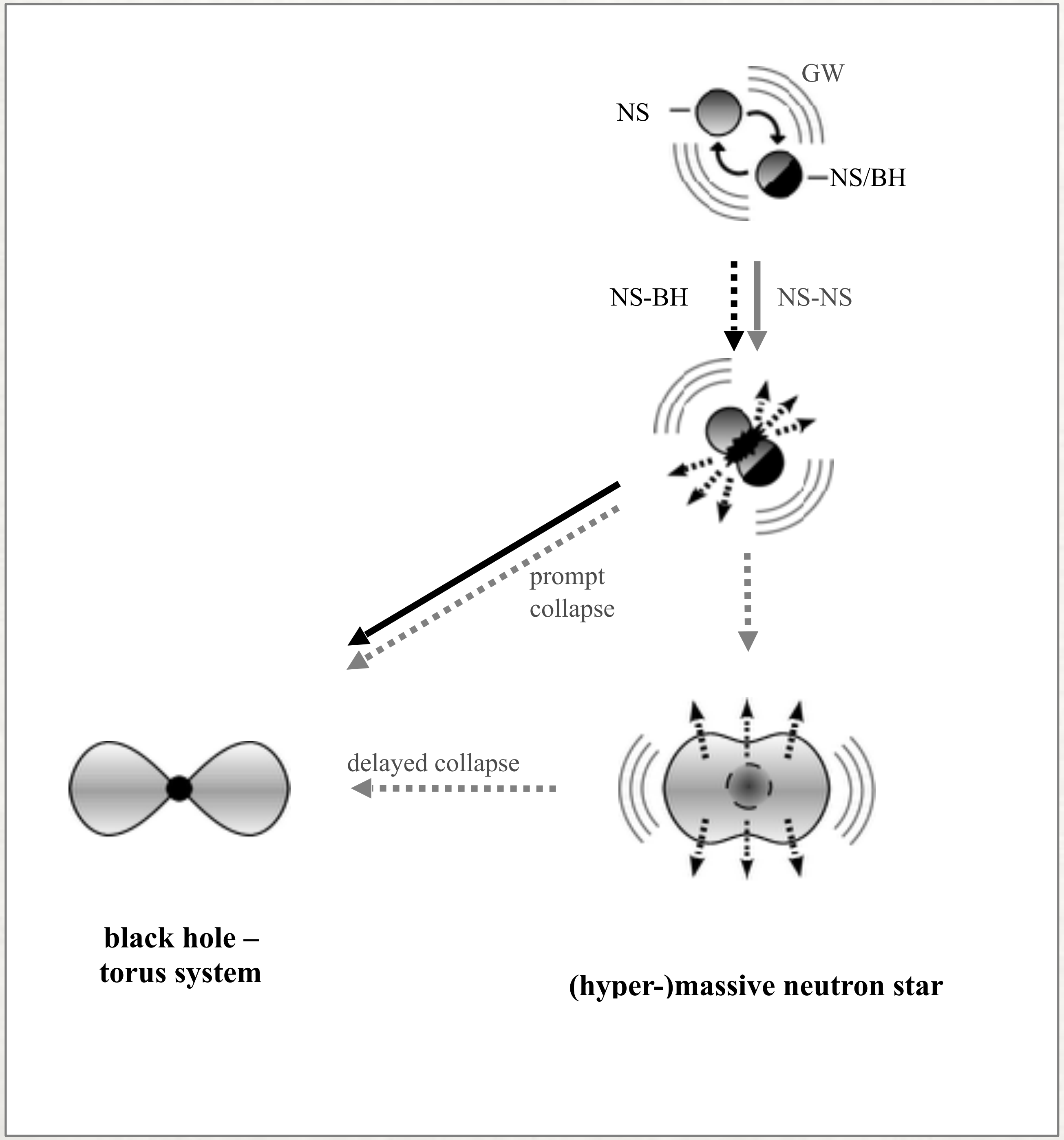


CCSN SUMMARY

- overall good agreement between M1 code ALCAR and Boltzmann code VERTEX
- impact of RbR+: amplification of (linear) SASI sloshing modes for high-mass model (confirms Skinner+'16, Sumiyoshi+'15); only small impact in convection-dominated low-mass model
- nu-e scattering, pair-process simplifications, velocity terms all can have significant impact on explosion time
- large (small) stochastic scatter of explosion times for SASI (convection) dominated model
- **CAVEATS:** limited set of investigated progenitors; results might be different in 3D; results only based on 2 codes
- further code comparisons with more codes warranted including other nu-transport approximations and discretization schemes

PART 2:
NS MERGERS

Neutron-Star Mergers: Overview



➔ GW signal
- ➔… progenitor masses
- ➔… nuclear EOS

➔ short GRB
- ➔… neutrino-pair annihilation
- ➔… Blandford-Znajek process
- ➔… magnetar spindown

➔ massive outflows
- ➔… r-process
- ➔… Kilonova

WHAT CAN WE LEARN ABOUT THE NUCLEAR EOS FROM GW OBSERVATIONS SUCH AS GW170817?

THRESHOLD MASS FOR PROMPT COLLAPSE

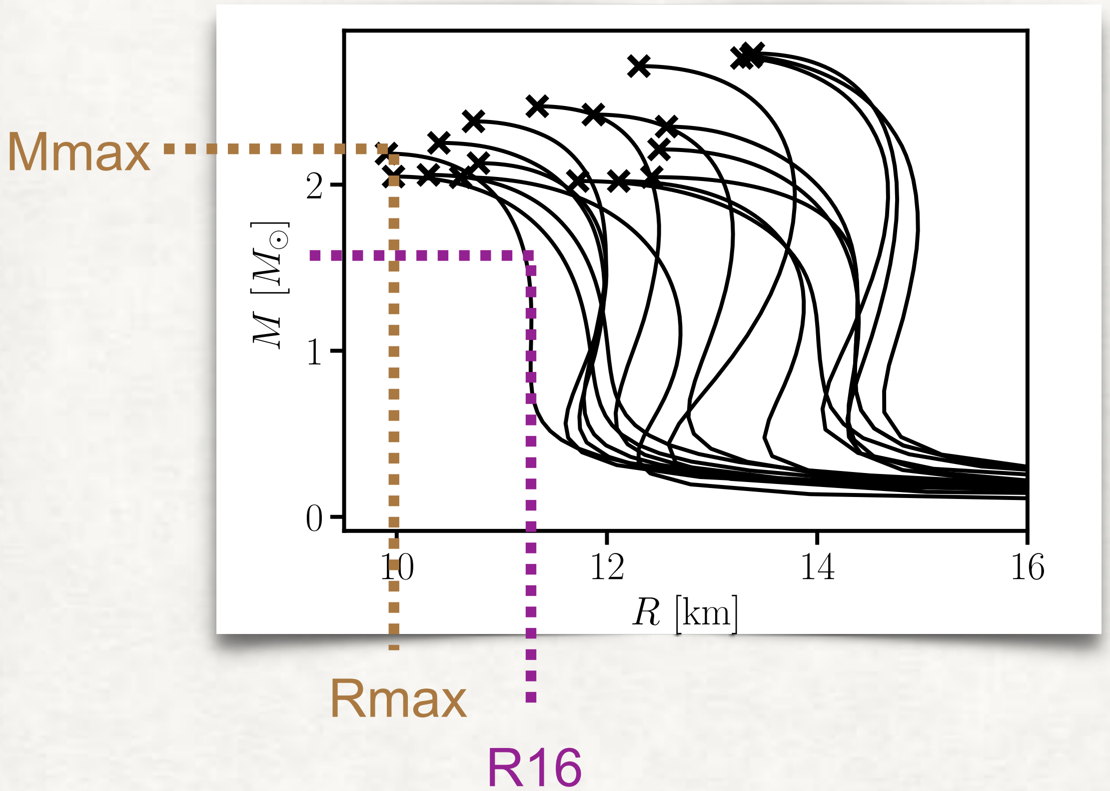
$$M_{\mathrm{thres}} = k \cdot M_{\mathrm{max}}.$$

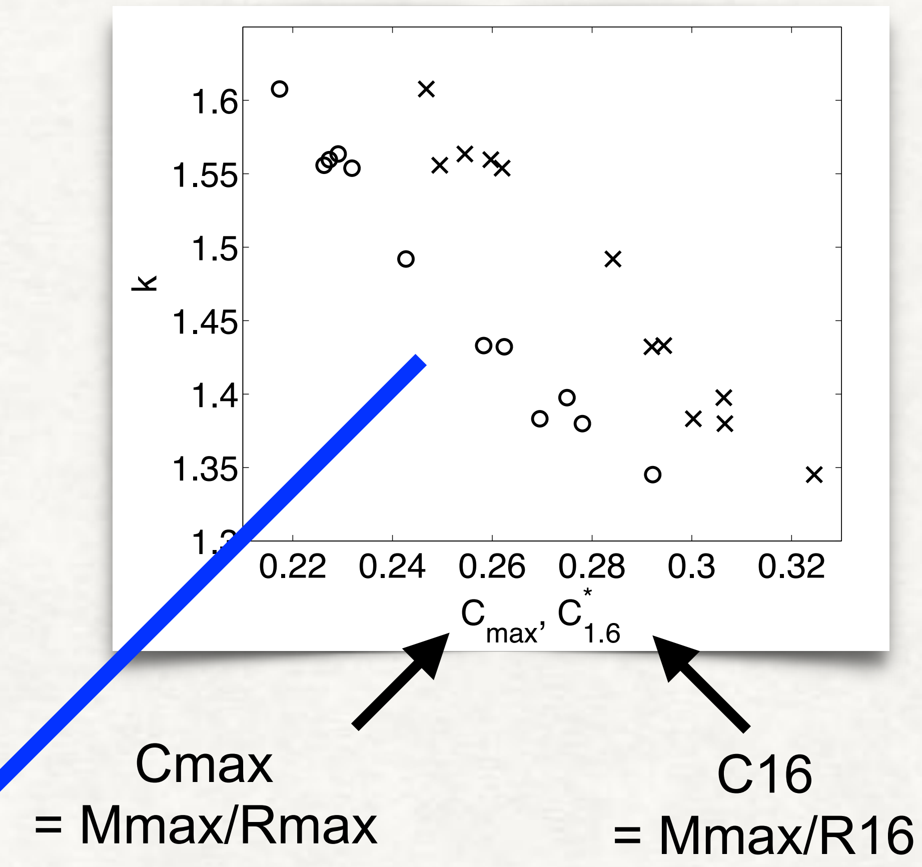
M1+M2 > M_thres -> prompt collapse
M1+M2 < M_thres -> delayed collapse

maximum mass
of cold, nonrotating NS

depends solely the nuclear EOS
for given mass ratio M1/M2

THRESHOLD MASS FOR PROMPT COLLAPSE





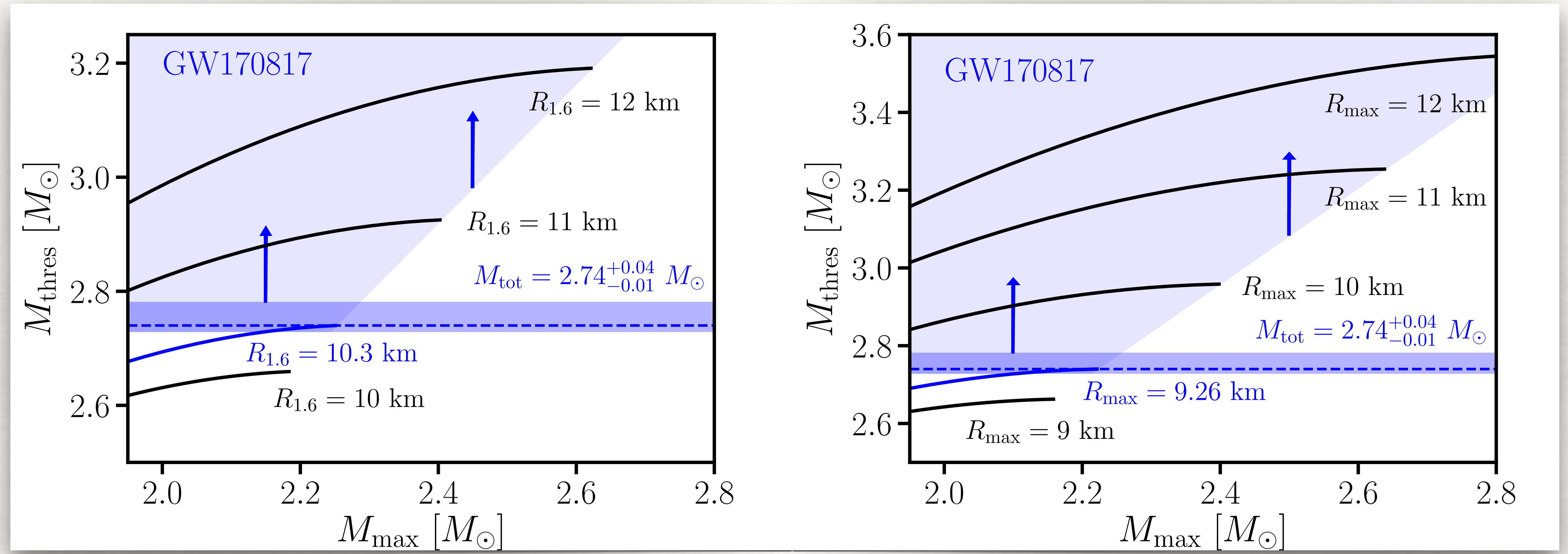
k is to very good accuracy a linear function of Cmax or C16

$$M_{\rm thres} = \left(-3.606\frac{GM_{\rm max}}{c^2 R_{1.6}} + 2.38\right)\cdot M_{\rm max}$$

$$M_{\rm thres} = \left(-3.38\frac{GM_{\rm max}}{c^2 R_{\rm max}} + 2.43\right)\cdot M_{\rm max}$$

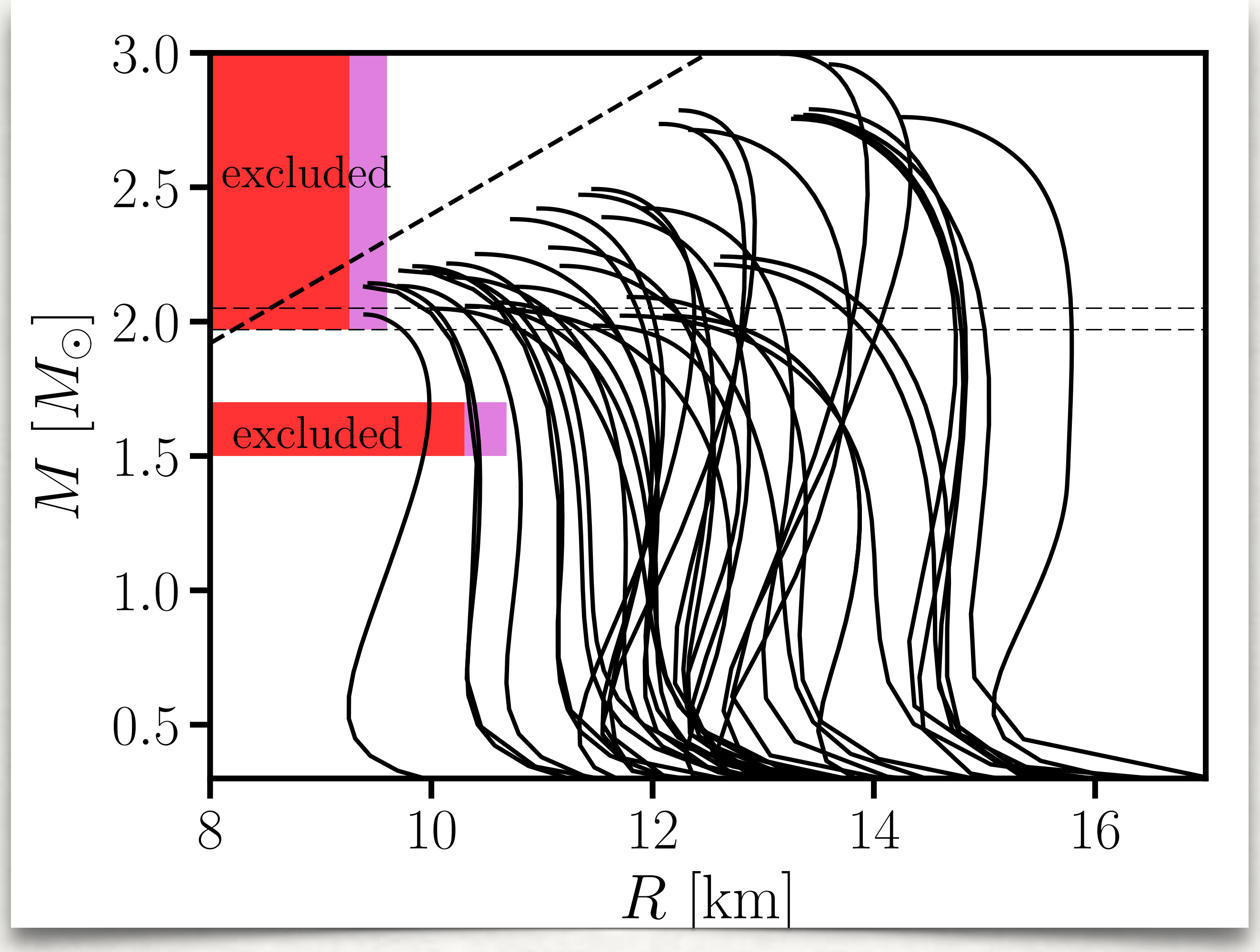
(see Bauswein+'13, PRL 111, 131101)

IMPLICATIONS OF DELAYED COLLAPSE FOR GW170817



=> observed M_thres only possible for sufficiently large radii

IMPLICATIONS OF DELAYED COLLAPSE FOR GW170817



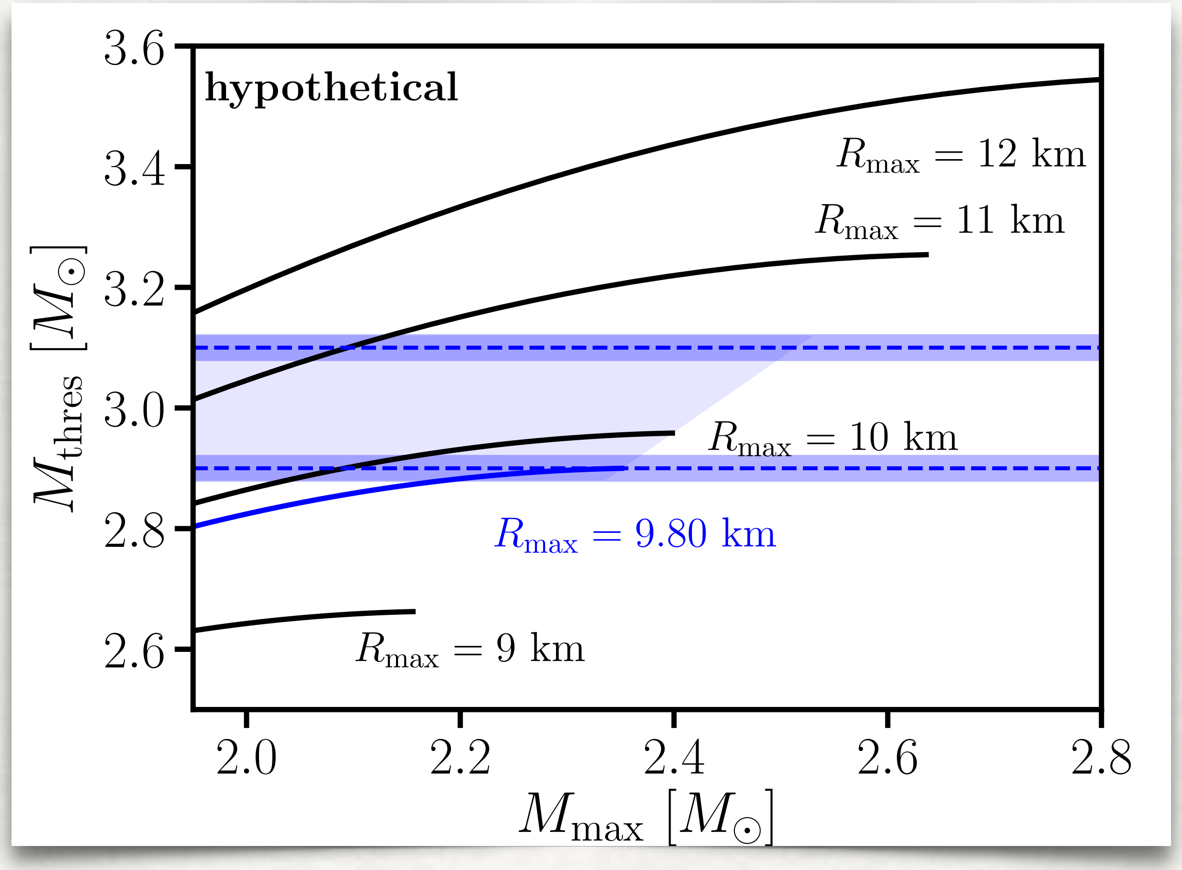
R_16 > 10.3 km
R_max > 9.3 km

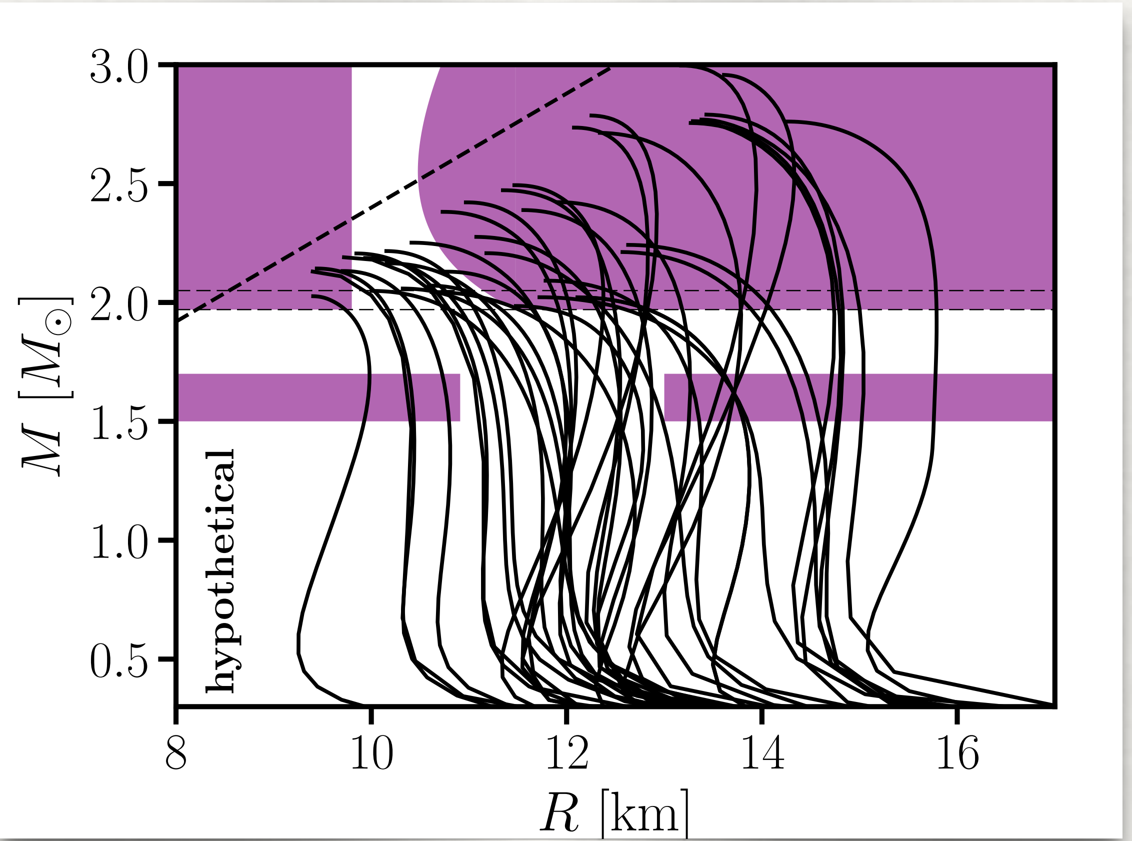
(assuming tau>0ms)

R_16 > 10.7 km
R_max > 9.6 km

(assuming tau>10ms)

IMPLICATIONS FOR HYPOTHETICAL FUTURE DETECTION OF PROMPT COLLAPSE WITH MTOT = 3.1MSUN





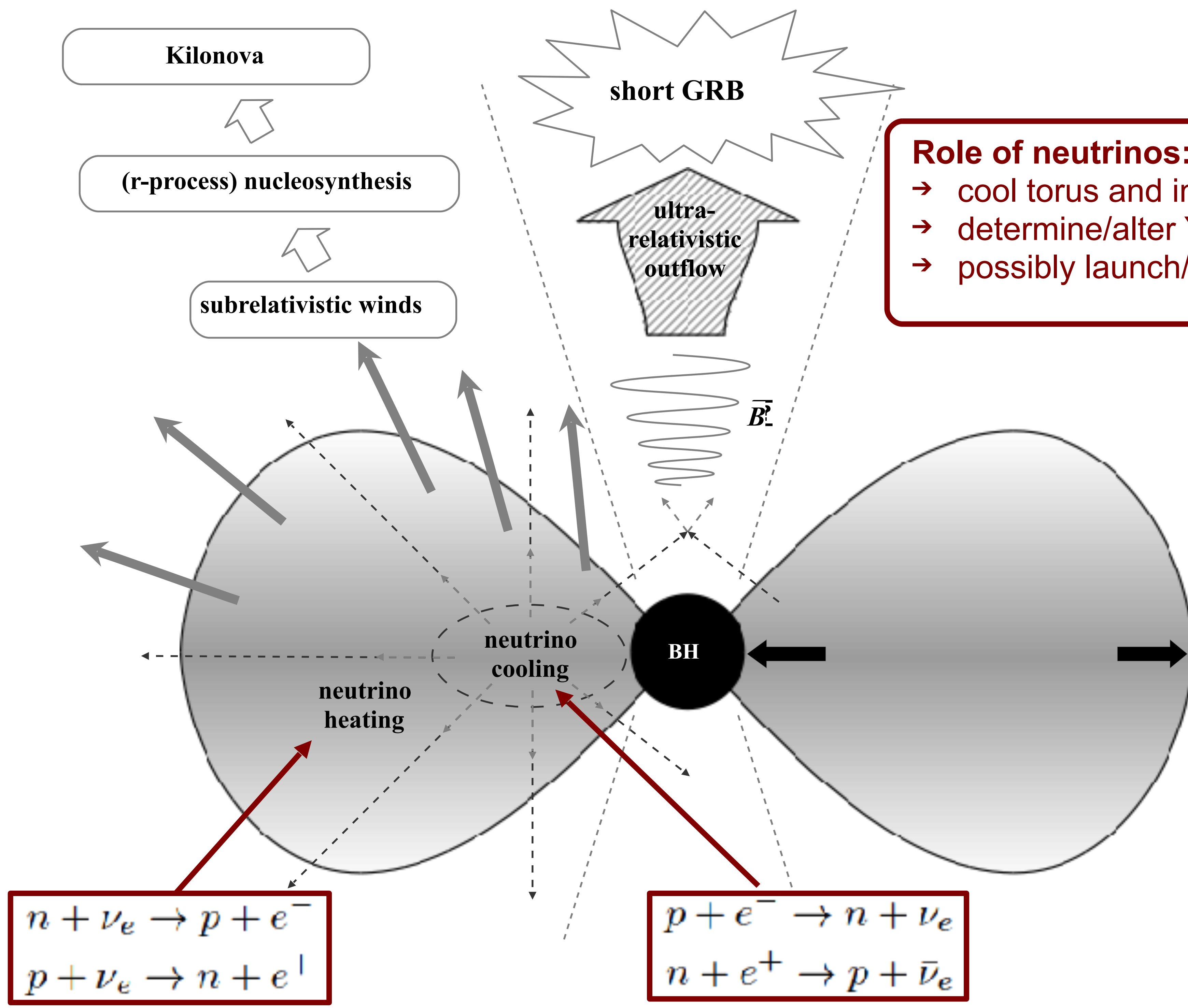
=> for more details see
Bauswein, OJ, Janka, Stergioulas, 2017ApJ, 850L, 34B

(also see talk by Luca Baiotti, as well as papers: Margalit & Metzger '17, Rezzolla+ '17, Ruiz+ '17, Most+18 for independent EOS constraints)

NU-OSCILLATIONS IN POST-MERGER BH-TORUS SYSTEMS

Post-Merger BH-Torus

(directly after its formation)



Role of neutrinos:

- cool torus and impact the accretion rate!
- determine/alter Ye in outflows!
- possibly launch/contribute to GRB jet!

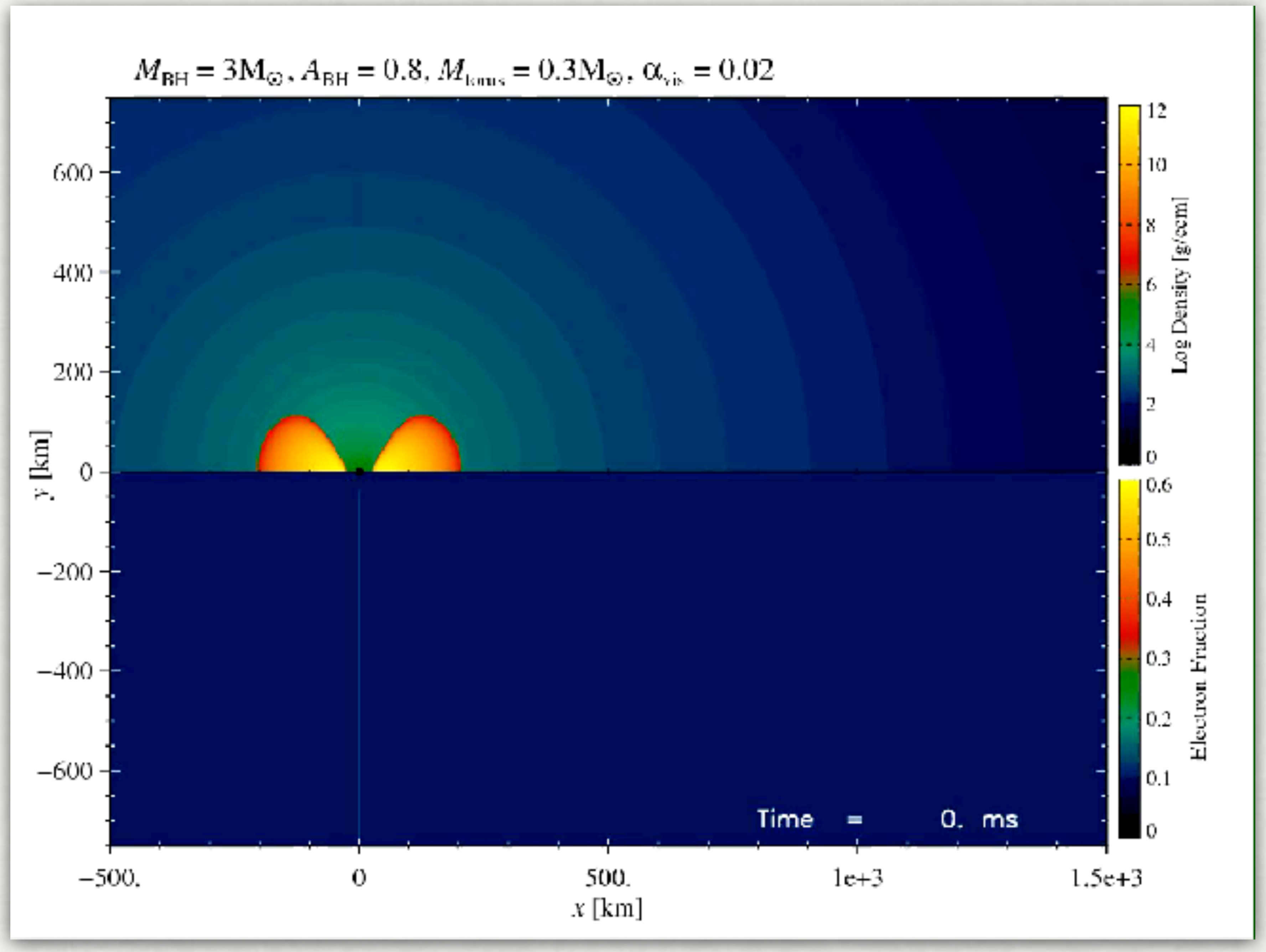
Post-Merger BH-Torus Remnant
(as obtained in OJ, Bauswein, Ardevol, Goriely, Janka '15)

Typical ejecta properties:

- outflow masses:
  ~ 5-20% of torus mass
- electron fraction:
  Ye ~ 0.1-0.3
- entropy per baryon:
  s ~ 10 – 30 kB
- velocity:
  v ~ 0.05– 0.1 c

- **small** neutrino-driven component

- **dominant** viscous component



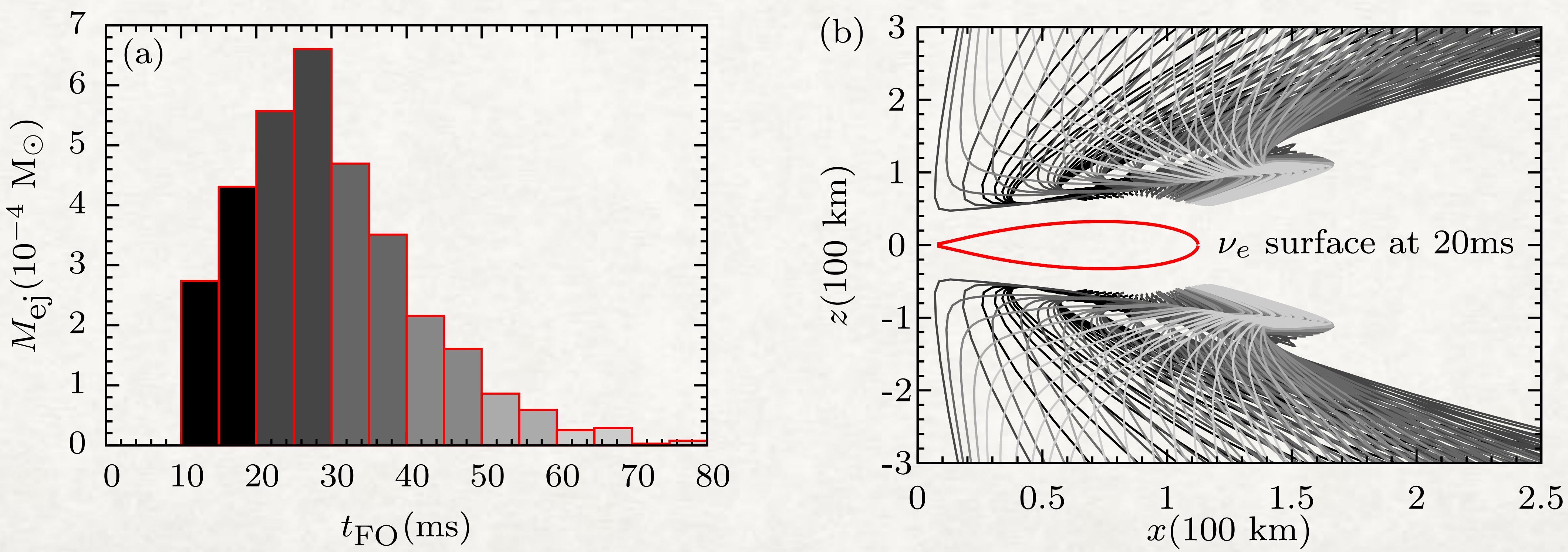
(for NS-torus remnant see Perego '14, Fujibayashi '17)

IMPACT OF NU-NU OSCILLATIONS ON THE NEUTRINO-DRIVEN WIND COMPONENT

(Wu, Tamborra, OJ, Janka, 2017PhRvD, 96l3015W)

- recently (re-)discovered that ***"fast pairwise flavor conversions"*** can lead to flavor equilibration on length scales of **O(10cm)** (e.g. Sawyer+ 05,09'16)
- take place whenever $n(\nu_e) - n(\bar{\nu}_e)$ changes sign in angular space

nu-driven wind properties



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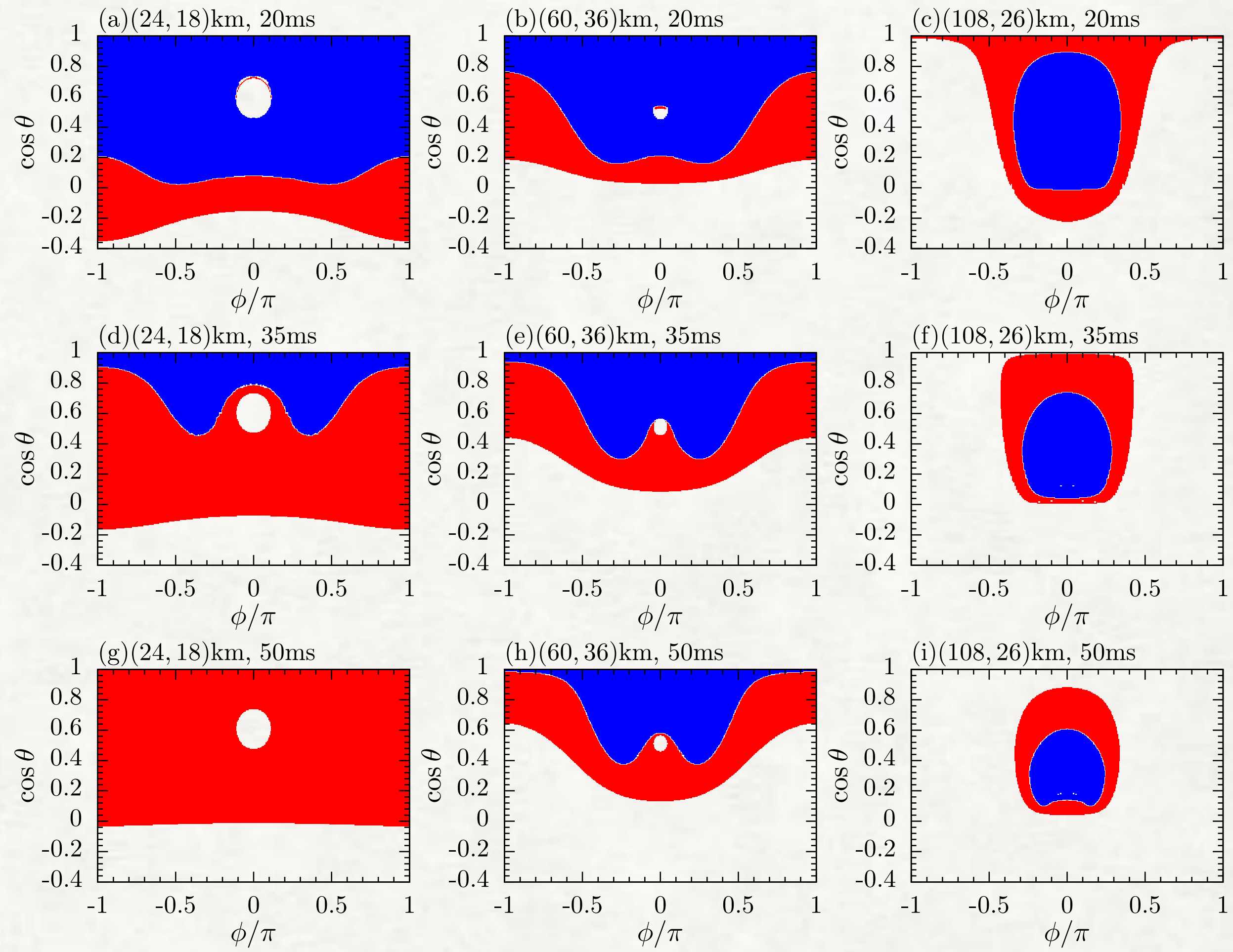

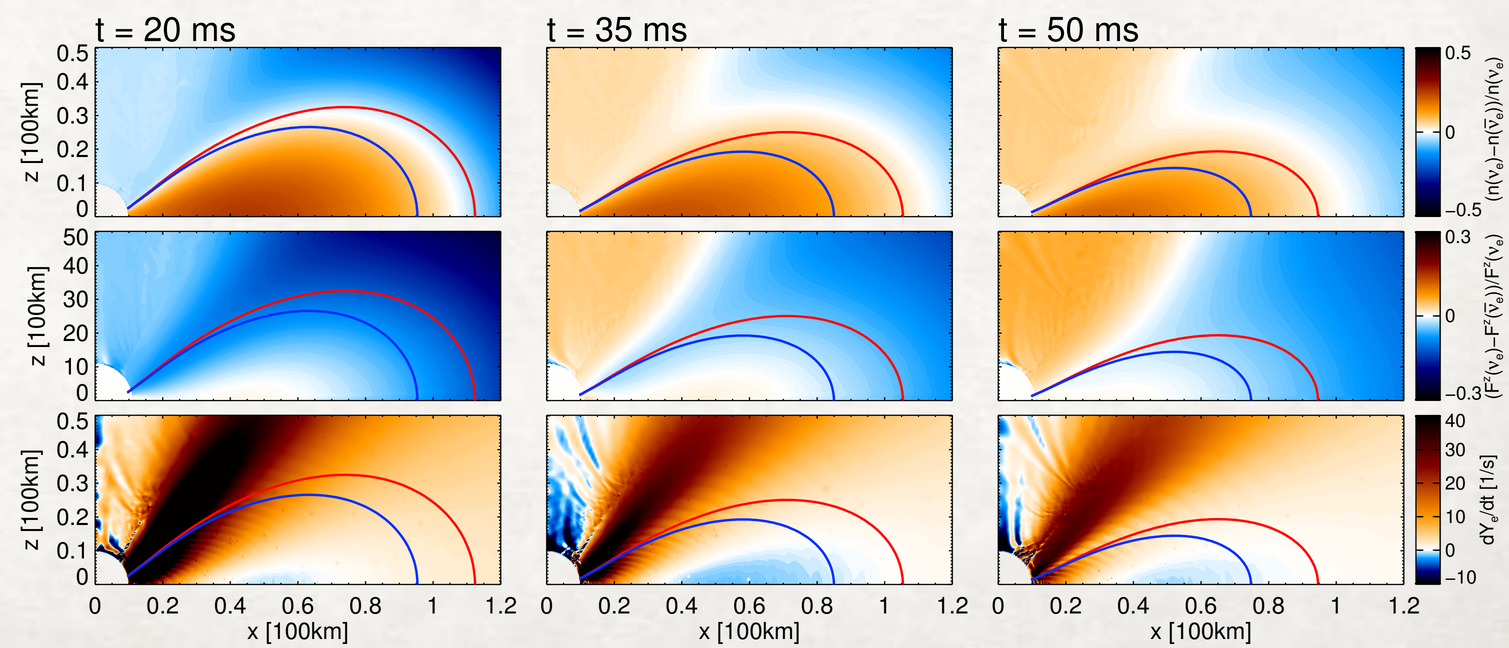

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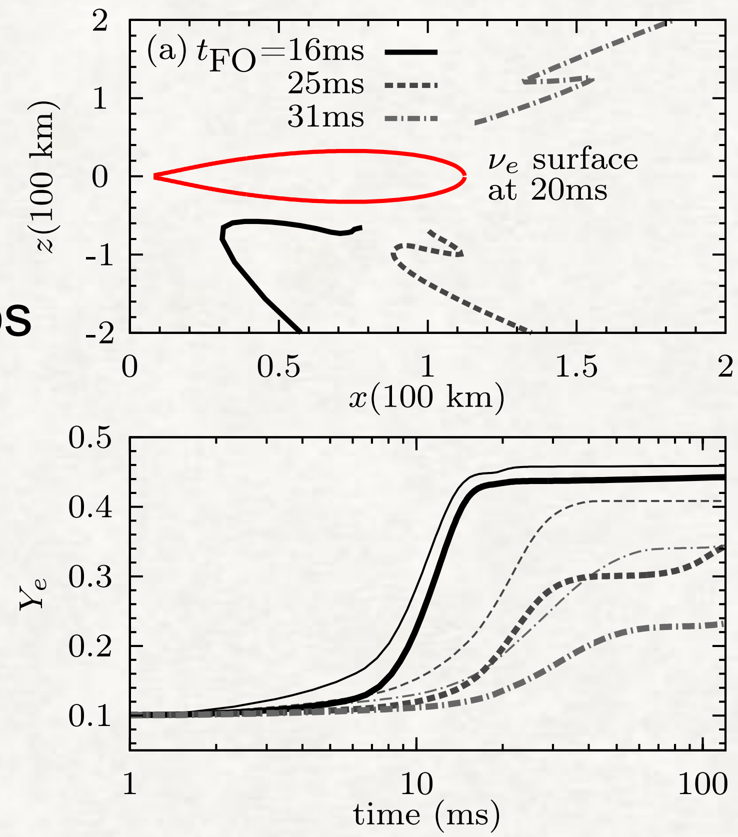
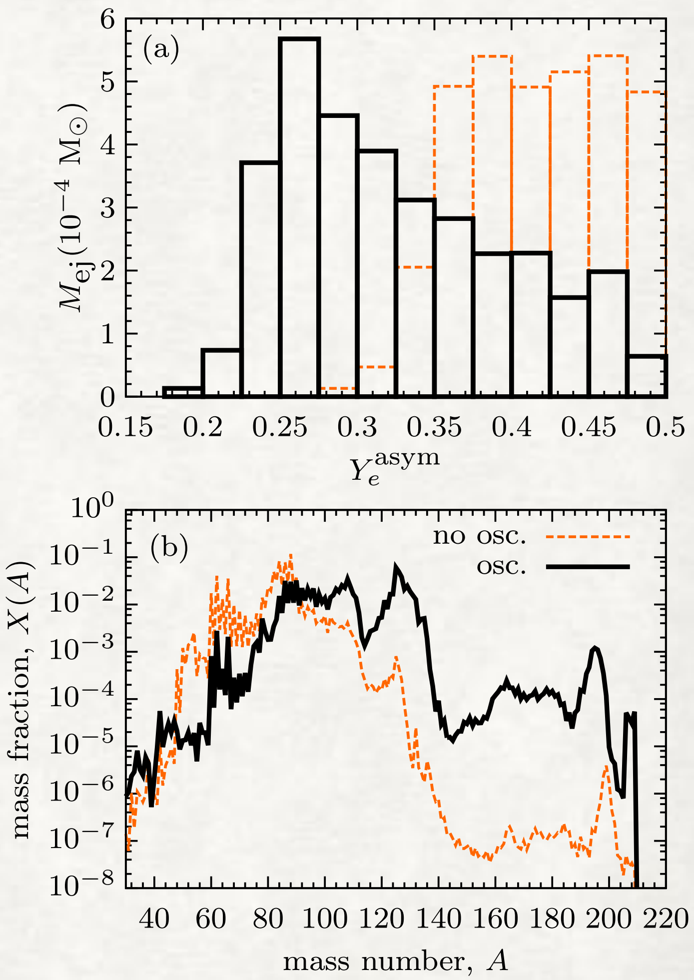
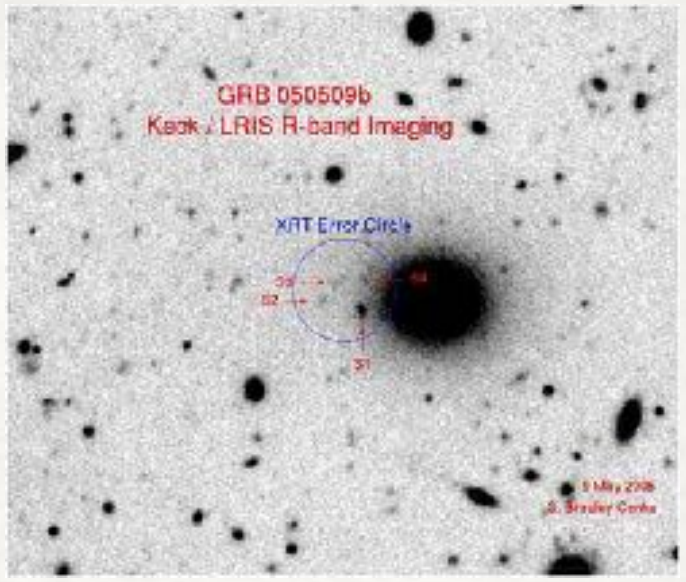
- recently (re-)discovered that ***"fast pairwise flavor conversions"*** can lead to flavor equilibration on length scales of **O(10cm)** (e.g. Sawyer+ 05,09'16)
- take place whenever $n(\nu_e) - n(\bar{\nu}_e)$ changes sign in angular space
- equilibration **reduces** effect of neutrinos to increase Ye
- more neutron-rich r-process material synthesized
- could be **relevant also for HMNS** remnants of NS mergers



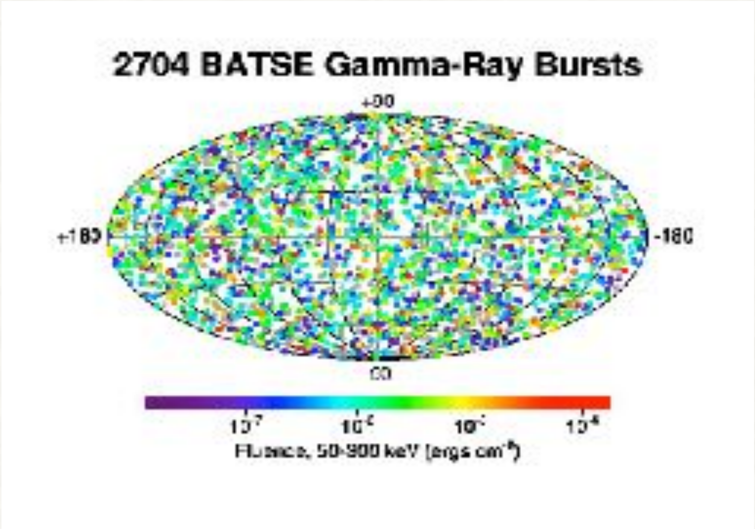


CAN NEUTRINO PAIR ANNIHILATION DRIVE SGRB JETS?

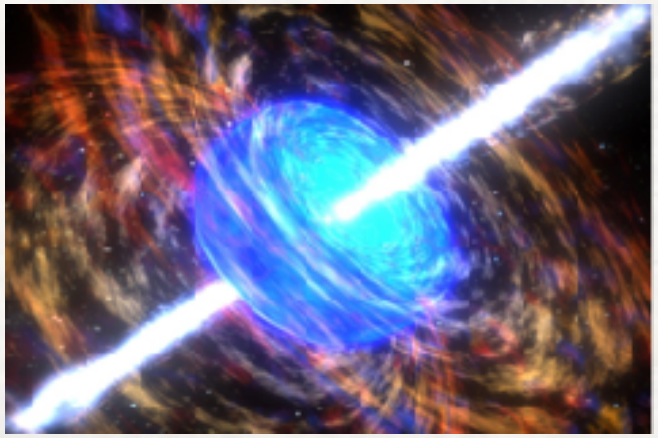
Gamma-Ray Bursts

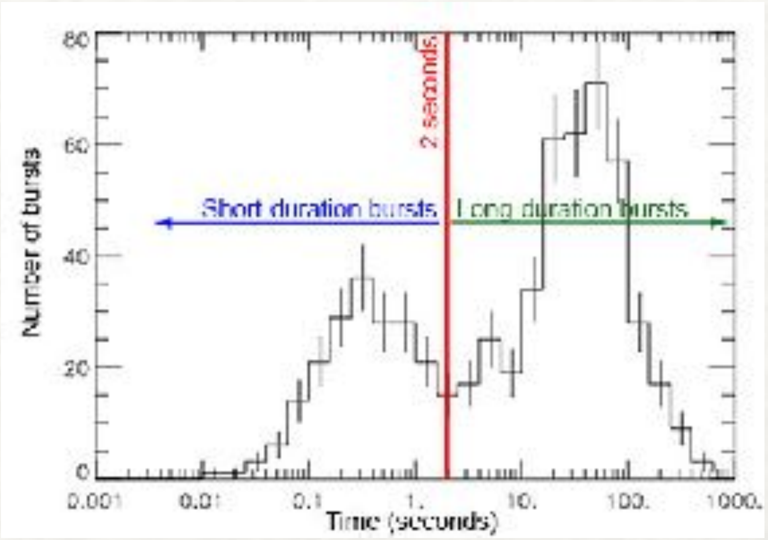


- first detected 1967 by VELA satellite
- source is moving highly relativistically
- natural suggestion: jet from rotating compact object
- long bursts (T>2s): connection to death of massive stars
- short bursts (T<2s) still mysterious, most likely from NS mergers

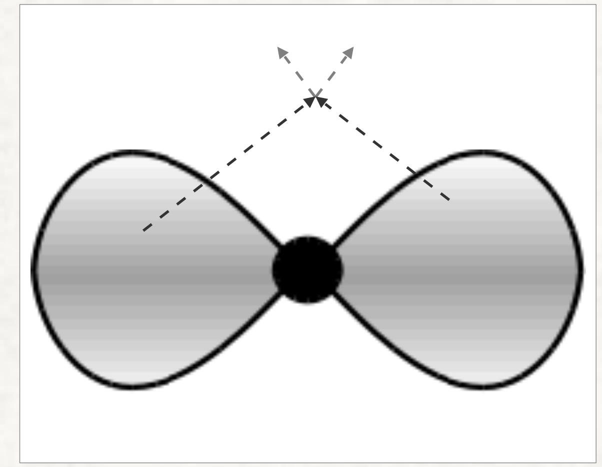


(NASA)



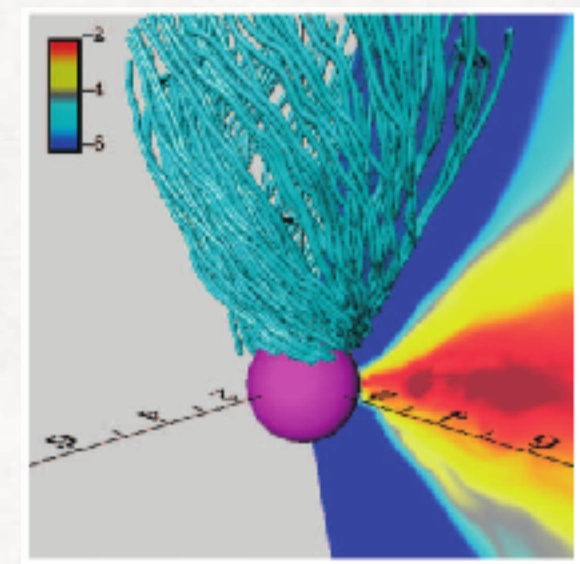


Popular Central Engine Scenarios



➔ neutrino-pair annihilation

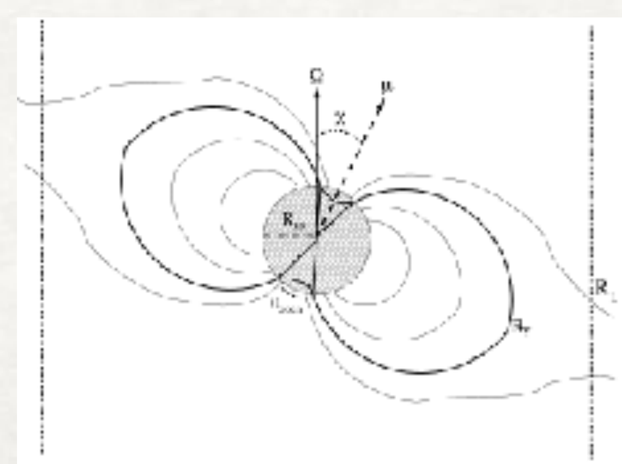
- neutrinos tap gravitational energy of disk
  e+-e- pairs thermalize → thermal fireball
- efficiency of converting gravitational energy into jet energy?
- baryon loading in the funnel?



(Hirose+ '04)

➔ Blandford-Znajek process

- B-field taps rotation energy of central BH
  → Poynting-dominated jet
- efficient only for large-scale poloidal B-fields
- can large-scale fields be produced and sustained? MRI? Dynamo?



(Metzger+ '11)

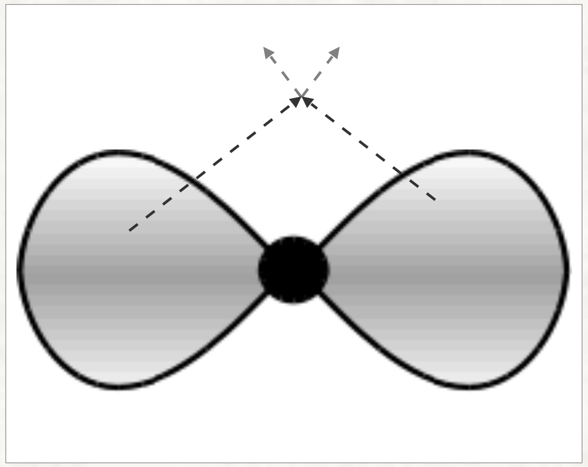
➔ magnetar spin-down emission

- B-field taps rotation energy of central NS
  → Poynting dominated jet
- is dipole model appropriate?
- consistent with short burst timescale?

Popular central engine scenarios

➔ **neutrino-pair annihilation**

- neutrinos tap gravitational energy of disk
  e+-e- pairs thermalize → thermal fireball
- efficiency of converting gravitational energy into jet energy?
- baryon loading in the funnel?



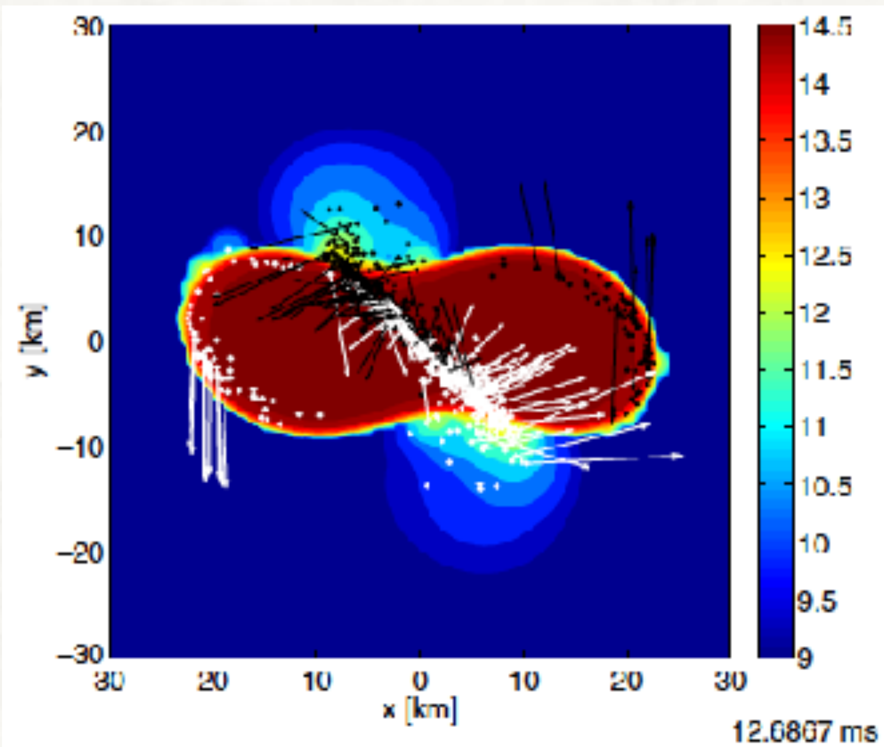
Tested using for the first time time-dependent neutrino-hydrodynamics simulations
(OJ, Obergaulinger, Janka, Bauswein ApJ, 816, L30)

Necessary conditions for the jet to explain sGRB:

- Total energy: $\mathbf{E \sim 10^{48} – 10^{50}}$ **erg**
- Lorentz factor: $\mathbf{\Gamma \sim 10\text{-}100}$

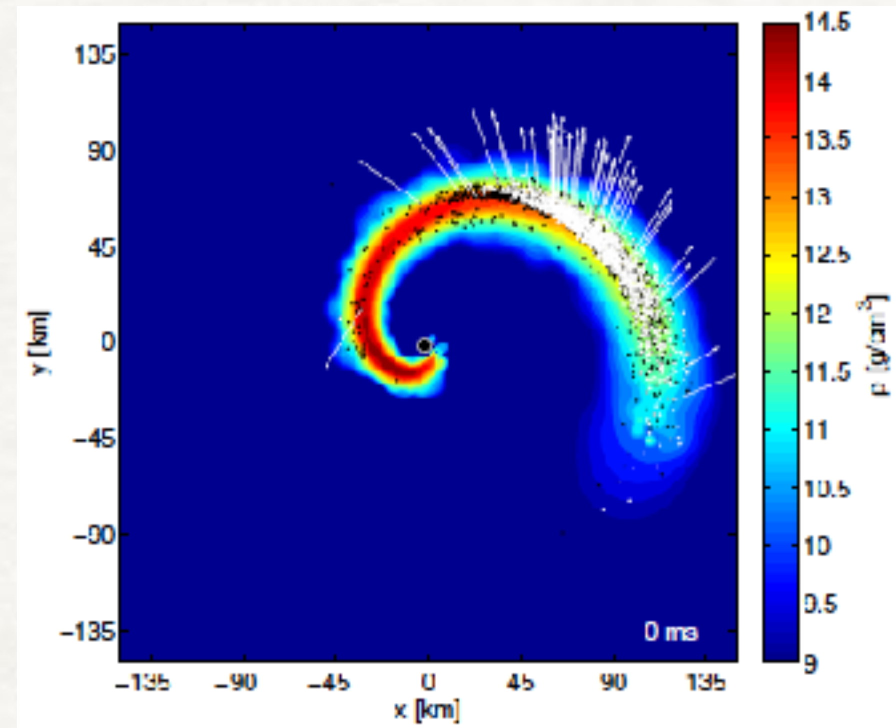
Geometry of Dynamical Ejecta

NS-NS

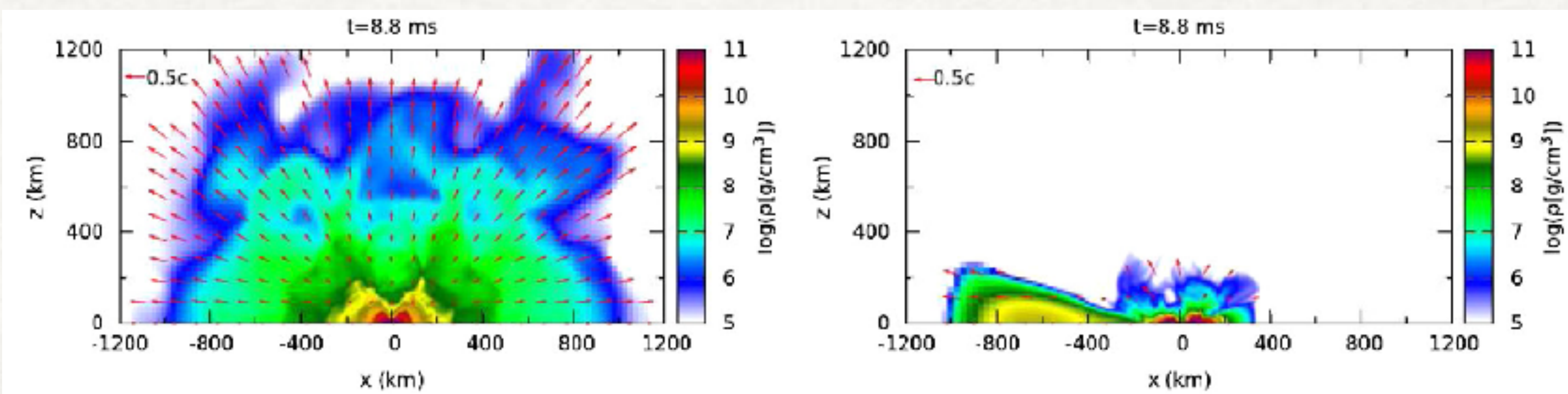


(Bauswein et. al. '13)

NS-BH



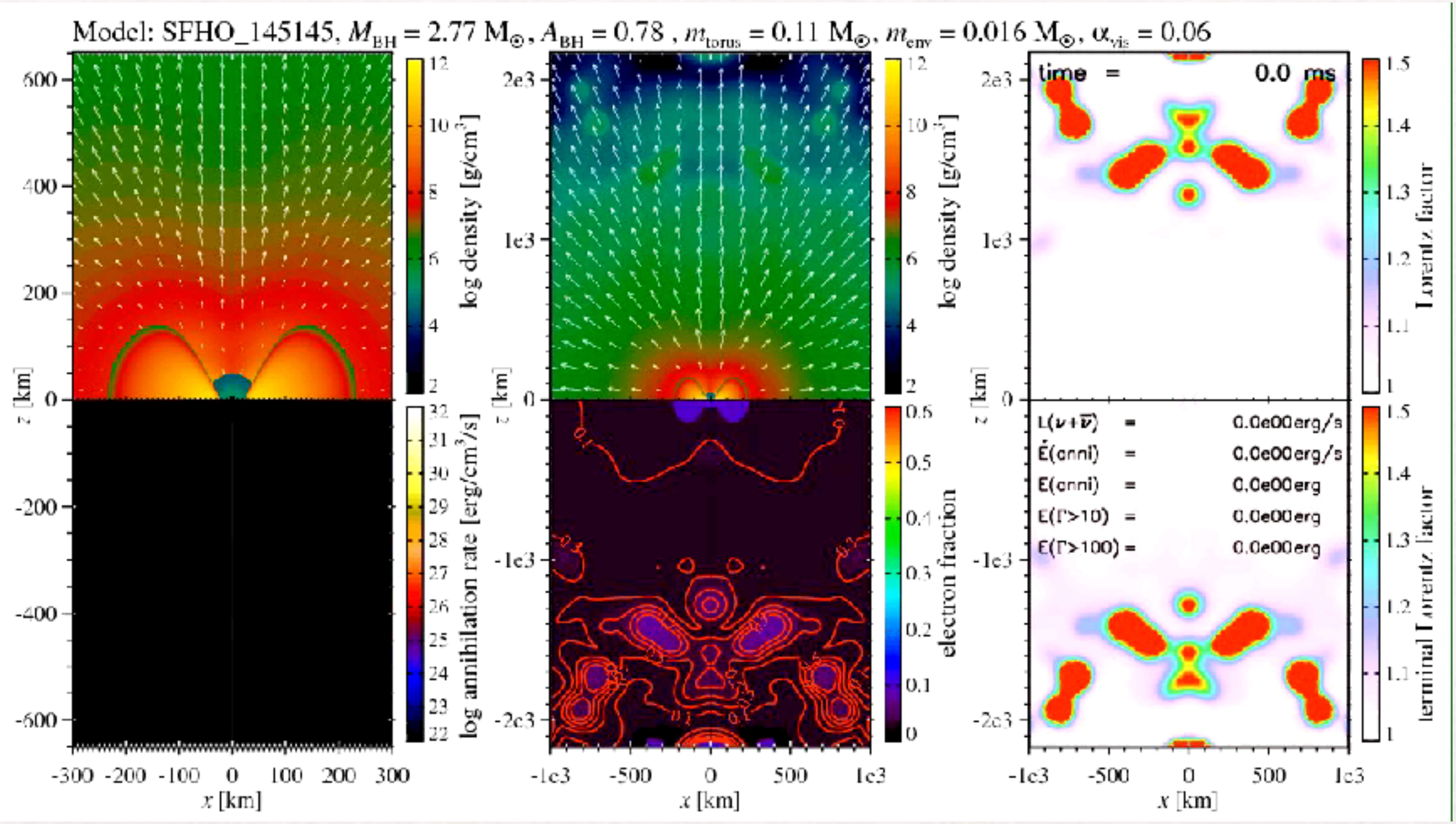
(Just et. al. '15)



(Hotokezaka et. al. '13)

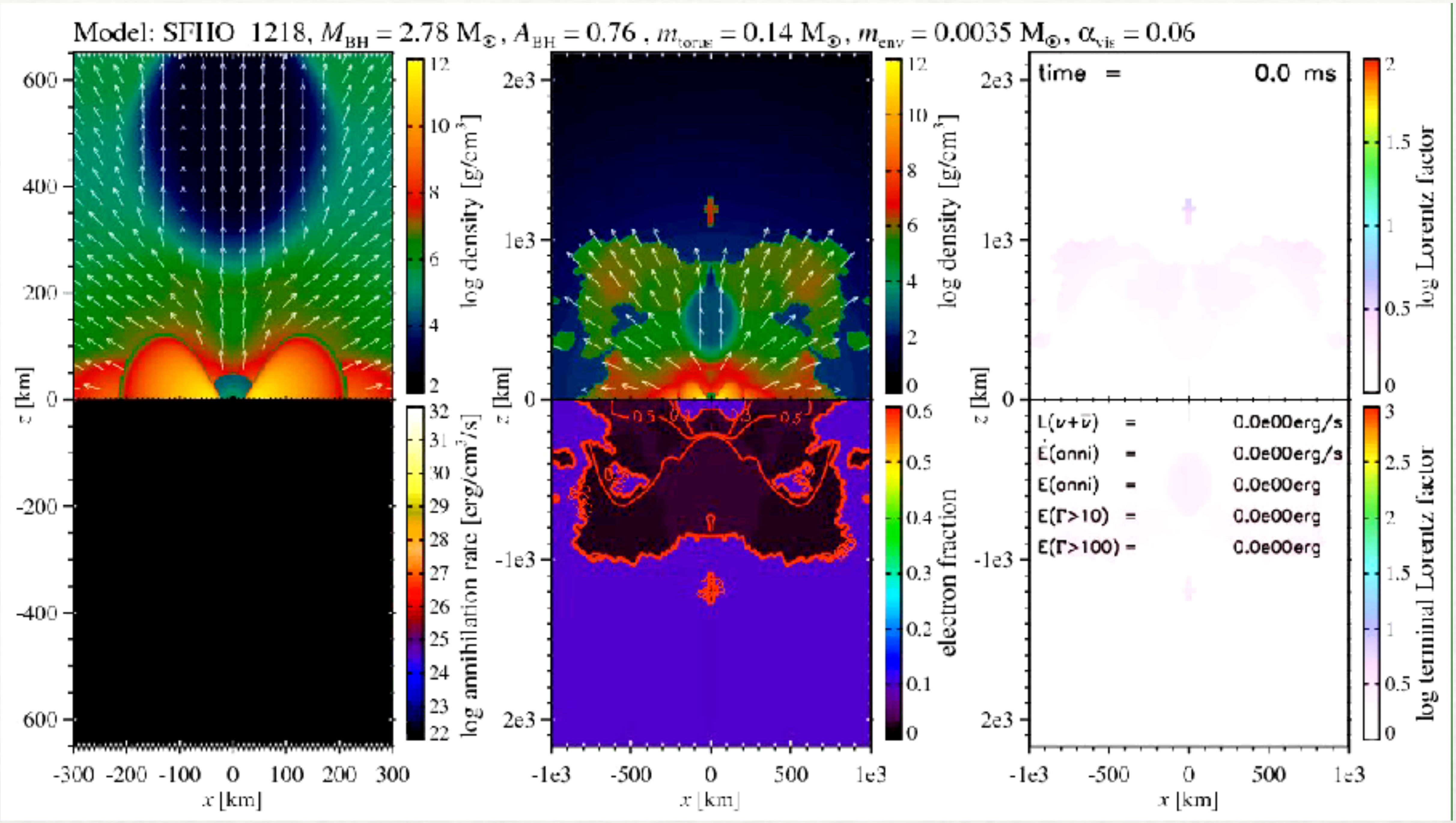
Symmetric NS-NS Merger

- baryon loading in the funnel too high, **no jet launched**



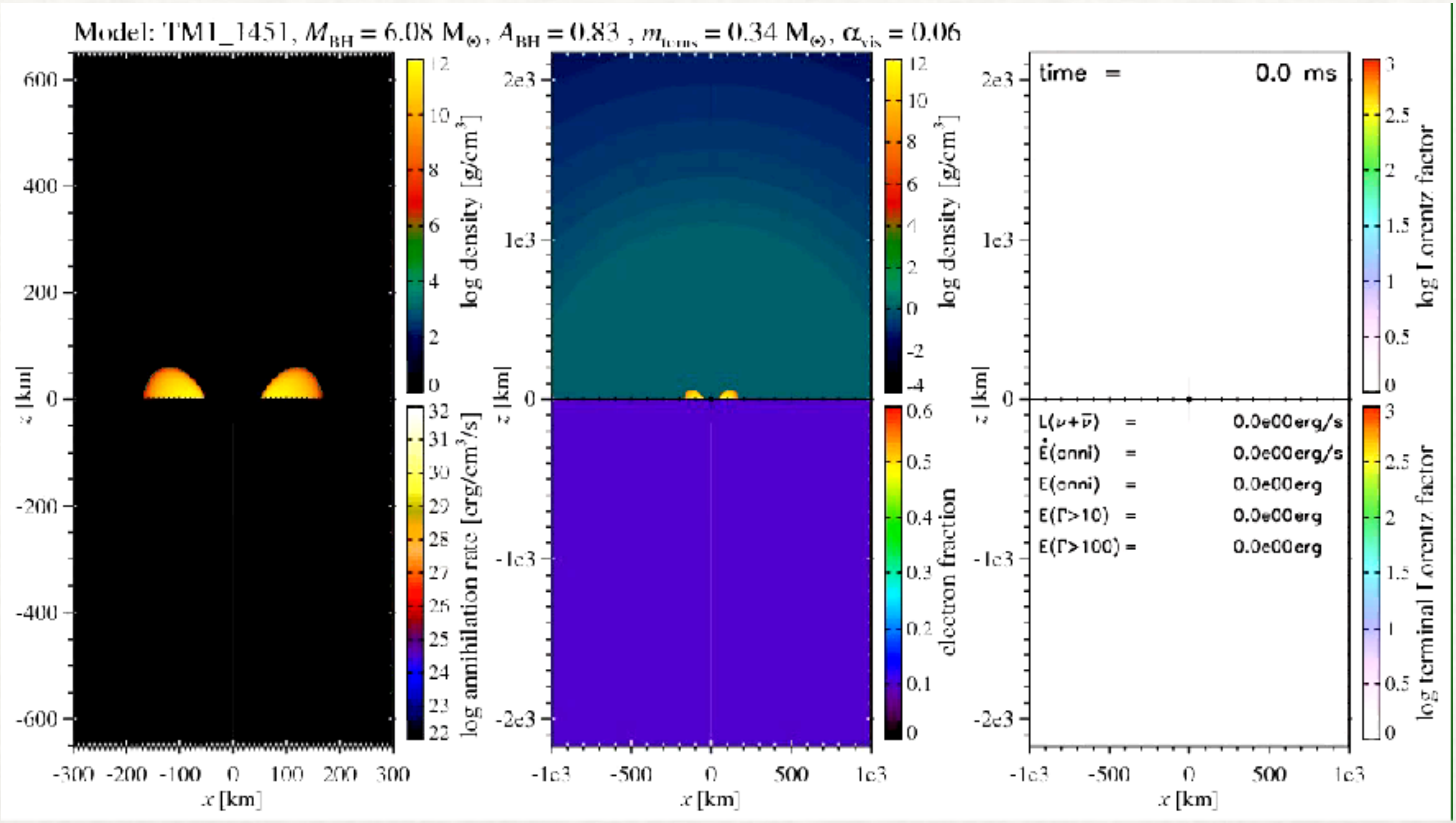
Asymmetric NS-NS Merger

- jet is **successfully launched**, but then dissipates most of its kinetic energy into cloud of dynamical ejecta



NS-BH Merger

- no dynamical ejecta in polar regions → jet can expand freely
- however, energy too low to explain majority of sGRBs



Merger Summary

- found **new robust radius constraints** that can be imposed as soon as a distinction between prompt and delayed collapse is possible
- **delayed collapse -> lower radius limit, prompt collapse -> upper limit**
- probably delayed collapse for GW170816 -> **R16 > 10.7 km**
- **“fast pairwise nu-oscillations”** might have significant impact on post-merger nu-irradiated outflows
- GRB central engine is **probably not solely driven by nu-nu pair annihilation**