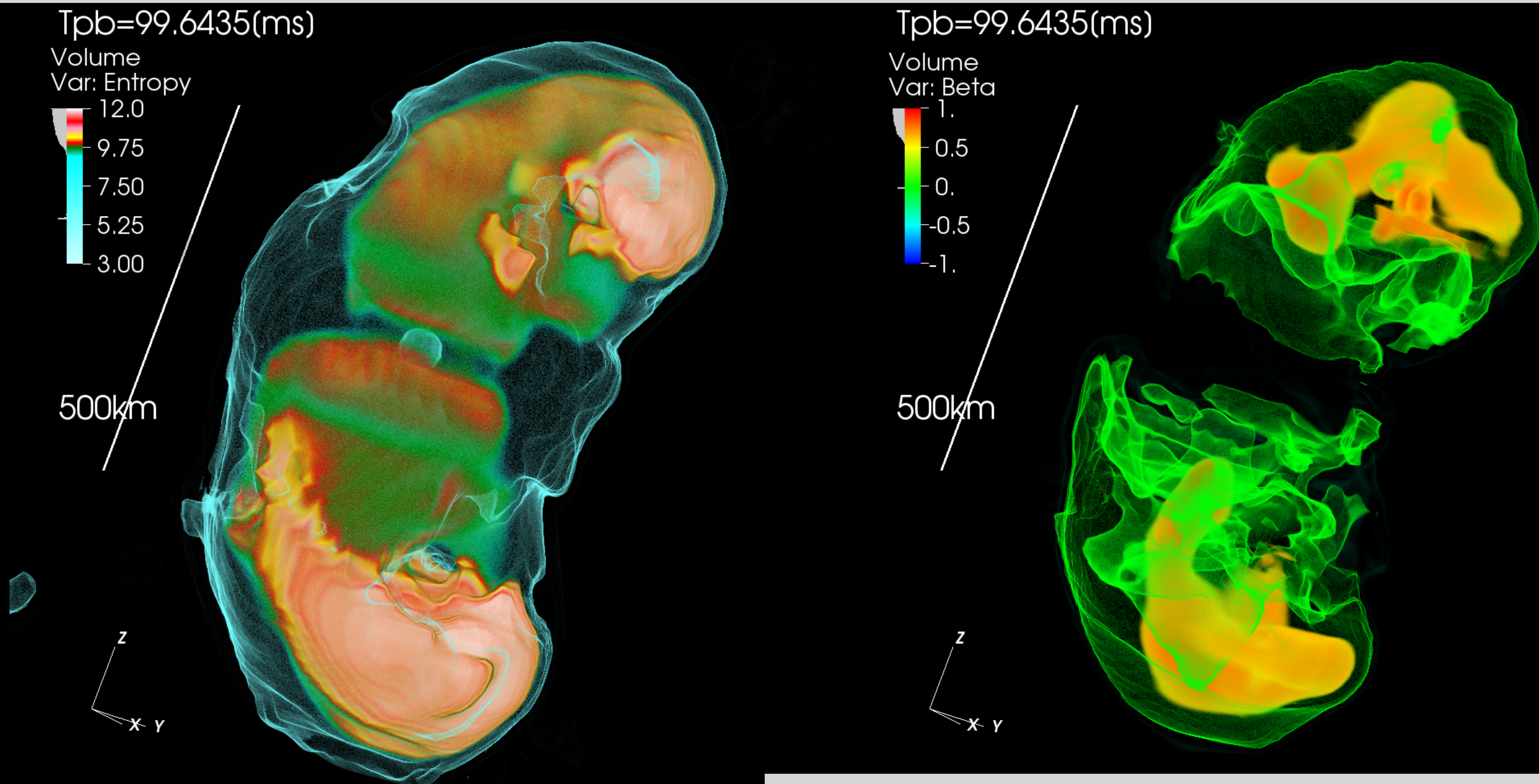
Magneto rotational explosion of a massive star supported by neutrino heating in full 3DGR simulation and its nucleosynthesis



- <u>Takami Kuroda (TU Darmstadt)</u>
- Moritz Reichert (TU Darmstadt)
- Marius Eichler (TU Darmstadt)
- Almudena Arcones (TU Darmstadt)
- Tomoya Takiwaki (NAOJ)
- Kei Kotake (Fukuoka Univ.)

TECHNISCHE UNIVERSITÄT DARMSTADT

erc European Research Council
Established by the European Commission

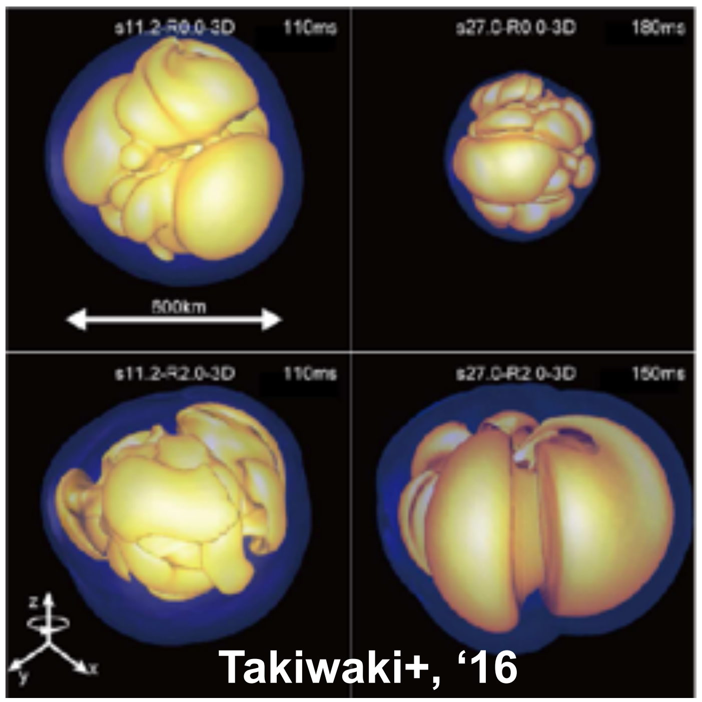
理論懇, 国立天文台, 25-27/12/2019

(1)The standard explosion mechanism

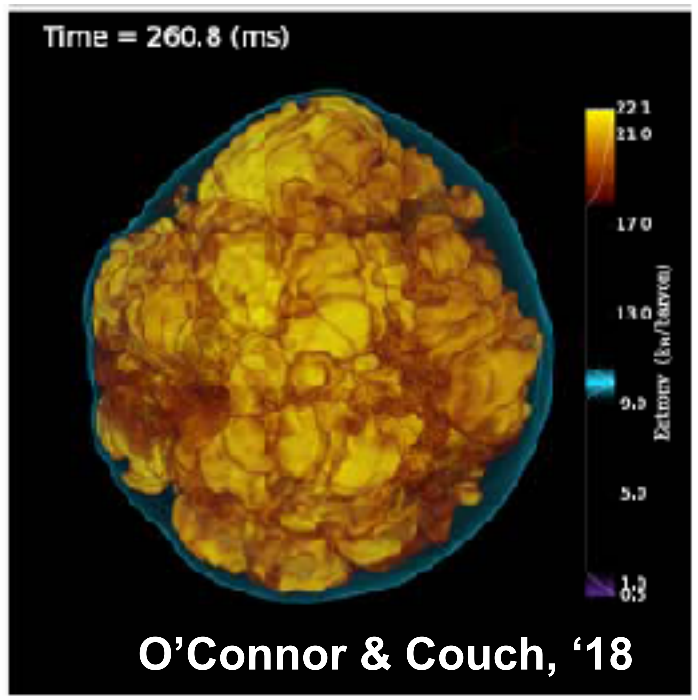
Neutrino driven explosion,

Colgate&White'66, Bethe&Wilson'85

For reviews, Janka'12, Kotake+,'12, Burrows+,'13



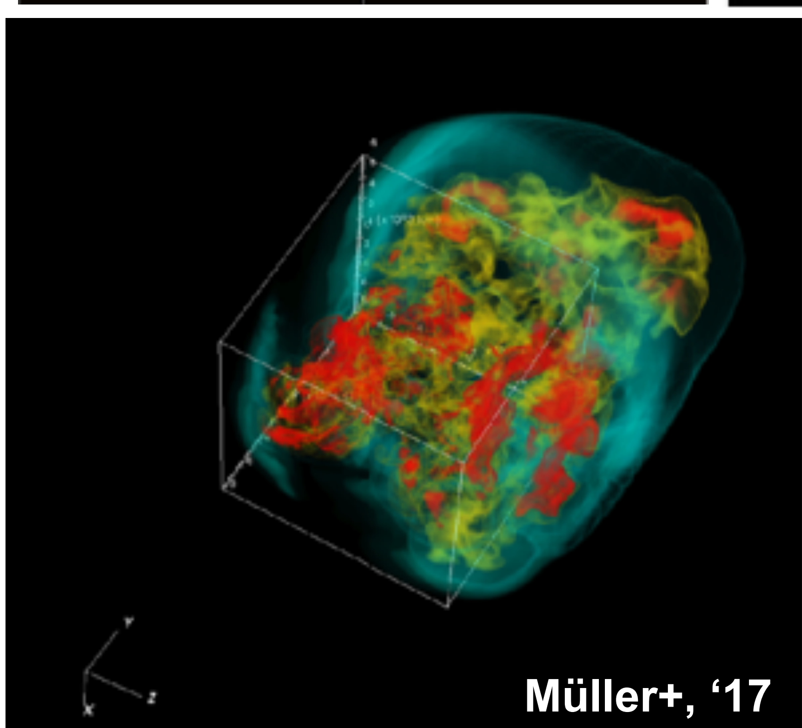
Takiwaki+, '16



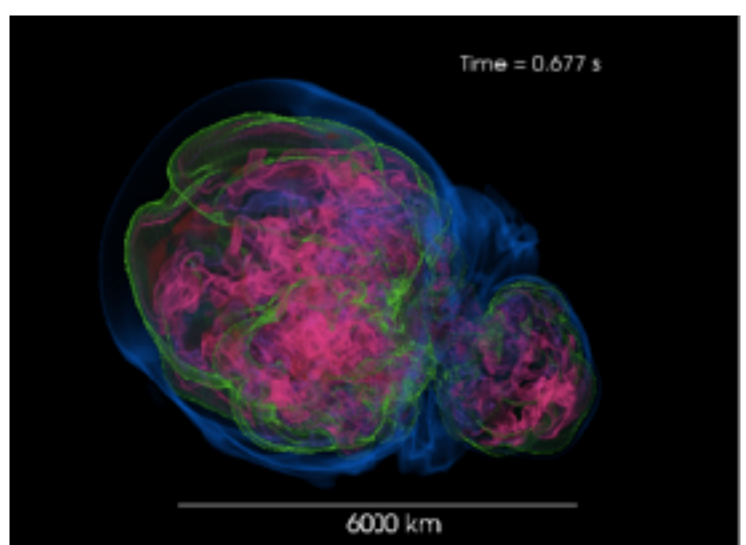
O'Connor & Couch, '18

~99% of internal energy is radiated away via neutrinos (~10^{53}ergs)

—> ~10% energy deposition is enough to explain E_{exp}~10^{51}ergs



Müller+, '17



Vartanyan+, '19

Numerical simulations can't fully explain canonical explosion energies

- neutrino-matter interactions?
- resolution problem?
- too short simulation time?

(1)The standard explosion mechanism
Neutrino driven explosion,

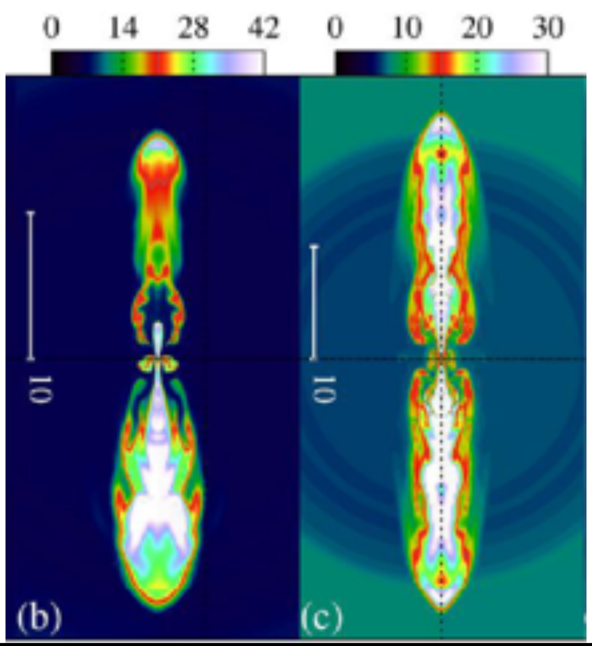
Colgate&White'66, Bethe&Wilson'85
For reviews, Janka'12, Kotake+,'12, Burrows+,'13

(2)If the magnetic field is strong enough

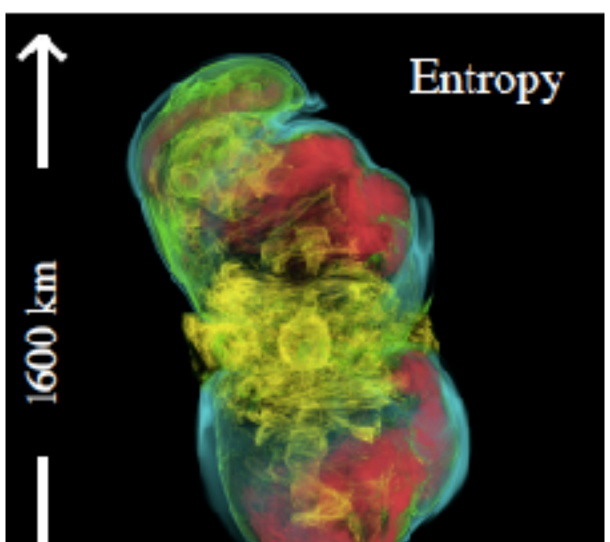
MHD explosion,
- Angular momentum transfer
- Mass ejection by B pressure
- efficient neutrino heating

2D: Ardeljan+,'00, Kotake+,'04, Obergaulinger+,'06,'17, Burrows+,'07, Takiwaki+,'09,

3D: Mikami+, '08; Newtonian, no neutrino, Polytropic EOS
Mösta+,'14; full GR but very simplified neutrino transport
Obergaulinger+,'19; SR with M1 neutrino transport (preliminary result)



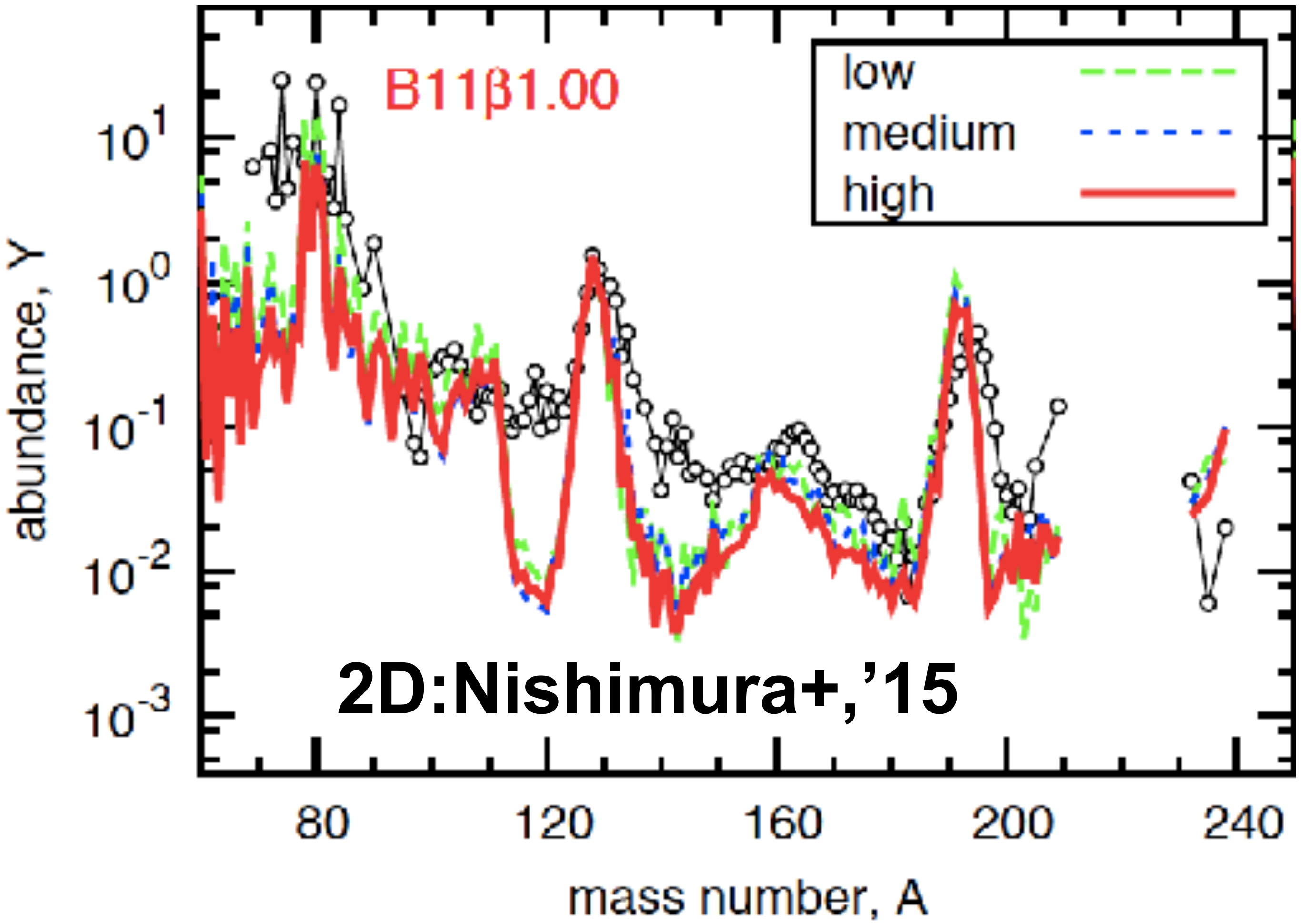
Obergaulinger+,'17

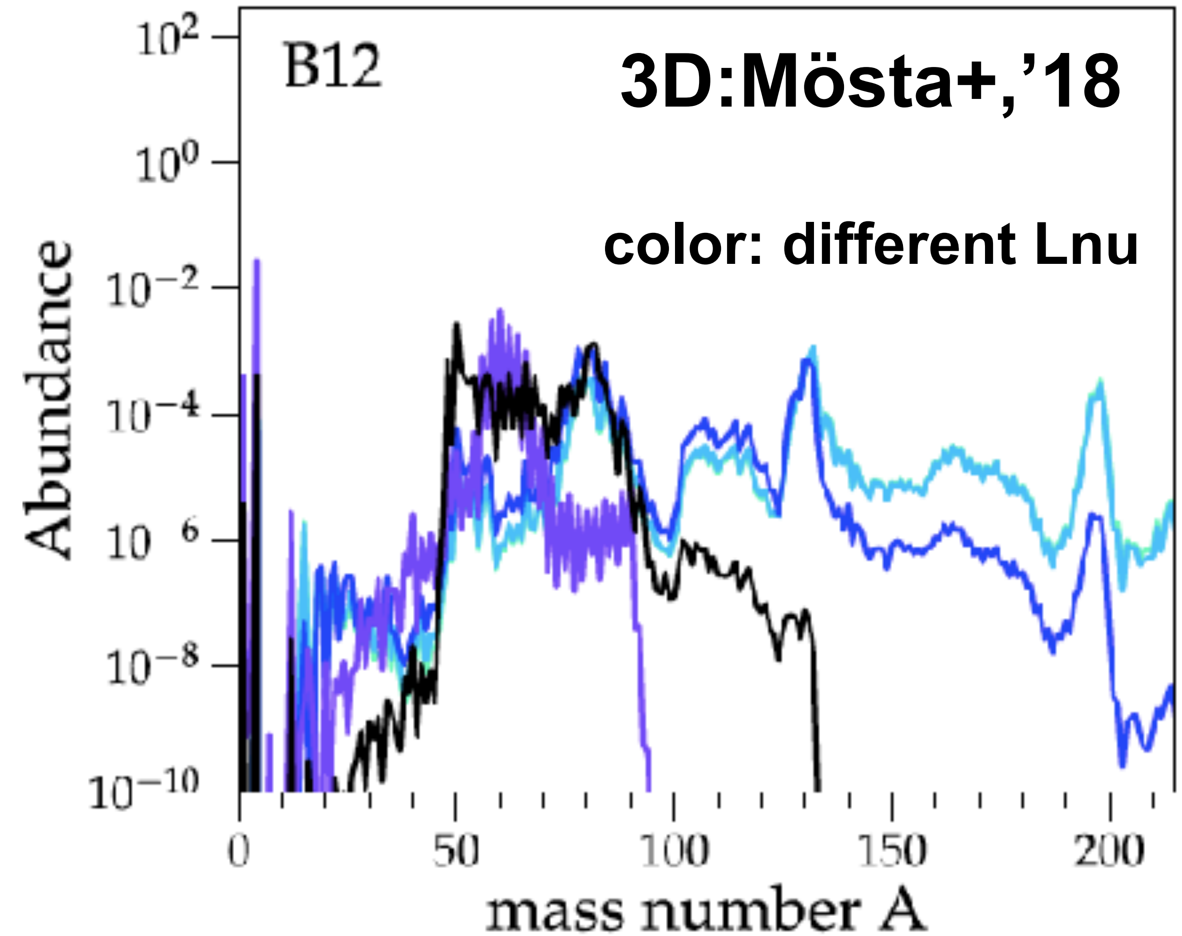


Mösta+,'14

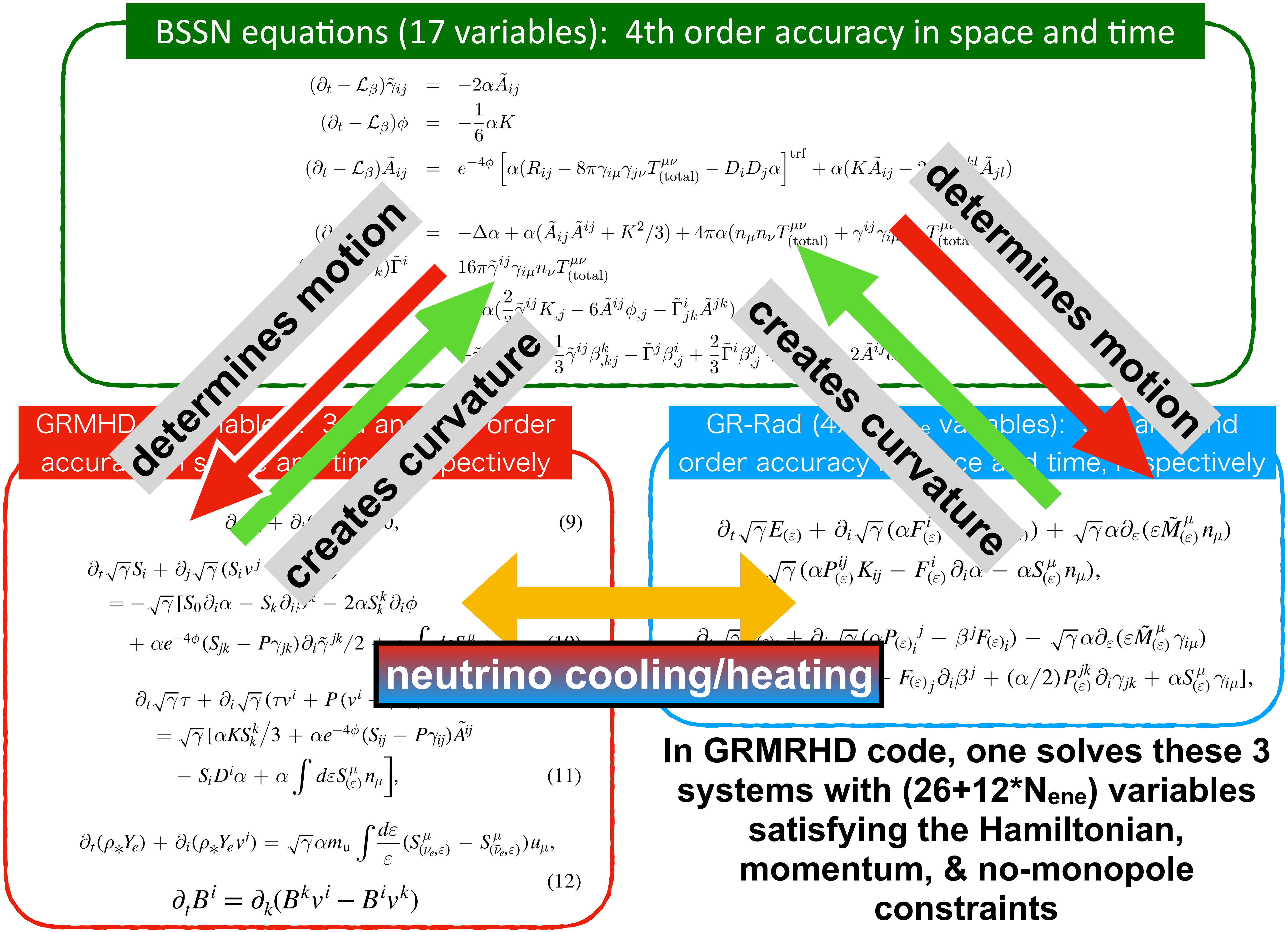
Things still to be explored
- resolution problem->MRI?
- 2D artefacts ->3D non-axisymmeties
- microphysics->neutrino effects

Can the MHD explosion be the r-process site?





- Strong MHD jet can potentially produce the 3rd peak (due to low-Ye ejeta)
- Neutrino radiation significantly influences on the ejecta Ye



BSSN equations (17 variables): 4th order accuracy in space and time
GRMHD variables: 3rd and 4th order accuracy in space and time, respectively
GR-Rad variables: 3rd and 4th order accuracy in space and time, respectively
determines motion
creates curvature
creates curvature
determines motion
neutrino cooling/heating
In GRMHD code, one solves these 3 systems with (26+12*Nene) variables satisfying the Hamiltonian, momentum, & no-monopole constraints

The basic equations for neutrino transport

$$T_{\mu\nu}^{neutrino} = E n_\mu n_\nu + F_\mu n_\nu + F_\nu n_\mu + P_{\mu\nu}$$

Shibata+'11, TK+'16

(E, F, P: 0th, 1st, 2nd momenta (in Euler))

advection — **gravitational redshift/Doppler**

$$\partial_t \sqrt{\gamma} E_{(\varepsilon)} + \partial_i \sqrt{\gamma} (\alpha F^i_{(\varepsilon)} - \beta^i E_{(\varepsilon)}) + \sqrt{\gamma} \alpha \partial_\varepsilon (\varepsilon \tilde{M}^\mu_{(\varepsilon)} n_\mu)$$

$$= \sqrt{\gamma} (\alpha P^{ij}_{(\varepsilon)} K_{ij} - F^i_{(\varepsilon)} \partial_i \alpha - \alpha S^\mu_{(\varepsilon)} n_\mu), \quad (4)$$

gravitational source — **neutrino-matter interaction**

and

$$\partial_t \sqrt{\gamma} F_{(\varepsilon)i} + \partial_j \sqrt{\gamma} (\alpha P_{(\varepsilon)i}{}^j - \beta^j F_{(\varepsilon)i}) - \sqrt{\gamma} \alpha \partial_\varepsilon (\varepsilon \tilde{M}^\mu_{(\varepsilon)} \gamma_{i\mu})$$

$$= \sqrt{\gamma} [-E_{(\varepsilon)} \partial_i \alpha + F_{(\varepsilon)j} \partial_i \beta^j + (\alpha/2) P^{jk}_{(\varepsilon)} \partial_i \gamma_{jk} + \alpha S^\mu_{(\varepsilon)} \gamma_{i\mu}], \quad (5)$$

TK+,'16

The Opacity Set Included in this Study and their References

Process	Reference	Summarized In
$n\nu_e \leftrightarrow e^- p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$p\bar{\nu}_e \leftrightarrow e^+ n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu_e A \leftrightarrow e^- A'$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.1
$\nu p \leftrightarrow \nu p$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu n \leftrightarrow \nu n$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu A \leftrightarrow \nu A$	Bruenn (1985), Rampp & Janka (2002)	Appendix A.2
$\nu e^\pm \leftrightarrow \nu e^\pm$	Bruenn (1985)	Appendix A.3
$e^- e^+ \leftrightarrow \nu\bar{\nu}$	Bruenn (1985)	Appendix A.4
$NN \leftrightarrow \nu\bar{\nu}NN$	Hannestad & Raffelt (1998)	Appendix A.5

Numerical setups

- 20Msun model (WHW07)
- dx~458m@center, ~3.2km@R=100km
- Basic neutrino opacities based on Bruenn'85 (same as TK+,'18)
- N_{ene}=12 bins (1<ε<300MeV)

- 3 models(R0B00, R1B00, R1B12)
- SFHo (Steiner+'13)
- Cylindrical rotational law

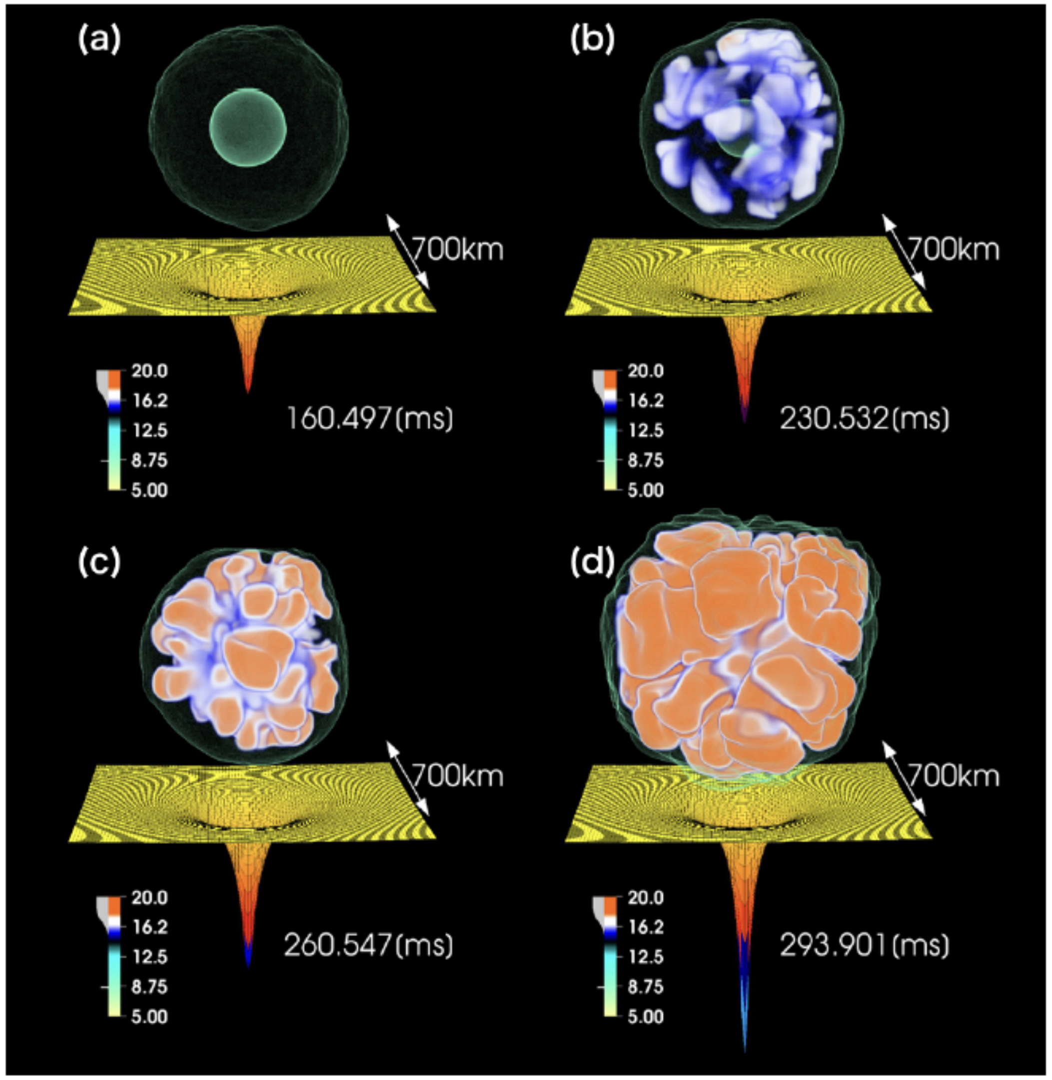
$$\Omega = \Omega_0 \frac{R_0^2}{\varpi^2 + R_0^2} \qquad \Omega_0 = 1(\mathrm{rad/s}) \qquad (\beta_\mathrm{b} \sim 1\%)$$

- Dipole-like B

$$A_\phi = \frac{B_0}{2}\frac{R_0^3}{R^3 + R_0^3} R\sin\theta \qquad B_0 = 10^{12}\mathrm{G} \quad (\beta_\mathrm{mag,b} \sim 1\%)$$

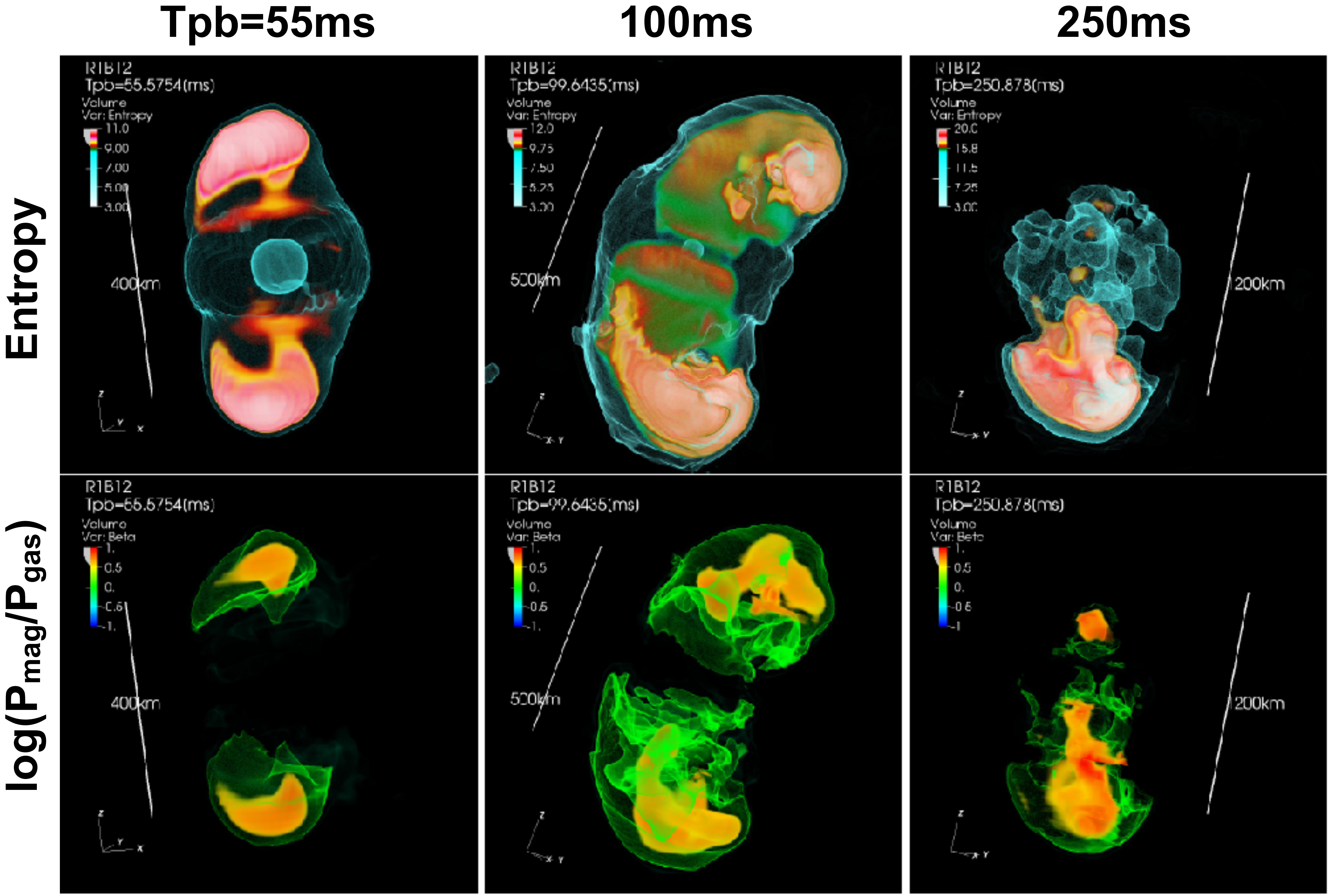
- CT method for divB=0

- XC40 @ NAOJ



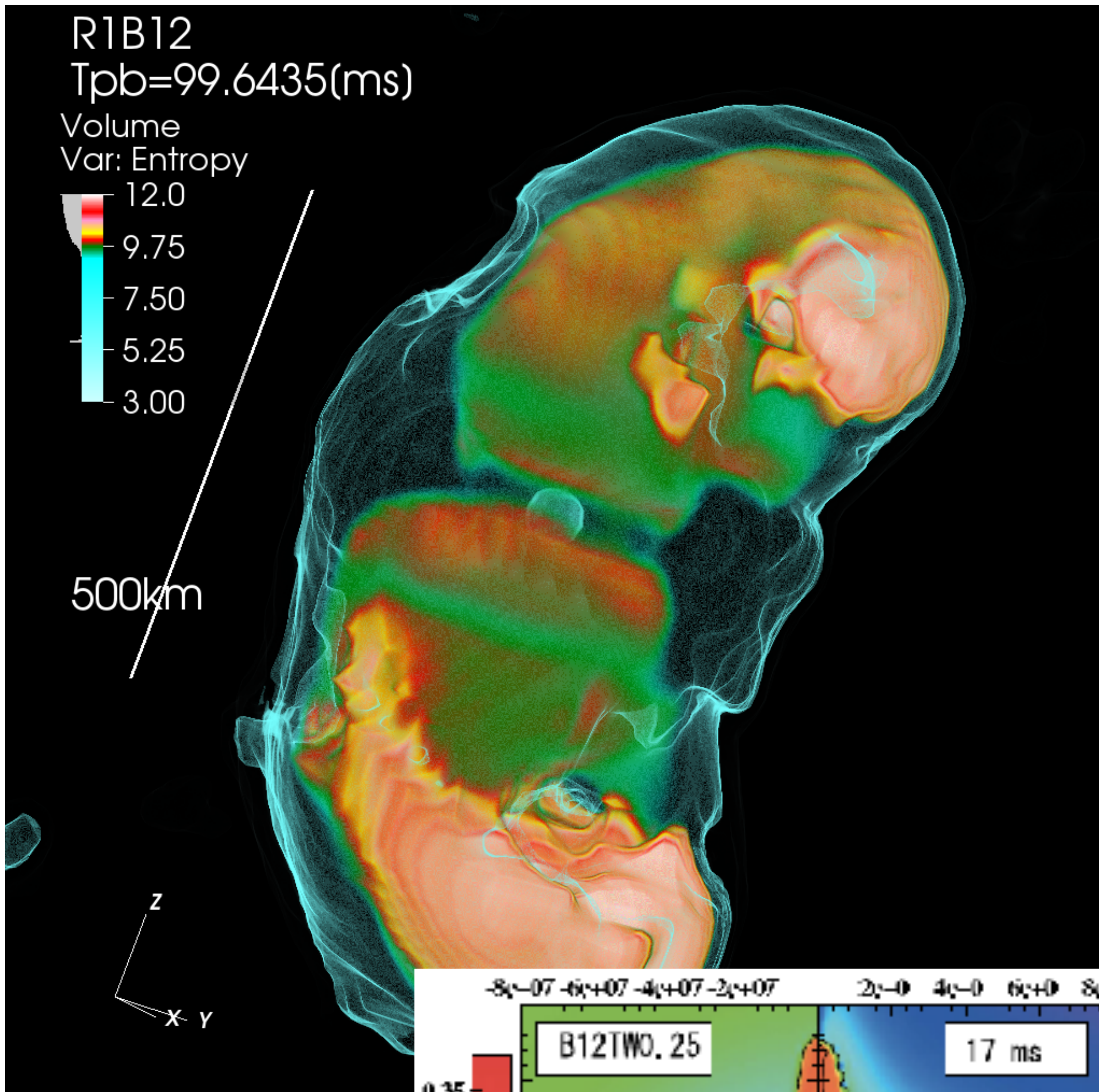
TK, Kei Kotake, T. Takiwaki, & F.-K. Thielemann 2018, MNRAS Letter

Rotating magnetized model (R1B12)

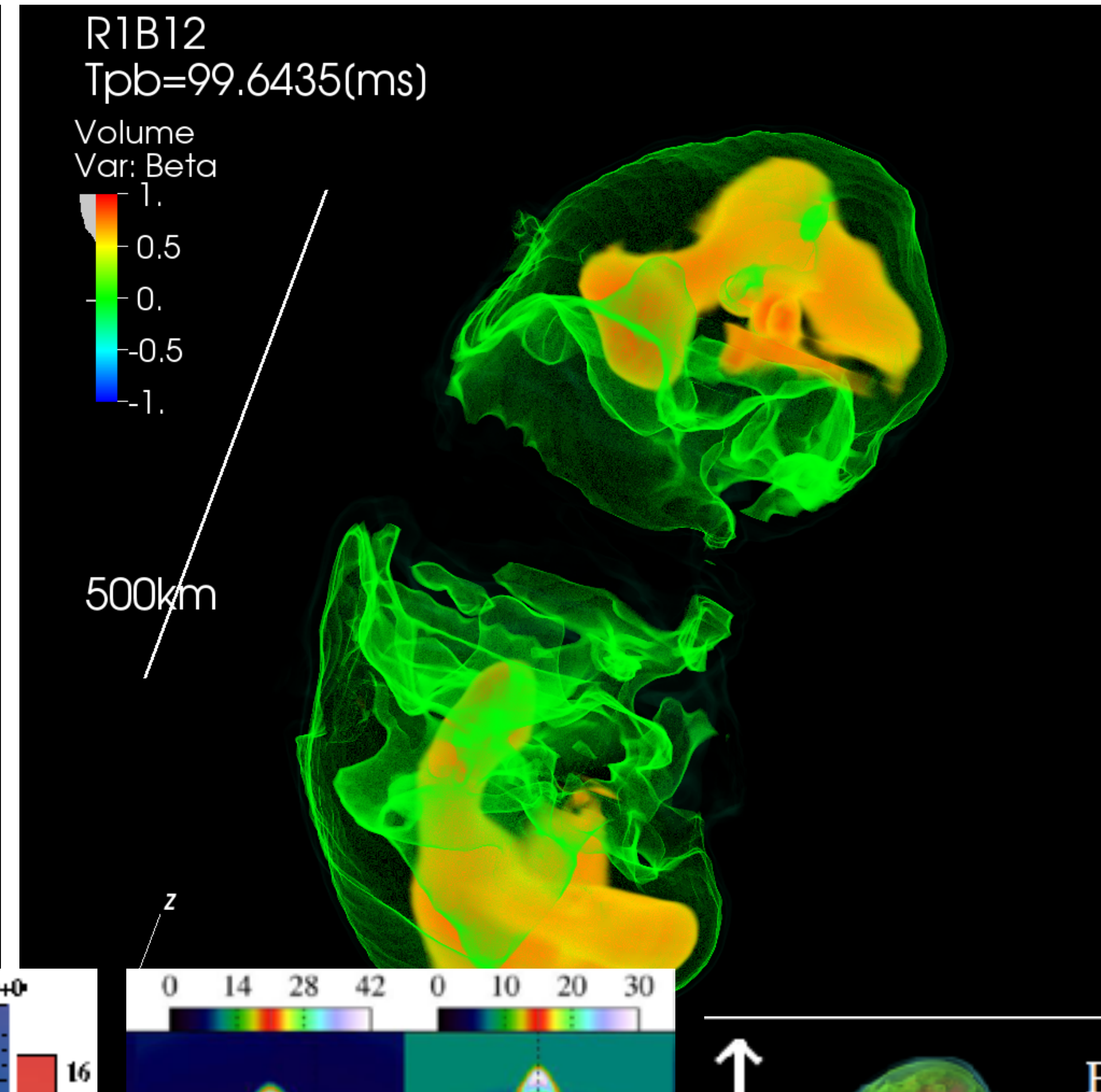


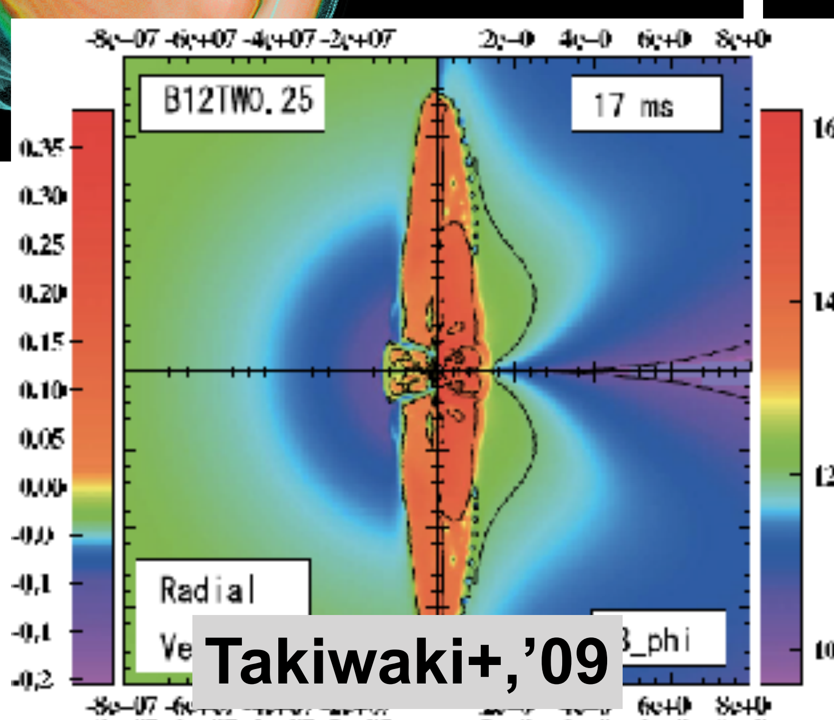
2D-3D comparison

Entropy

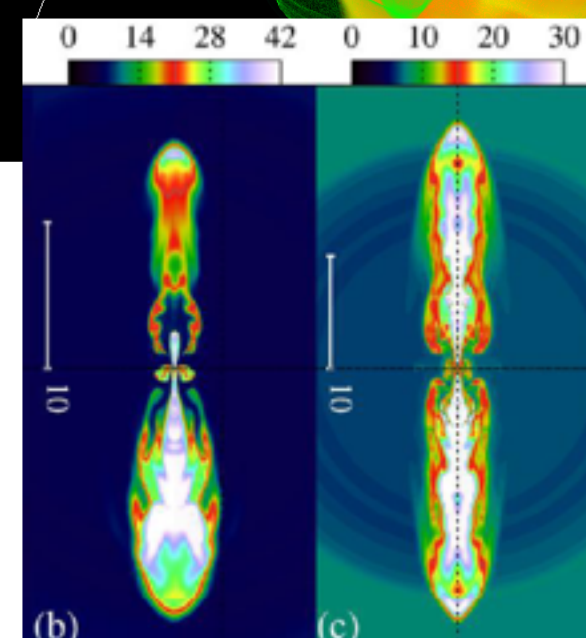


log(P_{mag}/P_{gas})

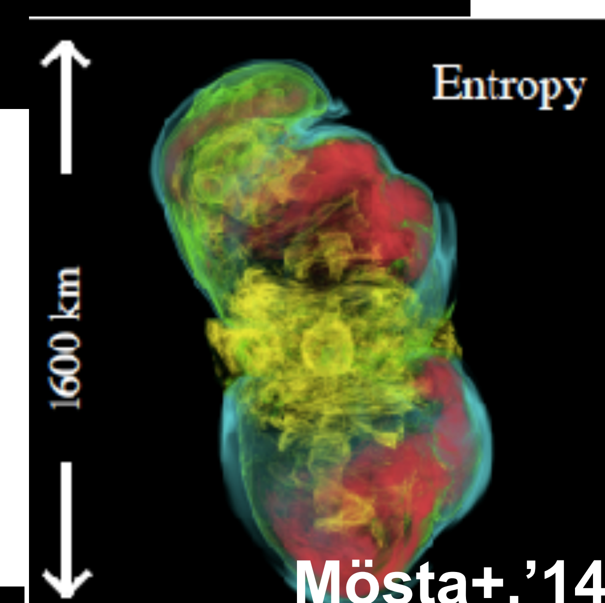




Takiwaki+,'09



Obergaulinger+,'17

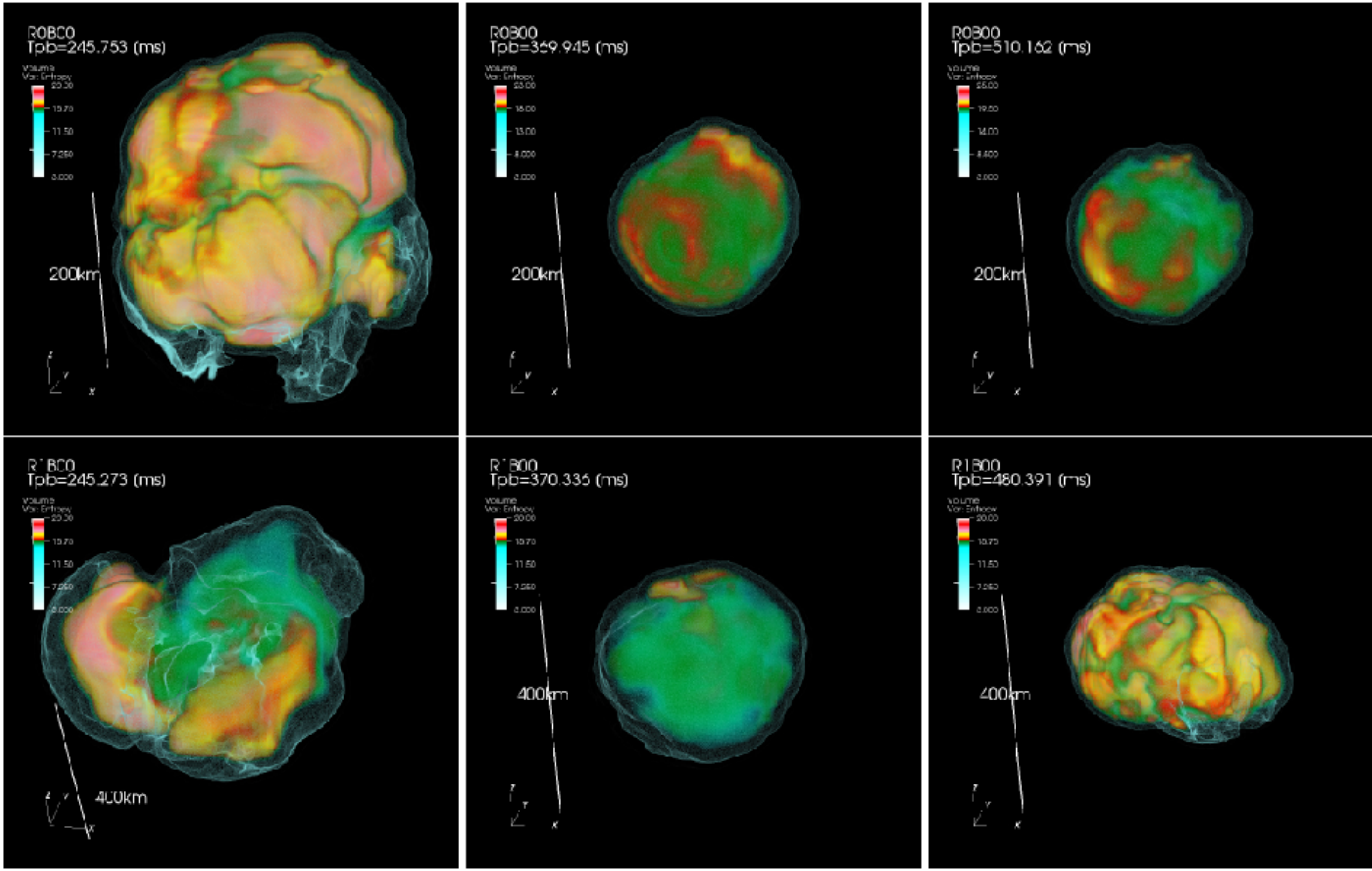


Mösta+,'14

Non-magnetized models

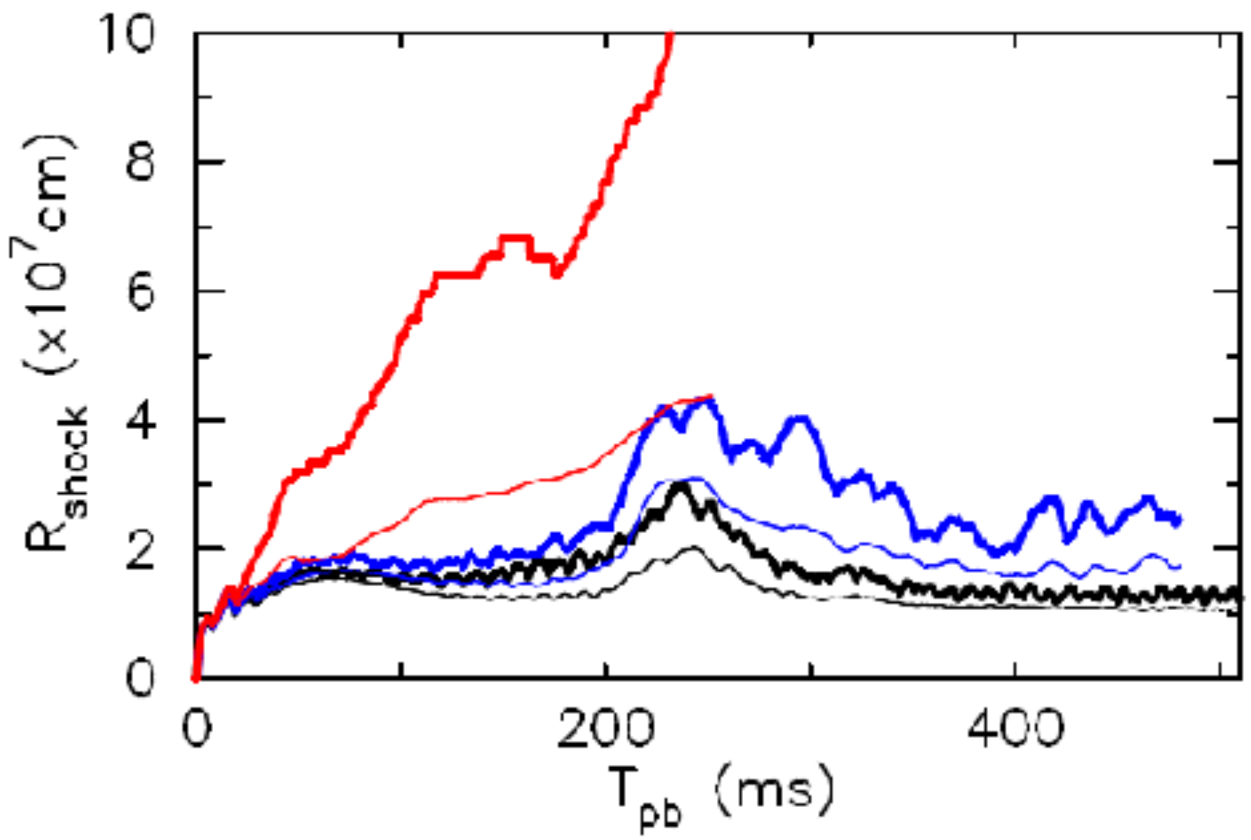
Non-rotating model

Rotating model

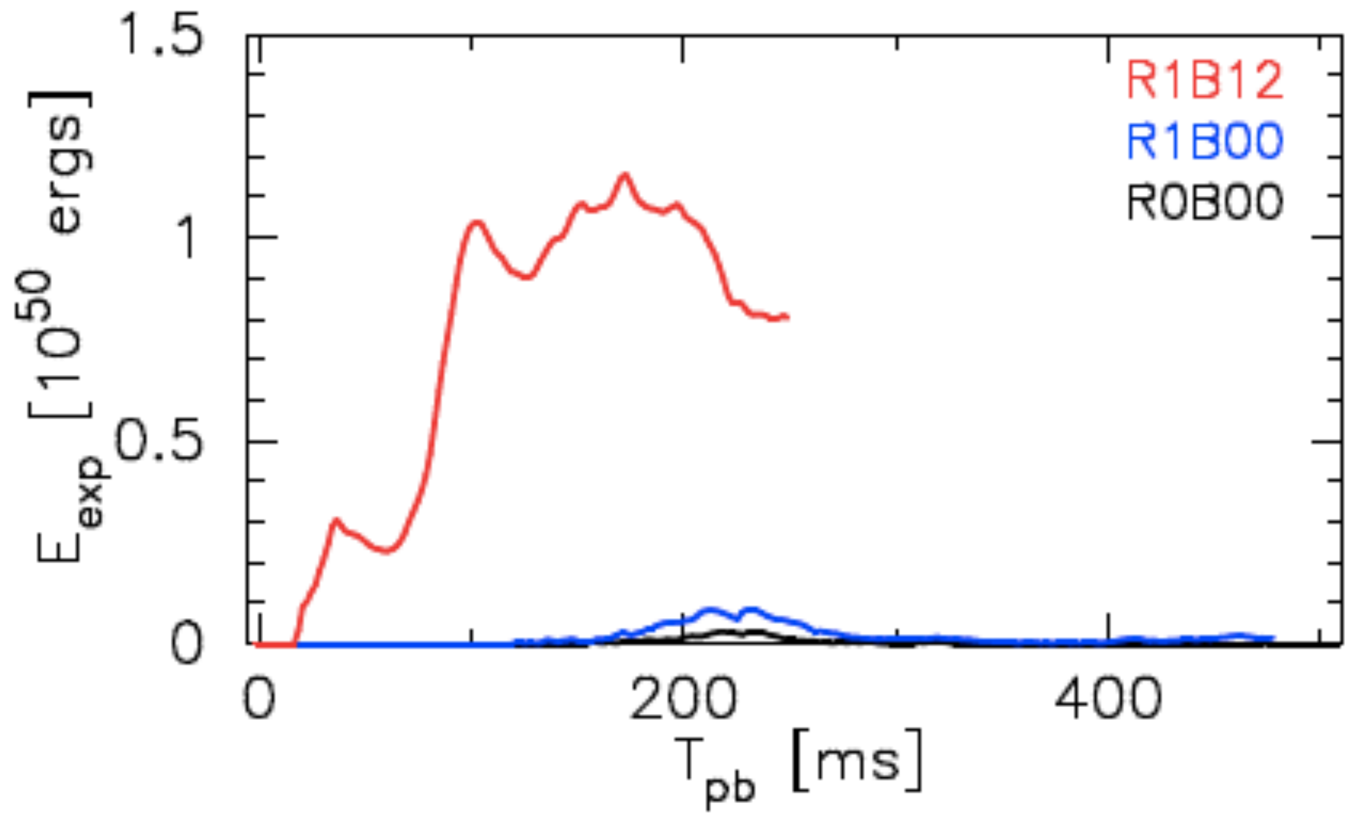


Energetics

Shock evolution

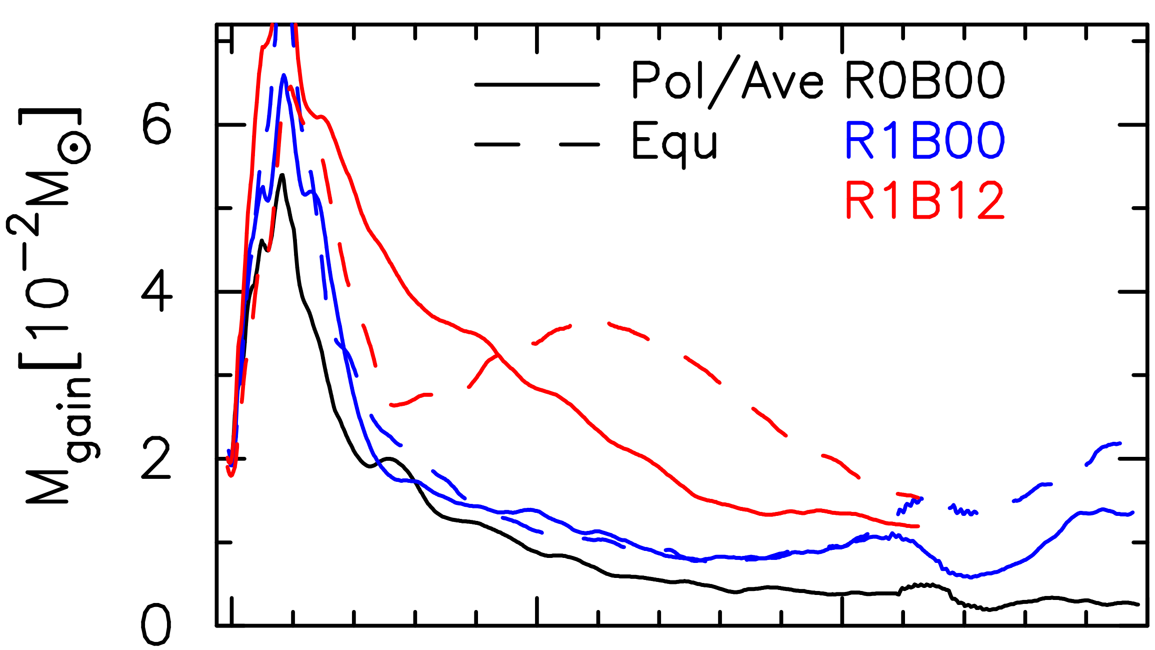


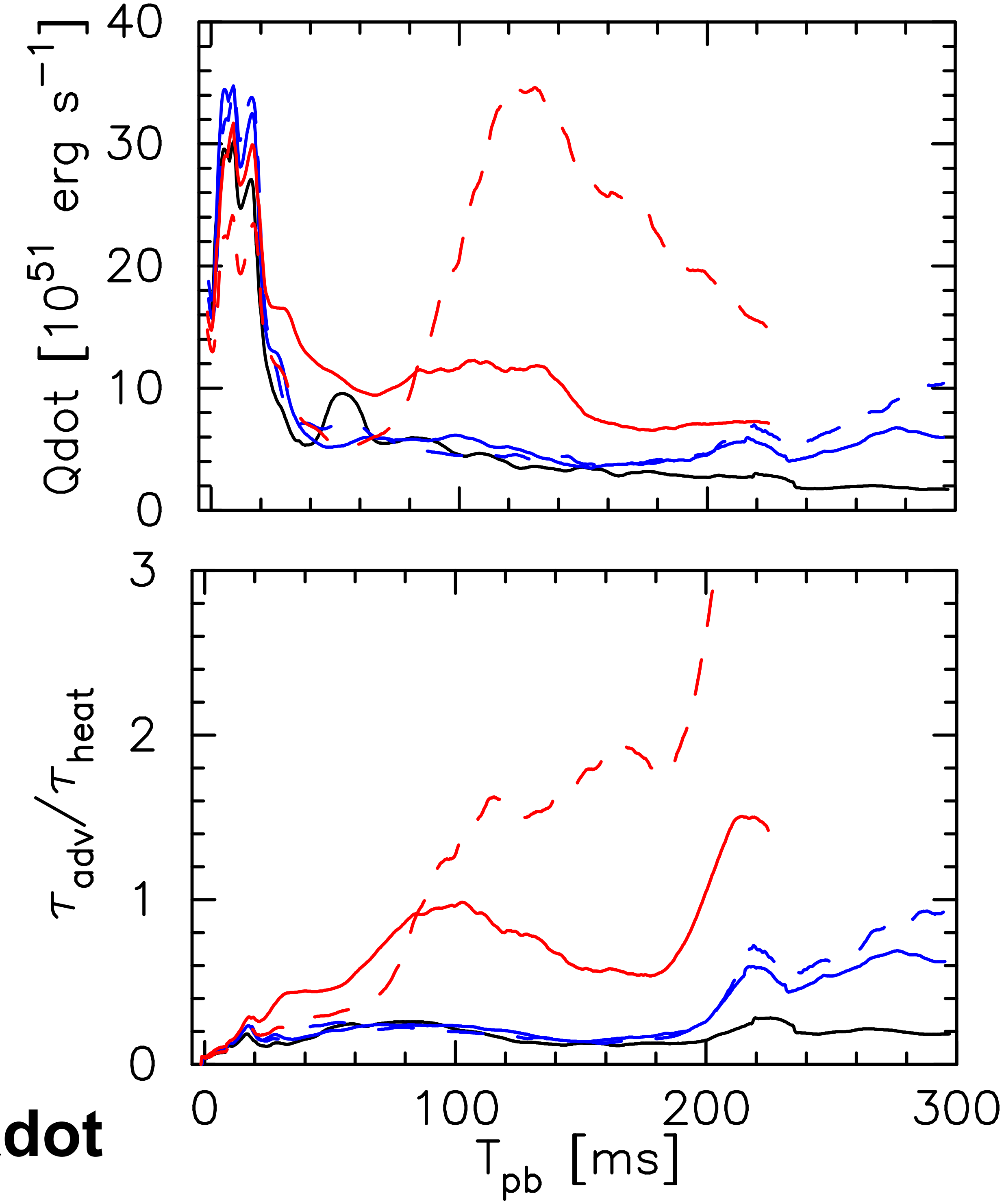
Diagnostic energy

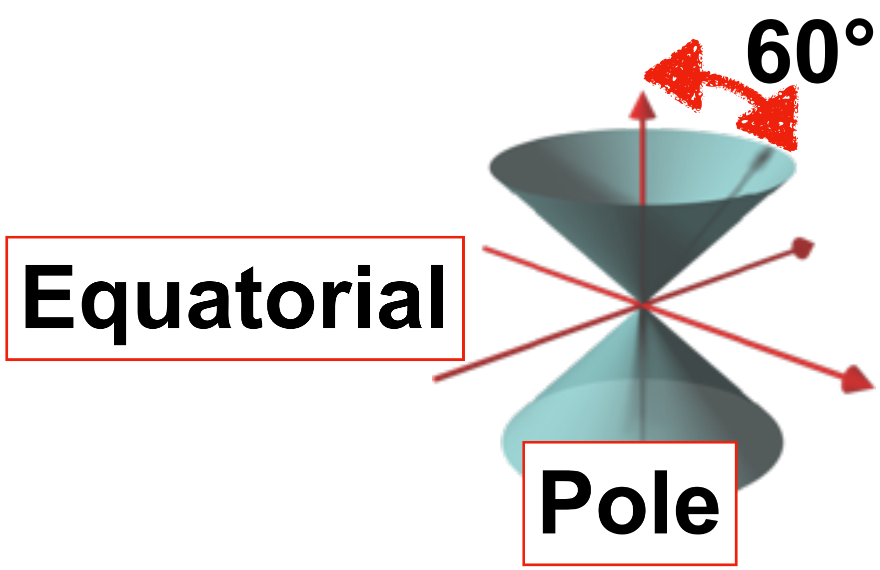


Rotation and Magnetic fields facilitate the explosion

Neutrino heated? or magneto-driven?

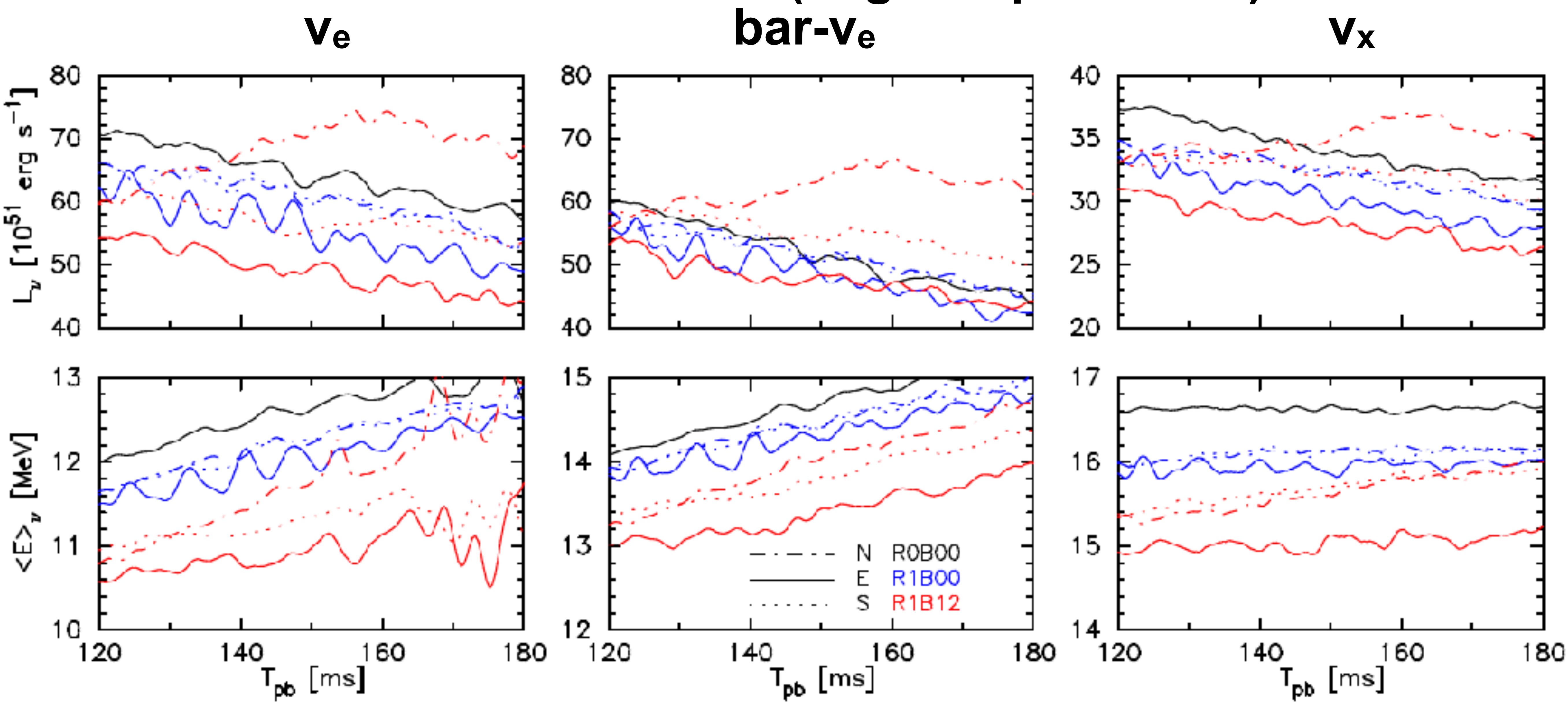




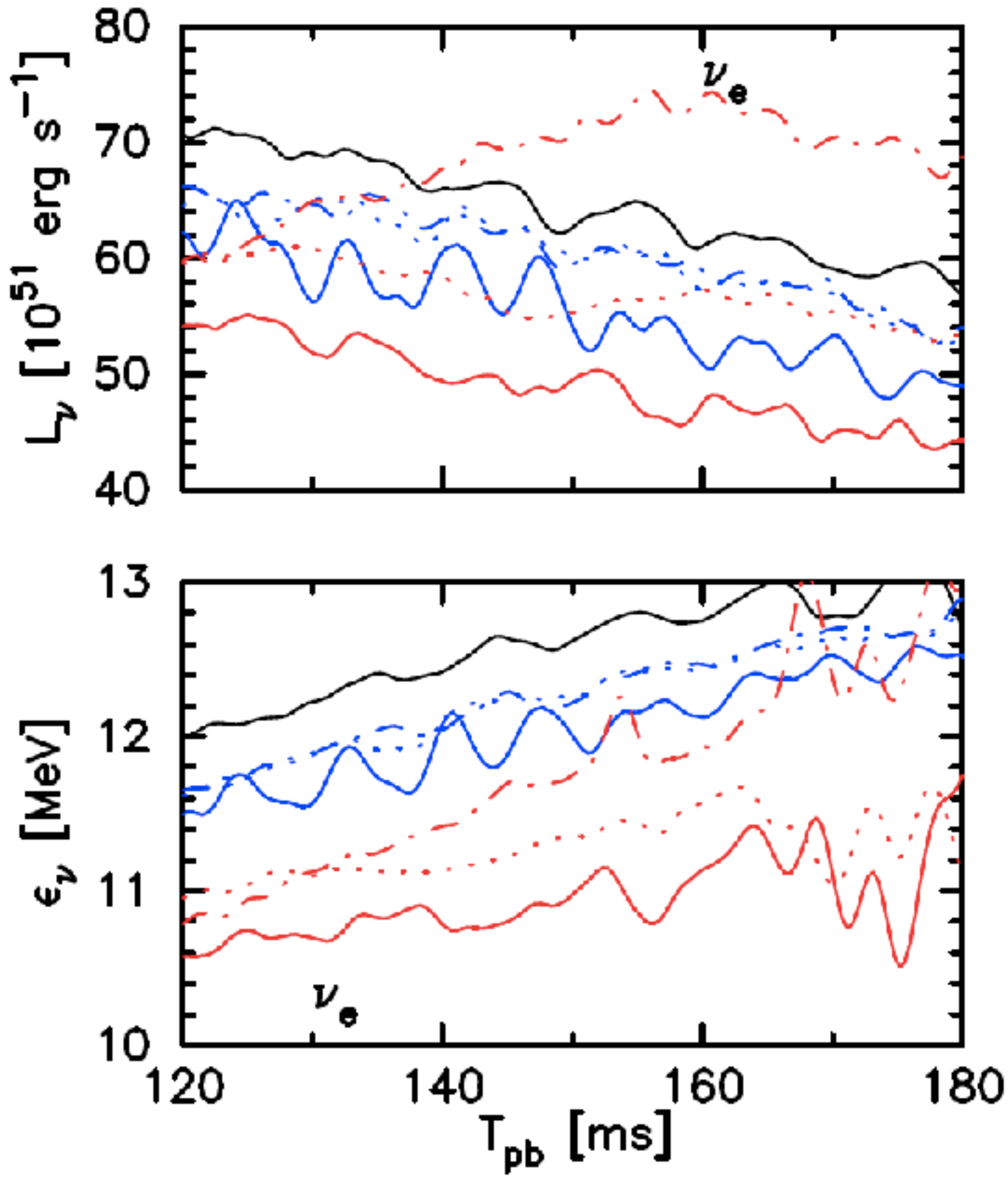


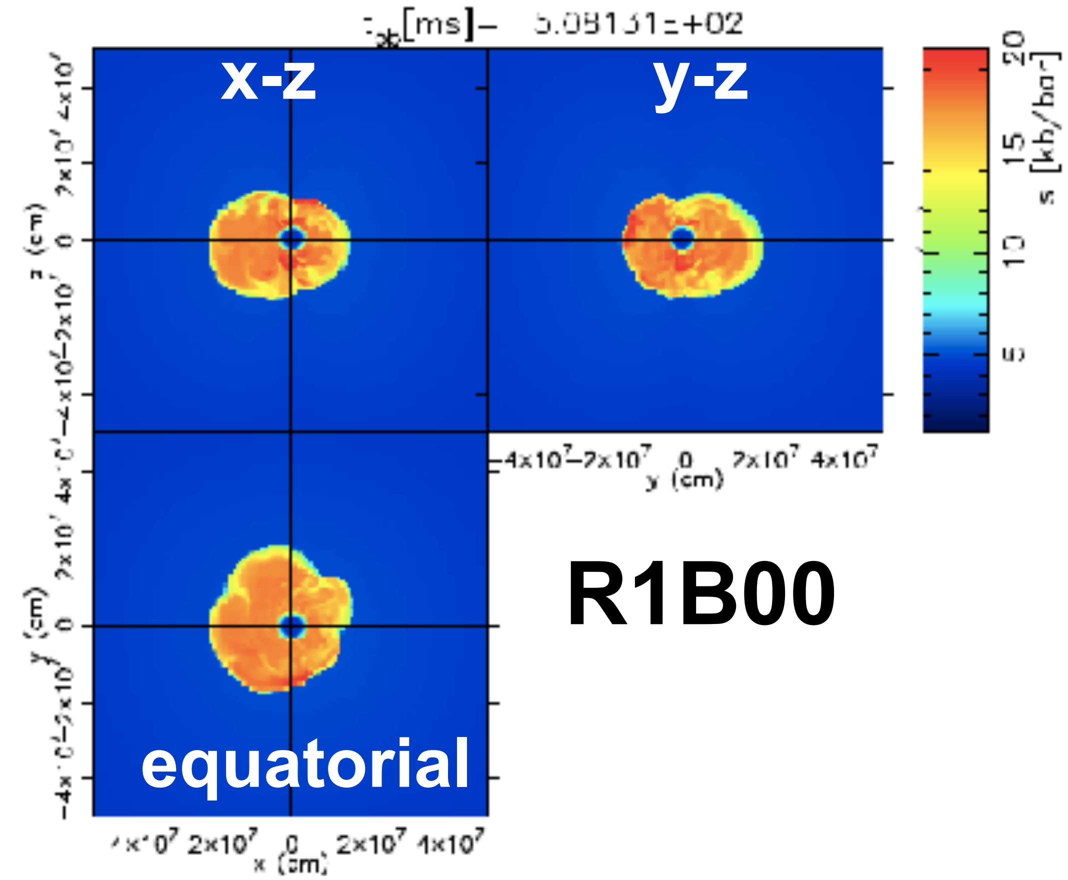
- **Rotation & B increase M_{gain} and Qdot**
- **For MHD model**
  - **Equatorial expansion is supported by v-heating** $\tau_{adv}/\tau_{heat} > 1$
  - **Prompt bipolar outflow is due to magnetic field** $\tau_{adv}/\tau_{heat} < 1$
  - **Later by v-heating** $\tau_{adv}/\tau_{heat} > 1$

Neutrino emission (angle dependence)

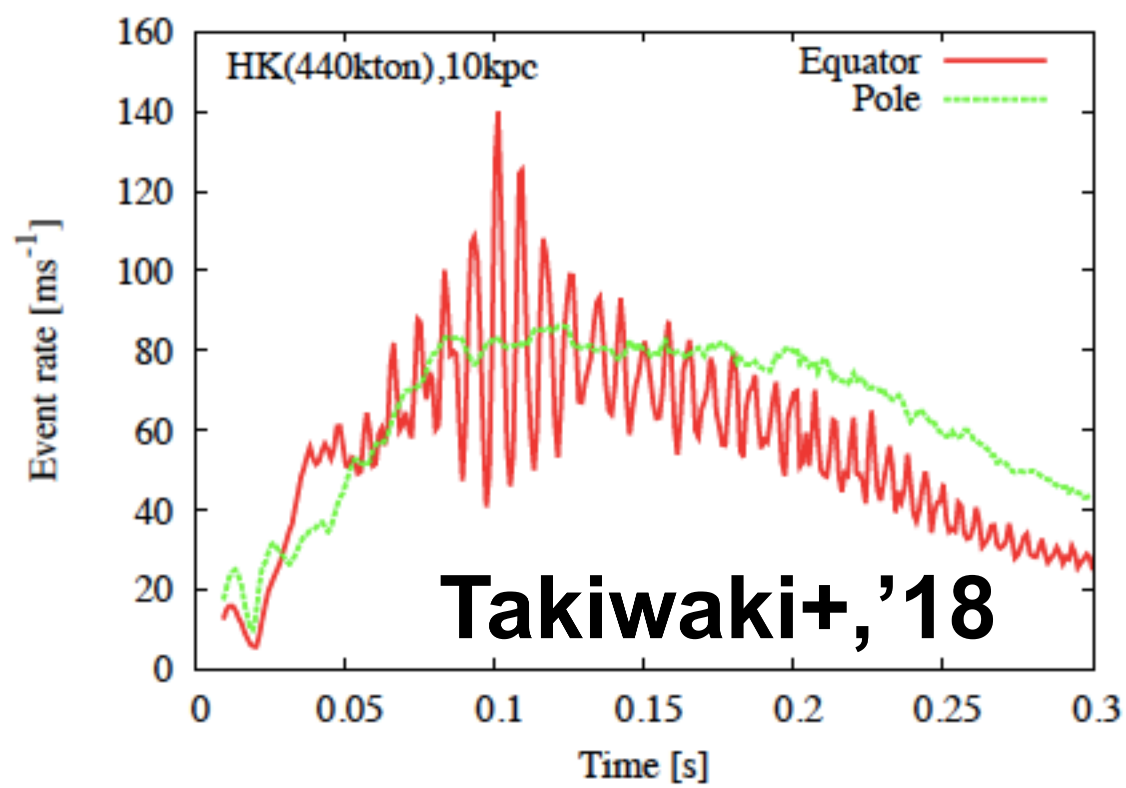


Neutrino emission (angle dependence)





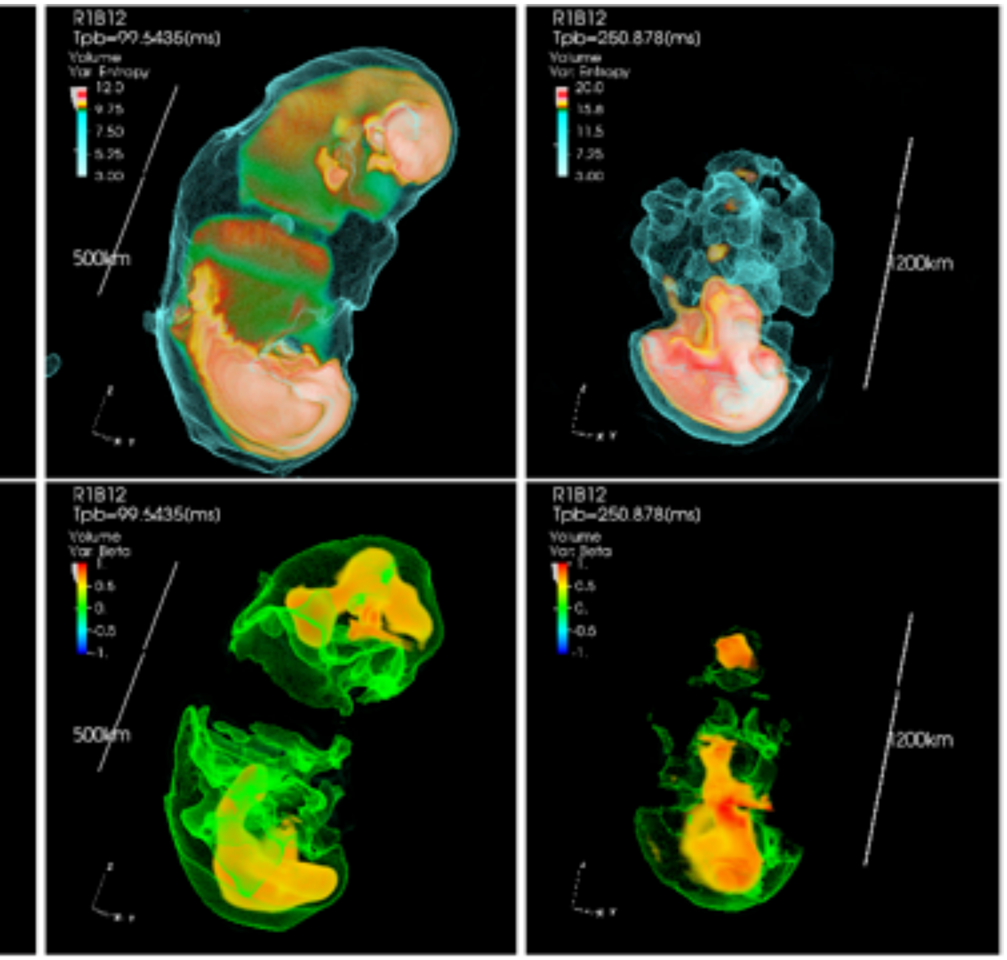
R1B00

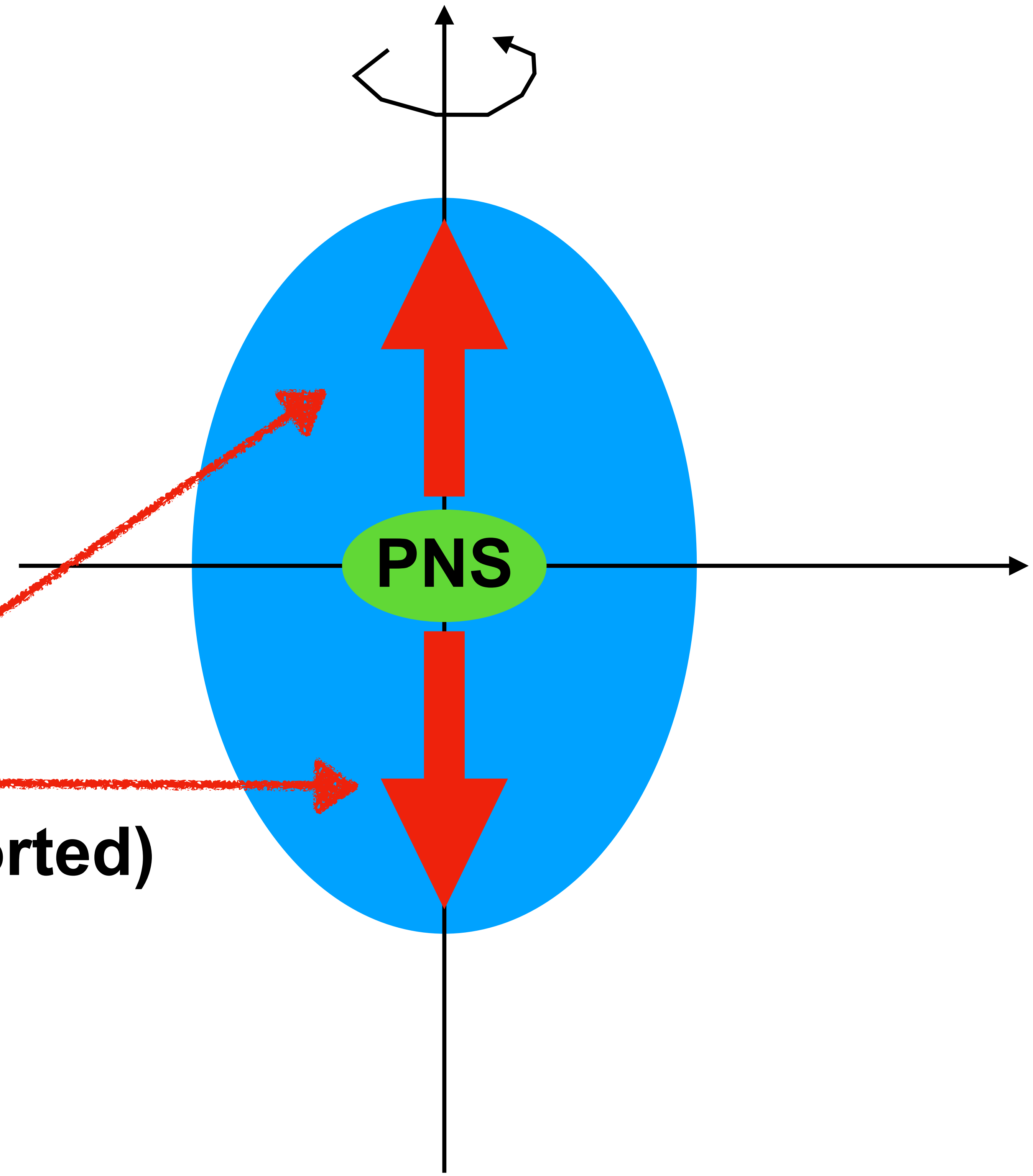


Takiwaki+,'18

g

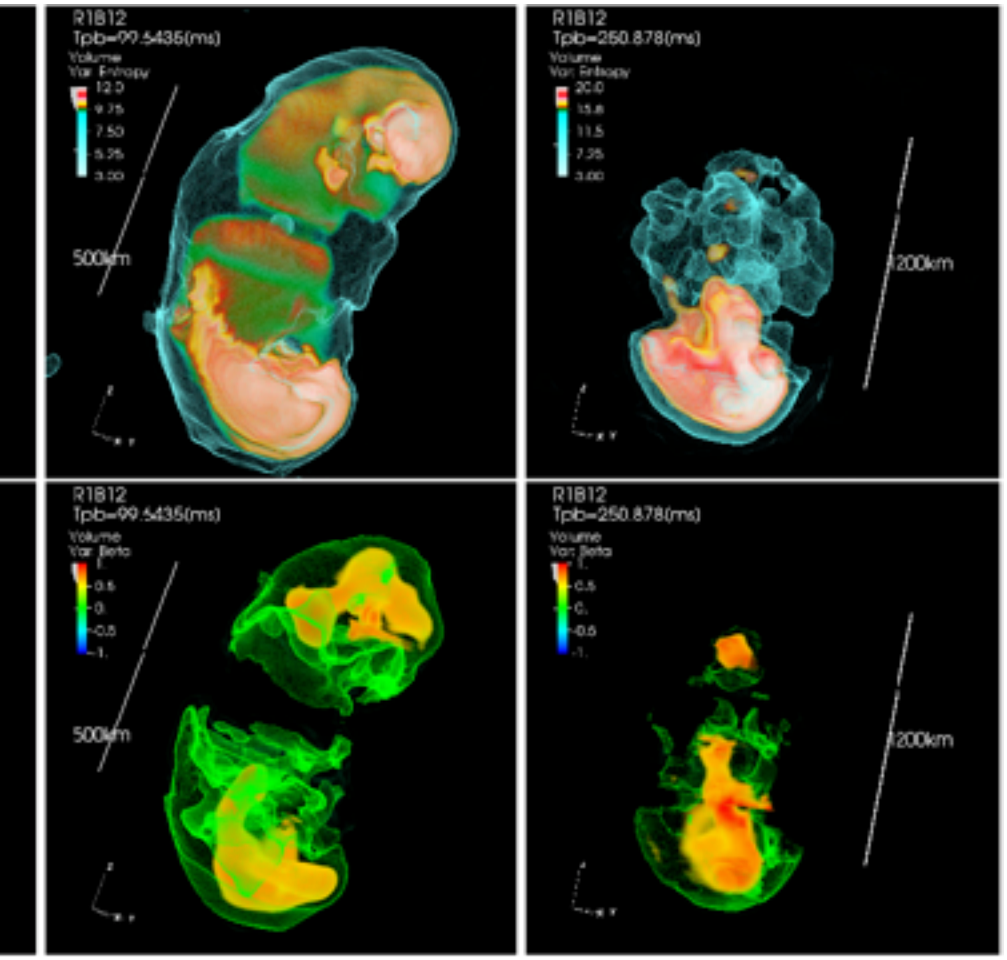
Ejecta structure

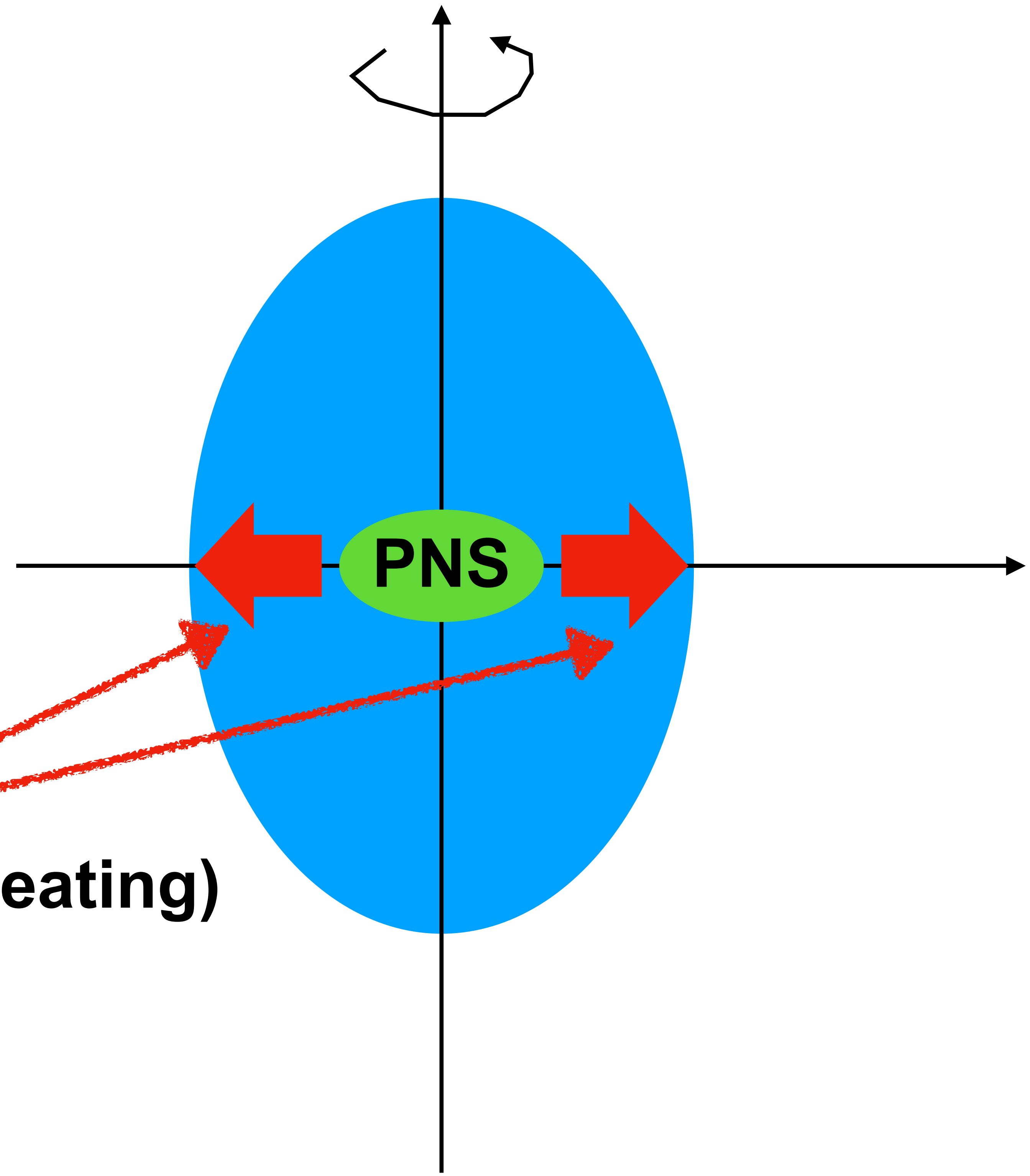




low Y_e (P_{mag} supported)

Ejecta structure





high Y_e (neutrino heating)

$$\nu_e n \rightarrow e^- p$$

Selection rule

(1) Ye and entropy unchanged (and low peak temperature), such that the progenitor composition does not change much

(2) Ye unchanged, but high peak temperature, with explosive nucleosynthesis

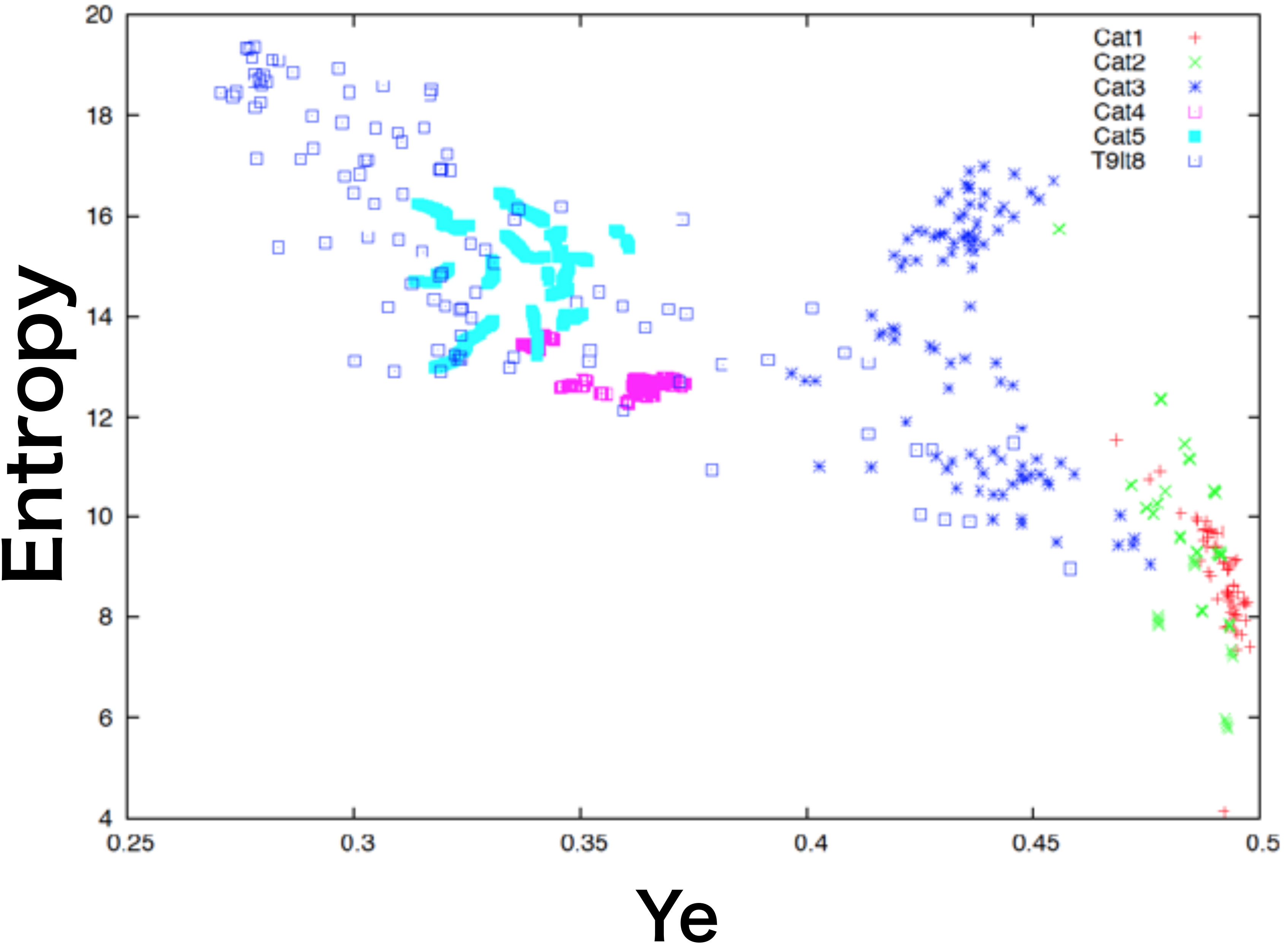
(3) Ye once <0.45 and at the end >0.38

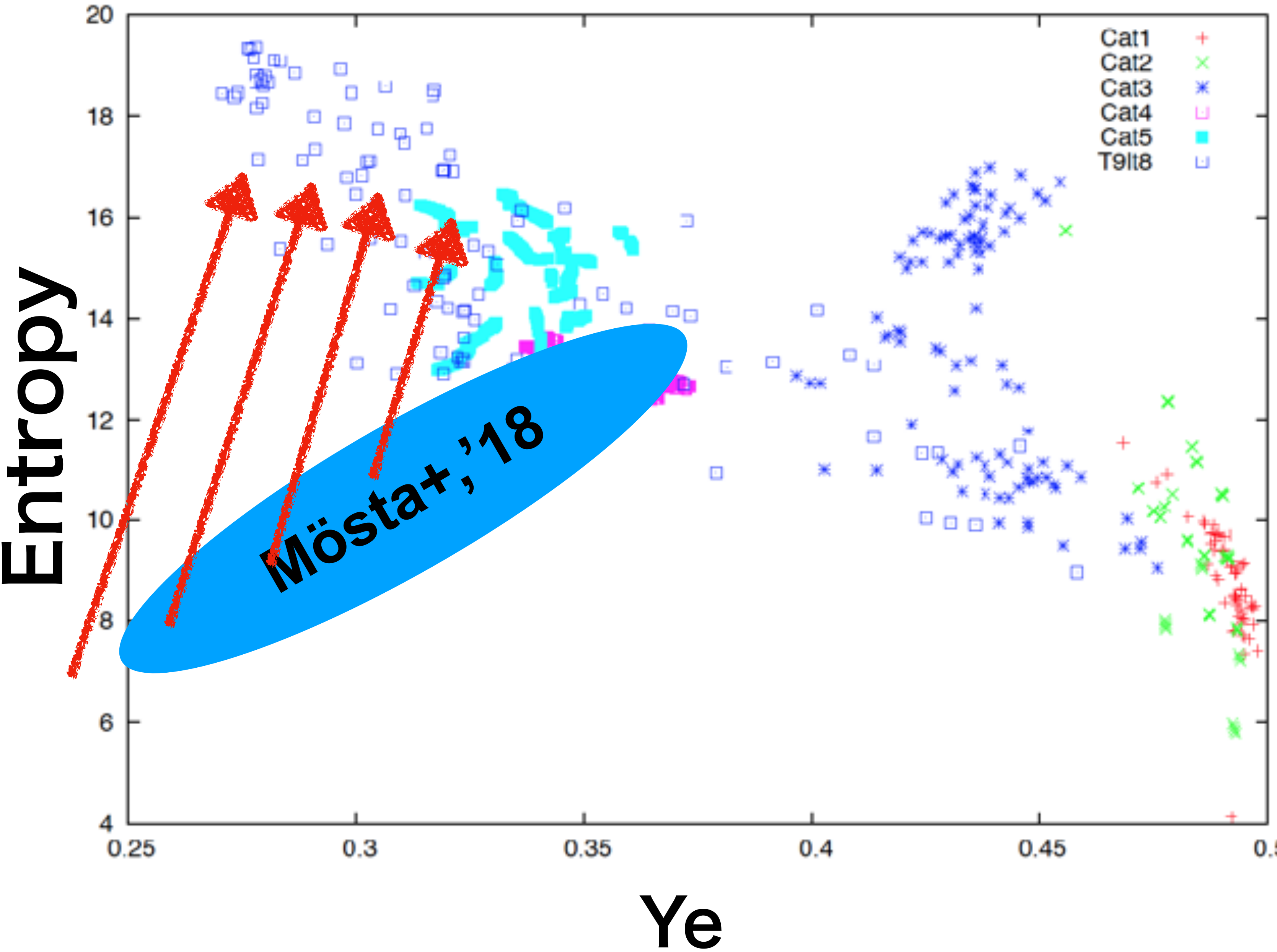
(4) Ye always <0.45 and entropy<15

(5) Ye always <0.45 and entropy>15

(6) T9lt8: final temperature (averaged in time of ~10ms) decreases below 8GK.

Scattering in S-Y_e plane

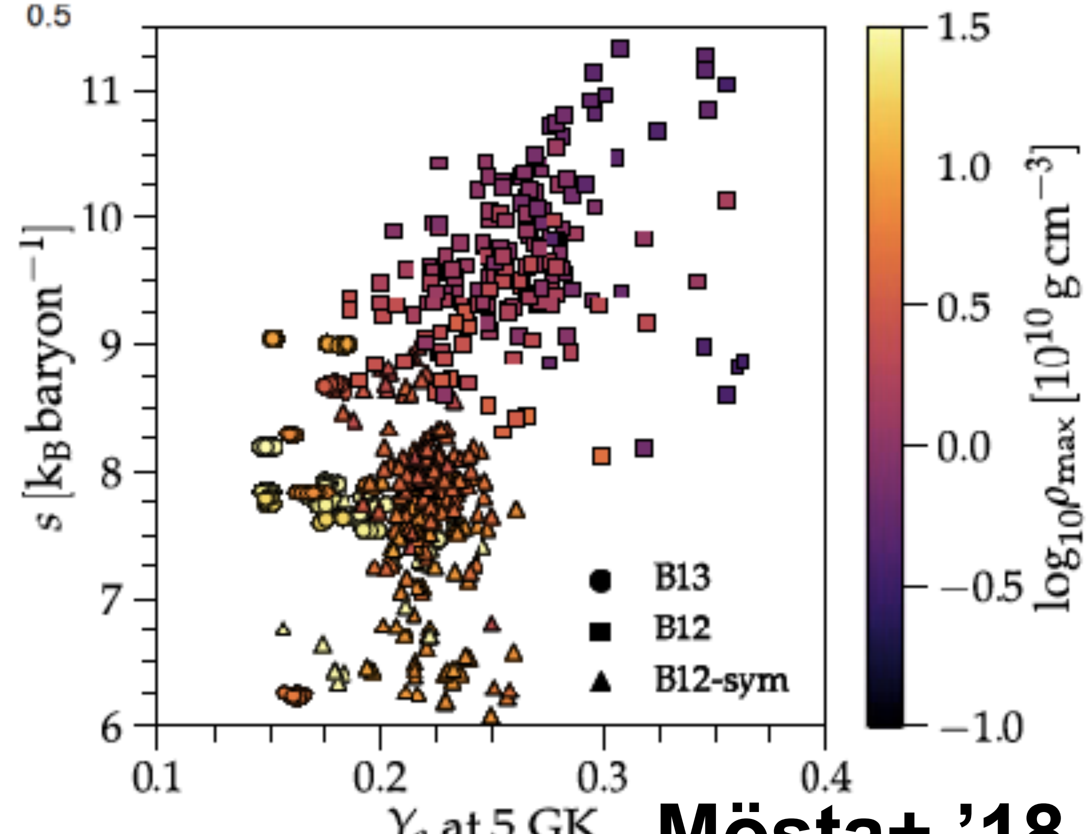




Scattering in S-Y_e plane

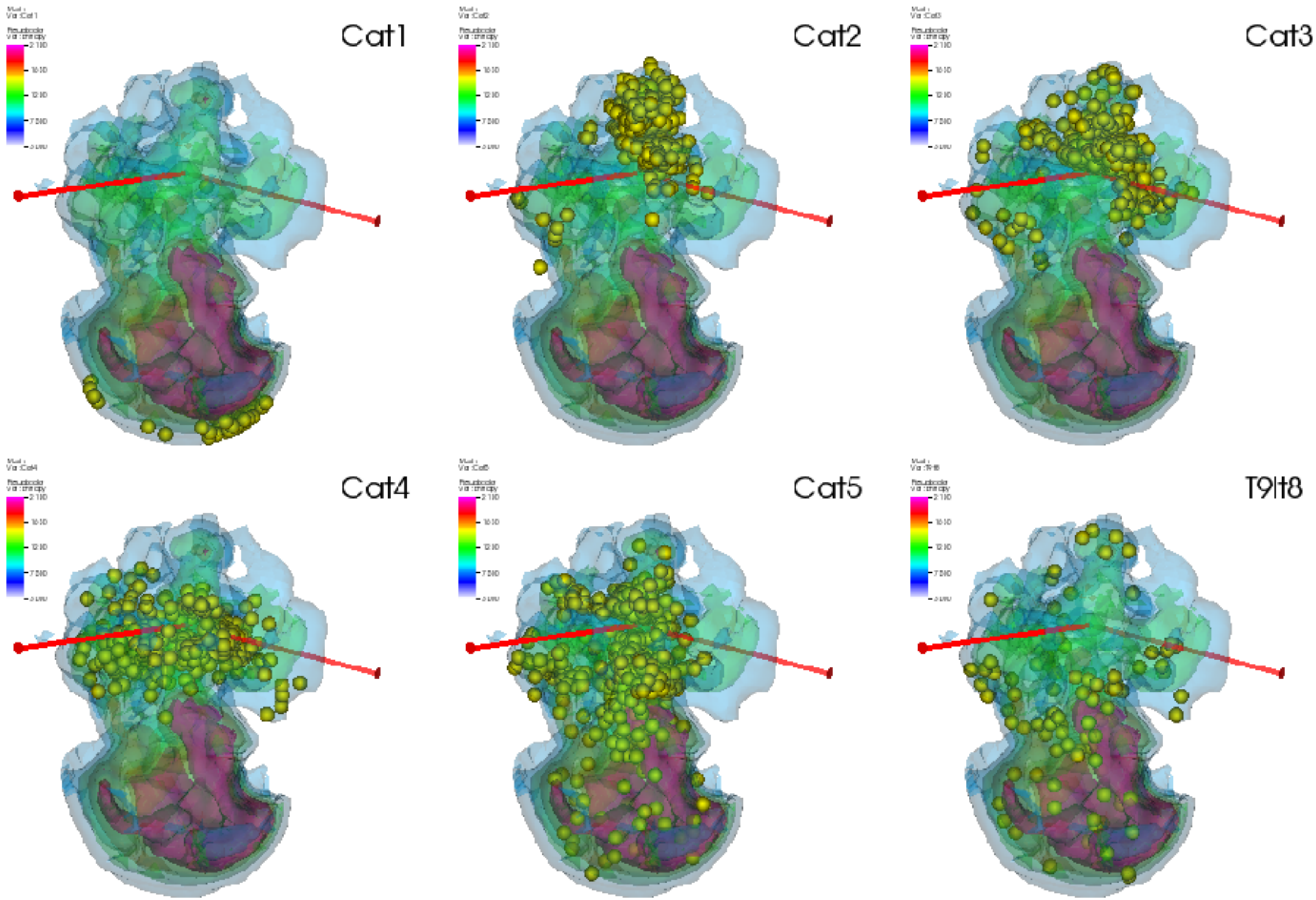
Due to the interaction $\nu_e n \rightarrow e^- p$

Ye & S tend to become higher

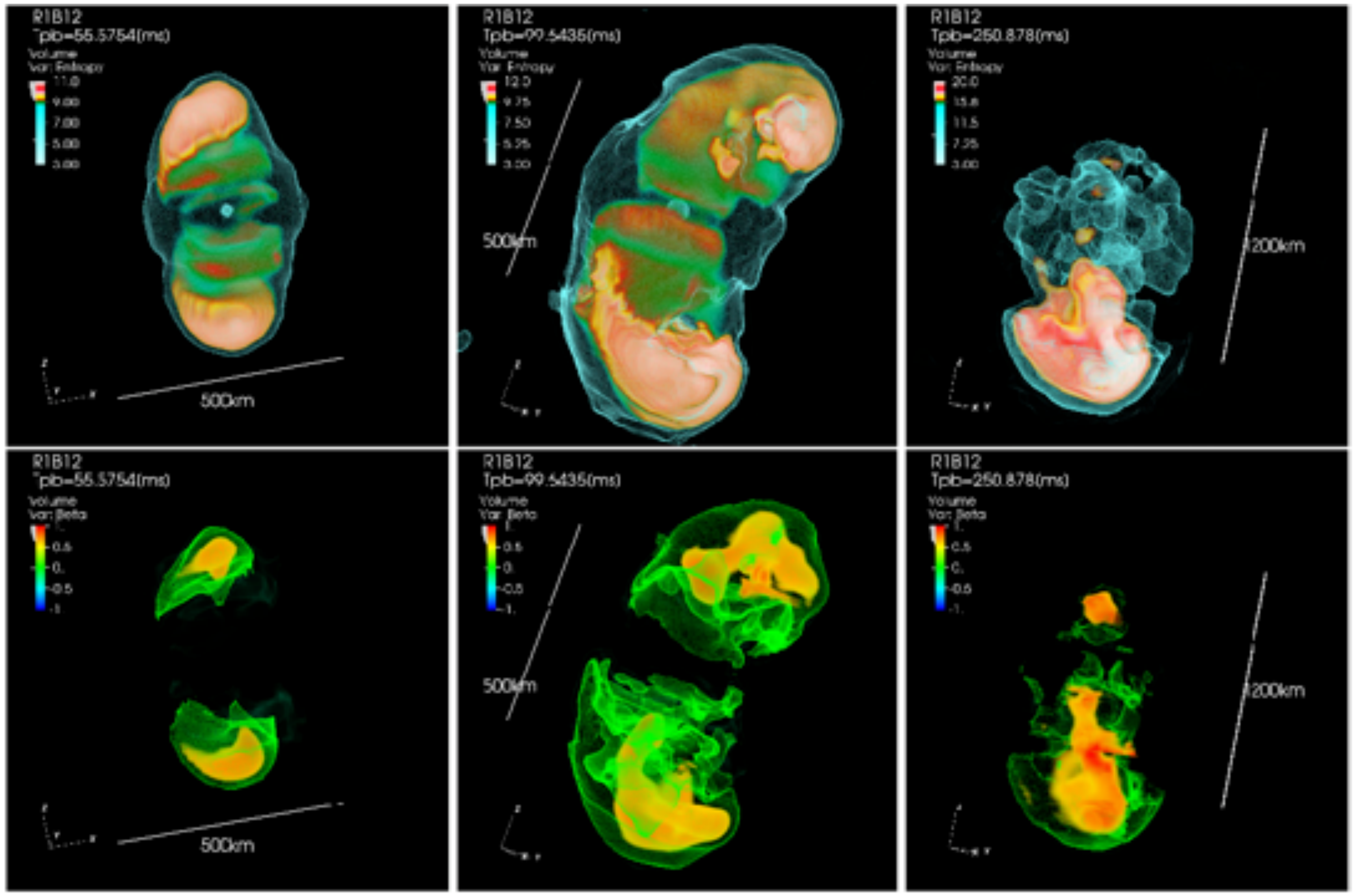


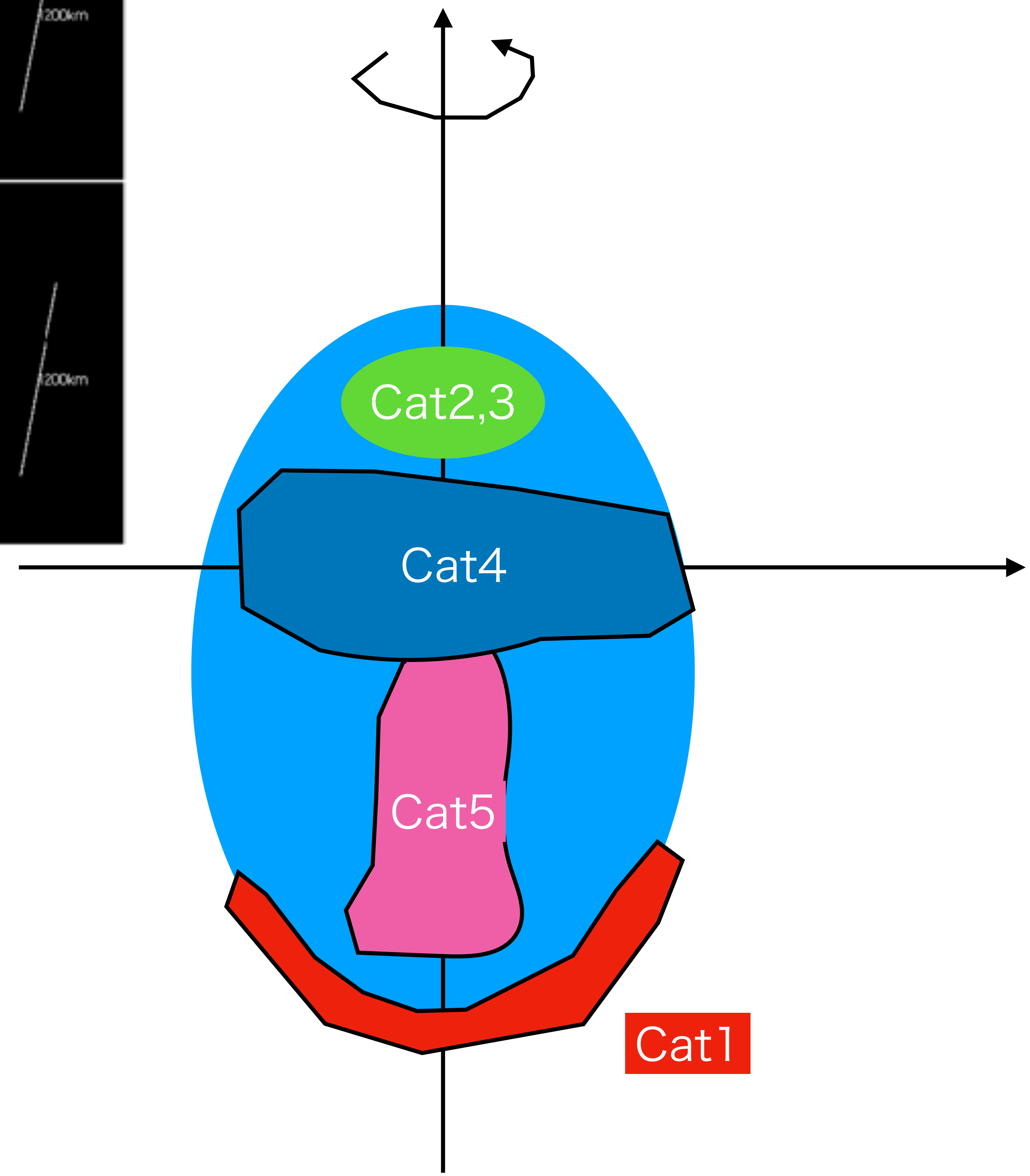
Mösta+,'18

Ejecta distribution

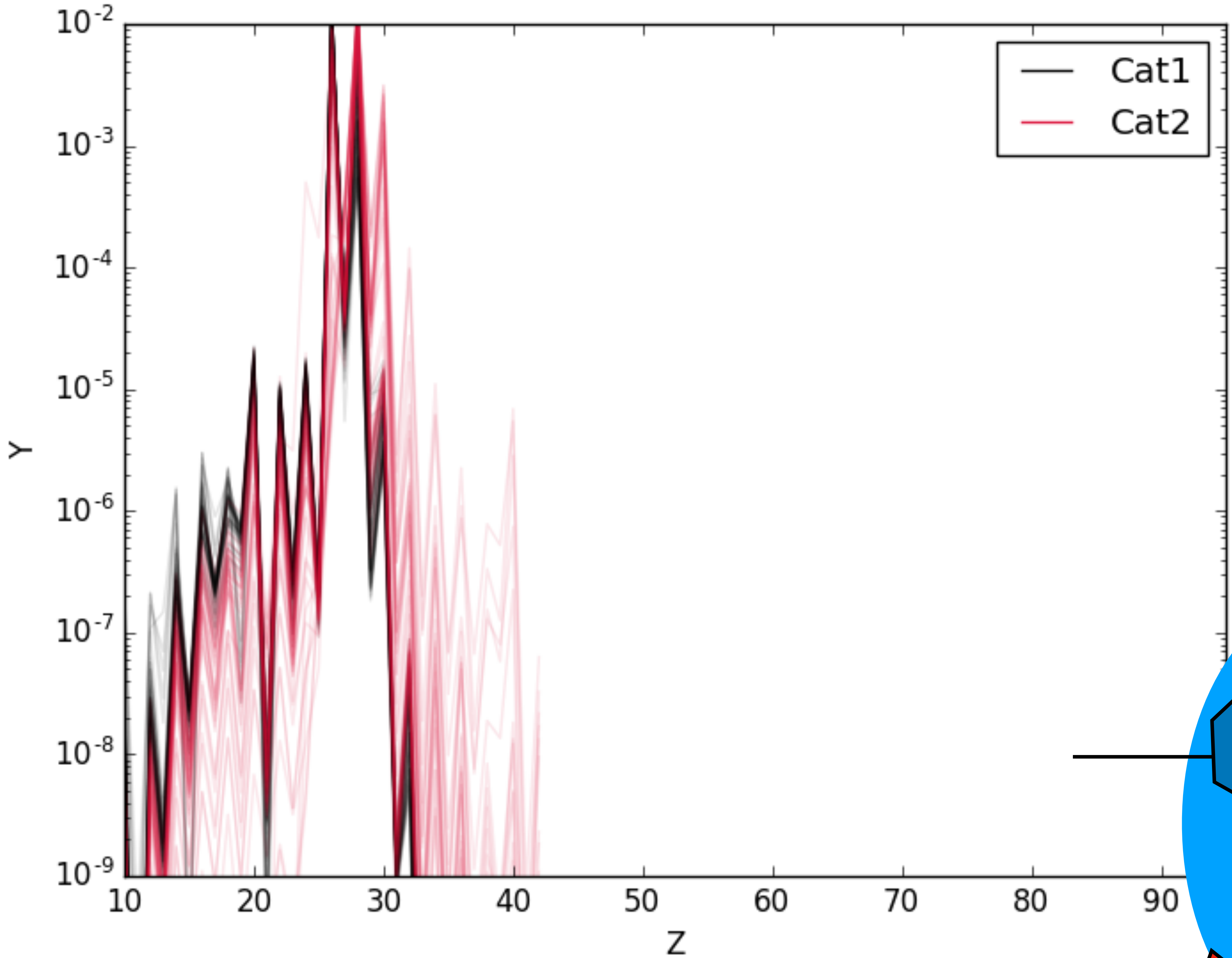


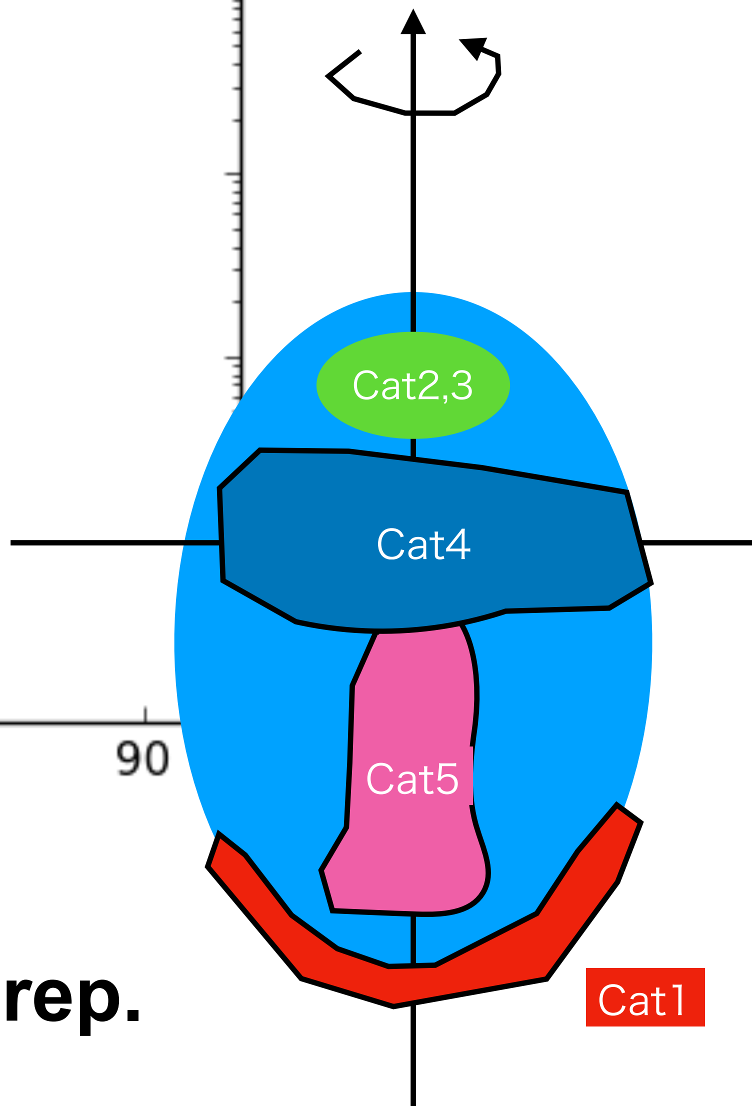
Ejecta distribution





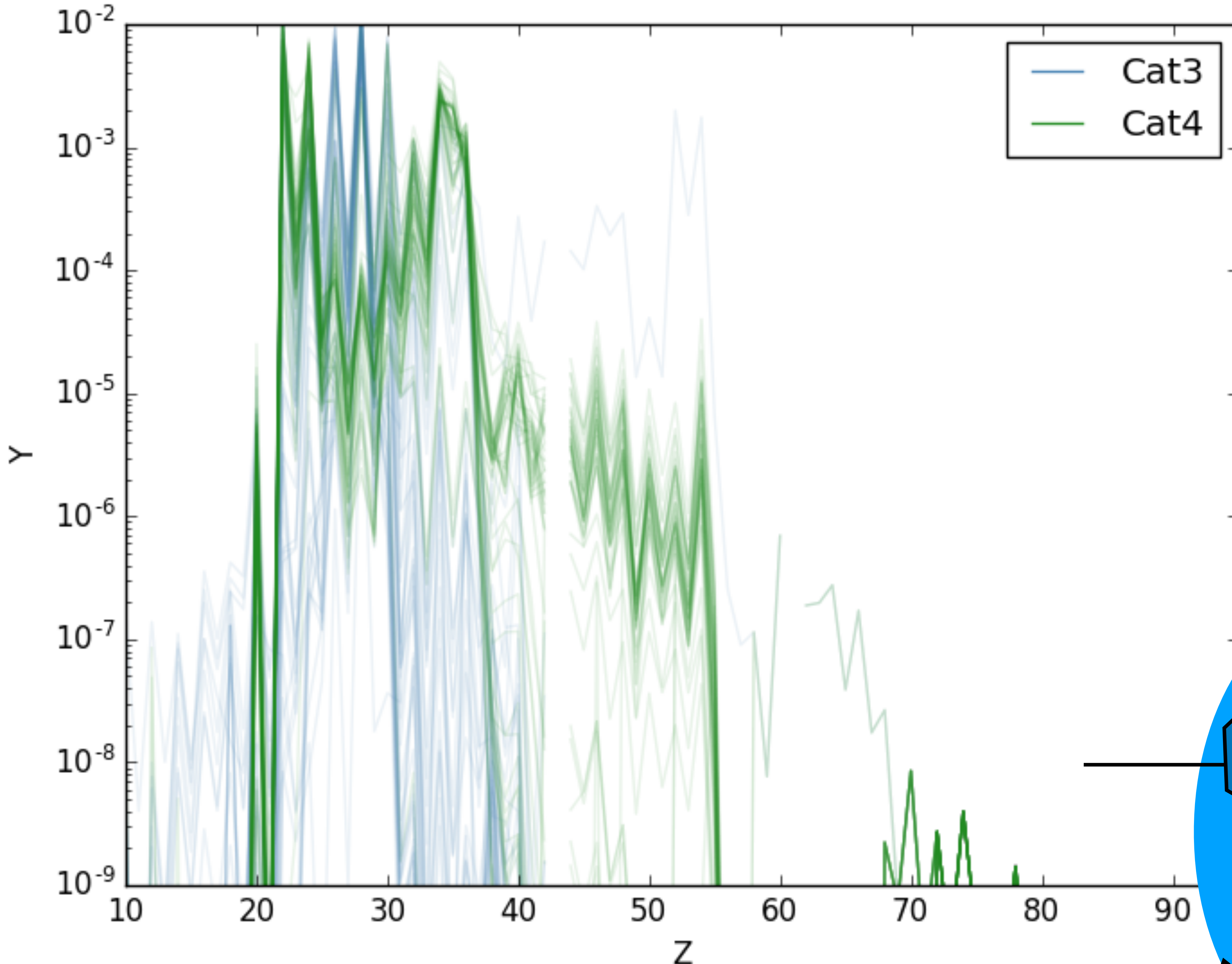
Nucleosynthesis (1st peak)

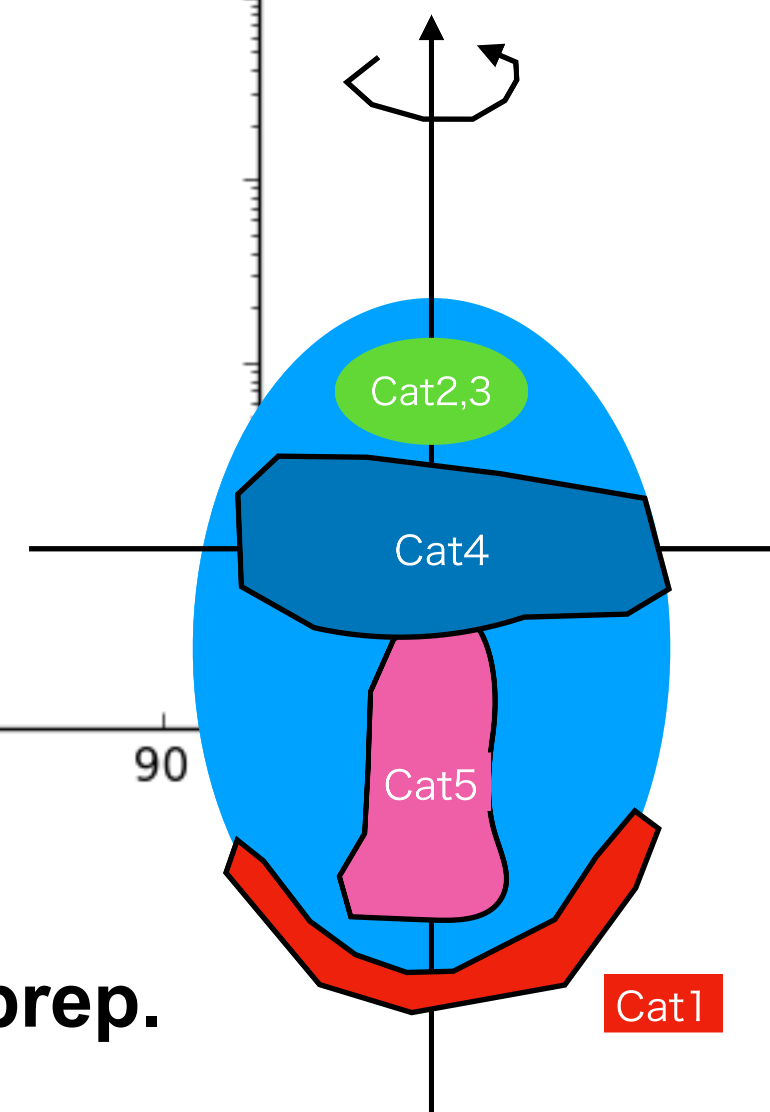




Reichert, Eichler, TK+, in prep.

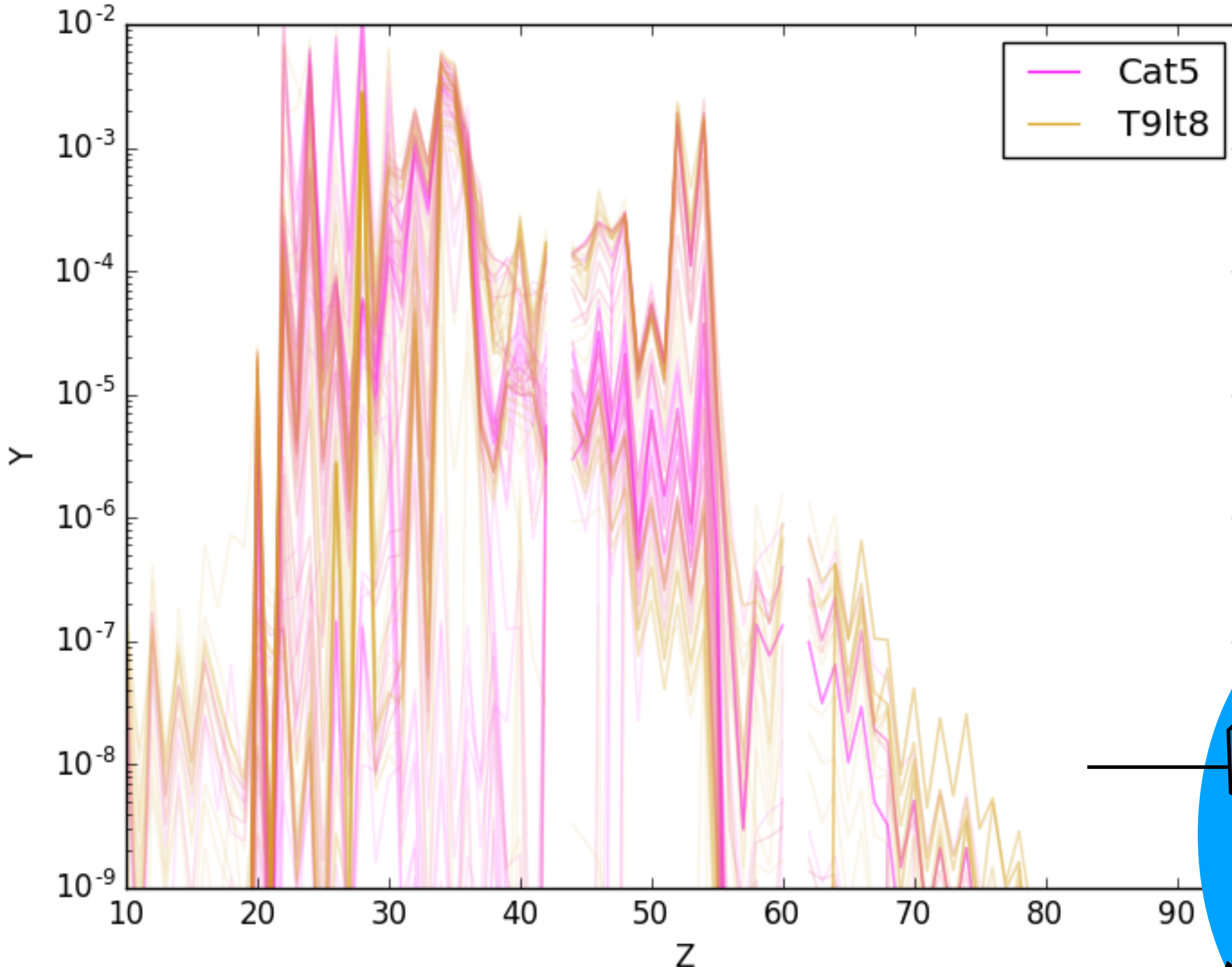
Nucleosynthesis (weak 2nd peak)

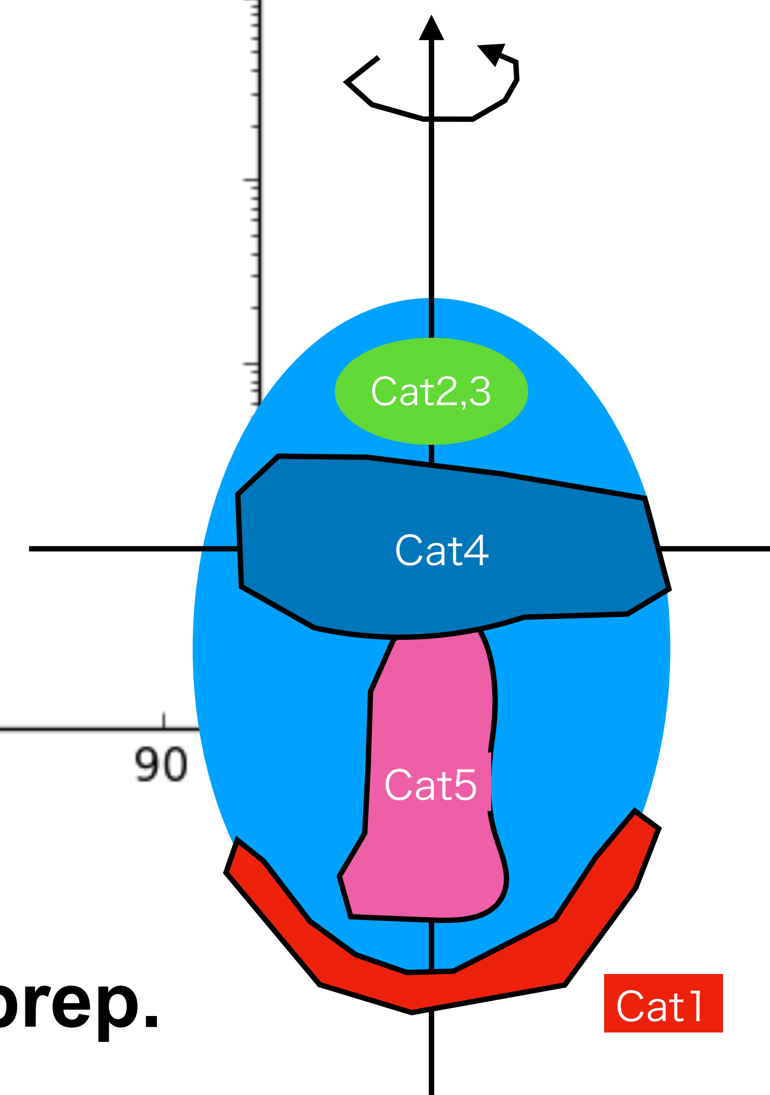




Reichert, Eichler, TK+, in prep.

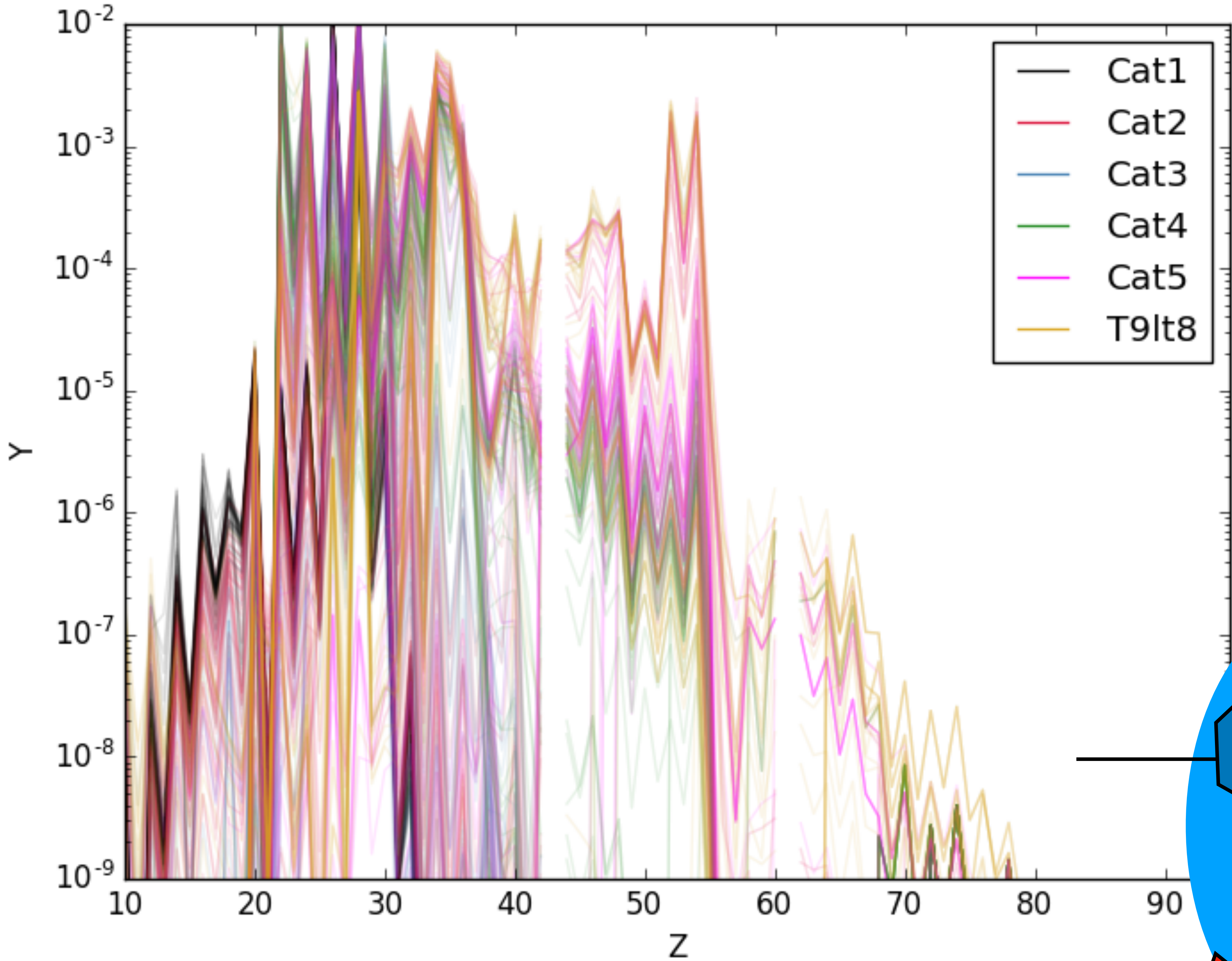
Nucleosynthesis (2nd + weak 3rd peak)

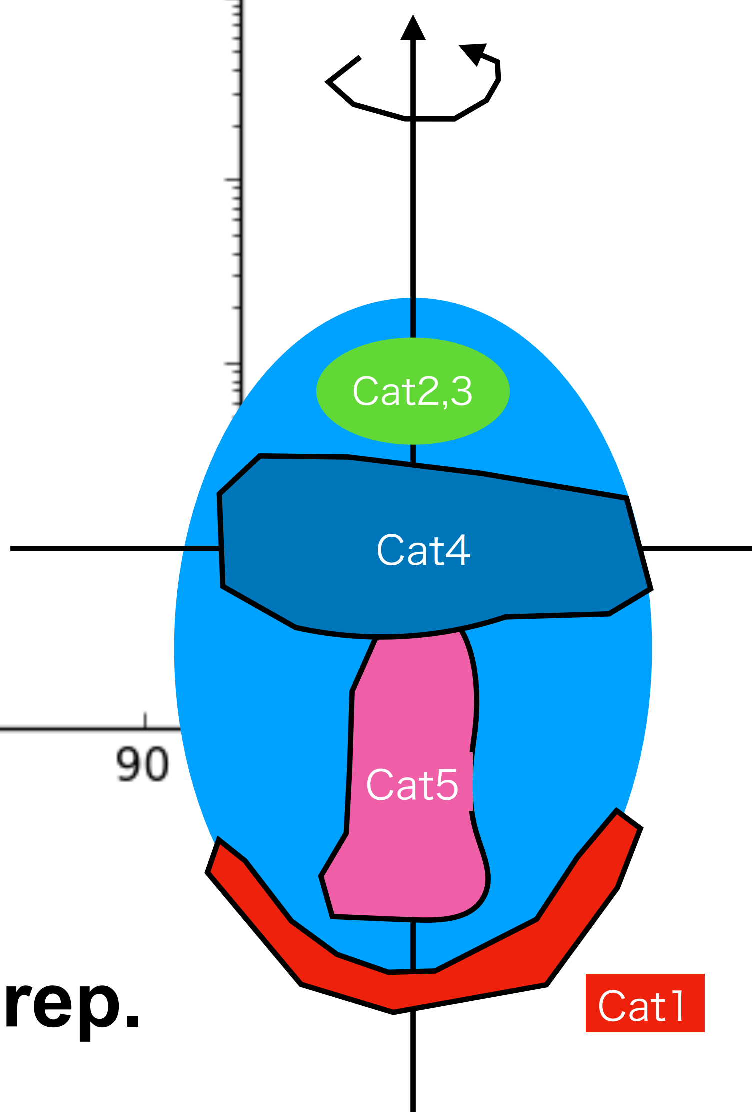




Reichert, Eichler, TK+, in prep.

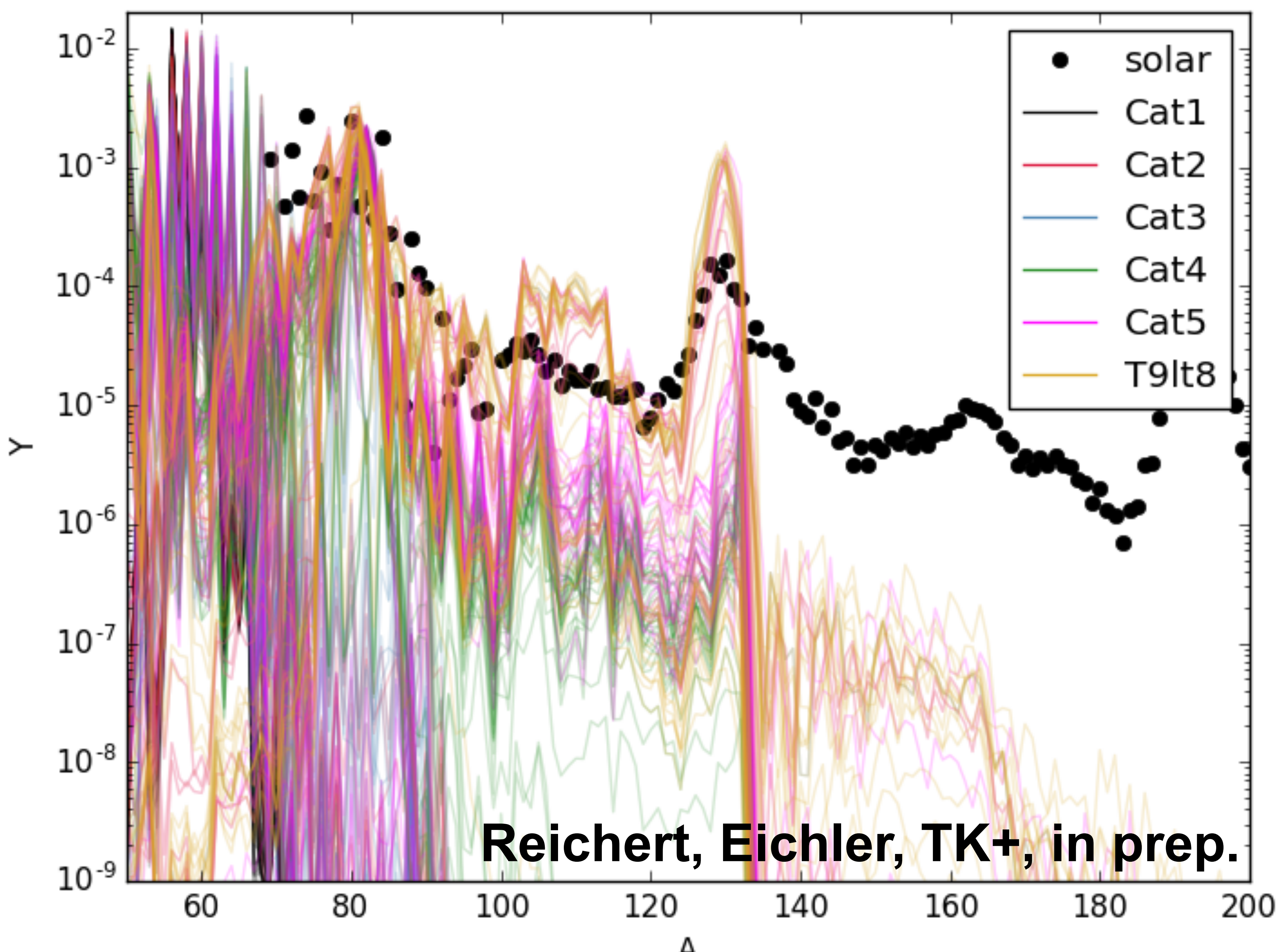
Nucleosynthesis





Reichert, Eichler, TK+, in prep.

Nucleosynthesis (1st peak)



- Not enough to produce 3rd peak
- consistent with Mösta+, ’18

Summary

1. SN simulations are becoming more realistic (full GR, 3D effects, sophisticated neutrino opacities)
   —> more reliable messages from SNe
   (GWs, neutrinos, and heavy elements)
2. In MHD model, the polar/equatorial explosion is boosted mainly by B/neutrinos.
3. 2nd & weak 3rd peak elements can be produced with significant B/neutrino effects depending on the trajectory
4. Temporal modulation in neutrinos reflecting the SASI motions.