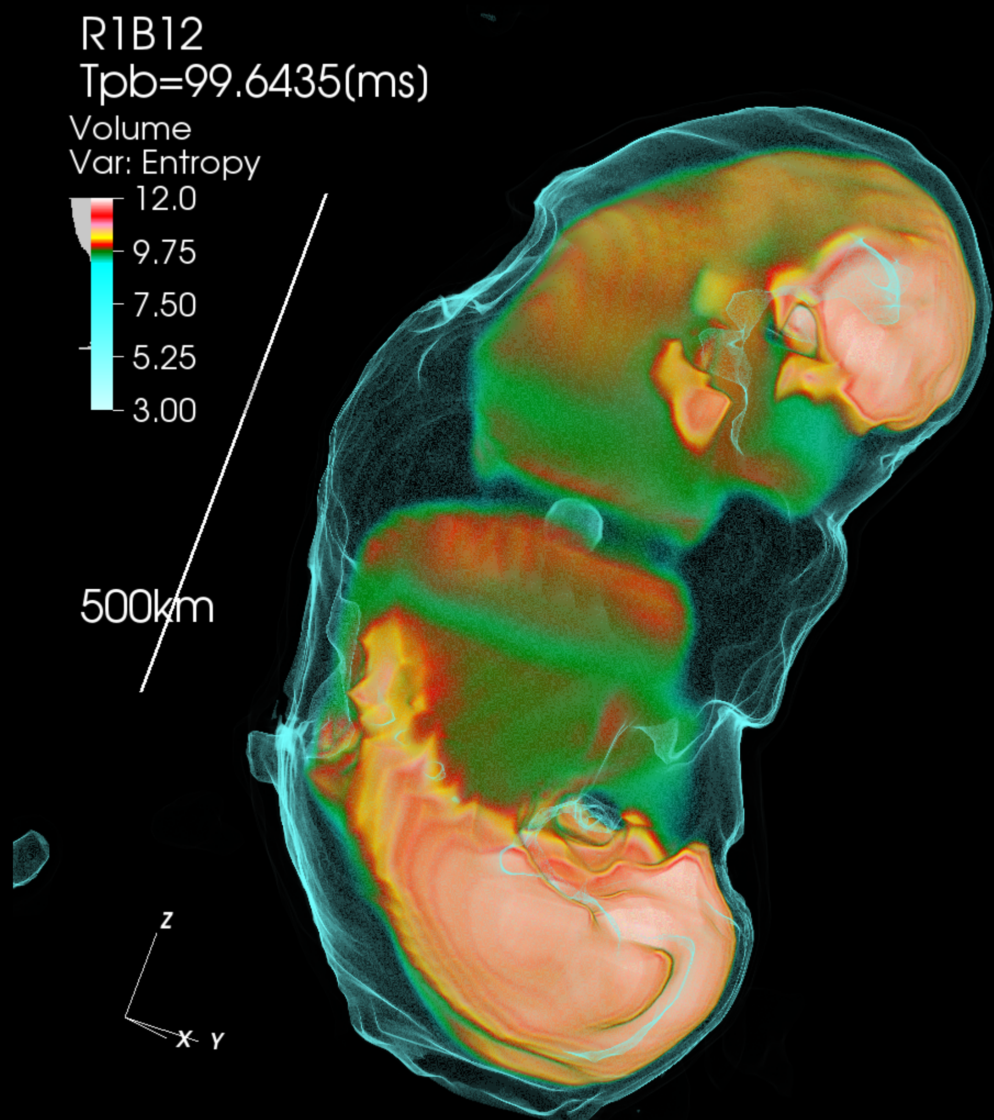
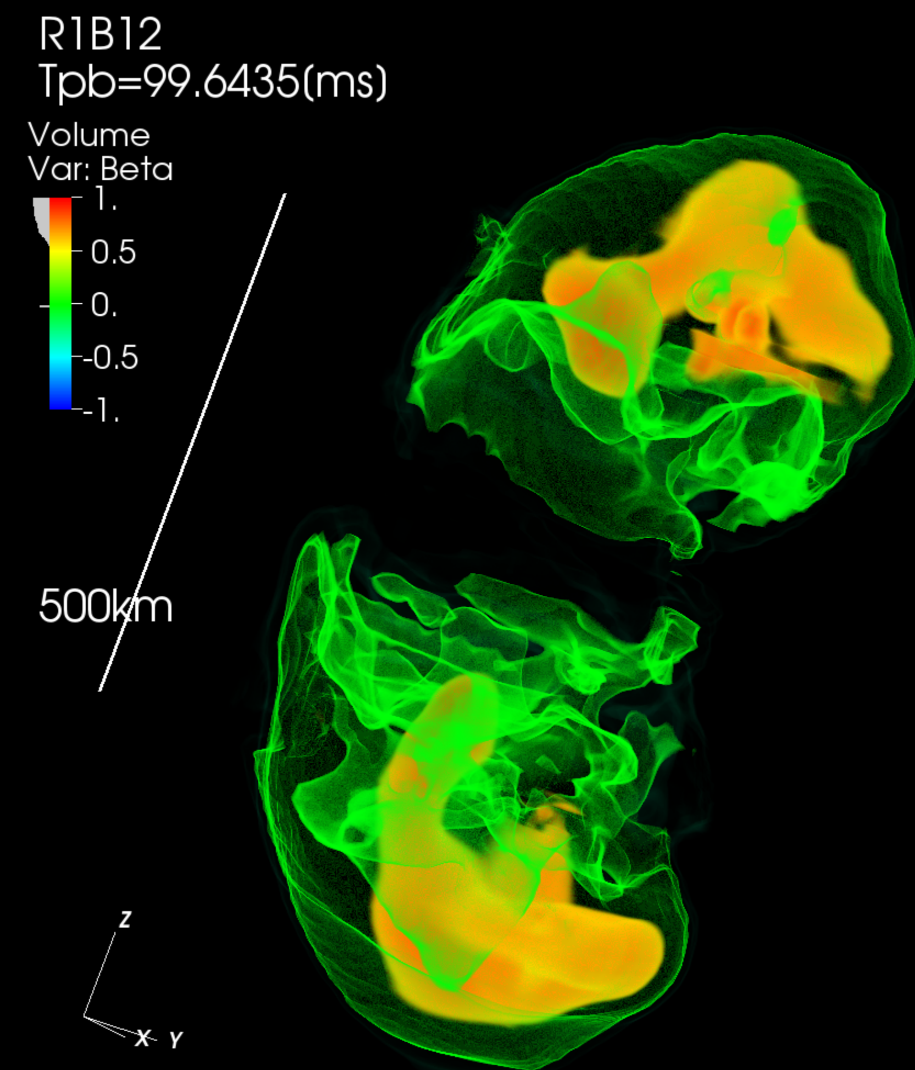
３次元一般相対論磁気流体計算による超新星爆発とニュートリノ放射





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TECHNISCHE UNIVERSITÄT DARMSTADT

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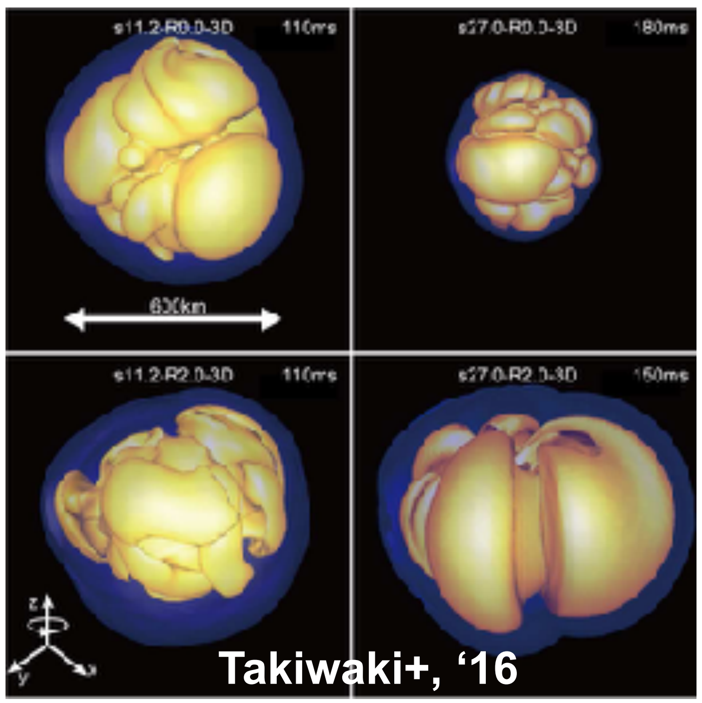
第６回超新星ニュートリノ研究会、東大柏キャンパス, 6-7/1/2020

(1)The standard explosion mechanism

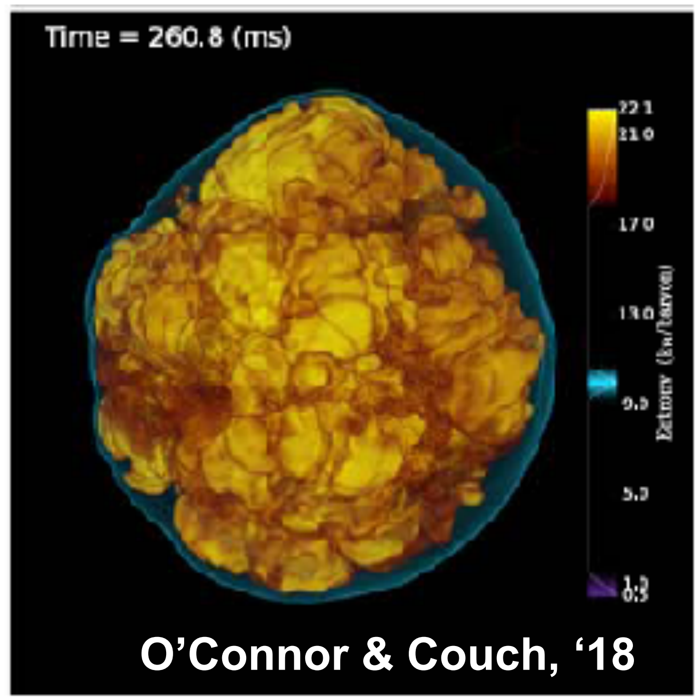
Neutrino driven explosion,

Colgate&White'66, Bethe&Wilson'85

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



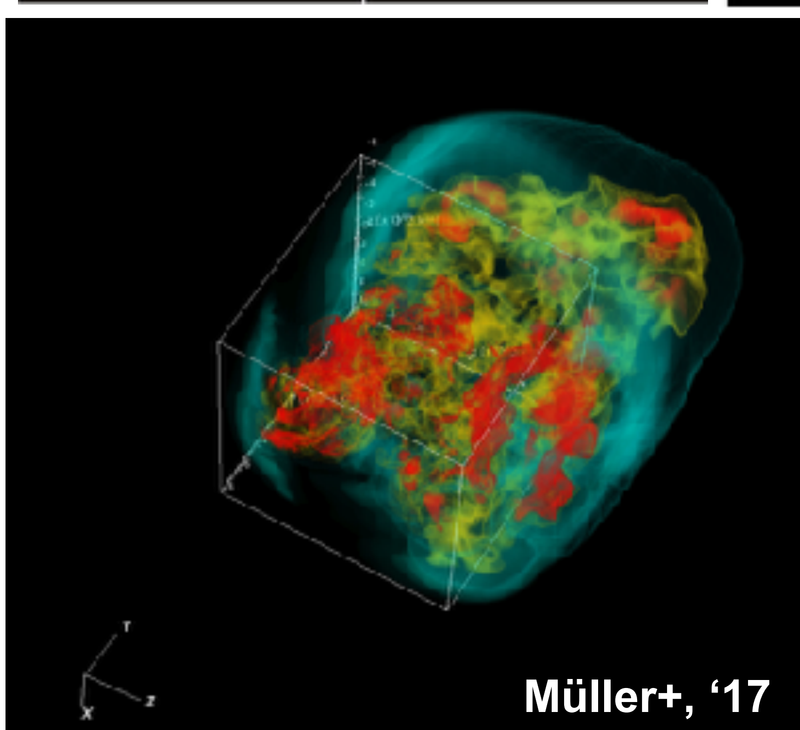
Takiwaki+, '16



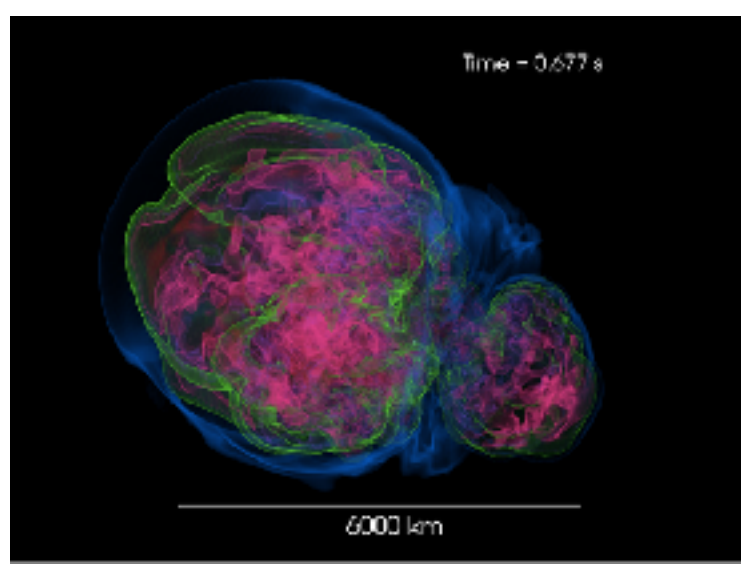
O'Connor & Couch, '18

~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,

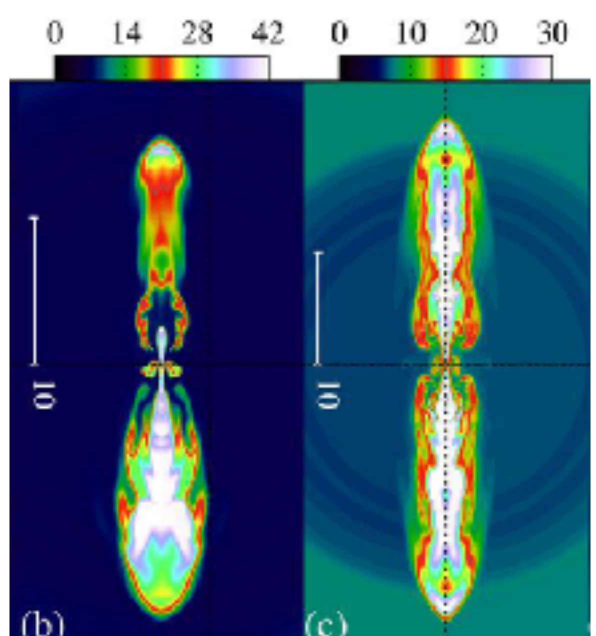
Colgate&White'66, Bethe&Wilson'85
For reviews, Janka'12, Kotake+,'12, Burrows+,'13

(2)If the magnetic field is strong enough
MHD explosion,

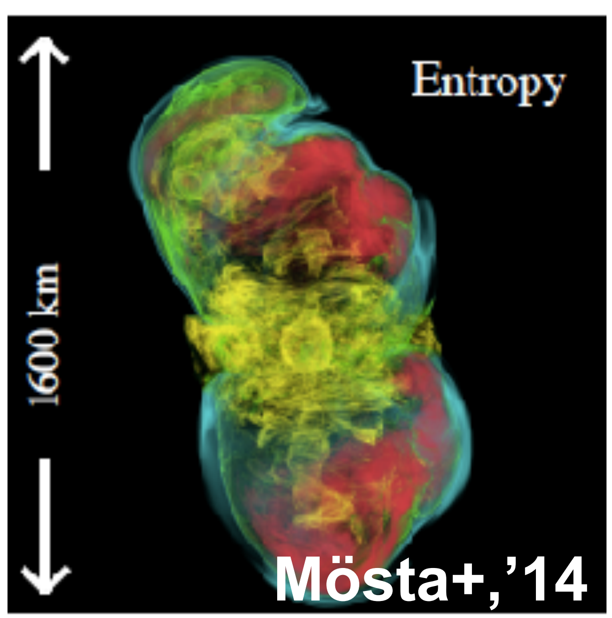
- Angular momentum transfer
- Mass ejection by B pressure
- efficient neutrino heating

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

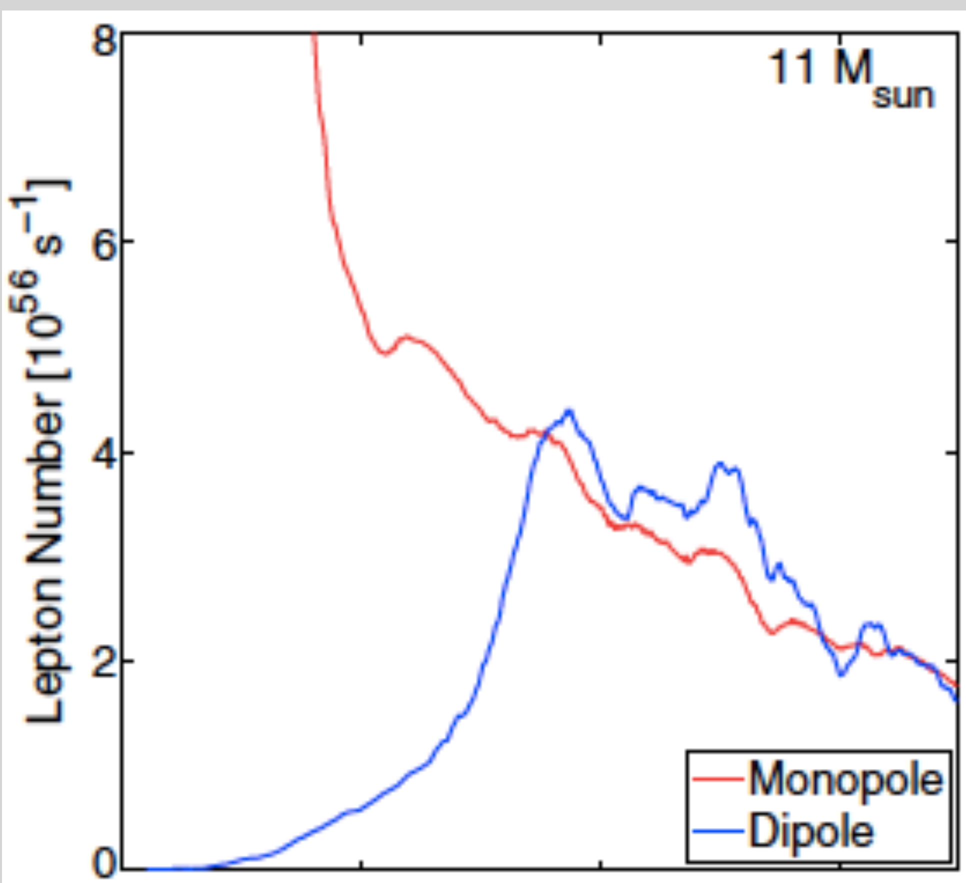


Things still to be explored
- resolution problem->MRI?
- 2D artefacts ->3D non-axisymmetries
- microphysics->neutrino effects

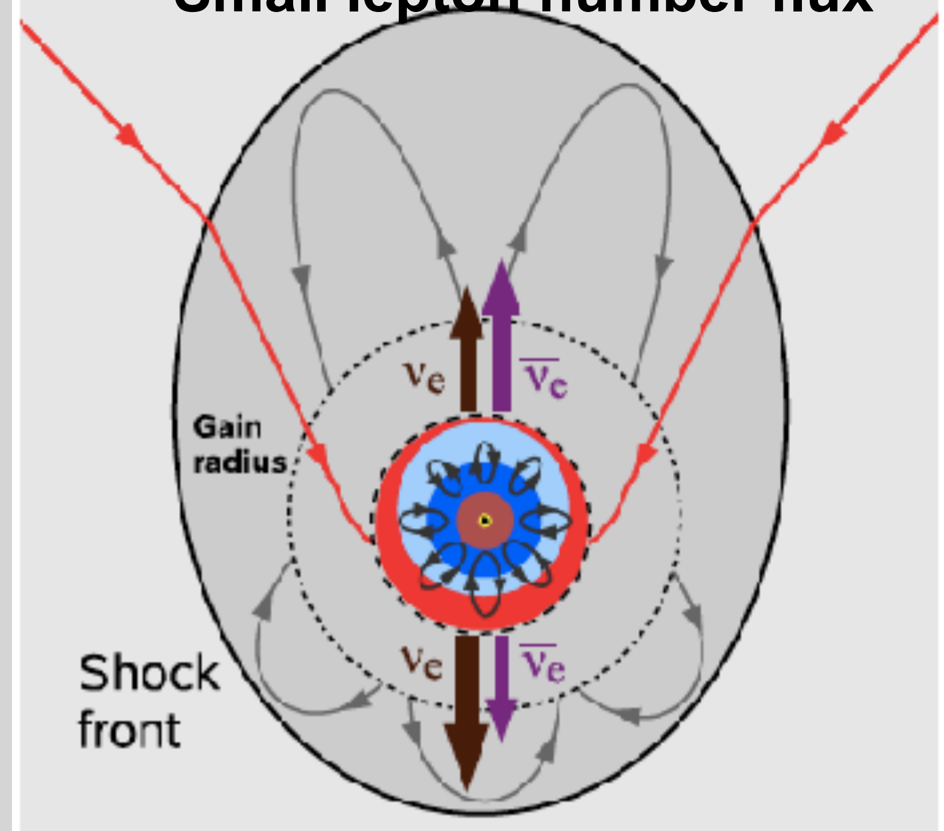
Motivations

- How do these different explosion mechanisms imprint their messages into neutrino signals?
- Does LESA appear ?
- How do neutrinos affect on the nucleosynthesis?

Lepton emission self-sustained asymmetry (LESA), Tamborra+2014



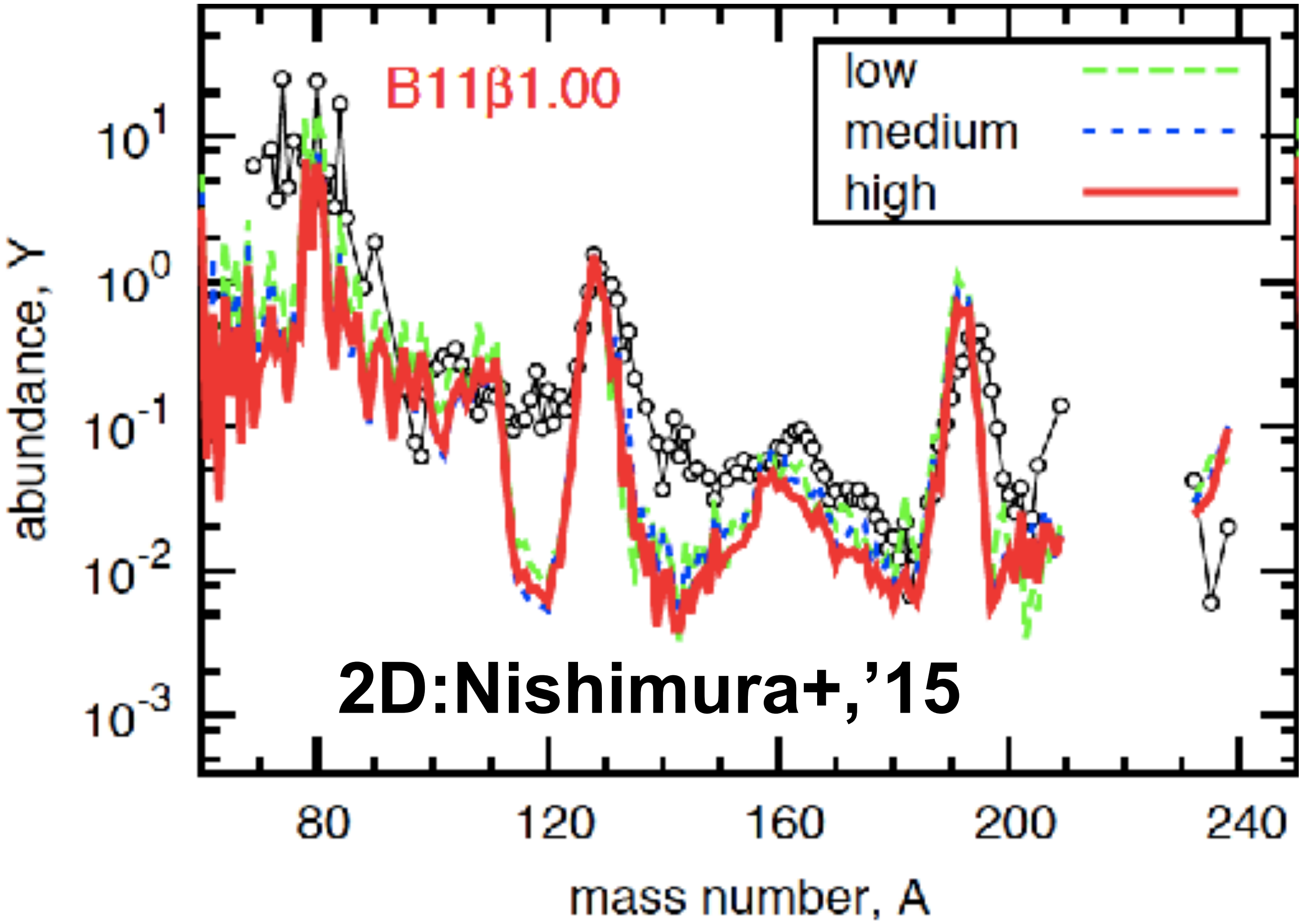
Small lepton number flux

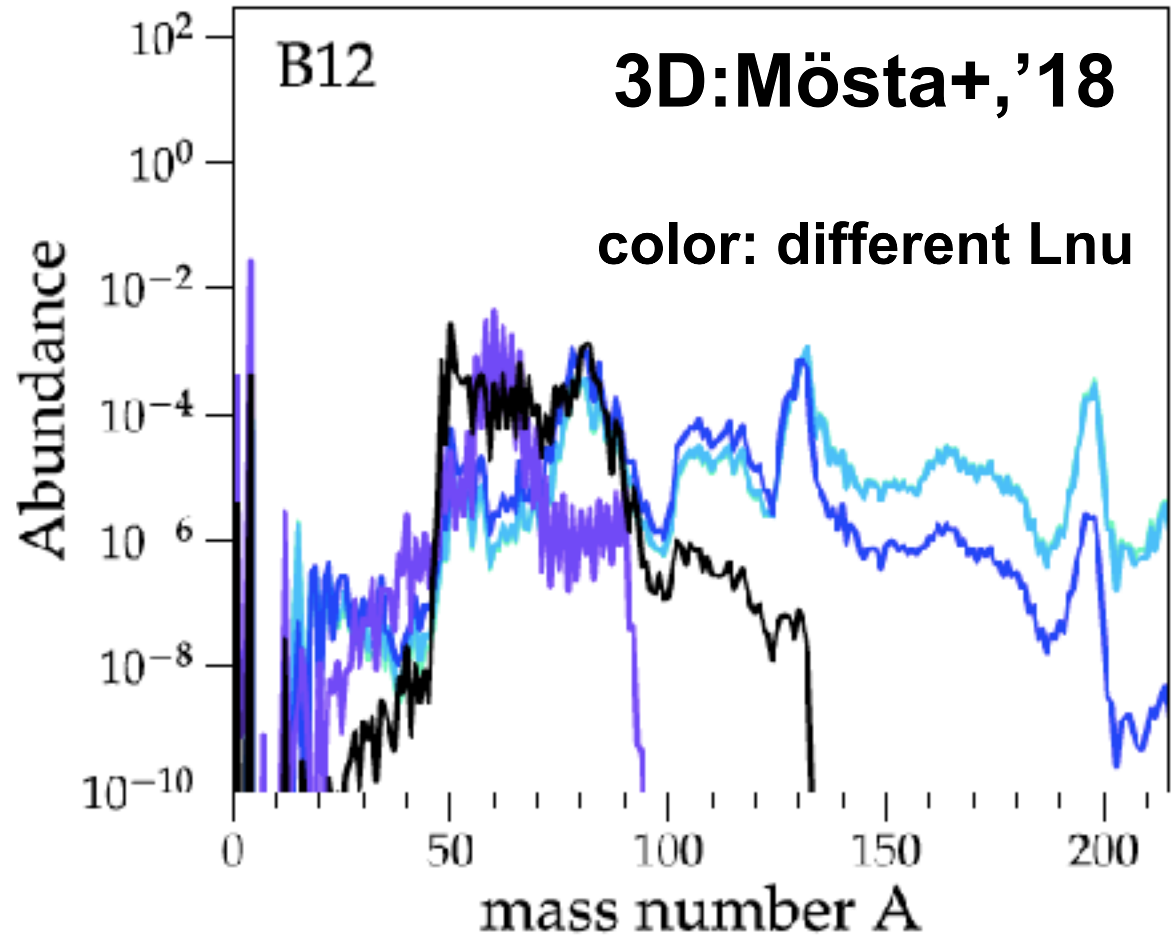


Large lepton number flux

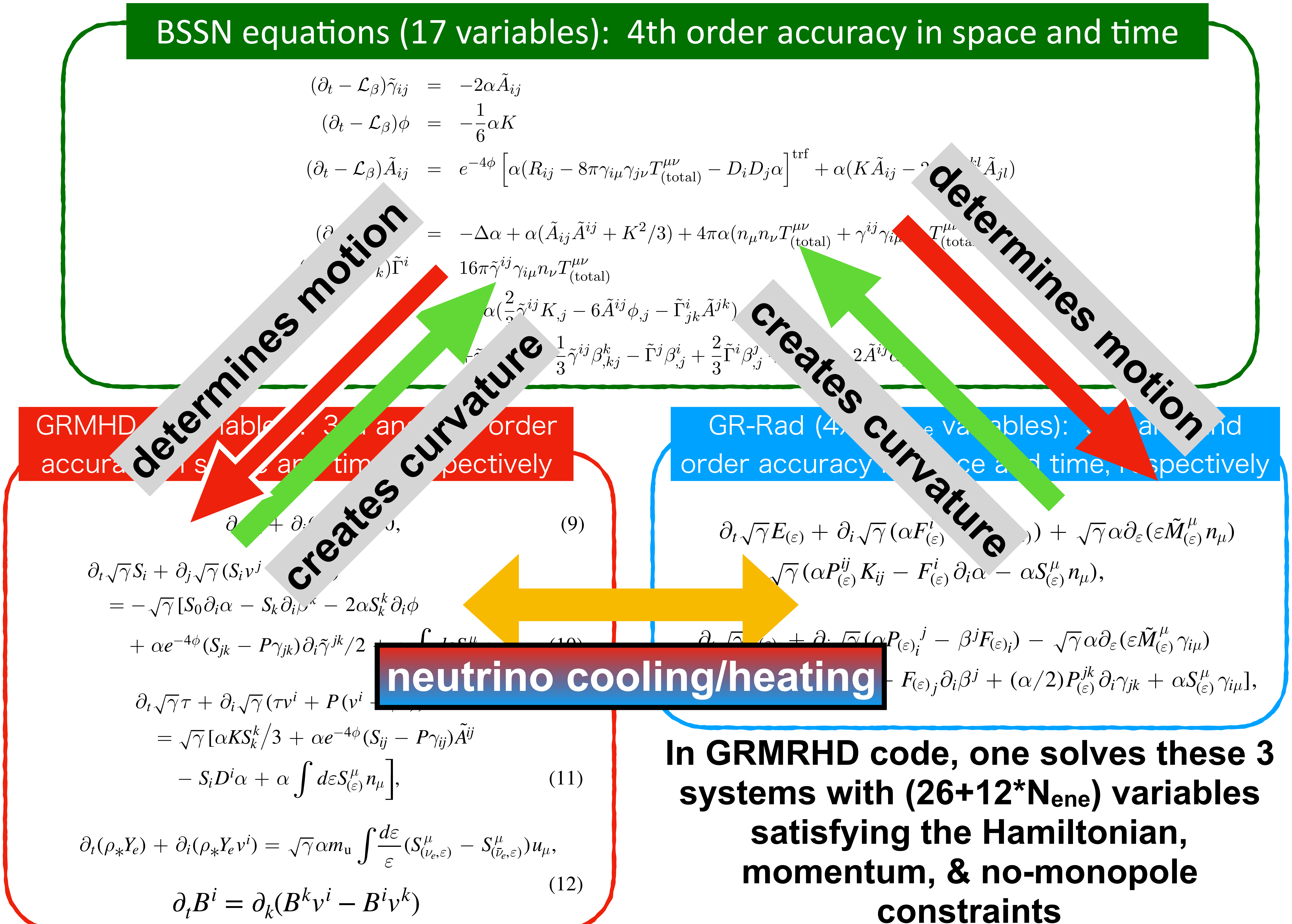
Numerical (RbR) artefact?

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 & 3D effects might significantly influence on the ejecta Ye (but still-to-be-explored)



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

The basic equations for neutrino transport

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

Shibata+'11, TK+'16

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

$$\partial_t \sqrt{\gamma} E_{(\varepsilon)} + \overbrace{\partial_i \sqrt{\gamma} (\alpha F^i_{(\varepsilon)} - \beta^i E_{(\varepsilon)})}^{\text{advection}} + \overbrace{\sqrt{\gamma} \alpha \partial_\varepsilon (\varepsilon \tilde{M}^\mu_{(\varepsilon)} n_\mu)}^{\text{gravitational redshift/Doppler}}$$
$$= \sqrt{\gamma} (\underbrace{\alpha P^{ij}_{(\varepsilon)} K_{ij} - F^i_{(\varepsilon)} \partial_i \alpha}_{\text{gravitational source}} - \underbrace{\alpha S^\mu_{(\varepsilon)} n_\mu}_{\text{neutrino-matter interaction}}), \qquad (4)$$

and

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

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 ($1<\varepsilon<300$MeV)

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

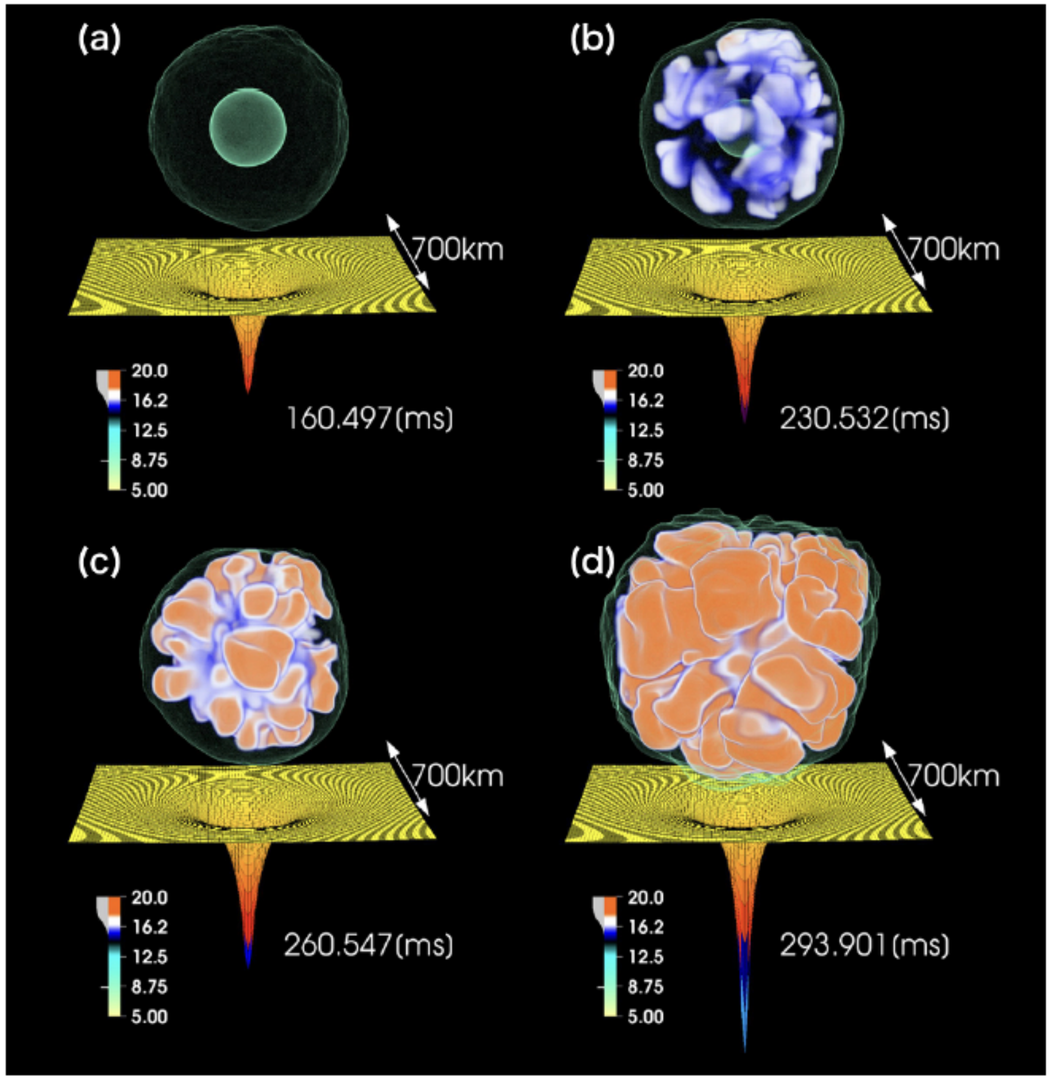
$$\Omega = \Omega_0 \frac{R_0^2}{\varpi^2 + R_0^2} \qquad \Omega_0 = 1(\mathrm{rad/s}) \qquad (\beta_{\mathrm{b}} \sim 1\%)$$

- 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

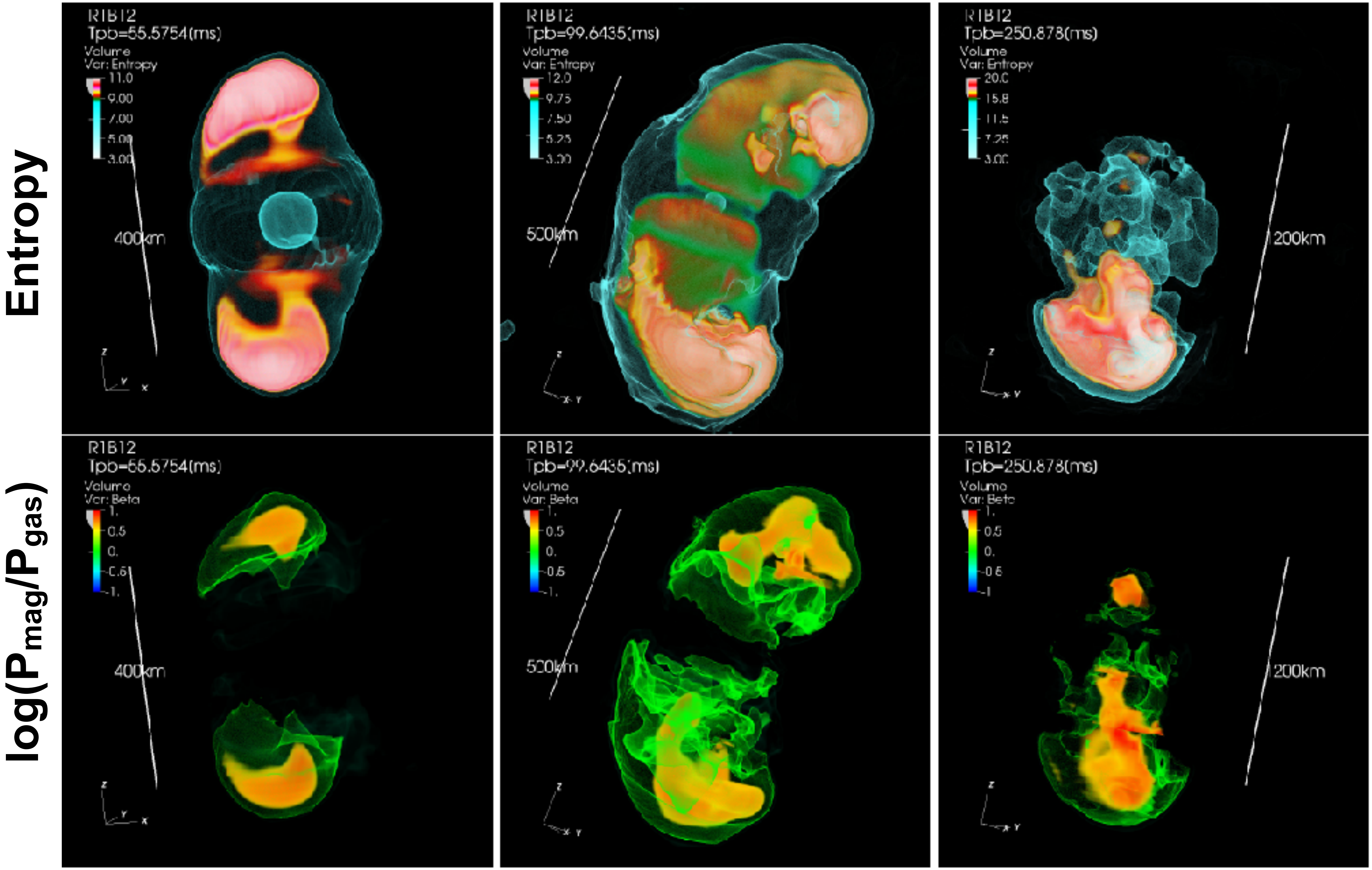
- XC50 @ NAOJ



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

Rotating magnetized model (R1B12)

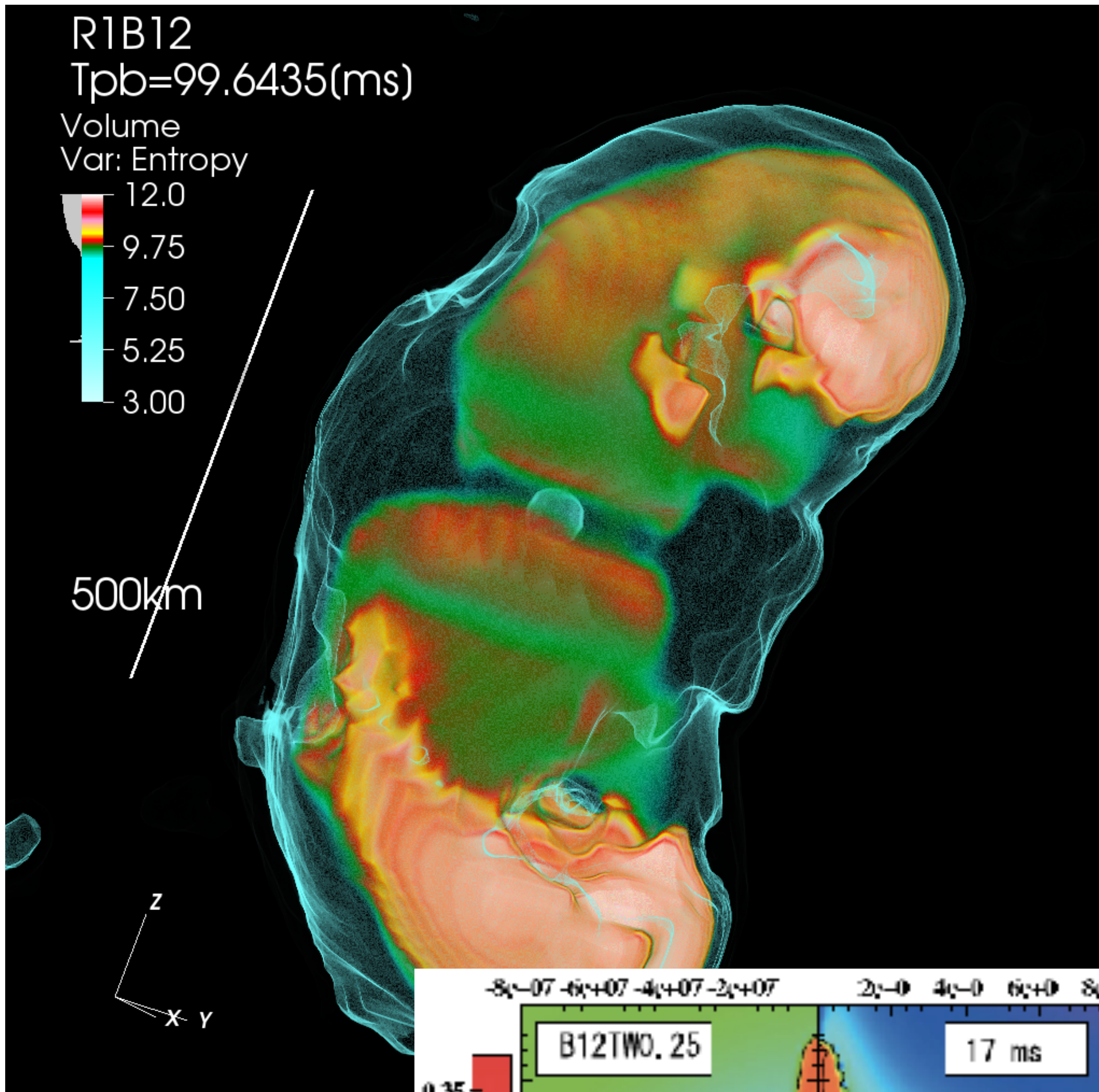
Tpb=55ms **100ms** **250ms**

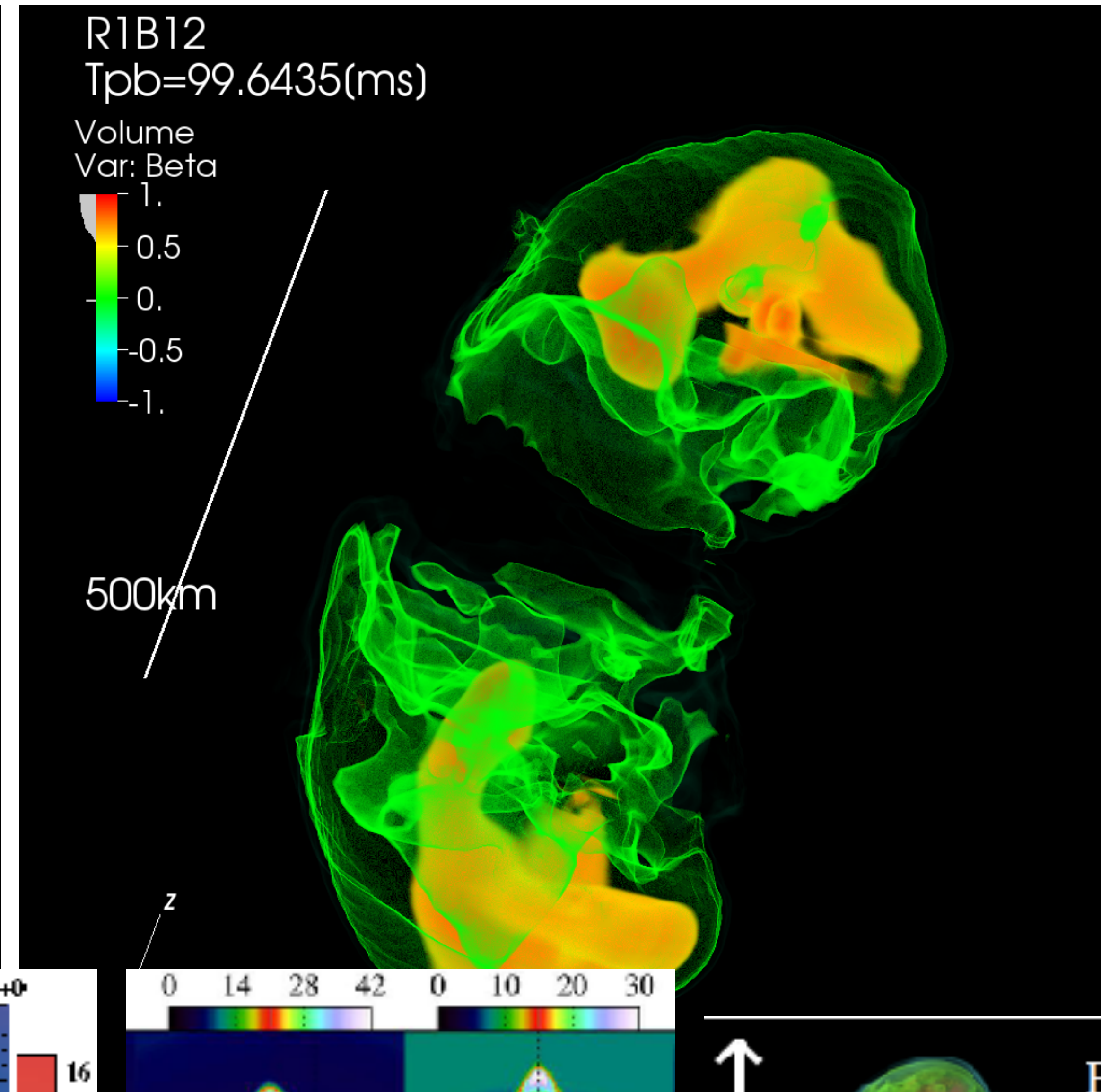


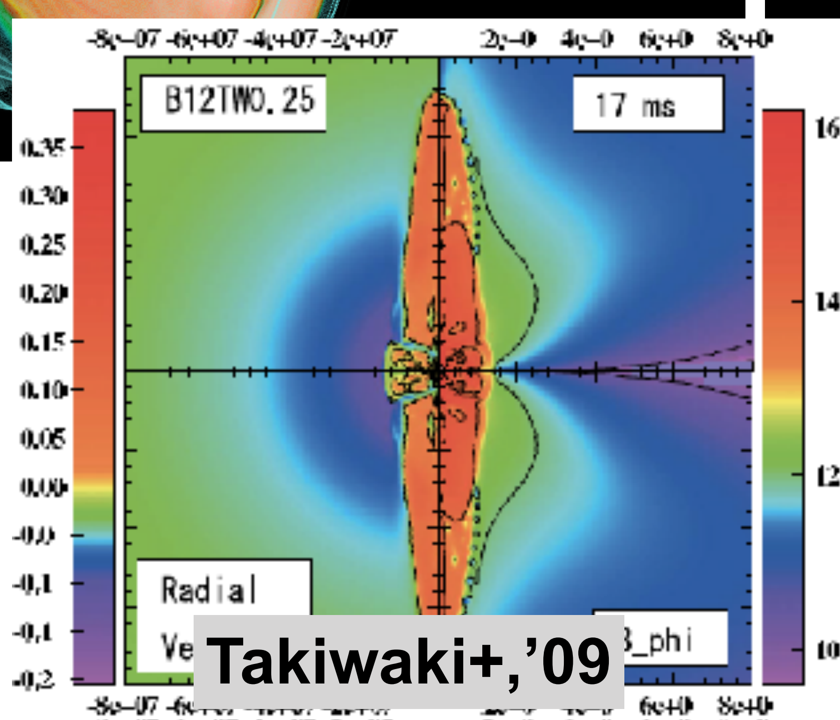
2D-3D comparison

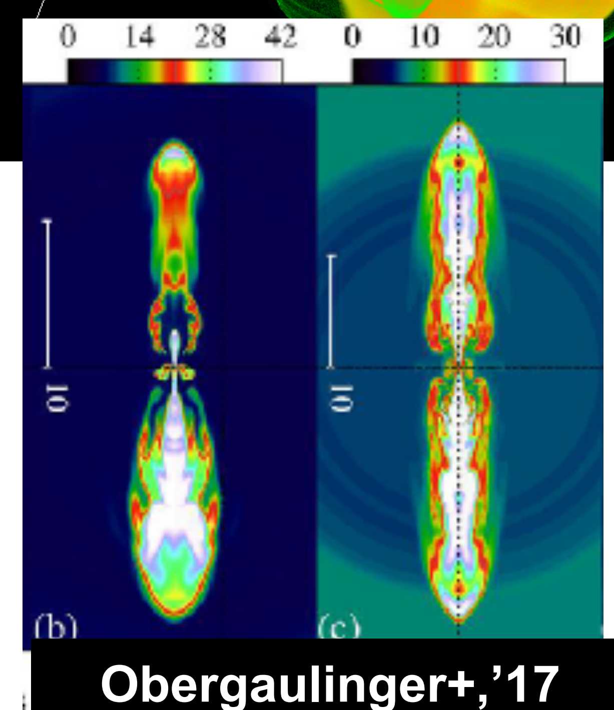
Entropy

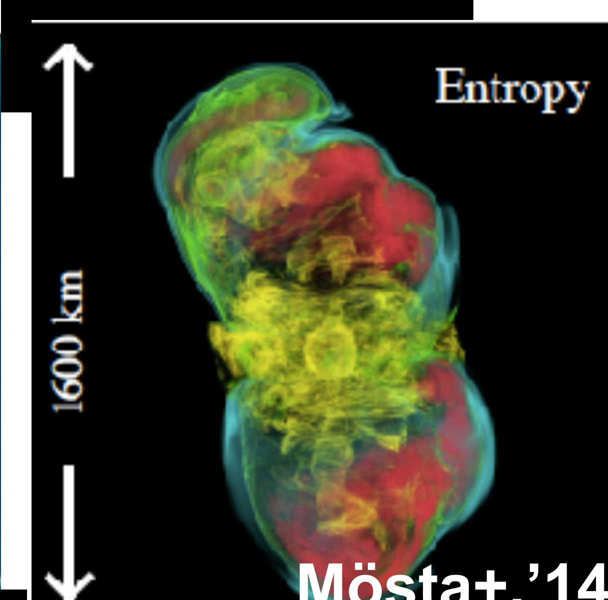
$\log(P_{mag}/P_{gas})$



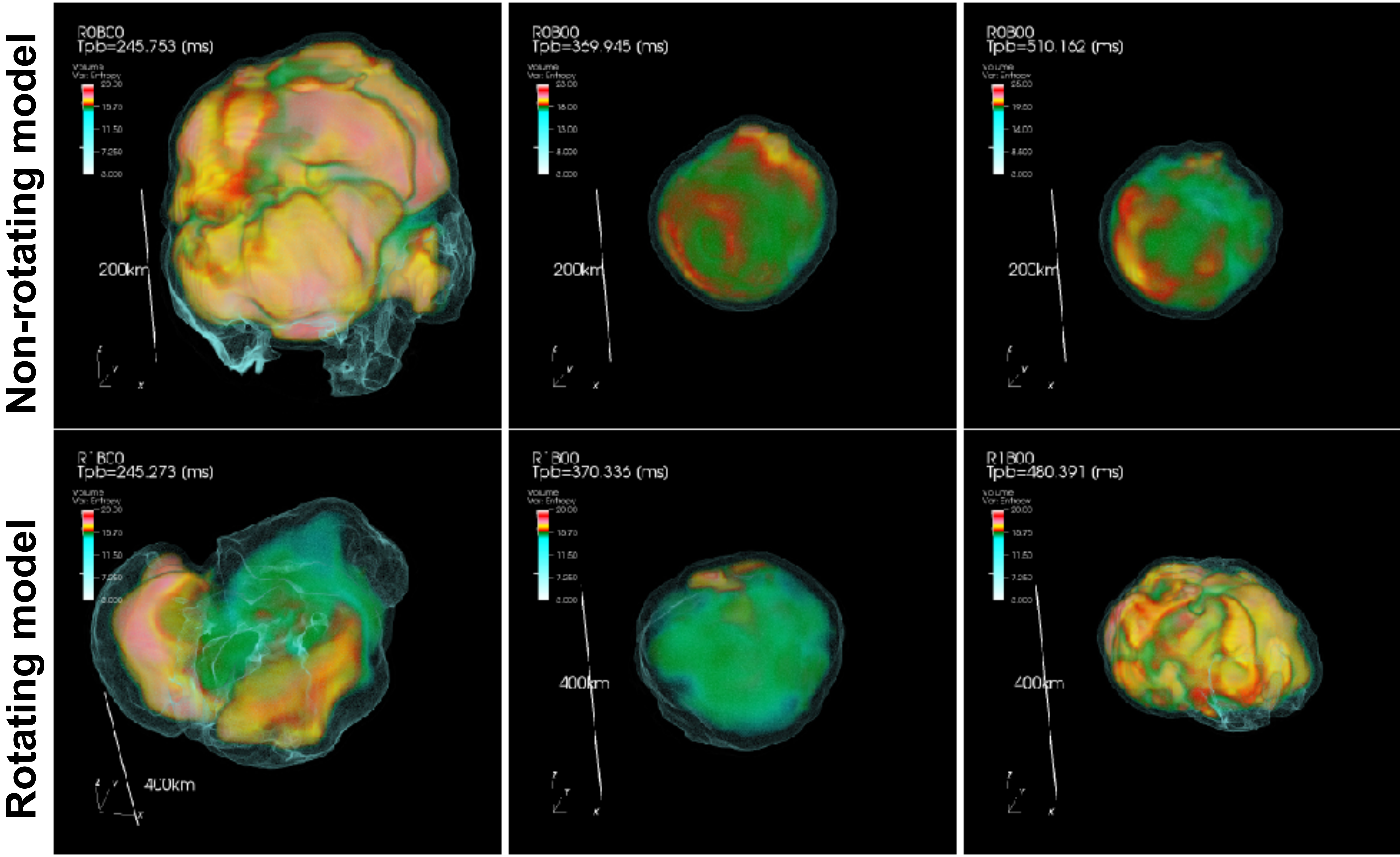








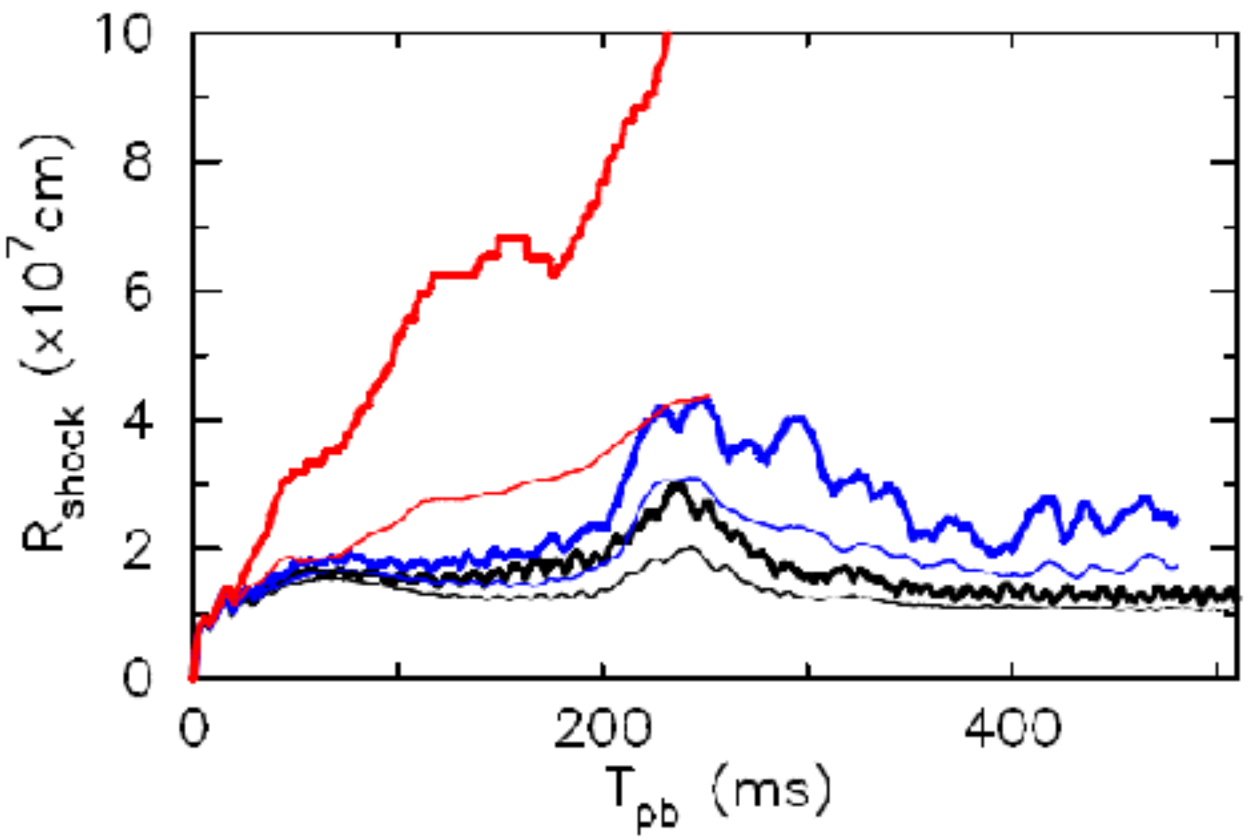
Non-magnetized models



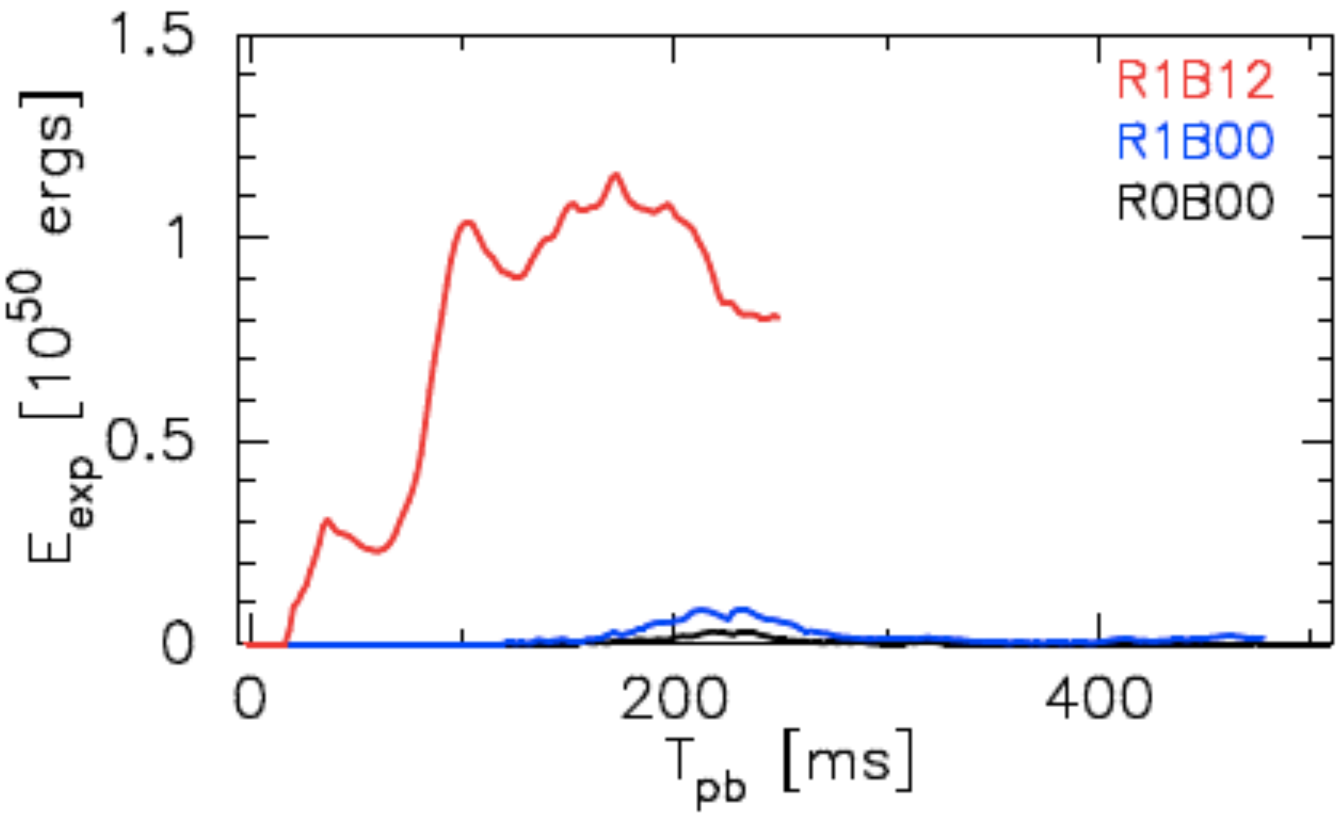
m=1 spiral SASI appears in R1B00 leading to the characteristic neutrino signals=>lighthouse effect (Takiwaki & Kotake,'18)

Energetics

Shock evolution

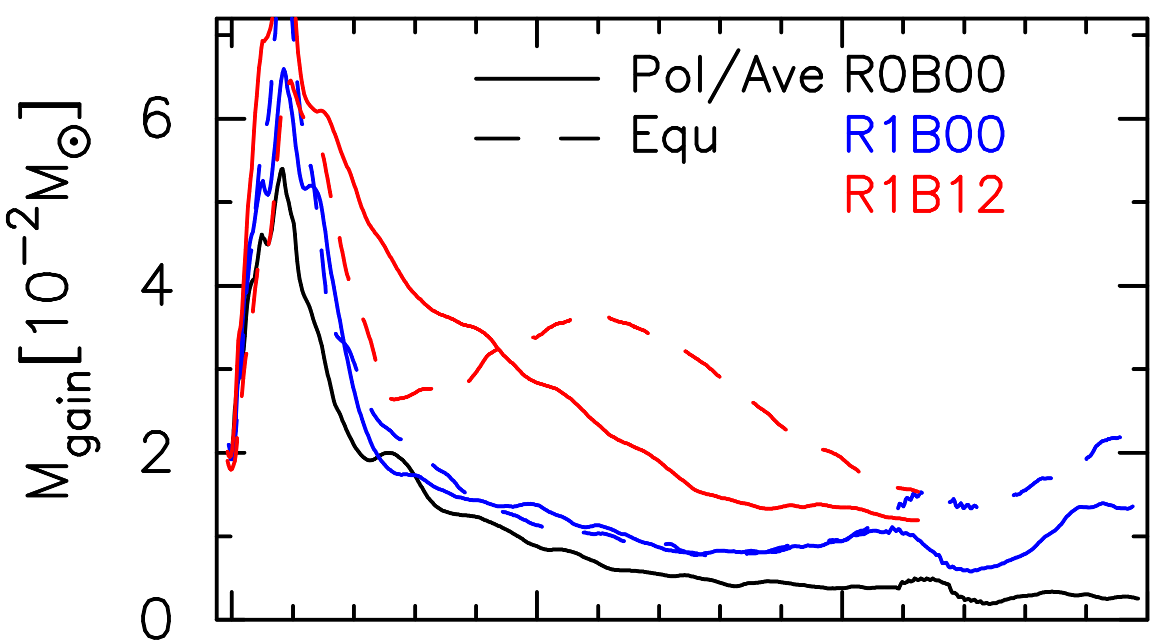


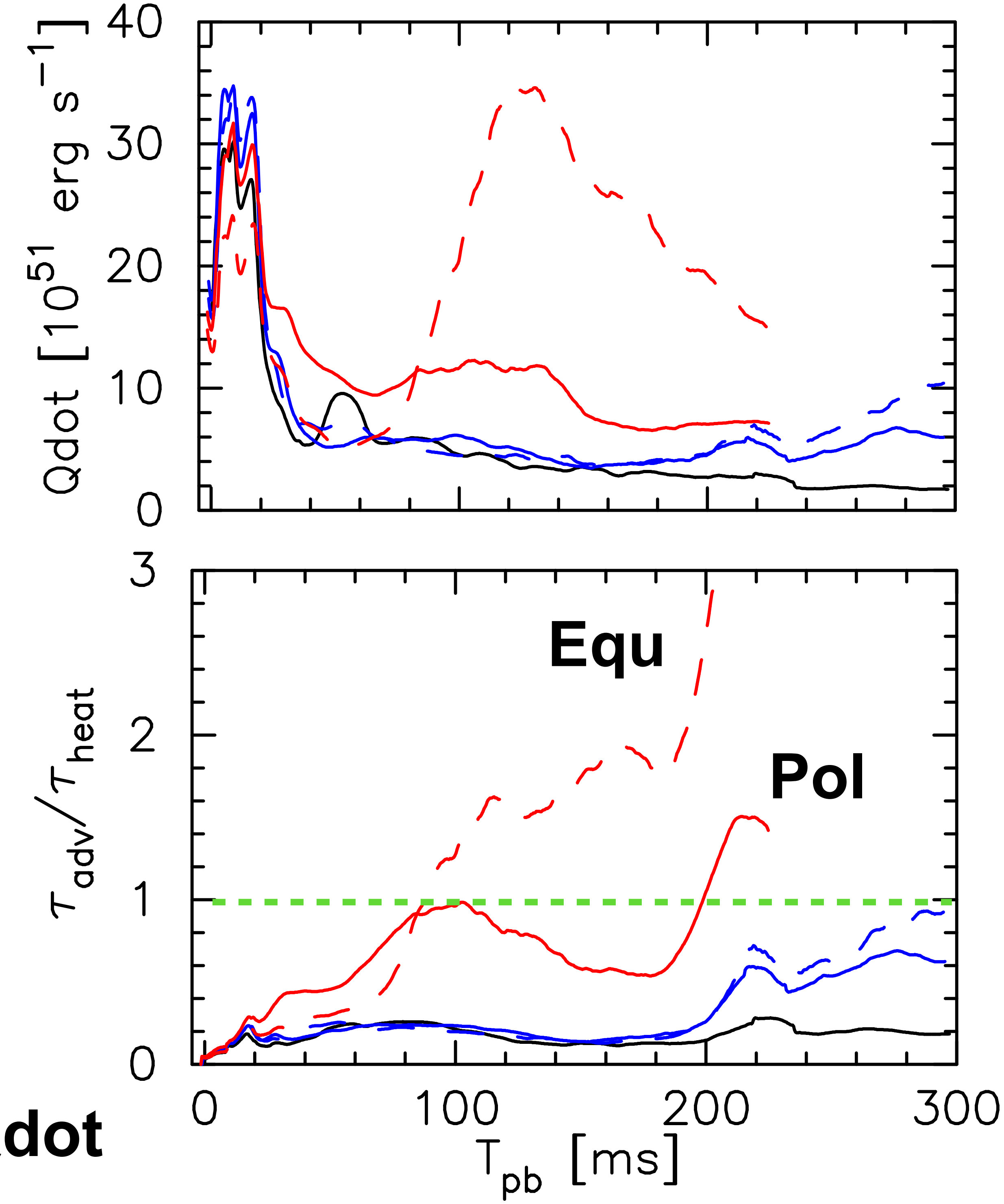
Diagnostic energy

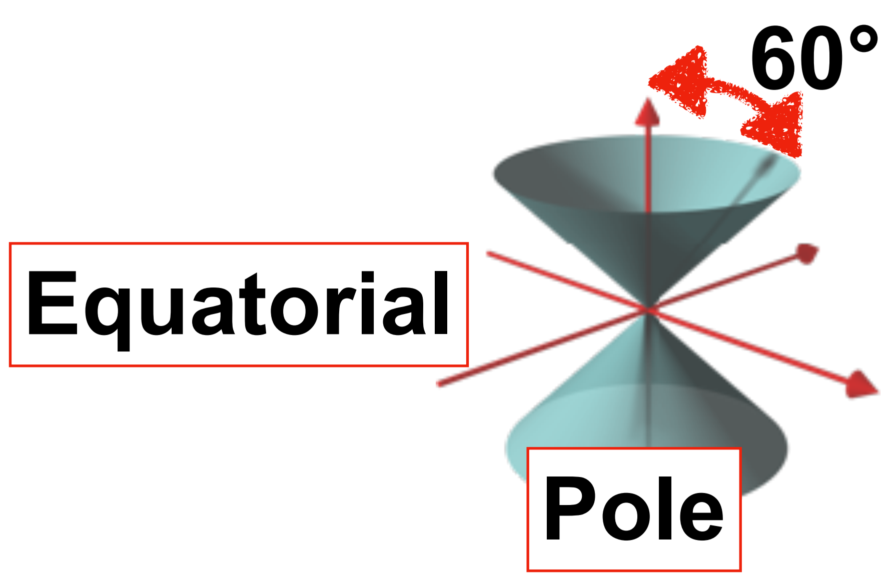


Rotation and Magnetic fields facilitate the explosion

Neutrino heated? or magneto-driven?



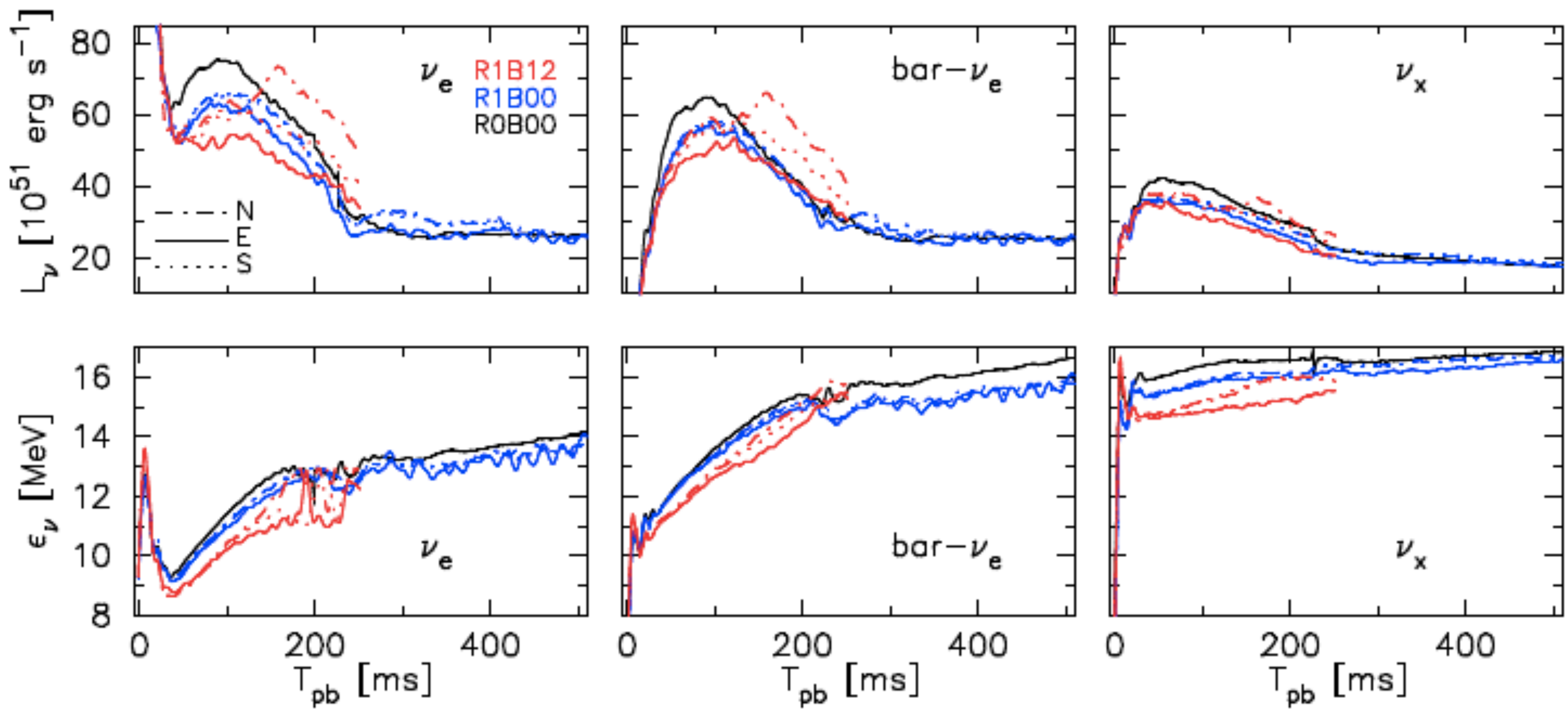




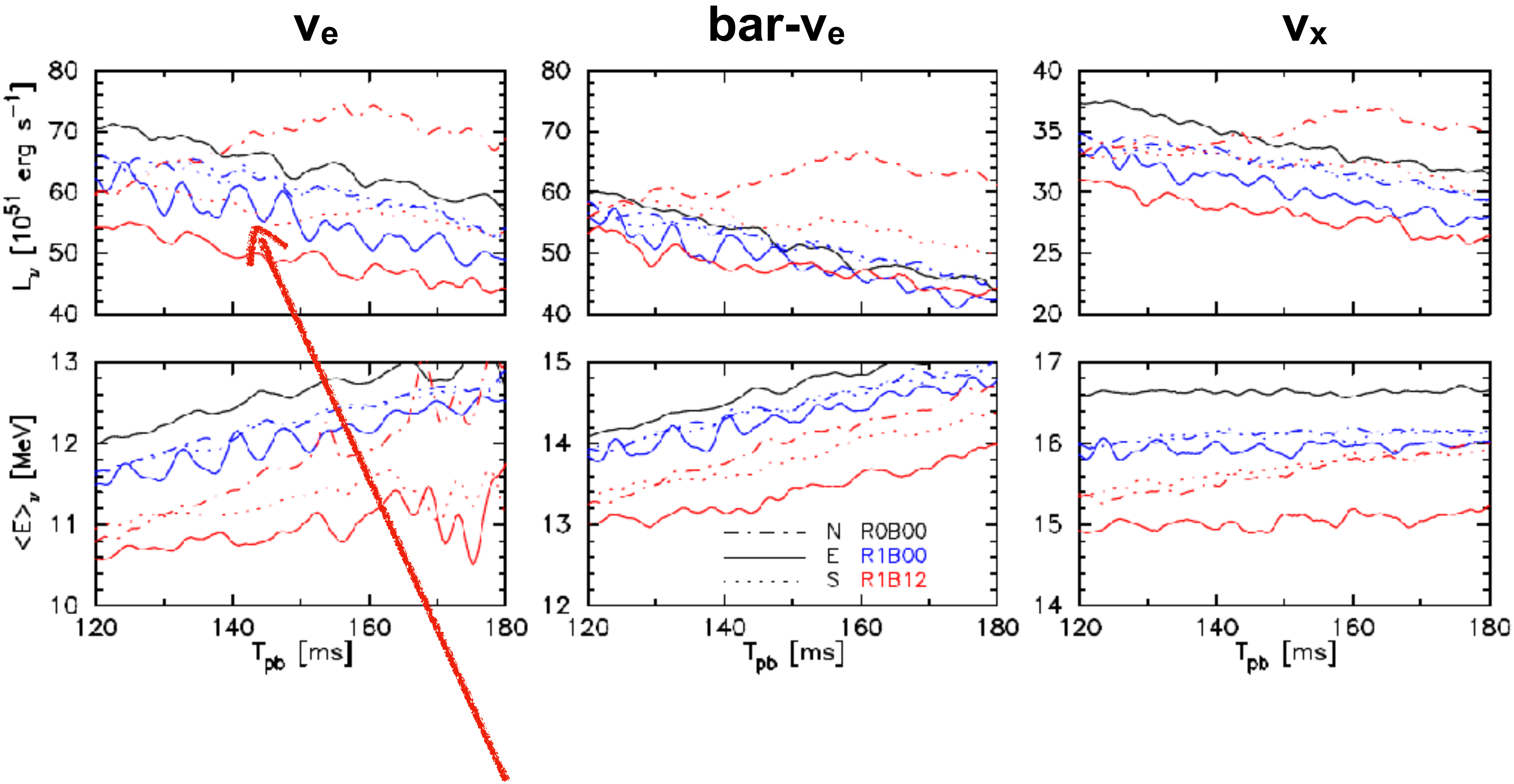
- **Rotation & B increase M_{gain} and Qdot**
- **For MHD model**
  - **Equatorial expansion is supported by ν-heating** $\tau_{adv}/\tau_{heat} > 1$
  - **Prompt bipolar outflow is due to magnetic field** $\tau_{adv}/\tau_{heat} < 1$
  - **Later by ν-heating** $\tau_{adv}/\tau_{heat} > 1$

Neutrino emission (model dependence)

ν_e | bar-ν_e | ν_x

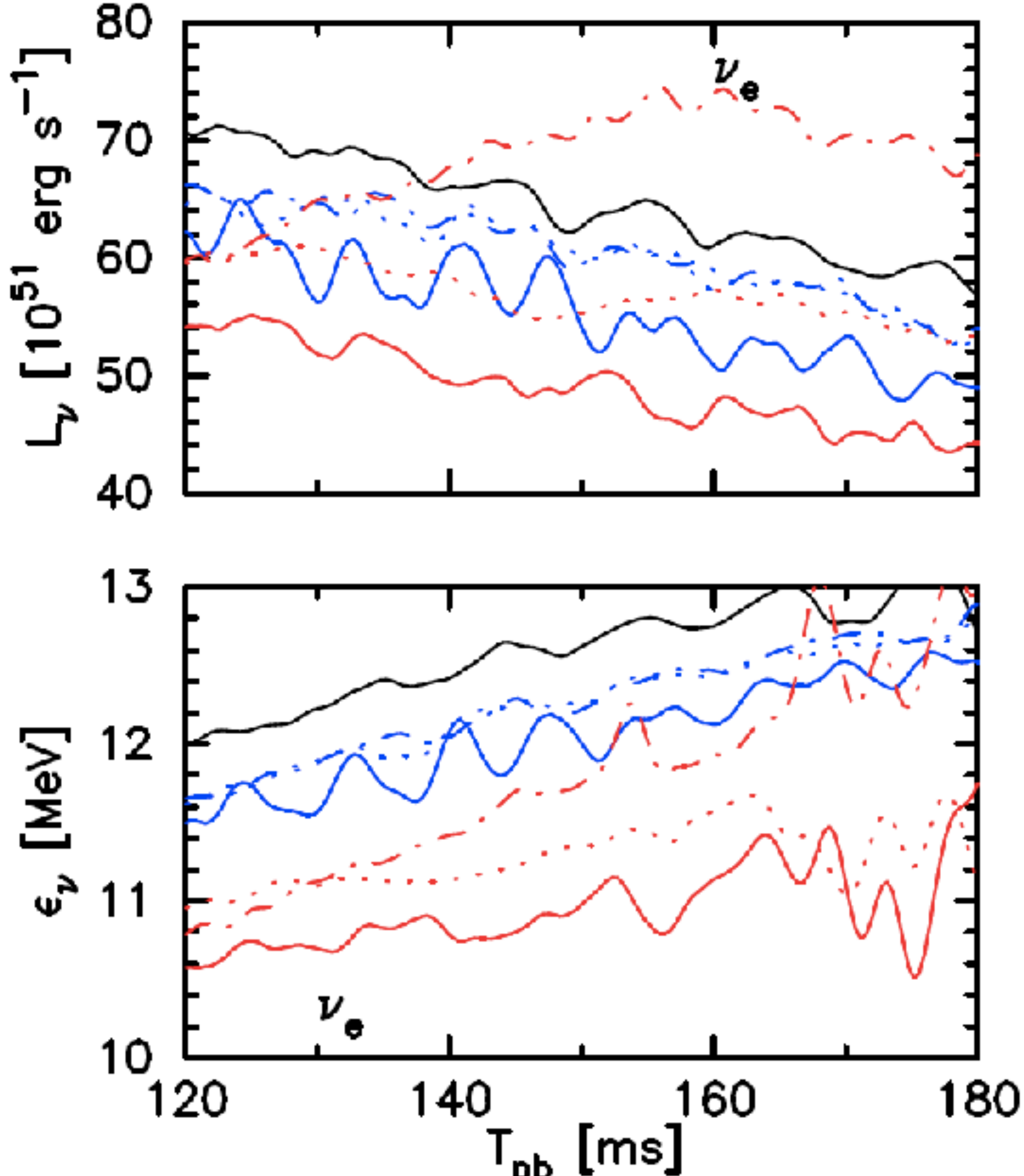


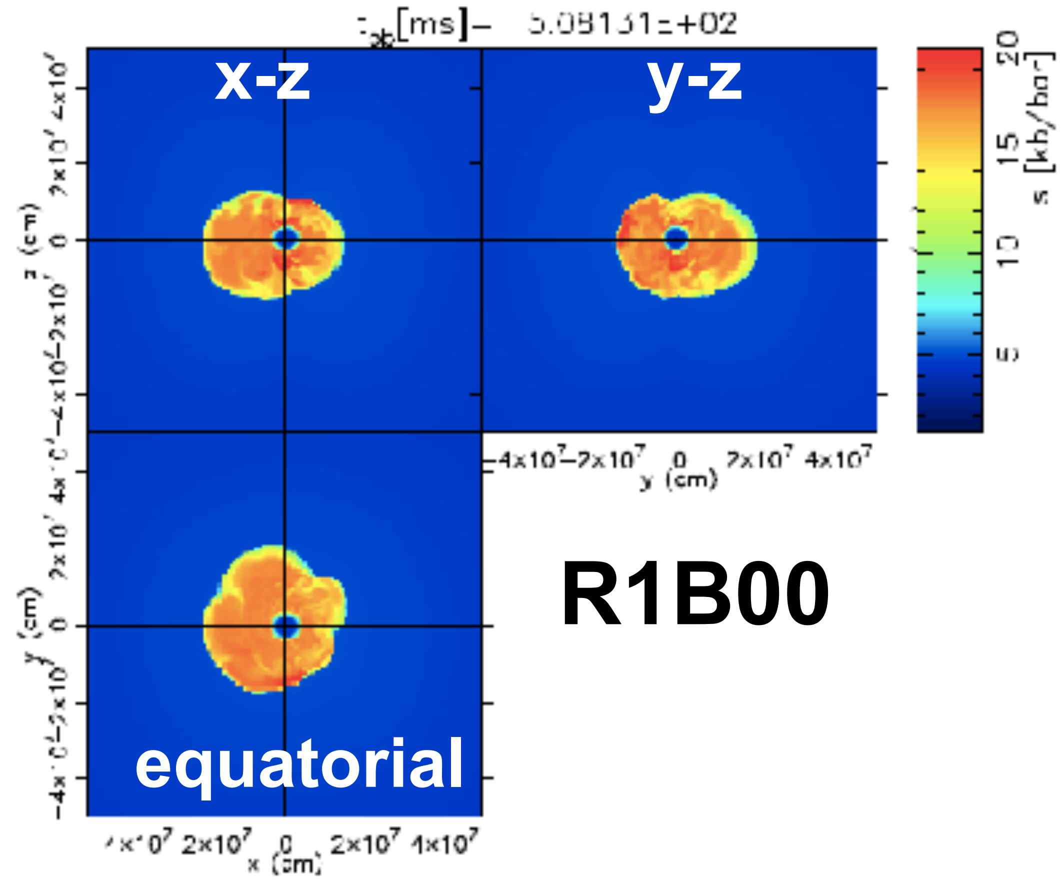
Neutrino emission (angle dependence)

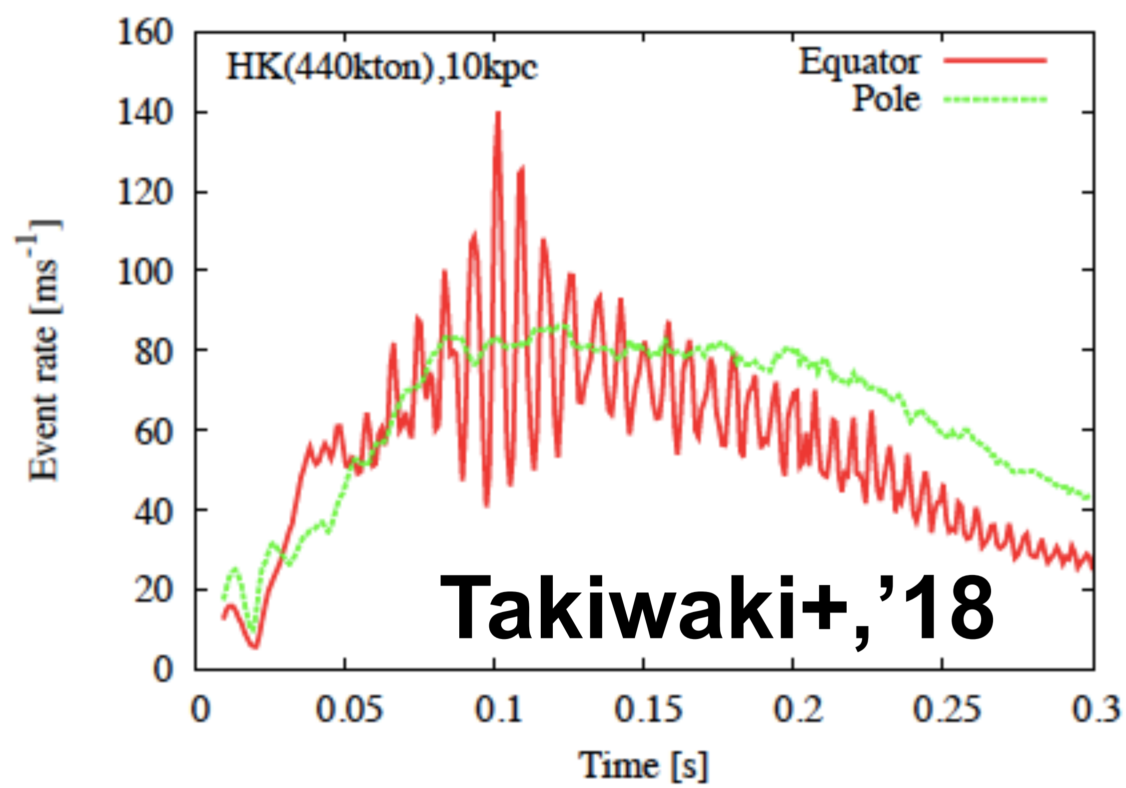


Rotation produces a time modulation

Neutrino emission (angle dependence)

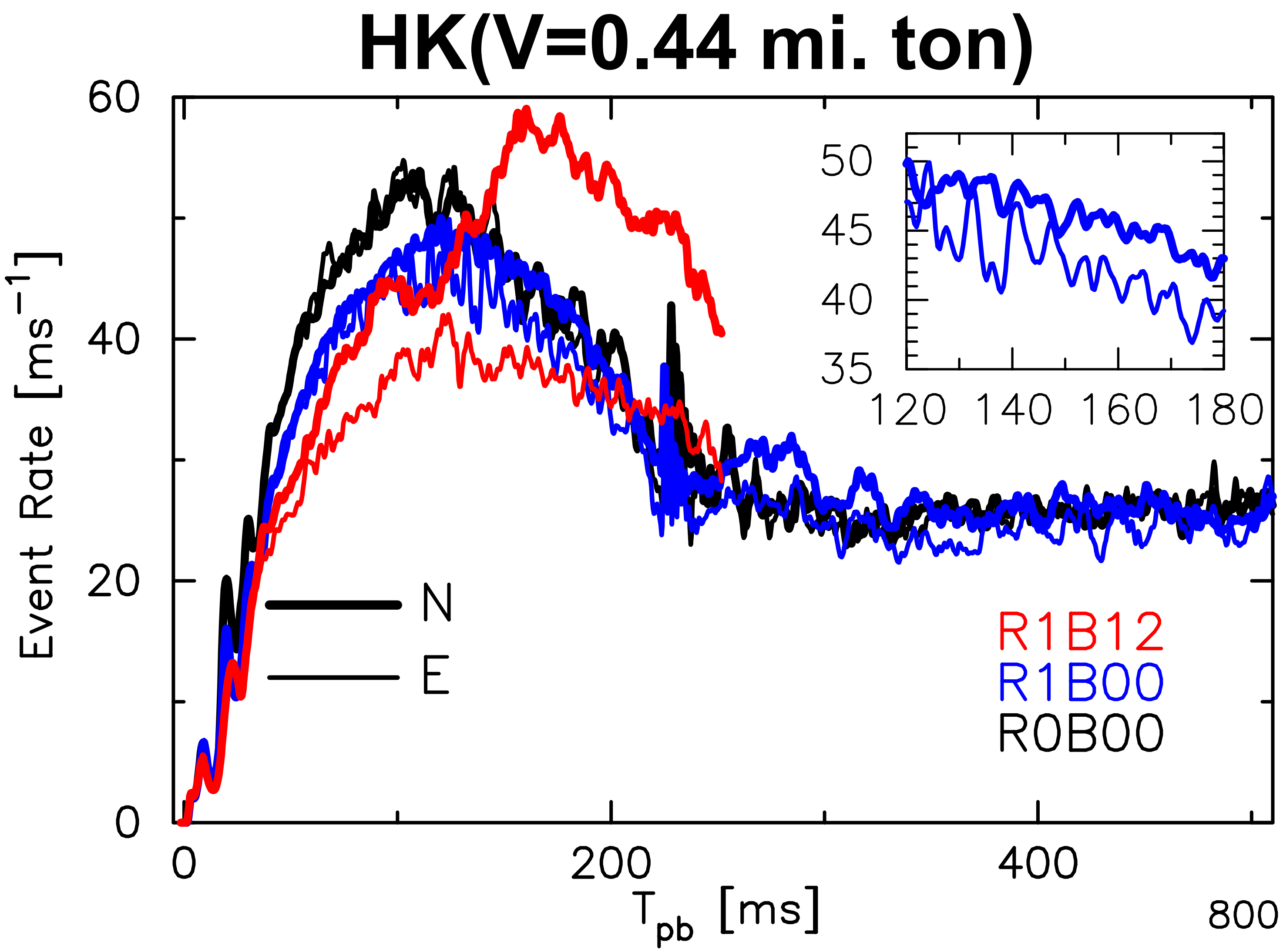


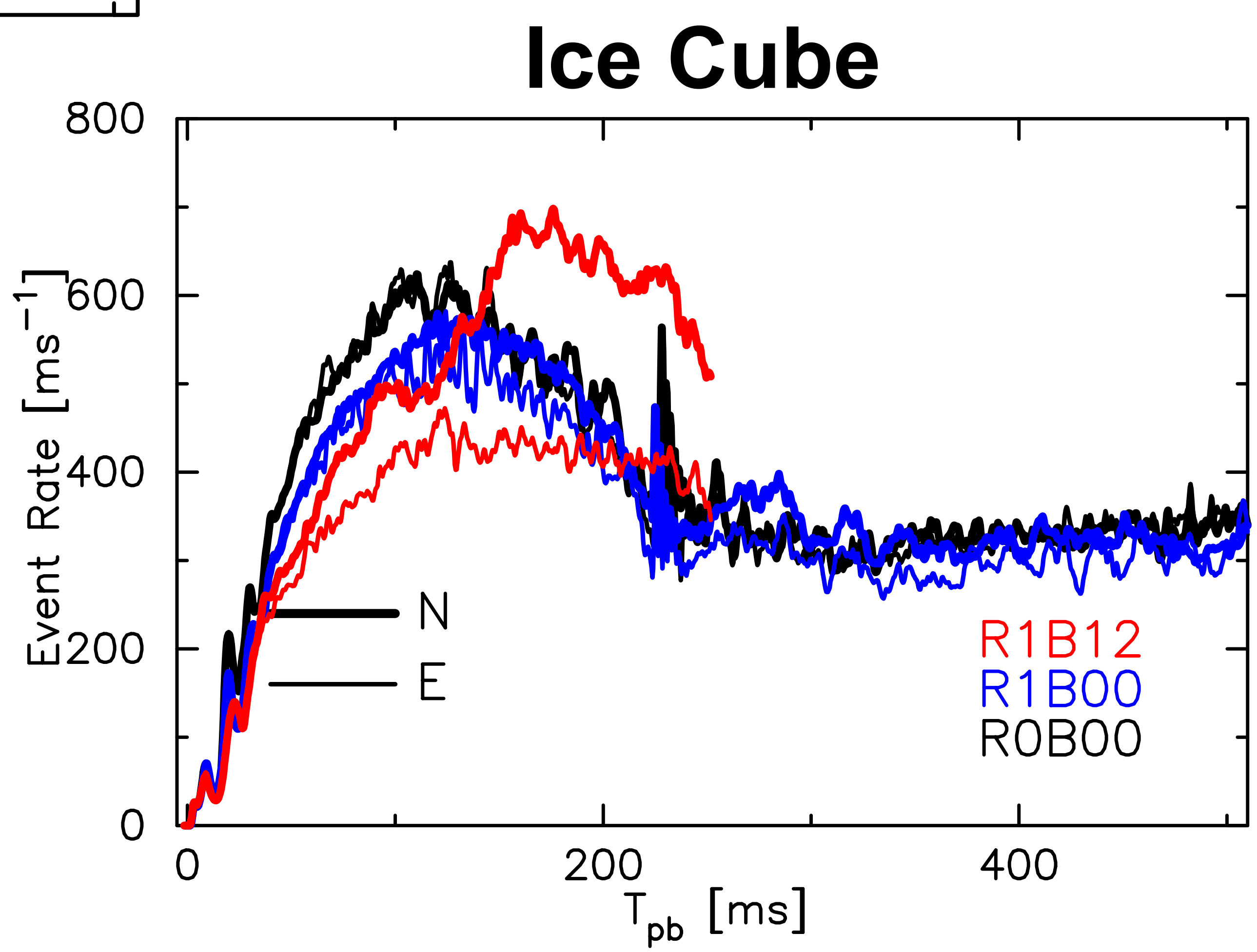




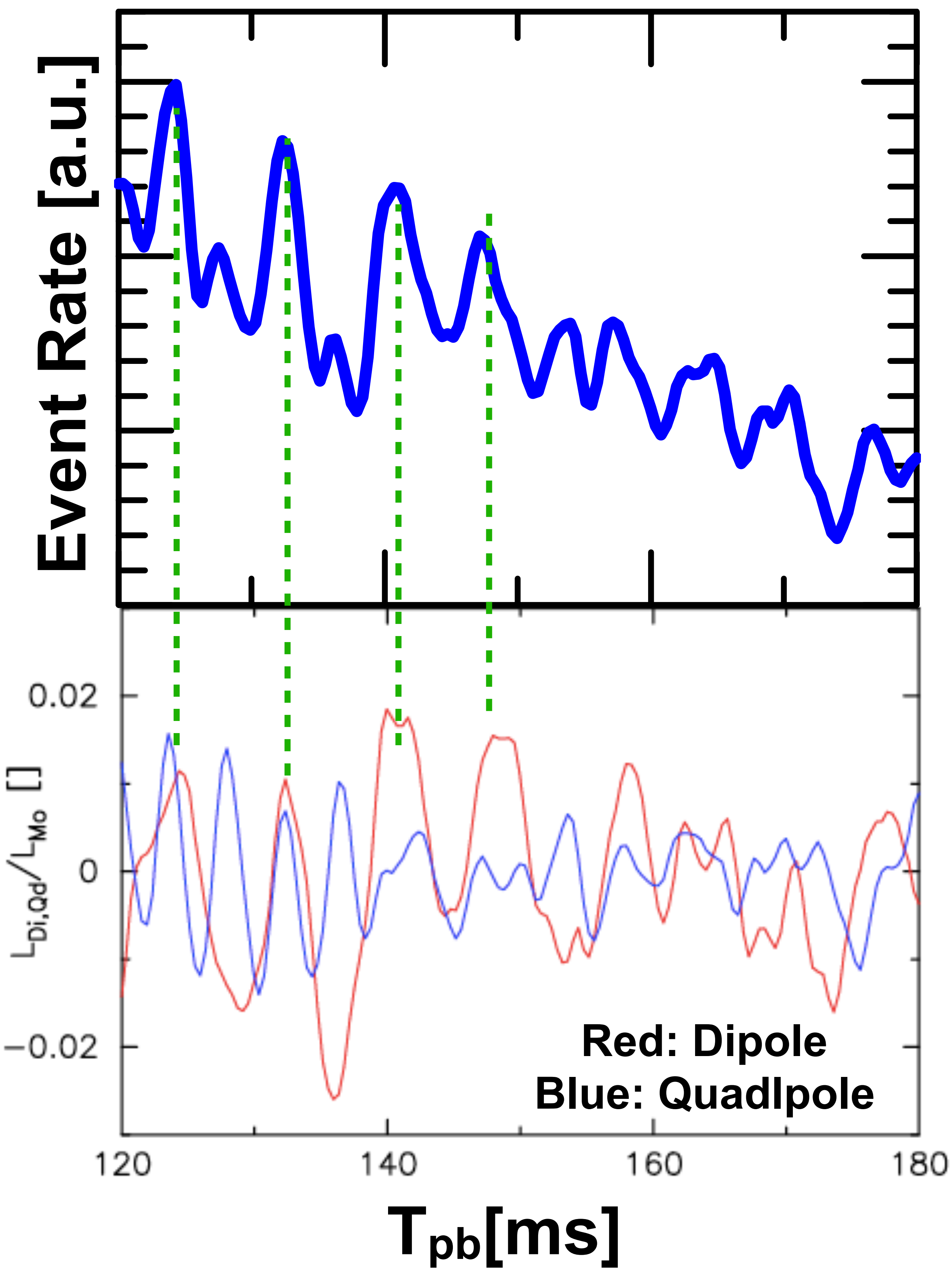
g

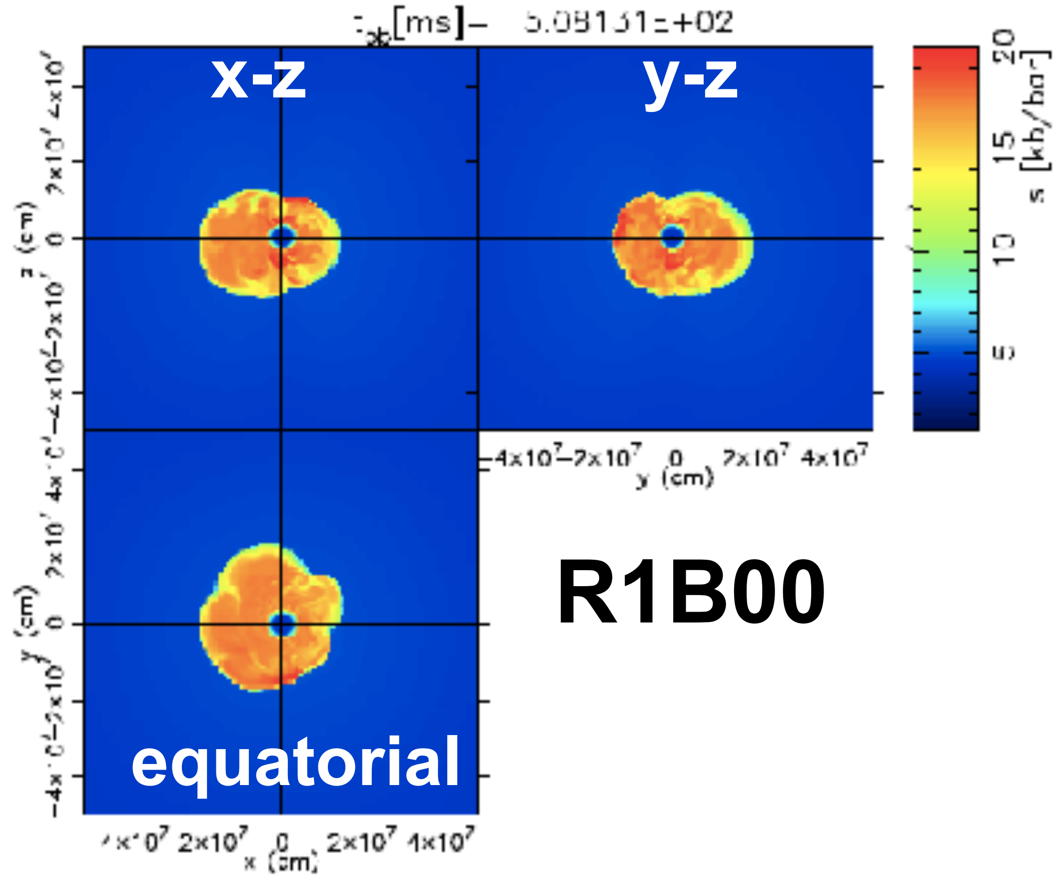
Neutrino detection rate (D=10kpc)



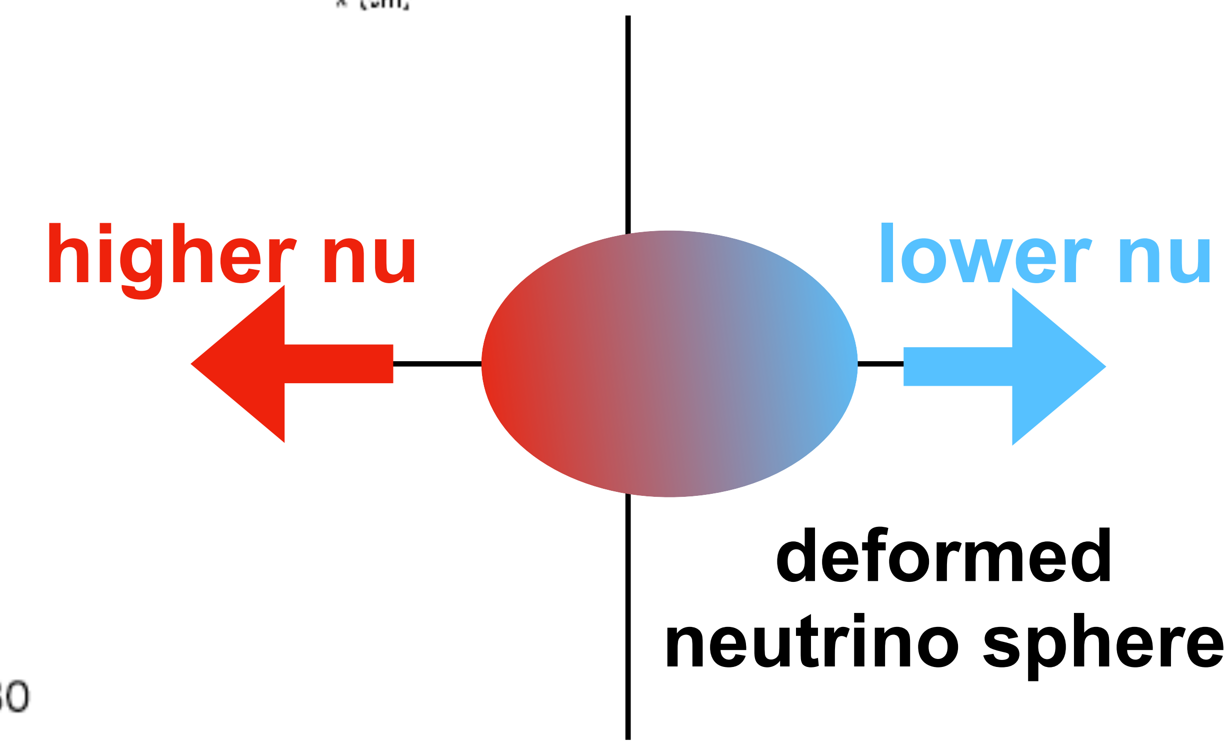


m=1 deformation of neutrino sphere

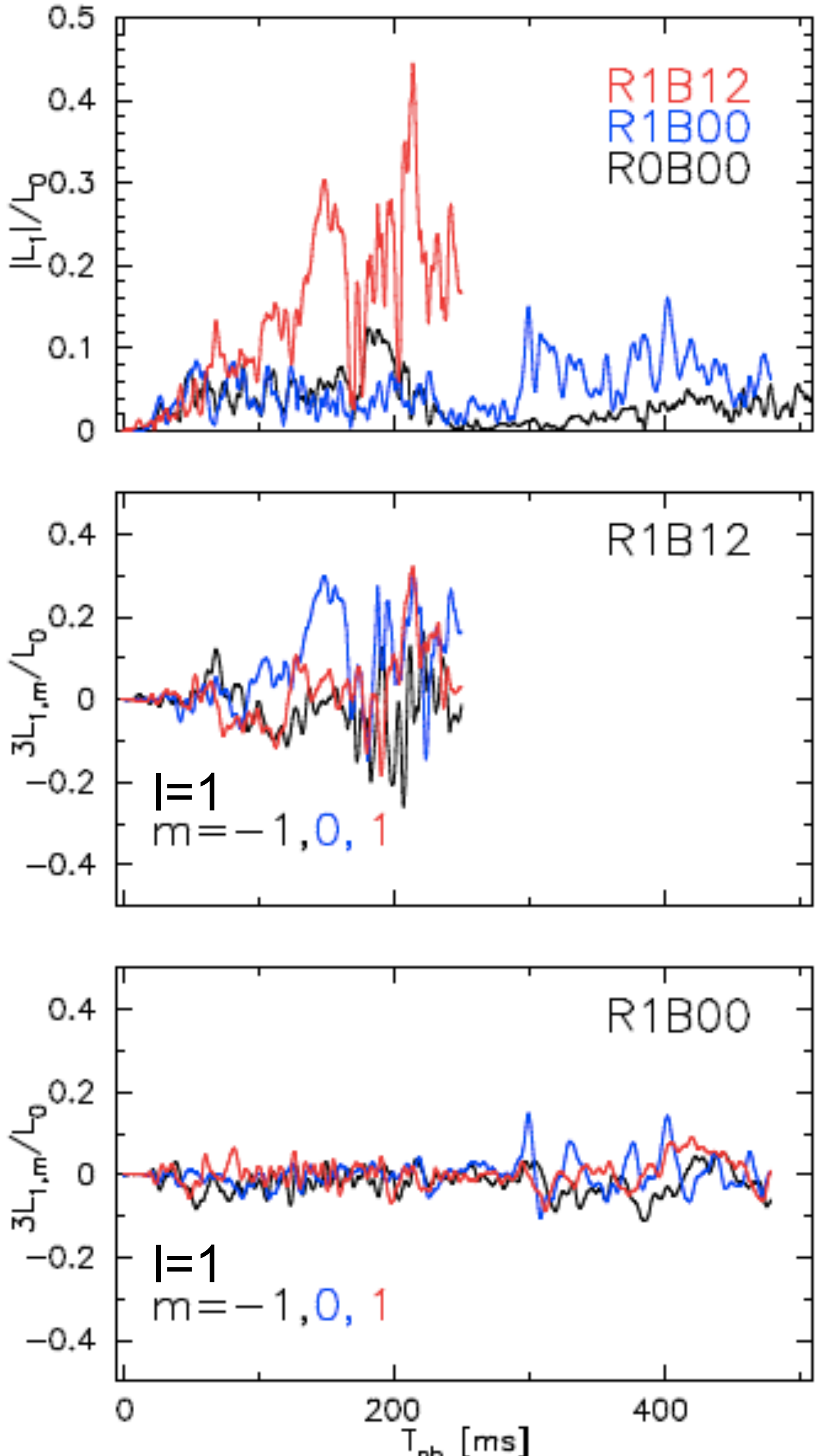




R1B00

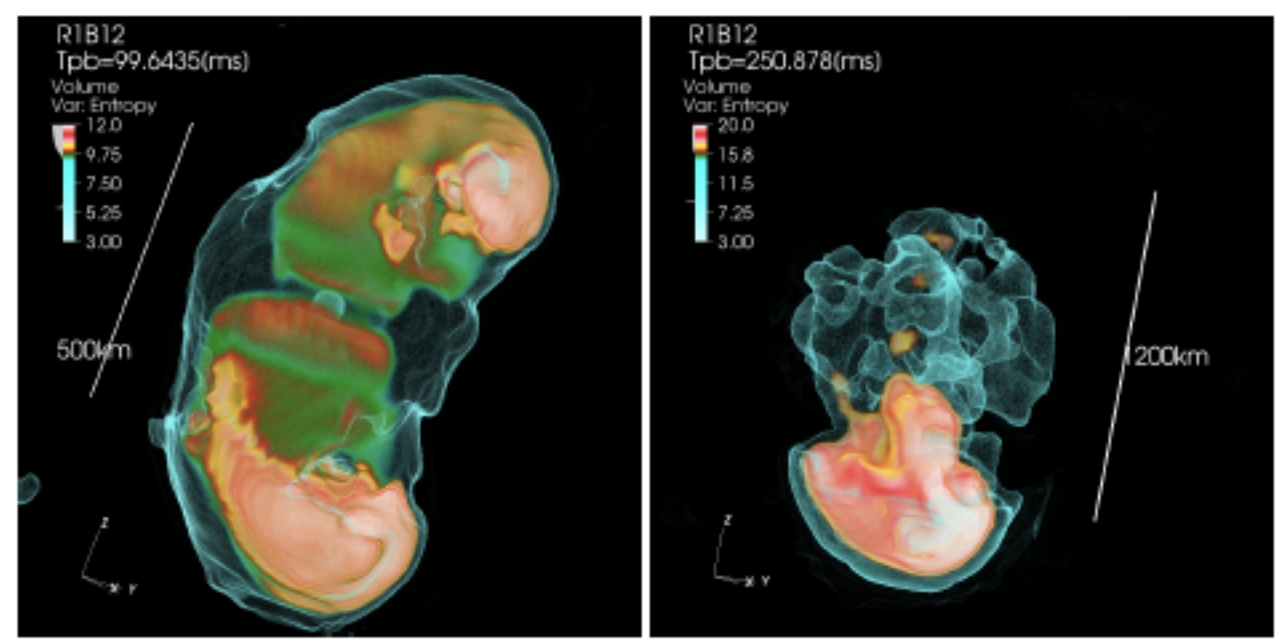


Evidence of LESA



Successful explosion model (R1B12) shows clear dipolar asymmetry

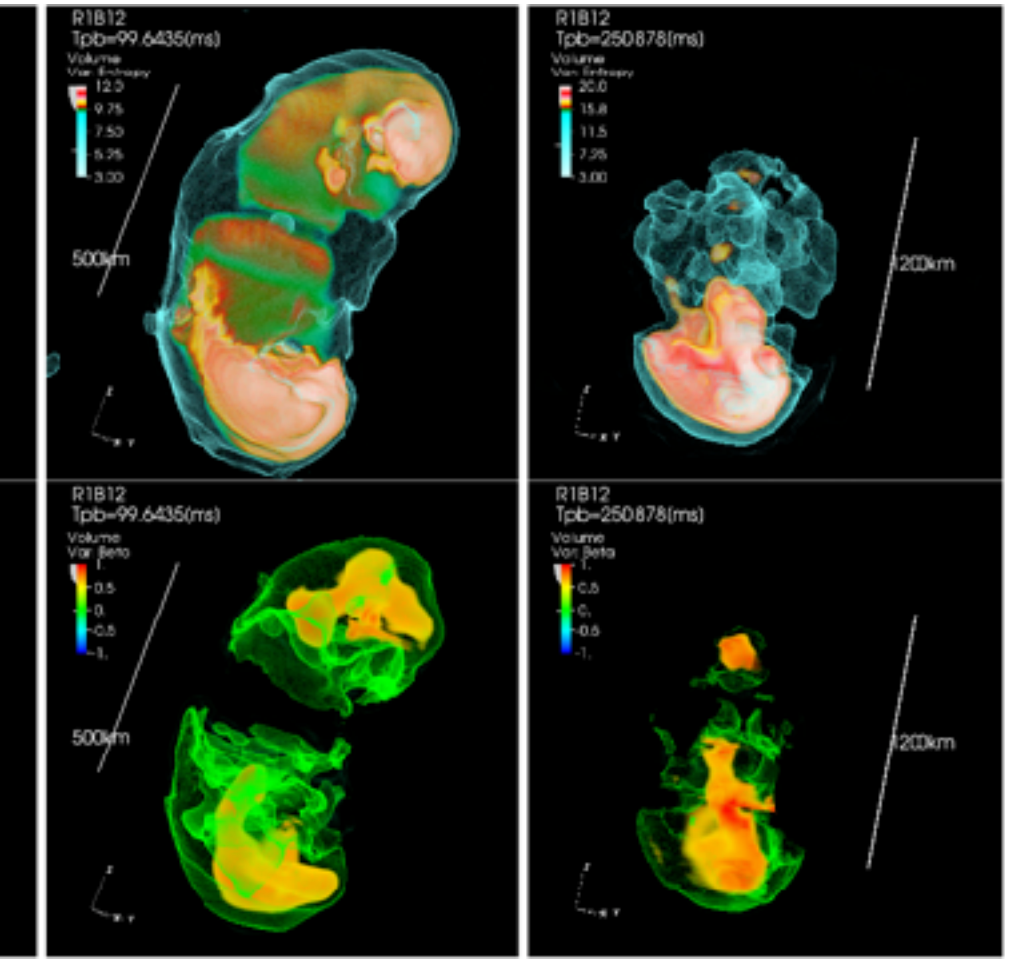
Blue line (l,m)=(1,0) is the dominant term reflecting ⬇ morphology

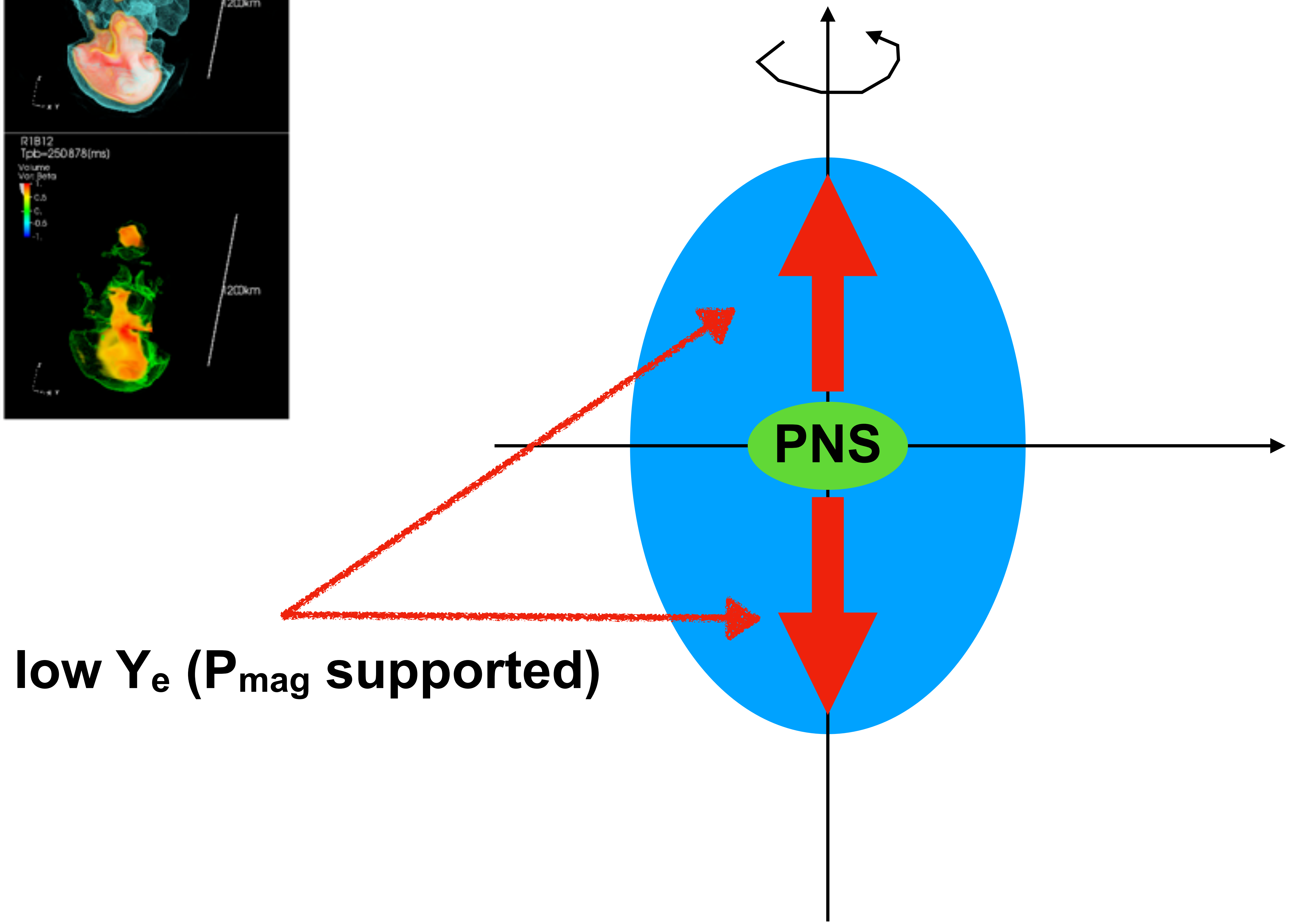


Summary

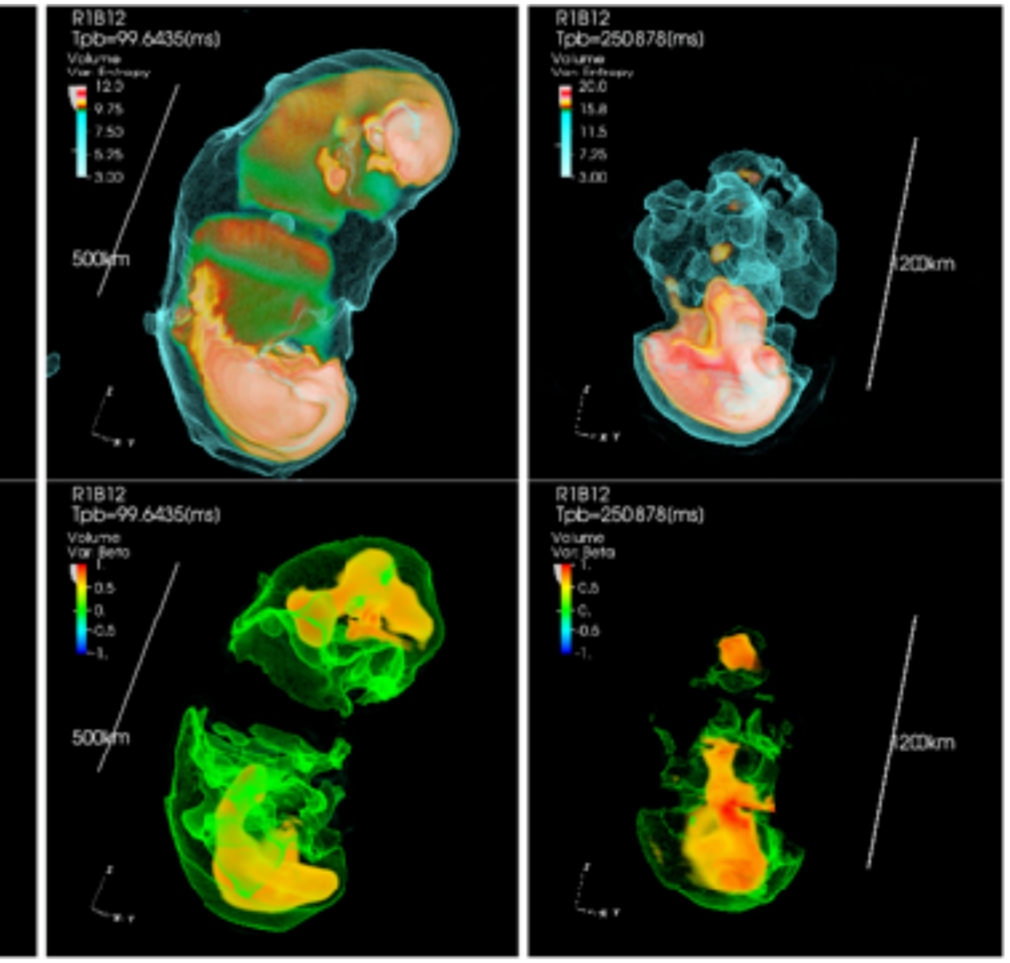
1. SN simulations are becoming more realistic (full GR, 3D effects, sophisticated neutrino opacities)
   —> more reliable messages from SNe
   (GWs, neutrinos, and heavy elements)
2. In MHD model, the polar/equatorial explosion is boosted mainly by B/neutrinos.
3. Temporal modulation in neutrinos reflecting the SASI motions.
4. LESA appears but not the similar magnitude as Tamborra

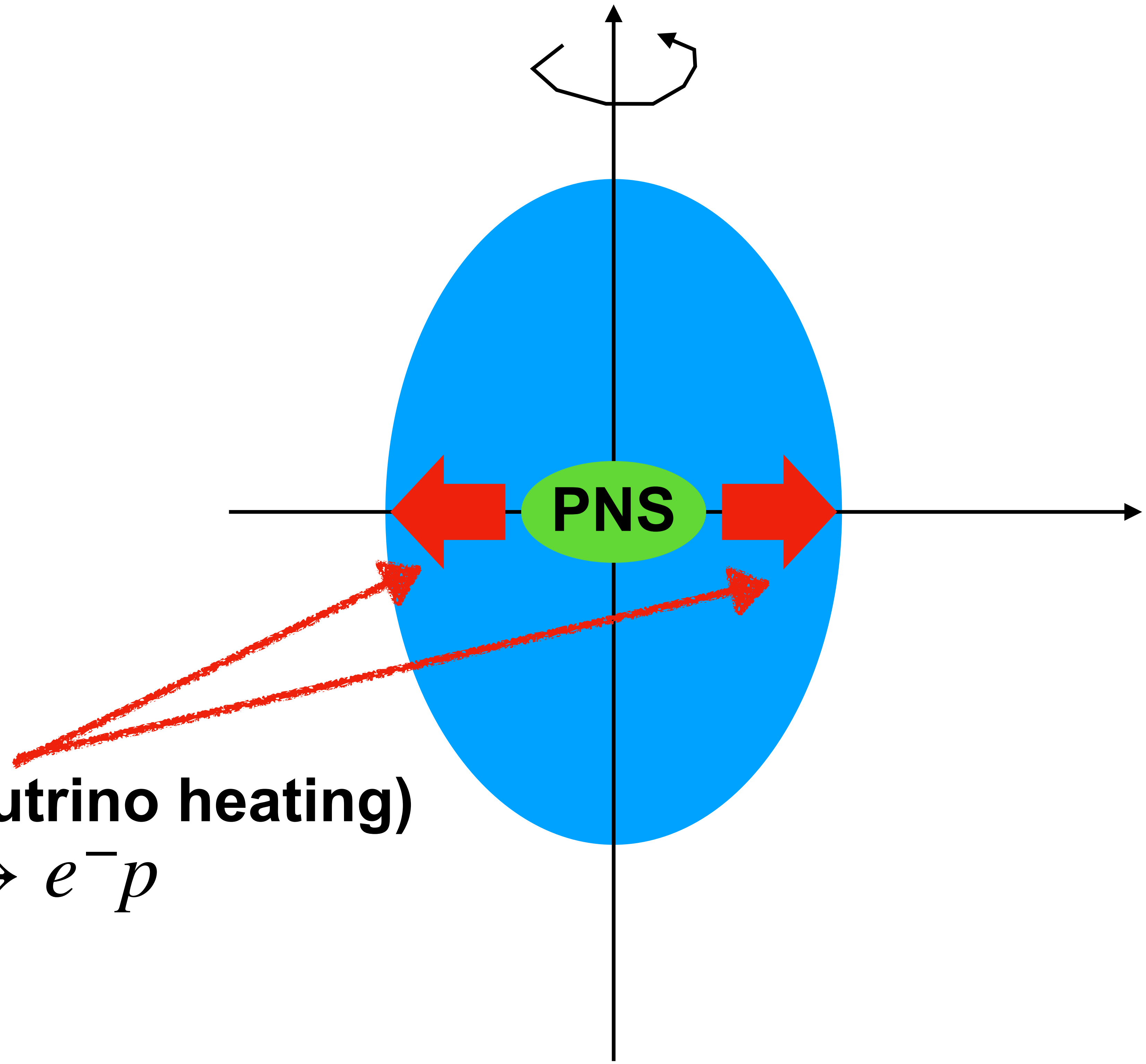
Ejecta structure





Ejecta structure





high Y_e (neutrino heating)

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

Selection rule (only by S&Ye history)

(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

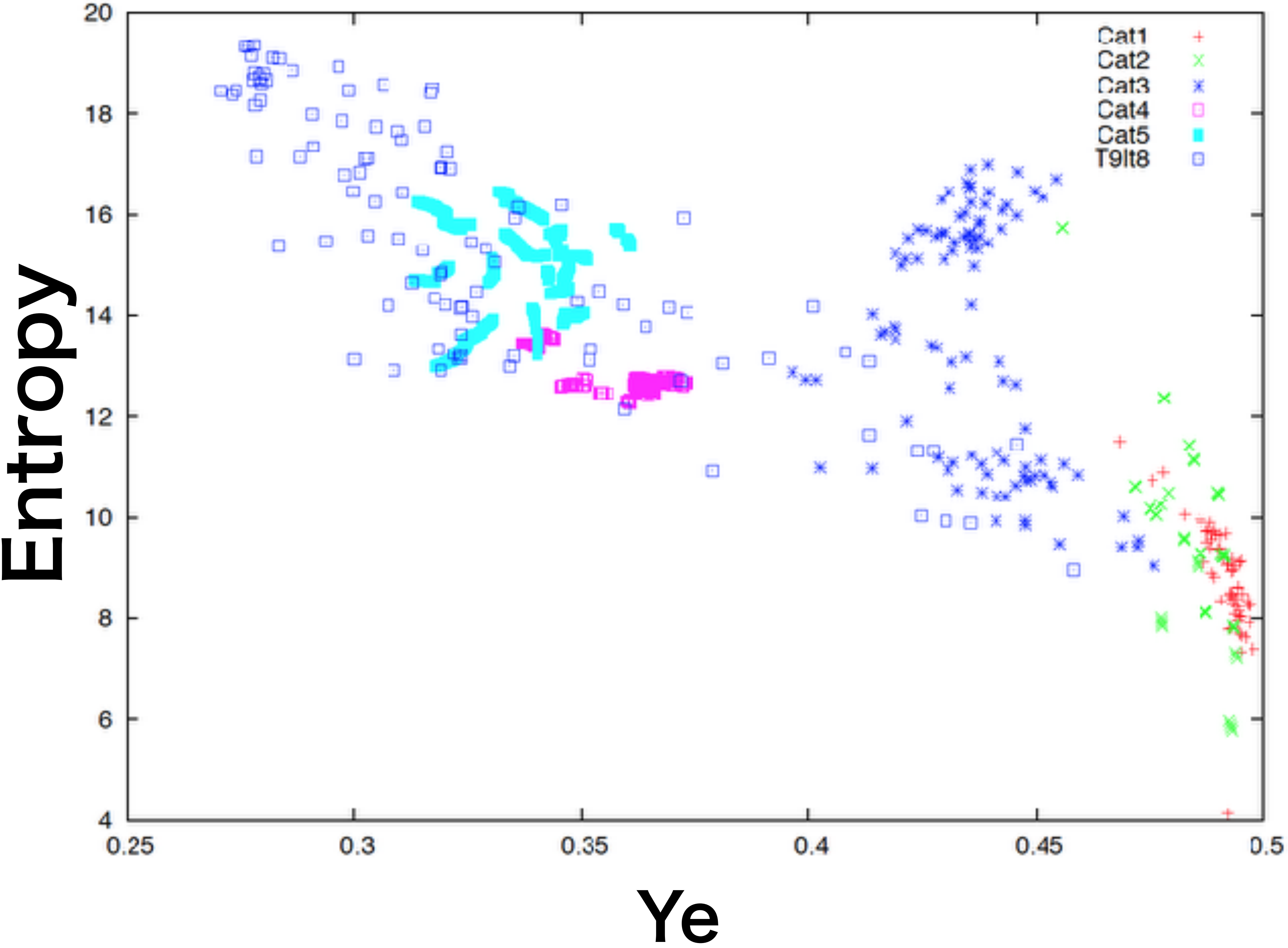
(3) Ye once <0.45 and at the end >0.38

(4) Ye always <0.45 and entropy<15

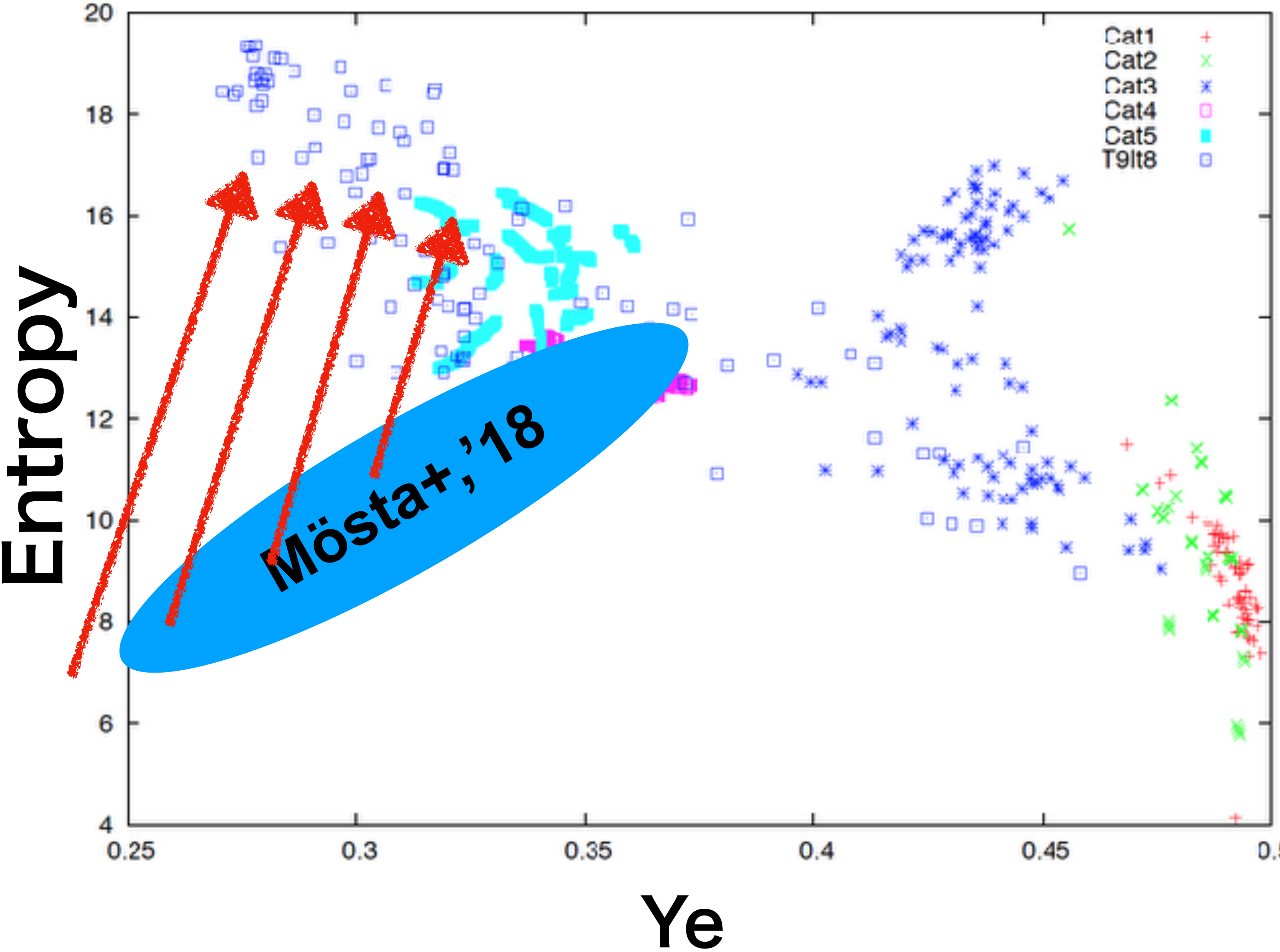
(5) Ye always <0.45 and entropy>15

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

Scattering in S-Y_e plane

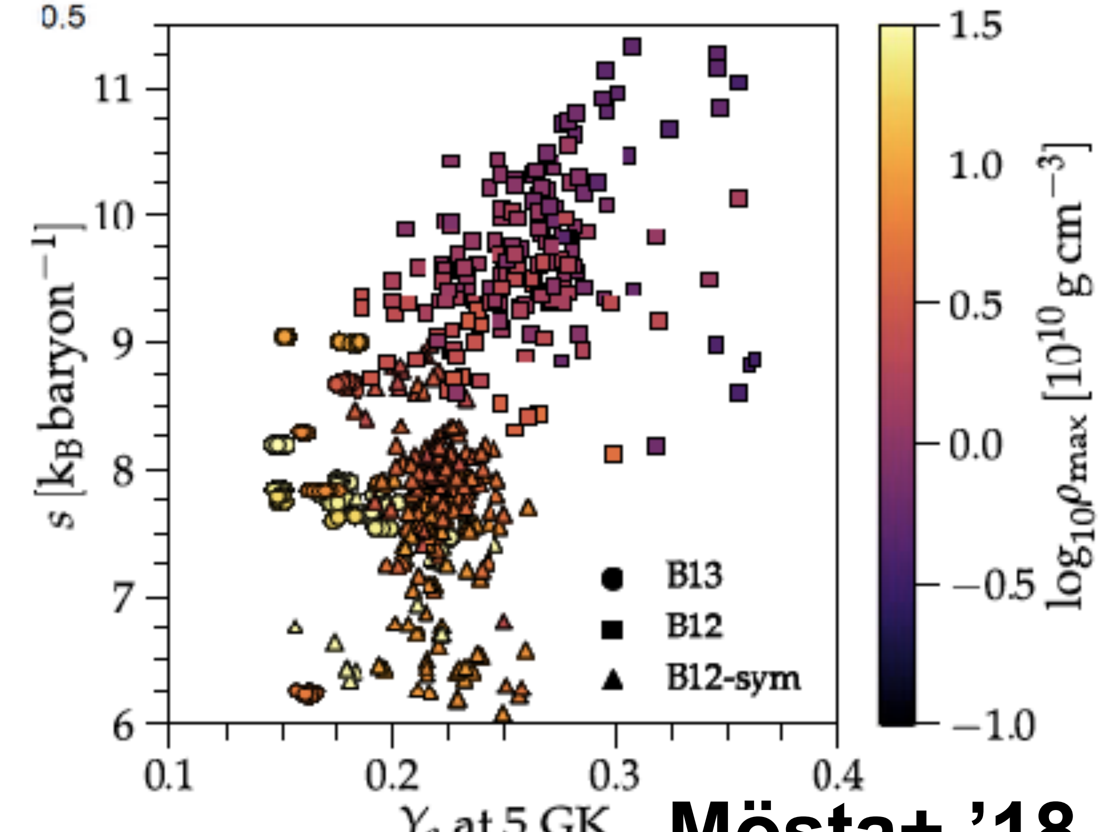


Scattering in S-Y_e plane



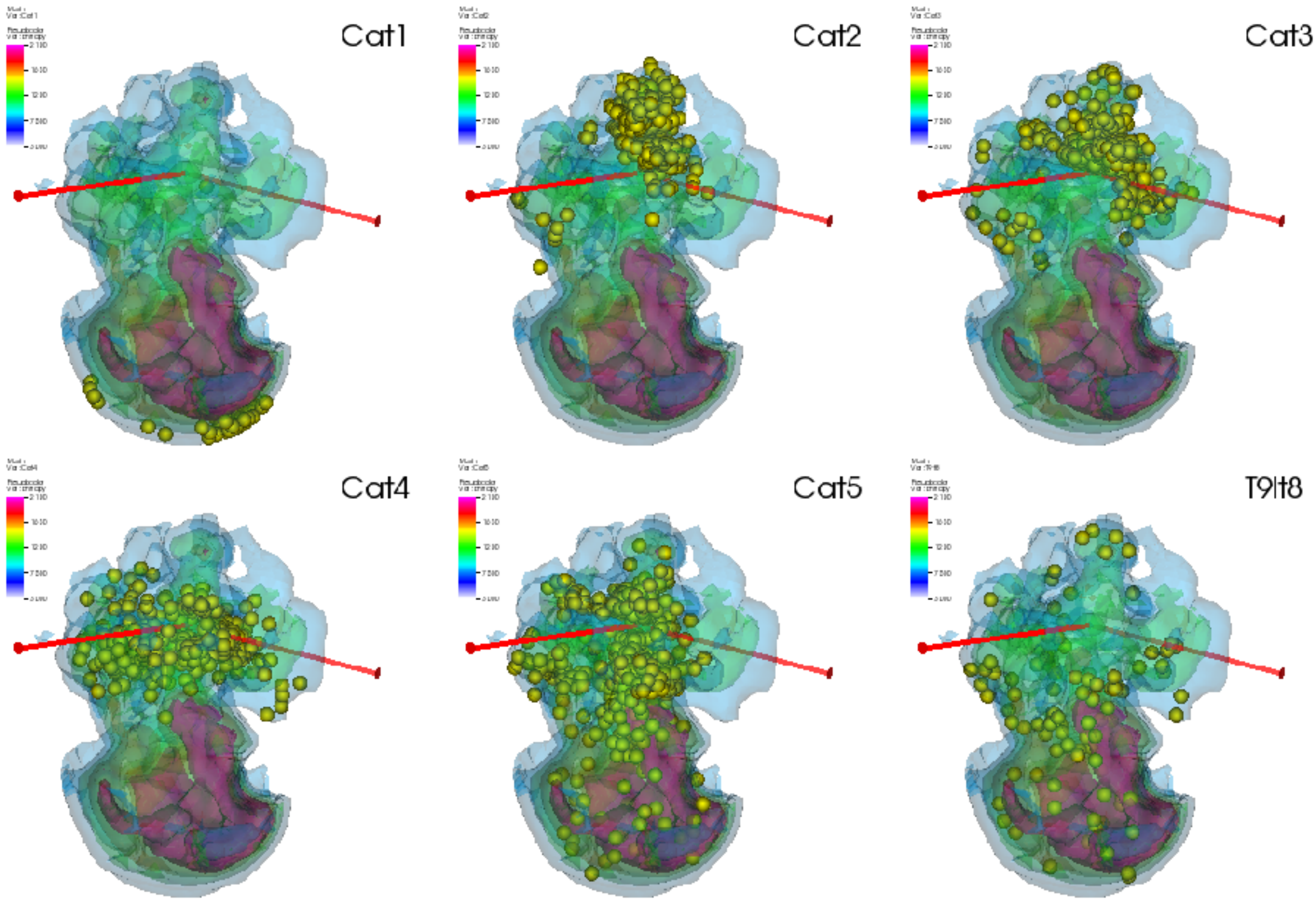
Due to the interaction $\nu_e n \rightarrow e^- p$

Ye & S tend to become higher

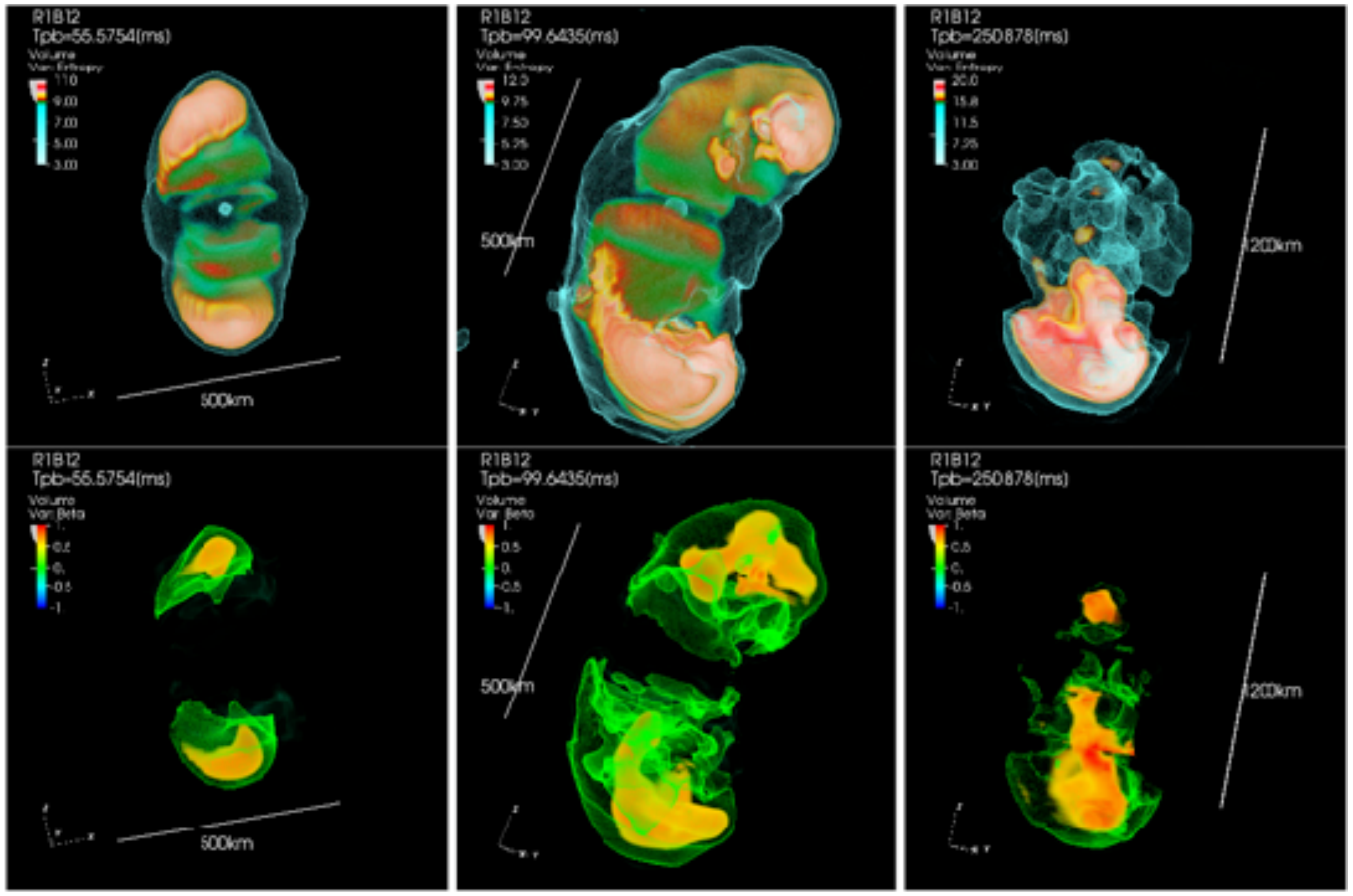


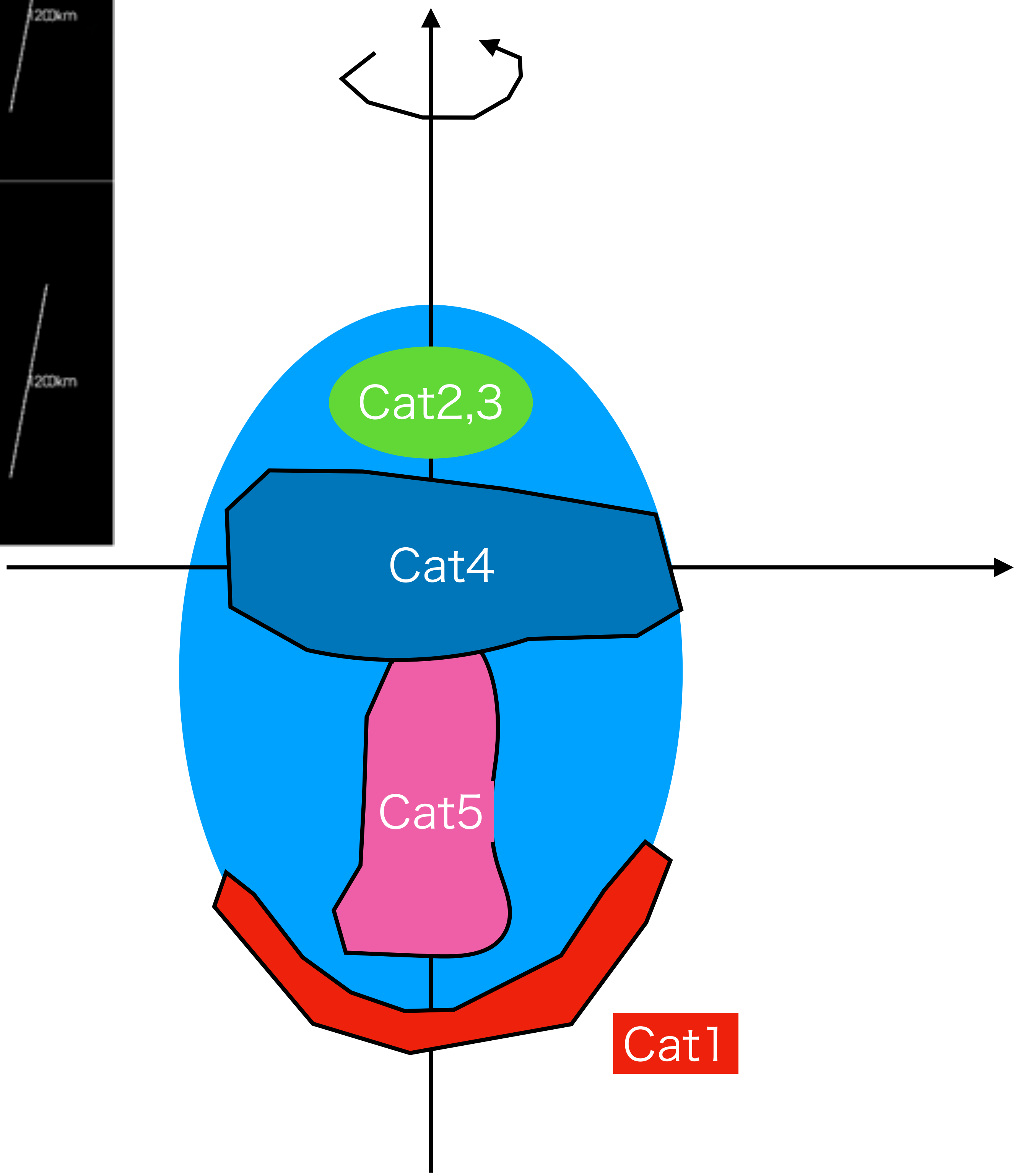
Mösta+,'18

Ejecta distribution

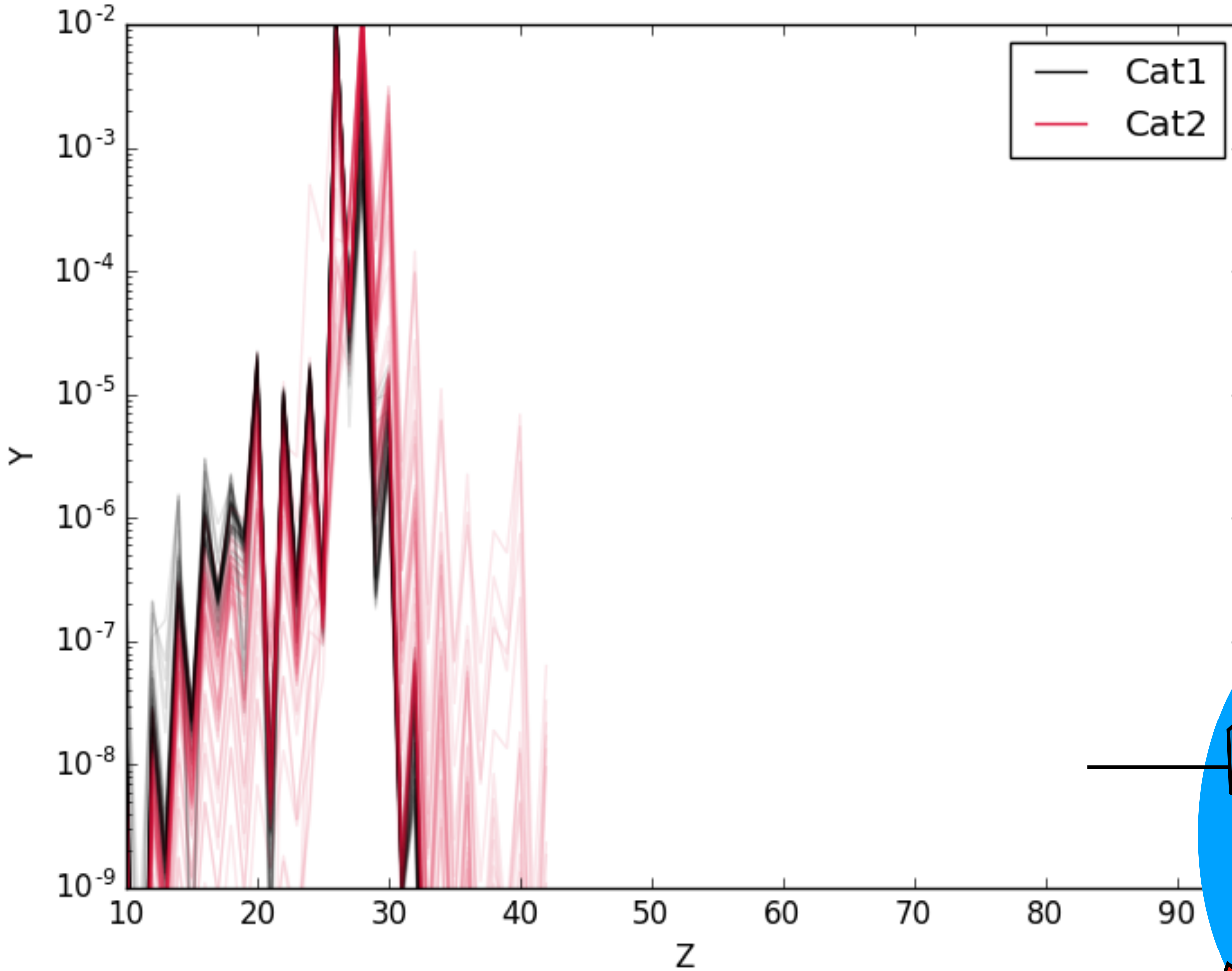


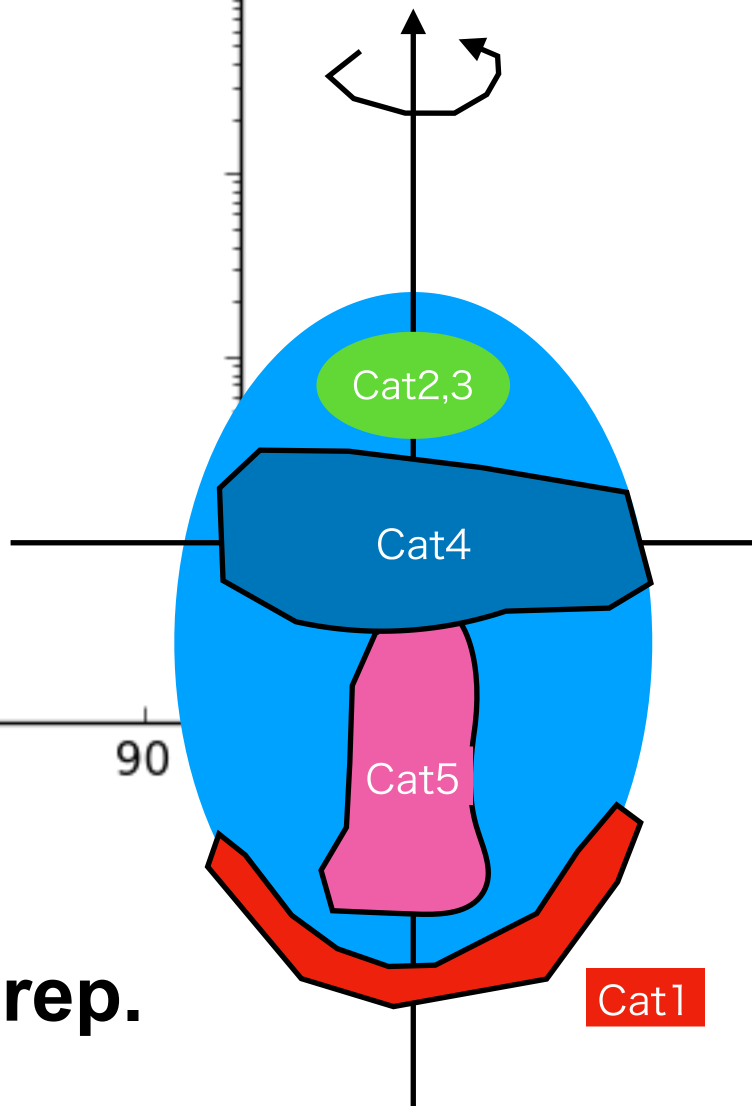
Ejecta distribution





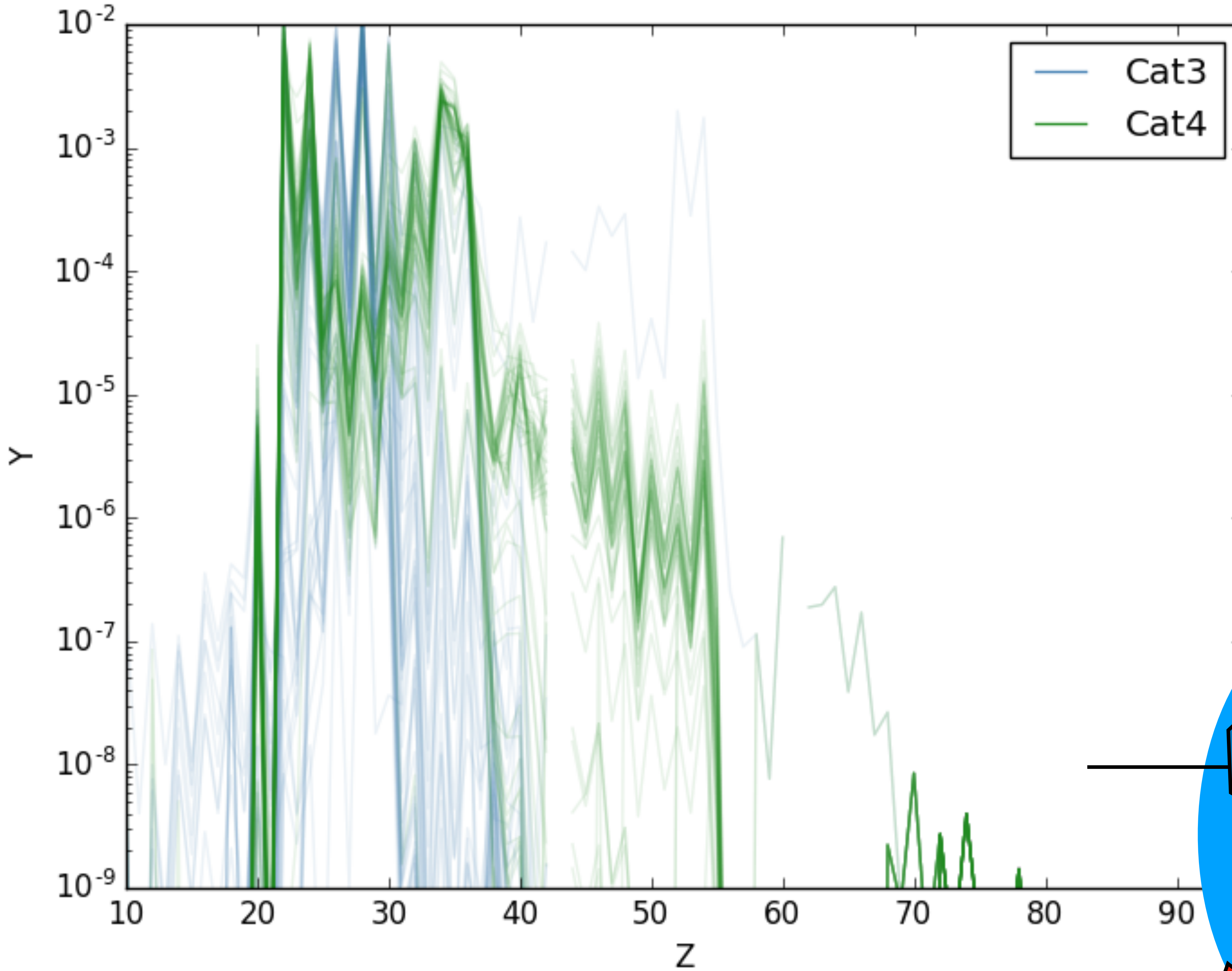
Nucleosynthesis (1st peak)

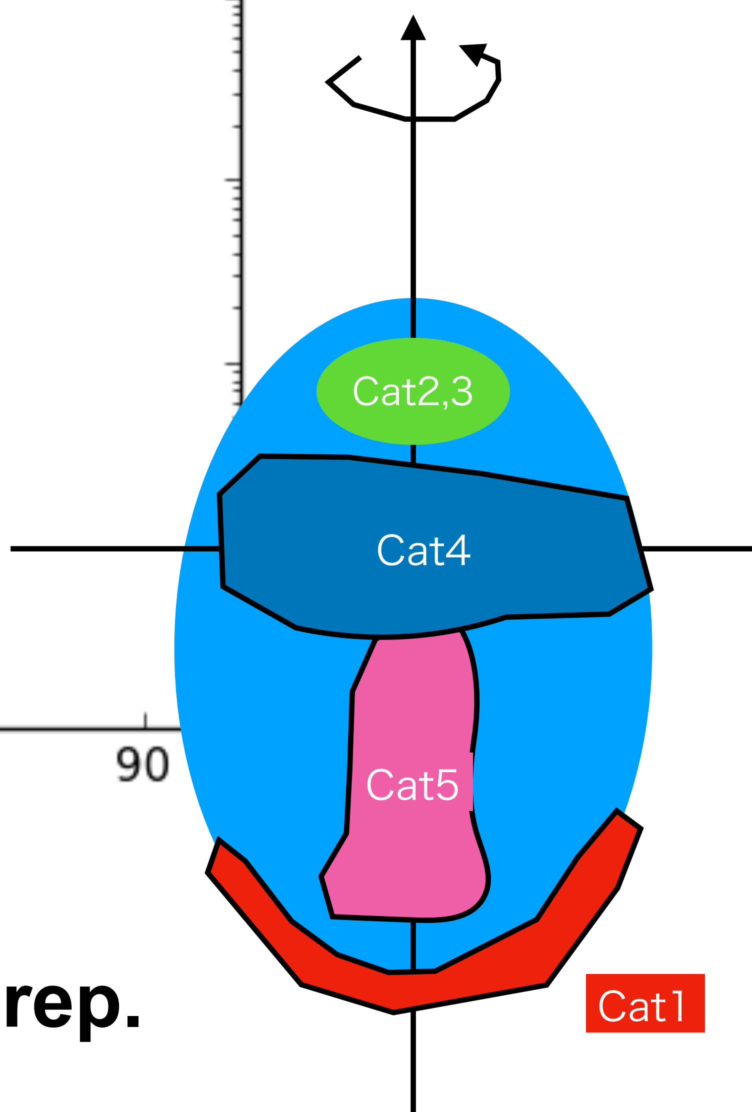




Reichert, Eichler, TK+, in prep.

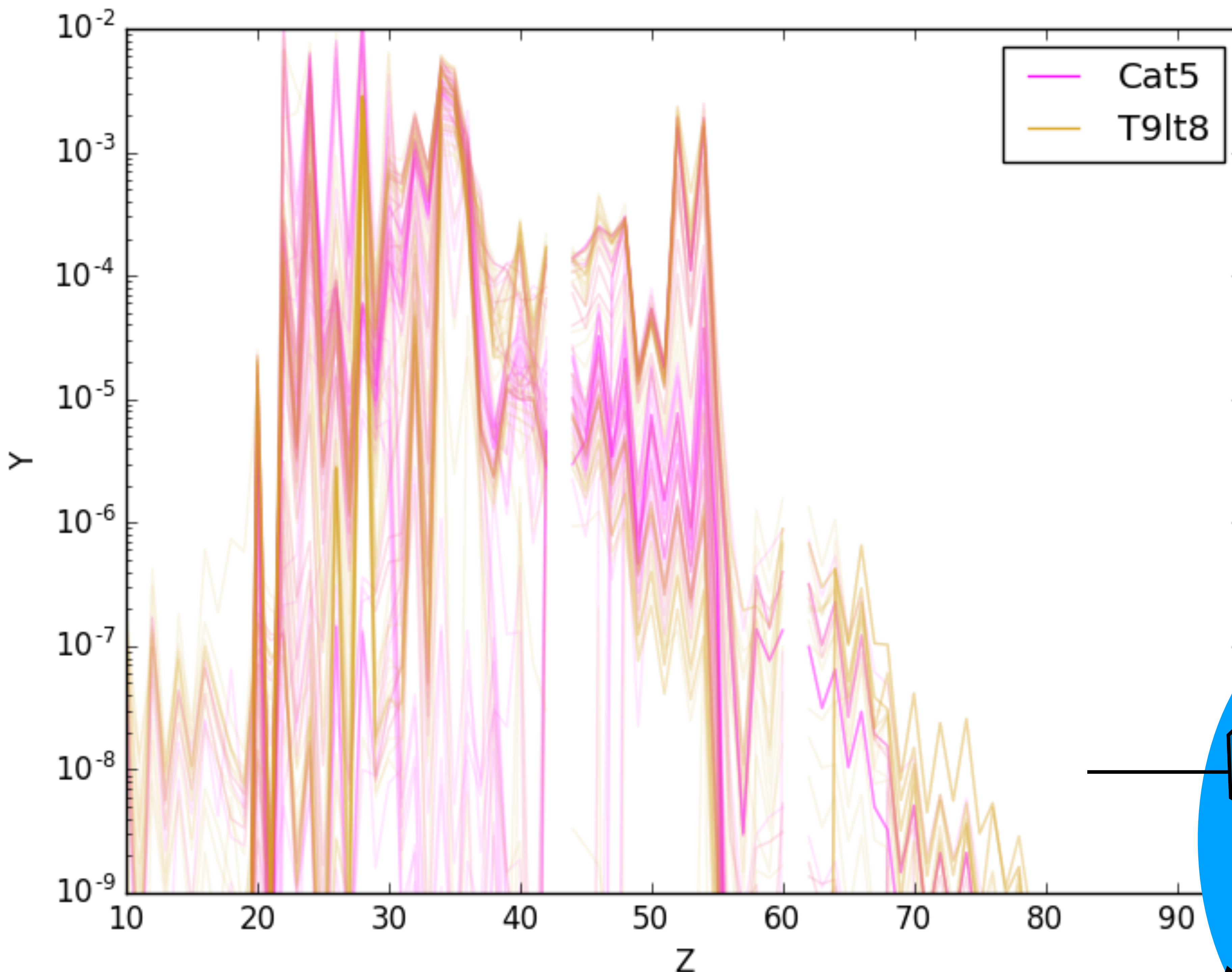
Nucleosynthesis (weak 2nd peak)

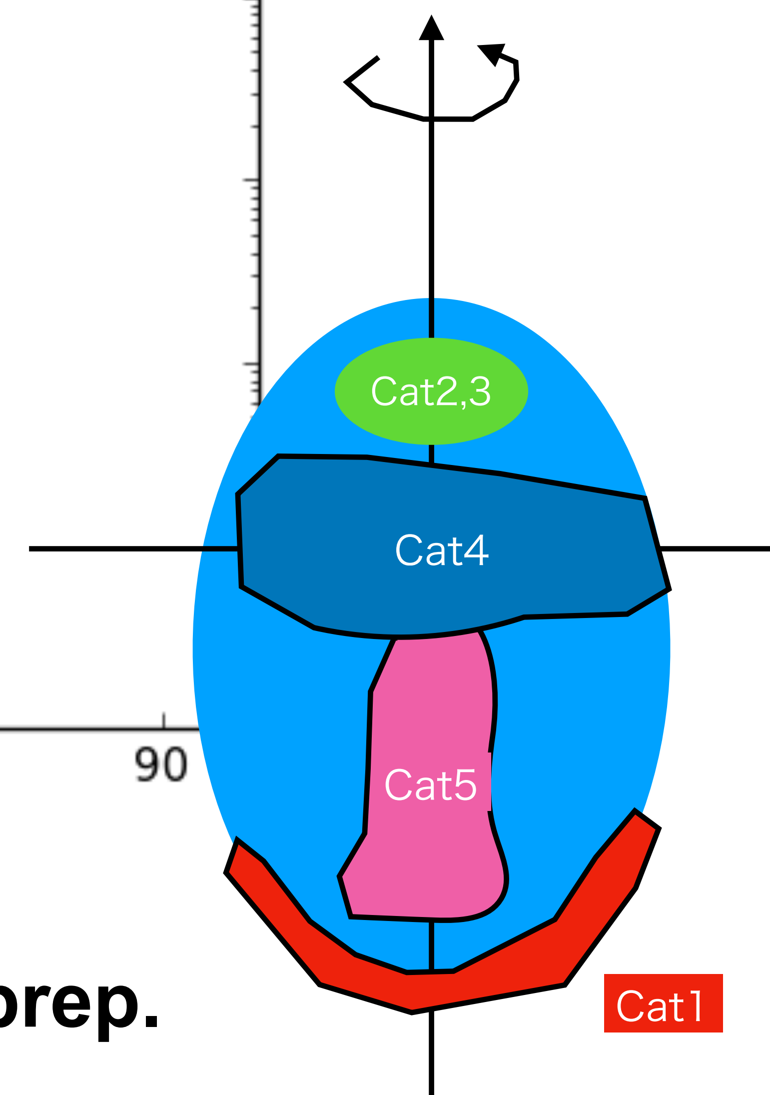




Reichert, Eichler, TK+, in prep.

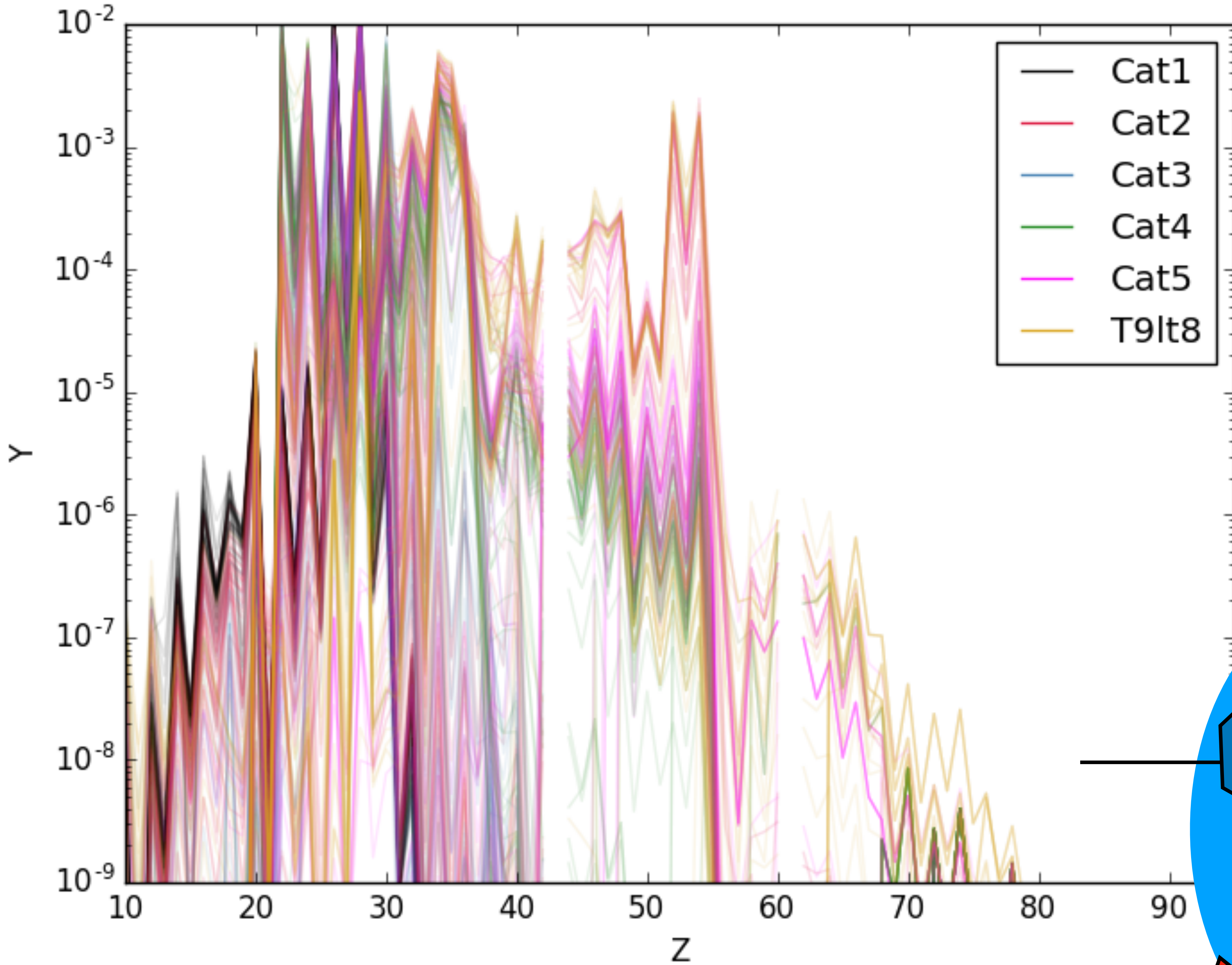
Nucleosynthesis (2nd peak + Lanthanides)

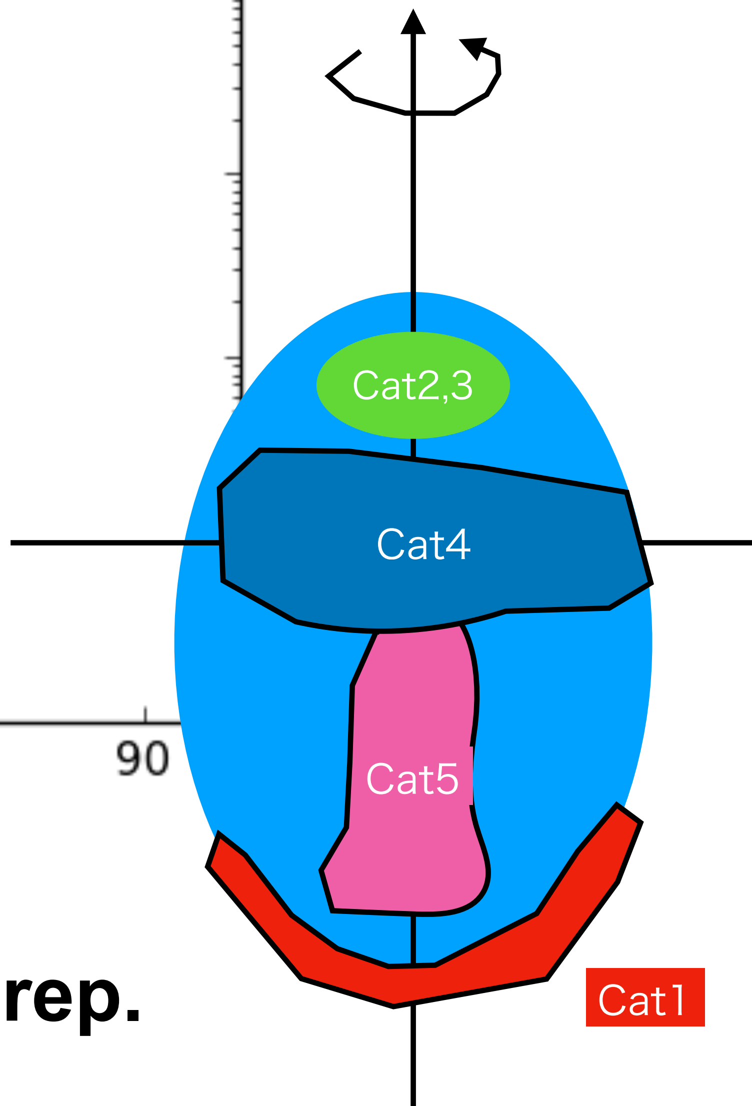




Reichert, Eichler, TK+, in prep.

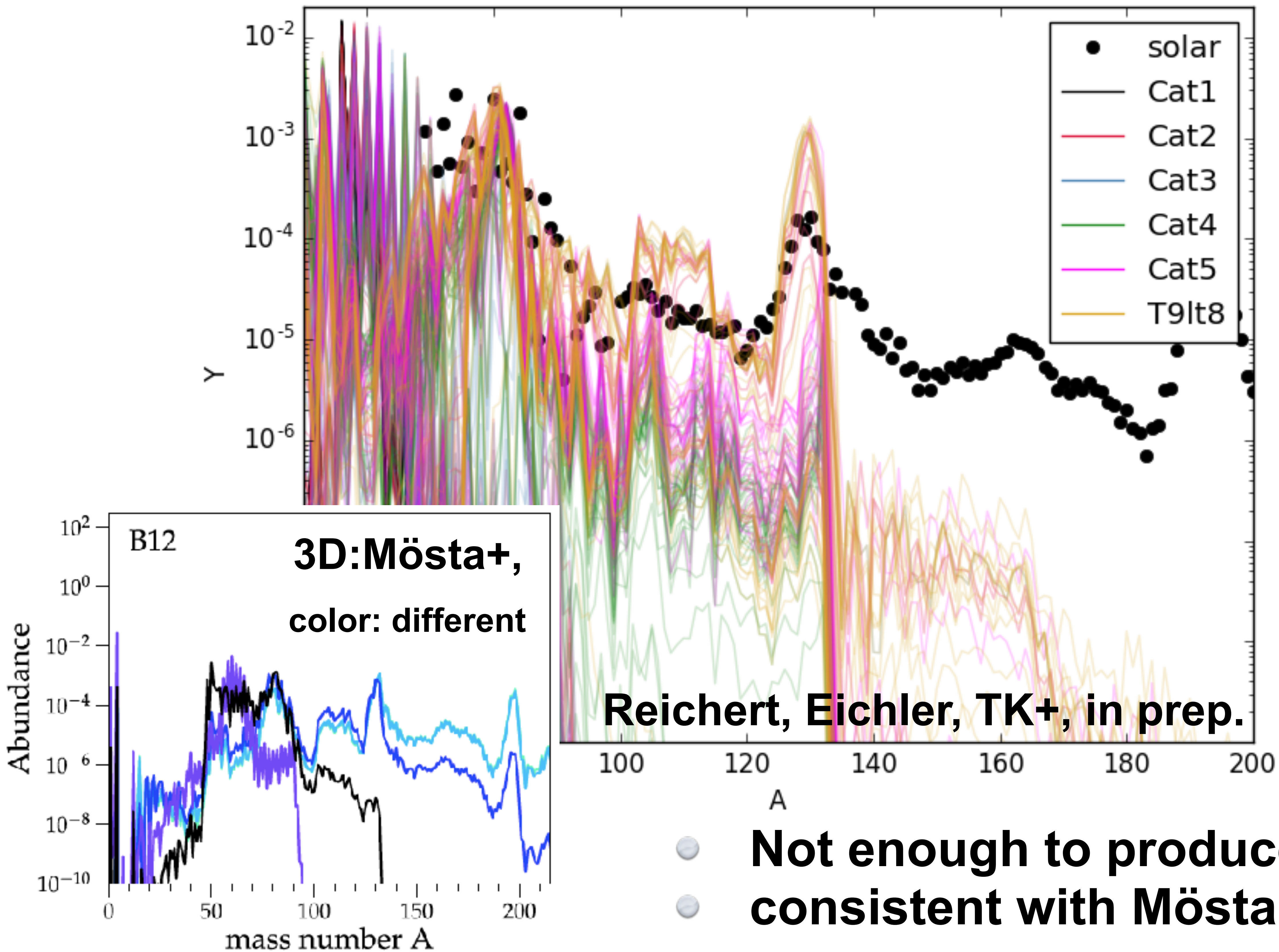
Nucleosynthesis





Reichert, Eichler, TK+, in prep.

Nucleosynthesis (total)



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