Nucleosynthesis yield of primordial supernovae by bipolar jet-induced explosion

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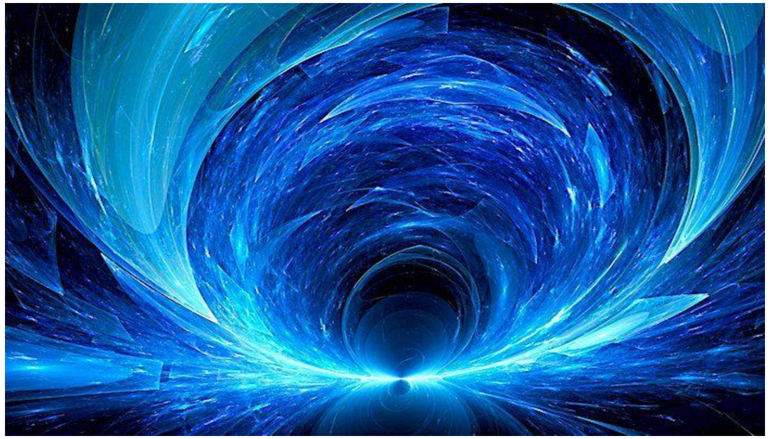
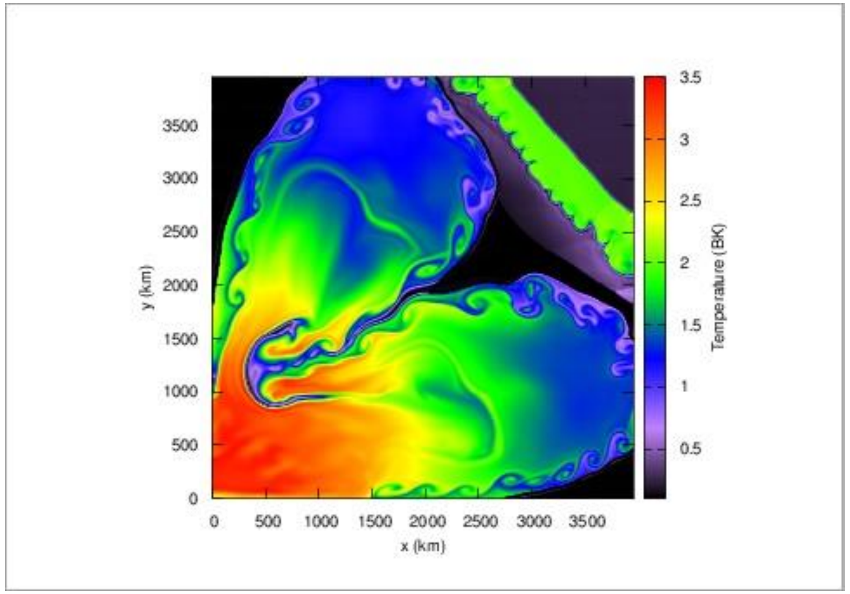


Stellar Archaeology as a Time Machine to the First Stars

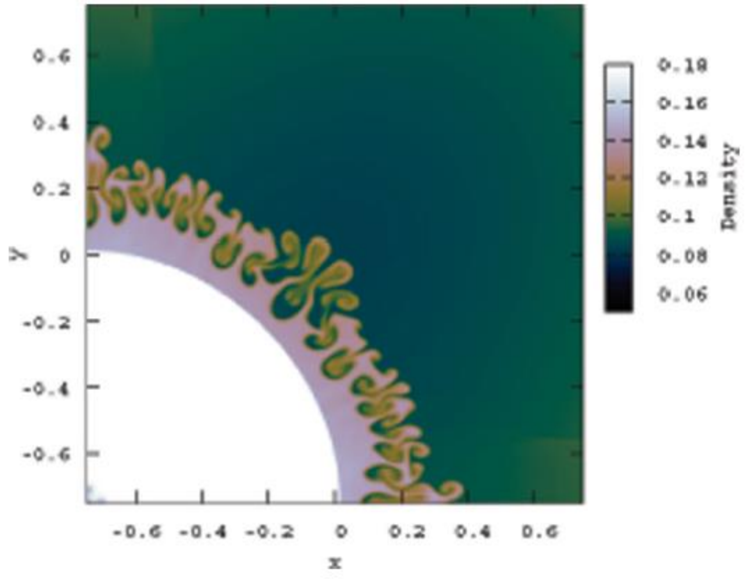
What do I do in Kavli IPMU?

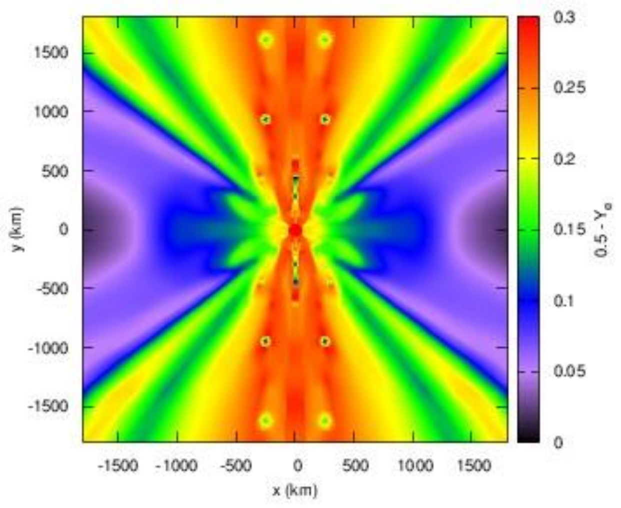
- Numerical hydrodynamics and nucleosynthesis of supernova

Pulsation Pair-instability supernova



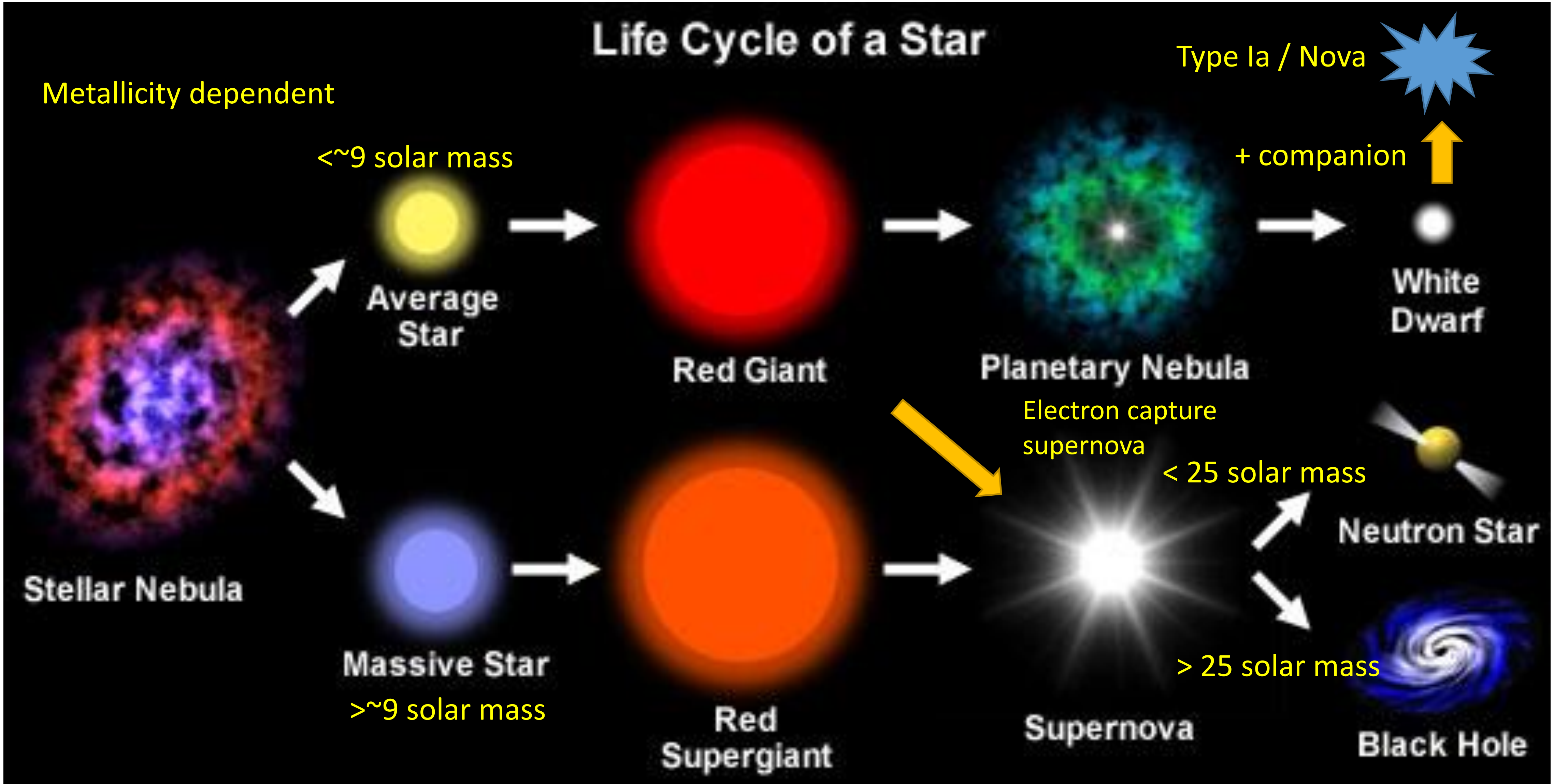
Thermonuclear runaway In Type Ia and Electron Capture Supernova





Massive star, collapsar and Jet formation

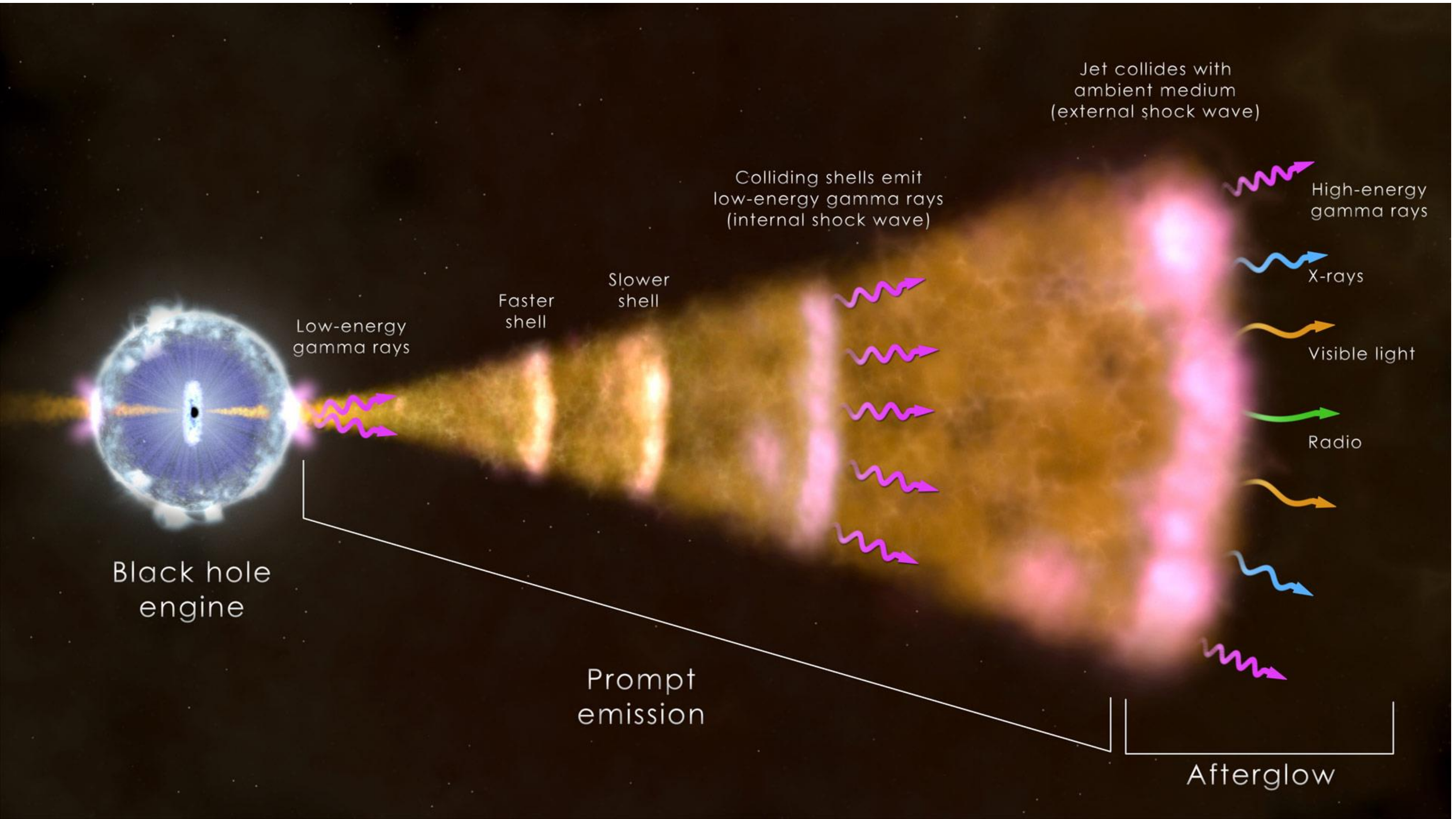
Black hole is not the end…



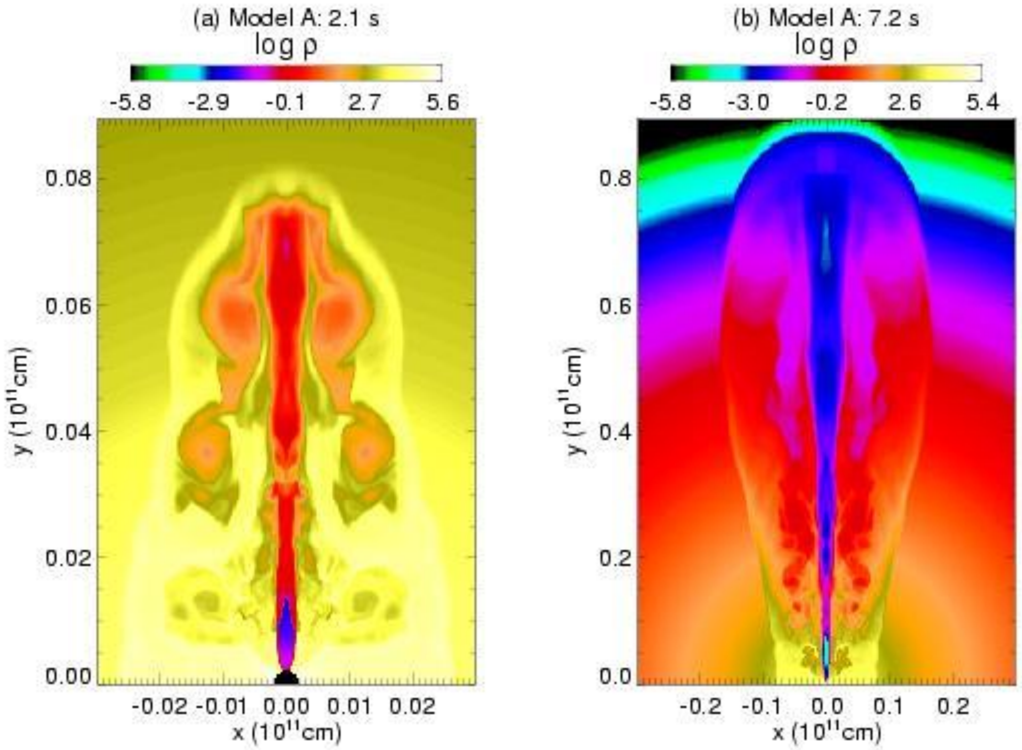
Collapsar

- Energy deposition from black hole accretion disk
- Gamma ray connection

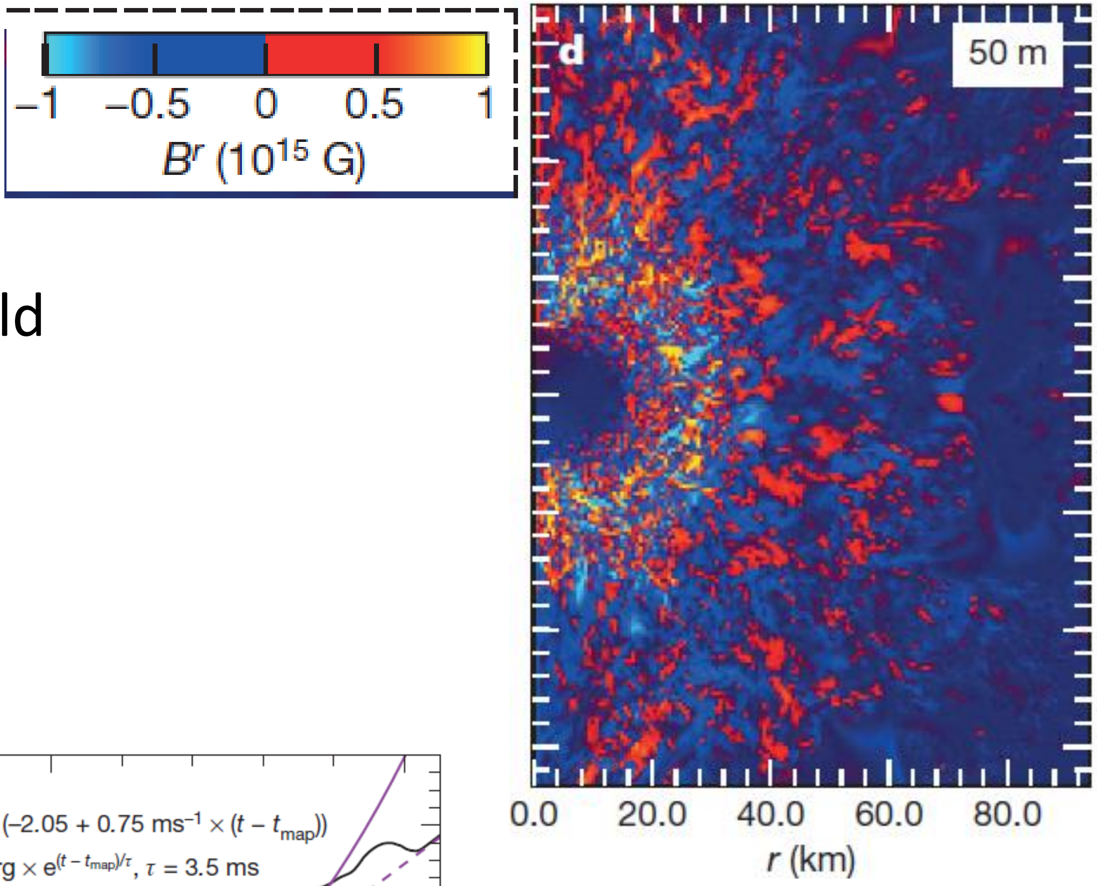
Example:
SN1998bw – GRB980425
Connection
Long duration GRB



Zhang et al., ApJ (2006)



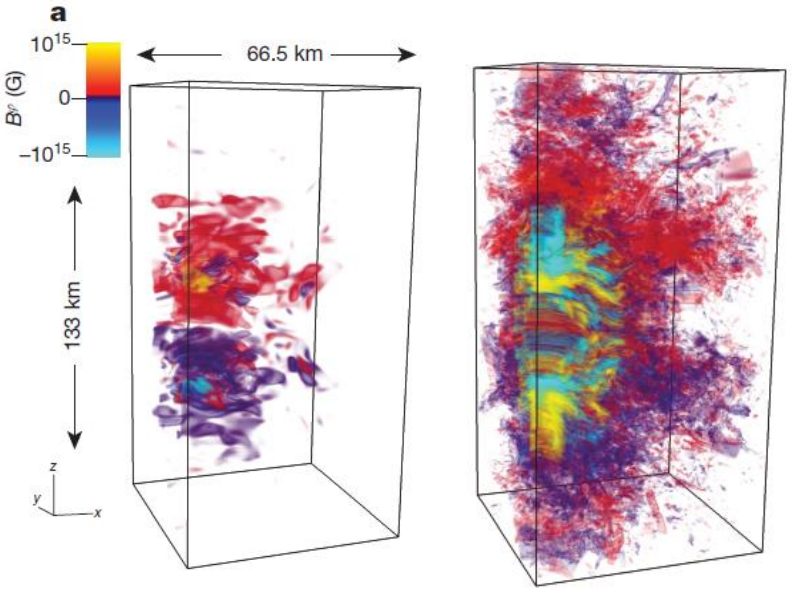
Instability of MHD

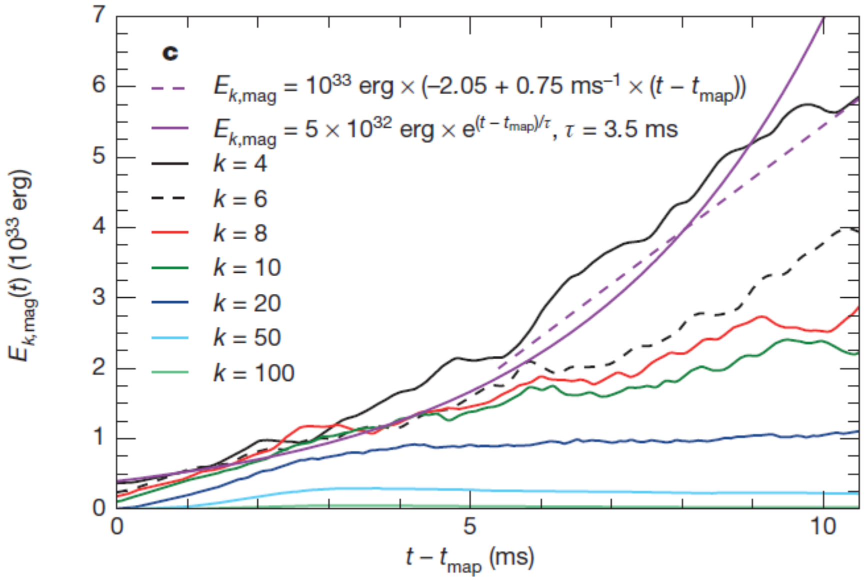


The local turbulence amplifies the magnetic field exponentially

- Magnetic Pressure
- Development of Toroidial magnetic field
    - MHD-powered outflow

Radial B-field at 7.5 ms



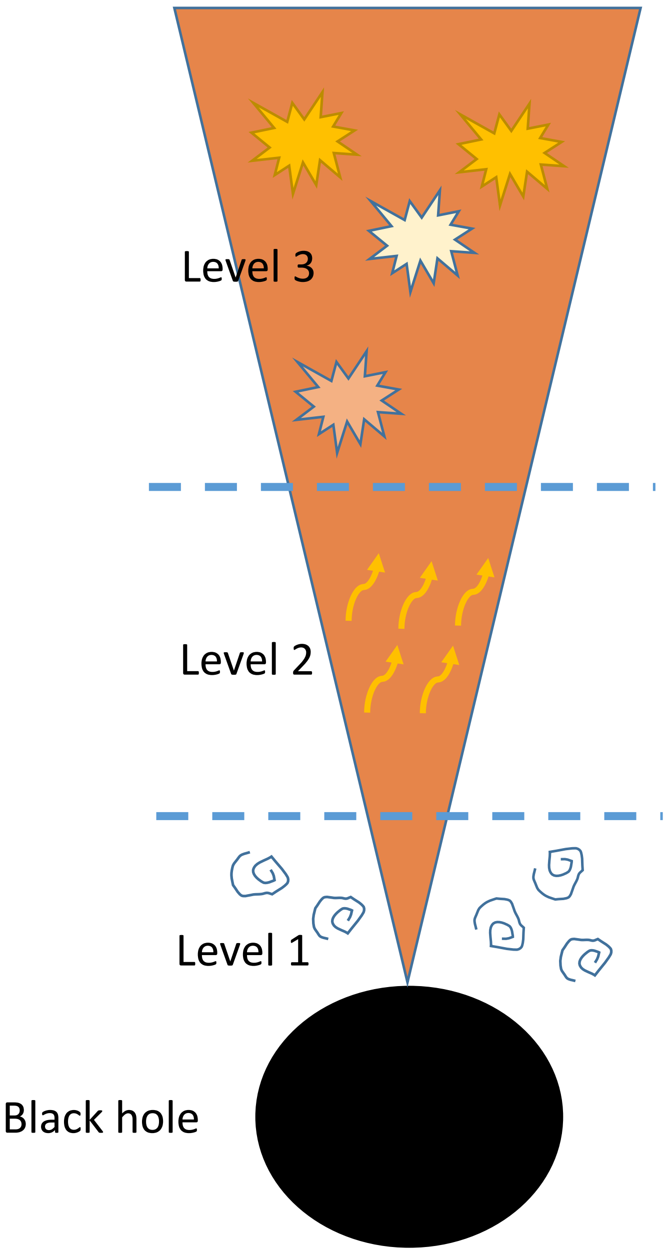


Initial toroidal B-field At 10 ms

Moesta et al., Nature (2015)

Multi-length-scale problem

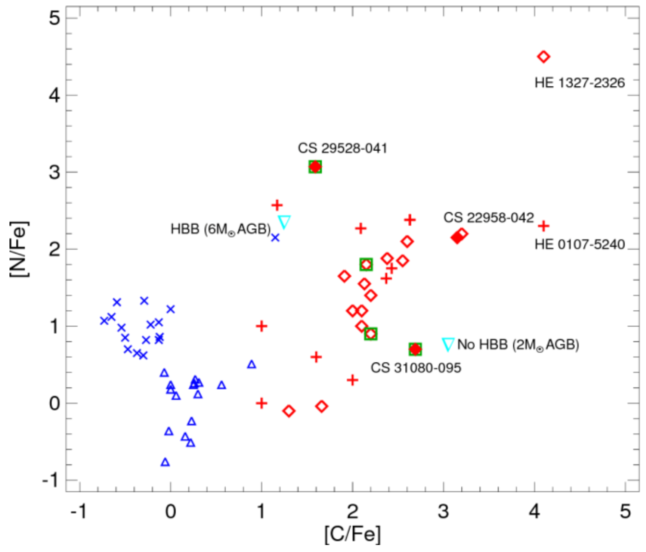
Level 3: Stellar envelope > 1000 km Nucleosynthesis in ejecta Gamma ray burst	Advanced nucleosynthesis Neutrino process
Level 2: Inside mass black hole 50 km - ~ 1000 km Accretion disk	Electron capture Neutrino cooling
Level 1: Black hole nearby Rs – 50 km MHD turbulence	Magneto-rotational instability General relativity



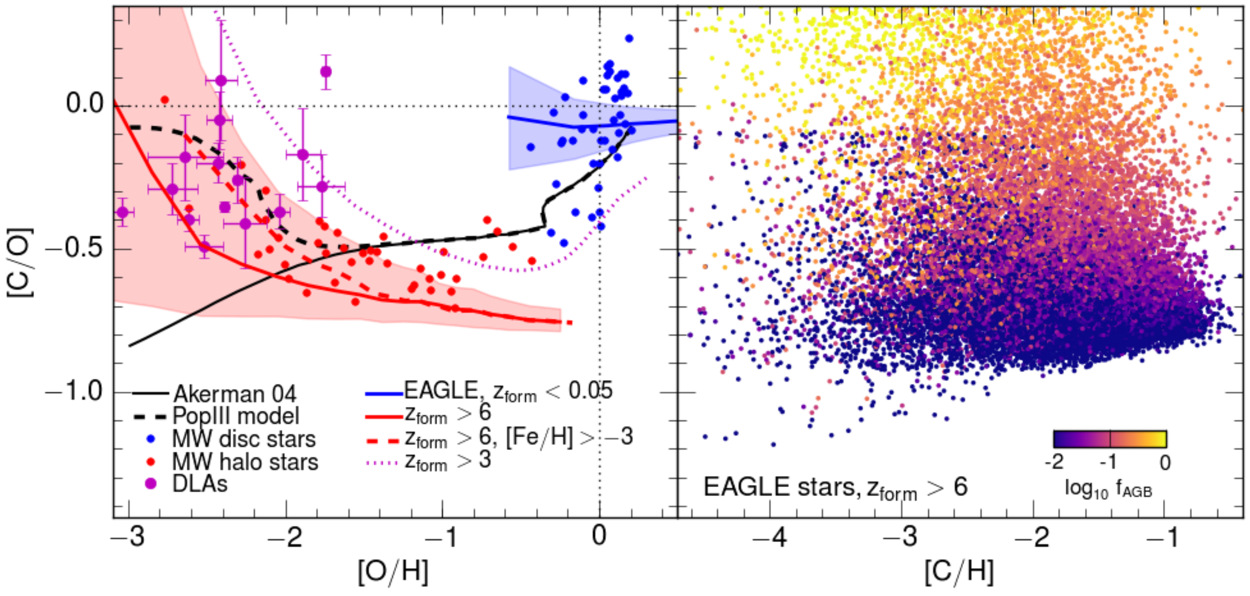
Not in scale

Metal poor stars

- Carbon-enhanced: [C/Fe]= 1-5
- Fallback of Fe-peak elements
  - Fine tune problem?
  - Robust mechanism?
- Formation path?
  - Why metal poor stars tend to be carbon enhanced?
- Stellar abundance survey



Sivarani et al., Franesca Primas (2006)

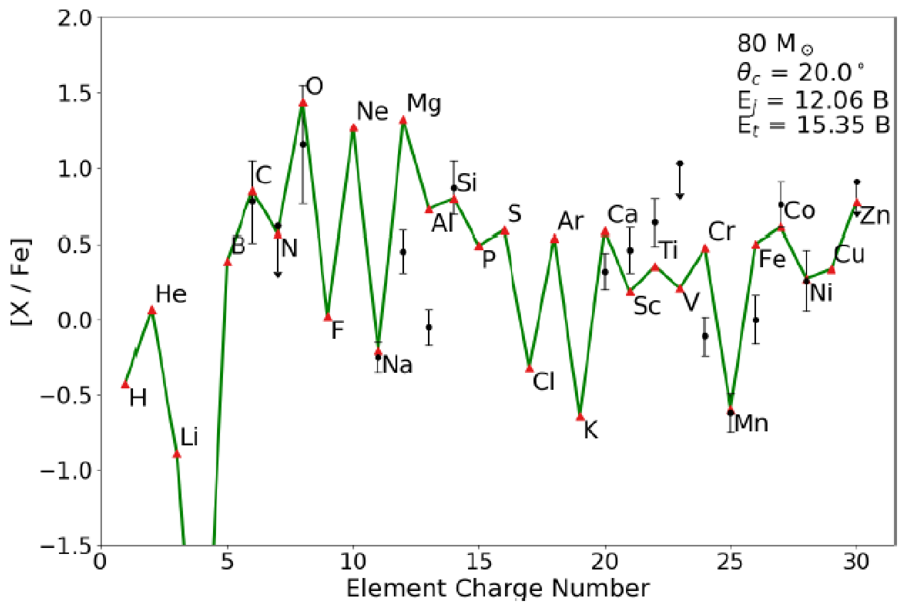


Sharma et al., MNRAS (2018)

Bipolar jet is the solution?

- Aspherical energy deposition by jet
  - Higher entropy production
  - Inhomogeneous mixing

Fitting from 1D model



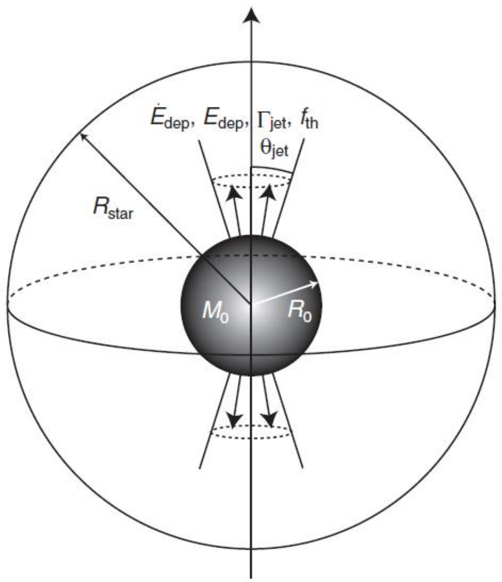
Grimmett et al., MNRAS (2018)

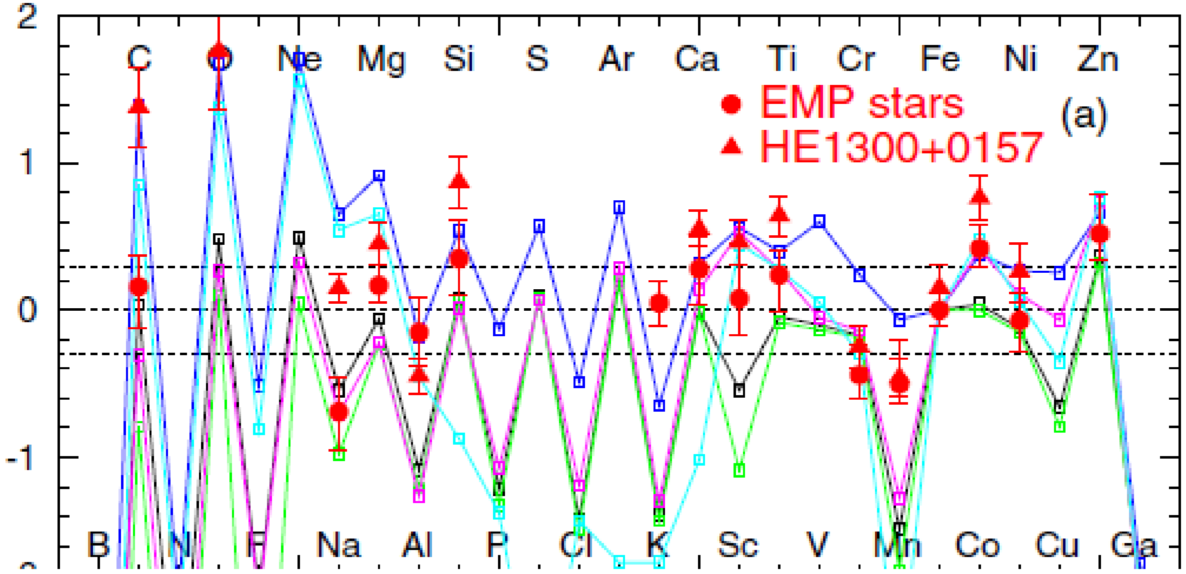
ABSTRACT

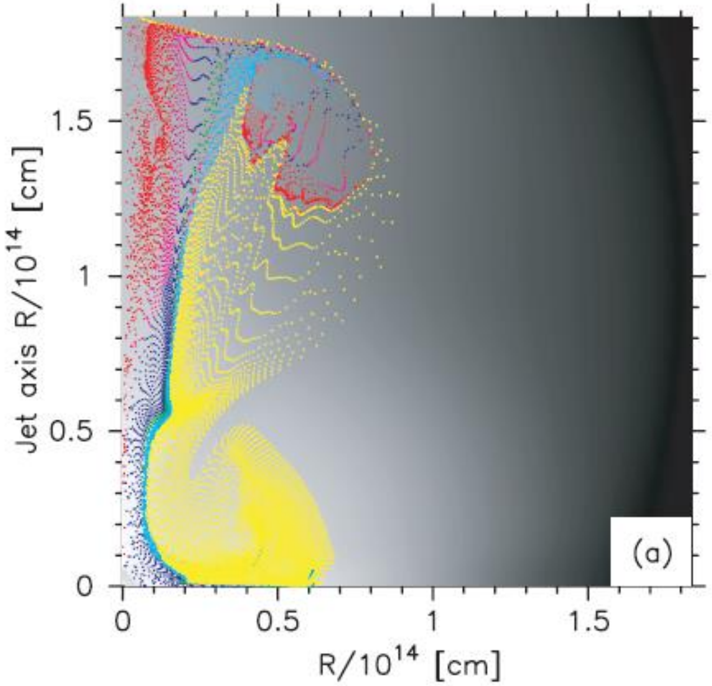
We investigate the relationship between explosion energy and nucleosynthesis in Population III supernovae and provide nucleosynthetic results for the explosions of stars with progenitor masses of 15 $M_\odot$, 20 $M_\odot$, 30 $M_\odot$, 40 $M_\odot$, 60 $M_\odot$, and 80 $M_\odot$, and explosion energies between approximately 10^{50} erg and 10^{53} erg. We find that the typical abundance pattern observed in metal-poor stars is best matched by supernovae with progenitor mass in the range 15 $M_\odot$ – 30 $M_\odot$ and explosion energy of $\sim(5-10)\times10^{51}$ erg. In these models, a reverse shock caused by jumps in density between shells of different composition serves to decrease synthesis of chromium and manganese, which is favourable to matching the observed abundances in metal-poor stars. Spherically symmetric explosions of our models with progenitor mass $\geq$40 $M_\odot$ do not provide yields that are compatible with the iron-peak abundances that are typically observed in metal-poor stars; however, by approximating the yields that we might expect from these models in highly aspherical explosions, we find indications that explosions of stars 40 $M_\odot$ – 80 $M_\odot$ with bipolar jets may be good candidates for the enrichment sources of metal-poor stars with enhanced carbon abundances.

Level 3: Outside accretion disk

- Depositing energy by bipolar jet
  - Deposition energy
  - Jet duration
  - Jet velocity (kinetic energy ratio)



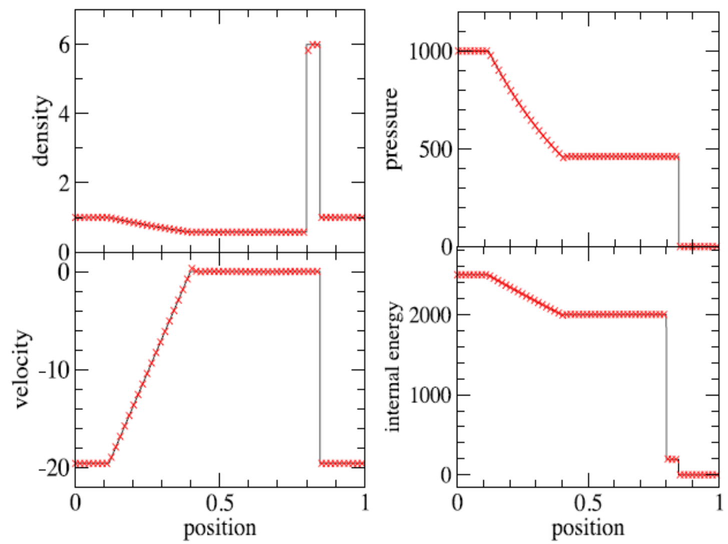


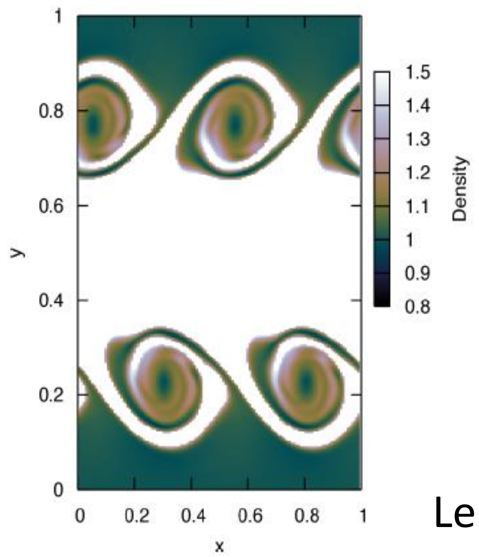


Tominaga, ApJ 2009

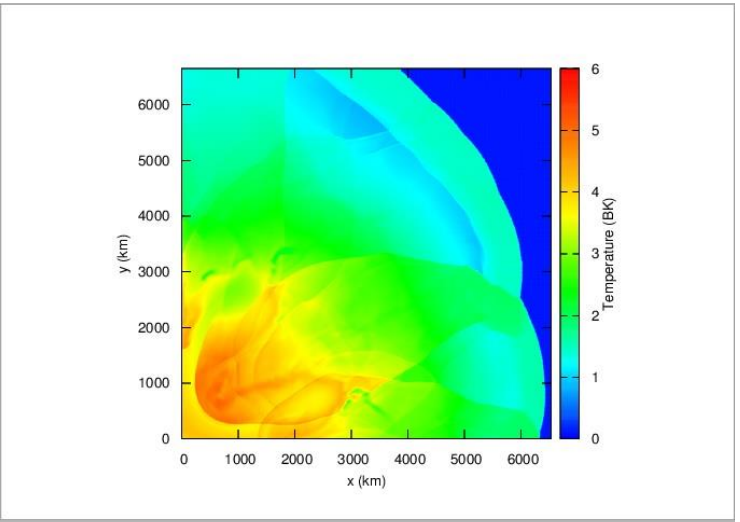
Change of input physics

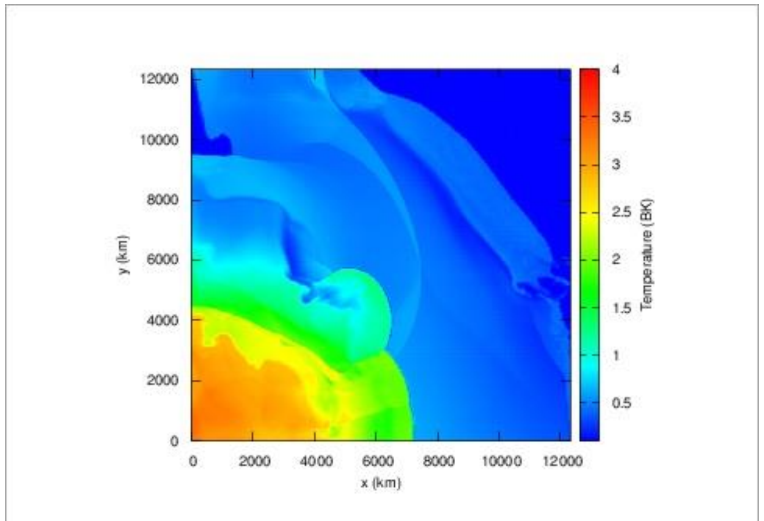
- Helmholtz equation of state
  - Temperature, composition dependent
- Nuclear Statistical Equilibrium
- WENO 5th order shock capturing scheme
- 495-isotope network post-processing
  - With neutrino neutral/charged processes





Leung et al., MNRAS (2015)





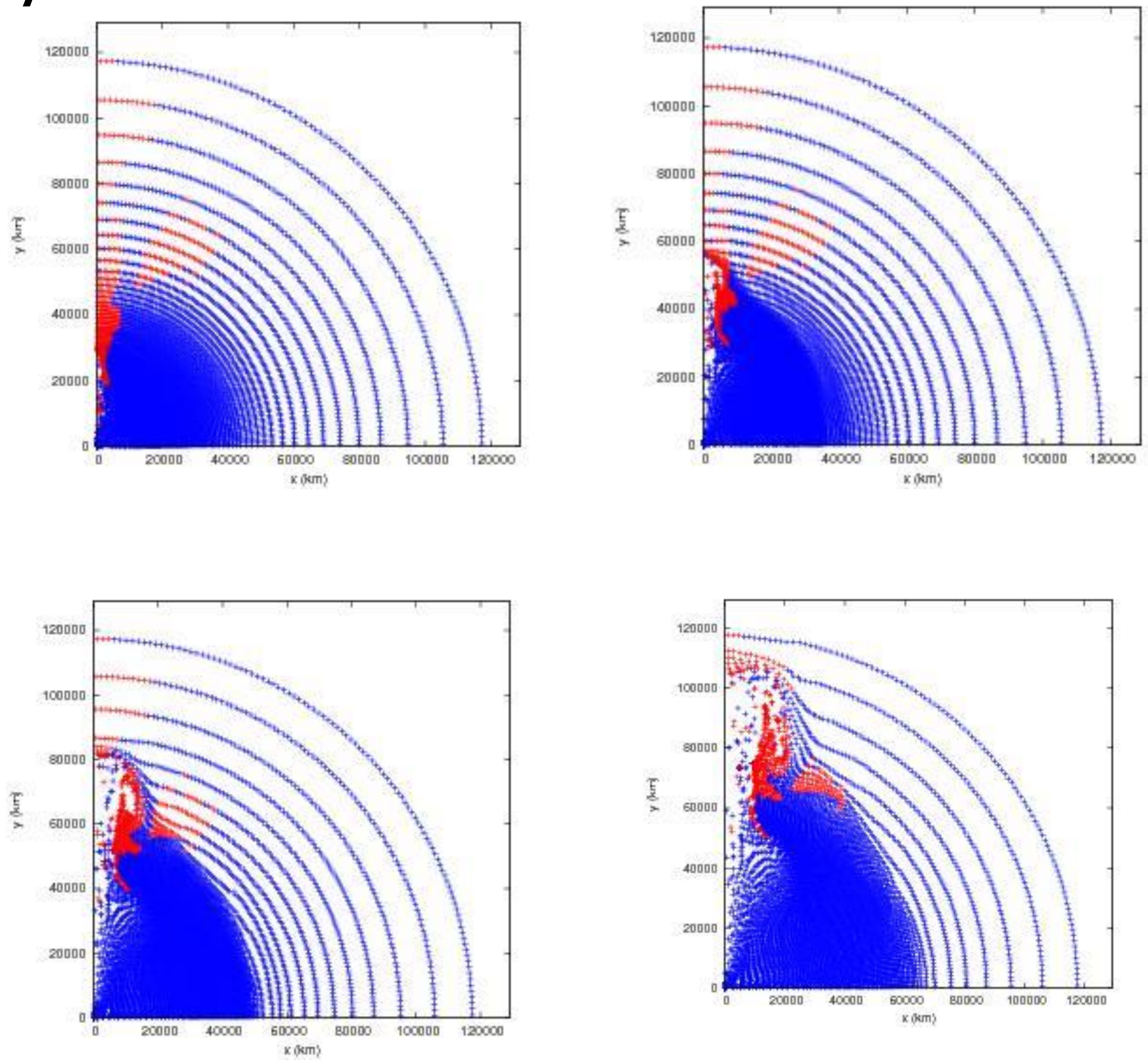
Model parameter survey

Survey on the nucleosynthesis from 2D models

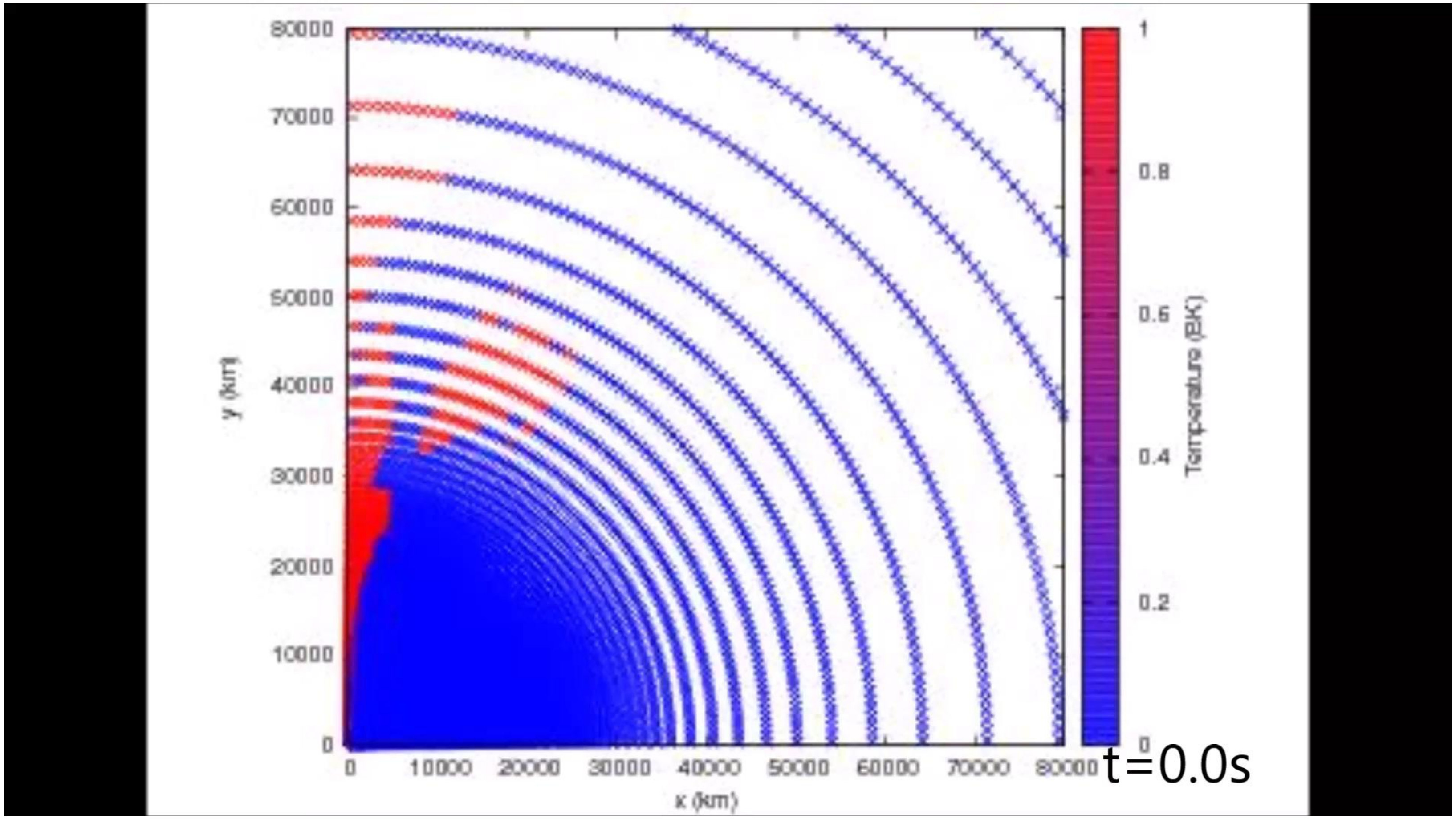
Black-hole progenitor

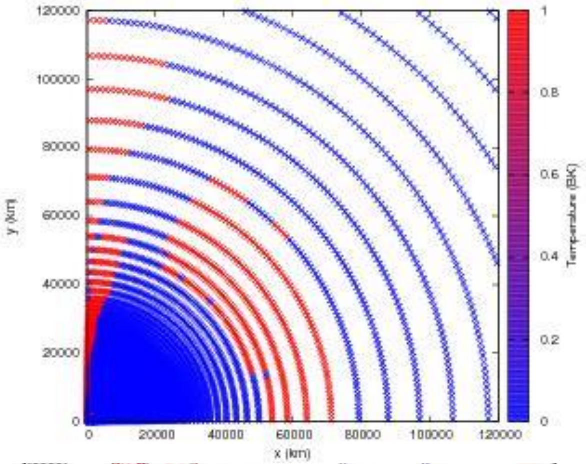
- Mass: 40, 50, 60, … 140 M_{sun}
- Metallicity: 0, 0.01, 0.1 Z_{sun}
- Explosion energy 10^{52} – 10^{53} erg

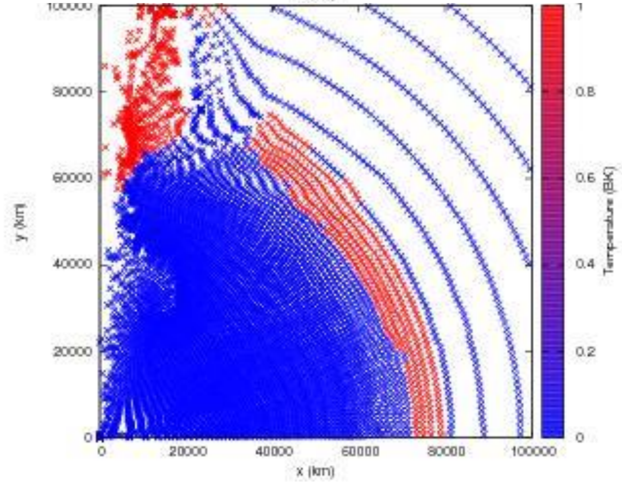
Some snapshot of the ejecta (40 solar mass, 0 Z)
Tracer particle (Lagrangian perspective)
Red: Can escape at the end of simulation



Ejecta evolution





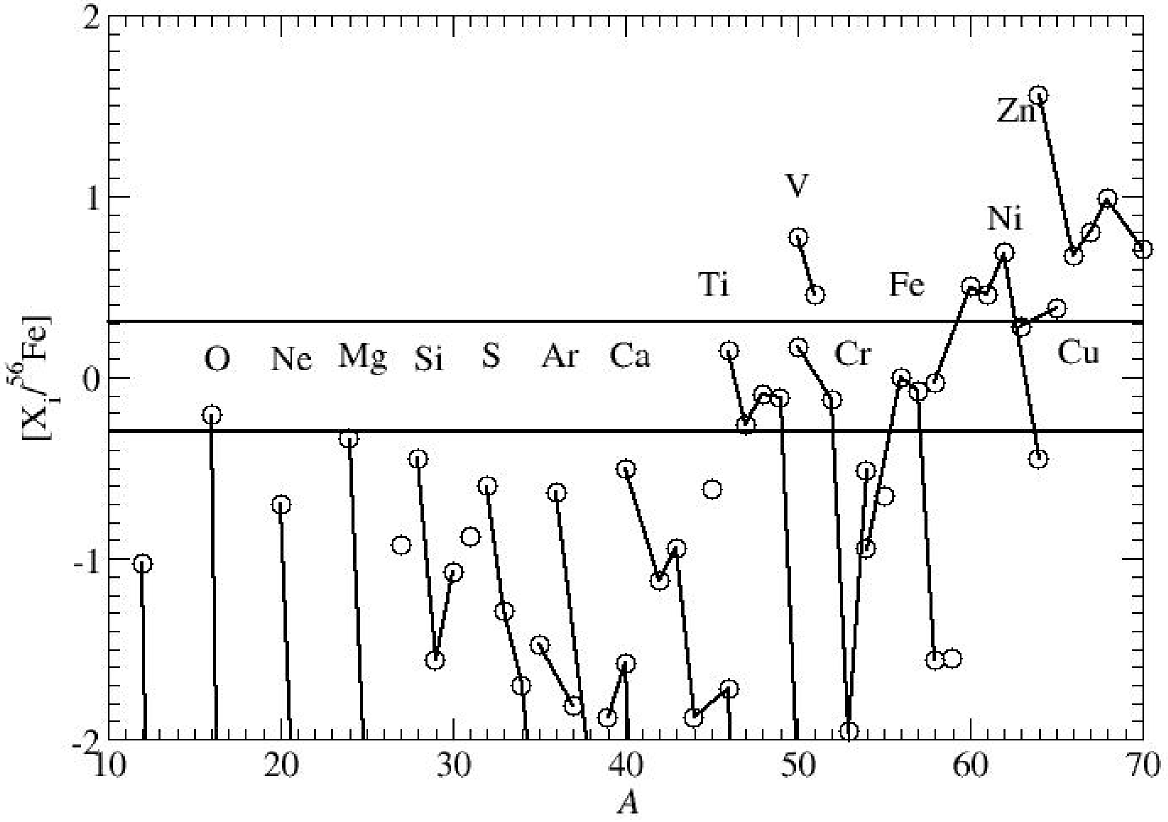


Final ejecta at 15.0 s
Upper: Distribution using initial position
Lower: Distribution using final position

Nucleosynthesis yield

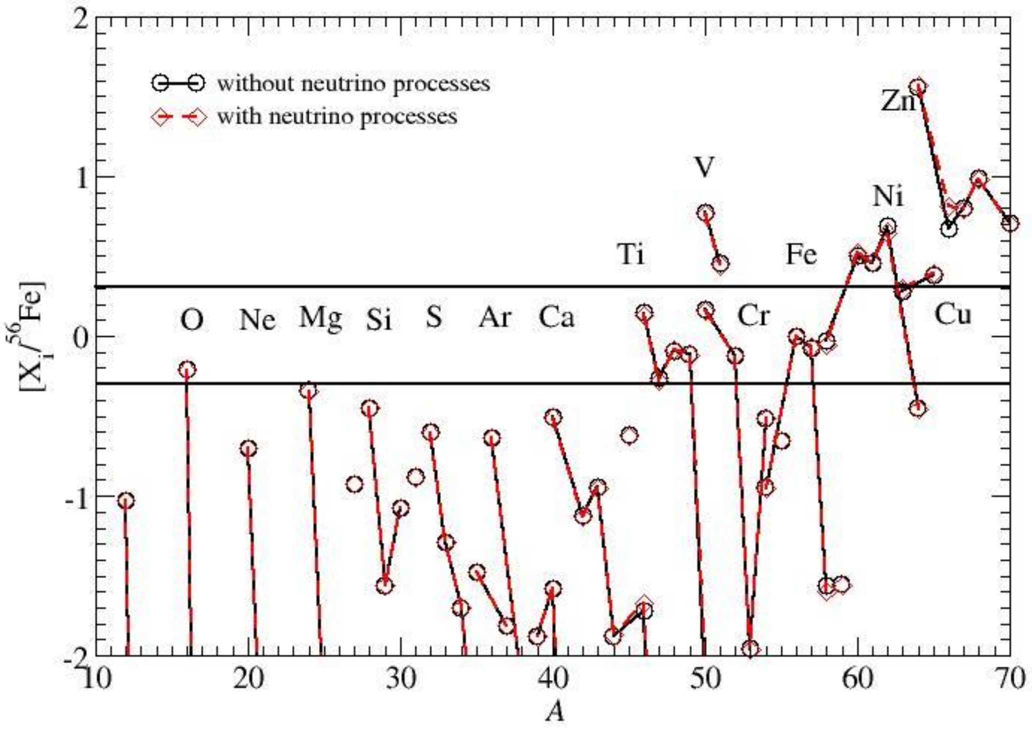
Progenitor mass 15 M_{sun}
Ejecta mass ~1 M_{sun}
Ejected ^{56}Ni: ~0.1 M_{sun}

Benchmark



Preliminary results, Leung et al., (2017, 2018)

Effects of neutrino



Preliminary results, Leung et al., (2018)

$$(Z, A) + \nu \rightarrow (Z, A)^* + \nu' \rightarrow (Z, A-1) + n + \nu' ,$$
$$\rightarrow (Z-1, A-1) + p + \nu' ,$$
$$\rightarrow (Z-2, A-4) + \alpha + \nu' . \quad (1)$$

Woosley, ApJ (1990)

And four more exotic neutrino reactions
-- neutral current reactions X8
-- charged current reactions X4

Parametrized neutrino luminosity (neutron star type)
Neutrino cross section table
- Isotope dependent

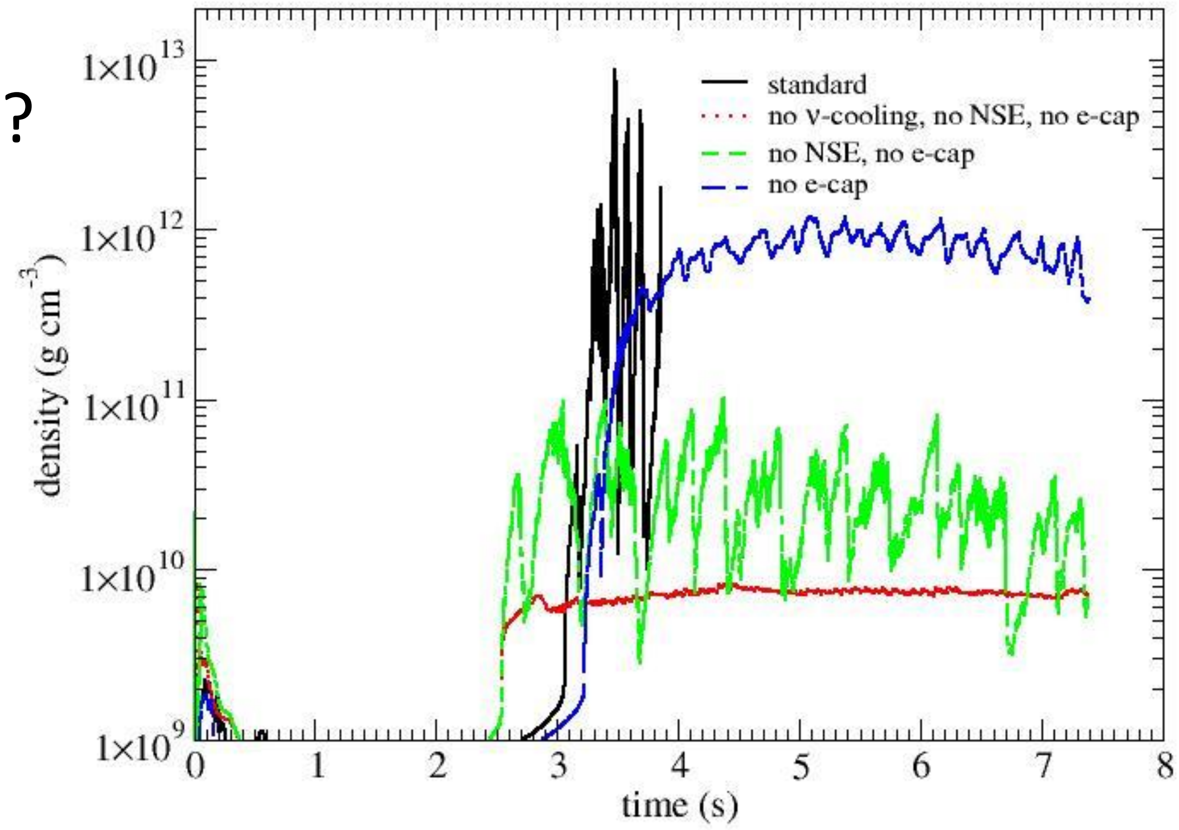
Very small effects
-- Time delay between neutrino emission and black hole jet?

Level 2: Accretion disk

Question: What is the typical neutrino pattern?

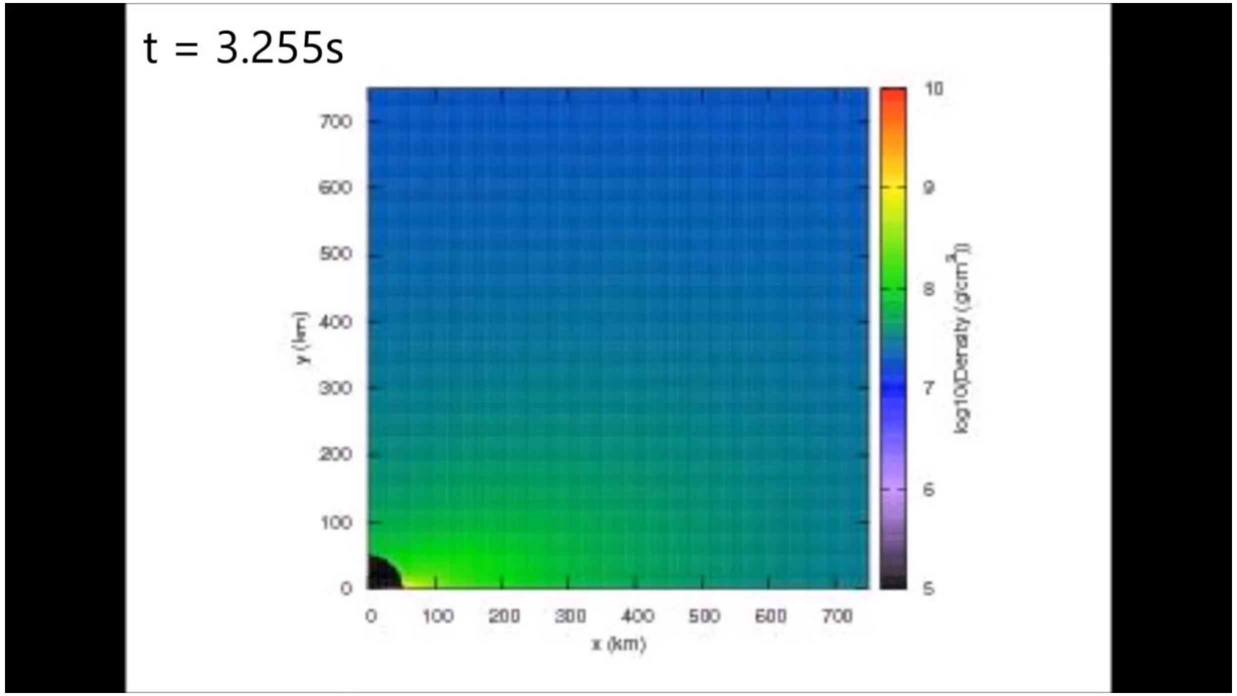
Input physics on the disk behaviour

- What is the outbreak condition?
- Extend the code
  - GR approximation
  - Parametrized e-cap scheme
  - Neutrino cooling



Preliminary results, Leung et al., (2018)

Stability of accretion disk

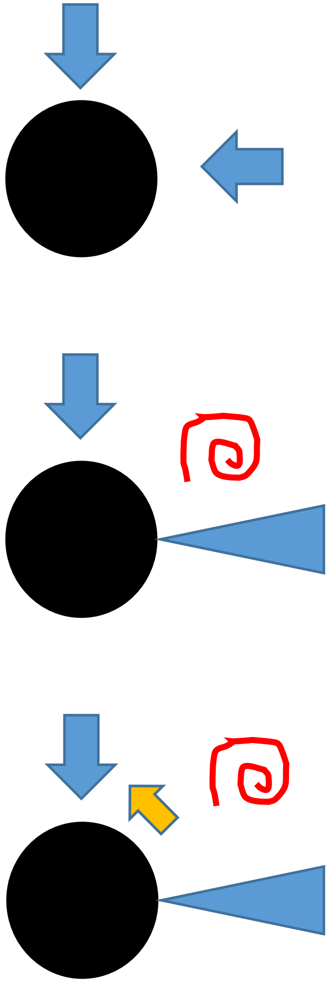


Beginning:
Freefall of matter onto black hole

>1s
Stacking of matter by rotation

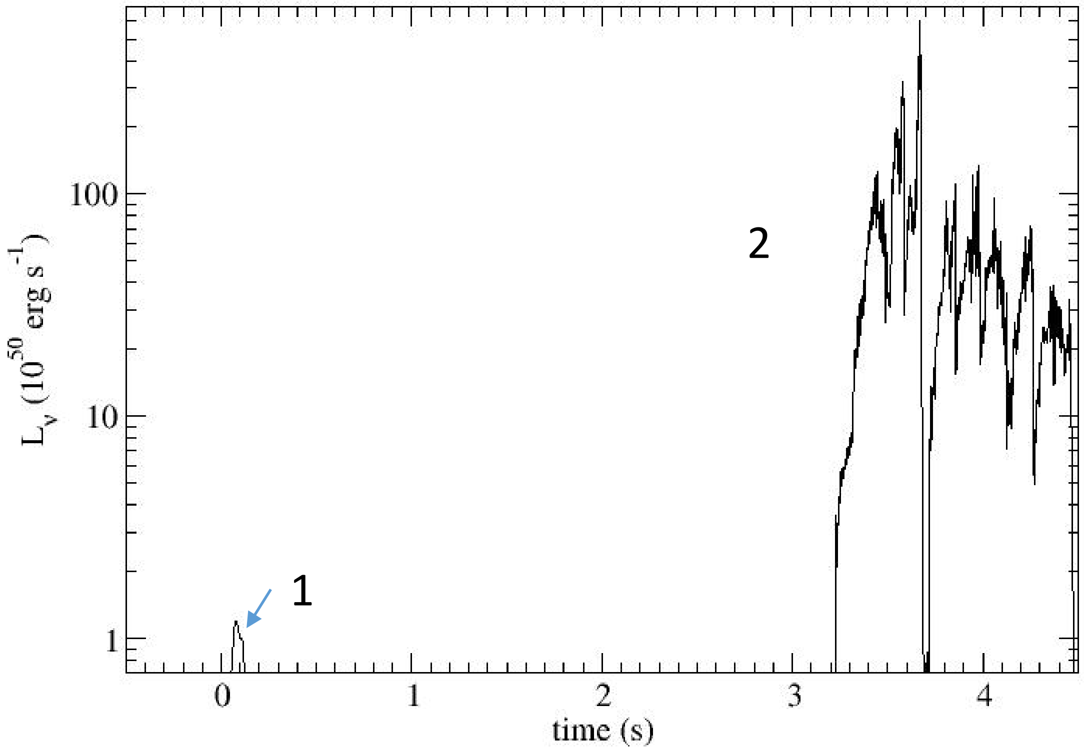
Density gradient between free fall channel and disk surface
Electron-capture

Accretion Disk oscillation
Disk outburst



Preliminary results, Leung et al., (2018)

Neutrino source (thermal neutrino)



1. Mild neutrino right after collapse

2. Much stronger neutrino emission after formation of accretion disk

Preliminary results, Leung et al., (2018)

Conclusion

2D simulation Jet induced explosion

- Realistic EOS
- Neutrino processes

Role of accretion disk to thermal neutrino

Future work

- More realistic neutrino emission

QUESTIONS?

THANK YOU!