Three-Dimensional Long-Term CCSN Simulations: New Insights and Challenges

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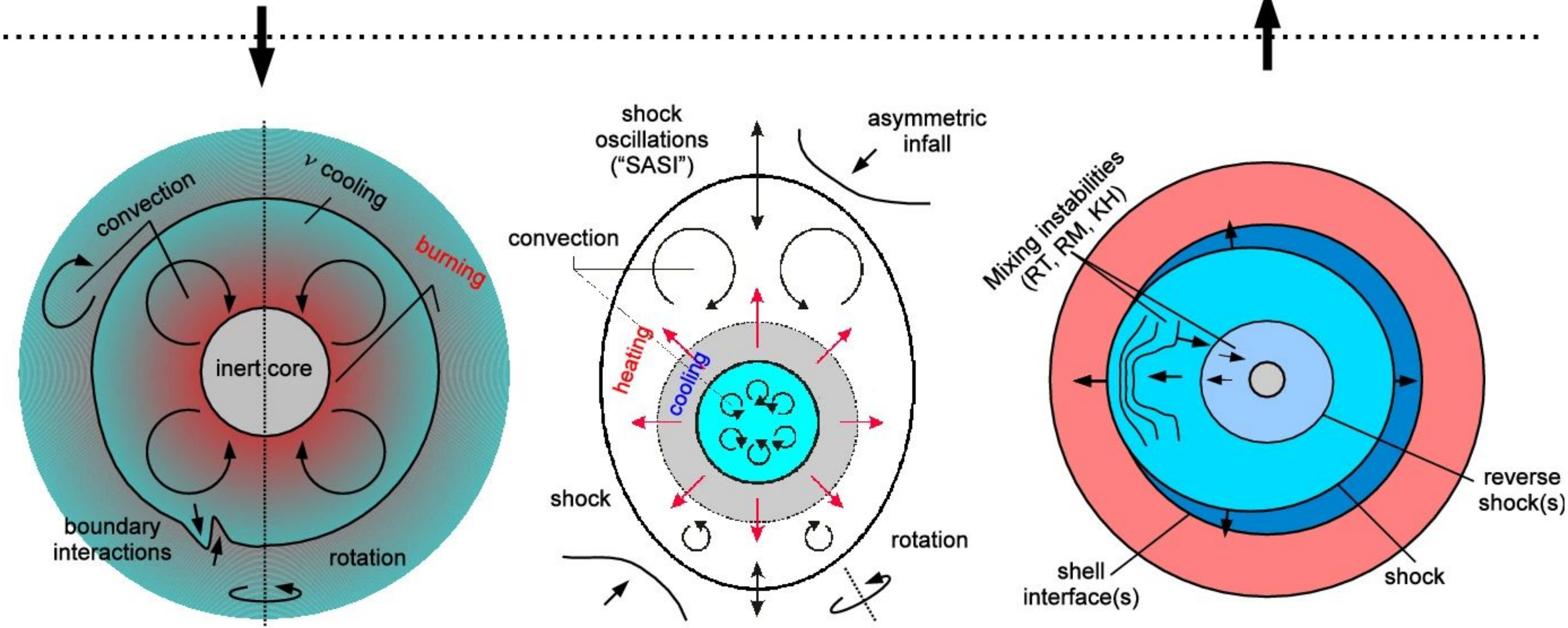
Muller+2020

Formation of CCSNe

Stellar evolution from the main sequence through H and He core burning to the beginning of C burning: $\mathcal{O}(10^7$ years)

Observable transient: $\mathcal{O}$(months)

Supernova remnant evolution: $\mathcal{O}(10^4$-10^5 years)

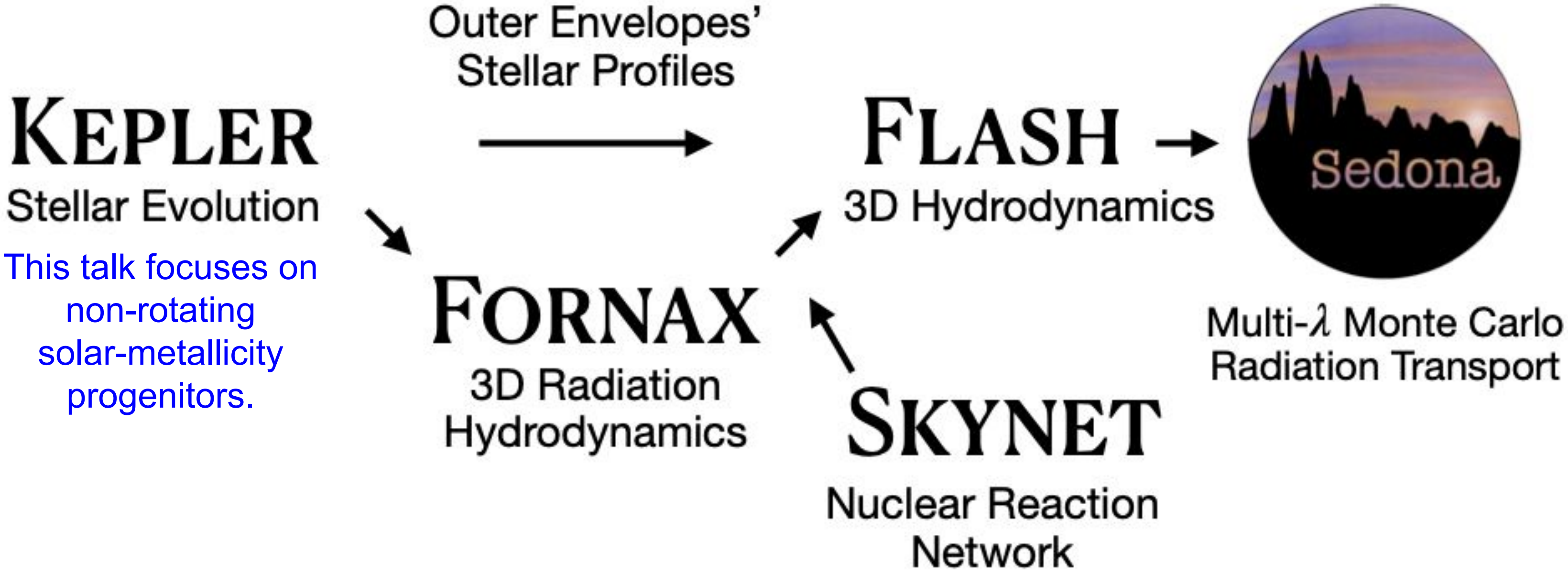


(a) C, Ne, O, and Si core and shell burning (years to hours)

(b) Core collapse and shock revival (hundreds of milliseconds)

(c) Explosion phase up to shock breakout (hours to days)

Our End-to-End Simulation Pipeline



This talk focuses on non-rotating solar-metallicity progenitors.

In this talk, "long-term simulation" has two meanings:

- The rad-hydro phase is extended to >5 seconds post-bounce.
- The CCSN model is calculated to days/weeks post-bounce.

Example 1: Solving the CCSN ^{44}Ti Problem

FORNAX
3D Radiation Hydrodynamics

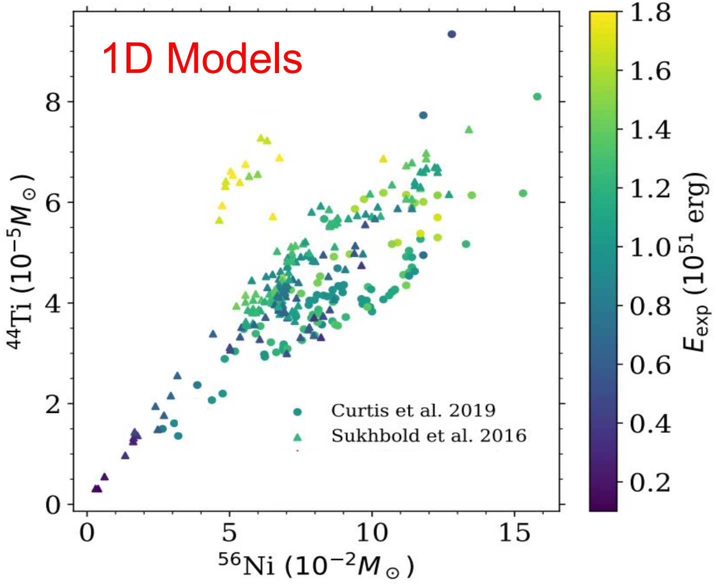
SKYNET
Nuclear Reaction Network

Sieverding+2023

What's the ^{44}Ti Problem?

Spherical symmetric (1D) models have difficulties explaining the observed ^{44}Ti abundance or ^{44}Ti/^{56}Ni ratios.

This is known as the "^{44}Ti problem" since pointed out in 2006.



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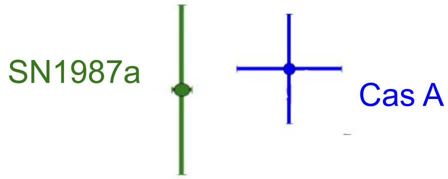

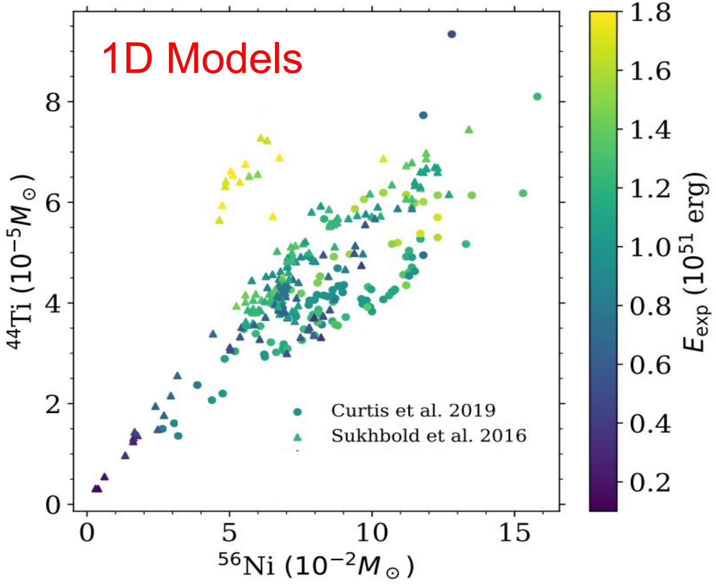

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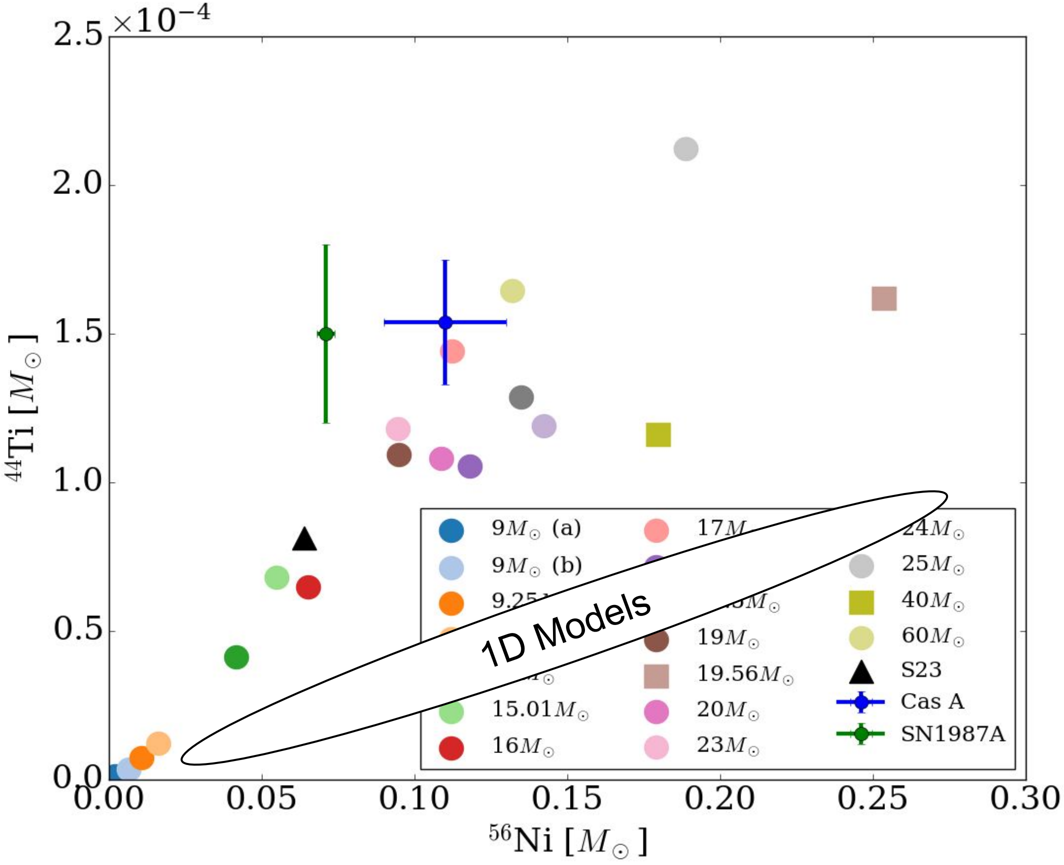
No ^{44}Ti Problem Seen in 3D Long-Term Simulations



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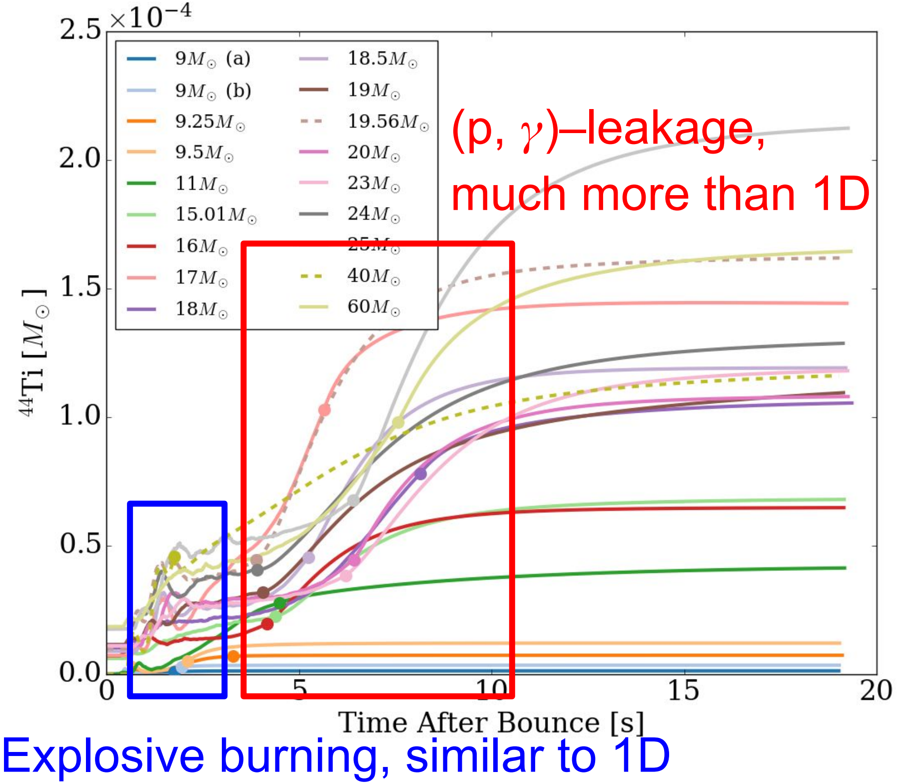


To boost (p, γ)–leakage, we need more matter with:

- Ye > 0.5
- Heated to a few GK

These conditions mean that the matter has interacted with neutrinos.

Why does 3D have more such neutrino-heated matter than 1D?

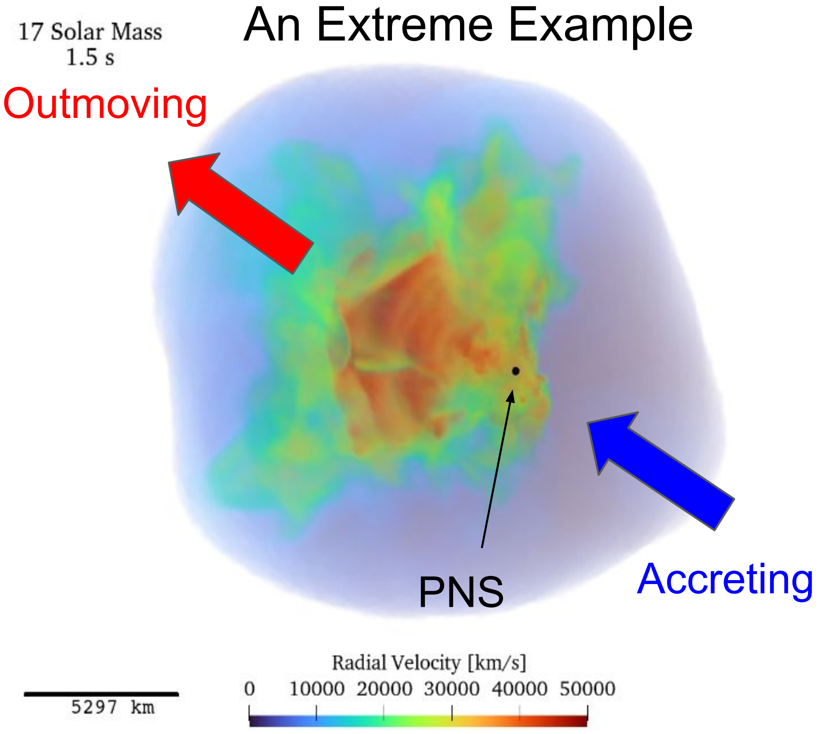
Simultaneous Explosion and Accretion

Accretion funnels form after the shock revival. Matter falls towards the PNS through the funnels, and most of them are ejected later.

This will influence:

- Nucleosynthesis (e.g., ^{44}Ti).
- Explosion energy.
- PNS mass, kick, spin.
- …

Such effects can last as long as ~10 seconds, and they require neutrino transport. Only long enough rad-hydro sims can show their effects.



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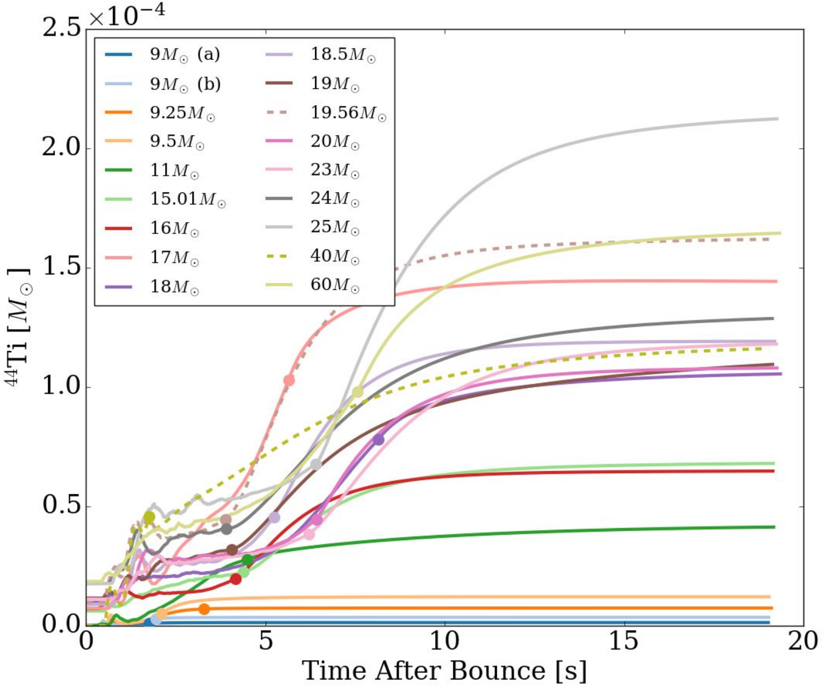


Summary: 3D Models Naturally Solve the ^{44}Ti Problem

Two channels to produce ^{44}Ti:

- Explosive burning — Subdominant, seen in both 1D and 3D.
- (p, γ)–leakage in neutrino heated matter (neutrino-driven winds) — Only seen in 3D.

The simultaneous explosion and accretion phenomenon allows more mass to interact with neutrinos, and thus enhances the (p, γ)–leakage channel of ^{44}Ti production.

This phenomenon lasts for ~10s and long rad-hydro simulations are required.

Arxiv: 2406.13746

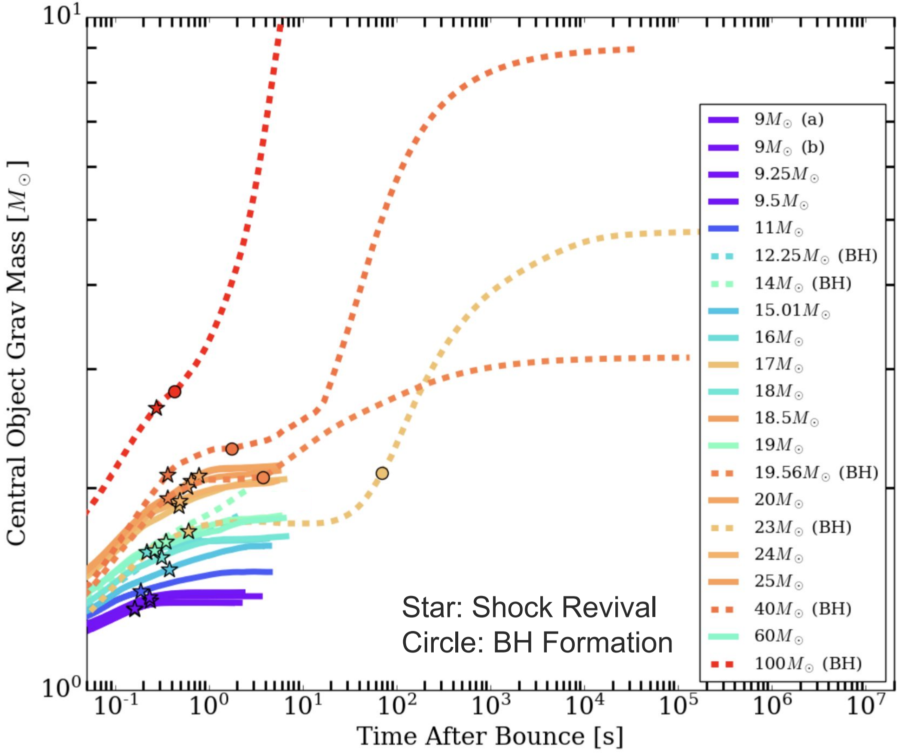
Example 2: Black Hole Formation Channels

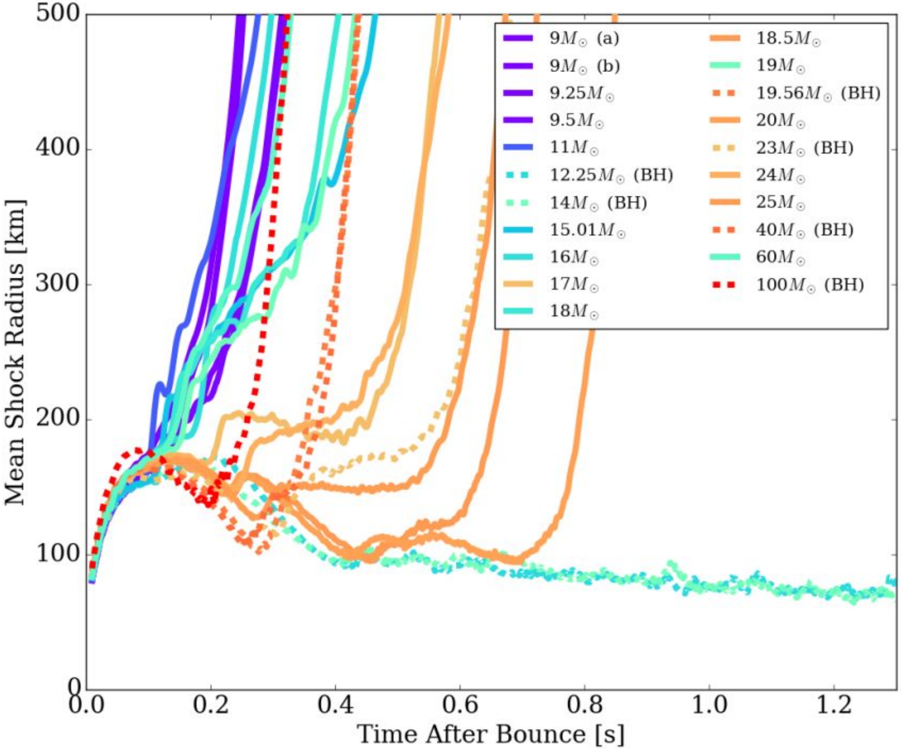
FORNAX
3D Radiation Hydrodynamics

FLASH
3D Hydrodynamics

Burrows+2024

BHs are Formed in Some 3D Models





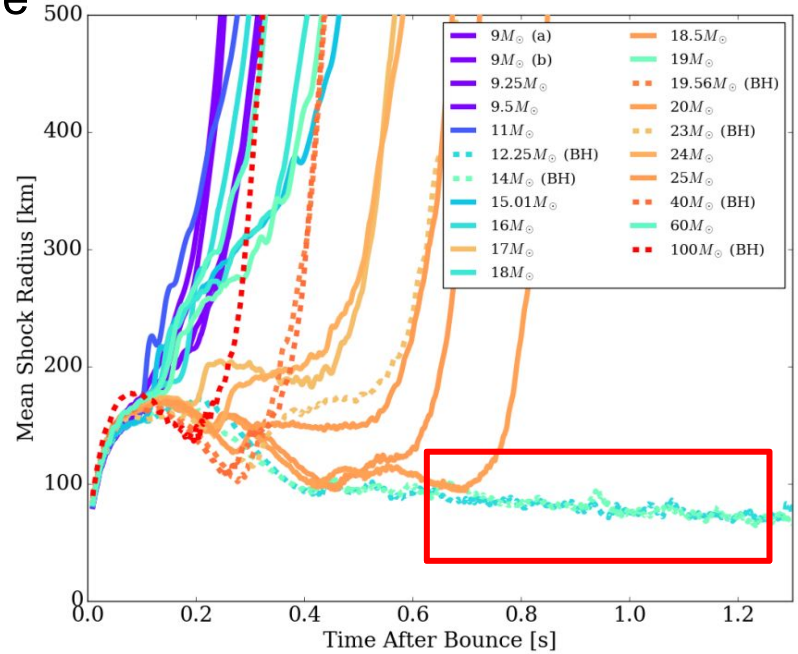
But they have very different properties. How to classify them?

Failed Supernovae Form BHs

If the shock never revives — typical failed SNe

- Silent formation.
- ~10 Msun (stellar mass at collapse)
- Near zero kick/spin due to neutrinos.

Example: 12.25 and 14 Msun models.



Burrows+2024

Failed Supernovae Form BHs

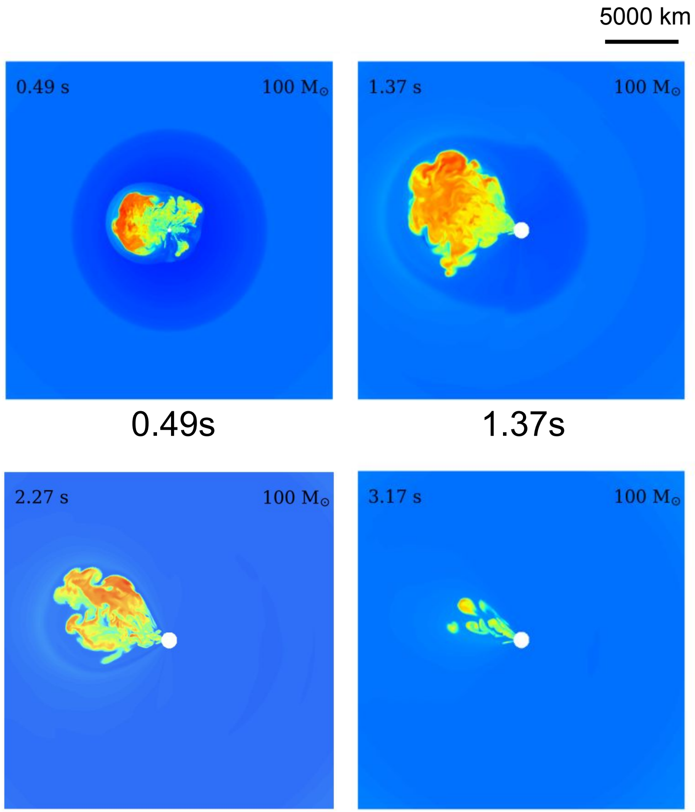
The shock never revives — typical failed SNe:

- Silent formation.
- ~10 Msun (~stellar mass at collapse).
- Near zero kick/spin due to neutrinos.

The shock revives, but explosion is aborted by BH formation — most massive progenitor:

- Silent formation.
- 30~40 Msun (~stellar mass at collapse).
- Near zero kick/spin due to neutrino.

Example: 100 Msun 0.1 solar metallicity model.



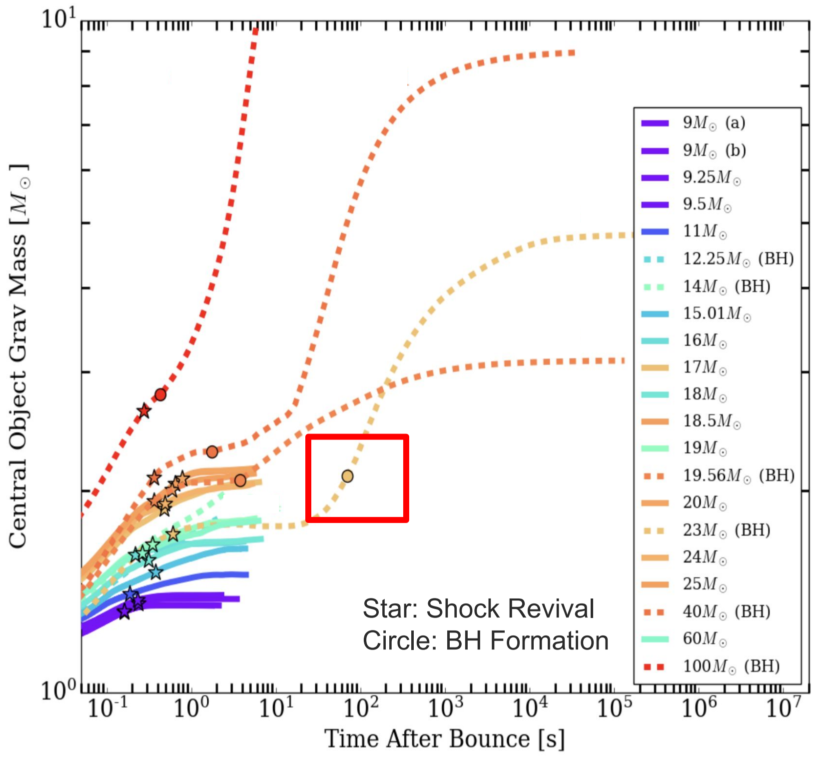
0.49s 1.37s 2.27s 3.17s

Successful Supernovae Also Form BHs

A weak explosion with strong fallback:

- Relatively low energy.
- 5~10 Msun, sensitive to fallback
- ~100 km/s kick, sensitive to fallback.

Example: 23 Msun model (E=0.5B).



Burrows+2024

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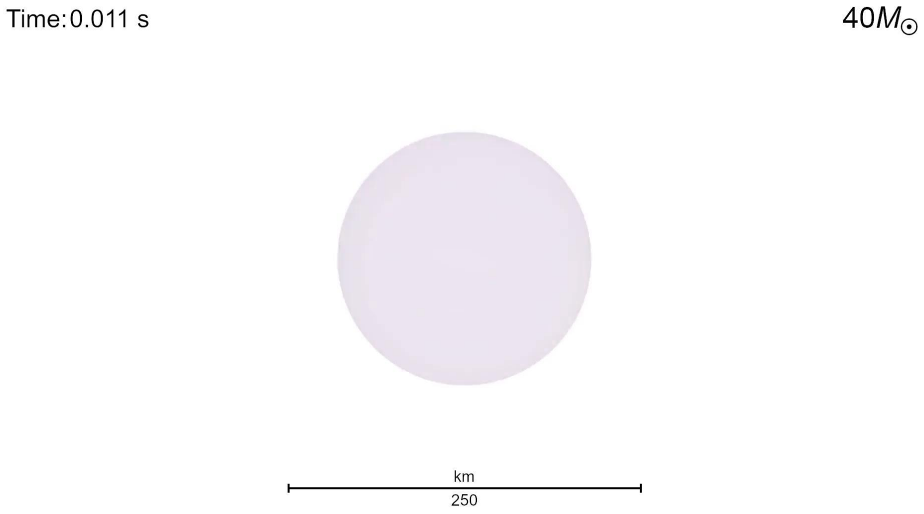
Example: 23 Msun model (E=0.5B).

The strongest explosions:

- ~2 B explosion energy.
- 3~9 Msun.
- 500~1300 km/s kick. Lowest mass ones can explain the NS-BH mass gap.

Example: 19.56 and 40 Msun models.

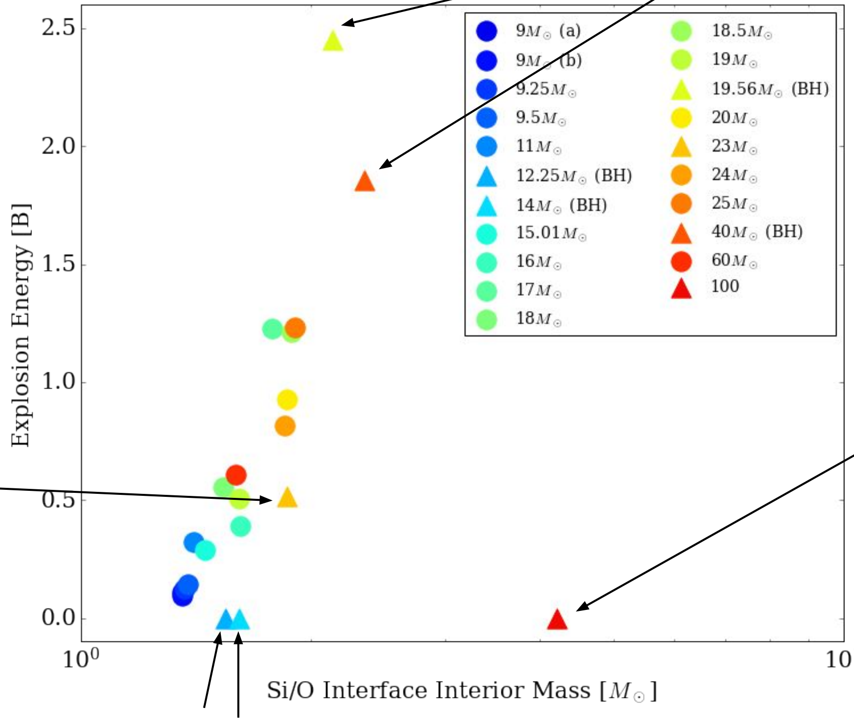


Four BH Formation Channels

BH with a strong explosion

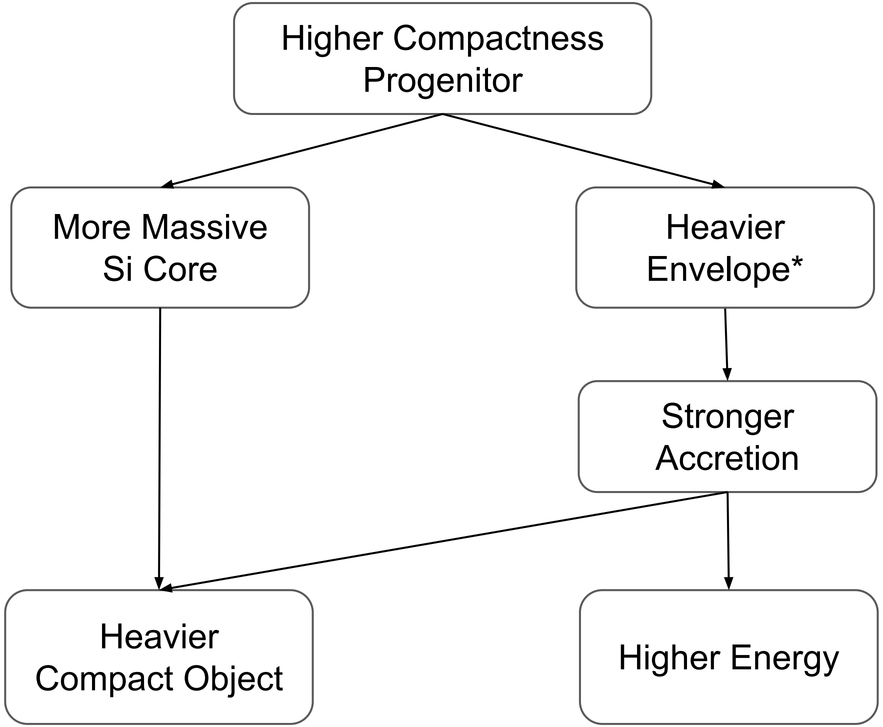
BH in weakly exploding models

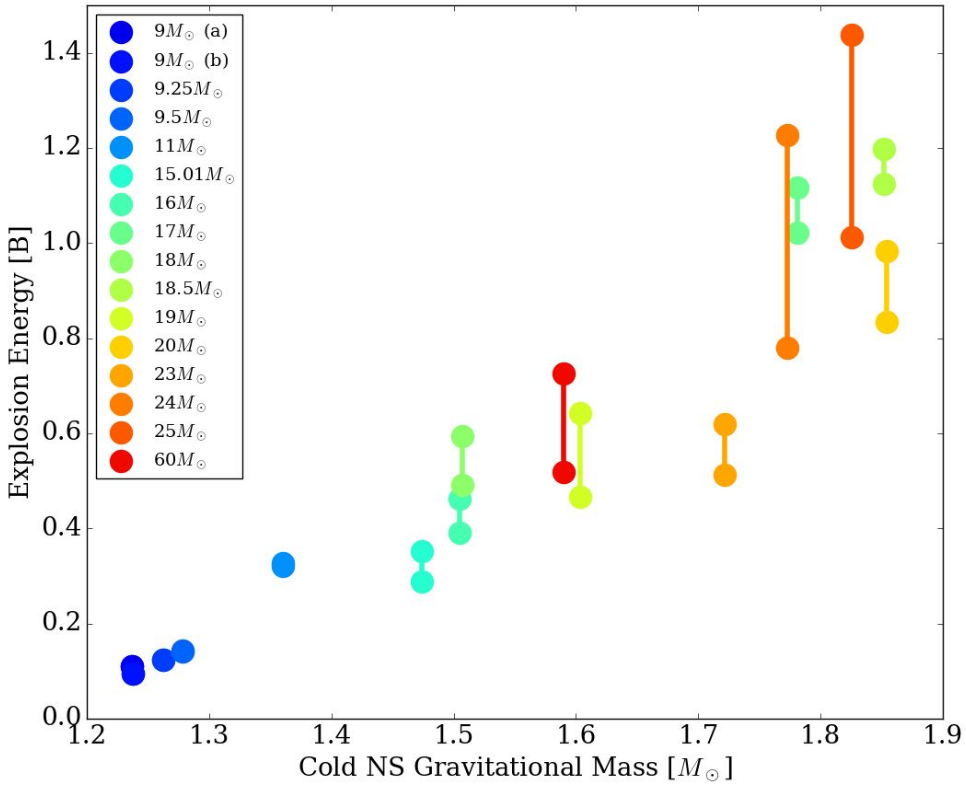
BH with aborted explosion



BH formed without shock revival, 11 and 12 Msun

Why Such Trend: Correlations in CCSN Explosions





*Envelope refers to matter roughly above the Si core.

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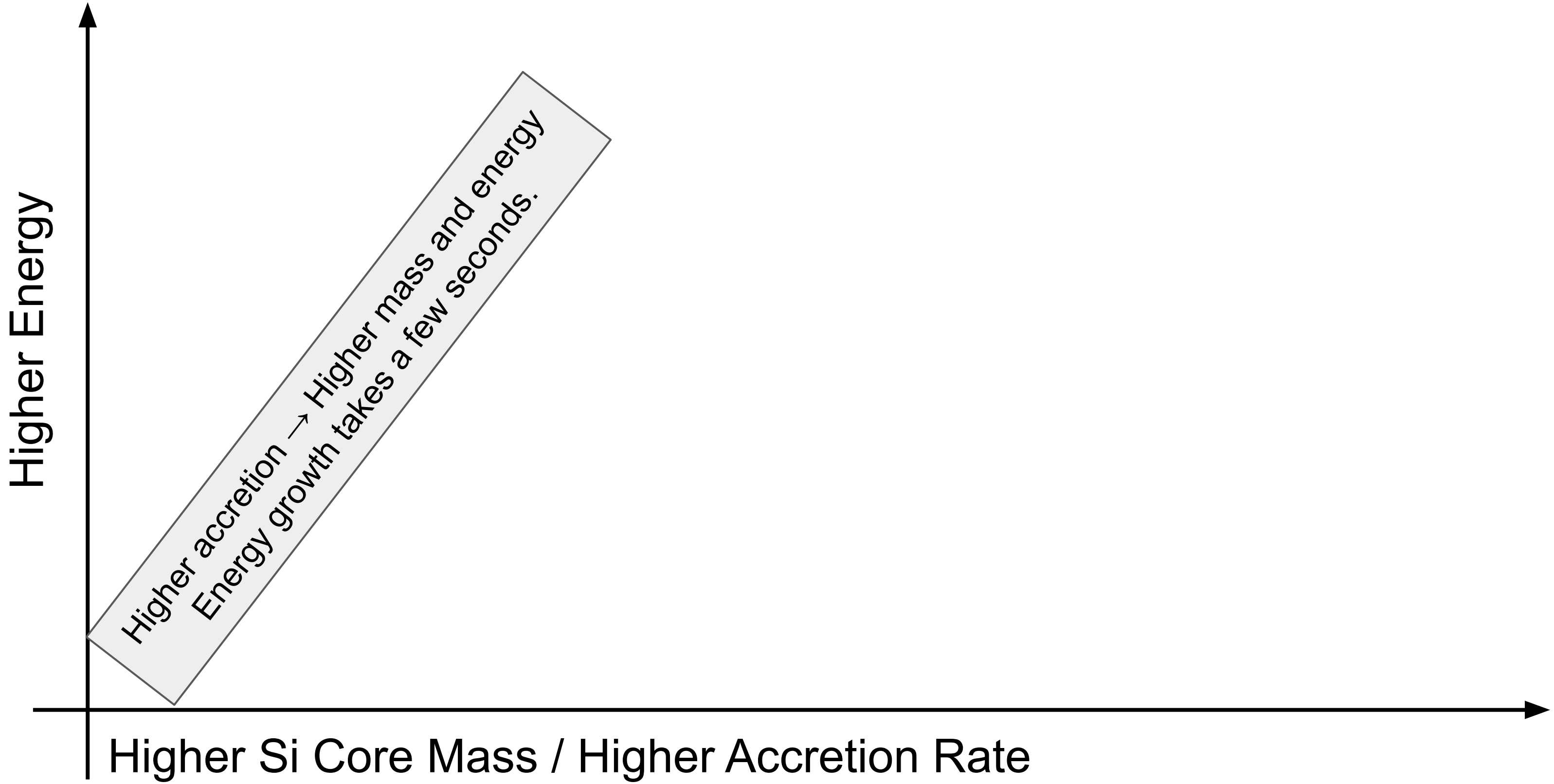

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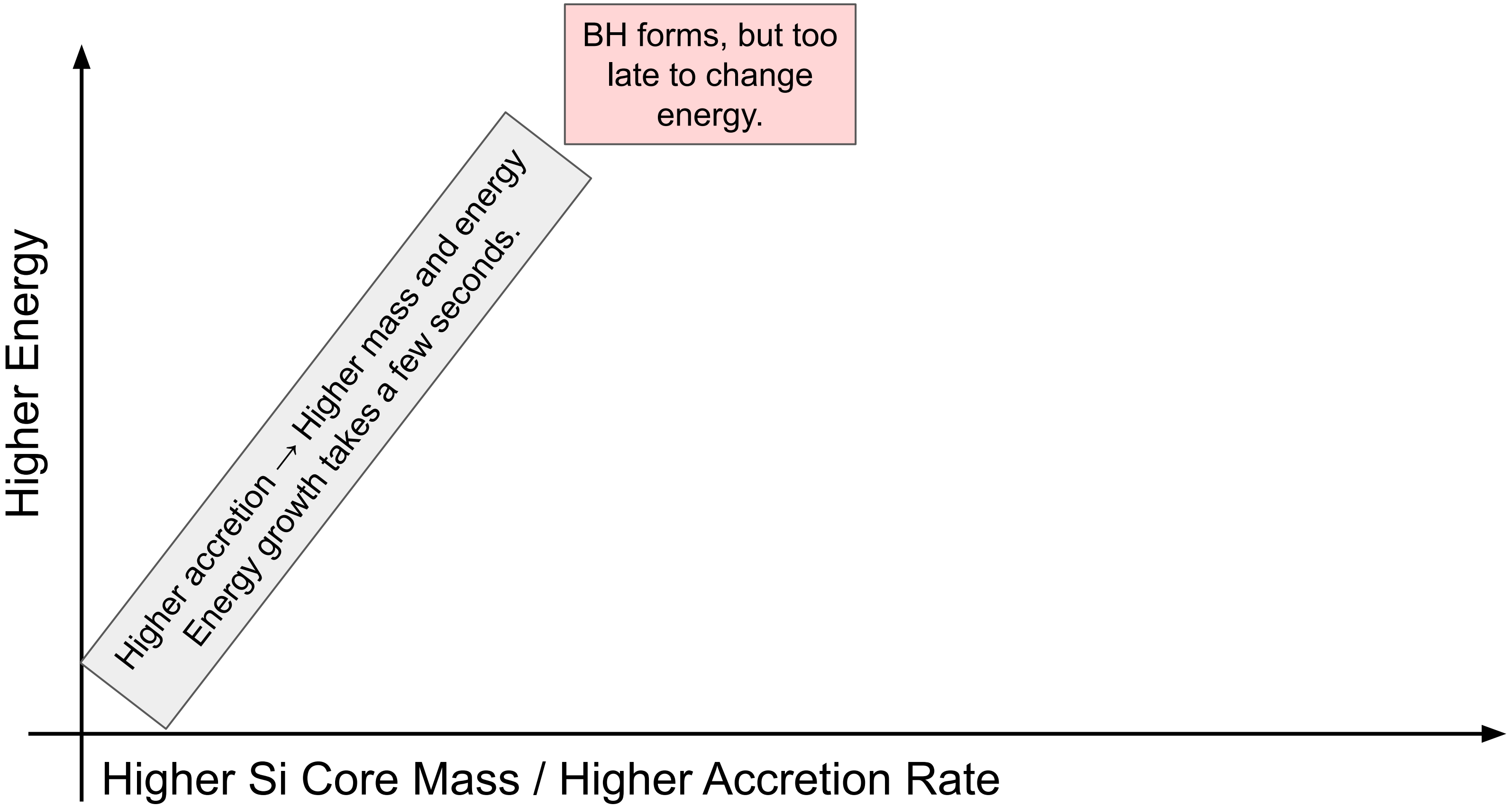

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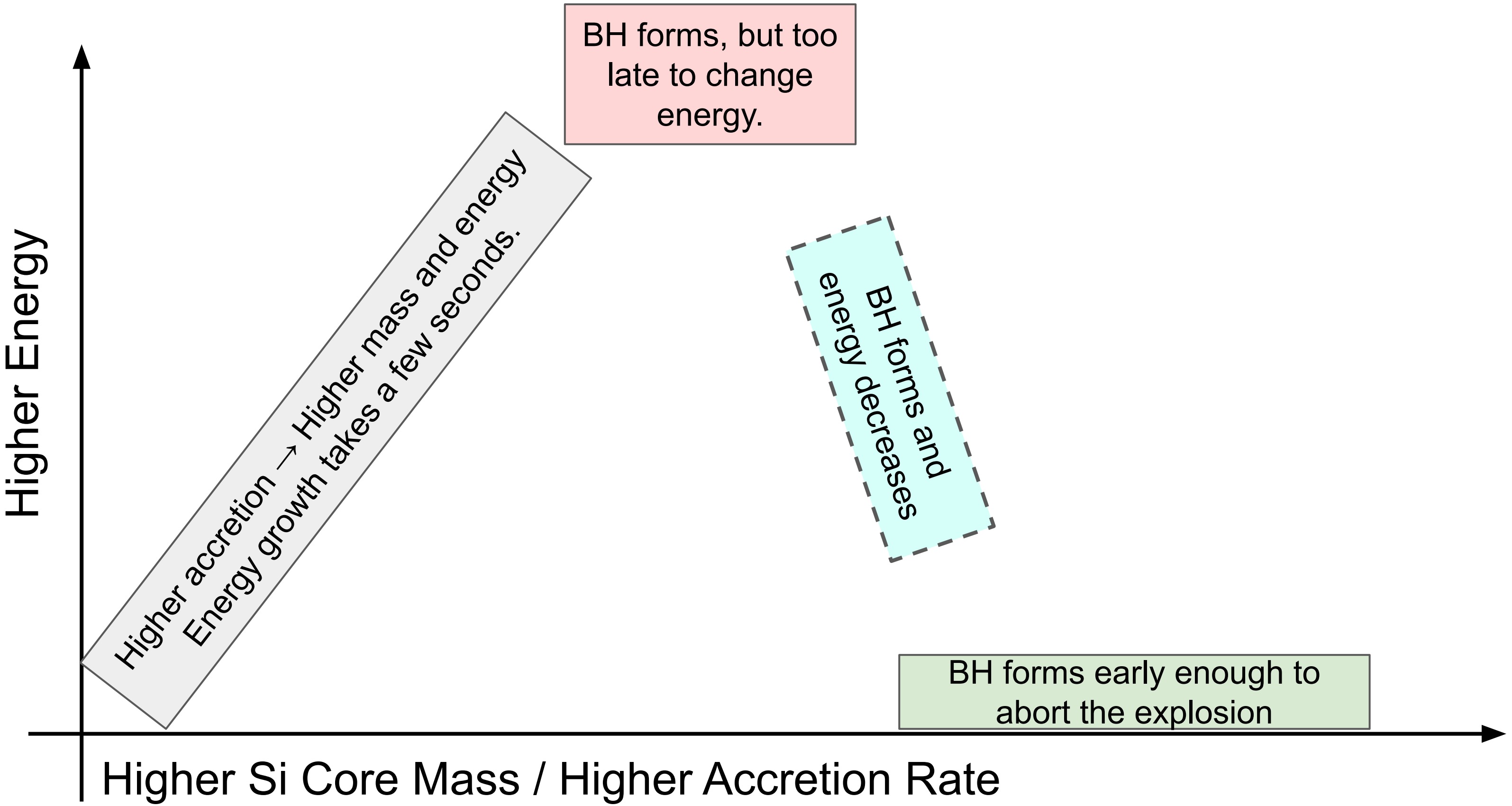

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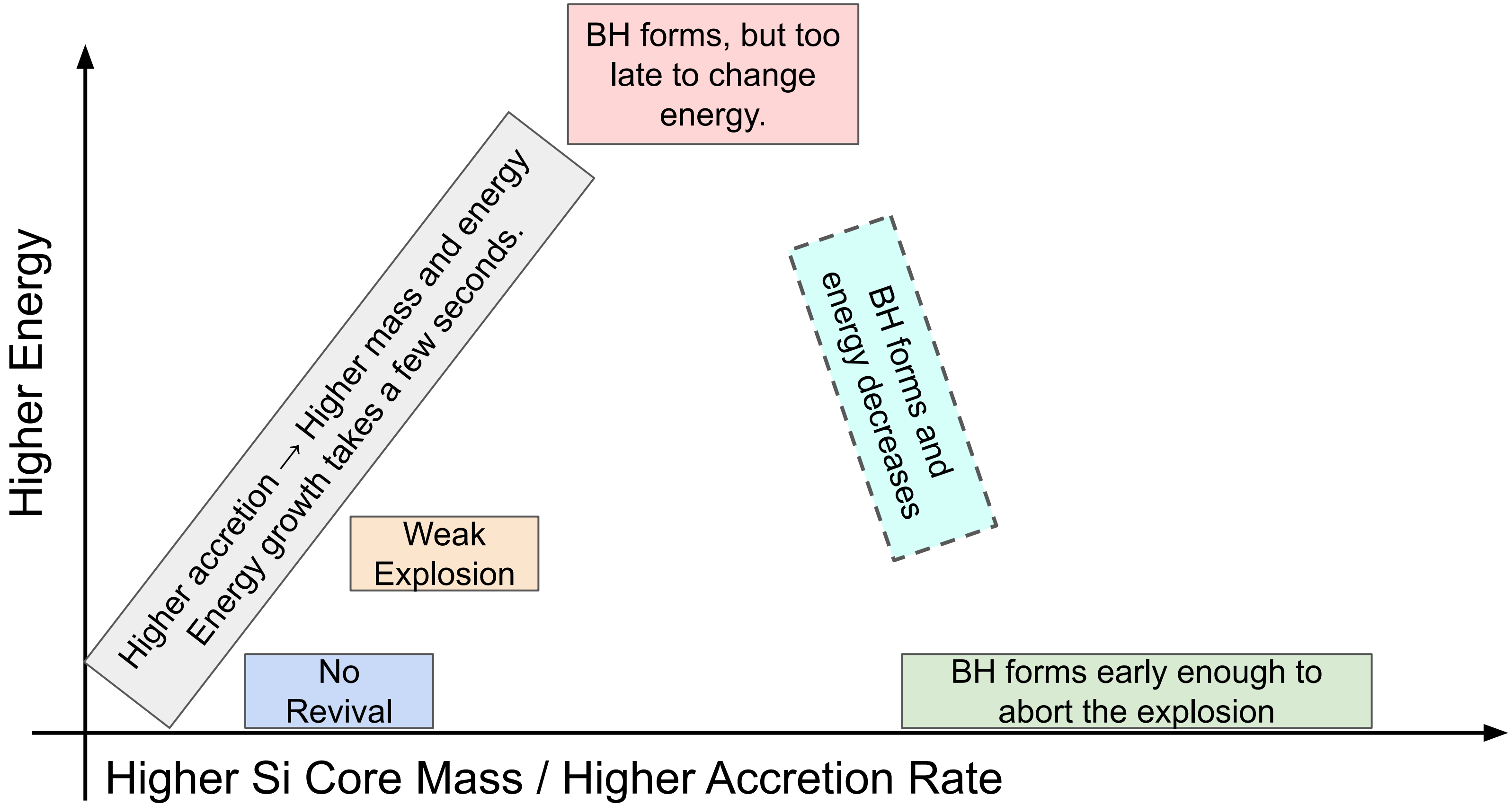

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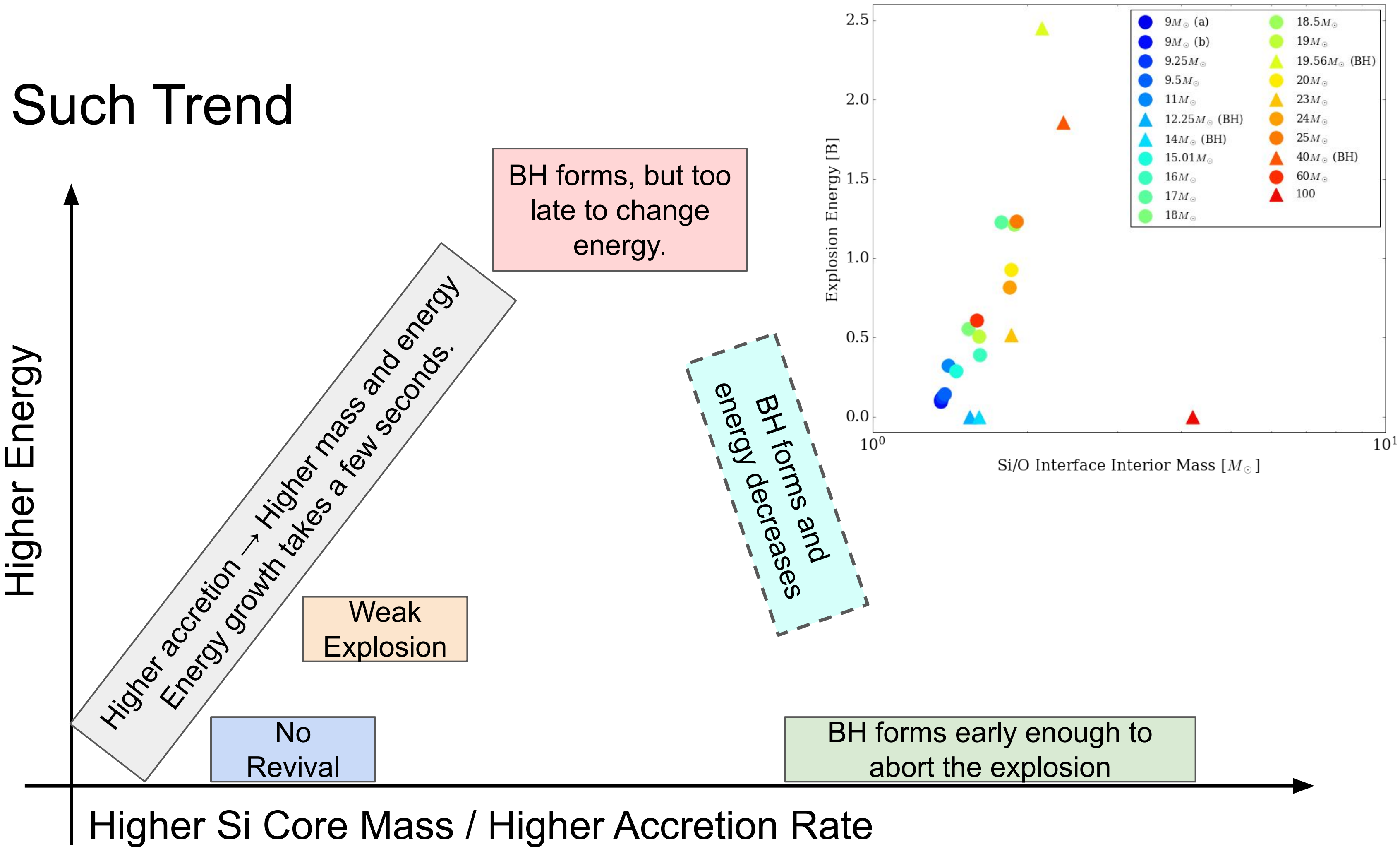


Summary: Four BH Formation Channels

Ch1: BH with very strong explosion. High energy, large kick, relatively low mass. An explanation to the NSBH mass gap.

Ch2: BH with weak explosion. Significant fallback. Low energy, relatively low kick, 5~10Msun (uncertain).

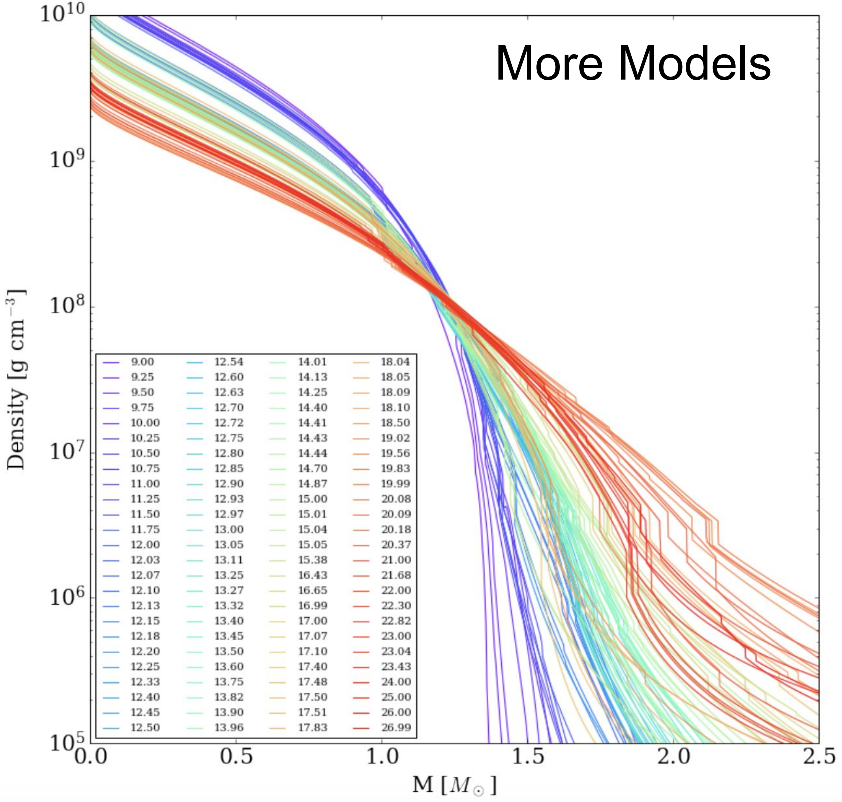
Ch3: BH formed by most massive models. Explosion aborted by BH formation. Tens of Msun, <5km/s kick.

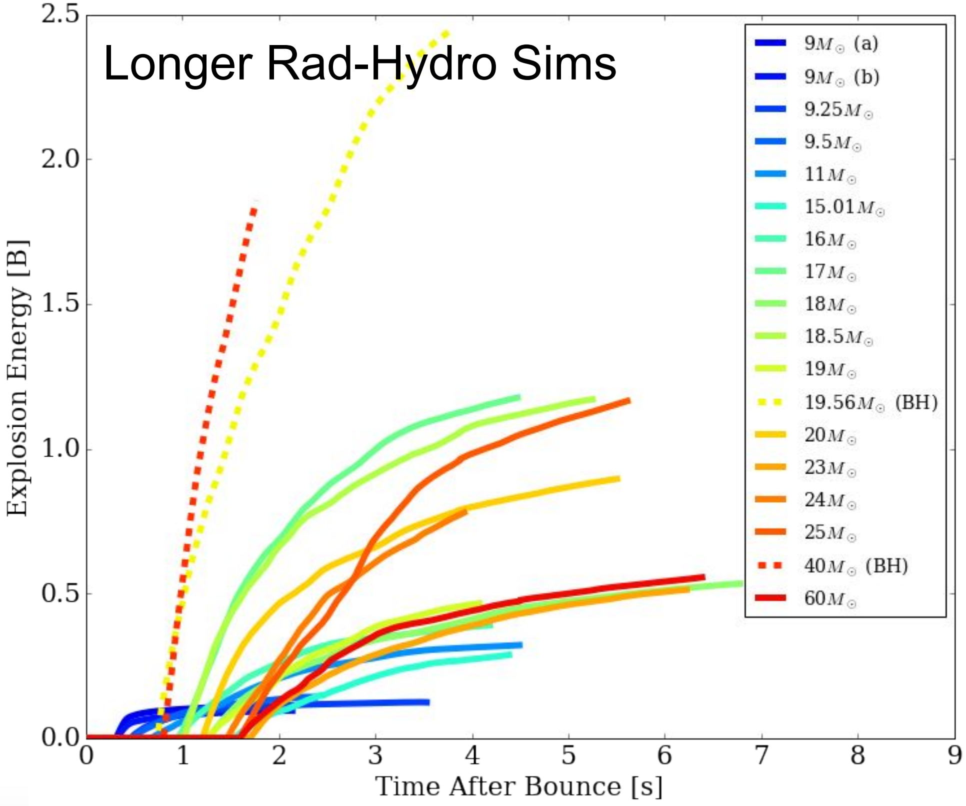
Ch4: Typical failed supernovae. Shock never revives. ~10 Msun, <10 km/s kick.

Arxiv: 2412.07831

Challenges and Conclusion

More and Longer





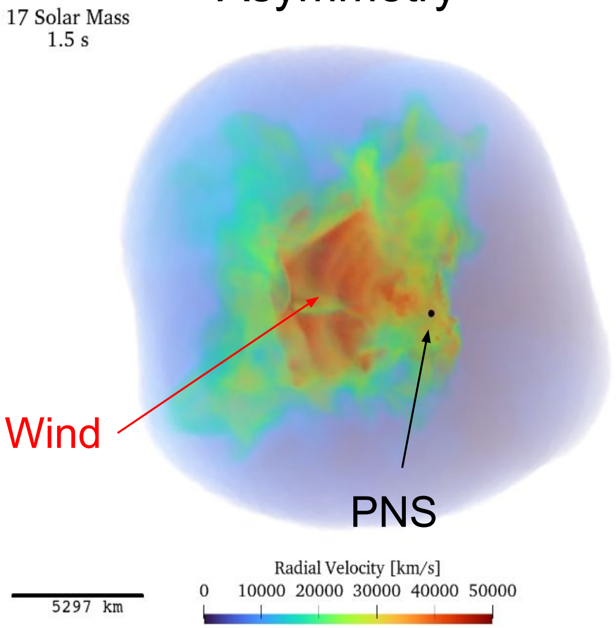
Neutrino-Driven Wind Boundary Condition?

Spherical wind BC

$$\rho_W(t) = \rho_W(t_{map}) \left(\frac{t}{t_{map}} \right)^{-7/2}$$

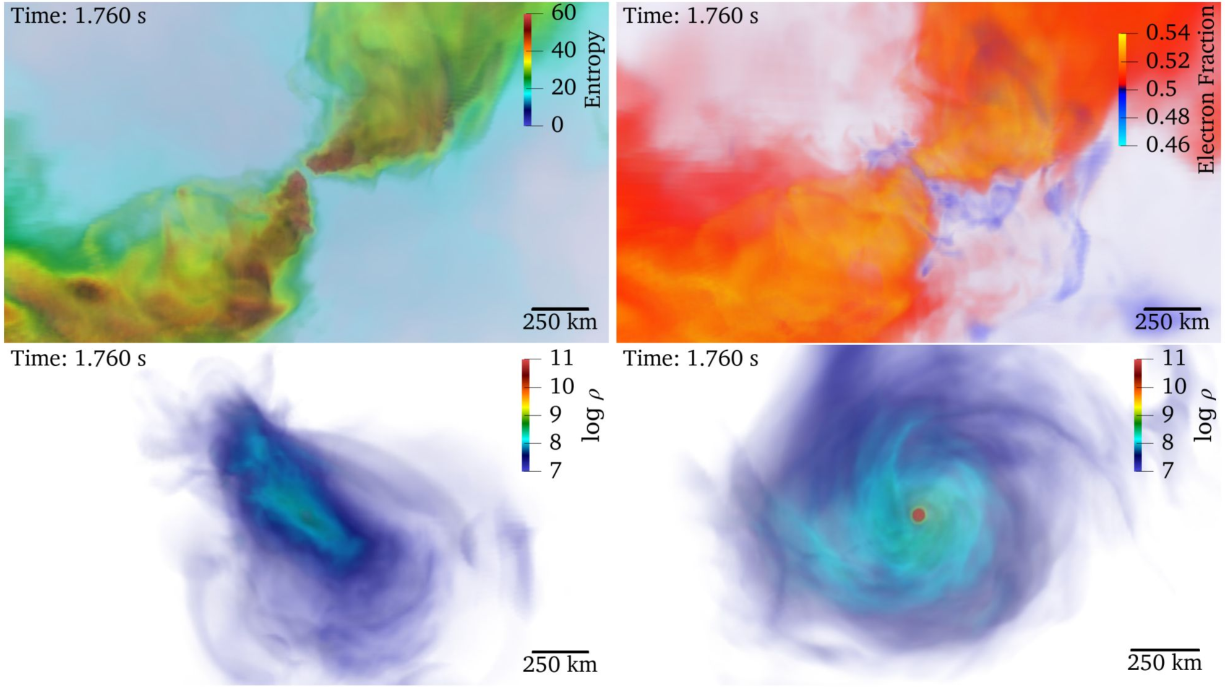
$$e_W(t) = e_W(t_{map}) \left(\frac{t}{t_{map}} \right)^{-7/6}$$

Asymmetry



Spherical wind BCs are typically used in hydro-only blast calculation. But uncertainty is large. How to include asymmetry?

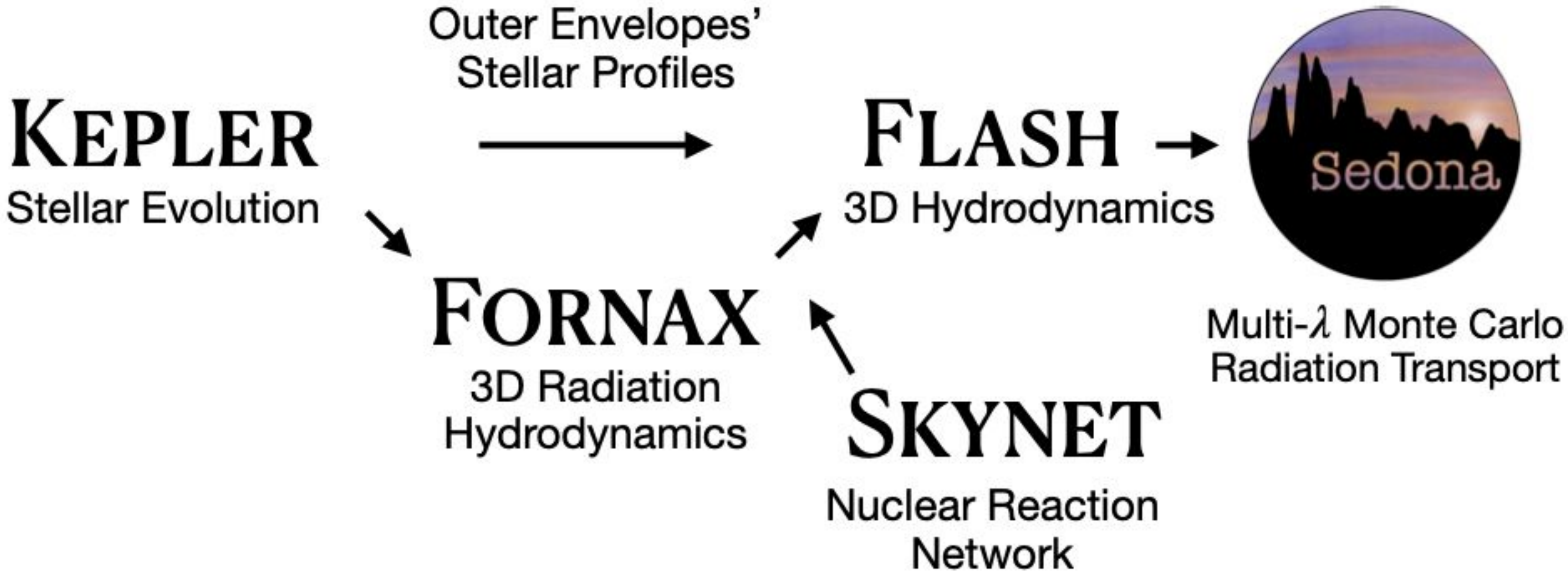
Central Engine?



Asymmetric accretion leads to fast BH spin. Will there be GRMHD jets after the BH formation?

Vartanyan+2024

Conclusion: From Collapse to Beyond Shock Breakout



Many new insights emerge from long-term 3D CCSN simulations!

Examples: ^{44}Ti Problem, BH Formation Channels, …