Impact of Type Ia Supernova Ejecta on Binary Companions

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Mr. Akhil Langer

Charm++ Workshop, April 18, 2011

What is supernova !?

Nuclear bomb ~ 10^{15} (J)
2011 Japan Earthquake ~ 10^{17} (J)
Supernova ~ 10^{44} (J)

Supernova 1994D in galaxy NGC 4526

Image credit: NASA

What is supernova !?

Nuclear bomb ~ 10^{15} (J)
2011 Japan Earthquake ~ 10^{17} (J)
Supernova ~ 10^{44} (J)

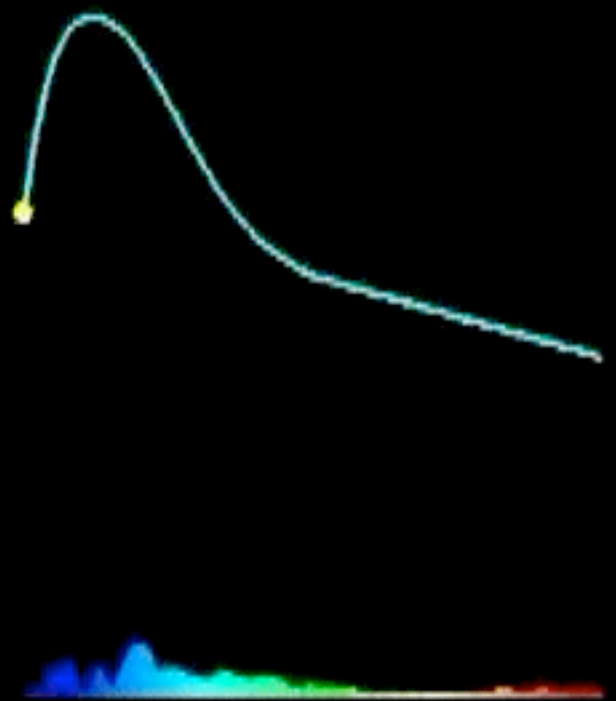
Tycho's Supernova Remnant (x-ray)

SN 1572

Supernova 1994D in galaxy NGC 4526

Image credit: NASA

http://www-supernova.lbl.gov/public/figures/snvideo.html

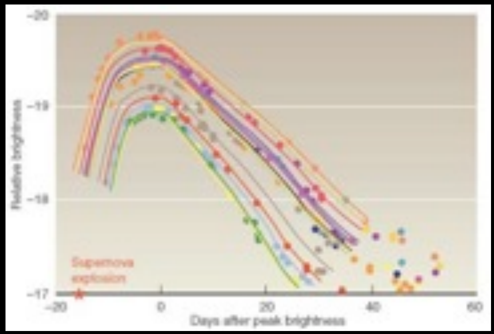


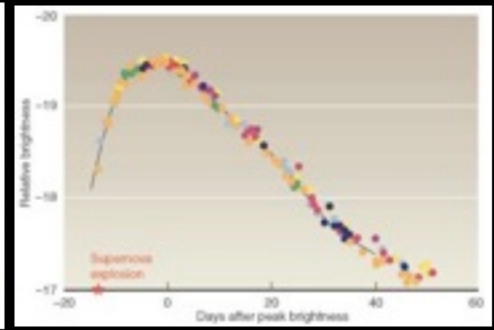
http://www-supernova.lbl.gov/public/figures/snvideo.html

Outline

- Introduction
- Numerical Methods (FLASH3)
- Scaling and code optimization
- Scientific results

Introduction





- Supernova (SN):

  Core collapse/ "Type II, Type Ib, ...etc." SN (massive star, with H-line)

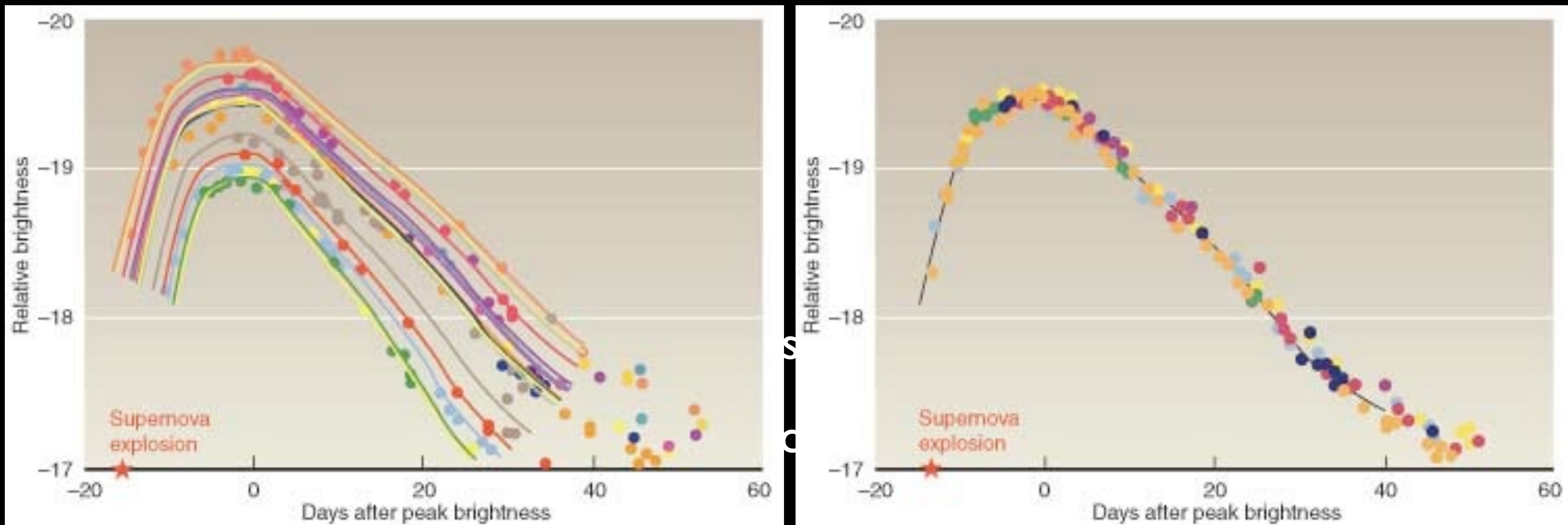
  Thermonuclear disruption of accreting Carbon-Oxygen white dwarfs/ "Type Ia" (without H-line)

- Light curves of Type Ia SN:

  Peak luminosity and decay time scale correlated (standard candle)

  All roughly similar, but real variations seen

Introduction



- Light curves of Type Ia SN:

  Peak luminosity and decay time scale correlated (standard candle)

  All roughly similar, but real variations seen

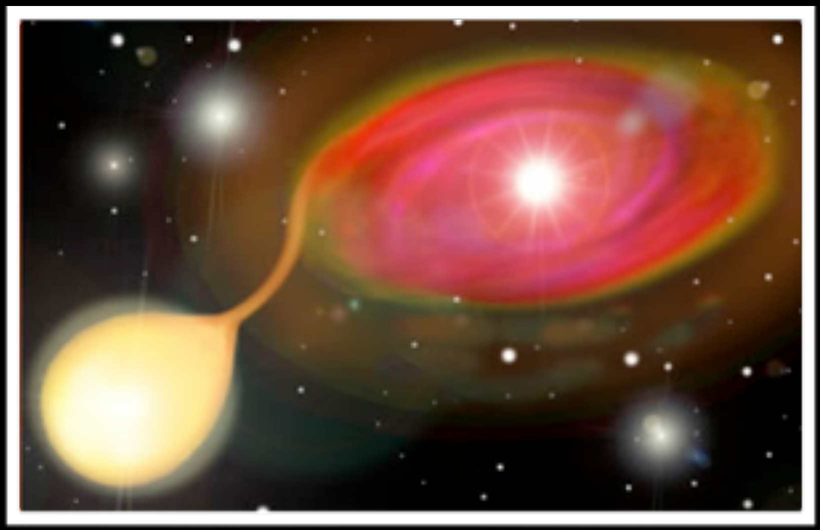
Why are SNe Ia important?

- The use of SNe Ia as one of the main ways to determine key cosmological parameters.
- Galaxy evolution depends on the radiative kinetic energy and nucleosynthetic output of SNe Ia.
- Estimating more accurate SN Ia rates and understanding the physics of SN remnants will help to place meaningful constraints on the theory of binary evolution.

Possible scenarios for SNe Ia

Possible scenarios for SNe Ia

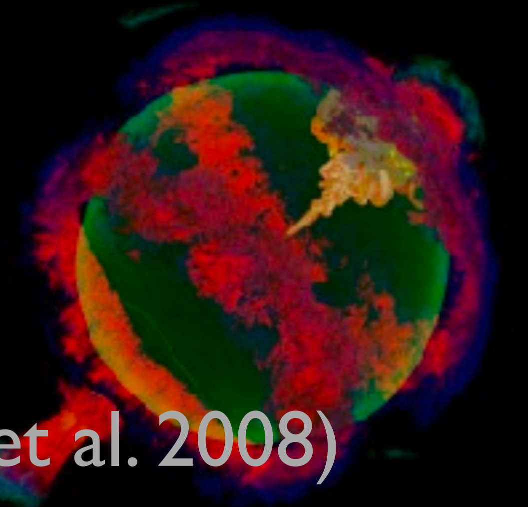
- Single-degenerate scenario (Whelan & Iben 1973)



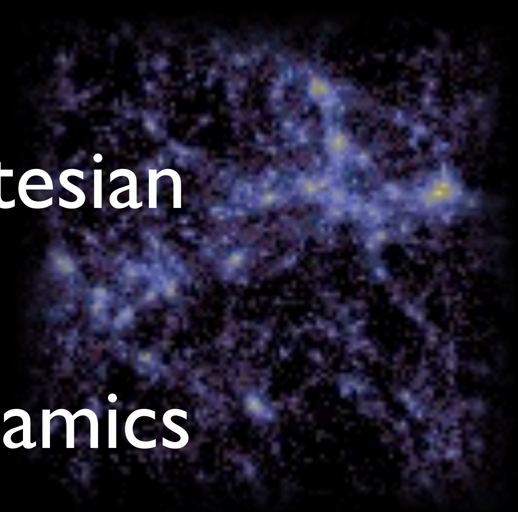
Key Questions

- Can companion's hydrogen be hidden?
- What happens to the companion after the supernova explosion?
- What is the intrinsic variation of Type Ia supernova?
- Can we detect the remnant companion star in the supernova remnant?

FLASH

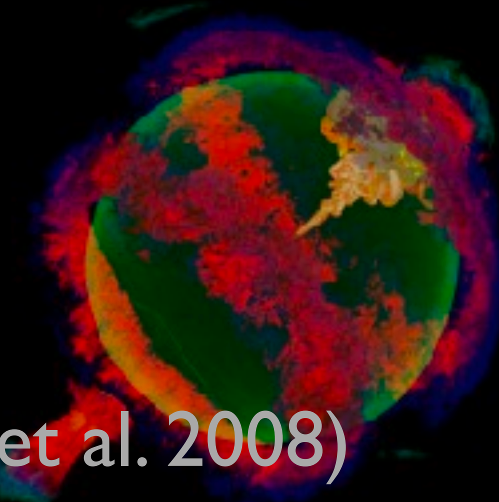


- FLASH3 (Fryxell et al. 2000; Dubey et al. 2008)
- Parallelized code based on adaptive mesh refinement (AMR)
- Grid- and particle- based
- Multi- dimensionality and non-Cartesian geometry
- PPM for shock-capturing hydrodynamics (Colella & Woodward 1984)



Web: http://flash.uchicago.edu

FLASH



- FLASH3 (Fryxell et al. 2000; Dubey et al. 2008)
- Parallelized code based on adaptive mesh

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P = \rho \mathbf{g}$$

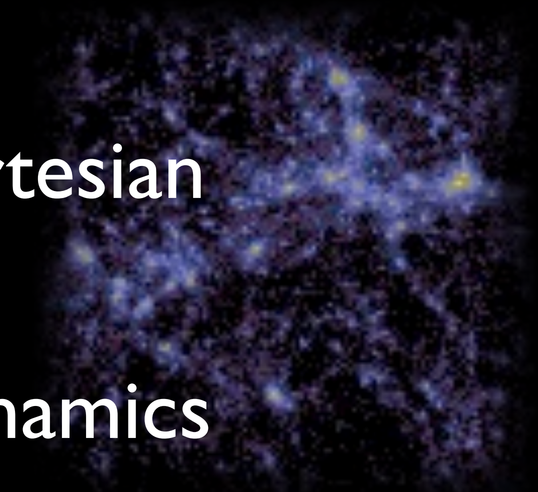
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\mathbf{v}] = \rho \mathbf{v} \cdot \mathbf{g} \ ,$$

$$E = \epsilon + \frac{1}{2}|\mathbf{v}|^2$$

n-Cartesian

drodynamics

.edu



FLASH

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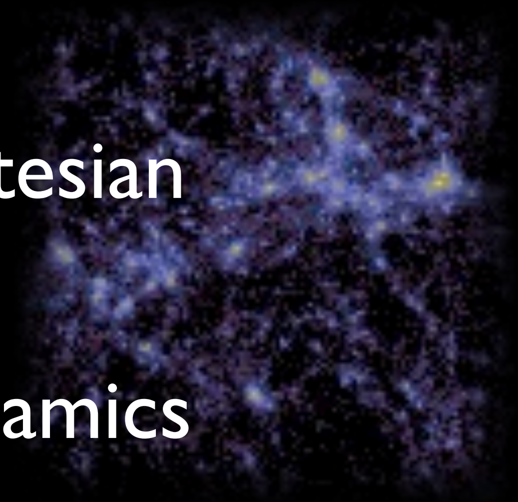

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FLASH

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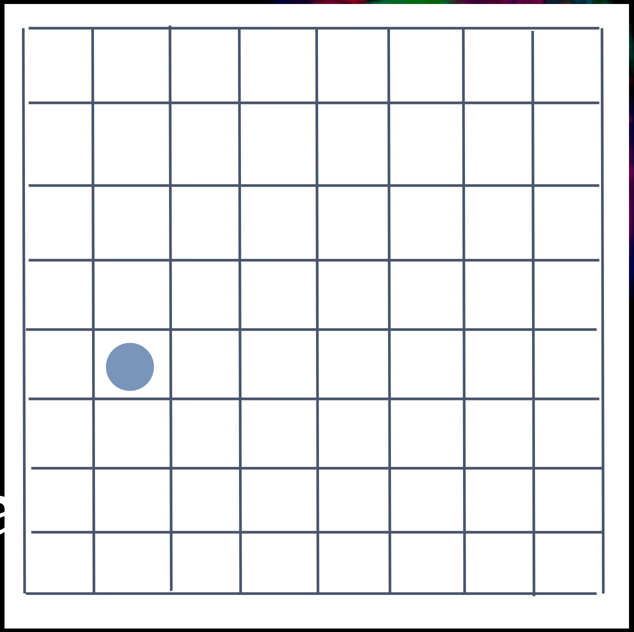

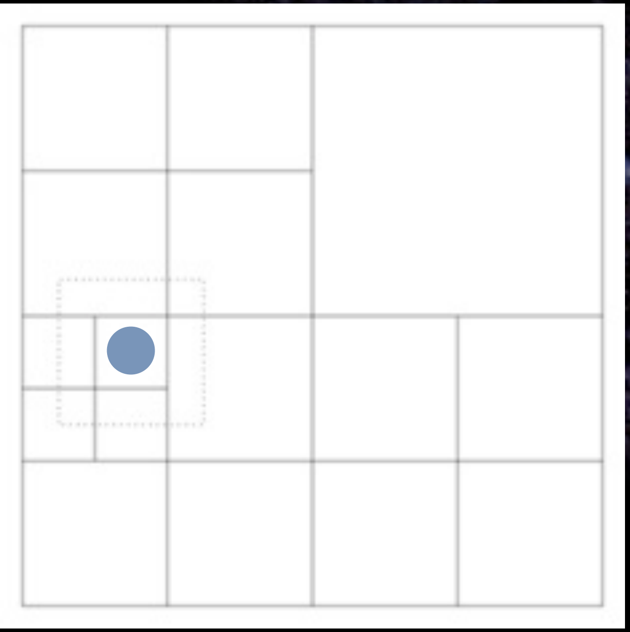

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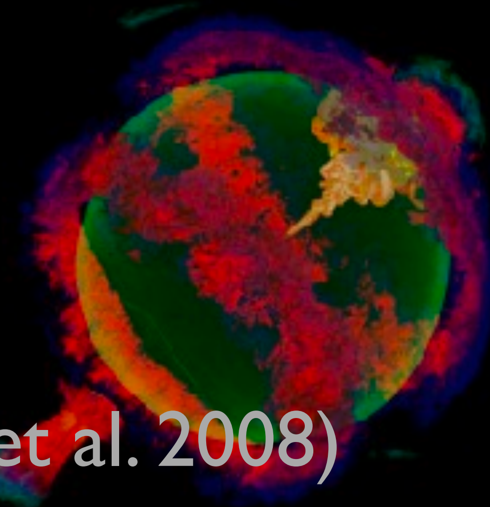
FLASH



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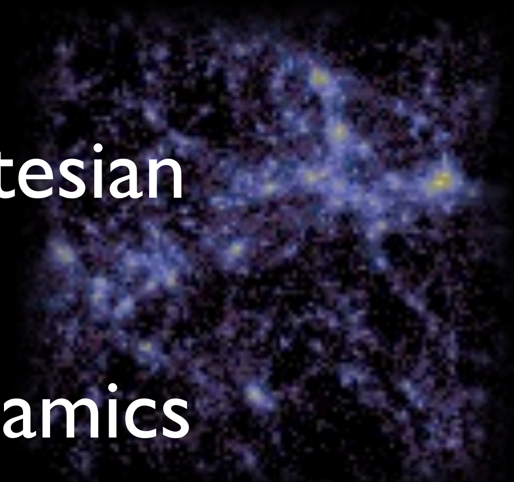

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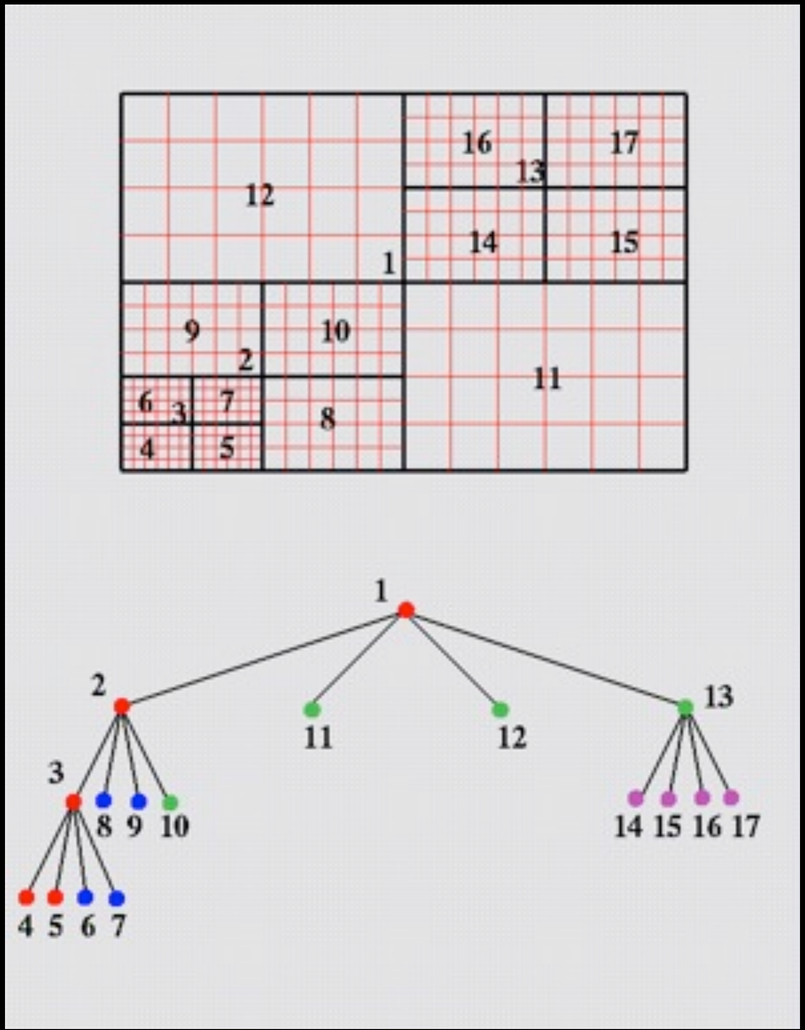
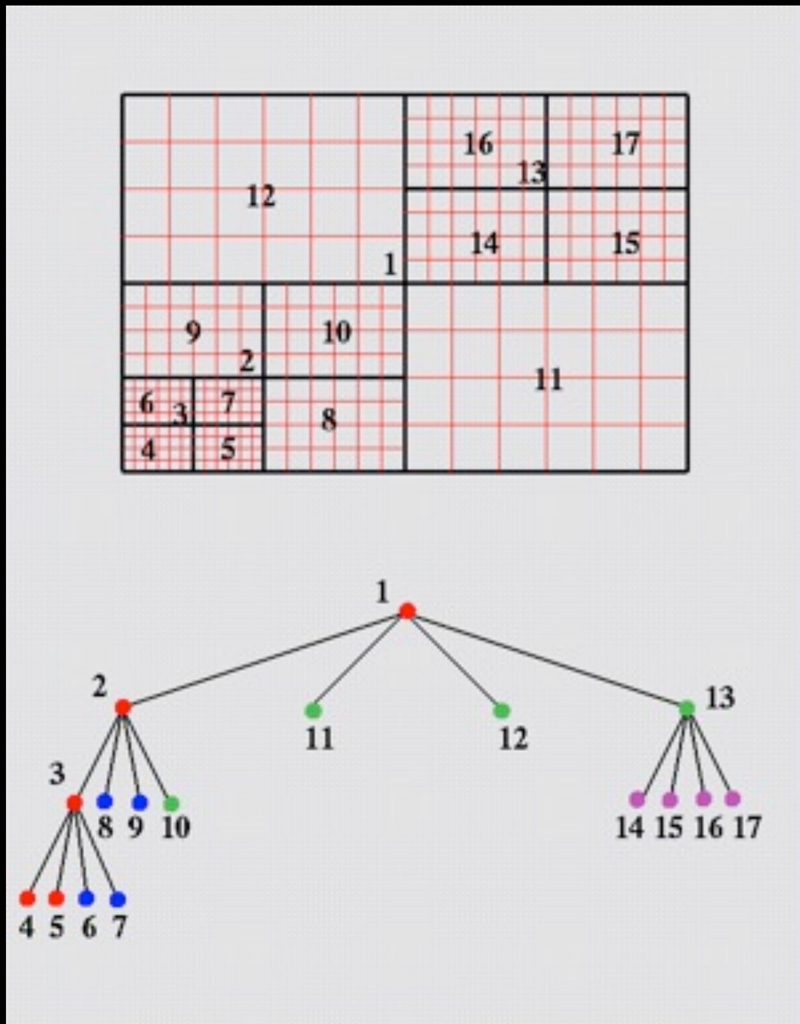
Parallel AMR: PARAMESH4

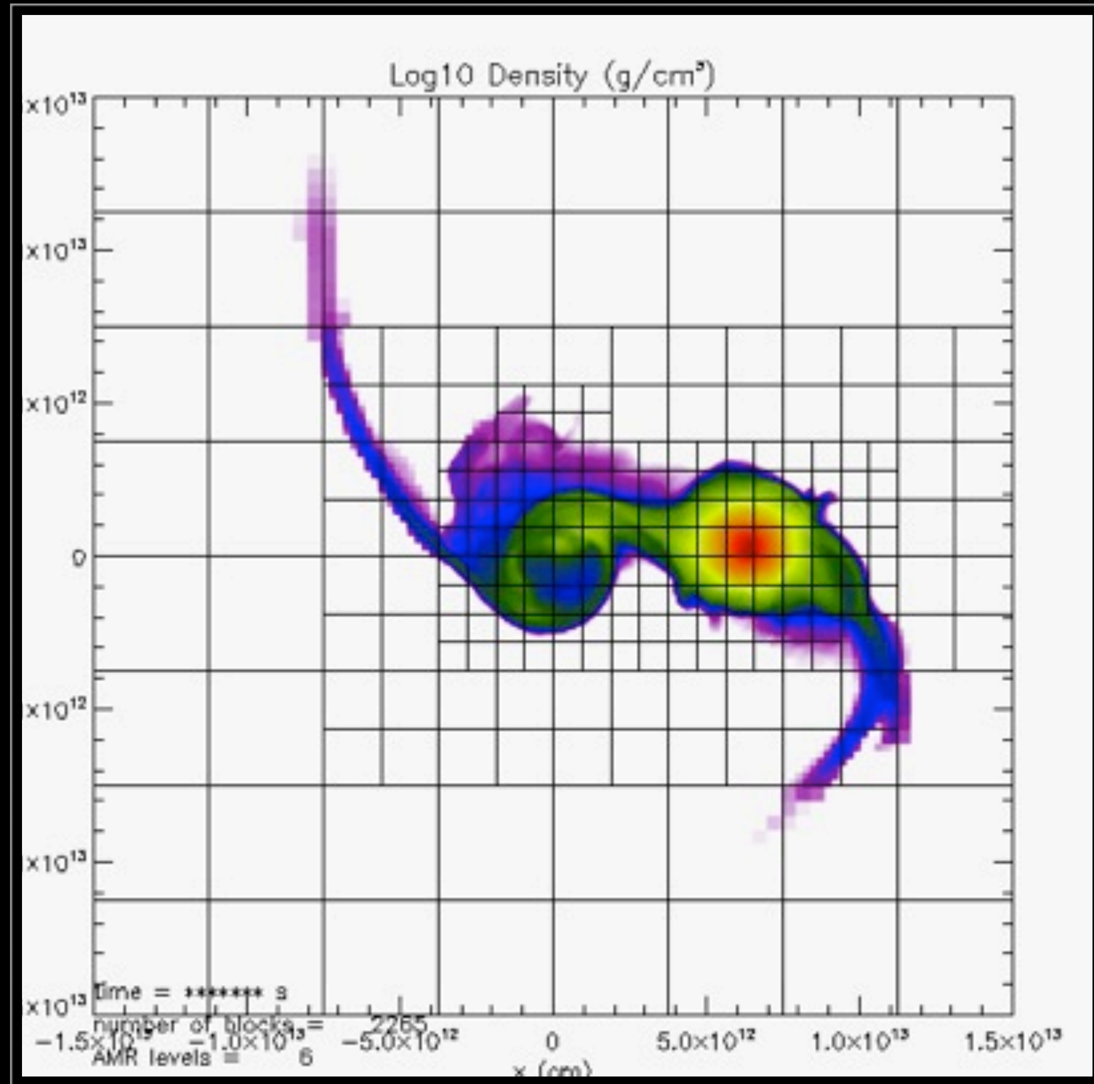


a block contains 6x4 zones

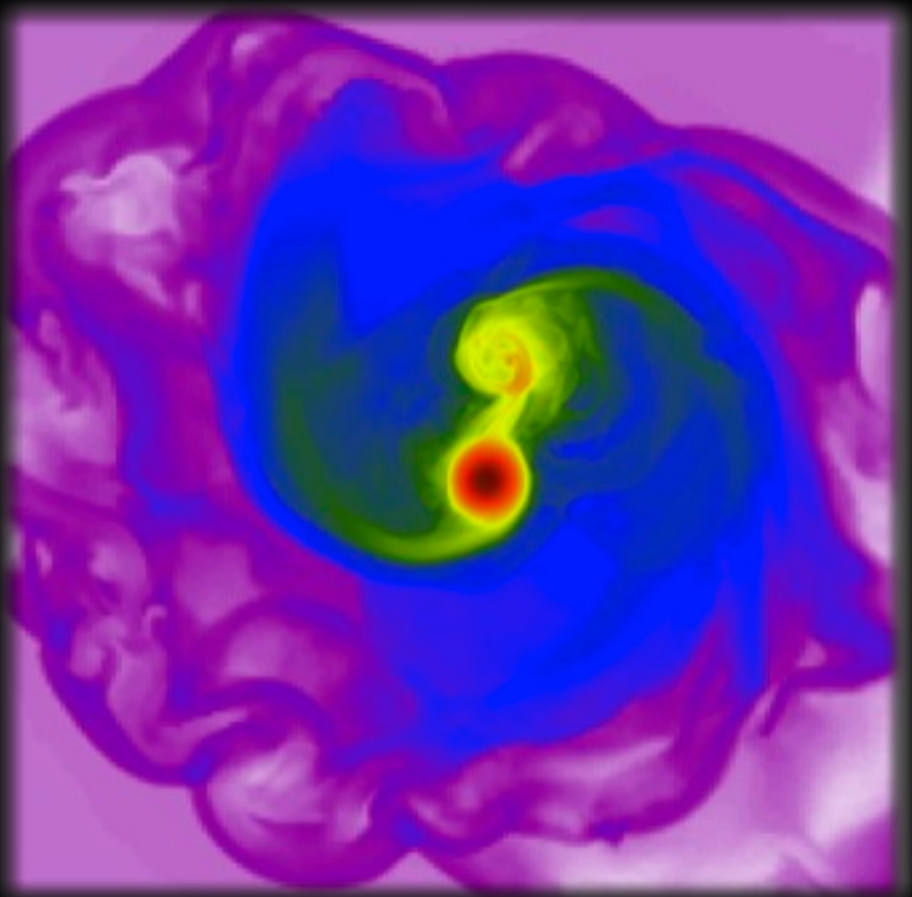
Parallel AMR: PARAMESH4

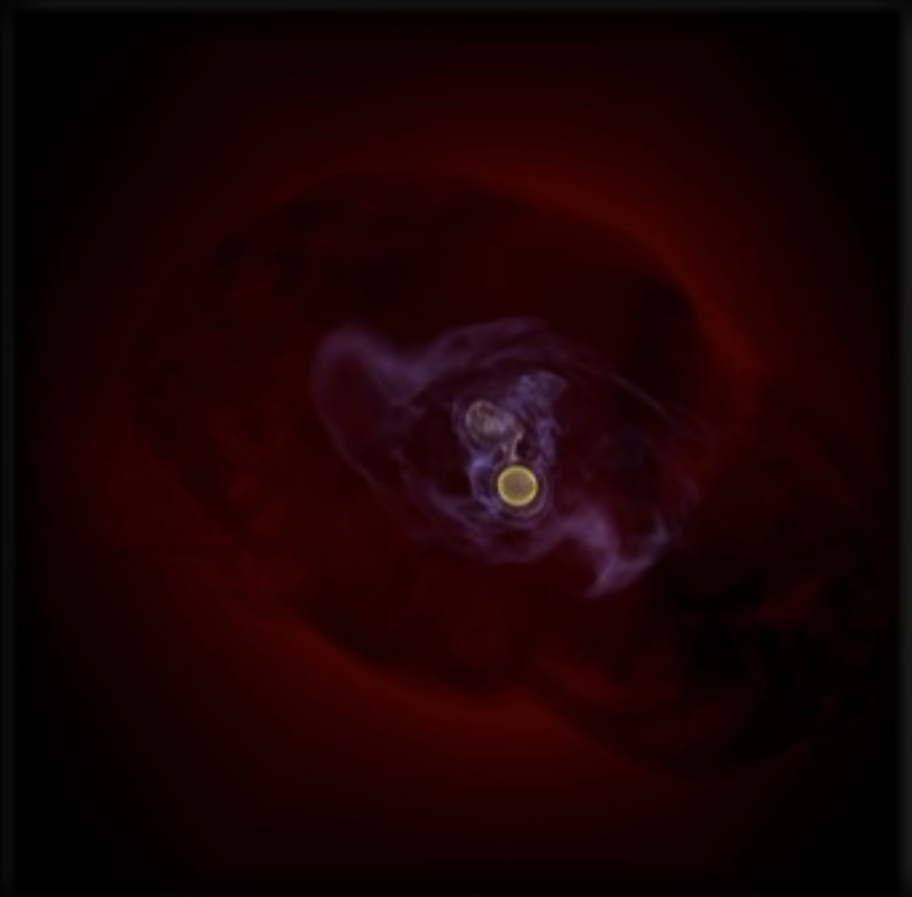


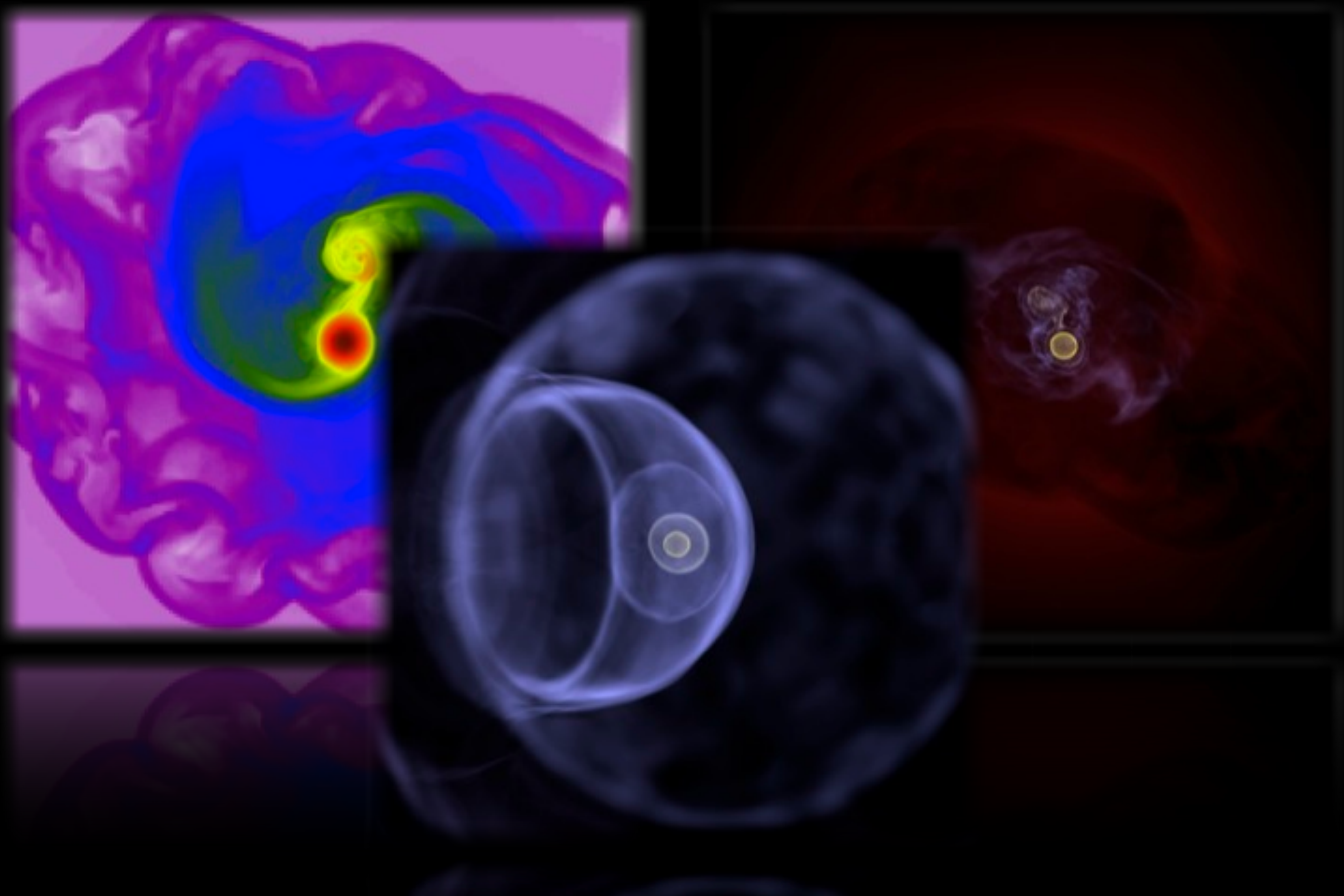
a block contains 6x4 zones



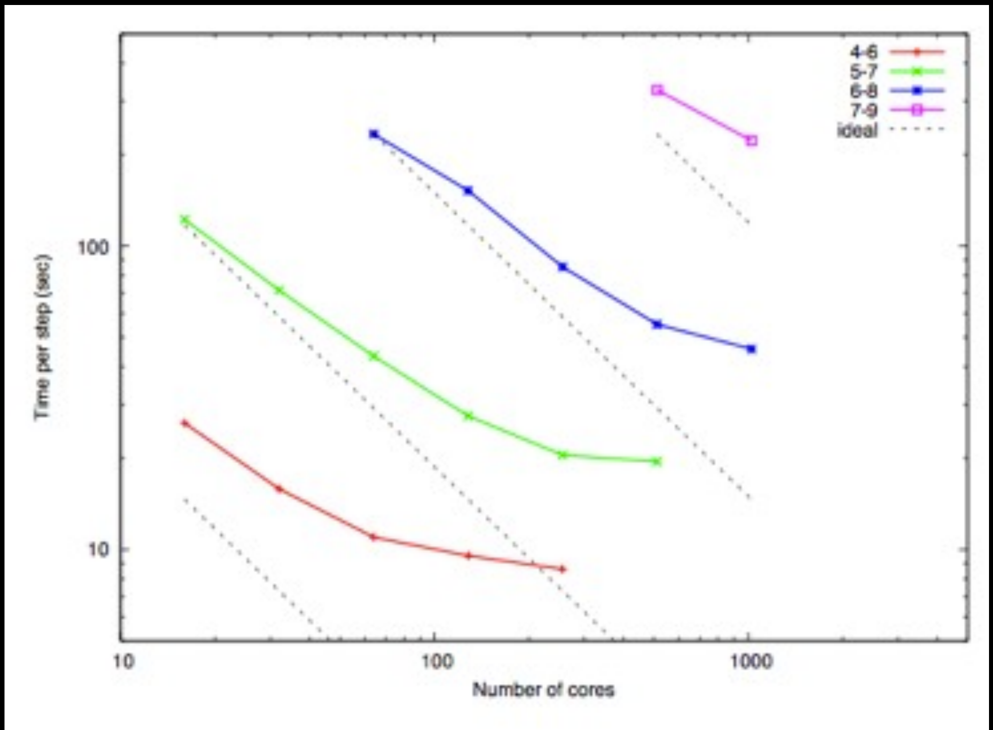
a block contains 8^3 zones

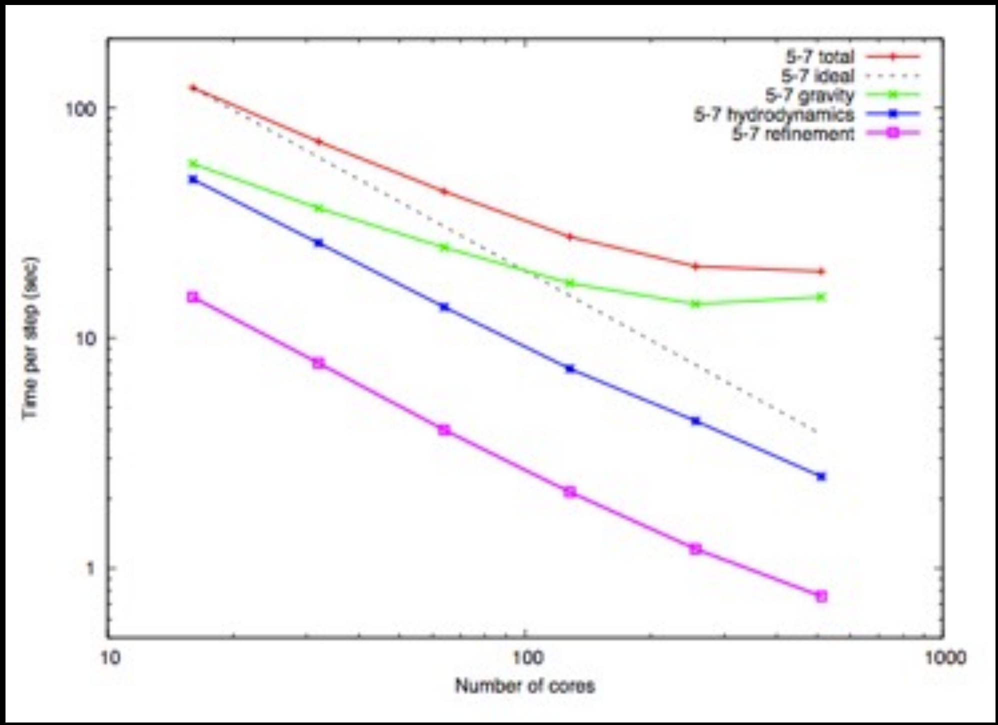


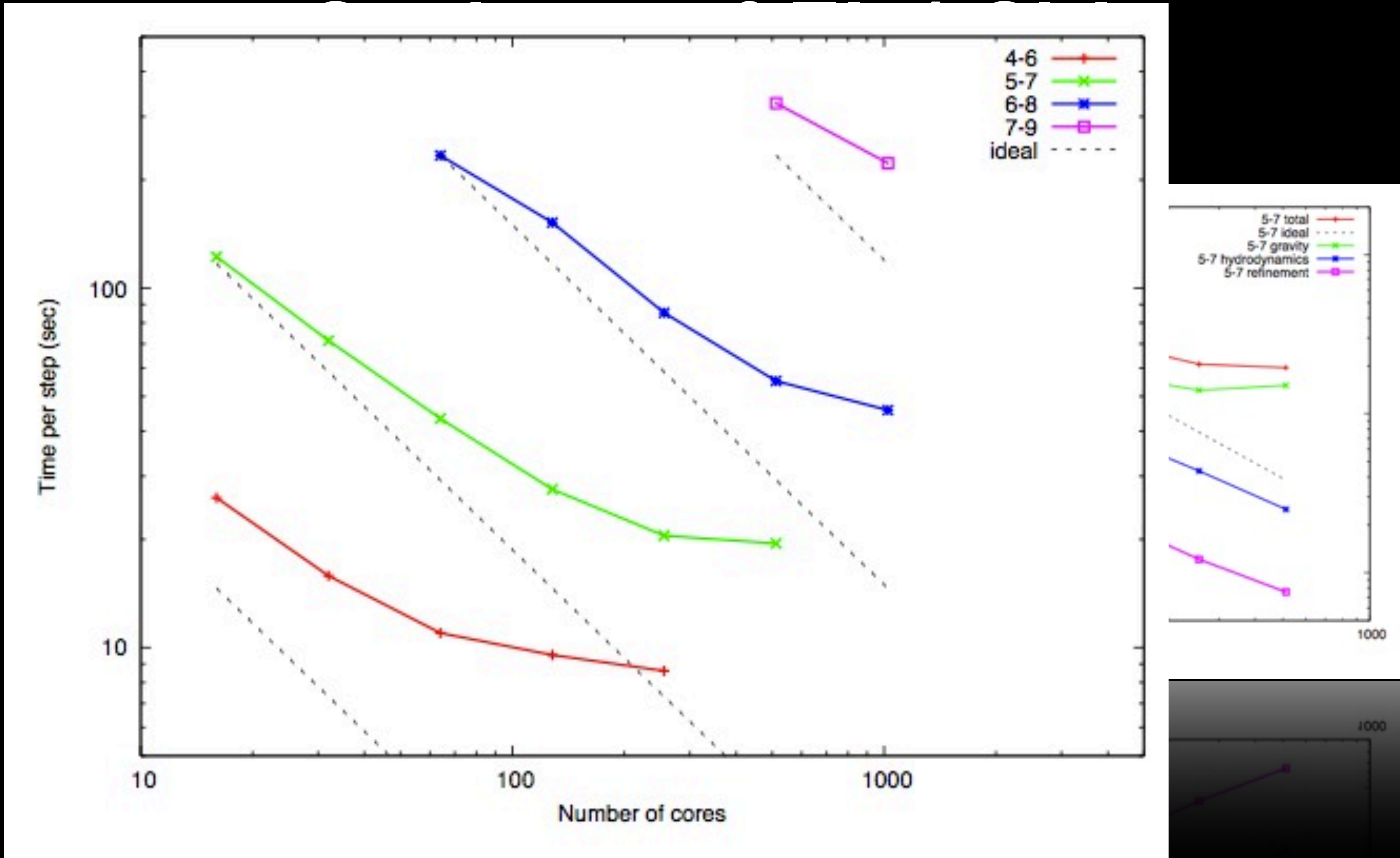




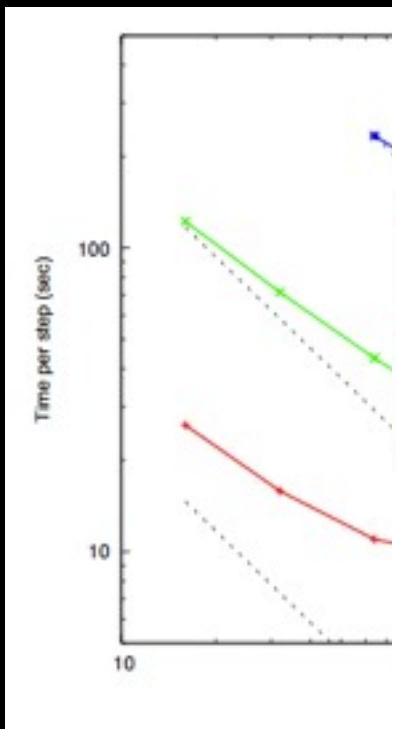
Scaling of FLASH

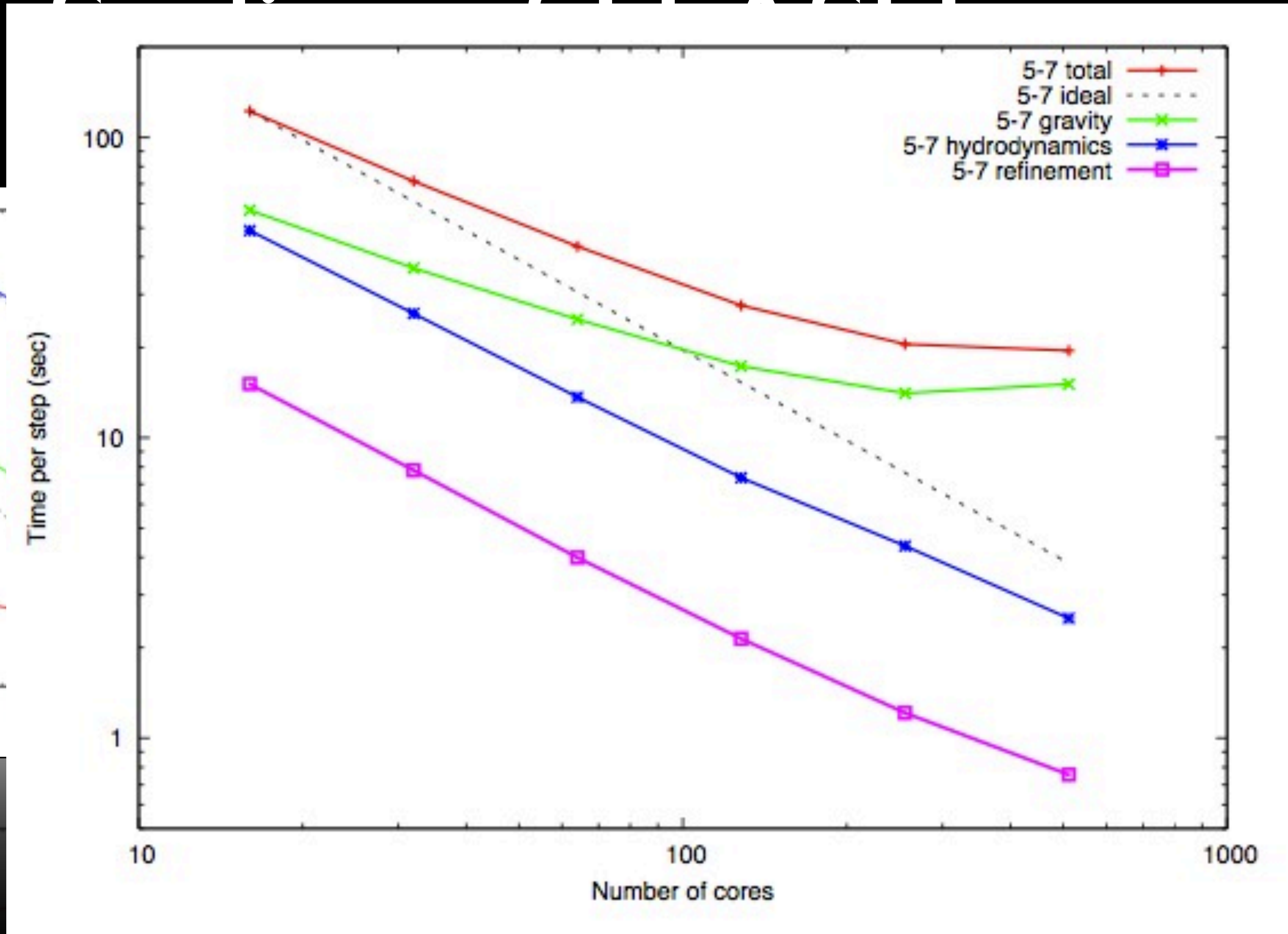




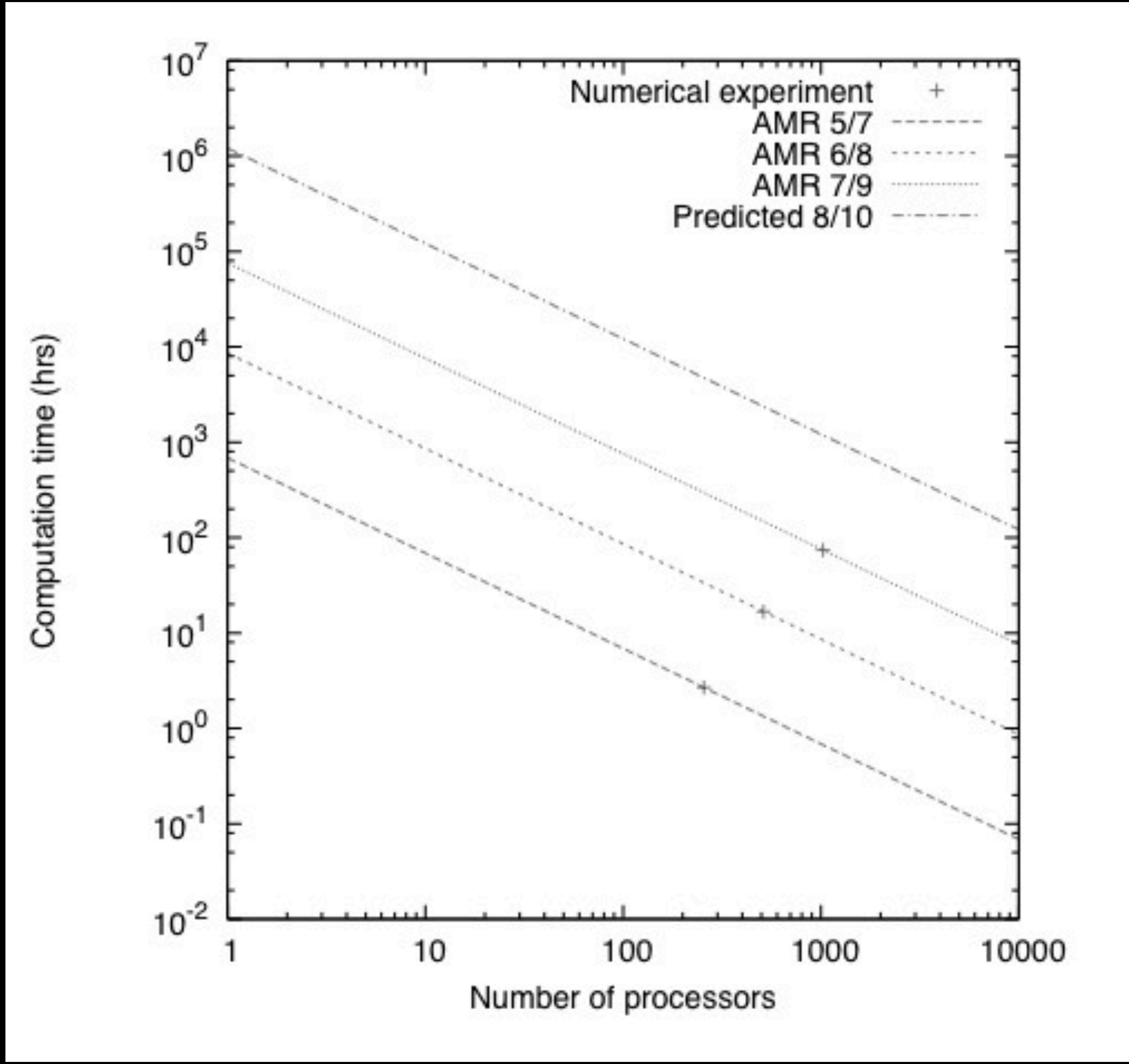


4-6
5-7
6-8
7-9
ideal
Time per step (sec)
100
10
10
100
1000
Number of cores
5-7 total
5-7 ideal
5-7 gravity
5-7 hydrodynamics
5-7 refinement
1000


Time per step (sec)
100
10
10


5-7 total
5-7 ideal
5-7 gravity
5-7 hydrodynamics
5-7 refinement
Time per step (sec)
100
10
1
10
100
1000
Number of cores

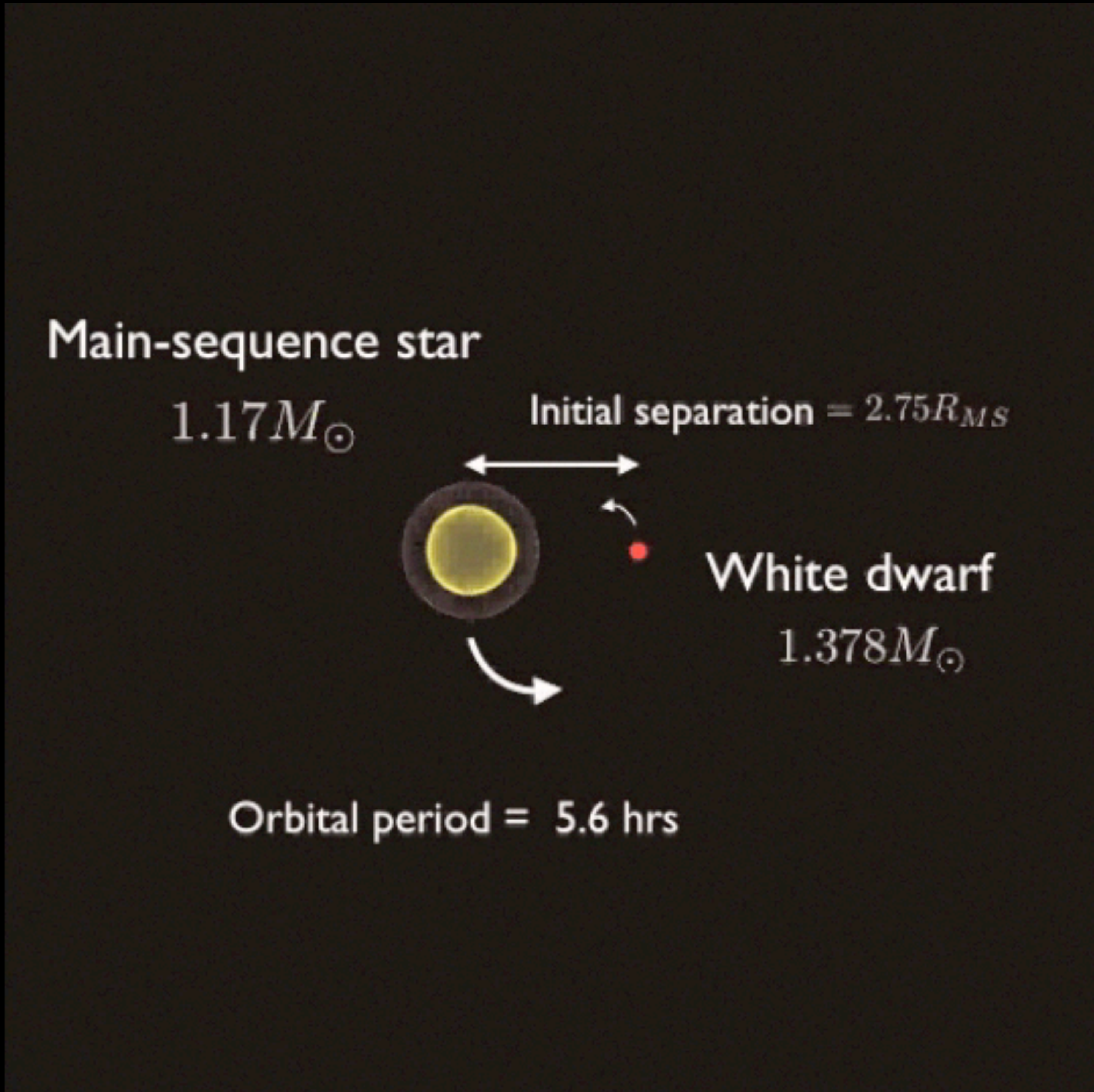
Cost Estimation

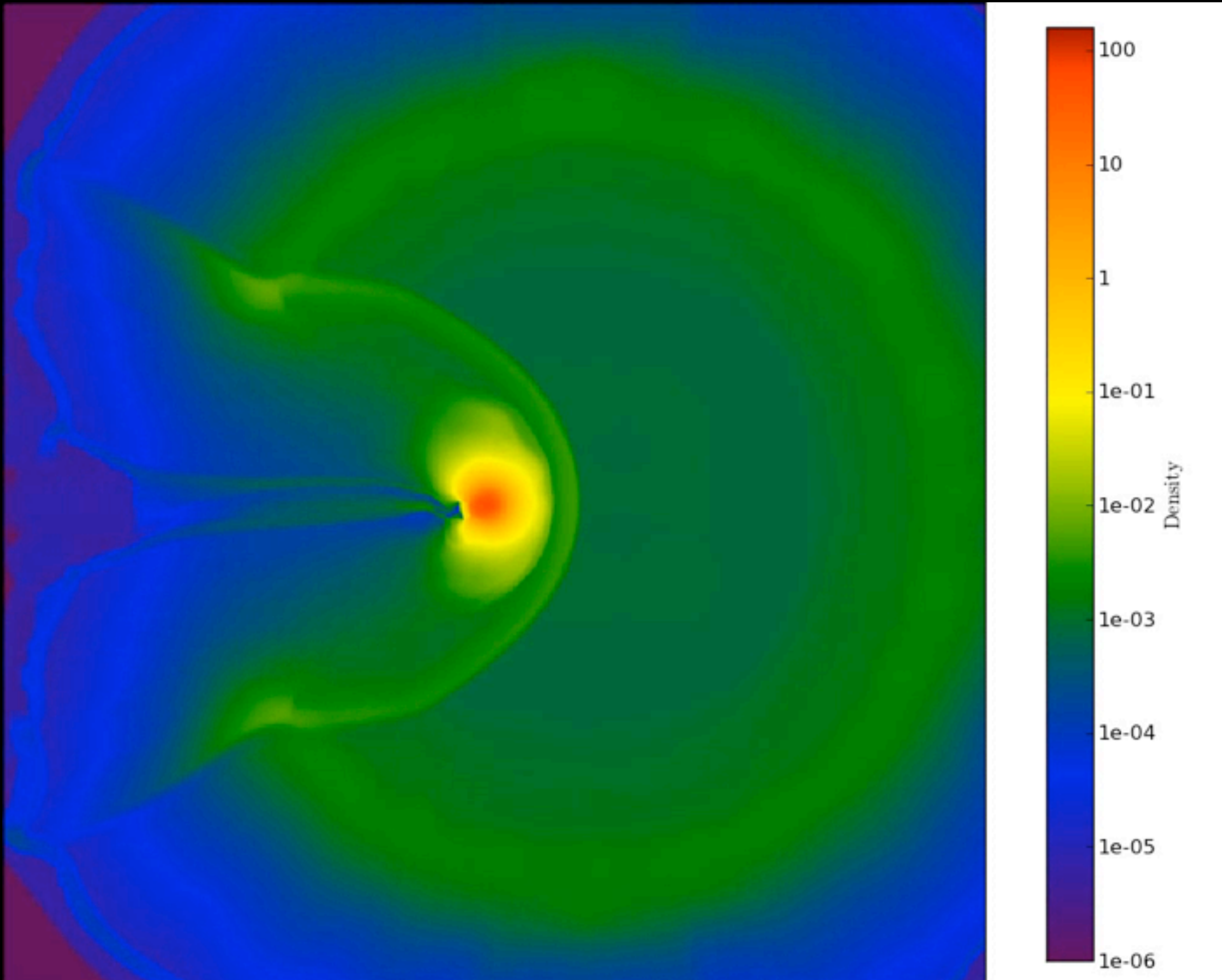


Code Optimization

- High performance computing is required in this project.
- We developed an automatic MPI to AMPI program transformation tool using Photran (Negara et al. 2010)
- Working on a AMR framework using Charm++ (Langer et al. 2011, in prep.)

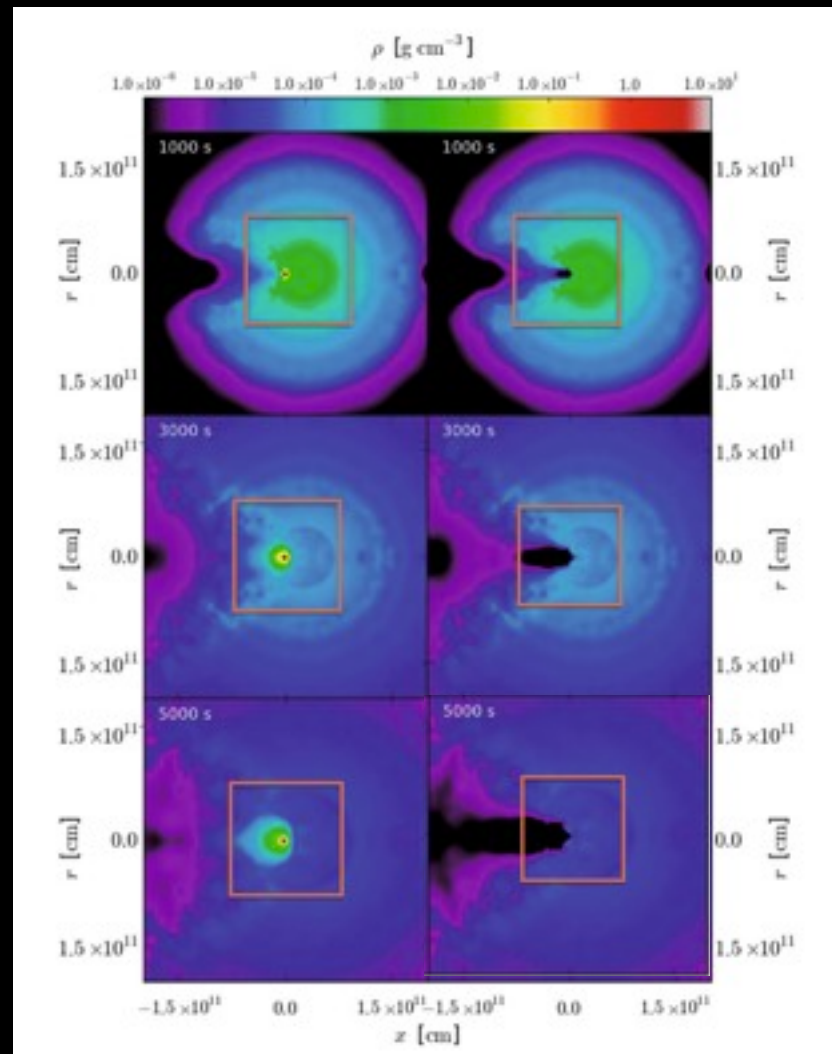
Simulation Results


Main-sequence star
$1.17M_\odot$
Initial separation = $2.75R_{MS}$
White dwarf
$1.378M_\odot$
Orbital period = 5.6 hrs


100
10
1
1e-01
1e-02
1e-03
1e-04
1e-05
1e-06
Density

Hole in the ejecta

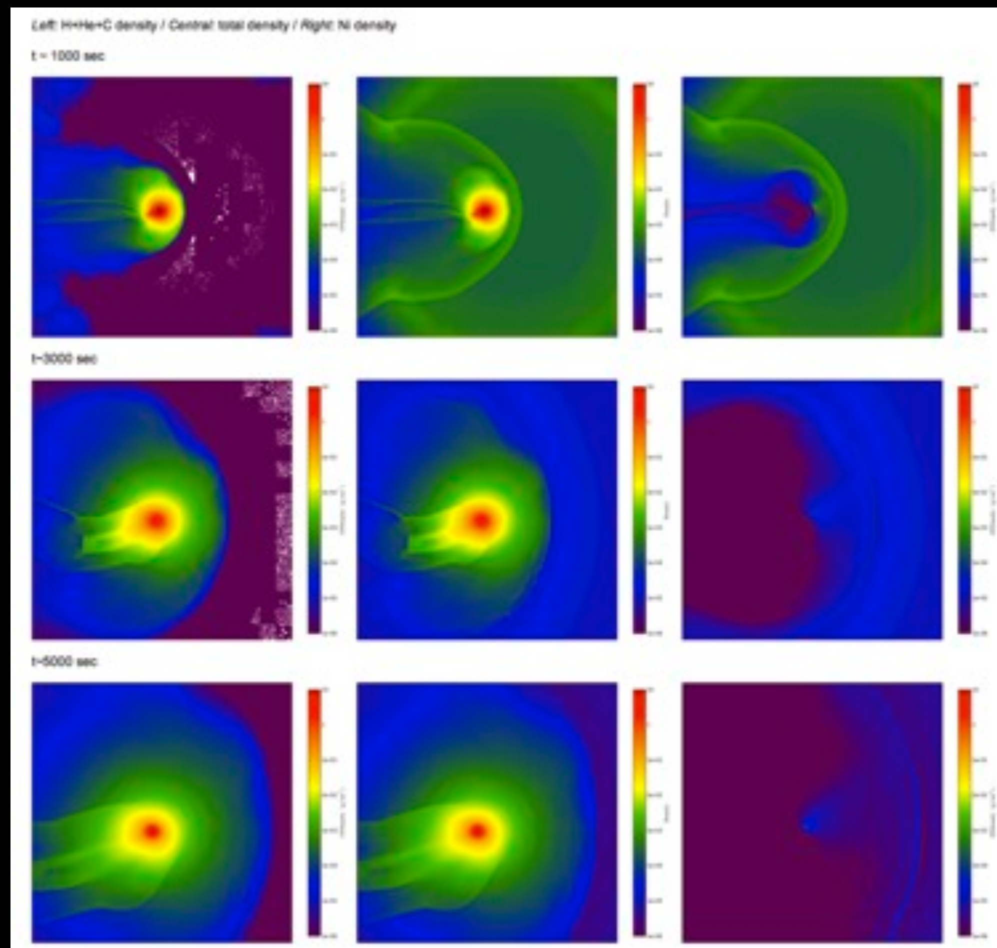
Pakmor et al. 2008



The opening angle of the cone-like hole is about ~45 degree in Pakmor et al. (2008)

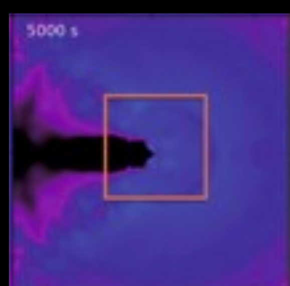
Hole in the ejecta

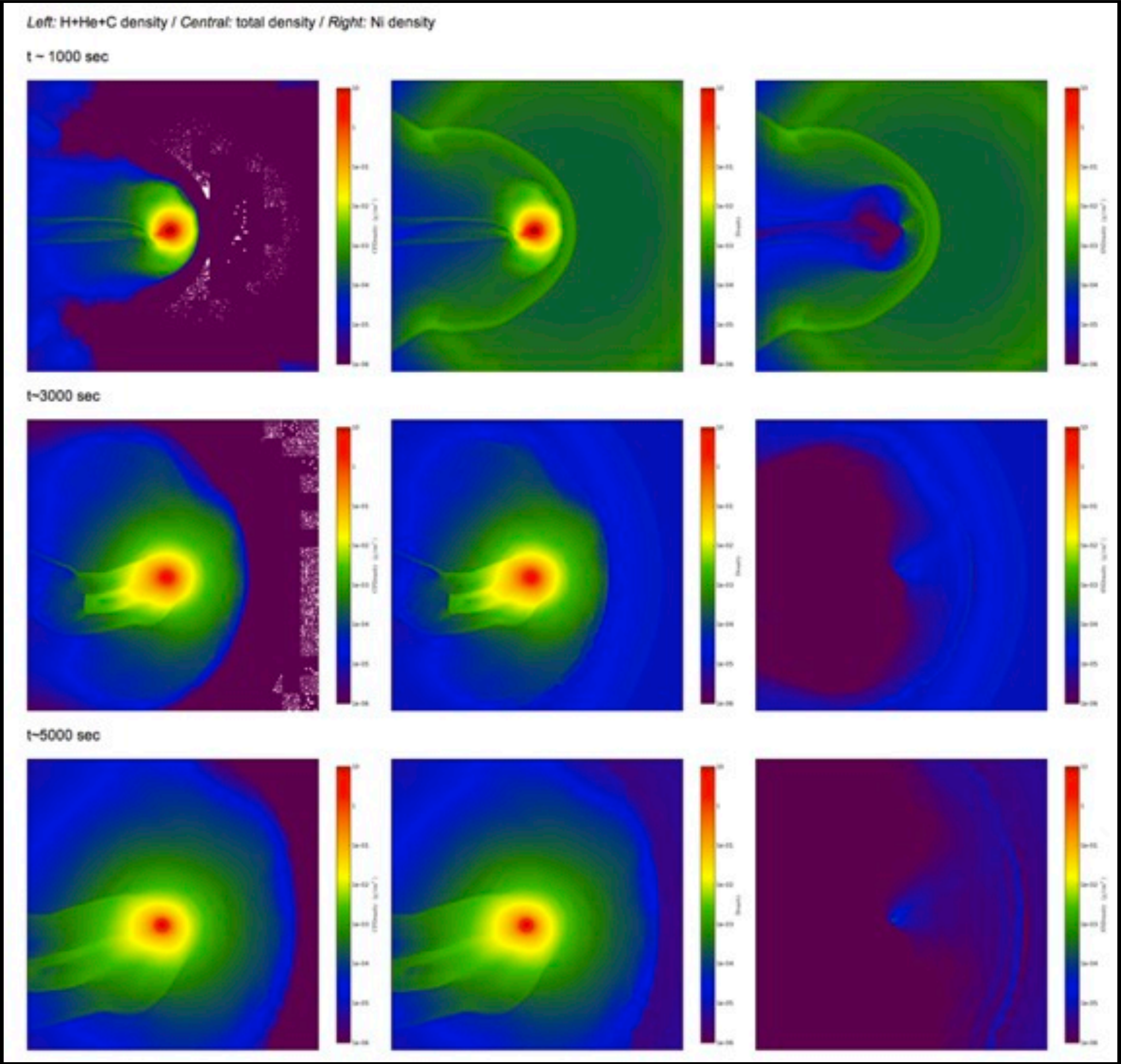
Pan et al. (2011)



The opening angle of the cone-like hole is about ~45 degree in Pakmor et al. (2008)

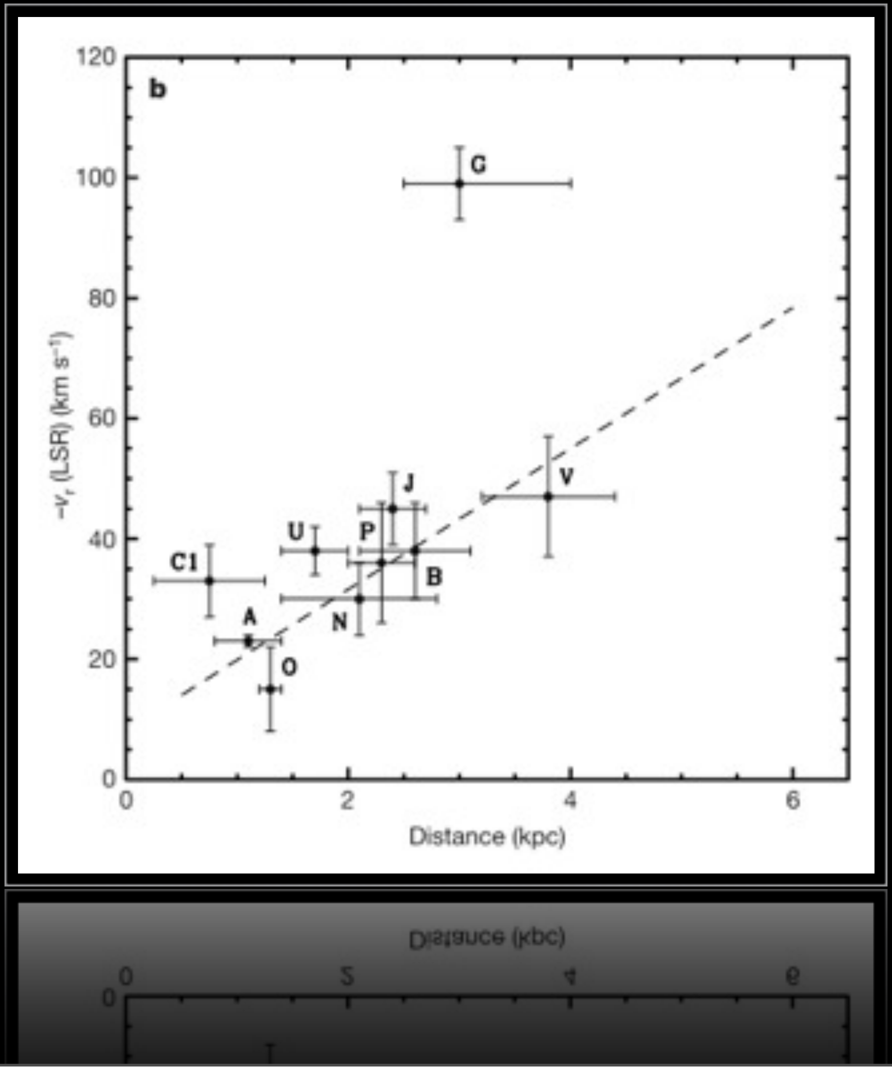
But the reverse shock is unclear in their SPH simulation




Left: H+He+C density / Central: total density / Right: Ni density
t ~ 1000 sec
t~3000 sec
t~5000 sec

Detectability of the remnant companion star

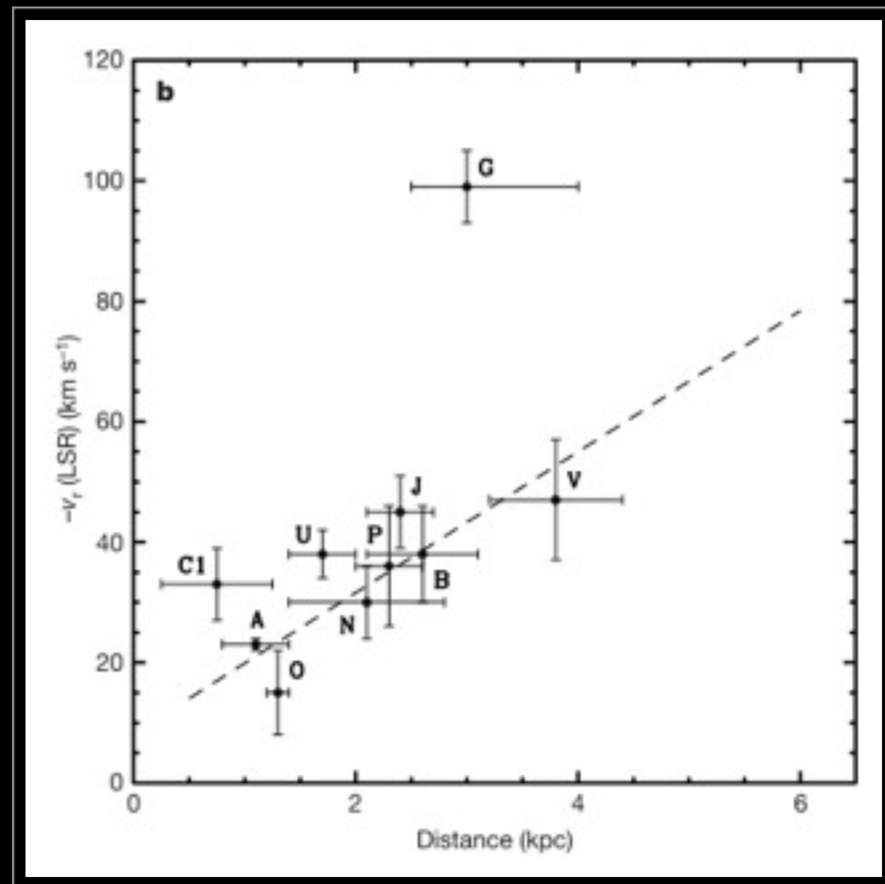
Ruiz-Lapuente et al. (2004)



Detectability of the remnant companion star

Ruiz-Lapuente et al. (2004)

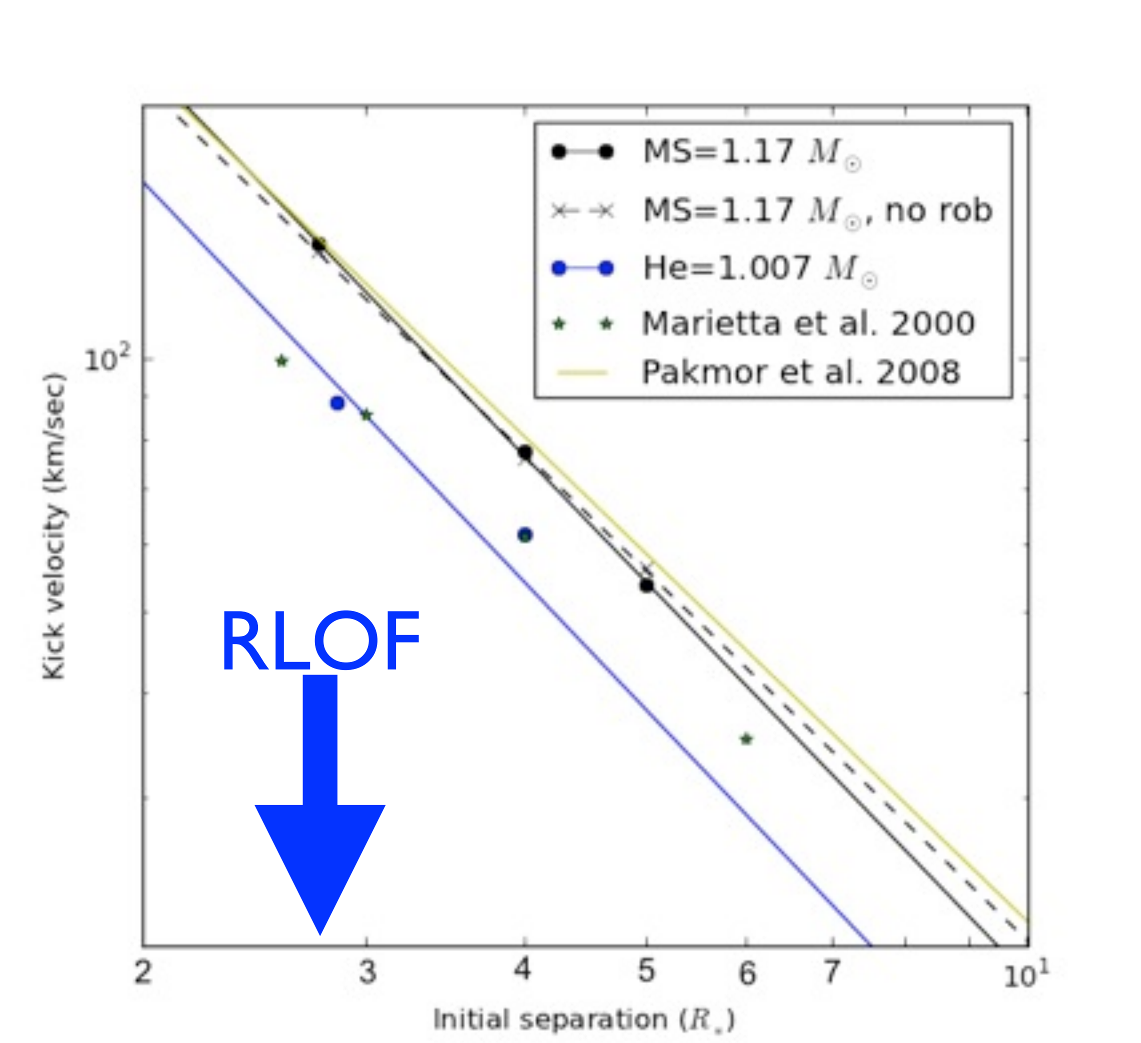
Tycho’s Supernova Remnant (x-ray)



Detectability of the remnant companion star

Orbital speed (RLOF)
MS: 256.7 km/sec
RG: 41.7 km/sec
He: 522.9 km/sec

Kick velocity (RLOF)
MS: 136.7 km/sec
RG: ~0
He: 88.4 km/sec



Detectability of the remnant companion star

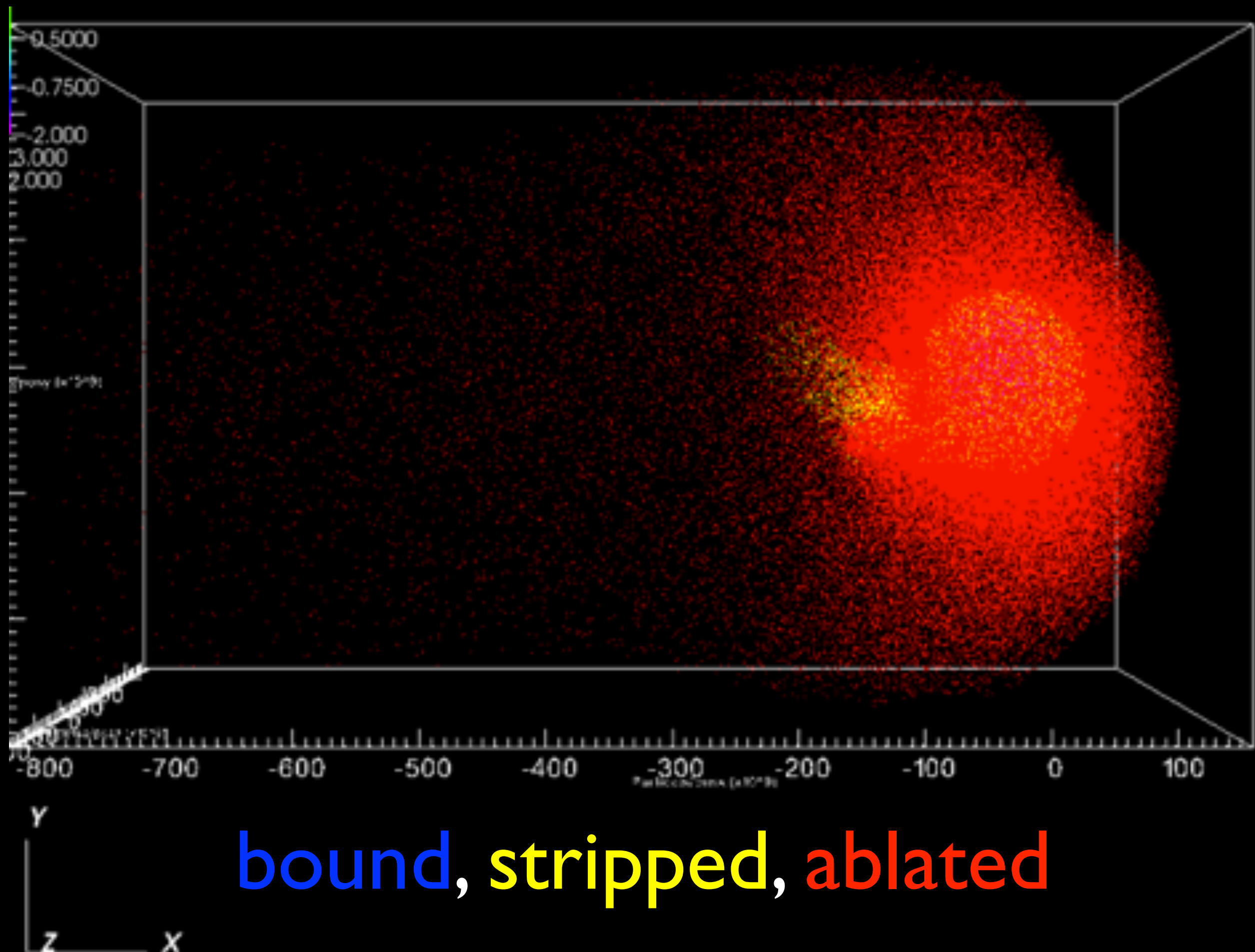
- Nickel Contamination

  MS: < 9 x 10^{-5} Solar mass (<0.09%)

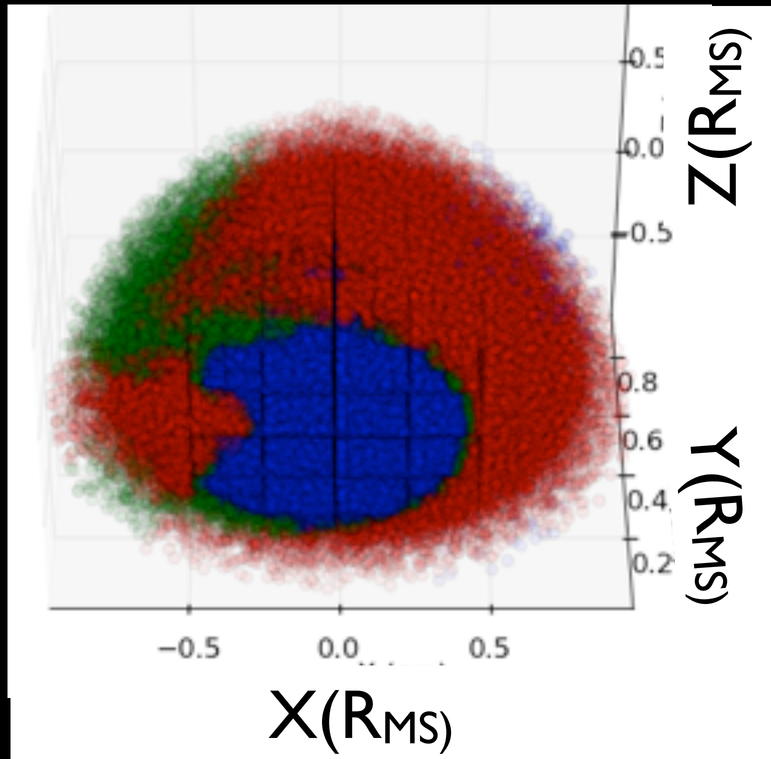
  RG: < 3 x 10^{-7} Solar mass (<0.06%)

  He: < 3 x 10^{-4} Solar mass (<0.03%)

Ablated and Stripped Mass



bound, stripped, ablated



bound, stripped, ablated

Conclusions

- Investigated the impact of SN Ia ejecta on a companion star.
- A power-law relation between the unbound mass and initial separation is found
- Kick velocity can also fitted by a power law
- ~10^{-4} solar mass nickel contamination which is larger than the solar abundance

- High performance computing is required in this project.
- A tool to automatic MPI to AMPI transformation
- Charm++ AMR framework

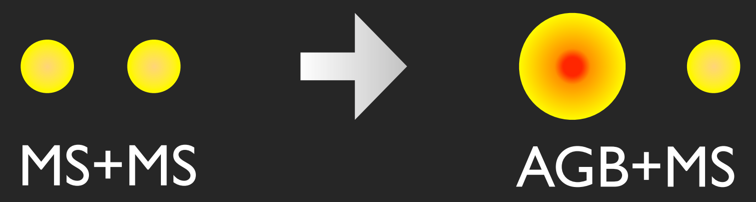
Future work

- Combine the radiation process with fluids
- Predict supernova light curves
- Compare with observations
- Improve the performance and load balancing
- Study possible replacement of PARAMESH with Charm++ library

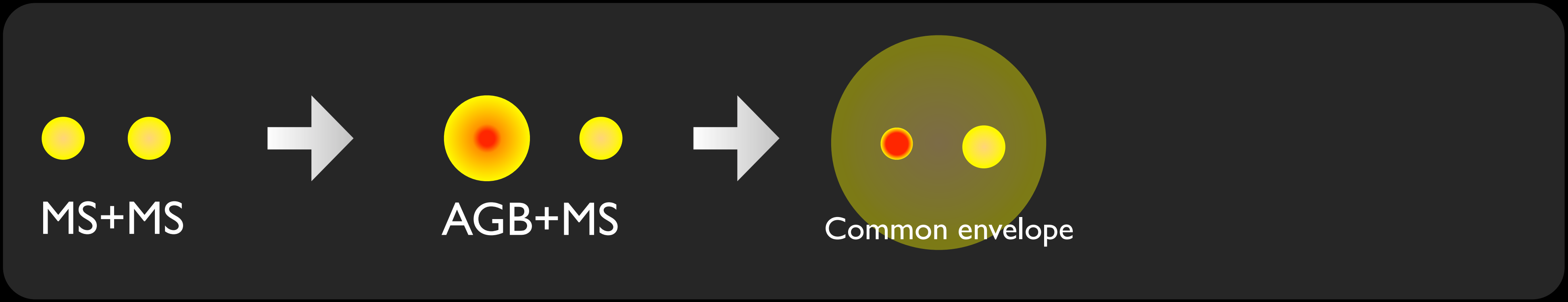
Binary evolution scenario

MS+MS

Binary evolution scenario



Binary evolution scenario



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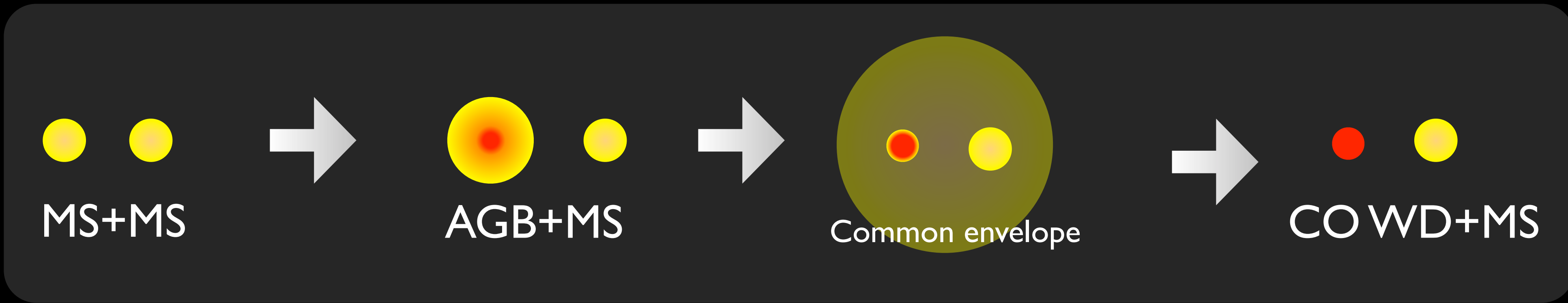

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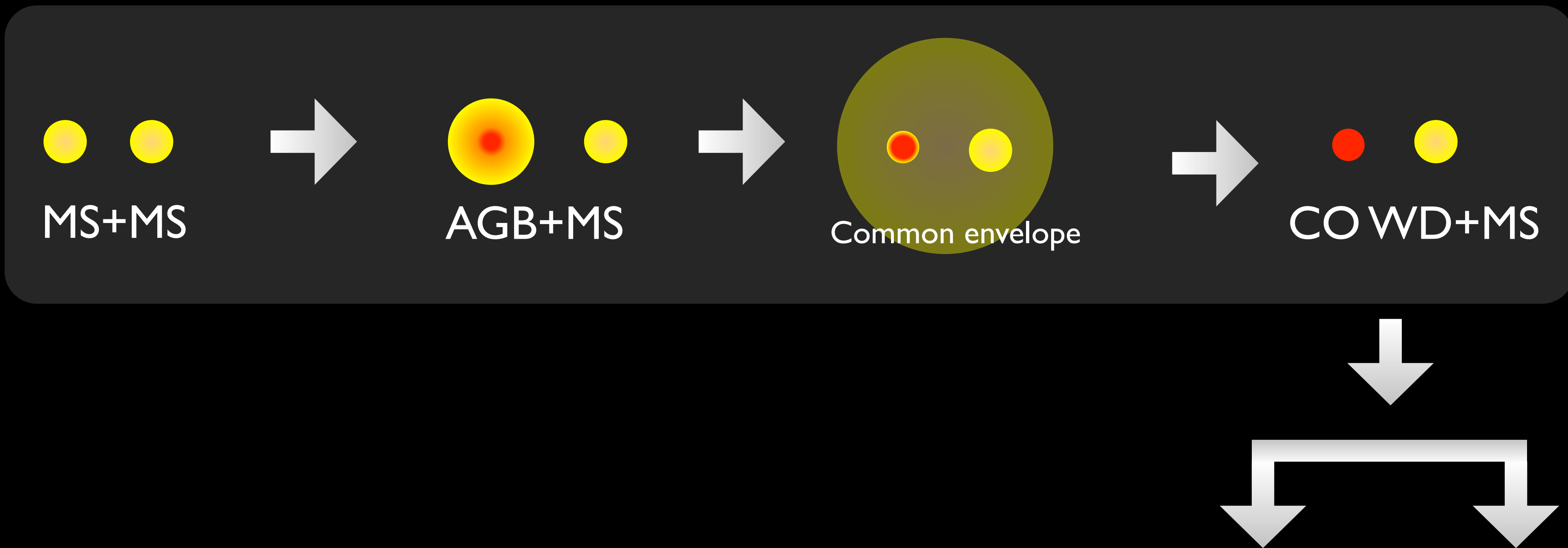

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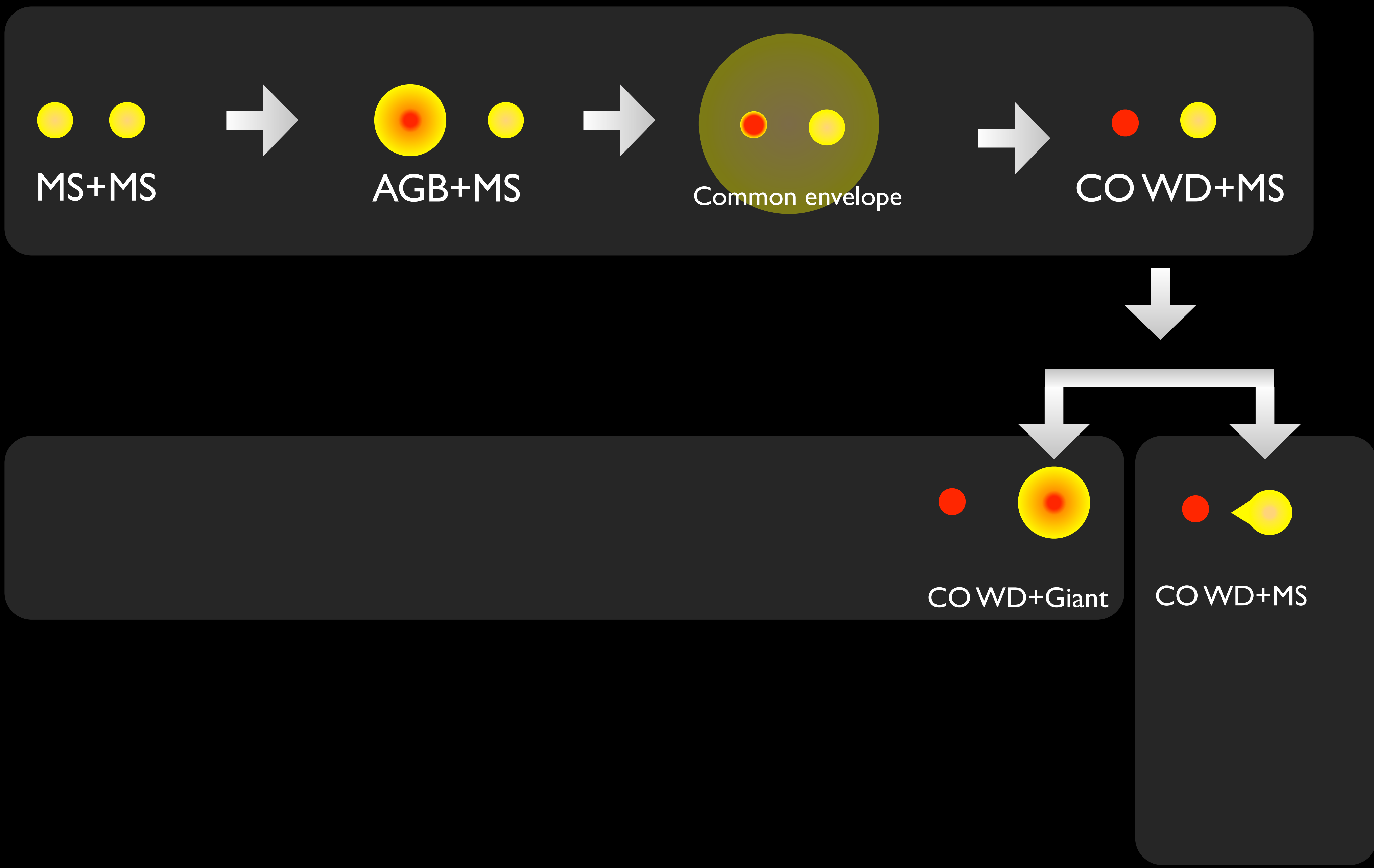

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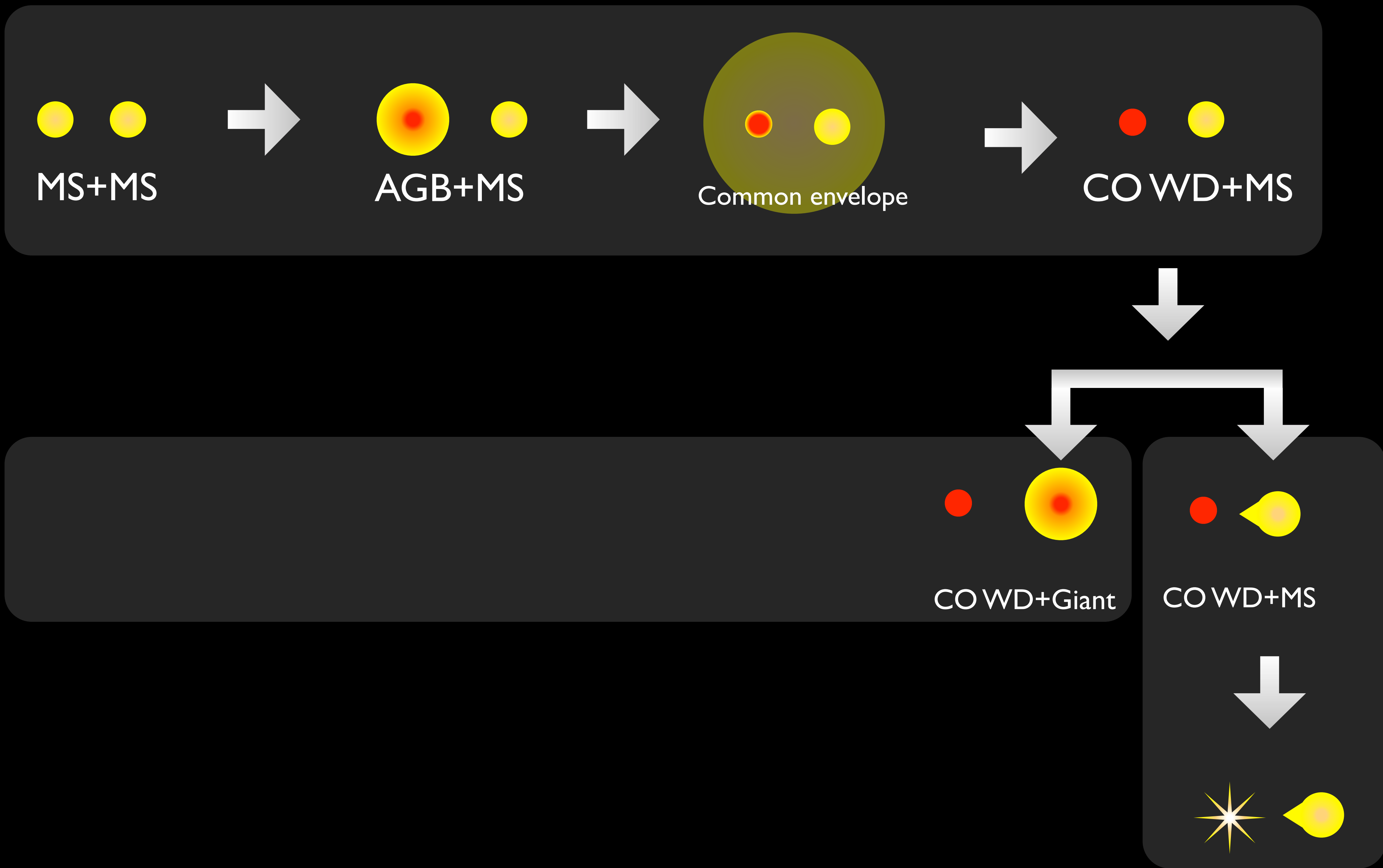

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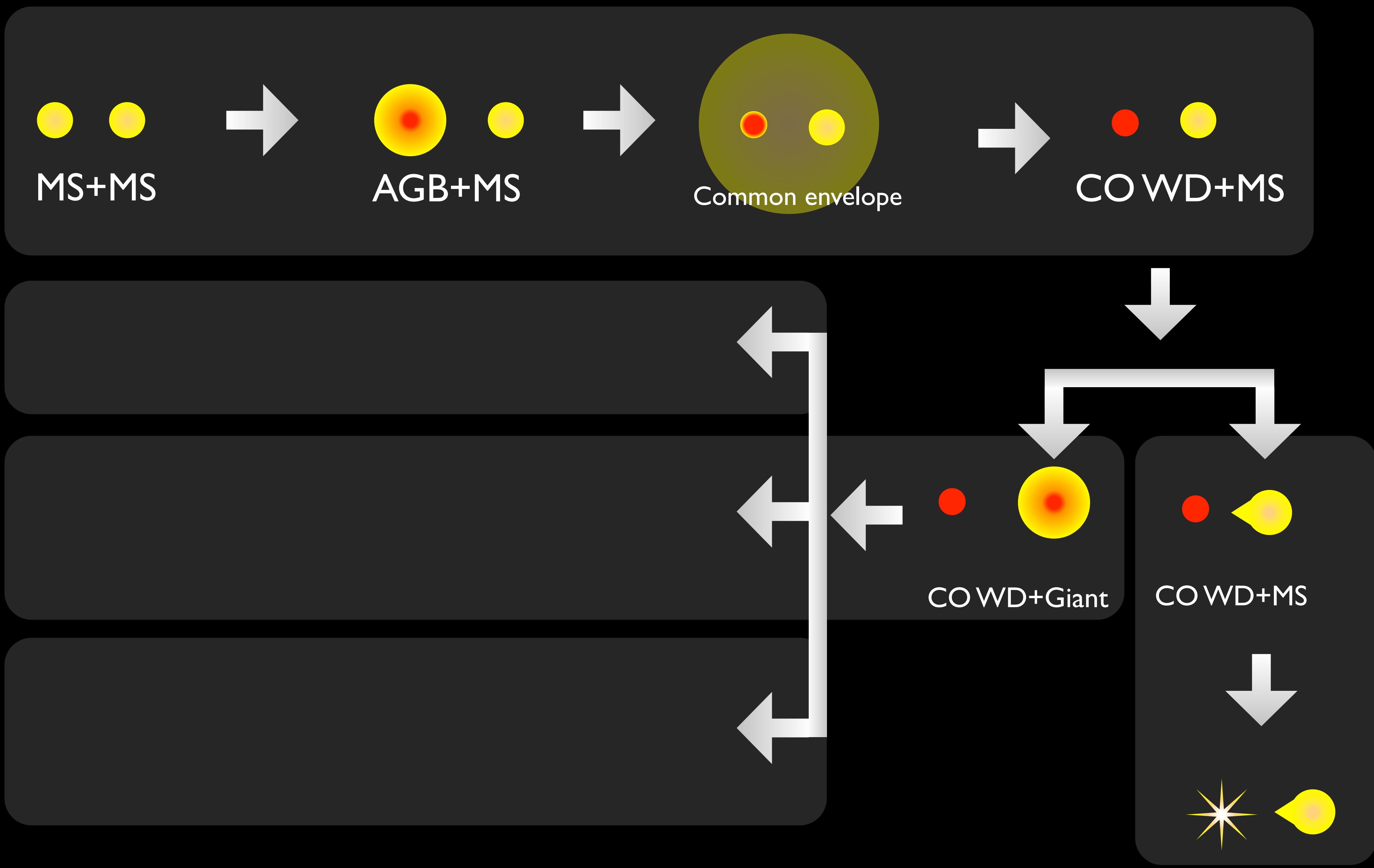
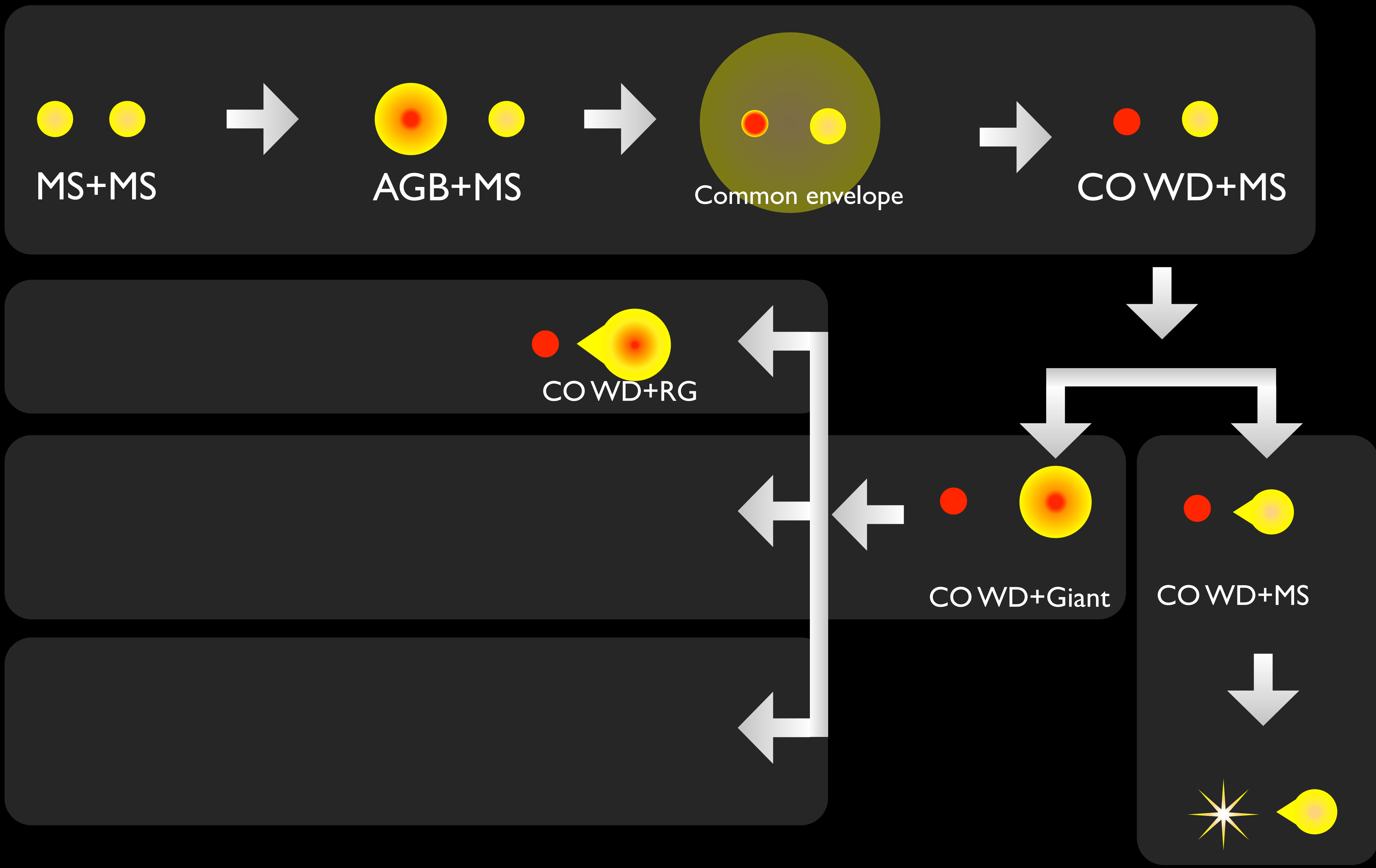


Binary evolution scenario



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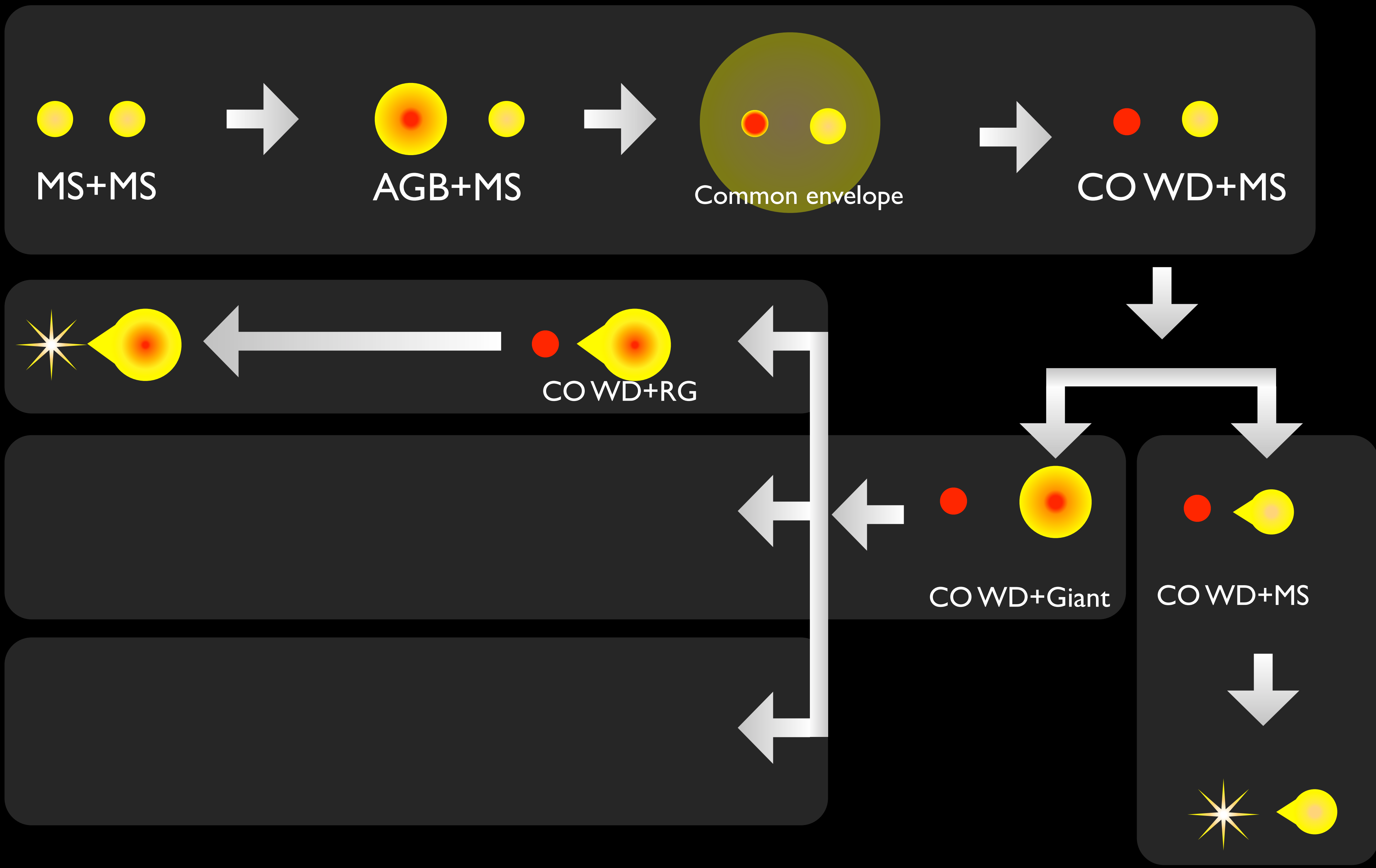

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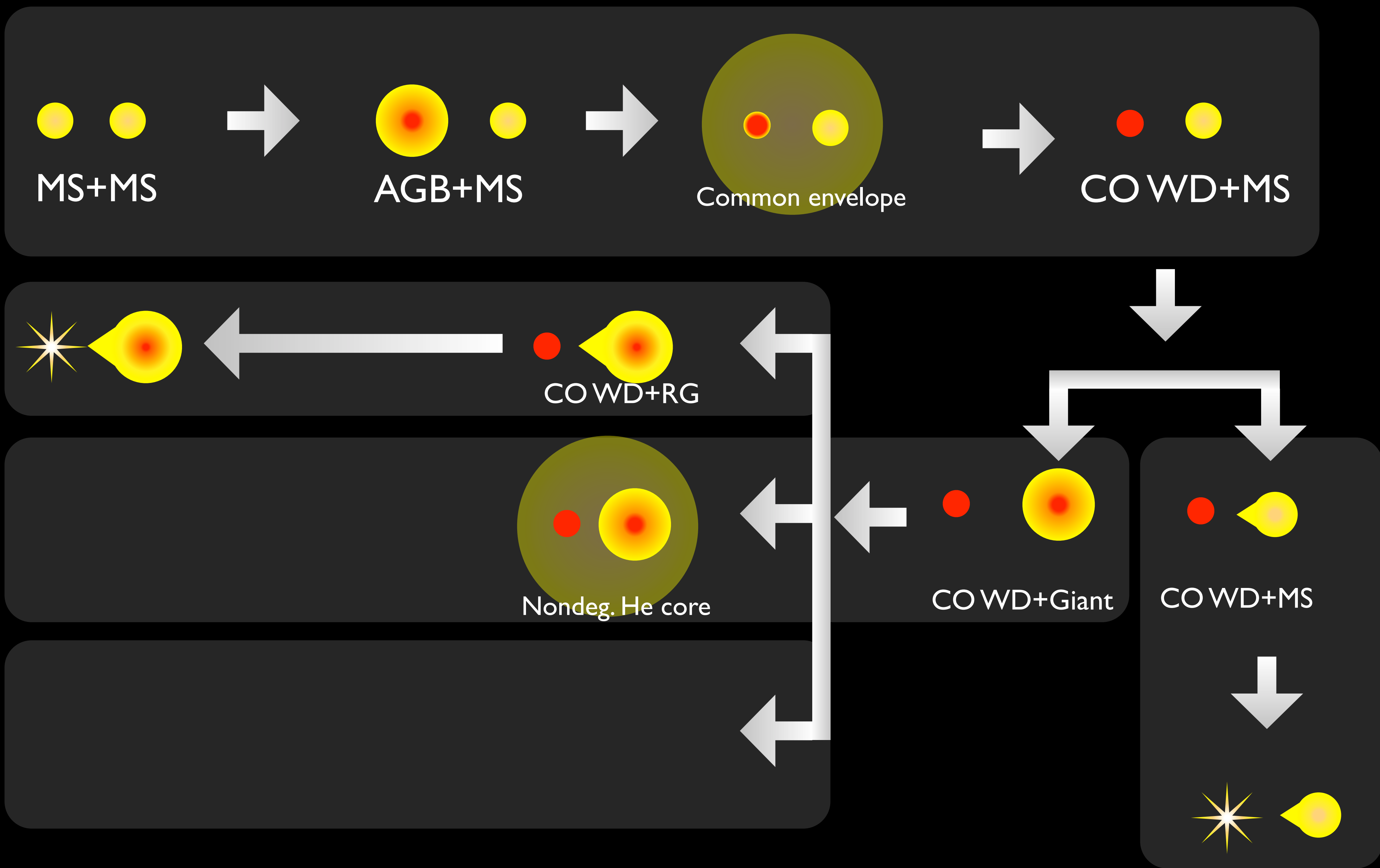

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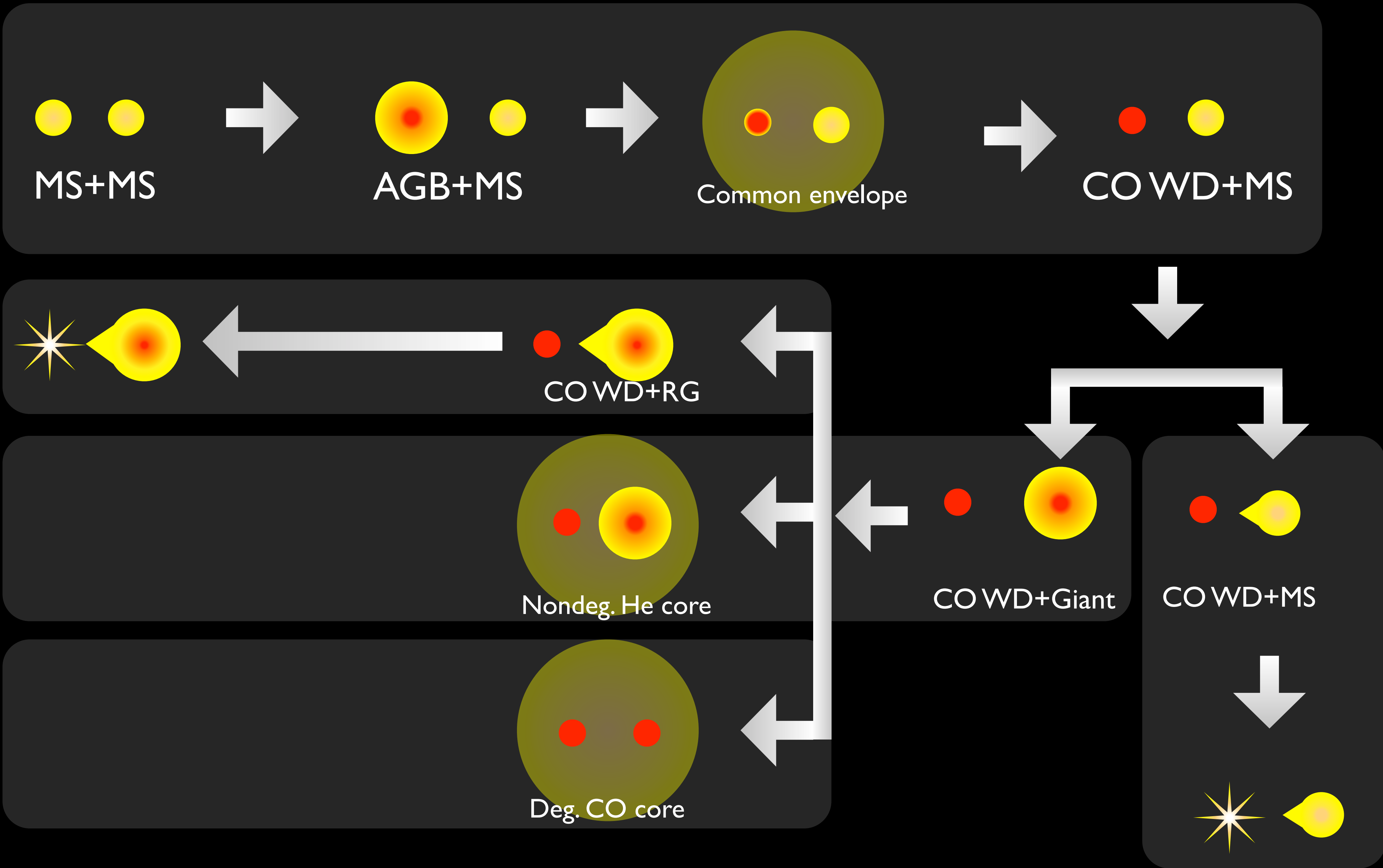

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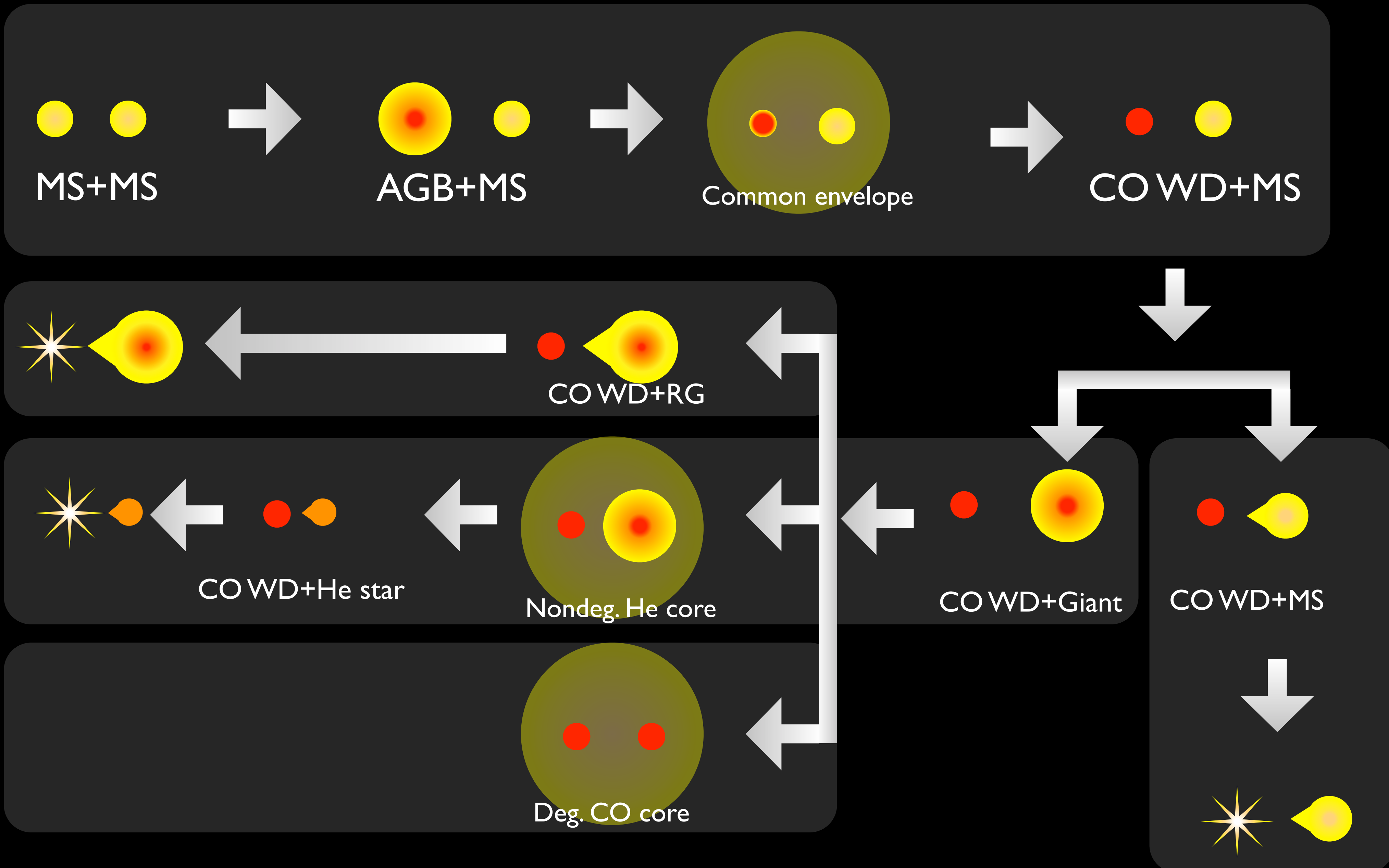

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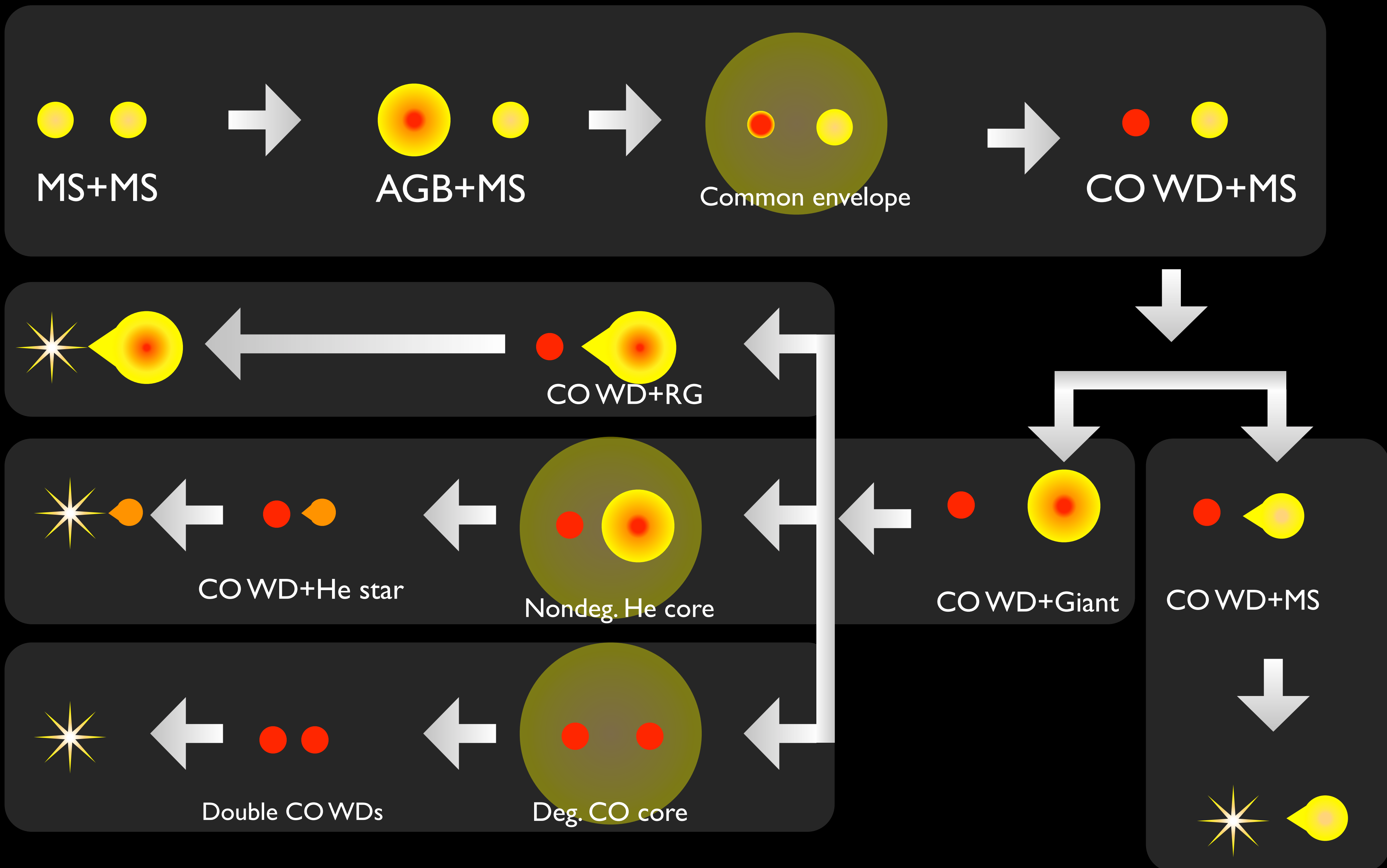


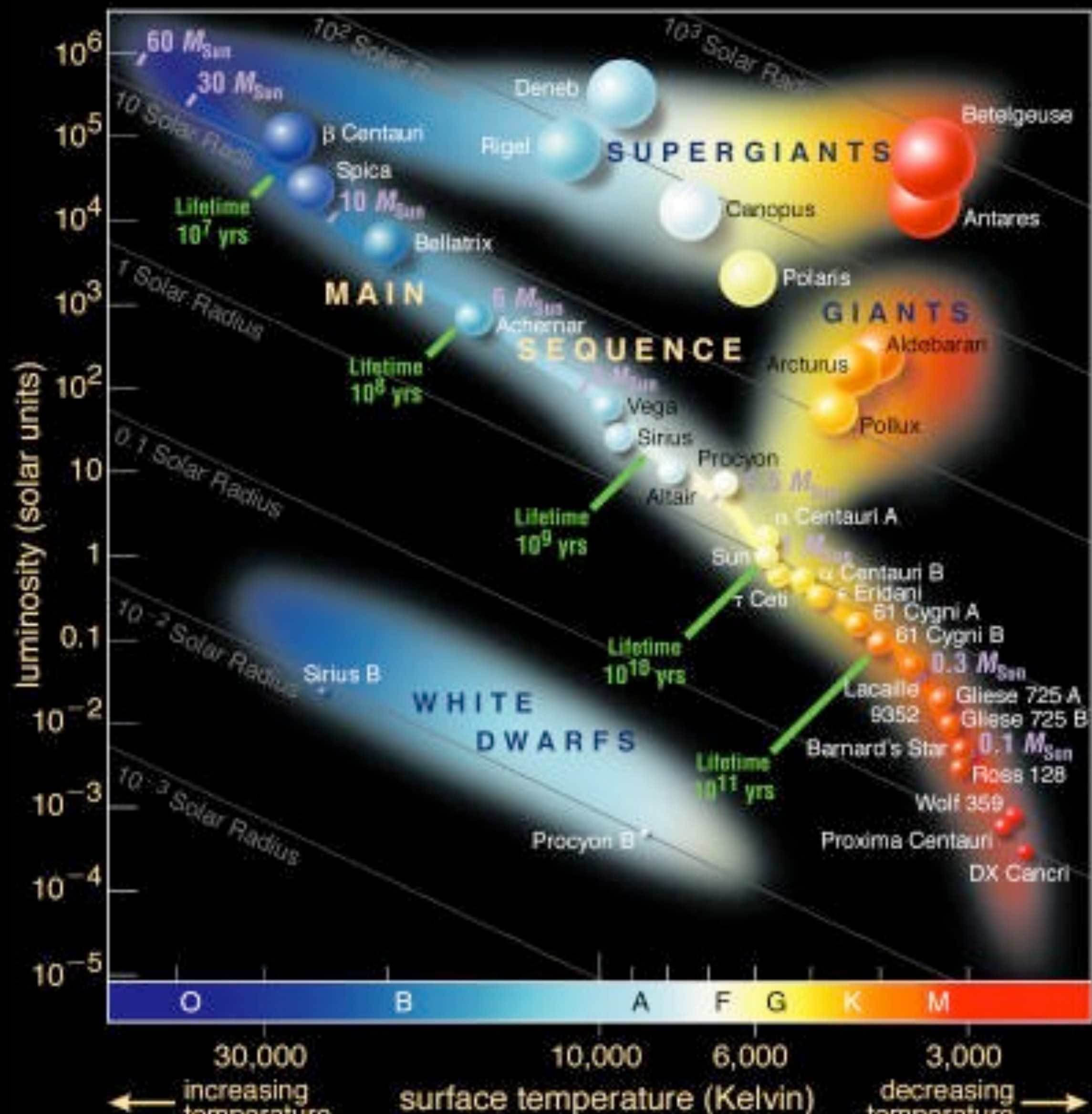
The Euler's equation for compressible hydrodynamics

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial \rho \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) + \nabla P = \rho \mathbf{g}$$

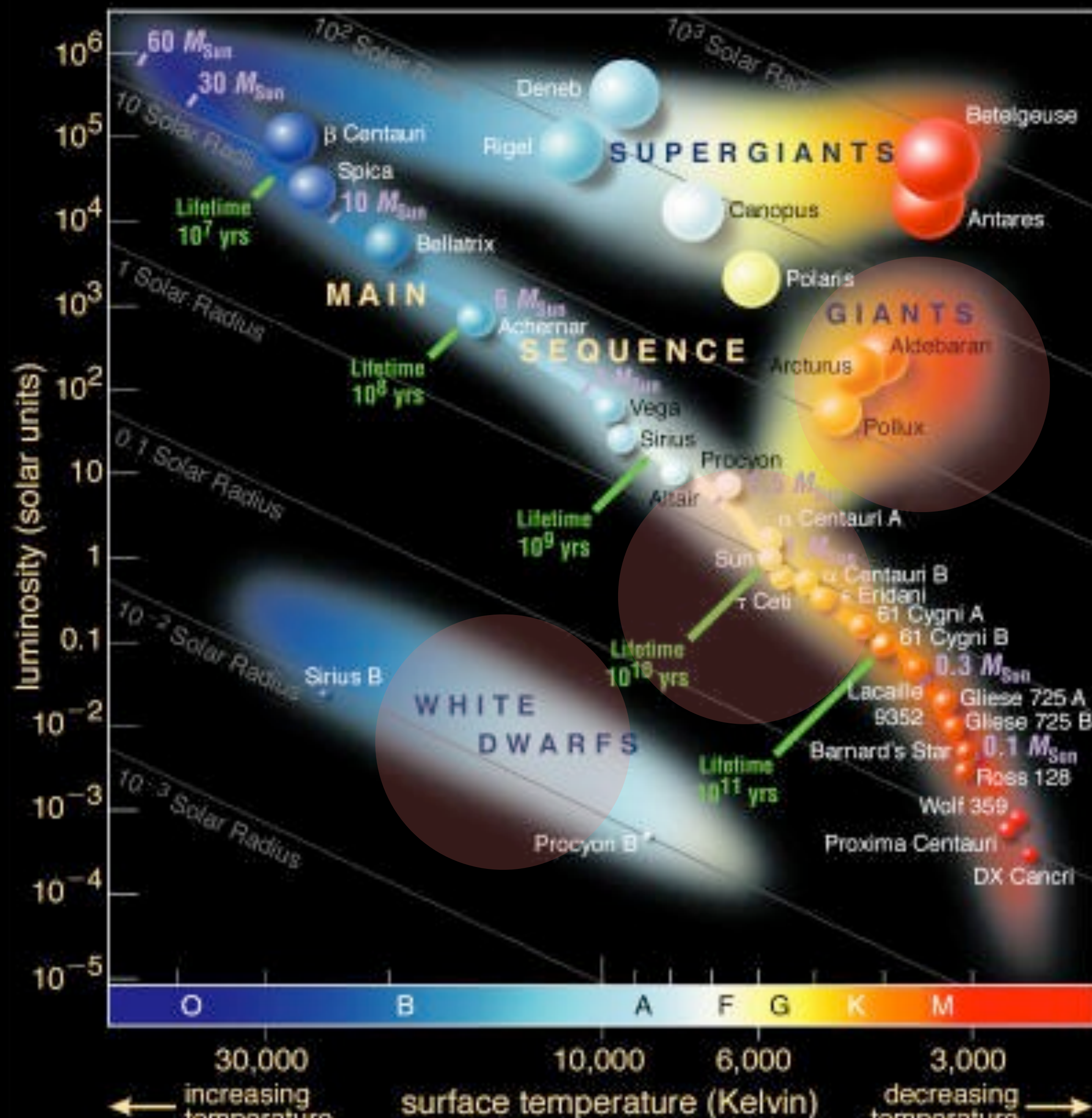
$$\frac{\partial \rho E}{\partial t} + \nabla \cdot [(\rho E + P)\mathbf{v}] + \nabla P = \rho \mathbf{v} \cdot \mathbf{g}$$

Star Types



Monday, April 18, 2011

Star Types



Monday, April 18, 2011

Delay Time Distribution (DTD)

- The long-delay-time population (3-4 Gyr)
  Main-Sequence &White Dwarf channel (Hachisu et al. 2008)
  Red Giant & White Dwarf channel (Hachisu et al. 1999,2008)
- The short-delay-time population (0.1 Gyr)
  Helium Star & White Dwarf channel (Wang et al. 2009)