Using adaptive nested mesh code HydroBox3D for numerical simulation of Type Ia supernovae: merger of carbon-oxygen white dwarf stars, collapse, and non-central explosion

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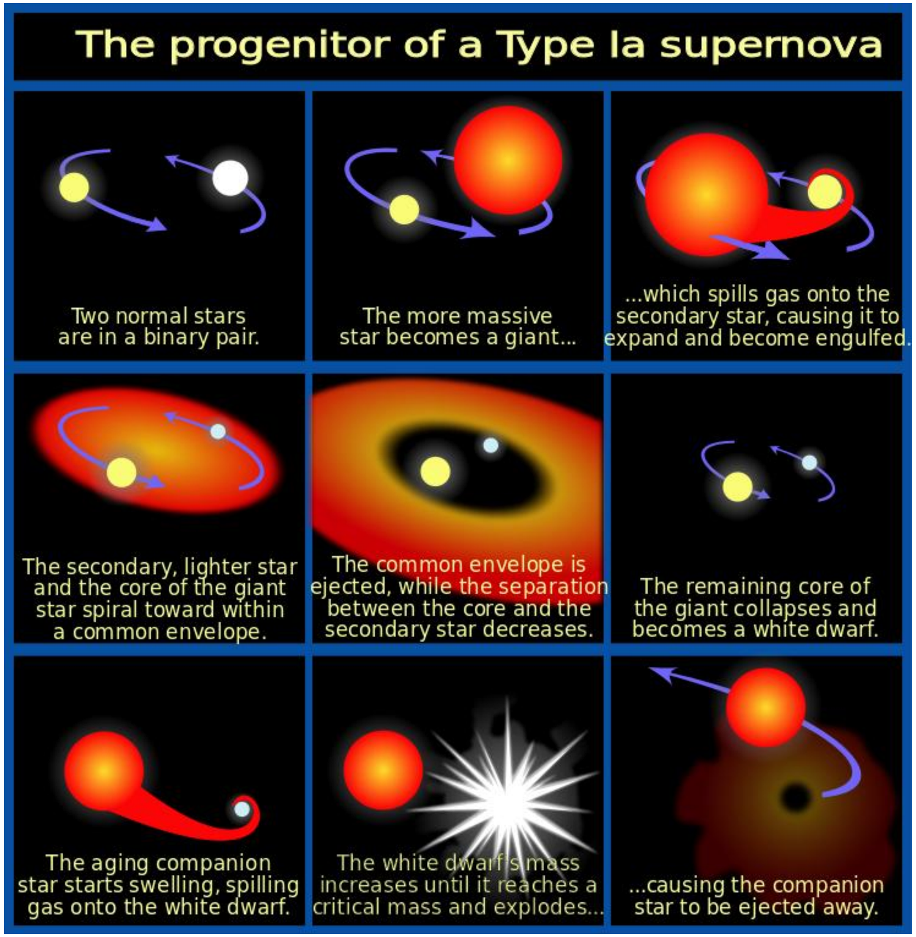
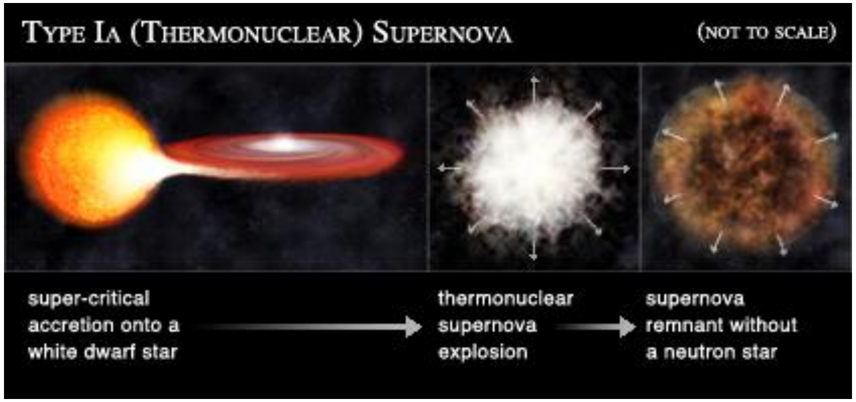
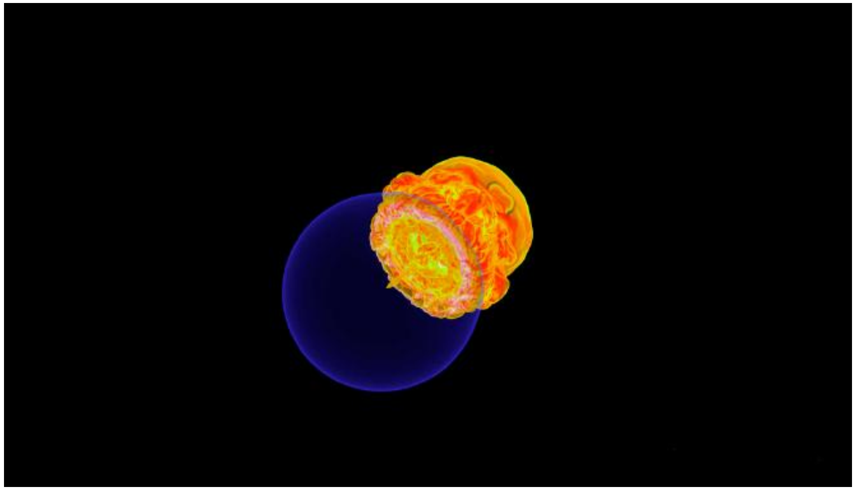
Moscow, Russia

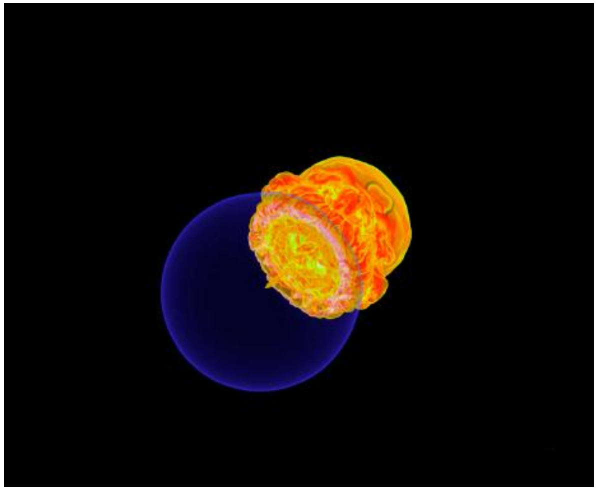
The motivation: white dwarf evolution







The motivation: white dwarf evolution (asymmetric explosion)



The mathematical challenges:

1. The numerical model construction
2. The numerical solver development
3. The efficiency parallel implementation

White dwarf expands less than in the Röpke et al. model, so the collision on the far side occurs at higher density and with less geometrical dilution. In the Chicago version, the temperature is sufficient to ignite a detonation that consumes the rest of the star.

Jordan et al. (2008)

The supernova explosion enriches interstellar medium with the elements of life: *O, C, Fe, N, Si, Mg, Ca,…*

The Hydrodynamic Model of White Dwarf

- The Euler hydrodynamics equations
- The gravity
- The stellar equation of state:
  - Ideal gas for low temperature
  - Adiabatic (non)relativistic degenerate gas for high temperature
  - Radiation term
- The carbon burning $^{12}C + {}^{12}C \rightarrow {}^{23}Na + p$

The numerical methods for hydrodynamics

SPH approach

- Robustness of the algorithm
- Galilean-invariant solution
- Simplicity of implementation
- Flexible geometries of problems
- High accurate gravity solvers

- Artificial viscosity is parameterized
- Variations of the smoothing length
- The problem of shock wave and discontinuous solutions
- Instabilities suppressed
- The method is not scalable

AMR approach

- Approved numerical methods
- No artificial viscosity
- Higher order shock waves
- Resolution of discontinuities
- No suppression of instabilities
- Correct turbulence solution

- The complexity of implementation
- The effects of mesh
- Problem of the minimal mesh
- Not Galilean-invariant solution
- The method is not scalable

Top10 (November 11, 2018)

The hybrid supercomputers

Rank	System	Cores	(TFlop/s)	(TFlop/s)	(kW)
1	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM DOE/SC/Oak Ridge National Laboratory United States	2,397,824	143,500.0	200,794.9	9,783
2	**Sierra** - IBM Power System S922LC, IBM POWER9 22C 3.1GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM / NVIDIA / Mellanox DOE/NNSA/LLNL United States	1,572,480	94,640.0	125,712.0	7,438
3	**Sunway TaihuLight** - Sunway MPP, Sunway SW26010 260C 1.45GHz, Sunway , NRCPC National Supercomputing Center in Wuxi China	10,649,600	93,014.6	125,435.9	15,371
4	**Tianhe-2A** - TH-IVB-FEP Cluster, Intel Xeon E5-2692v2 12C 2.2GHz, TH Express-2, Matrix-2000 , NUDT National Super Computer Center in Guangzhou China	4,981,760	61,444.5	100,678.7	18,482
5	**Piz Daint** - Cray XC50, Xeon E5-2690v3 12C 2.6GHz, Aries interconnect , NVIDIA Tesla P100 , Cray Inc. Swiss National Supercomputing Centre (CSCS) Switzerland	387,872	21,230.0	27,154.3	2,384
6	**Trinity** - Cray XC40, Xeon E5-2698v3 16C 2.3GHz, Intel Xeon Phi 7250 68C 1.4GHz, Aries interconnect , Cray Inc. DOE/NNSA/LANL/SNL United States	979,072	20,158.7	41,461.2	7,578
7	**AI Bridging Cloud Infrastructure (ABCI)** - PRIMERGY CX2570 M4, Xeon Gold 6148 20C 2.4GHz, NVIDIA Tesla V100 SXM2, Infiniband EDR , Fujitsu National Institute of Advanced Industrial Science and Technology (AIST) Japan	391,680	19,880.0	32,576.6	1,649
8	**SuperMUC-NG** - ThinkSystem SD530, Xeon Platinum 8174 24C 3.1GHz, Intel Omni-Path , Lenovo Leibniz Rechenzentrum Germany	305,856	19,476.6	26,873.9	
9	**Titan** - Cray XK7, Opteron 6274 16C 2.200GHz, Cray Gemini interconnect, NVIDIA K20x , Cray Inc. DOE/SC/Oak Ridge National Laboratory United States	560,640	17,590.0	27,112.5	8,209
10	**Sequoia** - BlueGene/Q, Power BQC 16C 1.60 GHz, Custom , IBM DOE/NNSA/LLNL United States	1,572,864	17,173.2	20,132.7	7,890

The original numerical methods

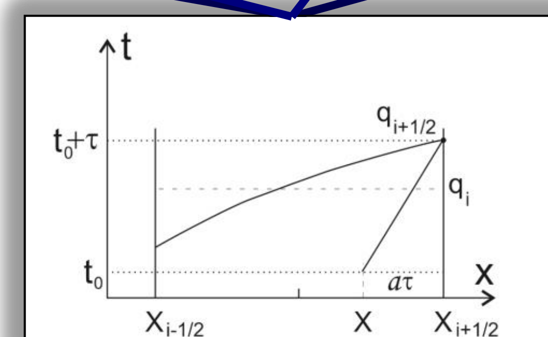
$$\frac{\partial}{\partial t}\begin{pmatrix}\rho \\ \rho\vec{v} \\ \rho E\end{pmatrix} + \nabla\bullet\begin{pmatrix}\rho\cdot\vec{v} \\ \rho\vec{v}\cdot\vec{v} \\ \rho E\cdot\vec{v}\end{pmatrix} = \begin{pmatrix}0 \\ -\nabla p \\ -\nabla\bullet\left(p\vec{v}\right)\end{pmatrix}$$

$$\frac{\vec{u}_k^{n+1} - \vec{u}_k^{n}}{\tau} + \frac{F_{k+1/2} - F_{k-1/2}}{h_i} = 0$$

Vectors

$$F = \frac{F\left(-\lambda\tau\right) + F\left(\lambda\tau\right)}{2} + \frac{c + \|\vec{u}\|}{2}\left(U\left(-\lambda\tau\right) - U\left(\lambda\tau\right)\right)$$

The piecewise-parabolic functions



The Parallel Implementation

Domain Decomposition

↓

Geometry Decomposition
(MPI + FFTW)

↓

Threads Decomposition
(OpenMP)

↓

Vectorization
(AVX 512)

_mm512_set1_pd
set value for a vector

_mm512_load_pd
load a vector from main memory

_mm512_mul_pd
vector multiply

_mm512_add_pd
vector summation

_mm512_sub_pd
vector substitution

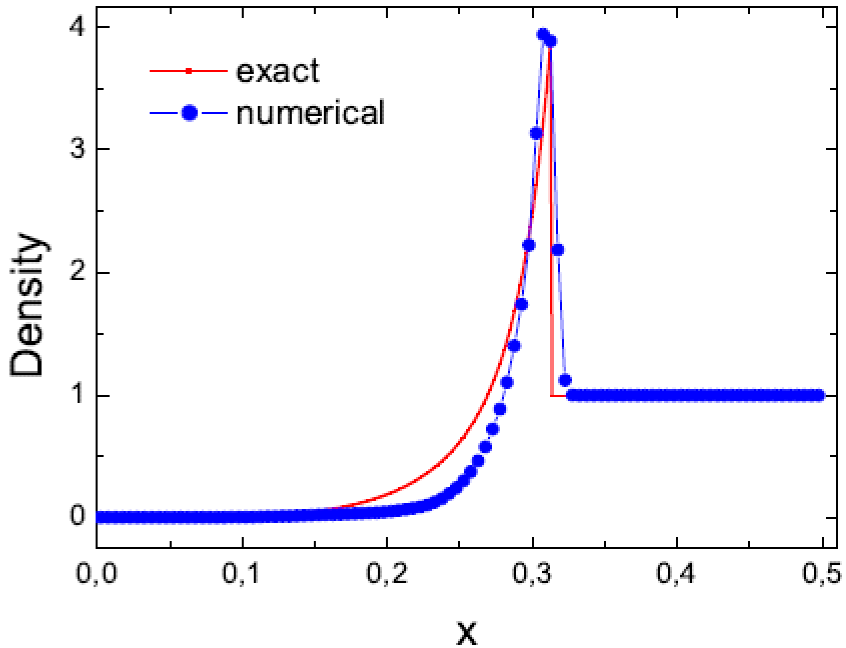
_mm512_store_pd
store a vector to main memory

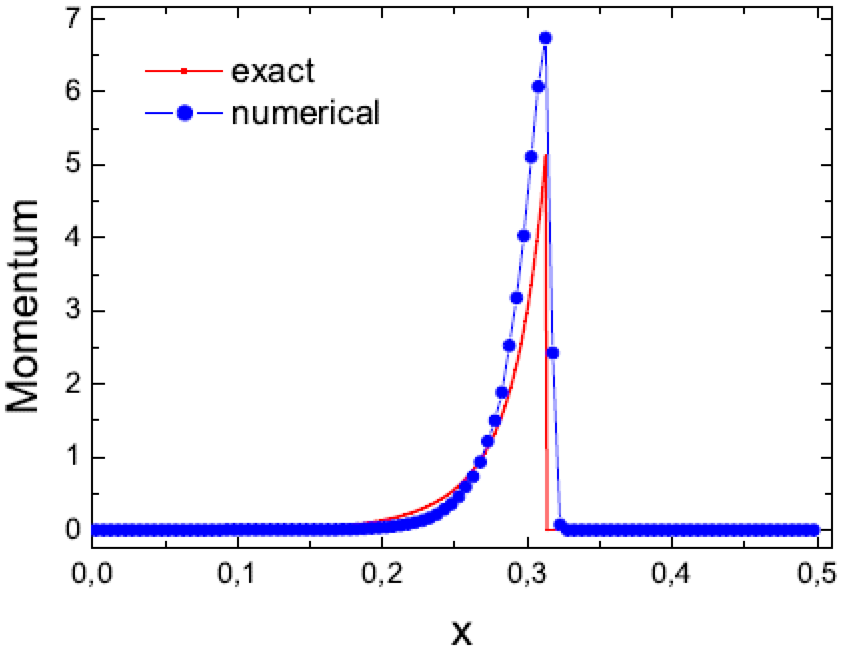
Main advantages is 302 GFLOPS on Intel Xeon Phi KNL

Main disadvantages – formation of the 8-double elements vector for computing

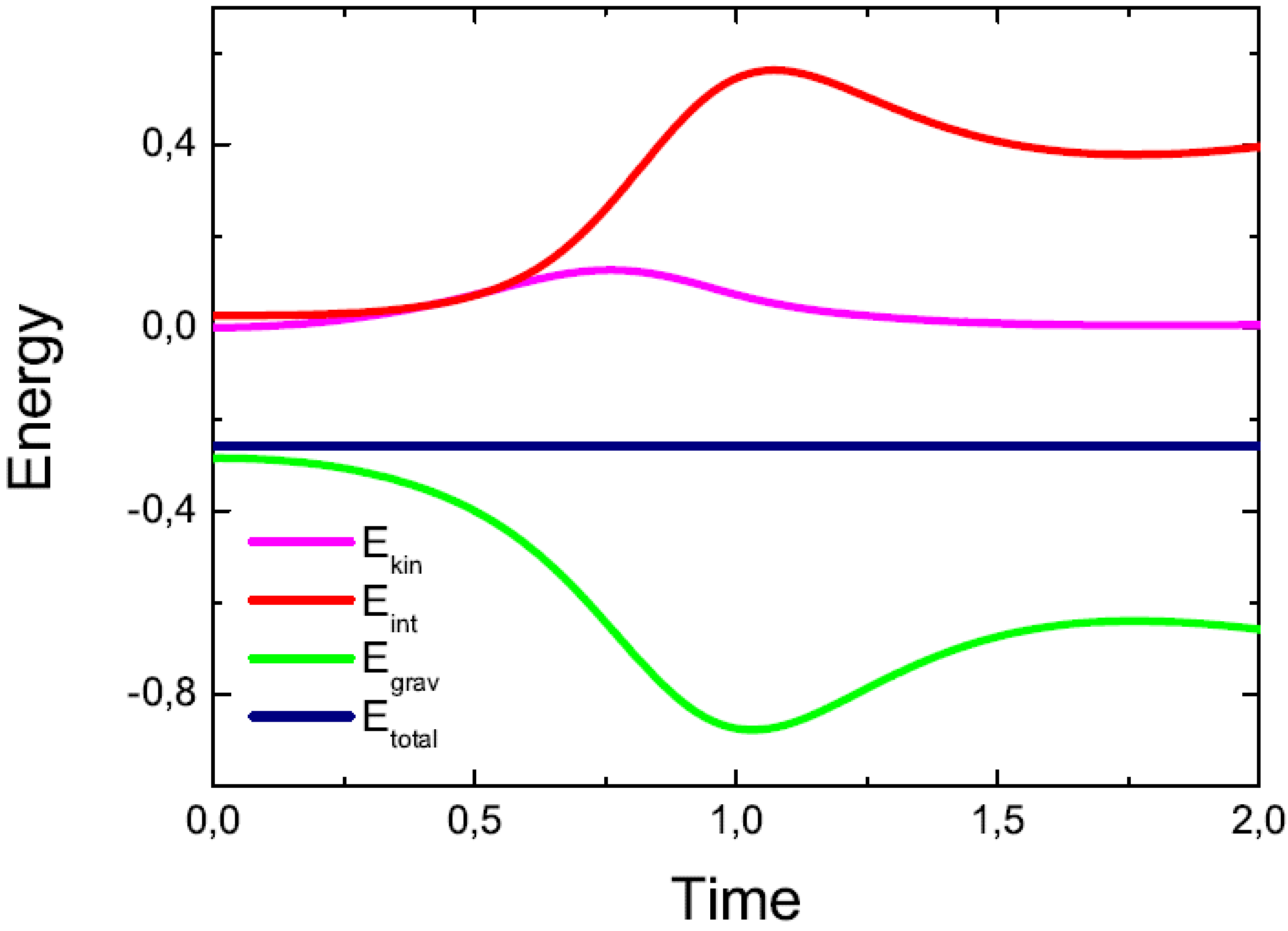
Pitfalls: associative of cache memory, align of memory, schedule distribution, data dependency

The Sedov explosion

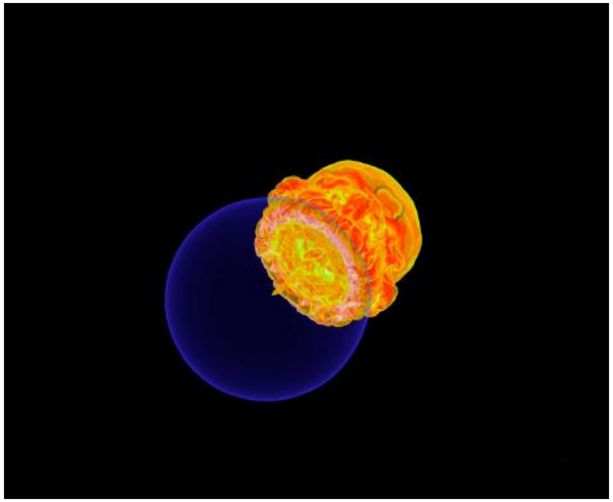




The Evrard collapse

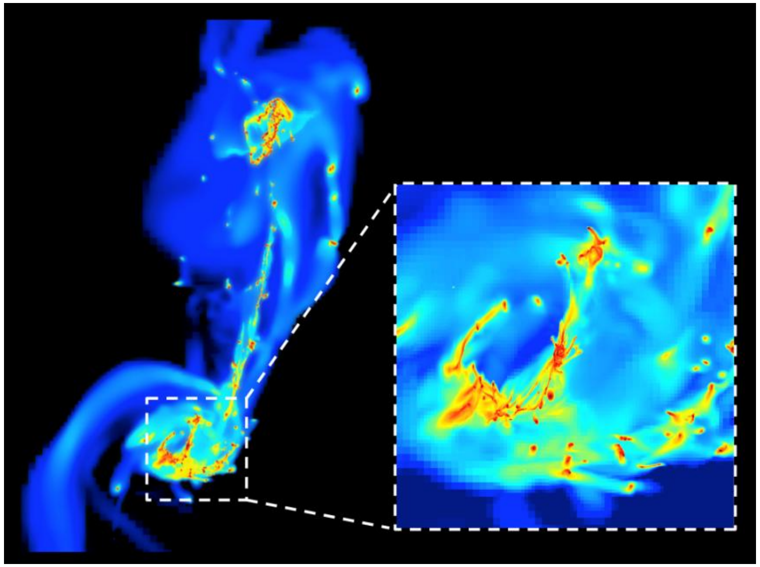


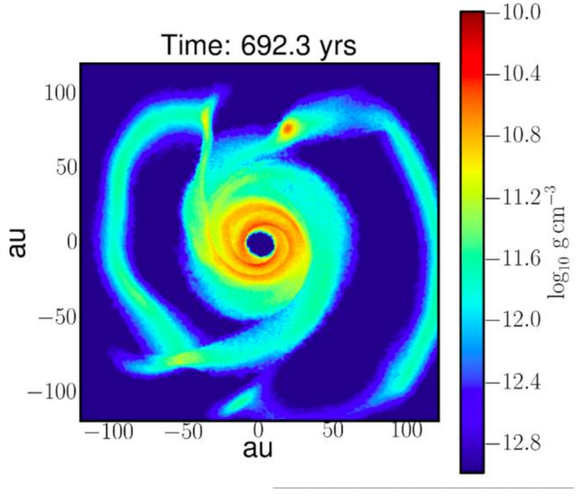
From subgrid to “subreal” models



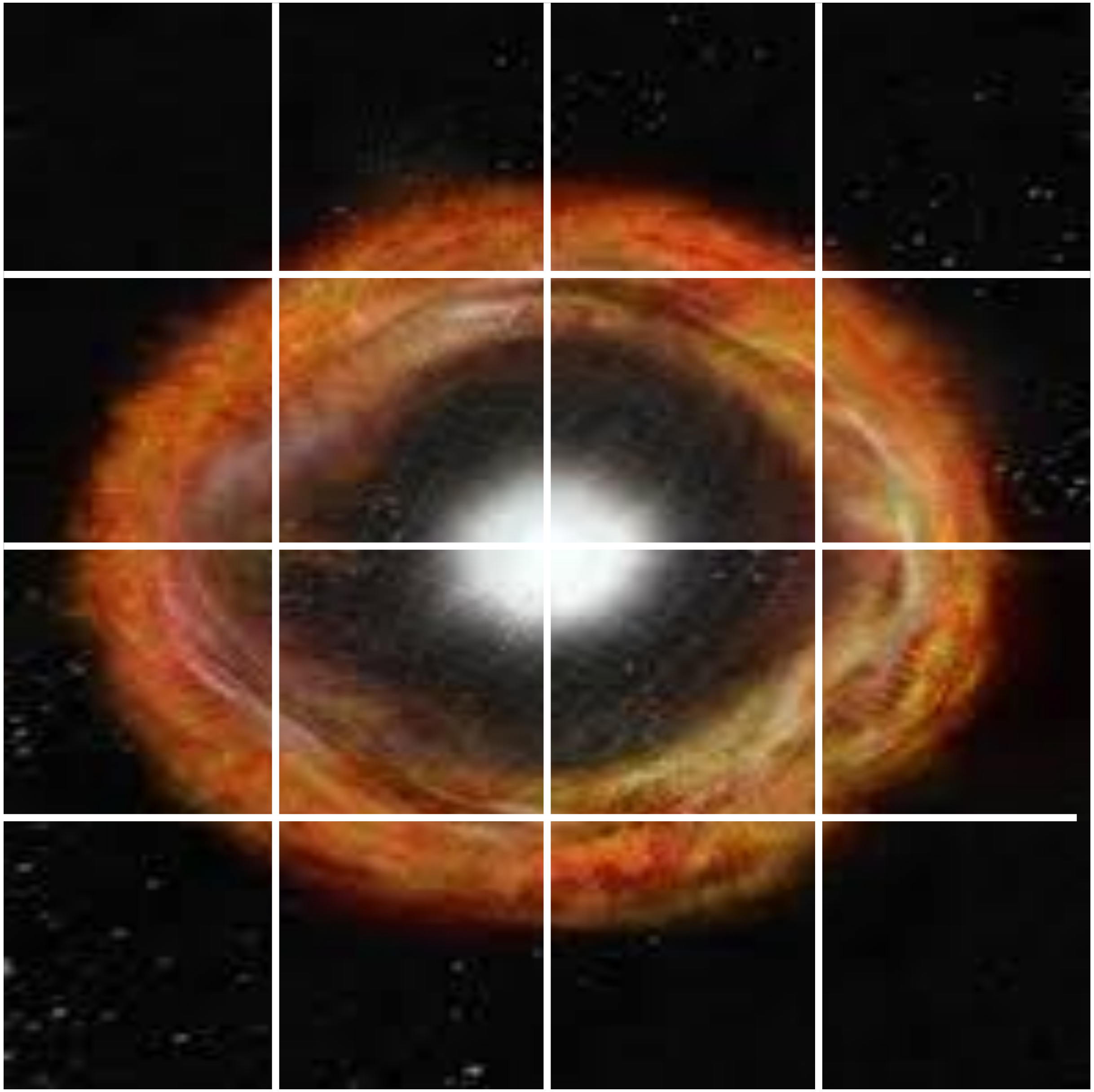
Supernovae explosion

Star formation



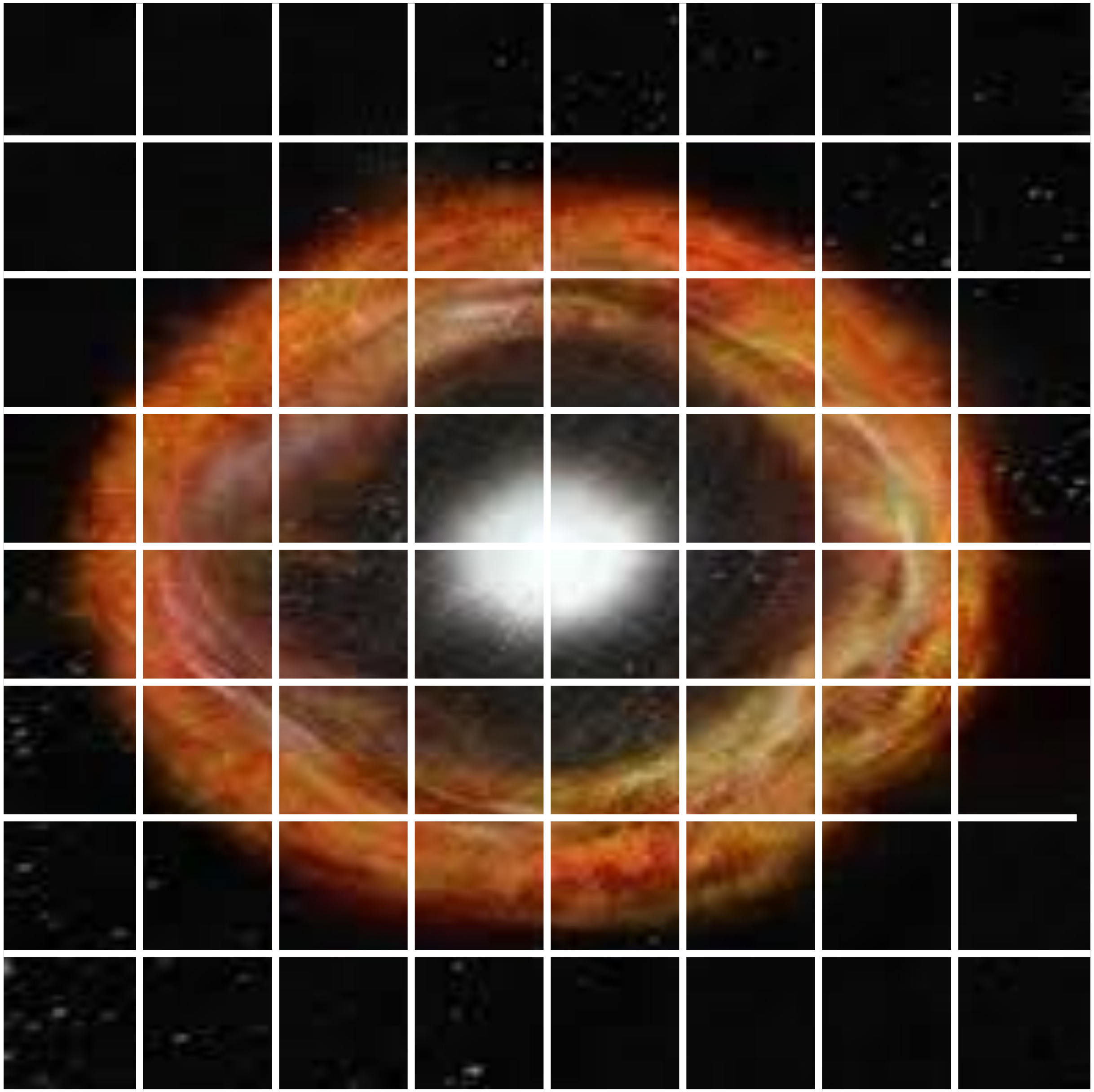


Protoplanetary disks and planet formation



From subgrid to "subreal" models

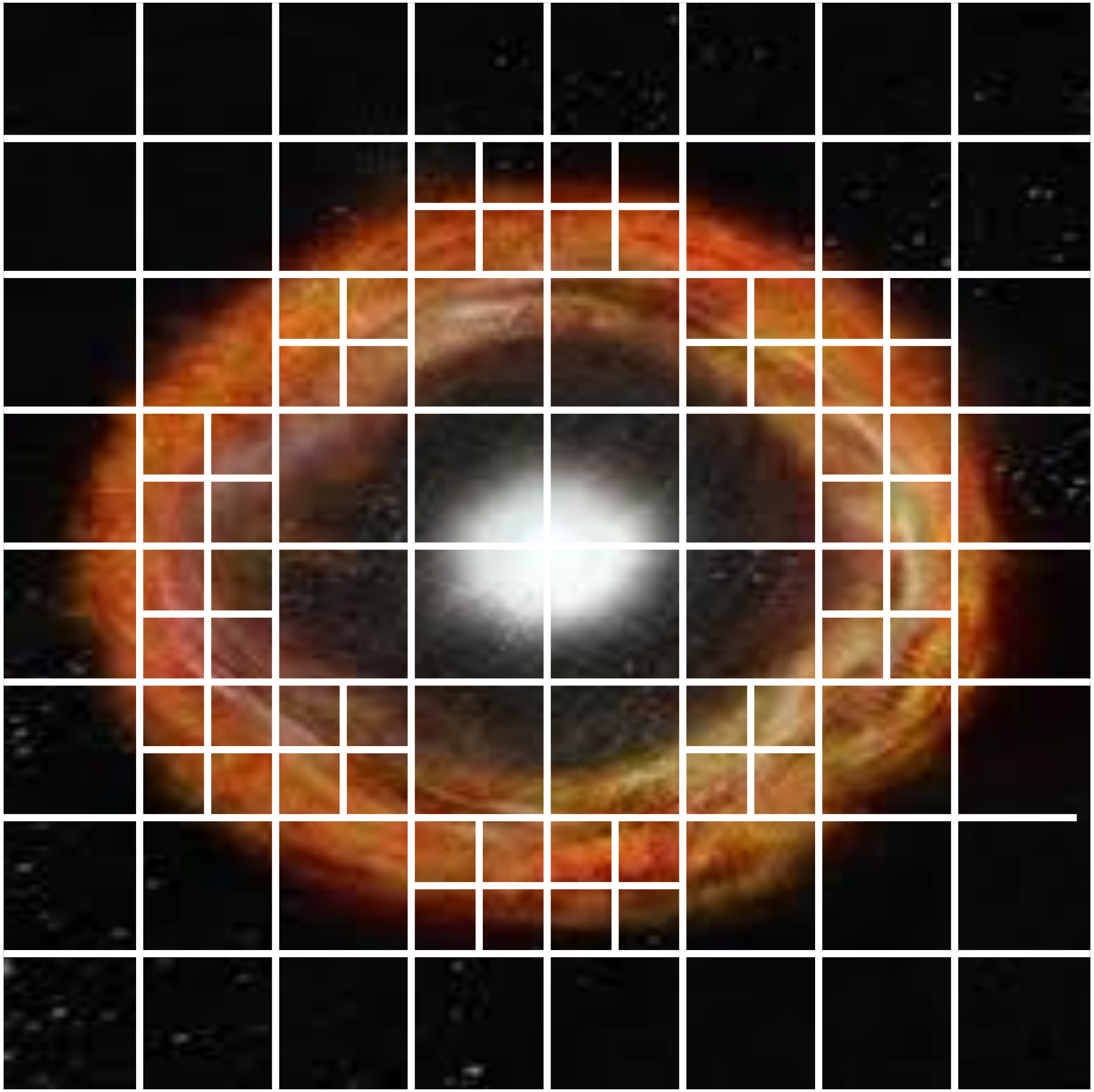
CPU



From subgrid to “subreal” models

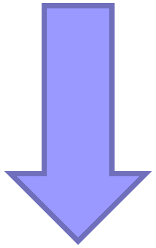
CPU

Many CPU

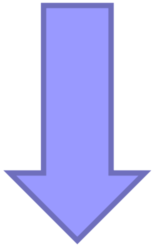


From subgrid to “subreal” models

CPU

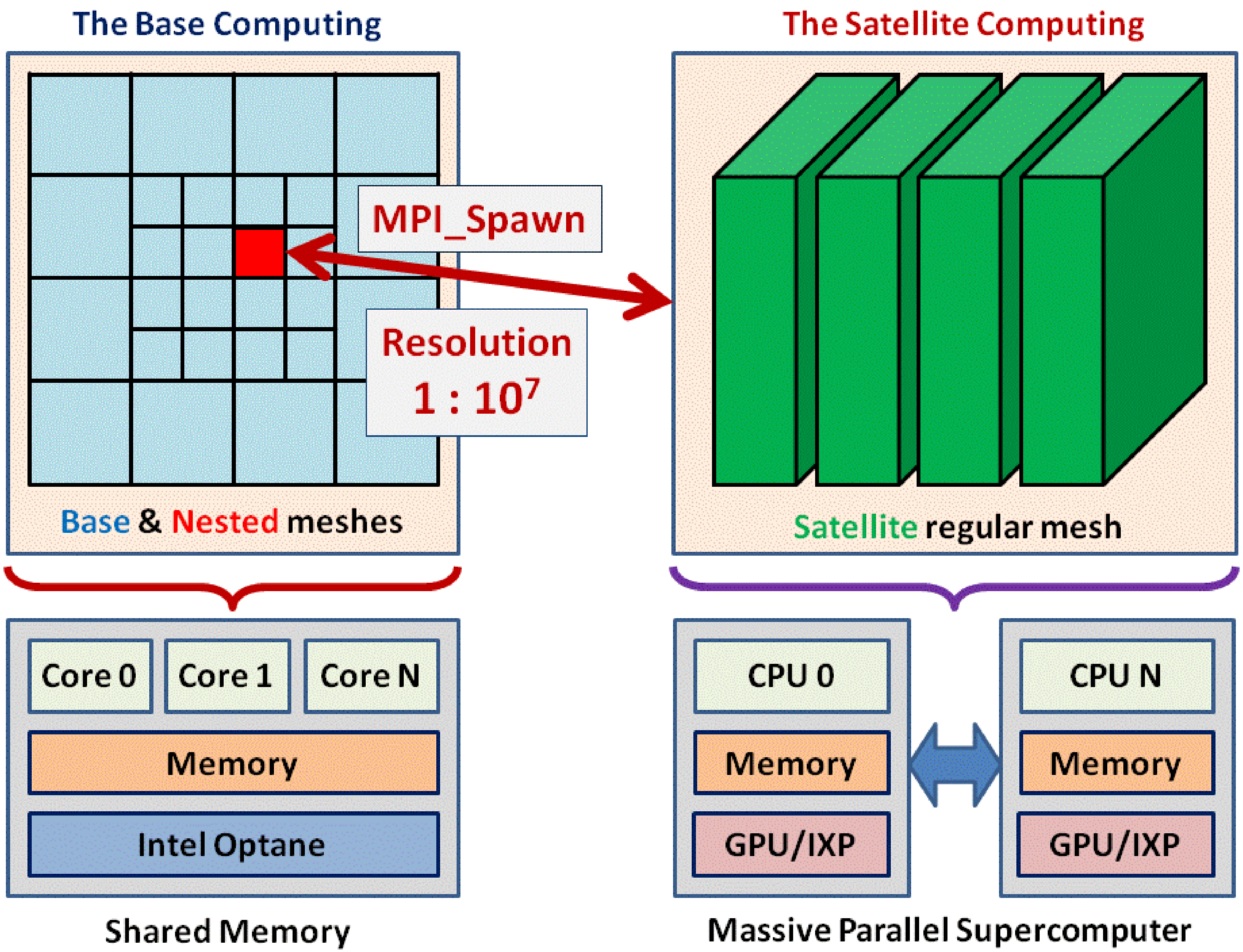


Many CPU

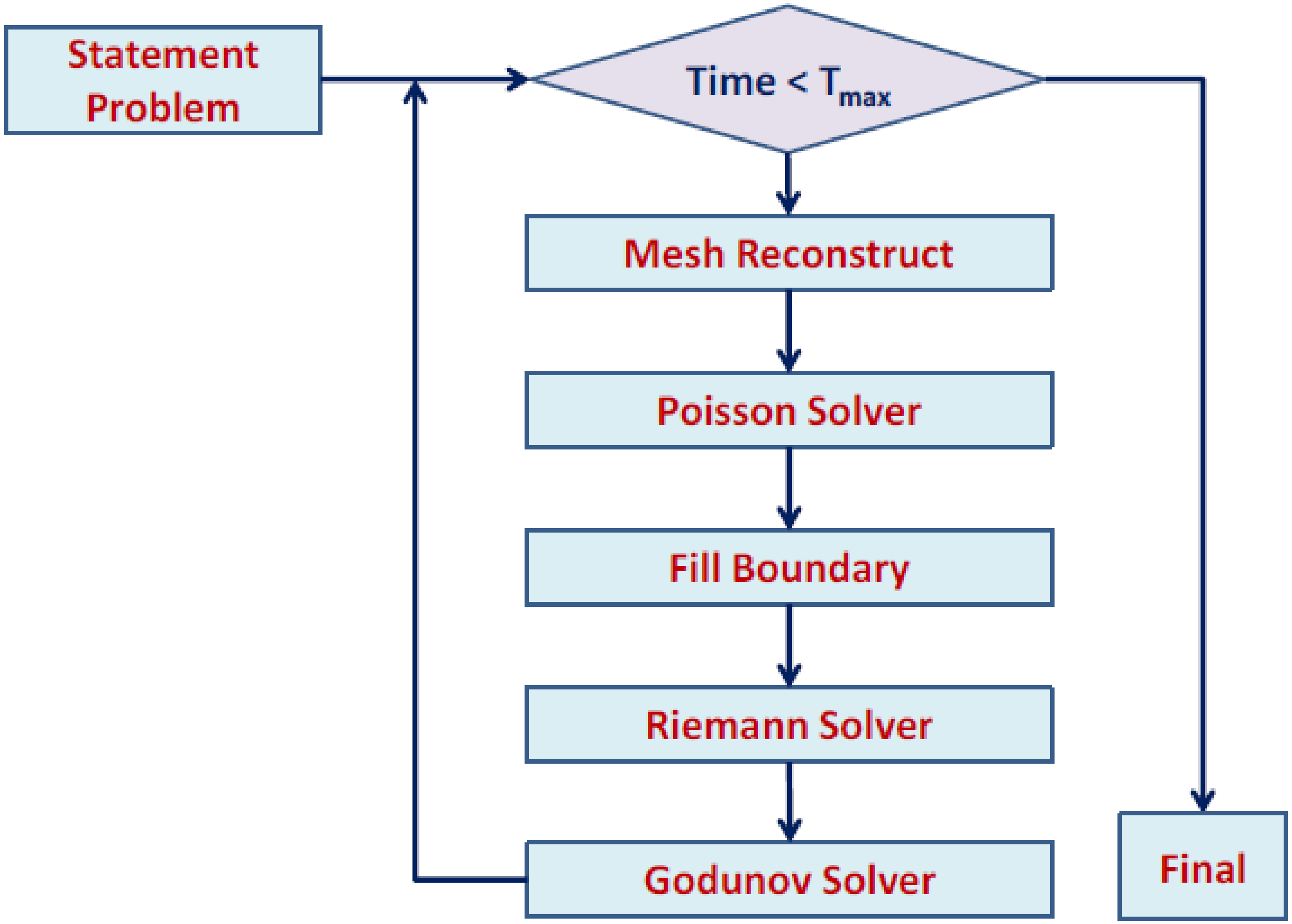


SMP

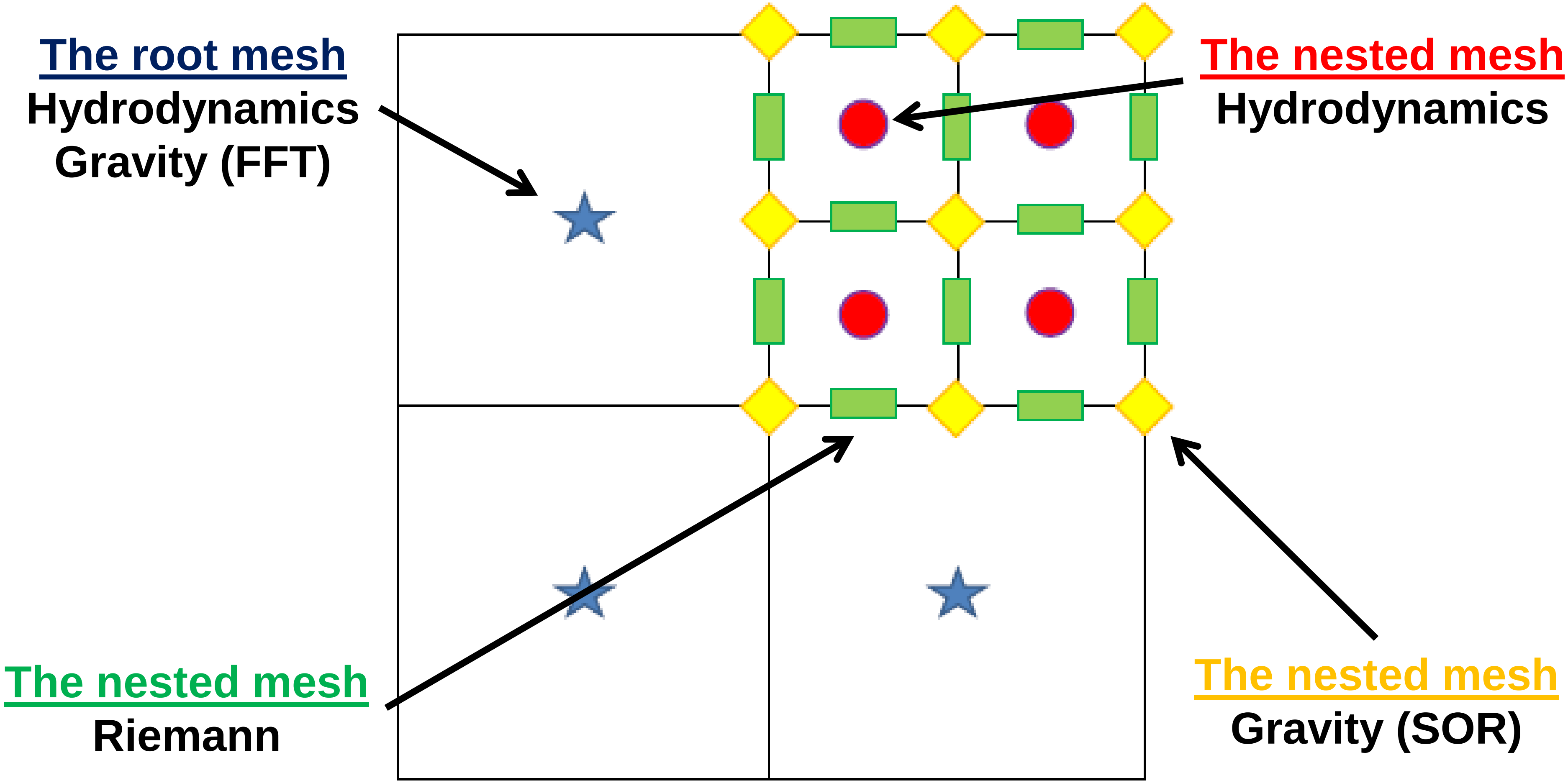
The Base/Satellite Computing



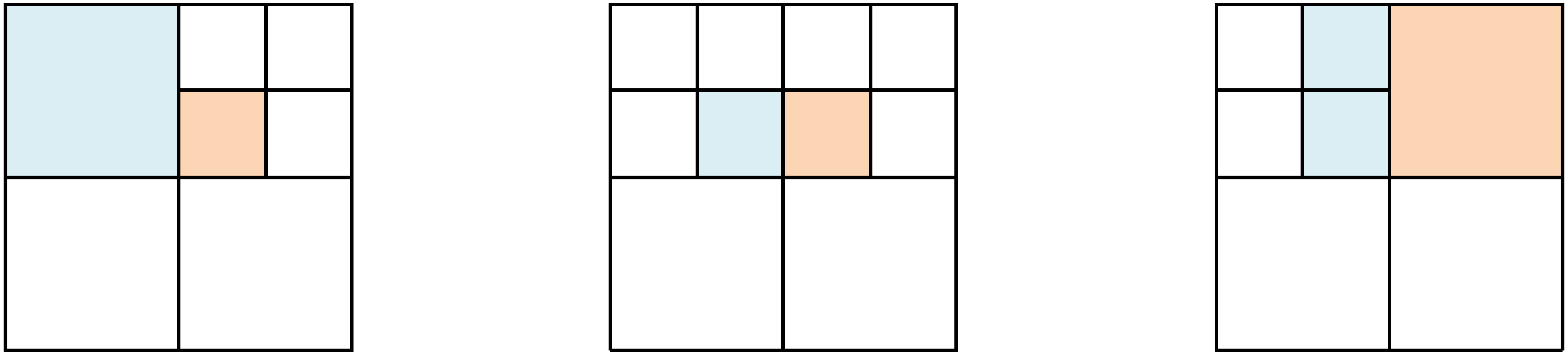
The organization of Base Computing



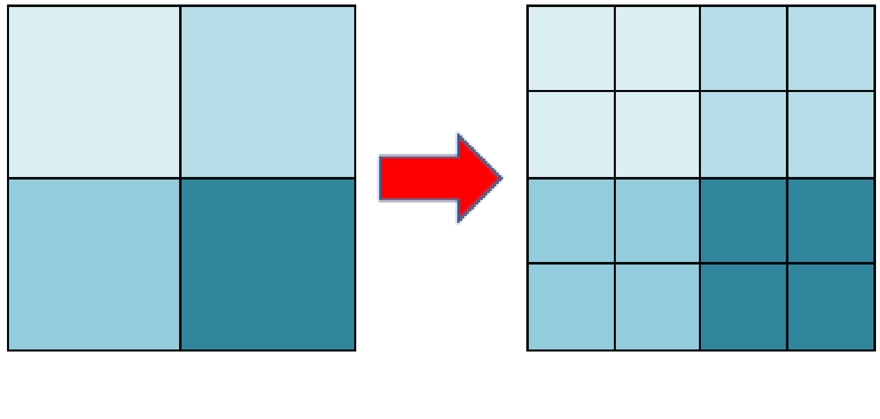
The variables

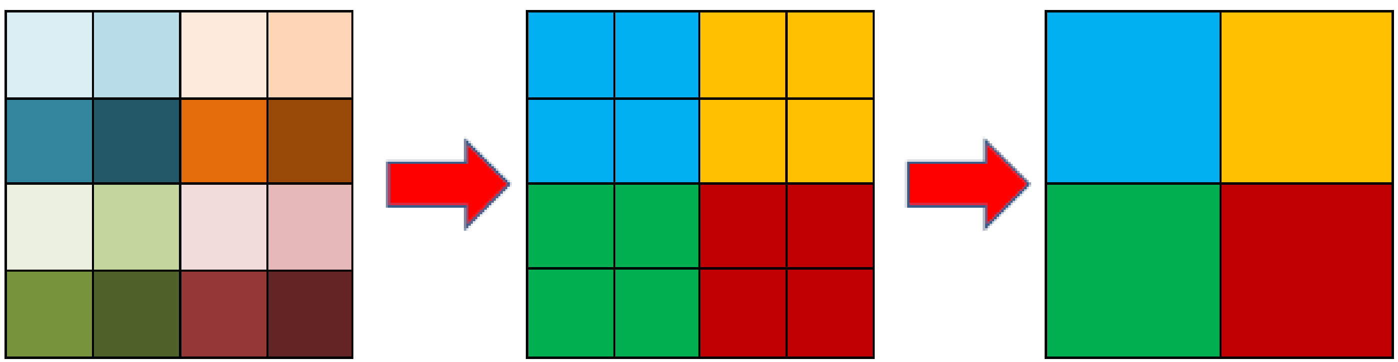


The adjacent for Riemann problem

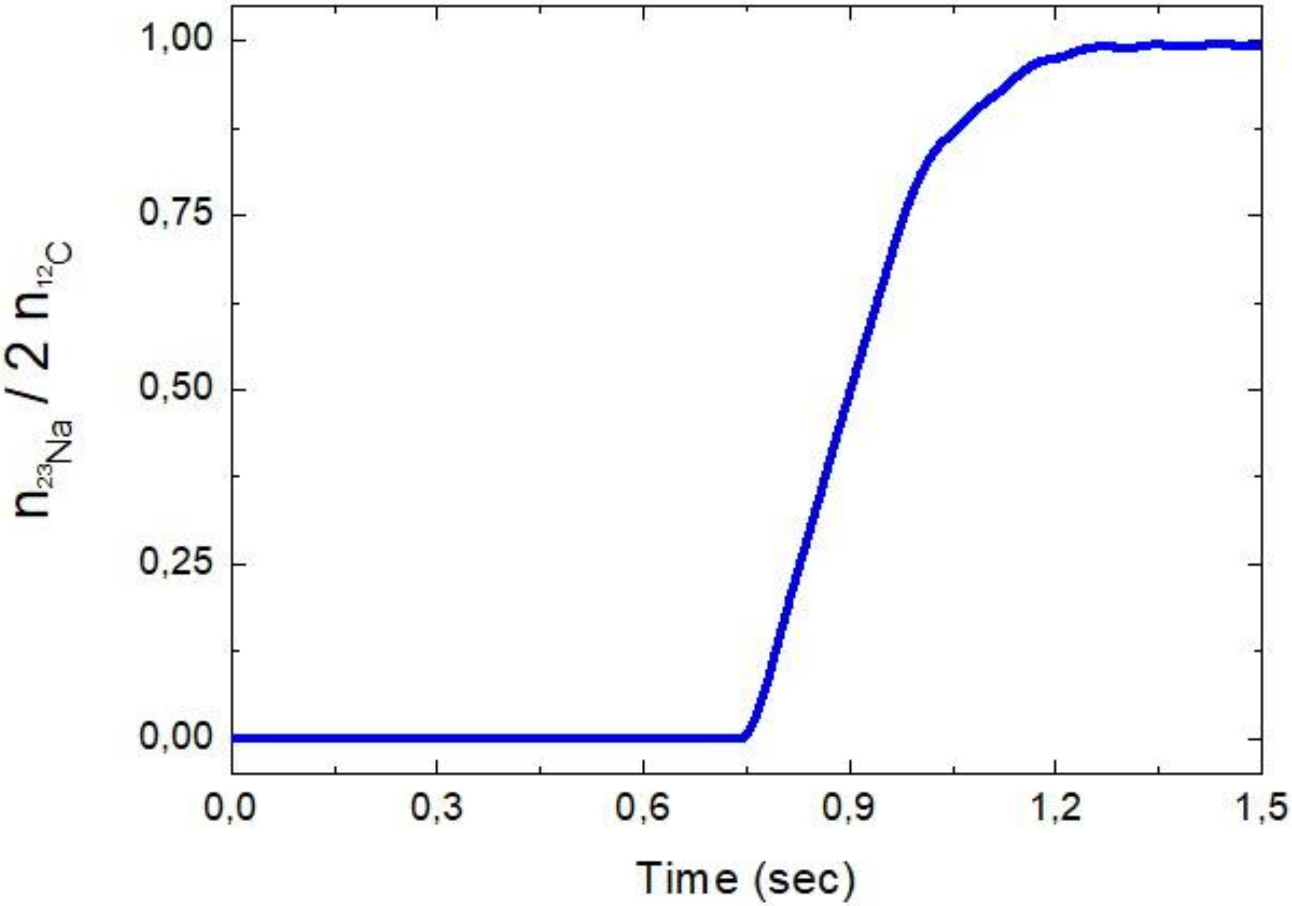


The mesh reconstruction

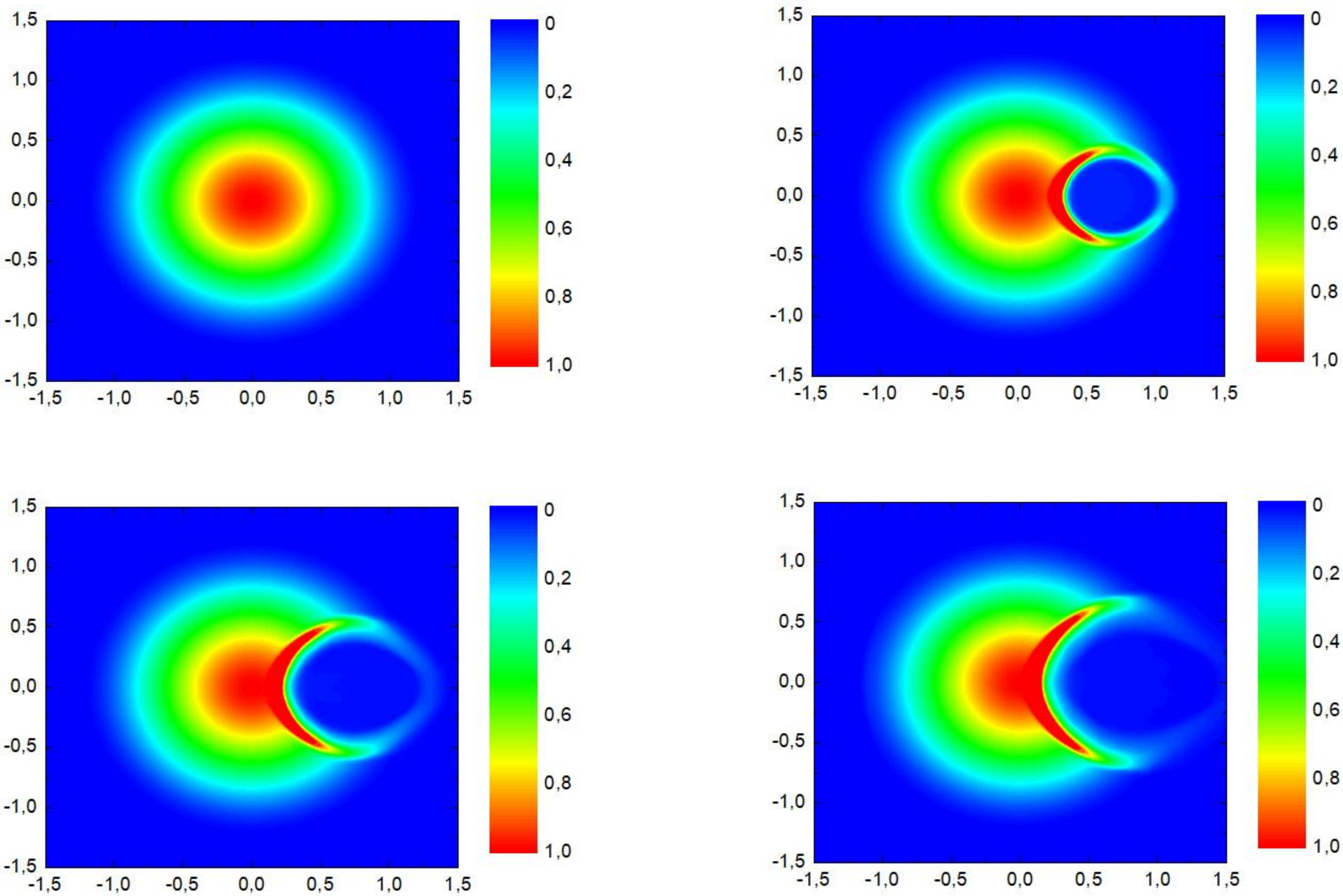




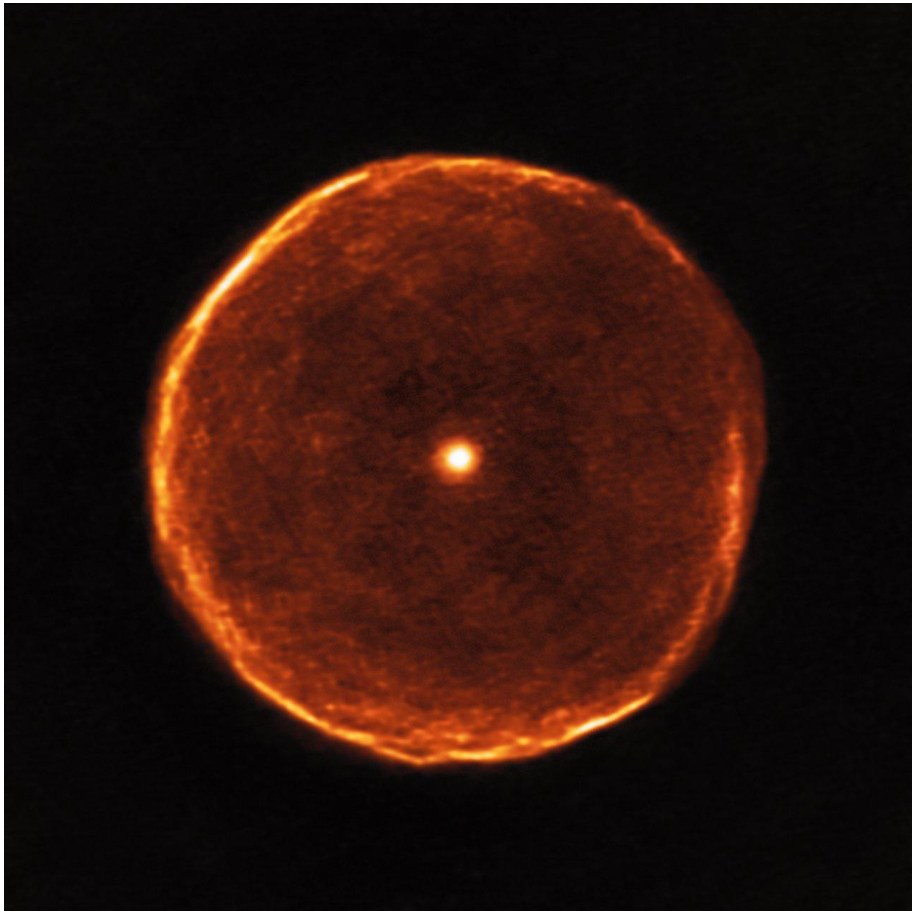
The Carbon burning
(The Satellite Computing)

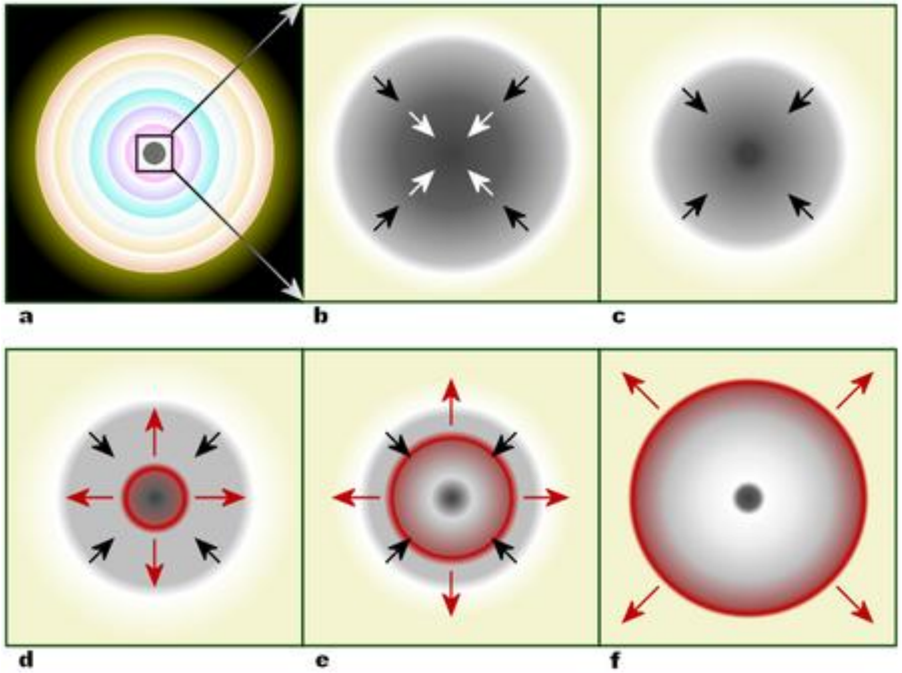


The asymmetric explosion of white dwarf (The Base Computing)



Supernovae Ib/Ic/II (*ISP RAS Open 2019*)





The Satellite Computing

The Base Computing

Credit ESO and Wiki

Conclusion

- **A new numerical model of Supernovae Ia type explosion is created.**
- **The Base/Satellite computing concept is described.**
- **The scenarios of a non-central SNIa is modeled.**
- **The SNIa is non standard problem!!!**

We thank:

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All of You for Your attention!