Сверхновые звезды: механизмы взрыва, суперкомпьютерное моделирование. Обзор конференции First Stars VI (Чили, март 2020)

Куликов Игорь, Черных Игорь

23 марта 2020

Новосибирск

Что общего?



?



Что общего?



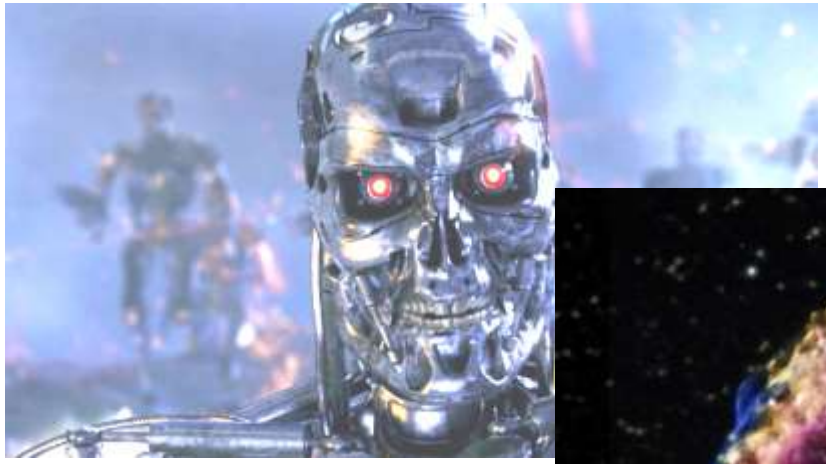


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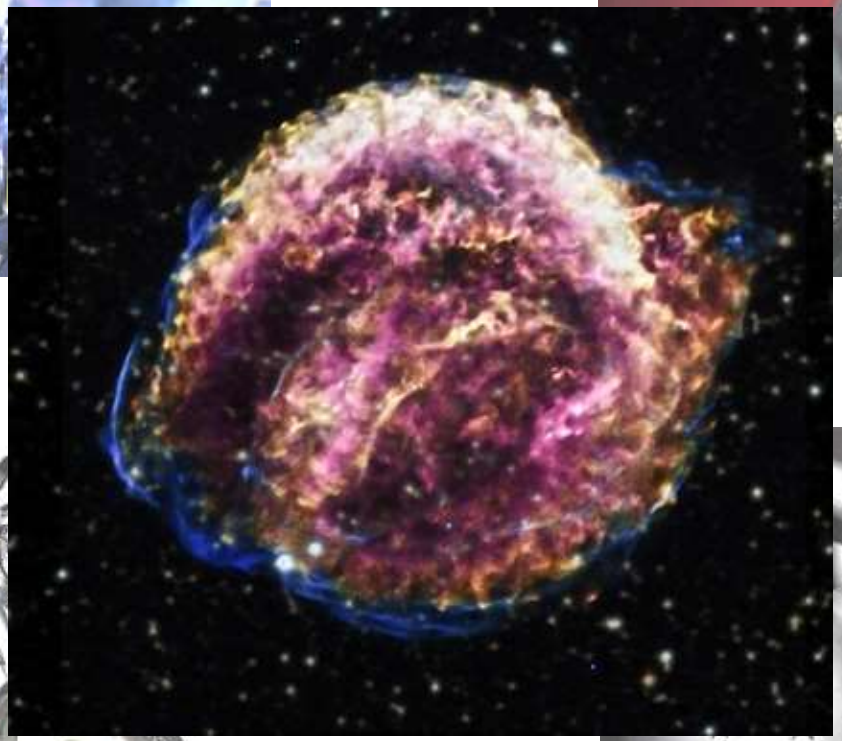




Правильно! SNeIa – основной источник железа



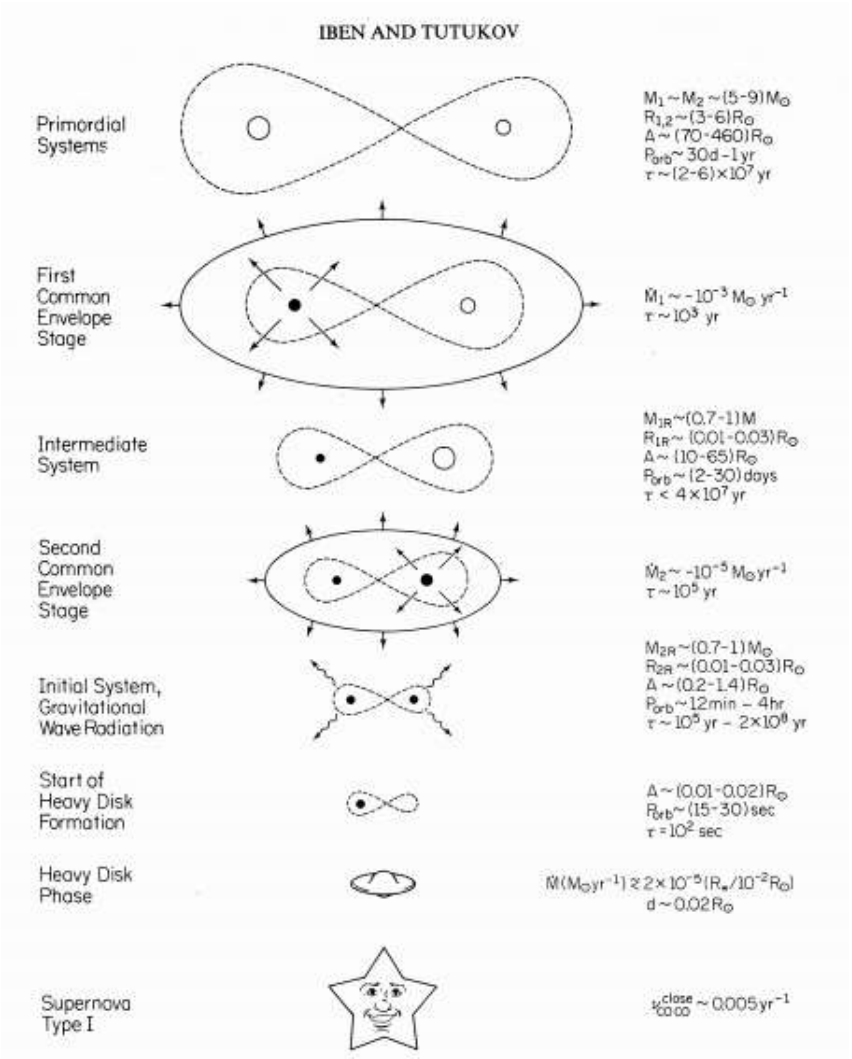








Термоядерный взрыв сверхновой типа Ia



Iben & Tutukov, ApJS, 1984



Сол Перлмуттер

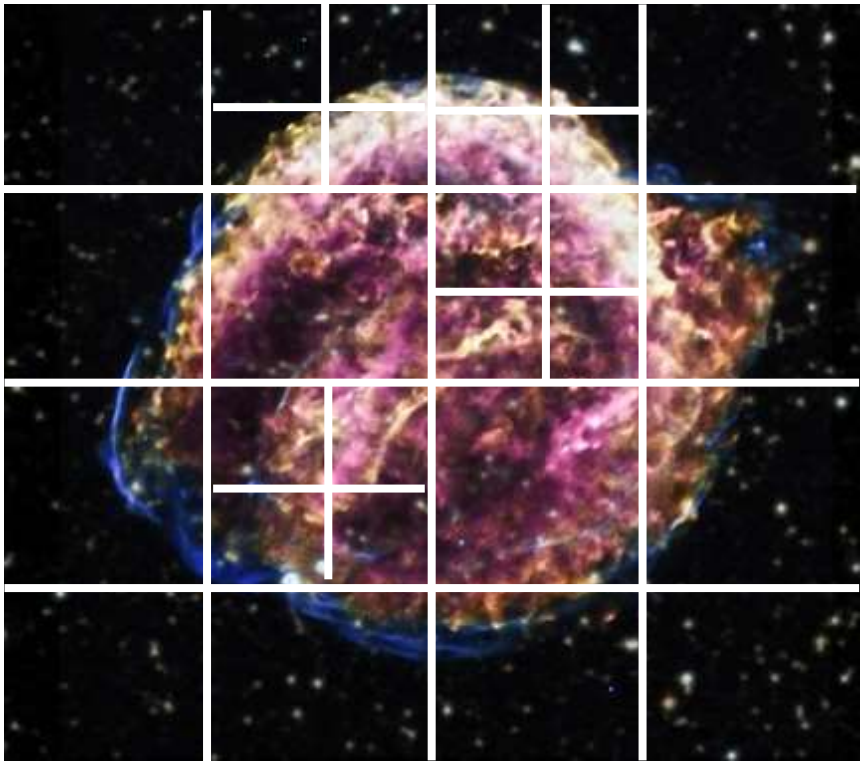
Нобелевская премия по физике 2011

Разномасштабность процессов

Массивно-параллельные суперЭВМ



Технология вложенных сеток



Гидродинамическая модель белых карликов

- Уравнения эйлеровой гидродинамики
- Гравитация
- Звездное уравнение состояния:
  - Идеальный газ при малой температуре
  - Адиабатический вырожденный газ
  - Компонента излучения
- Ядерное горение углерода $^{12}C \rightarrow \ldots \rightarrow {}^{56}Ni$

Гидродинамическая модель

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\vec{u}\\ \rho_i\vec{u}\\ \rho\vec{u}\vec{u}\\ \rho S\vec{u}\\ \rho E\vec{u}\end{pmatrix}=\begin{pmatrix}0\\ 0\\ -\nabla p\\ 0\\ -\nabla\cdot(p\vec{u})\end{pmatrix}+\begin{pmatrix}0\\ s_i\\ -\rho\nabla\Phi\\ (\gamma-1)\rho^{1-\gamma}(\Lambda-\Gamma)\\ -(\rho\vec{u},\nabla\Phi)+\Lambda-\Gamma\end{pmatrix}$$

Гравитация

$$\Delta\Phi=4\pi G\rho$$

Согласованность

$$\rho E=\rho\varepsilon(\rho,T,S)+\frac{\rho u^2}{2}$$

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}=\begin{pmatrix}0\\ 0\\ -\nabla p\\ 0\\ -\nabla\cdot(p\vec{u})\end{pmatrix}$$

Работа сил

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\vec{u}\\ \rho_i\vec{u}\\ \rho\vec{u}\vec{u}\\ \rho S\vec{u}\\ \rho E\vec{u}\end{pmatrix}=0$$

Адвекция

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}=\begin{pmatrix}0\\ s_i\\ -\rho\nabla\Phi\\ (\gamma-1)\rho^{1-\gamma}(\Lambda-\Gamma)\\ -(\rho\vec{u},\nabla\Phi)+\Lambda-\Gamma\end{pmatrix}$$

Химия + гравитация

Численный метод

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}=\begin{pmatrix}0\\ 0\\ -\nabla p\\ 0\\ -\nabla\cdot(p\vec{u})\end{pmatrix}$$

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}+\nabla\cdot\begin{pmatrix}\rho\vec{u}\\ \rho_i\vec{u}\\ \rho\vec{u}\vec{u}\\ \rho S\vec{u}\\ \rho E\vec{u}\end{pmatrix}=0$$

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho_i\\ \rho\vec{u}\\ \rho S\\ \rho E\end{pmatrix}=\begin{pmatrix}0\\ s_i\\ -\rho\nabla\Phi\\ (\gamma-1)\rho^{1-\gamma}(\Lambda-\Gamma)\\ -(\rho\vec{u},\nabla\Phi)+\Lambda-\Gamma\end{pmatrix}$$

$$\frac{\partial q}{\partial t}=\frac{\partial}{\partial x}G(q)$$

$$\frac{\partial q}{\partial t}+\frac{\partial}{\partial x}(q\vec{u})=0$$

$$\frac{\partial q}{\partial t}=Q$$

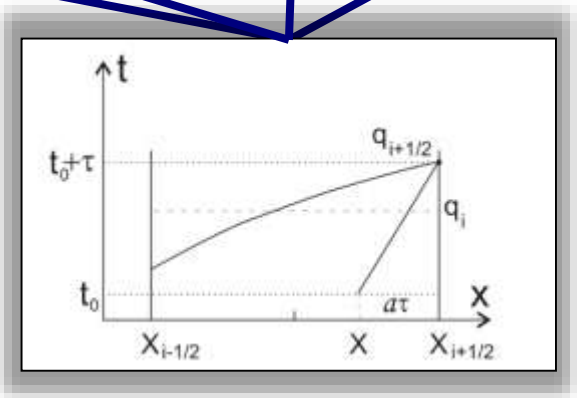
$$\frac{q_k^{n+1}-q_k^n}{\tau}+\frac{F_{k+1/2}-F_{k-1/2}}{h}=Q_k^n$$

Решение задачи Римана

$$\frac{q_k^{n+1} - q_k^n}{\tau} + \frac{F_{k+1/2} - F_{k-1/2}}{h} = Q_k^n$$

$$F_{k\pm 1/2} = \frac{F(-\lambda\tau) + F(\lambda\tau)}{2} + \frac{c + \| \vec{u} \|}{2}\left(q(-\lambda\tau) - q(\lambda\tau)\right)$$

Кусочно-полиномиальное представление решения



Все операции независимы и векторизуемы

Параллельная реализация вычислительного ядра

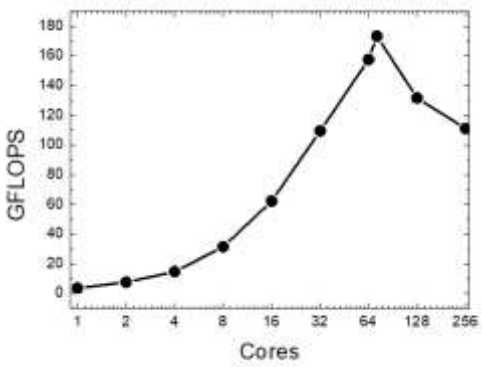
Декомпозиция расчетной области

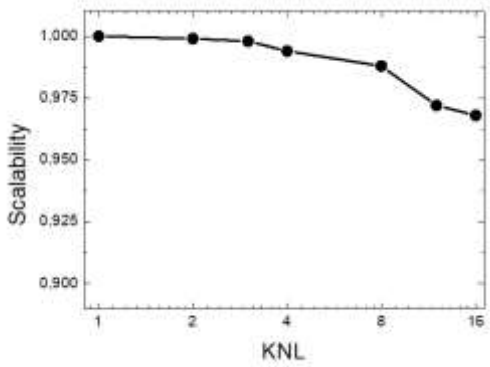
Распределение областей (MPI + FFTW)

Распределение потоков (OpenMP)

Векторизация (AVX 512)

Подводные камни: организация вычислений 8-элементными векторами, ассоциативность кэш памяти, выравнивание данных, распределение работ, зависимость по данным





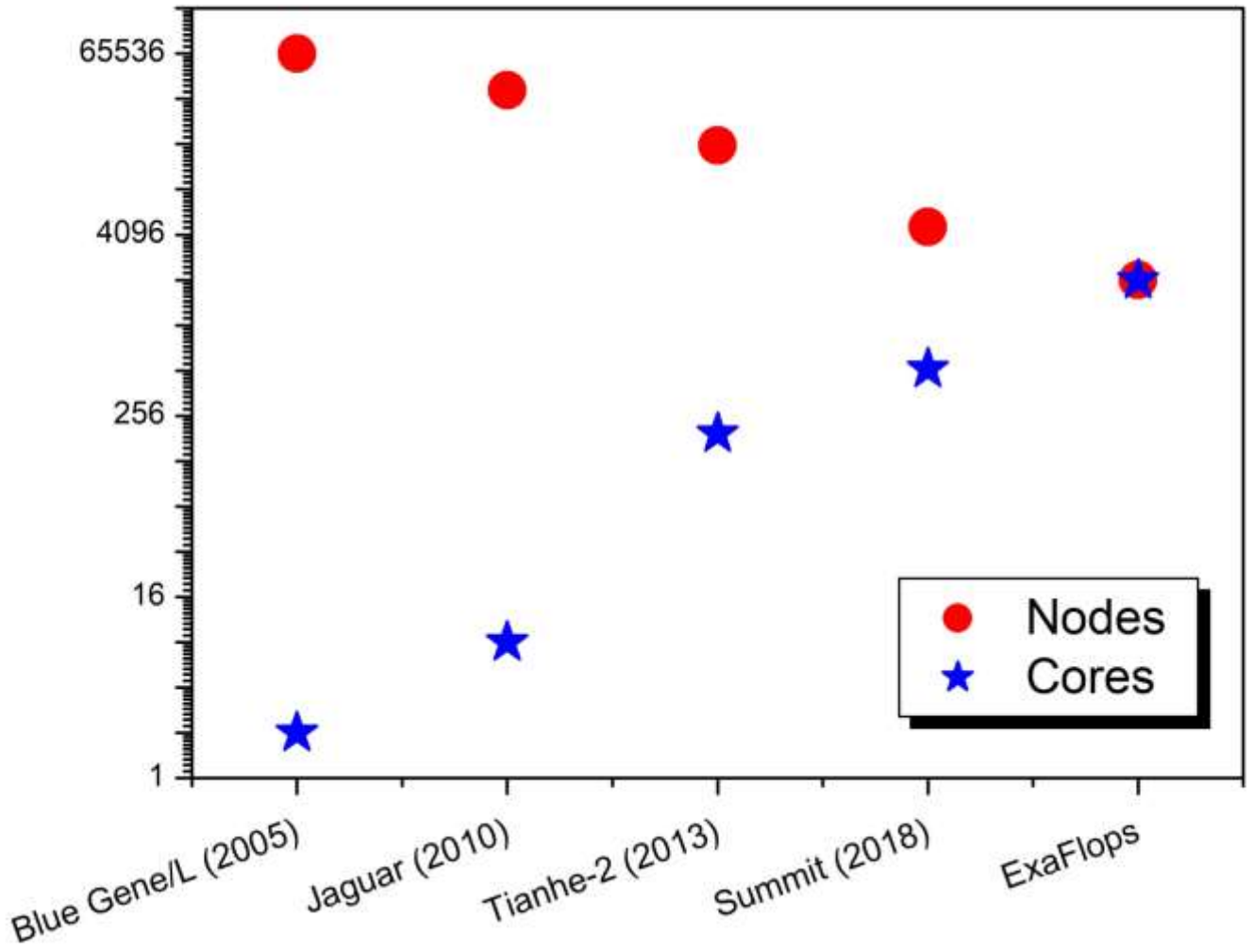
НКС-1П ССКЦ

48-кратное ускорение

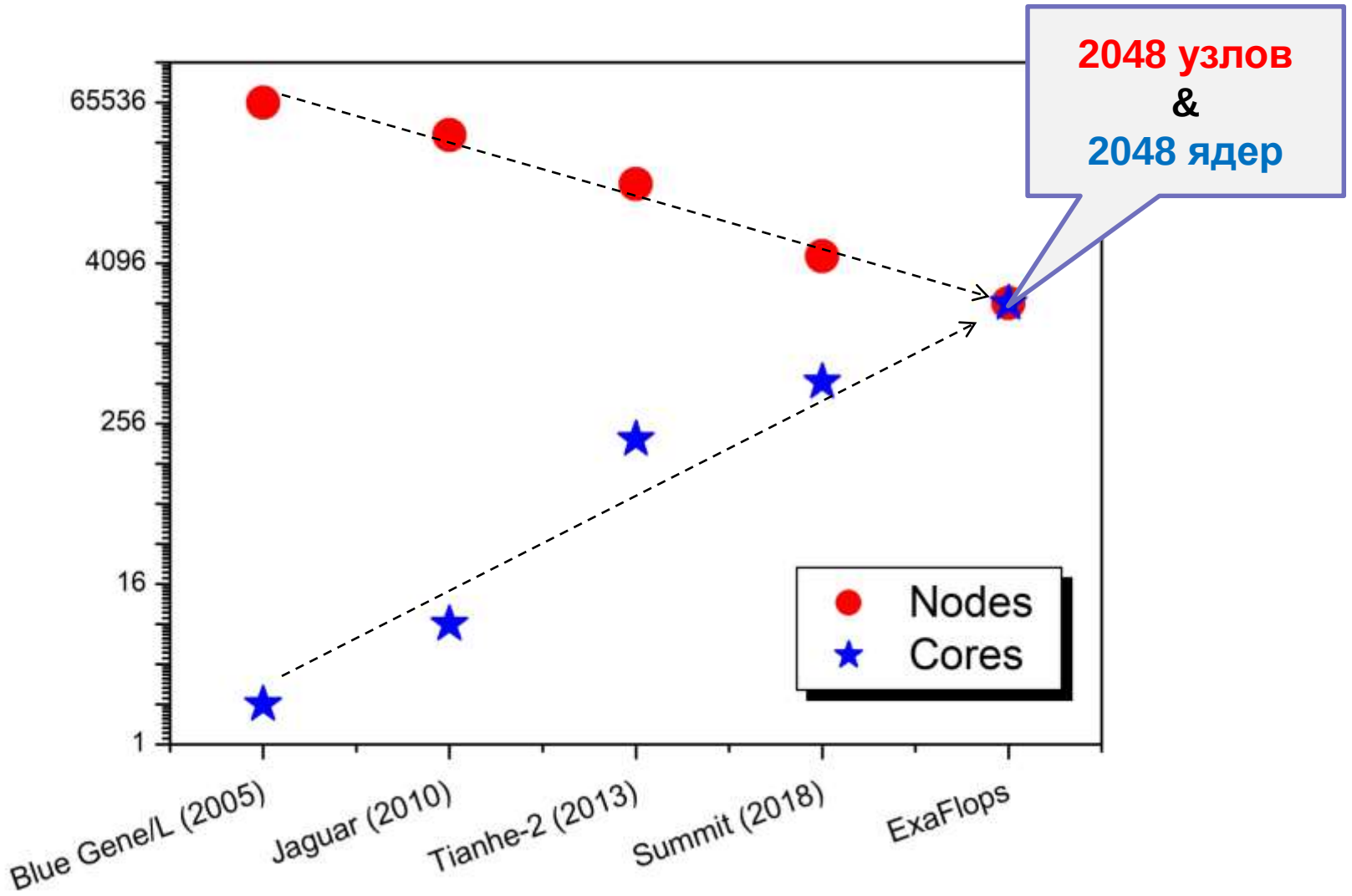
180 ГФЛОПС производительности

96% масштабируемость

Адаптивные вложенные сетки: стратегия



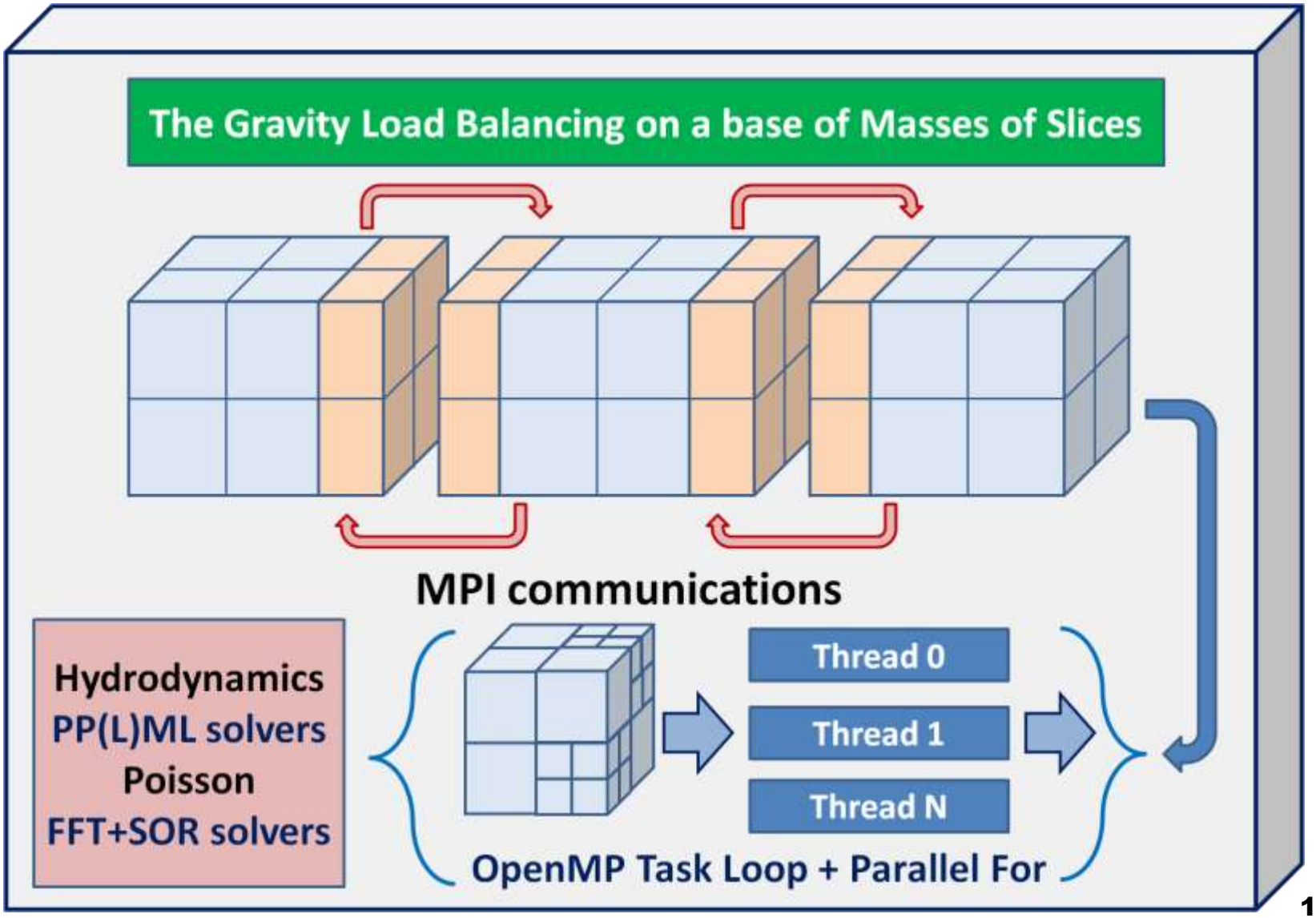
Адаптивные вложенные сетки: стратегия



Адаптивные вложенные сетки: стратегия

- Уменьшение числа MPI процессов
- Увеличение OpenMP потоков
- Использование новейших инструкций OpenMP
- Минимизация MPI коммуникаций
- Использование ускорителей и сопроцессоров
- Использование векторизации
- Со-дизайн от физики до реализации
- Архитектурно-ориентированные коды

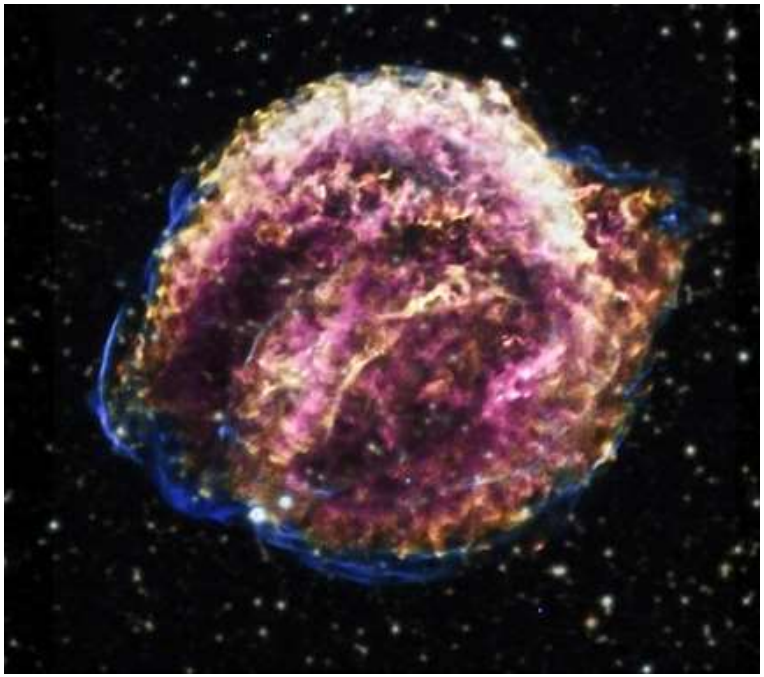
Адаптивные вложенные сетки: архитектура



«Нестандартность» взрыва сверхновой типа Ia

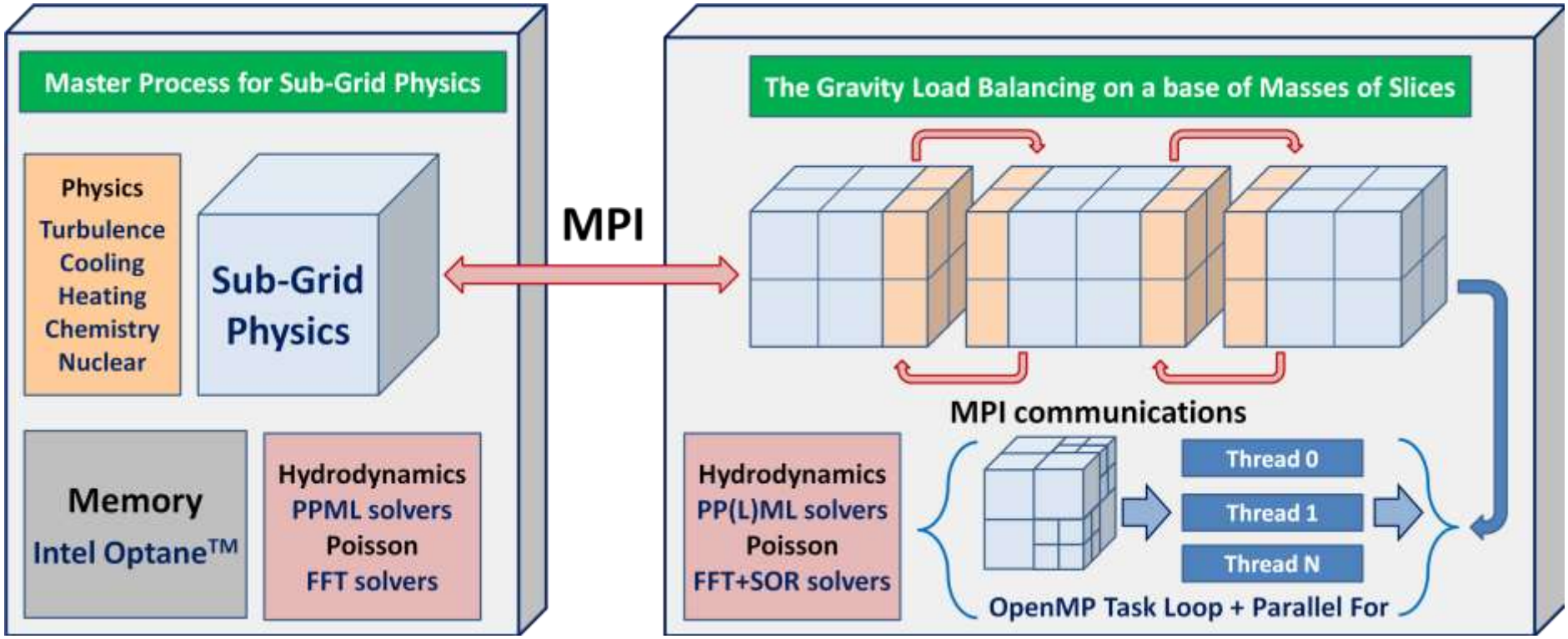
Наблюдения

- Состав ядерного топлива (Moreno-Raya, ApJL, 2016)
- Способ горения углерода (Fink, MNRAS, 2013)
- Дочандрасекарова масса карлика (Polin, ApJ, 2019)
- Нецентральность взрыва (Maeda, Nature, 2010)
- Поверхностный взрыв (Jiang, Nature, 2017)



Сверхновые Ia из-за вариации ядерного горения топлива суть нестандартные объекты во Вселенной!

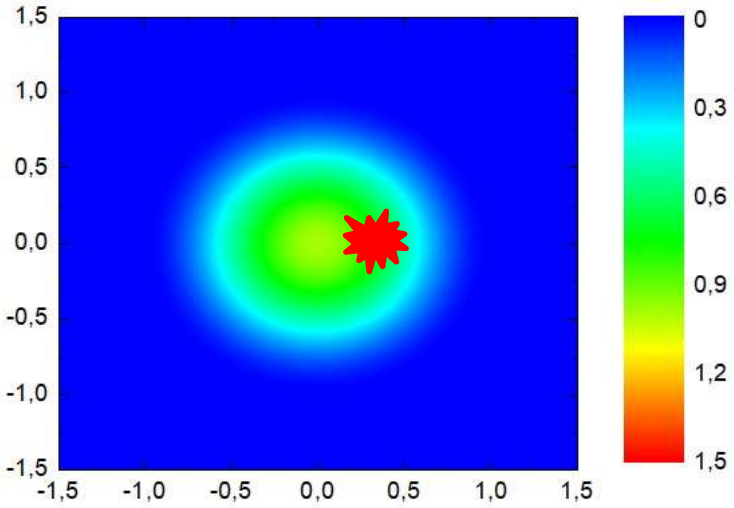
Адаптивные вложенные сетки :
от подсеточной к «подреальной» физике



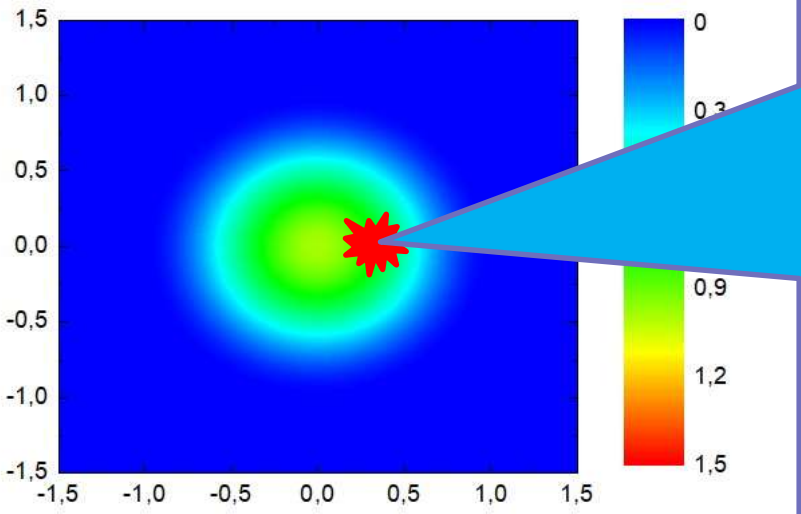
Для моделирования ядерного горения углерода запускается задача развития турбулентности.

Достигается 1:10^7 разрешение – фронта горения!

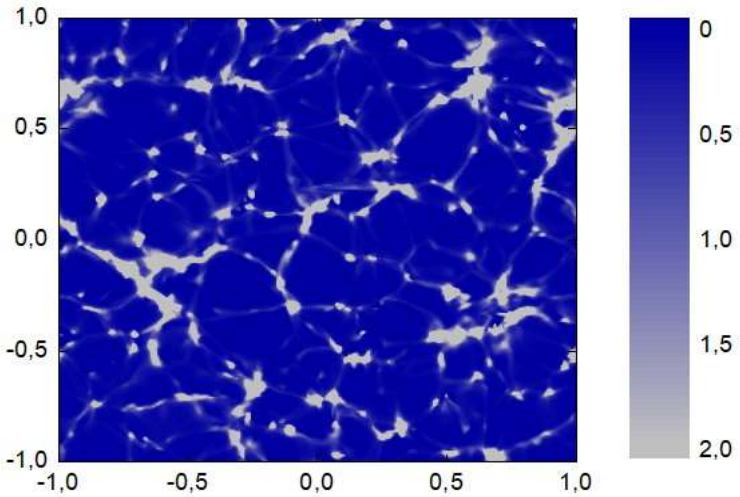
Ядерное горение углерода



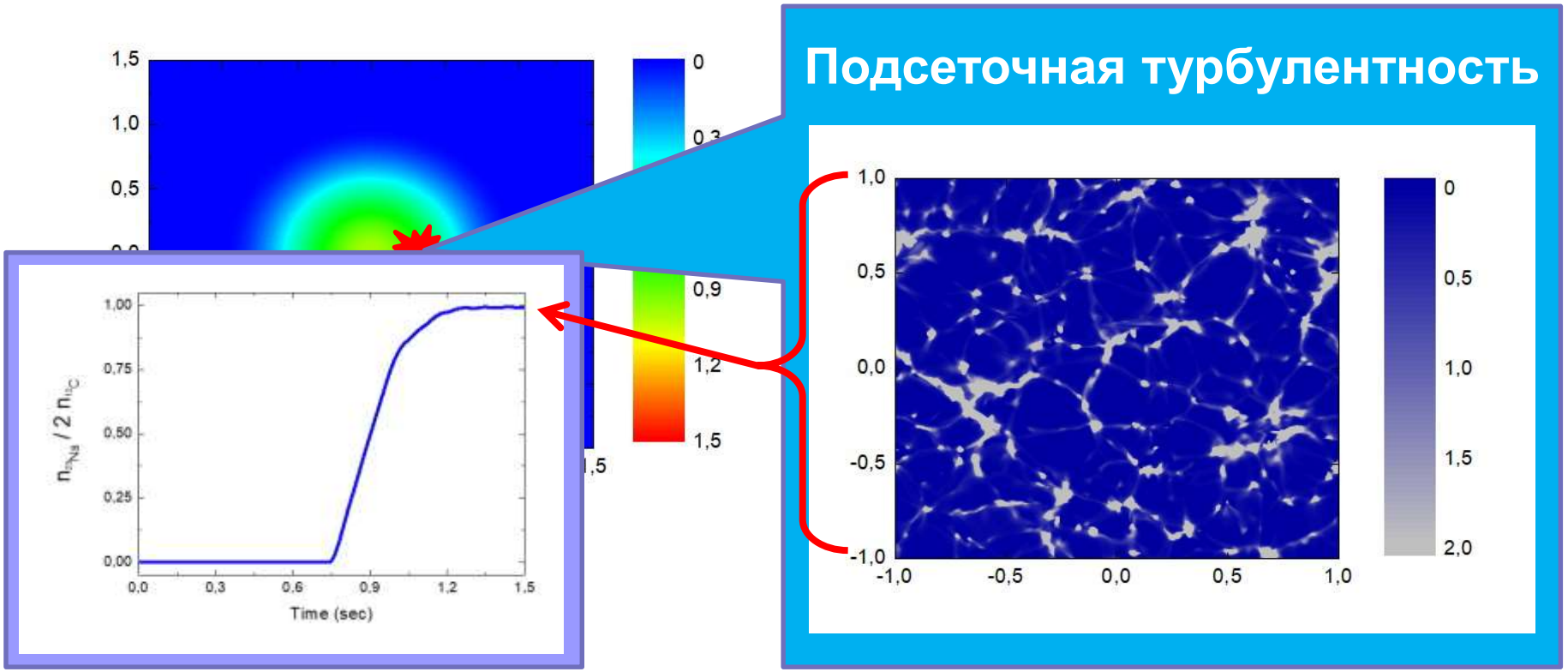
Ядерное горение углерода



Подсеточная турбулентность

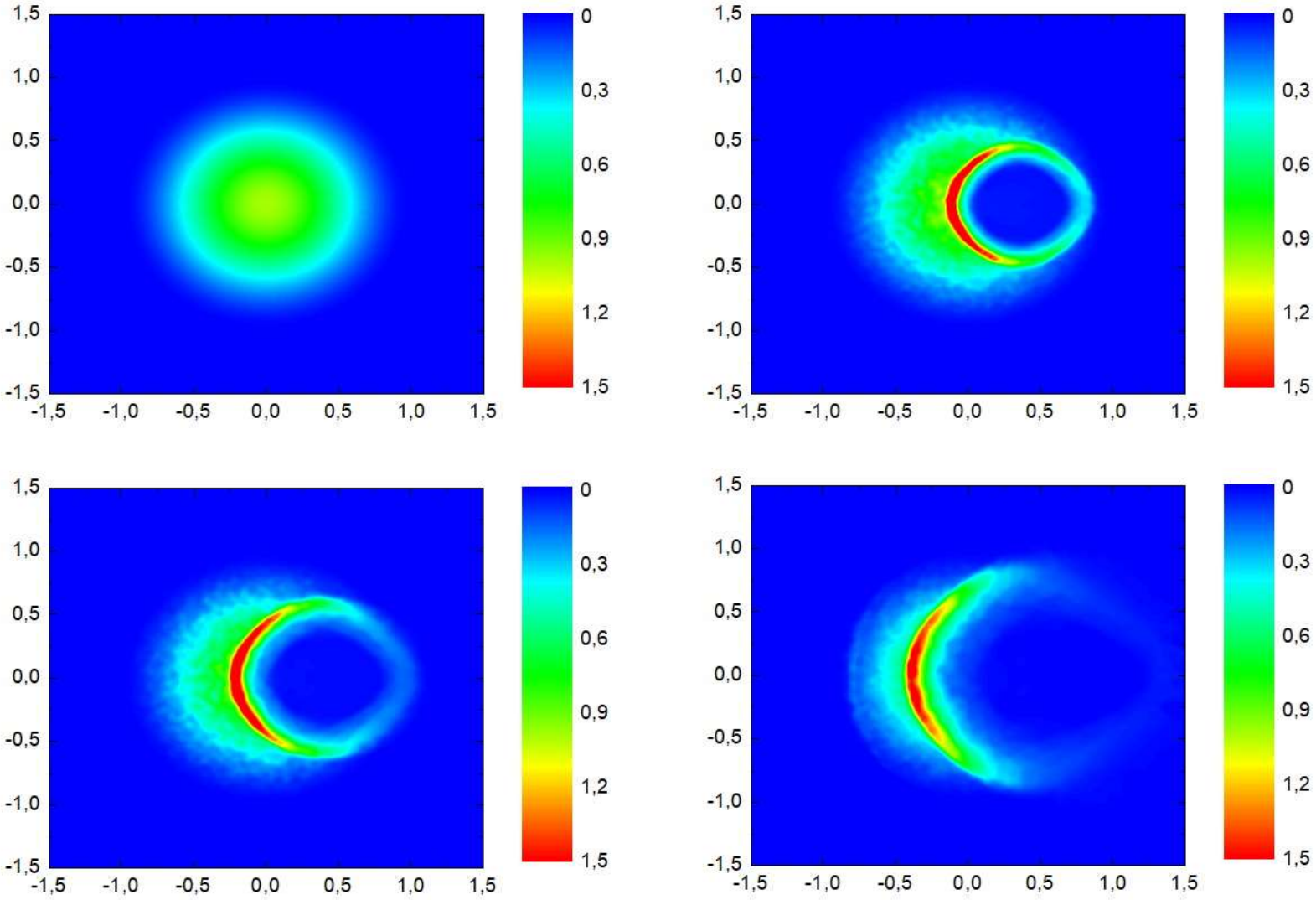


Ядерное горение углерода

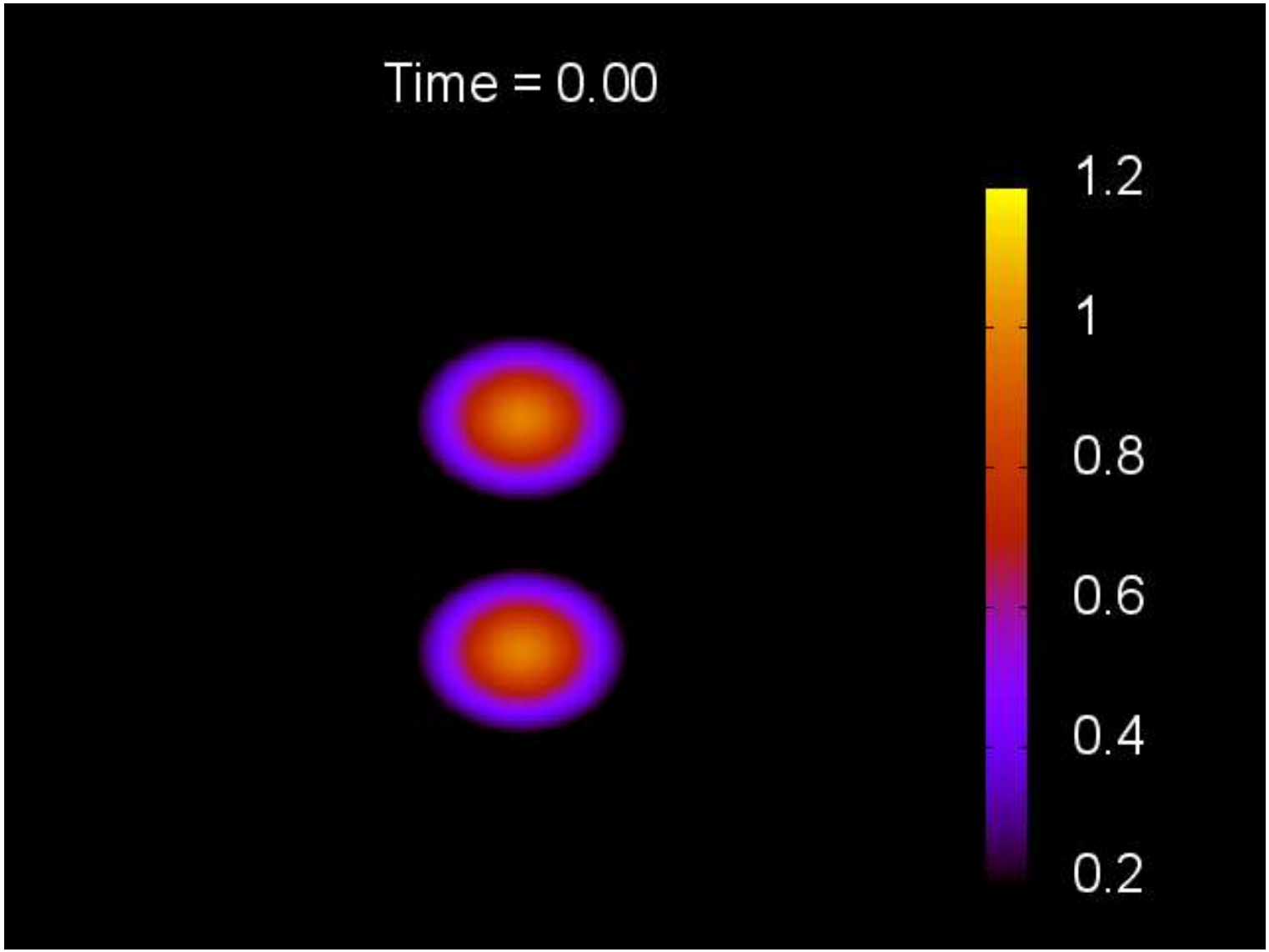


Финальная концентрация ^{12}C … ^{56}Ni возвращается в гидродинамическое моделирование

Асимметричный взрыв сверхновых Ia



Моделирование взрыва SNeIa



Взаимодействия во Вселенной









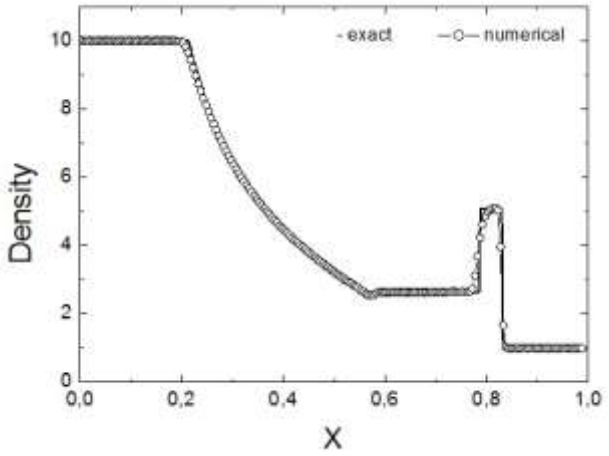
Специальная релятивистская гидродинамика

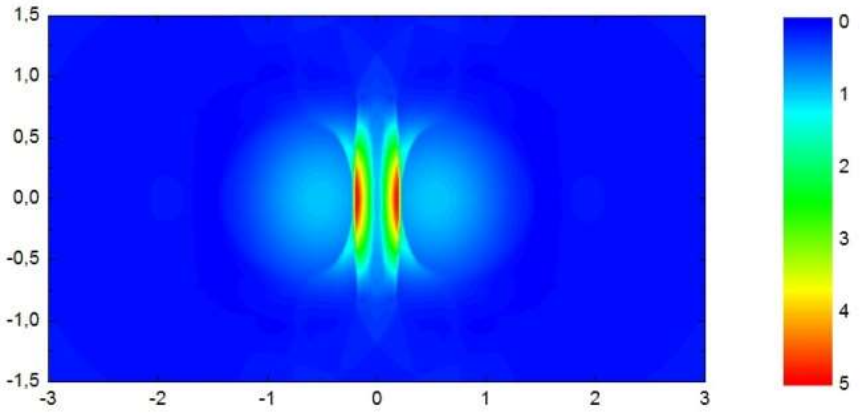
$$\frac{\partial}{\partial t}\begin{pmatrix}\Gamma\rho\\ \Gamma^2\rho h\vec{u}\\ \Gamma^2\rho h-p\end{pmatrix}+\nabla\begin{pmatrix}\Gamma\rho\vec{u}\\ \Gamma^2\rho h\vec{u}\vec{u}\\ \Gamma^2\rho h\vec{u}\end{pmatrix}=\nabla\begin{pmatrix}0\\ p\\ 0\end{pmatrix}$$

Численный метод был расширен на уравнения релятивистской гидродинамики

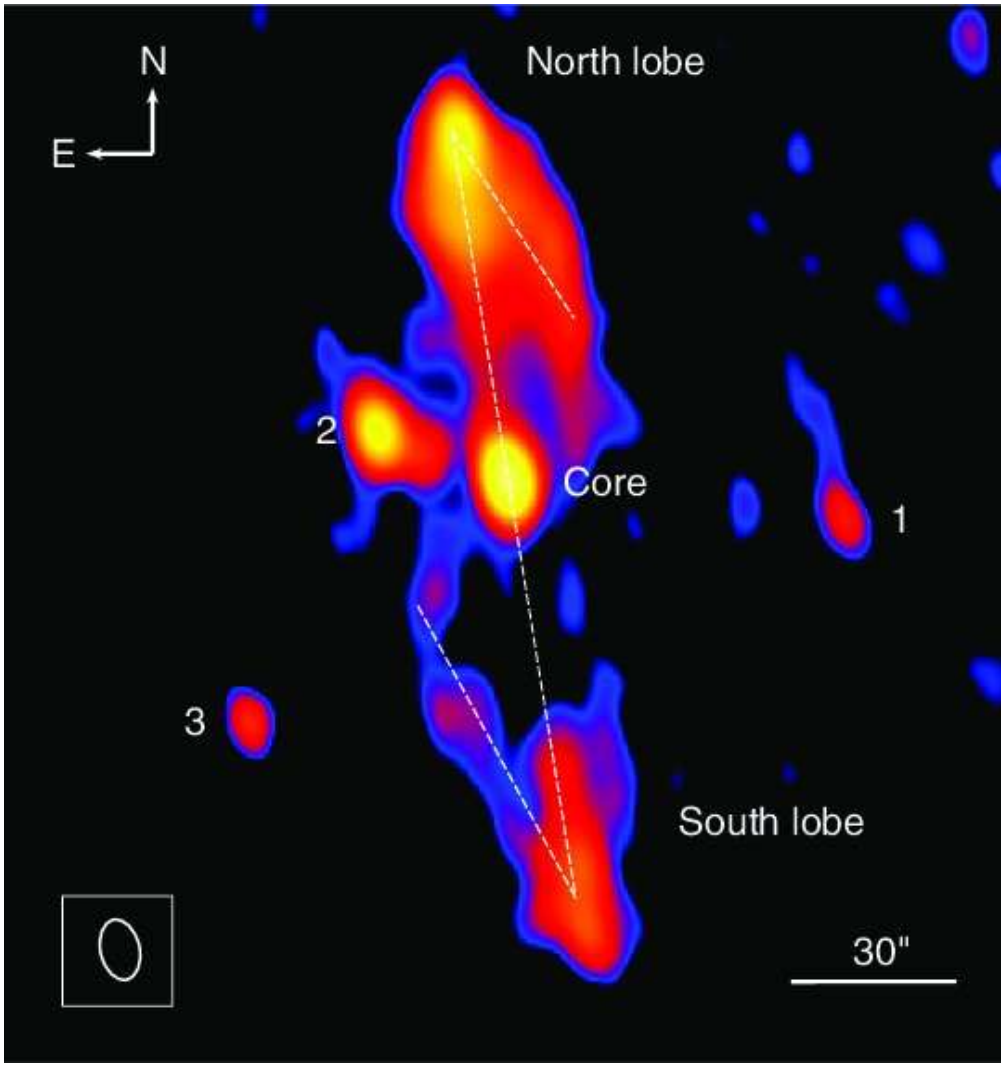
$$h=1+\frac{\gamma}{\gamma-1}\frac{p}{\rho}\qquad \Gamma=\frac{1}{\sqrt{1-u^2}}$$

Верификация численного метода





Эволюция релятивистского джета GRS 1758-258



Объяснение механизма образования лепестков #1, #2, #3

Эволюция релятивистского джета GRS 1758-258
Неустойчивость Кельвина-Гельмгольца

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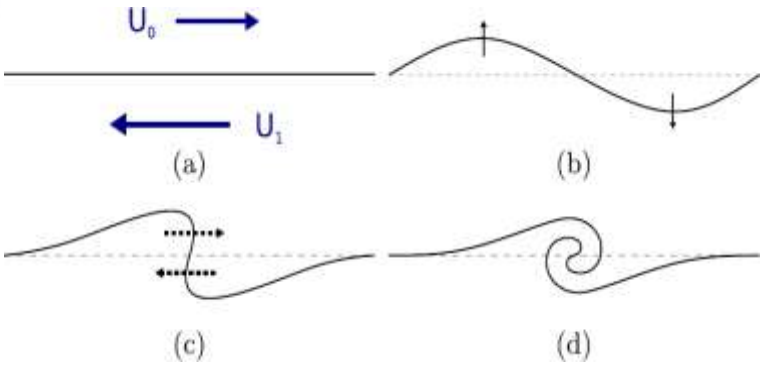
A galactic microquasar mimicking winged radio galaxies

Josep Martí, Pedro L. Luque-Escamilla, Valentí Bosch-Ramon & Josep M. Paredes

Nature Communications 8,
Article number: 1757 (2017)
doi:10.1038/s41467-017-01976-5
Download Citation

Galaxies and clusters
High-energy astrophysics

Received: 17 April 2017
Accepted: 27 October 2017
Published online: 24 November 2017

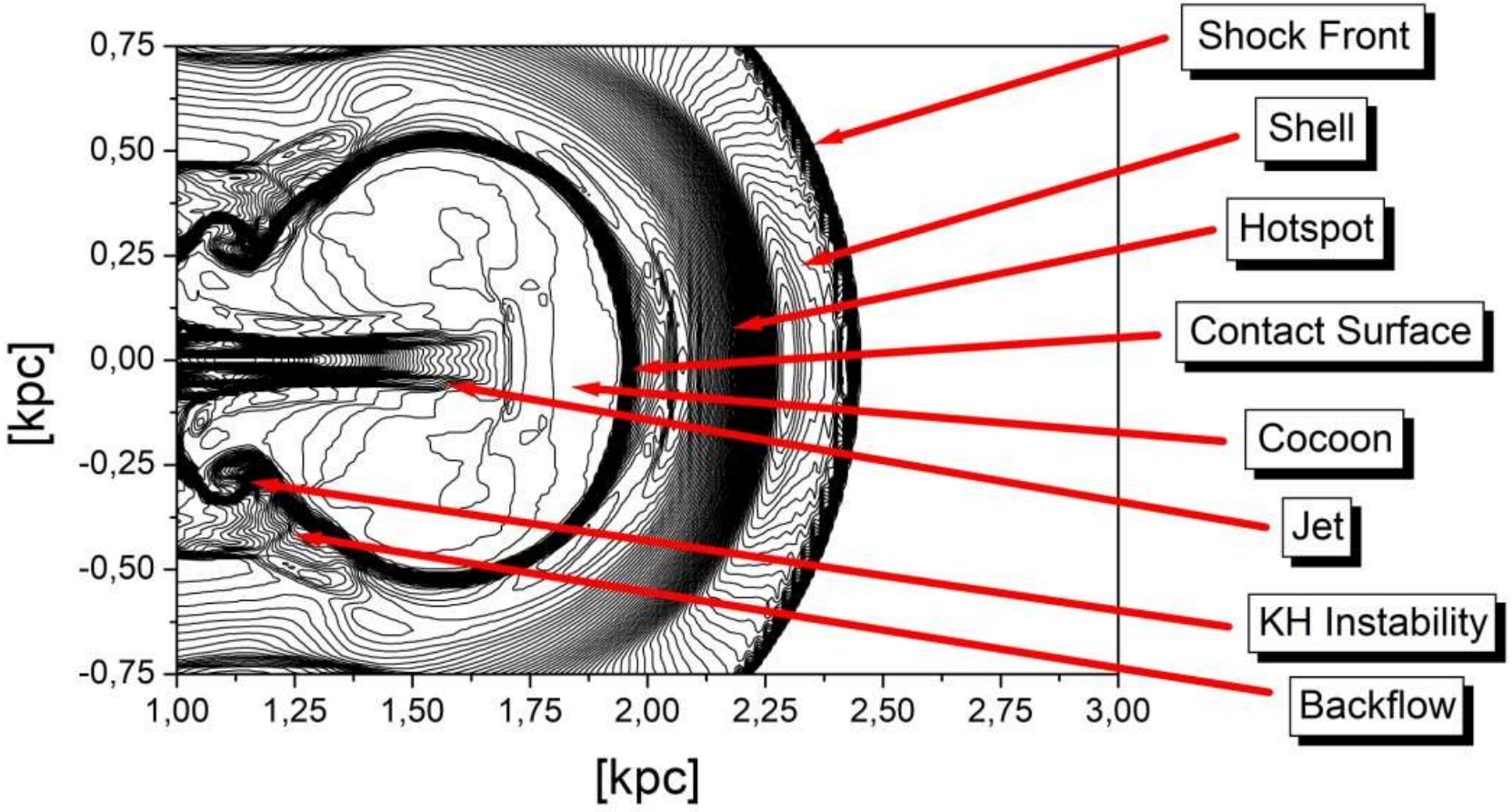




We have thus a clear case of a relativistic jet impinging on the ISM. This renders the **hydrodynamic backflow** as the most plausible explanation of the very, very long secondary lobes of GRS 1758−258.

Martí et al. 2017, Nature Communications

Эволюция релятивистского джета



Основные публикации

1. **Kulikov I., Chernykh I., Tutukov A.** A new hydrodynamic code with explicit vectorization instructions optimizations, dedicated to the numerical simulation of astrophysical gas flow. I. Numerical method, tests and model problems ***//*** **The Astrophysical Journal Supplement Series. – 2019. – V. 243. – Article Number 4.**

2. **Kulikov I., Chernykh I., Karavaev D., Berendeev E., Protasov V.** HydroBox3D: Parallel & Distributed Hydrodynamical Code for Numerical Simulation of Supernova Ia ***//*** **Lecture Notes in Computer Science. – 2019. – V. 11657. – P. 187-198.**

3. **Kulikov I.M., Chernykh I.G., Tutukov A.V.** A New Parallel Intel Xeon Phi Hydrodynamics Code for Massively Parallel Supercomputers ***//*** **Lobachevskii Journal of Mathematics. – 2018. – V. 39, I. 9. – P. 1207-1216.**

4. **Kulikov I., Chernykh I., Vshivkov V., Prigarin V., Mironov V., Tutukov A.** The Parallel Hydrodynamic Code for Astrophysical Flow with Stellar Equations of State // **Communications in Computer and Information Science. – 2019. – V. 965. – P. 414-426.**

5. **Kulikov I.** Using piecewise-parabolic method on local stencil for constructing low-dissipation numerical method for numerical simulation of relativistic flows ***//*** **Siberian Journal of Numerical Mathematics. – 2020. – V. 13, I. 2. – P. 143-153.**

Заключение & дискуссия

- Разработан метод решения уравнений ньютоновской и релятивистской гидродинамики с малой диссипацией на разрывах и высокого порядка точности на гладких решениях.
- Разработана технология параллельных и распределенных вычислений на вложенных сетках.
- Смоделирован сценарий ядерного горения углерода и взрыва сверхновой Ia с дочандрасекаровской массой.
- Смоделирован эффект обратного течения в основании релятивистского джета и развитие неустойчивости типа Кельвина-Гельмгольца.

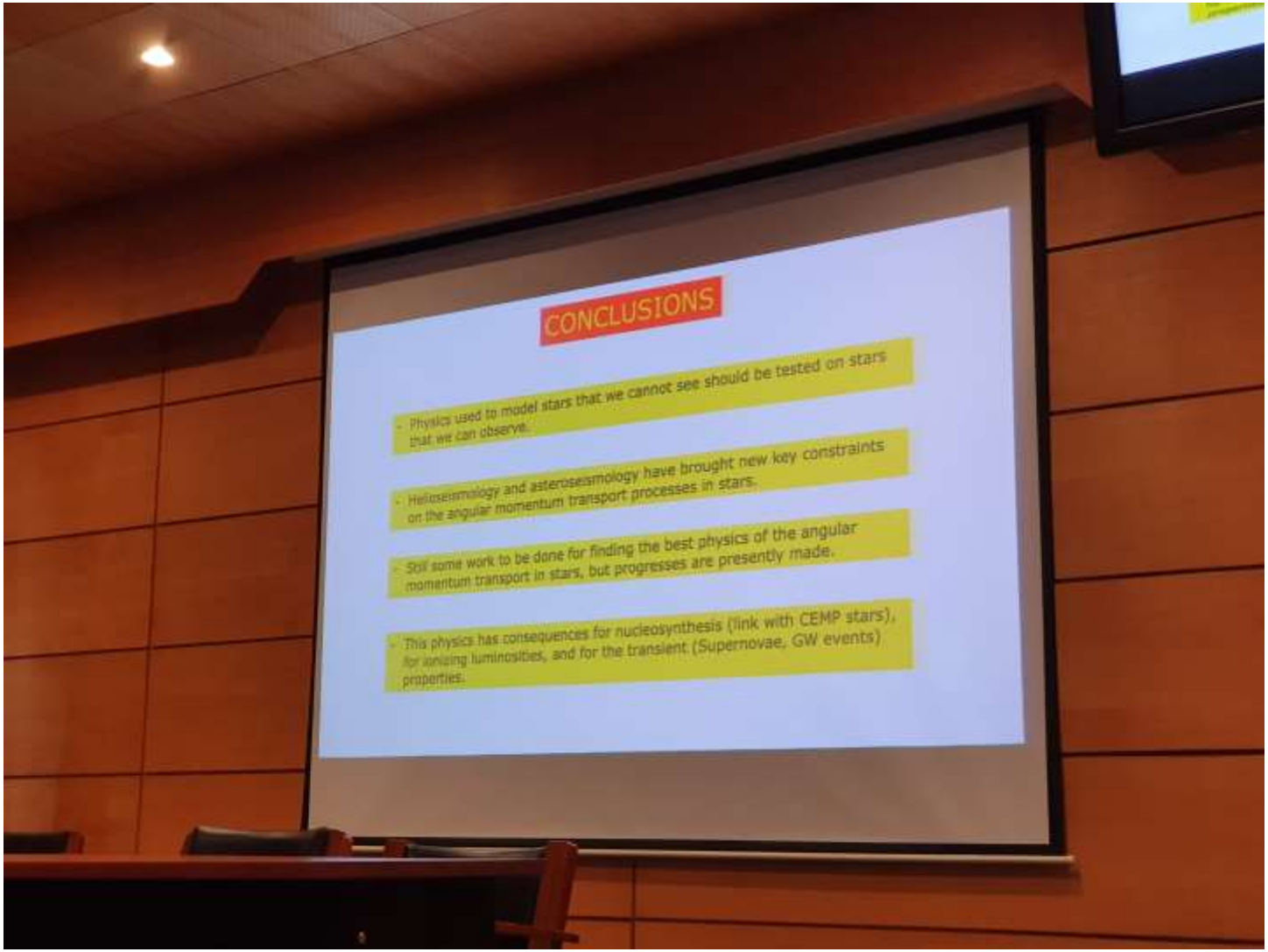


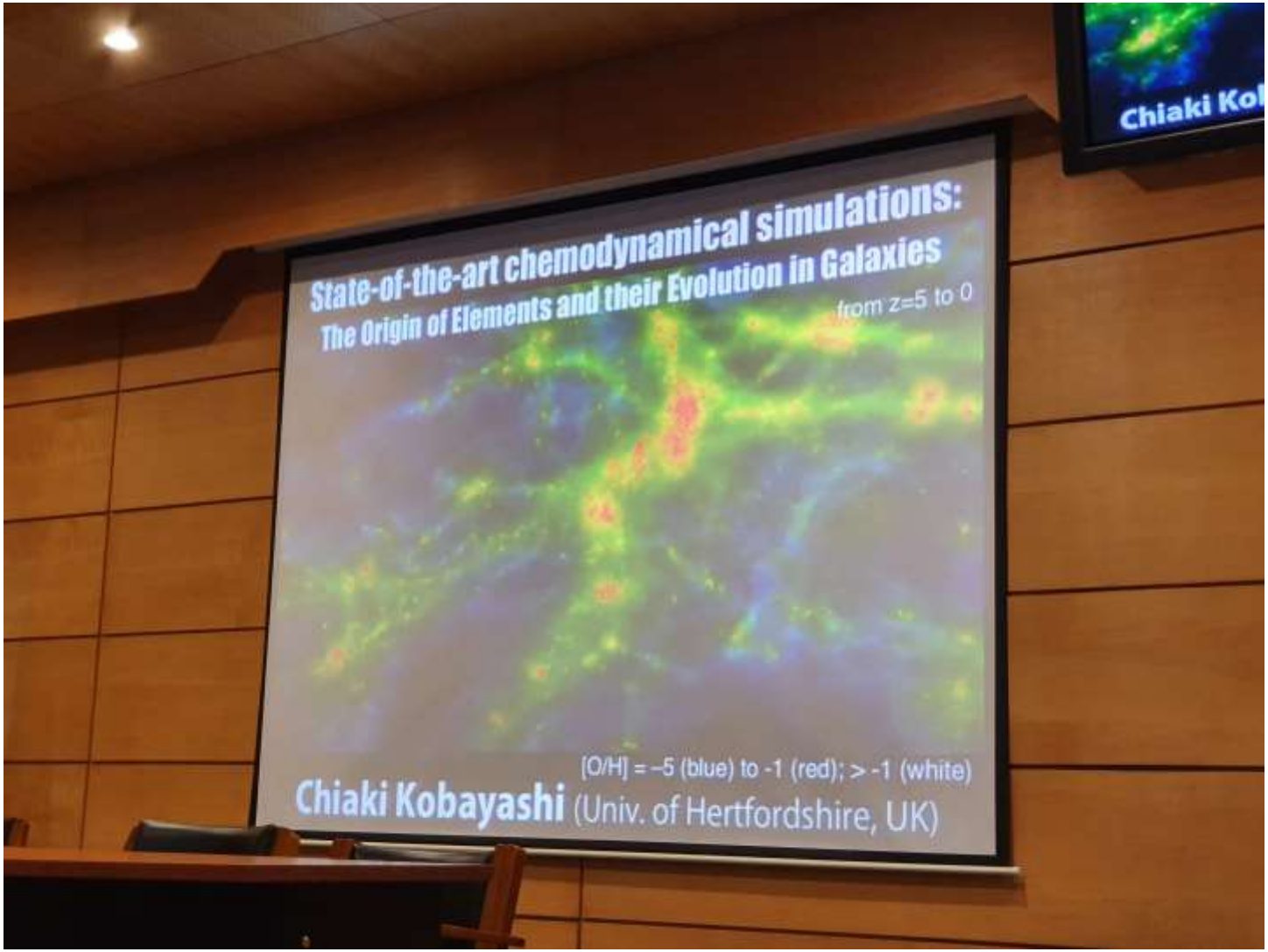


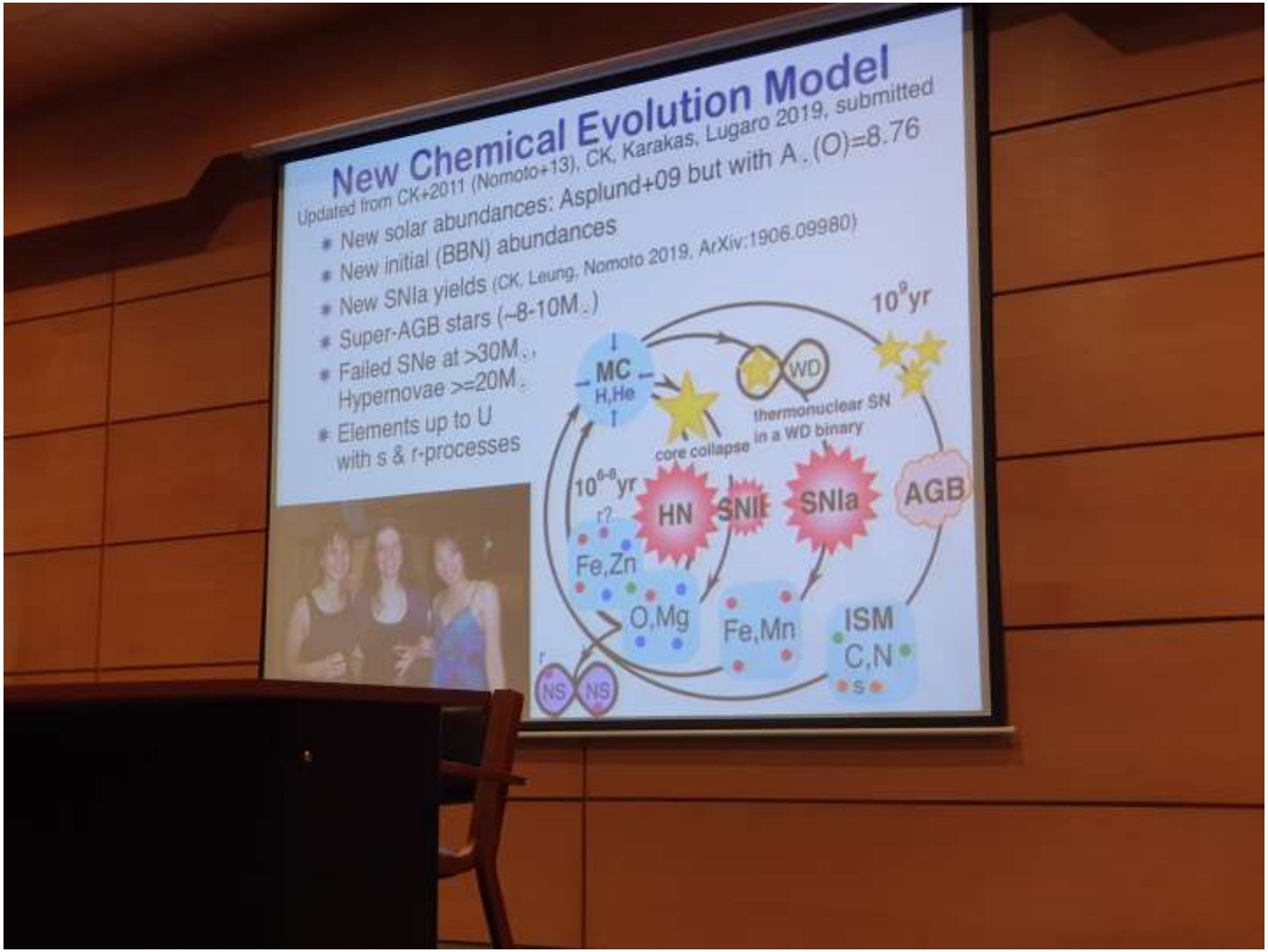
Структура и процессы нуклеосинтеза в предсверхновой и в следующее мгновение после вспышки для звезды 25$M_\odot$, масштаб не соблюдён



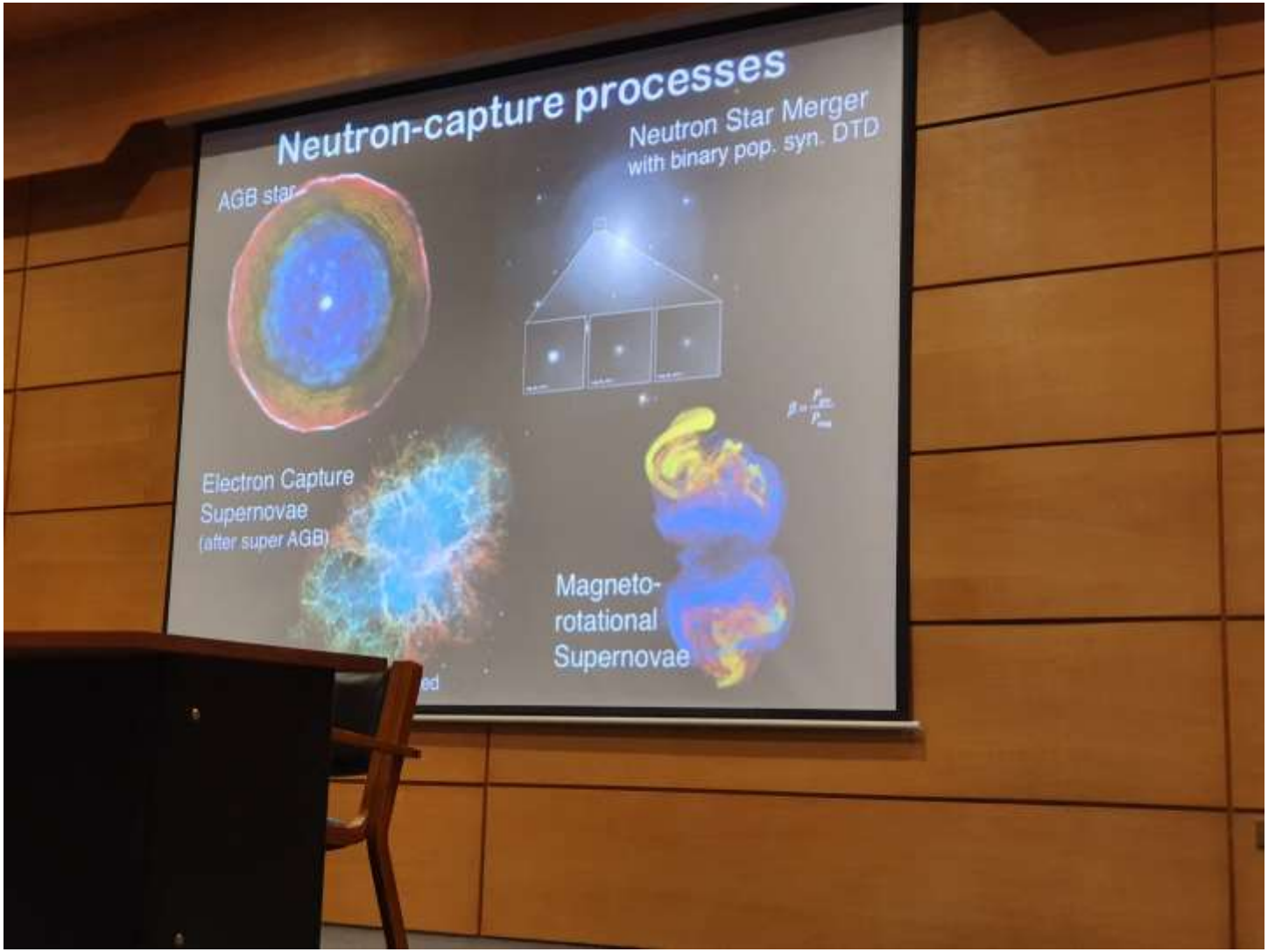

Rotations of first stars: need of a theory anchored on present-day observational constraints
Georges Meynet
UNIVERSITÉ DE GENÈVE
erc

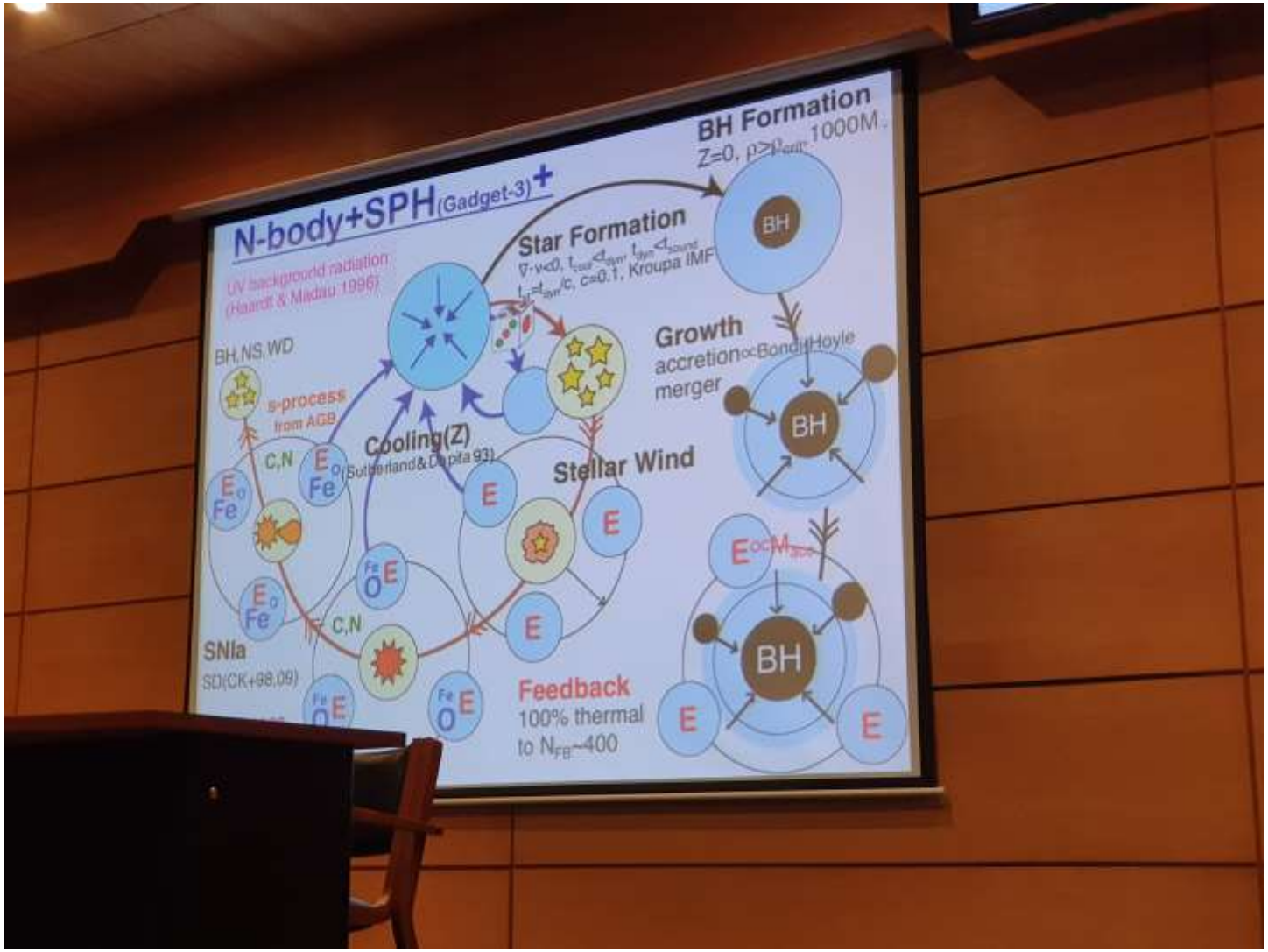

CONCLUSIONS
- Physics used to model stars that we cannot see should be tested on stars that we can observe.
- Helioseismology and asteroseismology have brought new key constraints on the angular momentum transport processes in stars.
- Still some work to be done for finding the best physics of the angular momentum transport in stars, but progresses are presently made.
- This physics has consequences for nucleosynthesis (link with CEMP stars), for ionizing luminosities, and for the transient (Supernovae, GW events) properties.

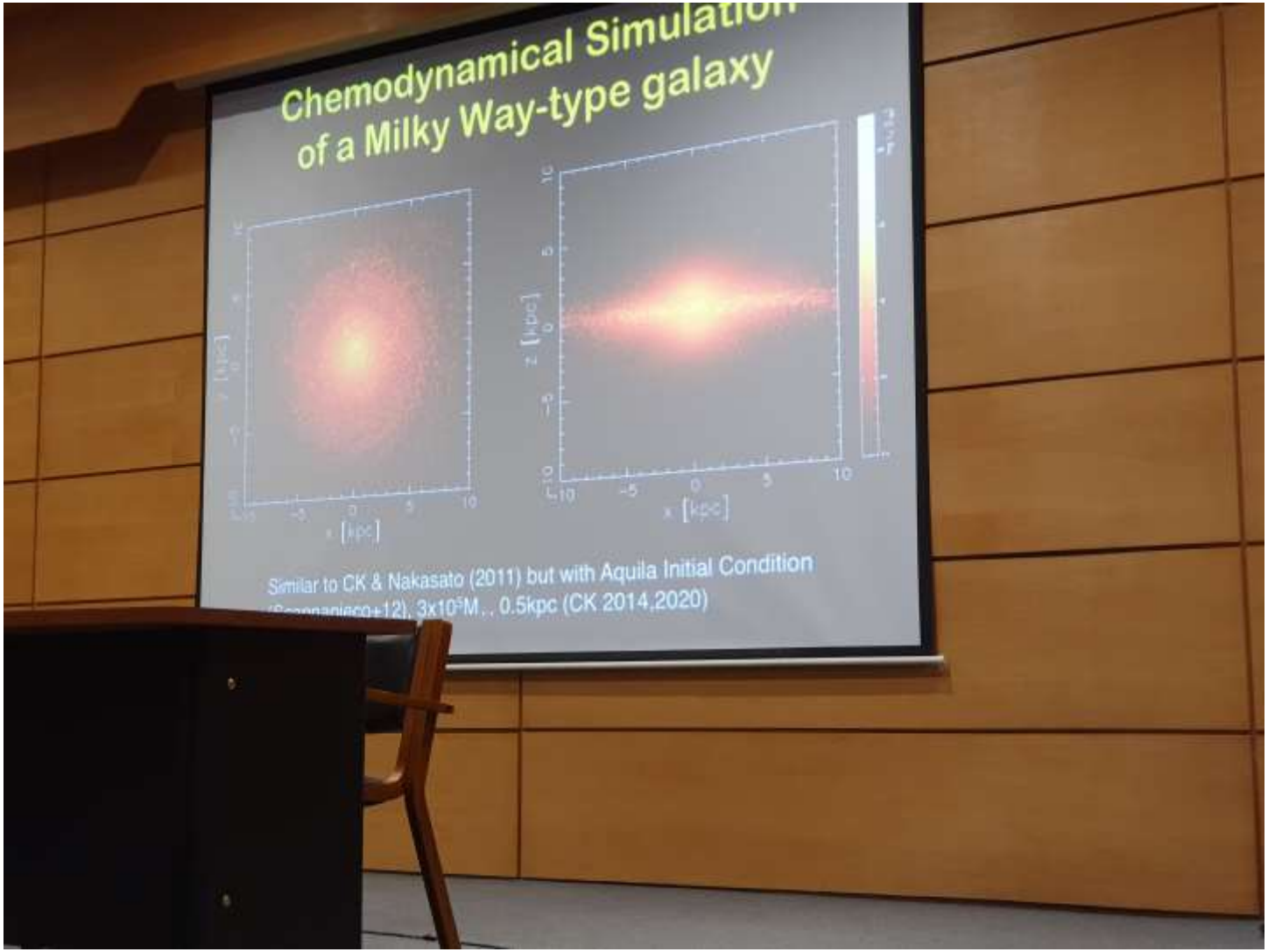

State-of-the-art chemodynamical simulations:
The Origin of Elements and their Evolution in Galaxies
from z=5 to 0
[O/H] = –5 (blue) to -1 (red); > -1 (white)
Chiaki Kobayashi (Univ. of Hertfordshire, UK)
Chiaki Kob


New Chemical Evolution Model
Updated from CK+2011 (Nomoto+13), CK, Karakas, Lugaro 2019, submitted
New solar abundances: Asplund+09 but with A(O)=8.76
New initial (BBN) abundances
New SNIa yields (CK, Leung, Nomoto 2019, ArXiv:1906.09980)
Super-AGB stars (~8-10M⊙)
Failed SNe at >30M⊙,
Hypernovae >=20M⊙
Elements up to U
with s & r-processes
10^9 yr
MC
H,He
WD
thermonuclear SN
in a WD binary
core collapse
10^6-8 yr
r?
HN
SNII
SNIa
AGB
Fe,Zn
O,Mg
Fe,Mn
ISM
C,N
s
r
NS
NS


Thermonuclear (Type Ia) Supernovae
Thermonuclear explosion in a binary with C+O white dwarf
+14
ArXiv:1906.09980 (2D nucleosynthesis)


Neutron-capture processes
Neutron Star Merger
with binary pop. syn. DTD
AGB star
Electron Capture
Supernovae
(after super AGB)
Magneto-
rotational
Supernovae


N-body+SPH(Gadget-3)+
UV background radiation
(Haardt & Madau 1996)
BH,NS,WD
s-process
from AGB
C,N
Cooling(Z)
(Sutherland & Dopita 93)
Star Formation
Stellar Wind
SNIa
SD(CK+98,09)
Feedback
100% thermal
to N_FB~400
BH Formation
Growth
accretion∝Bondi-Hoyle
merger
BH


Chemodynamical Simulation
of a Milky Way-type galaxy
y [kpc]
x [kpc]
z [kpc]
x [kpc]
Similar to CK & Nakasato (2011) but with Aquila Initial Condition
(Scannapieco+12), 3x10⁵M⊙, 0.5kpc (CK 2014,2020)


Gas cycling in galaxies
Nuclear Feedback
Stellar Feedback
Interstellar medium (ISM)
Circumgalactic medium (CGM)

Disk fragmentation and intermittent accretion onto supermassive stars

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Abstract

Supermassive stars, which are hypothesized to form by very rapid gas accretion with its rate exceeding 0.1 Msun/yr, are promising candidates for the progenitors of supermassive black holes. They are considered to grow by the accretion via the convective core, but its fragmentation due to gravitational instability can result in intermittent accretion with quiescent periods. If such a period is longer than the stellar KH timescale, the burning protostar contracts and becomes a main-sequence star and start emitting copious amount of ionizing photons, shutting off the accretion. Here, we study the formation of supermassive stars by accretion by way of two-dimensional hydrodynamical simulations and examine the time evolution of the accretion rate. We find that fragments vigorously and the accretion rate fluctuates significantly as a result of the chaotic accretion. The timescale of quiescent phase can be similar to the KH timescales when the central stars exceed 20000 Msun, and the ionization feedback can be important at this moment.

1. Introduction

Observation: more than 200 SMBHs with mass ~ 10^{9-10} Msun at $z > 6$

→ formation scenario? Massive seed BHs are preferred.

Direct collapse scenario (Bromm & Loeb 03)

A seed BH is formed from a supermassive star (SMS) with ~ 10^5 Msun that collapses into a BH with an almost equal mass by GR instability.

Conditions for SMS formation

The external far-UV radiation suppresses H_2 formation in the primordial gas cloud.

→ isothermal collapse (~ 10^4 K) by atomic cooling (Omukai 01)

Typical accretion rate:

$$\dot{M} \sim M_J/t_{ff} \sim c_s^3/G \sim 0.1\, M_\odot\, yr^{-1} \left(\frac{T}{10^4\,K}\right)^{3/2} \quad \text{very high!}$$

The gravitationally unstable disk appears under high accretion rate.

→ **The time variation of accretion rate due to disk fragmentation affects the stellar evolution.** (Sakurai+ 15, 16)

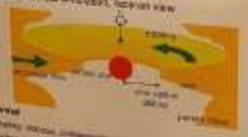
Sakurai+ (2016)

They have studied the time evolution of accretion rate in SMS formation, but their simulation uses barotropic EOS.

→ **In our work, we perform 2D hydrodynamical simulation with realistic treatment of thermal and chemical processes.**

2. Model

2D hydrodynamical simulation, face-on view



✓ **Thermal**

heating: viscous, compressional, stellar radiation

cooling: H2 line, CI, H-ff, gas-dust (H), chemical cooling

✓ **Chemistry**

20 species including H, electron (H, H_2, H^+, H^-, e)

✓ **Central stellar radiation**

L_{acc} = (Stefan-Boltzmann law), T_{eff} = 5500 K (Hosokawa+ 13, Haemmerle+ 16, Kuiper+ 16)

✓ **Initial condition**

(Chon et al. 2016)

They have examined the direct collapse (clouds from their cosmological simulation)

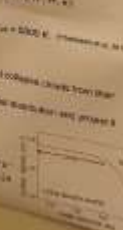
→ compact, 1 star mass (M is a 1D radial distribution) and grouped a wide & 2D axisymmetric cases

core radius: 1.6e16 cm

core mass: 4.5e19 Msun

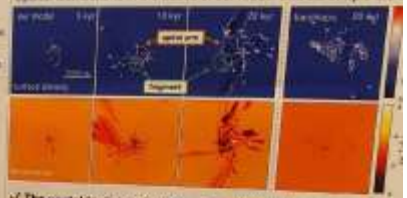
angular velocity at core: 2.0e-14 s^{-1}

(Mach no.) = (Ang. vel.) × 0.24



3. Result

Spatial distributions in the cases of our model and barotropic EOS

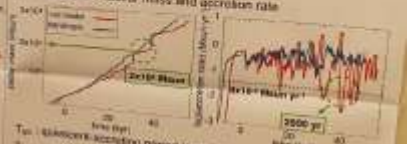


✓ **The unstable disk is formed.** → fragments & spiral arms

✓ The fragments are less frequently formed than in the case of barotropic EOS.

→ The individual fragments become more massive.

Time evolutions of stellar mass and accretion rate



T_{KH} : quiescent accreting period (accretion rate < 4x10^{-5} Msun yr^{-1})

$T_{KH,ZAMS}$: KH timescale at stellar surface, $\sim 10^7\ \mathrm{yr}\ (M_*/100\ M_\odot)^{-2}$

If $T_{max} > T_{KH,ZAMS}$

the forming protostar contracts and emits the ionizing photons.

→ The accreting flow is shut off by ionizing feedback. (Sakurai+ 15)

When $t \sim 40$ kyr, $T_{max} \sim 3500$ yr & $T_{KH,ZAMS} \sim 5300$ yr.

Both timescales are comparable

→ ionizing feedback can be important at this moment.

4. Discussion

More fragments than in 3D simulation (Chon et al. 2018)

formation process of fragments

The Collision of spiral arms increases density and promotes gravitational instability.

→ The collision more frequently occurs because spiral arms are on the same equatorial plane.

The number of fragments is smaller and fragments become more massive compared with the barotropic EOS.

The trend is also indicated in Clark et al. (2011)

→ The gas in the disk is hard to cool because the shock heating and viscous heating work.

Summary

The unstable disk fragments vigorously and the gas flow is intermittently accrete onto the protostar.

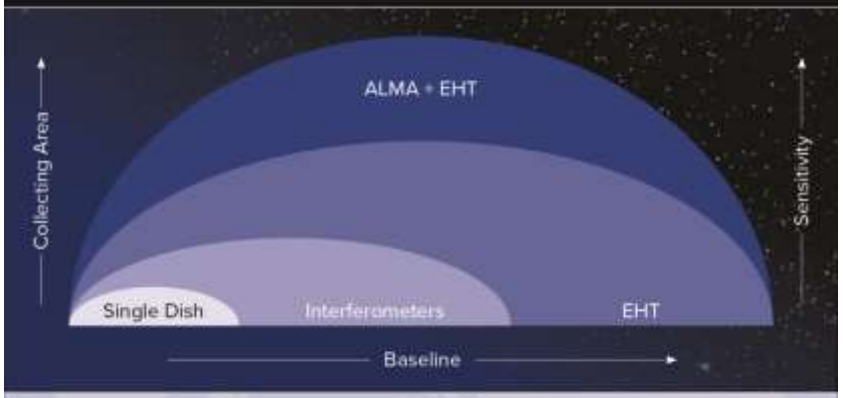
Completion of this research

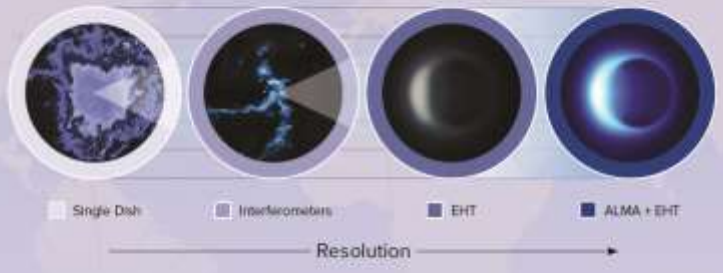



PABLO CARPINELLO

Tracing the Image of a Black Hole

www.nrao.edu





The Event Horizon Telescope (EHT) is a worldwide network of radio astronomy facilities, including the Atacama Large Millimeter/submillimeter Array (ALMA) in Chile, linked together to form a single, global telescope to study one of the most exciting objects in the known universe - Sagittarius A*, the supermassive black hole at the center of the Milky Way.

ALMA's light-gathering capabilities increase the EHT's ability to detect the faint light from the very center of our galaxy. Astronomers are observing the black hole in millimeter radio wavelengths, the wave band at which light can penetrate the dense concentrations of gas and dust at the center of the galaxy and travel relatively unimpeded to Earth.


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