Deutsche Forschungsgemeinschaft

The Evolution of

Tidal Dwarf Galaxies

Image Credit: Jean-Charles Cuillandre, Hawaiian Starlight

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Pavel Kroupa, Marcel Pawlowski (Bonn)

NAM 2012, March 30th, 2012

universität wien

institut für astronomie
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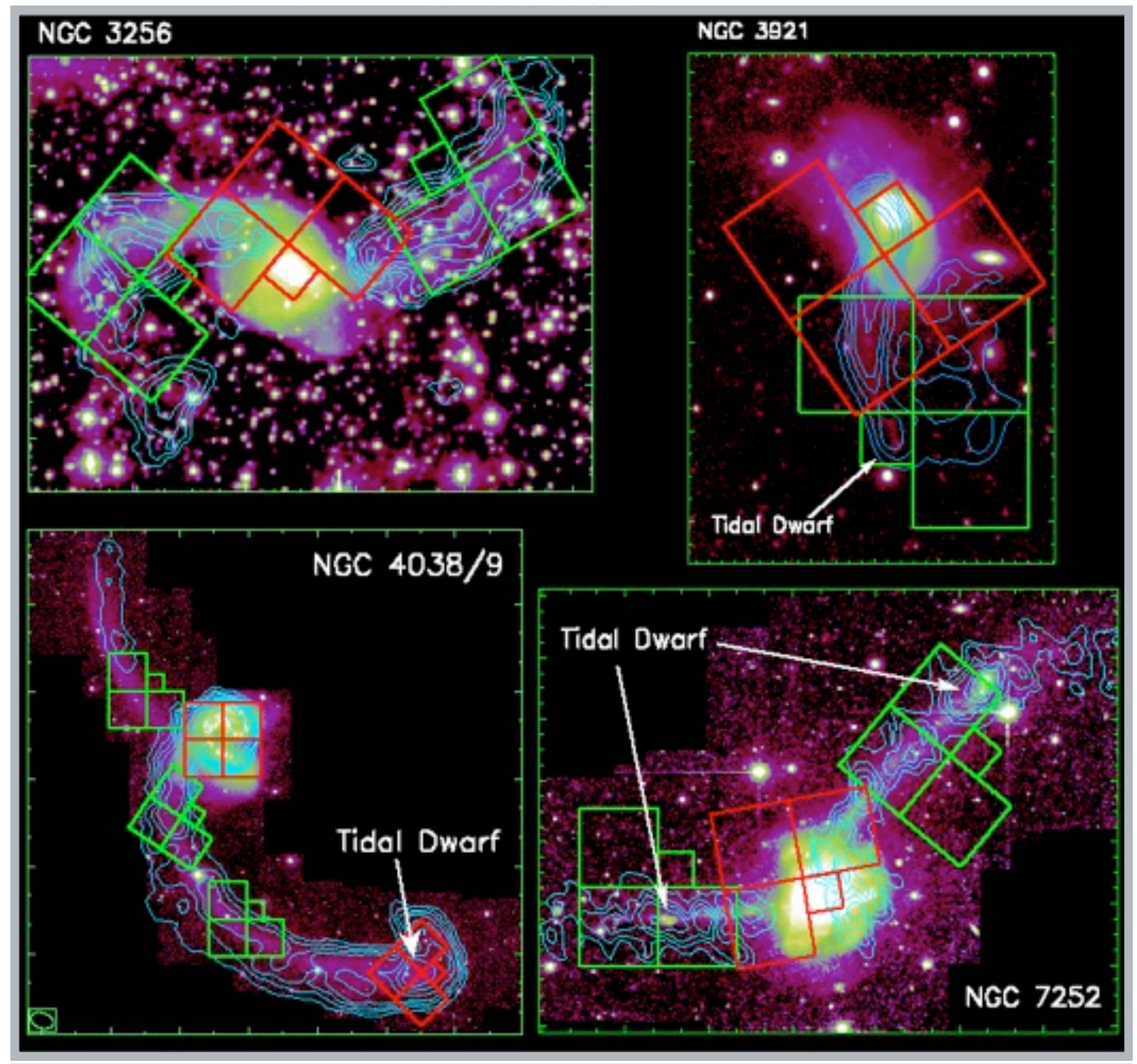
Argelander-Institut für Astronomie

universität bonn

Tidal Dwarf Galaxies

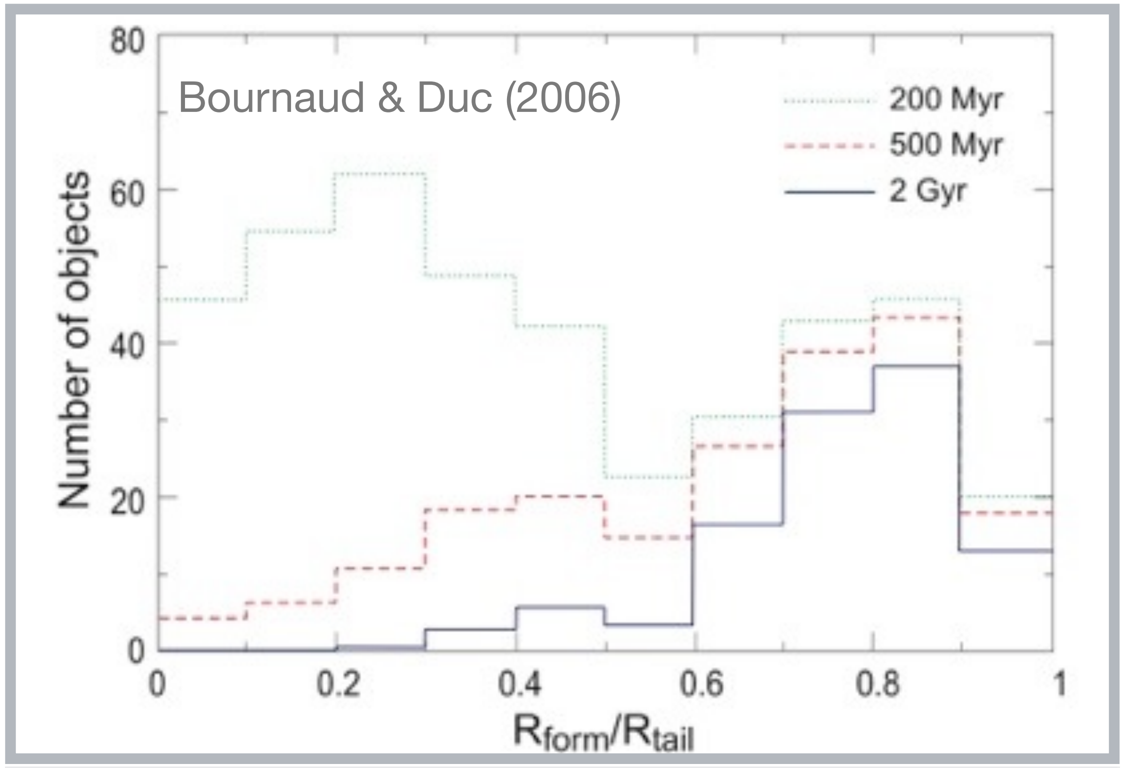
- *More than 60 TDG candidates observed.*
- *Internal kinematics show that they are gravitationally bound systems.*
- *They have active star formation.*
- *Should not contain dark matter.*
- *Stem from already pre-enriched material.*

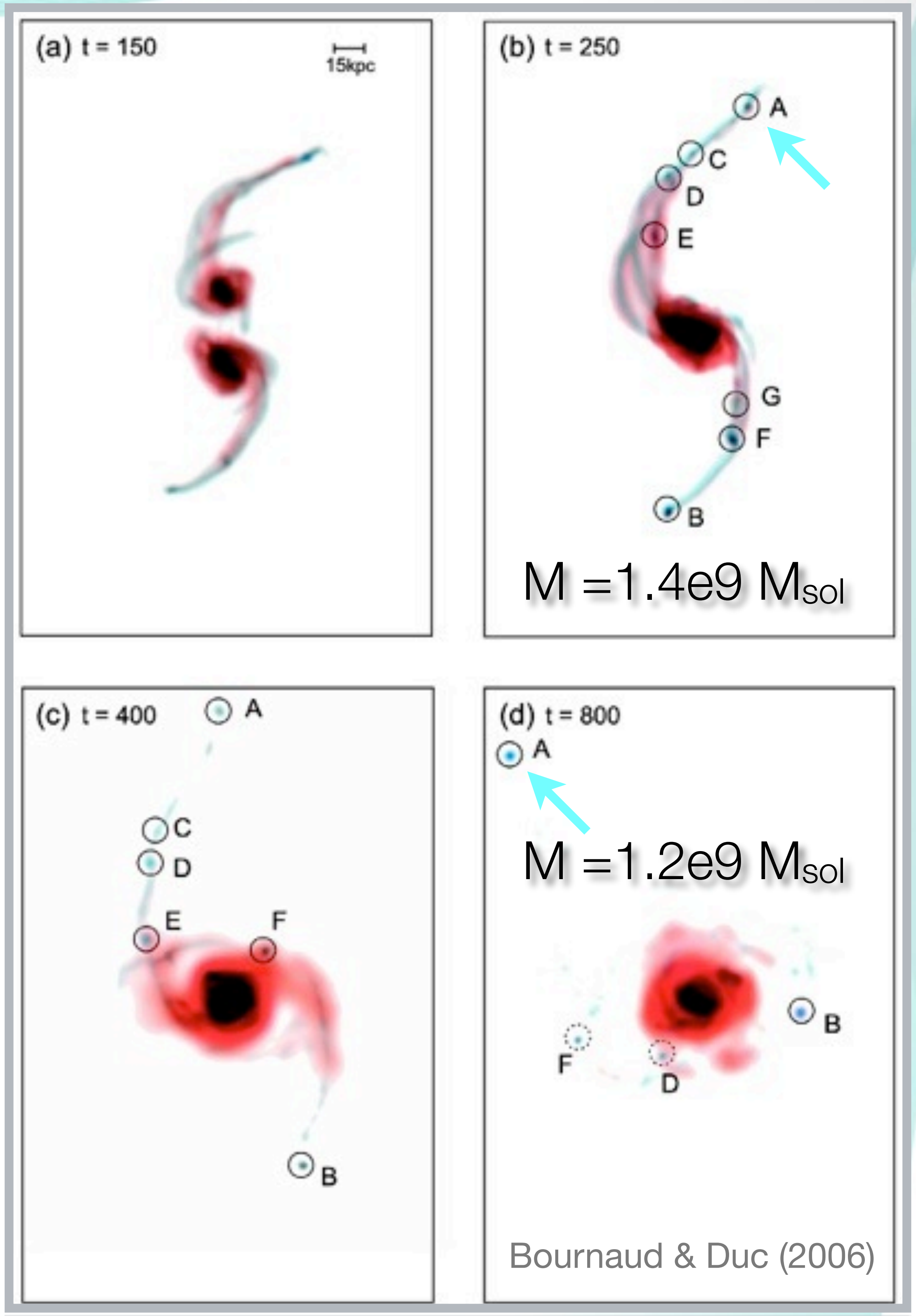


Kniermann et al. (2003)

Tidal Dwarf Galaxies

- *N-body simulations of interacting galaxies*
- *They found 593 substructures.*
- *75 % fall back, but 25 % survive more than 2 Gyrs.*





Motivation

We need high resolution simulations to answer the question:

Can TDGs turn into dSph/dE type galaxies?

against processes like:

- Dynamical Friction (orbital decay)
- Tidal Disruption
- Star Formation and Stellar Feedback

Some Numerical Details

- *FLASH Version 3.2 (by FLASH center for computational science, University of Chicago)*
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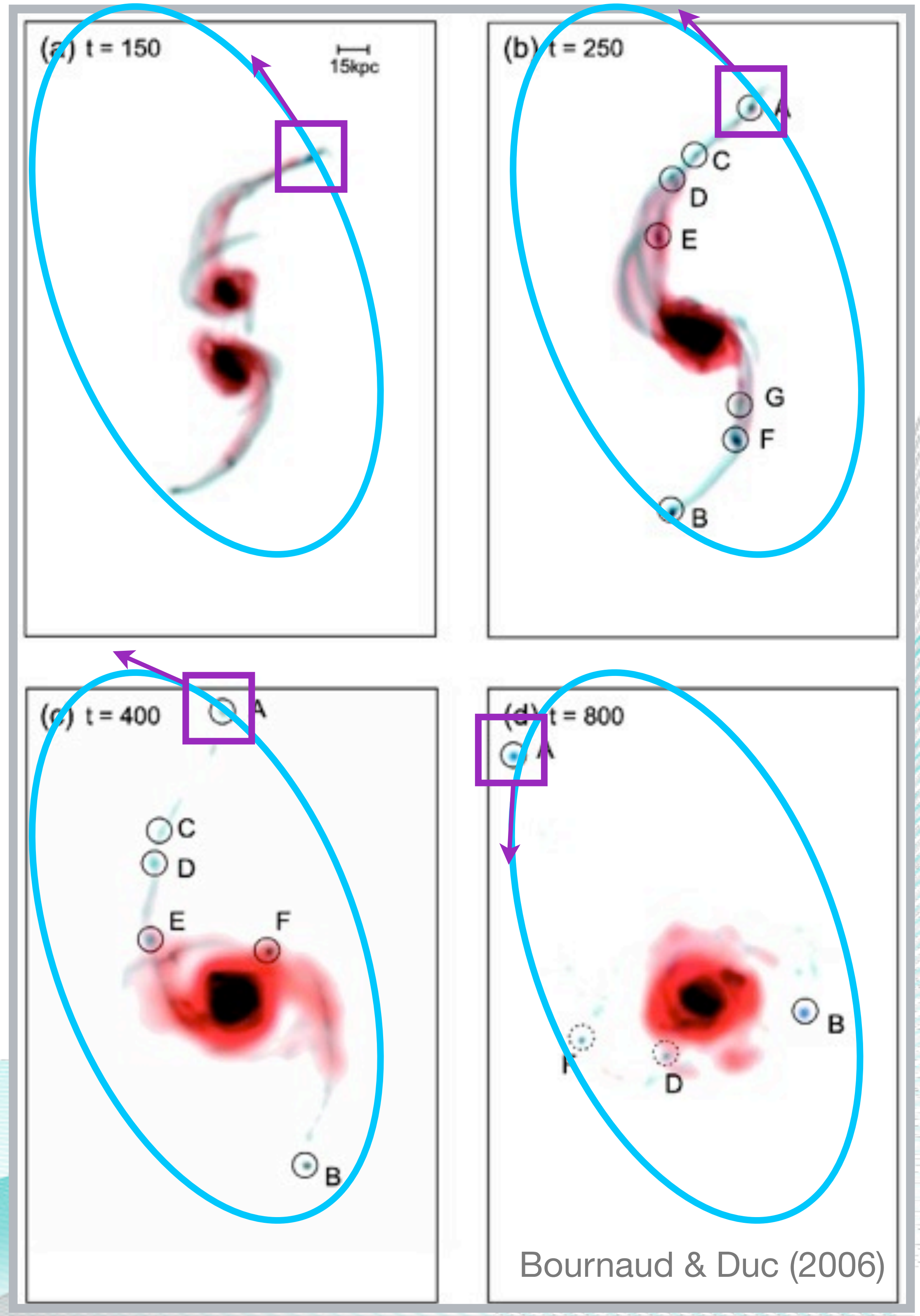
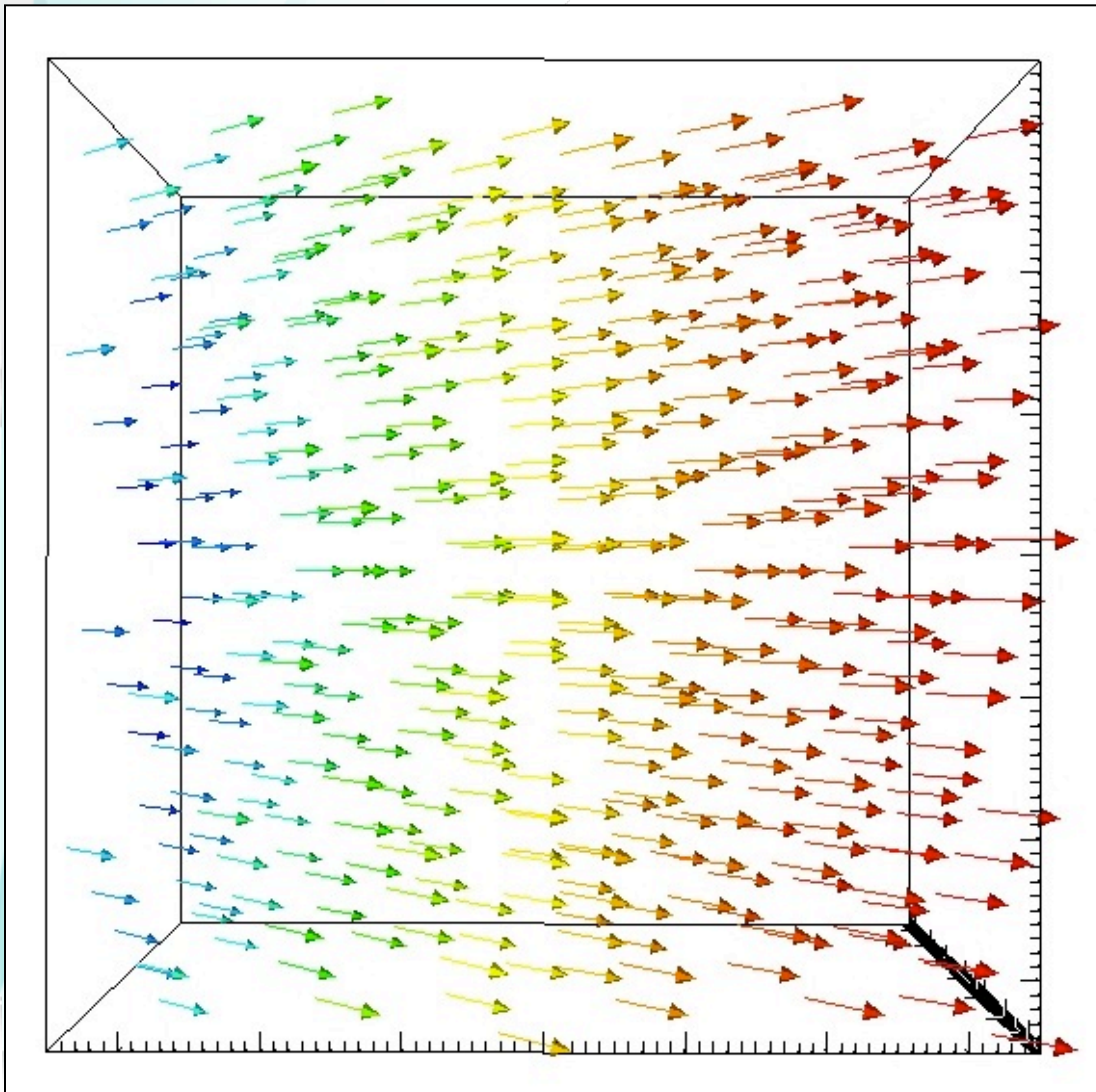
The Orbit Module

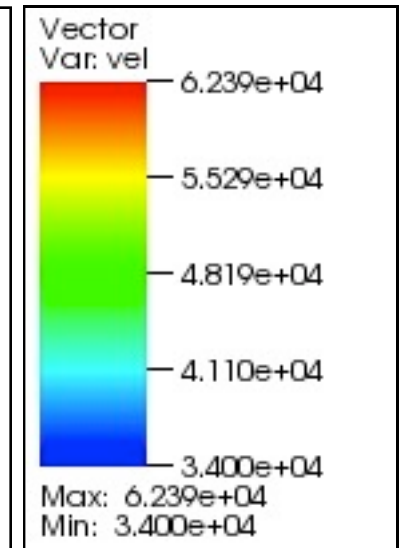
Within the simulation box:

- Time dependent external gravitational potential (additional to the self-gravity)
- Wind: velocity field due to the motion of the simulation box
- Tidal field



Tidal Field

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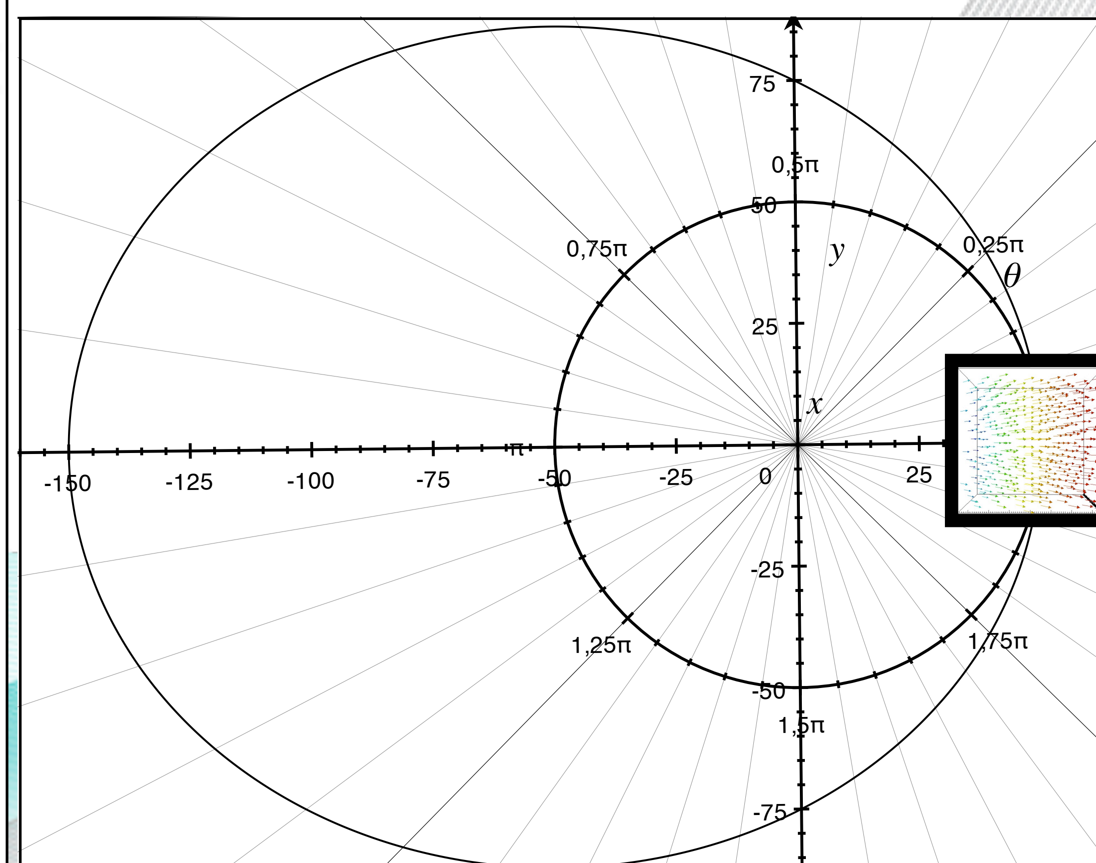
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-25
-50
-75
-150
-125
-100
-75
-50
-25
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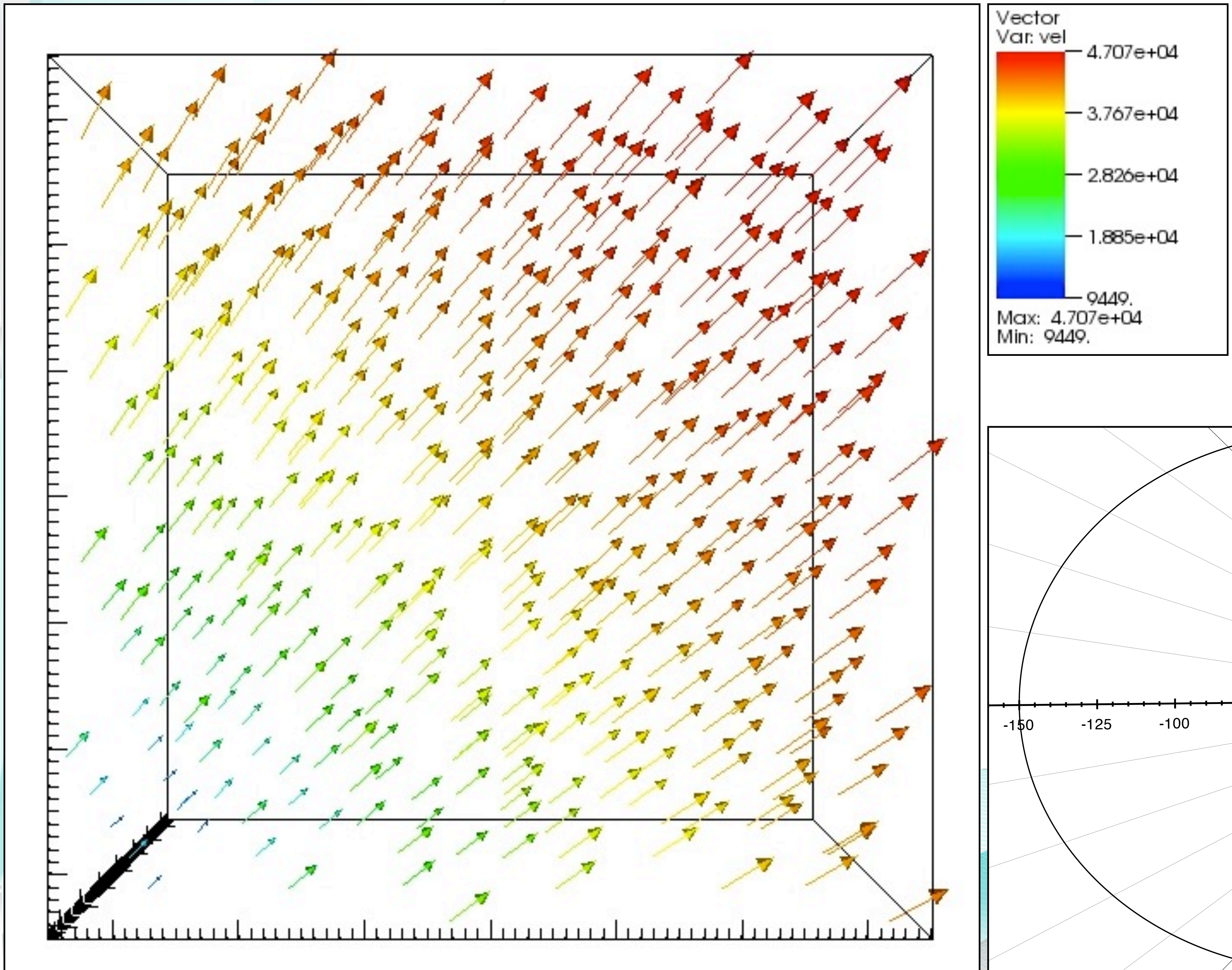
0,25π
0,75π
π
1,25π
1,5π
1,75π
y
θ
x

Tidal Field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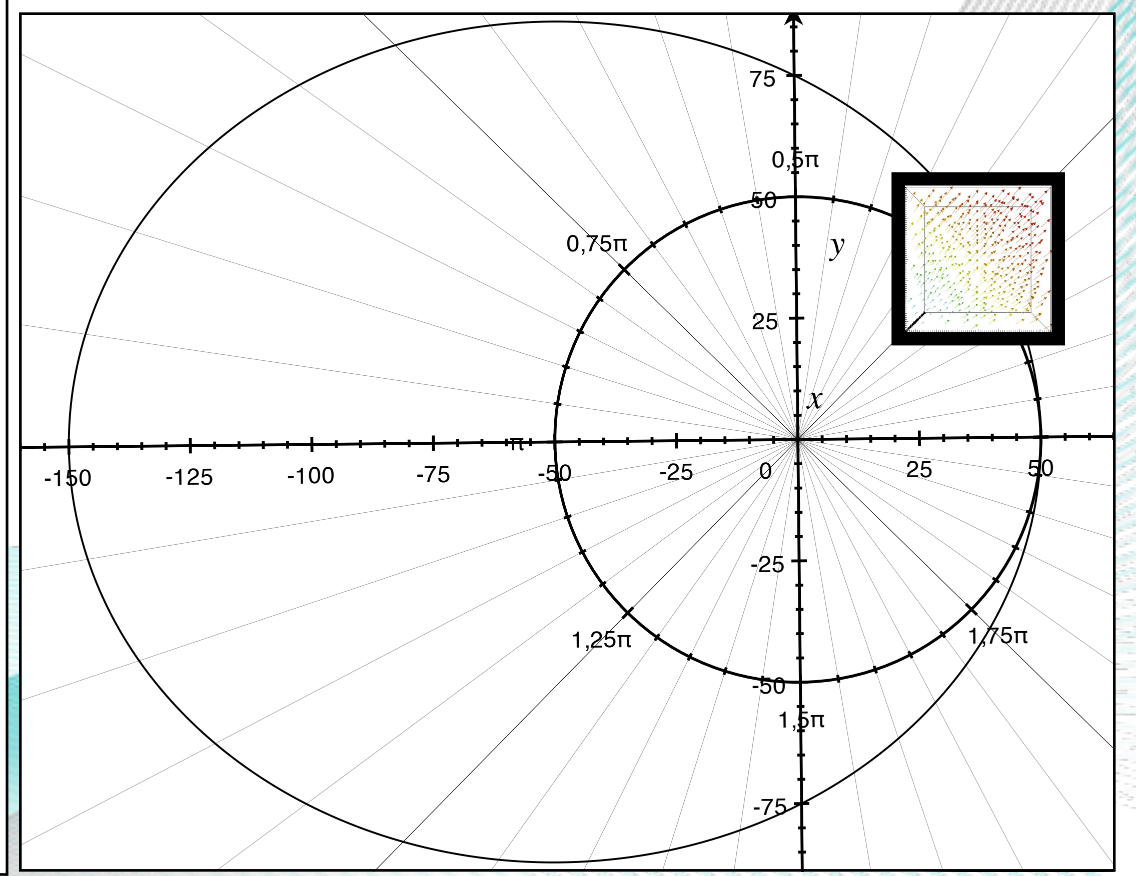
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0,75π
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x
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-125
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-25
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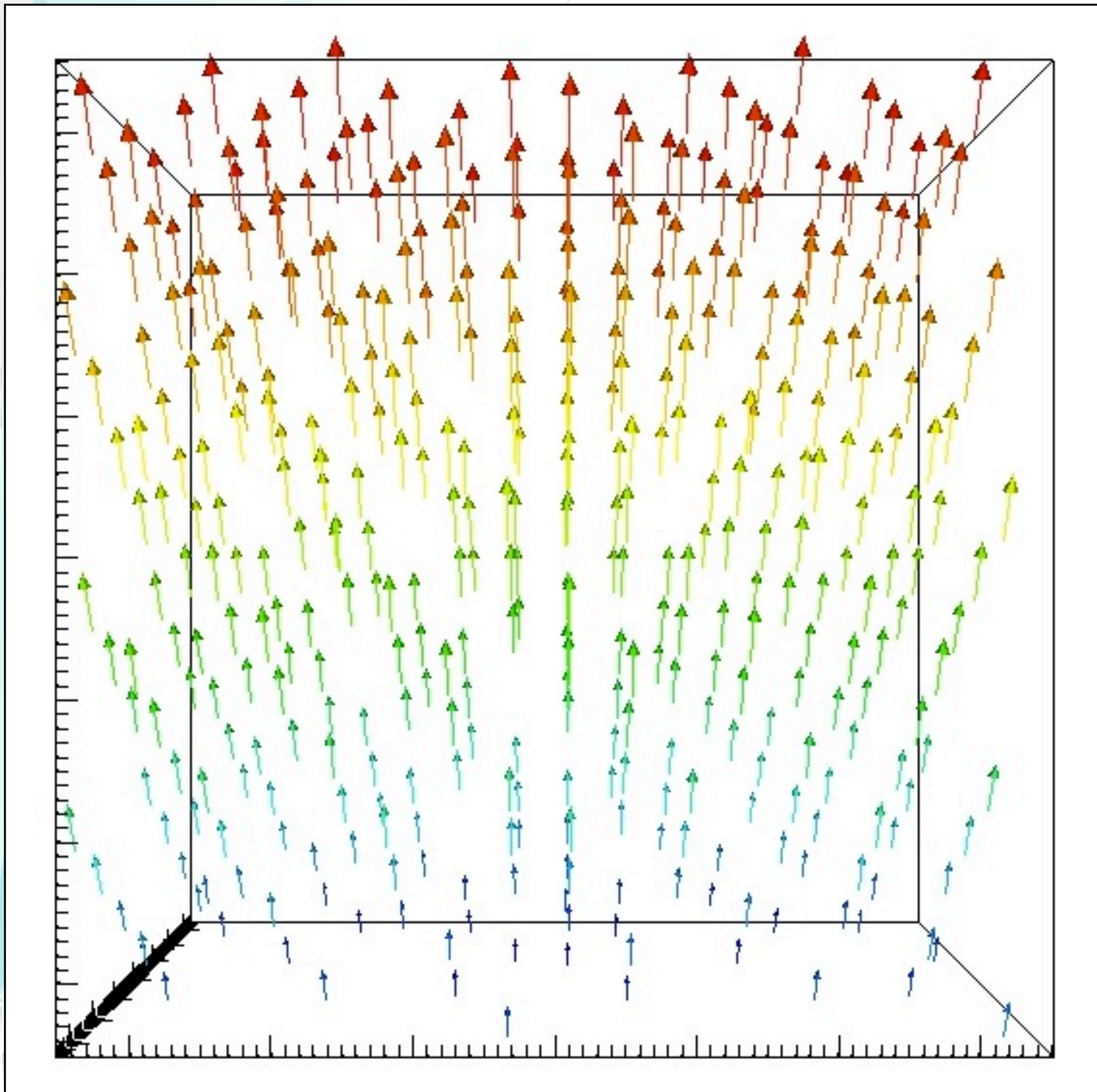
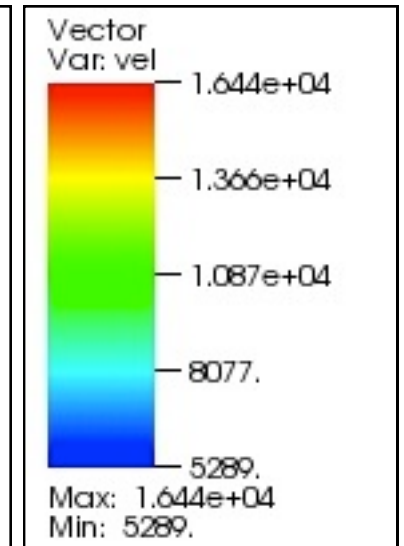
-25
1,25π
1,75π
-50
1,5π
-75

Tidal Field

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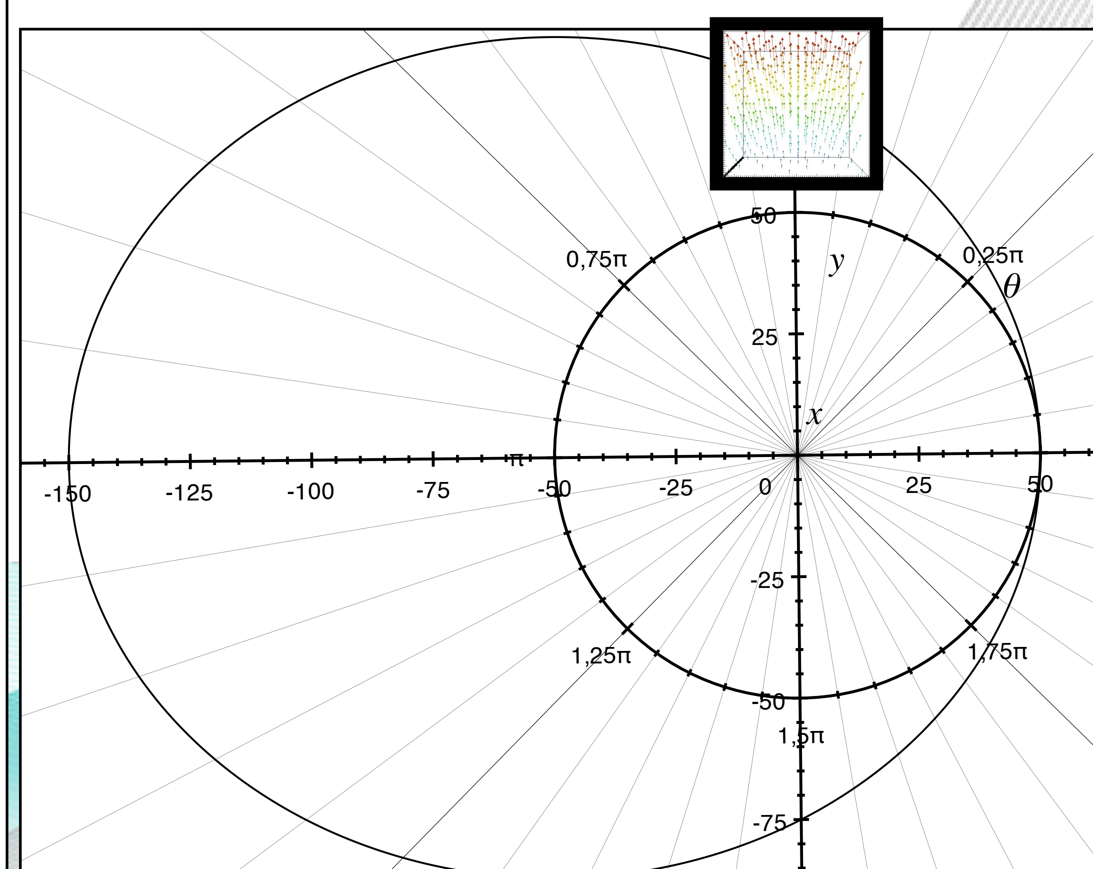
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1,75π
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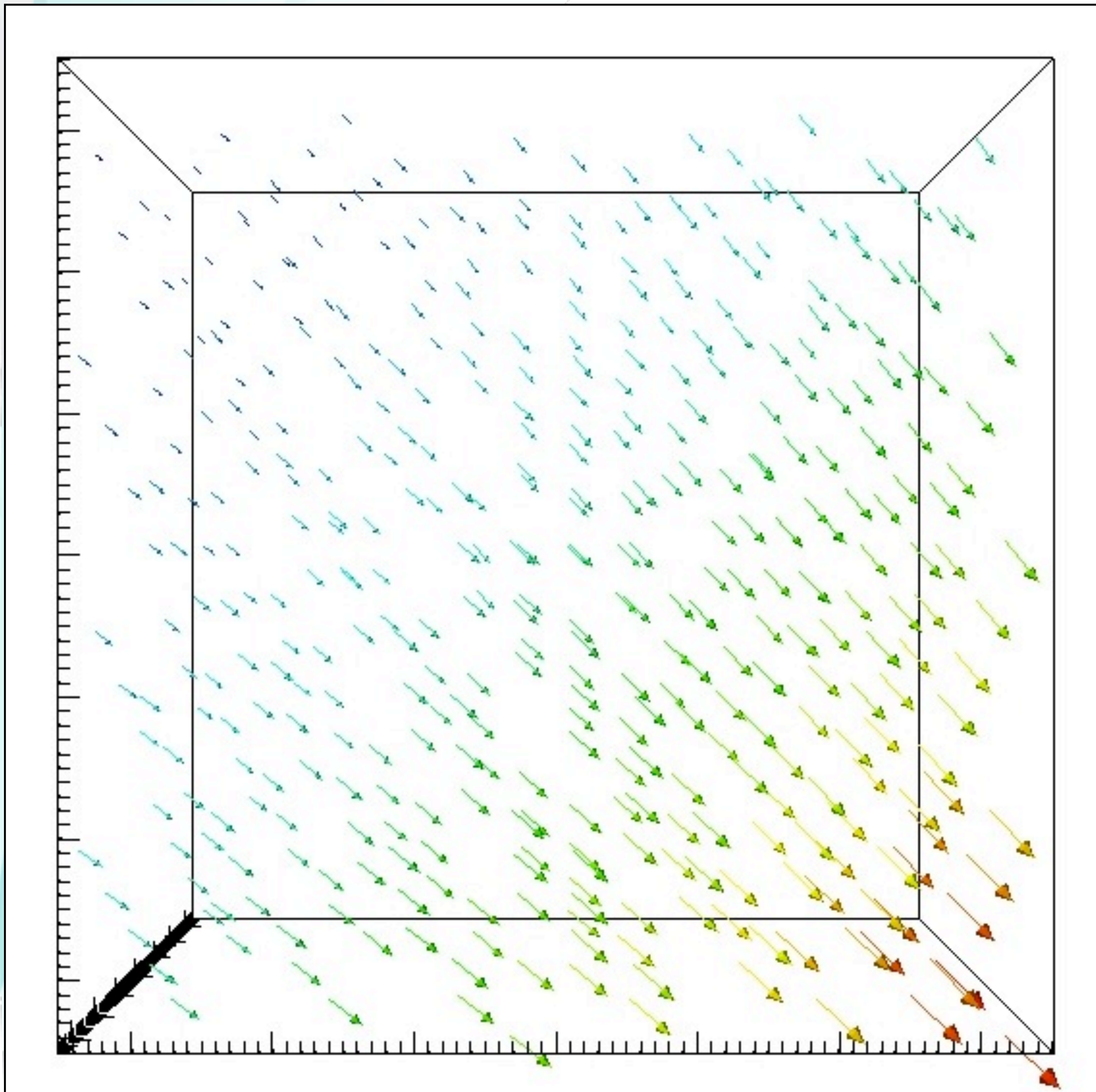
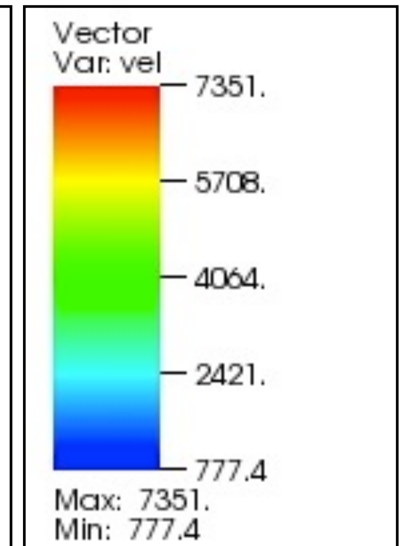
-125
-100
-75
-50
-25
0
25
50
-75

Tidal Field

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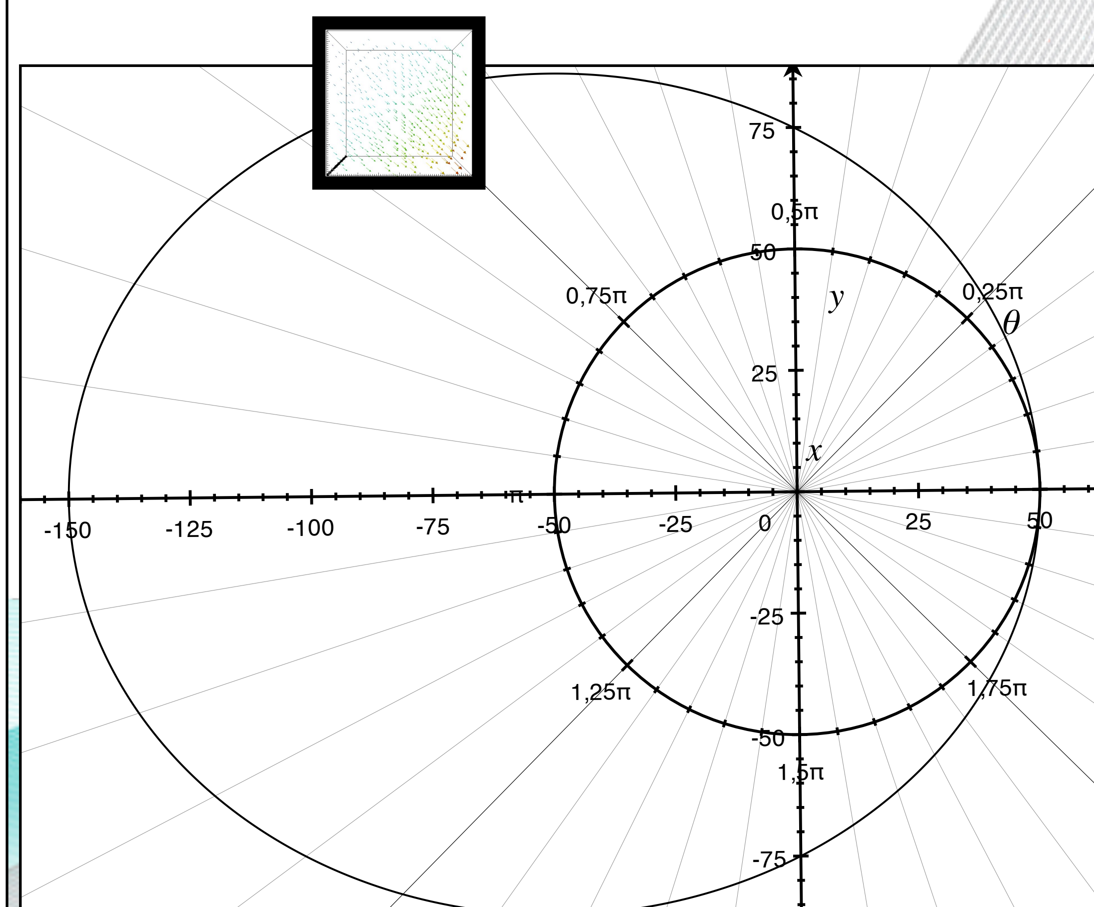
Min: 777.4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50
0,75π
y
0,25π
θ
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x
π
-150
-125
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-25
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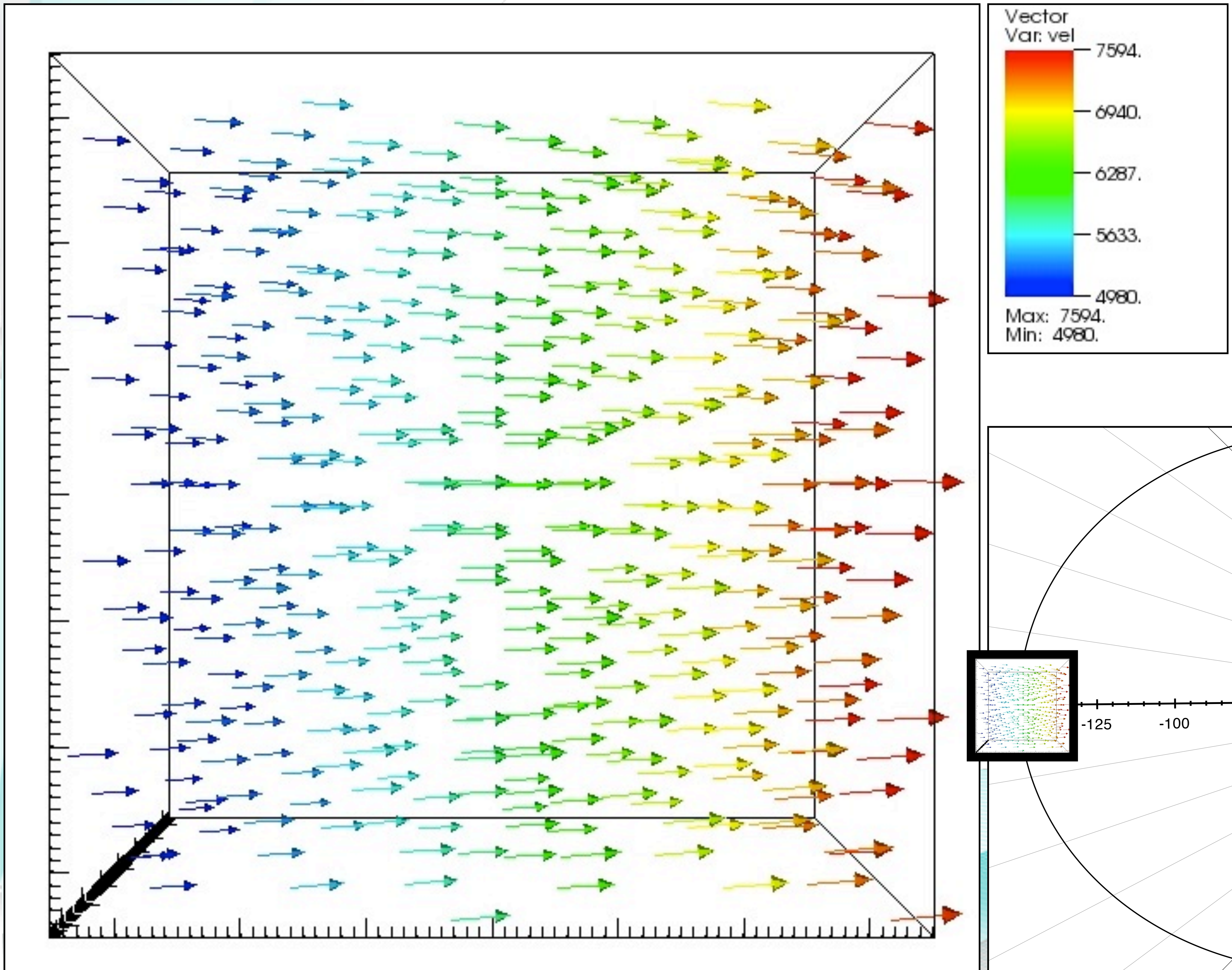
50
-25
1,25π
1,75π
-50
1,5π
-75

Tidal Field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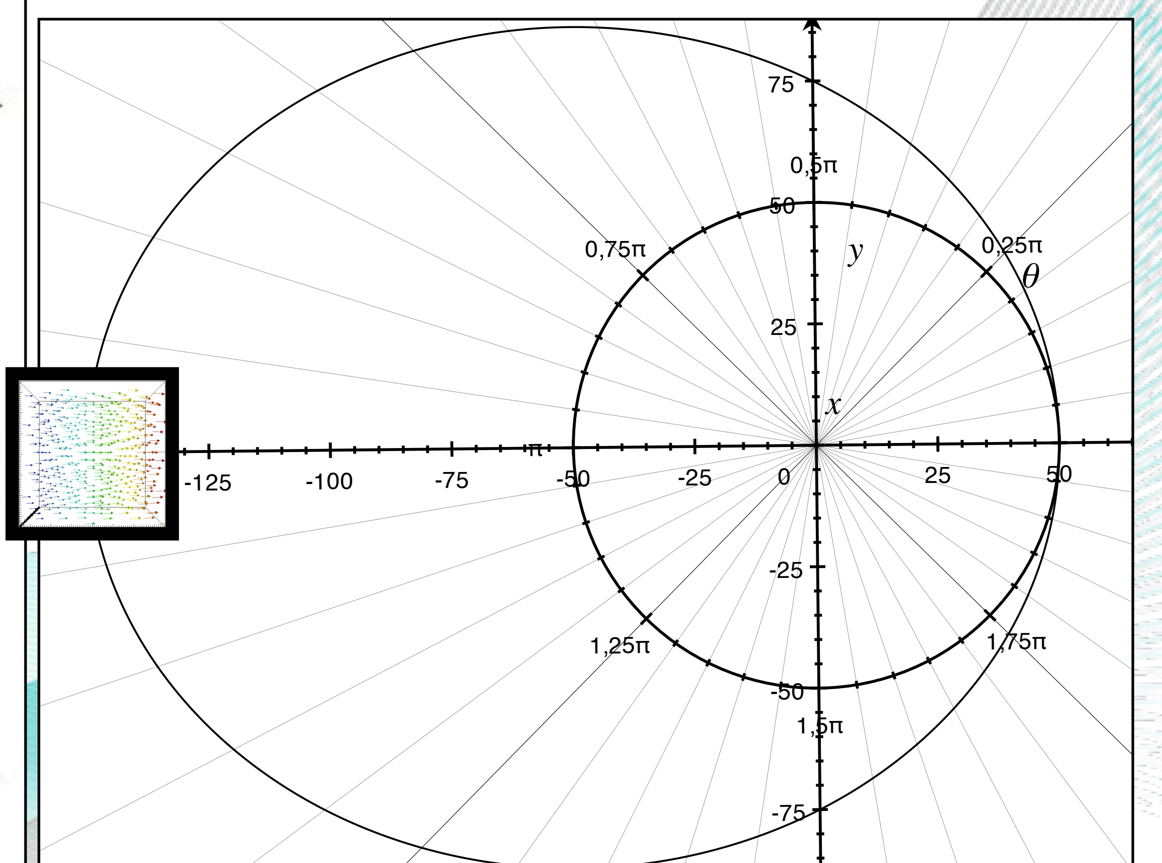
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y
0,25π
θ
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x
π
-125
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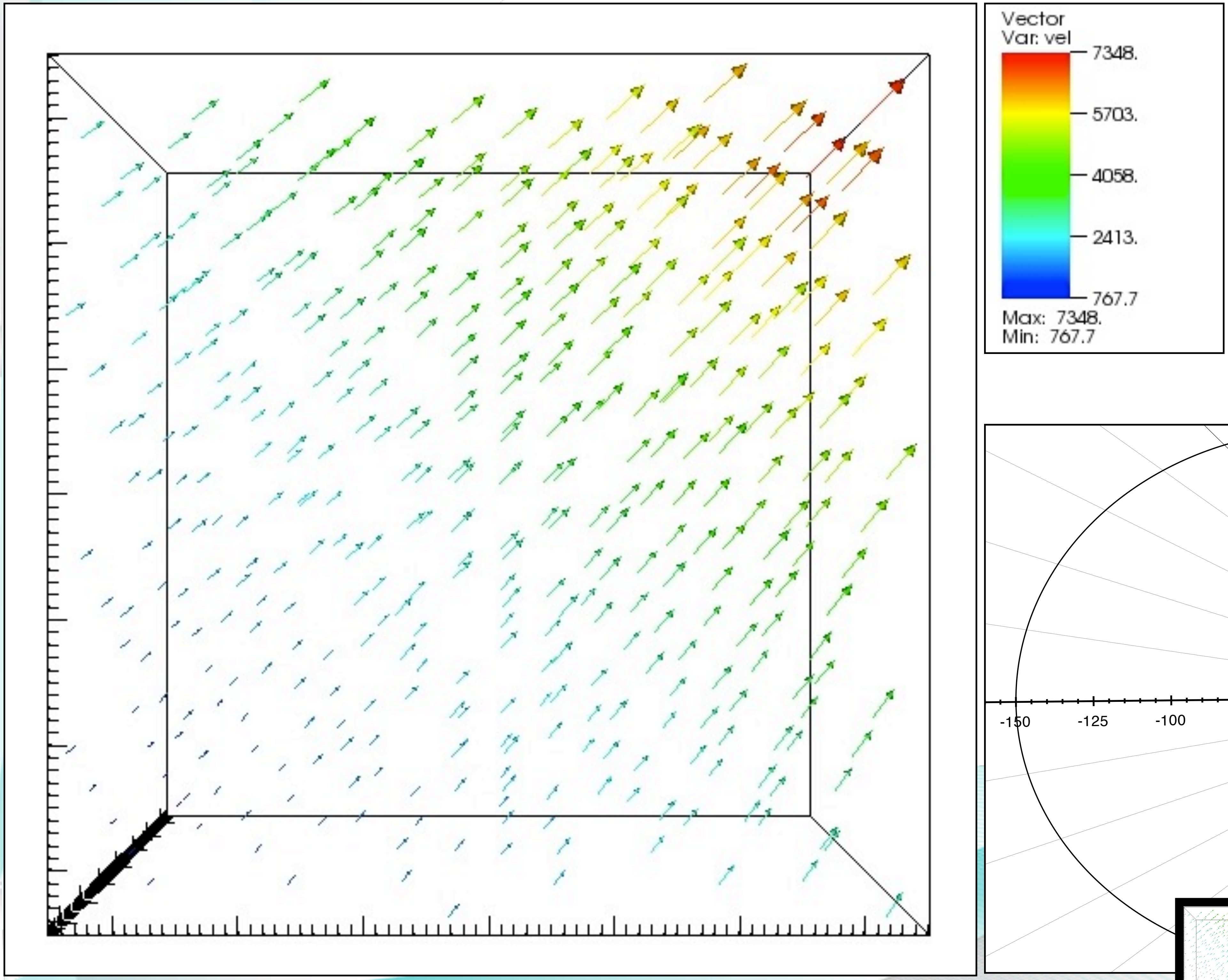
50
-25
1,25π
1,75π
-50
1,5π
-75

Tidal Field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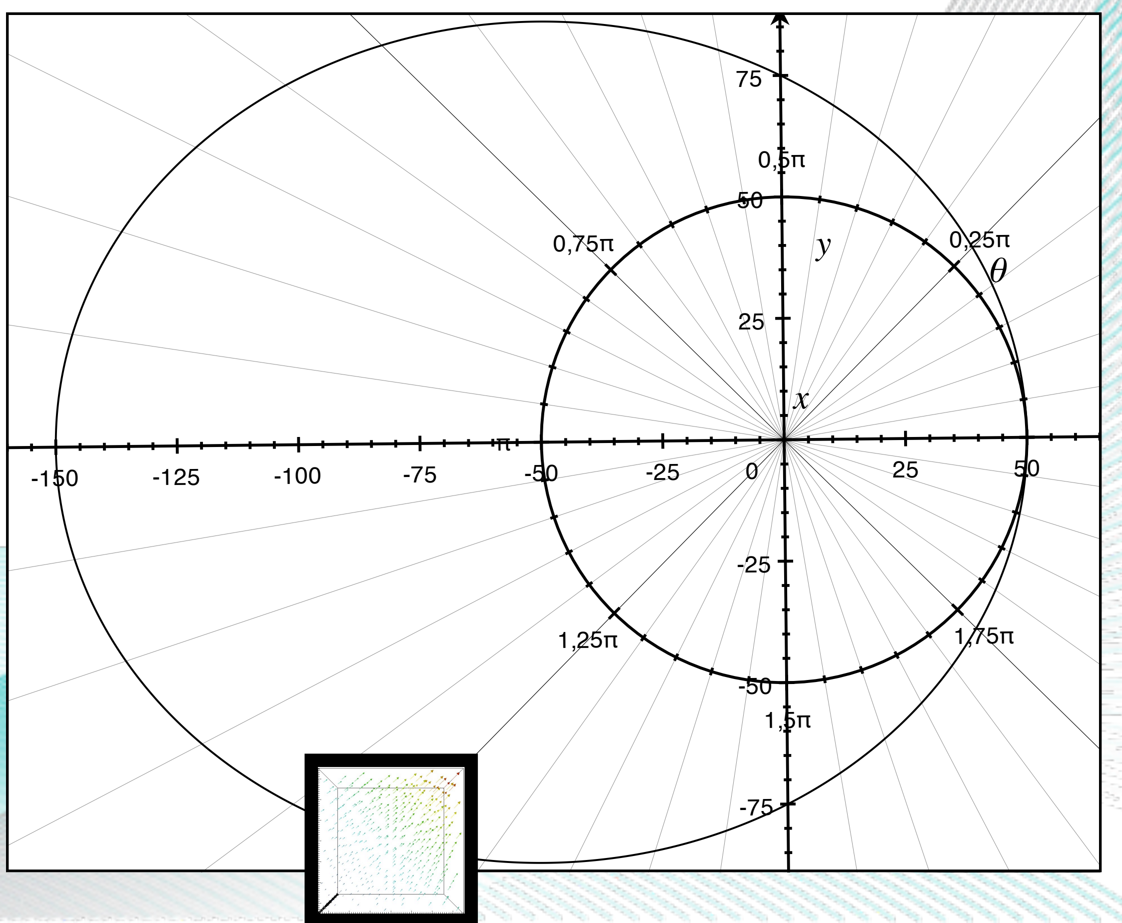
Min: 767.7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0,5π
50
0,75π
y
0,25π
θ
25
x
π
-150
-125
-100
-75
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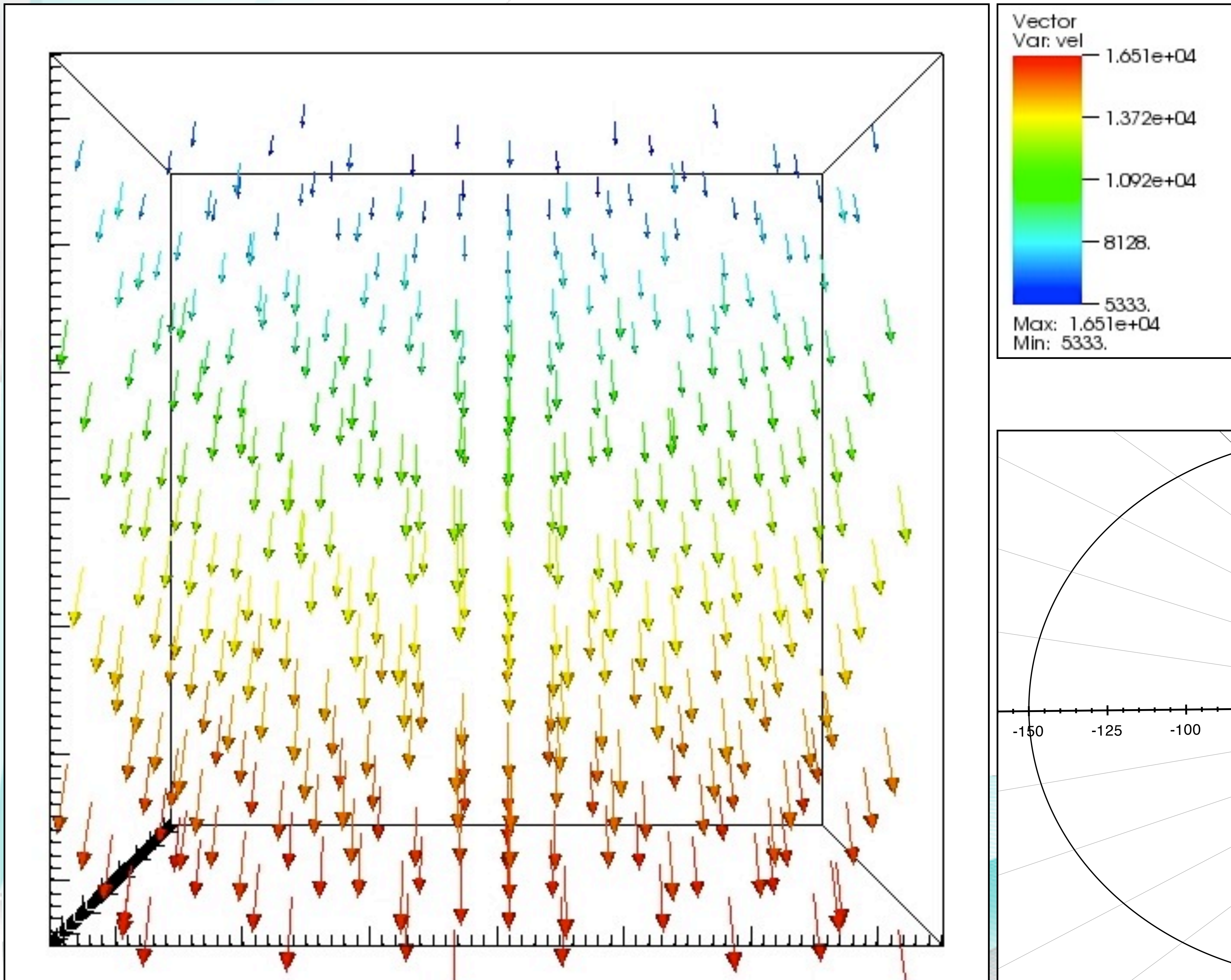
-25
0
25
50
-25
1,25π
1,75π
-50
1,5π
-75

Tidal Field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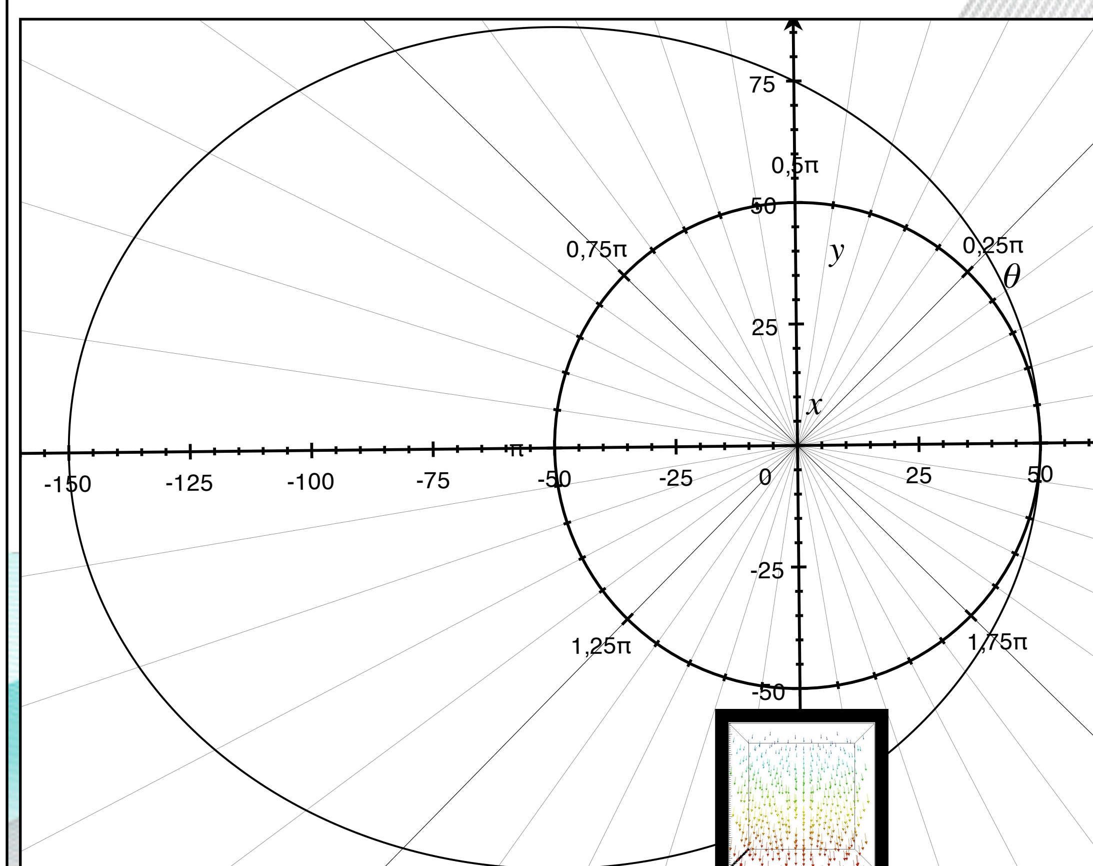
Min: 5333.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0,5π
50
0,75π
y
0,25π
θ
25
x
π
-150
-125
-100
-75
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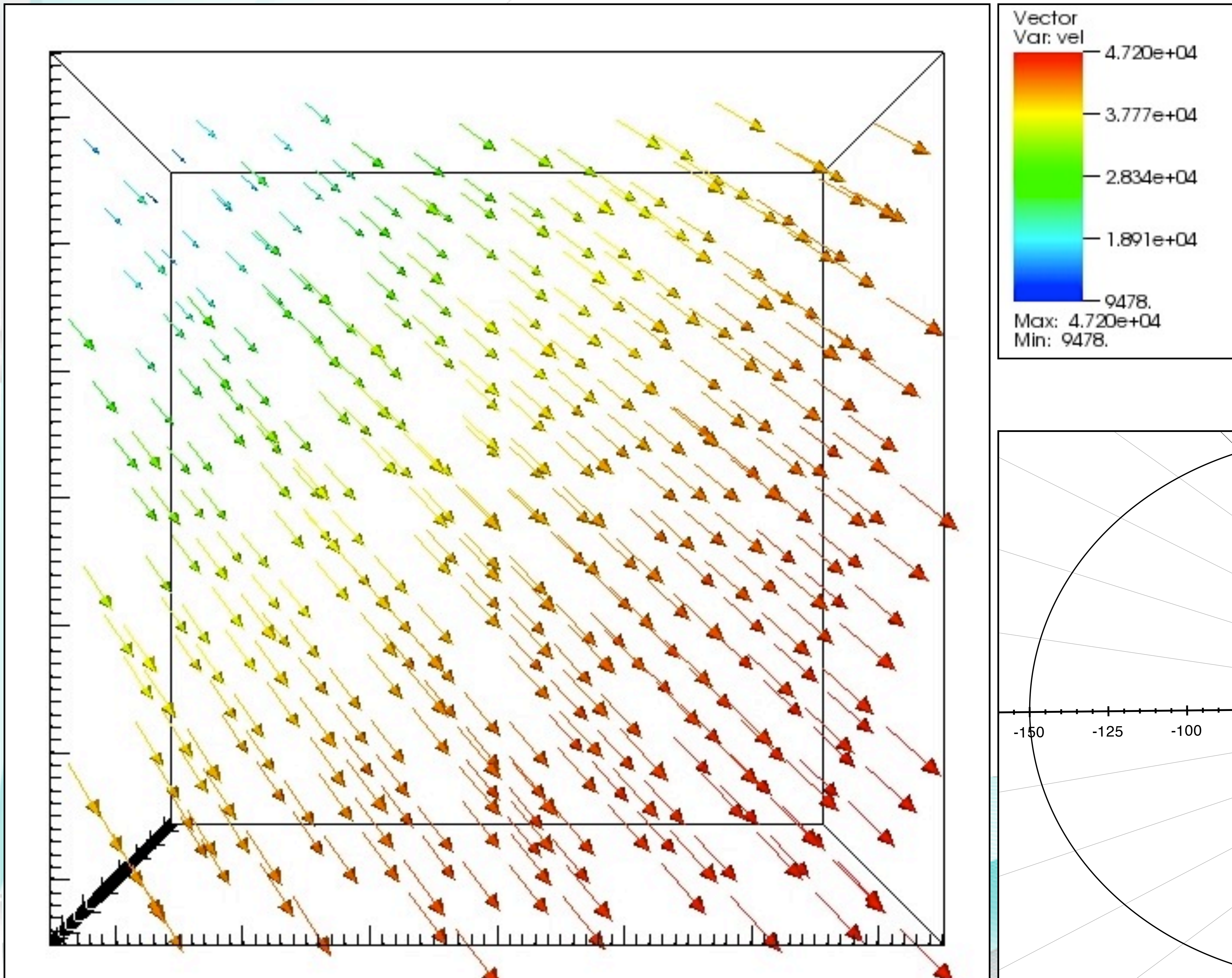
-25
0
25
50
-25
1,25π
1,75π
-50

Tidal Field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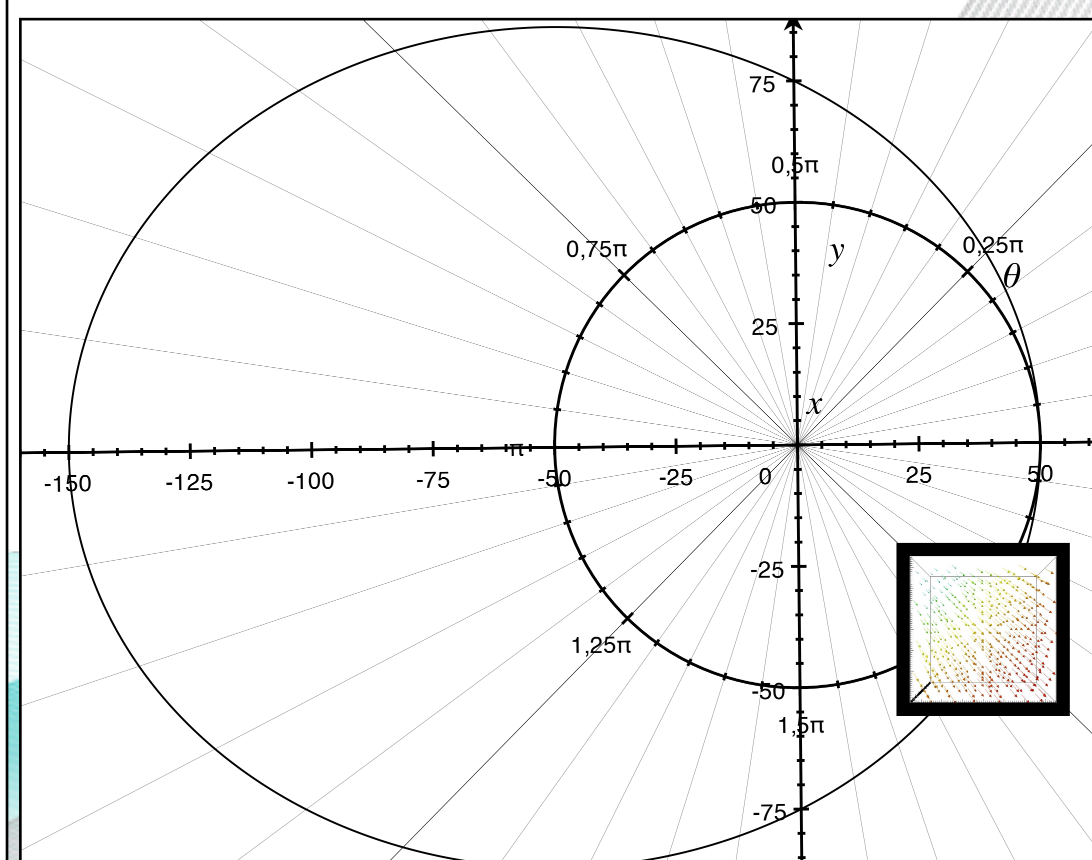
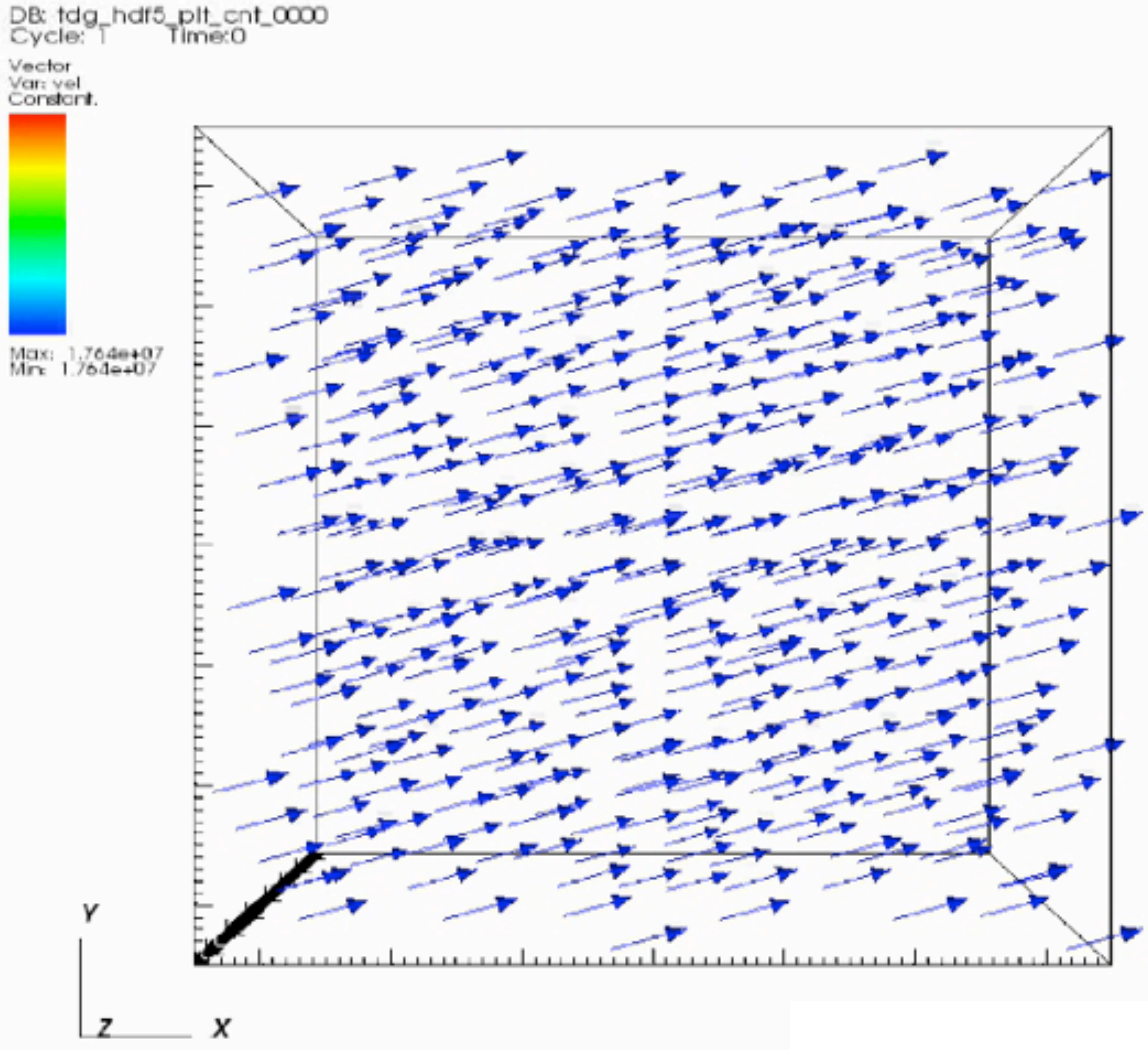
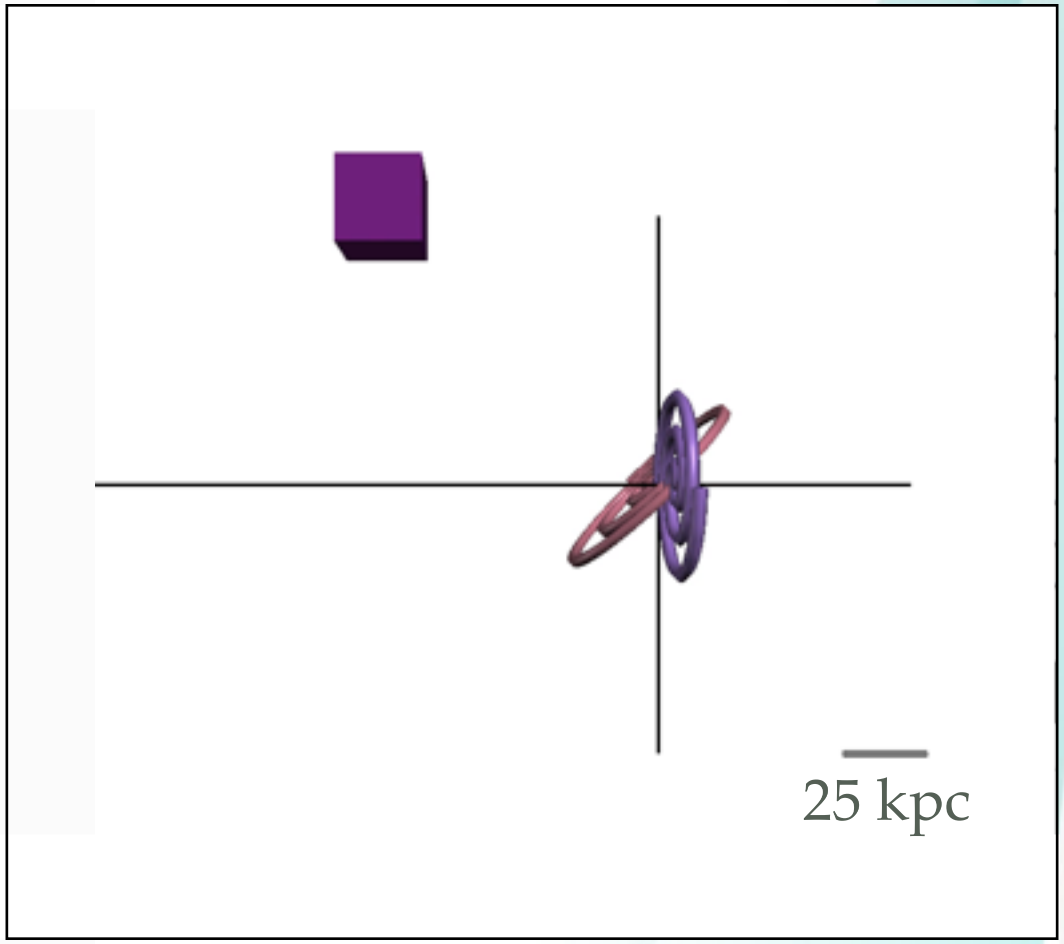

75
0,5π
50
0,75π
y
0,25π
θ
25
x
π
-150
-125
-100
-75
-50
-25
0
25
50
-25
1,25π
-50
1,5π
-75

Tidal Field + Wind





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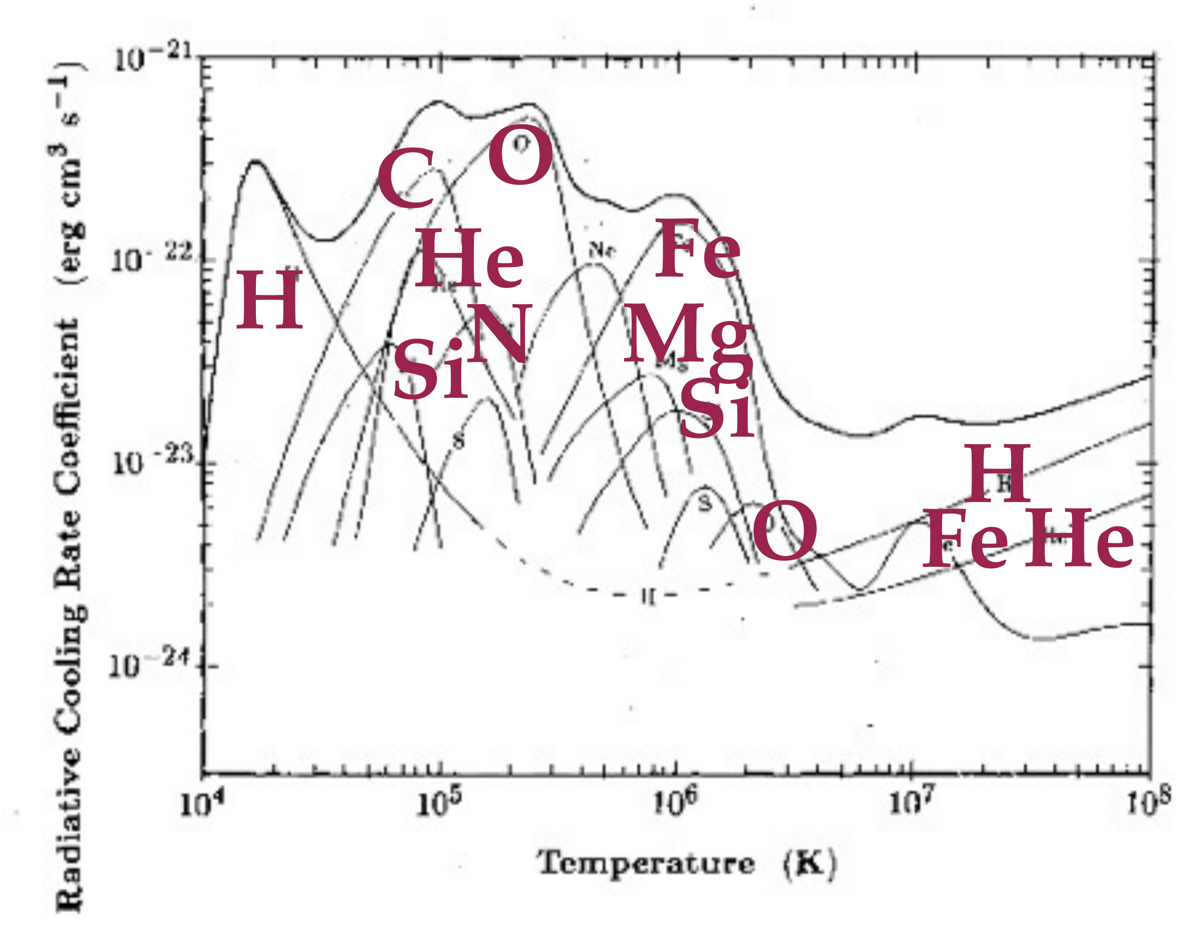
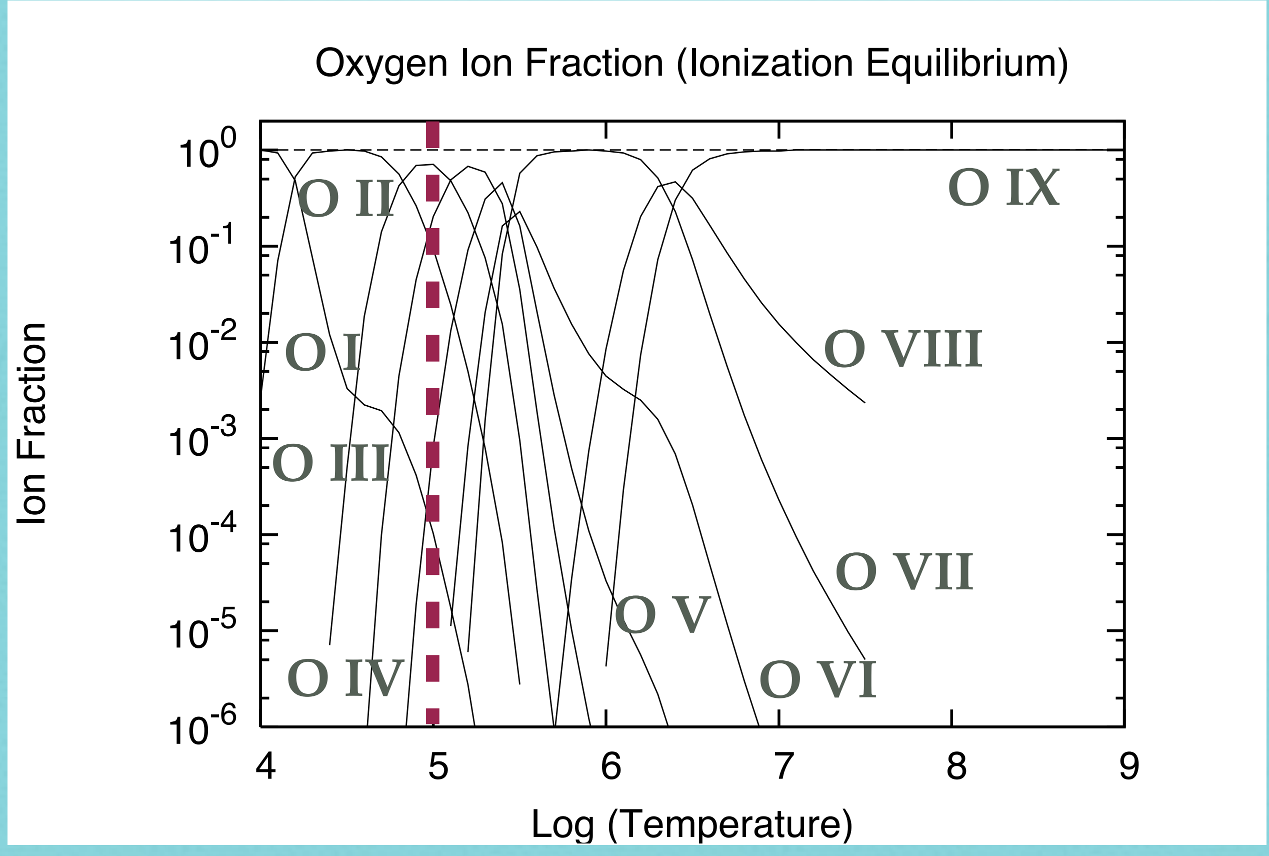
The Chemistry Module

- Radiative cooling
- Star Formation (IMF)
- Stellar Feedback
  - Stellar Wind Feedback
  - Supernova Feedback (incl. metal release)

Radiative Cooling + Ionization

Included elements: H, He, C, N, O, Mg, Si, Fe





T < 10^4 K: Dalgarno & McCray (1972)

T > 10^4 K: Boehringer & Hensler (1989)

Data from: Arnaud & Rothenflug (1985)

Self Regulated Star Formation

		Star Formation		Stellar Feedback	
$\frac{dg}{dt}$	$=$	$-$ $\Psi(g,T)$	$+$	η	$\frac{s}{\tau}$
$\frac{ds}{dt}$	$=$	ξ $\Psi(g,T)$	$-$		$\frac{s}{\tau}$
$\frac{dr}{dt}$	$=$	$(1-\xi)$ $\Psi(g,T)$	$+$	$(1-\eta)$	$\frac{s}{\tau}$

with stellar birth function:

$$\Psi(g,T) = C_n g^n e^{-T/T_s}$$

η ... fraction of gas ejected by SNe
ξ ... mass fraction of newly formed massive stars

Köppen, Theis & Hensler (1995)

Heating of the ISM by one massive star during its lifetime:

$$\left.\frac{\partial e_{th}}{\partial t}\right|_{OB} = \frac{1}{2}\dot{m}v_\infty^2 + \eta_{Ly}L_{Ly}(m)$$

stellar wind + radiation

with:

$$L_{Ly}(m) = 10^{40}\left(\frac{m}{M_\odot}\right)^6 \text{ photons s}^{-1}\text{ star}^{-1}$$

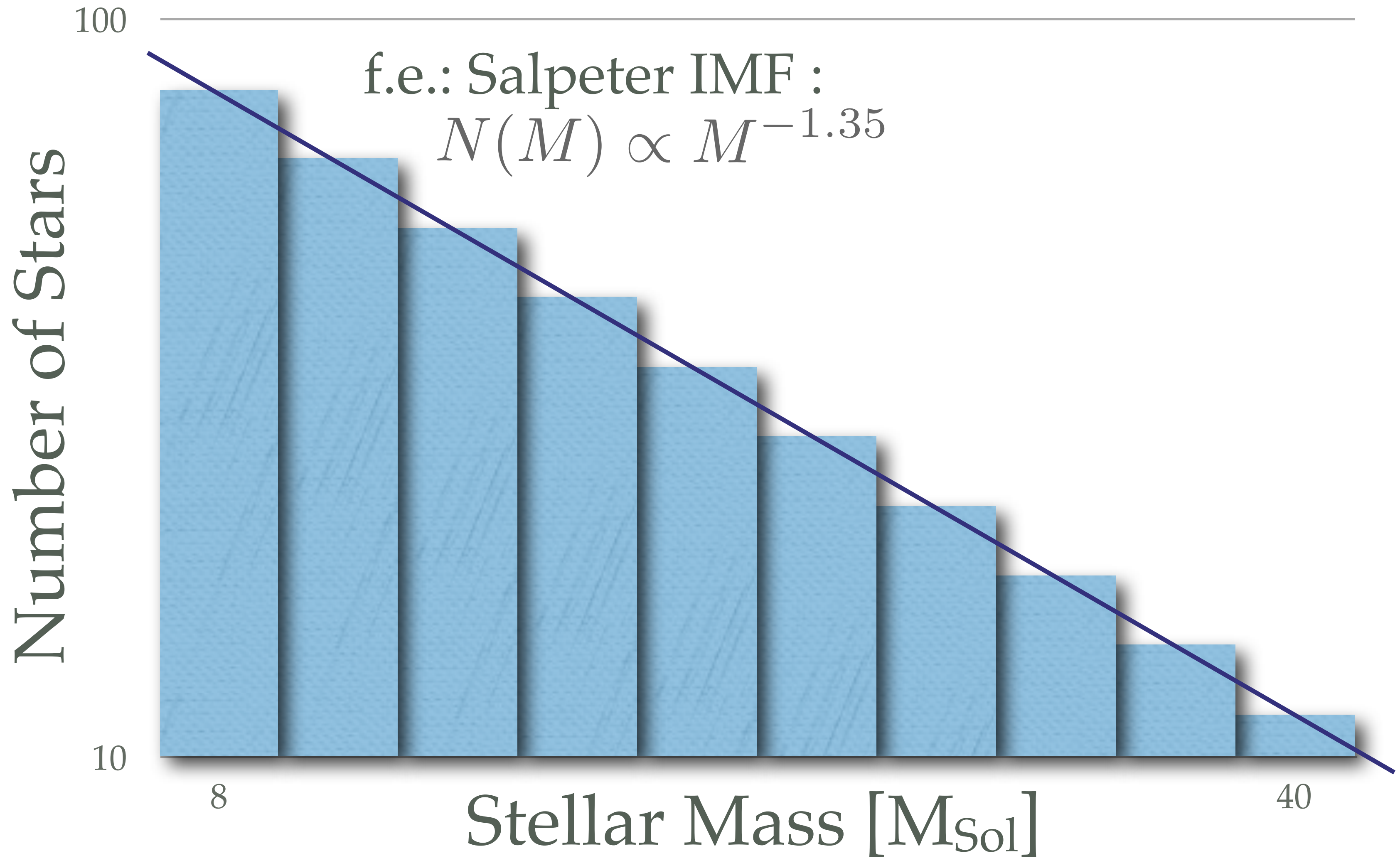
$$\dot{m} = -10^{-15}\left(\frac{Z}{Z_\odot}\right)^{0.5}\left(\frac{L}{L_\odot}\right)^{1.6} \mathrm{M_\odot\,yr^{-1}}$$

$$v_\infty = 3\cdot 10^3\left(\frac{m}{M_\odot}\right)^{0.15}\left(\frac{Z}{Z_\odot}\right)^{0.08} \text{km s}^{-1}$$

Theis, Burkert & Hensler (1992)

Stellar Feedback I - Energy

Maeder (1989): $\tau(m) = 1.1 \times 10^8 \left(\frac{m}{M_\odot}\right)^{-0.75} \text{yr}$



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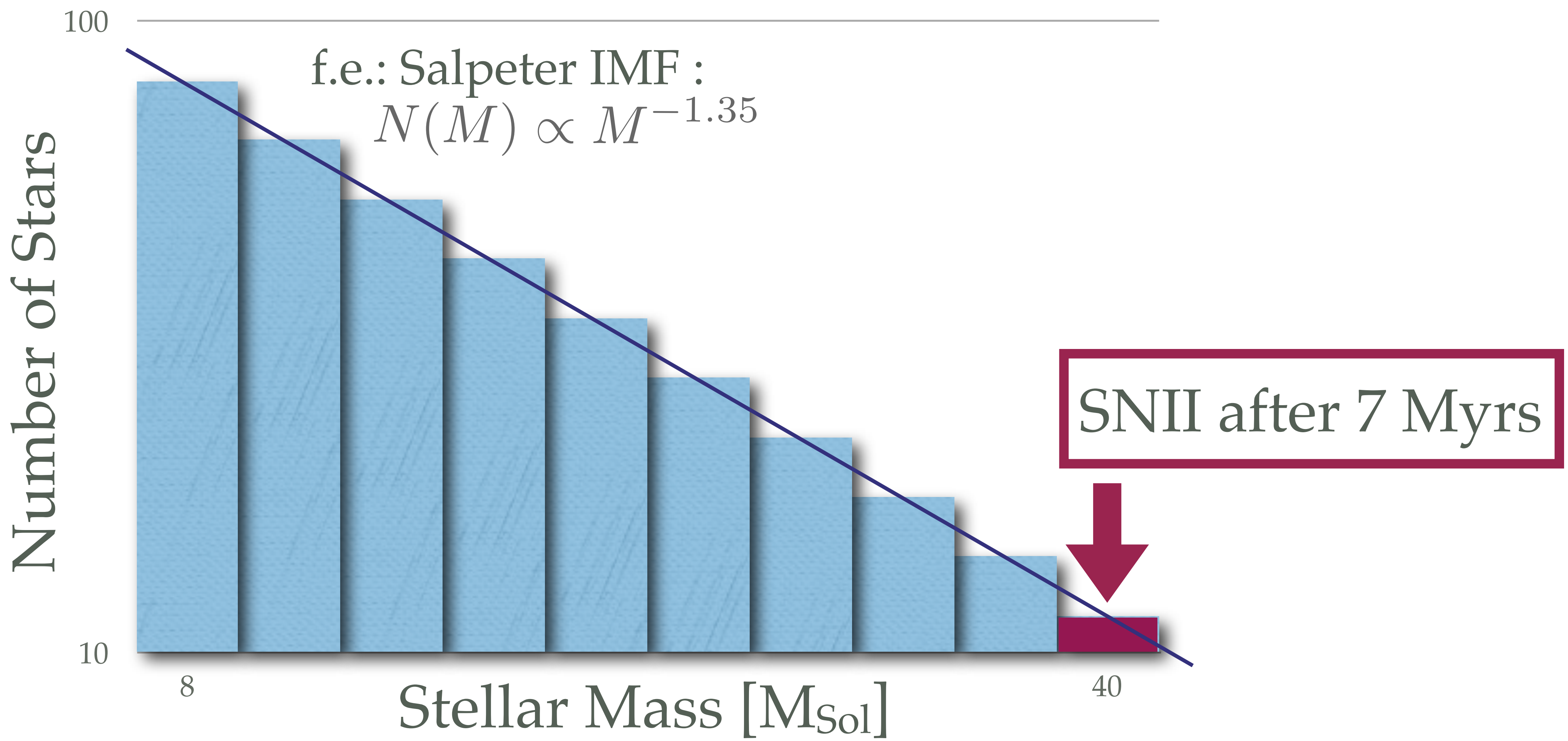

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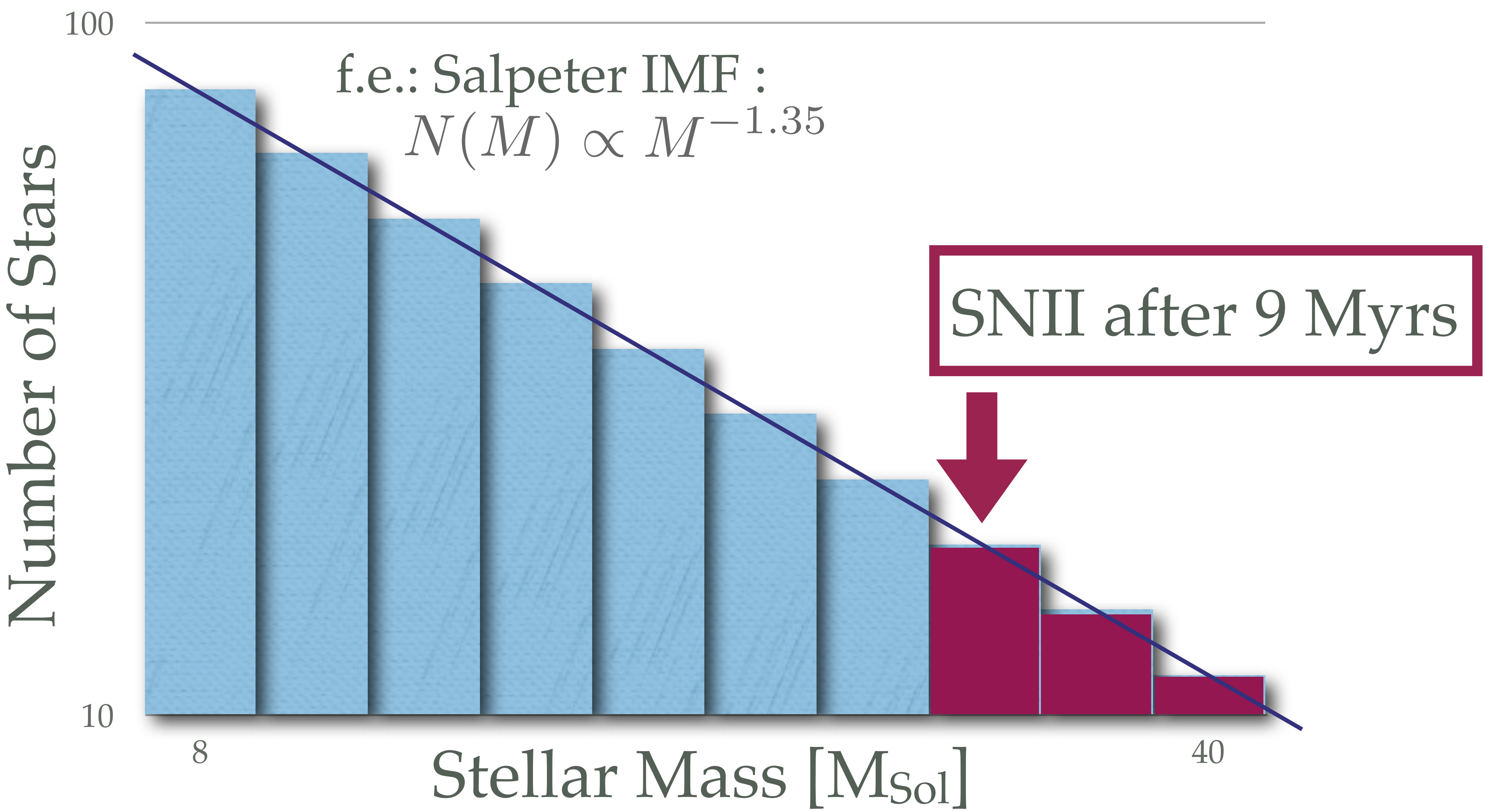


SN Feedback - Overcooling

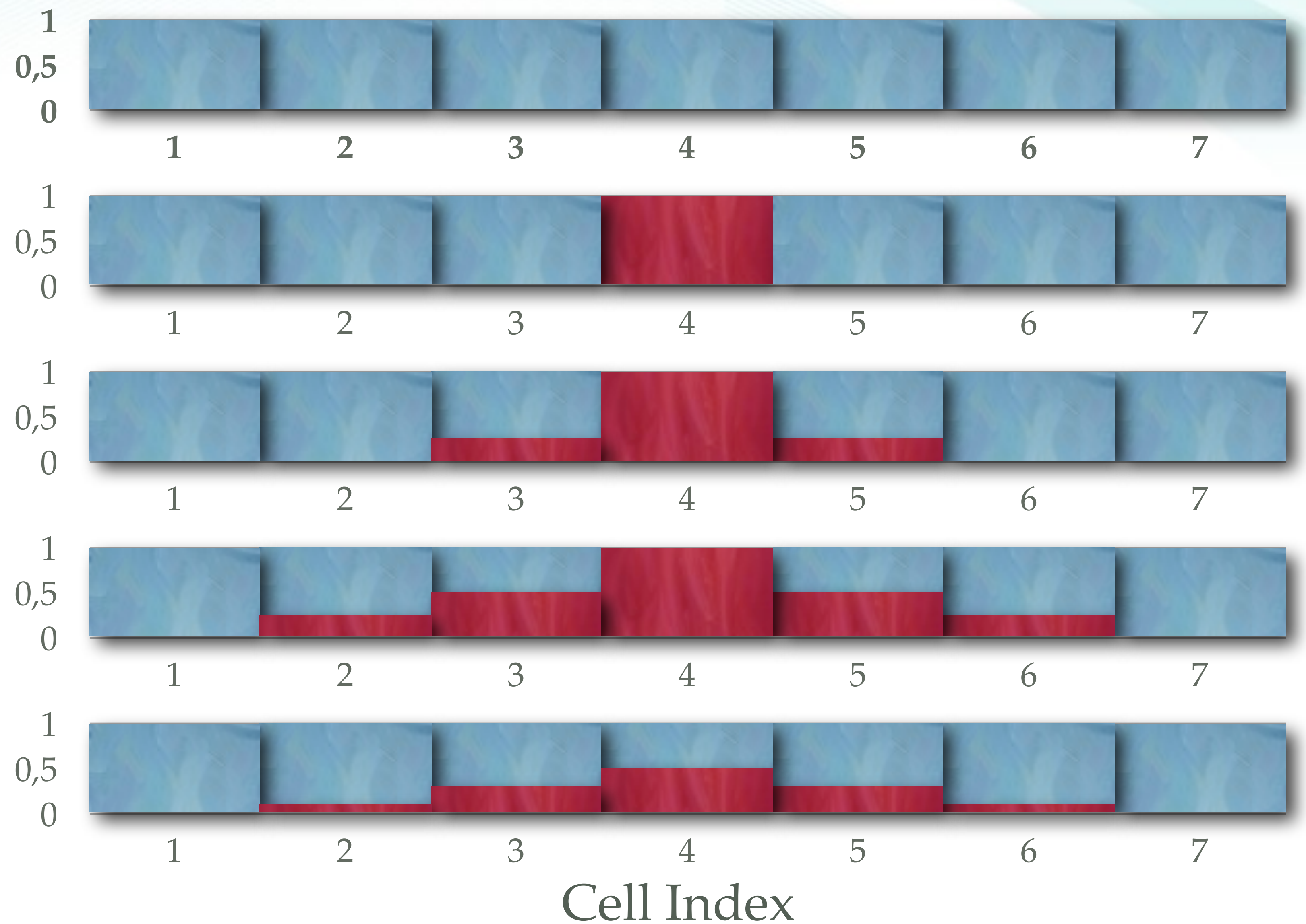
1. Stars are formed but no SN yet

2. SN explosion in cell #4

3. + 4. SN material is advected (still SNe in #4)

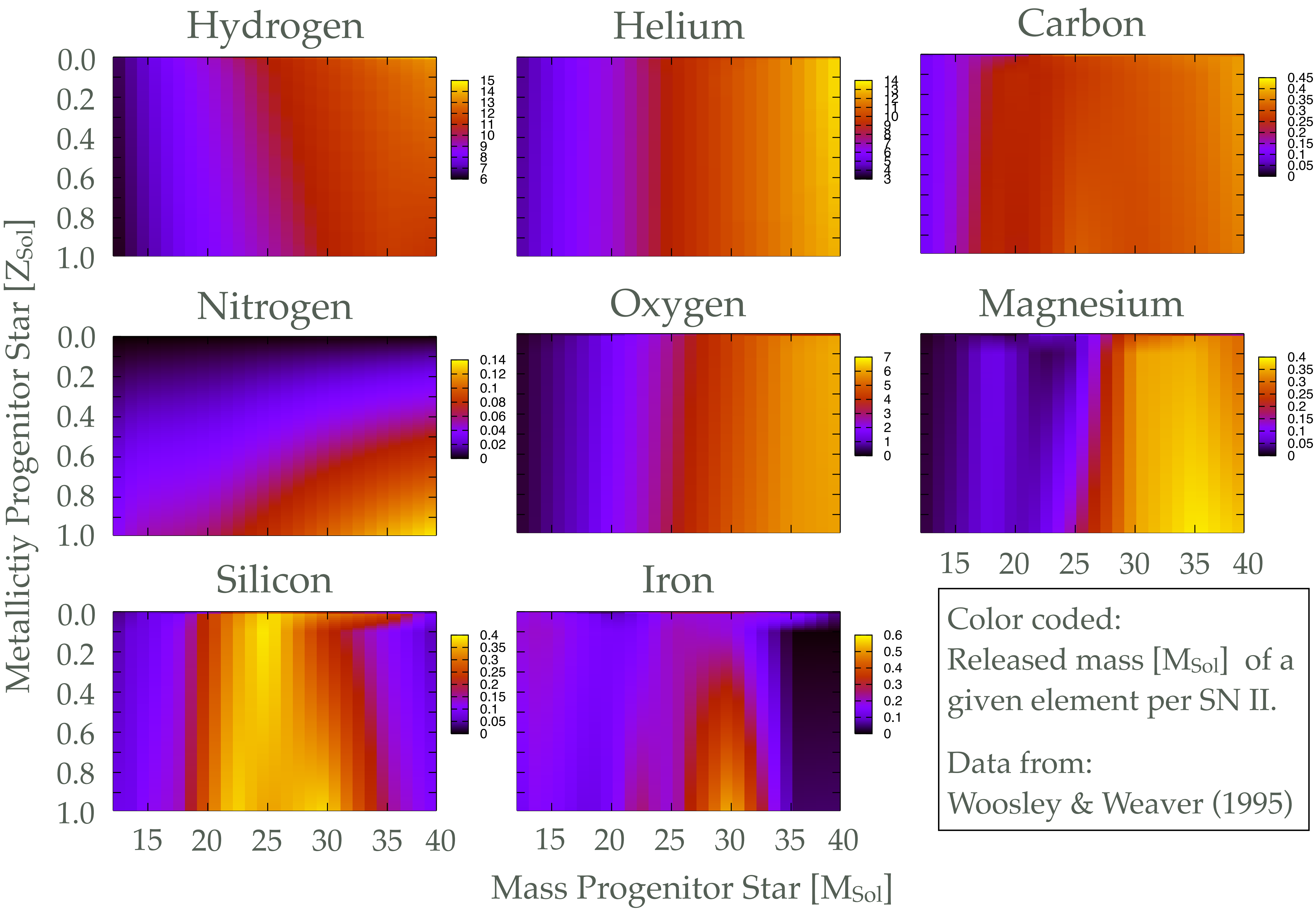
5. Fraction of SN material is decreasing with time:

$$\frac{d\,\mathrm{snwi}}{d\,t} = \frac{\mathrm{snwi}}{t_w}$$



Cooling is only applied to the non-SN material.

Stellar Feedback II - Chemistry



Color coded:
Released mass [MSol] of a given element per SN II.

Data from:
Woosley & Weaver (1995)

Results

Work in Progress!

First high resolution runs:

Simulation parameter:

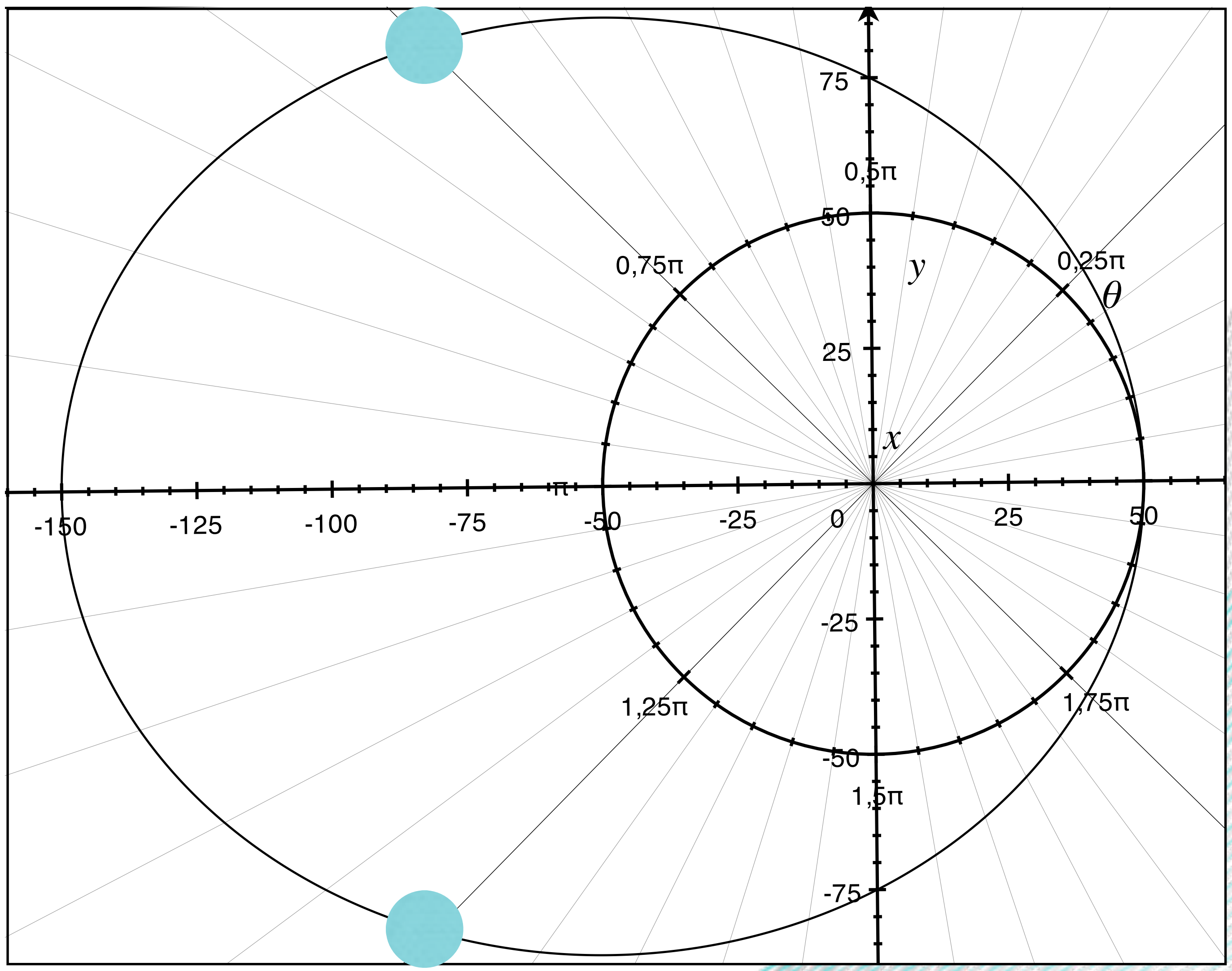
$$r_{min} = 50\,\mathrm{kpc}$$
$$ecc = 0.5$$
$$M_{ext} = 10^{12}\,M_\odot$$
$$\tau_w = 3\,\mathrm{Myrs}$$

Effective resolution:

$$\Delta x = 75\,\mathrm{pc}$$

Initial gas mass = $1.29 \cdot 10^8\,M_\odot$

Initial cloud radius = $4.4\,\mathrm{kpc}$

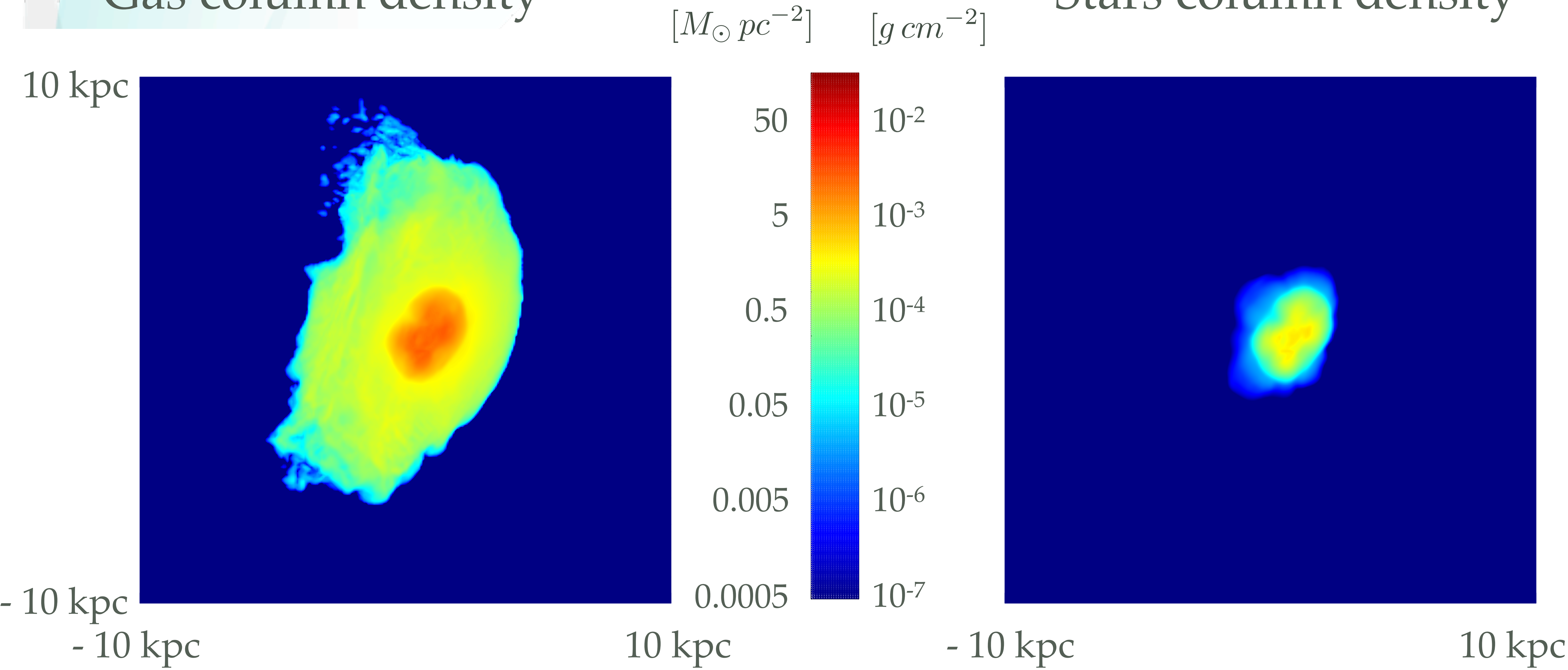


t = 390 Myrs

Initial gas mass = $1.29 \cdot 10^8 \, M_\odot$

Gas column density

Stars column density



$M_{Gas} = 1.23 \cdot 10^8 \, M_\odot$

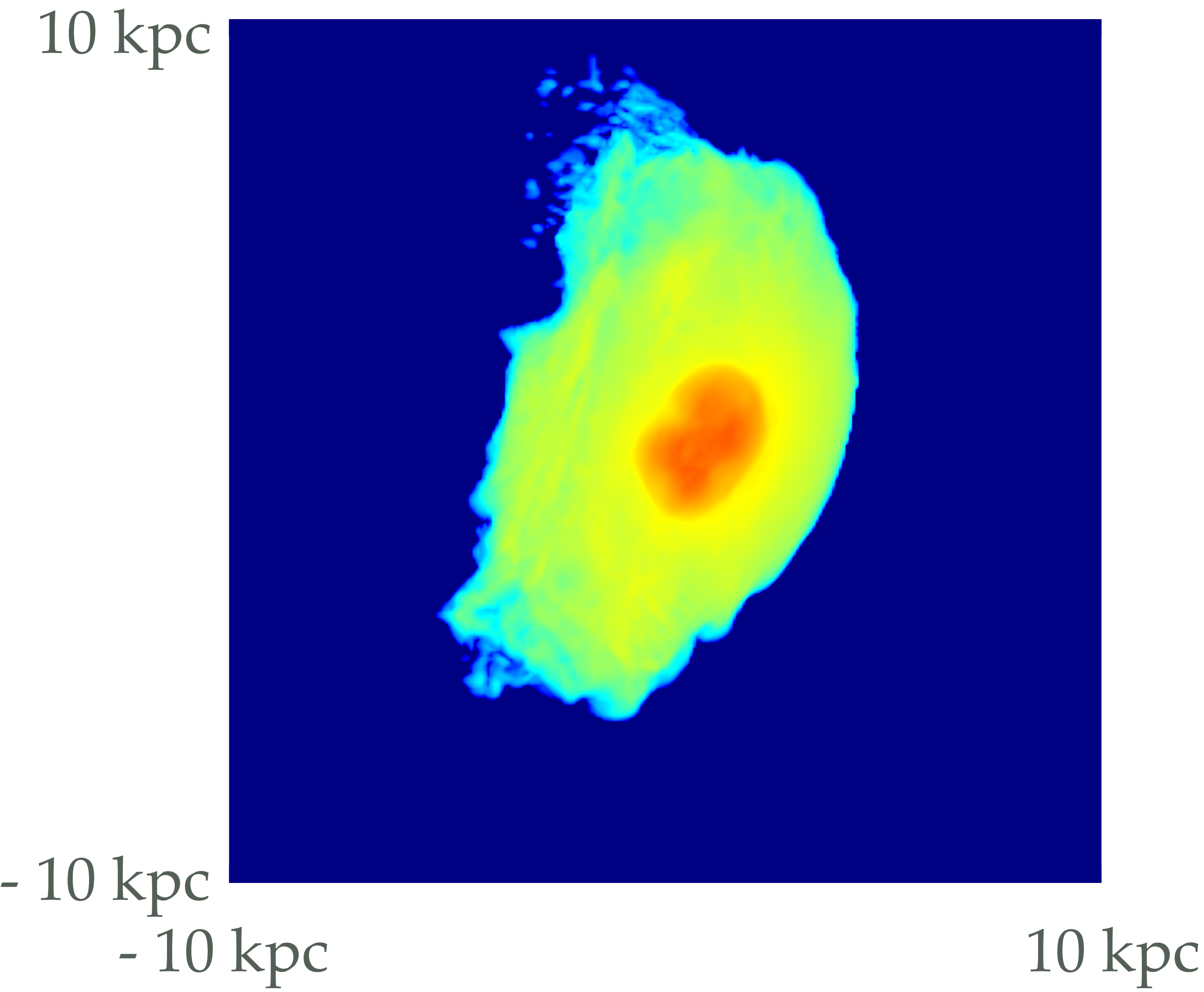
$M_{Stars} = 6.60 \cdot 10^6 \, M_\odot$

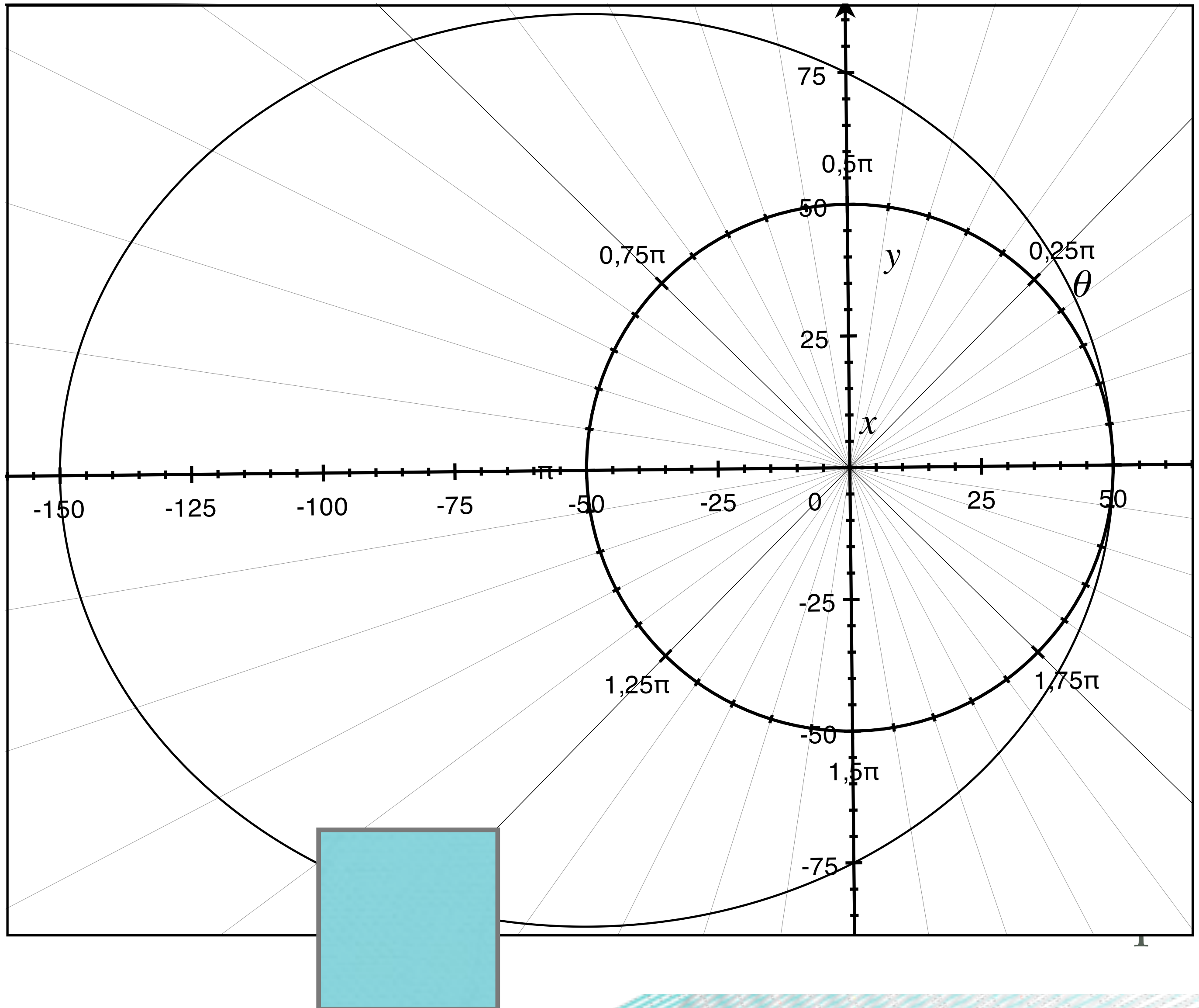
Runtime on 128 processors: 6d 9h 26m

t = 390 Myrs

Initial gas mass: $1.29 \cdot 10^8\, M_\odot$

Gas column density





$M_{Gas} = 1.23 \cdot 10^8\, M_\odot$ $M_{Stars} = 6.60 \cdot 10^6\, M_\odot$

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t = 390 Myrs

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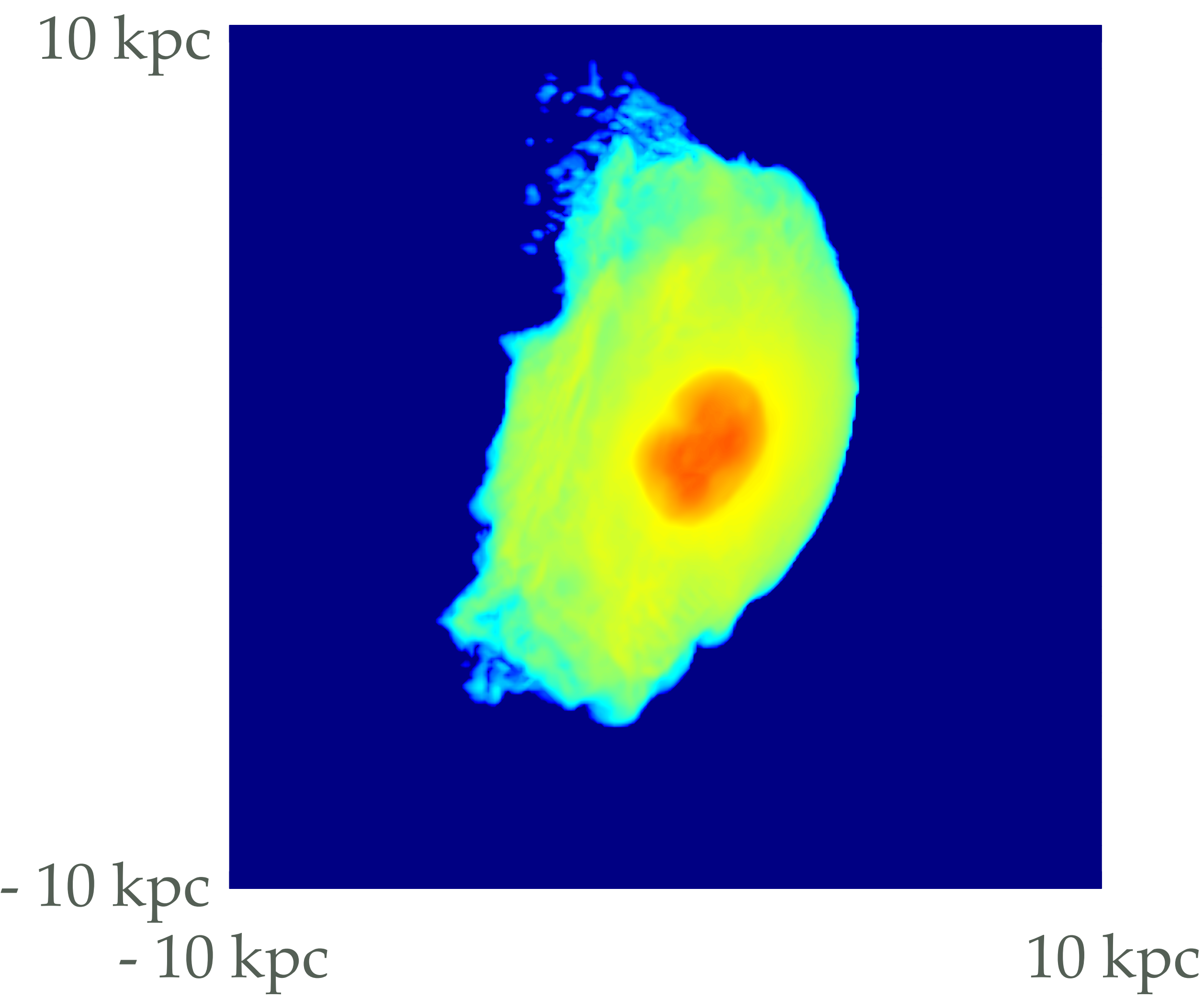
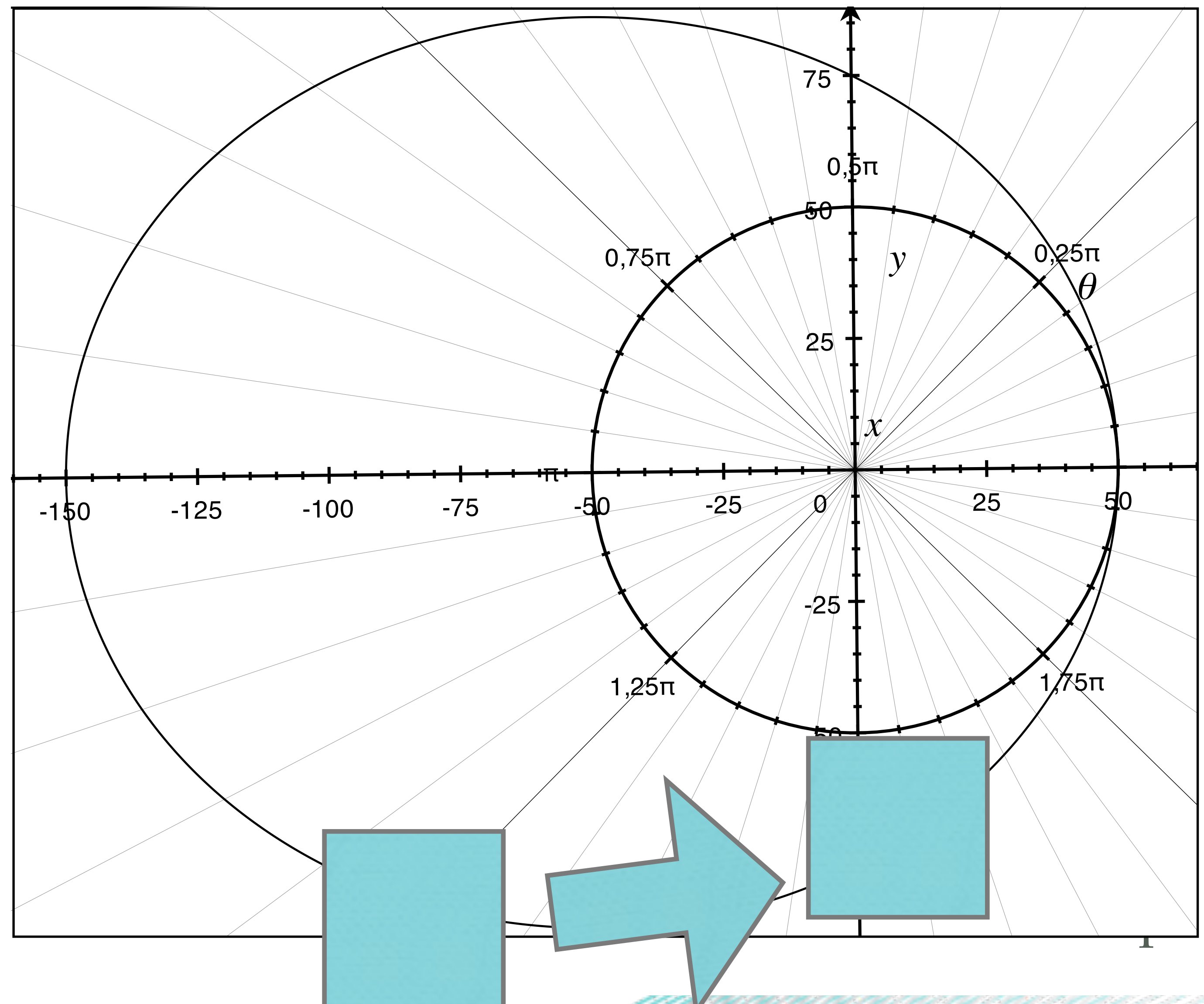
Gas column density

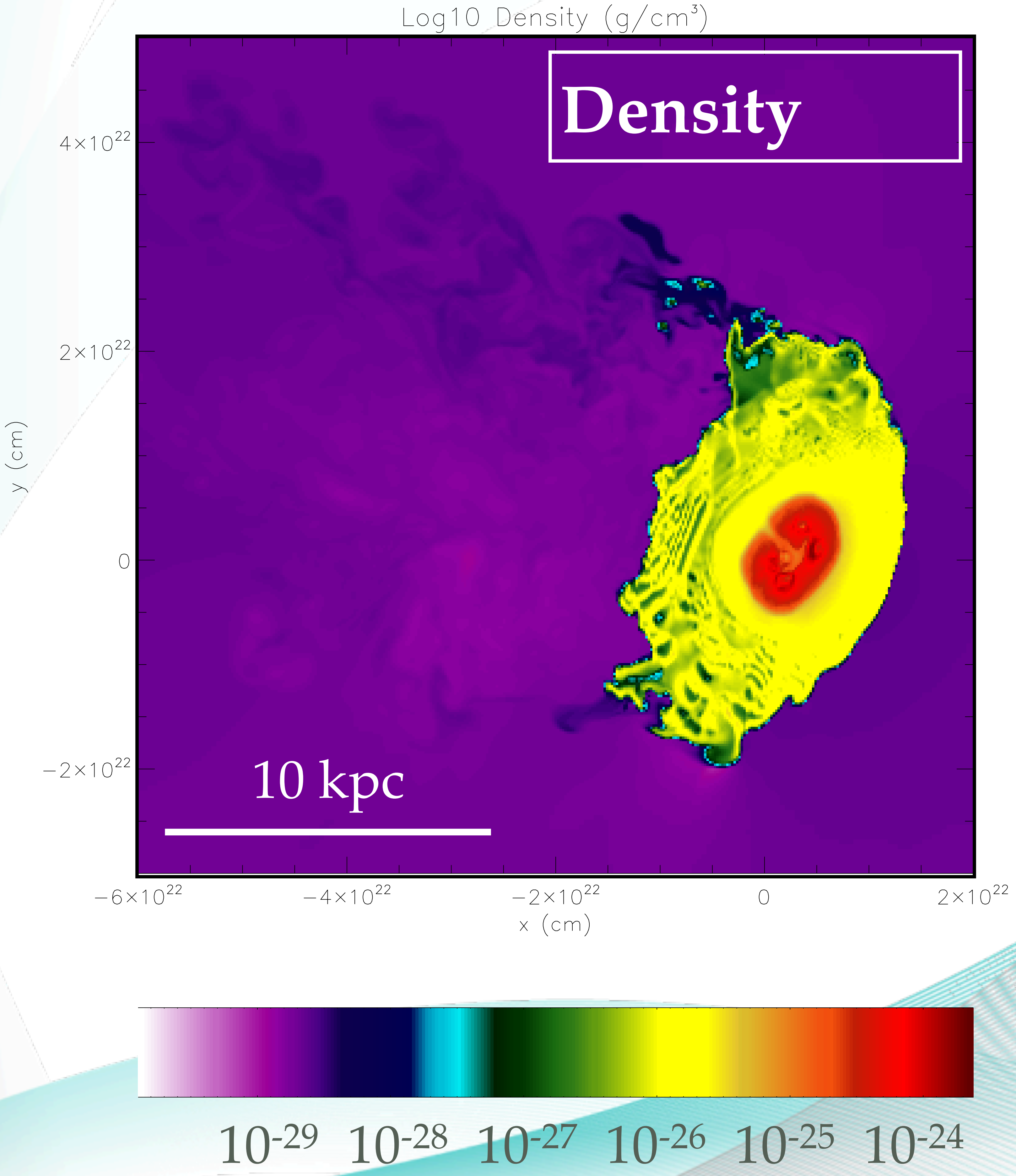




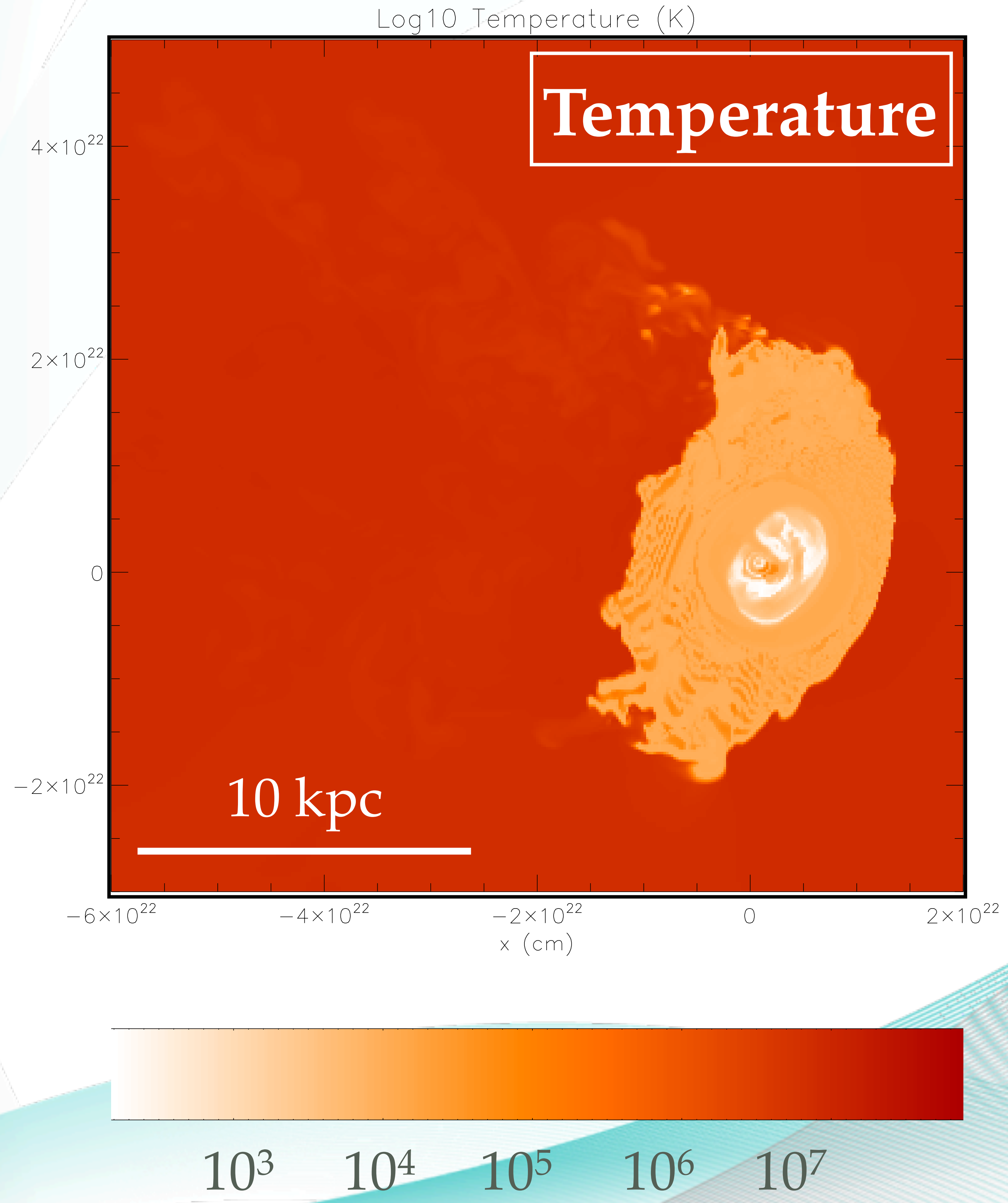
$M_{Gas} \quad = \quad 1.23 \cdot 10^8 \, M_\odot$

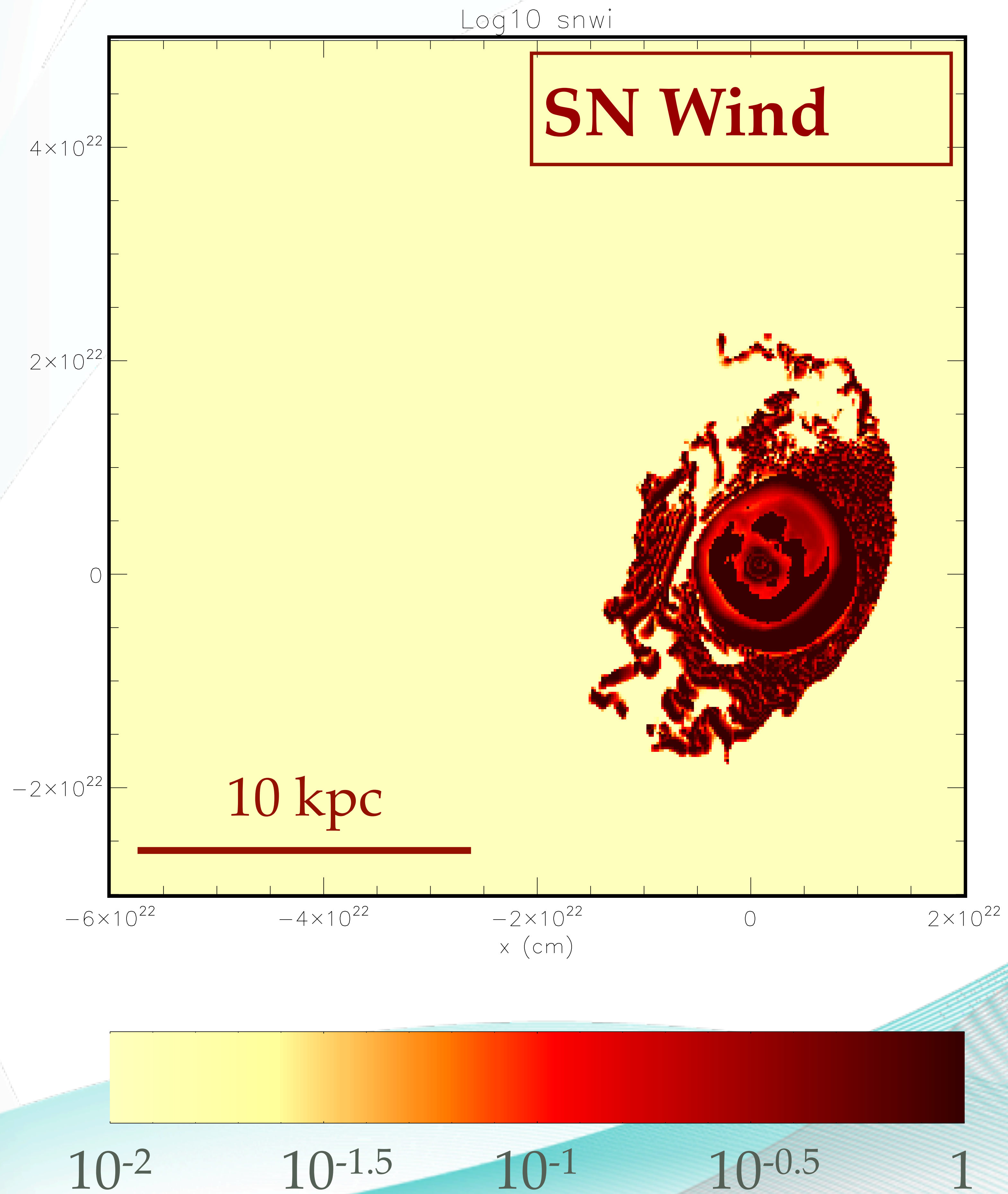
$M_{Stars} \quad = \quad 6.60 \cdot 10^6 \, M_\odot$

Runtime on 128 processors: 6d 9h 26m



Log10 Density (g/cm³)
Density
10 kpc
4×10²²
2×10²²
0
−2×10²²
y (cm)
−6×10²²
−4×10²²
−2×10²²
0
2×10²²
x (cm)
10⁻²⁹ 10⁻²⁸ 10⁻²⁷ 10⁻²⁶ 10⁻²⁵ 10⁻²⁴


Log10 Temperature (K)
Temperature
4×10^{22}
2×10^{22}
0
-2×10^{22}
y (cm)
10 kpc
-6×10^{22}
-4×10^{22}
-2×10^{22}
0
2×10^{22}
x (cm)
10^3 10^4 10^5 10^6 10^7



Log10 snwi
SN Wind
10 kpc
4×10^22
2×10^22
0
−2×10^22
y (cm)
−6×10^22
−4×10^22
−2×10^22
0
2×10^22
x (cm)
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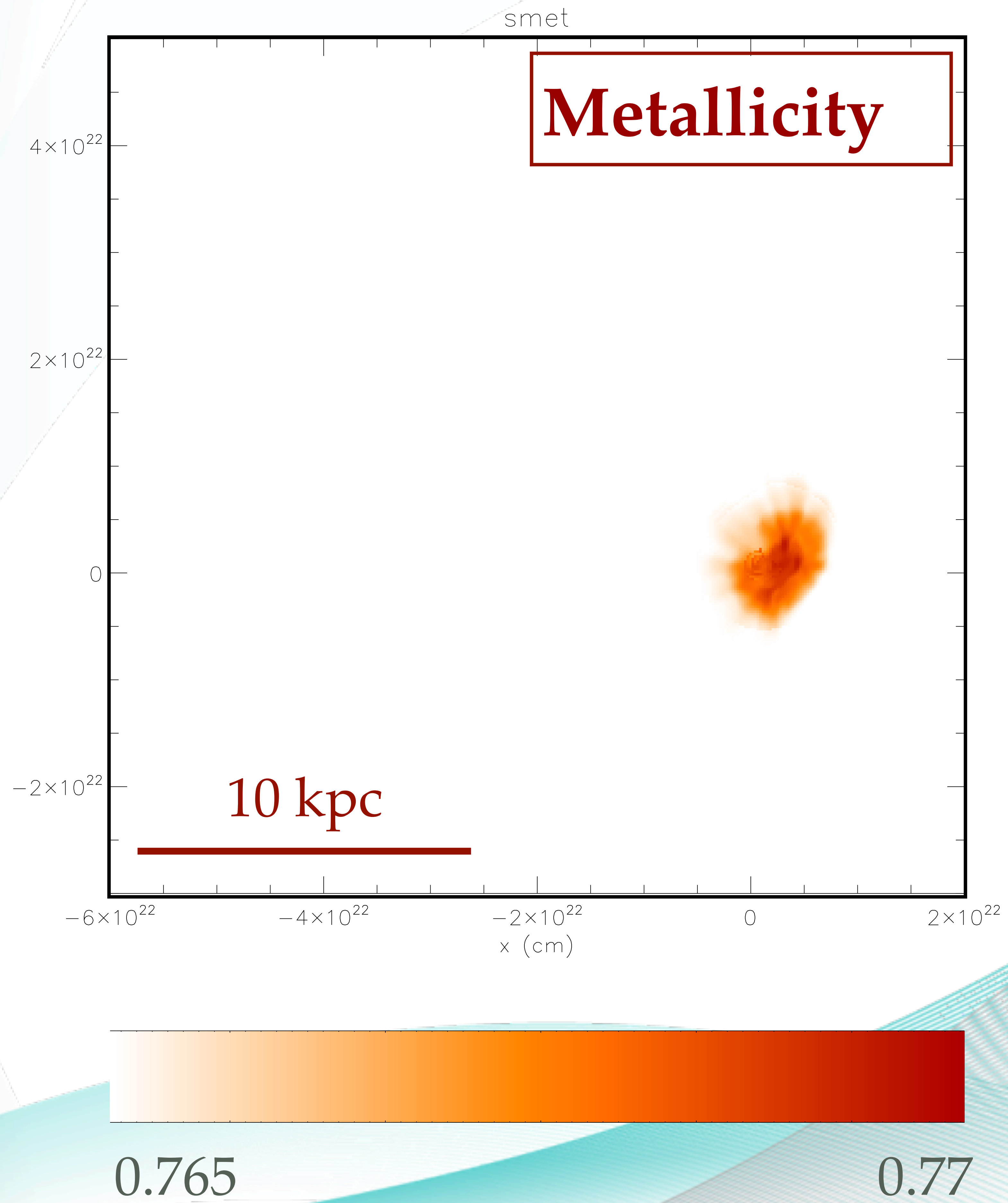
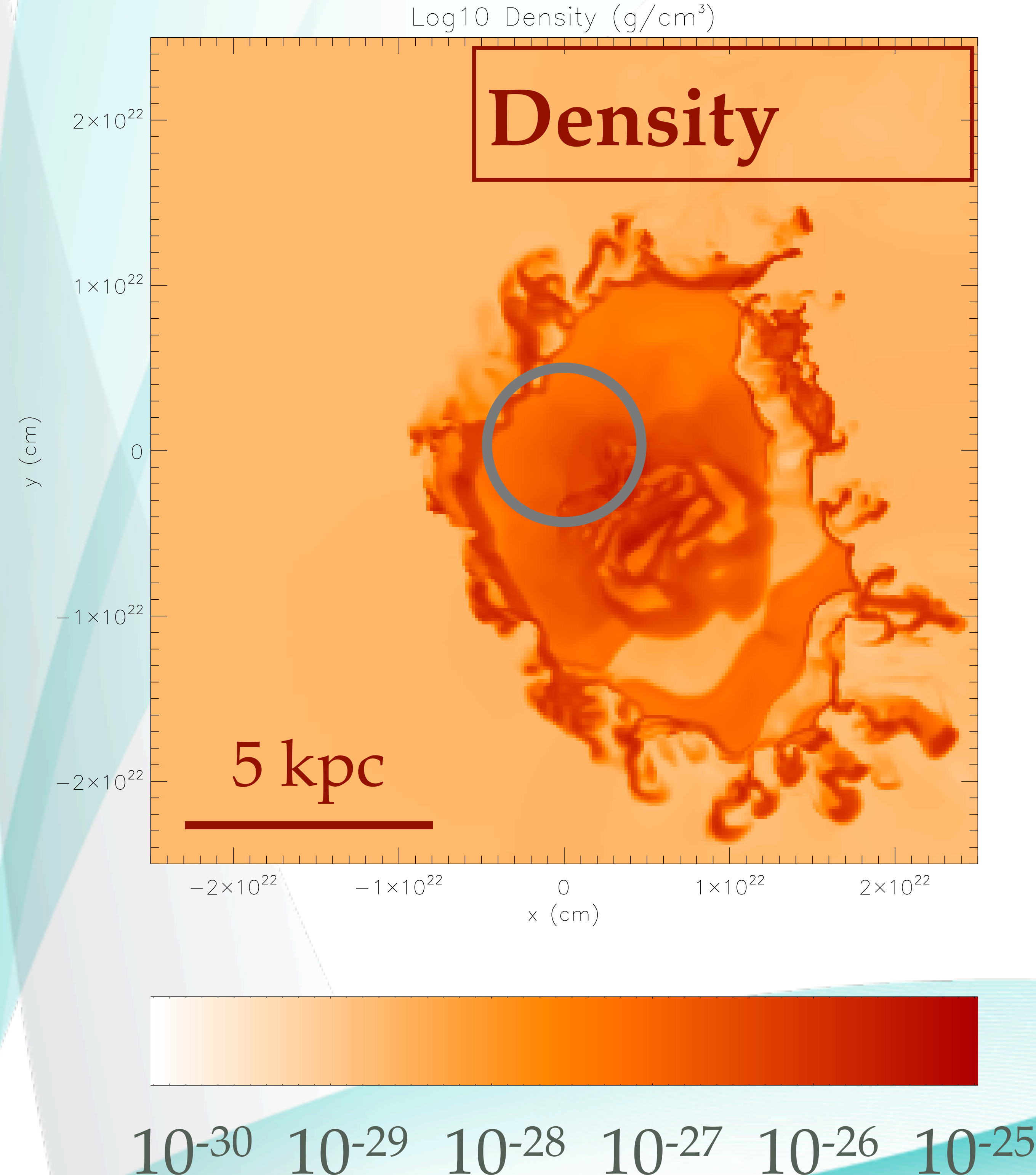
10^-1.5
10^-1
10^-0.5
1


smet
Metallicity
4×10^22
2×10^22
0
−2×10^22
y (cm)
10 kpc
−6×10^22
−4×10^22
−2×10^22
0
2×10^22
x (cm)
0.765
0.77

Low Mass Run



Effective resolution:
$\Delta x = 63\,\mathrm{pc}$

Initial gas mass:
$1.6 \cdot 10^7\ M_\odot$

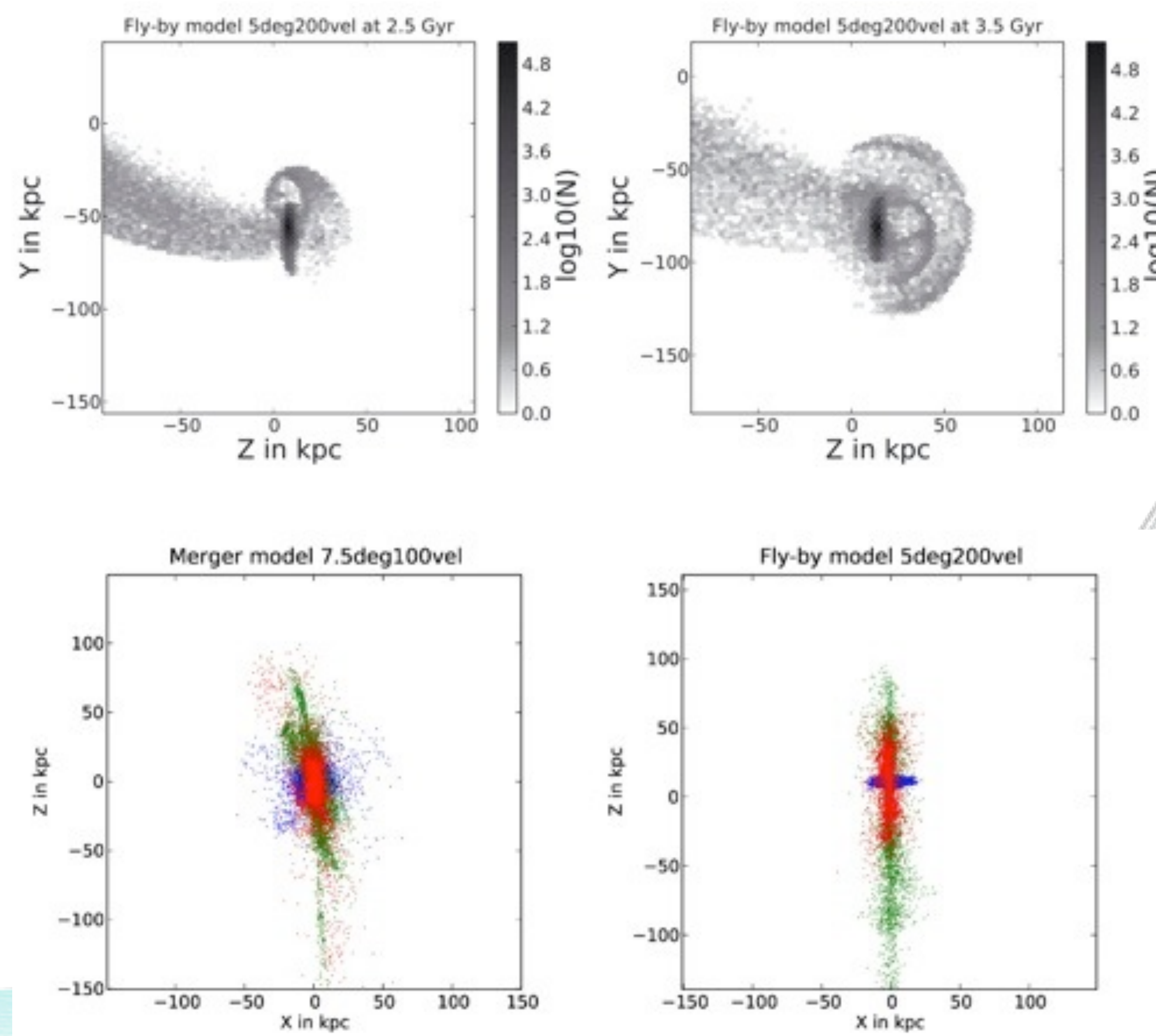
Initial cloud radius:
1.5 kpc

$$\begin{aligned} r_{min} &= 50\,\mathrm{kpc} \\ ecc &= 0.5 \\ M_{ext} &= 10^{12}\ M_\odot \\ \tau_w &= 3\,\mathrm{Myrs} \end{aligned}$$

Outlook

- *Mass flow along the tidal arm*
- *Old stellar population*
- *Include SN I*
- *More realistic gravitational potential*
- *Better initial distribution*
- *Include Stellar Hydrodynamics*

(with N. Mitchell, E. Vorobiev)



Pawlowski, Kroupa & de Boer (2011)

Thank you for your attention!

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