More on Thermohaline Mixing

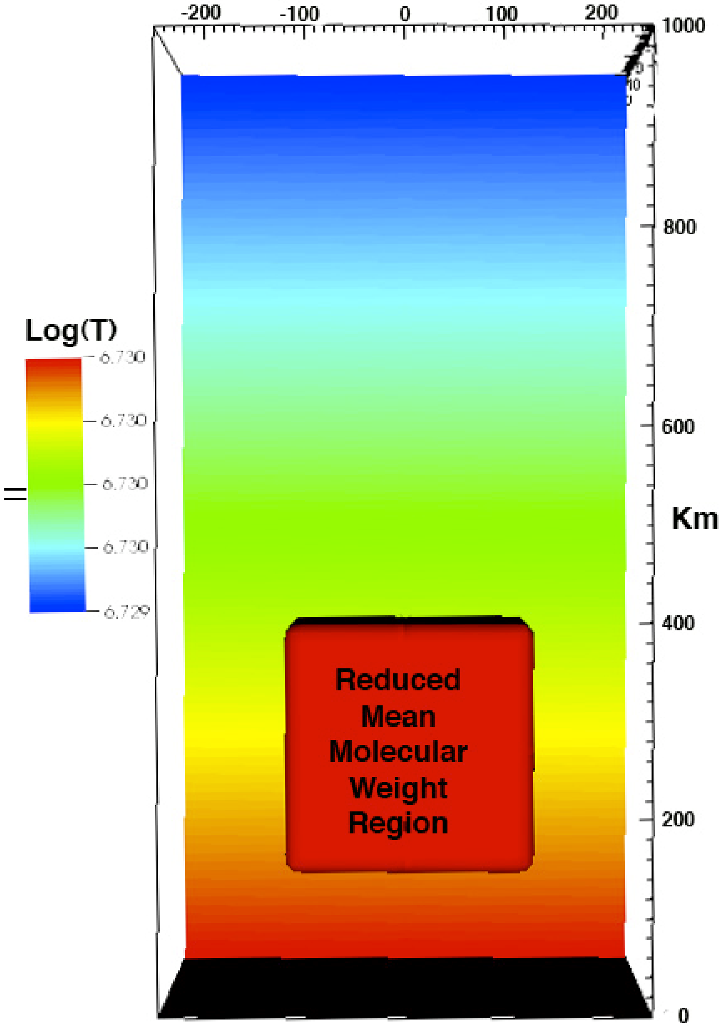
We must understand it from first principles!

That means hydro simulations…

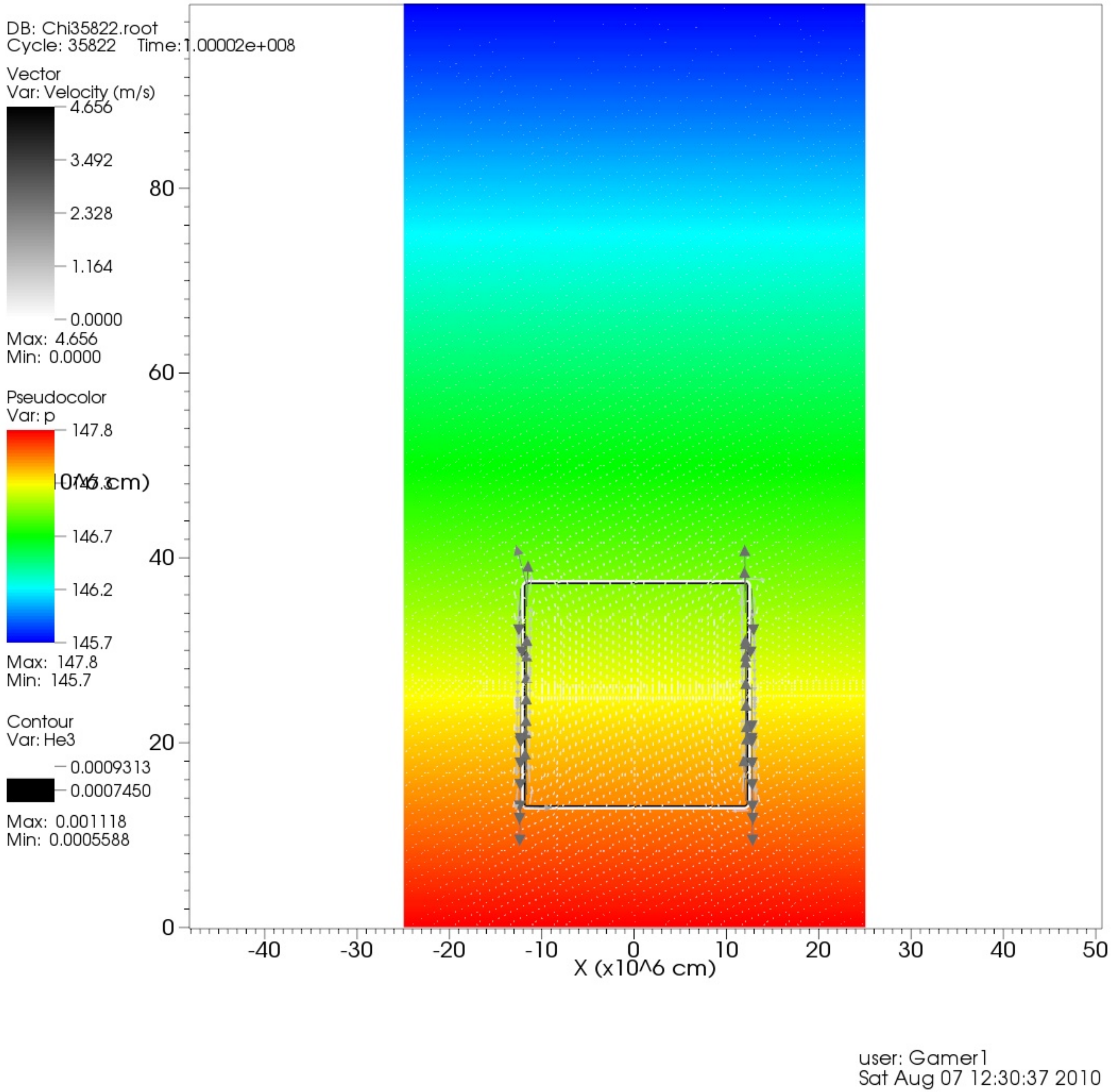
John Lattanzio
David Dearborn
Richard Stancliffe
George Angelou

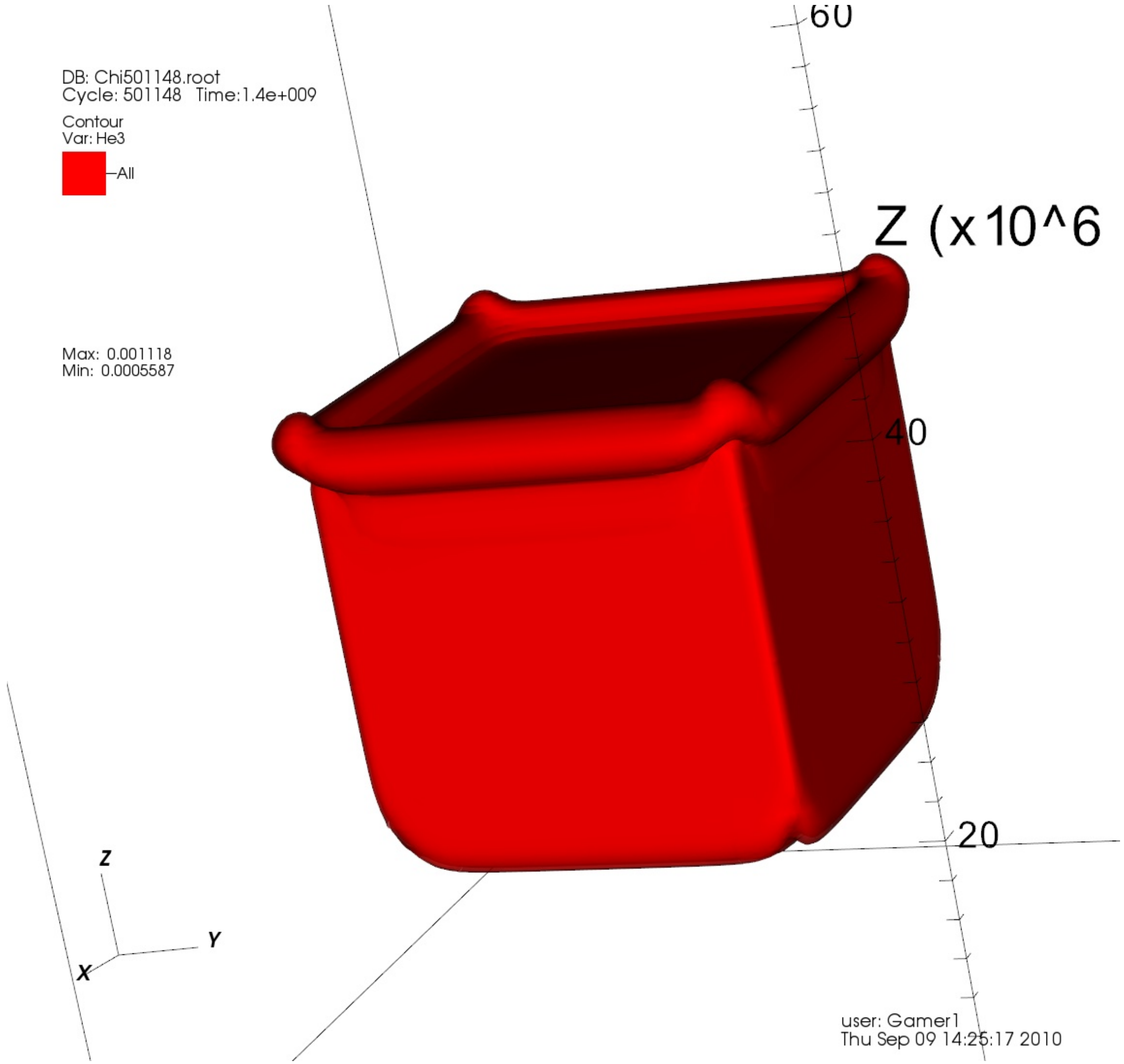
Initial Model

- This was a 1 MSun Z=0.02 model
- He^3 was reduced by a factor of 2
- Cube was 250km x 250km x 250km
- Calculation volume is 500km x 500km x 1000km
- This run has 150 x 150 x 300 = 6,750,000 = 6.75 million zones

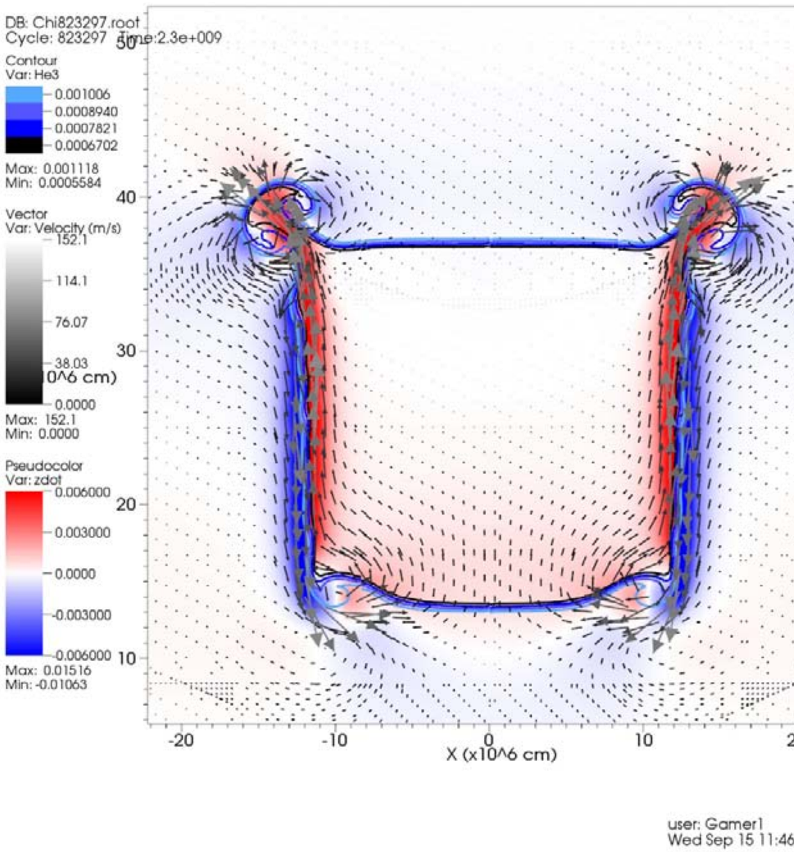


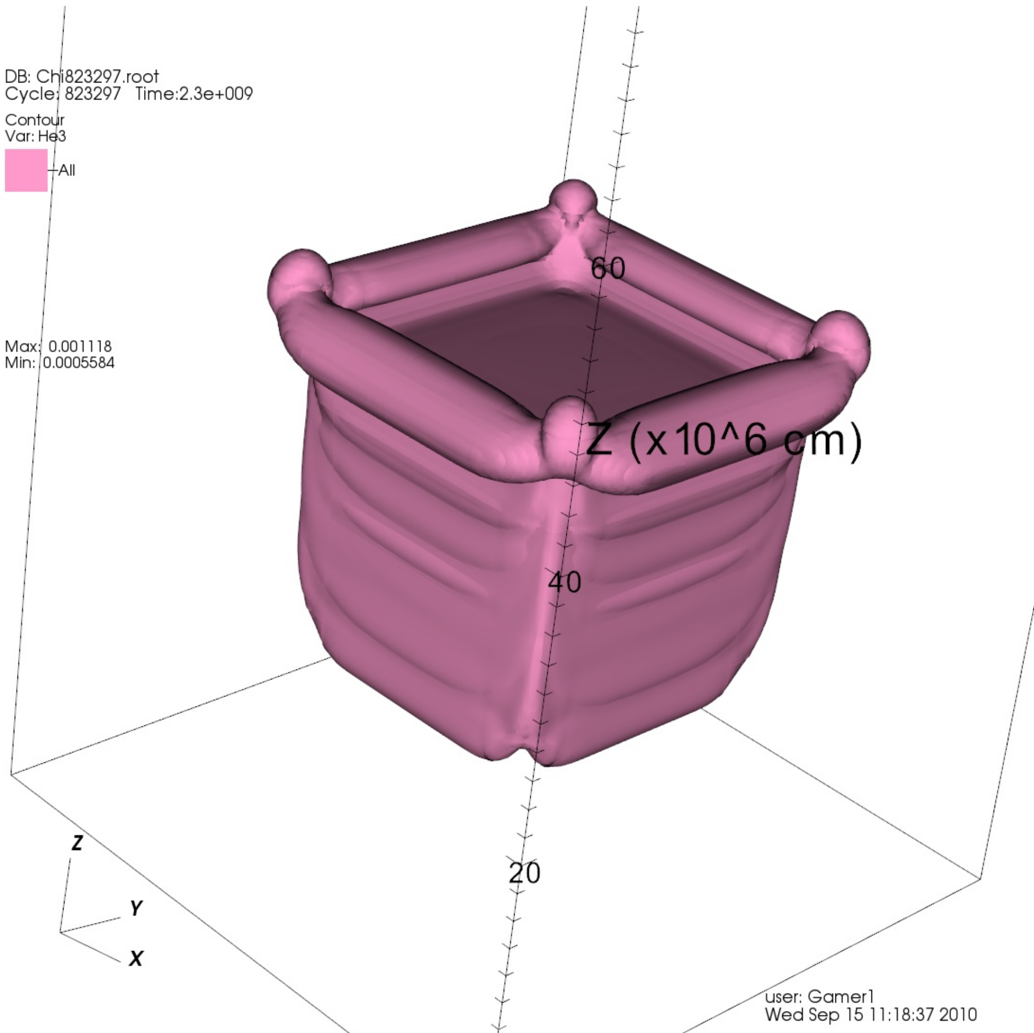
End Run 1
Cycle 35822
t=100 seconds
Pressure



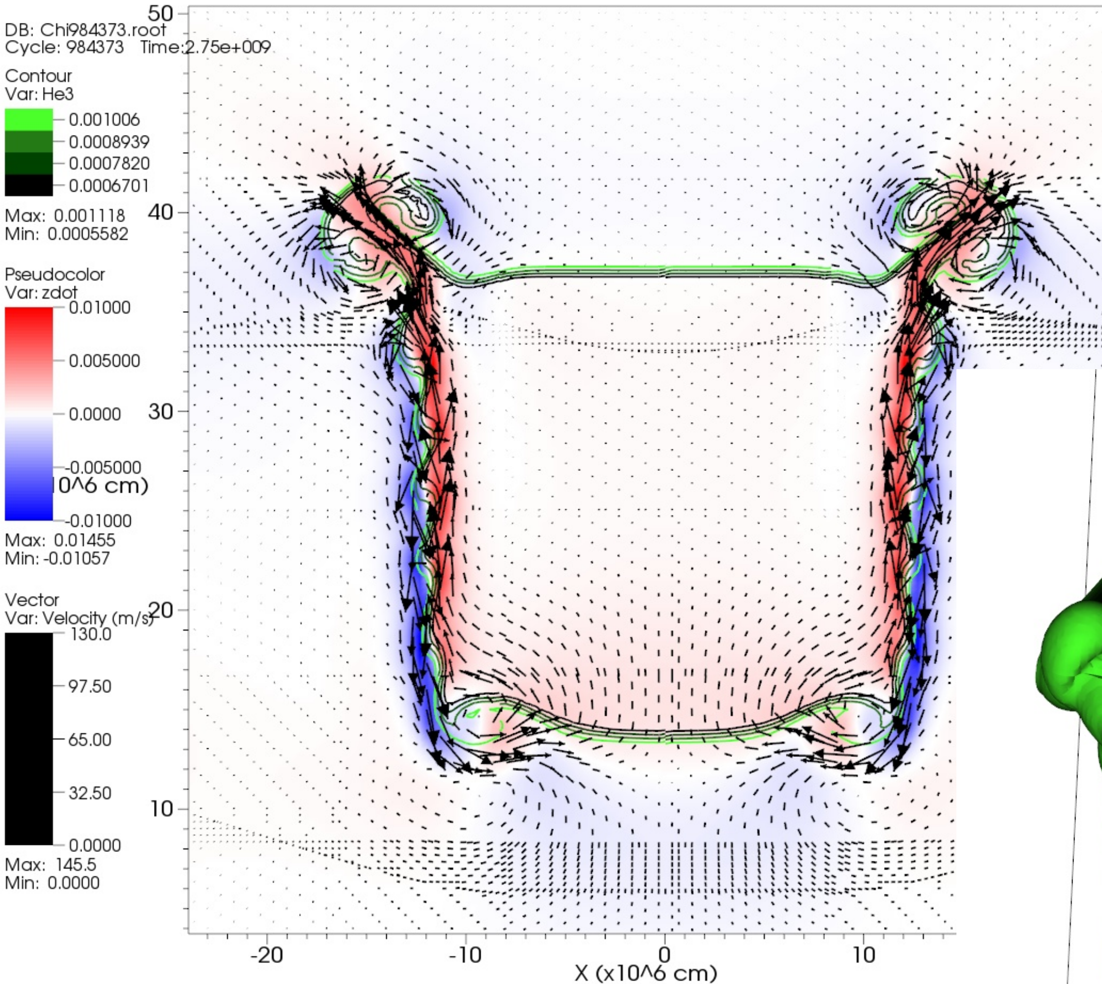

DB: Chi501148.root
Cycle: 501148 Time:1.4e+009
Contour
Var: He3
All
Max: 0.001118
Min: 0.0005587
Z (x10^6
60
40
20
Z
Y
X
user: Gamer1
Thu Sep 09 14:25:17 2010

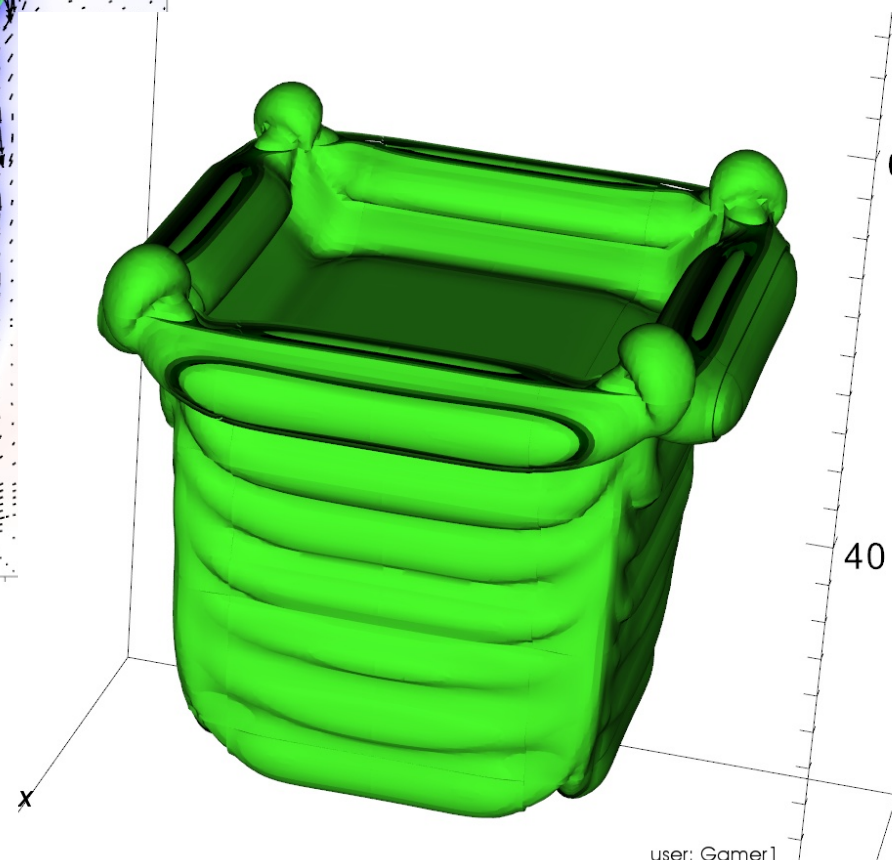
Run 26: XCHI-Cont.o134845



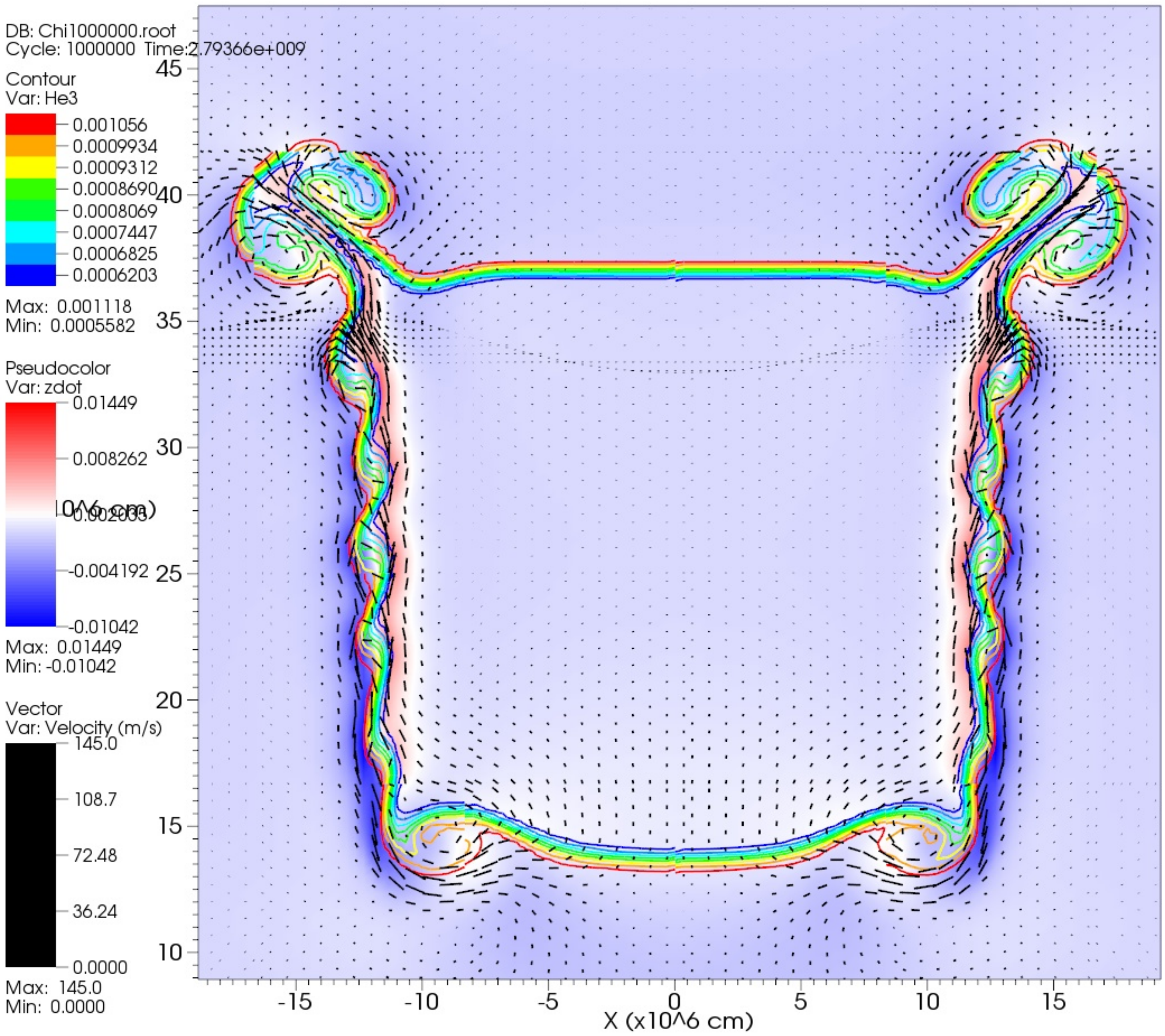


Run 31: XCHI-Cont.o136618

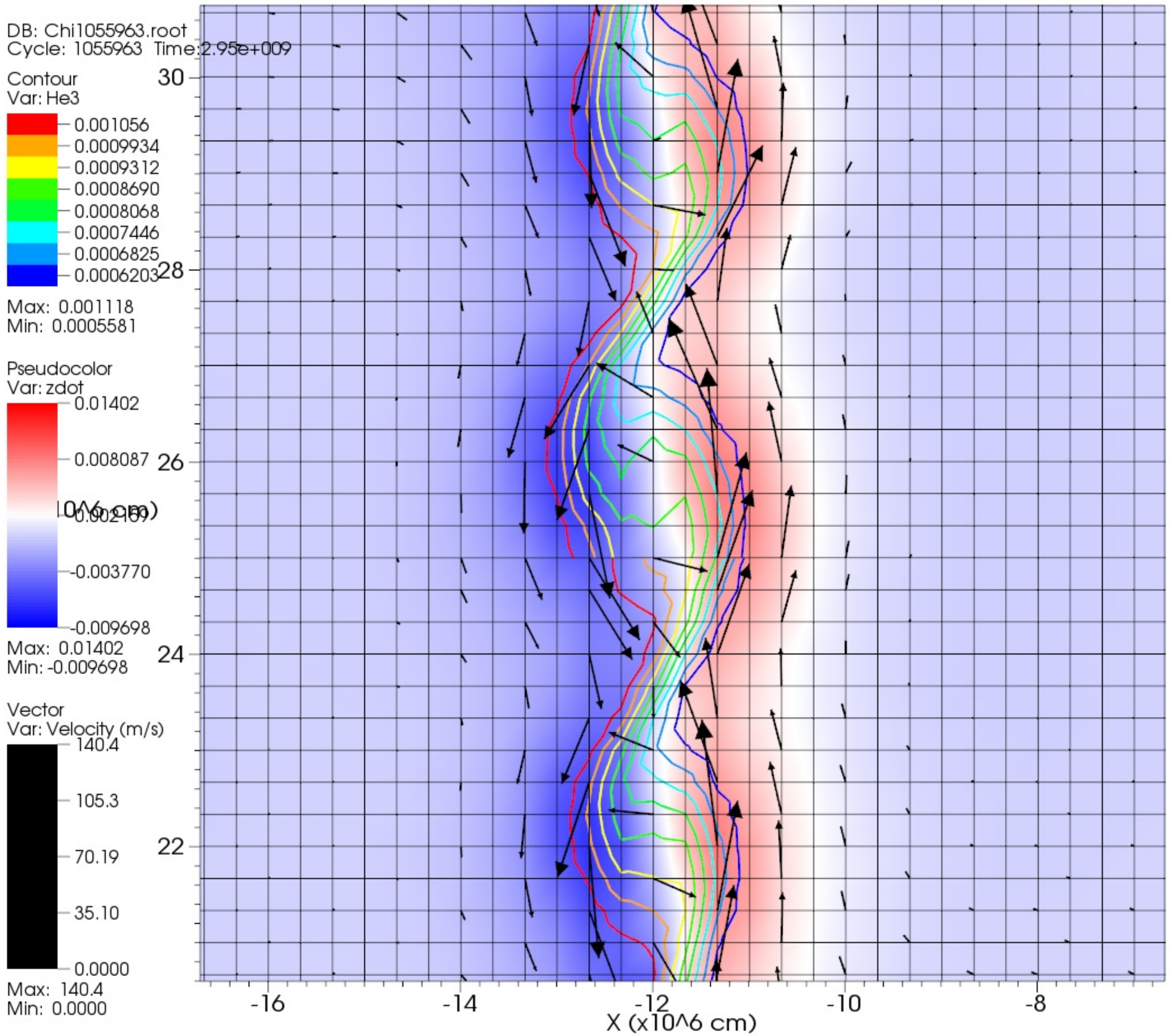




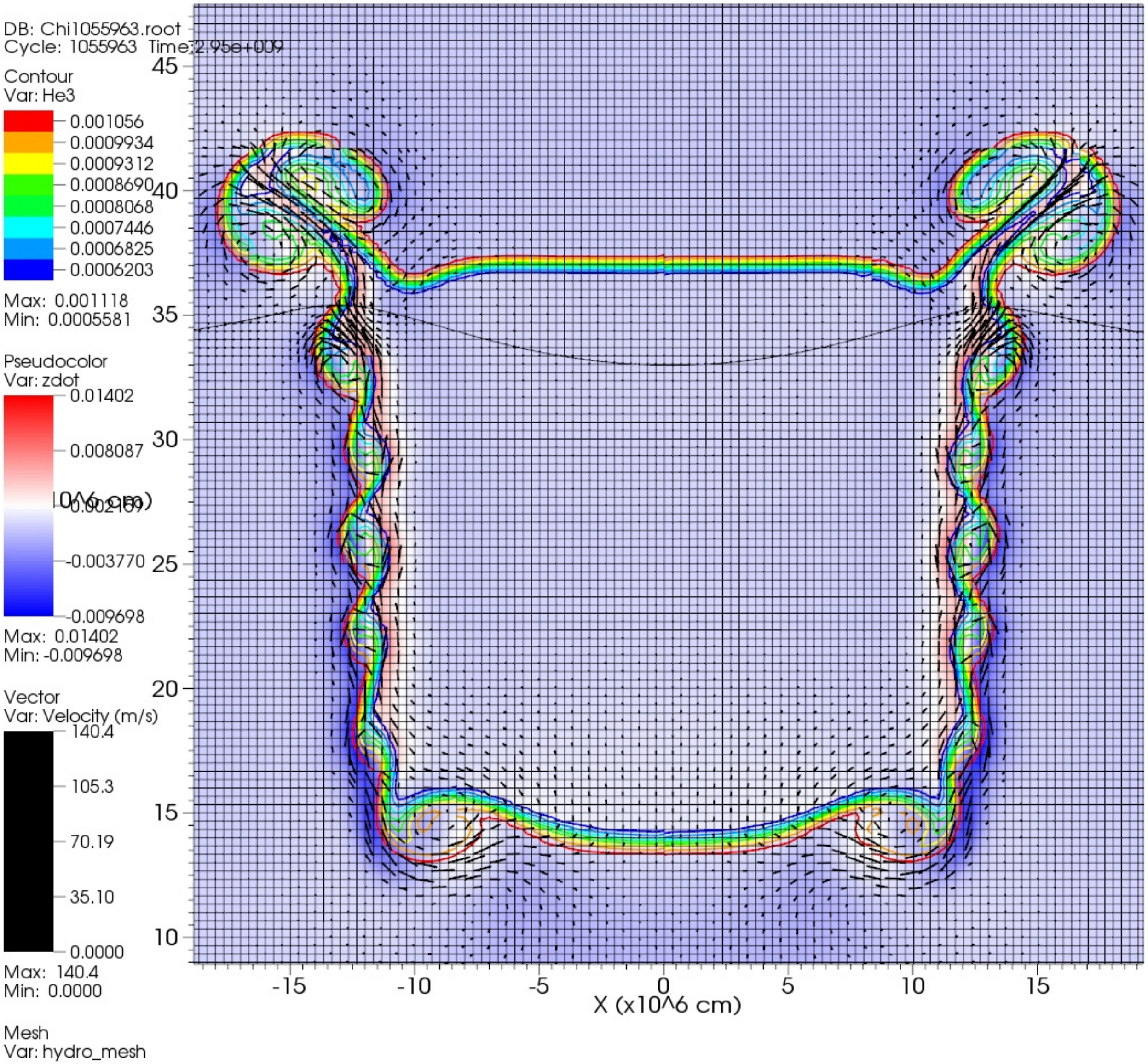
Run 32:


DB: Chi1000000.root
Cycle: 1000000 Time:2.79366e+009
Contour
Var: He3
0.001056
0.0009934
0.0009312
0.0008690
0.0008069
0.0007447
0.0006825
0.0006203
Max: 0.001118
Min: 0.0005582
Pseudocolor
Var: zdot
0.01449
0.008262
0.002033
-0.004192
-0.01042
Max: 0.01449
Min: -0.01042
Vector
Var: Velocity (m/s)
145.0
108.7
72.48
36.24
0.0000
Max: 145.0
Min: 0.0000
45
40
35
30
25
20
15
10
-15
-10
-5
0
5
10
15
X (x10^6 cm)

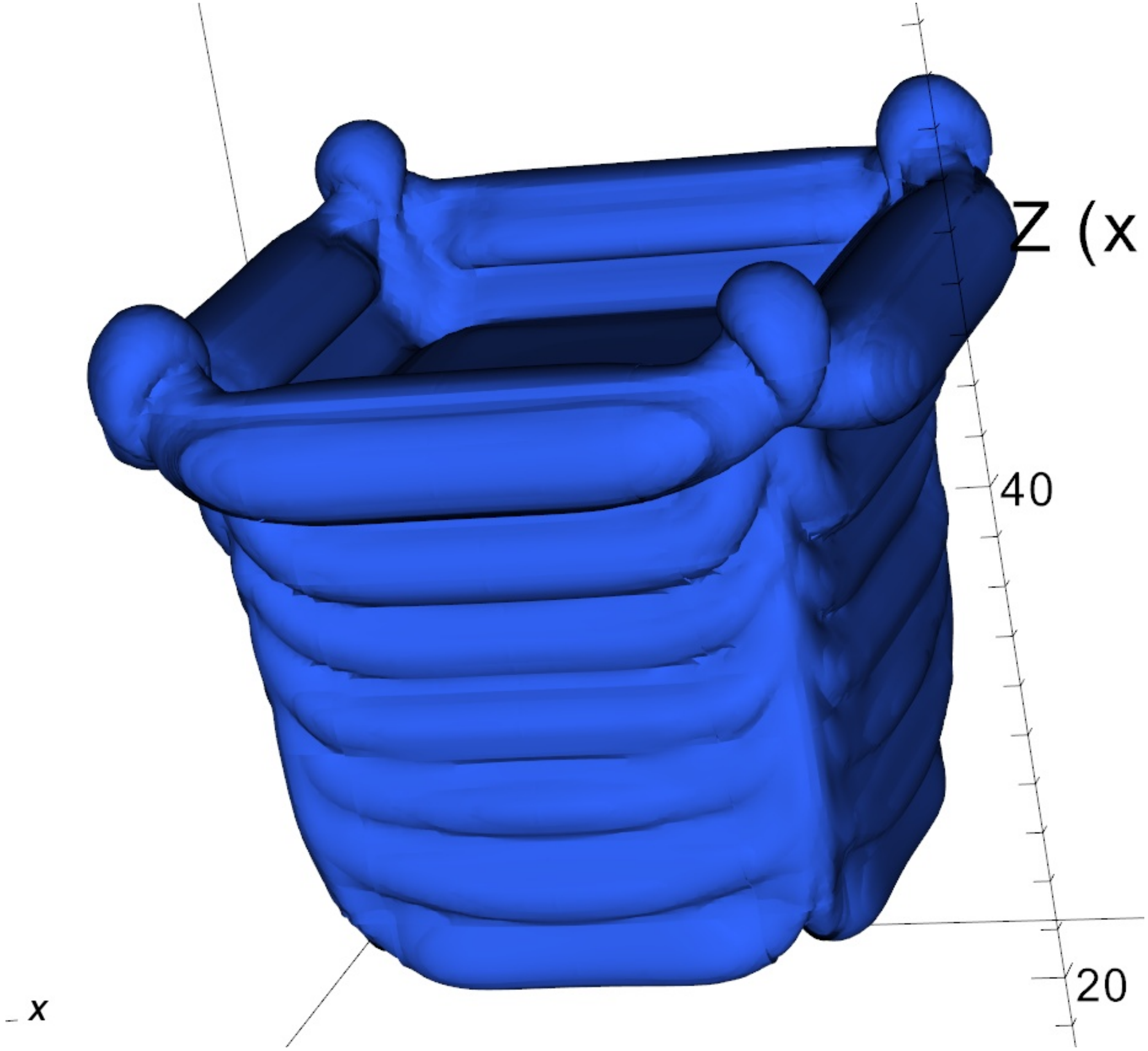
Run 34: XCHI-Cont.o140429



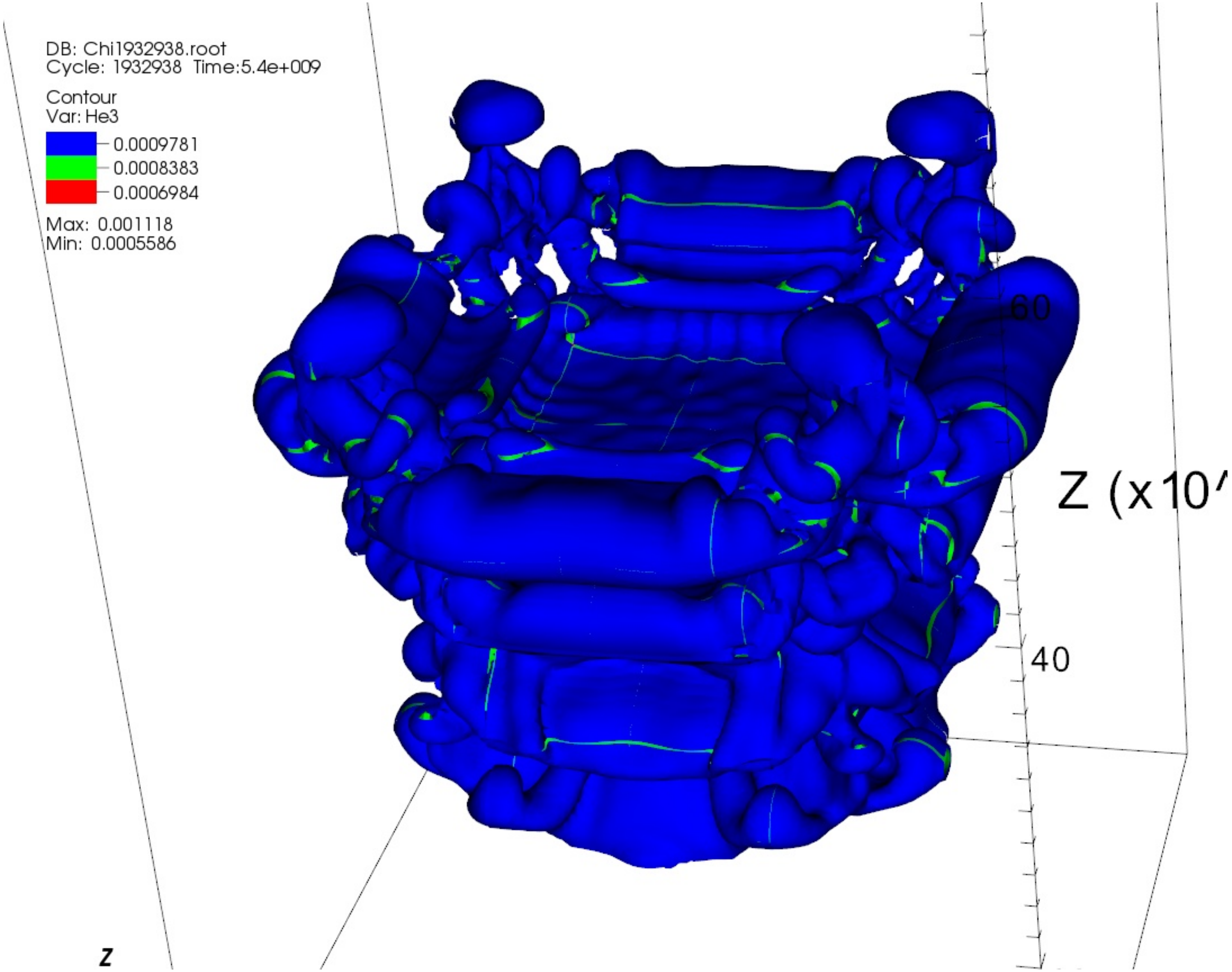
Run 34: XCHI-Cont.o140429



Run 34: XCHI-Cont.o140429

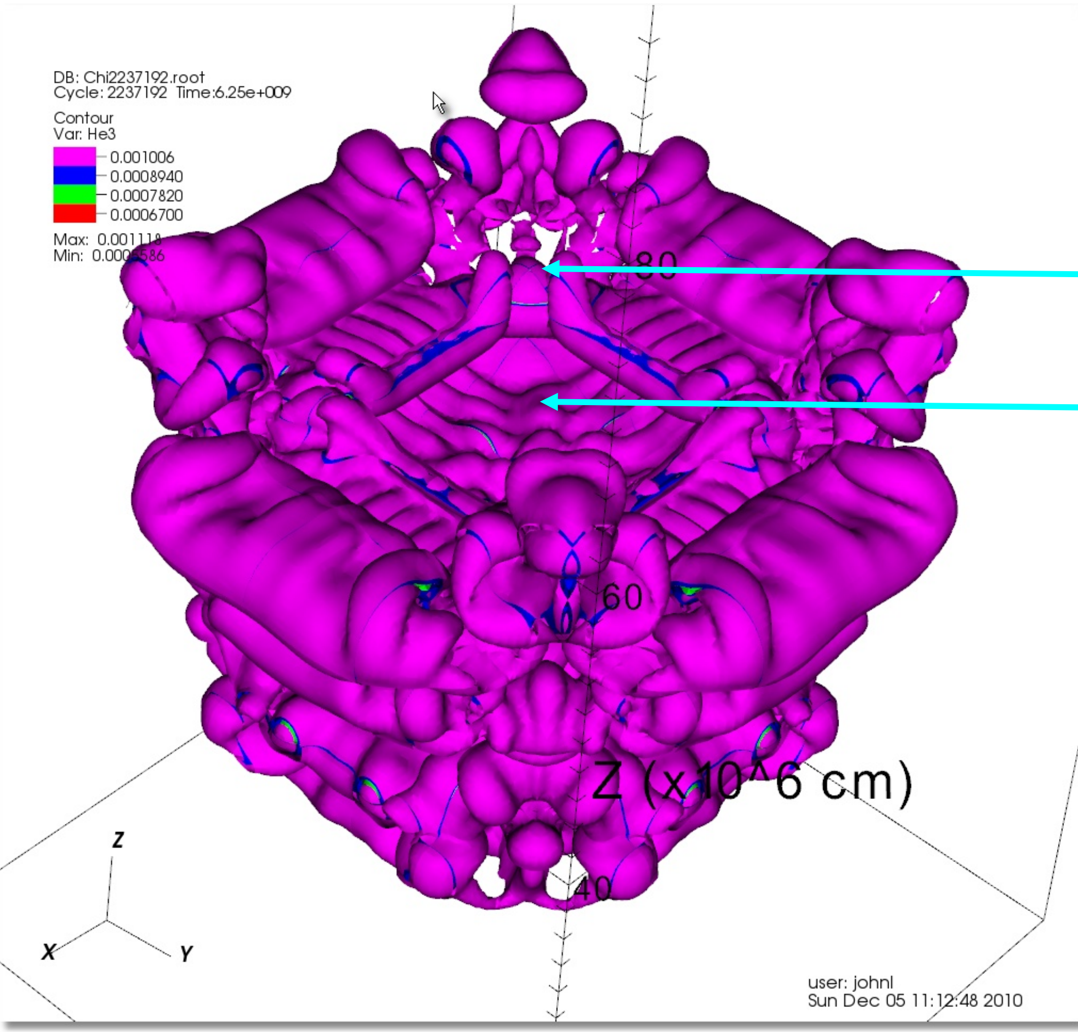


Run 63: XCHI-Cont.o159944



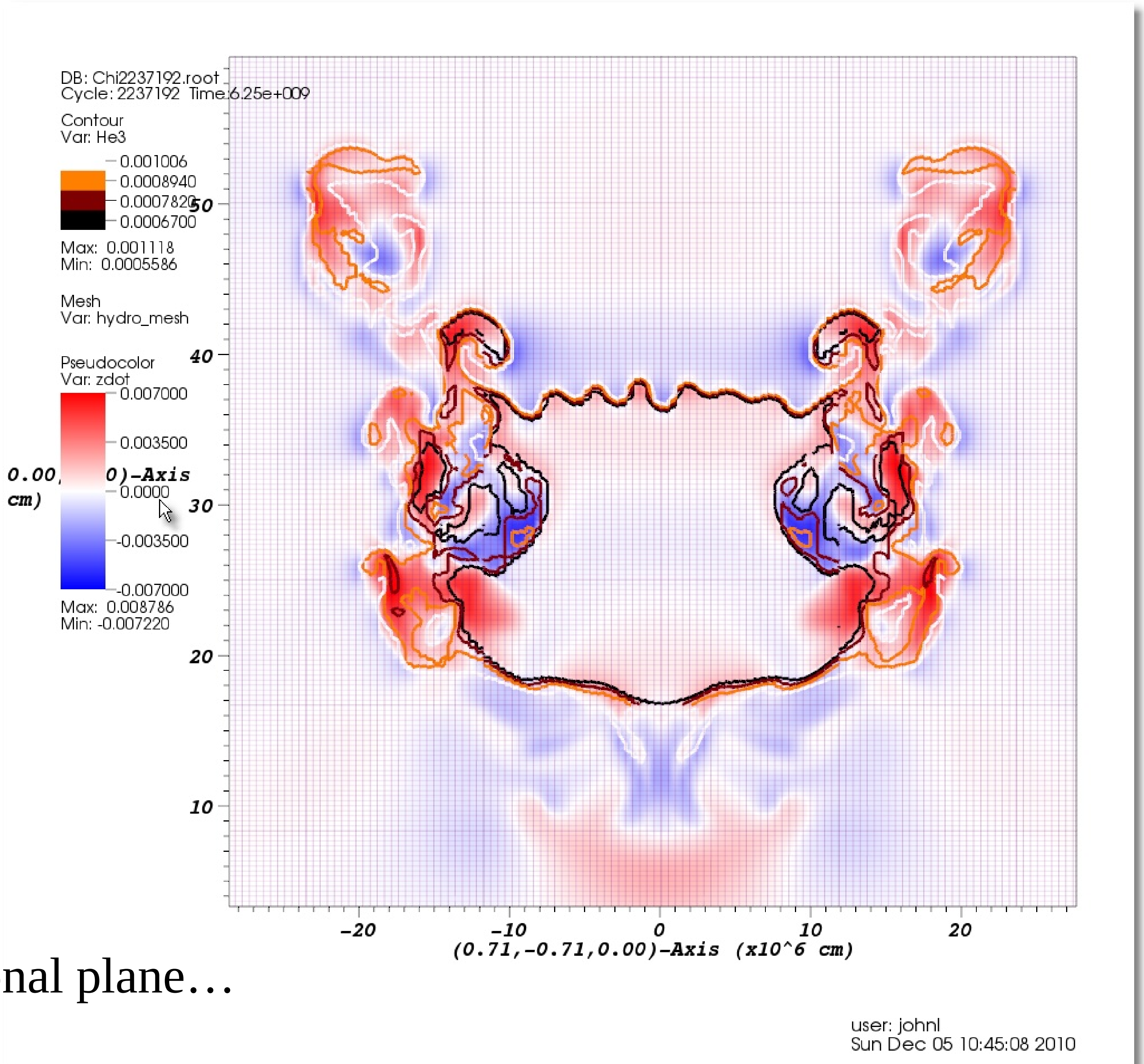
Run 74: XCHI-Cont.o174520

- Stored on Dec 6

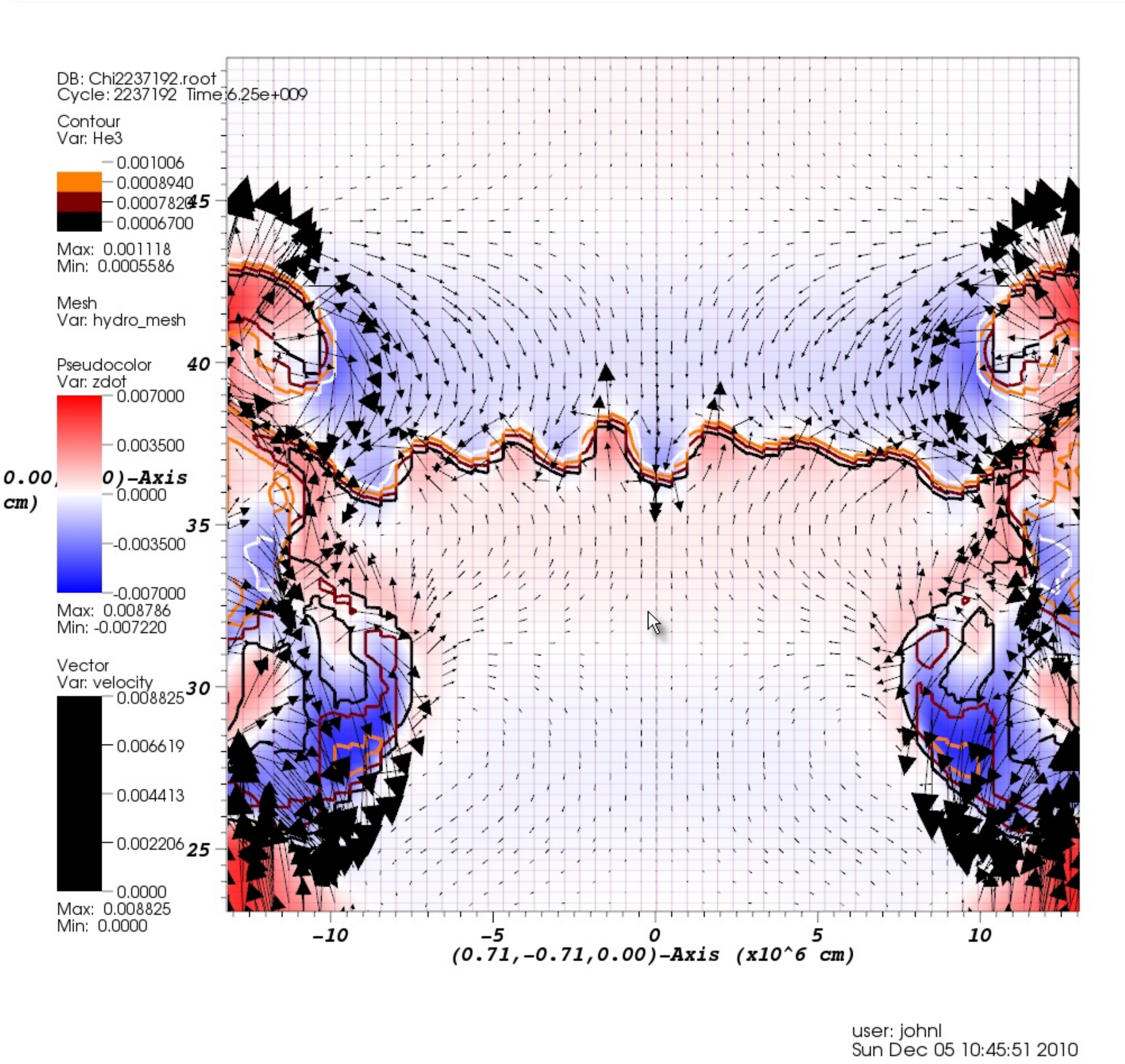


Secondary corners now starting to rise also, just as in the low res cube

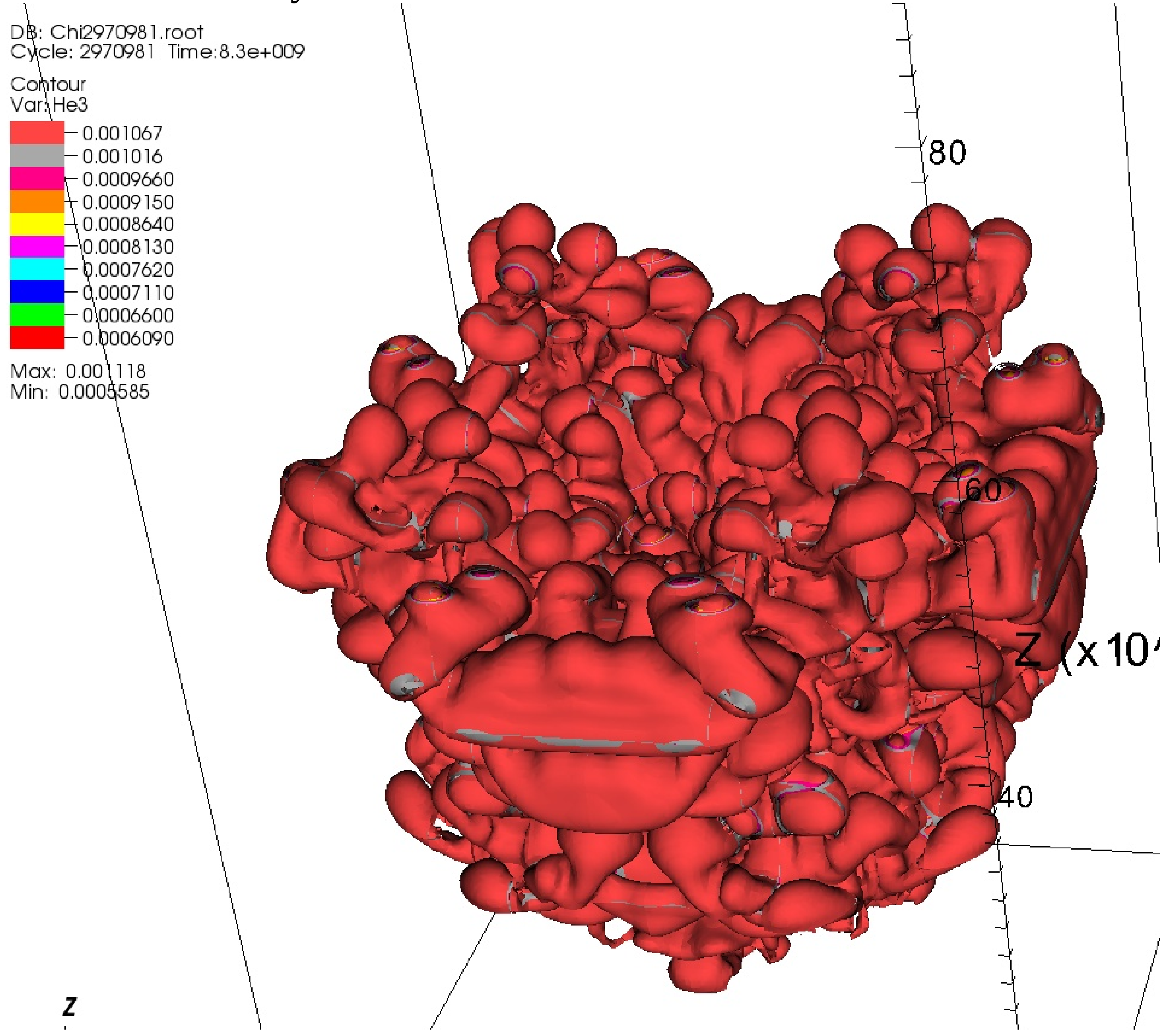
These ripples are now starting to grow into fingers also. Again, like the lo res and nipple/slab run.



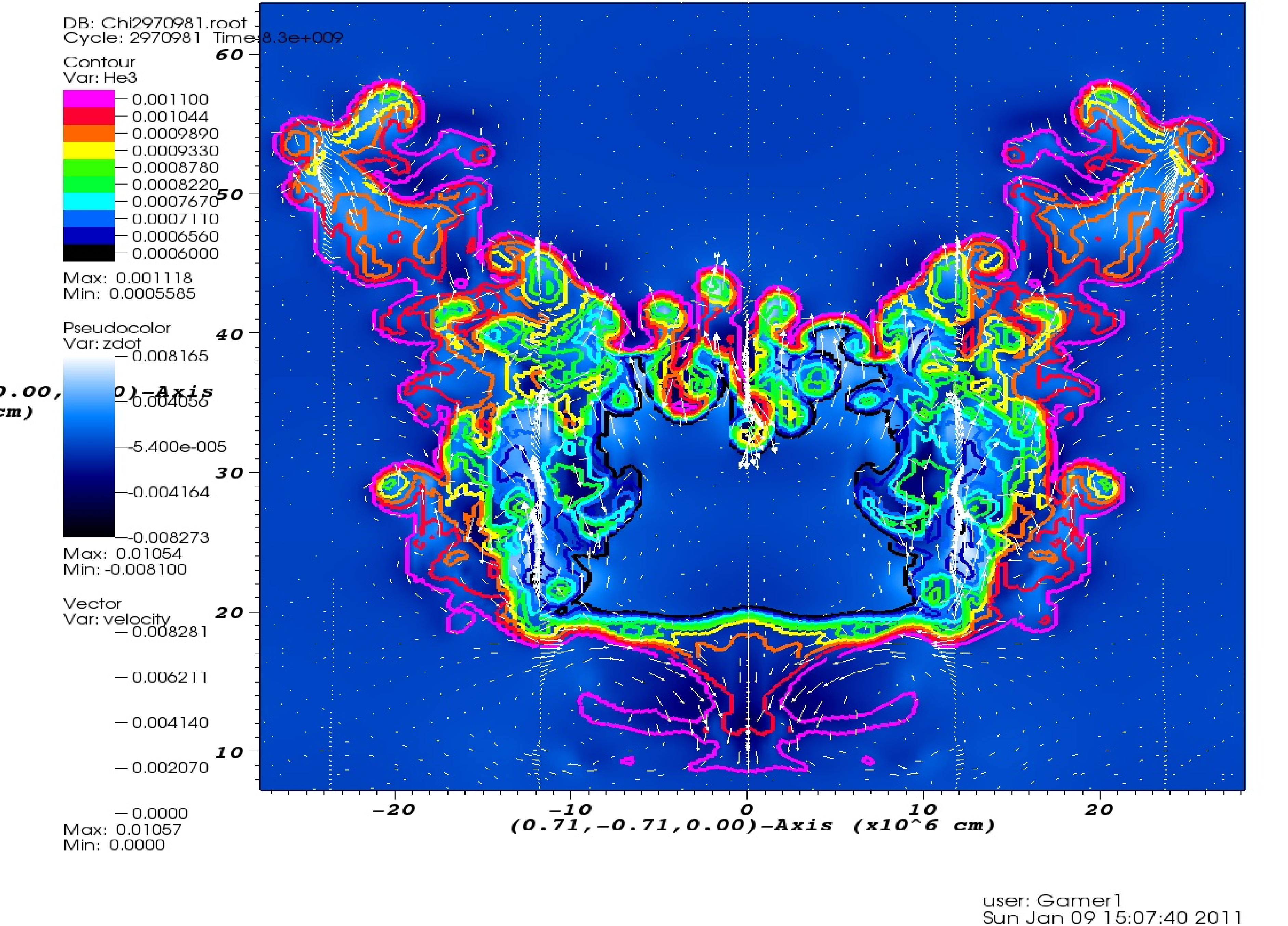
Diagonal plane…

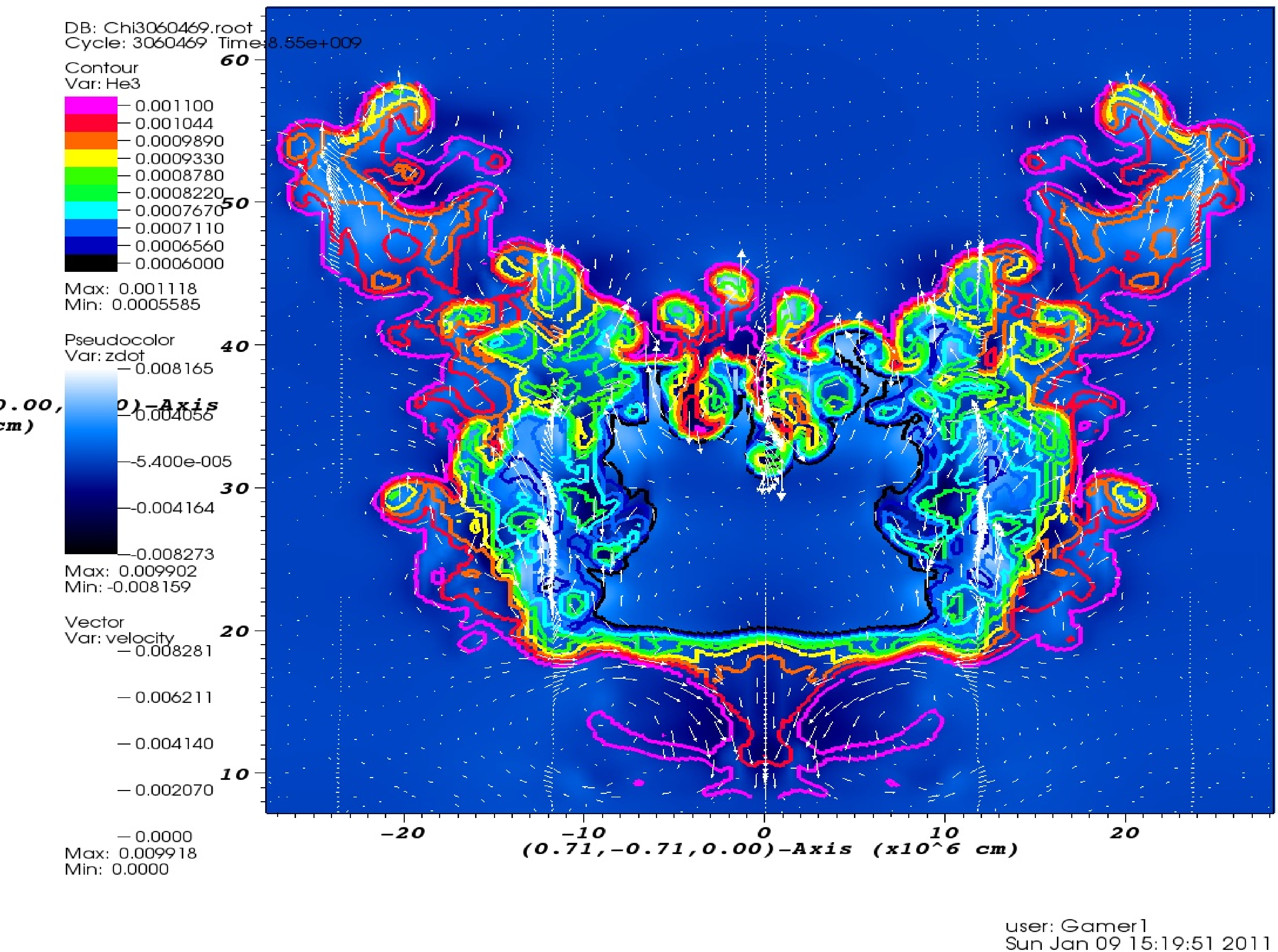

DB: Chi2237192.root
Cycle: 2237192 Time:6.25e+009
Contour
Var: He3
0.001006
0.0008940
0.0007820
0.0006700
Max: 0.001118
Min: 0.0005586
Mesh
Var: hydro_mesh
Pseudocolor
Var: zdot
0.007000
0.003500
0.0000
-0.003500
-0.007000
Max: 0.008786
Min: -0.007220
Vector
Var: velocity
0.008825
0.006619
0.004413
0.002206
0.0000
Max: 0.008825
Min: 0.0000
45
40
35
30
25
-10
-5
0
5
10
(0.71,-0.71,0.00)-Axis (x10^6 cm)
user: johnl
Sun Dec 05 10:45:51 2010

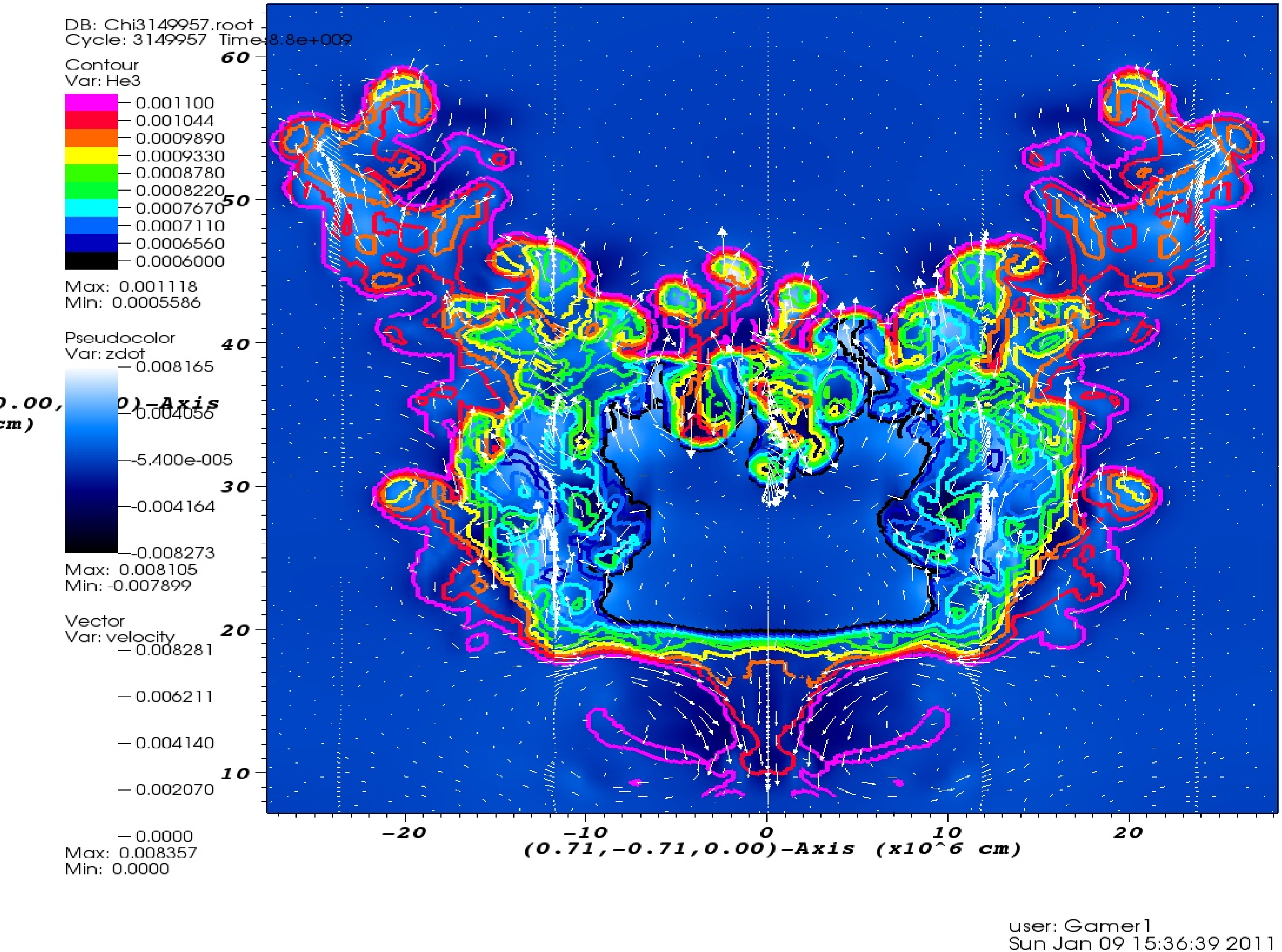
Run 97 Cycle 2970981 t = 8300s = 2 hours and 20 mins

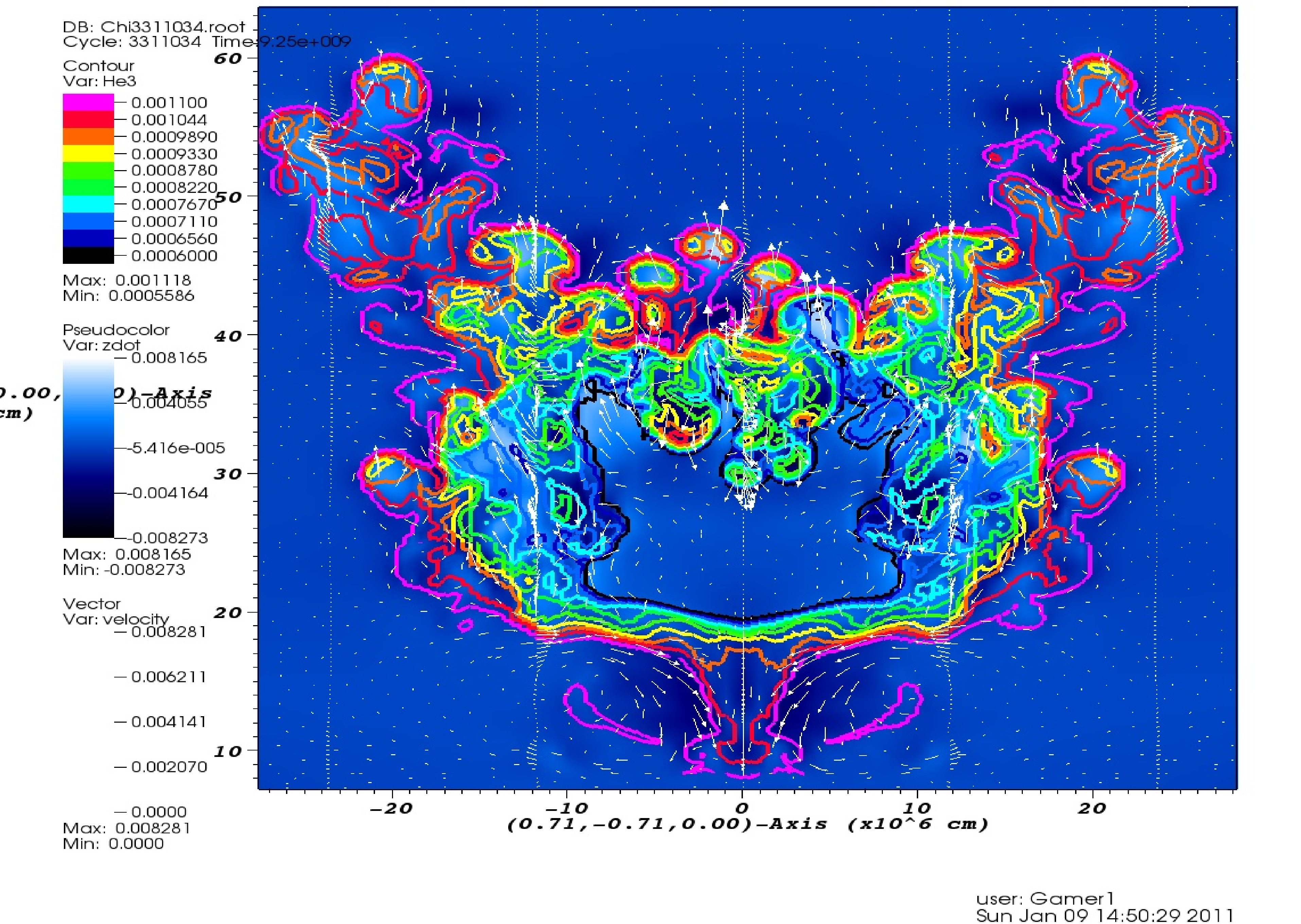


A few slides to make a small movie ☺

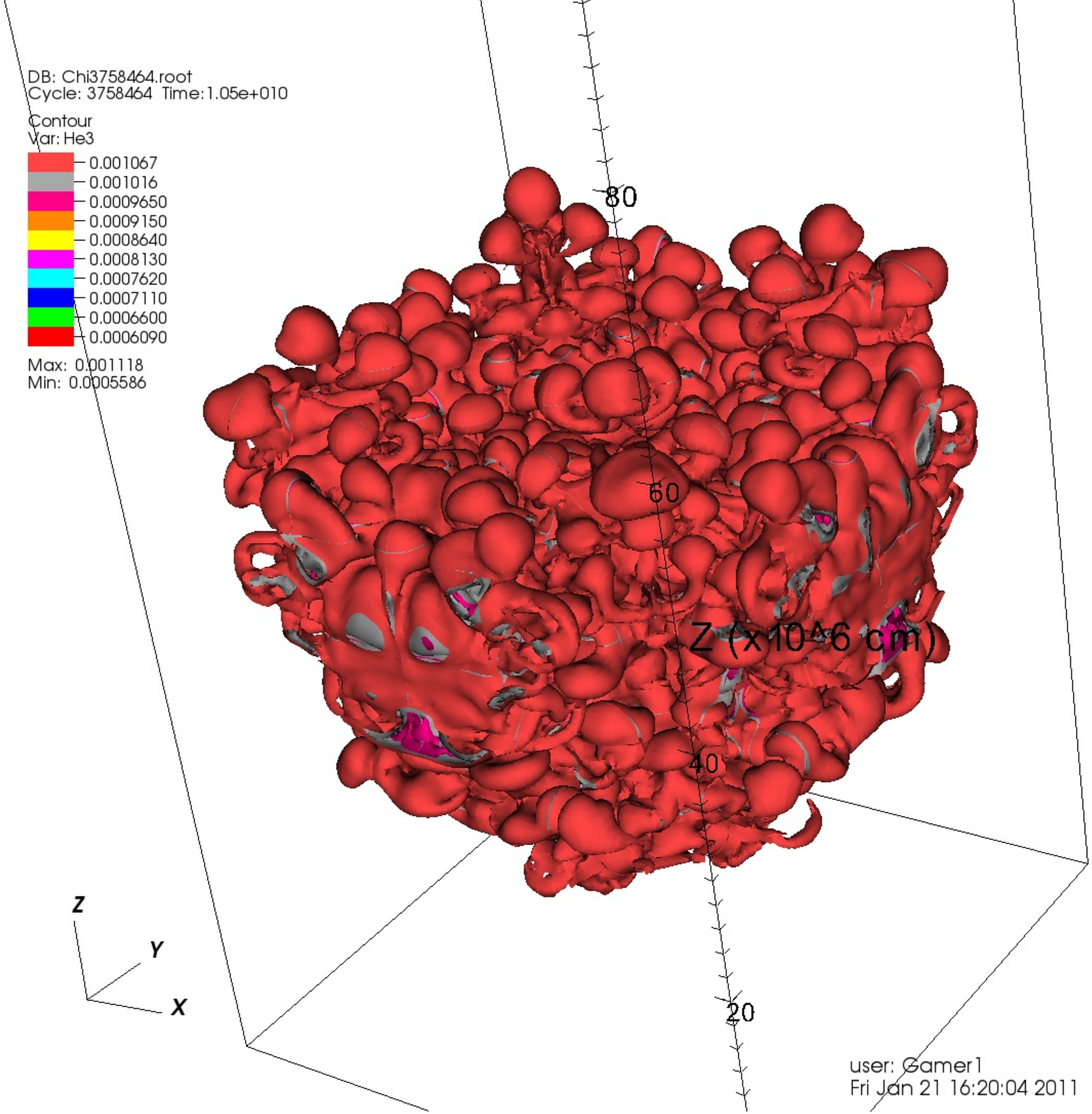



DB: Chi3060469.root
Cycle: 3060469 Time:8.55e+009
Contour
Var: He3
0.001100
0.001044
0.0009890
0.0009330
0.0008780
0.0008220
0.0007670
0.0007110
0.0006560
0.0006000
Max: 0.001118
Min: 0.0005585
Pseudocolor
Var: zdot
0.008165
0.004056
-5.400e-005
-0.004164
-0.008273
Max: 0.009902
Min: -0.008159
Vector
Var: velocity
0.008281
0.006211
0.004140
0.002070
0.0000
Max: 0.009918
Min: 0.0000
60
50
40
30
20
10
-20
-10
0
10
20
(0.71,-0.71,0.00)-Axis (x10^6 cm)
user: Gamer1
Sun Jan 09 15:19:51 2011

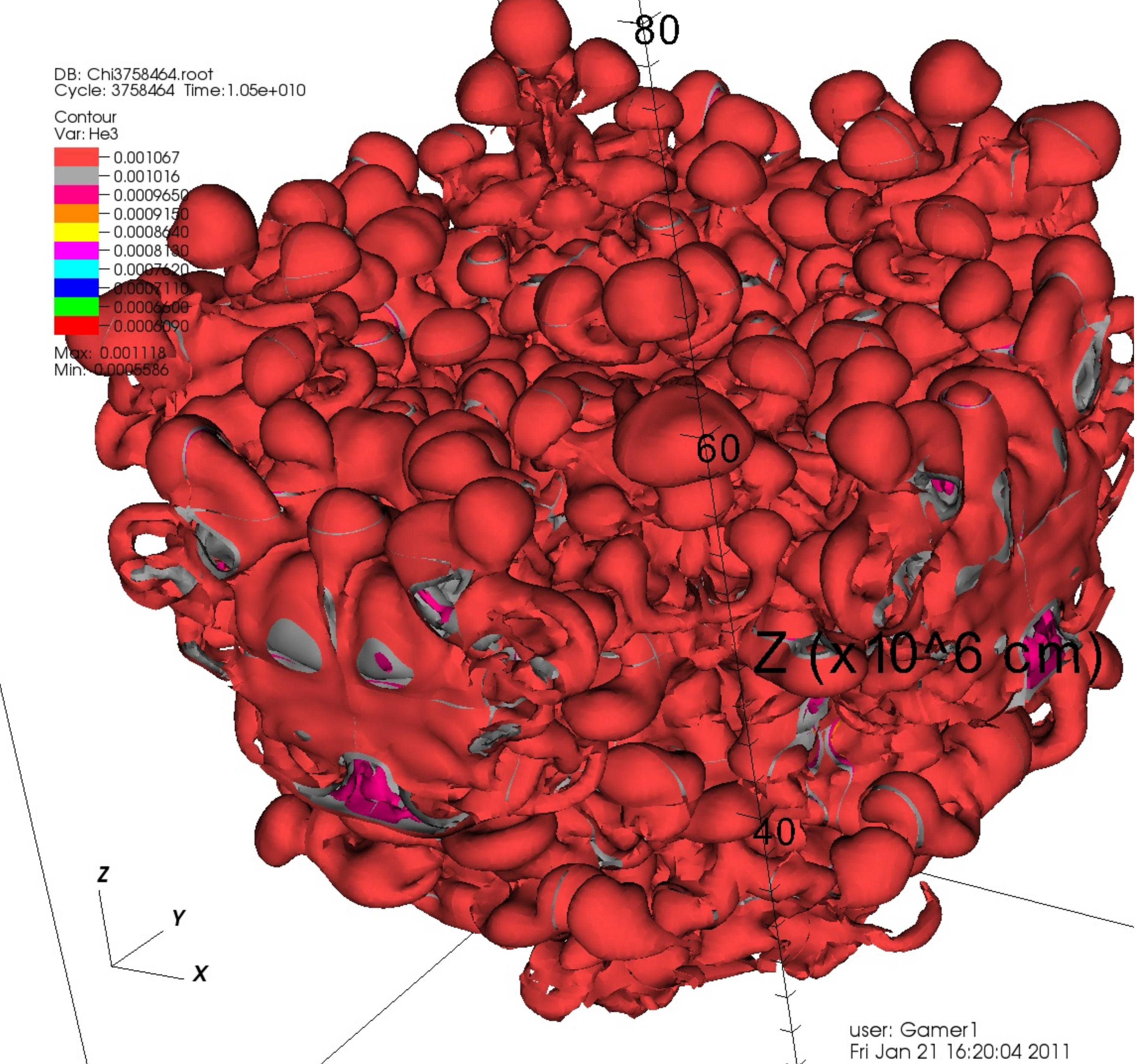

DB: Chi3149957.root
Cycle: 3149957 Time:8.8e+009
Contour
Var: He3
0.001100
0.001044
0.0009890
0.0009330
0.0008780
0.0008220
0.0007670
0.0007110
0.0006560
0.0006000
Max: 0.001118
Min: 0.0005586
Pseudocolor
Var: zdot
0.008165
0.004056
-5.400e-005
-0.004164
-0.008273
Max: 0.008105
Min: -0.007899
Vector
Var: velocity
0.008281
0.006211
0.004140
0.002070
0.0000
Max: 0.008357
Min: 0.0000
60
50
40
30
20
10
-20
-10
0
10
20
(0.71,-0.71,0.00)-Axis (x10^6 cm)
user: Gamer1
Sun Jan 09 15:36:39 2011

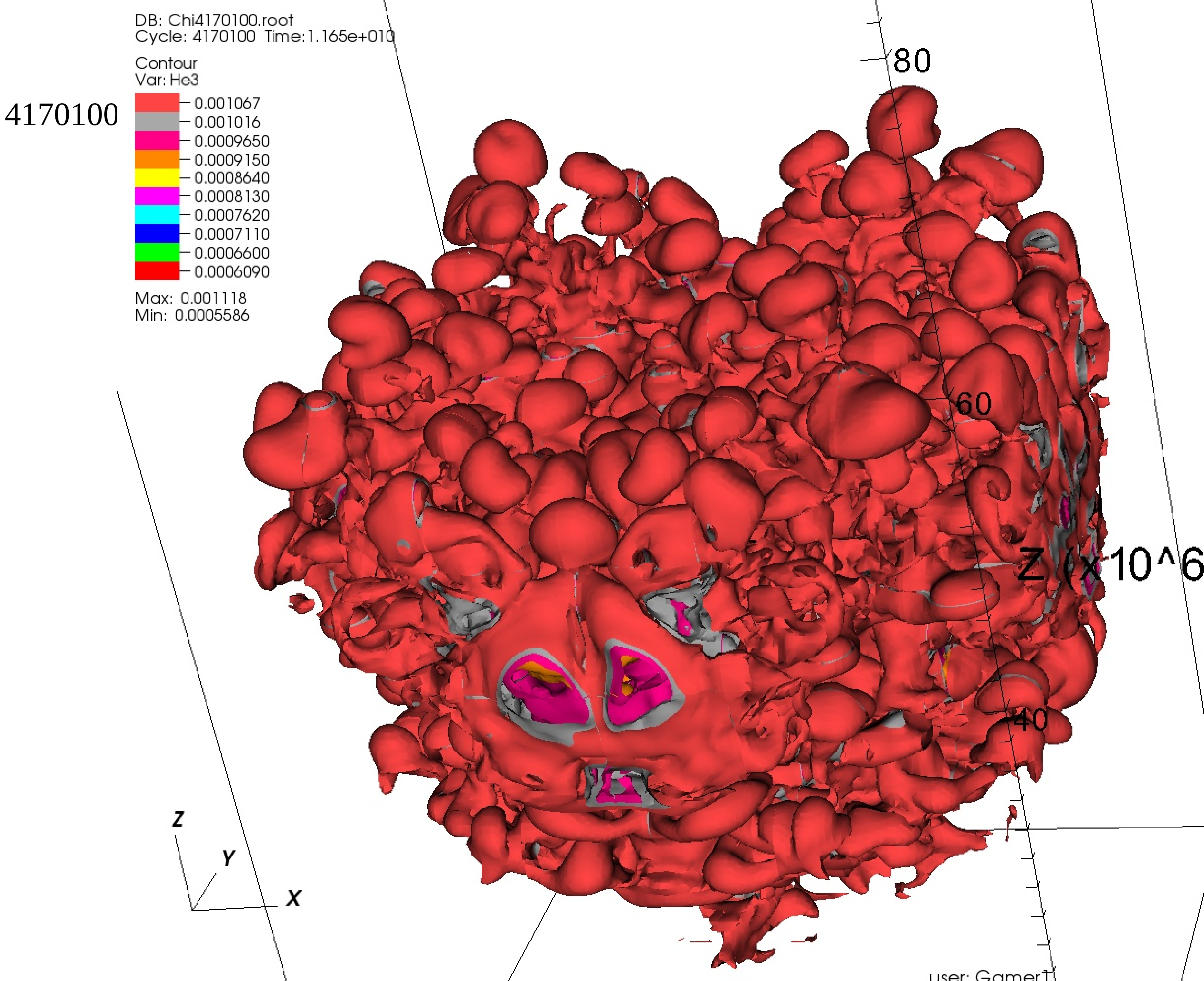


DB: Chi3311034.root
Cycle: 3311034 Time:9.25e+009
Contour
Var: He3
0.001100
0.001044
0.0009890
0.0009330
0.0008780
0.0008220
0.0007670
0.0007110
0.0006560
0.0006000
Max: 0.001118
Min: 0.0005586
Pseudocolor
Var: zdot
0.008165
0.004055
-5.416e-005
-0.004164
-0.008273
Max: 0.008165
Min: -0.008273
Vector
Var: velocity
0.008281
0.006211
0.004141
0.002070
0.0000
Max: 0.008281
Min: 0.0000
(0.71,-0.71,0.00)-Axis (x10^6 cm)
user: Gamer1
Sun Jan 09 14:50:29 2011

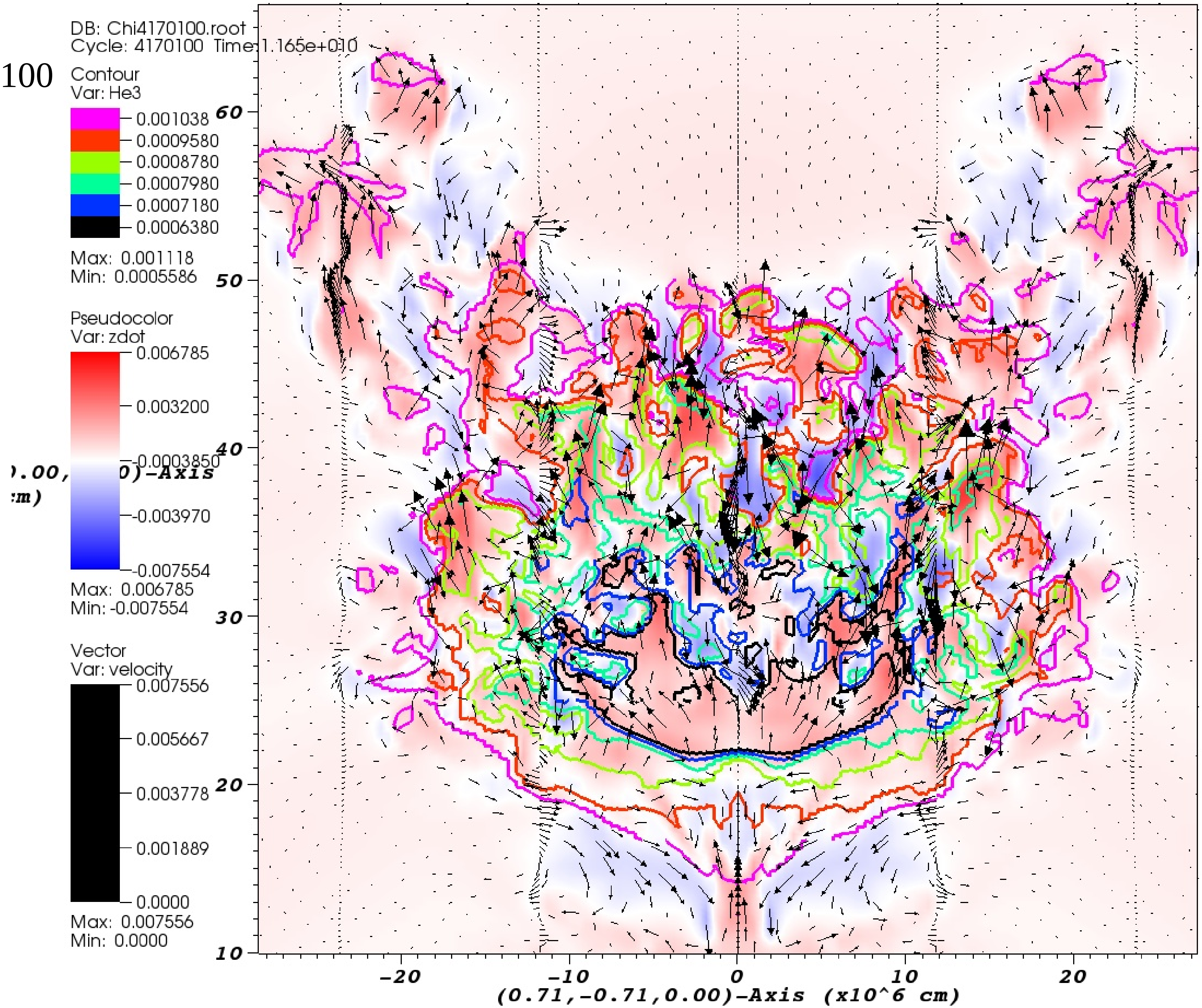


DB: Chi3758464.root
Cycle: 3758464 Time:1.05e+010
Contour
Var: He3
0.001067
0.001016
0.0009650
0.0009150
0.0008640
0.0008130
0.0007620
0.0007110
0.0006600
0.0006090
Max: 0.001118
Min: 0.0005586
80
60
Z (x10^6 cm)
40
20
Z
Y
X
user: Gamer1
Fri Jan 21 16:20:04 2011


DB: Chi3758464.root
Cycle: 3758464 Time:1.05e+010
Contour
Var: He3
0.001067
0.001016
0.0009650
0.0009150
0.0008640
0.0008130
0.0007620
0.0007110
0.0006600
0.0006090
Max: 0.001118
Min: 0.0005586
80
60
40
Z (x10^6 cm)
Z
Y
X
user: Gamer1
Fri Jan 21 16:20:04 2011


4170100
DB: Chi4170100.root
Cycle: 4170100 Time:1.165e+010
Contour
Var: He3
0.001067
0.001016
0.0009650
0.0009150
0.0008640
0.0008130
0.0007620
0.0007110
0.0006600
0.0006090
Max: 0.001118
Min: 0.0005586
80
60
40
Z (x10^6
Z
Y
X

4170100



DB: Chi4170100.root
Cycle: 4170100 Time:1.165e+010
Contour
Var: He3
0.001038
0.0009580
0.0008780
0.0007980
0.0007180
0.0006380
Max: 0.001118
Min: 0.0005586
Pseudocolor
Var: zdot
0.006785
0.003200
-0.0003850
-0.003970
-0.007554
Max: 0.006785
Min: -0.007554
Vector
Var: velocity
0.007556
0.005667
0.003778
0.001889
0.0000
Max: 0.007556
Min: 0.0000
60
50
40
30
20
10
-20
-10
0
10
20
(0.71,-0.71,0.00)-Axis (x10^6 cm)

Show Movies

It remains to relate this to a 1D diffusion co-efficient (!)

The fate of S-AGB stars

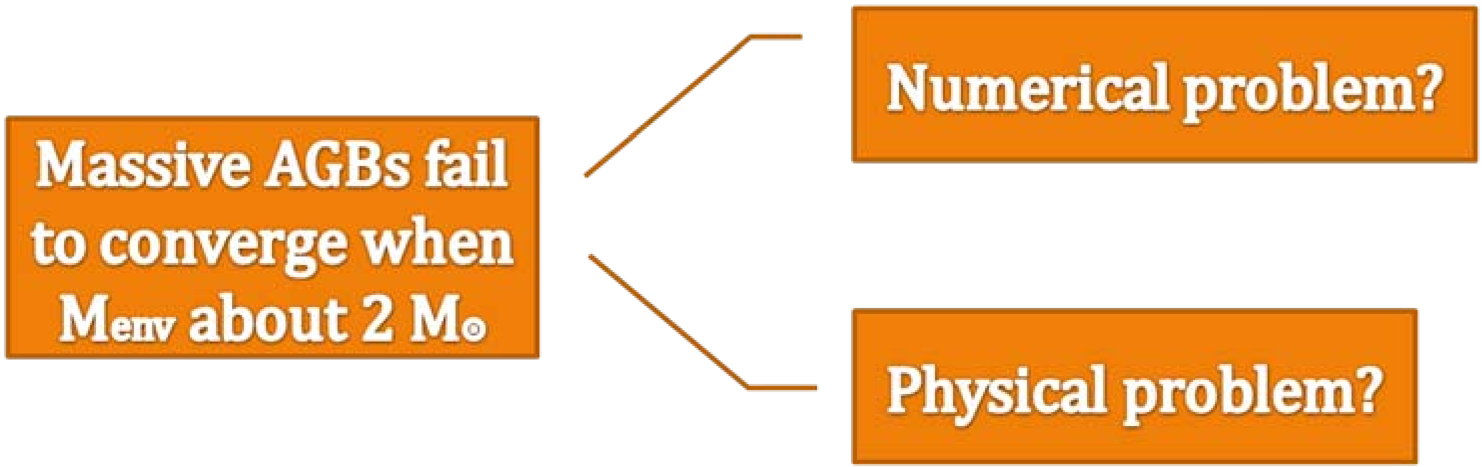
or

Why won't my code converge?

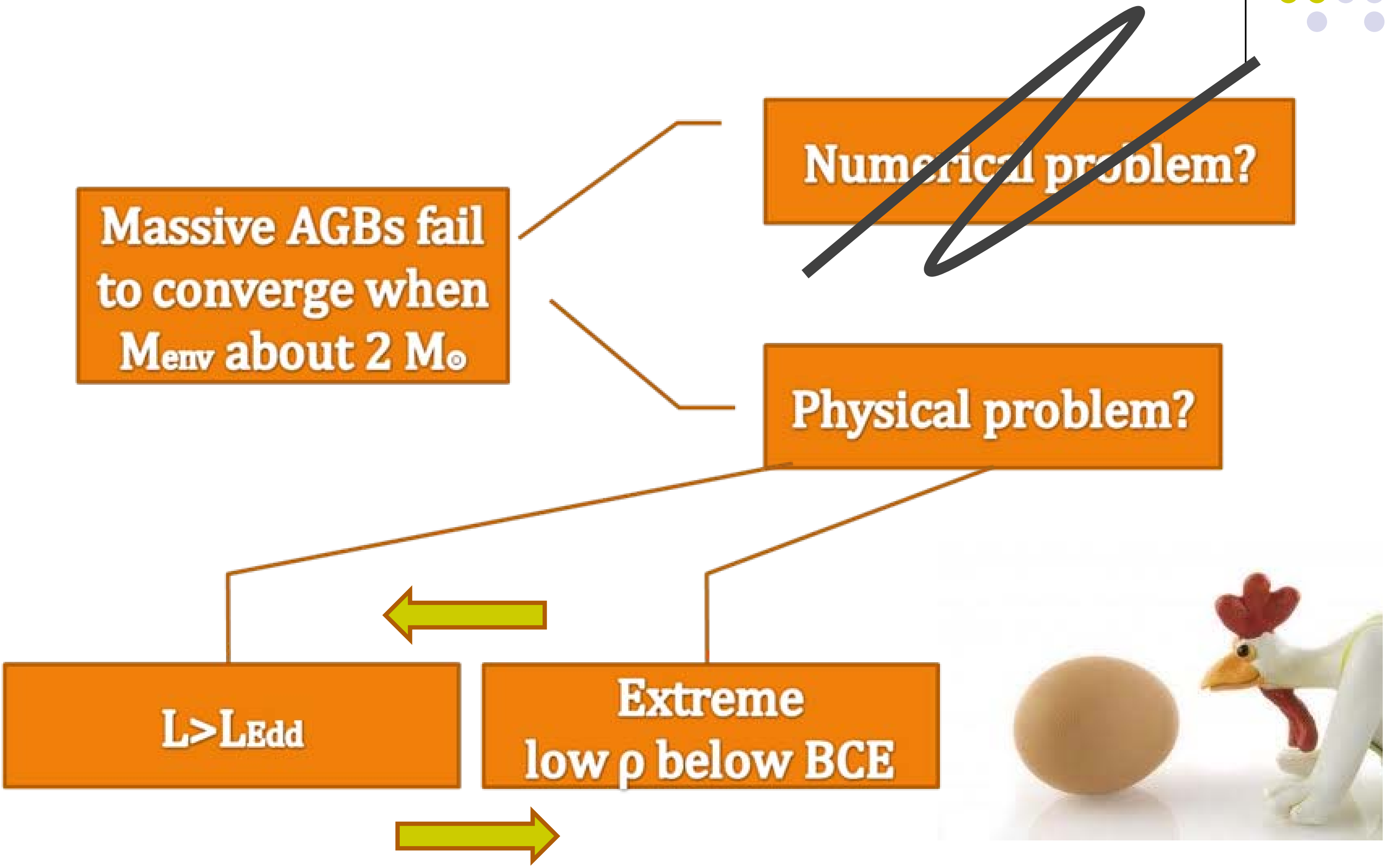
Work in Progress!
No answer yet!

- Herbert Lau
- Pilar Gil Pons
- Carolyn Doherty
- Me

Overview


Massive AGBs fail to converge when M_{env} about 2 $M_\odot$
Numerical problem?
Physical problem?

Overview


Massive AGBs fail to converge when M_{env} about 2 $M_\odot$
Numerical problem?
Physical problem?
$L>L_{Edd}$
Extreme low ρ below BCE

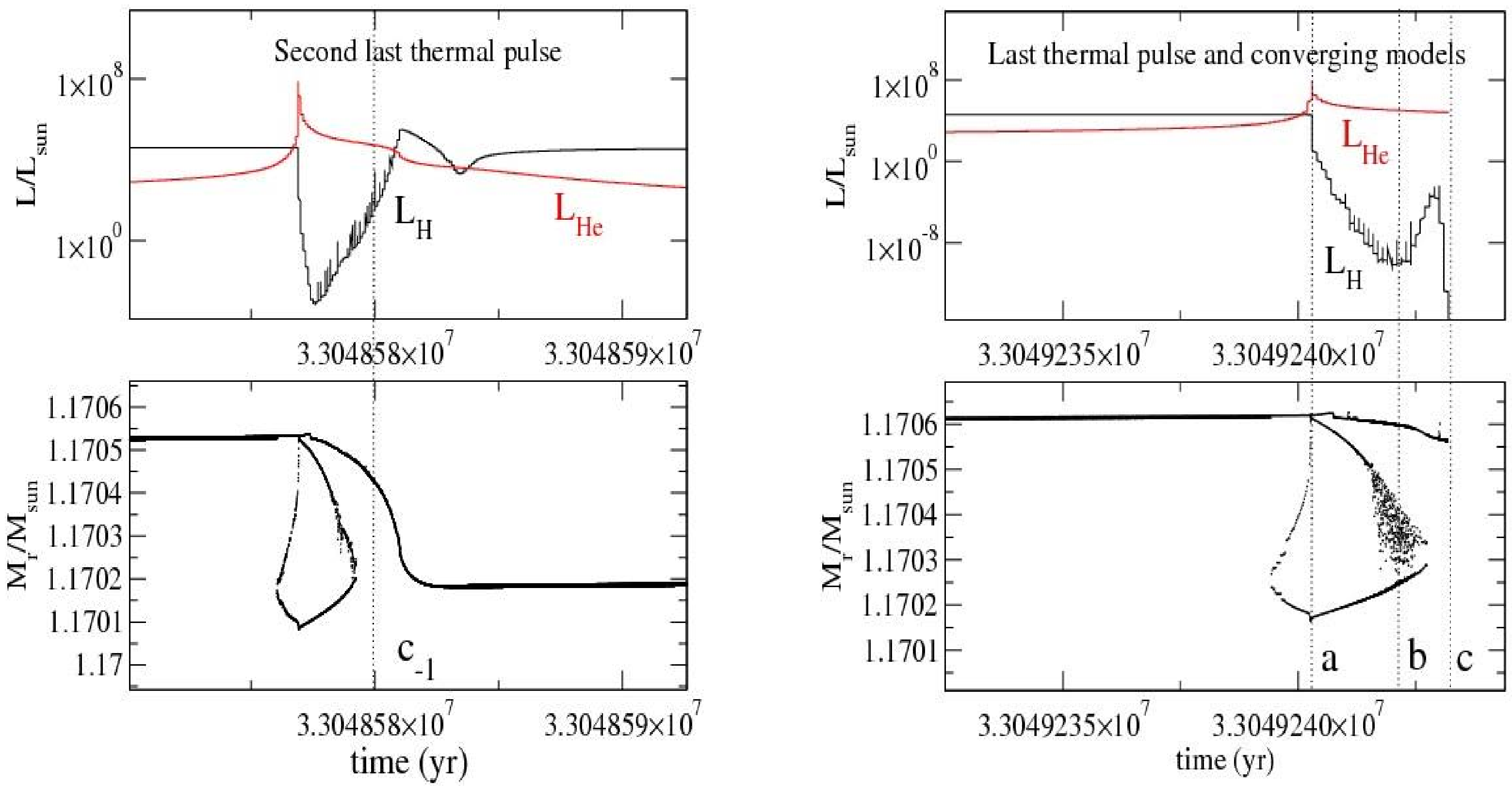
Looking at the facts: when does it happen?

- The divergence happens for different evolution codes (EVOLV, MONSTAR)
- Can be delayed by increasing alpha (MLR)=>

  increasing mixing efficiency (Herwig et al., Althaus et al,…)

Looking at the facts: when does it happen?

Comparison: the last two TPs



Pg < 0

- Code dies with negative gas pressure
- T and P are dependent variables
  - So values chosen by matrix solution
  - $P_{rad} = 1/3aT^4$ then known
  - $P_{gas} = P - Prad$ is known
  - Then the e.o.s. tells us ρ
- So a Pg < 0 error means P_{rad} provides all of P
- ie $\beta < 0$ and $L > L_{Edd}$
- See Wood and Faulkner 1986!!

Looking at the facts: contribution P/P$_{rad}$ in the hydrostatic case

$$\beta \to 0$$

Radiative case:

$$\frac{dP_{rad}}{dP} = \frac{\kappa \rho L_r}{4\pi c G M_r}$$

then:

$$\frac{P_{rad}}{P} = 1 - \beta \approx \frac{L}{L_{Edd}}$$

with: $L_{Edd} = \dfrac{4\pi c G M}{\langle \kappa \rangle}$

Convective case:

$$\frac{dP_{rad}}{dP} = \frac{\kappa \rho L_r}{4\pi c G M_r} \frac{\nabla}{\nabla_r}$$

then:

$$\frac{P_{rad}}{P} = 1 - \beta \approx \frac{L}{L'_{Edd}}$$

with: $L'_{Edd} = \dfrac{4\pi c G M}{\langle \kappa \rangle} \dfrac{\nabla_r}{\nabla}$

Looking at the facts

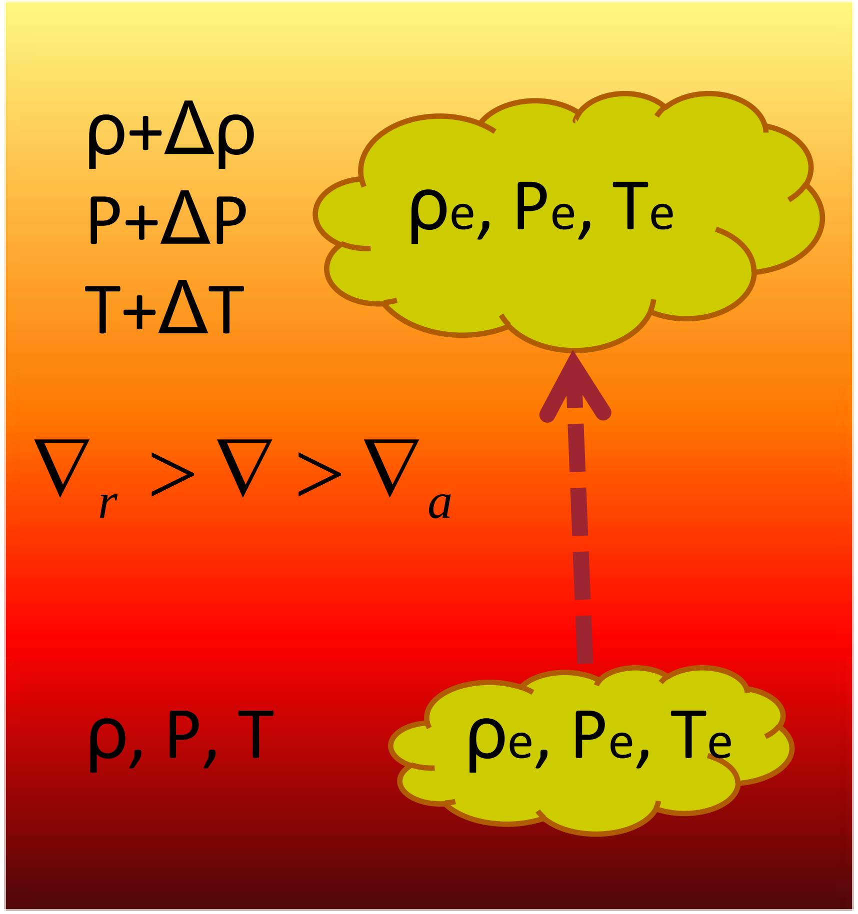
Conductivity radiation-to-convection

$$(\nabla - \nabla_e)^{3/2} = \frac{8}{9} U (\nabla_r - \nabla)$$

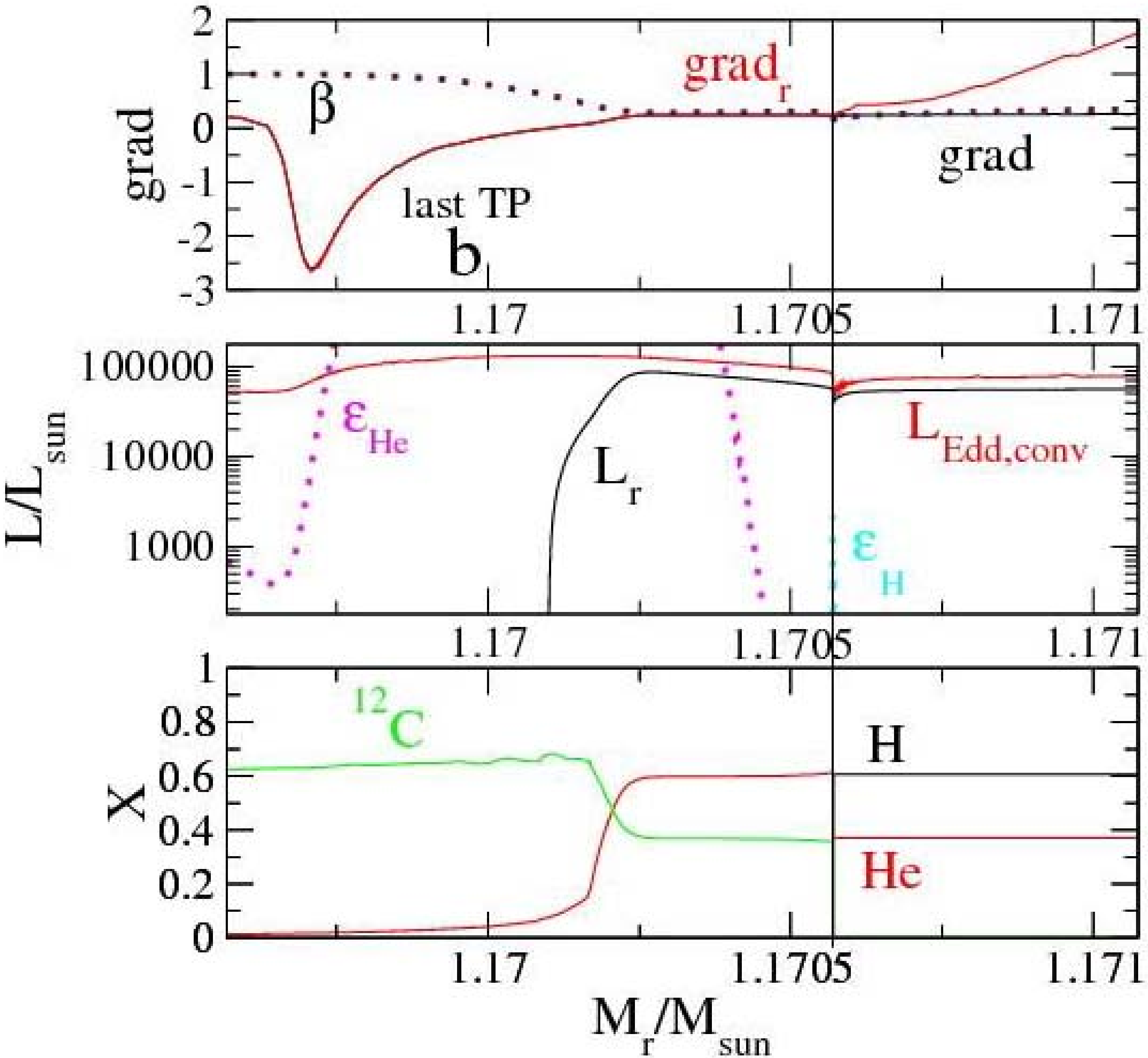
$$U = \frac{3acT^3}{C_p \rho^2 \kappa \lambda_m^2} \sqrt{\frac{8H_p}{g\delta}}$$

U >> convection inefficient

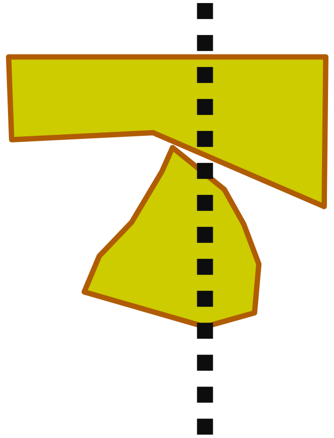
U << convection efficient



We have very inefficient convection here…



After last TP



What pushes L > L_{Edd} ?

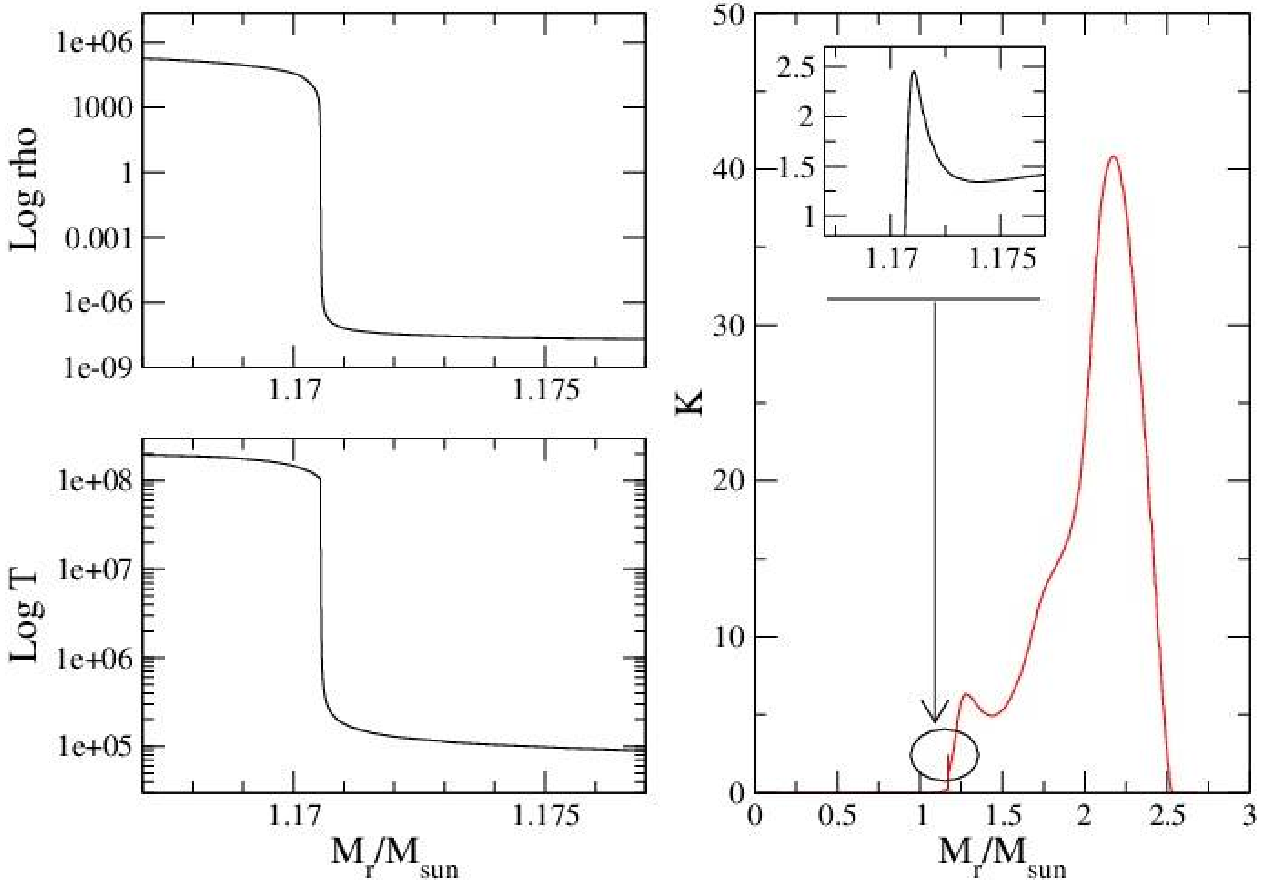
$$L'_{Edd} = \frac{4\pi cGM}{\langle \kappa \rangle} \frac{\nabla_r}{\nabla}$$

Reduce L_{Edd} by increasing <κ> ???

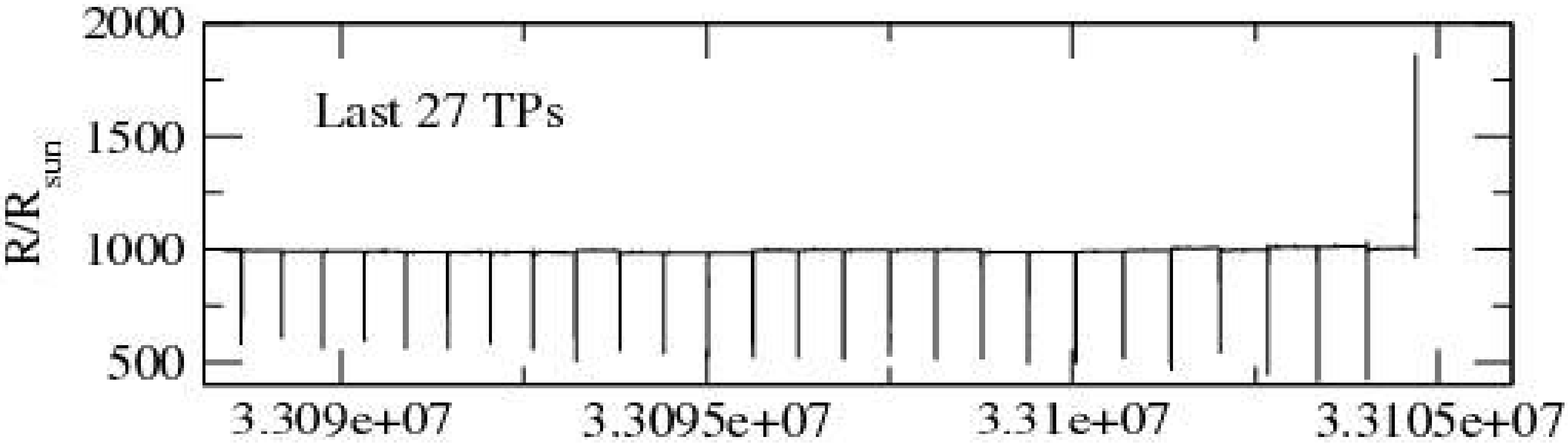
Hypothesis κ-peak

- Petrovic et al (2006)
  - OPAL opacity tables display a peak due to presence of Fe, Ni at T aprox. 250000 K
  - This peak causes ***huge inflation*** and departure of hydrostatic equilibrium in WR stars
- Could this be our case?

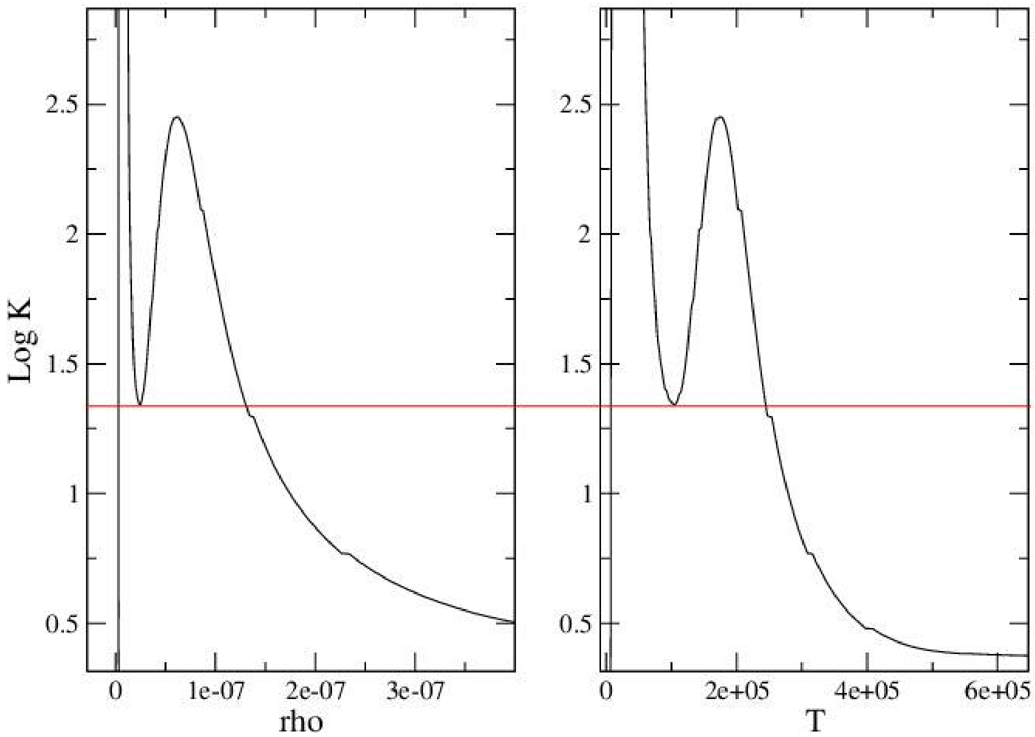
Testing the κ-peak hypothesis:
We do find the κ-peak



Look at that radius!

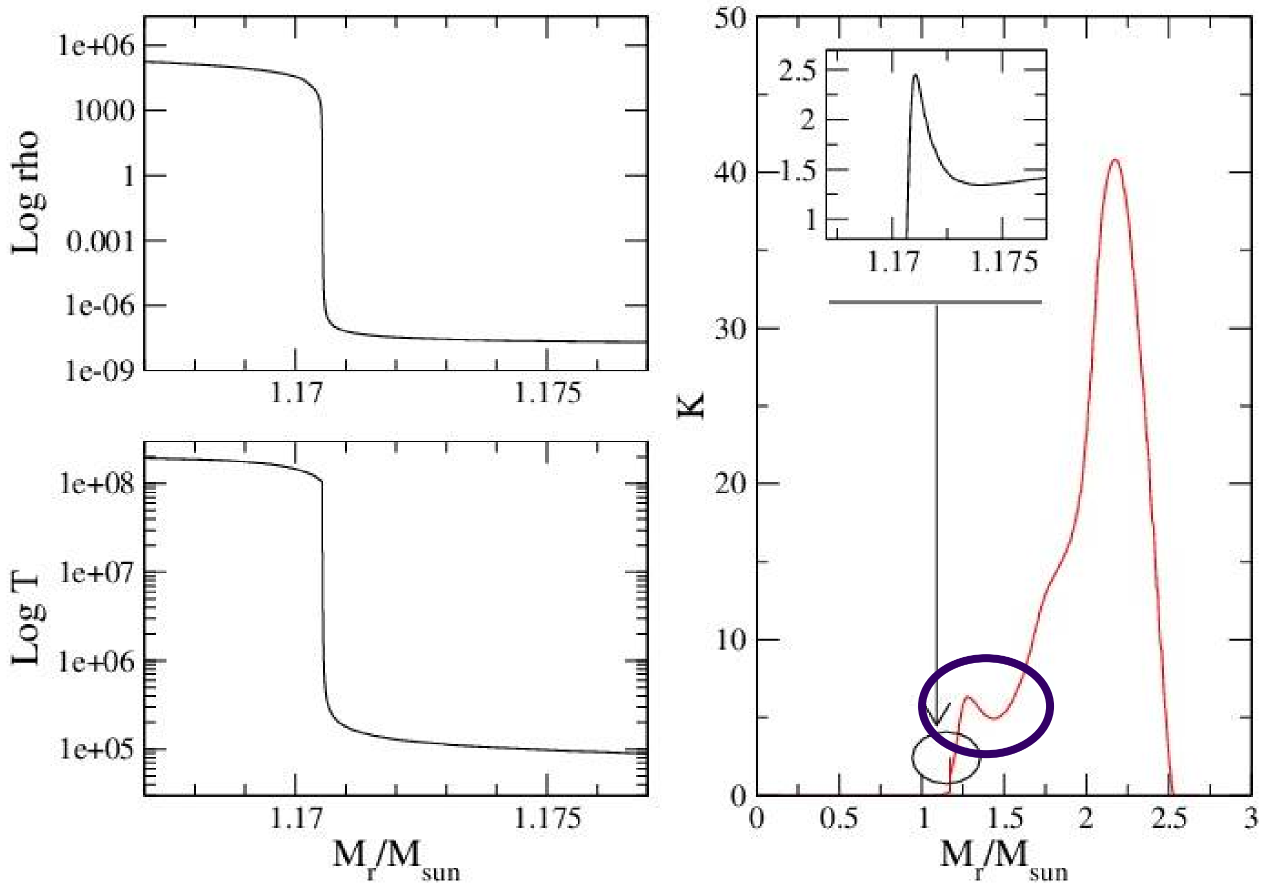


Testing the κ-peak hypothesis:

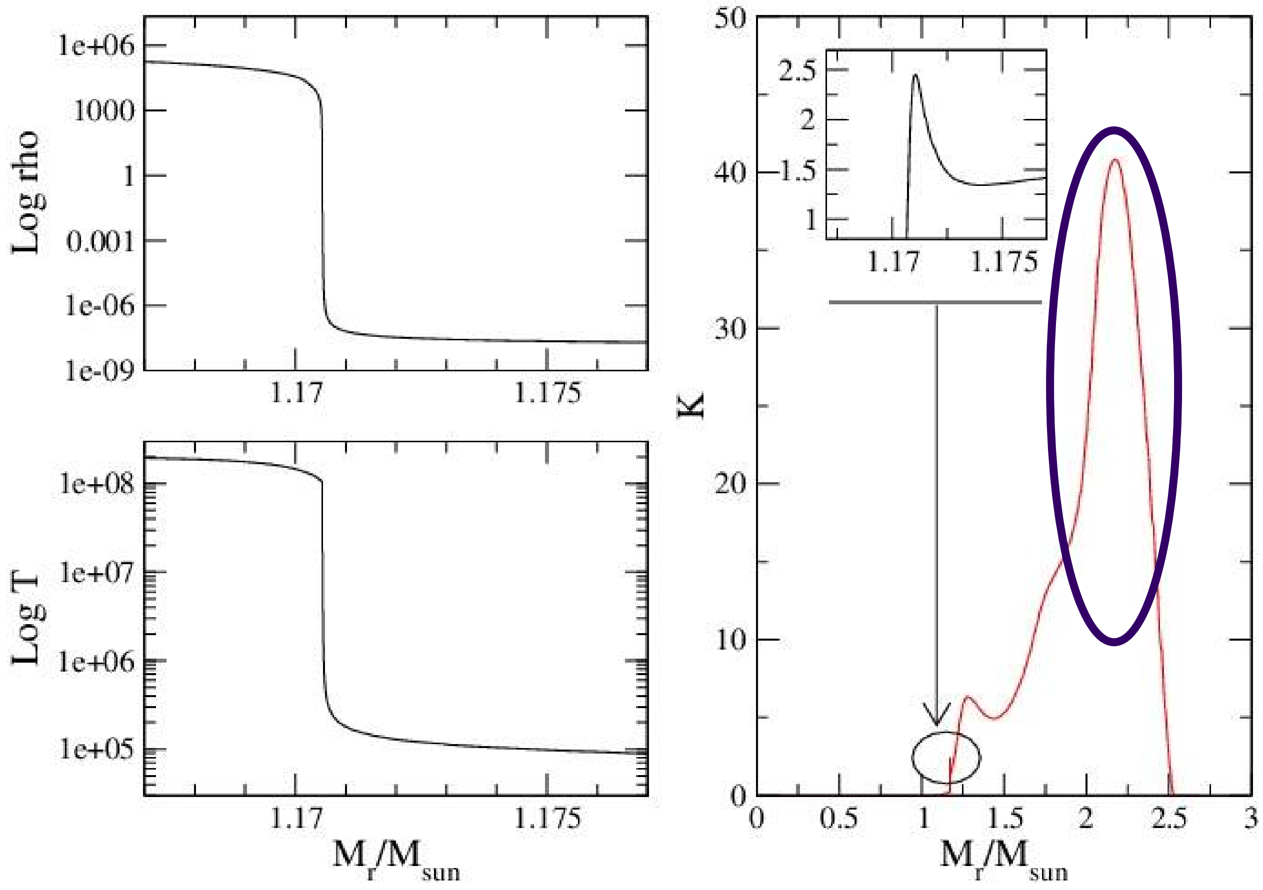


- We smoothed out the peak
- and the code keeps converging!
- The star lost a further 0.5 M_{sun}
- Before it died again!.

But there is another larger opacity peak…

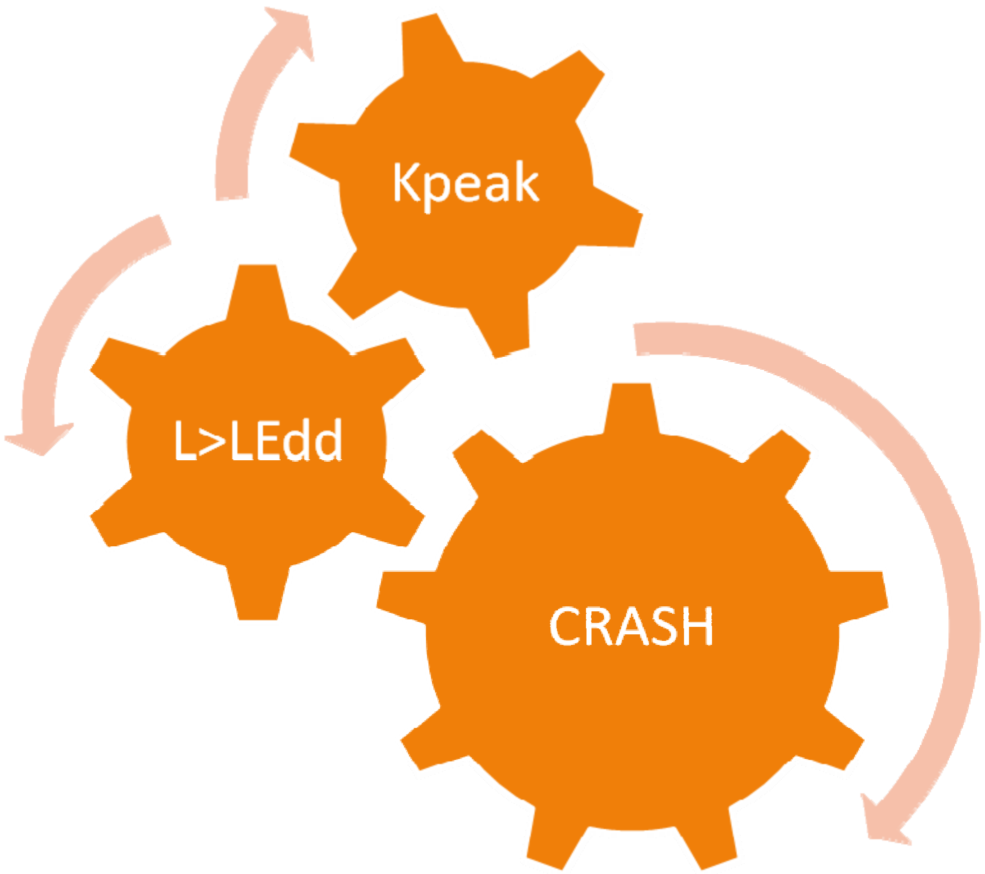


And another!



Log rho
1e+06
1000
1
0.001
1e-06
1e-09
1.17
1.175
Log T
1e+08
1e+07
1e+06
1e+05
1.17
1.175
M_r/M_sun
K
50
40
30
20
10
0
2.5
2
1.5
1
1.17
1.175
0
0.5
1
1.5
2
2.5
3
M_r/M_sun

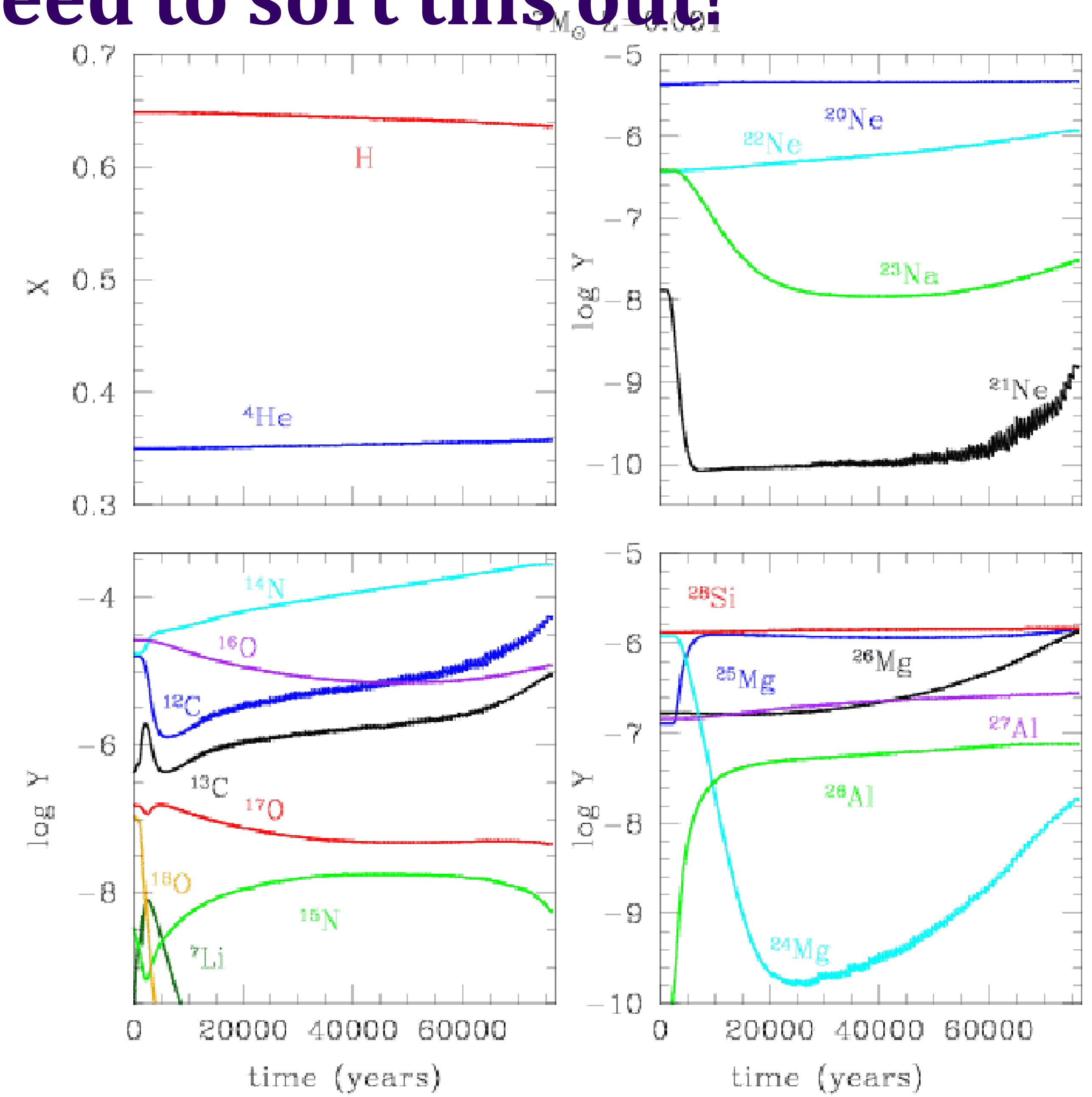
Hypothesis κ-peak



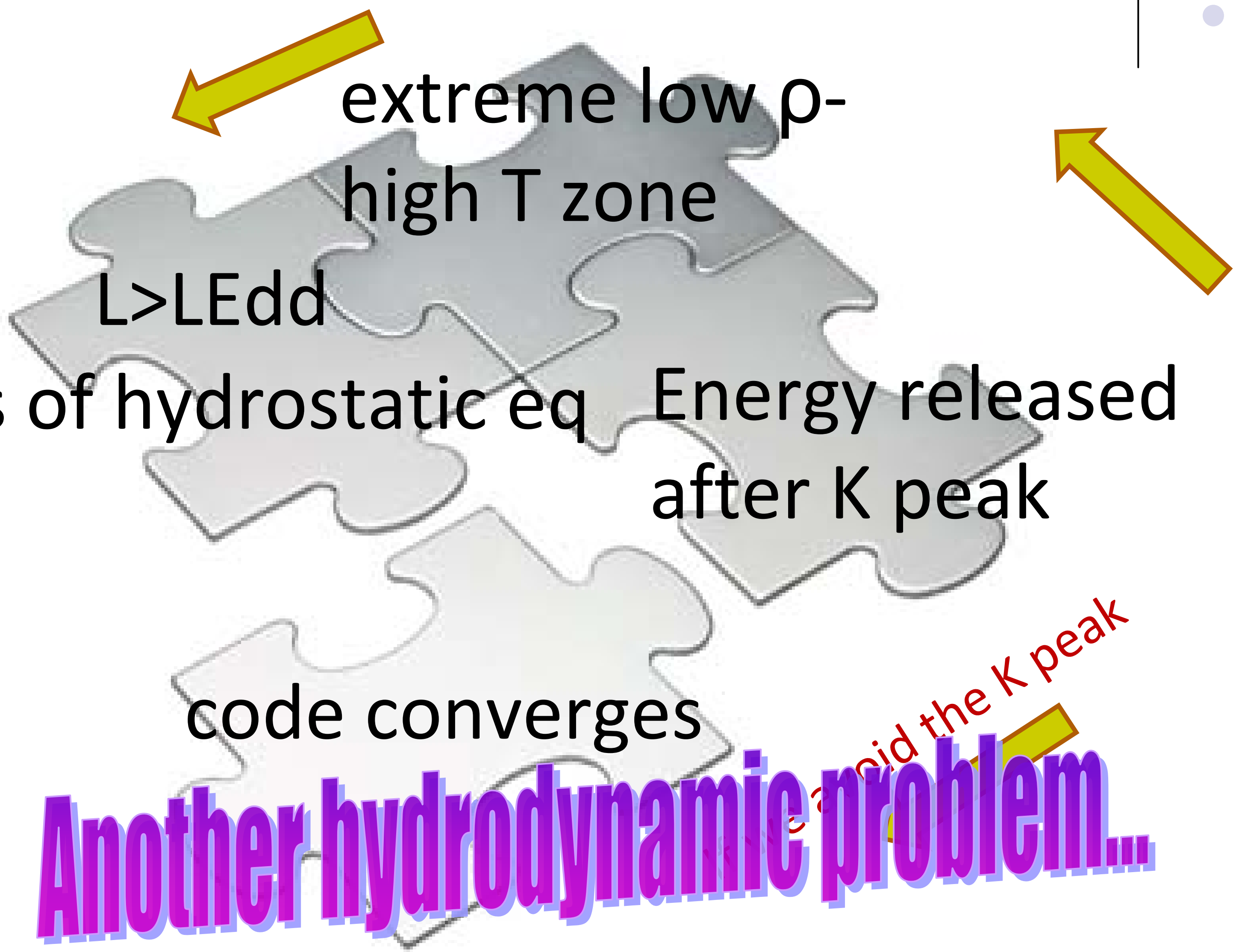
Multiple κ-peaks

- We doubt the star can avoid its fate…
- Deep envelope and low density mean a region of increasing opacity
- The high luminosity drives dramatic expansion
- In our hydrostatic case its supersonic!
  - $10^3 - 10^4\ R_\odot$ per year!
- What does a REAL star do?
- We think the energy involved < binding energy of the envelope
- But it might drive periodic, enhanced mass-loss at least?

We need to sort this out!



The general picture



Another hydrodynamic problem...

Calculating PIEs with DJEHUTY

Richard Stancliffe
David Dearborn
Stuart Heap
Simon Campbell
John Lattanzio

PIE = Proton Ingestion Episode

- Where convection mixes protons into a region that is much hotter than normal Hburning
- Dual Core Flash
- Dual Shell Flash

Dual Core Flash: Very low Z

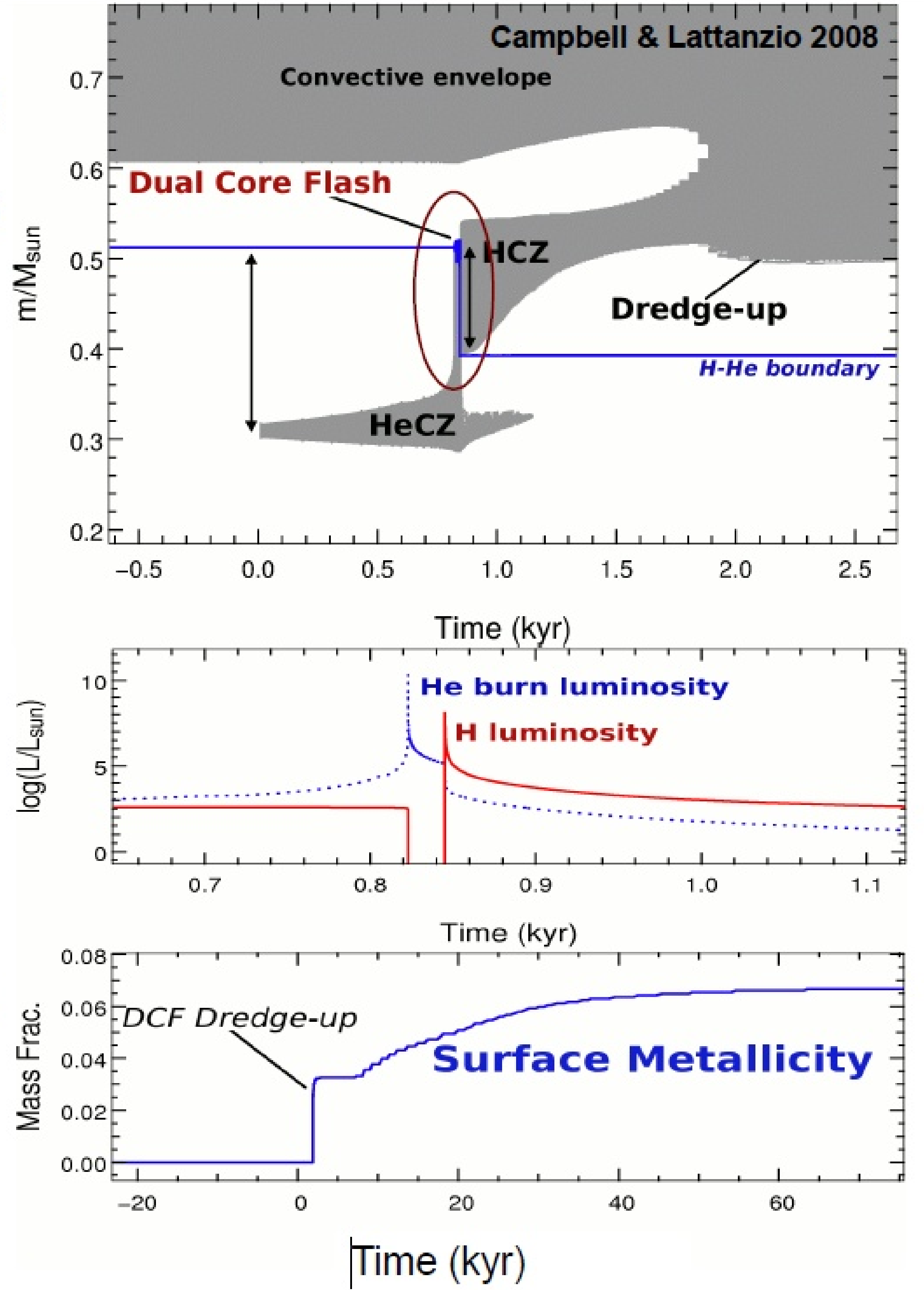
- Off-centre ignition
- But strong convection
- Mixing reaches H-rich envelope
- Does not (?)happen at “normal” Z

Dual Core Flash: Details

- The mixing of protons downwards into high temperature regions naturally causes very rapid H burning.
- → **Hydrogen Flash!**
- **The He flash is still ongoing** (hence name 'dual flash')
- He burning products are mixed upwards also.

➢ This material is later dredged up into the envelope, polluting the surface.

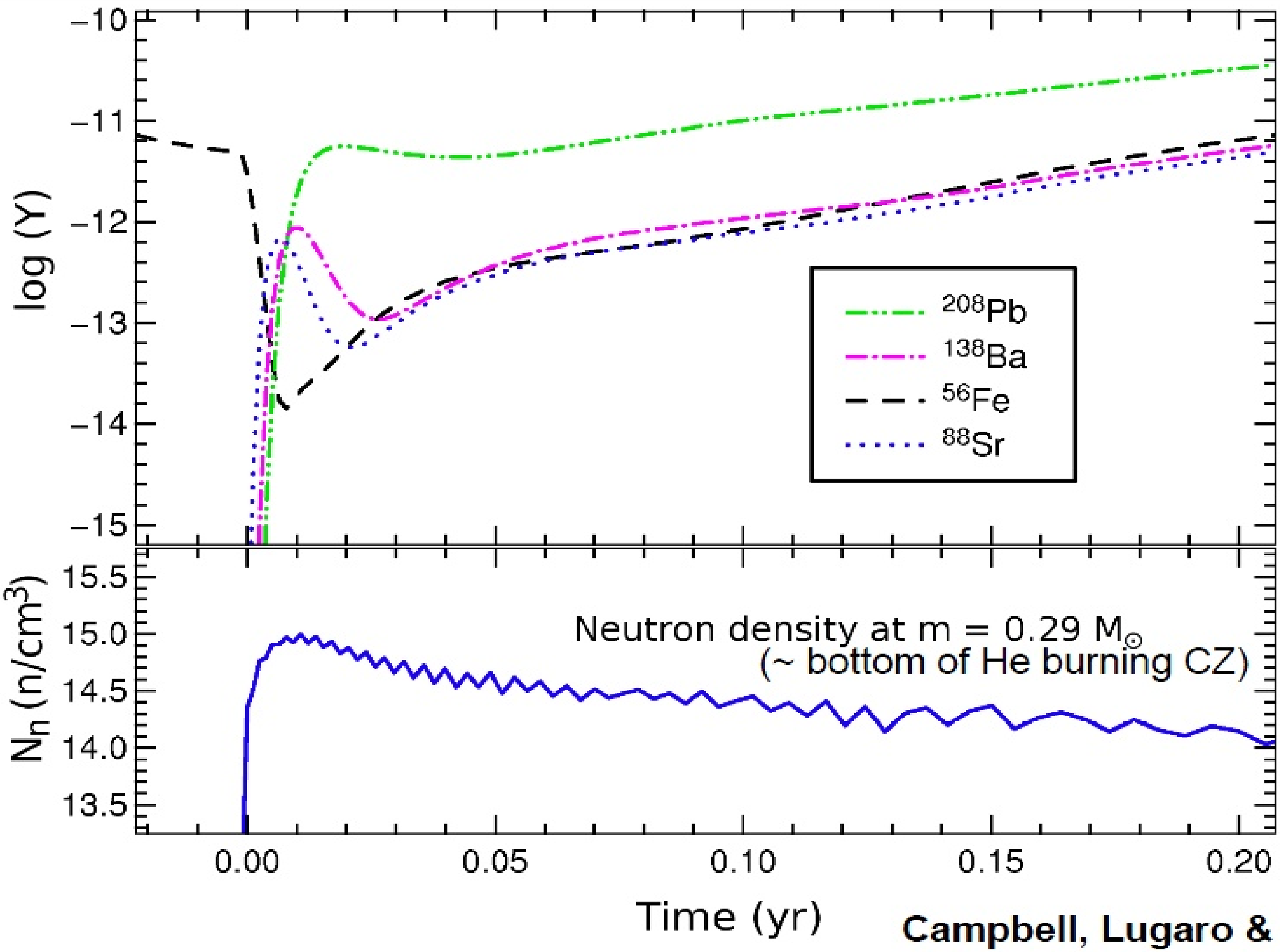
➢ Fujimoto et al. (1990) suggested **that the excess C in the CEMPs may come from these peculiar surface pollution events**.



Neutron Super-burst!

Resulting abundances as function of time

(sampled at the location of the maximum of the neutron density)

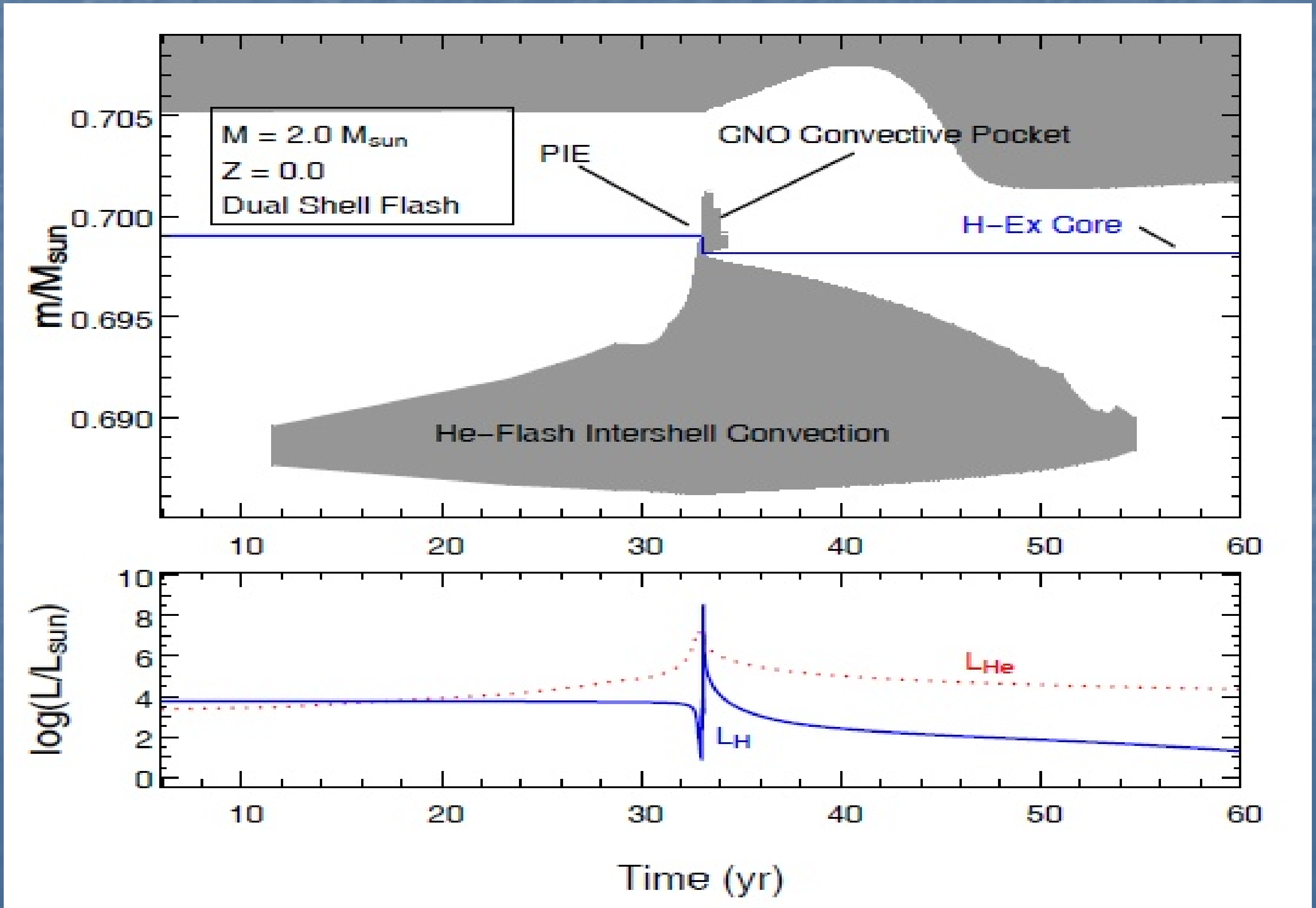


- Strong s-processing!
- Abundances of Ba, Pb reach ***absolute*** Solar abundances!!
- [Pb/Fe] ~ +6 after dredge-up to surface
- s-process continues until ^{14}N becomes more abundant than ^{13}C and soaks up most of the free neutrons.
- n exposure ~ 250 mbarn^{-1}

Campbell, Lugaro & Karakas 2010

Dual Shell Flashes

- For low Z stars on the AGB
- PIE can occur



PIEs

- Expect neutron production
- Expect s-processing
- But how to calculate the time-dependent mixing?

Wrong!

- Mostly treat mixing with diffusion equation

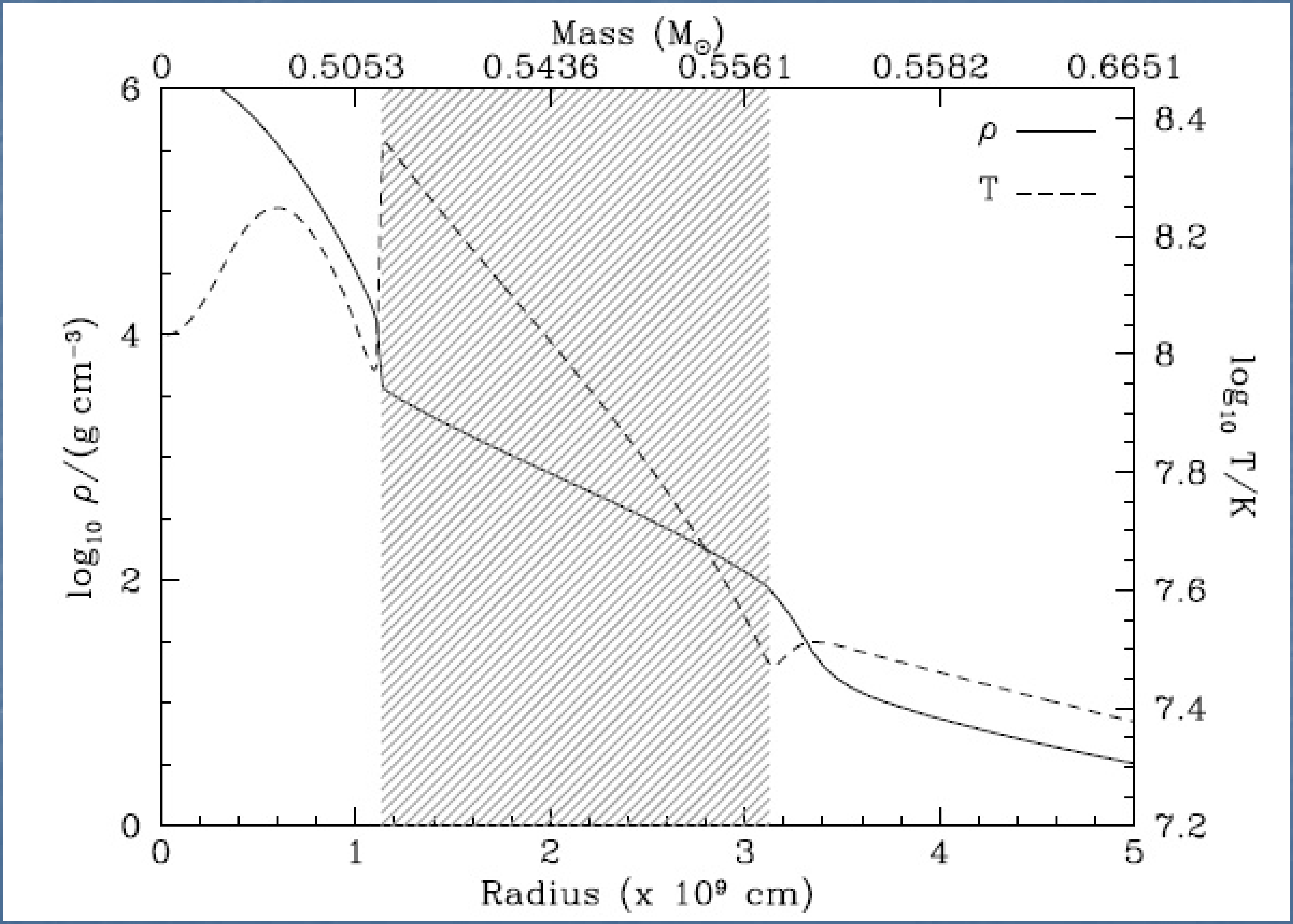
Wrong!

- Mostly use MLT for values of v

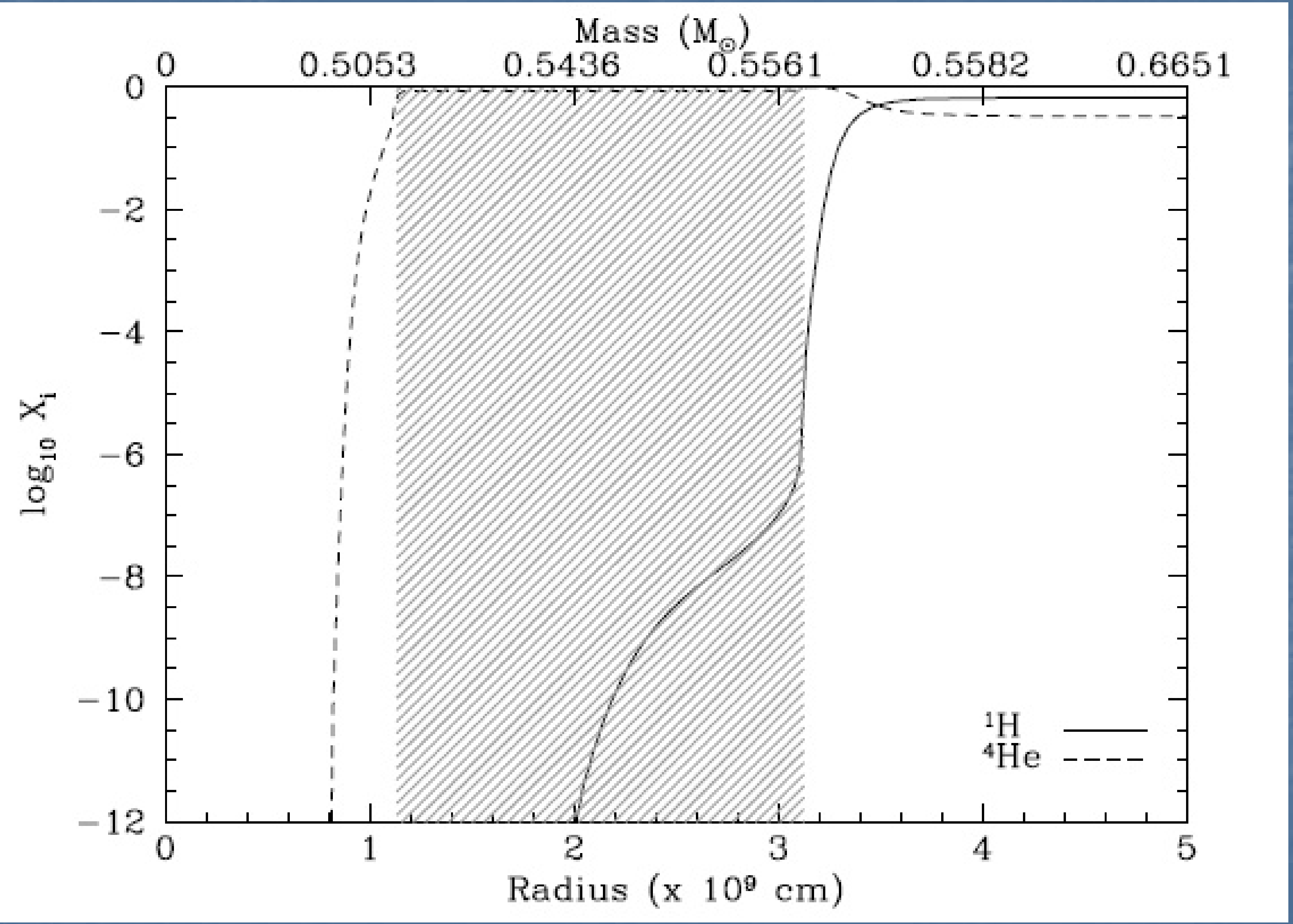
Try to do in 3D using DJEHUTY

- Paper just submitted to ApJ
- Dual shell flash
  - M=1
  - Z=0.0001
- He shell flash convection reaches bottom of H-shell and ingests protons

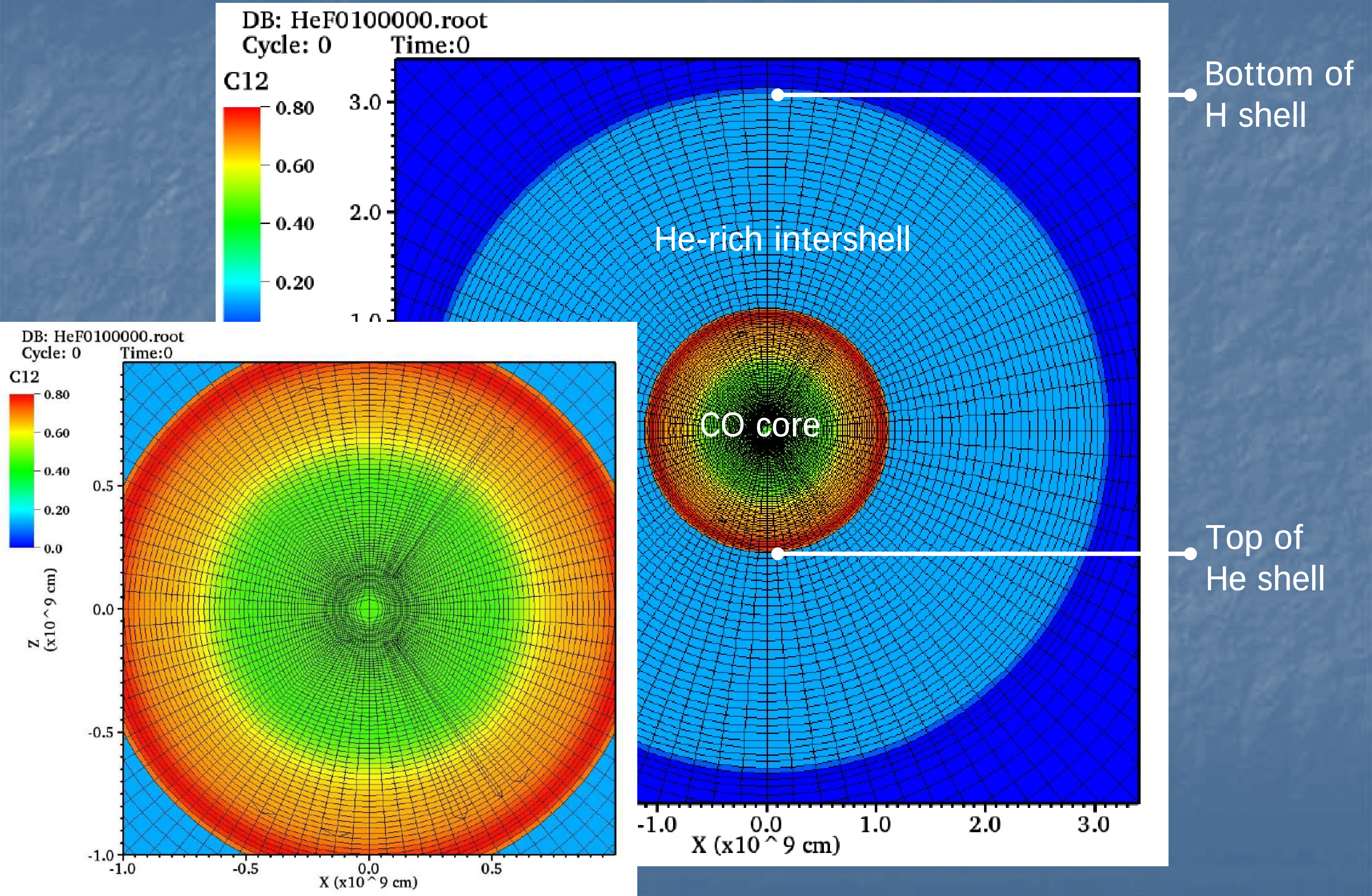
1D input model



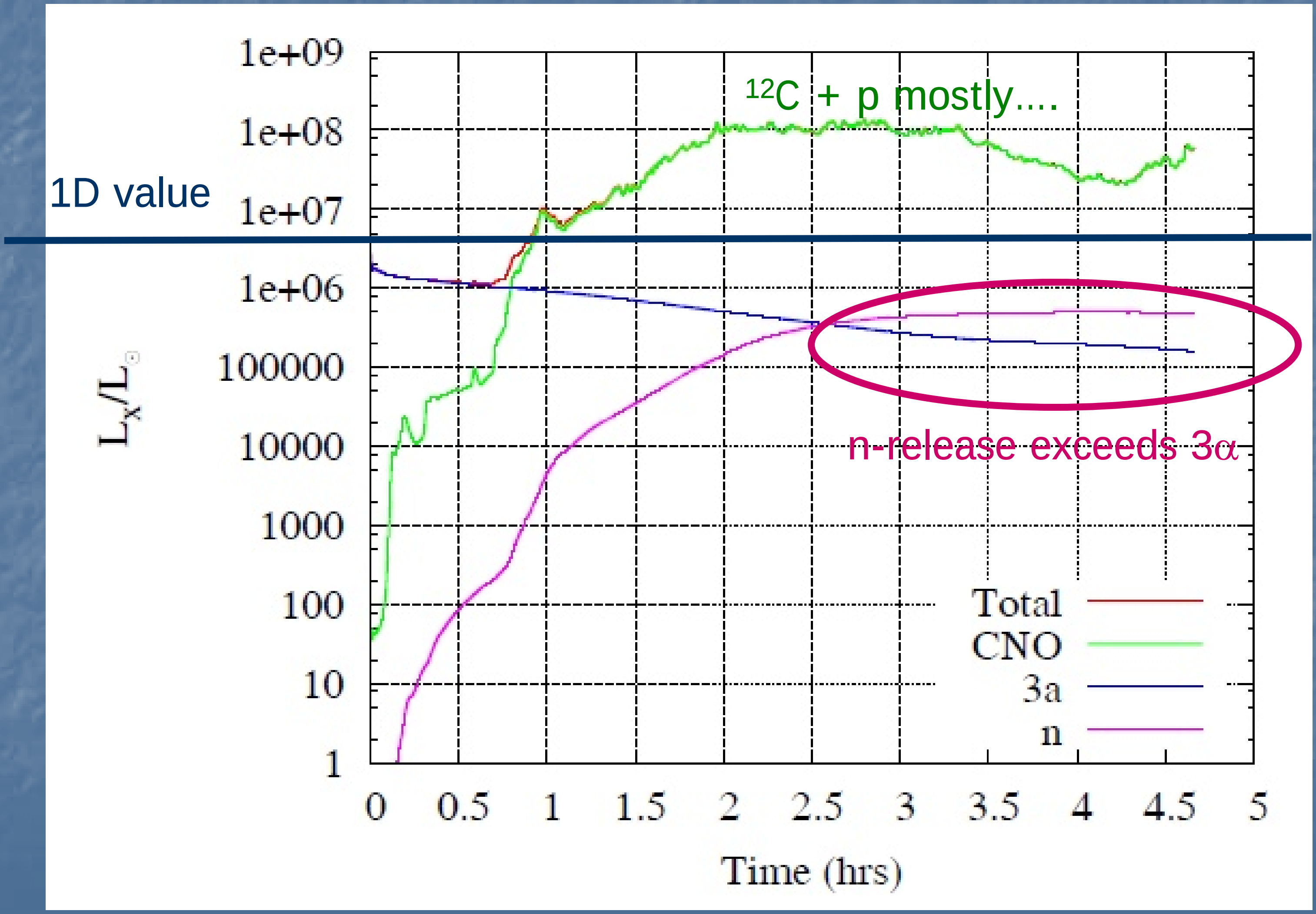
1D input model



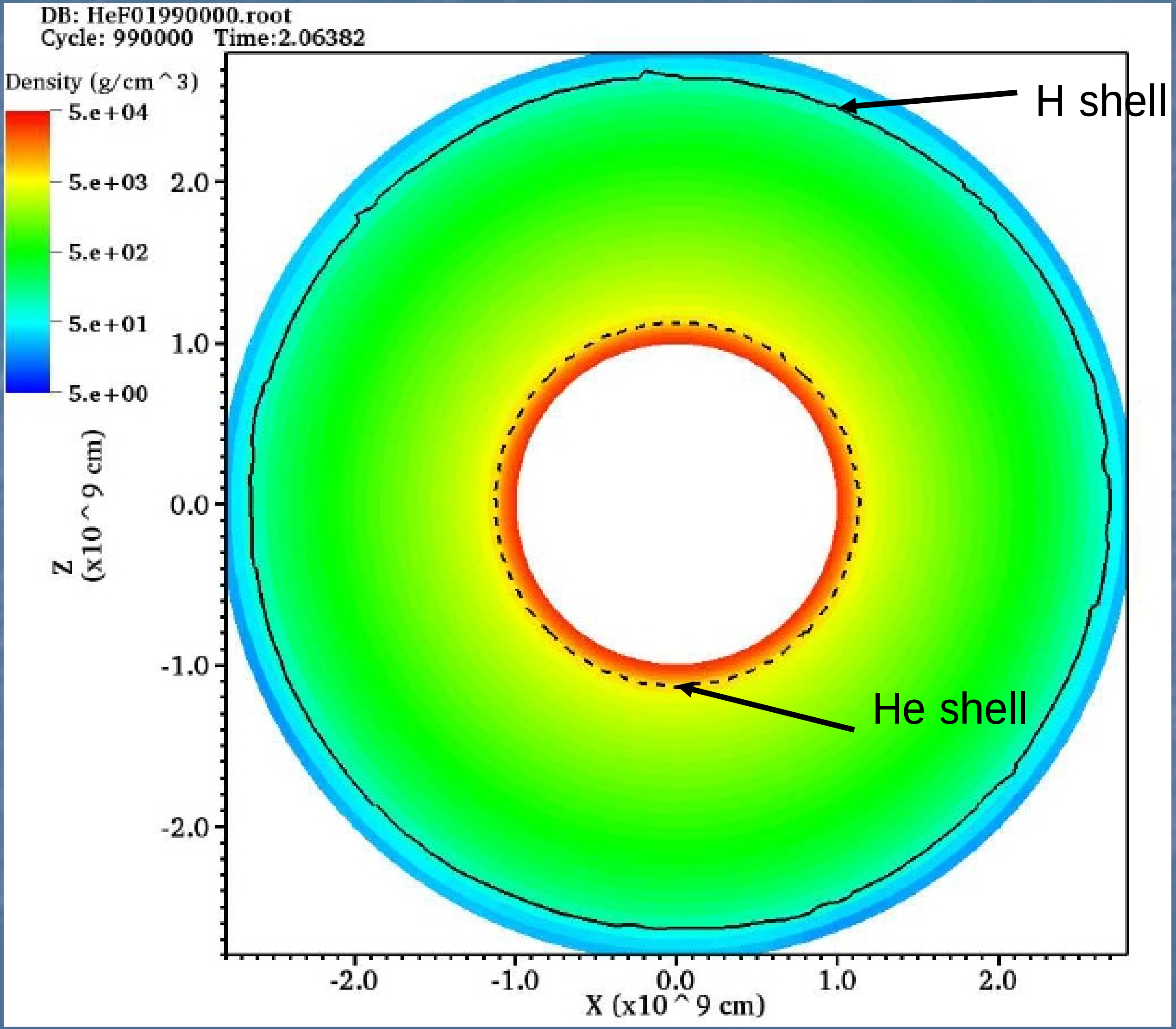
The 3D calculation (2 million zones)



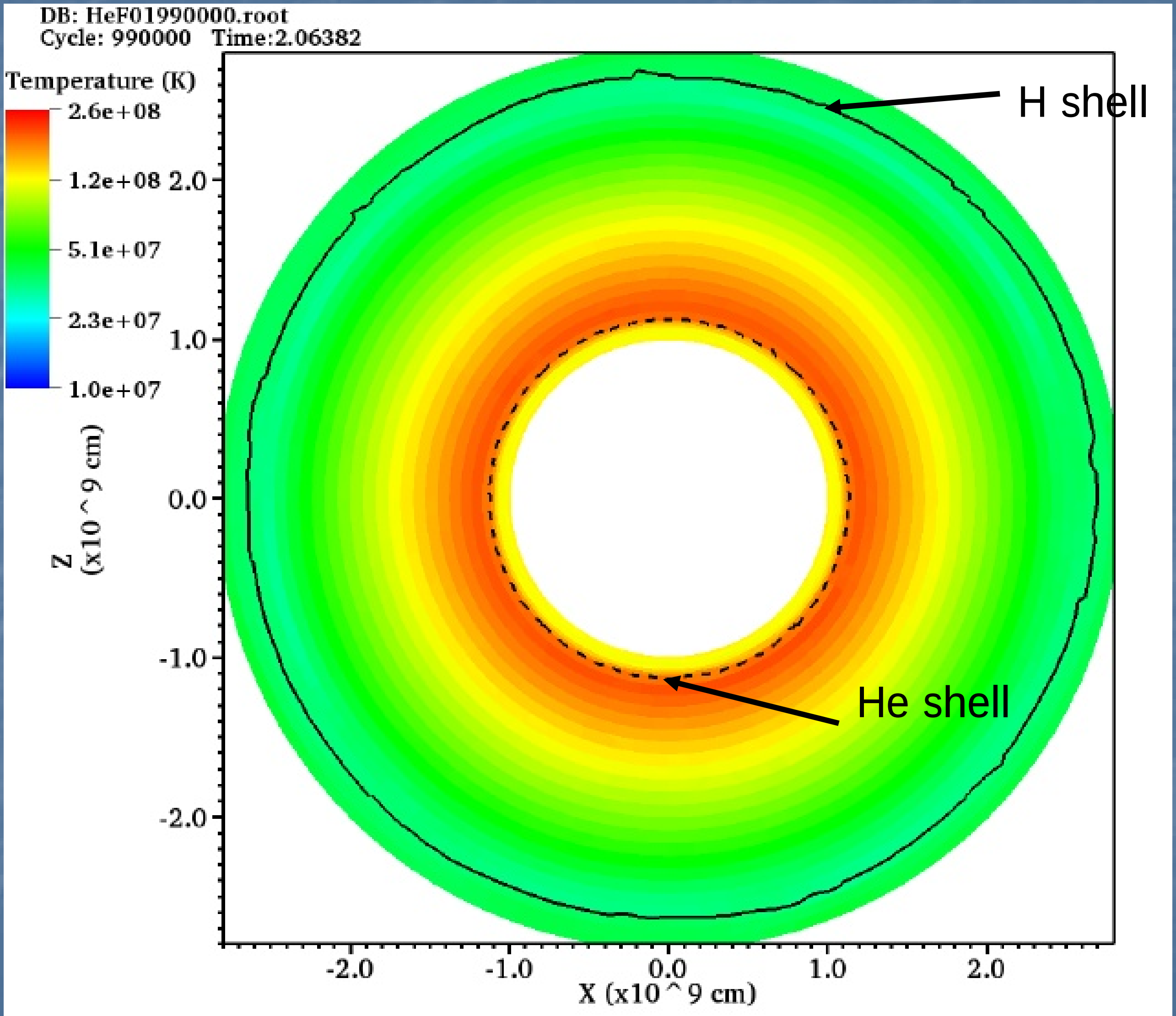
Luminosity variation/increase!



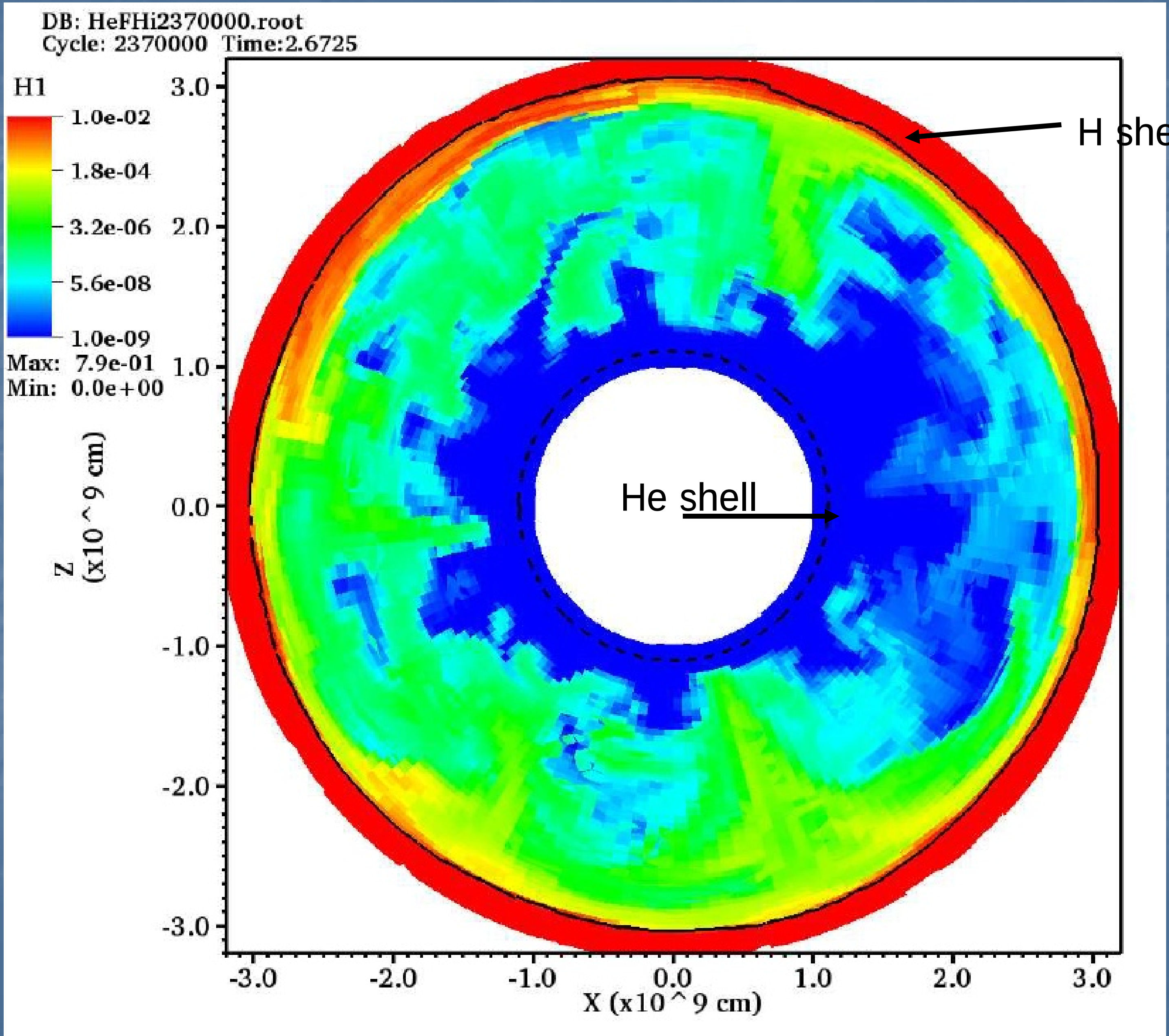
Density (on a slice) t=2.0hrs



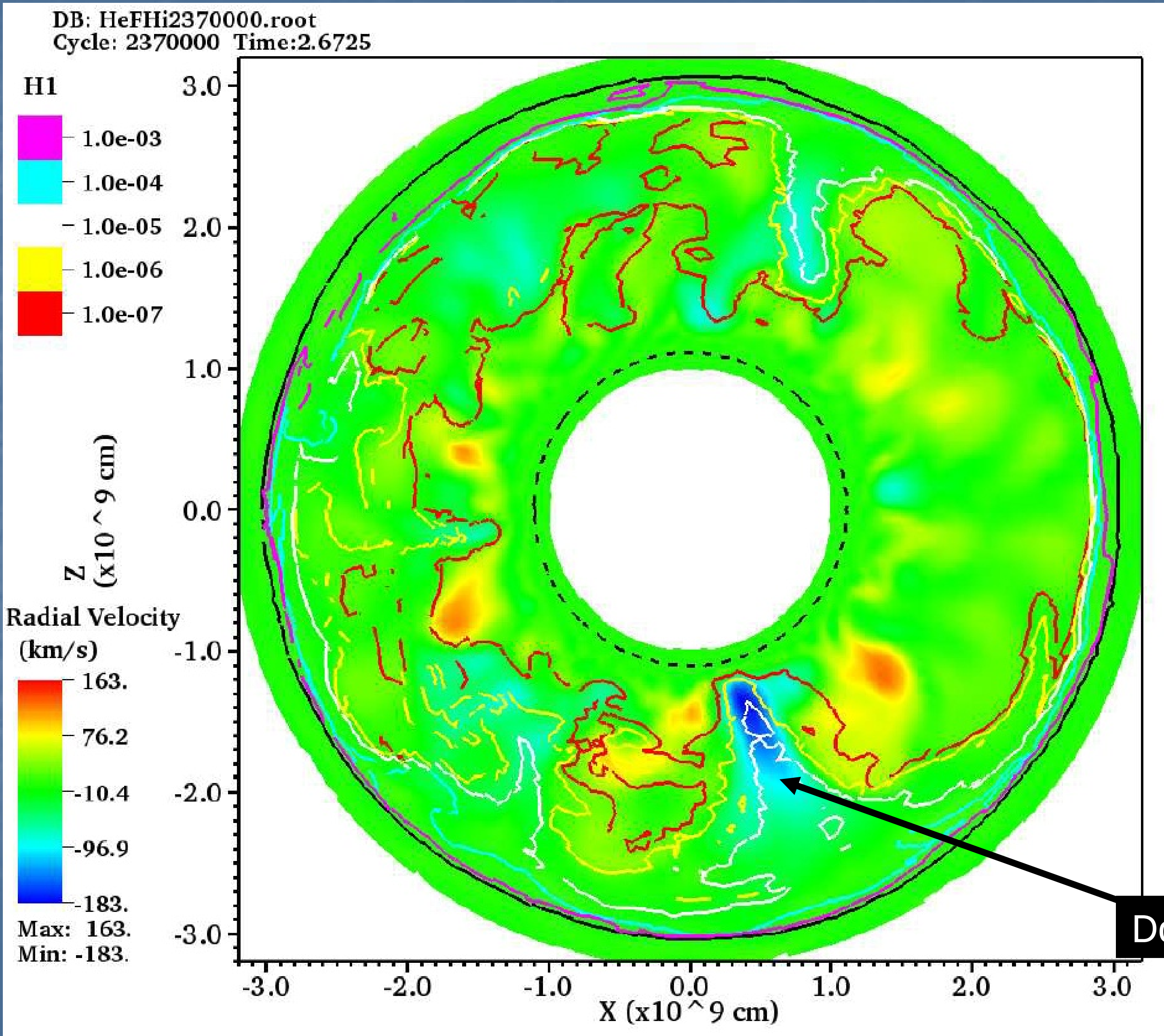
Temperature (on a slice) t=2.0hrs



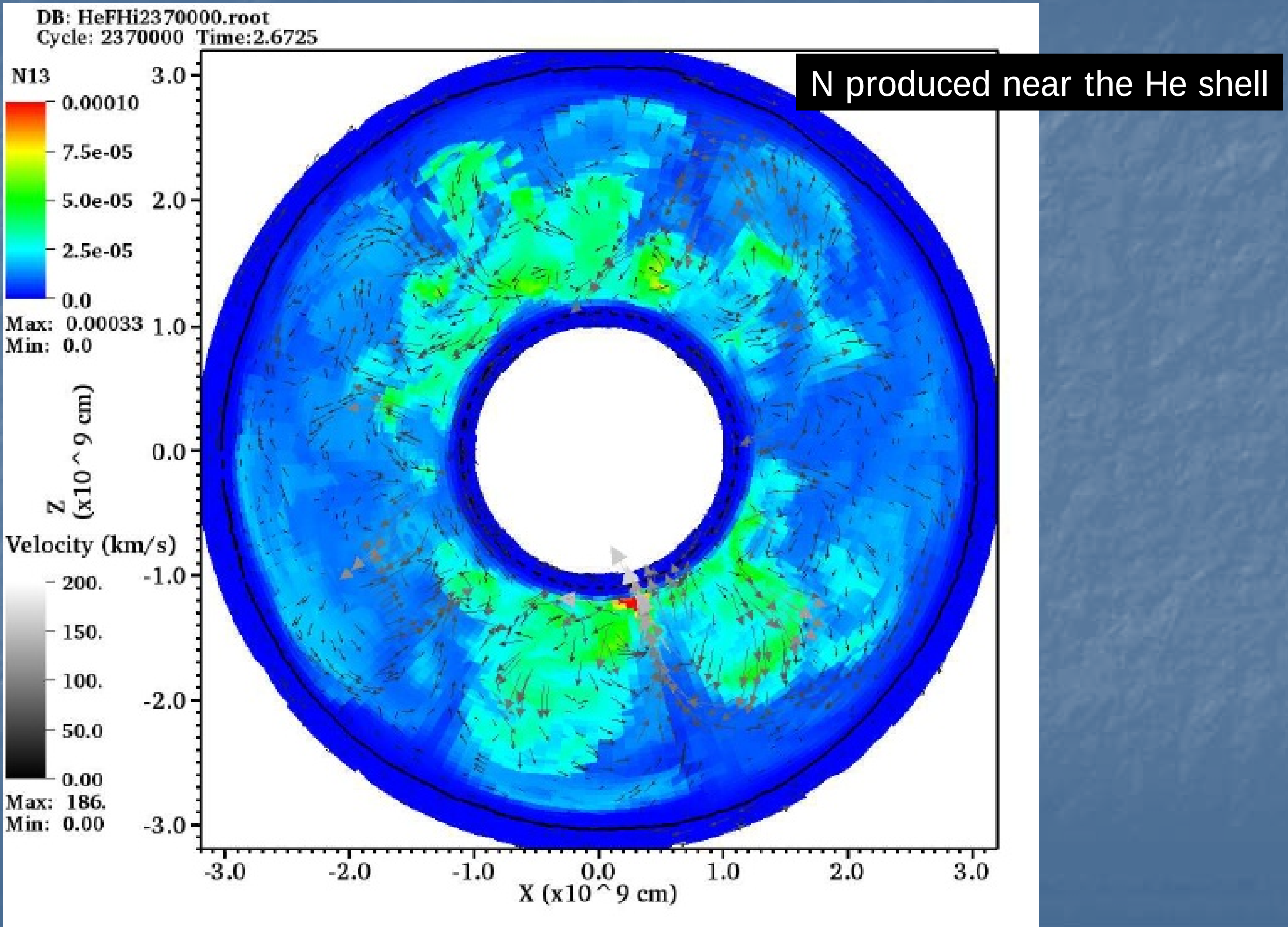
Hydrogen (on a slice) t=2.7hrs



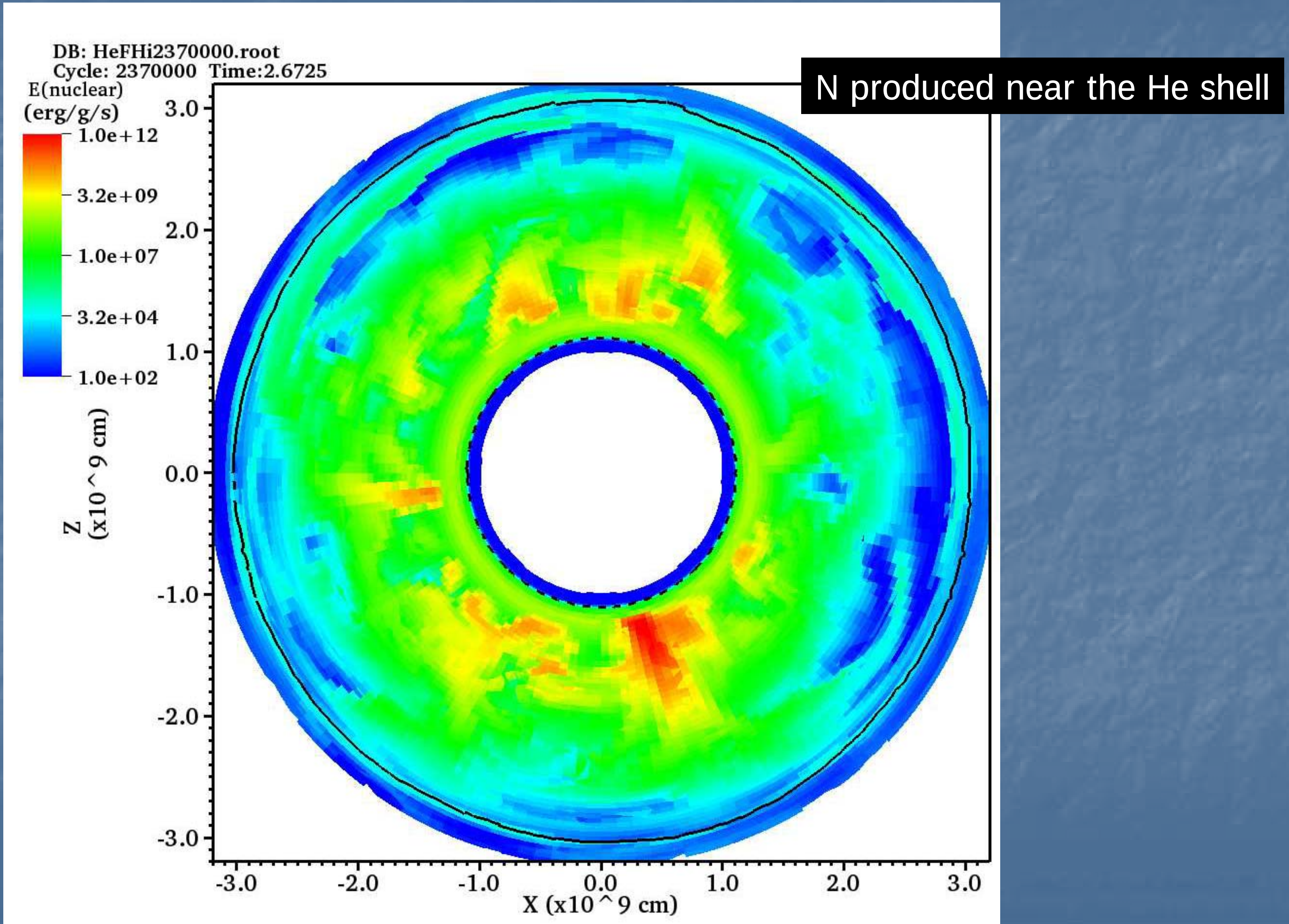
Hydrogen (on a slice) t=2.7hrs



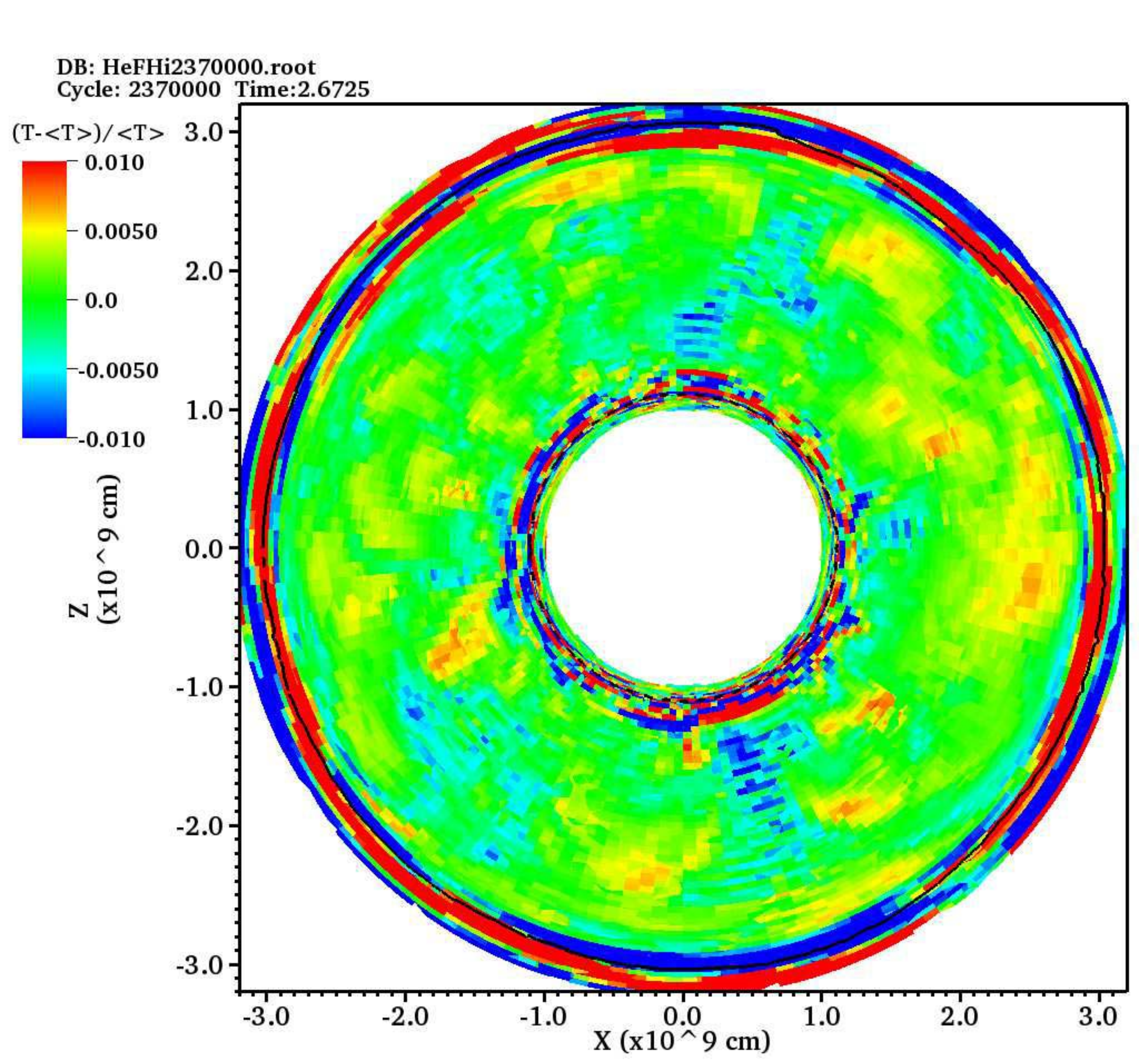
^{13}N and v (in plane) (on a slice) t=2.7hrs



Energy generation (on a slice) t=2.7hrs



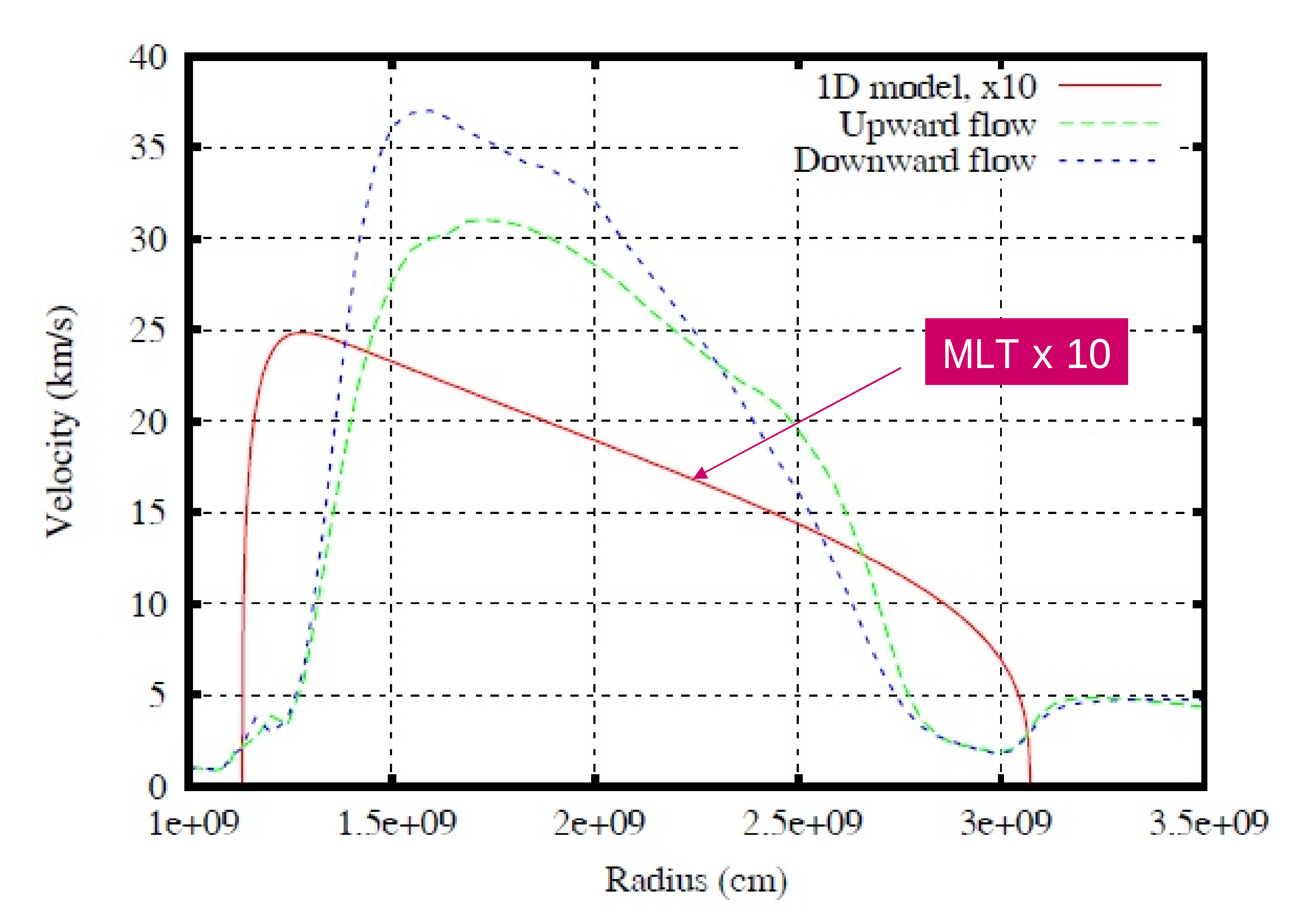
T variation (on a slice) t=2.7hrs



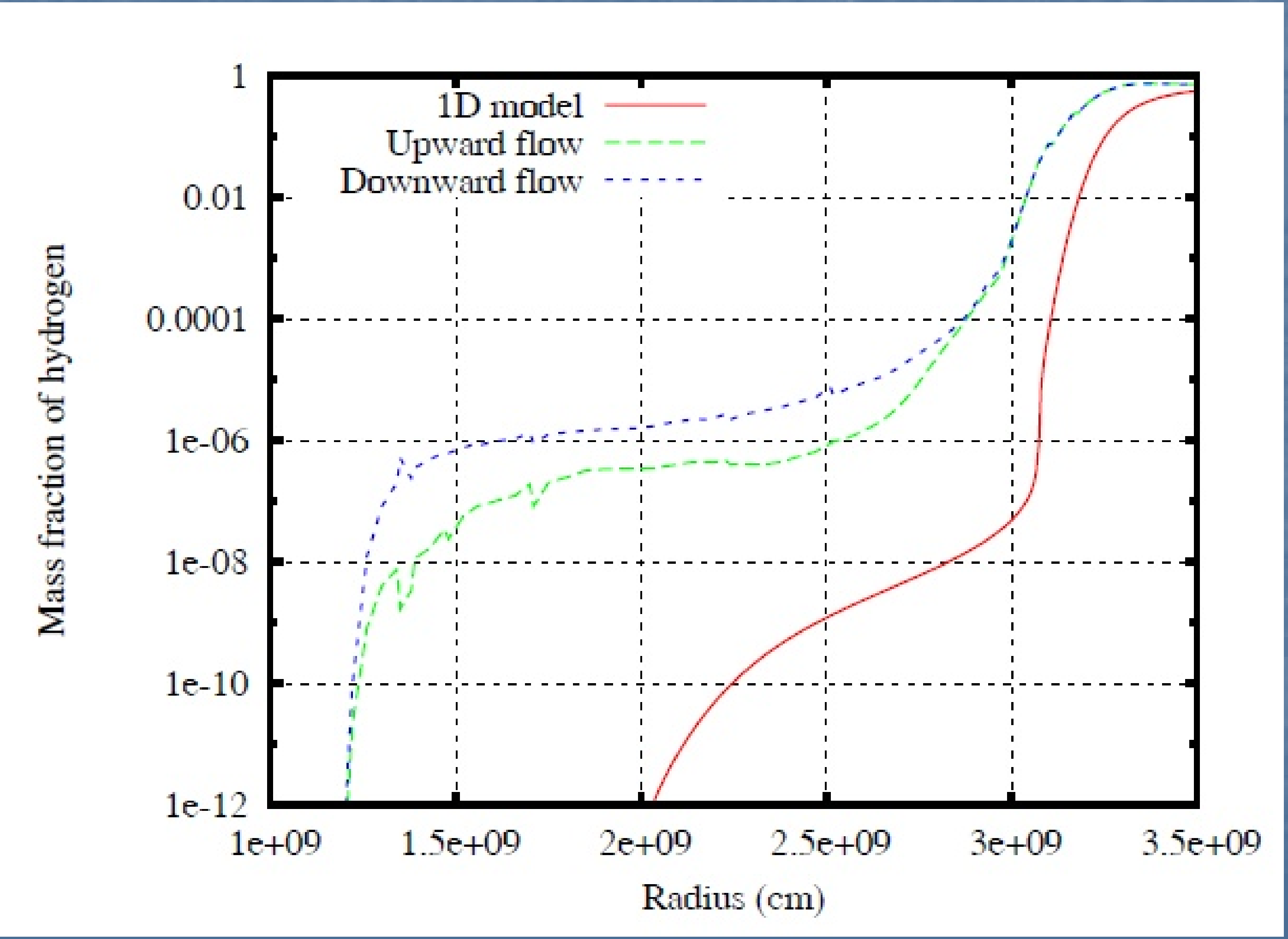
Very minor!

T-<T>
-------- ≈ ± 1%
<T>

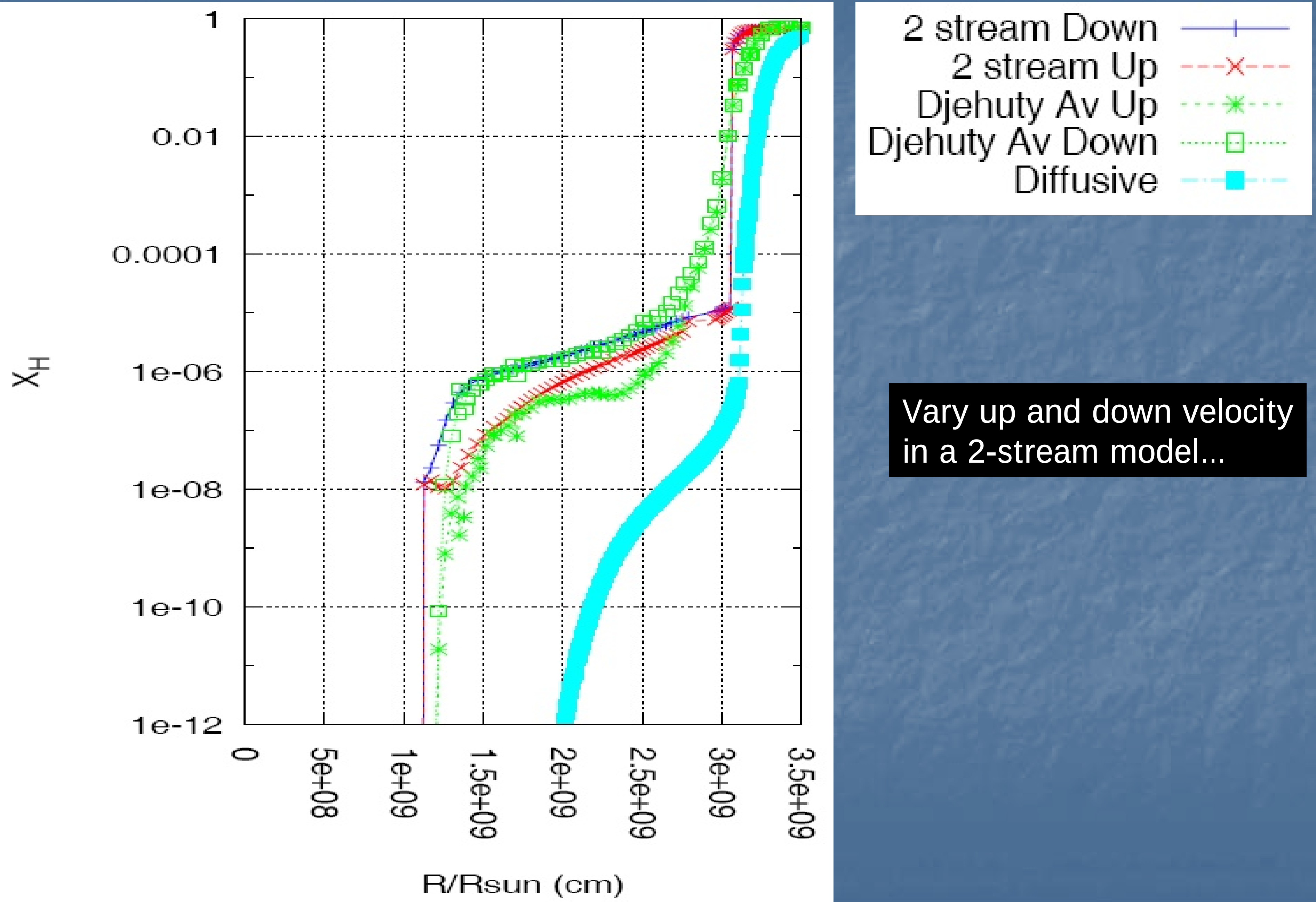
Comparison to 1D: velocity profiles



Comparison to 1D: H profiles



321D Theory (with Arnett et al)



Vary up and down velocity in a 2-stream model...