Title: Recipes to energize core-collapse supernova explosions

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Abstract: Recent multidimensional supernova simulations seem to support an assumption that the neutrino-driven mechanism might work to blow up massive stars. However the explosion energies obtained in those simulations are usually not enough to account for the canonical explosion energy of 10^51 ergs. In this contribution we'd like to address whether some new physical elements so far ignored in the supernova simulations would or would not have an impact on the neutrino-heating mechanism such as the effects of neutrino self-interactions nuclear burning and the turbulent heatingdue to the magneto-rotational instability. These effects are included in our 2D simulations with the spectral neutrino transport (Suwa et al. (2010)).In addition we will report our 3D results based on the 3D version of the code and discuss their potential impacts on the explosion mechanism. Based on these results we will compute the gravitational radiation and neutrinoemission and then discuss some prospects towards multi-messenger astronomyof supernova explosions.

What do we have as **a microphysical tool** to solve the long-standing supernova puzzle ?

"Several toolkits in our group (NAOJ)"

- ✓ Leakage and light-bulb scheme
- ✓ Energy-integrated M1 scheme (in progress)
- ✓ IDSA scheme (developed by M.Liebendoerfer (2009))
- ✓ General relativistic ray-tracing scheme

Equations of State (EOSs): (Lattimer & Swesty (1991), Shen et al.(98))

- ✓ Lattimer-Swesty (Kx3) and H-Shen

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“Several lessons” (we have recently learned)
in ever-lasting , day&night (unhealthy!), trial & error
debugging to implement “*microphysics*”
in our supernova code.

The first topic is about the IDSA scheme

(Liebendoerfer et al. (2009))

Pros: can reproduce the 1D Boltzmann results

: can save computational time (100 faster) than Boltzmann solvers
(good for the 1st generation 3D simulations!)

Cons: heavy lepton neutrinos :not yet included.

- should affect the post-bounce dynamics.

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✓ The best way : implement them in the IDSA, but not yet done (ultimate goal: Ott et al.(08), Sumiyoshi+(11))

✓ We treat cooling via nu_X by the following three schemes, either by leakage, FLD , or **M1-closure scheme.**

Rosswog & Liebendoerfer (2003)

Bruenn et al. 1985, Livne et al. 2005

The M1-based neutrino transport scheme for SN simulations

$$\partial_t E_\nu + \nabla F_\nu = Q^0_\nu \quad (0^{\text{th}}\text{-order moment equation})$$
$$\partial_t F_\nu + \nabla P_\nu = Q^1_\nu \quad (1^{\text{st}}\text{-order moment equation})$$

Obergaulinger and Janka (2010)

✓In the M1-closure scheme, one solves up to the 1st -order moment of the B ec

$P_\nu = P_\nu(E_\nu, F_\nu)$ For closing the hierarchy, one assumes the following relations

Eddington factor

$$P^{ij}_\nu = \left(\frac{1-p_\nu}{2}\delta^{ij} + \frac{3p_\nu - 1}{2}\frac{F^i_\nu F^j_\nu}{F^2_\nu}\right)E_\nu$$

(Audit et al. 2002)

$$p_\nu = \frac{1}{3} + \frac{1}{15}\left(6f^2_\nu - 2f^3_\nu + 6f^4_\nu\right)$$

Flux factor

$$f_\nu = F_\nu / cE_\nu$$

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☆Taking the diffusion limit, fv →0

p_ν →1/3, Pv→ 1/3 Ev

☆streaming limit, fv →1

p_ν →1, Pv→ Ev

✓Like the FLD scheme, the M1 scheme bridges the two limits.

✓ This scheme may be better than FLD, because it can be used in GR simulations.

Two steps in evolving the radiation variables of E_{nu}, F_{nu}

electron-type neutrino absorption on neutrons $\nu_e + n \rightarrow e^- +$

$f(\omega,\mu) = f_{\rm FD}(\omega)\left(1 + 3 f_{\rm rad}\mu\right.$

$$
\begin{aligned}
\left(\frac{\partial E_\nu}{\partial t}\right) &= \frac{c}{(2\pi\hbar c)^3}\int \omega^3 {\rm d}\omega j(\omega)(1 - f(\omega,\mu,T)) - f(\omega,\mu,T)/\lambda^{(a)}(\omega) \\
&= \frac{c}{(2\pi\hbar c)^3}\int \omega^3 {\rm d}\omega j(\omega) - \left(j(\omega) + 1/\lambda^{(a)}\right) f(\omega,\mu,T) \\
&= \frac{c}{(2\pi\hbar c)^3}\int \omega^3 {\rm d}\omega j(\omega) - j(\omega)\left(1 + \exp\left(\frac{\omega-\mu_0}{kT}\right)\right) f(\omega,\nu,T) \\
&= \frac{c}{(2\pi\hbar c)^3}\int \omega^3 {\rm d}\omega j(\omega) - j(\omega)/f_{\rm FD}(\omega,\mu_0,T)\, f(\omega,\mu,T) \\
&\sim J_\beta E_e - K_\beta E_\nu
\end{aligned}
$$

$$
\begin{aligned}
\left(\frac{\partial F_\nu}{\partial t}\right) &= \frac{1}{2(2\pi\hbar c)^3}\int \mu {\rm d}\mu \int \omega^3 {\rm d}\omega j(\omega)(1 - f(\omega,\mu)) - f(\omega,\mu)/\lambda^{(a)}(\omega) \\
&= \frac{1}{2(2\pi\hbar c)^3}\int \mu {\rm d}\mu \int \omega^3 {\rm d}\omega - \left(j(\omega) + 1/\lambda^{(a)}\right) 3\mu f_{\rm rad} f(\omega,\mu,T) \\
&= \frac{1}{(2\pi\hbar c)^3}\int \omega^3 {\rm d}\omega - j(\omega)/f(\omega,\mu_0,T)\, f_{\rm rad} f(\omega,\mu,T) \\
&= -K_\beta F_\nu
\end{aligned}
$$

✓ In computing the neutrino-matter coupling (r.h.s. of the B-eqns

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$$\left(\frac{\partial E_\nu}{\partial t}\right) = \frac{c}{(2\pi\hbar c)^3}\int \omega^3 \mathrm{d}\omega j(\omega)(1 - f(\omega,\mu,T)) - f(\omega,\mu,T)/\lambda^{(a)}(\omega)$$

$f(\omega,\mu) = f_{\mathrm{FD}}(\omega)(1 + 3 f_{\mathrm{rad}}\mu$

$= \frac{c}{(\ldots}$

$\sim J_{\ldots}$

The second step is "advection" by the characteristic speed, which can be straightforwardedly done.

$$\partial_t E + \partial_x F^{\hat{x}} = 0$$

$$\partial_t F^{\hat{x}} + \partial_x\left(\frac{1-\chi}{2}E + \frac{3\chi-1}{2}F^{\hat{x}}F^{\hat{x}}/E\right) = 0$$

$$\left(\frac{\partial F_\nu}{\partial t}\right) = \frac{\ldots}{2\ldots}$$

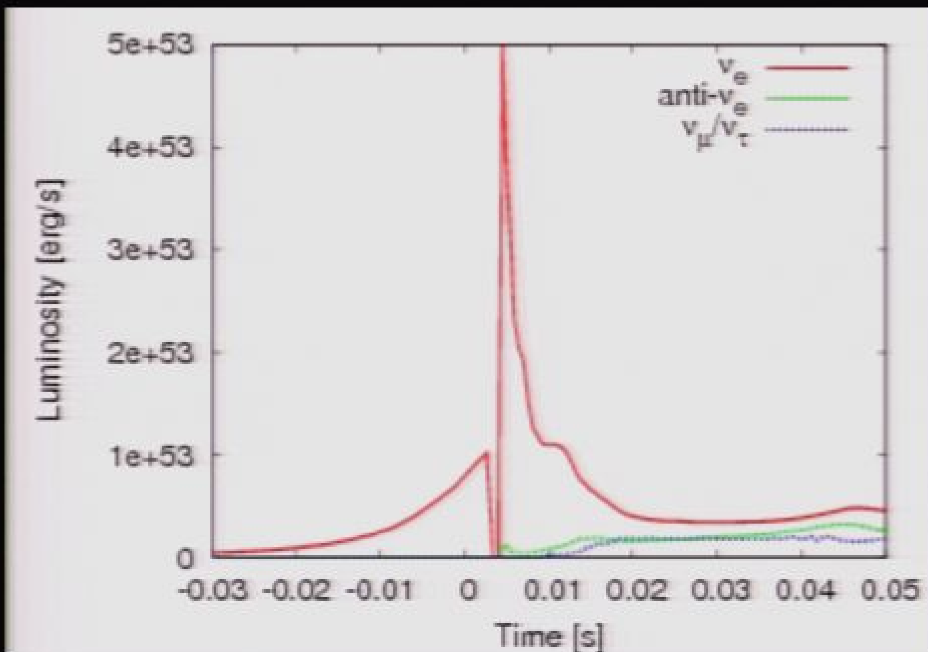
$$\partial_t \begin{pmatrix} E \\ F^{\hat{x}} \end{pmatrix} + \begin{pmatrix} 0 & 1 \\ \frac{1-\chi}{2} - \frac{3\chi-1}{2}\frac{F^{\hat{x}2}}{E^2} & \frac{3\chi-1}{2}2\frac{F^{\hat{x}}}{E} \end{pmatrix} \partial_x \begin{pmatrix} E \\ F^{\hat{x}} \end{pmatrix} = 0$$

$= -K_\beta F_\nu$

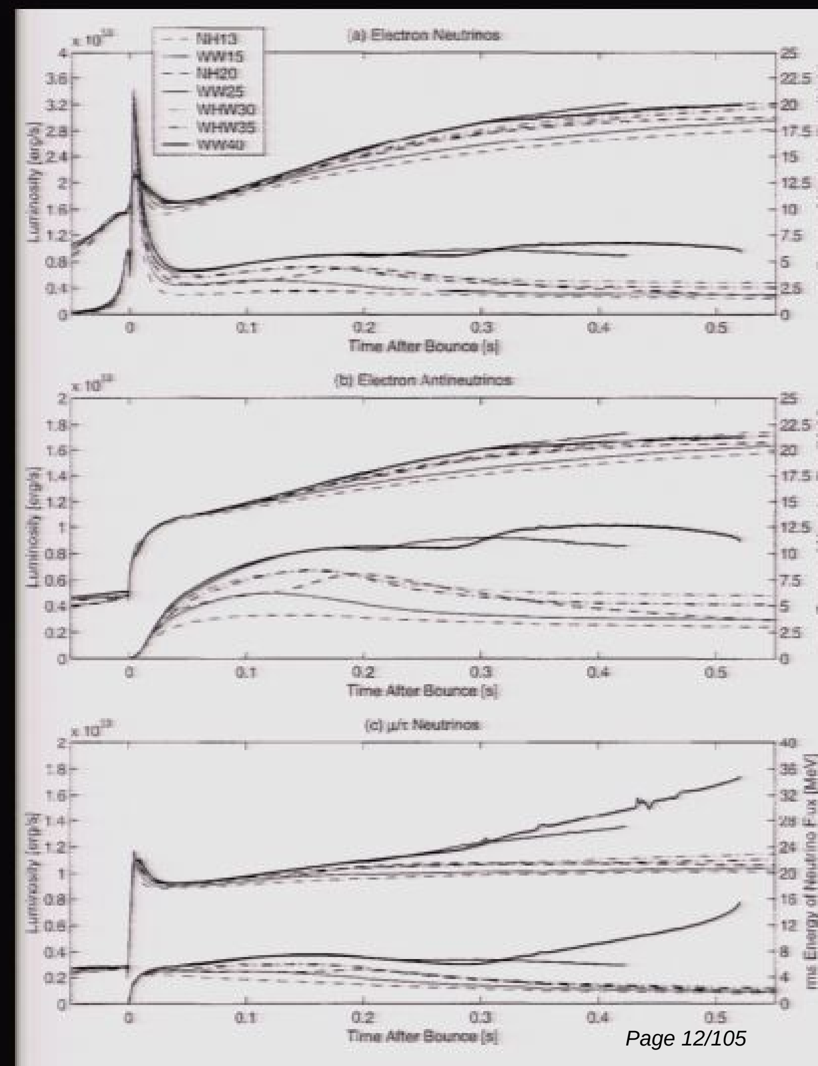
✓ In computing the neutrino-matter coupling (r.h.s. of the B-eqns

Preliminar

Neutrino luminosities in M1



1D Boltzmann results



✓ **The M1 scheme:**
Overall trends in agreement with the Boltzmann results.

✓ More detailed comparison will be given in our forthcoming paper(in progress).

Liebendoerfer et al. (2003


My bed in the Waterloo hotel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3D Results with IDSA +

Preliminary

(Takiwaki, KK, Suwa in prep)

✓ 11.2 Ms progenitor (Woosley, Heger, Weaver '02)

✓ Numerical Resolution

- Grid: 300(r)x32(Θ)x64(φ) × 20(energy)
- Non-rotating case

✓ **IDSA+ means IDSA for nu_e + nu_e bar**
leakage for nu_X

3D Results with IDSA +

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t= 0001ms

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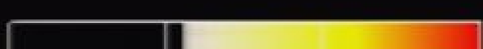

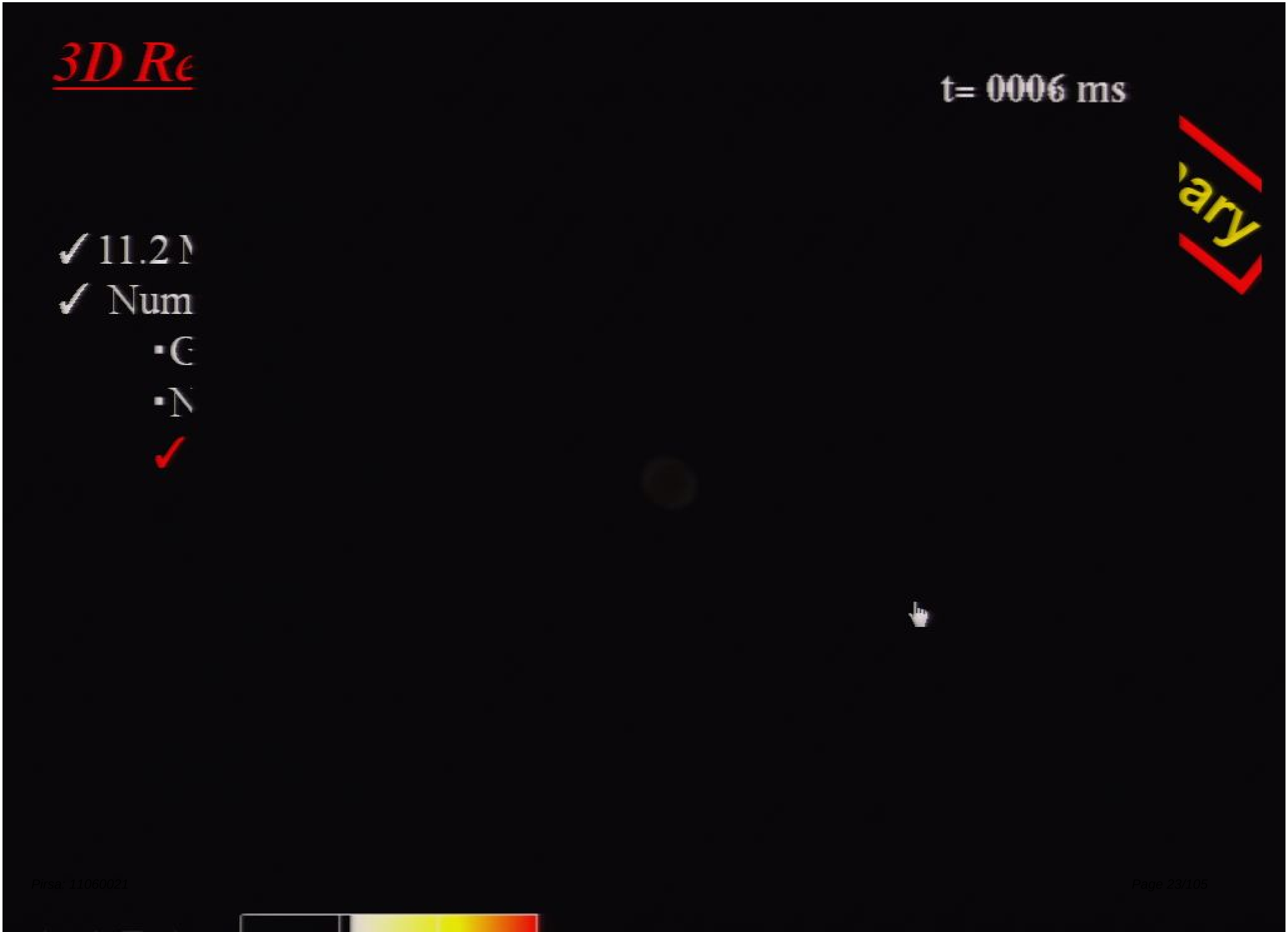
3D Re
t= 0006 ms
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✓ Num
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3D Re
t= 0048 ms
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✓11.2
✓ Num


3D Re
t= 0059 ms
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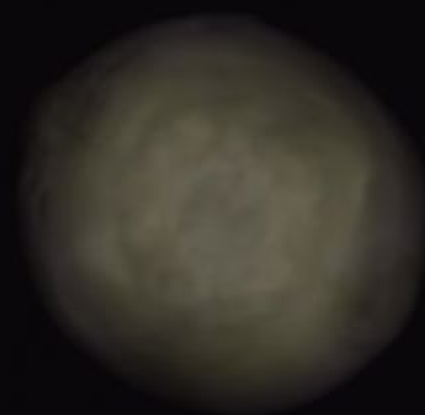


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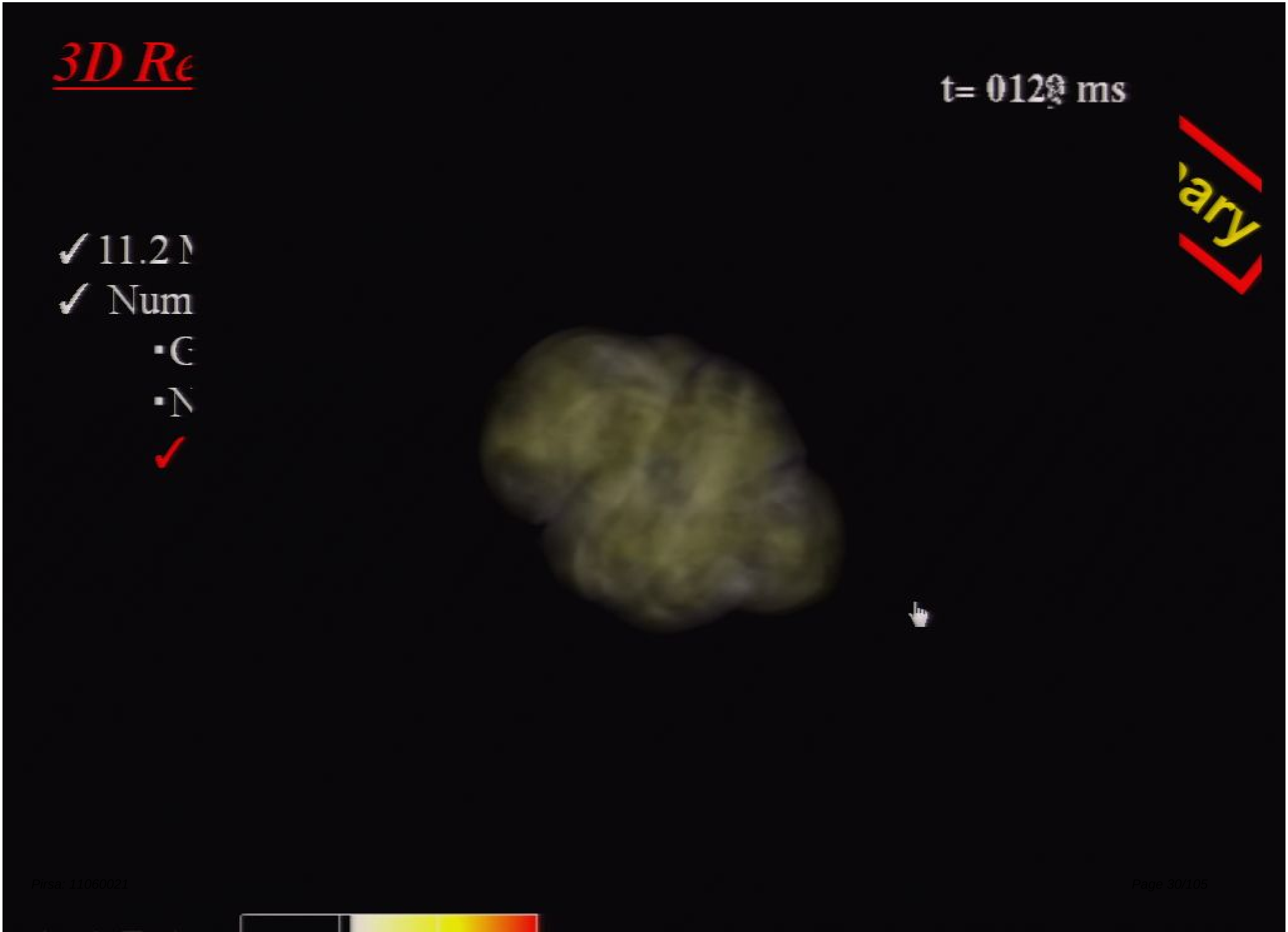
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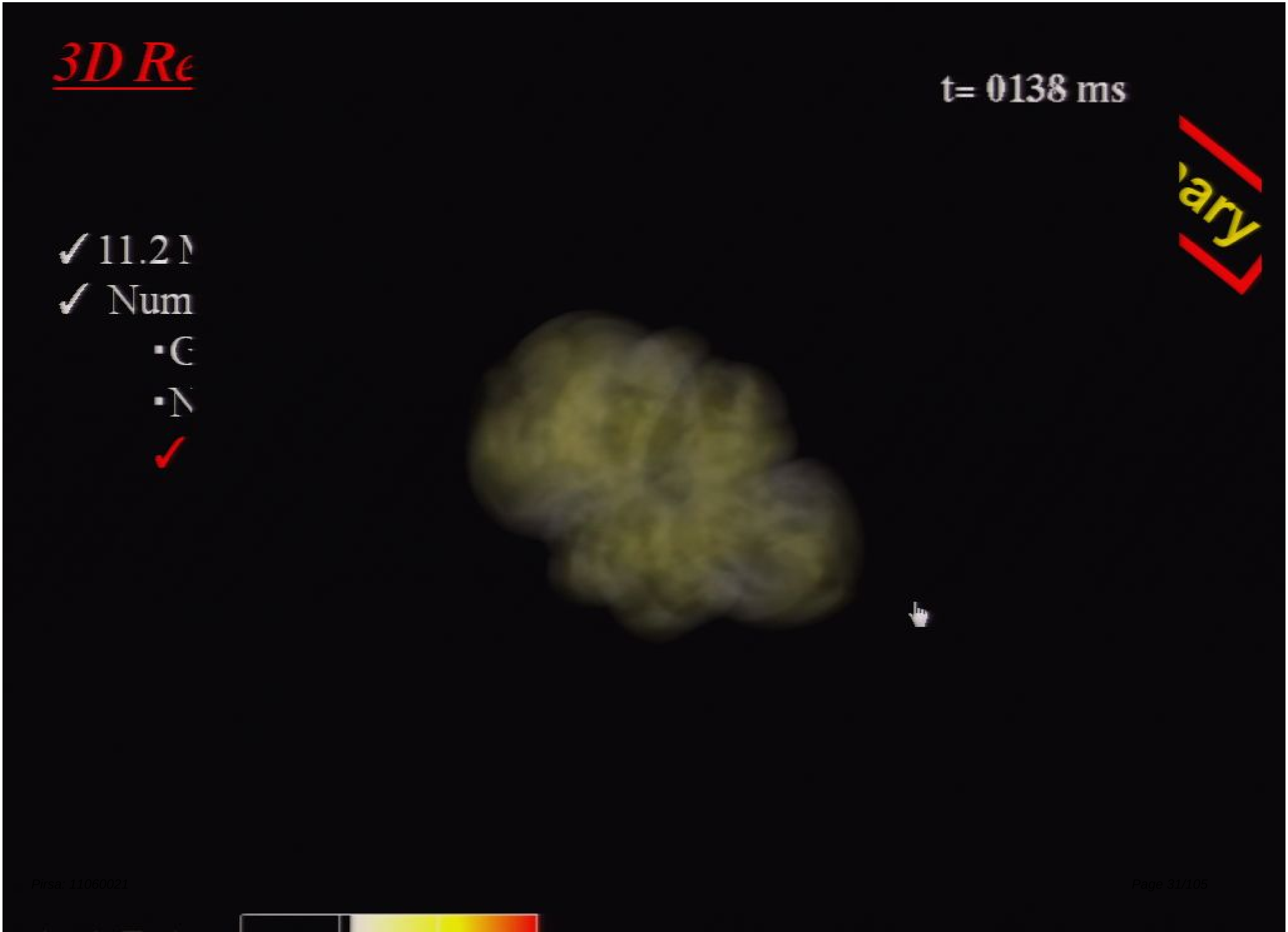
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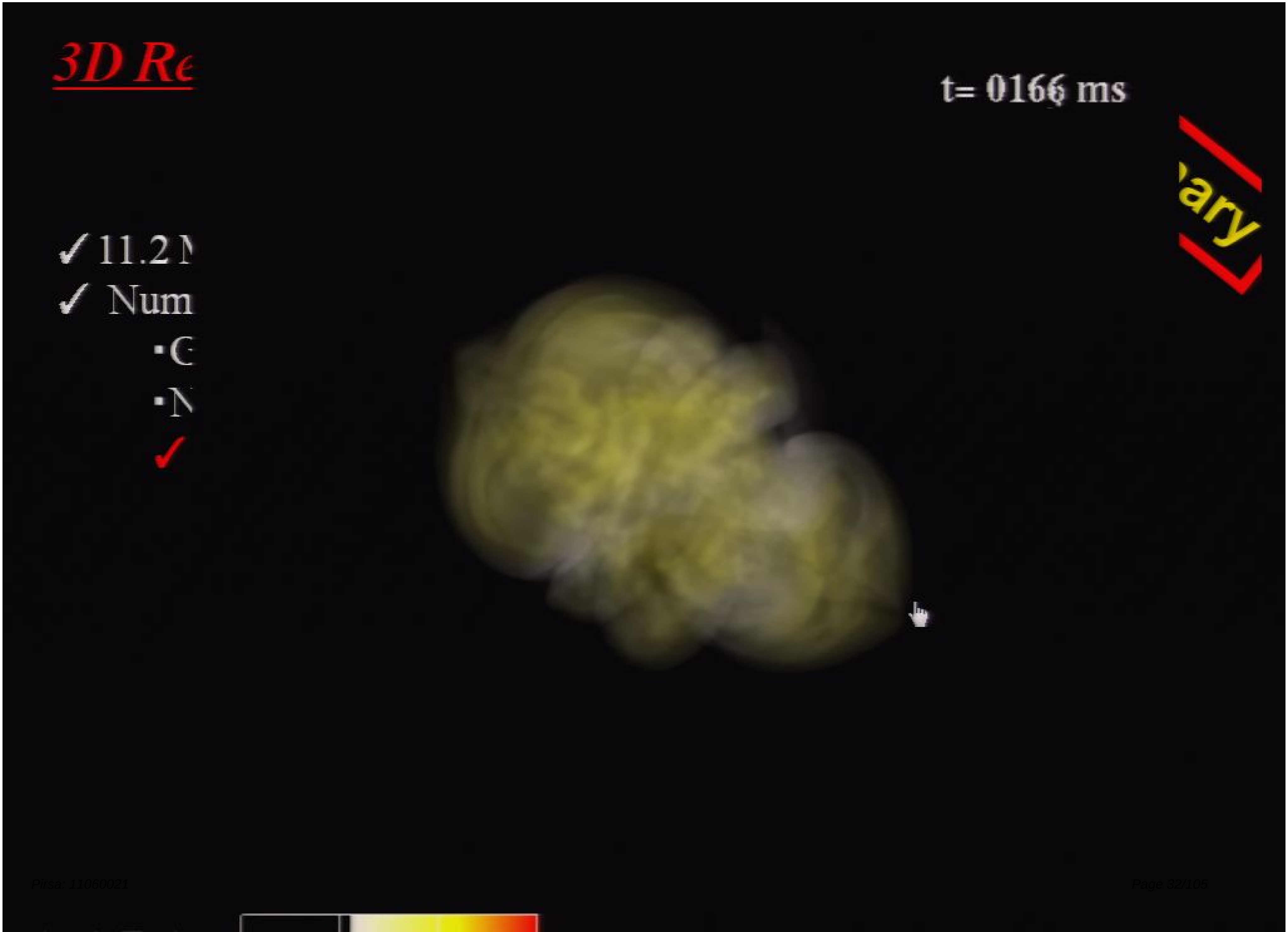
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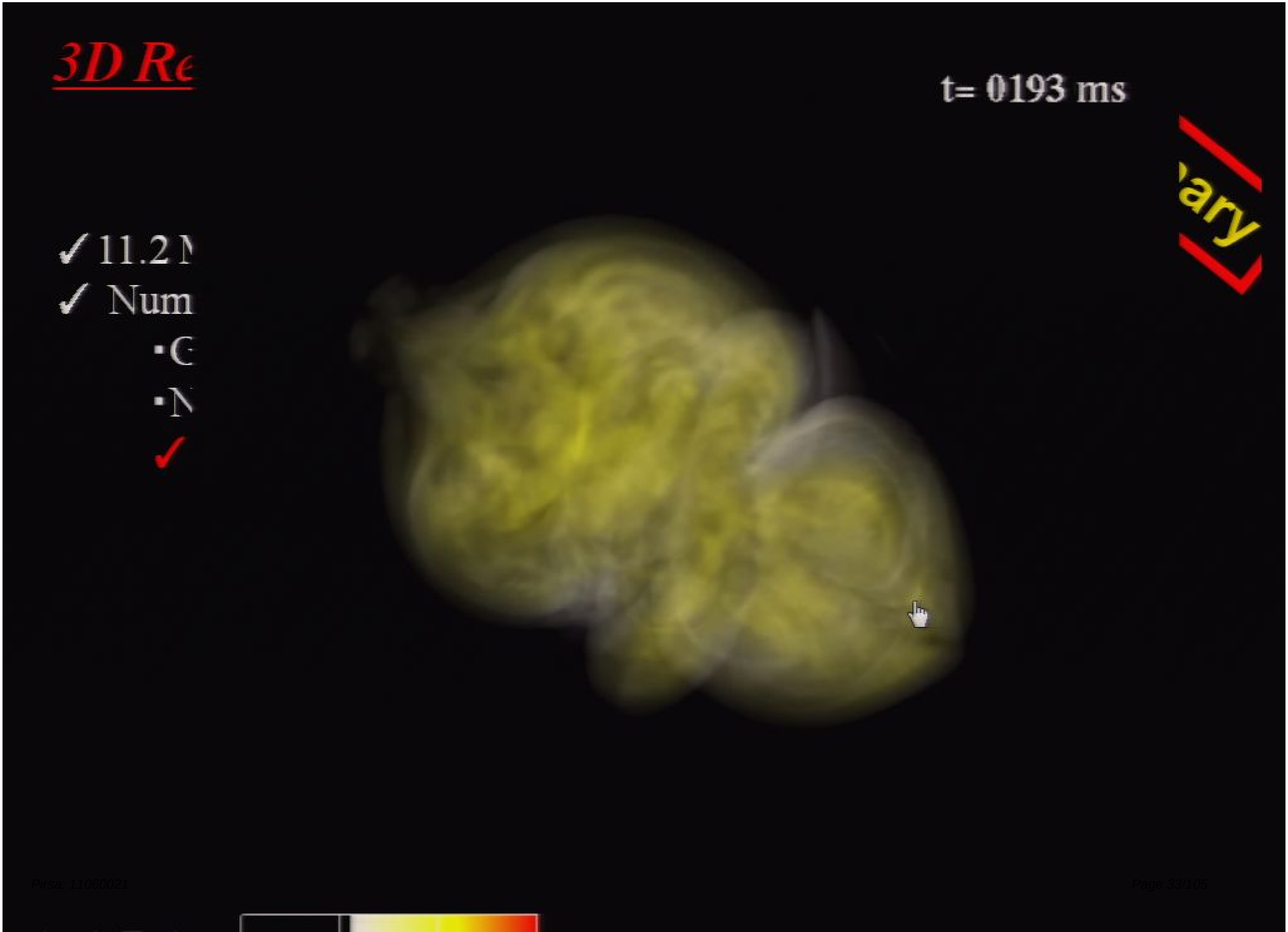
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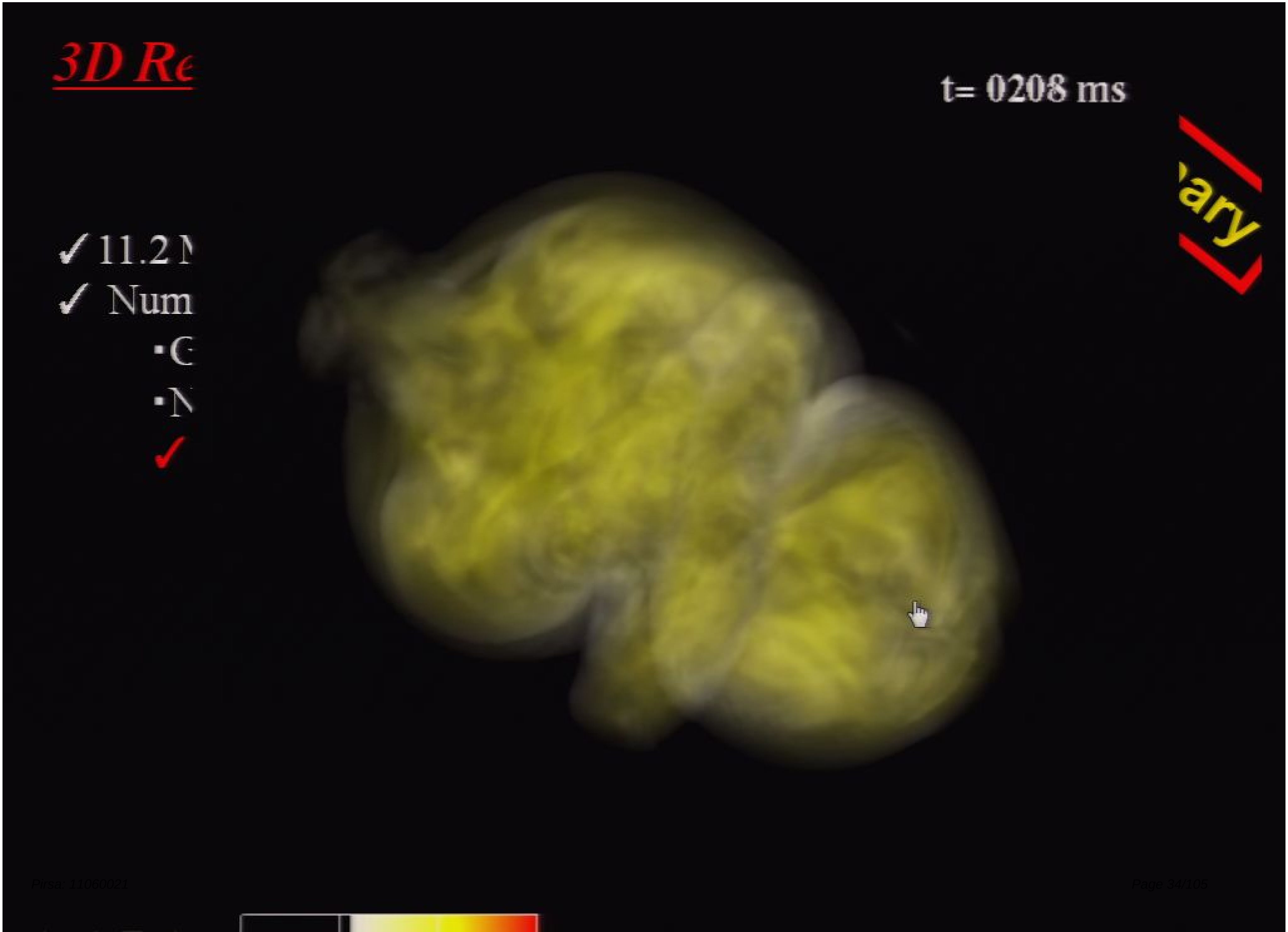
3D Re
t= 0208 ms
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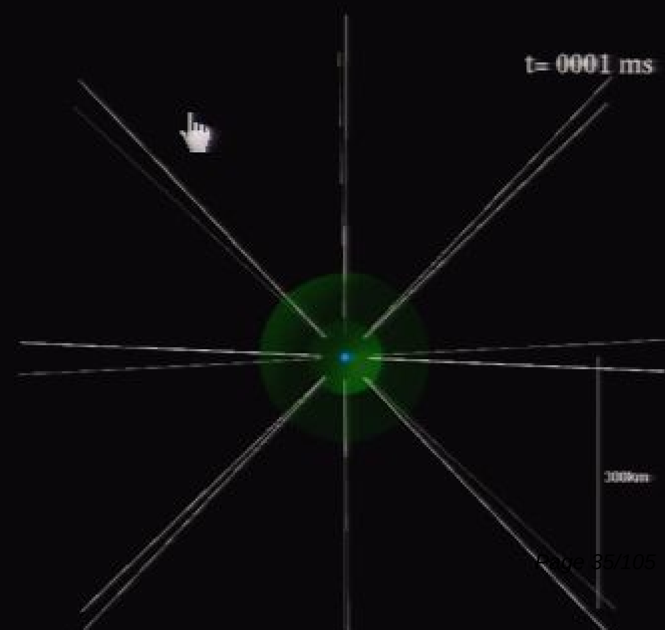
Pressure perturbation for equatorial observer (δP/P)

Sketch of streamline for polar observer



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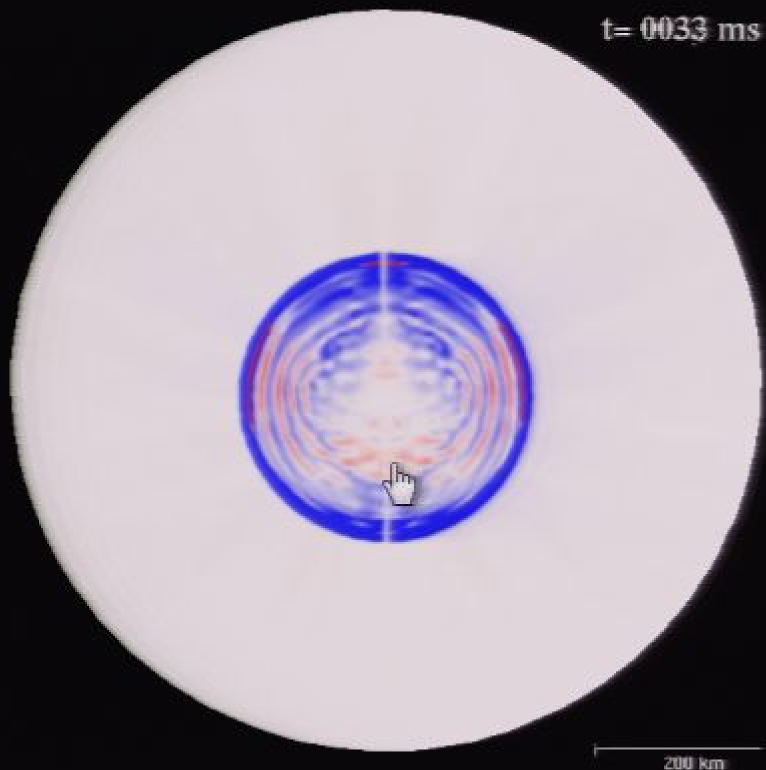

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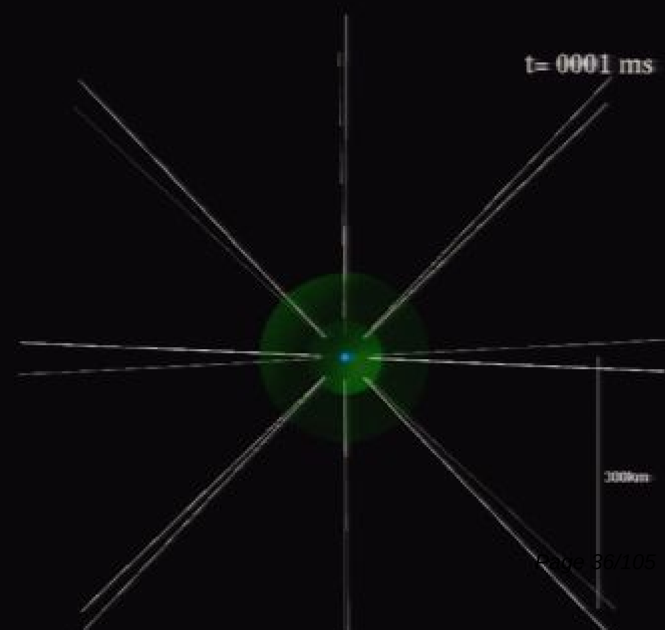

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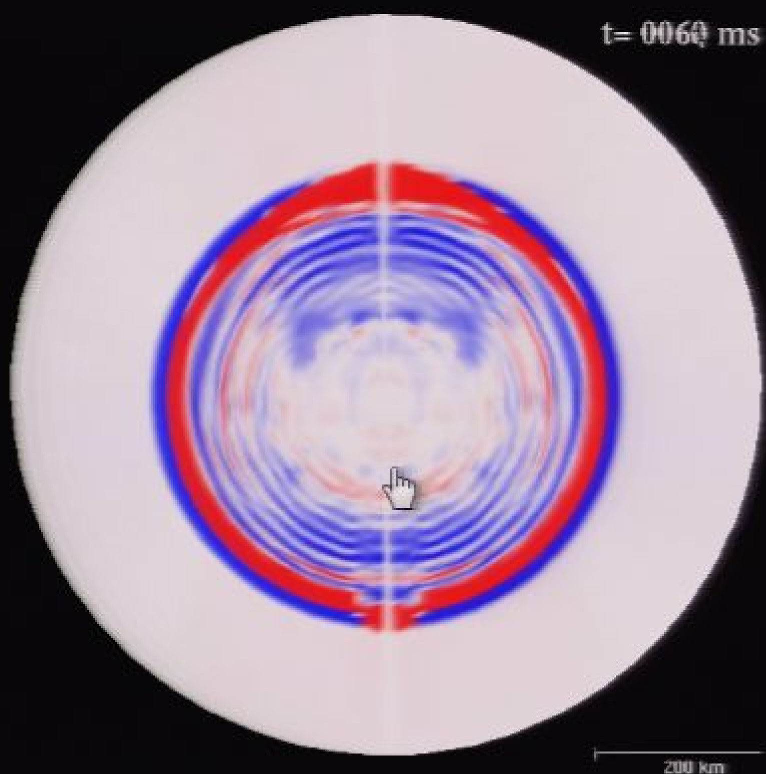

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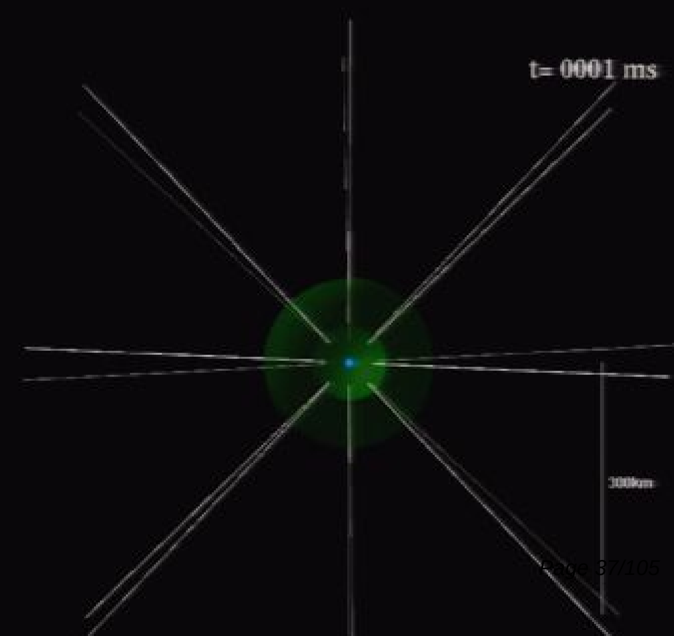

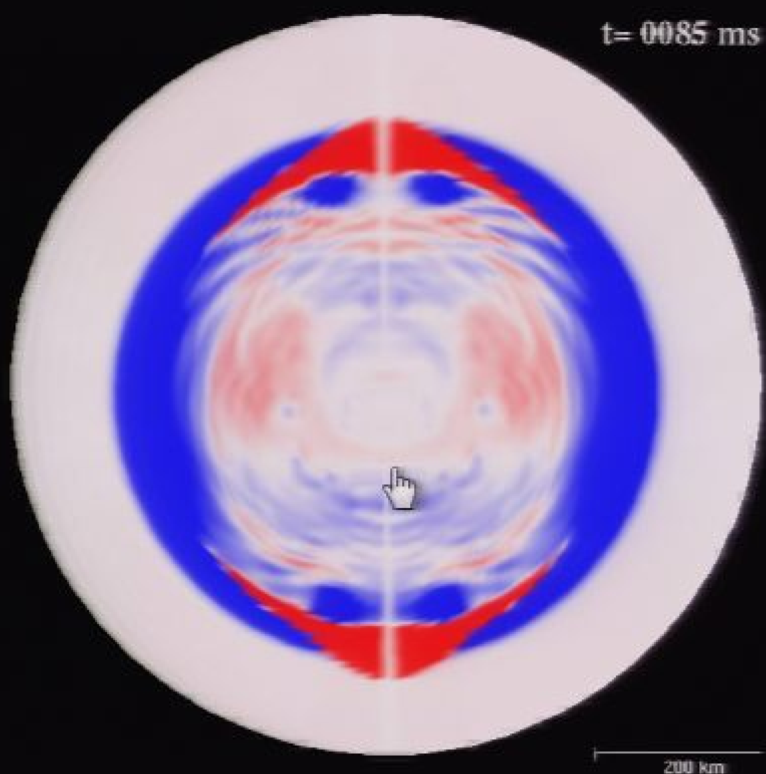

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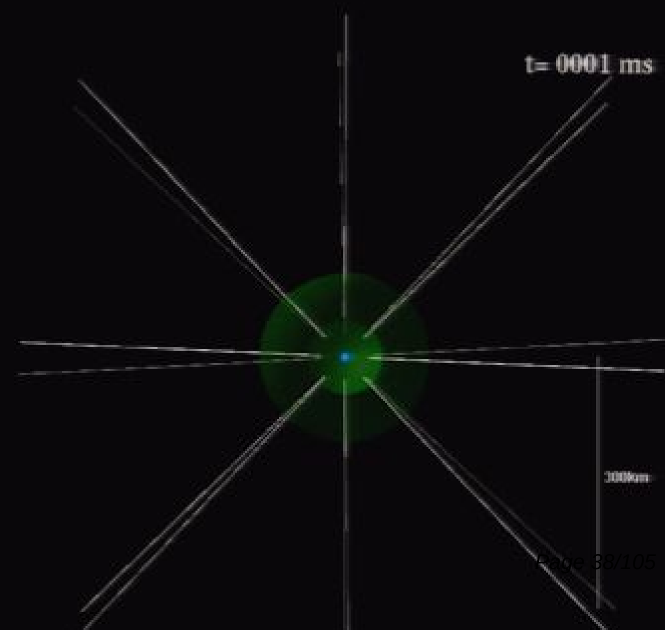

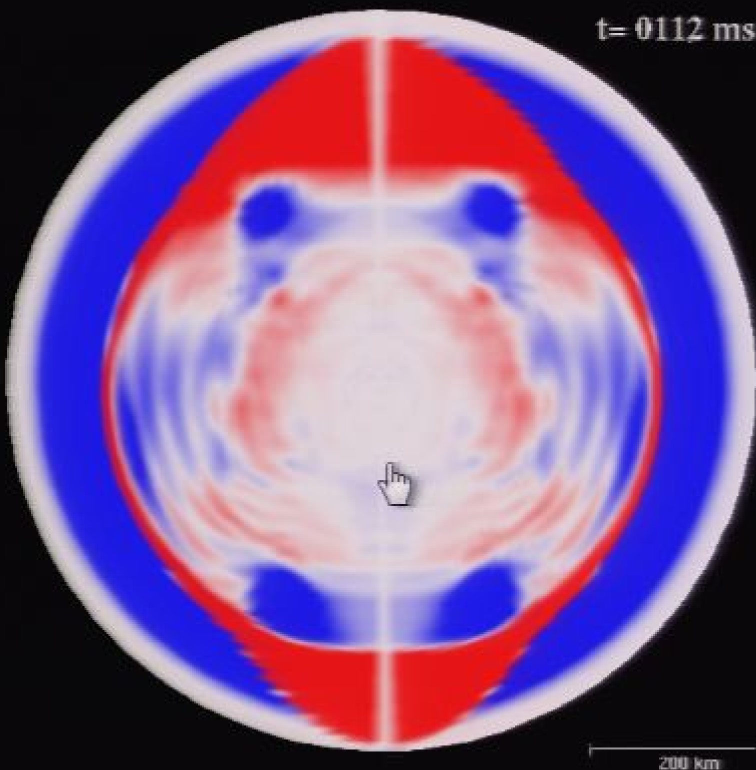

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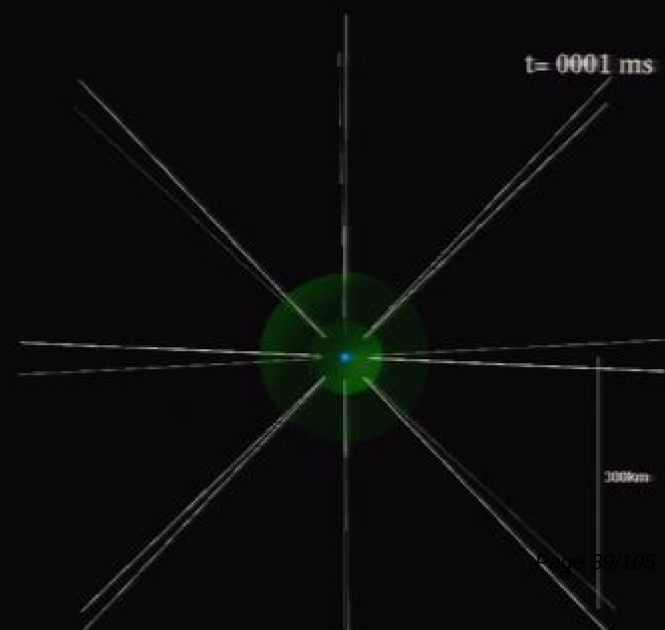

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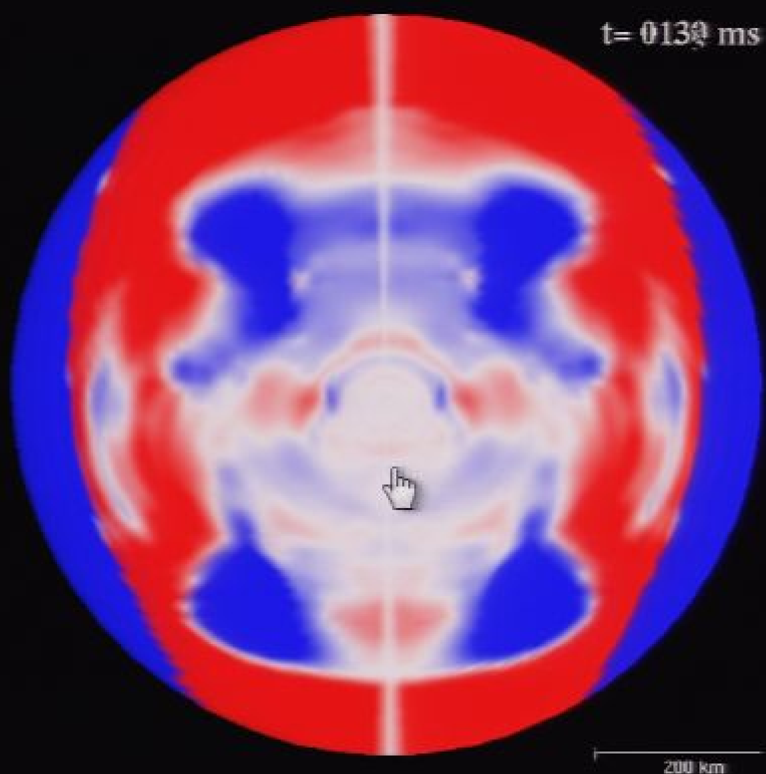

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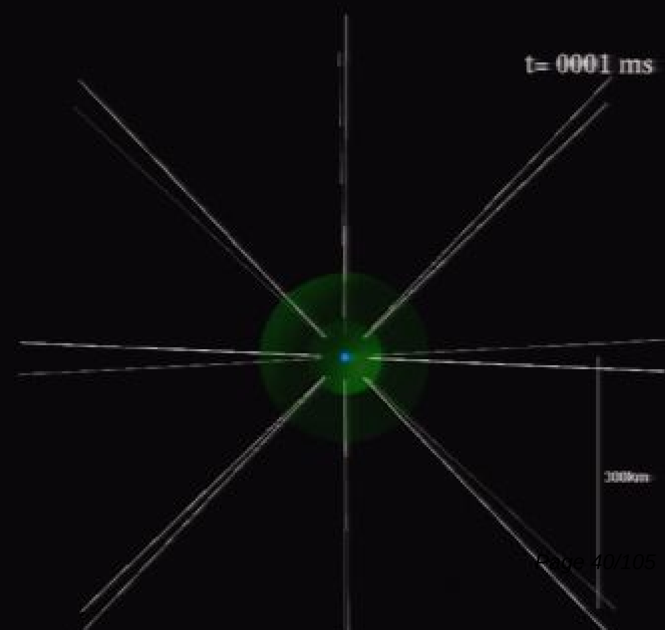

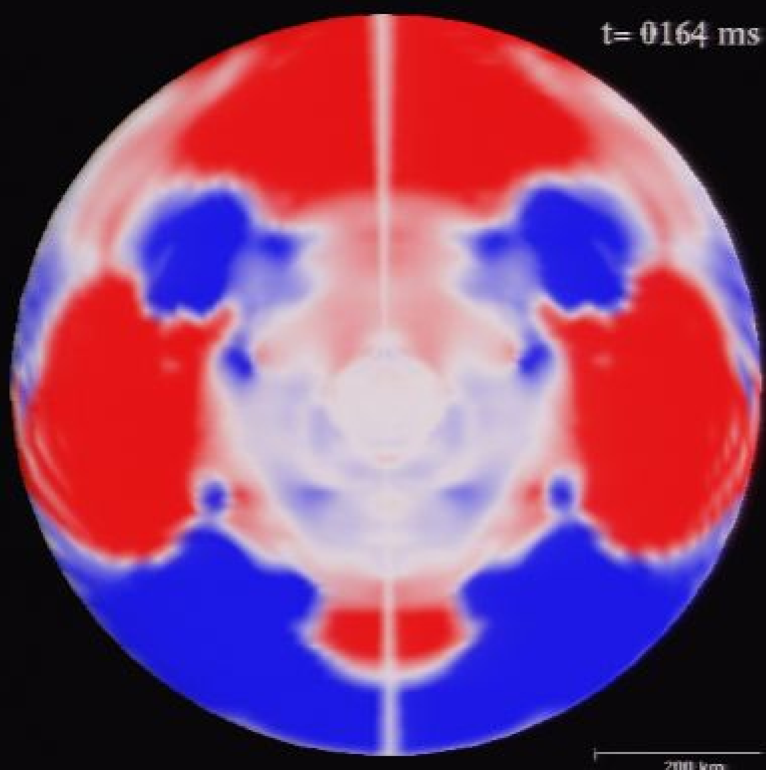

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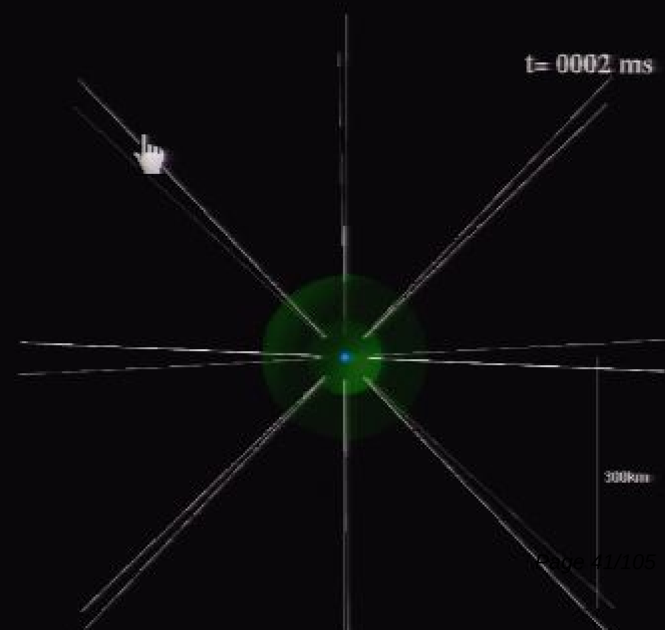

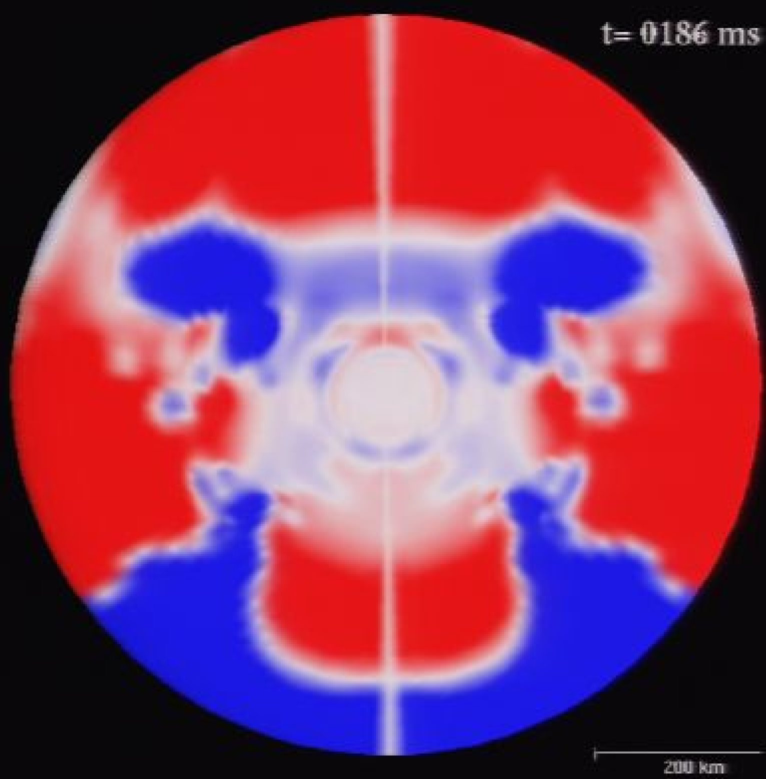

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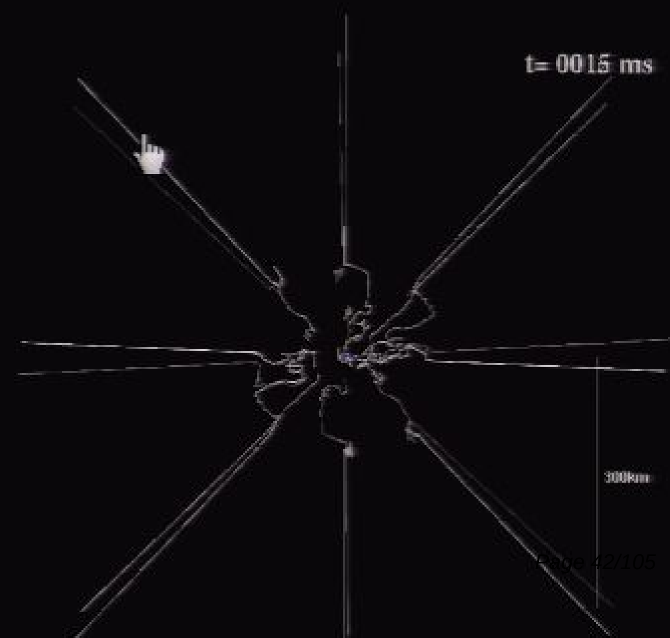

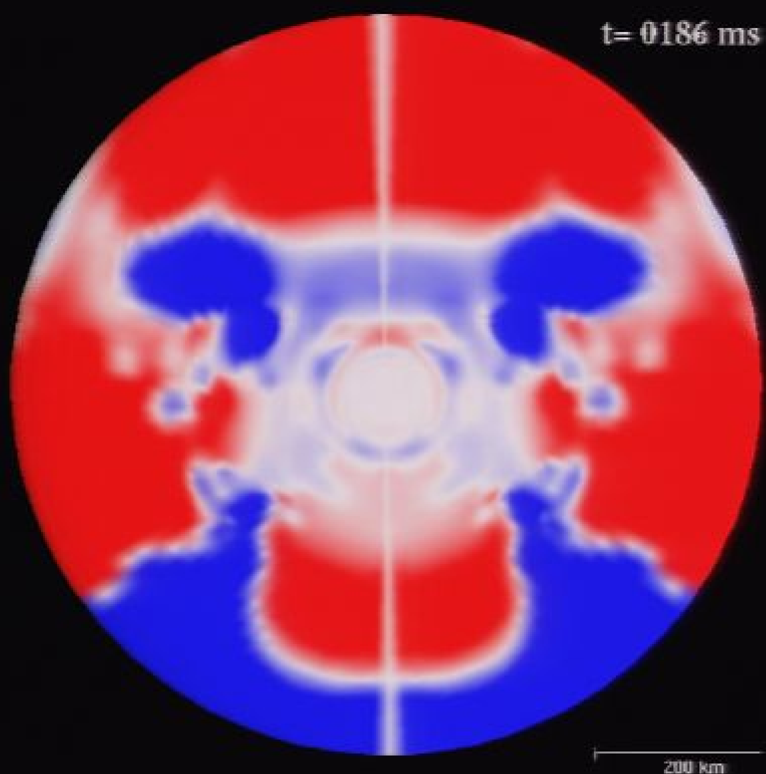

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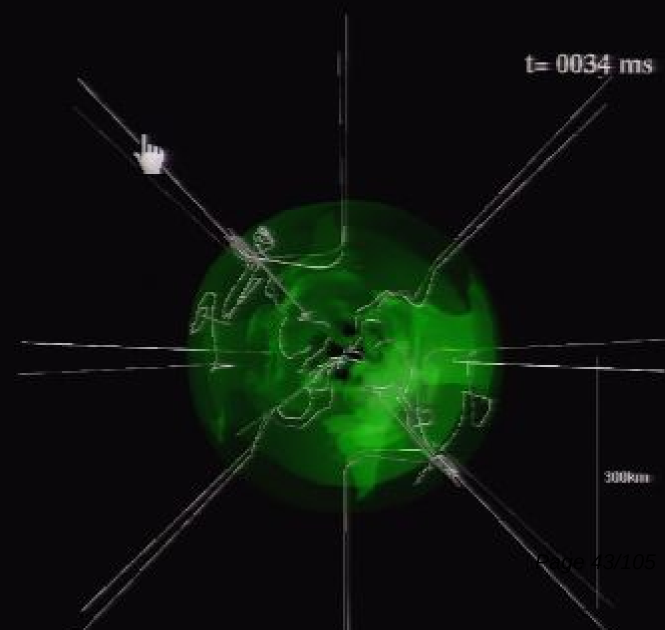

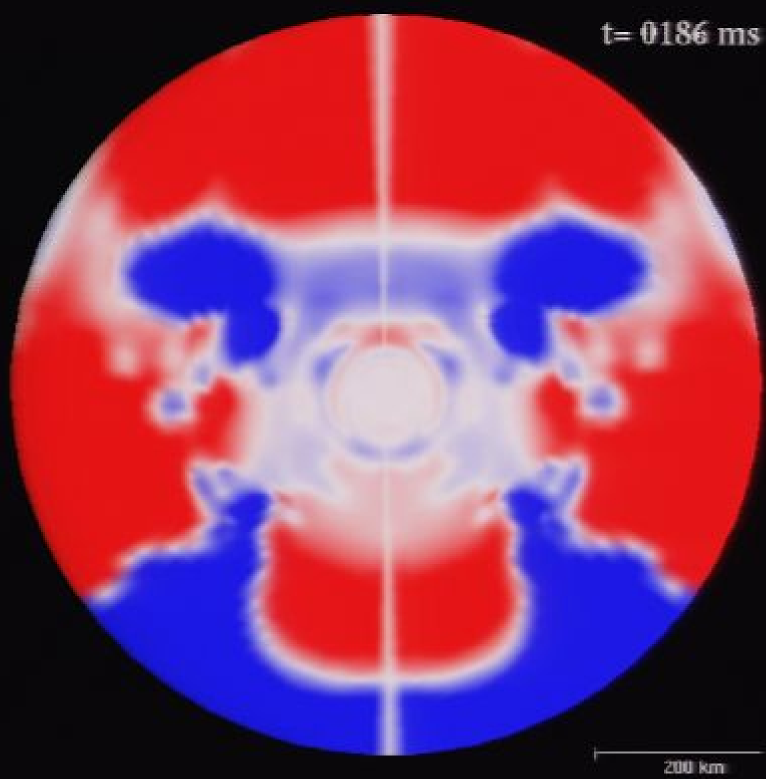

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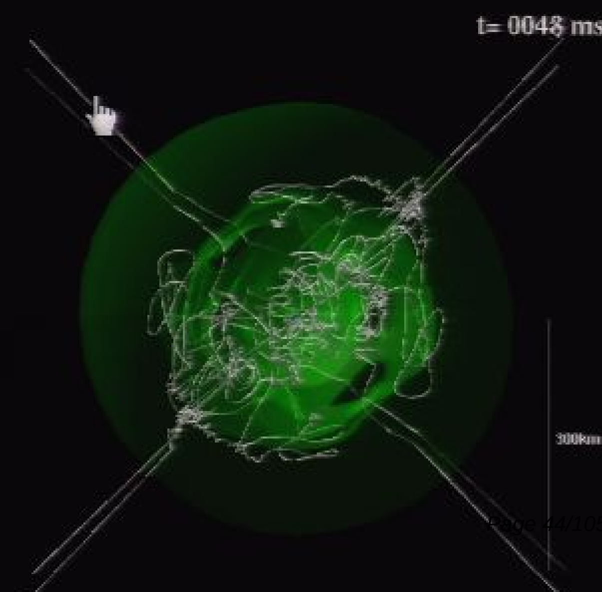

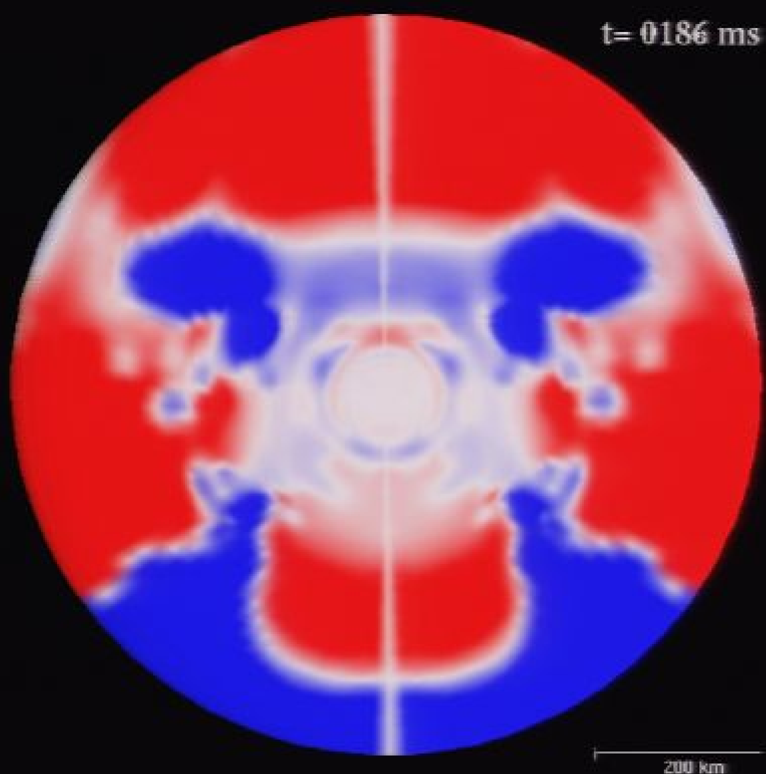

Pressure perturbation for equatorial observer (δP/P)

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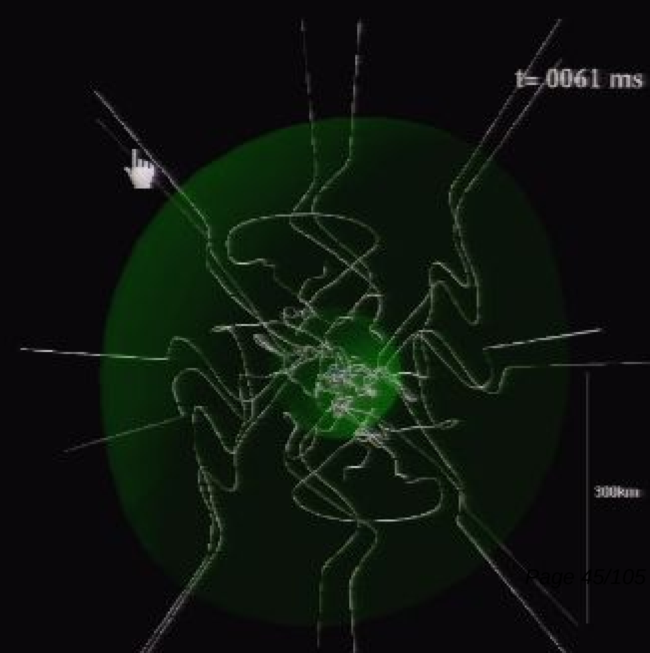
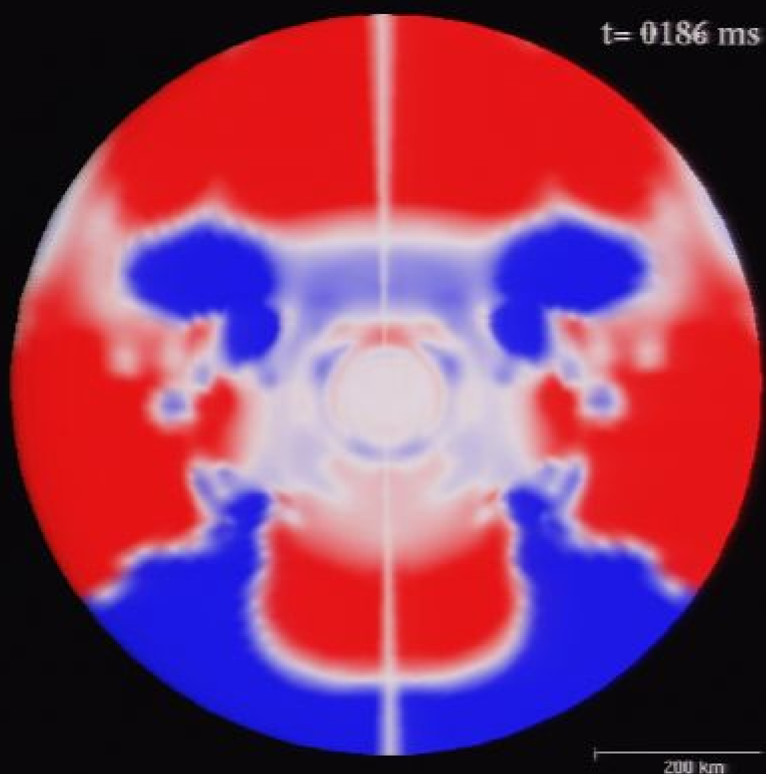
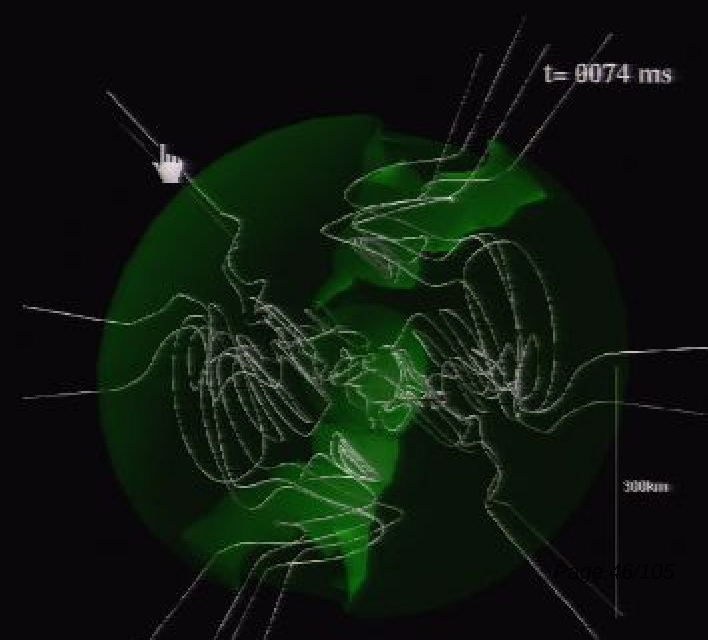
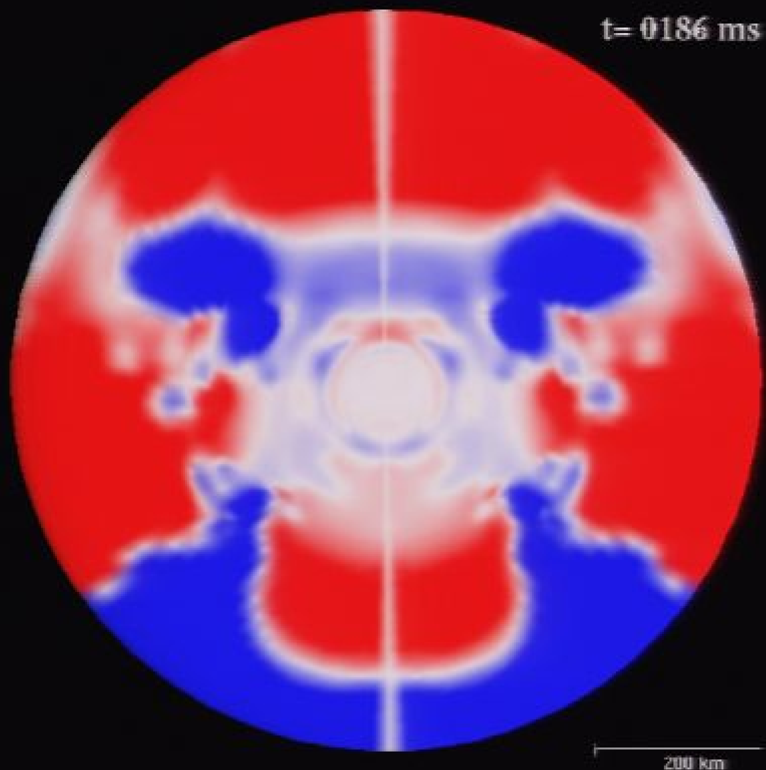




Pressure perturbation for equatorial observer ($\delta P/P$)

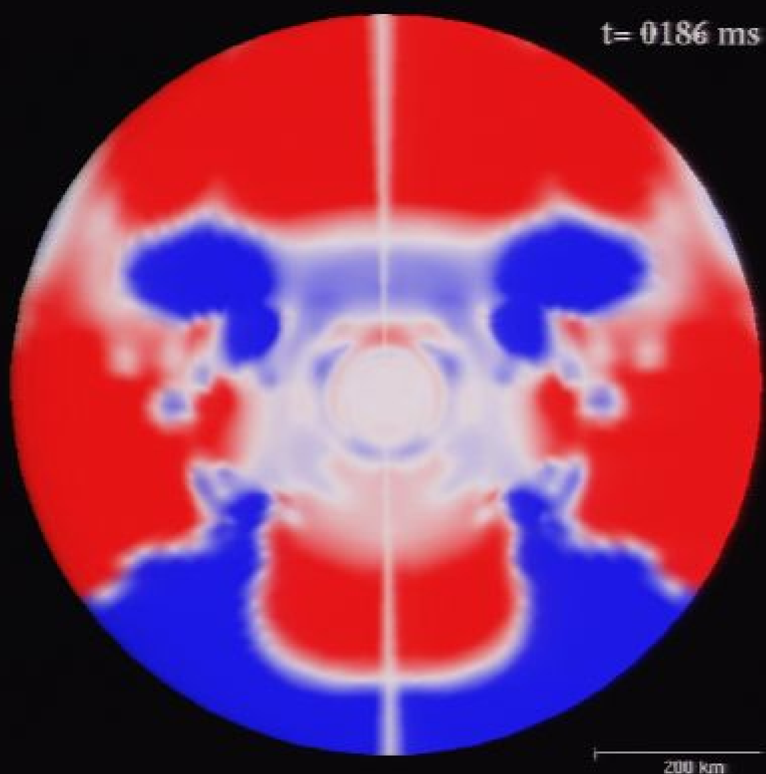
Sketch of streamline for polar observer





Pressure perturbation for equatorial observer (δP/P)

Sketch of streamline for polar observer



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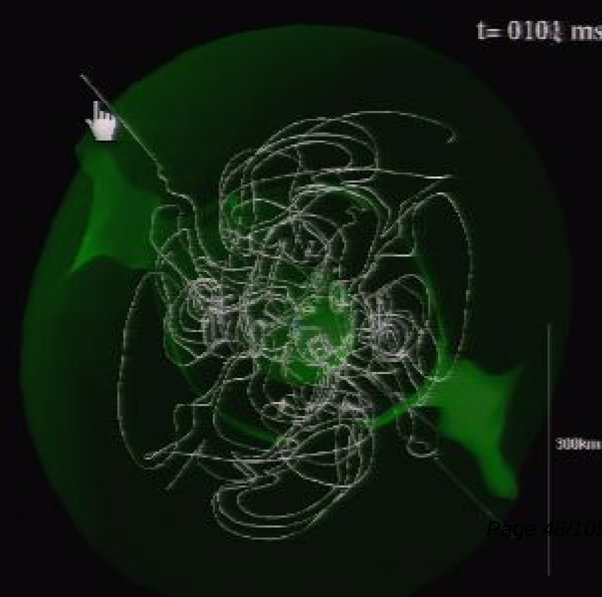
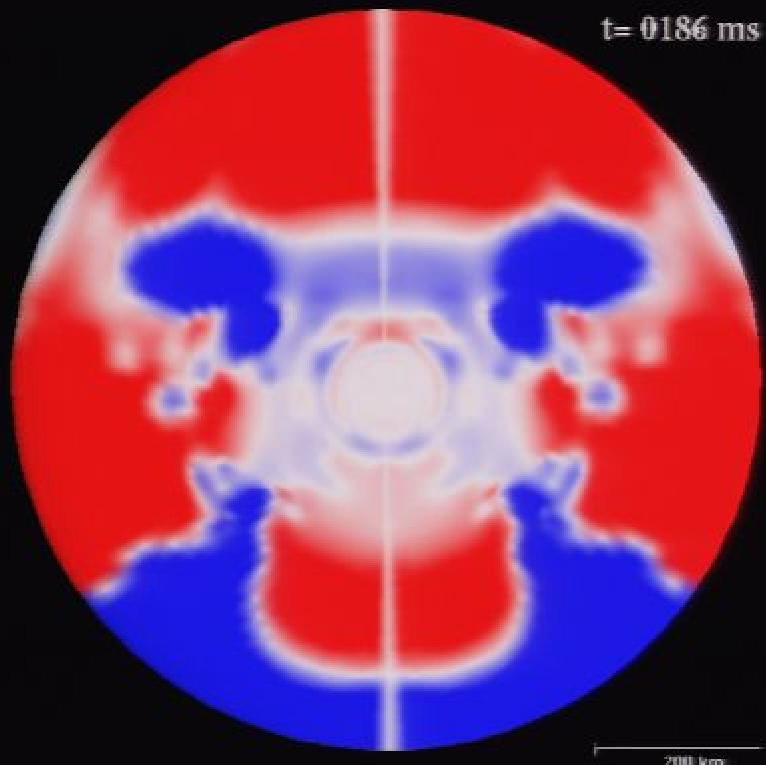
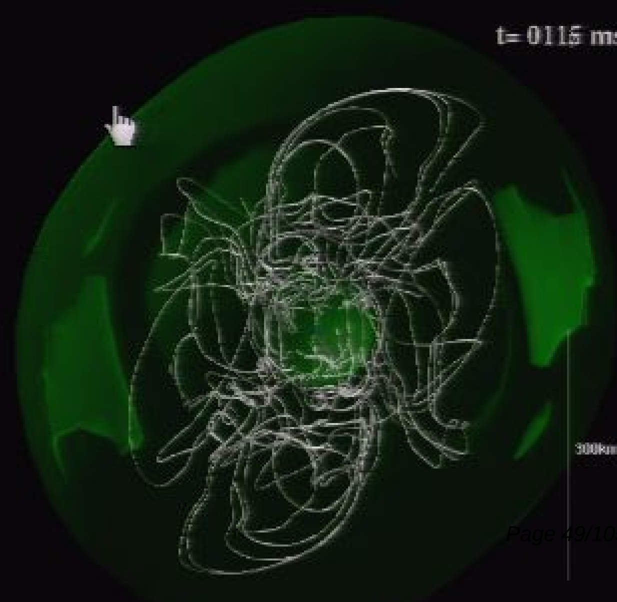
Sketch of streamline for polar observer

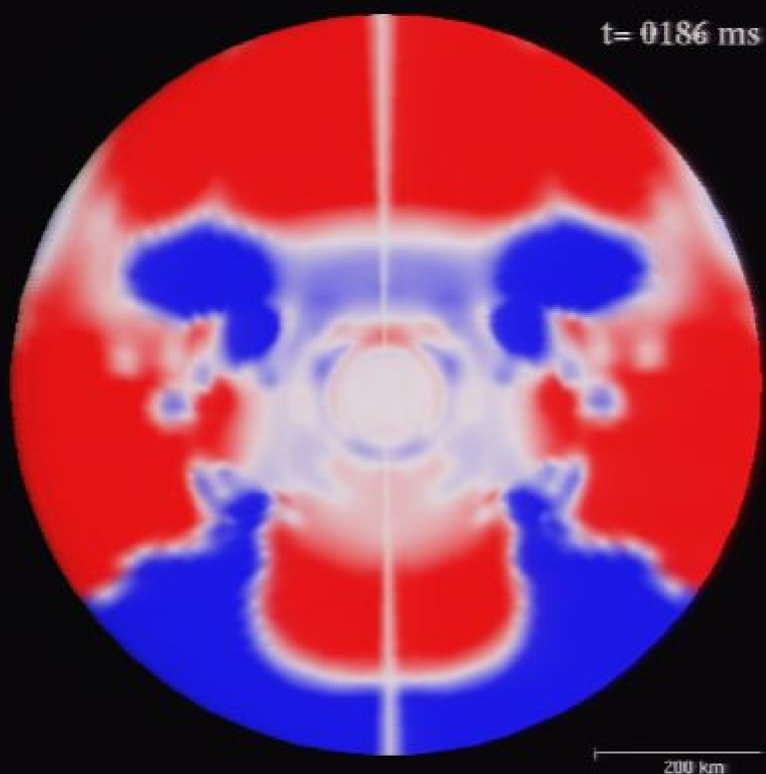




Pressure perturbation for equatorial observer (δP/P)

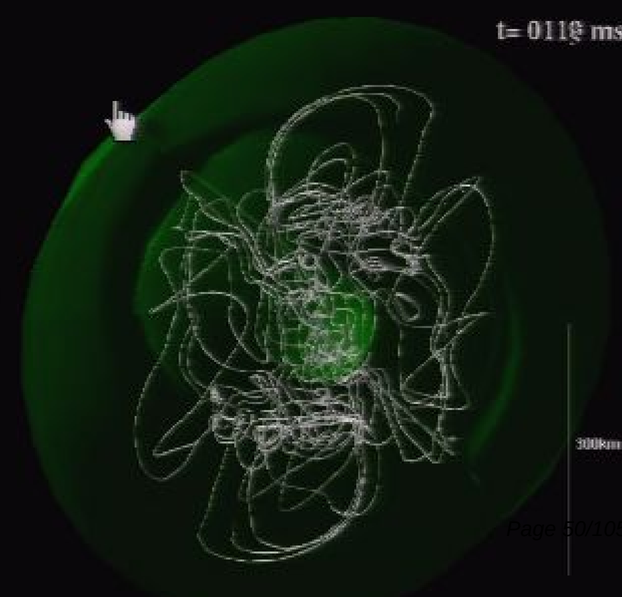
Sketch of streamline for polar observer



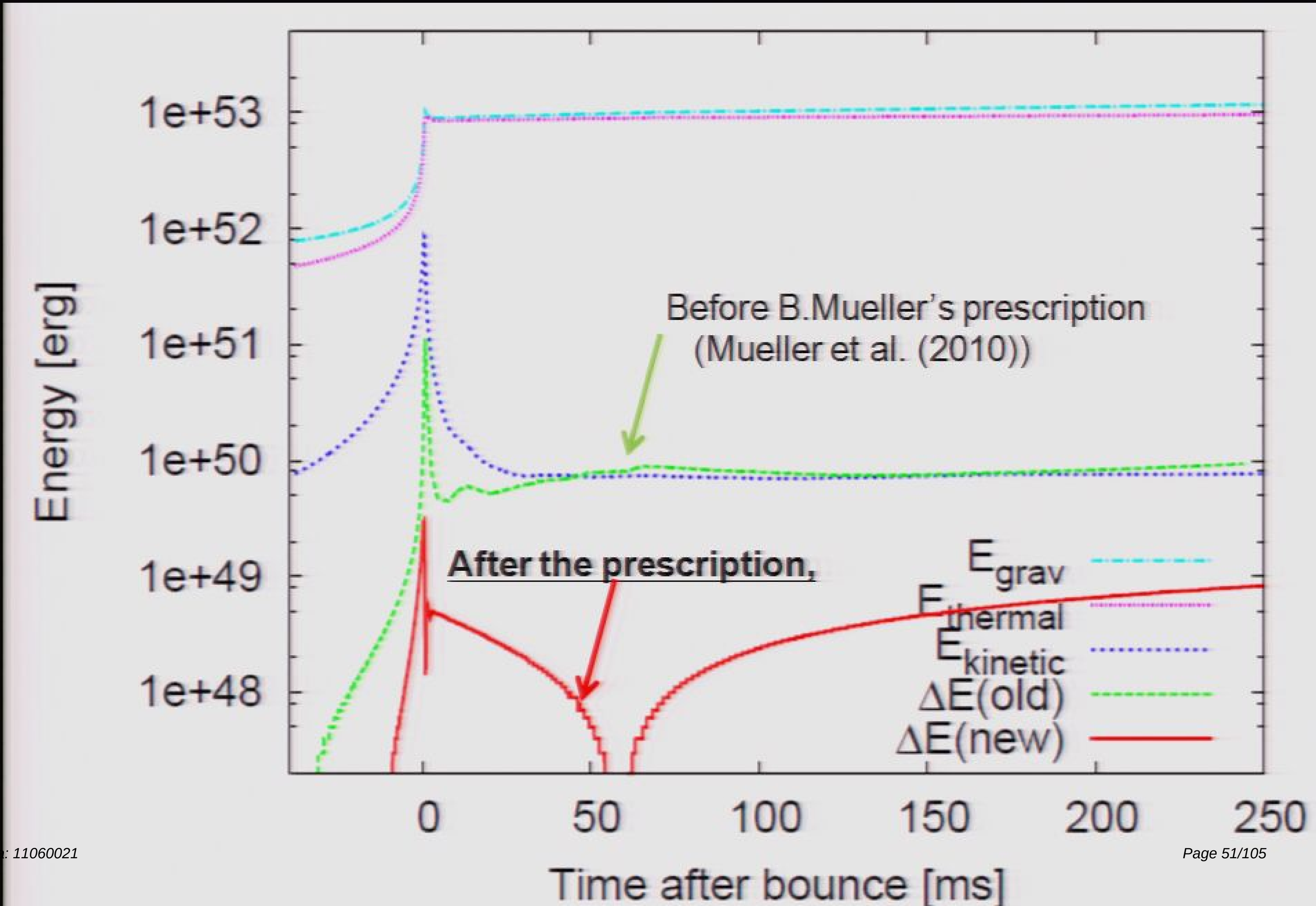


Pressure perturbation for equatorial observer ($\delta P/P$)

Sketch of streamline for polar observer



Energy conservation should be kept in good accuracy!



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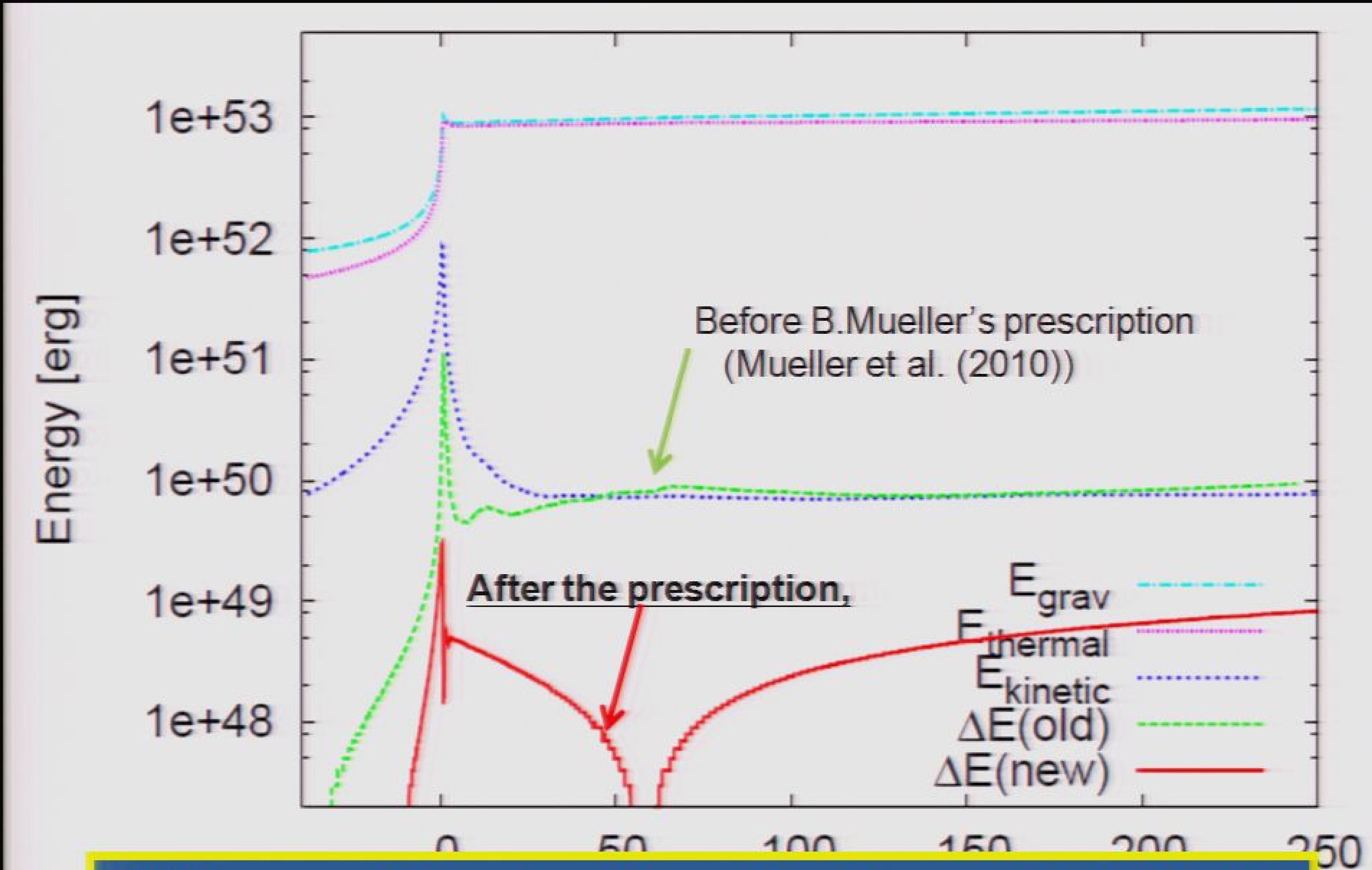
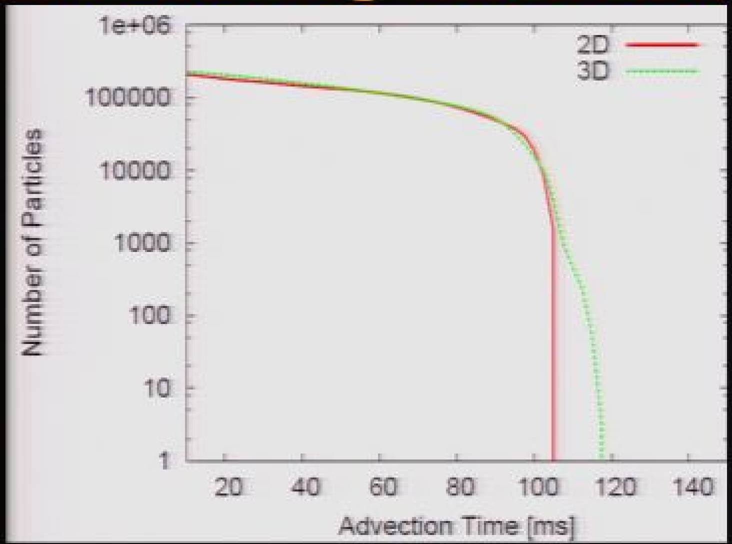


2nd lesson: Bernhard's recipe is very helpful !

Easy to obtain explosions in 3D than 2D ?

(e.g., Nordhaus et al. (1

✓ **For working the neutrino-heating mechanis**



The advection timescales become longe in 3D than in 2D.

t= 0107 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1

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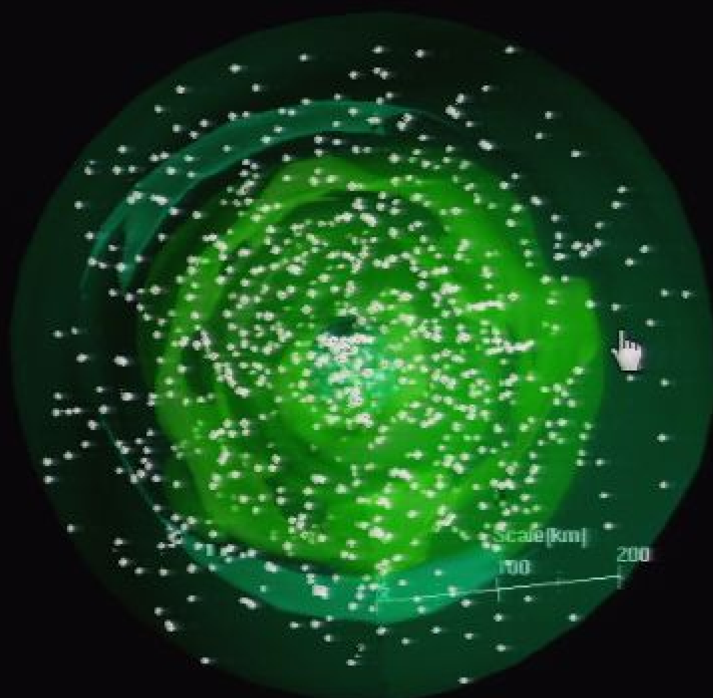

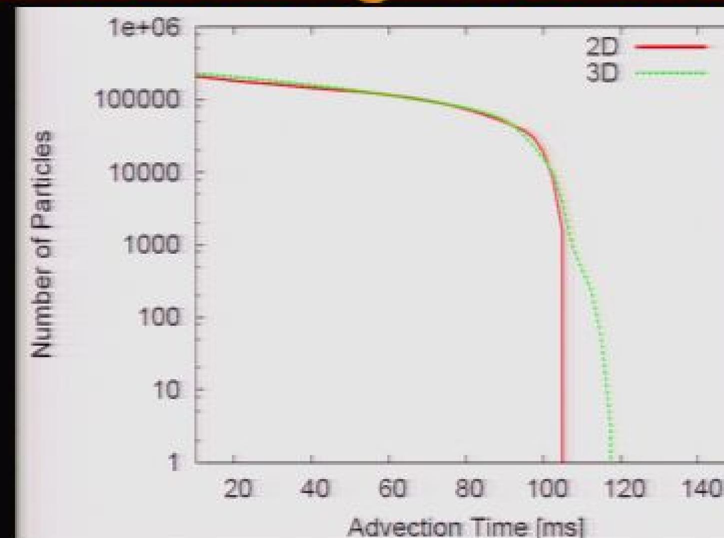

The advection timescales become longe
in 3D than in 2D.

t= 0116 ms losions in 3D than 2D ?

(e.g., Nordhaus et al. (1

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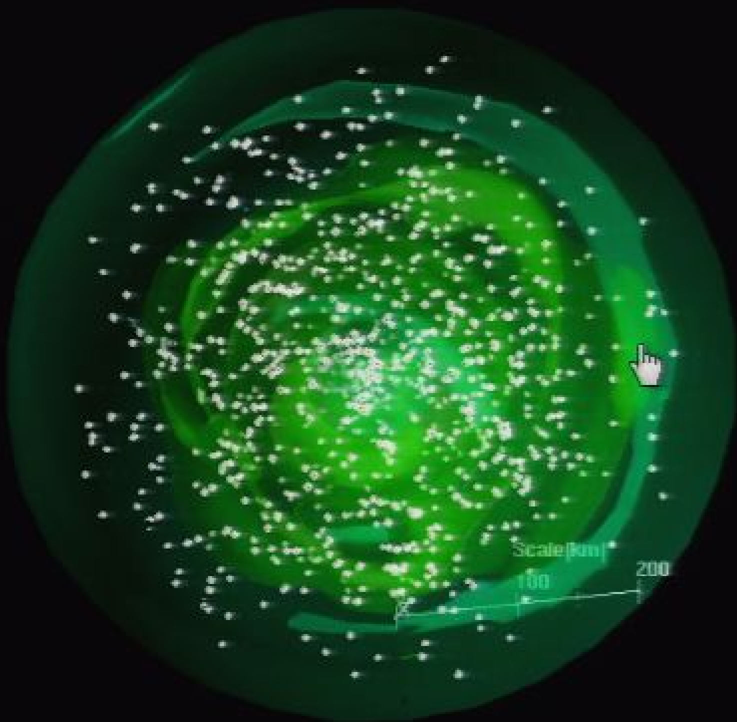
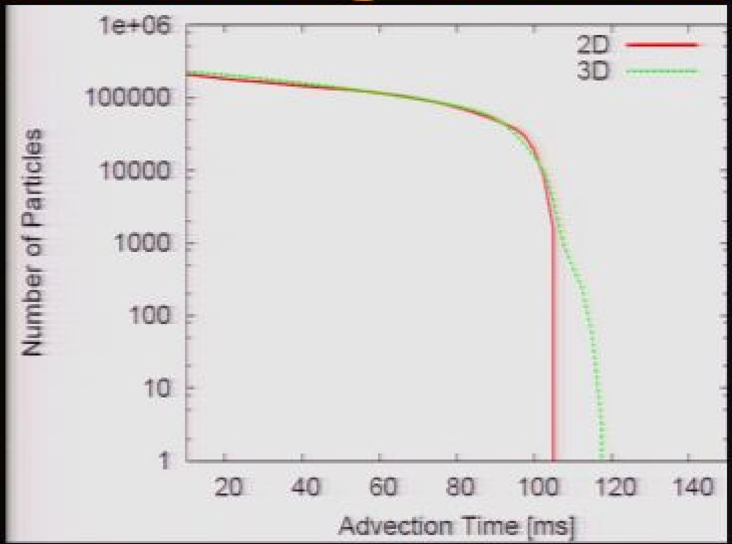


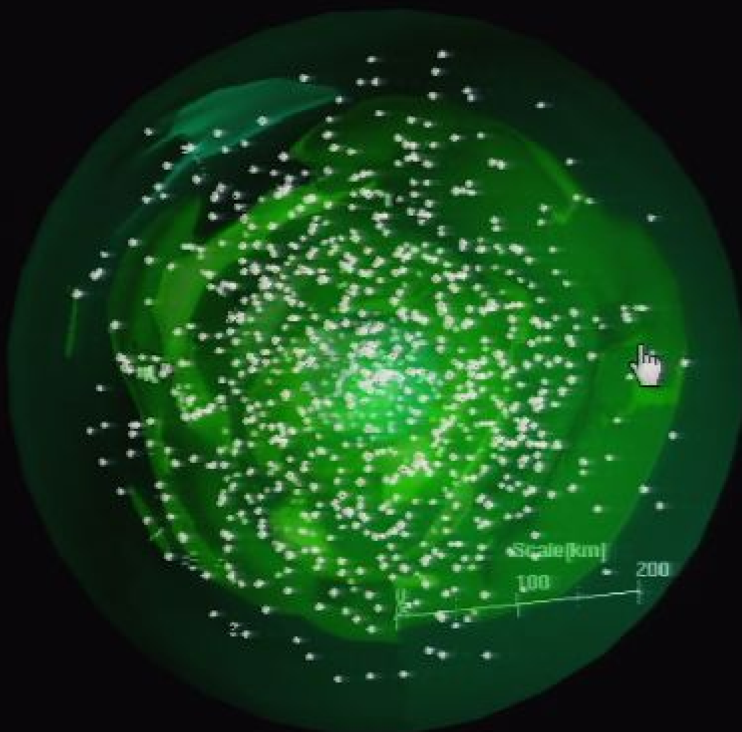


The advection timescales become longe
in 3D than in 2D.

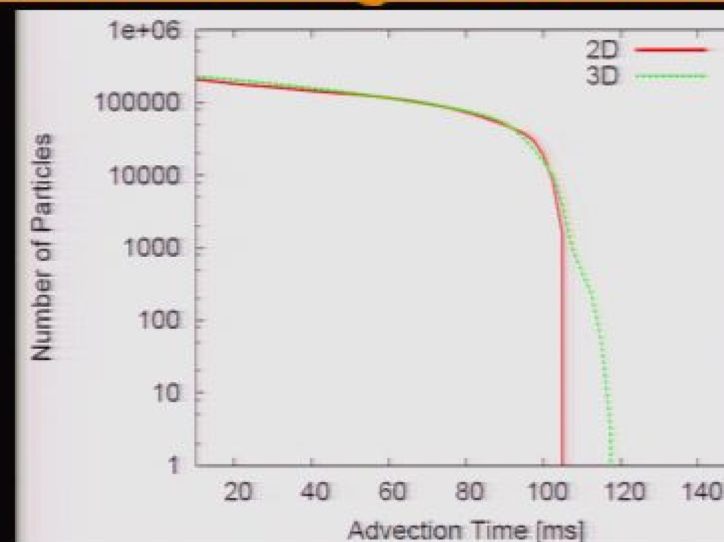
t= 0123 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1



✓ **For working the neutrino-heating mechanis**

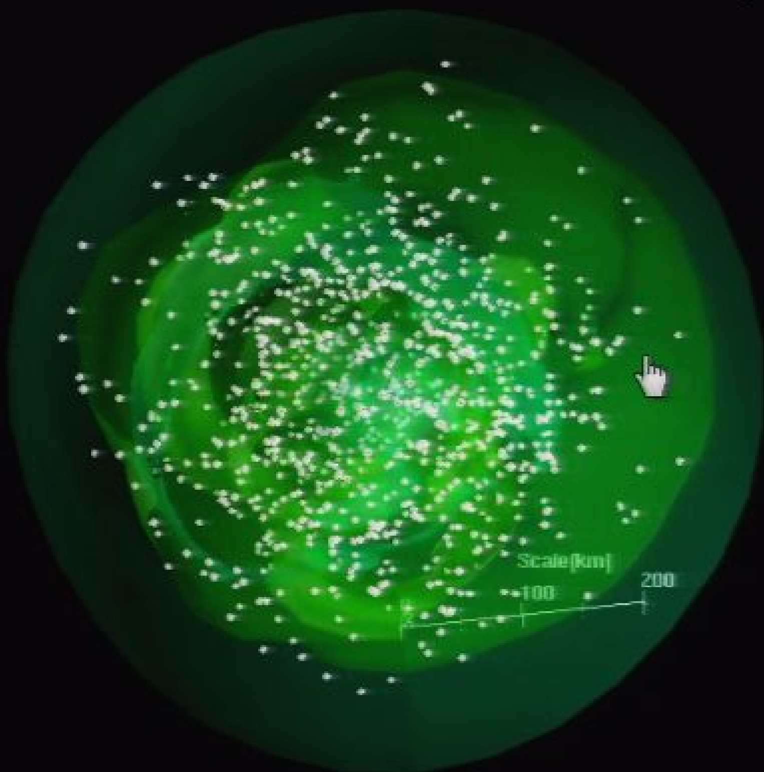


The advection timescales become longe
in 3D than in 2D.

t= 0131 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1



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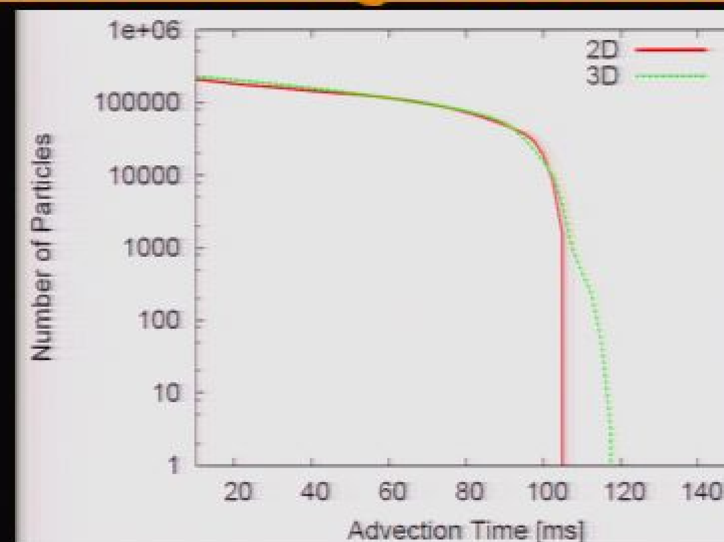

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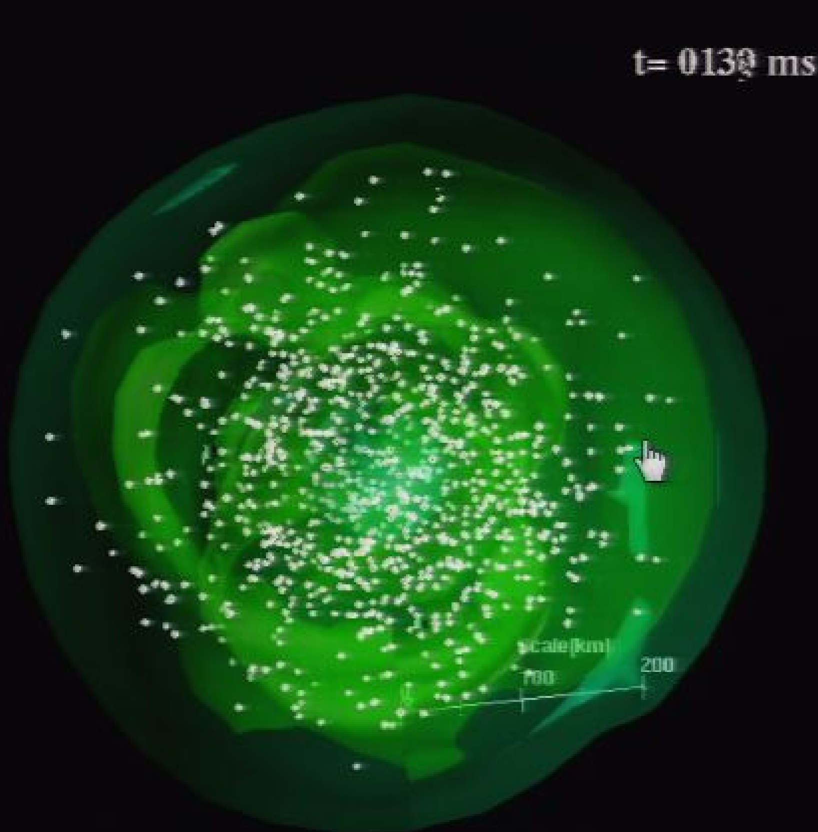

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(e.g., Nordhaus et al. (1

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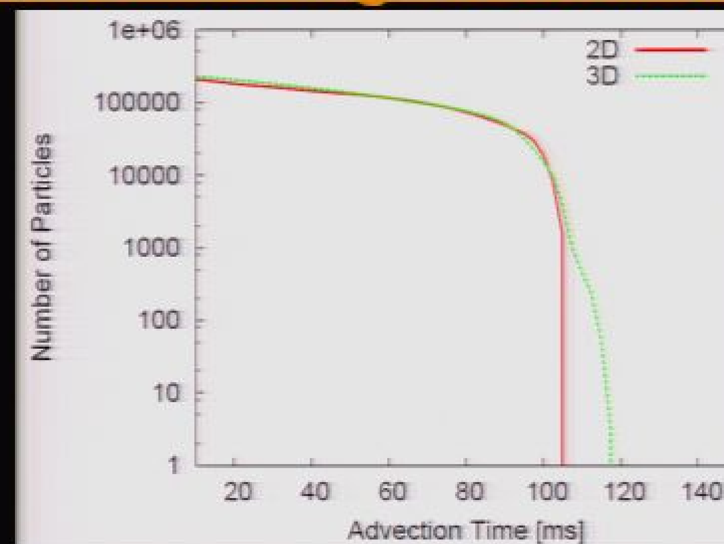

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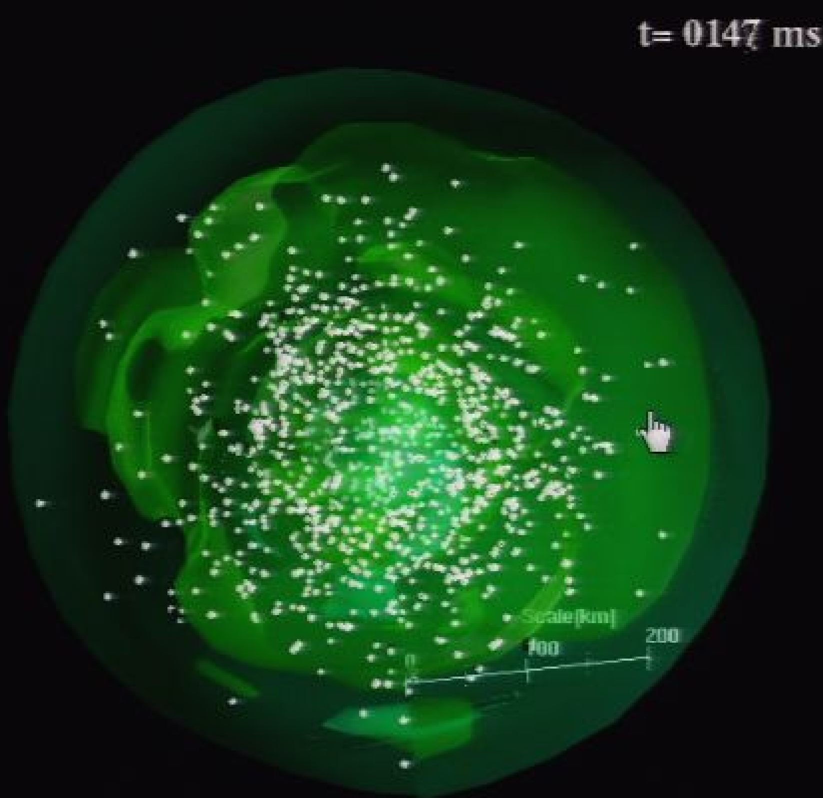

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1

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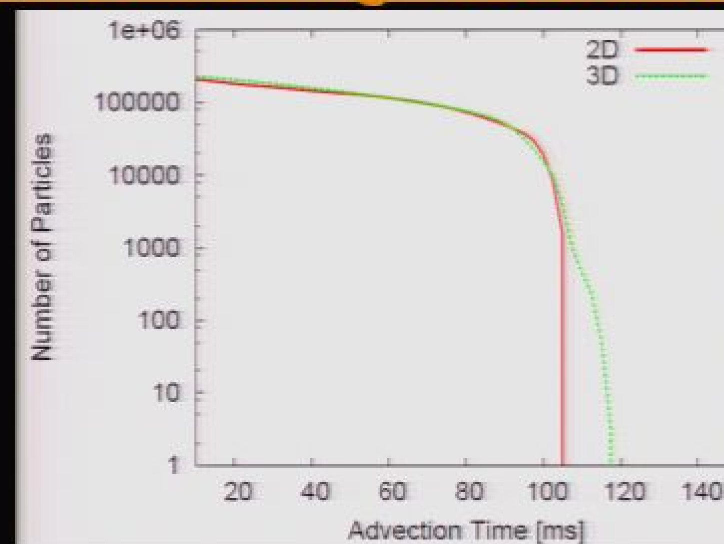
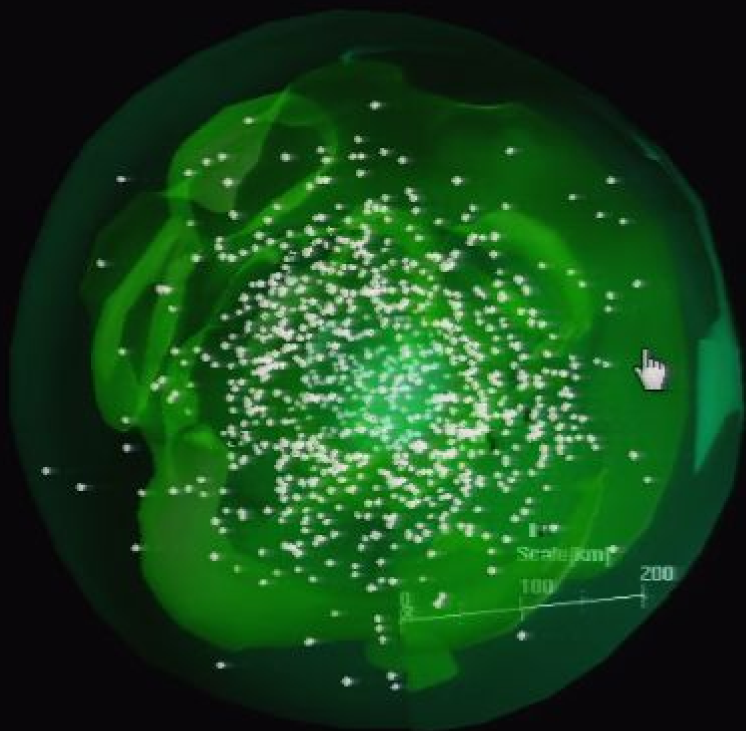


The advection timescales become longe
in 3D than in 2D.

t= 0155 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1



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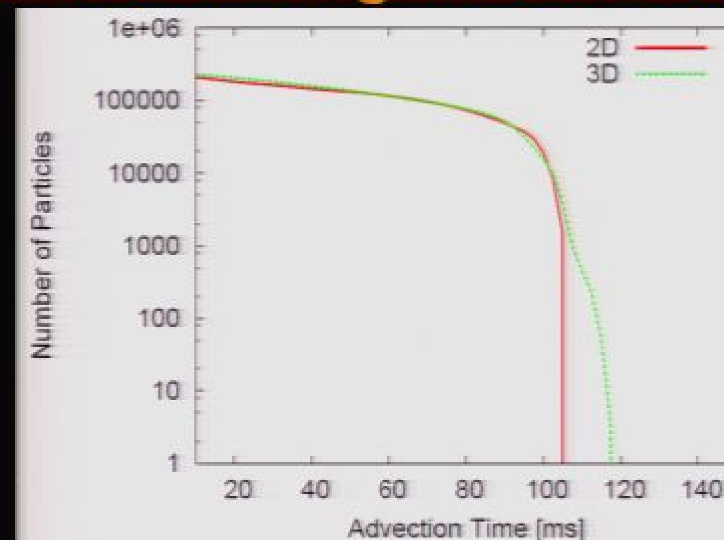
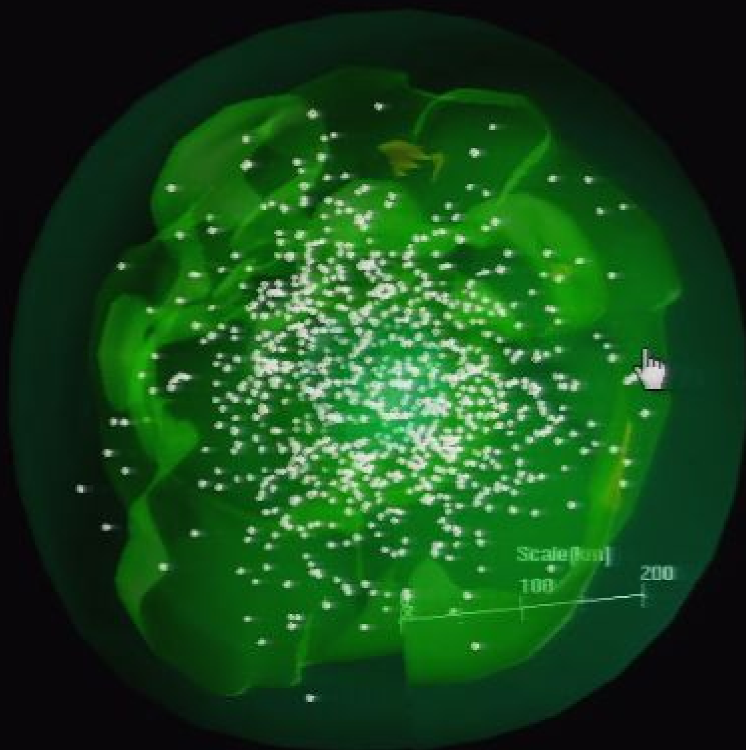


The advection timescales become longe
in 3D than in 2D.

t= 0163 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1



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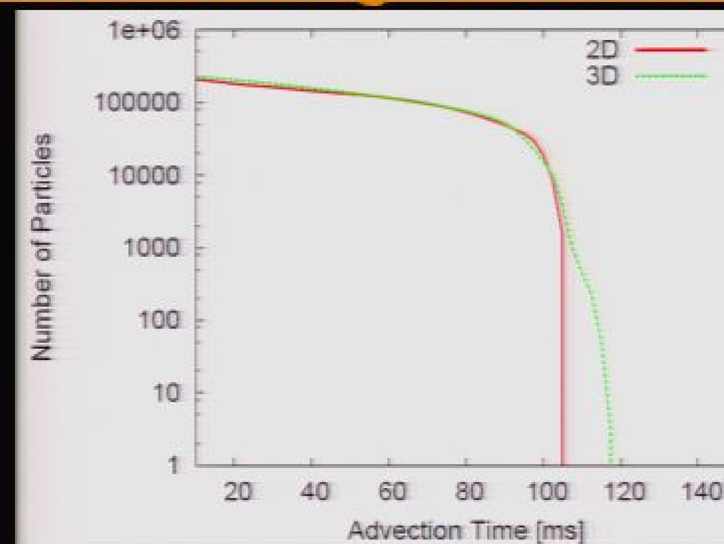

The advection timescales become longe
in 3D than in 2D.

t= 0165 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1

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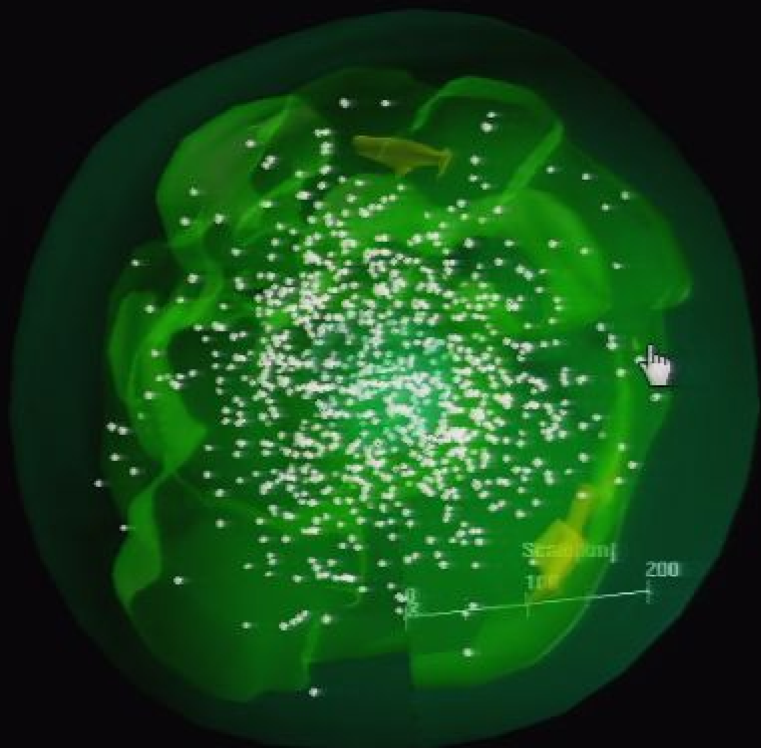

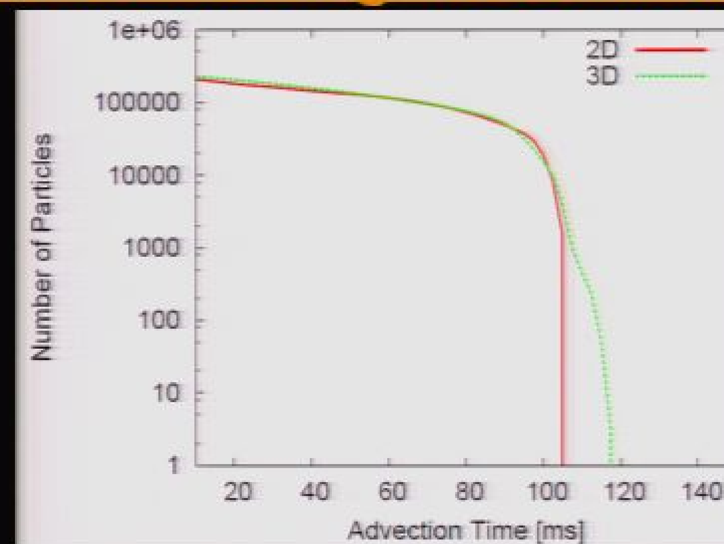

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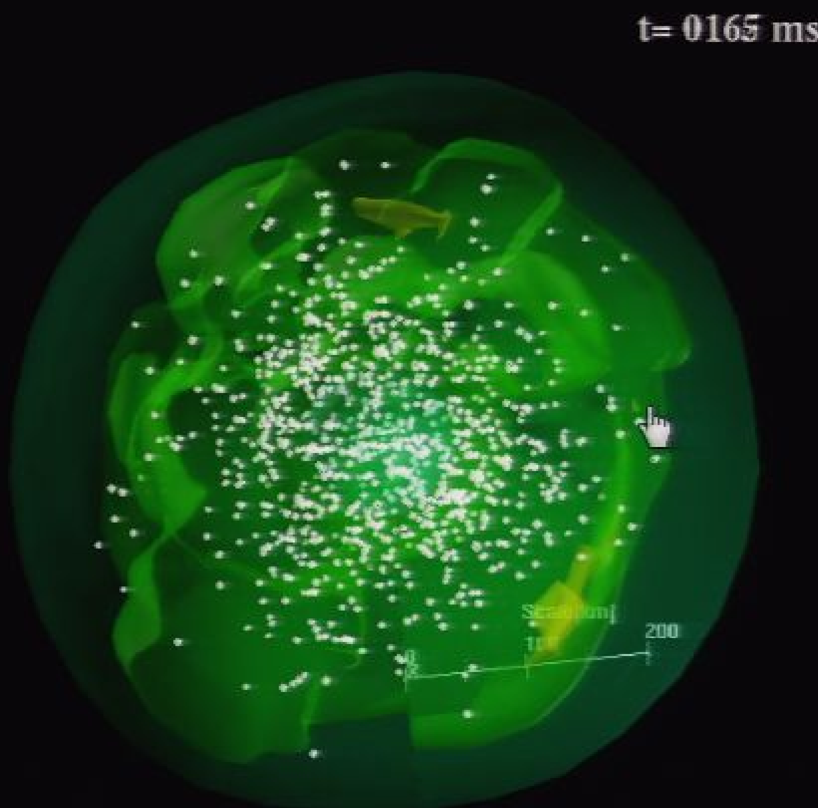

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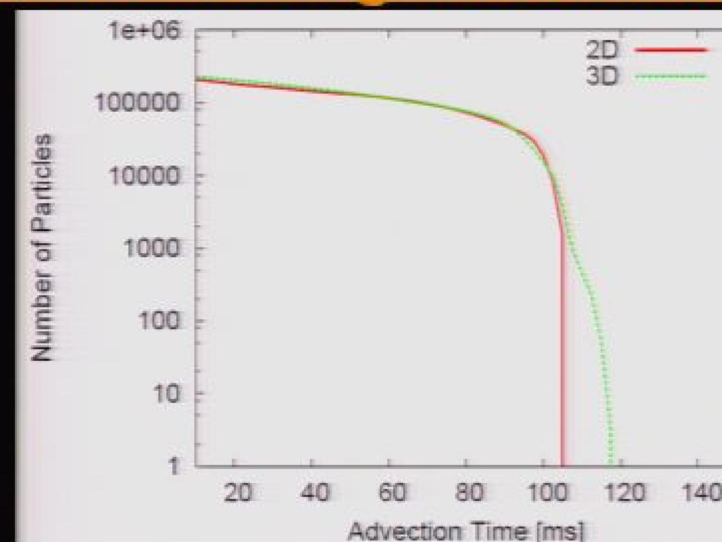

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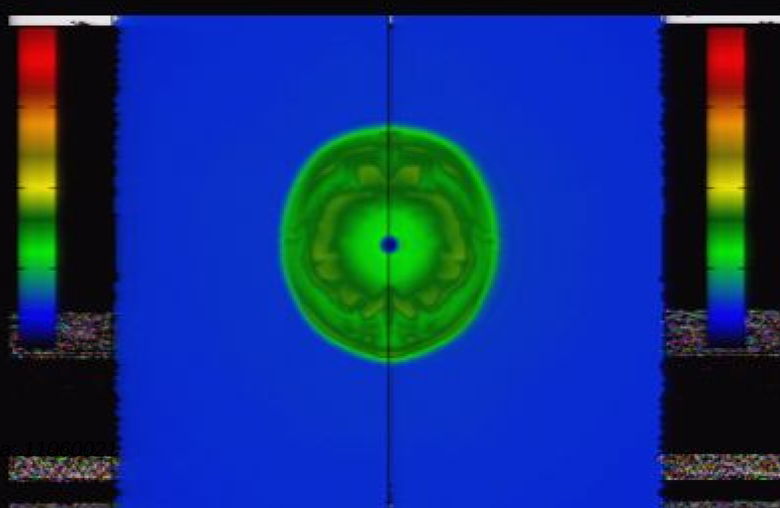


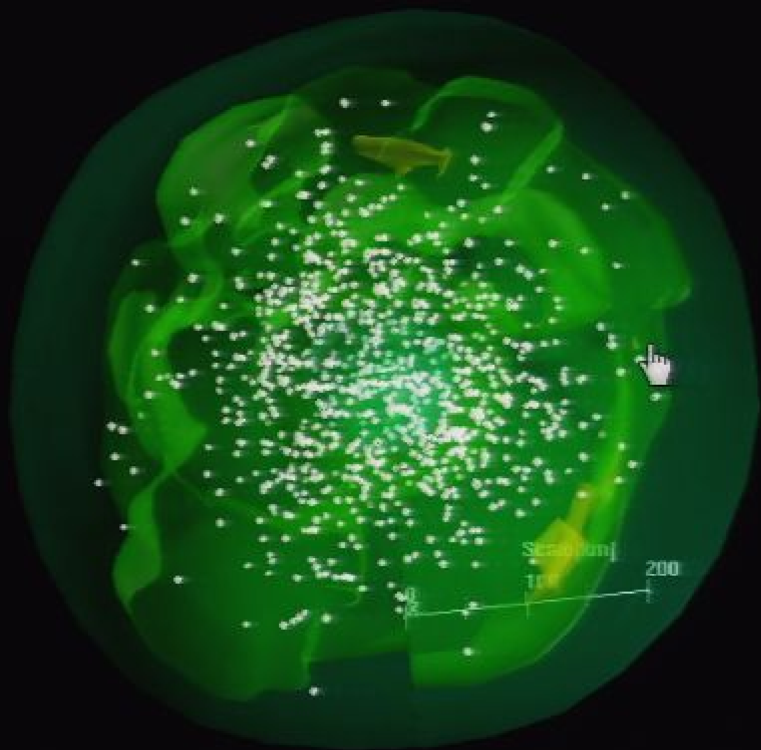
✓ **For the hydrodynamic point of view it may be more easier for 2D.**

(because matter motions can be concentrated along the special direction)

t= 0165 ms

losions in 3D than 2D ?

(e.g., Nordhaus et al. (1



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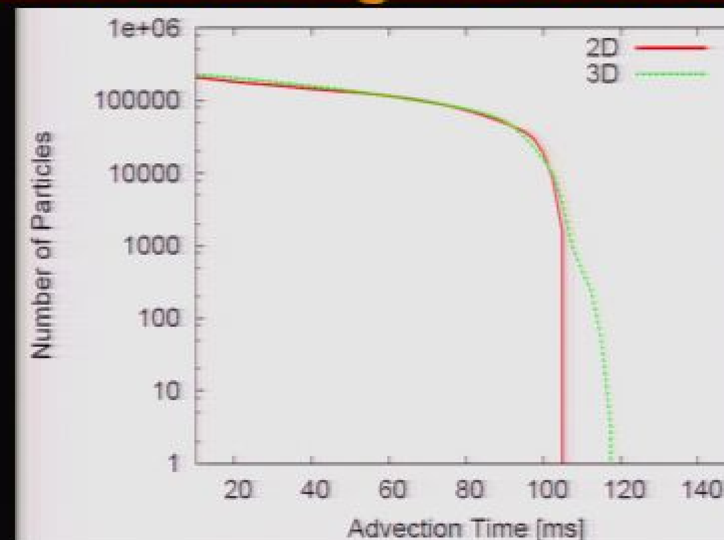

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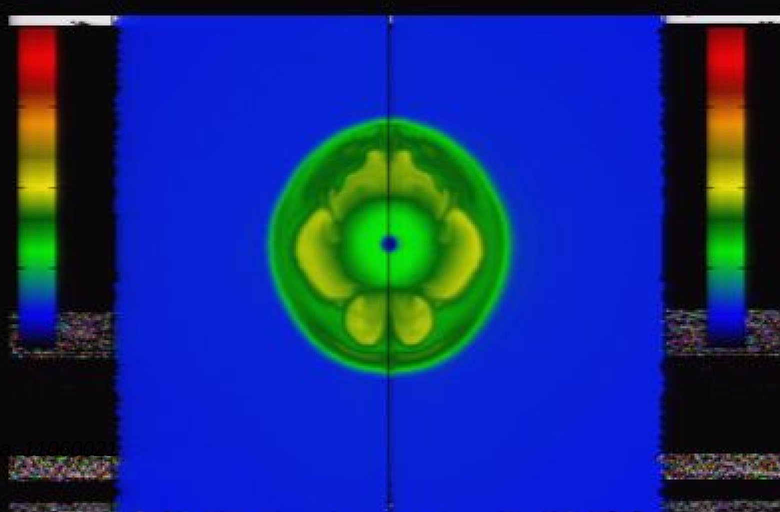

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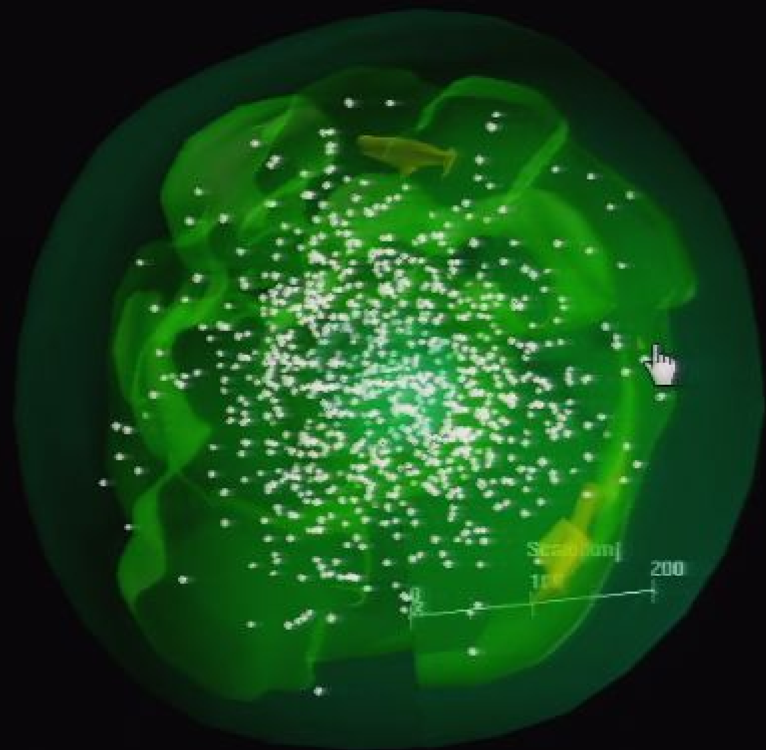

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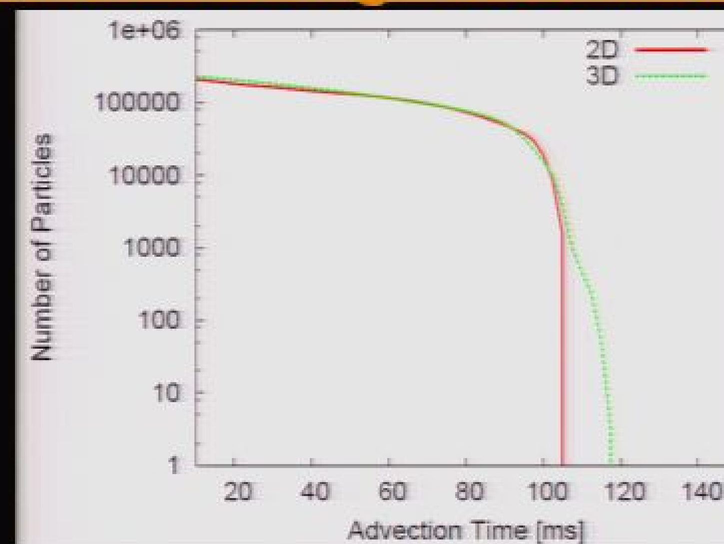

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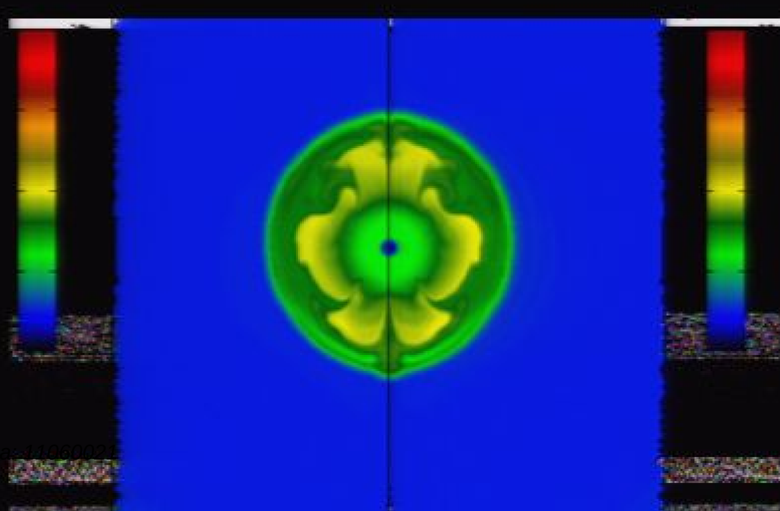

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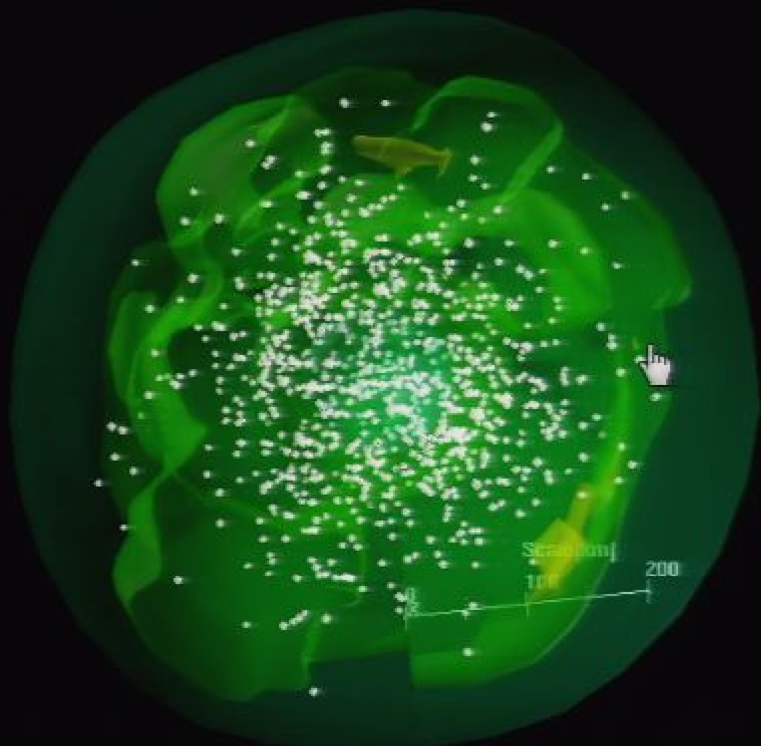

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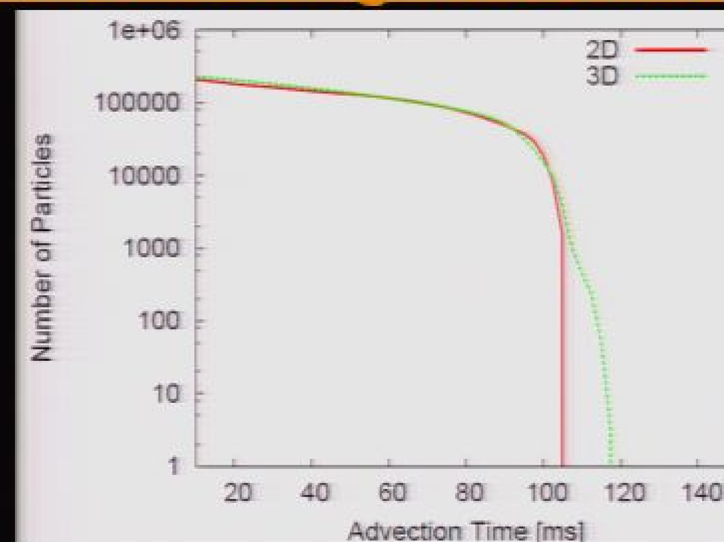

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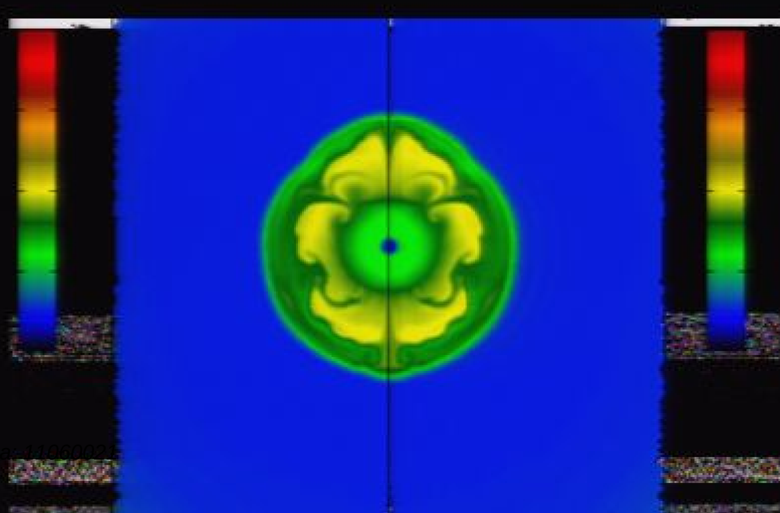

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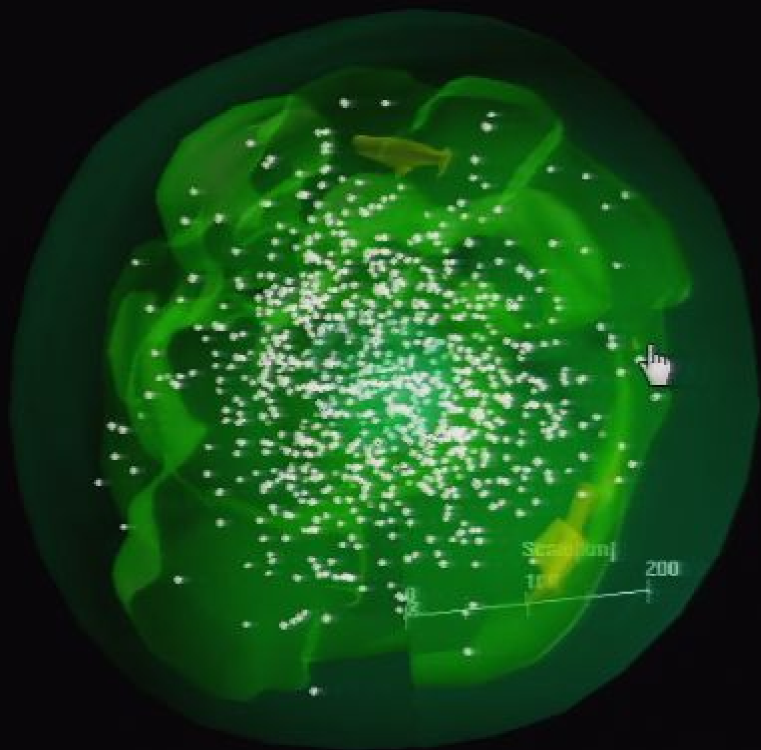

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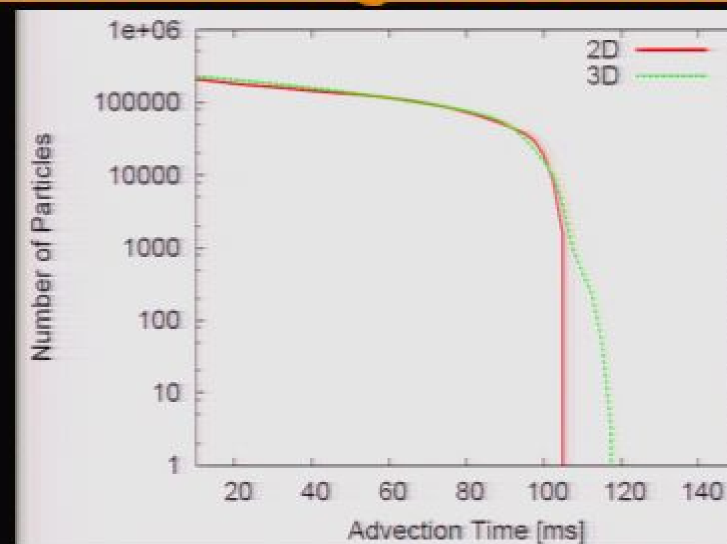

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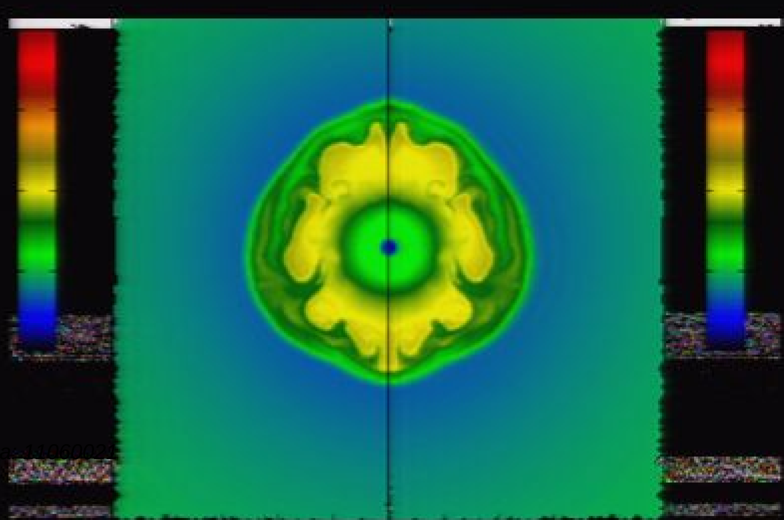

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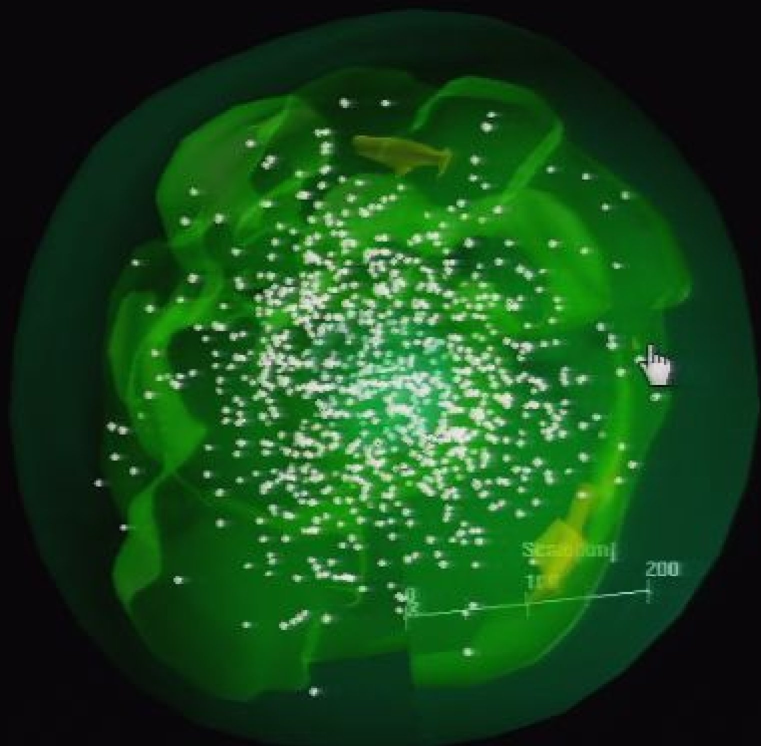

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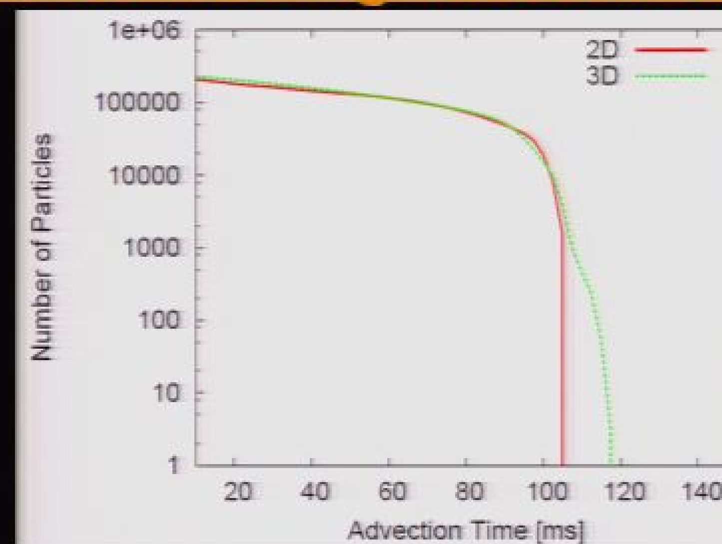

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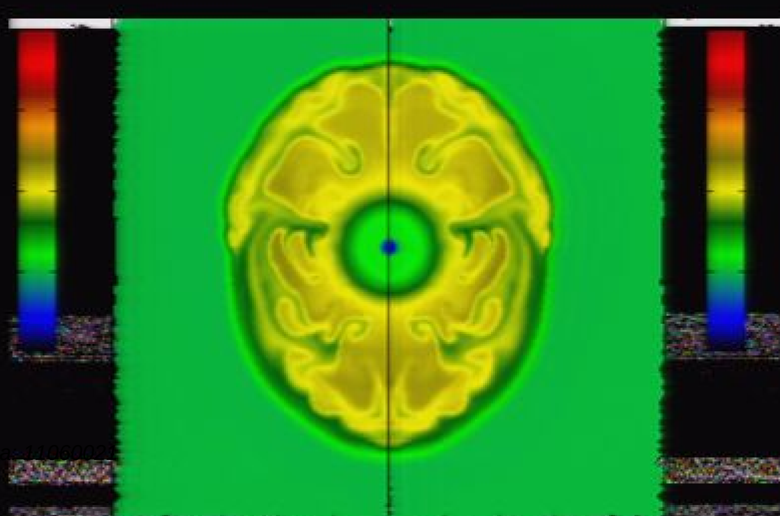

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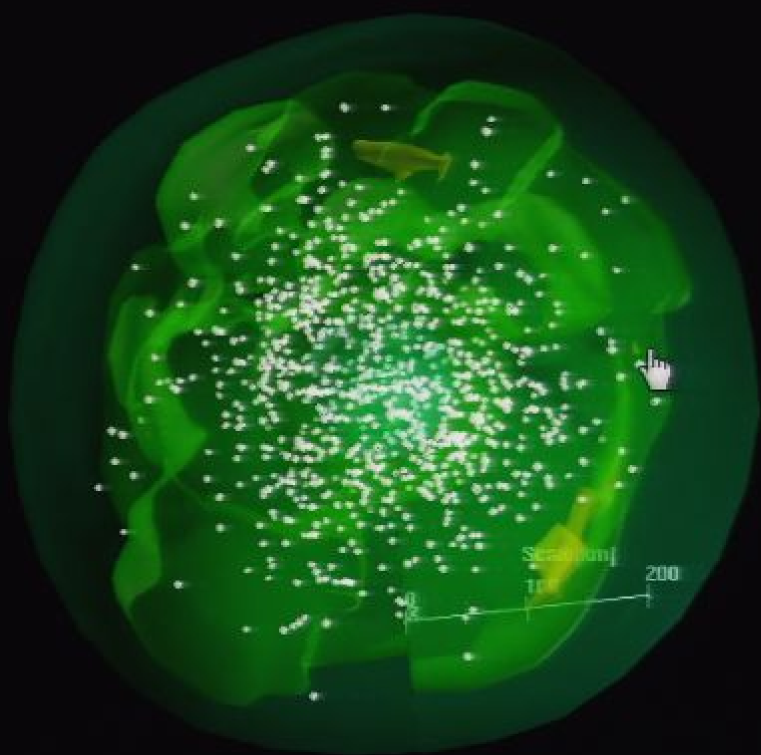

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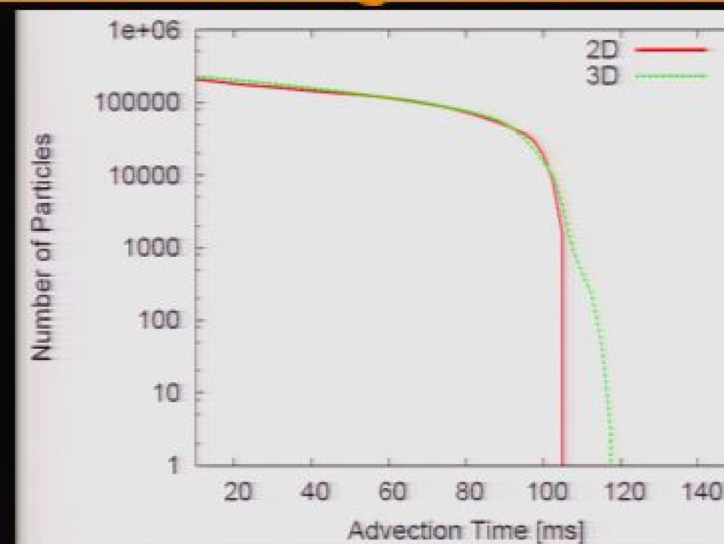

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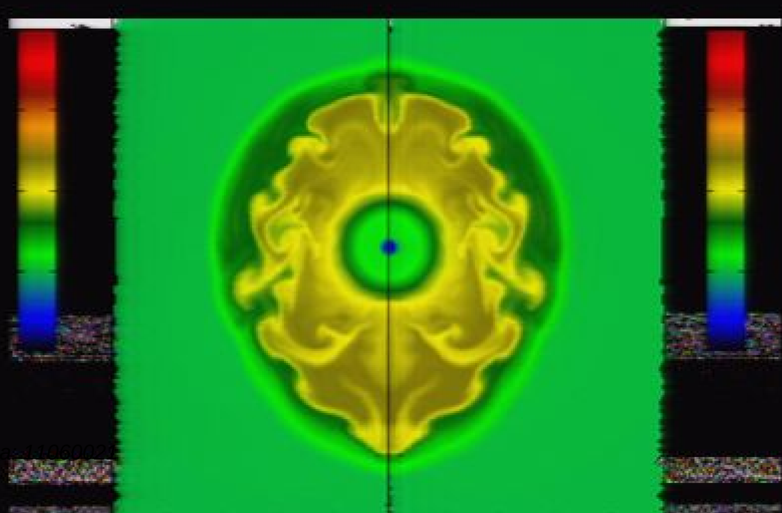

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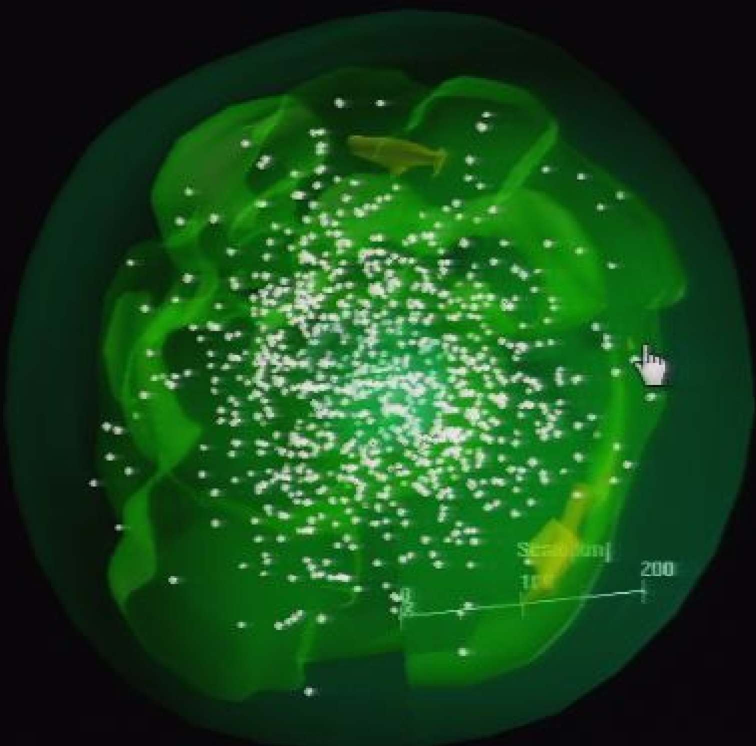

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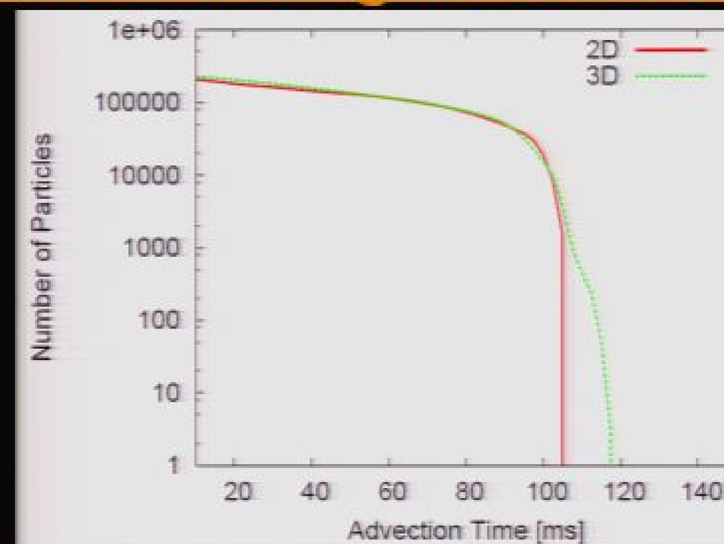

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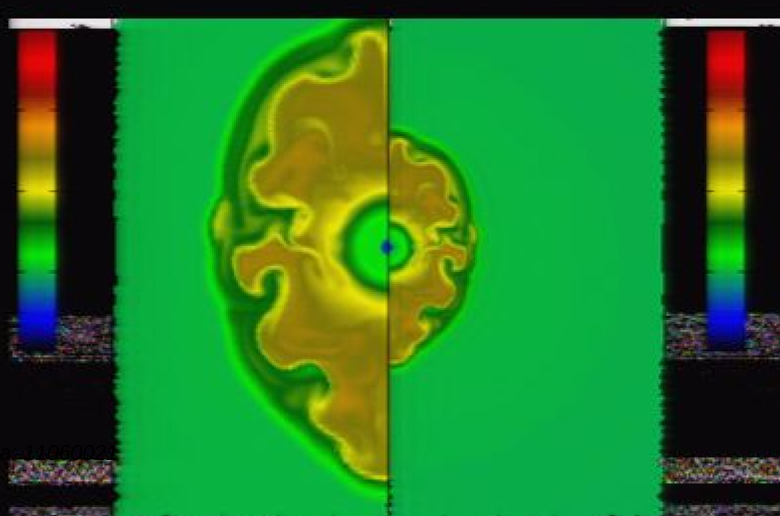

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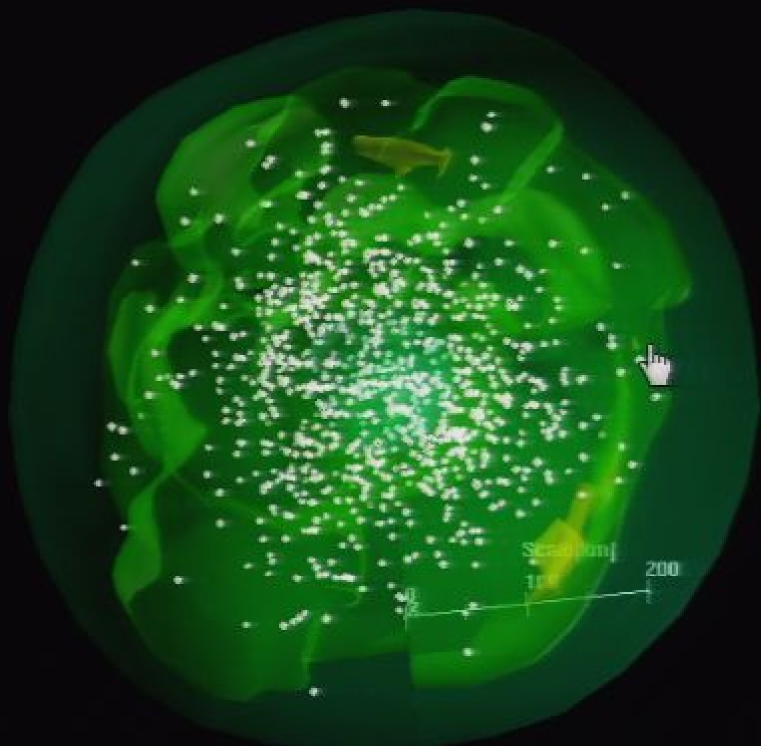

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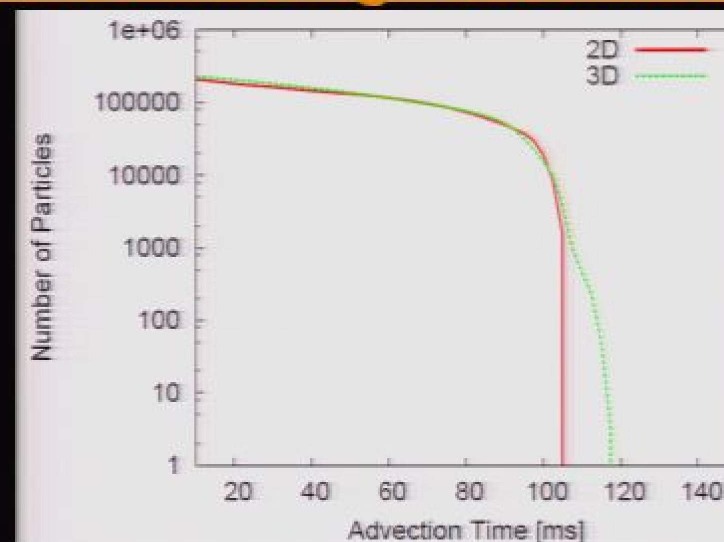

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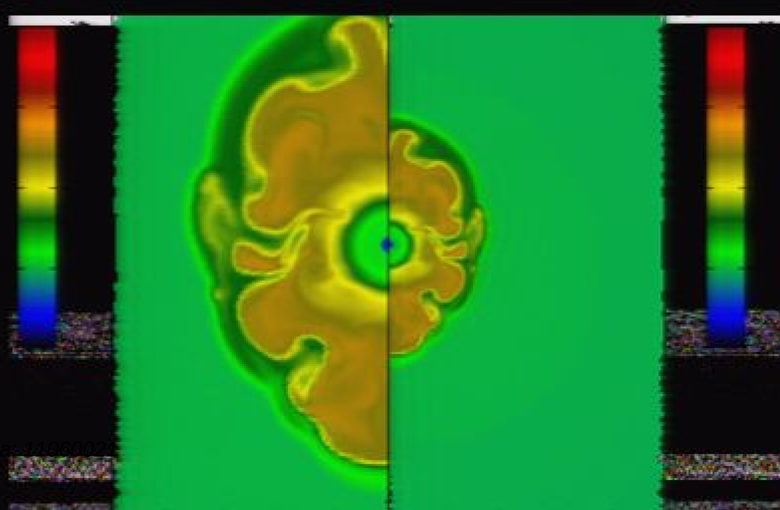

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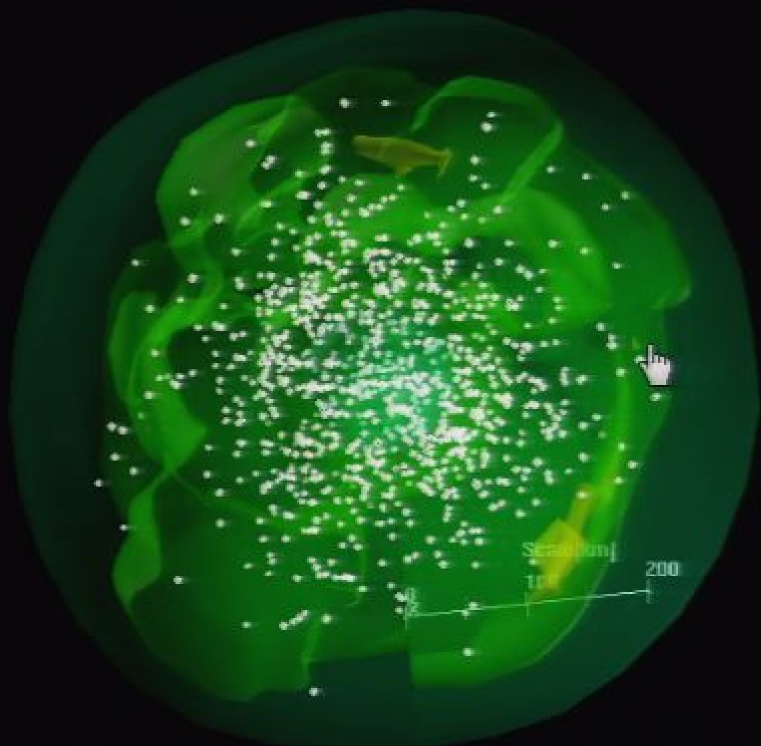

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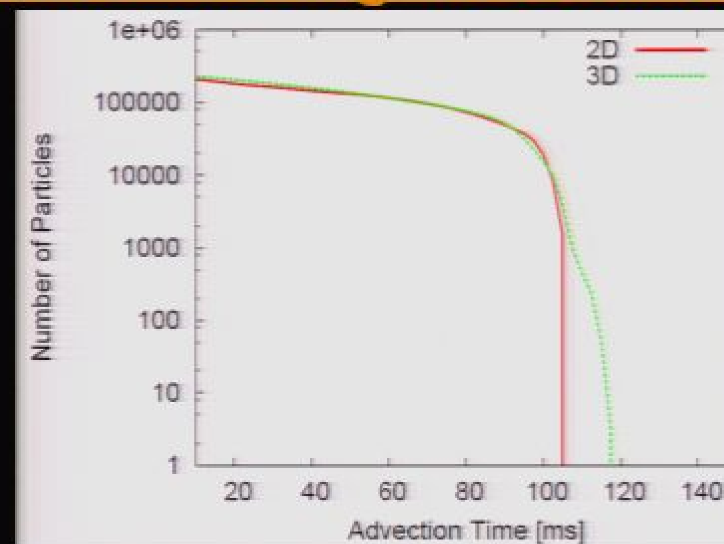

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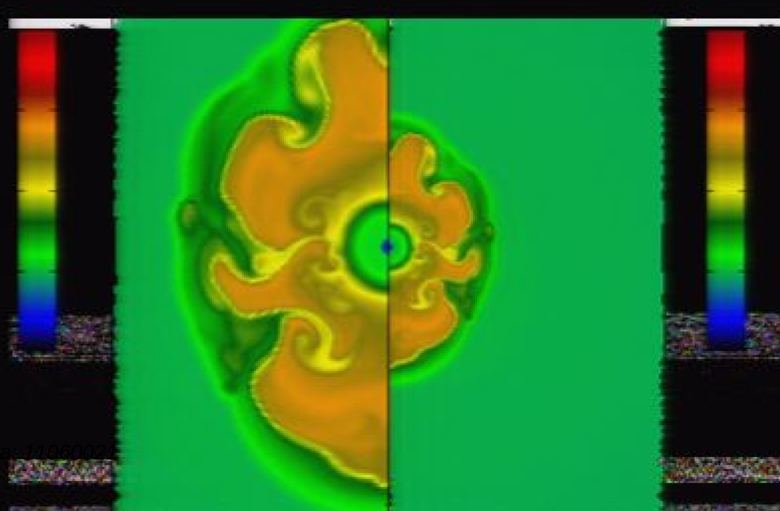

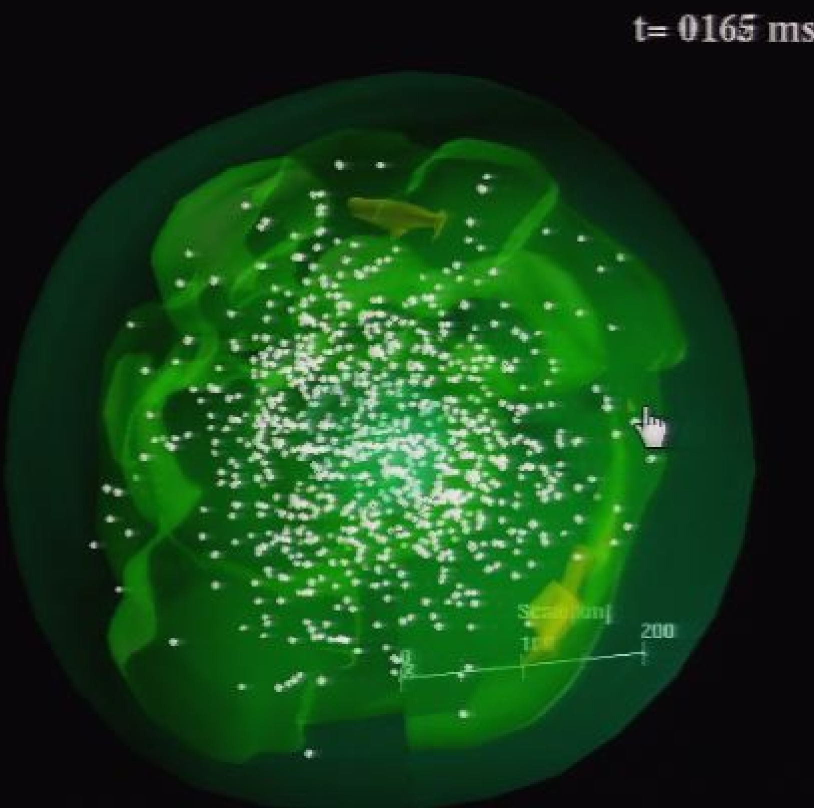

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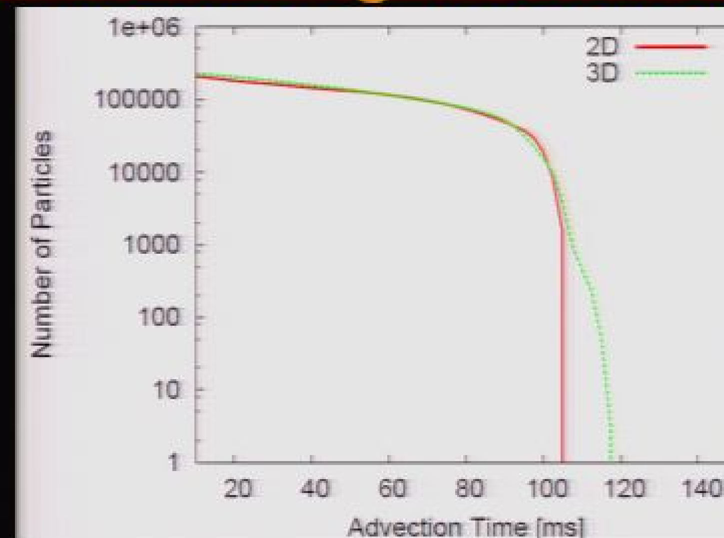

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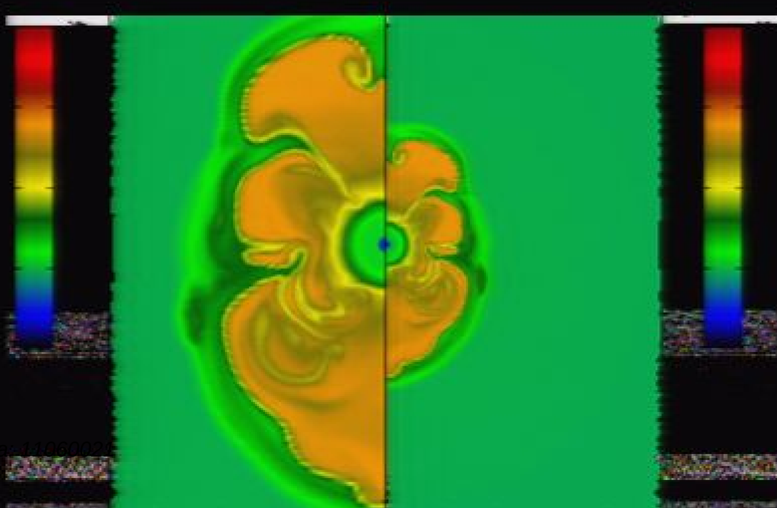

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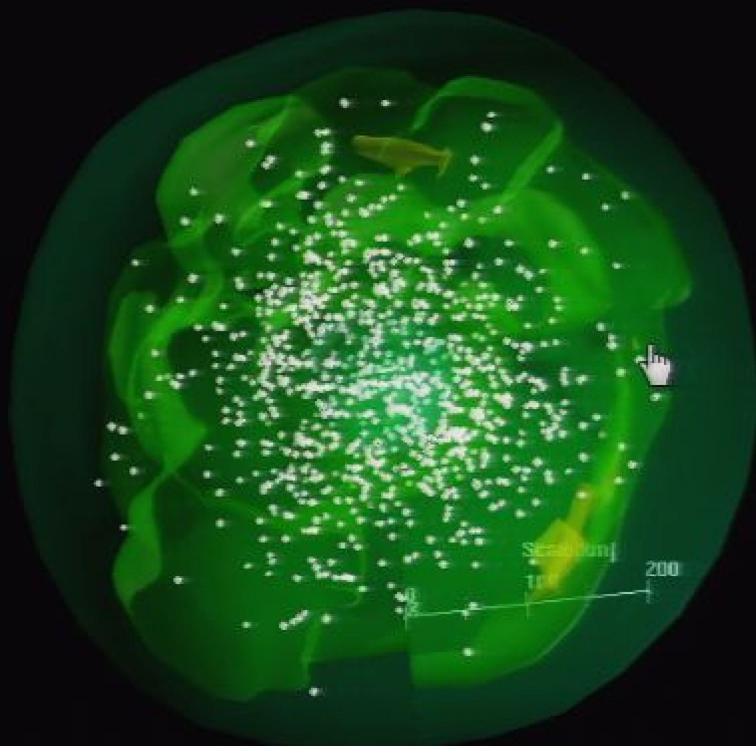

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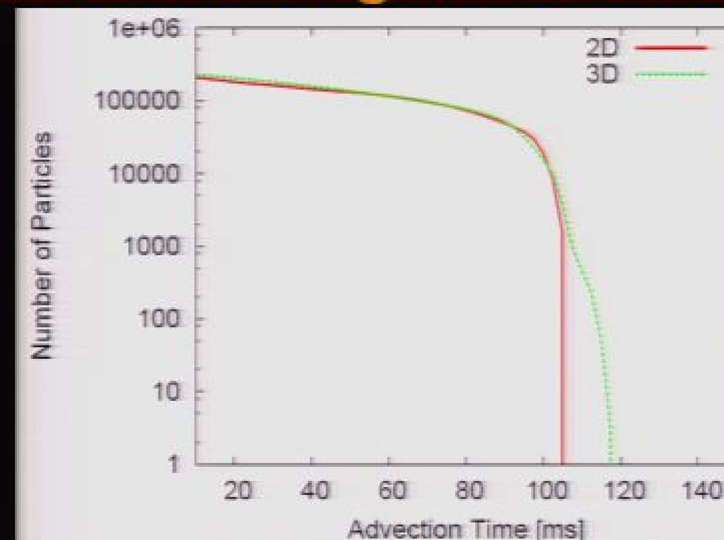

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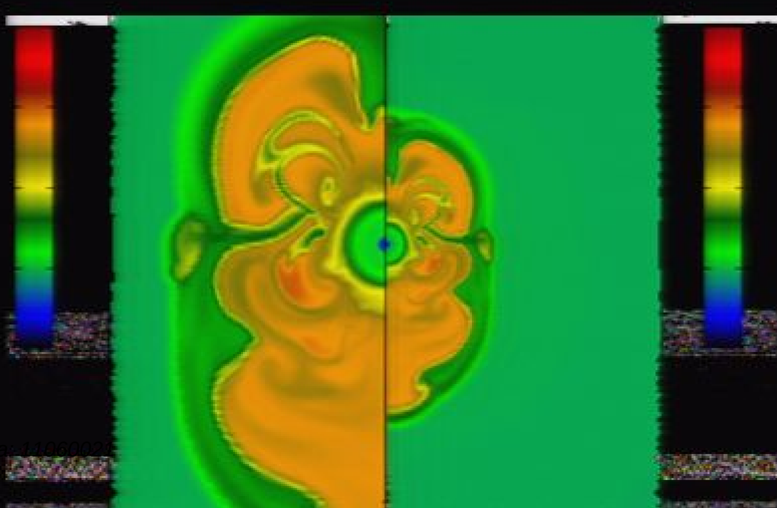

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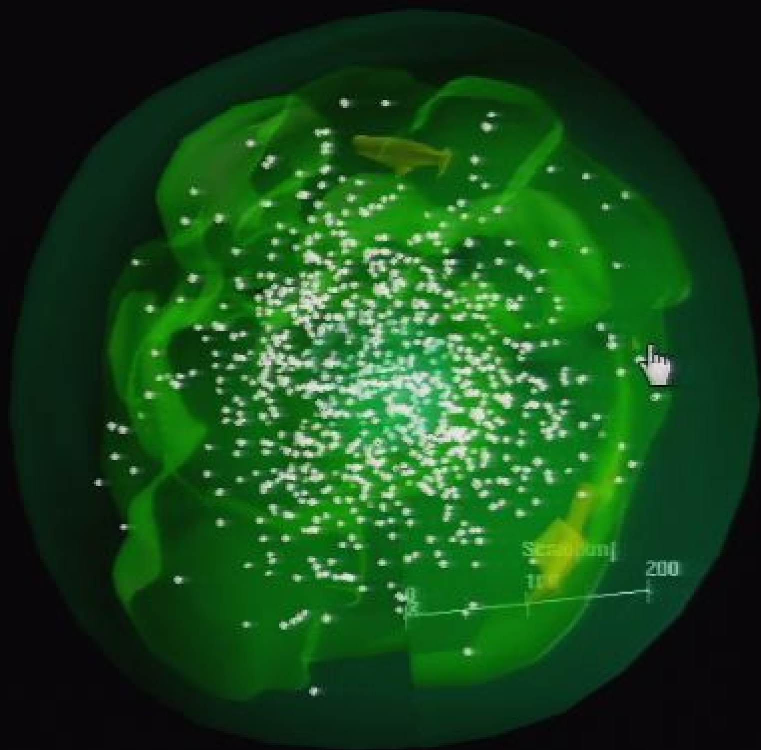
(e.g., Nordhaus et al. (1



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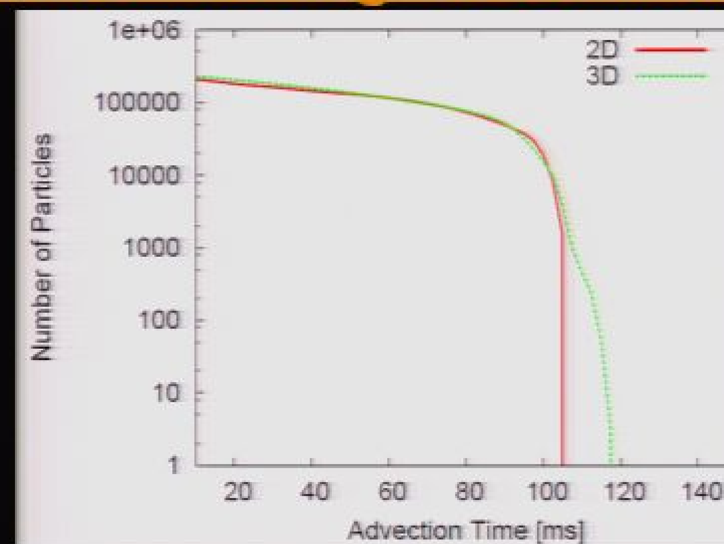

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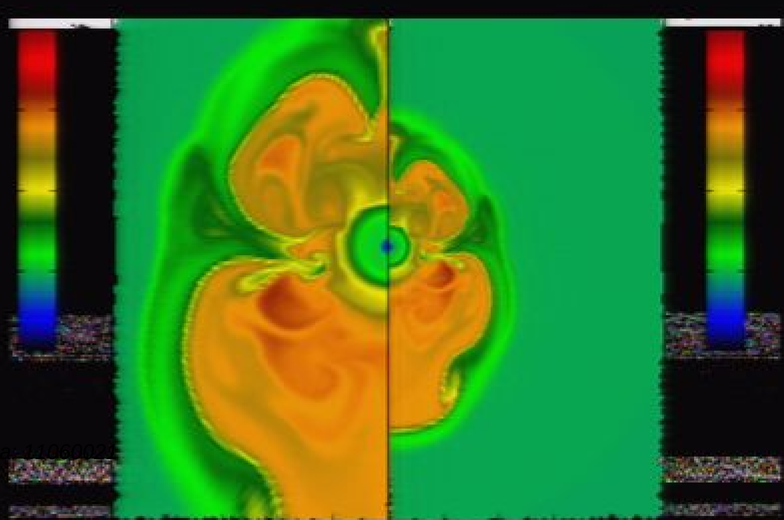

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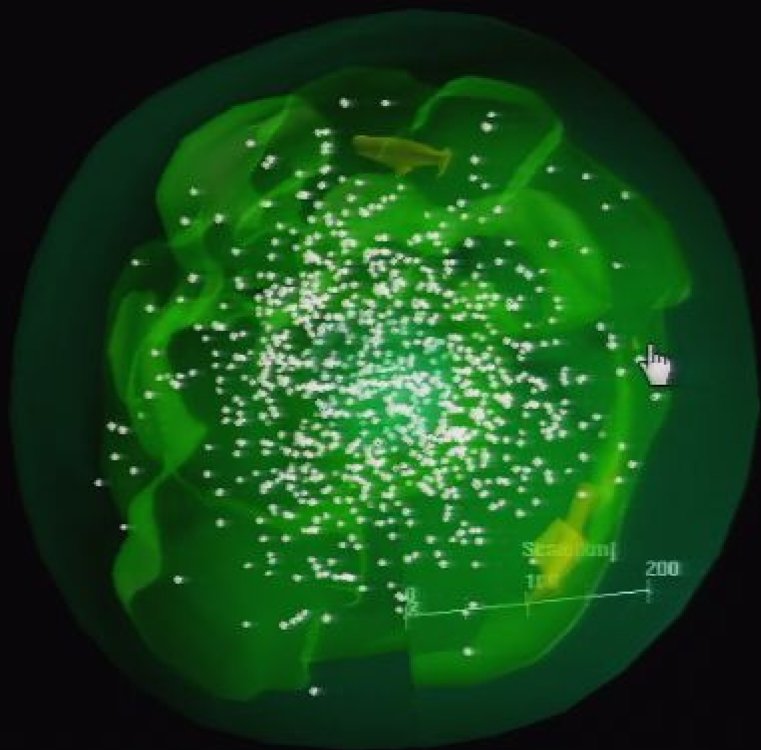

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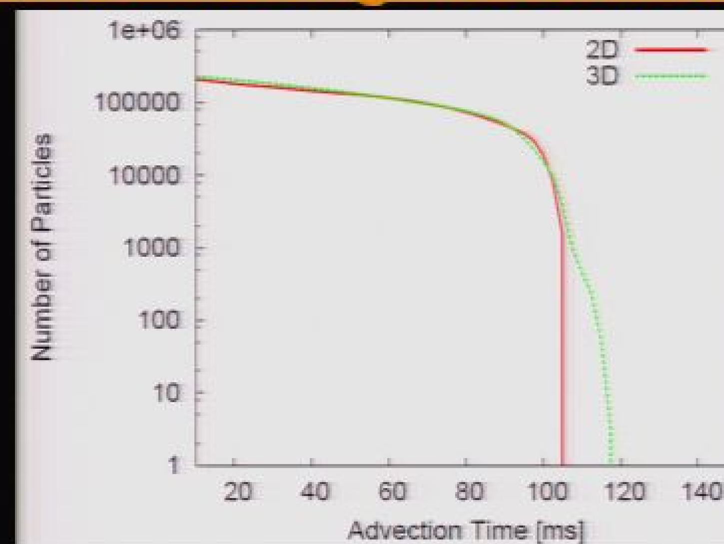

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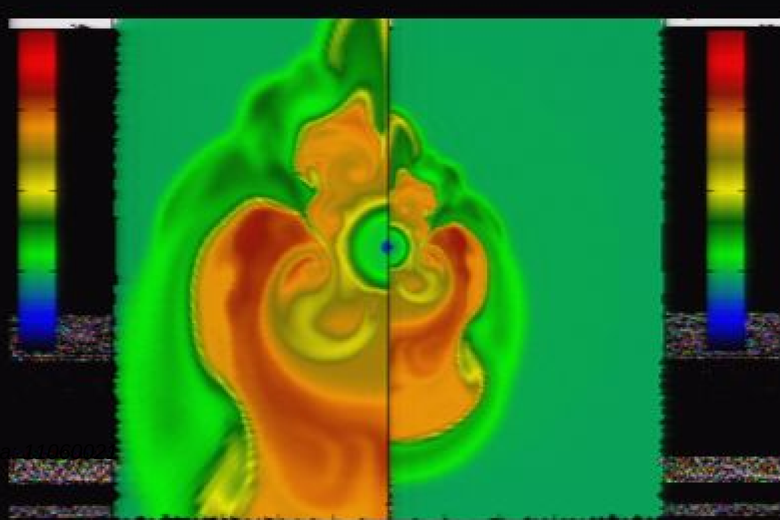

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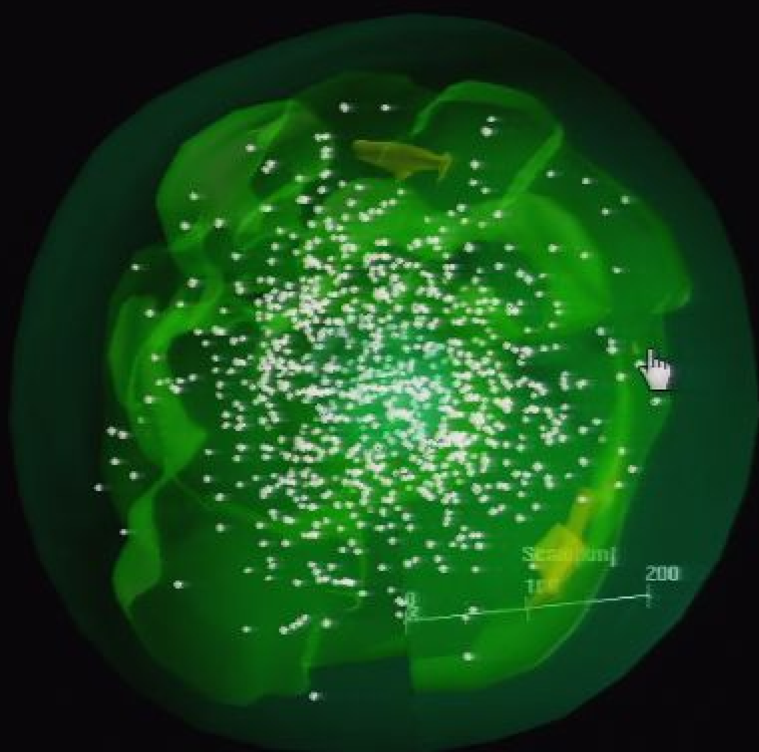

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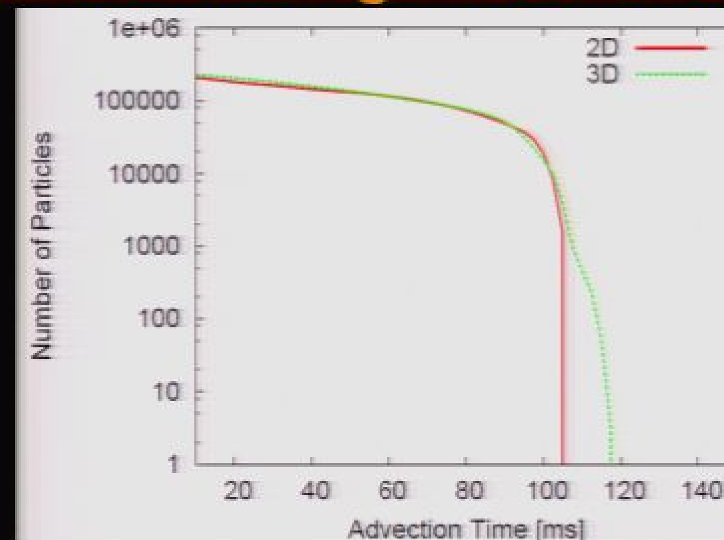

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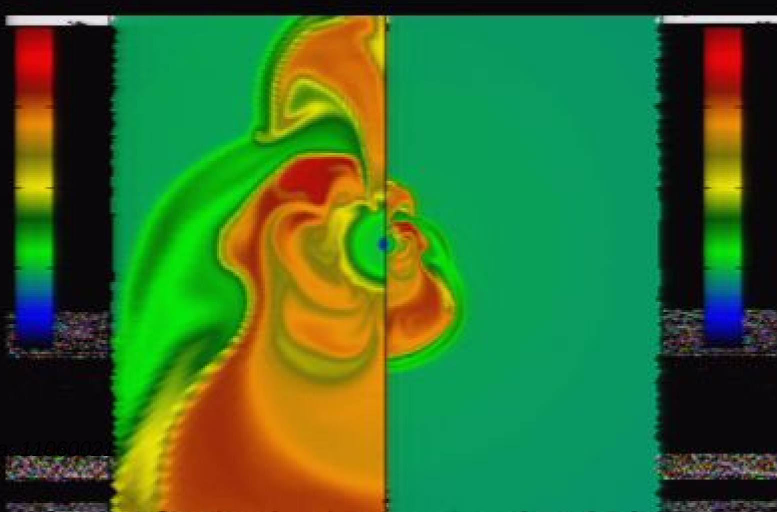

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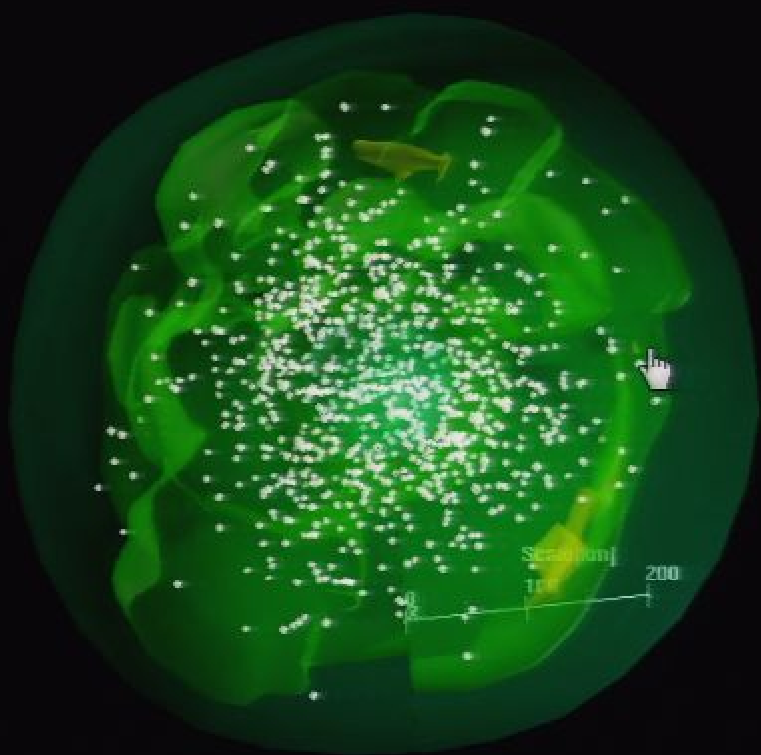

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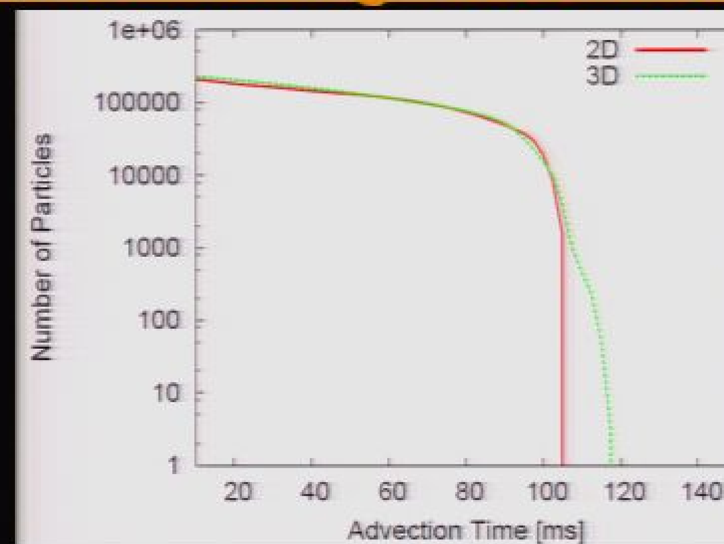

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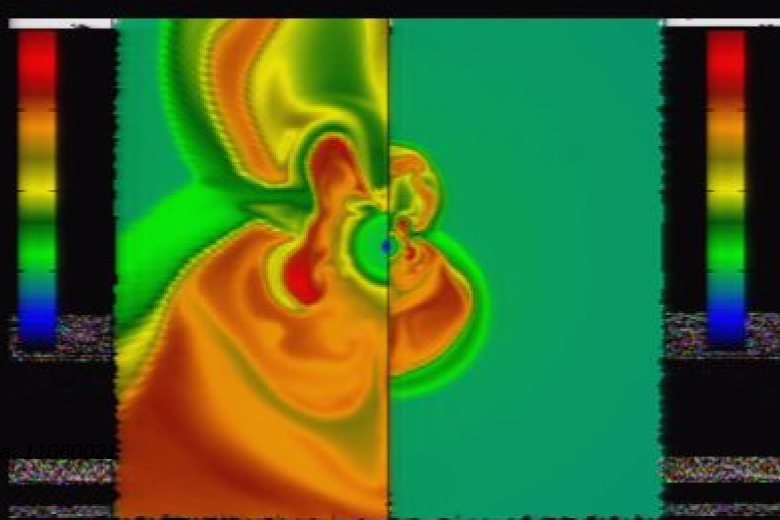

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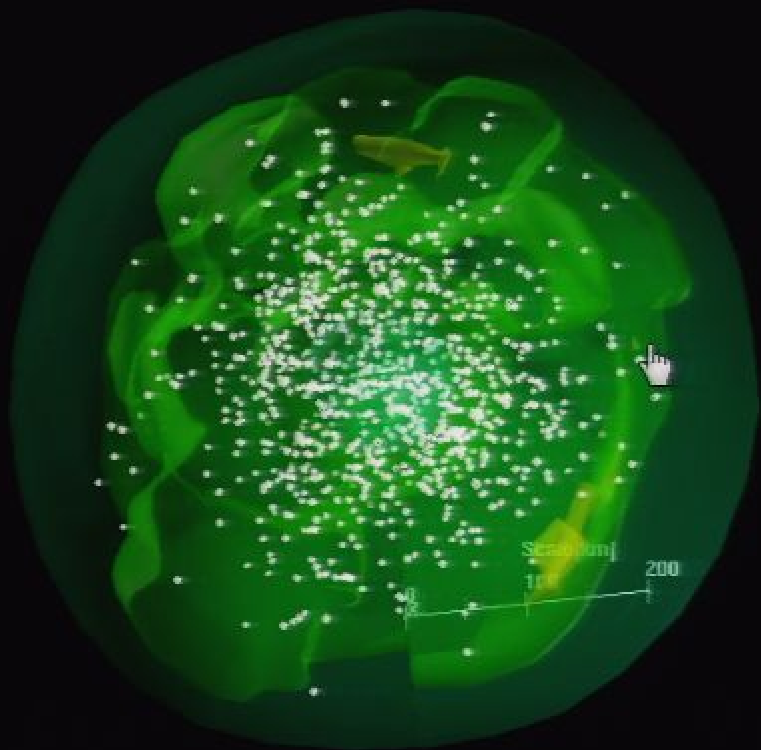

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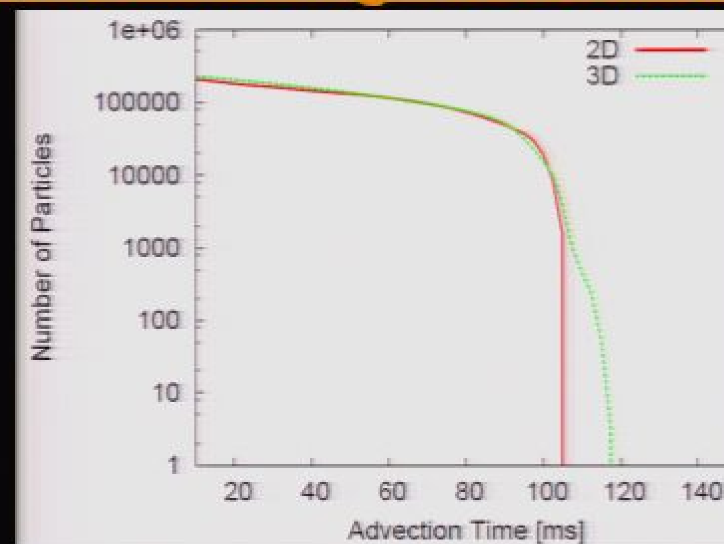

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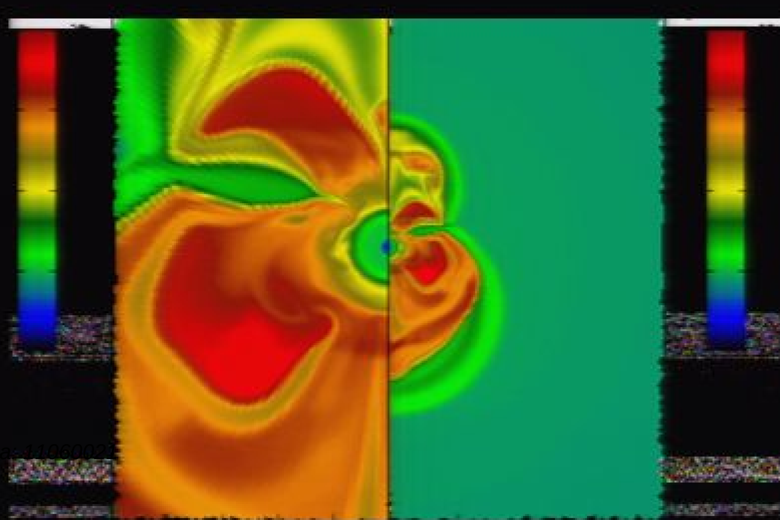

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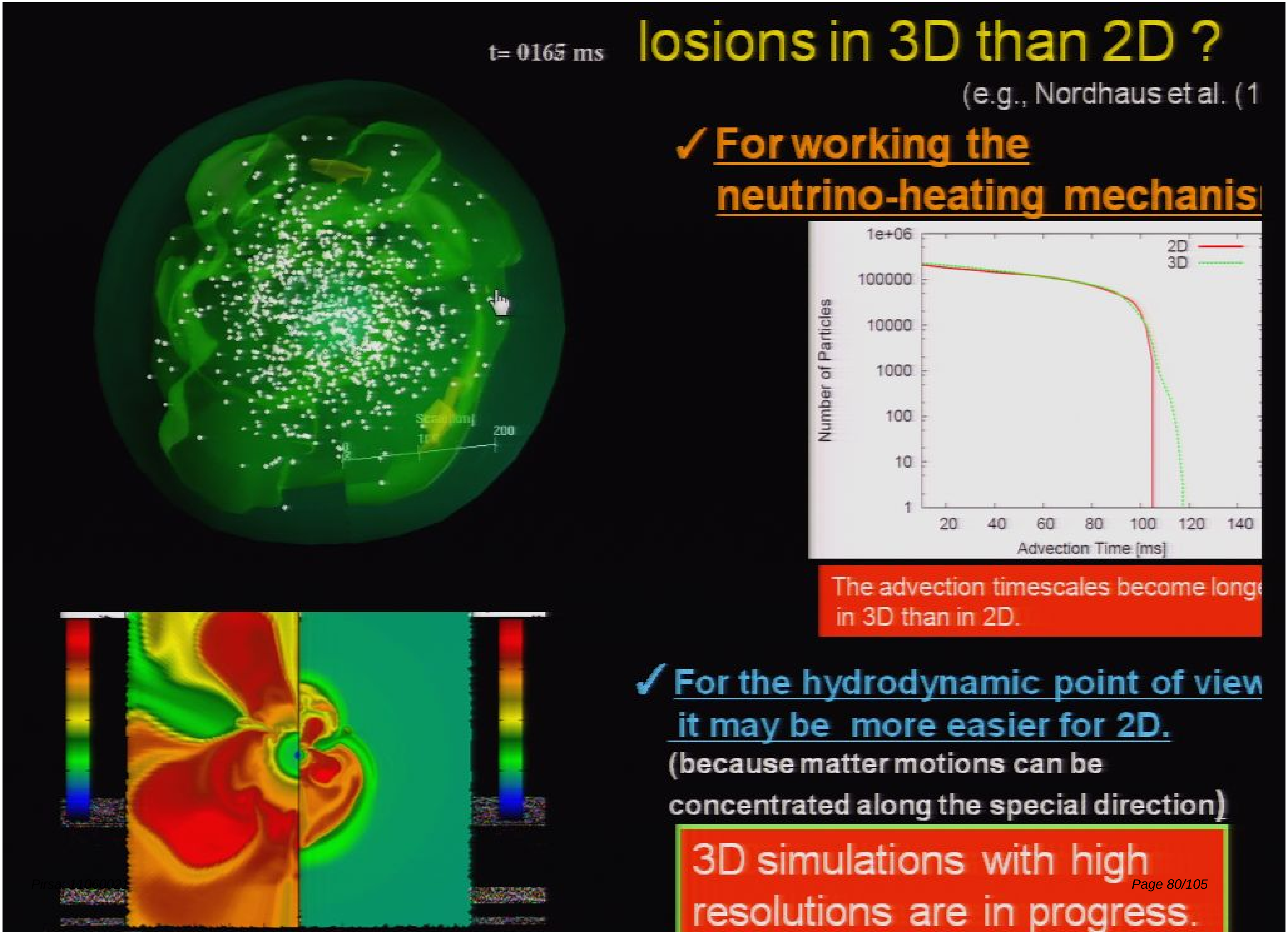
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✓For working the
neutrino-heating mechanis
1e+06
100000
10000
1000
100
10
1
Number of Particles
2D
3D
20
40
60
80
100
120
140
Advection Time [ms]
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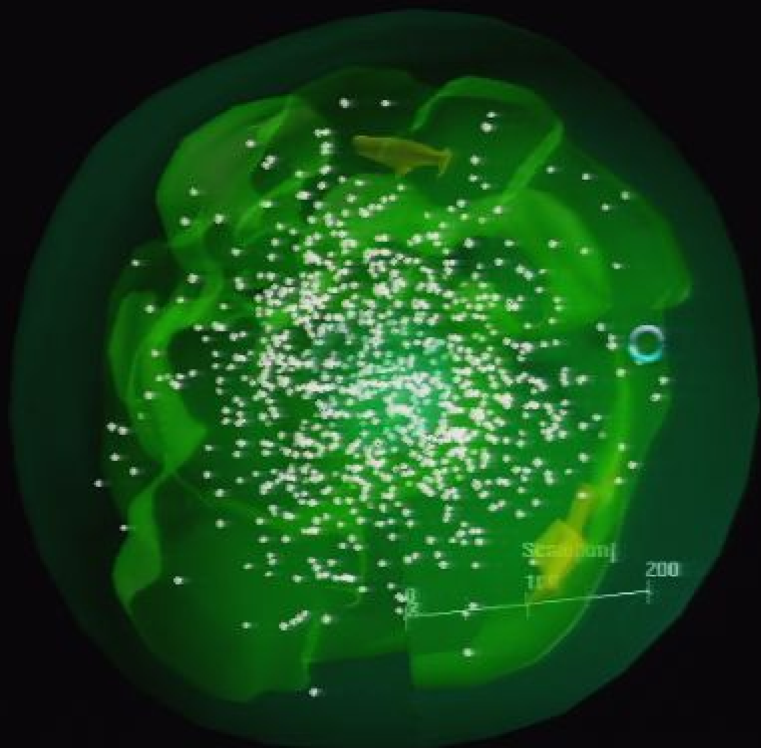

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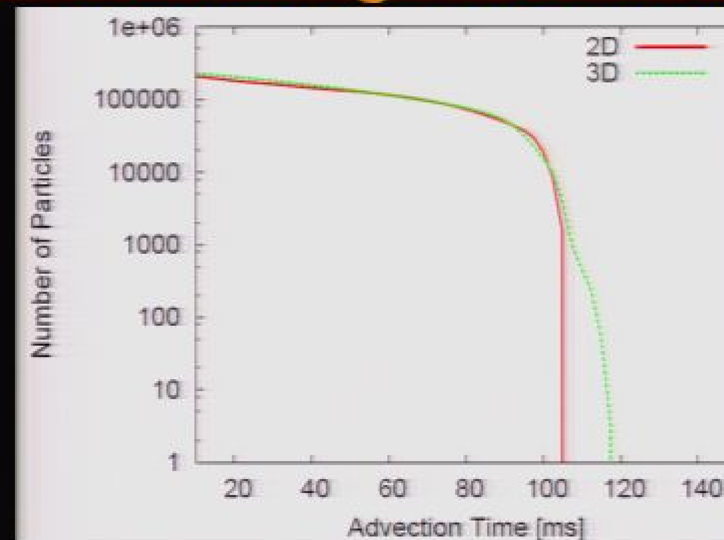

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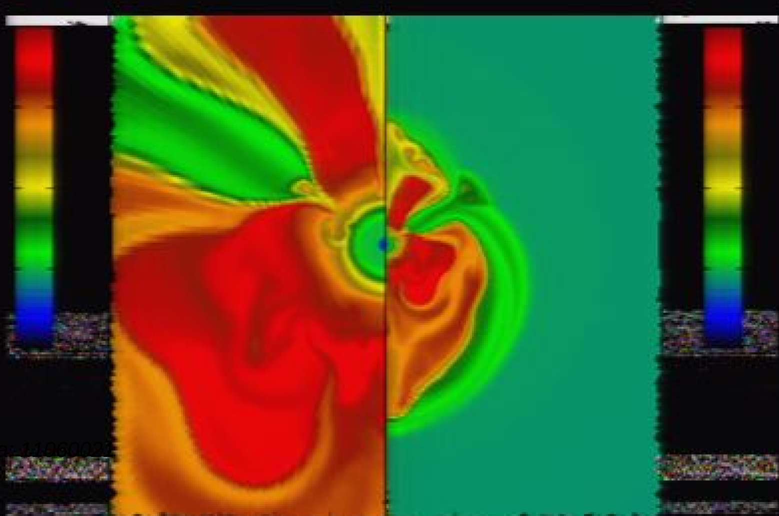

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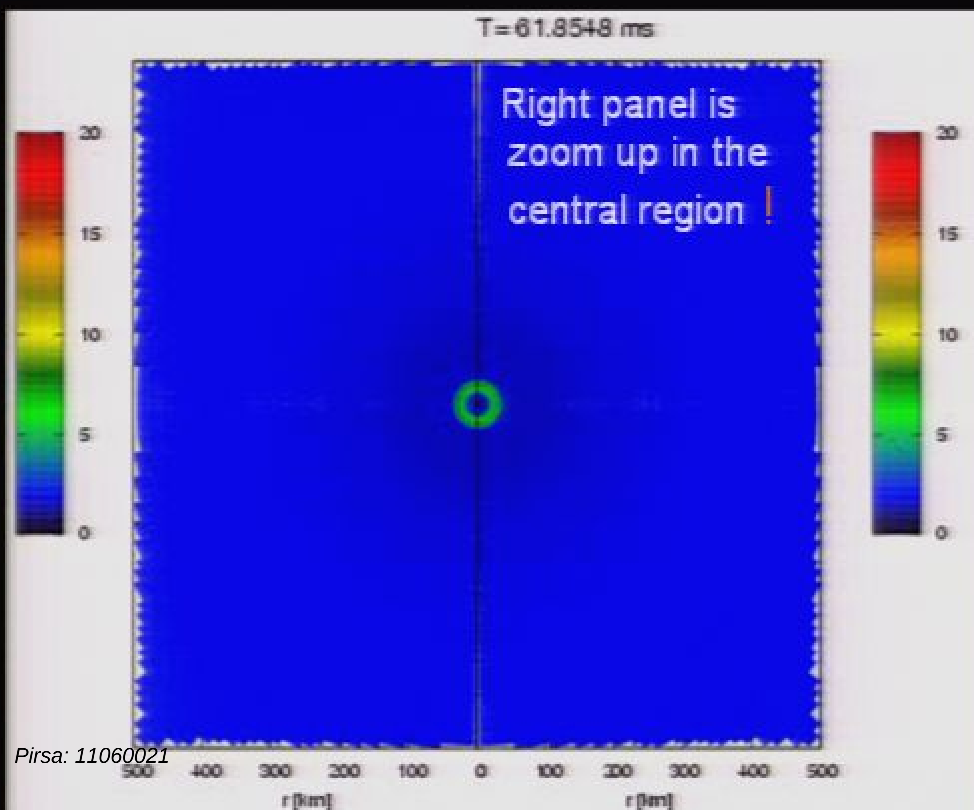
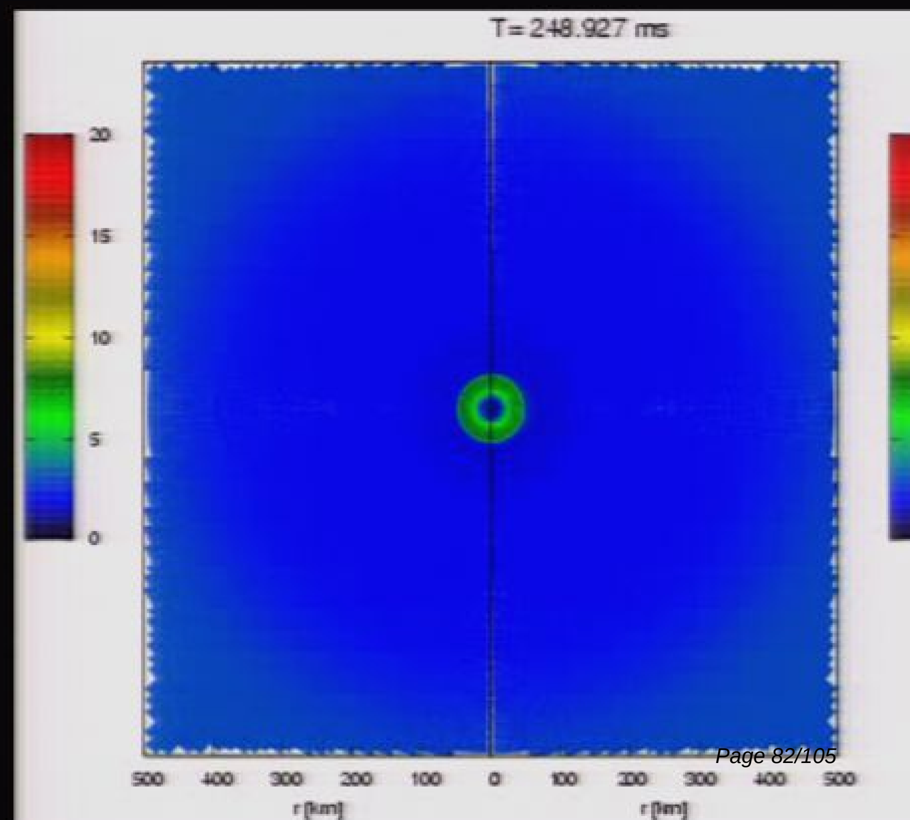
The third lesson is about EOSs(1/2)

✓ 2D models of a $15M_{sun}$ progenitor by WW (1995)
✓ The IDSA is implemented (nu_X 's : not yet).

LS EOS(K=180MeV)



H-Shen EOS(K=281MeV



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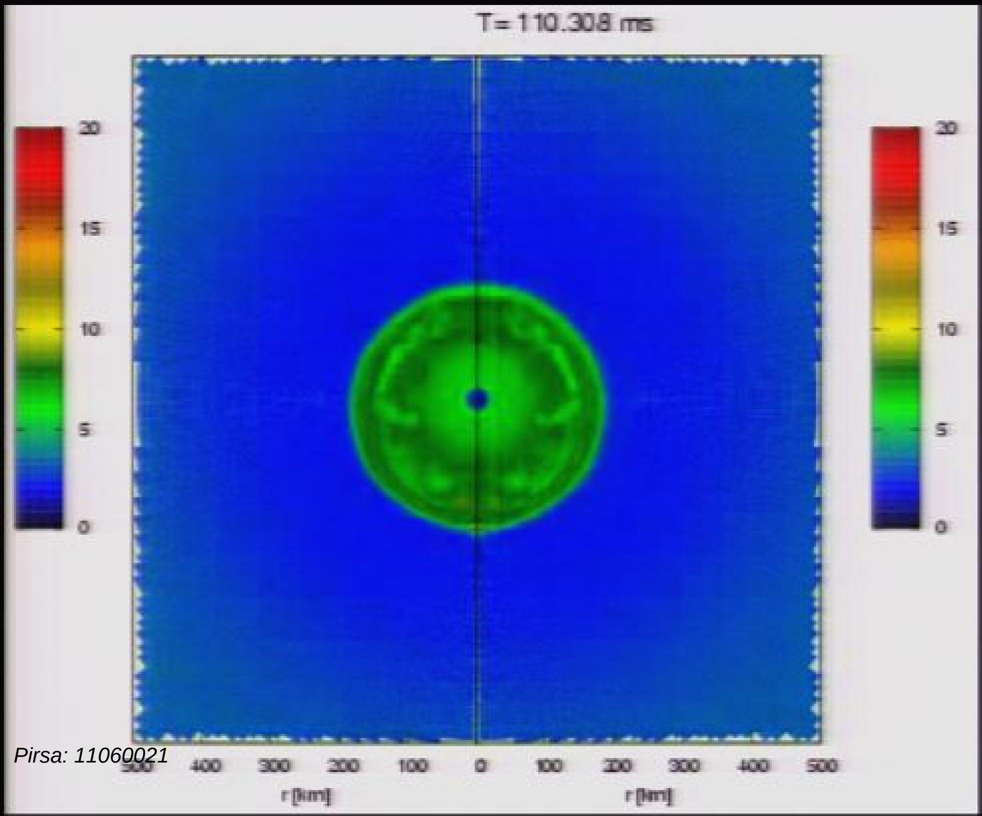

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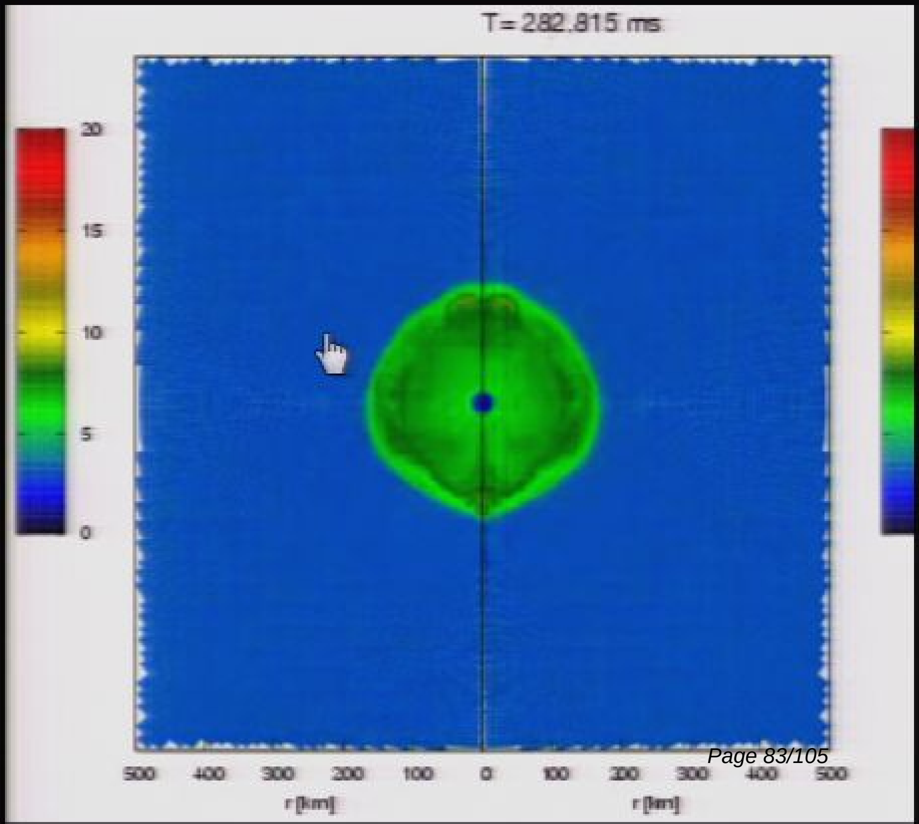

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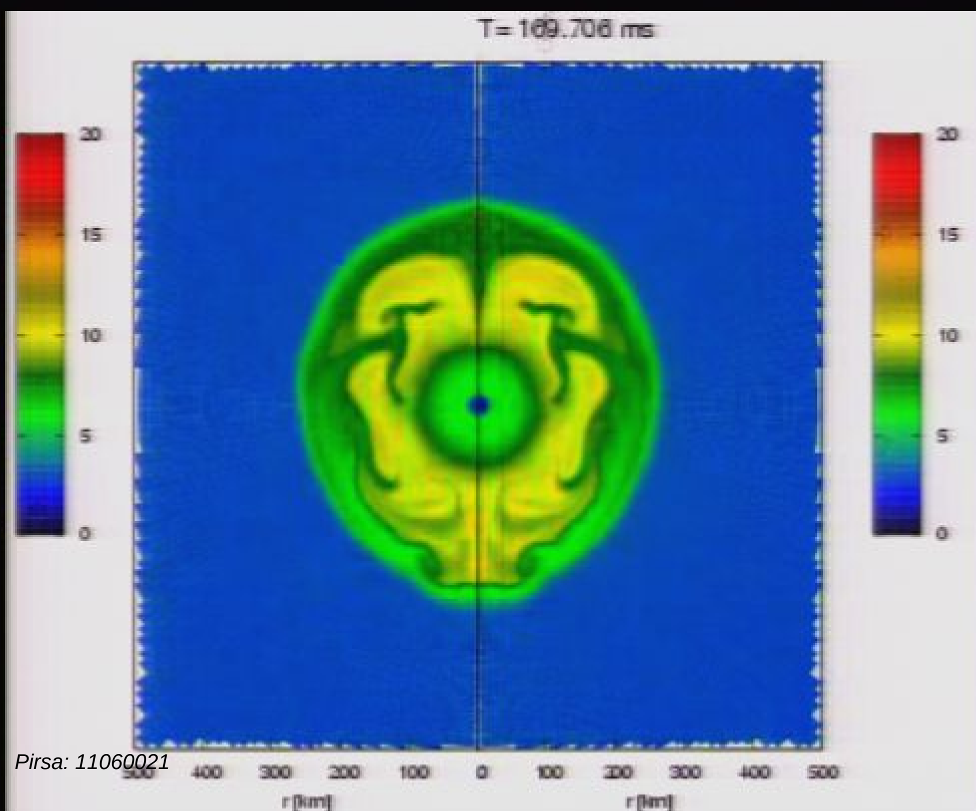

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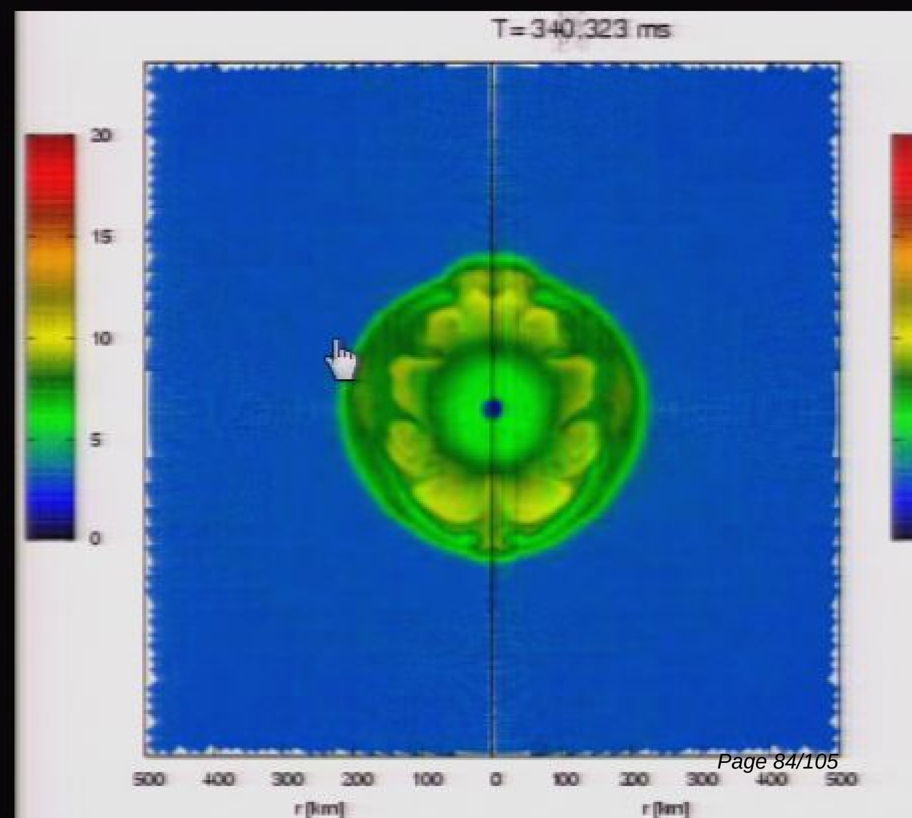

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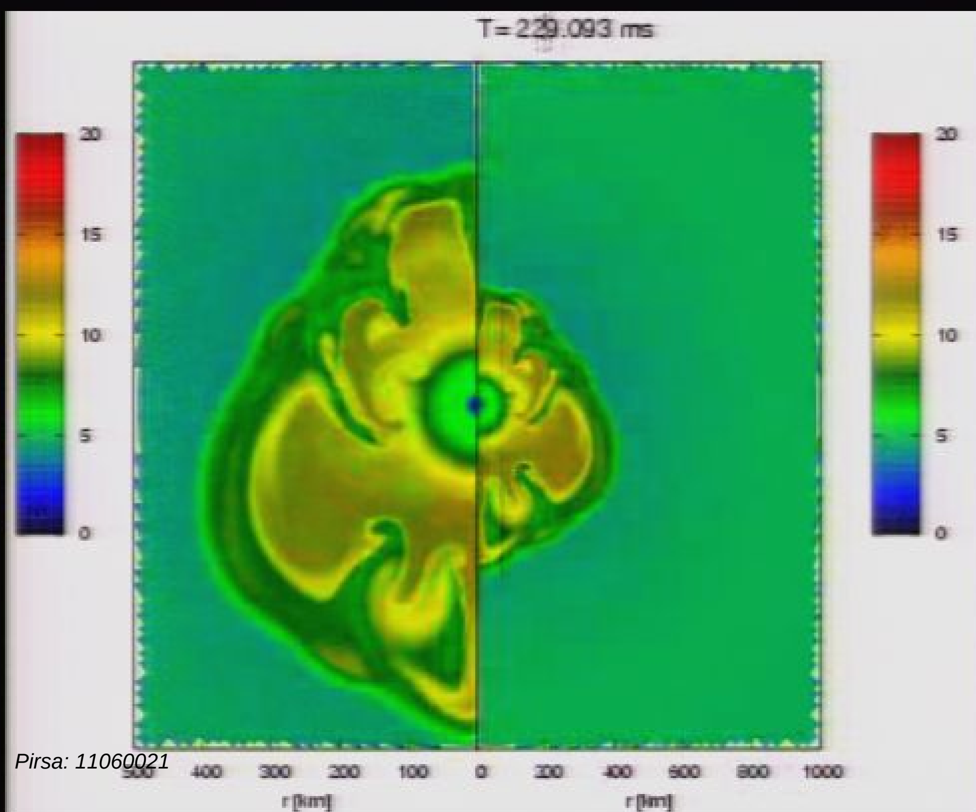

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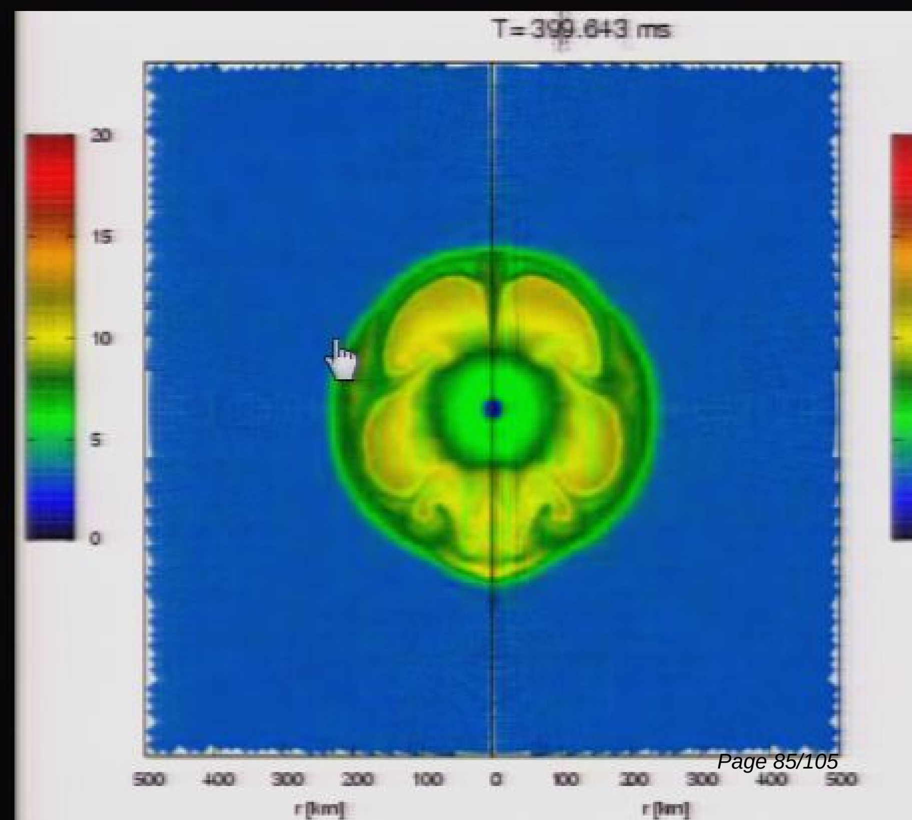

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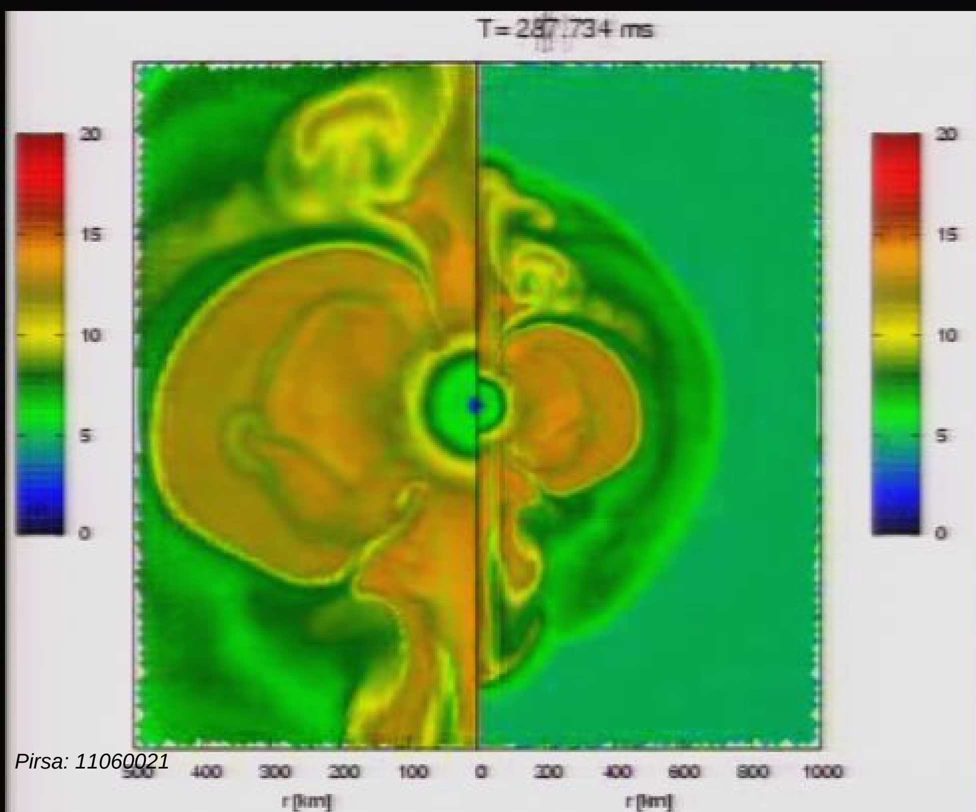

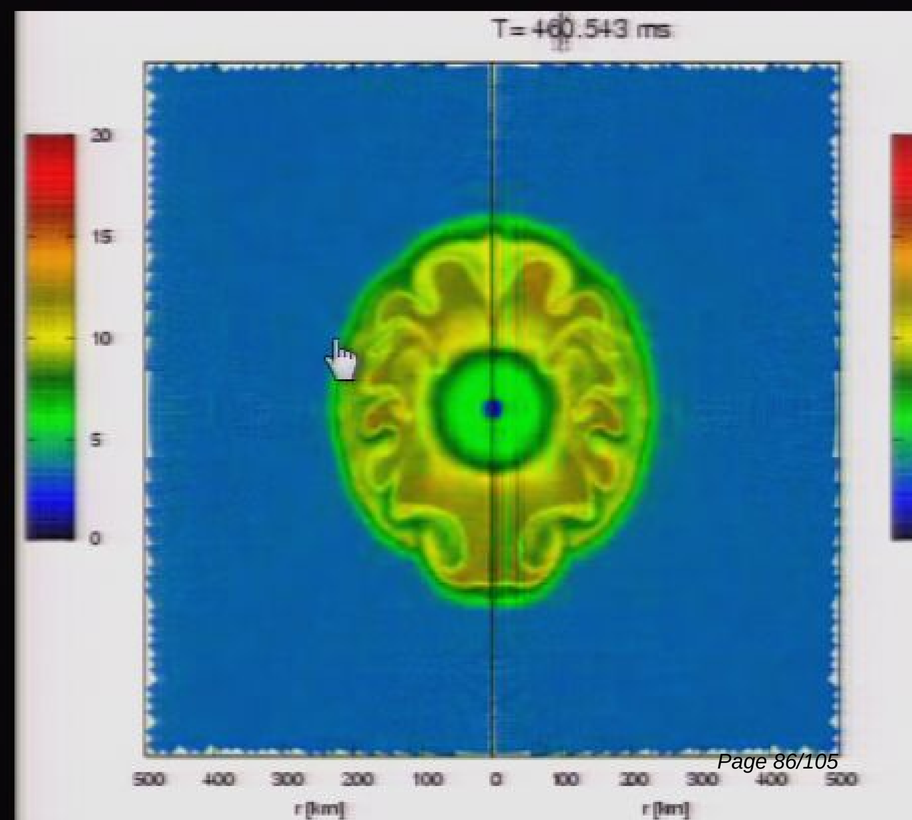

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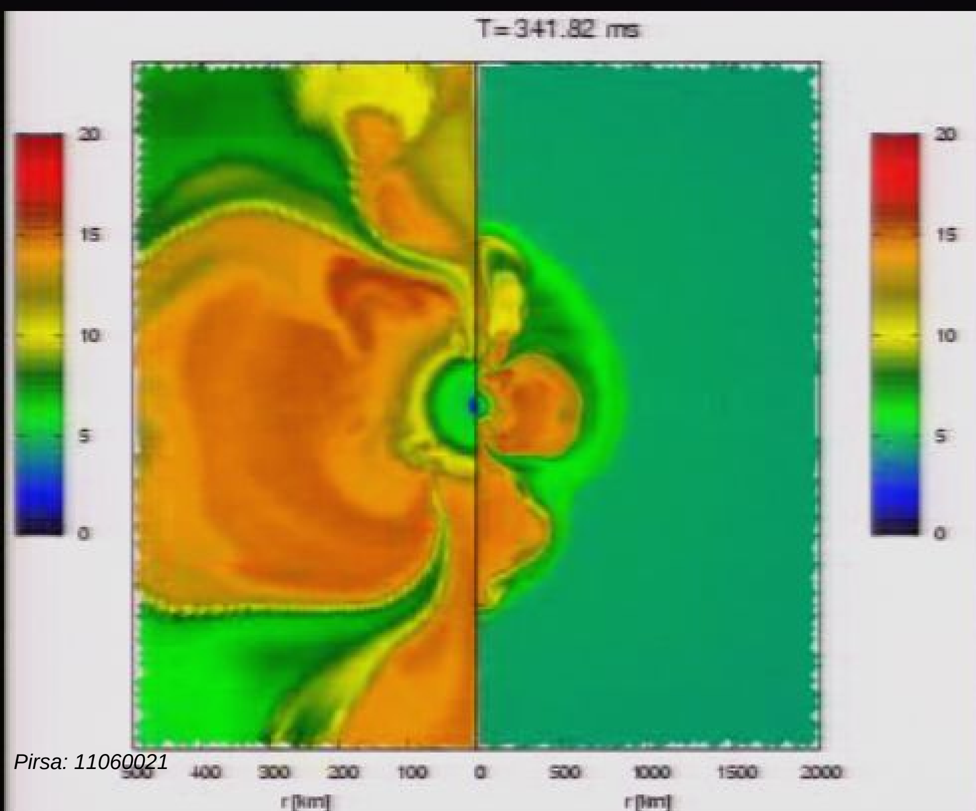

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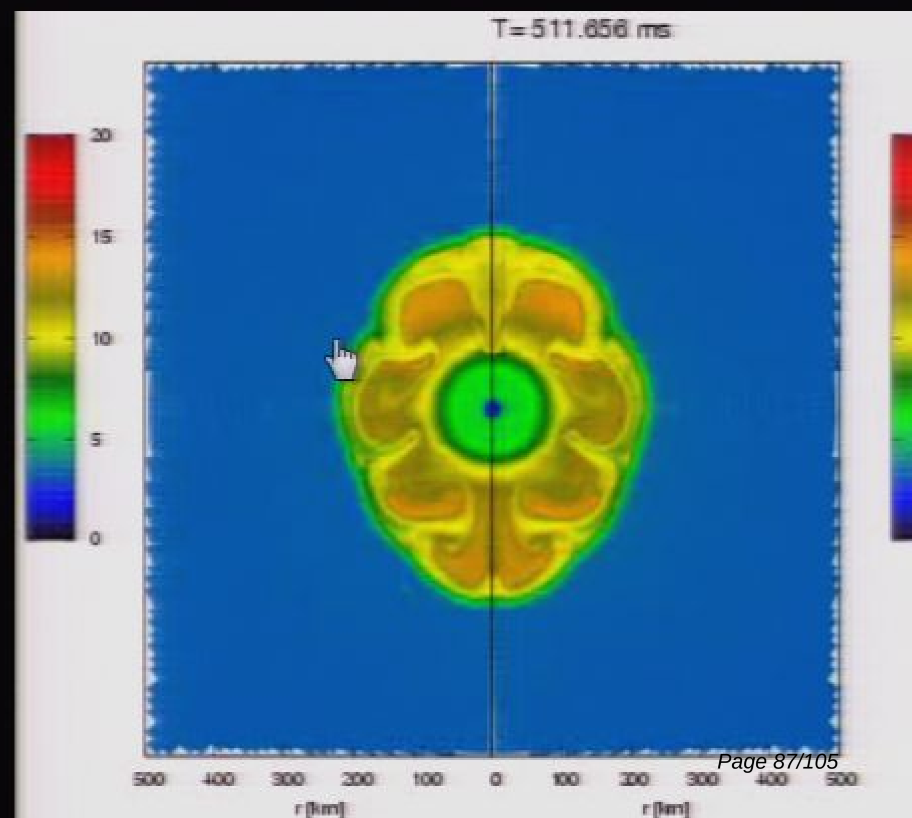

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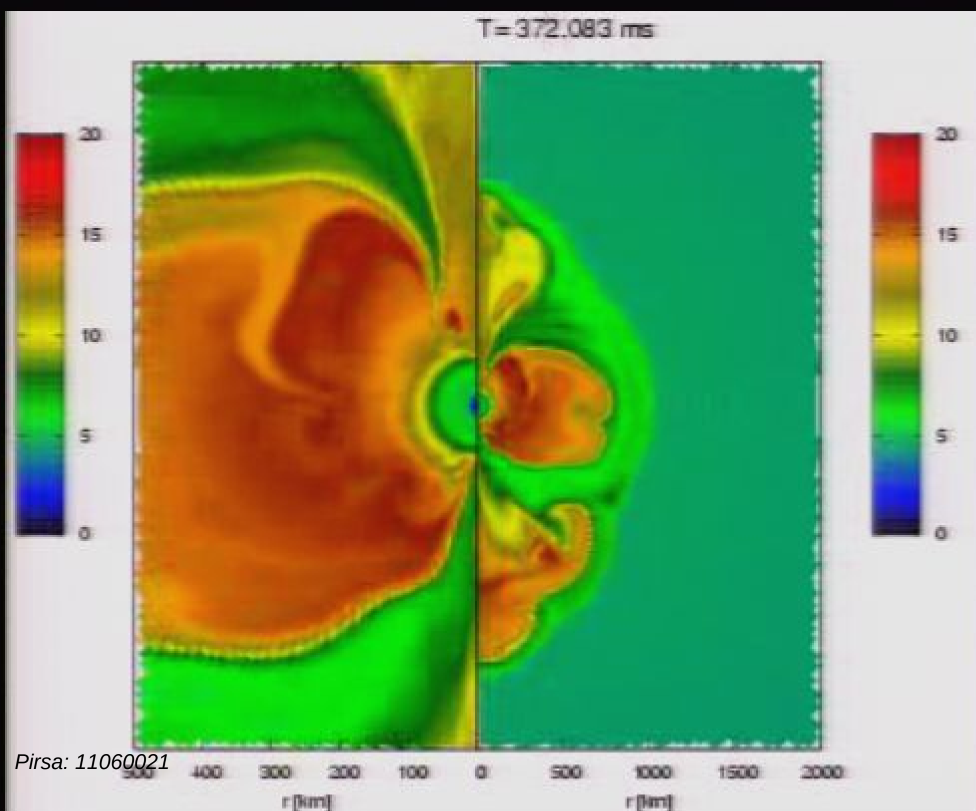

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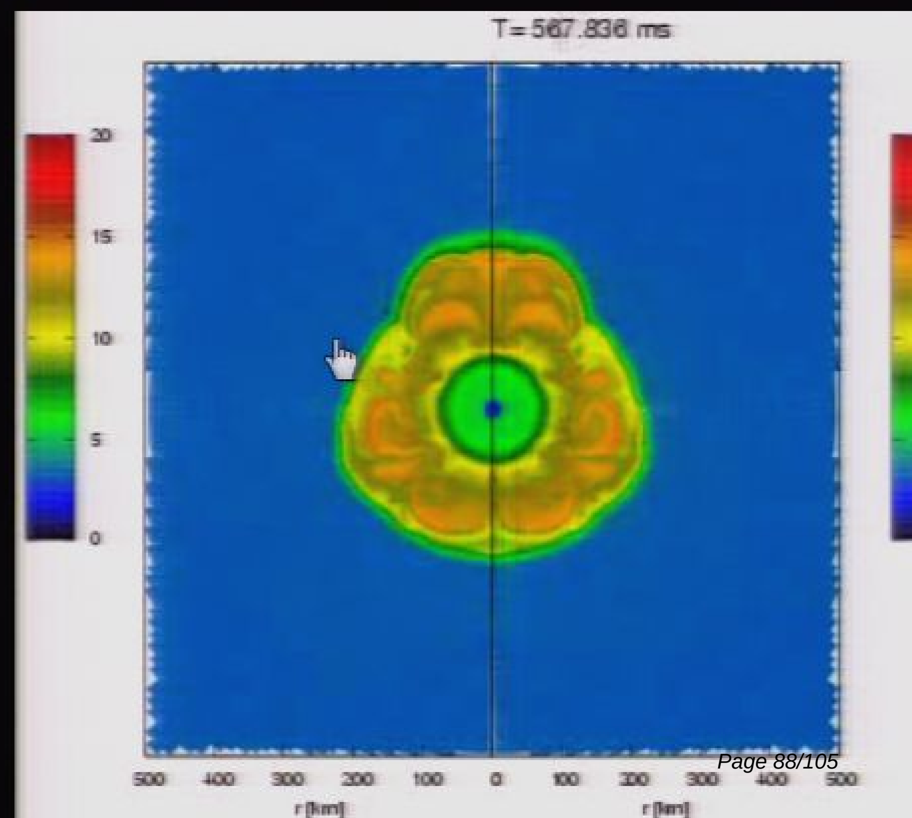

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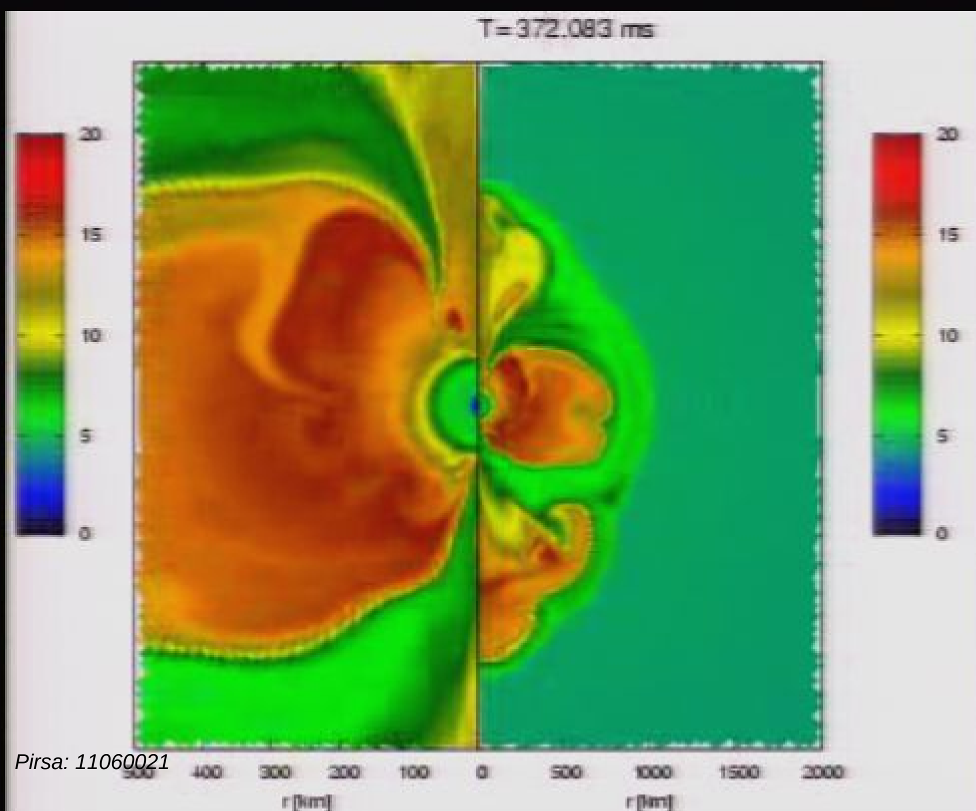

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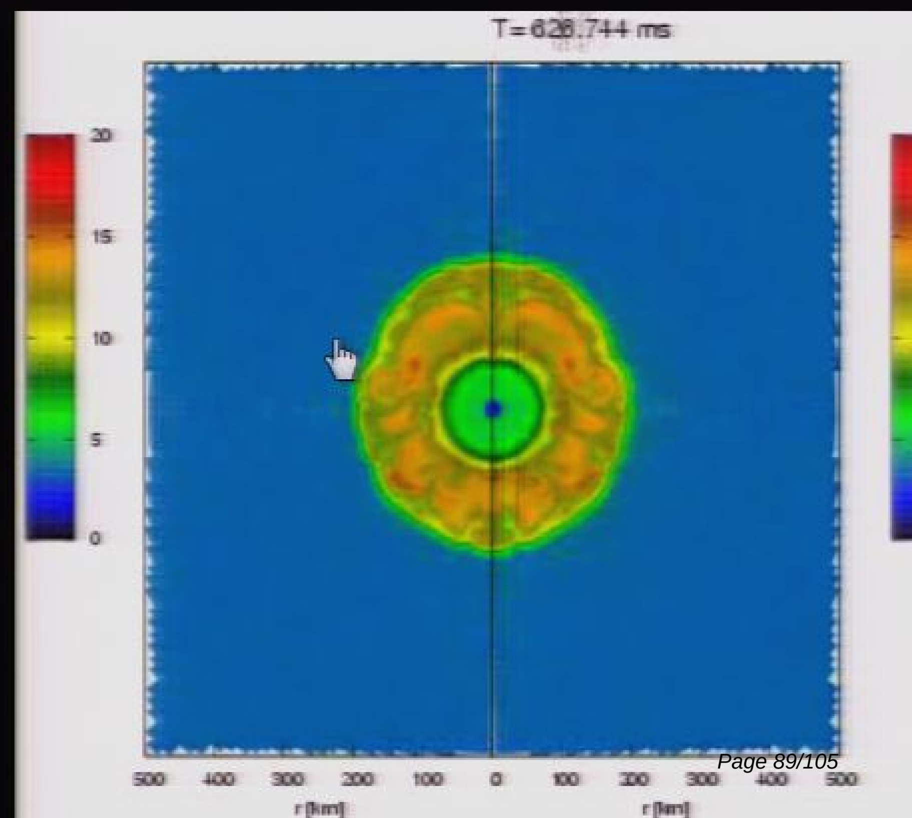

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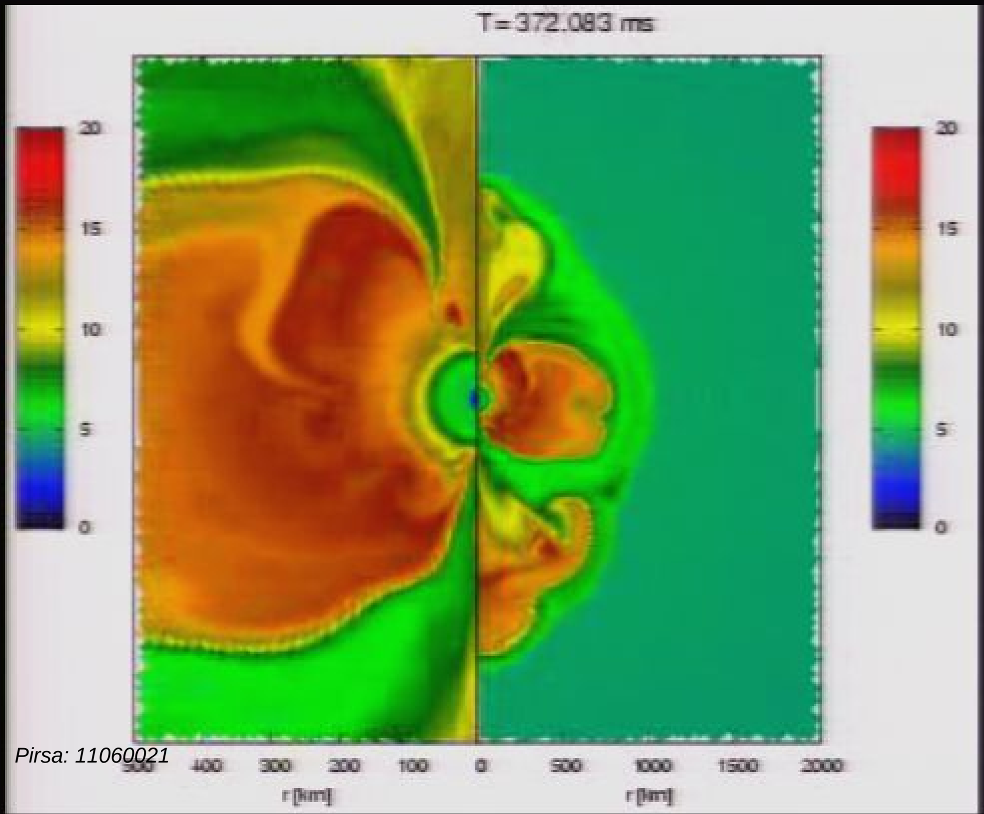

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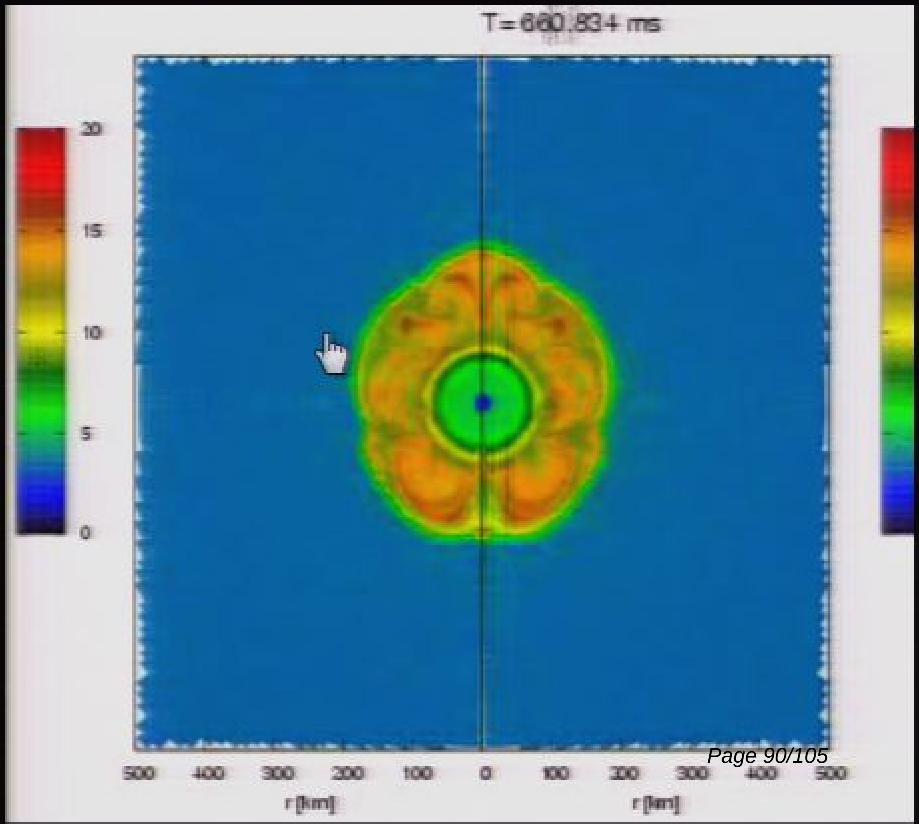
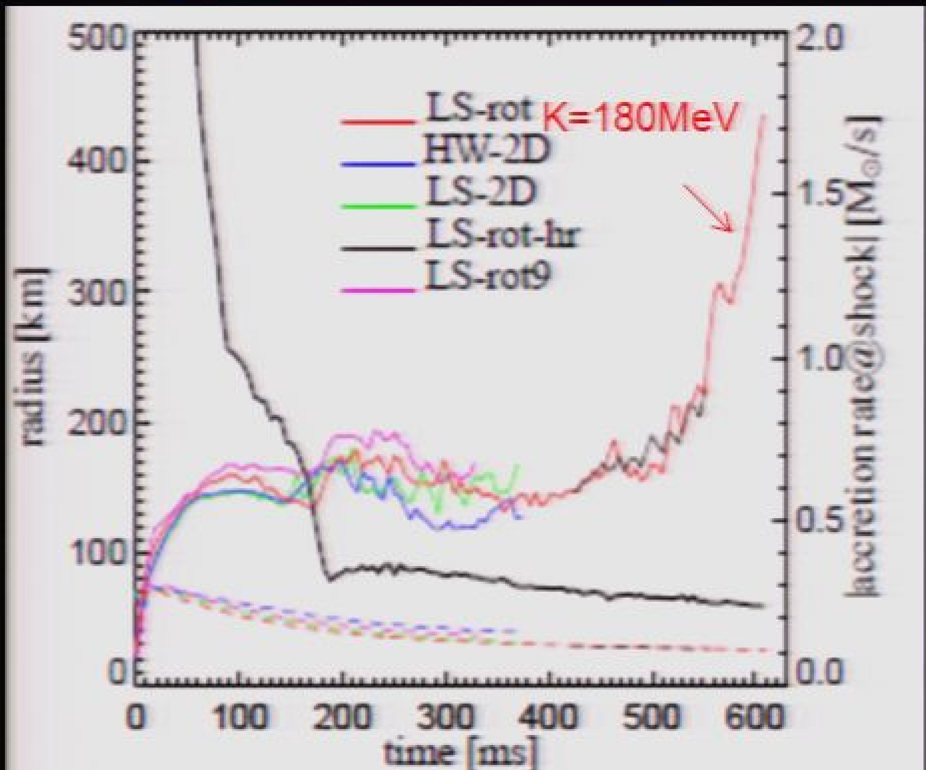


Marek & Janka (2009)



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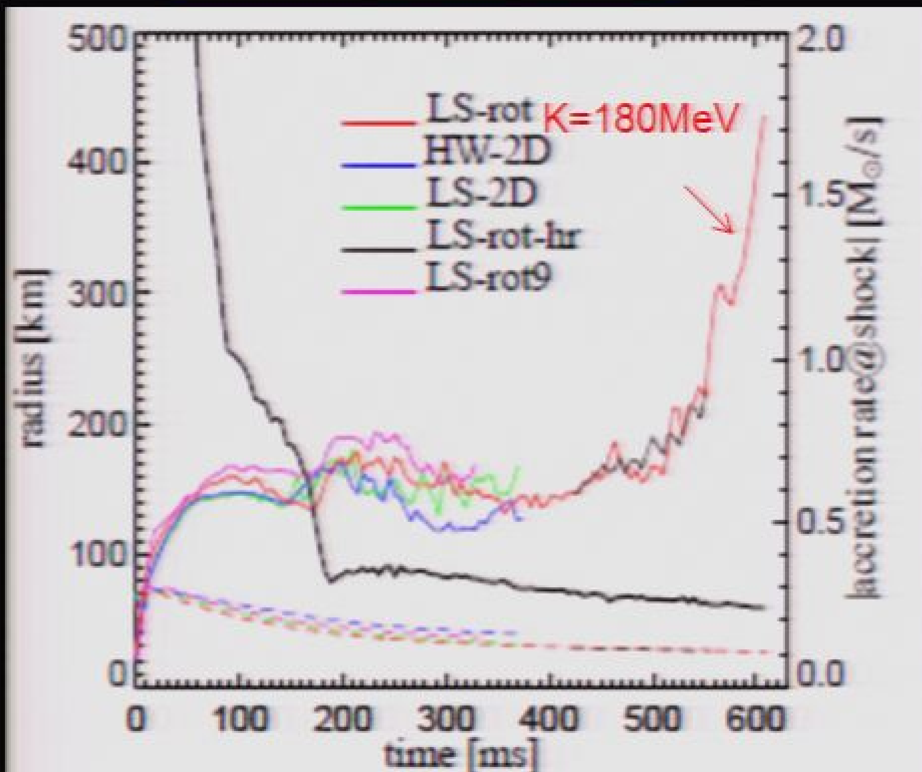
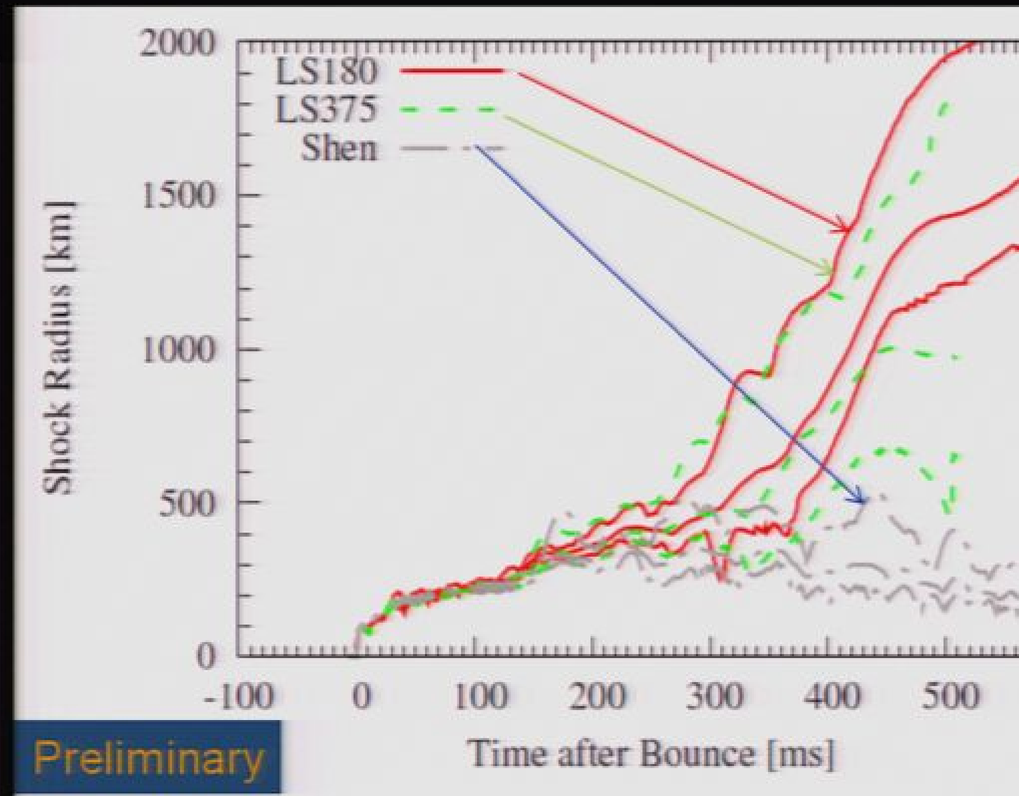
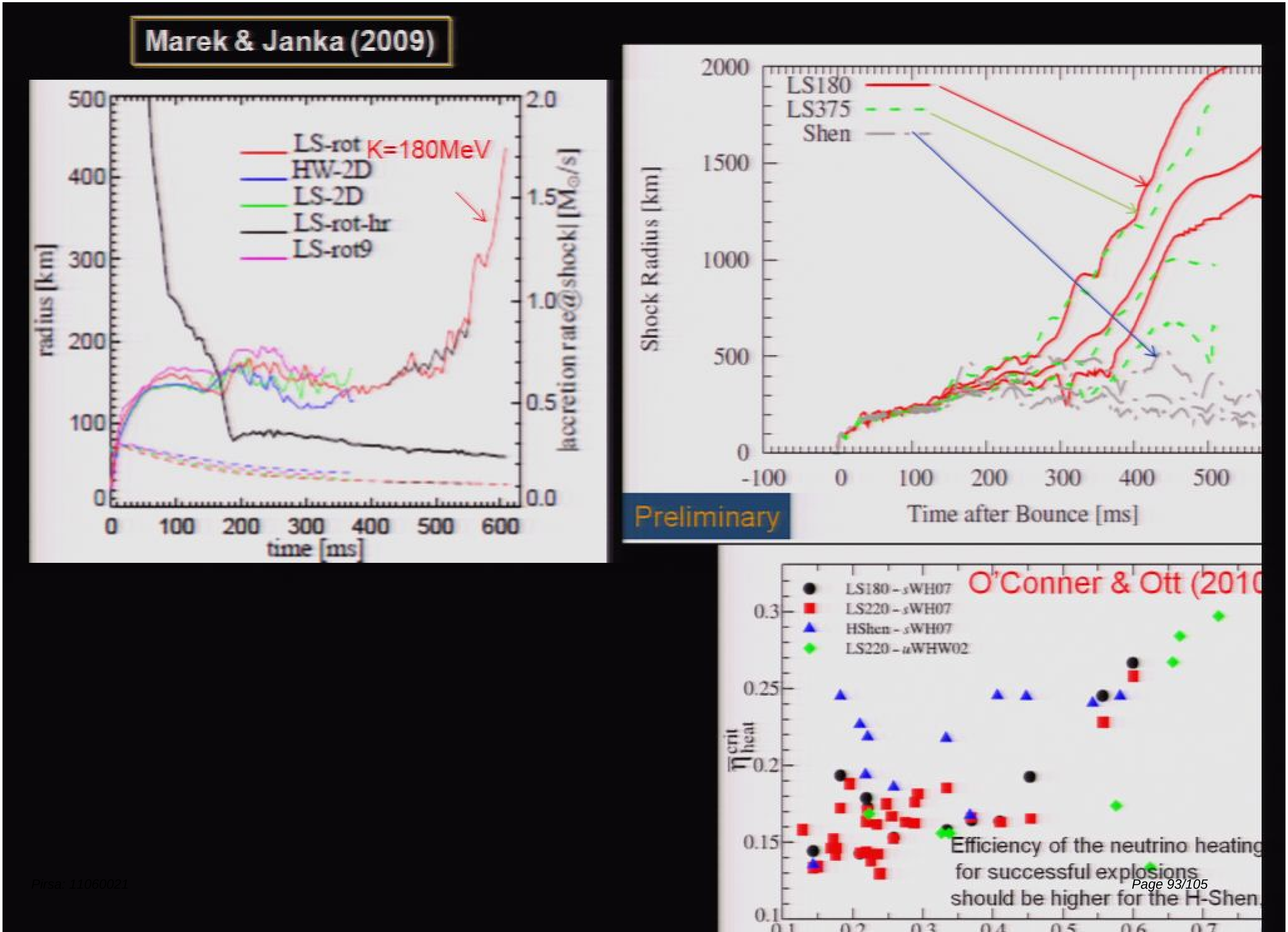
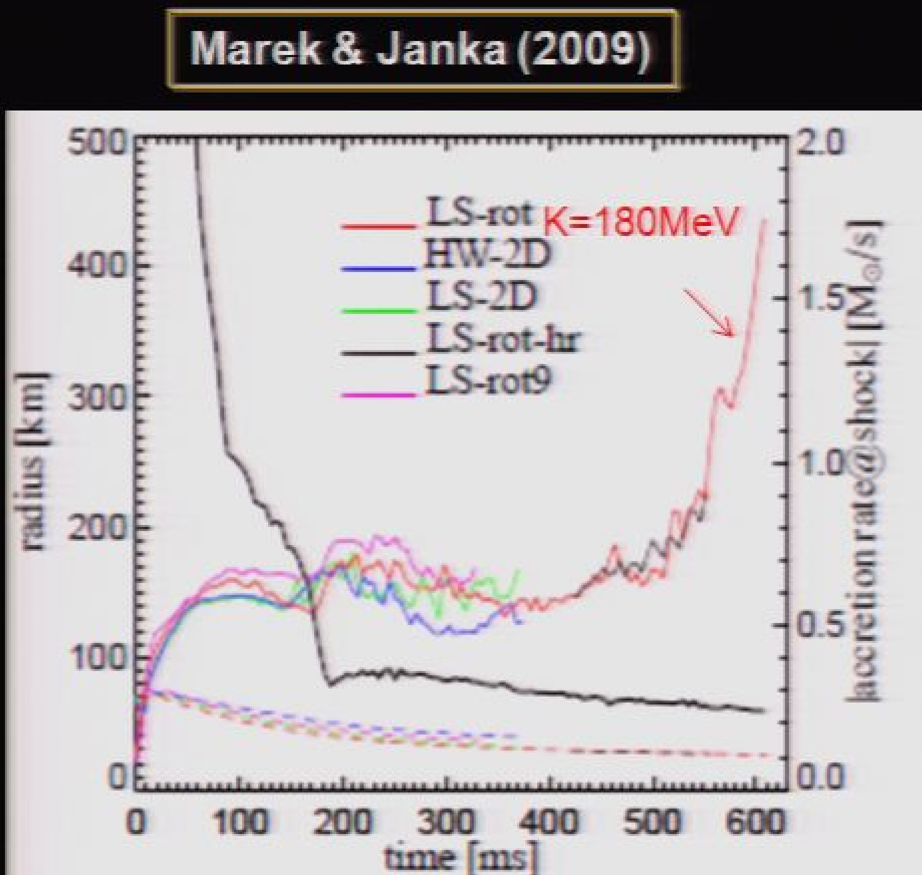
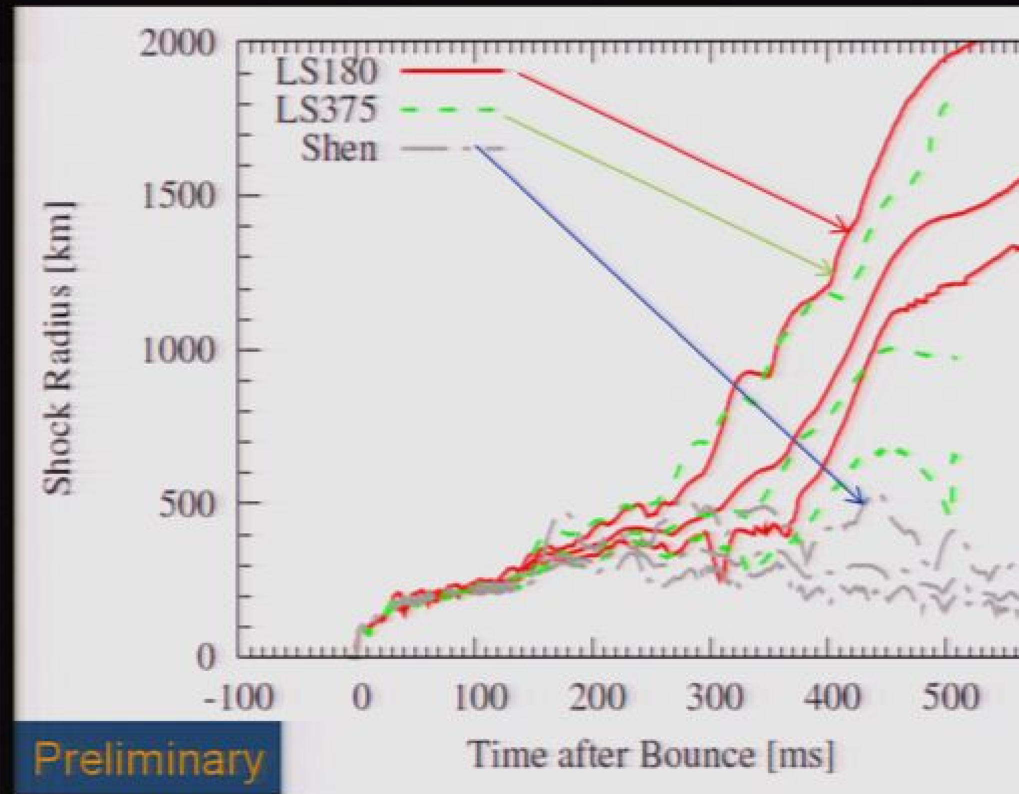


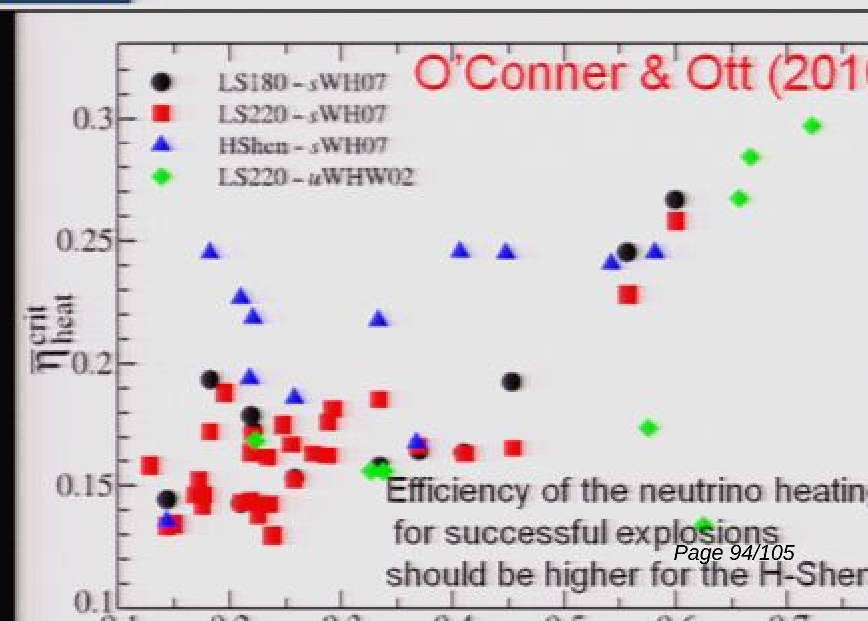



Marek & Janka (2009)
500
400
300
200
100
0
radius [km]
LS-rot
K=180MeV
HW-2D
LS-2D
LS-rot-hr
LS-rot9
2.0
1.5
1.0
0.5
0.0
accretion rate@shock| [M☉/s]
0
100
200
300
400
500
600
time [ms]
2000
1500
1000
500
0
Shock Radius [km]
LS180
LS375
Shen
-100
0
100
200
300
400
500
Time after Bounce [ms]
Preliminary
O'Conner & Ott (2010
LS180 - sWH07
LS220 - sWH07
HShen - sWH07
LS220 - uWHW02
0.3
0.25
0.2
0.15
0.1
Efficiency of the neutrino heating
for successful explosions
should be higher for the H-Shen.



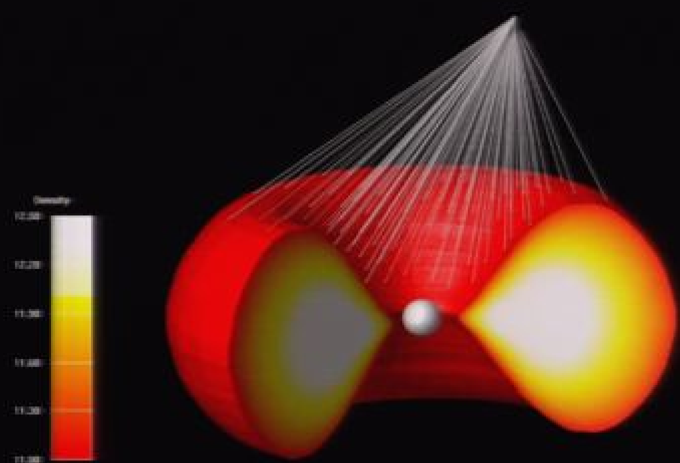


The third lesson is that the roles of "symmetry energy" in the explosion dynamics may still remain to be studied.
(thank to Sumi, O'Conner, Fernandes, Gabriel, Matthias)



Neutrino pair annihilation $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$
: important heating source in collapsars

(Goodman '87,Asano & Fukuyama 2000, Dessart +07, Birkl +06)



✓ We proposed a GR ray-tracing method (Harikae, KK+ (10))

Energy/Momentum deposition rates

$$Q^{\mathrm{L}}_{\mu}(r) = 2KG_{\mathrm{F}}^{2} \int d^{3}p^{\mathrm{L}}_{\nu} d^{3}p^{\mathrm{L}}_{\bar{\nu}} \times (\epsilon^{\mathrm{L}}_{\nu}\epsilon^{\mathrm{L}}_{\bar{\nu}})(p^{\mathrm{L}}_{\nu} + p^{\mathrm{L}}_{\bar{\nu}})_{\mu} \underline{f^{\mathrm{L}}_{\nu}(p^{\mathrm{L}}_{\nu}, r)}\, \underline{f^{\mathrm{L}}_{\bar{\nu}}(p^{\mathrm{L}}_{\bar{\nu}}, r)} \times [1 - \sin\theta_{\nu}\sin\theta_{\bar{\nu}}\cos(\varphi_{\nu} - \varphi_{\bar{\nu}}) - \cos\theta_{\nu}\cos\theta_{\bar{\nu}}]^{2}$$

Neutrino distribution functions: determined by B-eqn.

$$\frac{df_{\nu(\bar{\nu})}}{d\lambda} = p^{\alpha}\frac{Df_{\nu(\bar{\nu})}}{Dx^{\alpha}} = \left(\frac{df_{\nu(\bar{\nu})}}{d\lambda}\right)_{\mathrm{coll}}$$

$$\frac{D}{Dx^{\alpha}} \equiv \frac{\partial}{\partial x^{\alpha}} - \Gamma^{\beta}_{\alpha\gamma}p^{\gamma}\frac{\partial}{\partial p^{\beta}},$$

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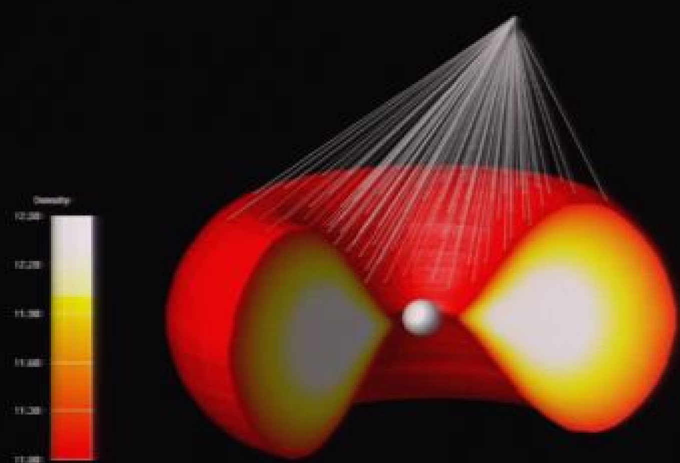


Boltzmann eqn (for photons)

$$\frac{df}{d\lambda} = n(Q - \kappa f)$$

$$Q(x, p) = Q_{\rm e}(x, \epsilon^{\rm R}) + Q_{\rm s}(x, p)$$

$$Q_{\rm e}(x, \epsilon^{\rm R}) = \frac{j(x, \epsilon^{\rm R})}{4\pi(\epsilon^{\rm R})^2},$$

Energy coupling scattering reactions are neglected.

$$Q_{\rm s}(x, p) = \int \epsilon'^{\rm R} d\epsilon'^{\rm R} d\Omega(x, p')\xi(x; p' \rightarrow p)f(x, p$$

Formal solution of the Boltzmann equation.

$$f(\epsilon, \Omega) = \int_{\lambda_0}^{\lambda_S} n(\lambda'')Q(\lambda,'' f)e^{-\int_{\lambda''}^{\lambda_S} n(\lambda')\kappa(\lambda')d\lambda'} d\lambda,''$$

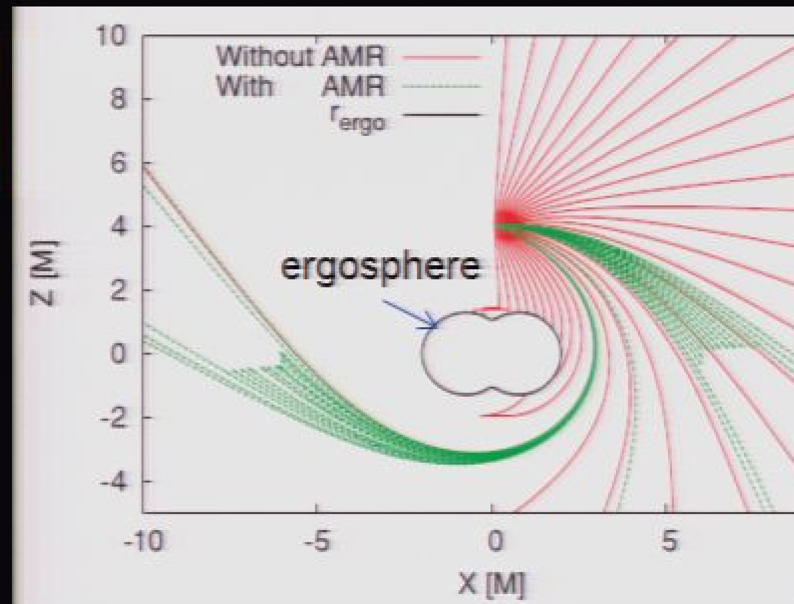
(e.g., Zink (07))

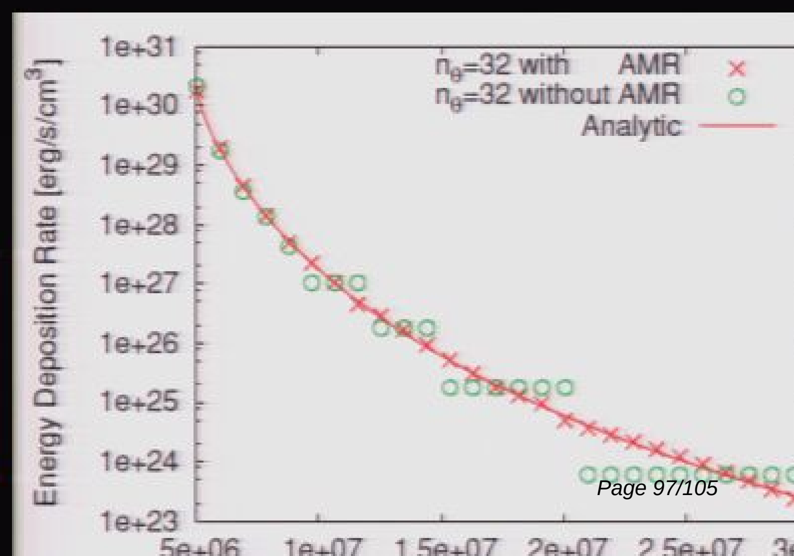
✓ Along the geodesics, we perform a (backward) ray-trace calculation.

✓ For casting rays as much as possible in the regions where the intensity is large

$$I_{\rm crit}(\epsilon, \theta, \phi) \geqslant KI_{\rm max}$$

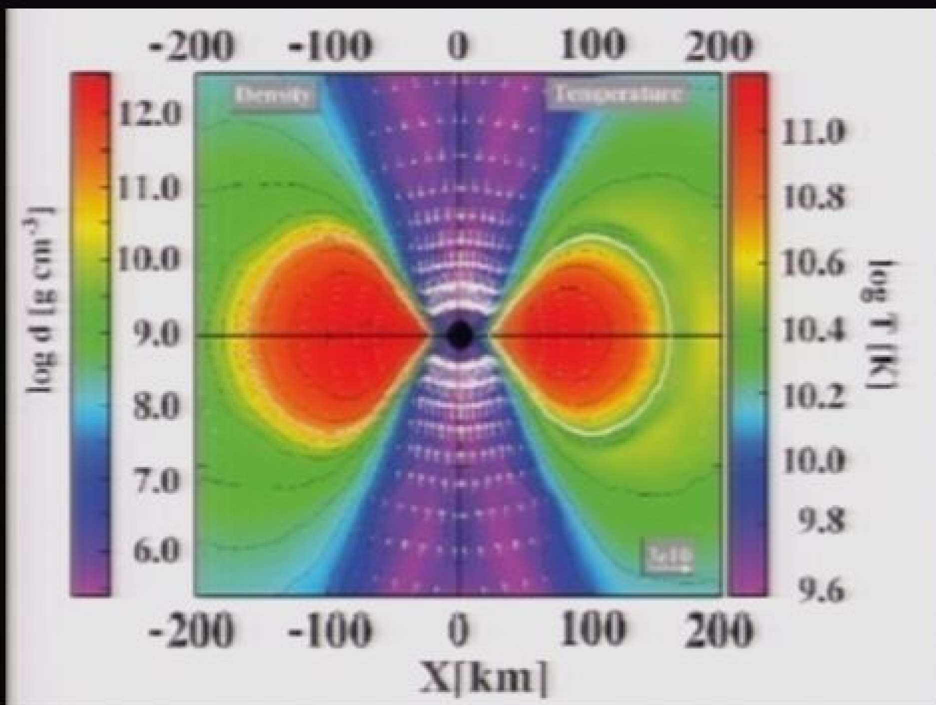
We choose the rays that satisfy the condition, and refine the resolutions for them.

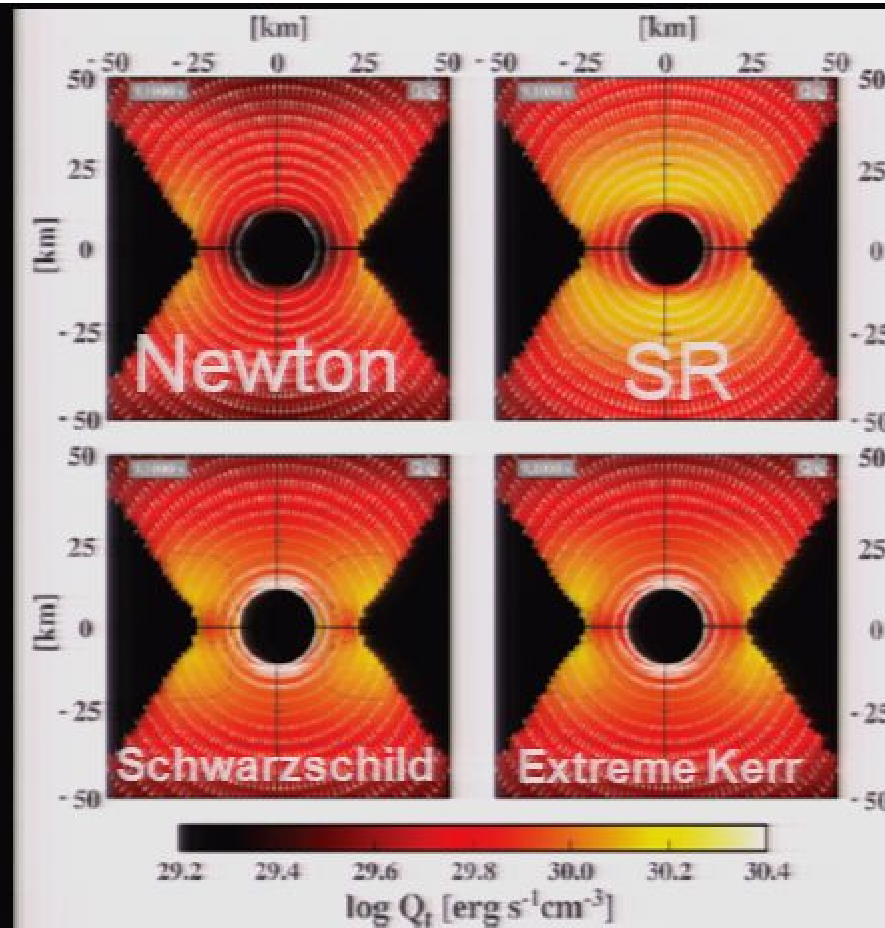


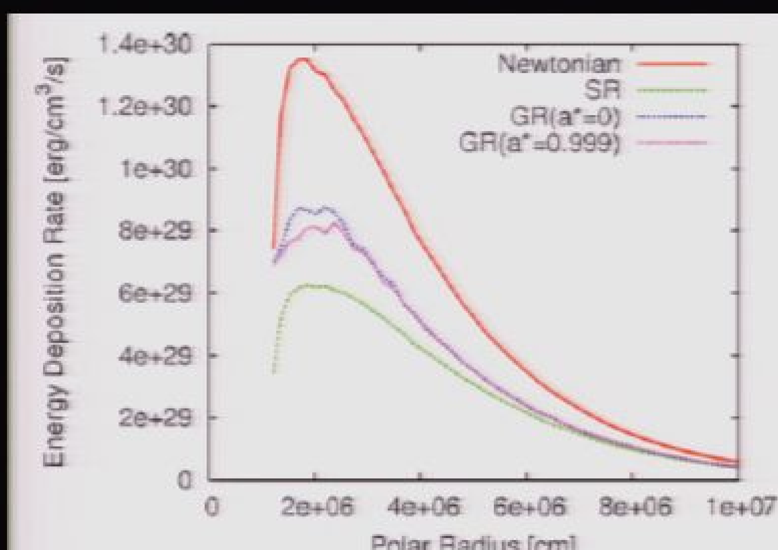


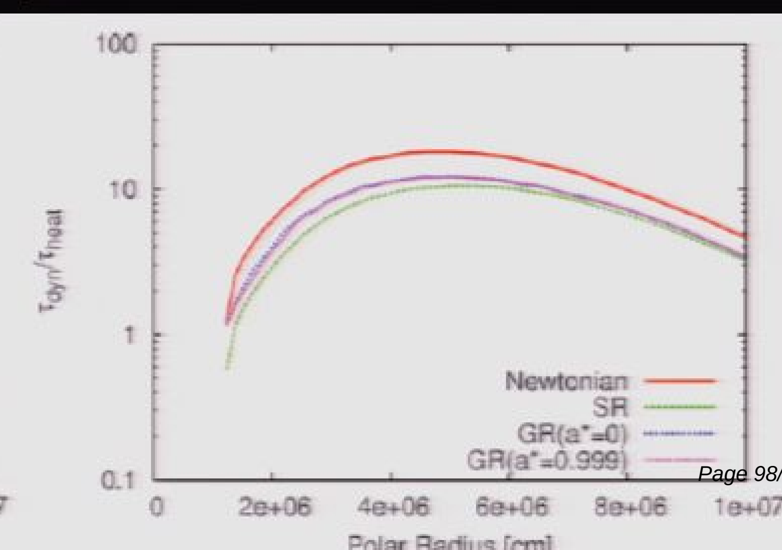
Our GR ray-trace method:
✓ Adaptive-Ray-Casting is very useful !
✓ Limited to reaction (e.g., scattering)

Applications to collapsars









Summary

☆ **Cooling by nu_x is being treatable** in the IDSA simulations, either by leakage or grey-M1 scheme.

☆ **A good energy conservation in multi-D simulations:** the recipe in Mueller et al. (2010)).

☆ **"Symmetry energy"** may hold a key importance.

☆ **"Adaptive-Ray-Casting" in the GR ray-trace scheme** reduces the computational cost significantly.
Scattering reactions: remained to be included.
This scheme would **be powerful in collapsar simulations.**

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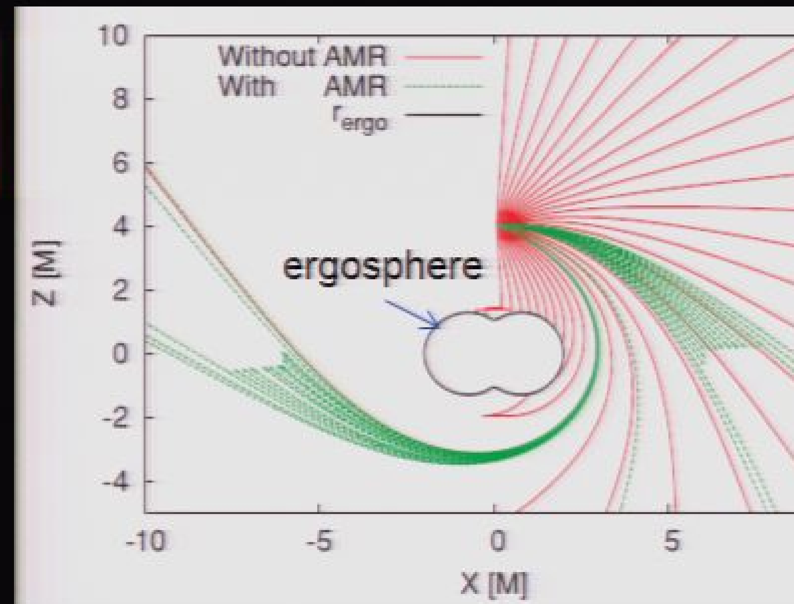
Thank you very much !

Formal solution of the Boltzmann equation.

$$f(\epsilon, \Omega) = \int_{\lambda_0}^{\lambda_S} n(\lambda'')Q(\lambda,'' f) e^{-\int_{\lambda''}^{\lambda_S} n(\lambda')\kappa(\lambda')d\lambda'} d\lambda,''$$

(e.g., Zink (07))

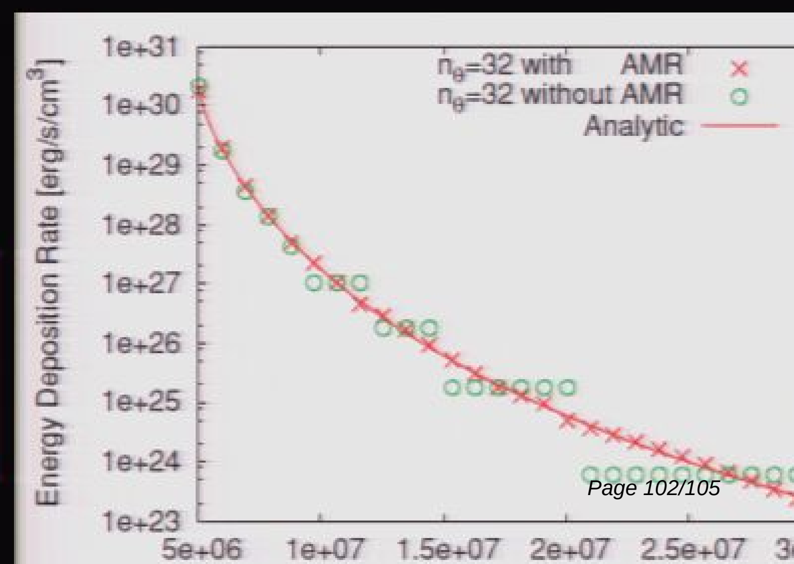


✓ Along the geodesics, we perform a (backward) ray-trace calculation.

✓ For casting rays as much as possible in the regions where the intensity is large

$$I_{\rm crit}(\epsilon, \theta, \phi) \geqslant \mathcal{K} I_{\rm max}$$

We choose the rays that satisfy the condition, and refine the resolutions for them.



Our GR ray-trace method:

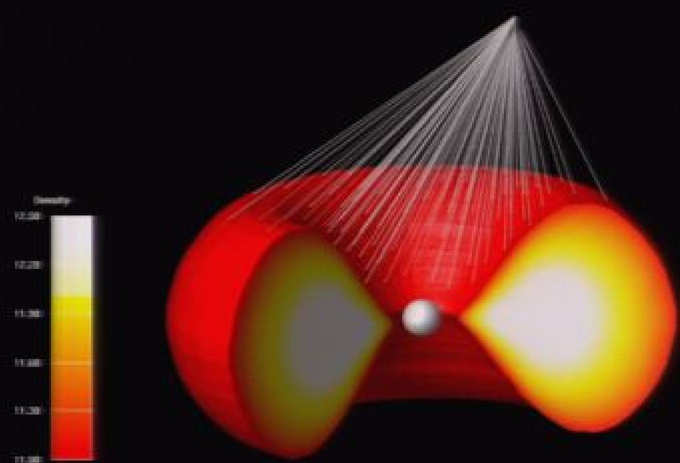
✓ Adaptive-Ray-Casting is very useful !

✓ Limited to reaction (e.g., scattering)

Neutrino pair annihilation $\nu + \bar{\nu} \rightarrow e^{+} + e^{-}$
: important heating source in collapsars

(Goodman '87,Asano & Fukuyama 2000, Dessart +07, Birkl +06)

✓ We proposed a GR ray-tracing method (Harikae, KK+ (10))



Boltzmann eqn (for photons)

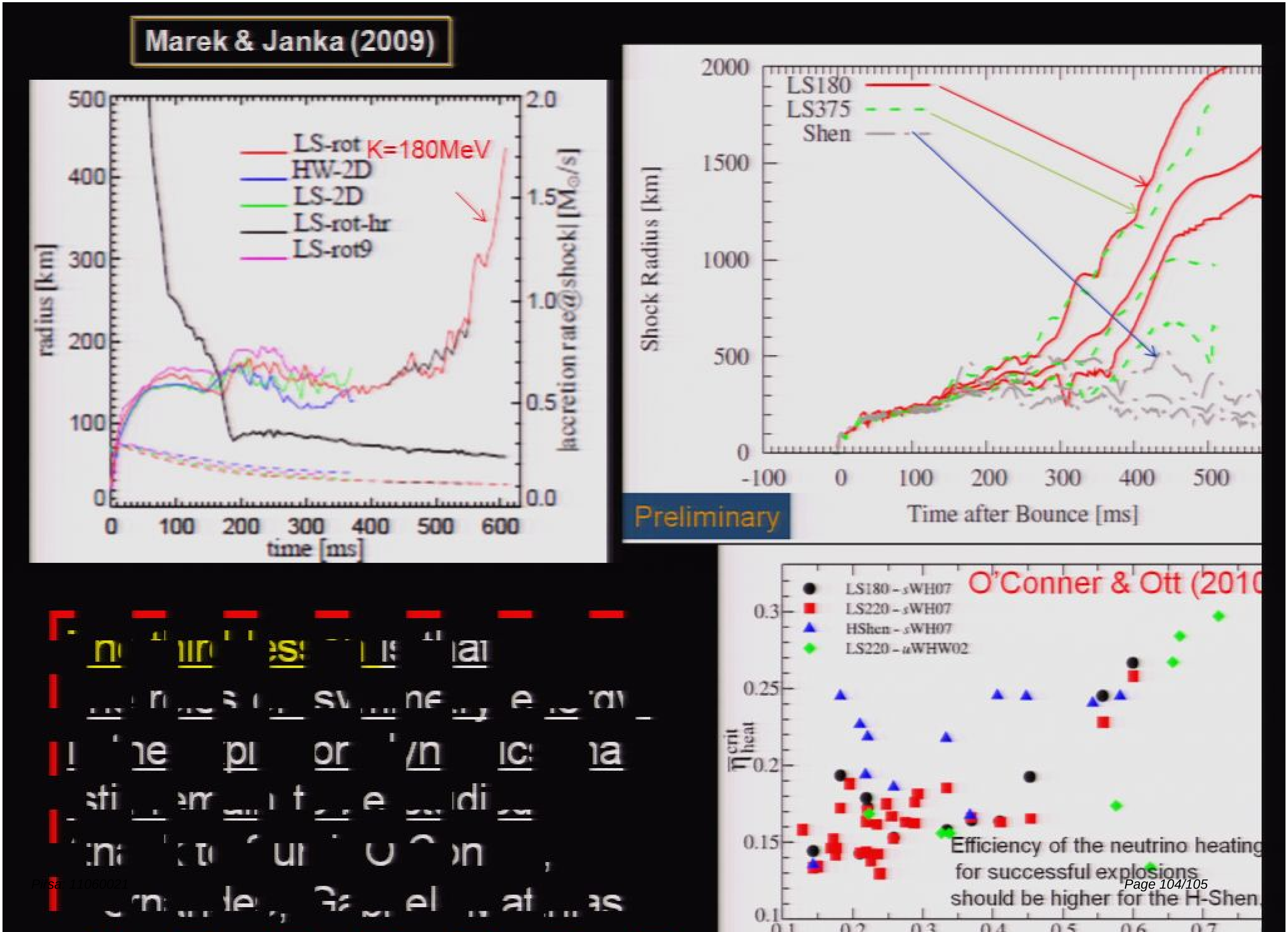
$$\frac{df}{d\lambda} = n(Q - \kappa f)$$

$$Q(x, p) = Q_{e}(x, \epsilon^{R}) + Q_{s}(x, p)$$

$$Q_{e}(x, \epsilon^{R}) = \frac{j(x, \epsilon^{R})}{4\pi(\epsilon^{R})^{2}},$$

Energy coupling scattering reactions are neglected.

$$Q_{s}(x, p) = \int \epsilon'^{R} d\epsilon'^{R} d\Omega(x, p')\xi(x; p' \rightarrow p) f(x, p$$


Marek & Janka (2009)
LS-rot
K=180MeV
HW-2D
LS-2D
LS-rot-hr
LS-rot9
radius [km]
time [ms]
|accretion rate@shock| [$M_\odot$/s]
LS180
LS375
Shen
Shock Radius [km]
Time after Bounce [ms]
Preliminary
O'Conner & Ott (2010
LS180 - sWH07
LS220 - sWH07
HShen - sWH07
LS220 - uWHW02
η_{heat}^{crit}
Efficiency of the neutrino heating
for successful explosions
should be higher for the H-Shen.

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