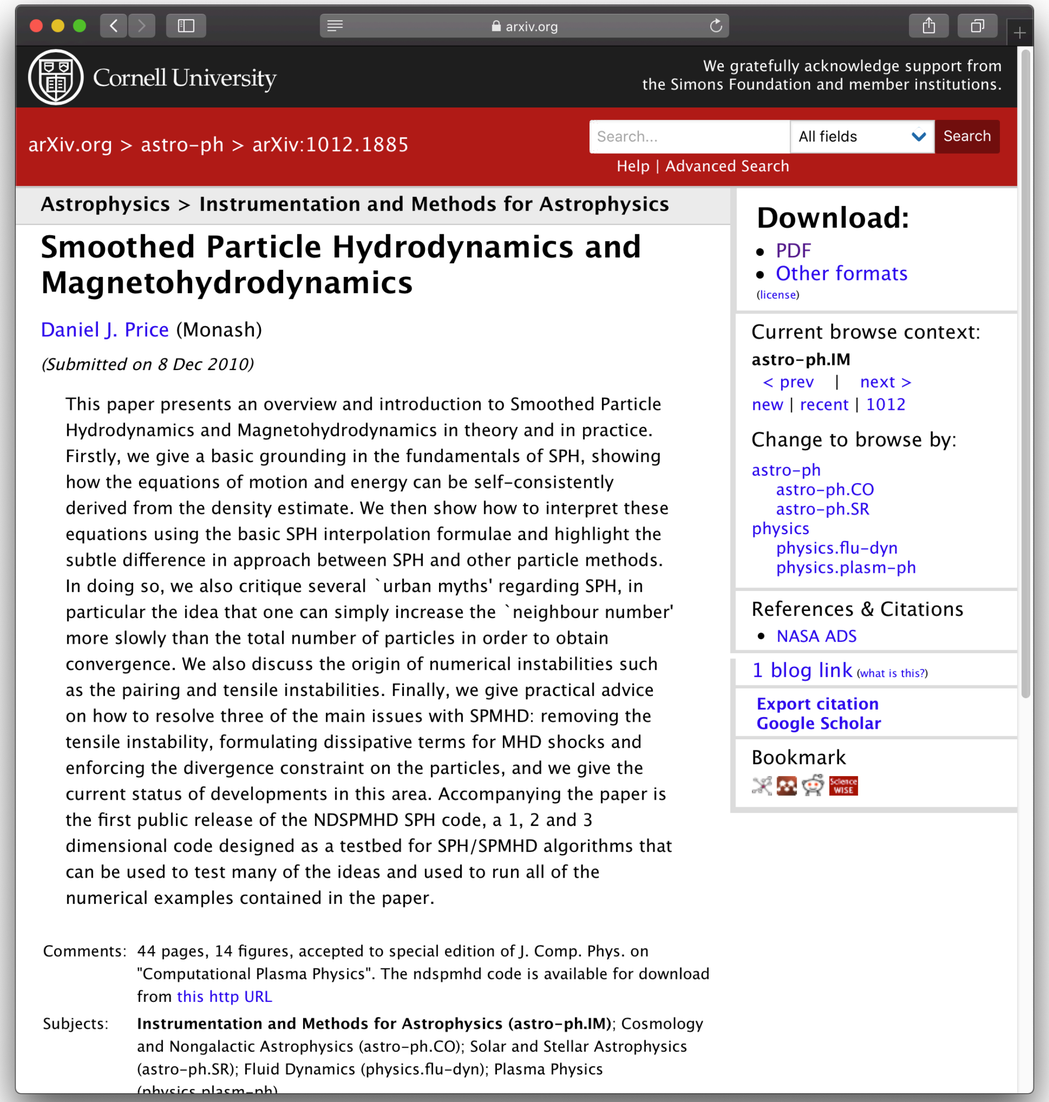
SPHENIX:
Hydrodynamics for the next generation of EAGLE simulations

Josh Borrow *Institute for Computational Cosmology*
Matthieu Schaller, Claudio Dalla Vecchia, Richard Bower

Disclaimer

- This talk **assumes a high amount of SPH knowledge**!
- If you want to discuss fundamentals, I'm happy to do this afterwards.



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Smoothed Particle Hydrodynamics and Magnetohydrodynamics

Daniel J. Price (Monash)

(Submitted on 8 Dec 2010)

This paper presents an overview and introduction to Smoothed Particle Hydrodynamics and Magnetohydrodynamics in theory and in practice. Firstly, we give a basic grounding in the fundamentals of SPH, showing how the equations of motion and energy can be self-consistently derived from the density estimate. We then show how to interpret these equations using the basic SPH interpolation formulae and highlight the subtle difference in approach between SPH and other particle methods. In doing so, we also critique several `urban myths' regarding SPH, in particular the idea that one can simply increase the `neighbour number' more slowly than the total number of particles in order to obtain convergence. We also discuss the origin of numerical instabilities such as the pairing and tensile instabilities. Finally, we give practical advice on how to resolve three of the main issues with SPMHD: removing the tensile instability, formulating dissipative terms for MHD shocks and enforcing the divergence constraint on the particles, and we give the current status of developments in this area. Accompanying the paper is the first public release of the NDSPMHD SPH code, a 1, 2 and 3 dimensional code designed as a testbed for SPH/SPMHD algorithms that can be used to test many of the ideas and used to run all of the numerical examples contained in the paper.

Comments: 44 pages, 14 figures, accepted to special edition of J. Comp. Phys. on "Computational Plasma Physics". The ndspmhd code is available for download from this http URL

Subjects: **Instrumentation and Methods for Astrophysics (astro-ph.IM)**; Cosmology and Nongalactic Astrophysics (astro-ph.CO); Solar and Stellar Astrophysics (astro-ph.SR); Fluid Dynamics (physics.flu-dyn); Plasma Physics (physics.plasm-ph)

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An excellent introduction to SPH by Daniel Price.

Background

- SPH scheme used for the **EAGLE** simulations was called '**ANARCHY**'
- This was a **Pressure-Entropy** based formulation that included **switches** for artificial **viscosity** and artificial **conductivity**

Viscosity

$$S_i = -h_i^2 \min(\dot{\nabla} \cdot \mathbf{v}_i, 0) \qquad \alpha_{\mathrm{loc},i} = \alpha_{\mathrm{max}} S/(S + v_{\mathrm{sig}_i}^2)$$

$$\alpha_i \rightarrow \begin{cases} \alpha_{\mathrm{loc},i} & \text{if } \alpha_i < \alpha_{\mathrm{loc},i}, \\ \alpha_{\mathrm{loc},i} + (\alpha_i - \alpha_{\mathrm{loc},i}) e^{-4\mathrm{d}t/\tau_{\mathrm{sc},i}} & \text{if } \alpha_i > \alpha_{\mathrm{loc},i}, \\ \alpha_{\mathrm{min}} & \text{if } \alpha_i < \alpha_{\mathrm{min}}, \end{cases}$$

Simplified version of Cullen & Dehnen 2010

Conductivity

$$\frac{\mathrm{d}u}{\mathrm{d}t} \propto \sum_j (\alpha_i + \alpha_j) v_{\mathrm{D},ij} (u_i - u_j)$$

$$\frac{\mathrm{d}\alpha_{\mathrm{D},i}}{\mathrm{d}t} = \beta_{\mathrm{D}} h_i \frac{\nabla^2 u_i}{\sqrt{u_i}} + \frac{\alpha_{D,i} - \alpha_{D,\mathrm{min}}}{\tau_{\mathrm{sc},i}},$$

Modified from Price 2008, presented in Schaye+ 2015

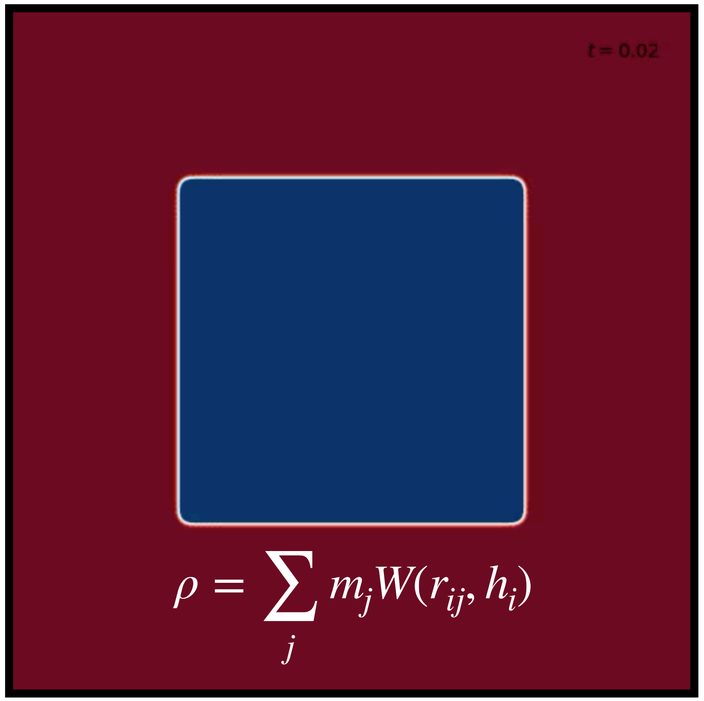
Why use Pressure SPH?

Square test (2D) reproduced from Hopkins 2013.

- **Agertz+ 2007** brought up some issues with '**surface tension**' in traditional SPH schemes.

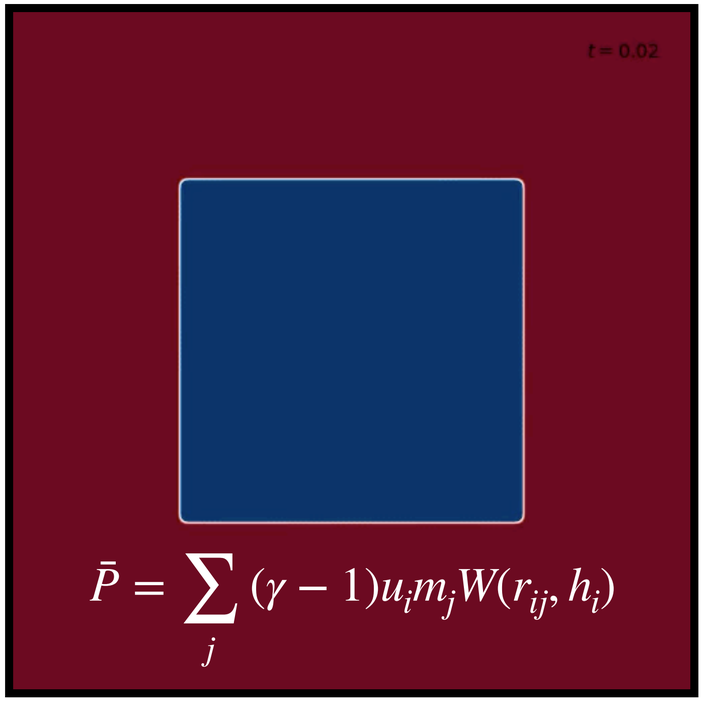
- Despite this being **resolved** in **Price 2008** with the addition of **artificial conduction**, this issue remained in the communities mind until **Hopkins 2013**, which introduced Pressure-SPH.

Density Smoothing



$$\rho = \sum_j m_j W(r_{ij}, h_i)$$

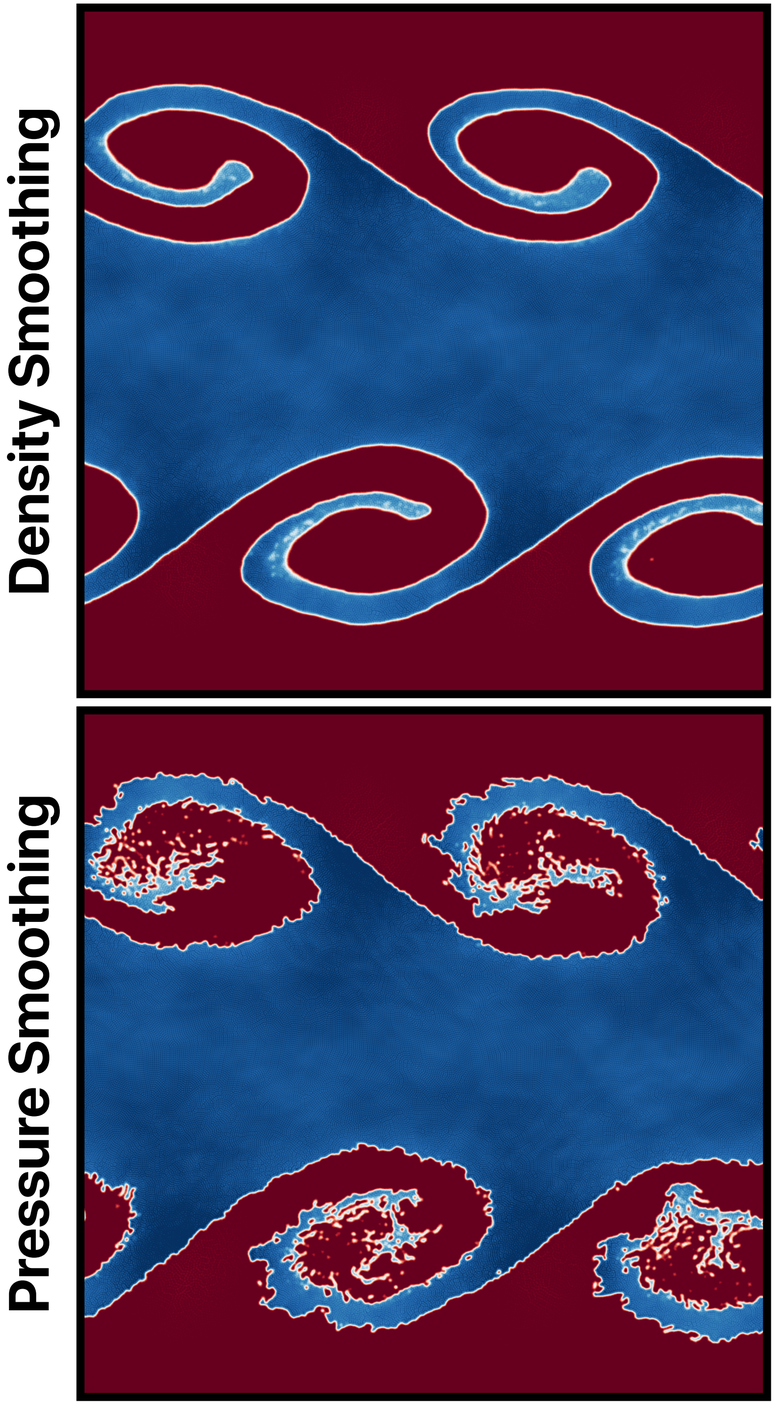
Pressure Smoothing



$$\bar{P} = \sum_j (\gamma - 1) u_i m_j W(r_{ij}, h_i)$$

Pressure Problems

Kelvin-Helmholtz test (2D)
reproduced from Agertz+ 2007



- Due to **smoothing over a rapidly varying quantity** (*u* or *A*), Pressure-SPH schemes are inherently **very unstable** in ***dynamic*** situations.

- This is **amplified in cosmological simulations** with the EAGLE model, where **cooling is applied** by an **additional d*u*/d*t***.

Pressure-SPH in multi-dt?

- A major issue arises when **drifting** smoothed **pressure** in a **multi-dt scenario**.

- In simulations **with cooling**, this can lead to **pressures** and **energies** that are **inconsistent** for the fluid.

Density Smoothing

$$\rho(t+\Delta t) \to \exp\left(-\frac{3}{h}\frac{\mathrm{d}h}{\mathrm{d}t}\Delta t\right)\cdot\rho(t) = D_\rho(t,\Delta t)\cdot\rho(t)$$

$$u(t+\Delta t) \to u(t) + \frac{\mathrm{d}u}{\mathrm{d}t}\Delta t = D_u(t,\Delta t)\cdot u(t)$$

$$\begin{aligned} P(t+\Delta t) &\to (\gamma-1)u(t+\Delta t)\rho(t+\Delta t) \\ &= P(t)D_\rho(t,\Delta t)D_u(t,\Delta t) \end{aligned}$$

Pressure Smoothing

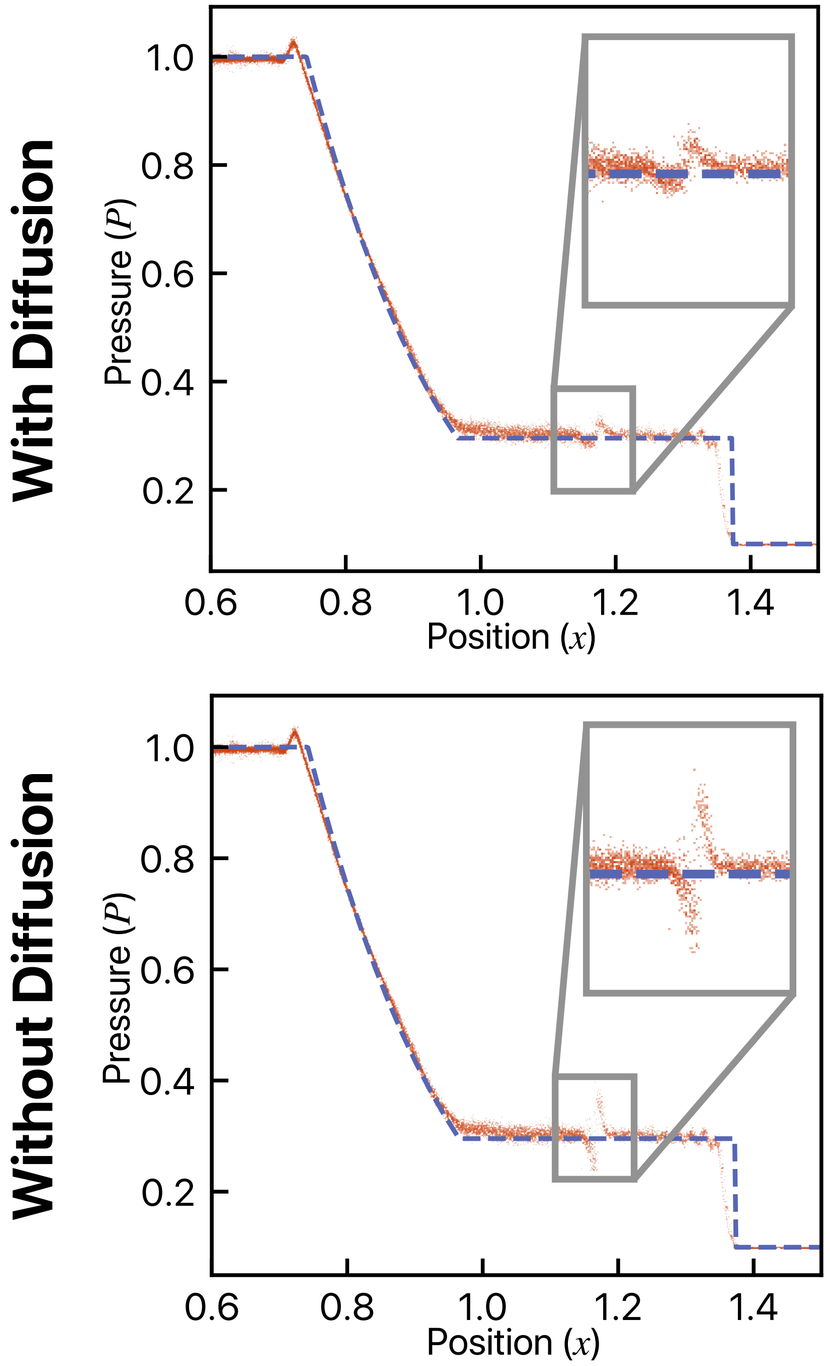
$$\bar{P}(t+\Delta t) \to \exp\left(\frac{1}{\bar{P}}\frac{\mathrm{d}\bar{P}}{\mathrm{d}t}\Delta t\right)\cdot\bar{P}(t) = D_P(t,\Delta t)\cdot\bar{P}(t)$$

Yikes!

$$\frac{\mathrm{d}\bar{P}_i}{\mathrm{d}t} = (\gamma-1)\sum_j m_j\left(W_{ij}\frac{\mathrm{d}u_j}{\mathrm{d}t} + u_j\left[\mathbf{v}_a - \mathbf{v}_a\right]\cdot\nabla_j W_{ij}\right)$$

Back to "TSPH"

A Sod Shock test illustrating the improvements possible with diffusion for contact discontinuities.



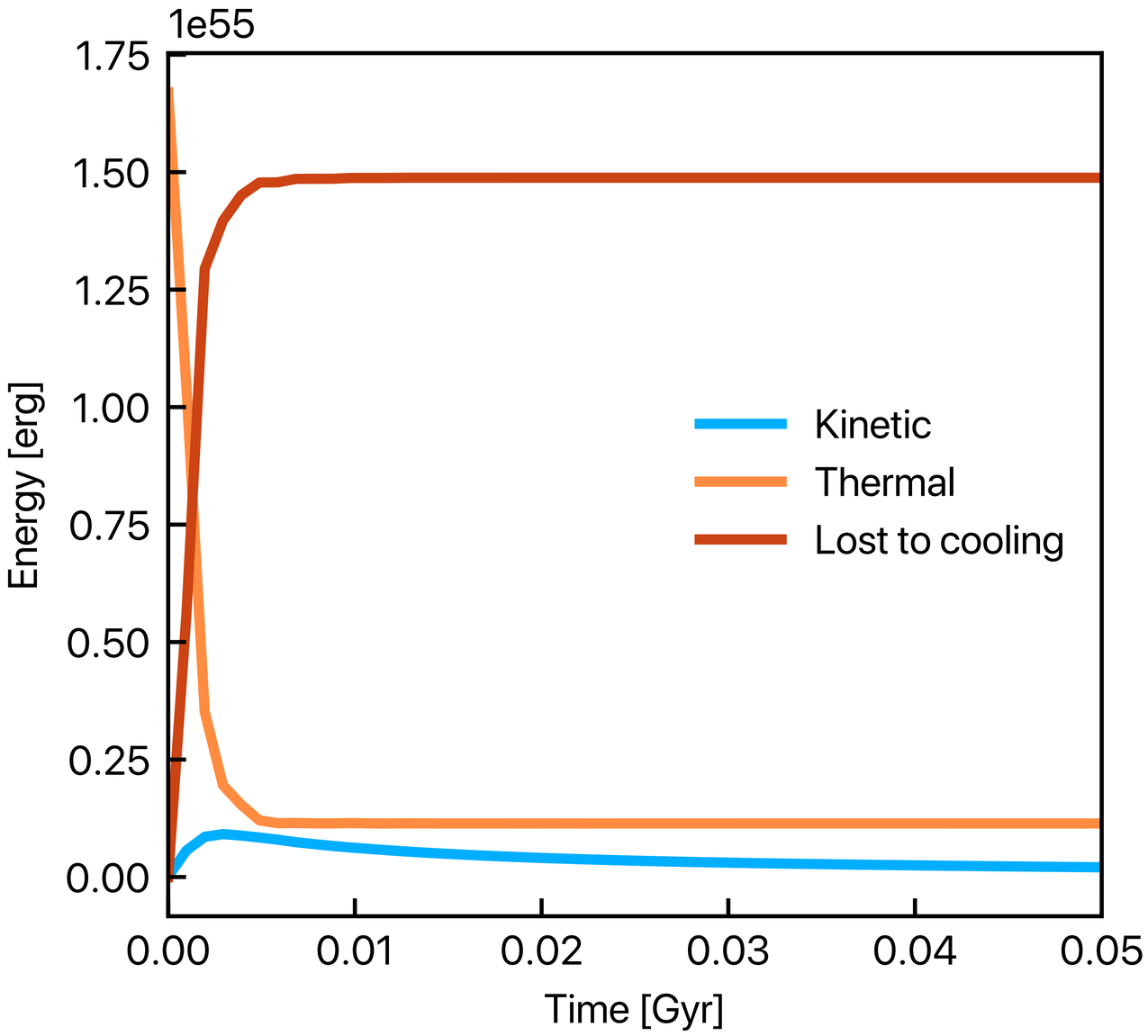
- **Energy diffusion** can solve issues at **contact discontinuities** that cause the artificial **surface tension** present in Density-Energy SPH.

- This was actually previously **used in the ANARCHY** scheme (among others) to **promote entropy mixing**.

Thermal Feedback

- The **EAGLE** simulations use a **thermal feedback** model, injecting **energy** directly into a **single particle**.

- The original **diffusion limiter** picked this up as a huge **contact discontinuity** and **rapidly diffused energy out** of the hot particle!



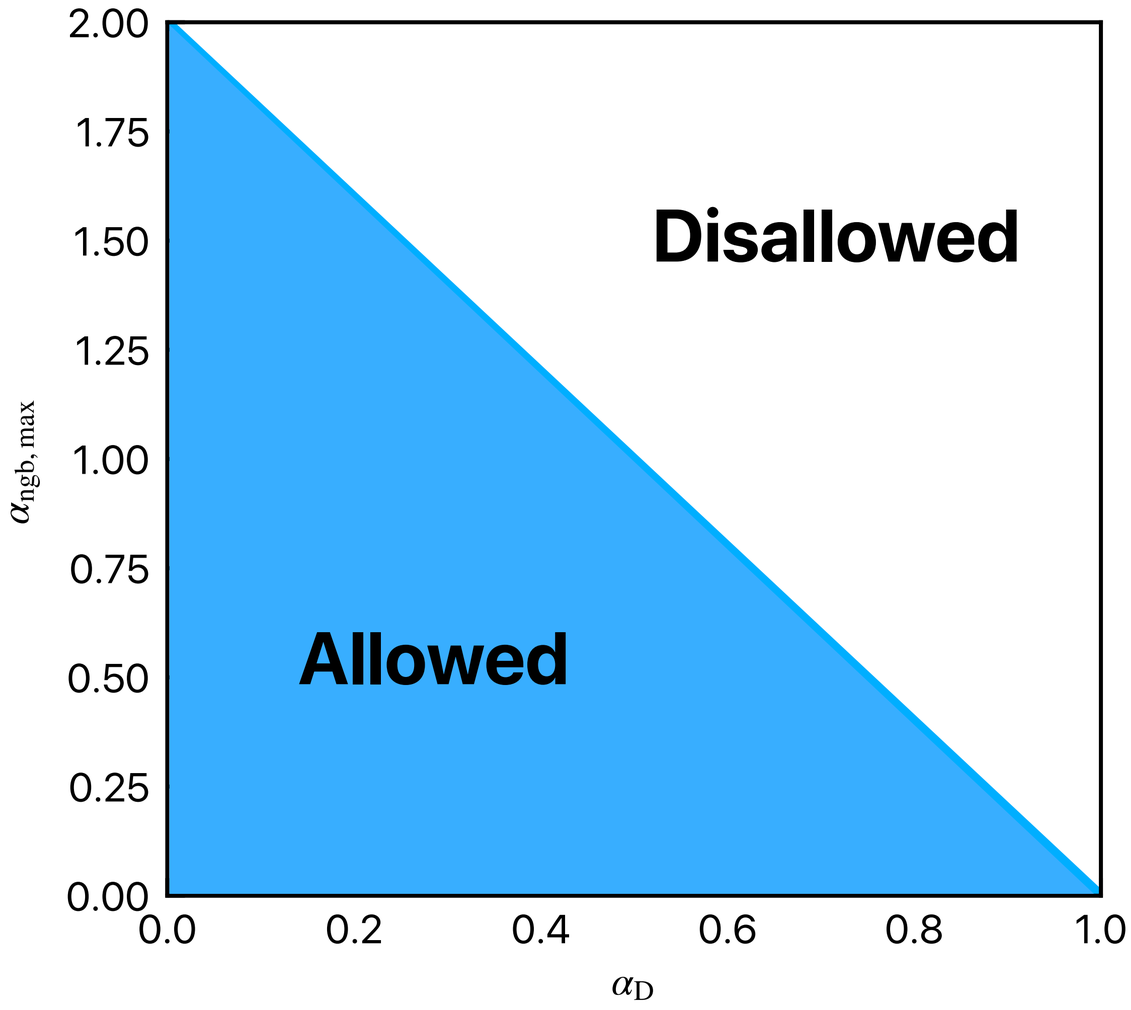
Example test of an EAGLE supernova in an isolated 0.1 g/cm^3 background.

A Shocking Diffusion Limiter

$$\alpha_{\mathrm{ngb,max}} = \max_j(\alpha_j) \qquad \alpha_D = \max\left(\alpha_D, 1 - \frac{\alpha_{\mathrm{ngb,max}}}{\alpha_{max} = 2}\right)$$

- To remedy this issue, we need to **turn off diffusion** when **feedback** events take place.

- We already have a **shock detector** in the **artificial viscosity**; use it to **dampen** the **diffusion** based on **shock strength**.



A Shocking Diffusion Limiter

- To fully apply the diffusion limiter in cases with incredibly strong pressure discontinuities (e.g. a feedback event), in interactions each **diffusion parameter** is **weighted by** that particle's **pressure**.

- This is required as **some particles** may not have **re-calculated** their maximal **local alpha since the feedback event** occurred.

Weighted diffusion parameter

$$\kappa_{ij} = \frac{P_i \alpha_{\mathrm{D},i} + P_j \alpha_{\mathrm{D},j}}{P_i + P_j}$$

Note each parameter is evolved separately

Diffusion equation

$$\frac{\mathrm{d}u}{\mathrm{d}t} \propto \sum_j \kappa_{ij} v_{\mathrm{D},ij} (u_i - u_j)$$

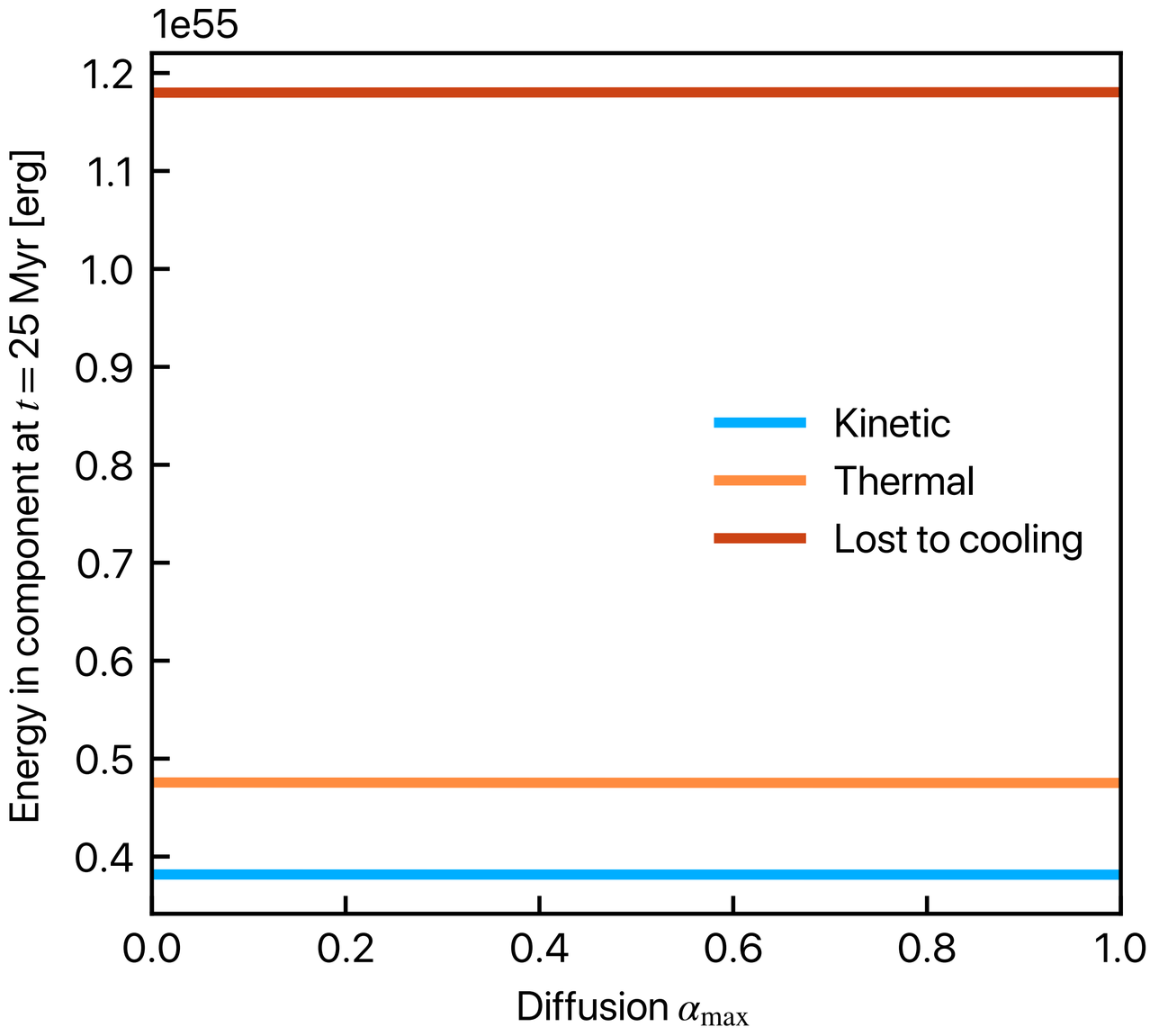
Diffusion velocity

$$v_{D,ij} = \sqrt{\frac{|P_i - P_j|}{\frac{1}{2}(\rho_i + \rho_j)}} + \frac{|\mathbf{v}_{ij} \cdot \mathbf{r}_{ij}|}{r_{ij}}$$

Testing the Limiter

- The new limiter manages to allow the **same energy impact** in scenarios **with and without diffusion** for feedback.

- This has **no impact** in situations **without significant shocks**, where surface tension issues arise.



Same test as previously (0.1 g/cm³ background) but with new diffusion limiter.

SPHENIX

GIZMO-MFM

Conclusions

- The **ANARCHY** SPH model used for the original **EAGLE** used the **Pressure-Entropy SPH** equation of motion.

- This formulation of SPH **suffers** in **regimes** where **particle cooling rates are high**, which occurs frequently in cosmological simulations.

- To remedy this, we now use **SPHENIX**; a model based on **Density-Energy SPH** with **energy diffusion** (also known as artificial conduction).

- This **fixes** the classic '**surface tension**' problem with Density-based SPH schemes.

- SPHENIX includes a **custom diffusion limiter** to prevent **overzealous diffusion** in regions that have just been hit with the EAGLE **energetic feedback**.