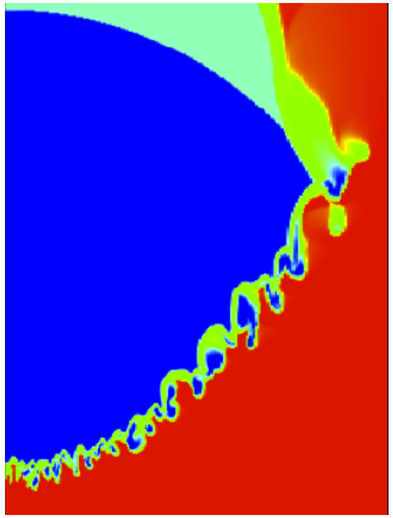
The enrichment and triggered formation of our solar system



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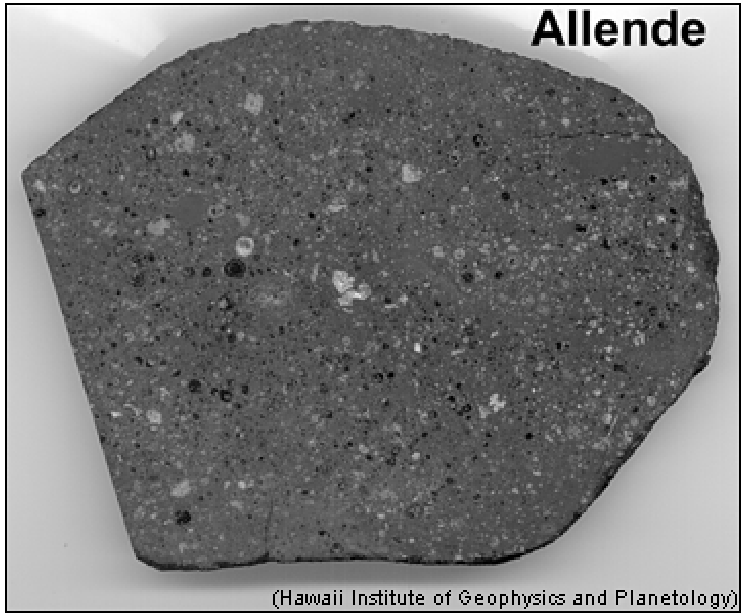
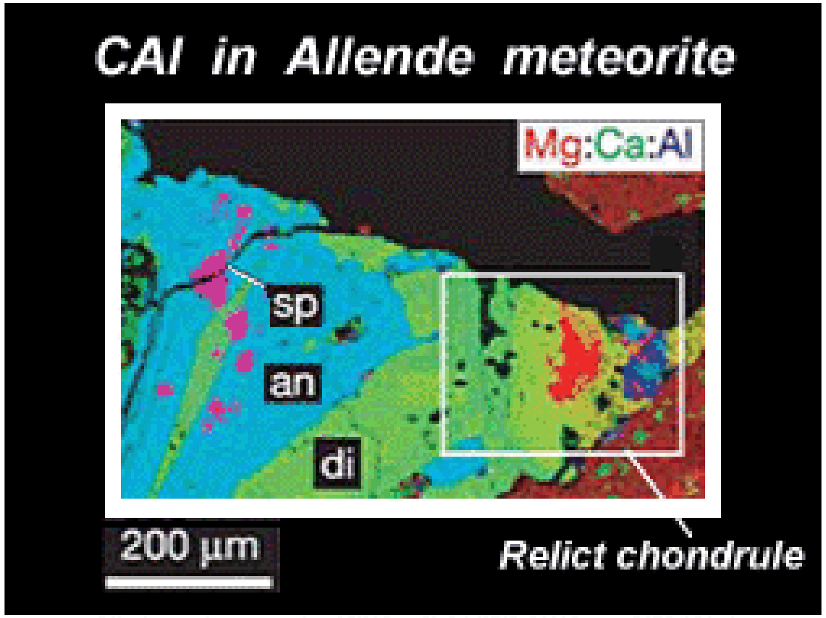
Ca-Al-rich inclusions (CAIs)

- CAI: Calcium-aluminum-rich inclusions (CAIs) are found in chondritic meteorites. CAIs are primitive objects that formed in the solar nebula before the planets formed. CAIs are light-colored objects rich in refractory elements (that condense at a high temperature). Besides calcium and aluminum, this includes magnesium, titanium, and rare earth elements. CAIs range in size from about a millimeter to a centimeter.
- Within the CAIs Mg^{26} as well as Al^{27} is found



(Hawaii Institute of Geophysics and Planetology)

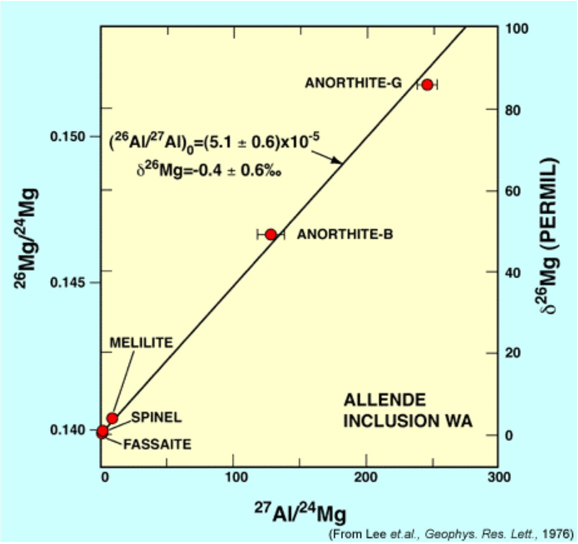


(From Krot, *et al.*, (2005) *Nature*, v. 434, p. 999.)

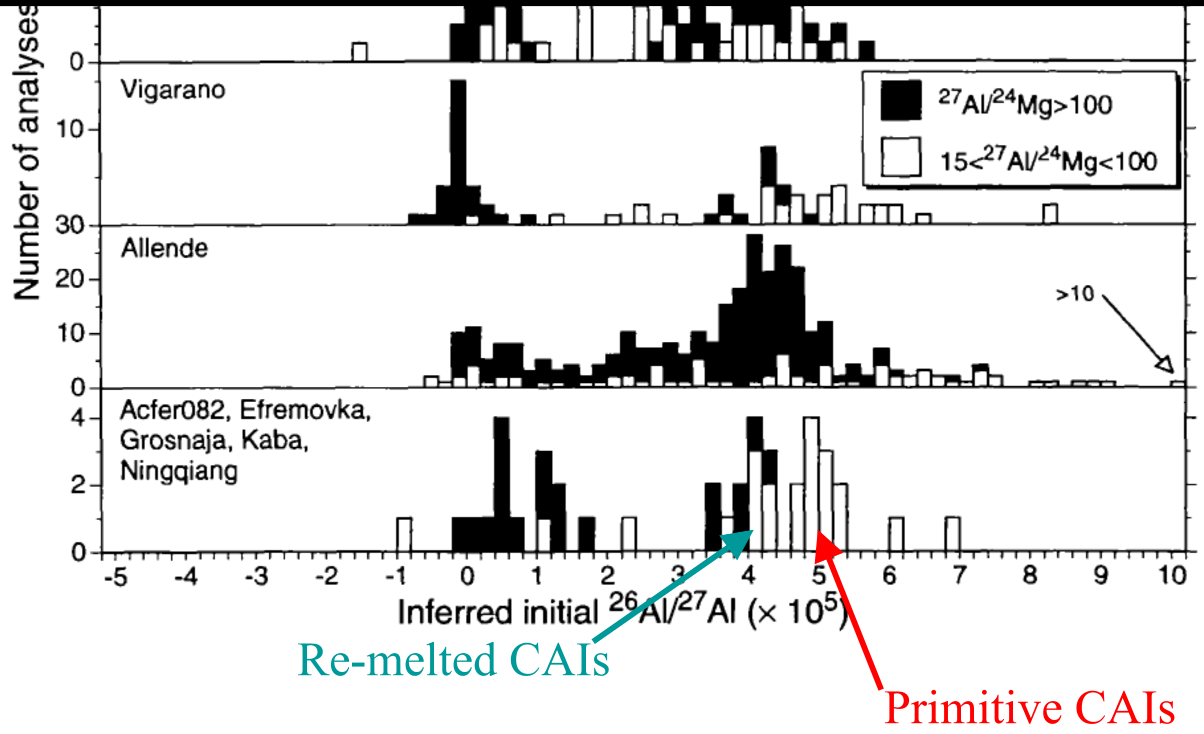
Al^{26}/Al^{27} ratio in CAIs

- Al^{26} decays into Mg^{26} (t=0.7Myr)
- Mg^{26} and Al^{27} condense at different temperatures
- Al^{26} and Al^{27} condense at the same temperature

$\Rightarrow$ if a CAI contains both Mg^{26} and Al^{27} it was formed with inclusions of Al^{27} as well as Al^{26}, which then decayed to Mg^{26}



The Formation Time of CAIs



From the spread among CAIs one can derive a relative condensation timescale of t≈20kyr
From Pb-Pb measurements one can derive an absolute formation timescale of t≈4.6Gyr

⇒The first generation of CAIs condensed 4.6 billion years ± 20 thousand years ago
(e.g. Jacobsen et al, 2008, Earth and Planetary Science Letters 272, 353)

Enrichment Scenarios

How to supply such a high abundance of a radioactive material in such a short time?

$$\frac{\mathrm{Al}^{26}}{\mathrm{Al}^{27}} \approx 5\cdot 10^{-5} \quad \Rightarrow \quad \mathrm{Al}^{26} = 5\cdot 10^{-5} * \mathrm{Al}^{27} \approx 5\cdot 10^{-9} M_{\Theta}$$

(e.g. MacPhersen et al, 1995, Meteoretics, 30, 365)

A. In situ

B. External

1. AGB-star
2. Runaway Wolf-Rayet star
3. Supernova
   a) In the disk stage
   b) In the pre-solar cloud stage

In general, continuous enrichment faces the problem that the freefall-time (100kyr) is much longer than 20kyr => A violent triggering event is most likely

External Enrichment - Supernovae

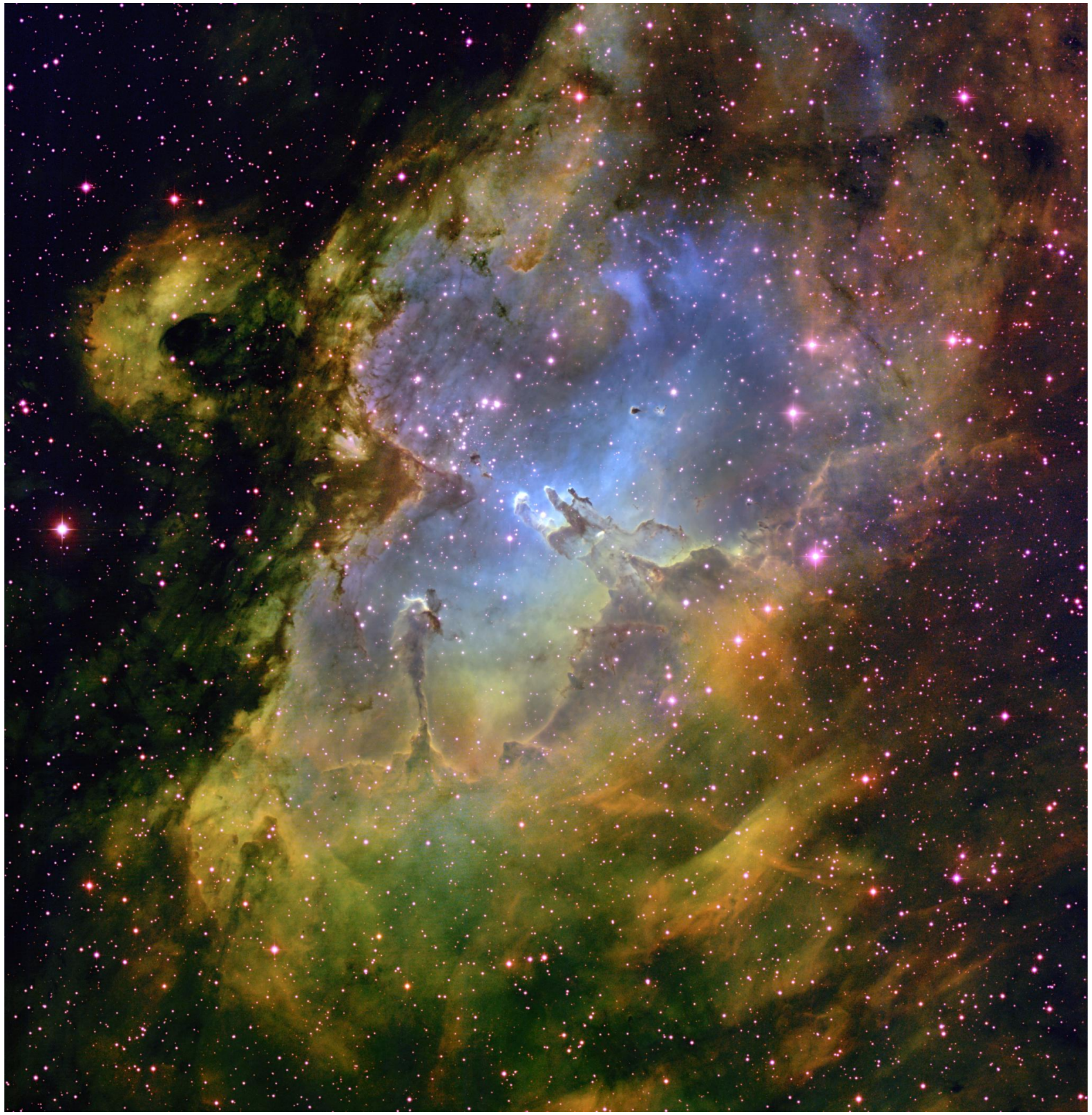
Supernova: From the produced amount of Al^{26} to the required amount of Al^{26} we can derive a size -distance relation:

$$R = \sqrt{\frac{4 \cdot \mathrm{Al}^{26}_{\mathrm{req}}}{\mathrm{Al}^{26}_{\mathrm{SN}}}} D$$

e.g.: $\mathrm{Al}^{26}_{\mathrm{SN}} \approx 1 \cdot 10^{-5} M_{\Theta}$, $D = 5\,pc \quad \Rightarrow \quad R = 0.22\,pc$

- In the disk-phase the cross-section is too small
- In the pre-solar core phase maybe possible. Problems:
  - Survivability
  - Time-scales
  - Mixing

Pre-Supernova Survivability - M16

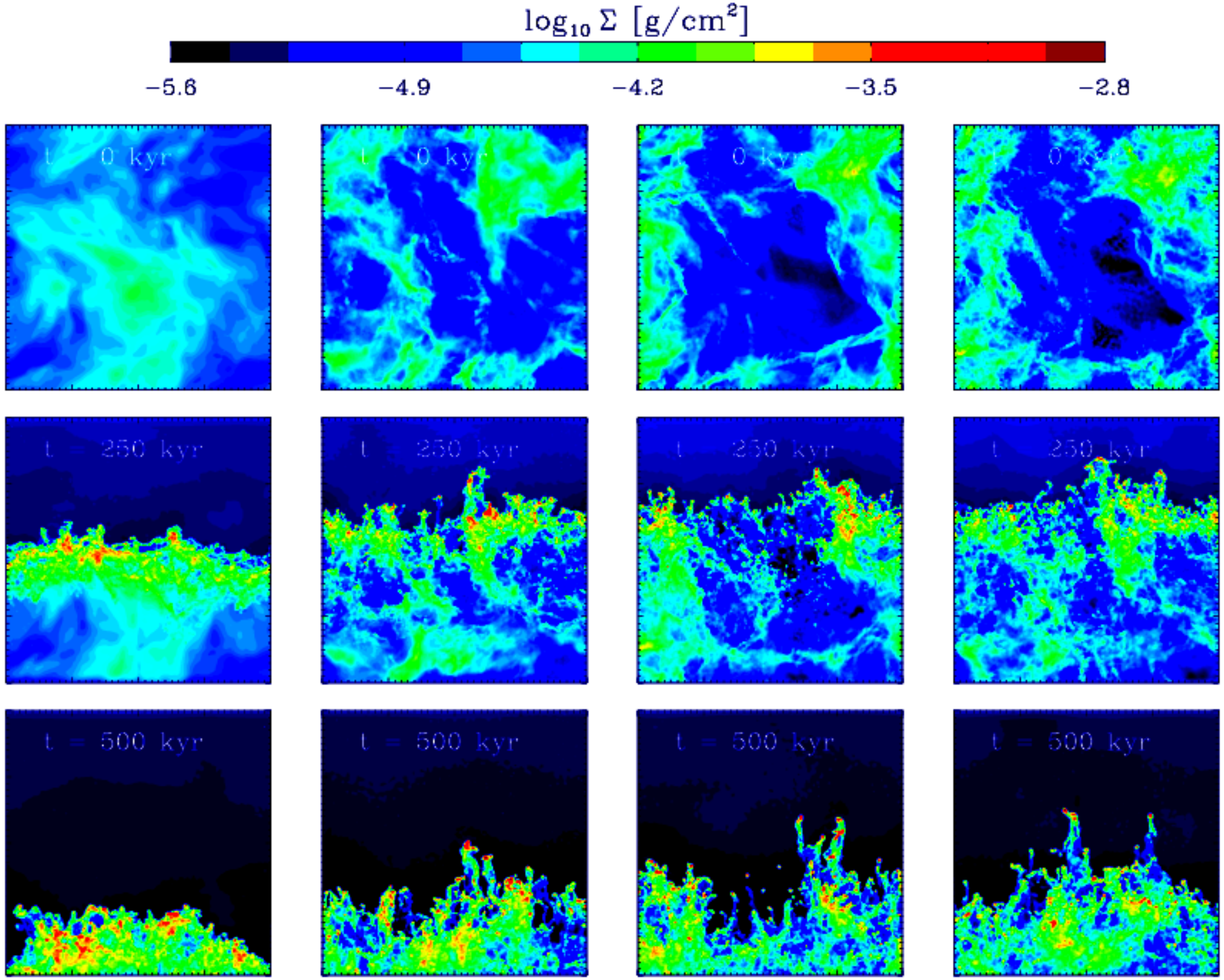


T. A. Rector & B. A. Wolpa, NOAO, AURA

Pre-Supernova Survivability - M16

McCaughrean & Andersen 2002, A&A, 389, 513

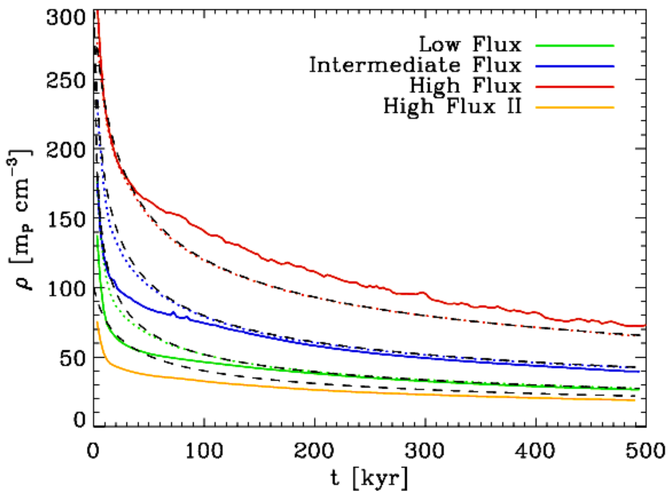
Pre-Supernova Survivability - Simulations



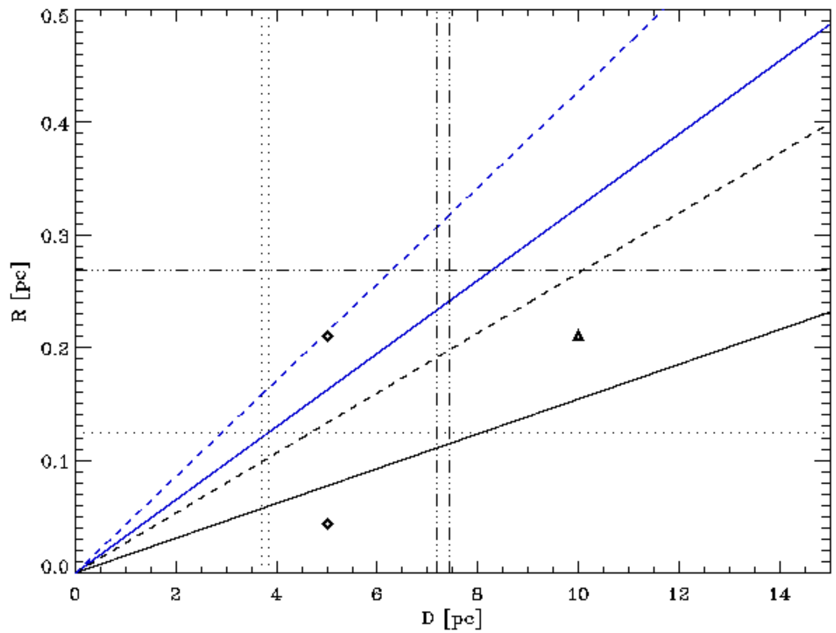
Mach 1.5 | Mach 5 | Mach 7 | Mach 12.5

Survivability

Even in the turbulent case shown before the average front position agrees with the analytical expectation



Combining the size-distance relation and the front position as a survivability criterion we can narrow down the parameter space:



Numerical Simulations

- COSMOS: grid based, parallel, multidimensional, radiation-chemo-hydrodynamics code
  (Anninos & Fragile 2003, Anninos, Fragile & Murray, 2003, cf Boss+, 2008, 2010)

- Initial Conditions:

  - Bonnor-Ebert-Sphere with

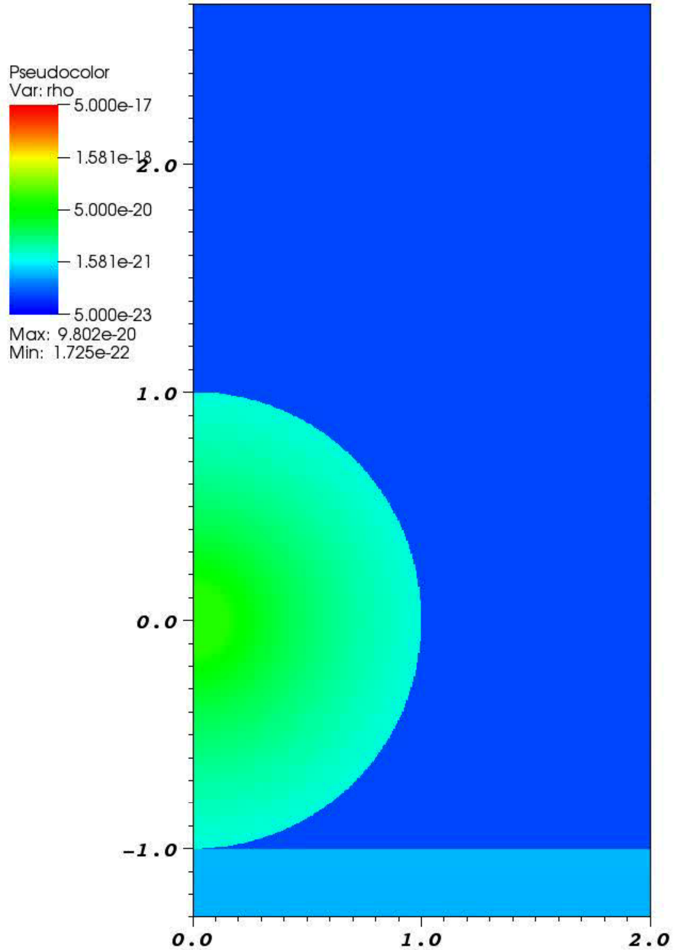
$$n_{center} = 5.6 \cdot 10^5 cm^{-3}$$
$$T = 20K$$
$$R = 0.2pc$$
$$\Rightarrow M = 10 M_\Theta$$

  - SN-Shock in the Sedov-phase with

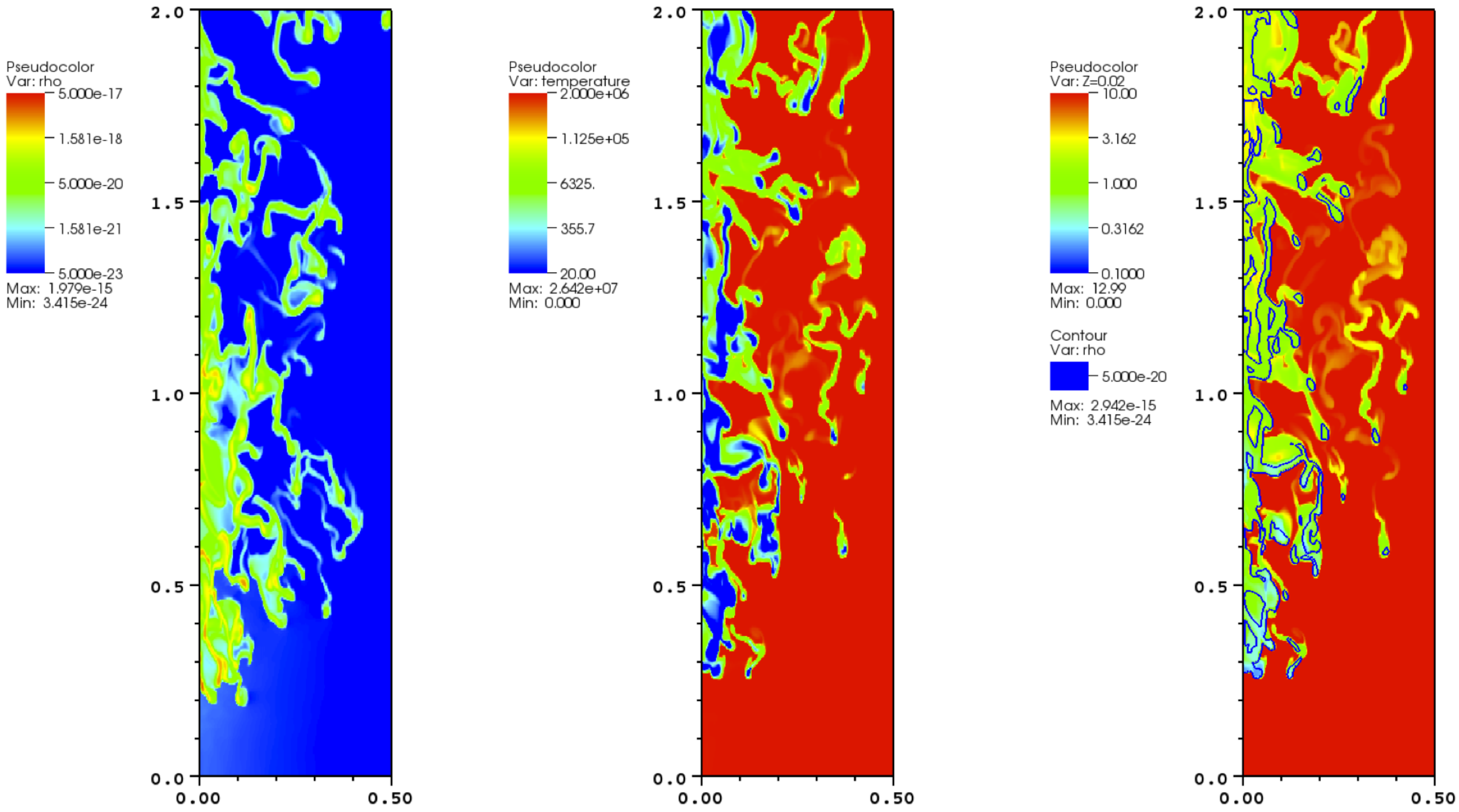
$$E = 10^{51} erg$$
$$D = 5pc$$

$$\Rightarrow v_{postshock} = 276 km\ s^{-1},\ c_{post-shock} = 129 km\ s^{-1},\ \Delta t = 8500 yr$$

Numerical Simulations I - Density

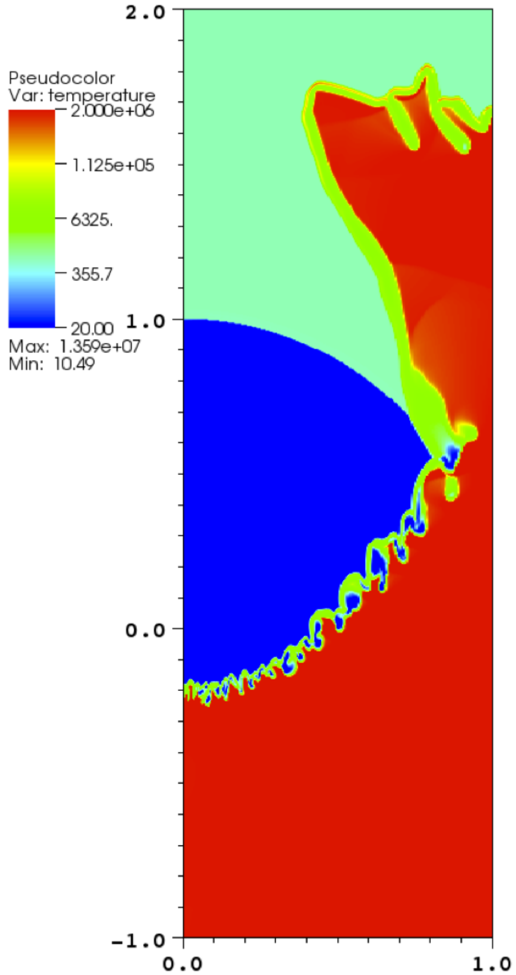


Numerical Simulations I

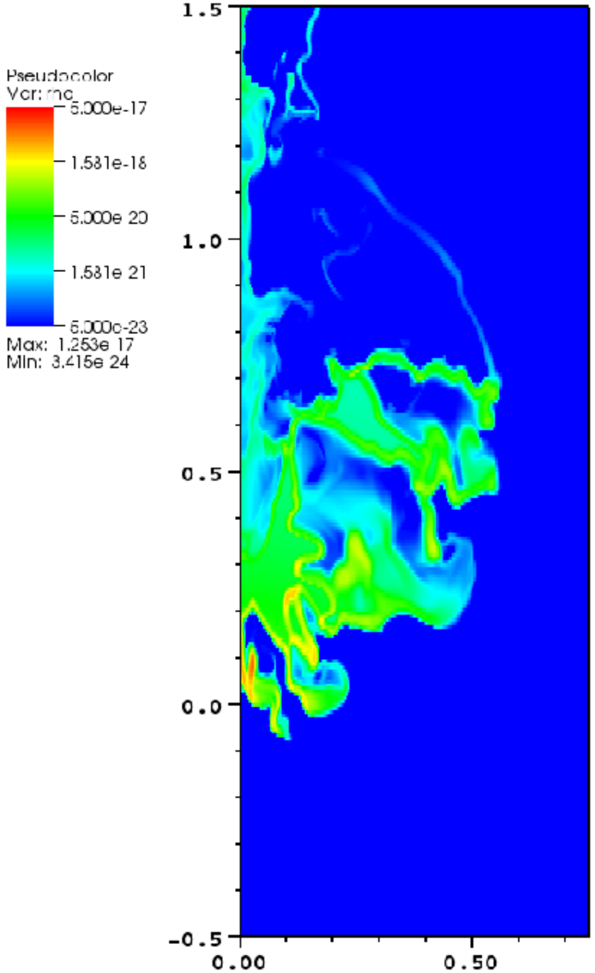


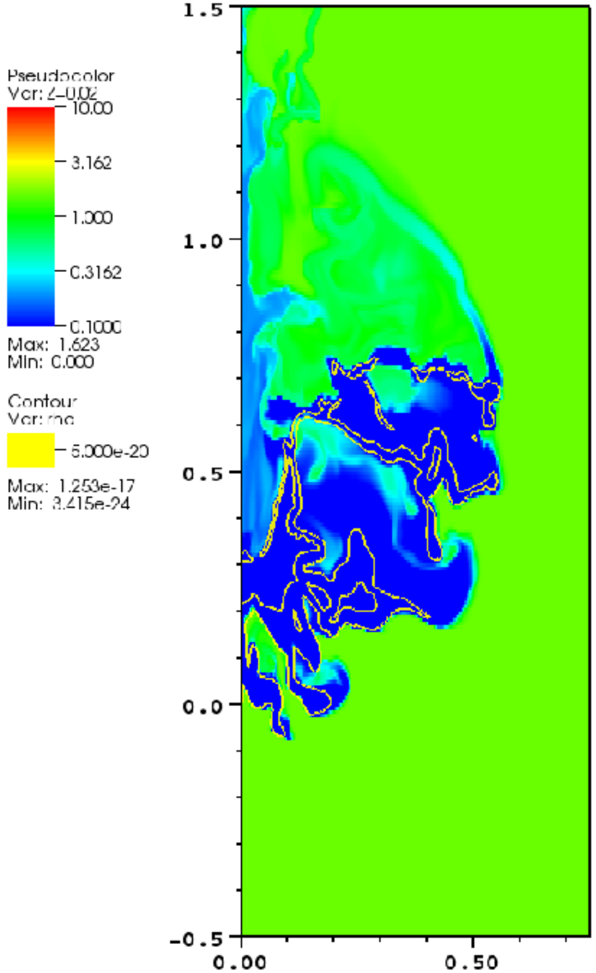
$$t = 8340\ yr,\ M_{\text{core}} = 0.1 M_{\Theta}$$

The mixing happens in the cold phase



Numerical Simulations II





If the BES is a D=10pc the shock is too weak to trigger collapse.
In addition, the SN-material is already too diluted.

Metallicity and Mixing in the SN-shell

Distance	Mass	Metallicity	SNe mixing	Conversion	Sufficient
5 pc	40 $M_\odot$	$Z = 0.02$	shell	3.69	yes
			complete	1	yes
		$Z = 0.004$	shell	1.23	yes
			complete	0.36	unlikely
	20 $M_\odot$	$Z = 0.02$	shell	0.83	yes
			complete	0.23	no
		$Z = 0.004$	shell	0.48	unlikely
			complete	0.13	no
10 pc	40 $M_\odot$	$Z = 0.02$	shell	3.69	unlikely
			complete	1	no
		$Z = 0.004$	shell	1.23	no
			complete	0.36	no
	20 $M_\odot$	$Z = 0.02$	shell	0.83	no
			complete	0.23	no
		$Z = 0.004$	shell	0.48	no
			complete	0.13	no

Future Evolution

- Either a very fast further collapse (<10kyr)

- Or the system gets very dense (<0.1AU) and therefore hot (>3000K). Thus the CAIs only condense when this hot disk starts to cool (but what about the angular momentum…)

- Later on, some CAIs get partially re-melted, which demands detailed simulations on the disk evolution

Conclusions

Measurements on the Al^{26}/Al^{27} ratio in CAIs provide tight constraints on the enrichment of the early solar system ($t<20$kyr!):

- The enrichment can not happen in the disk itself
- External enrichment can not happen in the disk phase
- External enrichment can not be provided by AGB stars
- External enrichment can not be provided by a runaway Wolf-Rayet star

External Enrichment by a nearby (D~5pc) supernova seems to be the only possible way (up to now)