Simulating the Life-Cycle of Molecular Clouds:

From massive star formation to galactic outflows

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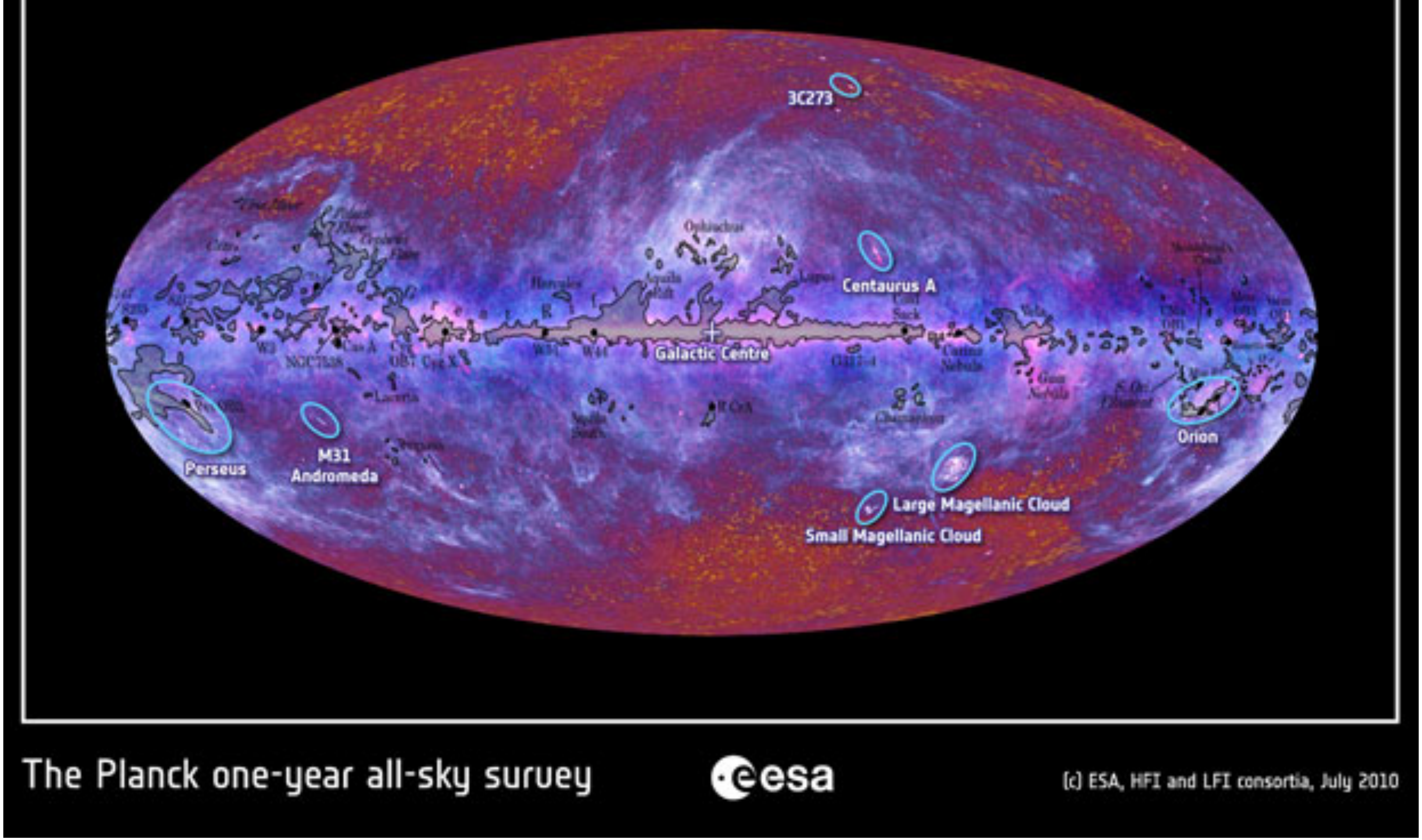
The SILCC project

Leibniz-Rechenzentrum · Universität Heidelberg · Max-Planck-Institut für Astrophysik · Astronomický ústav AV ČR · Universität Zürich

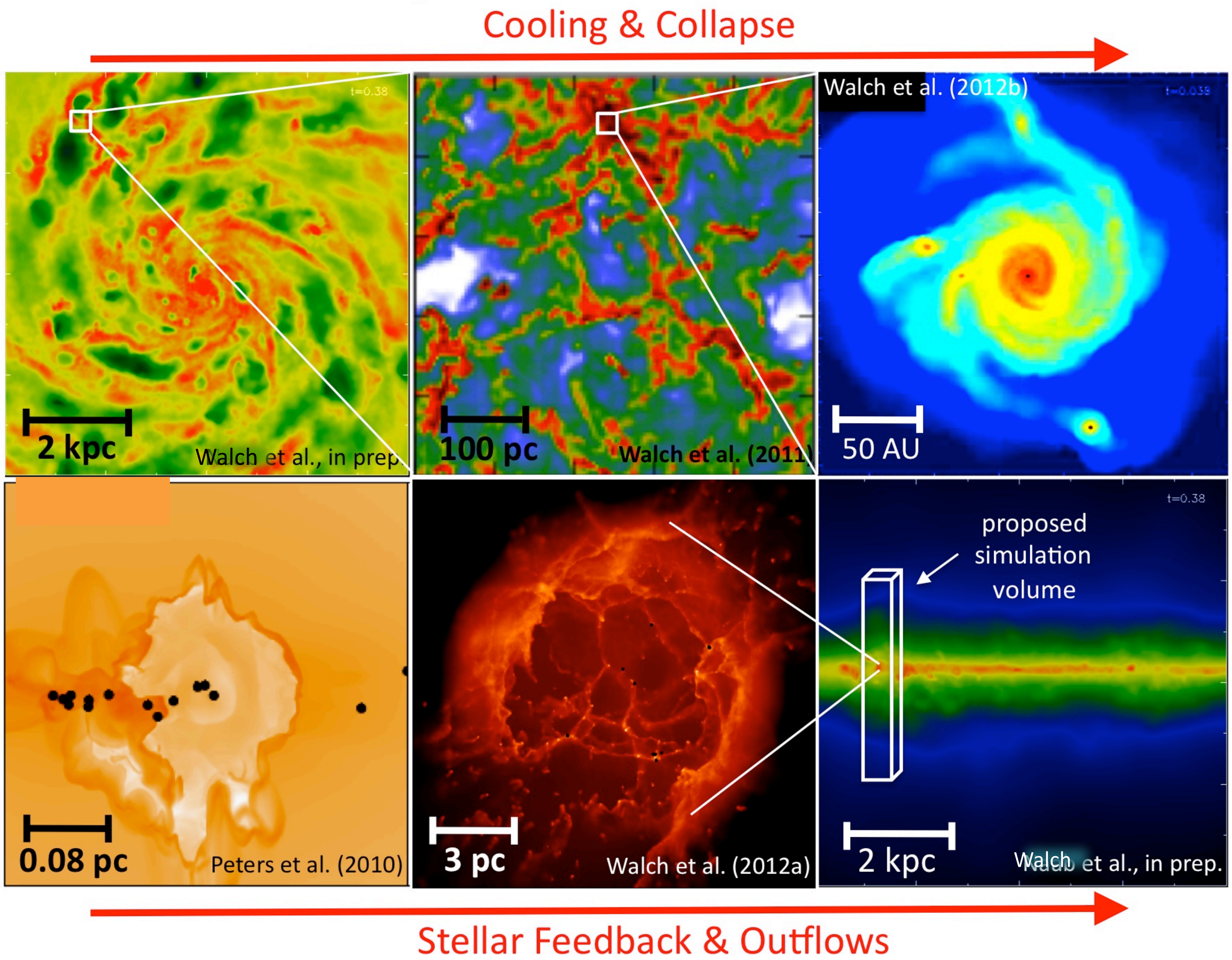
Phases of the ISM – Heidelberg – 29.07.2013

Multi-phase ISM

superimposed: CO survey (Dame et al. 2001)



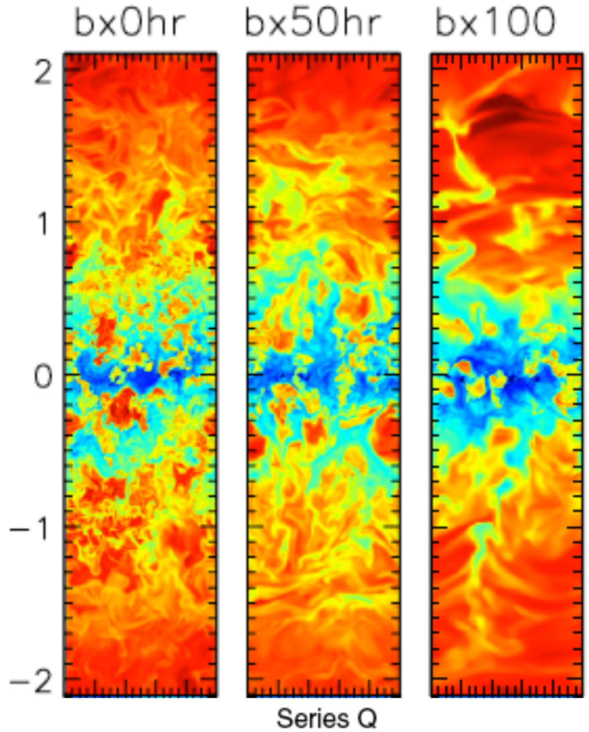
"Life-cycle of molecular clouds"

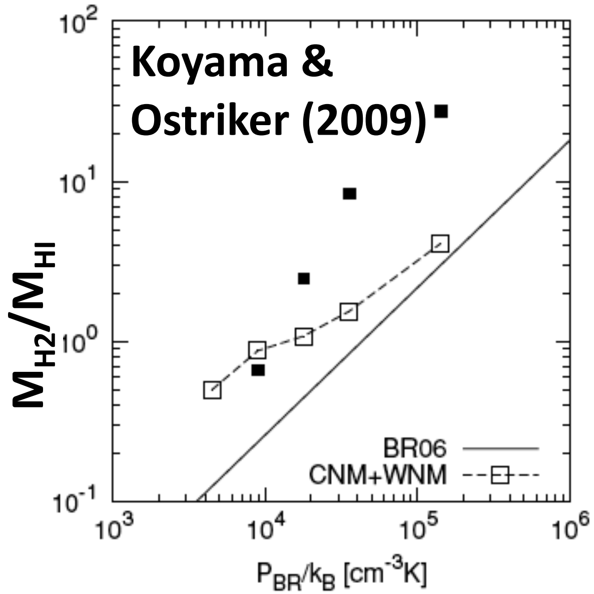


Previous work

- Joung & MacLow (2006); Hill et al. (2012): Supernovae drive turbulence and determine the vertical stratification of the disk;
- Koyama & Ostriker (2009), Shetty & Ostriker (2011): Include shear: Shear seems to be important for high Σ environments: limits the size of cold clouds;
- Gent et al. (2013): Find a velocity correlation scale of ~100 pc from SN energy input (similar to Avillez & Breitschwerdt)
- Creasey et al. (2013): Mass loading in winds; Mass loading decreases with increasing surface density

Hill et al. (2012)

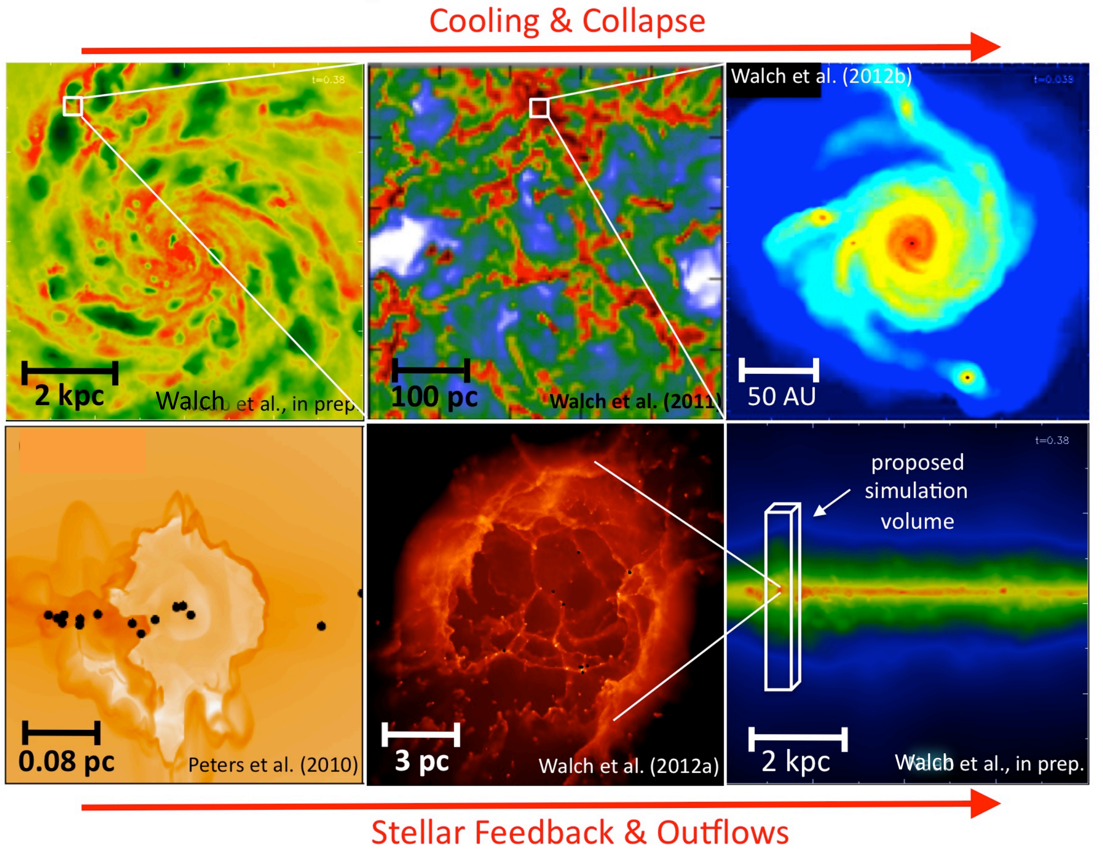




SILCC Project

SImulating the LifeCycle of Molecular Clouds

Team Munich: S. Walch, T. Naab, P. Girichidis, A. Gatto
Team Heidelberg: R. Klessen, S. Glover, P. Clark, C. Baczynski
Team Prague: R. Wünsch
Team Zurich: T. Peters



AMR code FLASH 4.0 with…

- Tree self-gravity (R. Wünsch)
- External potential
- ideal MHD
- Heating & Cooling
- Molecule Formation (S. Glover)
- TreeCol (Walch & Wünsch)
- Sink Particles with subgrid cluster model/massive star model
- Wind (Walch)
- Radiation transport (C. Baczynski, T. Peters)
- Supernova Feedback (A. Gatto)

42 million core hours on SuperMuc @ Leibniz-Rechenzentrum Garching

Physics in SILCC

- **Adaptive mesh refinement: FLASH 4.0**
- **Mixed boundary conditions (periodic in x and y, outflow in z)**
- **Tree self-gravity (R. Wünsch)**
- **External potential (Girichidis)**
- **ideal MHD (Bouchut 5-wave solver)**
- **Heating & Cooling (S. Glover)**
- **Molecule Formation (S. Glover)**
- **TreeCol (Walch & Wünsch)**
- **Sink Particles with subgrid cluster model/massive star model**
- **Stellar feedback:**
  - **Radiation transport (C. Baczynski, T. Peters)**
  - **Stellar Winds**
  - **Supernova Feedback from density peaks/random/sinks (Talk by Andrea Gatto)**

Gas Chemistry & Implementation

- **Simplified chemical network coupled with detailed heating and cooling function (e.g. Glover et al. (2011):**
- **Only major coolants (see Wolfire 1995, 2003)**
  - ➢ **COOLING for (T>8000K): excitation of H, He, etc resonance lines (tabulated Sutherland & Dopita 1993) + recombination of e^- with dust (Wolfire 2003)**
  - ➢ **COOLING in WNM (T~ 8000K): Lyα emission from H, e^- recombination with small grains, O fine-structure emission, also Si^+; CNM (T < 300K): C^+ fine-structure emission, also O;**
  - ➢ **HEATING: Photoelectric emission from dust => determined by UV background, dust-to-gas ratio, e^- abundance. Also X-Rays, Cosmic Rays**
- **Molecule formation:**
  - **H_2 formation on dust (Hollenbach & McKee 1979)**
  - **Conversion from C+ <-> CO: Nelson & Langer (1997)**

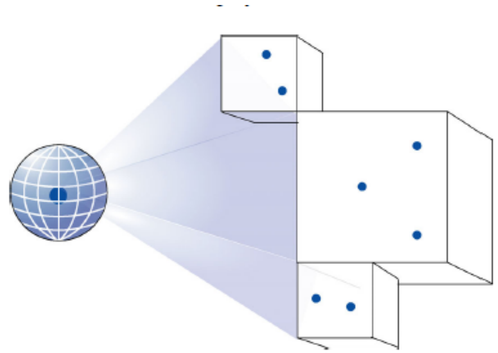
- **Only one additional field variable: ionisation degree (e^- abundance).**
- **Self-consistently follows chemical rate equations as well as radiative and compressional heating and cooling.**

- **Time step for chemistry: $\Delta t_{cool}=0.3\, e/|\Lambda|$**
- **Subcycling where necessary.**

- **Standard solar abundances (e.g. Sembach et al. 2000):**
  $X_C=1.4 \bullet 10^{-4}$; $X_O=3.2 \bullet 10^{-4}$; $X_{Si}=1.5 \bullet 10^{-5}$

TreeCol

Clark, Glover & Klessen(2012)

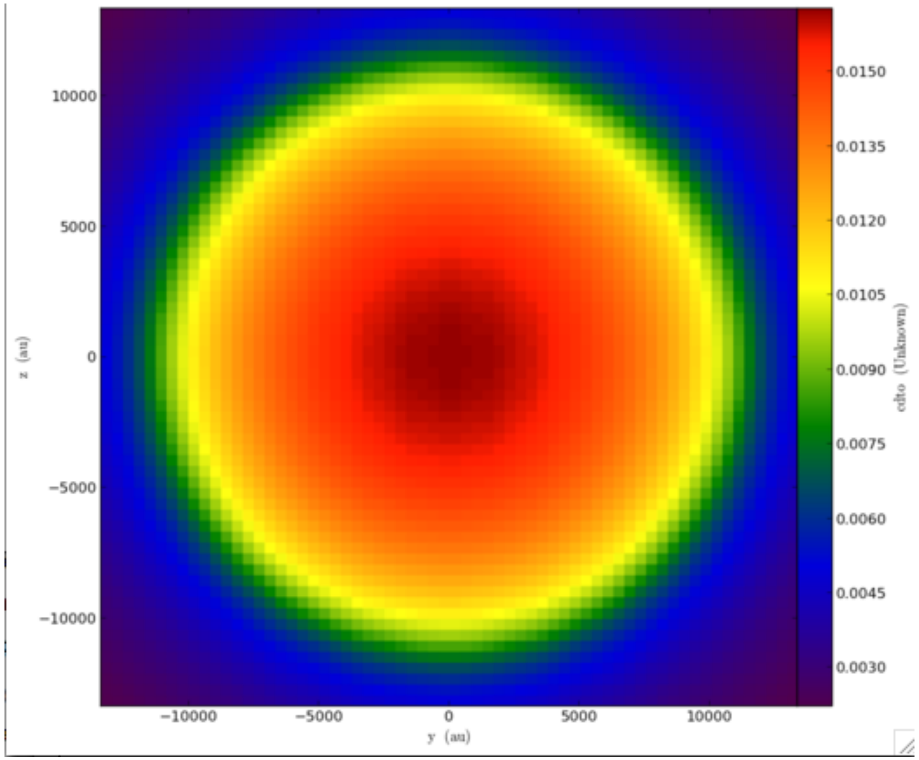


- Implementation based on an improved
  version of the Barnes-Hut tree written by R. Wünsch (FLASH 4.0 release)
- Large number of rays still too expensive
- Make use of fact that each tree node stores information necessary for computing column densities
- Span a HealPix sphere from each cell
- During tree-walk to compute gravitational forces: map projected column density of tree-nodes onto this sphere
- To compute the projected column density we need
  - the mass of the node
  - the node position with respect to the current cell
  - the size of the node
- We compute:
  - total column density -> total Av
  - total H2 and CO column -> self-shielding
  - dust attenuation

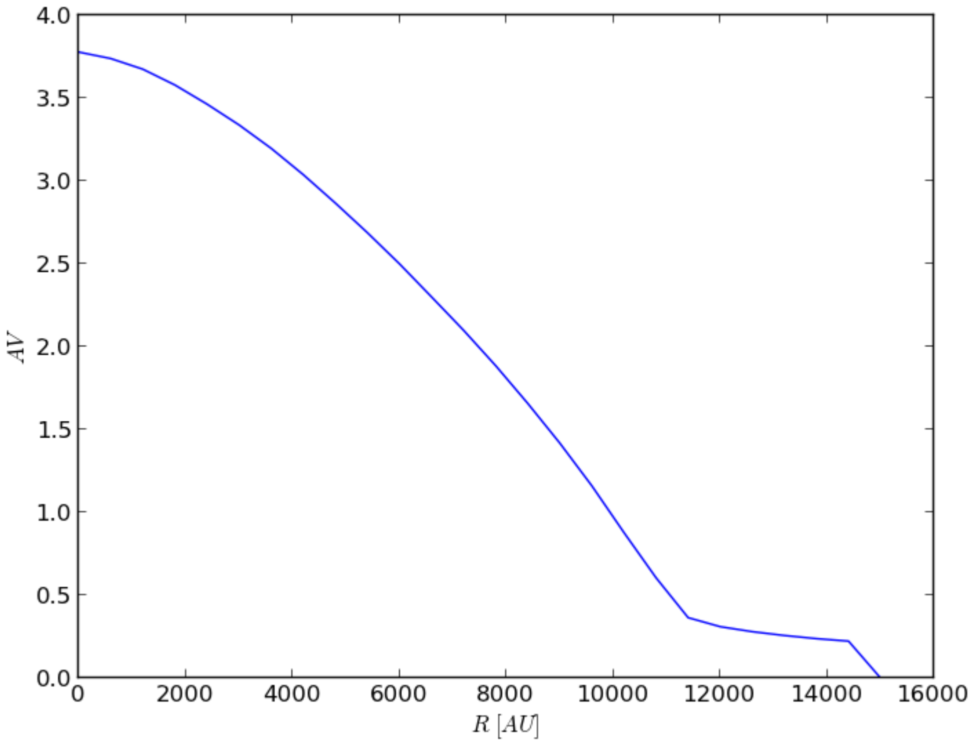
$$\chi(N_{\rm H}) = \frac{4\pi \int_0^\infty J_\nu \kappa_\nu \exp\left(-\kappa_\nu \Sigma\right) \, {\rm d}\nu}{4\pi \int_0^\infty J_\nu \kappa_\nu \, {\rm d}\nu},$$

Dust heating by ISRF
Test: uniform density sphere with $M=1M_{sun}$

Av slice through z=0



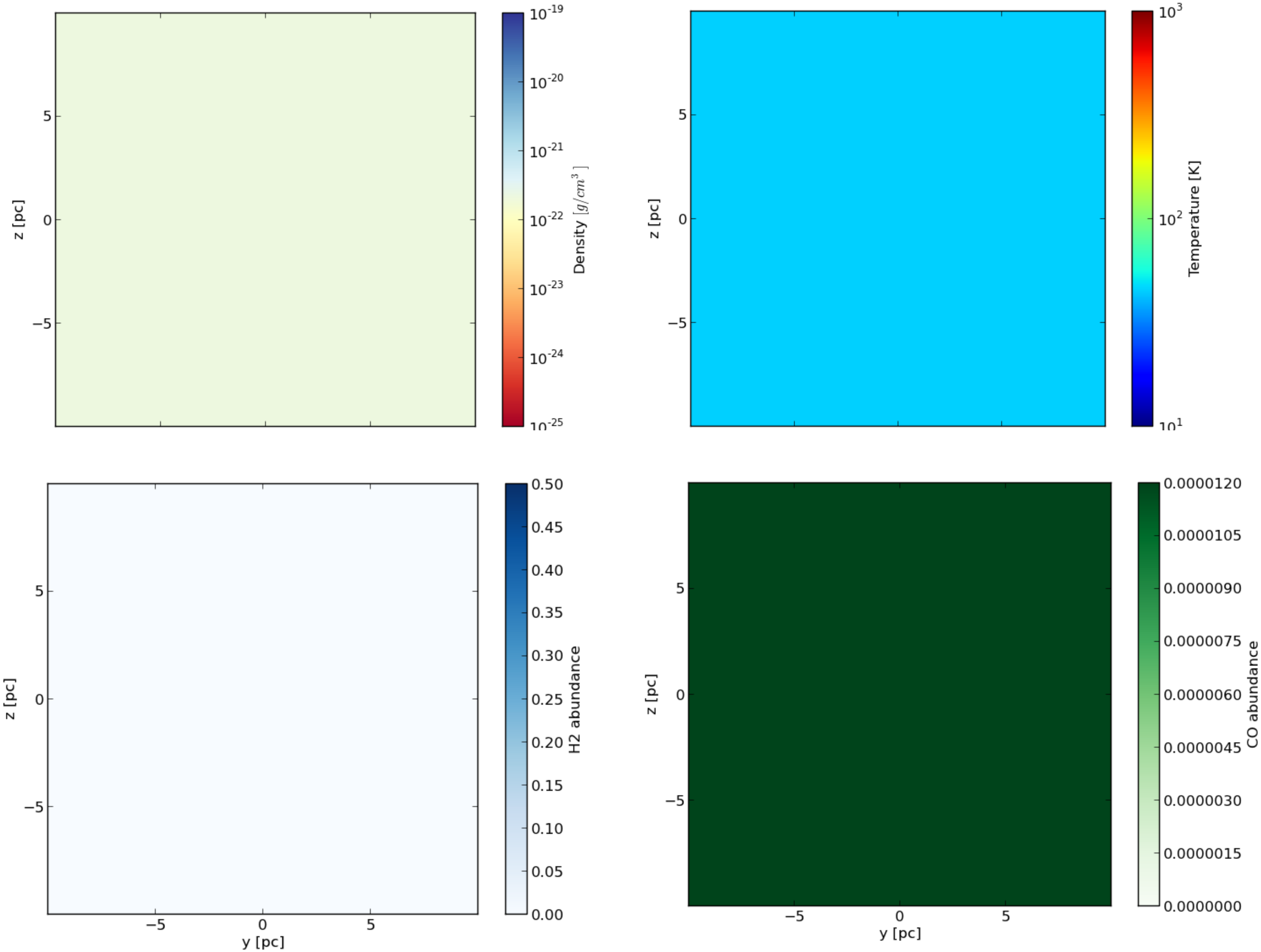
Radial profile of Av



TEST: Chemistry in a box with and without TREECOL

- **L= 128 pc**
- **n= 3 cm^{-3}**
- **T= 6000K**
- **Turbulence driving with v_{rms}= 10 km/s**

- **Compare the results with and without TreeCol**

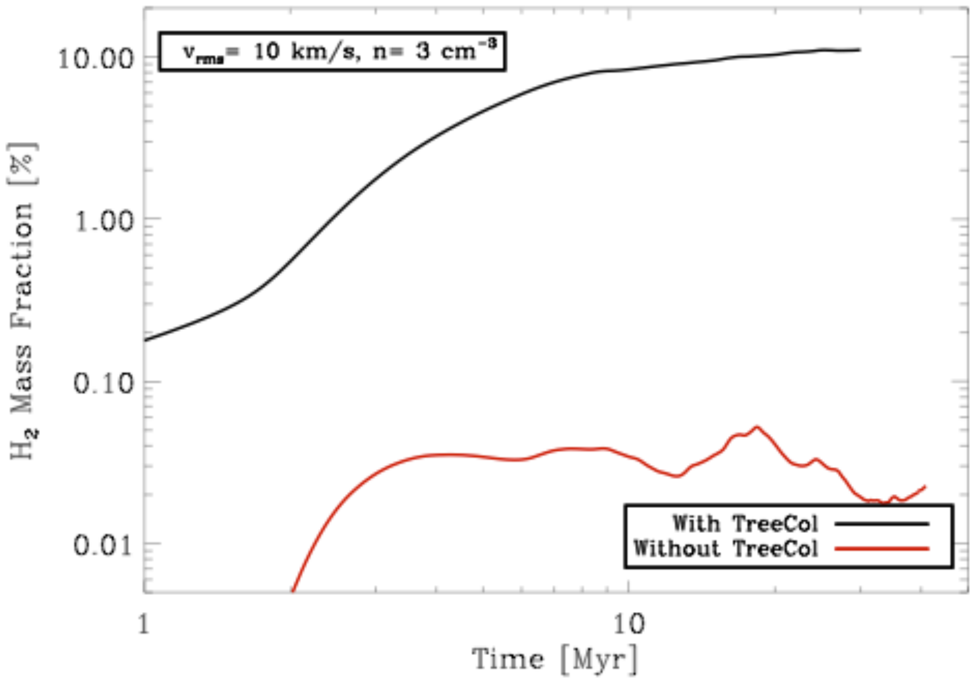


z [pc]
y [pc]
Density $[g/cm^3]$
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{-25}
Temperature [K]
10^{3}
10^{2}
10^{1}
H2 abundance
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
CO abundance
0.0000120
0.0000105
0.0000090
0.0000075
0.0000060
0.0000045
0.0000030
0.0000015
0.0000000

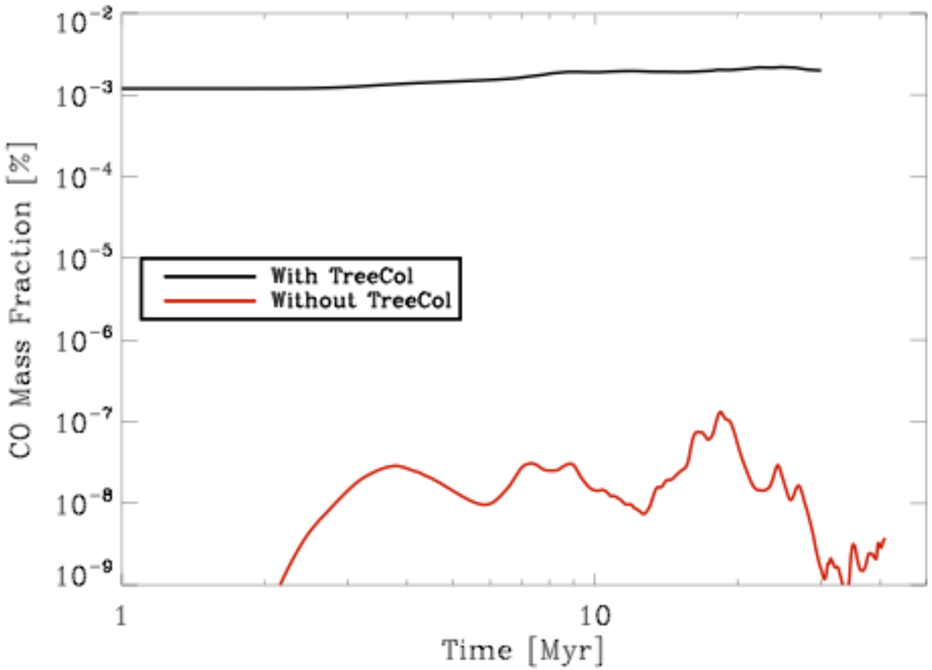
TEST: Chemistry in a box with and without TREECOL

Without TreeCol the
… H_2 mass fraction is a factor of ~100 lower
… CO mass fraction is a factor of ~10^5 lower

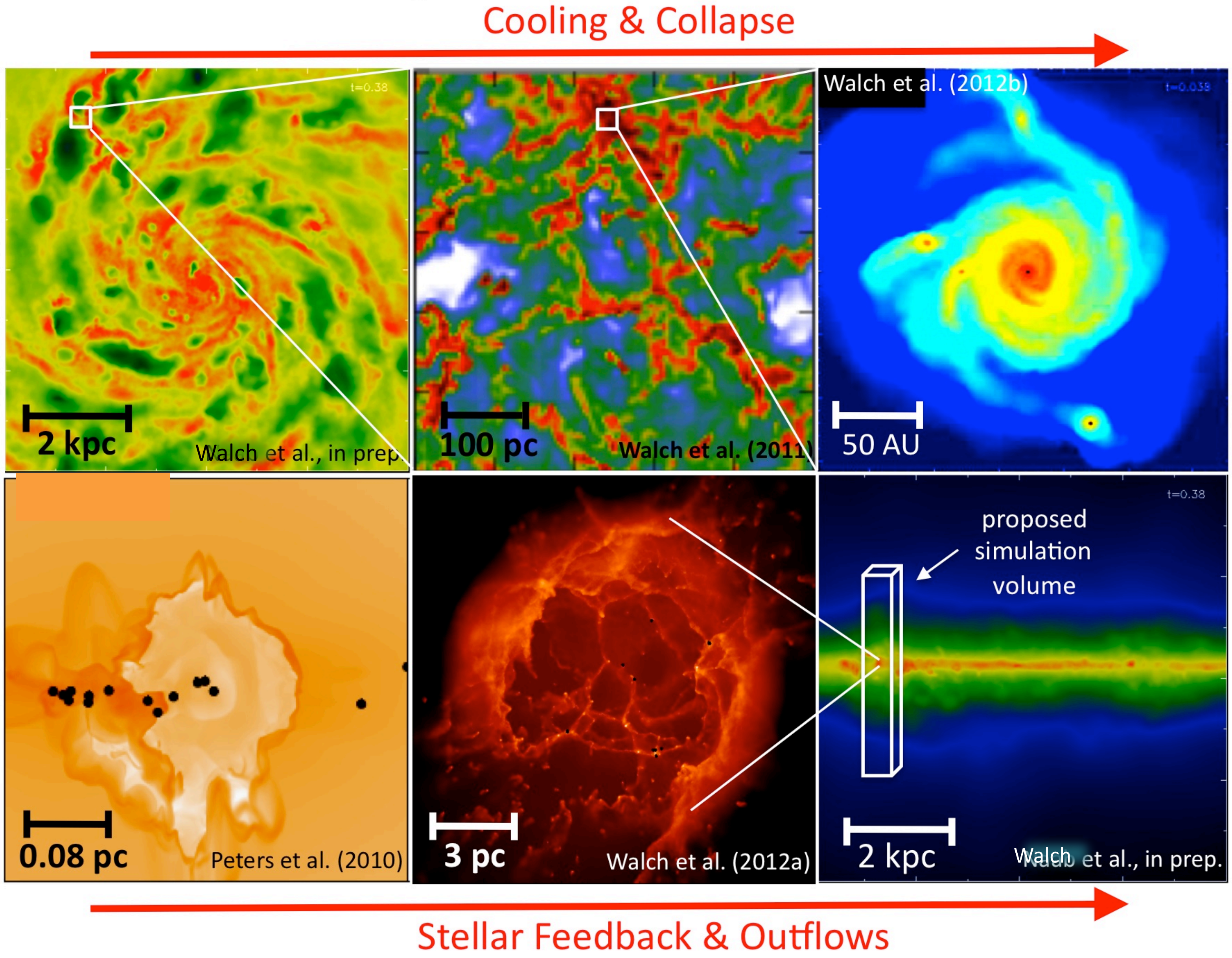
H_2 formation



CO formation



“Life-cycle of molecular clouds”



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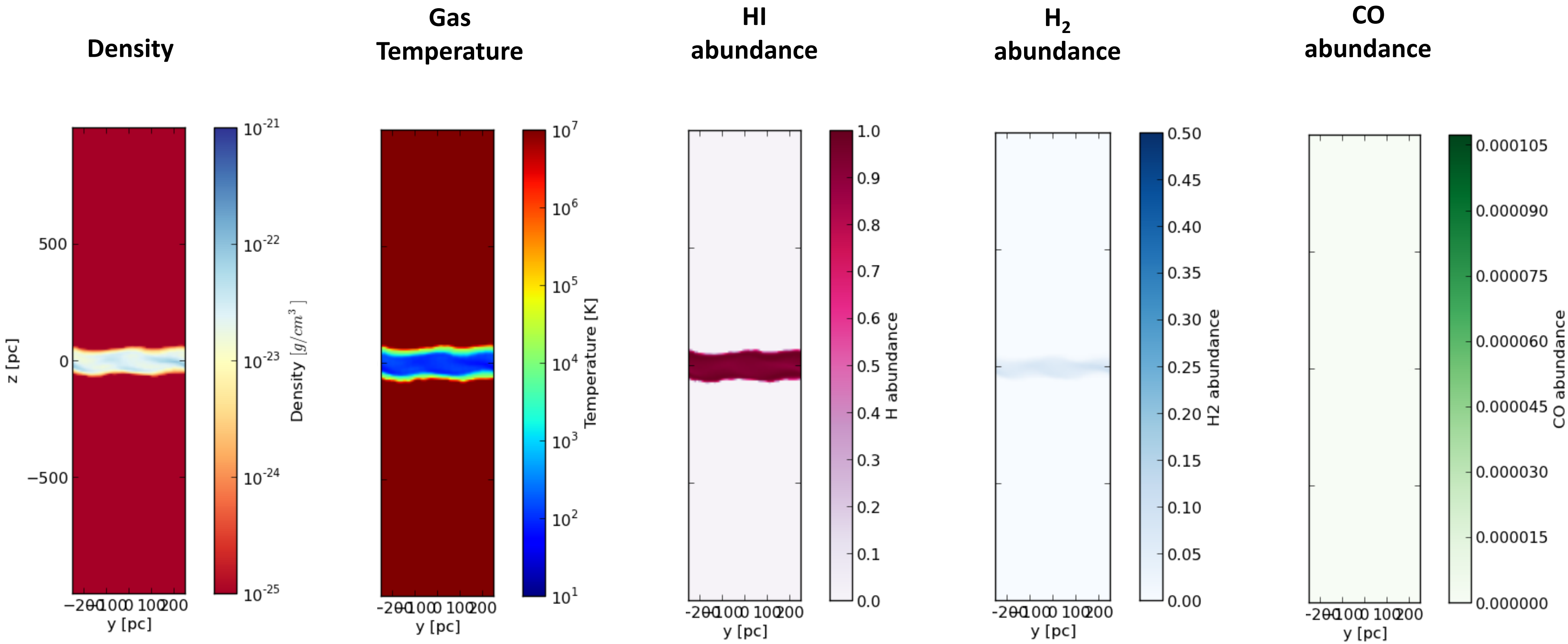
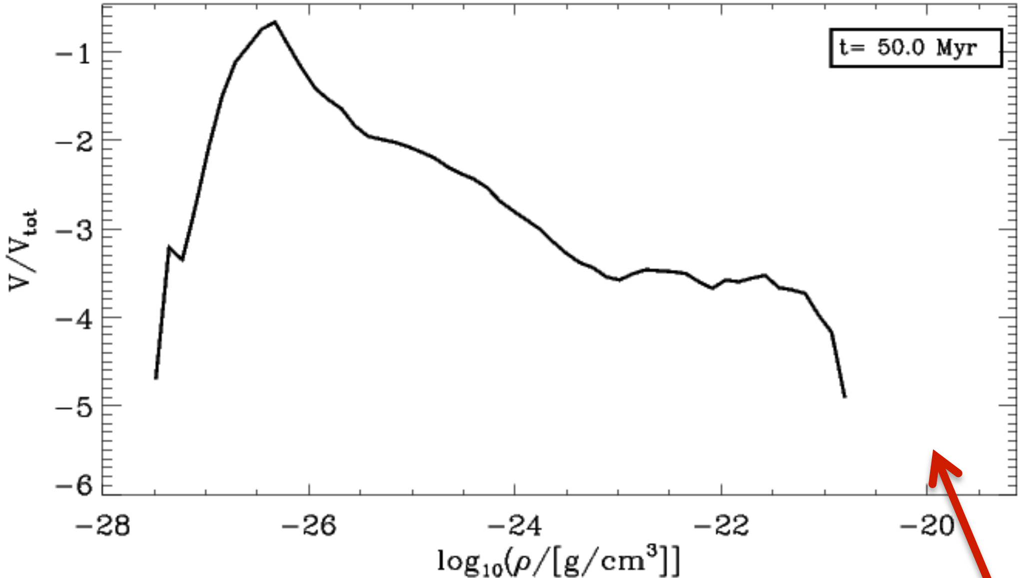
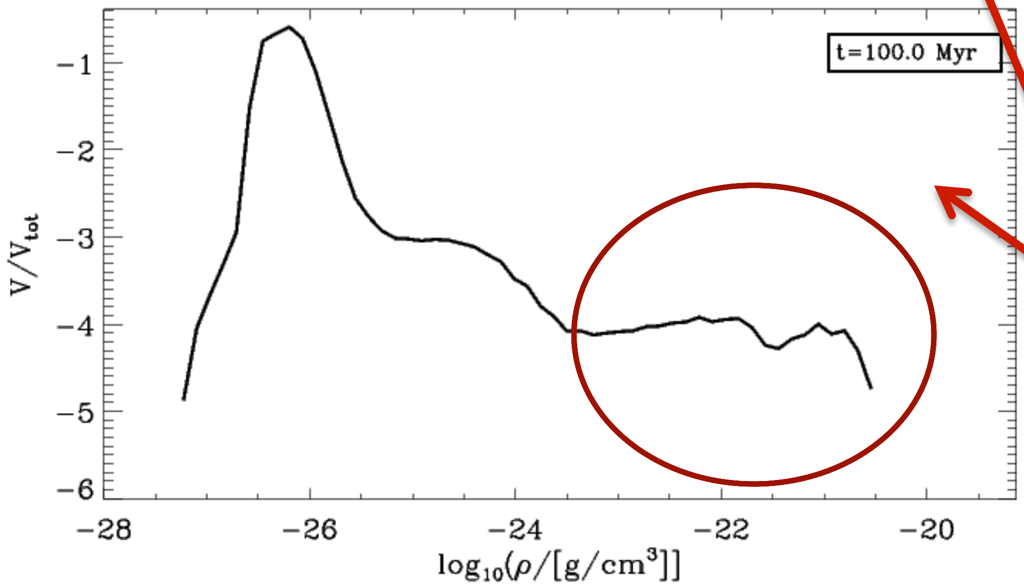
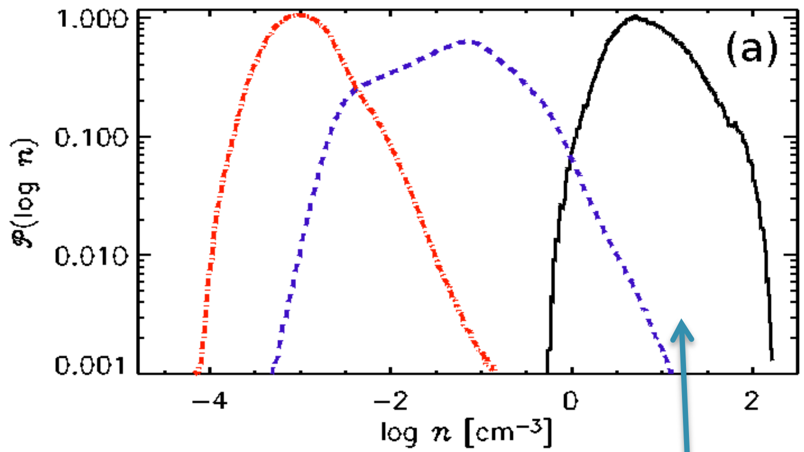


Low-resolution run with Σ_{gas} = 30 $M_\odot/pc^2$;
Initial turbulent stirring at 10 km/s;
SN driving from density peaks at reasonable rate (few/Myr);

Density PDFs



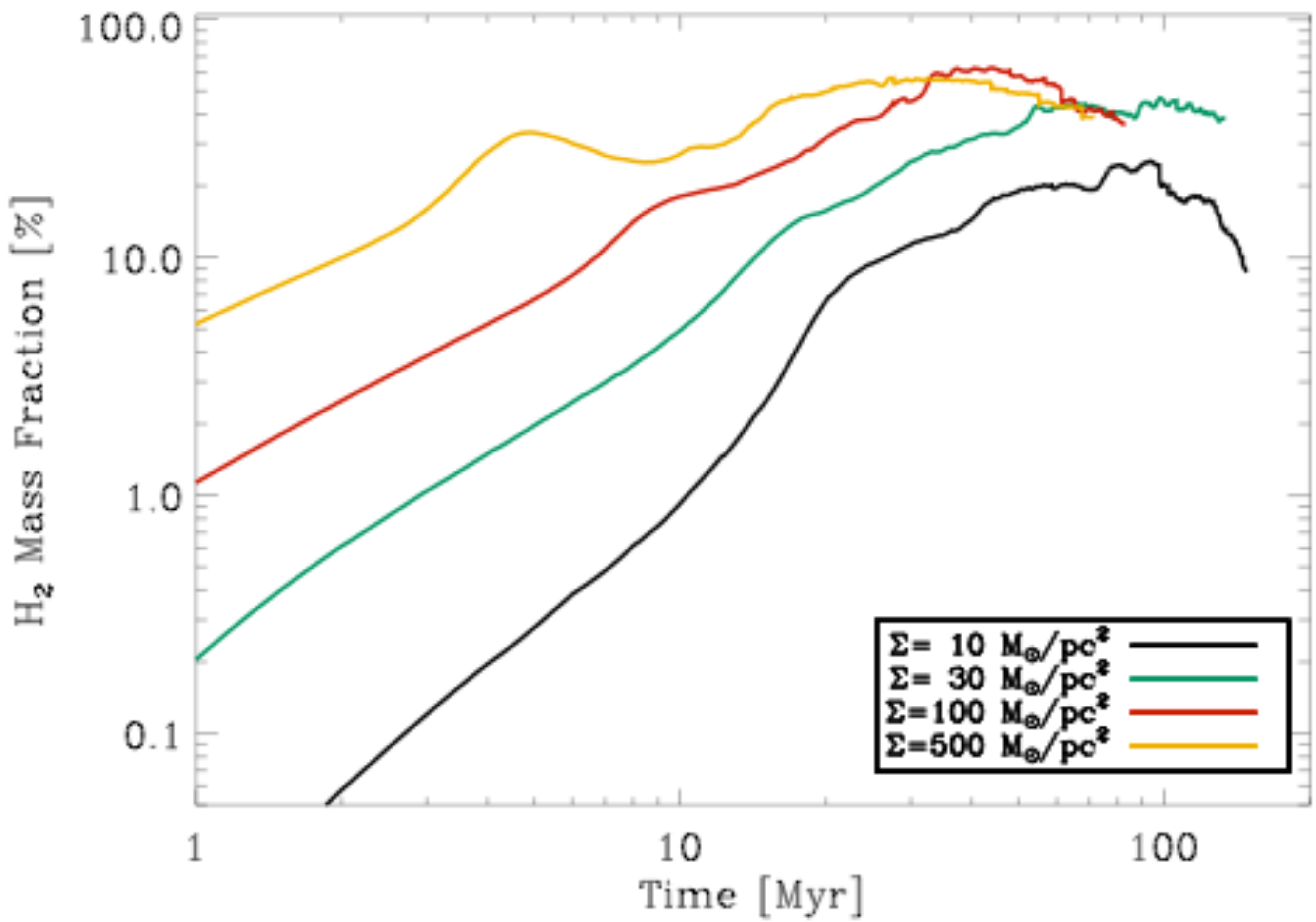




Gent et al. (2013):
3 components
- **T< 1000K,**
- **T> 5x10^5 K,**
- **and in between**
- **Peak probability ratios ~ 100**

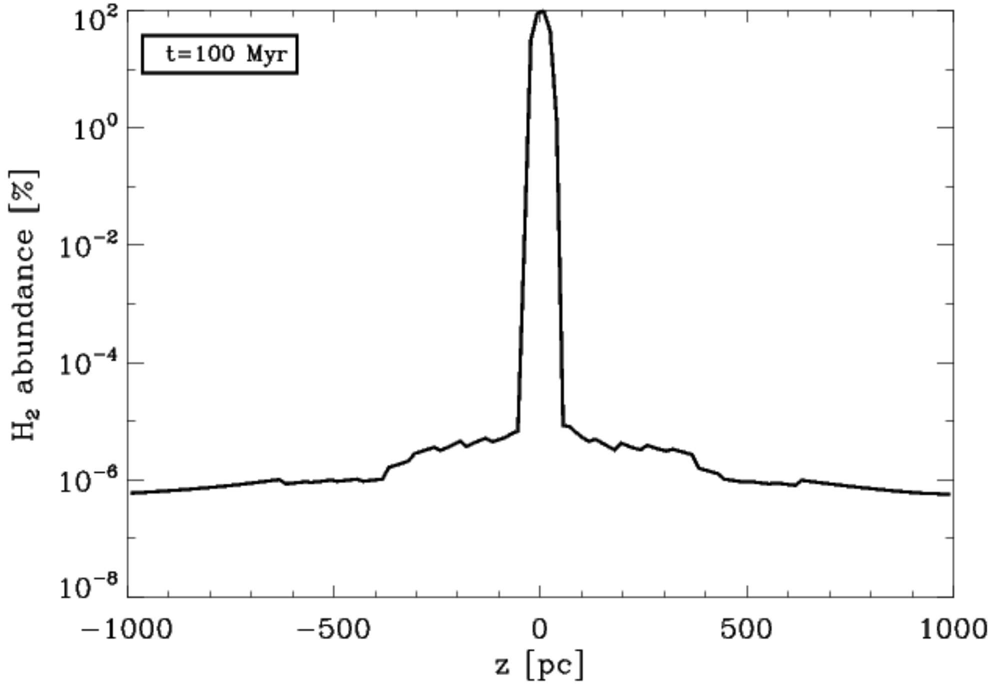
SILCC Run with random driving and Σ = 30 M_{sun}/pc^2: no clear distinction intro 3 phases

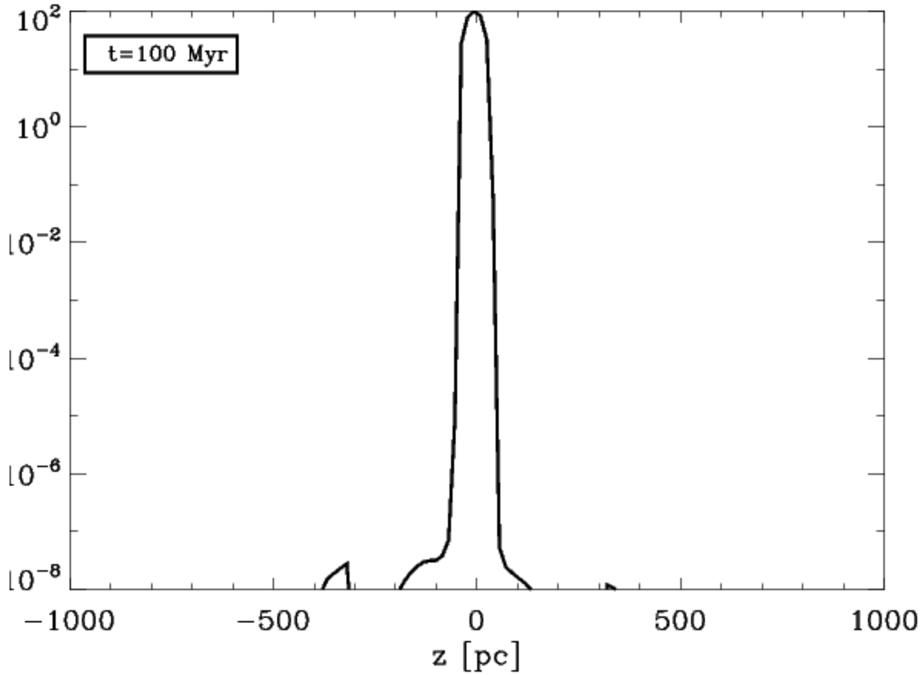
H_2 mass fraction for different surface densities



Random driving

Vertical H_2 profiles: SN peak vs. random driving





Peak driving

Random driving

Peak driving causes molecular outflows in H_2

This is not seen in CO => dark H_2 gas?

Conclusions

- **Understanding molecular cloud formation and feedback from massive stars is complex and requires simulating a lot of physics at high resolution.**

- **We developed a powerful computational tool by including major improvements to the FLASH code, e.g. we include self-shielding and molecule formation, self-gravity, etc.**

- **We find that:**
  - **Fractional mass in different temperature regimes is comparable for all Σ**
    => more cold, molecular gas in high Σ environments
  - **Same applies for the VFFs and Outflow rates**
    => mass loading seems to decrease for higher Σ
  - **No clear, persisting distinction into 3 different phases!**
  - **Outflow of molecular hydrogen (not CO!) from embedded (peak-driven) Supernovae**
    => dark molecular gas?