Irfu

Institut de recherche sur les lois fondamentales de l'Univers

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# MAGMIST
# From the magnetized ISM to the stars

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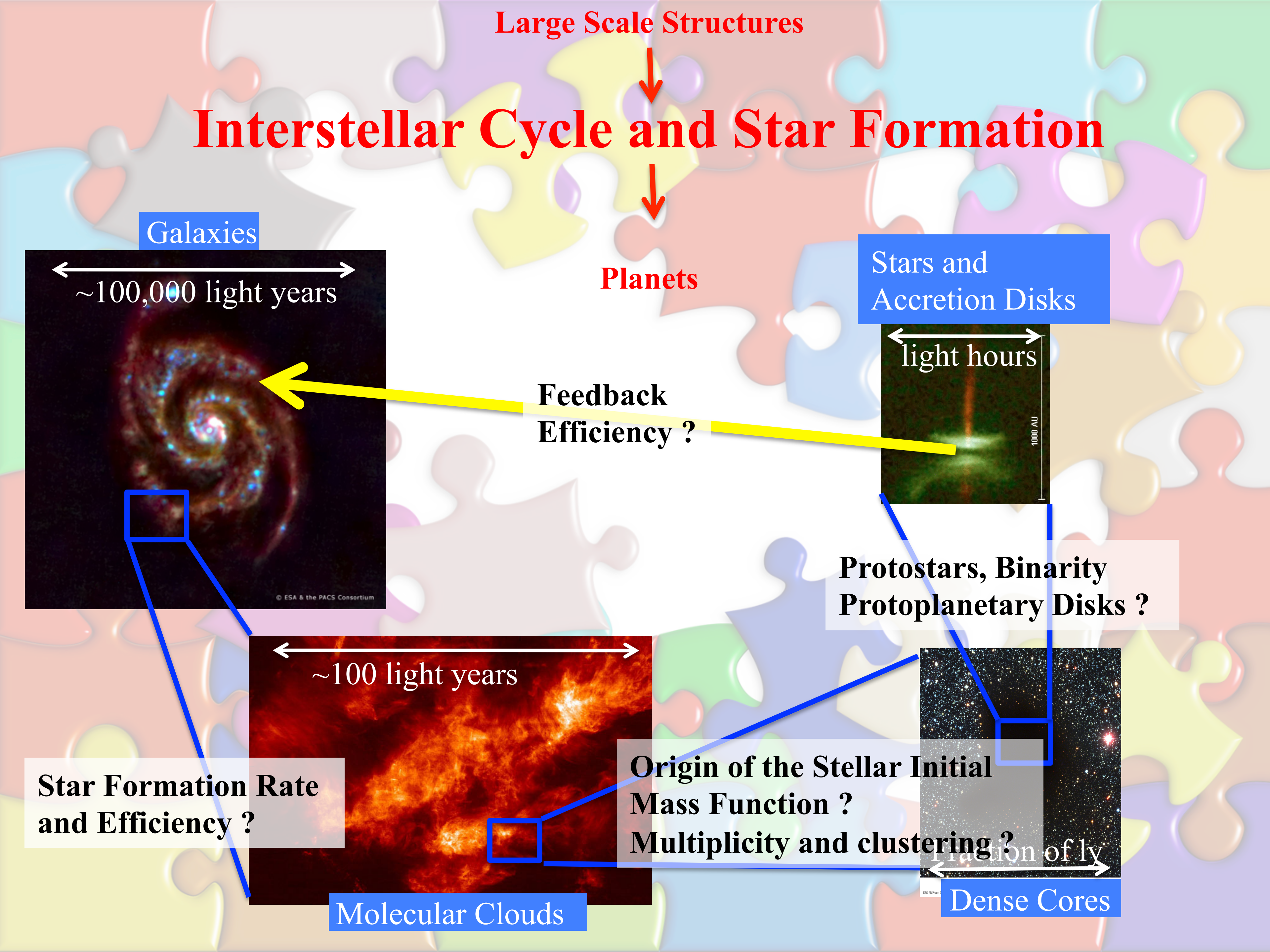

Large Scale Structures
Interstellar Cycle and Star Formation
Planets
Galaxies
~100,000 light years
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Stars and
Accretion Disks
light hours
1000 AU
Feedback
Efficiency ?
Protostars, Binarity
Protoplanetary Disks ?
~100 light years
Star Formation Rate
and Efficiency ?
Origin of the Stellar Initial
Mass Function ?
Multiplicity and clustering ?
Fraction of ly
Molecular Clouds
Dense Cores

## Feedback and the star formation efficiency

-Influence of supernova remnants on a molecular cloud
-Influence of ionising radiation
-global models and their uncertainties

## Zooming in: the FRIGG project

**Feedback and the star formation efficiency**

-Influence of supernova remnants on a molecular cloud

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**Zooming in: the FRIGG project**

# Total momentum injected by a supernova onto the ISM
# Uniform Medium
(e.g. Sedov 1959, Cioffi et al. 1988, Blondin et al. 1998)

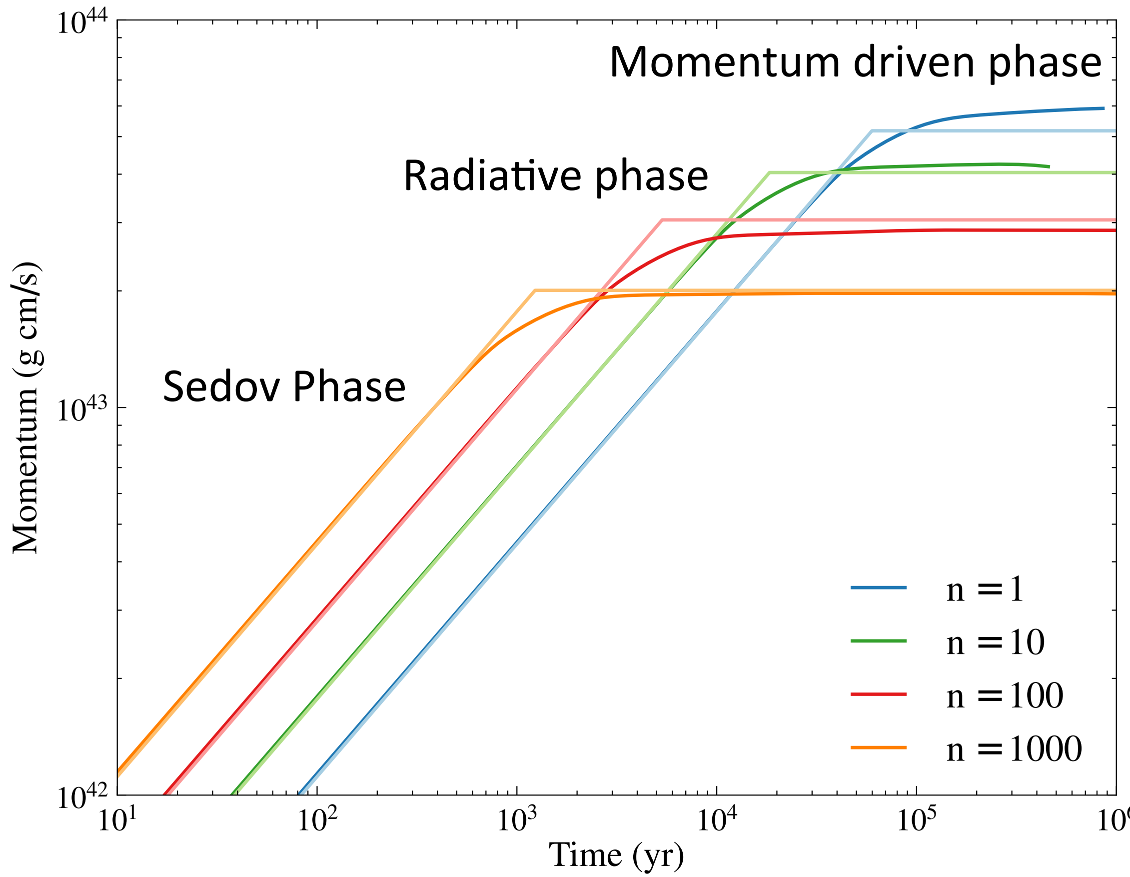
$10^{51}$ erg

1/50 yr in the MW

First phase:
adiabatic expansion
Sedov phase: $r_i(t) = 1.77 n^{1/5} E_{51}^{4/5} t_4^{3/5}$

Second phase:
radiative lost in the shell

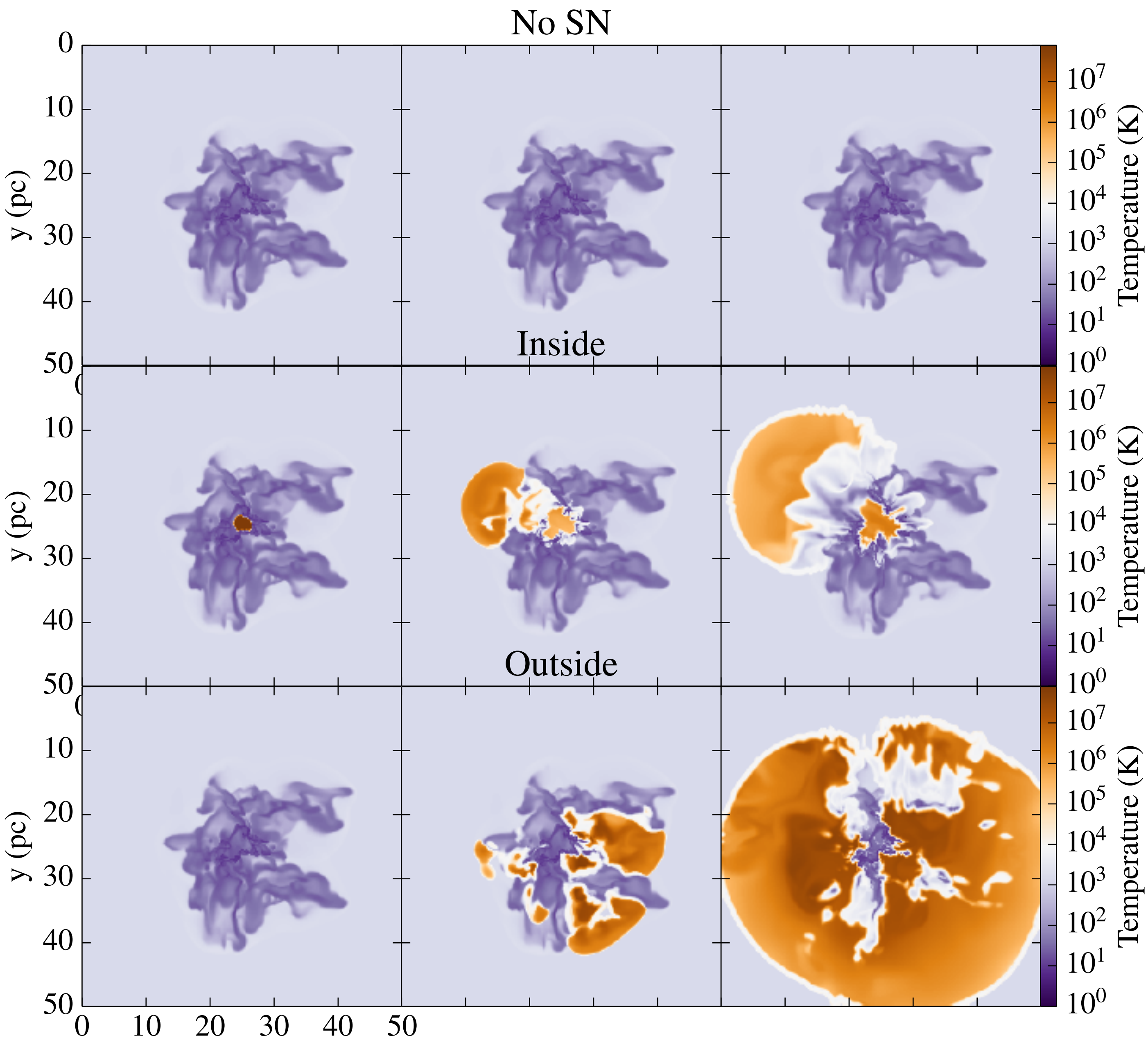
Third phase:
Momentum driven phase




Iffrig & H 2015

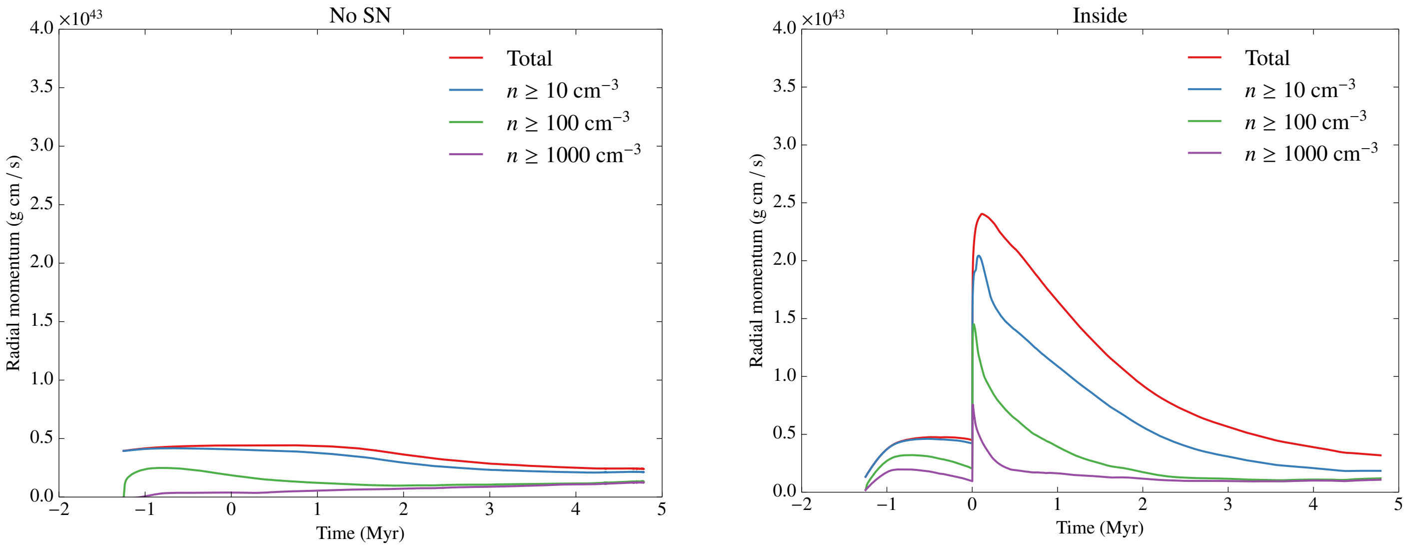
# Mutual interaction between supernovae and molecular cloud

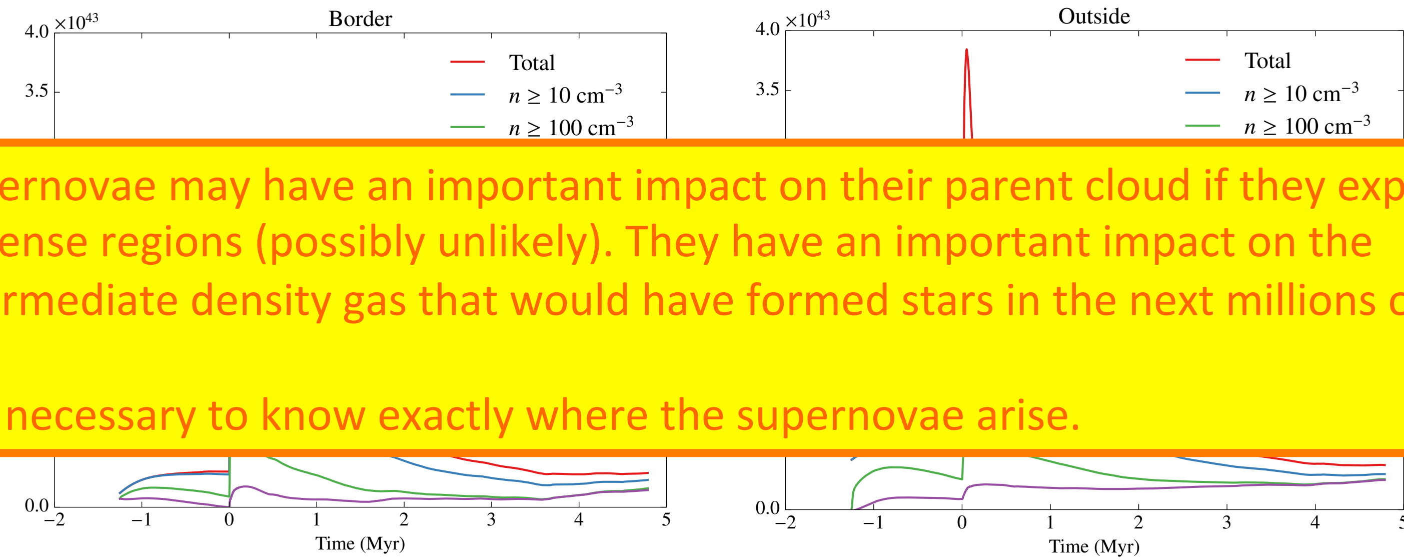
A turbulent cloud of $10^4$ Ms – 2-phase ISM- MHD+hydro-self-gravity




Iffrig & H 2015

# Momentum injected in gas above various density thresholds as a function of time




Supernovae may have an important impact on their parent cloud if they explode in dense regions (possibly unlikely). They have an important impact on the intermediate density gas that would have formed stars in the next millions of years.

It is necessary to know exactly where the supernovae arise.

Iffrig & H 2015

# Effect of ionising radiation onto the ISM

(e.g. Spitzer 1978, Whitworth 1979, Matzner 2002)

First phase: the radiation ionises a bubble up to the Strongrem radius

Temperature of the ionised gas ~8000 K

Second phase: due to the large overpressure it enters a dynamical phase and expands

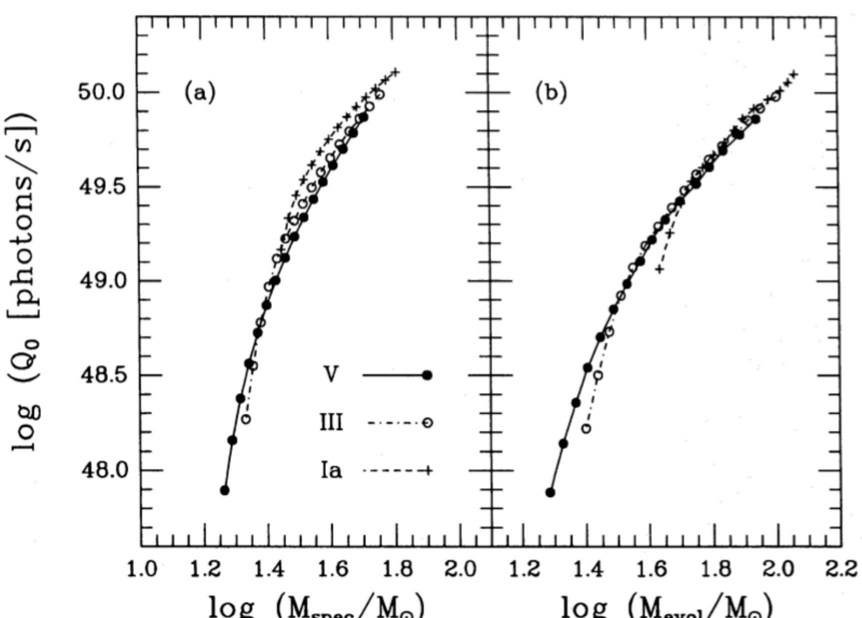
Strongren radius: $$r_{rst} = \left( \frac{3}{4\pi} \frac{S_*}{n_i n_e \alpha_B} \right)^{1/3}$$

$S_*$ : number of ionising per seconde

$n_i, n_e$ : ion, electron density

First phase: $$r_i(t) = r_{rst}\left(1 - \exp(-n_i \alpha_B t)\right)$$

Second phase: $$r_i(t) = r_{rst}\left(1 + \frac{7}{4}\frac{C_i t}{r_{rst}}\right)^{4/7}$$

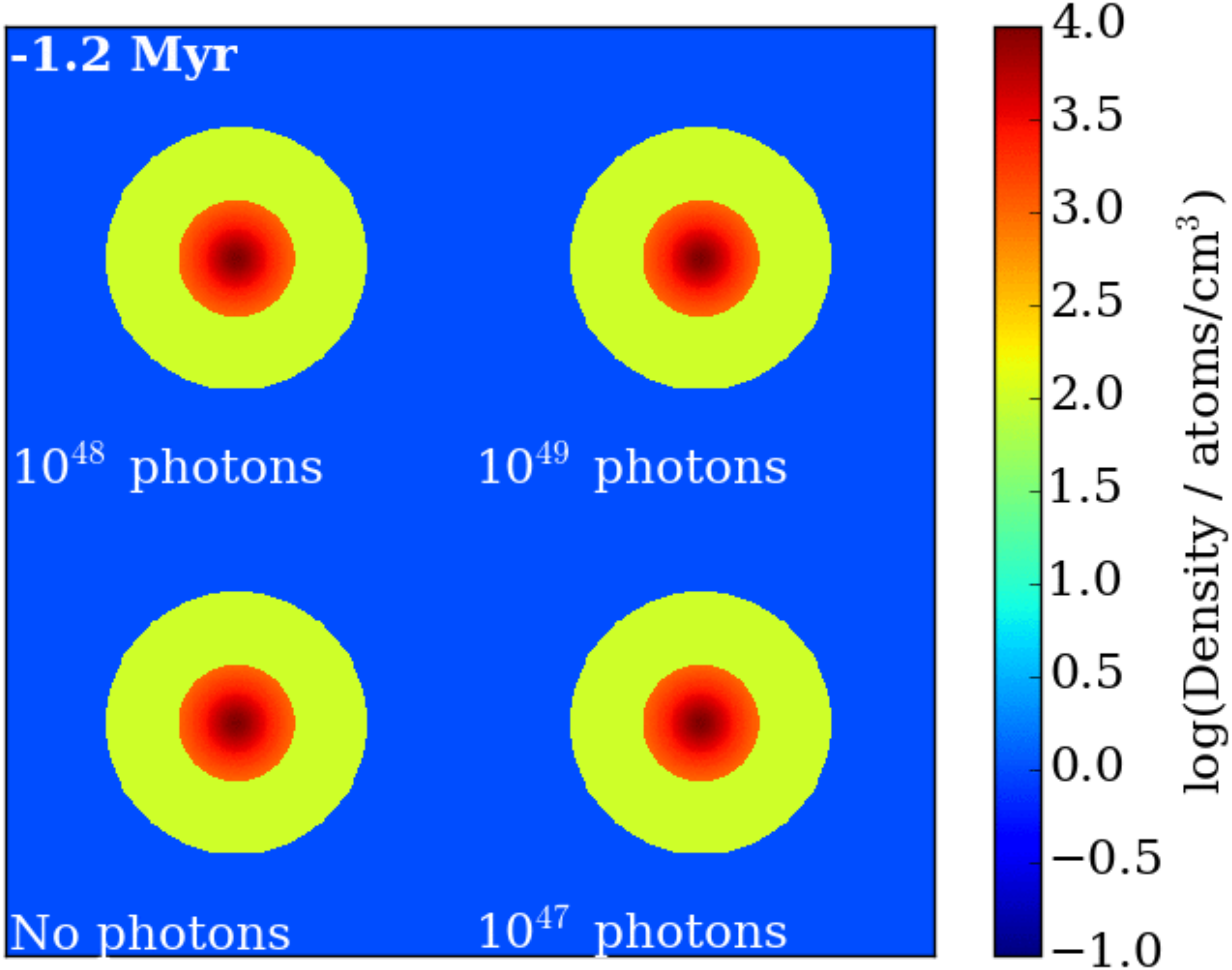



Vacca et al. 1996

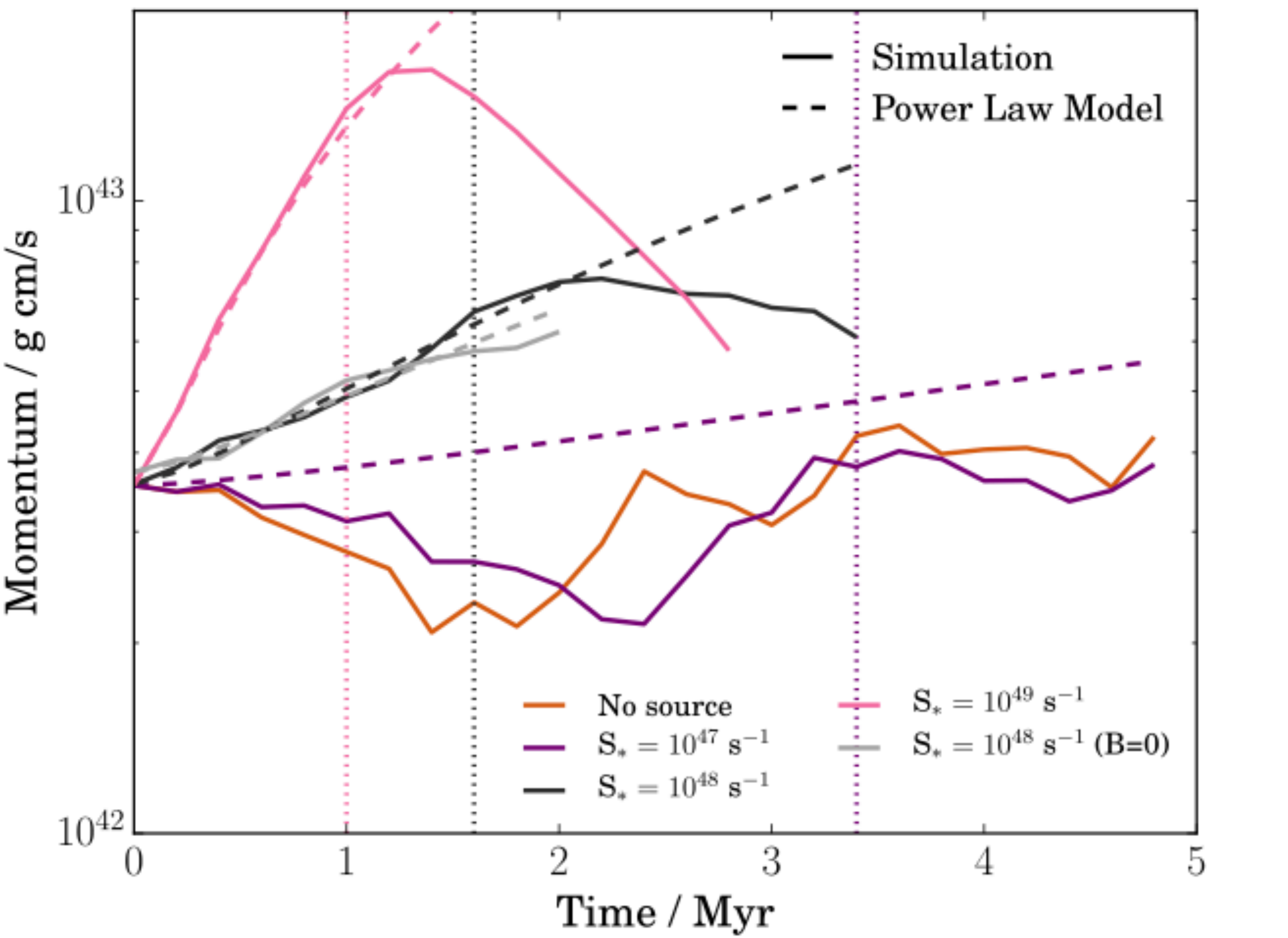
# Investigating the impact of HII regions onto molecular clouds

(Walch+2012, Arthur+2012, Dale et al. 2012-2014)

A $10^4$ $M_s$ cloud evolves durng 1ff time. A central source is then introduced in the middle.




Geen et al. 2015



Simulation
Power Law Model
Momentum / g cm/s
$10^{43}$
$10^{42}$
0
1
2
3
4
5
Time / Myr
No source
$S_* = 10^{47}$ s$^{-1}$
$S_* = 10^{48}$ s$^{-1}$
$S_* = 10^{49}$ s$^{-1}$
$S_* = 10^{48}$ s$^{-1}$ (B=0)


Geen+2015

## Feedback and the star formation efficiency

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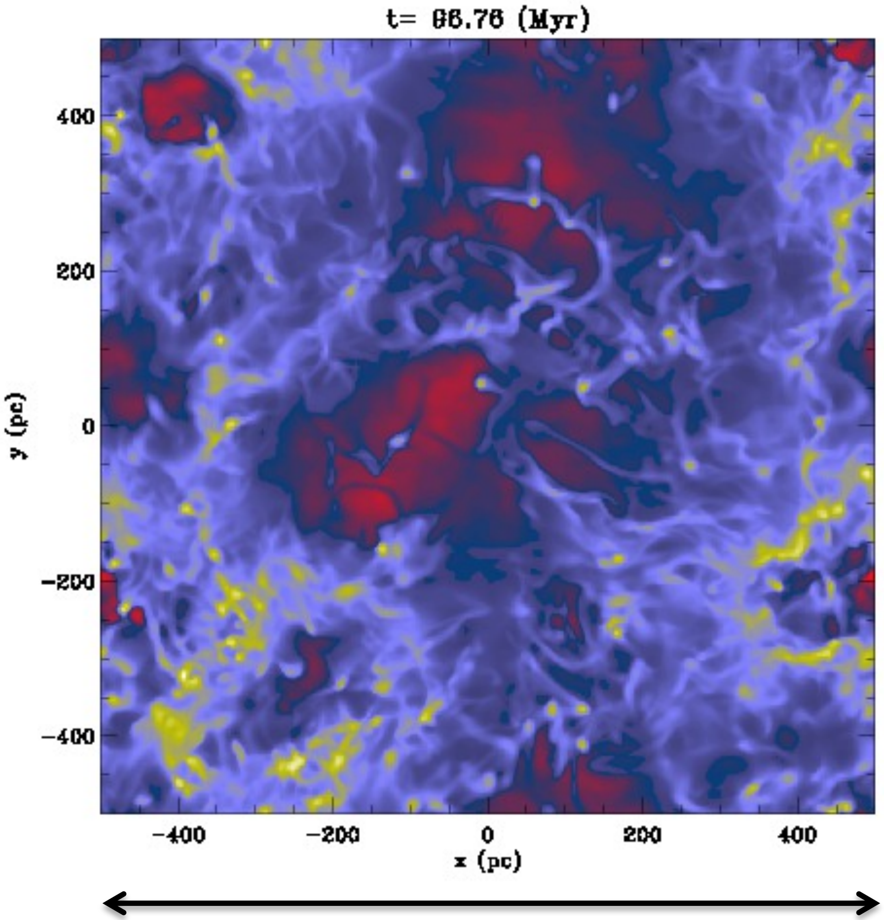
-Influence of ionising radiation

-global models and their uncertainties

**Zooming in: the FRIGG project**

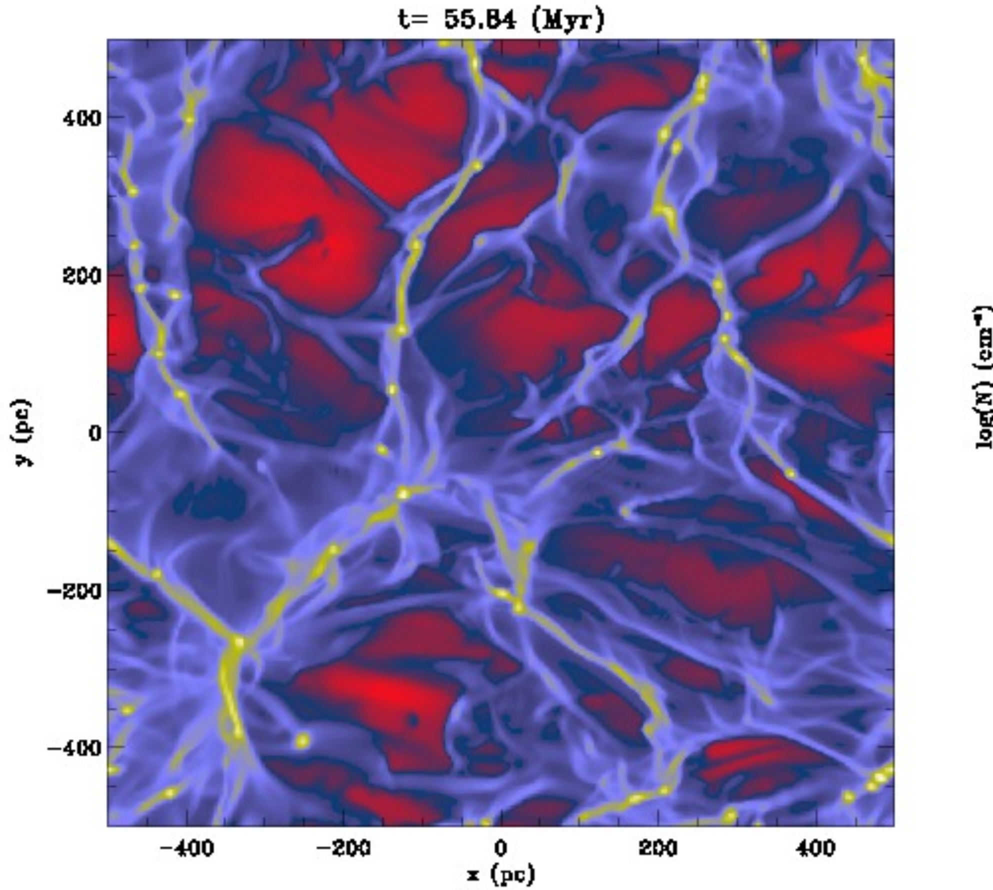
# Need for feedback to prevent catastrophic collapse and star formation

Supernovae (ref)




1 kpc

No supernova



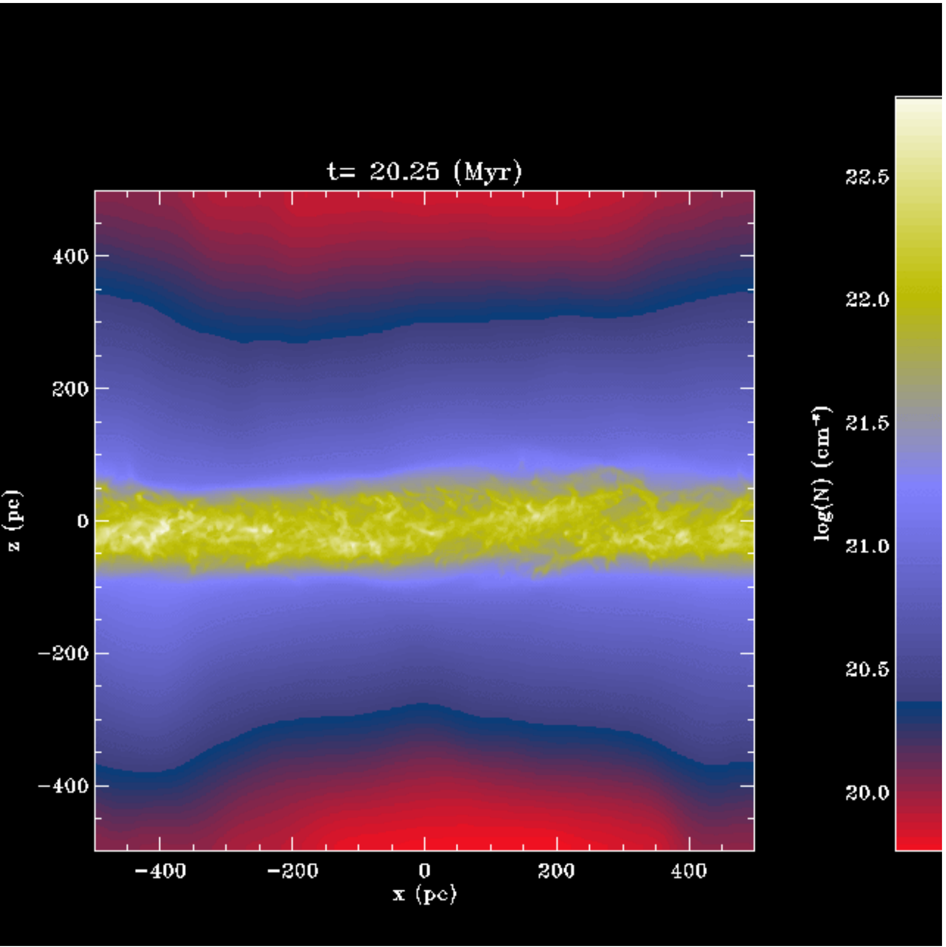

H&Iffrig 2014

# Supernovae regulated ISM (from few 100 pc to 1kpc)

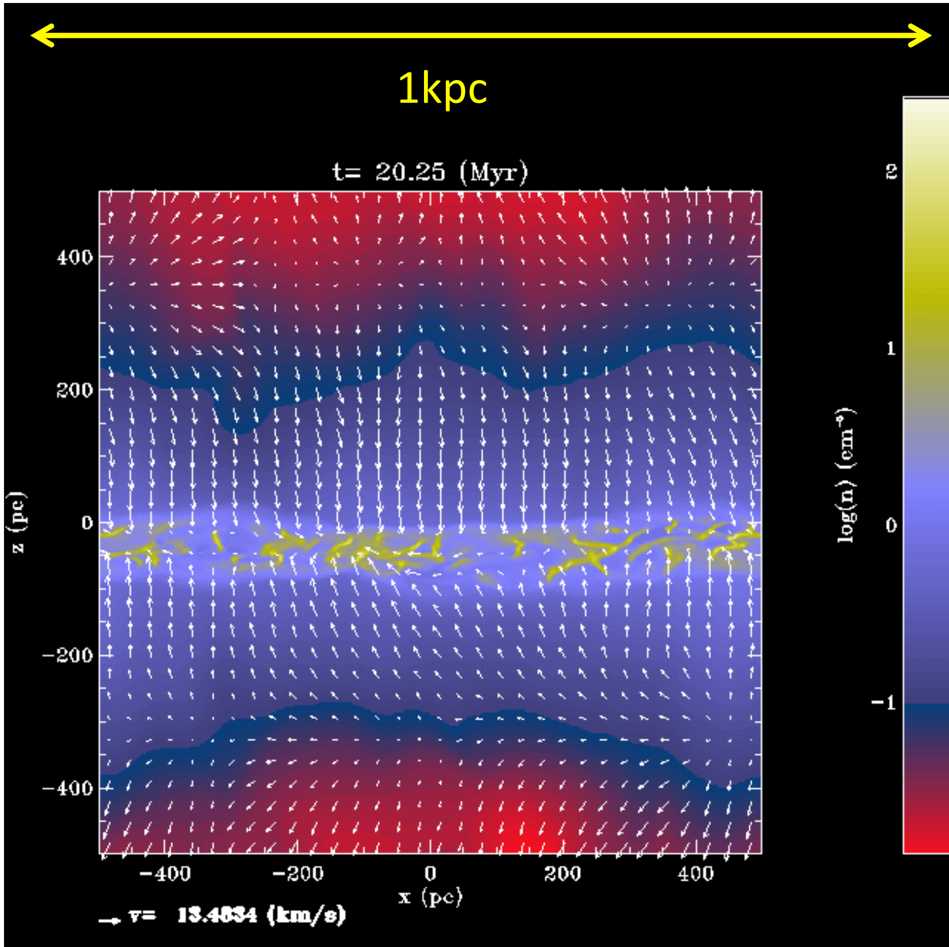
(Slyz et al. 2005, de Avillez & Breitschwerdt 2005,2007, Joung & MacLow 2006, Hill et al. 2012, Kim et al. 2011, Hennebelle & Iffrig 2014, Gato et al. 2014)

External gravitational field (due to stars and DM), multi-phase ISM, self-gravity, magnetic field
Supernovae explosions (different schemes)

Column density

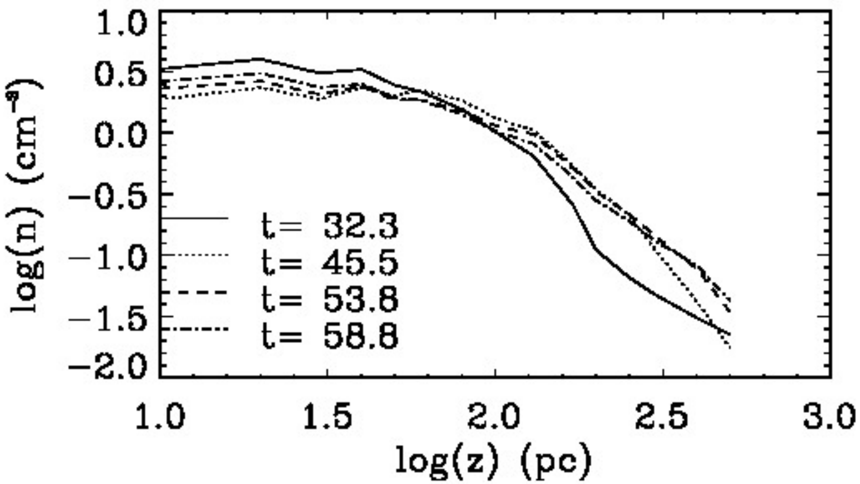



density

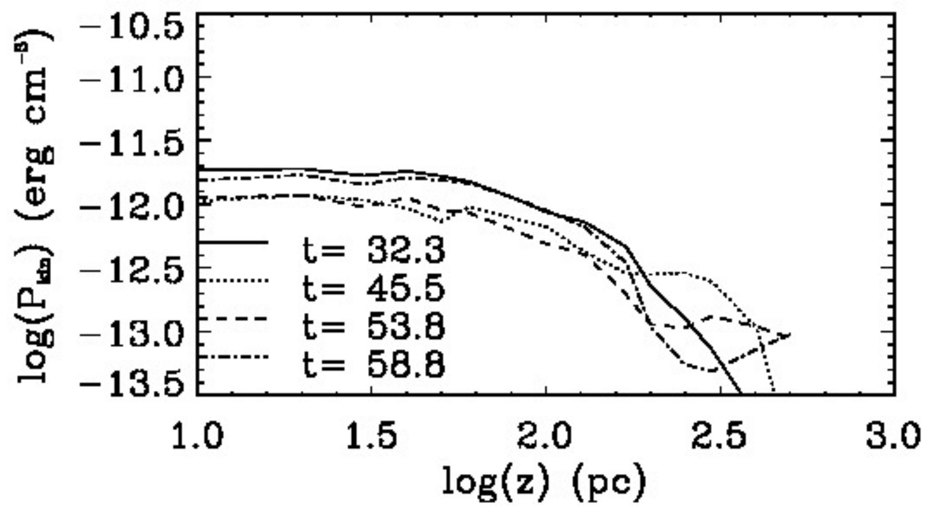


# Density profile of the galactic disk and pressure (turbulent, magnetic, thermal)

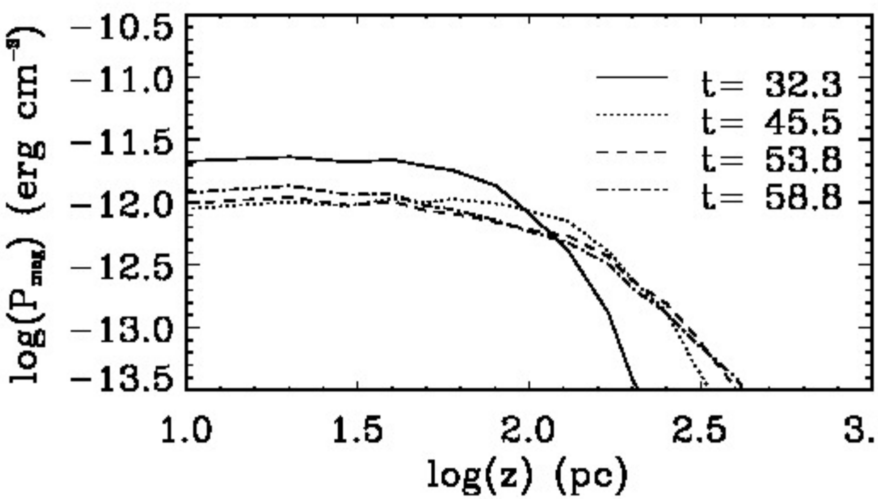
Density vs z



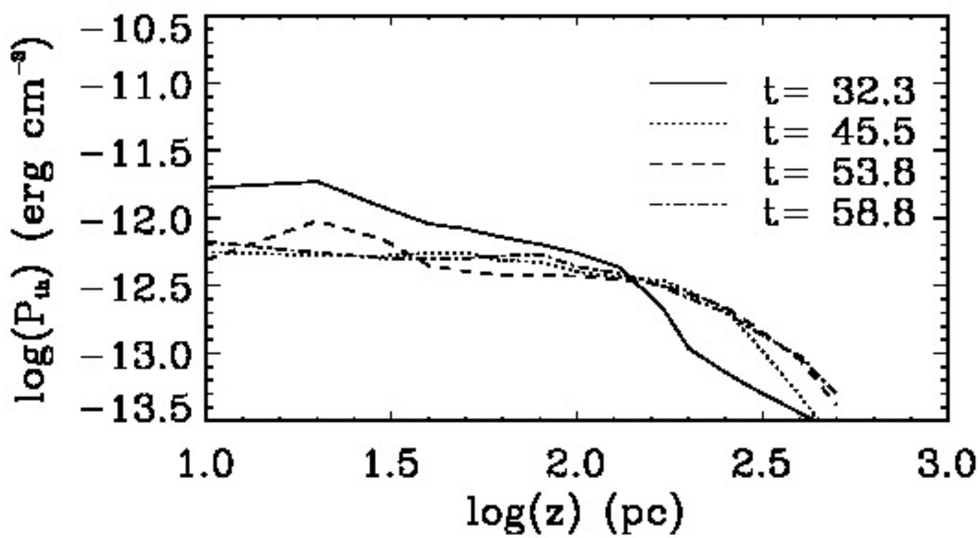

Kinetic pressure vs z



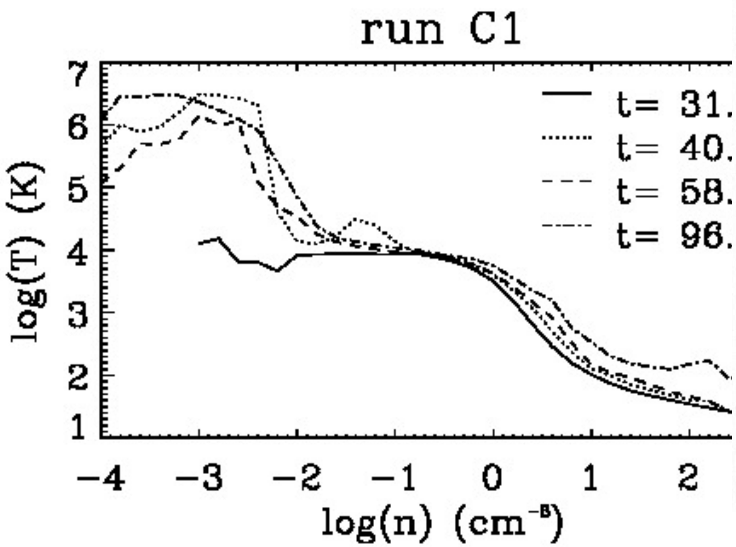

Magnetic pressure vs z

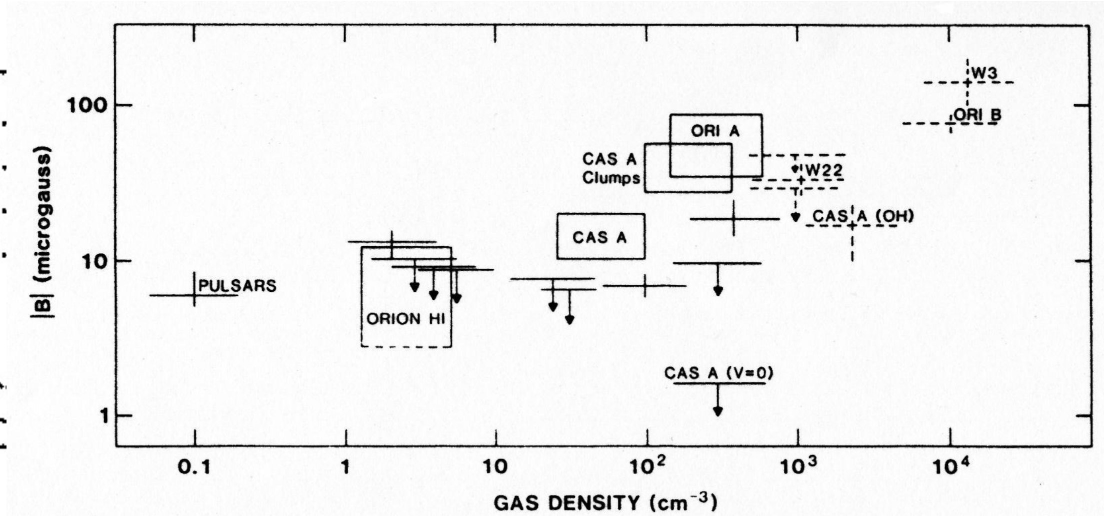



Thermal pressure vs z

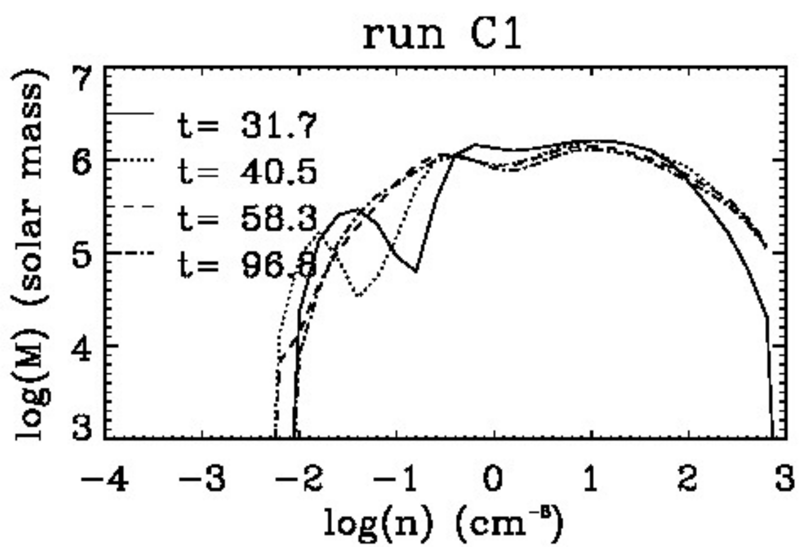


# Mean temperature, densities, magnetic field distributions

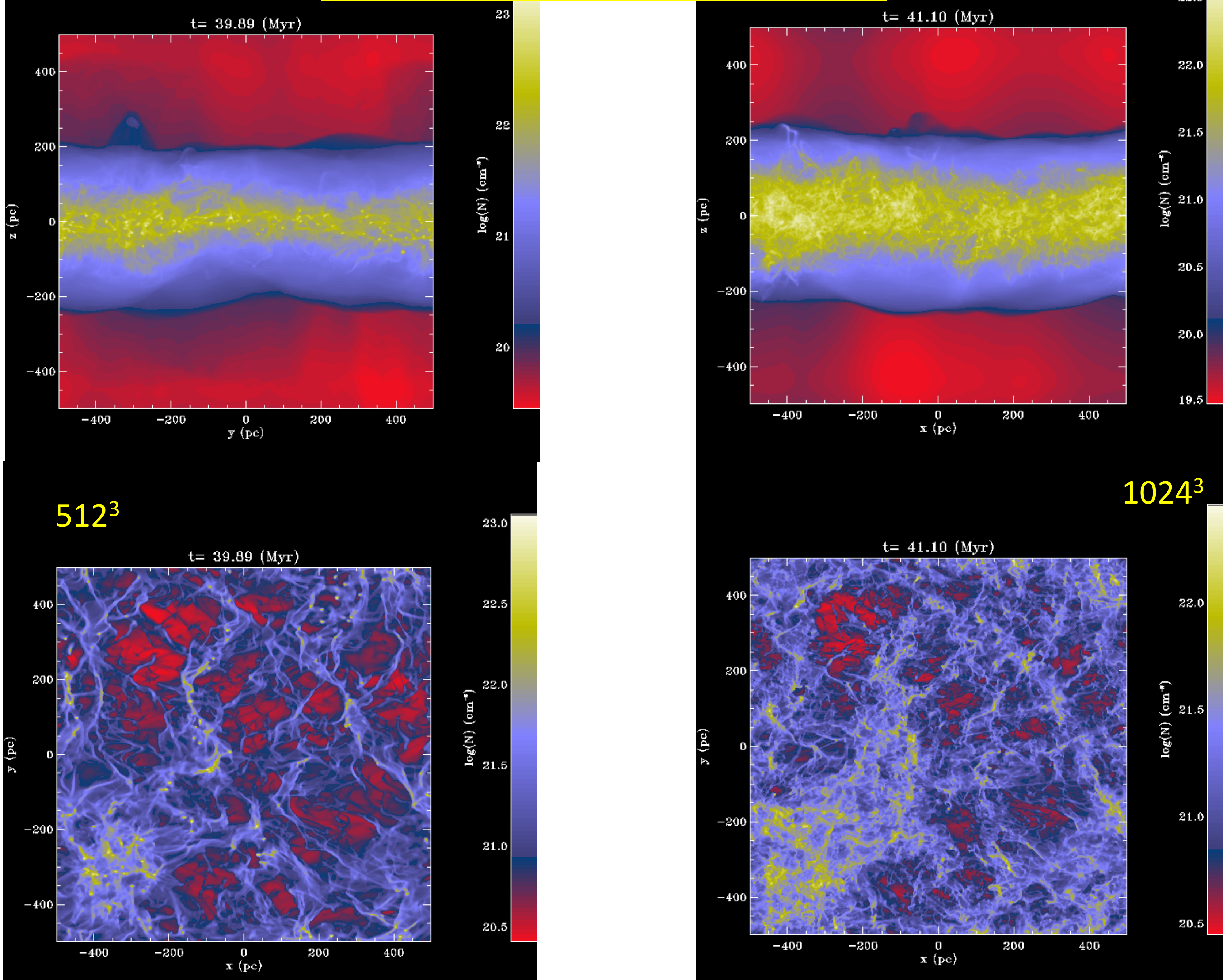



Troland & Heiles 1986

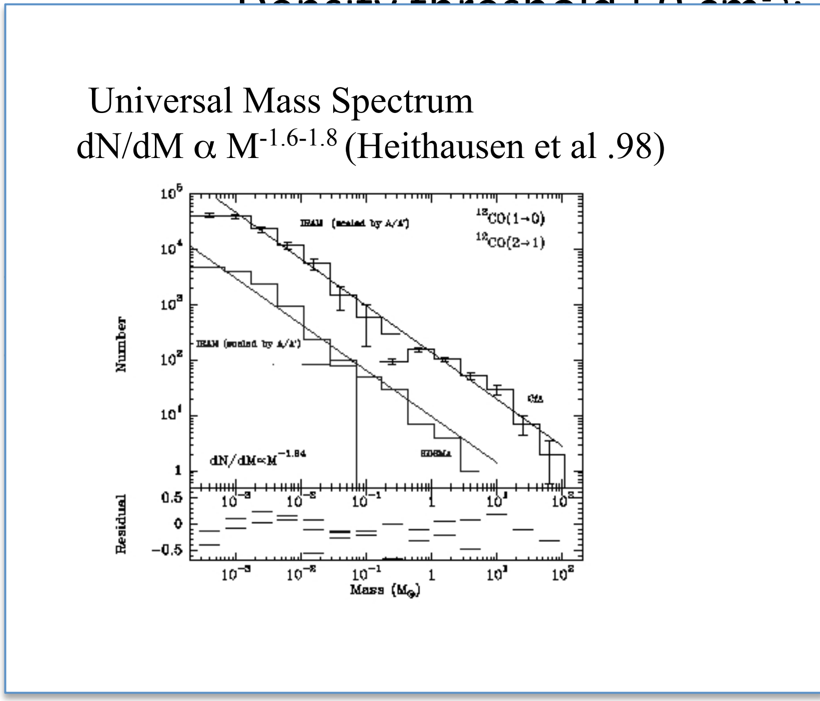


# High resolution simulations

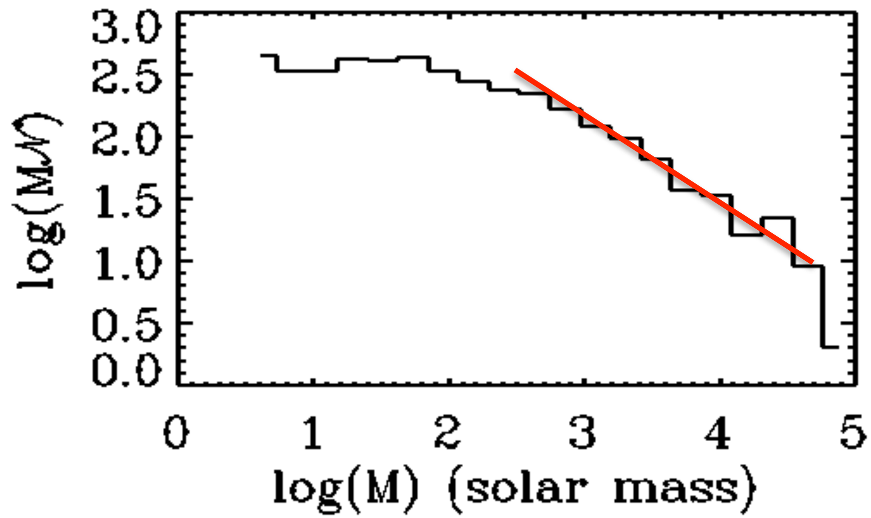


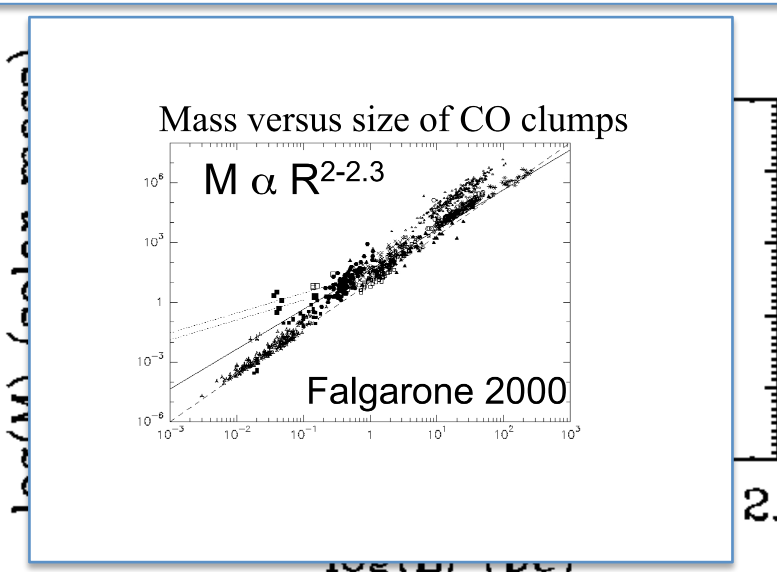
# Clump properties

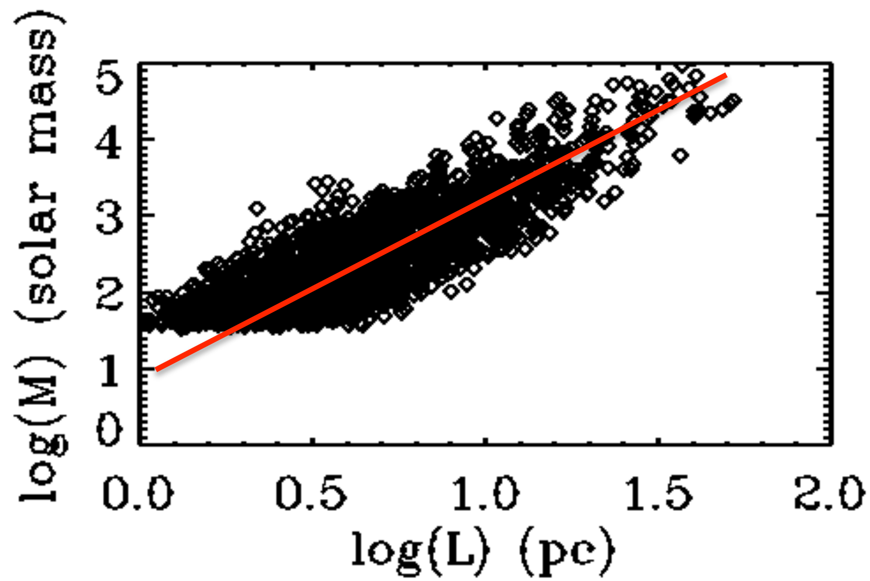
Density threshold 50 $cm^{-3}$: mass spectrum, mass-size




1024³

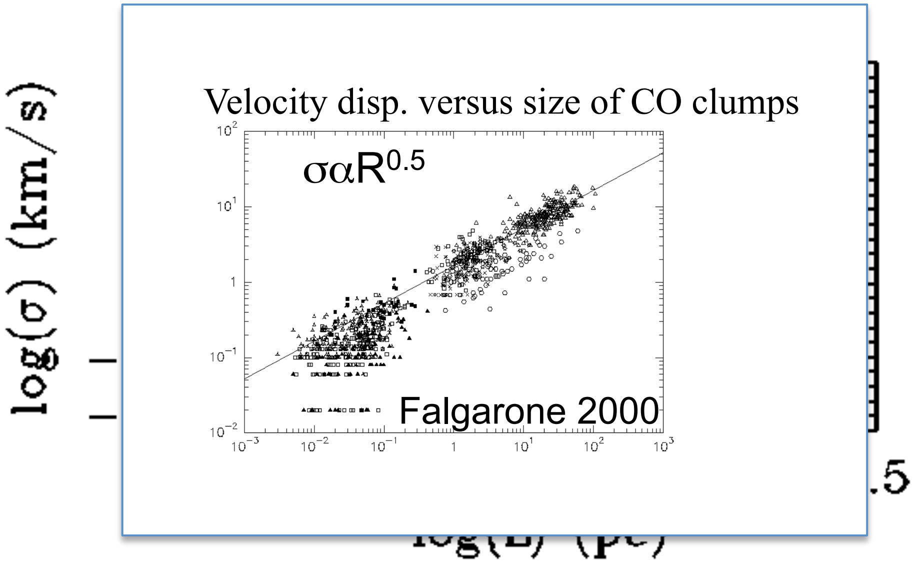


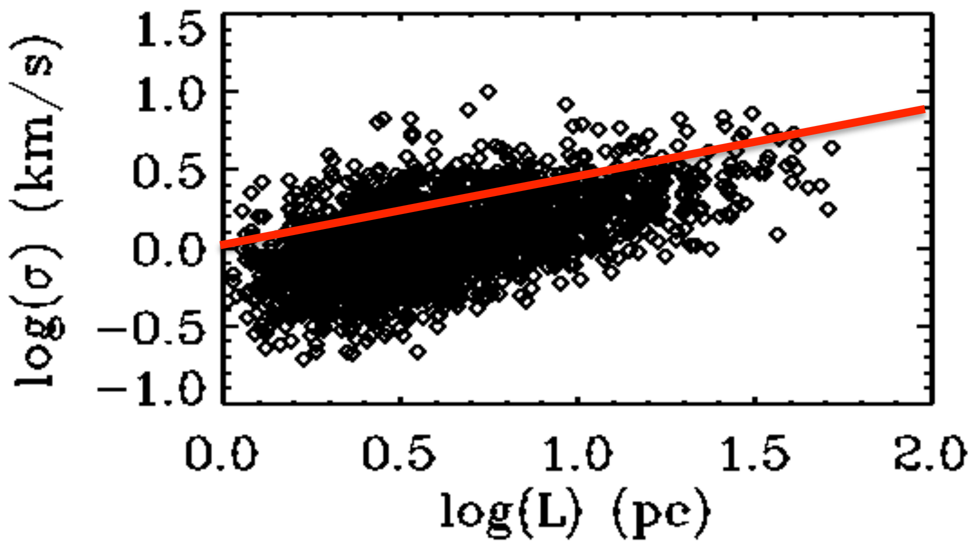
# Clump properties

Density threshold 50 cm$^{-3}$: mass spectrum, mass-size




Larson relations

Enough energy ?



# The issue of Injection of supernovae in galactic scale simulations

thermal energy and/or momentum are damped in a sphere of 12pc or radii

**Different distributions:**

-galactic rate is imposed
    -no correlation at all with the gas
    -correlation with the density peaks

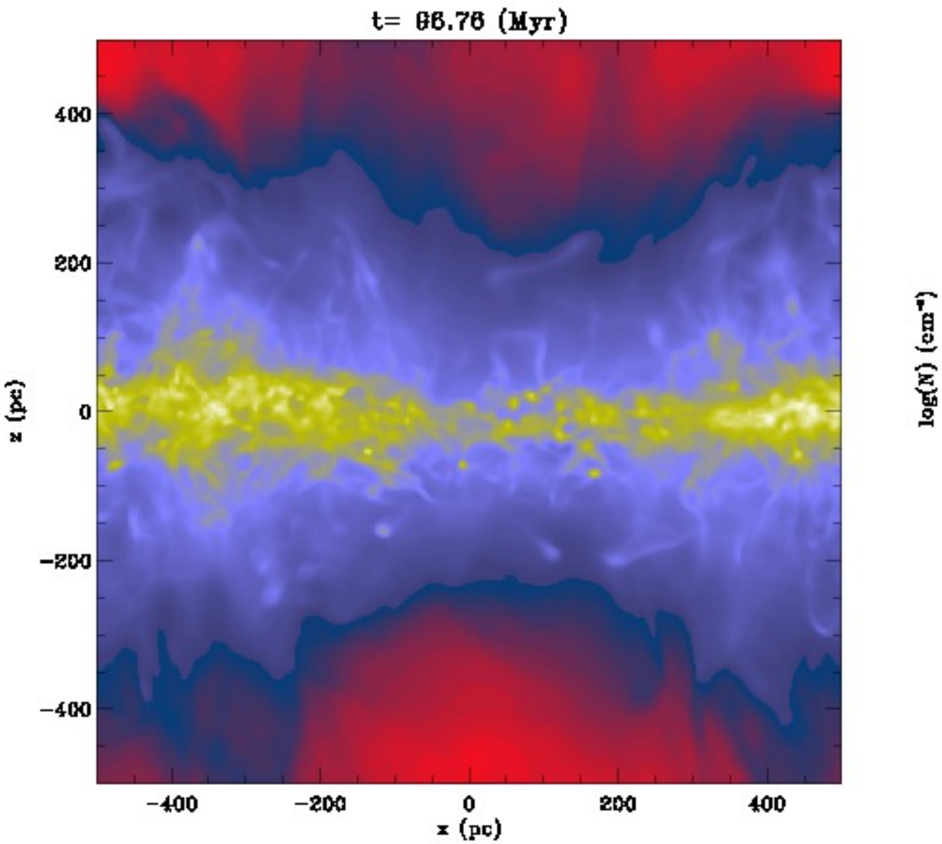
-each time a sink particle accretes 120 Ms of gas, a supernova explodes
    -supernovae are distributed randomly within a sphere of 10 pc around the sink (ref)
    -supernovae are distributed randomly within a shell  between 10 and 20 pc (shell)

H & Iffrig 2014

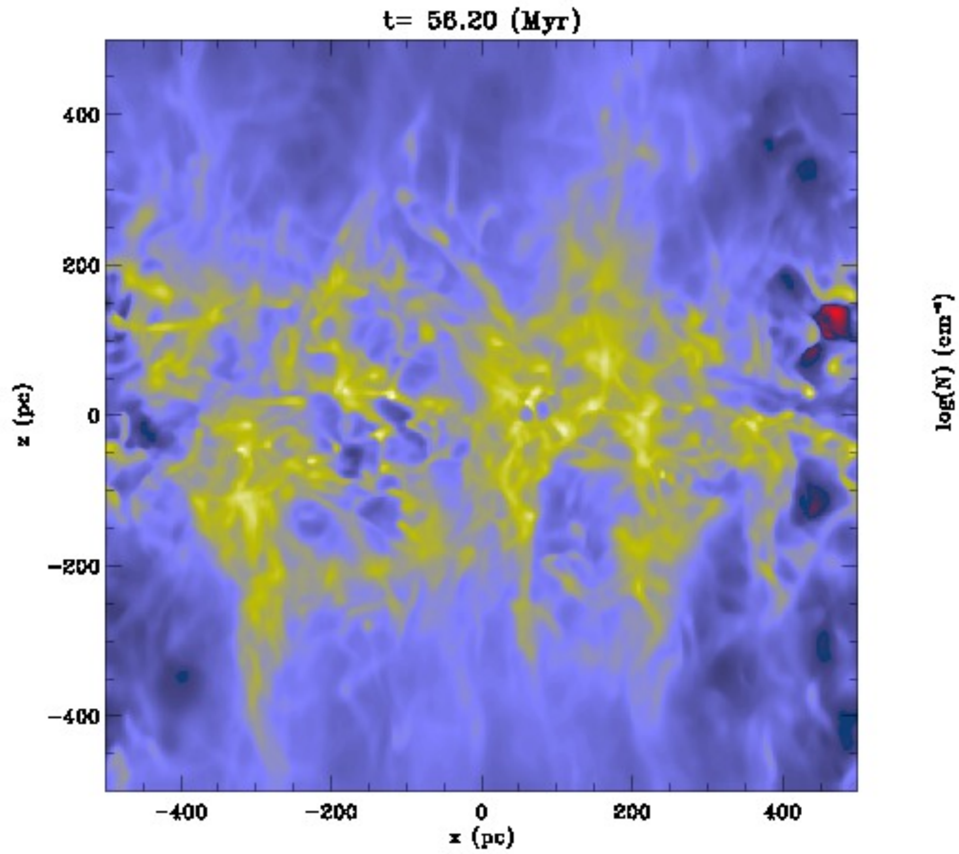
**Different answers depending on how exactly are the supernovae injected**

(see also Gatto et al. 2014)

Supernovae (sphere of 16 pc around the sink)



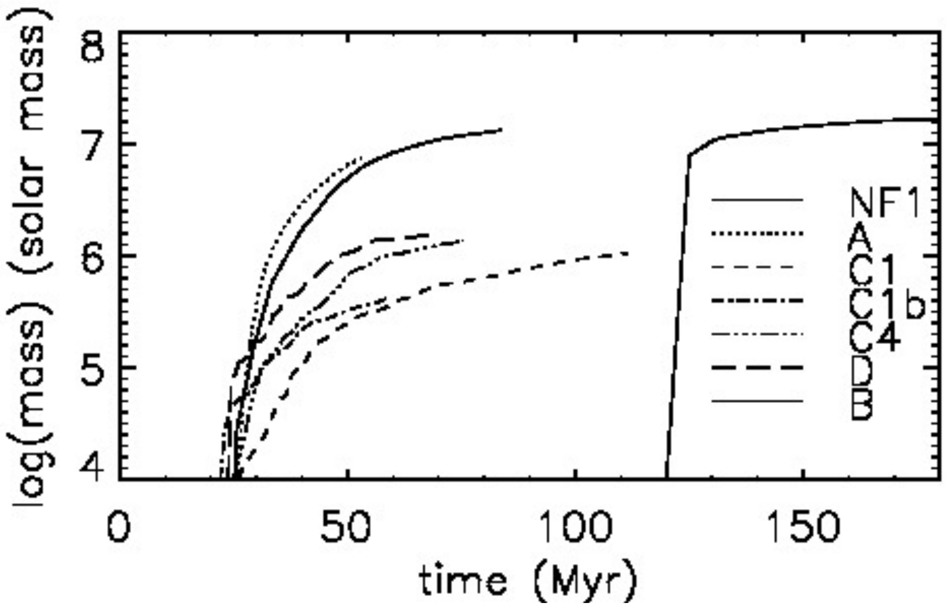

Supernovae (shell of 16 pc around the sink)



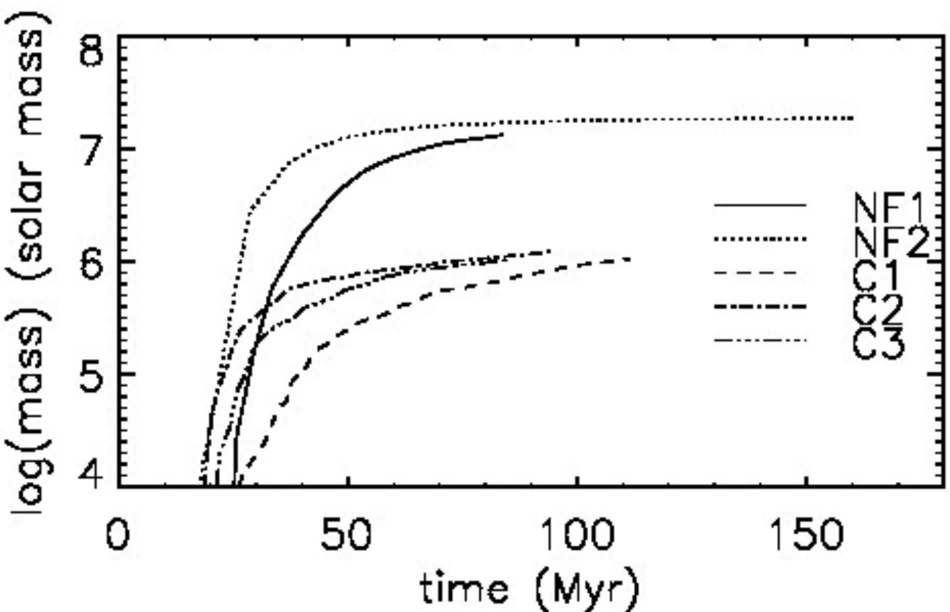

H & Iffrig 2014

# Star formation rate: very sensitive to the supernovae scheme

SFR for
various supernovae
schemes




SFR for
various
magnetisation




H & Iffrig 2014

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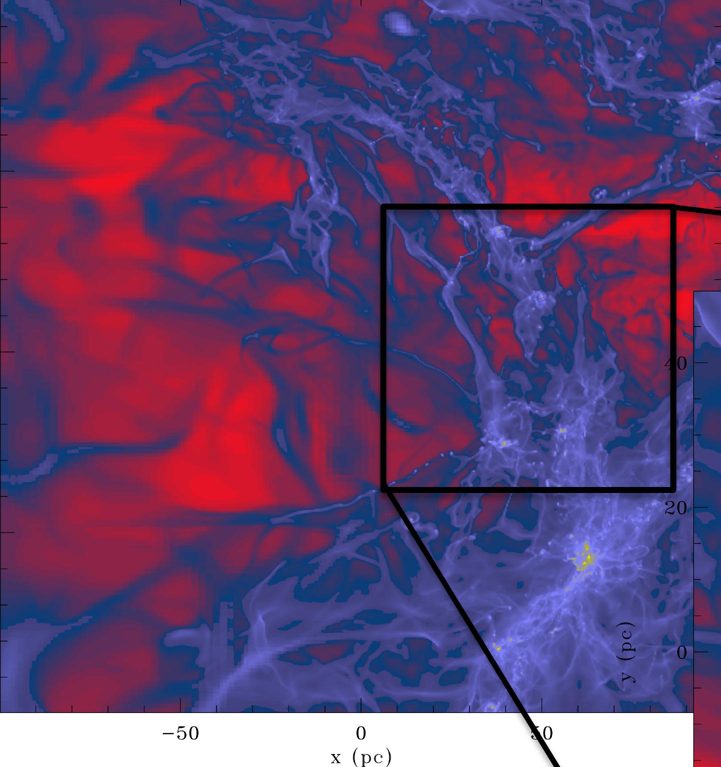
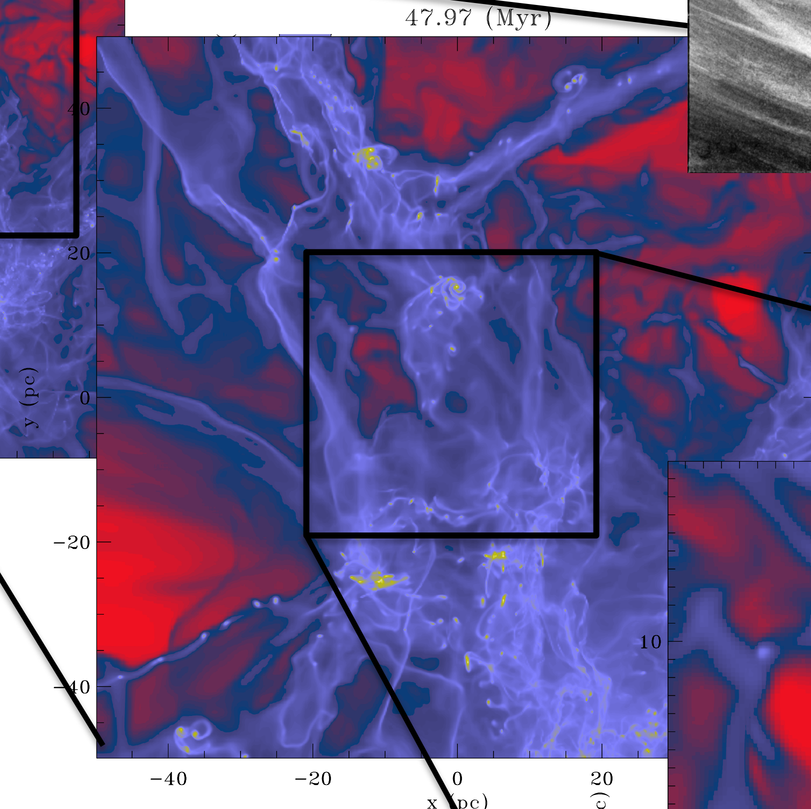
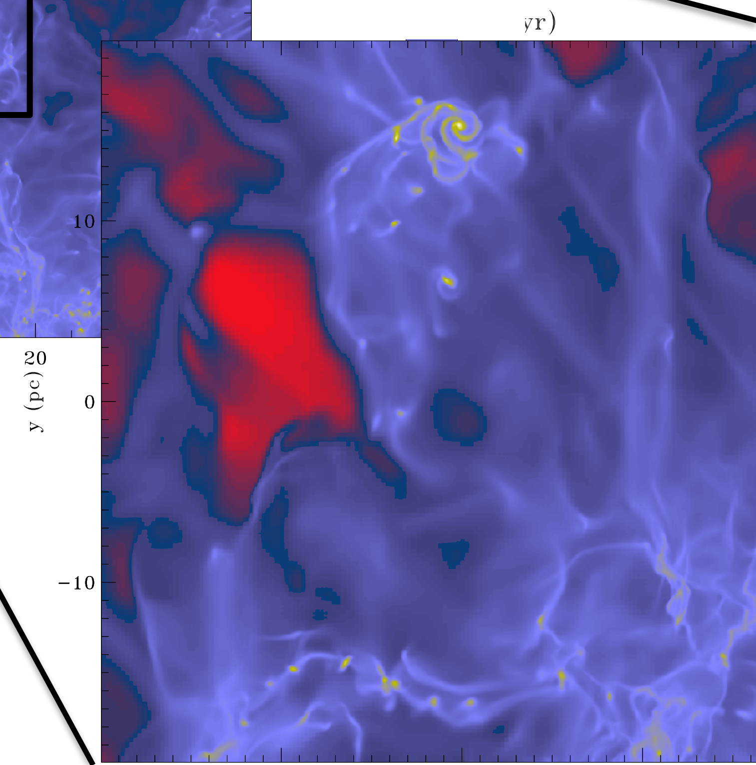
**Zooming in: the FRIGG project**

# FRIGG




*Frigg spinning the clouds*

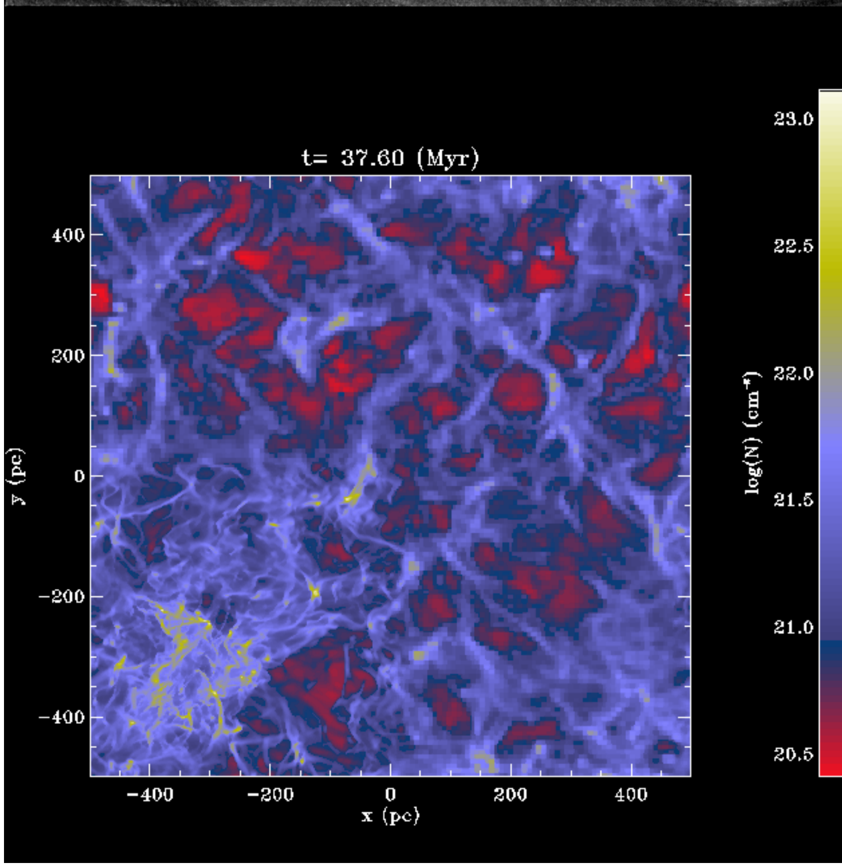
**FRIGG:**
FRom InterGalactic scale to Gravitationally bound cores
A PRACE proposal (15 Millions cpu hours)

512^3 to start
Supernovae forcing:
-correlated to density peaks (no sink)
-prescribed SN rate
-momentum forcing

Zoom:
From level 9-11 : uniform refinement of 200*200*100 pc area
Level 12-14 : uniform refinement for n>100cc
Level 15-18: 10 points per Jeans length

De-refine the region outside the zoom

Stop feedback when zoom start

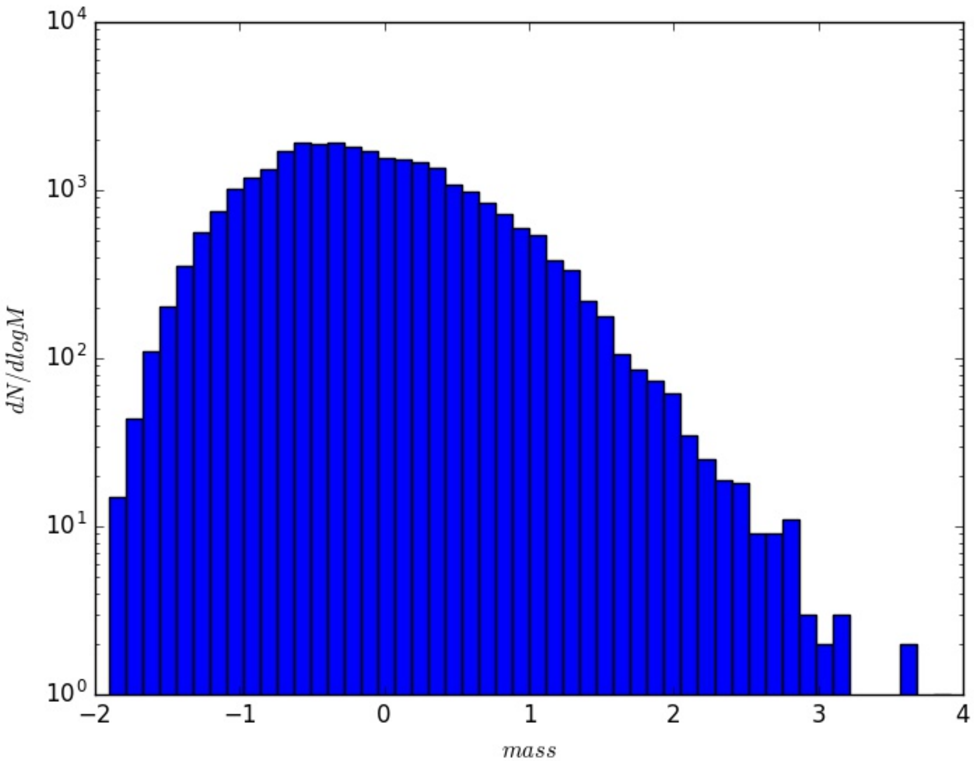


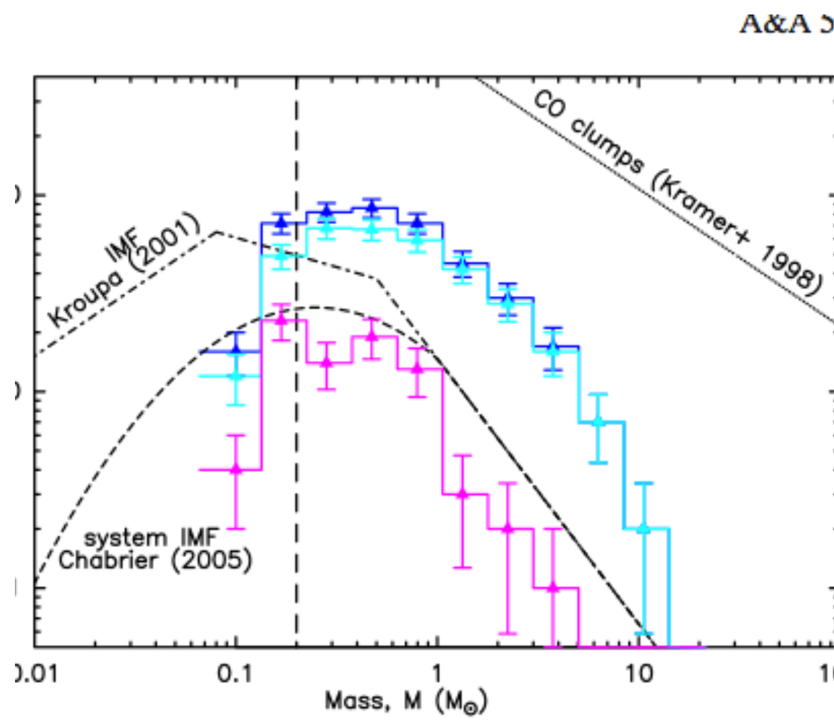
**Numerical simulation of a star forming molecular clouds**

Magneto-hydrodynamics, gravity , star formation

The core mass function (preliminary) extracted from the FRIGG simulation using the "HOP" algorithm

The core mass function from the Gould belt survey with Herschel (Konyves et al. 2015)



# Conclusions

Understanding star formation and the *details* of the ISM is unavoidable

Molecular clouds are likely multi-phase, accreting objects. Statistical properties are reasonably reproduced

The origin of the IMF likely rooted in the physics of molecular clouds. Combination of turbulence and gravity appear to be reasonably successful

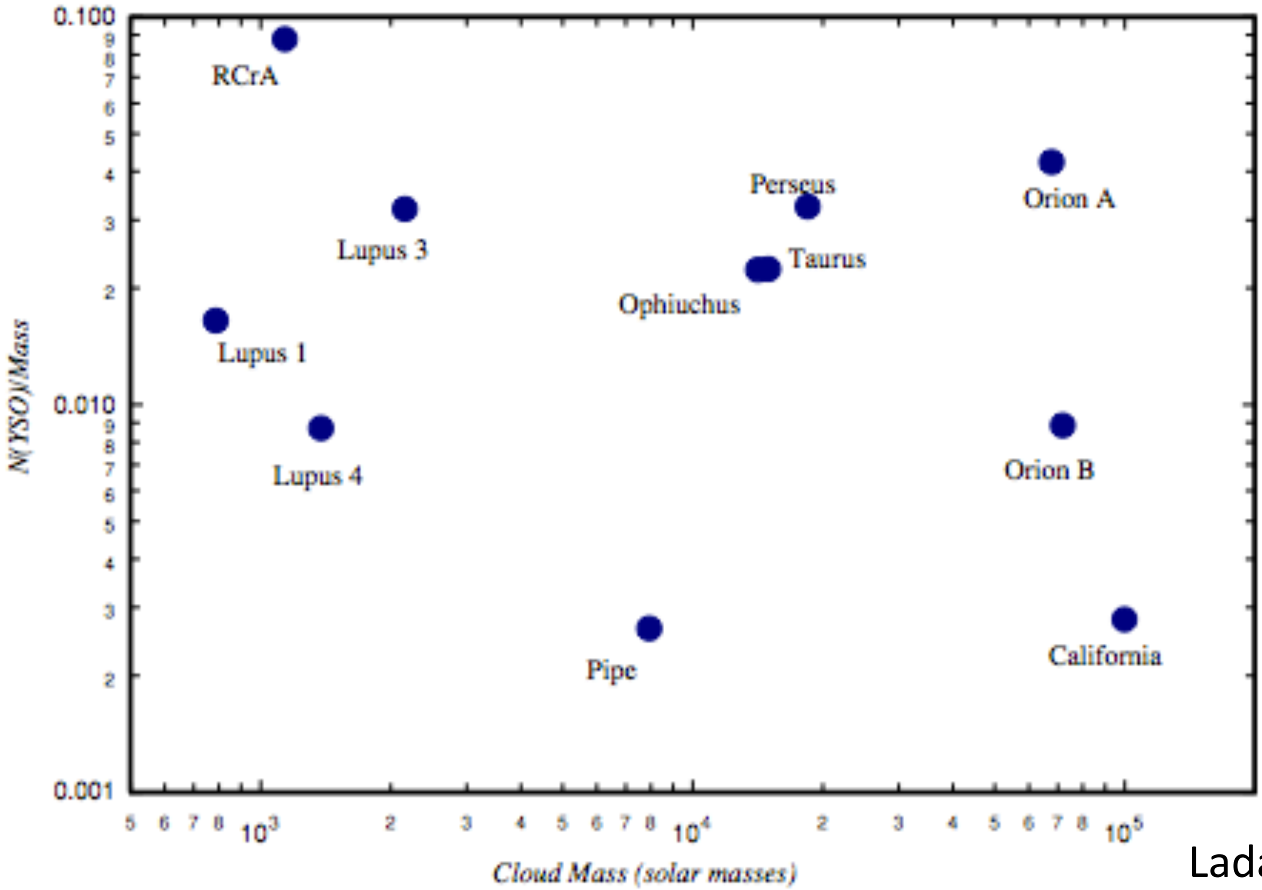
Feedback seems unavoidable both from observation and theory

Many uncertainties regarding its exact influence and how it should be implemented
$\Rightarrow$ hugely difficult: multi-scale and complex stellar physics

Particularly true for large scale supernovae driving which crucially depends on their location

## Star formation efficiency in nearby molecular clouds

Mass of stars vs Mass of gas



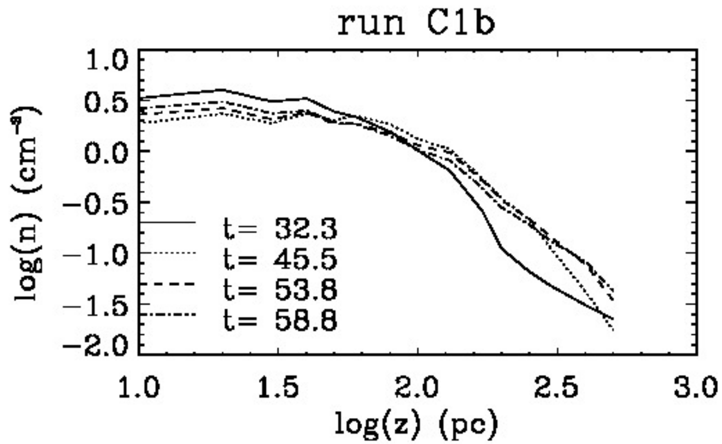

Lada et al. 2010

Star formation efficiency seems always below 10%

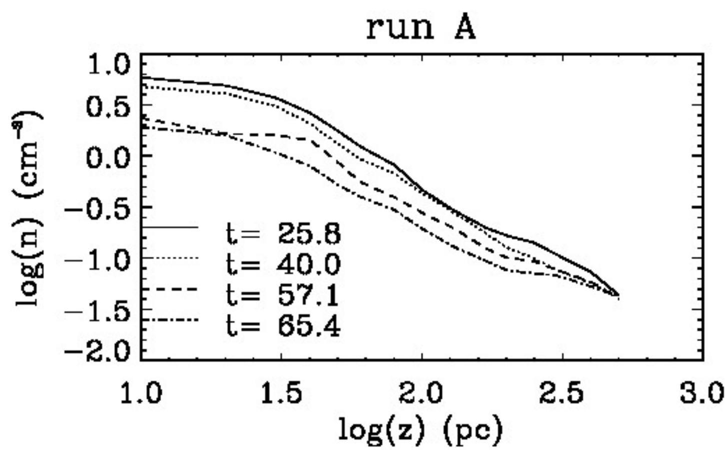
=> Is stellar feedback destroying the clouds ?

## The results depend a lot on the way supernovae are being introduced….

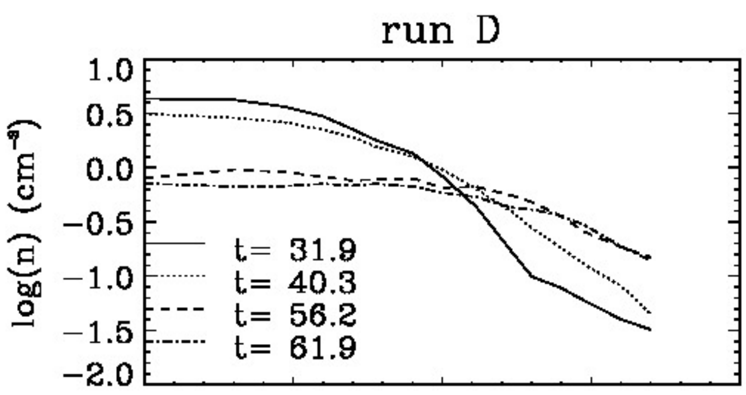
Supernovae (ref)




Supernovae
fix rated
no spatial correlation




Supernovae (shell)




H & Iffrig 2014