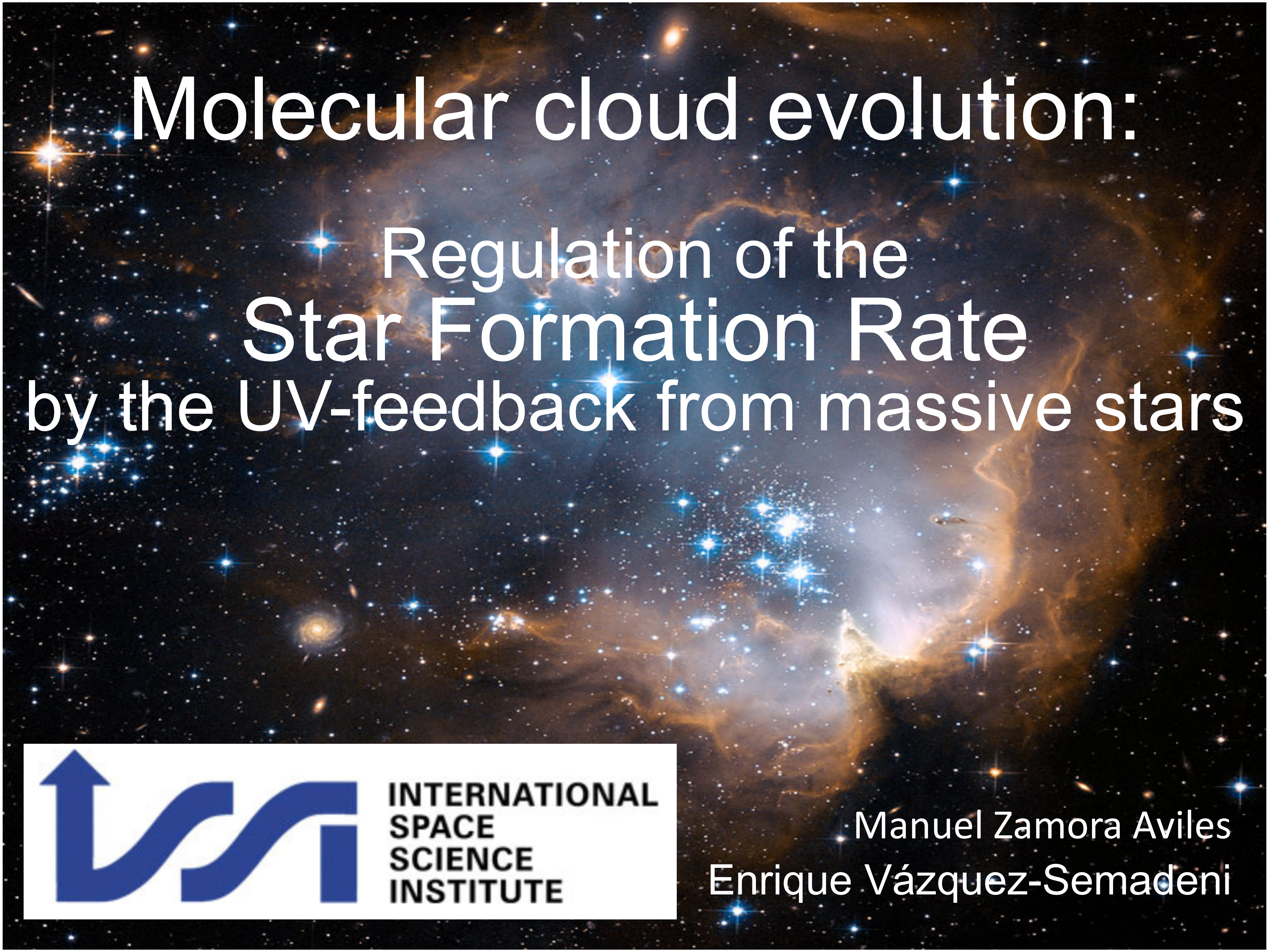
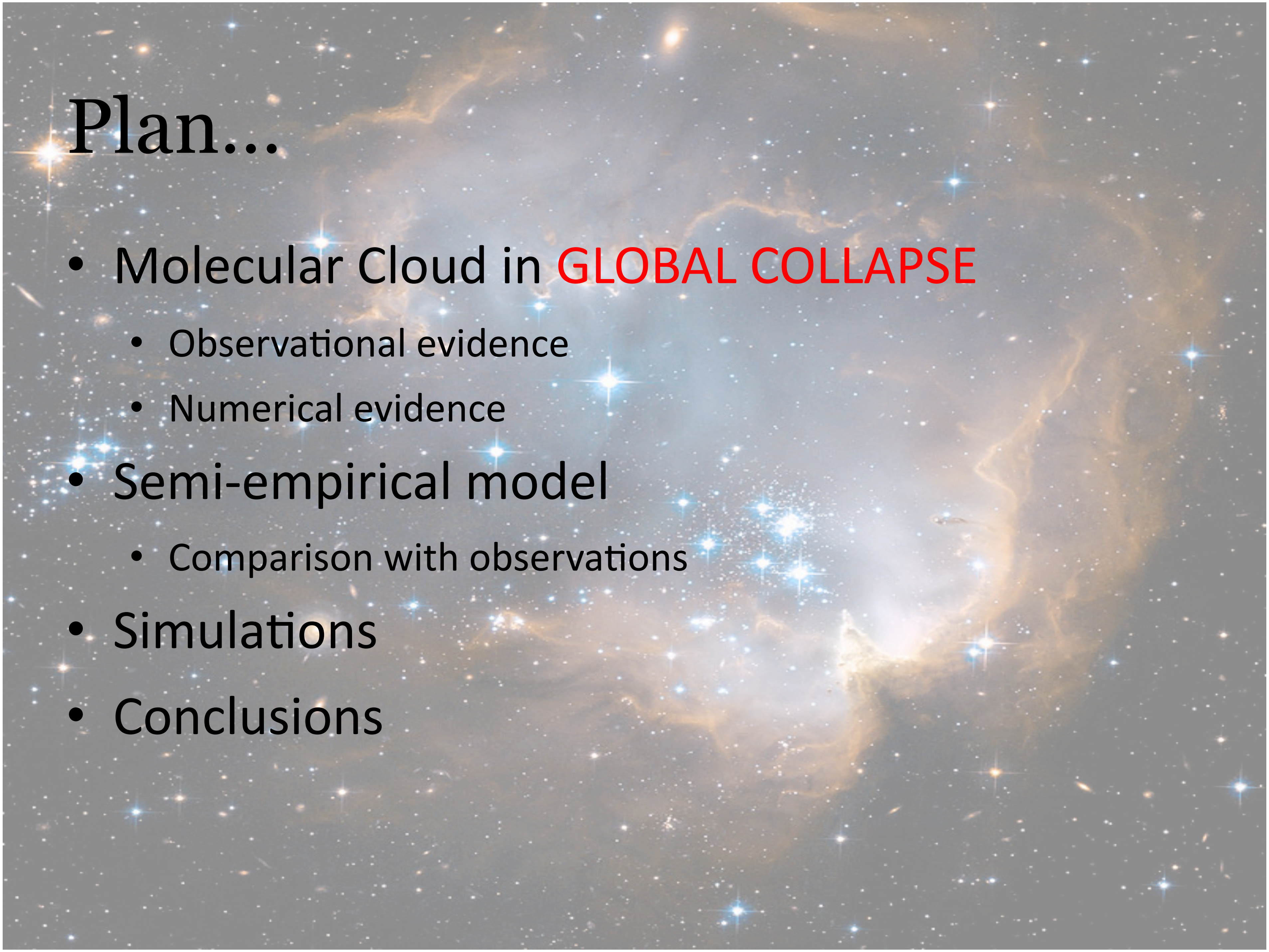


Molecular cloud evolution:

Regulation of the Star Formation Rate by the UV-feedback from massive stars

INTERNATIONAL
SPACE
SCIENCE
INSTITUTE

Manuel Zamora Aviles
Enrique Vázquez-Semadeni



Plan…

- Molecular Cloud in GLOBAL COLLAPSE
  - Observational evidence
  - Numerical evidence
- Semi-empirical model
  - Comparison with observations
- Simulations
- Conclusions

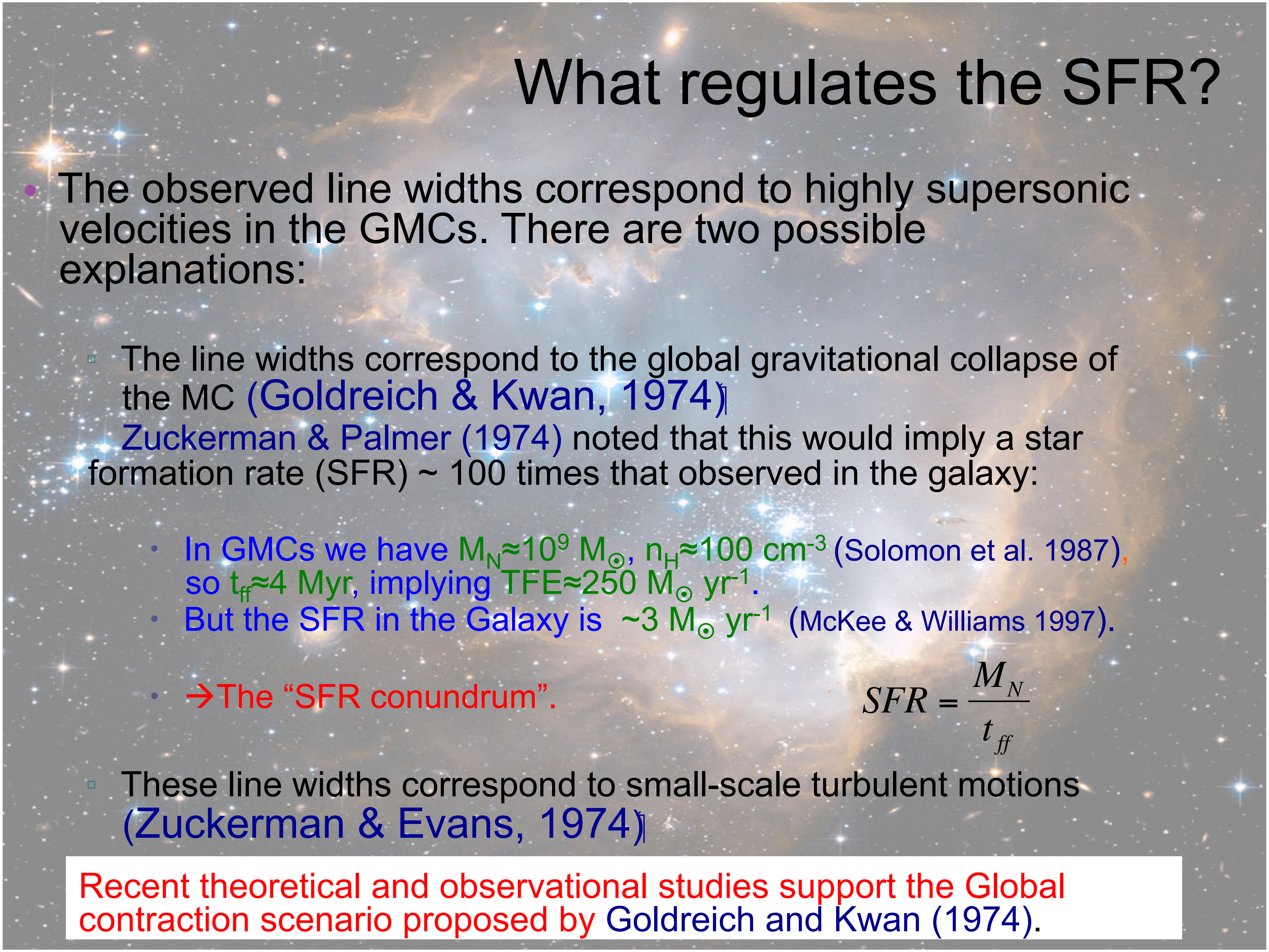
What regulates the SFR?

- The observed line widths correspond to highly supersonic velocities in the GMCs. There are two possible explanations:
  - The line widths correspond to the global gravitational collapse of the MC (Goldreich & Kwan, 1974)

    Zuckerman & Palmer (1974) noted that this would imply a star formation rate (SFR) ~ 100 times that observed in the galaxy:
    - In GMCs we have $M_N \approx 10^9\ M_\odot$, $n_H \approx 100\ \mathrm{cm}^{-3}$ (Solomon et al. 1987), so $t_{ff} \approx 4$ Myr, implying TFE≈250 $M_\odot\ \mathrm{yr}^{-1}$.
    - But the SFR in the Galaxy is ~3 $M_\odot\ \mathrm{yr}^{-1}$ (McKee & Williams 1997).
    - →The "SFR conundrum".

$$SFR = \frac{M_N}{t_{ff}}$$

  - These line widths correspond to small-scale turbulent motions (Zuckerman & Evans, 1974)



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  - These line widths correspond to small-scale turbulent motions (Zuckerman & Evans, 1974)

Recent theoretical and observational studies support the Global contraction scenario proposed by Goldreich and Kwan (1974).

Observational evidence…

Peretto et al. (2007)

- They compare numerical simulations with observations of NGC 2264-C clump.
- They find that the scenario of global contraction and fragmentation is plausible.

Galván-Madrid et al. (2009):

Observations in Radio towards massive star formation region (G20.08-0.14N) in order to investigate the dynamic.

They find that:

- A large scale (0.5 pc), they find molecular accretion flows toward the cluster.
- The two brightest and smaller regions are surrounded by accretion flows on a small scale (0.05 pc).

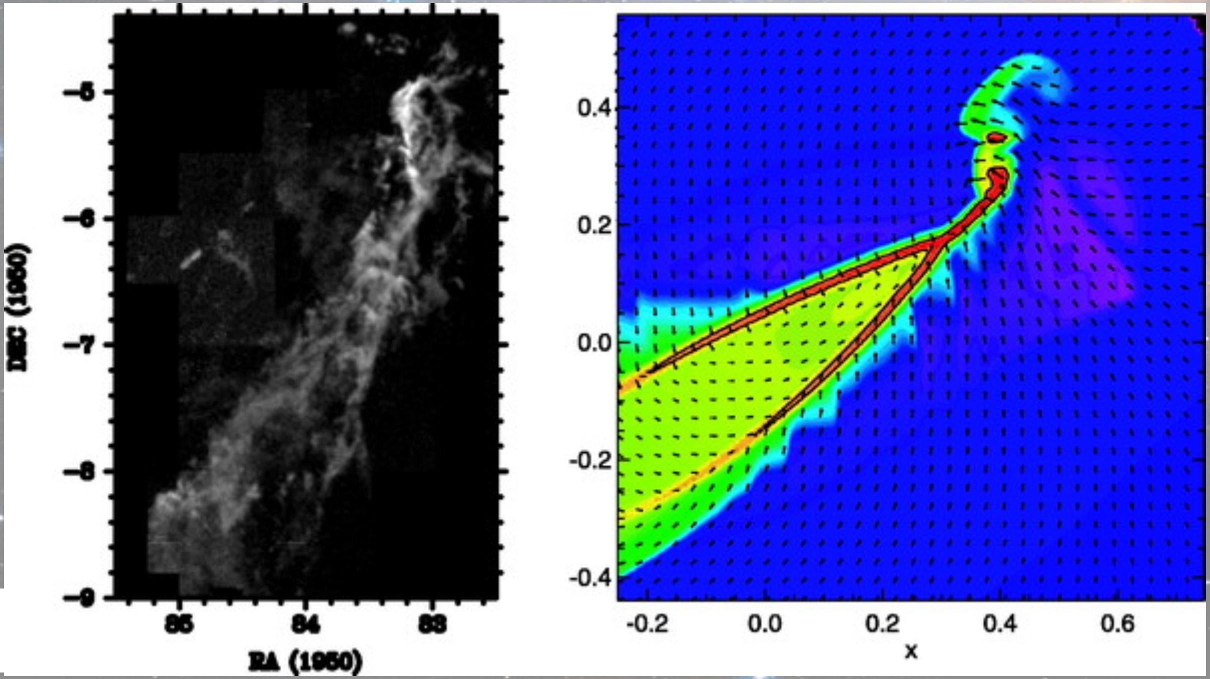
➔ This suggests that the accretion occurs at all scales.

Numerical evidence…

Hartmann & Burkert (2007) developed a numerical model of global collapse to simulate Orion A, and conclude that:

- The model matches the morphology of Orion A and reproduces the mass concentration.

➔The Global gravitational contraction may be a common feature of MCs than previously thought.

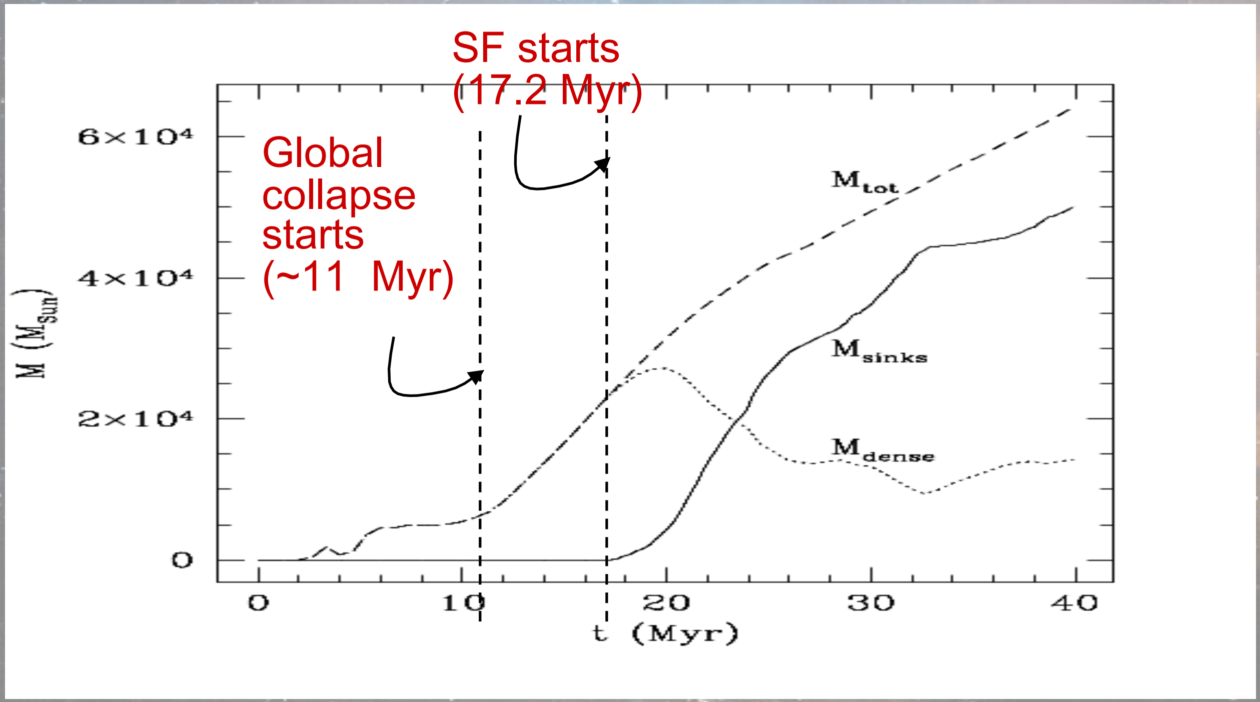


Orion A

Vázquez-Semadeni et al. (2011)

Vázquez-Semadeni et al. (2007, 2011):

Star formation begins *long* after onset of global gravitational contraction.



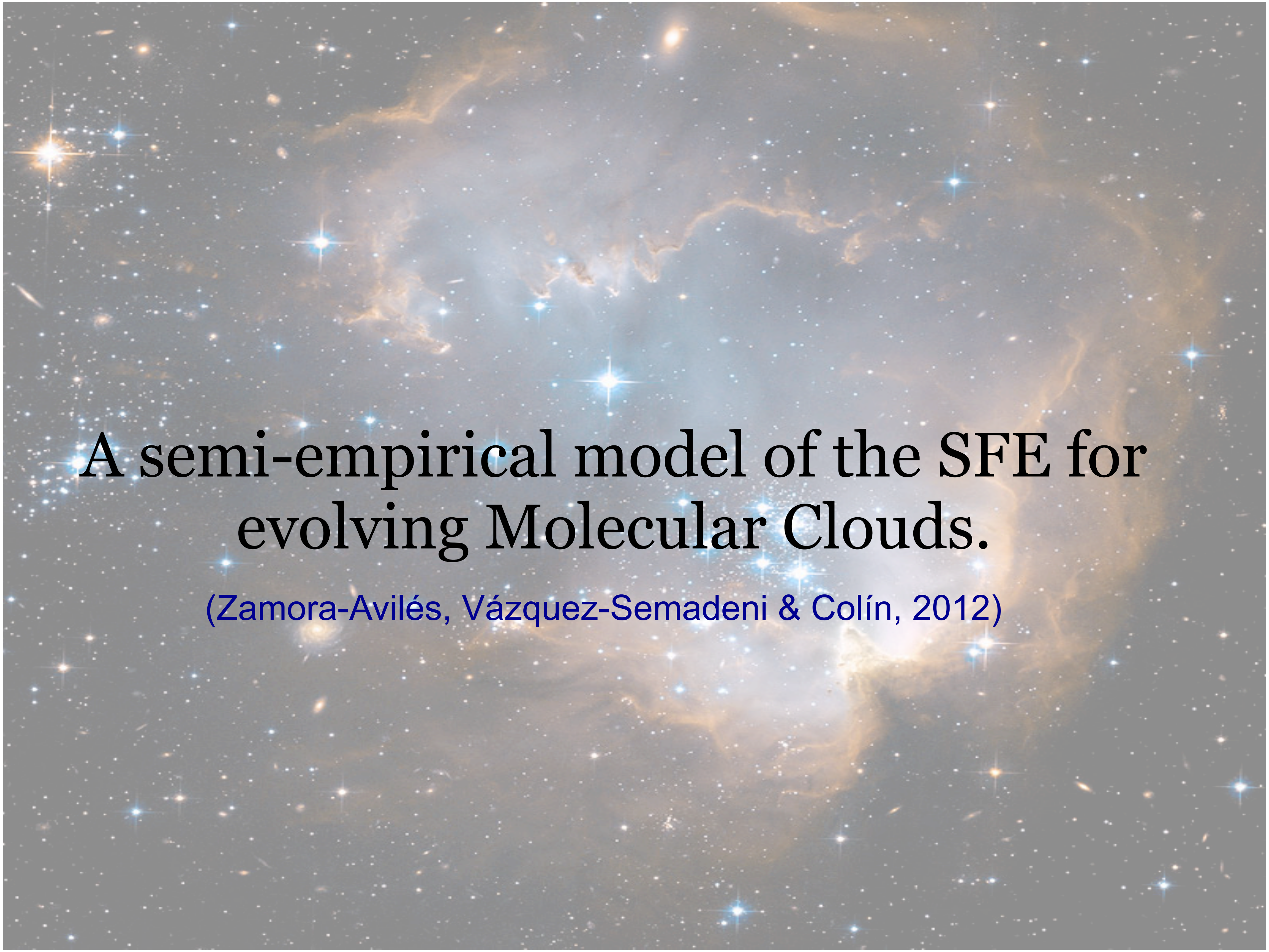
SF starts (17.2 Myr)

Global collapse starts (~11 Myr)

… but long before the global collapse terminates.

Goal:

- Attempt to resolve the SFR conundrum (Zuckerman & Palmer, 1974) in the collapsing cloud scenario.
  - Based on the stellar feedback.



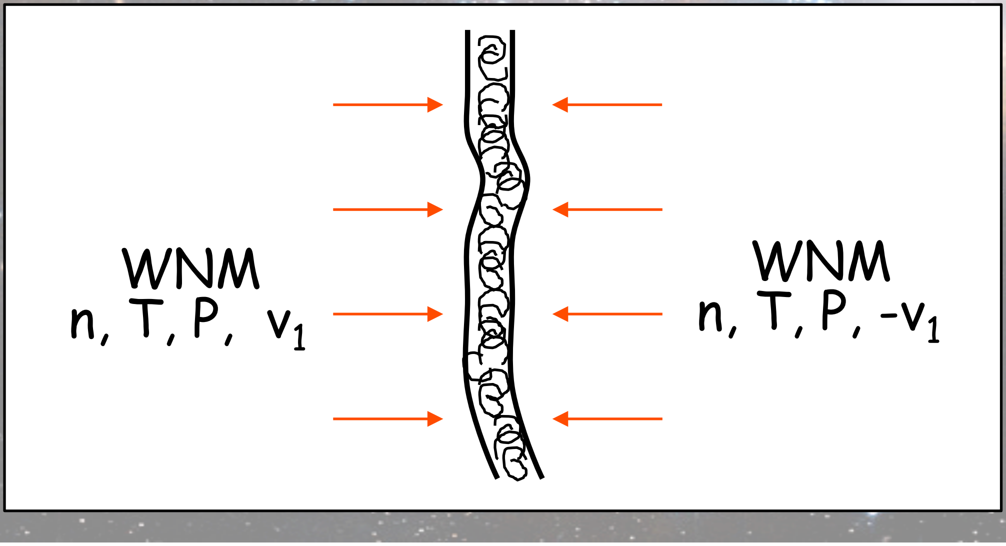
A semi-empirical model of the SFE for evolving Molecular Clouds.

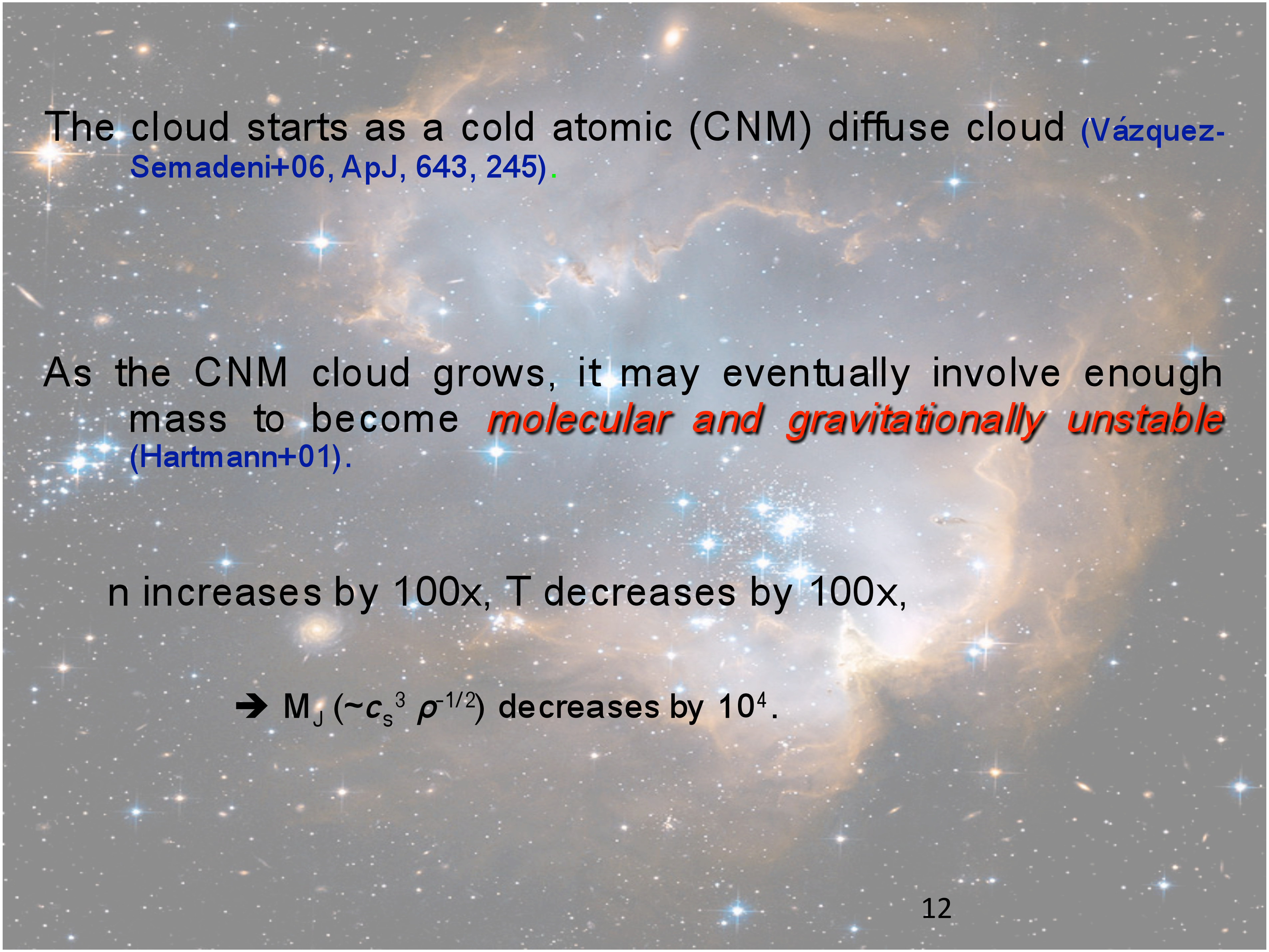
(Zamora-Avilés, Vázquez-Semadeni & Colín, 2012)

When a dense cloud forms out of a compression in the WNM, (Ballesteros-Paredes+99ab, Henebelle & Pérault99) it "automatically"

- acquires mass.
- cools down (from WNM to CNM)
- acquires turbulence (through TI, NTSI, KHI) (Hunter+86; Vishniac 1994; Walder & Folini 1998, 2000; Koyama & Inutsuka 2002, 2004; Audit & Hennebelle 2005; Heitsch+2005, 2006; Vázquez-Semadeni+2006).

The compression may be driven by large-scale turbulence, large-scale instabilities (spiral arms), etc.





The cloud starts as a cold atomic (CNM) diffuse cloud (Vázquez-Semadeni+06, ApJ, 643, 245).

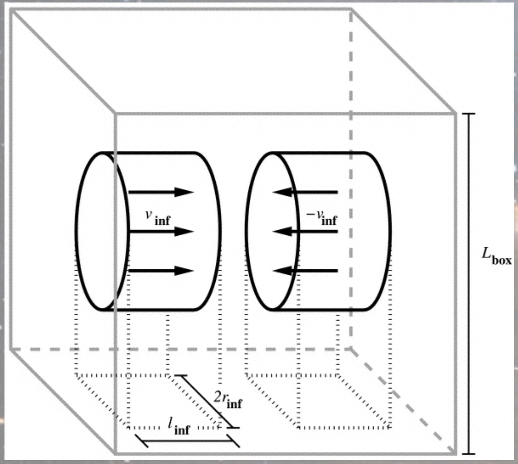
As the CNM cloud grows, it may eventually involve enough mass to become ***molecular and gravitationally unstable*** (Hartmann+01).

n increases by 100x, T decreases by 100x,

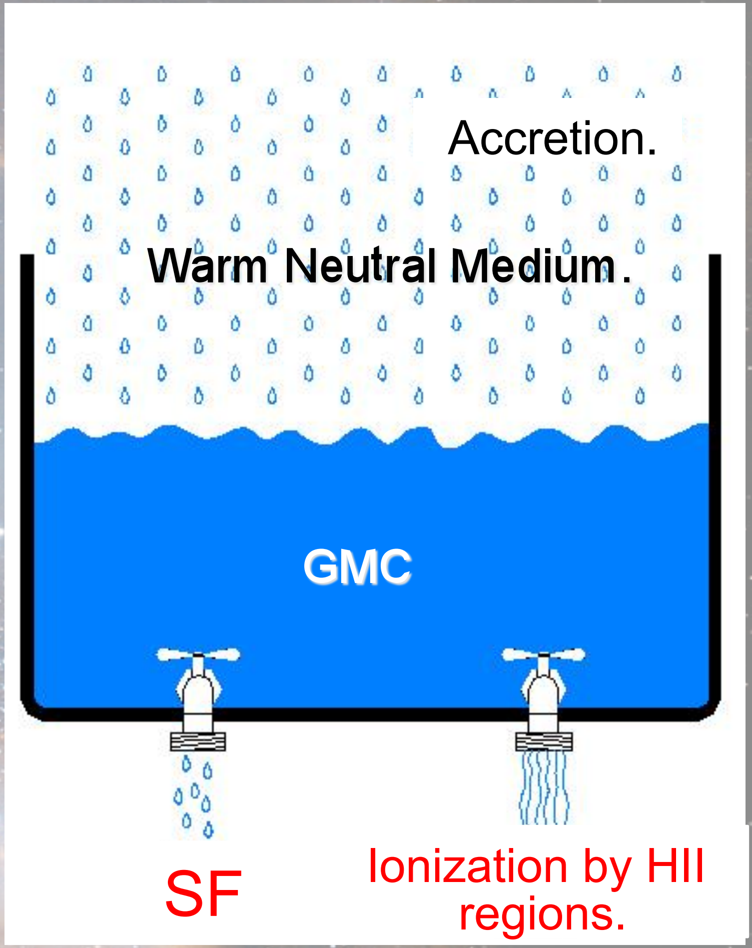
➔ M_J ($\sim c_s^3\, \rho^{-1/2}$) decreases by 10^4.

The idea ...

- The Molecular Cloud (MC) is formed by converging flows of the warm neutral medium (WNM).
- Thus, the MC:
  - Accretes mass of the WNM.
  - But it loses mass by:
    - The SF, and
    - Induced ionization by HII Regions.
- We investigate the combined effect of destruction vs. regeneration.



Scheme used by Vázquez-Semadeni et al. 2007.

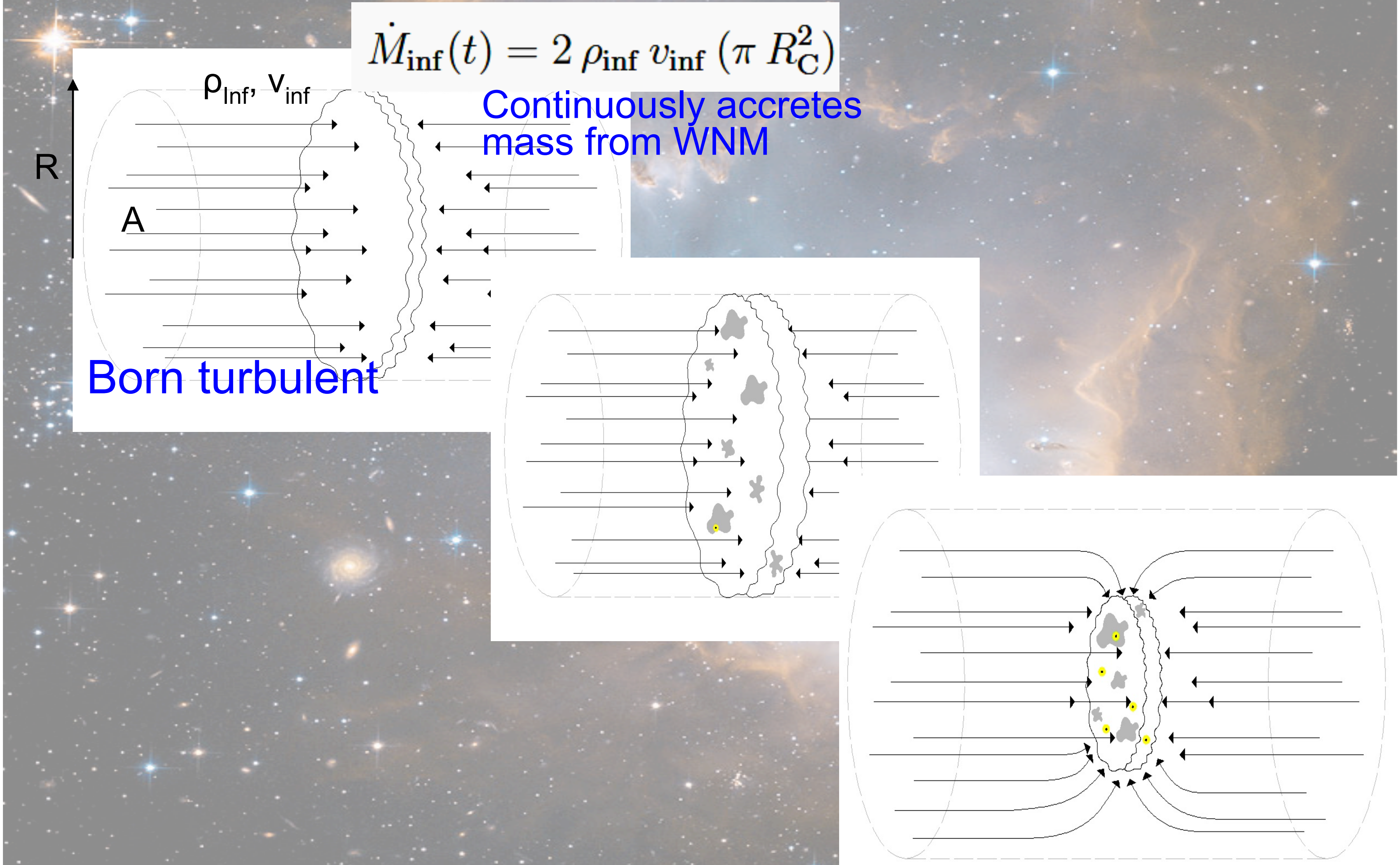


Thus, the cloud evolves according to:

$$M_{\rm C}(t) = \int_0^t \dot{M}_{\rm inf}(t')\,{\rm d}t' - M_{\rm S}(t) - M_{\rm I}(t)$$

Cloud forms by phase transition ***from warm to cold*** phase of atomic medium triggered by the converging flows.

$$\dot{M}_{\rm inf}(t) = 2\,\rho_{\rm inf}\,v_{\rm inf}\,(\pi\,R_{\rm C}^2)$$



Continuously accretes mass from WNM

Born turbulent

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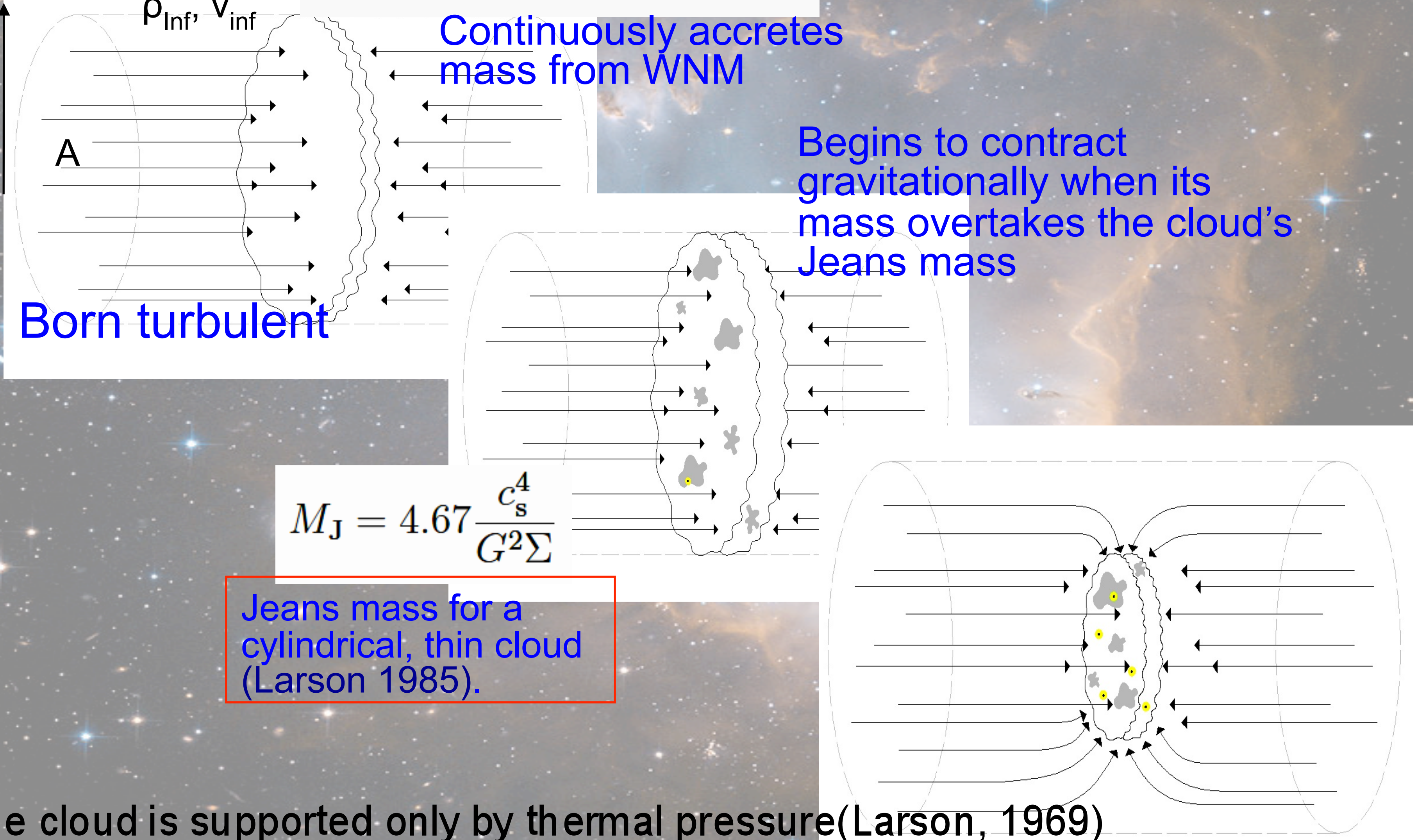


$$\dot{M}_{\rm inf}(t) = 2\,\rho_{\rm inf}\,v_{\rm inf}\,(\pi\,R_{\rm C}^2)$$

Continuously accretes mass from WNM

Born turbulent

Begins to contract gravitationally when its mass overtakes the cloud's Jeans mass

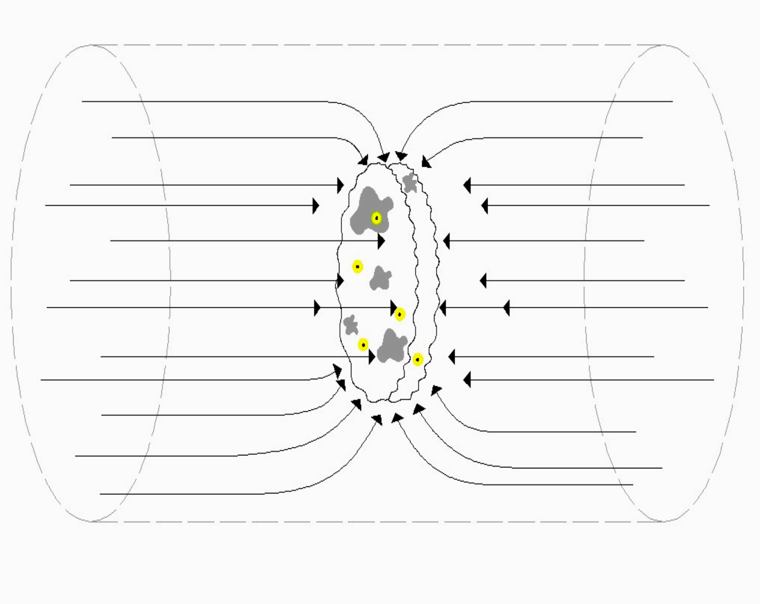
$$M_{\rm J} = 4.67\frac{c_{\rm s}^4}{G^2\Sigma}$$

Jeans mass for a cylindrical, thin cloud (Larson 1985).

The cloud is supported only by thermal pressure(Larson, 1969)

No turbulent or magnetic support is assumed.

- Cloud is turbulent by combined action of thermal, KH, nonlinear thin shell instabilities (Heitsch+05, 06; VS+06).
  - M_s = 3 = cst. (random motions apart from infall) (Heiles & Troland 03).



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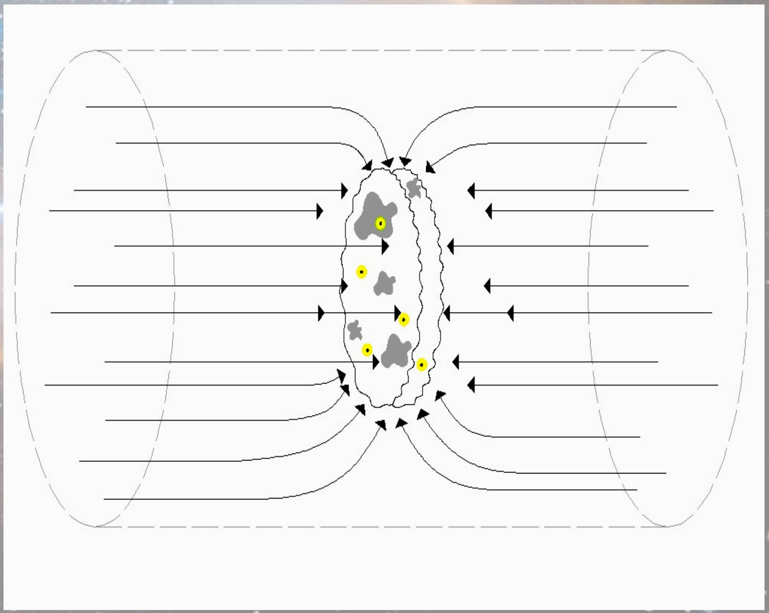
  Assume cold cloud is nearly isothermal → lognormal PDF

  (Vazquez-Semadeni94).

$$P_s = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s-s_\mathrm{p})^2}{2\sigma_s^2}\right]$$

$$s = \ln(\rho)$$



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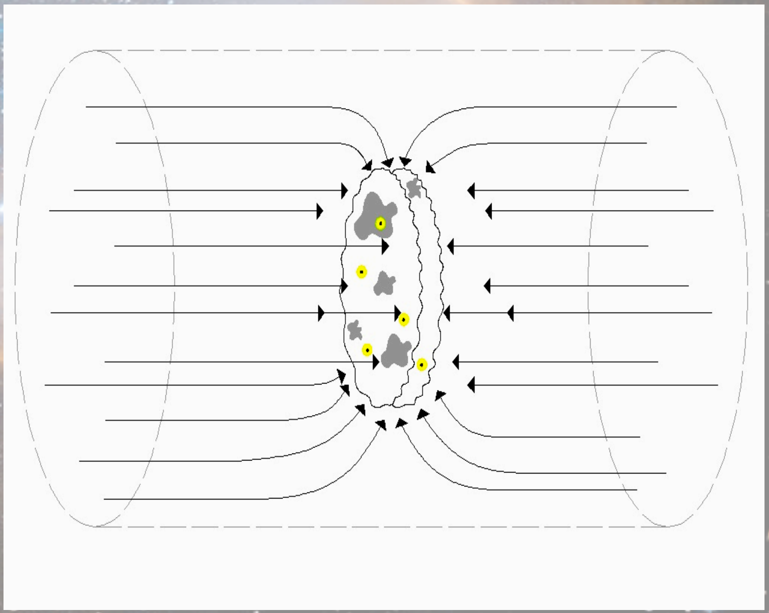
$$P_s = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp\left[-\frac{(s-s_\mathrm{p})^2}{2\sigma_s^2}\right]$$

$$s = \ln(\rho) \qquad \sigma_s^2 = \ln[1+M^2]$$



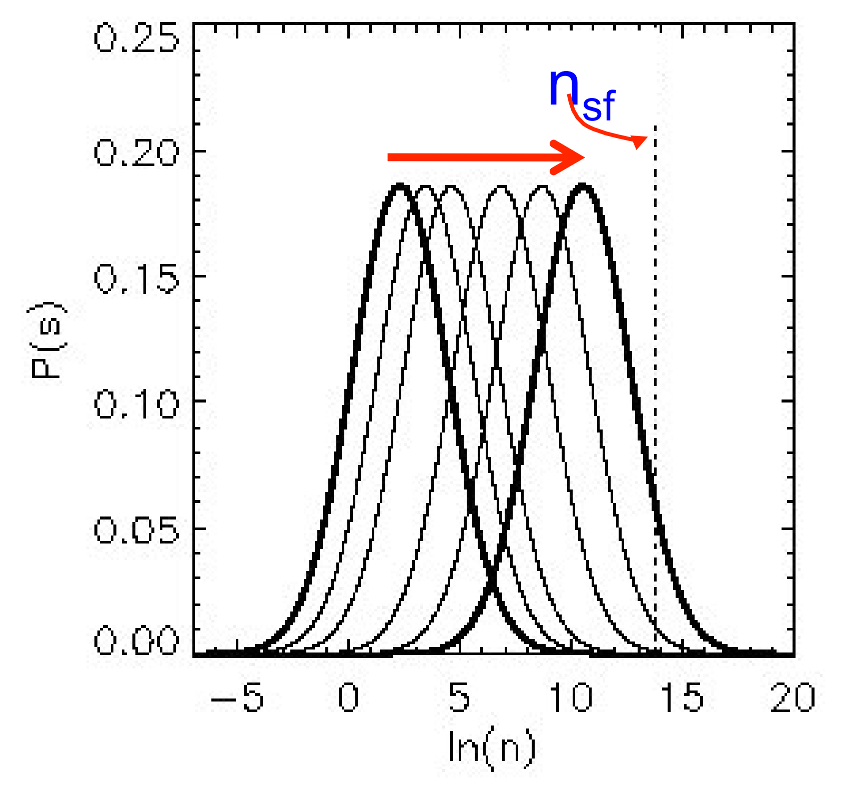
Assume SFR given by mass at high density ($n > n_{sf}$) divided by its free-fall time.

$$\mathrm{SFR}(t) = \frac{M_\mathrm{cl}(t)}{t_\mathrm{ff}(n_\mathrm{sf},t)} f(n_\mathrm{sf},t),$$

$$f(n_\mathrm{sf},t) = \int_{s=\ln(n_\mathrm{sf})}^{\infty} P(s,t)\, ds\ e^s$$

As the cloud contracts, its mean density increases, and the density PDF shifts to higher densities.

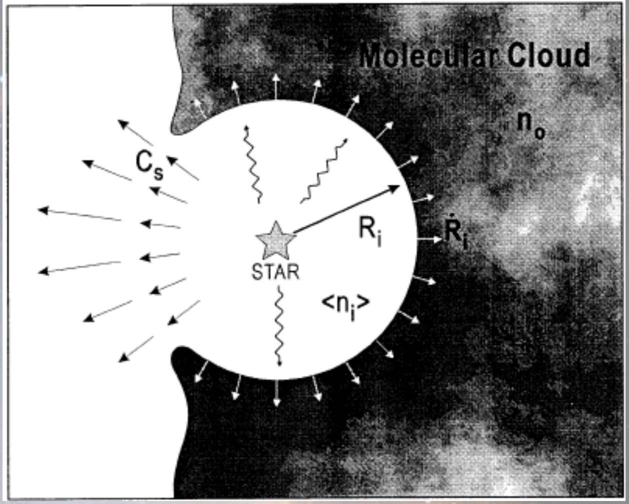
➔ the mass at $n > n_{sf}$ increases with time.



Ionized mass:

We use the formula by Franco et al. (1994) for the mass ionization rate caused by a typical OB star:

$$\dot{M}_{\rm I}(t) \approx 2\pi R_{\rm S,0} m_{\rm p} \bar{n} c_{\rm s,I} \left(1 + \frac{5c_{\rm s,I}t}{2R_{\rm S,0}}\right)^{1/5}$$



Where….

$$R_0 = \left[\frac{3F_*}{4\pi\alpha_B(2n_0)^2}\right]^{1/3}$$

Initial Strömgren radius

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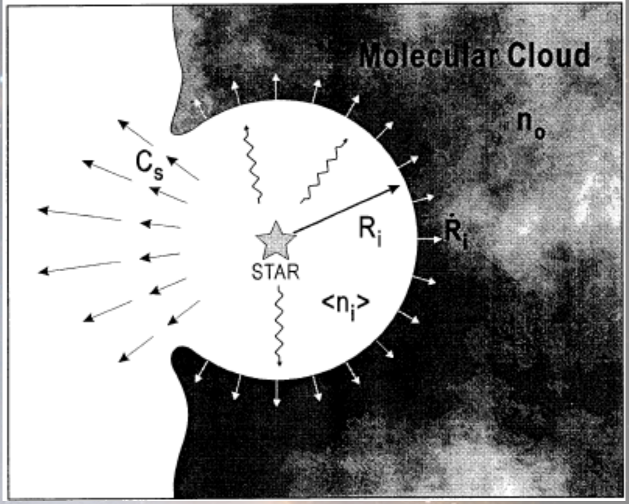


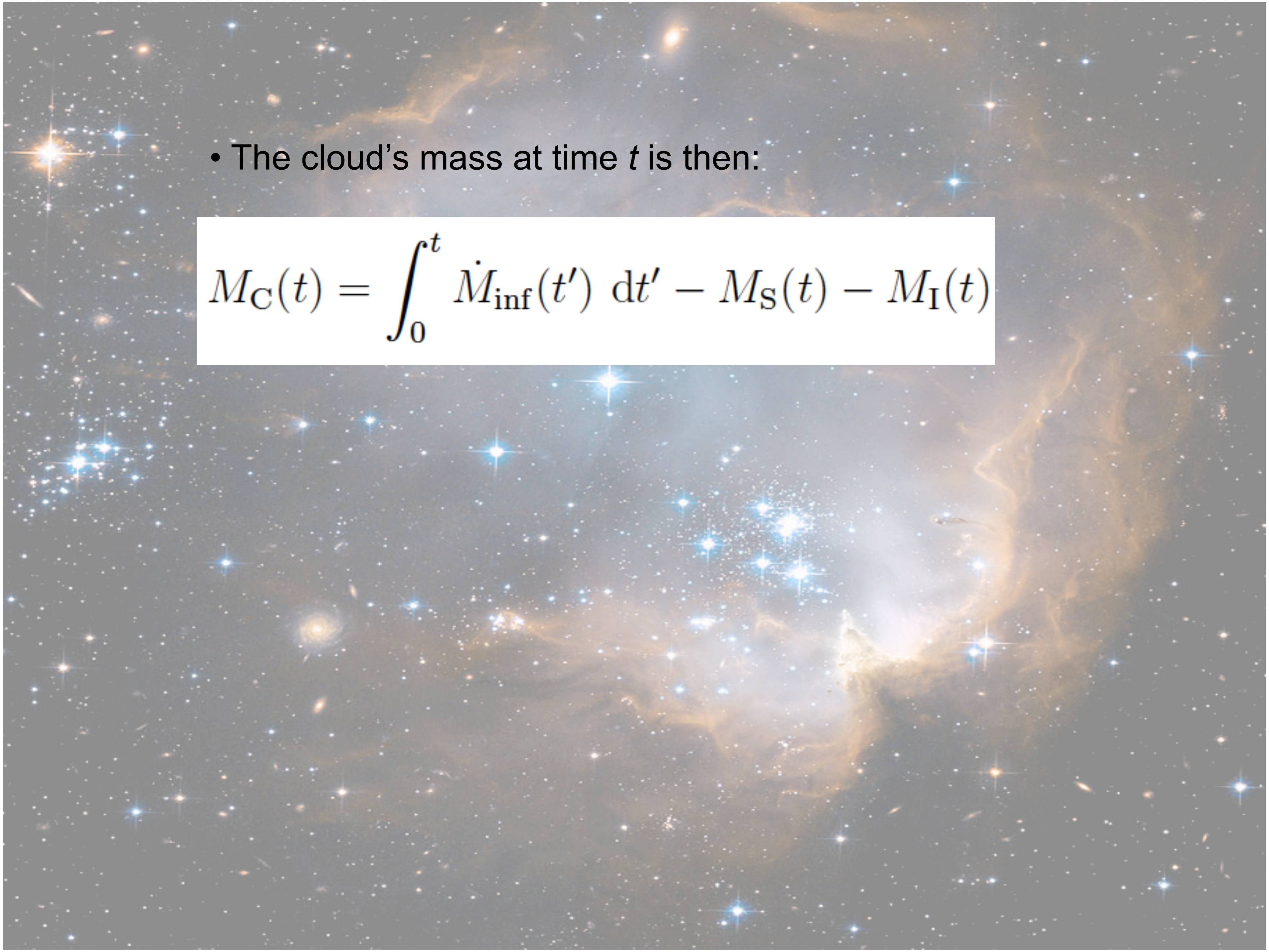
Time dependent.

Where….

$$R_0 = \left[\frac{3F_*}{4\pi\alpha_B(2n_0)^2}\right]^{1/3}$$

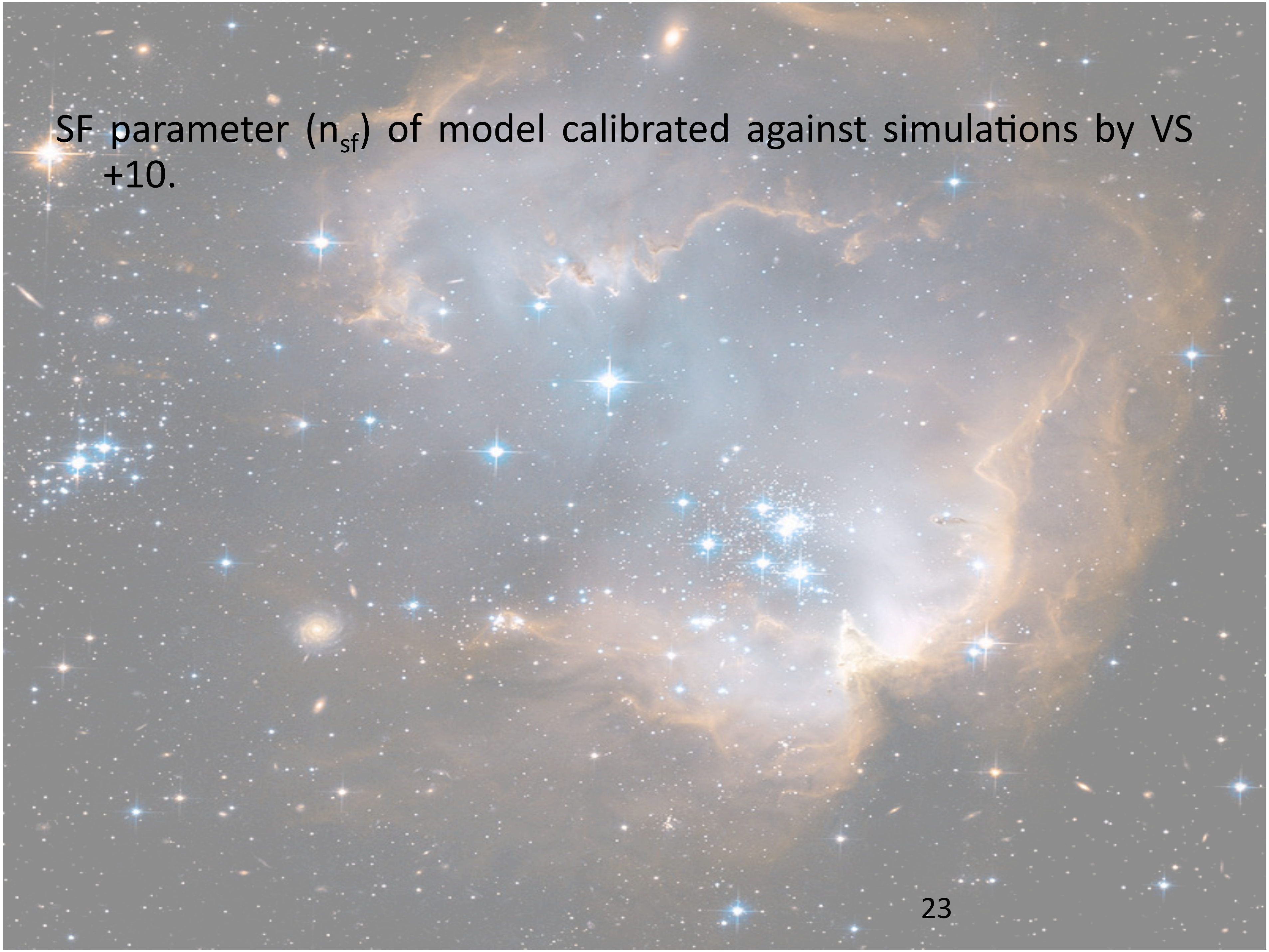
Initial Strömgren radius

To obtain the instantaneous number of massive stars, assume a Salpeter (1955) IMF.



- The cloud’s mass at time *t* is then:

$$M_{\mathrm{C}}(t) = \int_0^t \dot{M}_{\mathrm{inf}}(t')\ \mathrm{d}t' - M_{\mathrm{S}}(t) - M_{\mathrm{I}}(t)$$



SF parameter (n_{sf}) of model calibrated against simulations by VS +10.

Calibration

Parameters that best fit the simulations:

$v_{\rm inf} = 4.5$ km s^{-1} (7.5 km s^{-1} in the simulations)

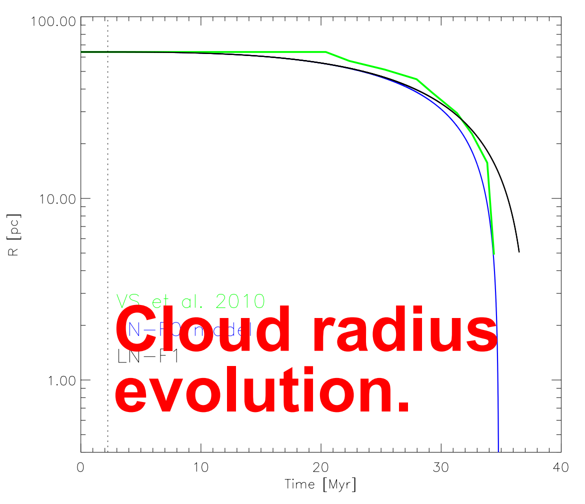
Mach = 3

$f_{\rm L} = 1.7$ (Larson, 1969)

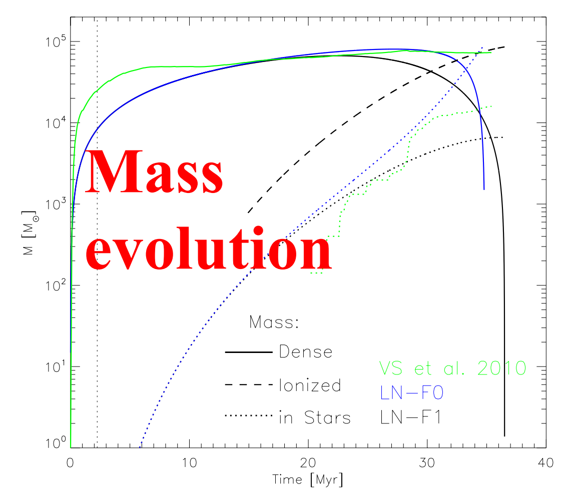
Simulations by Vázquez-Semadeni et al. (2010)

Model with Feedback

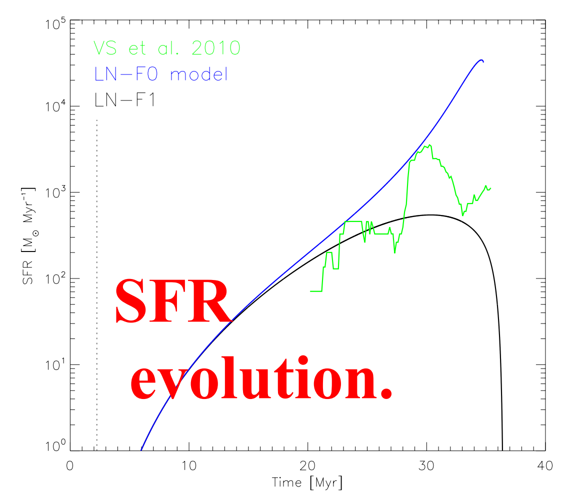
Model without Feedback.



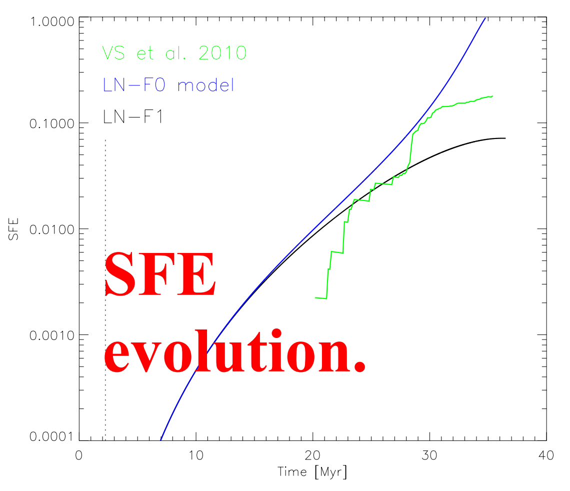
Cloud radius evolution.



Mass evolution



SFR evolution.



SFE evolution.

Notes:

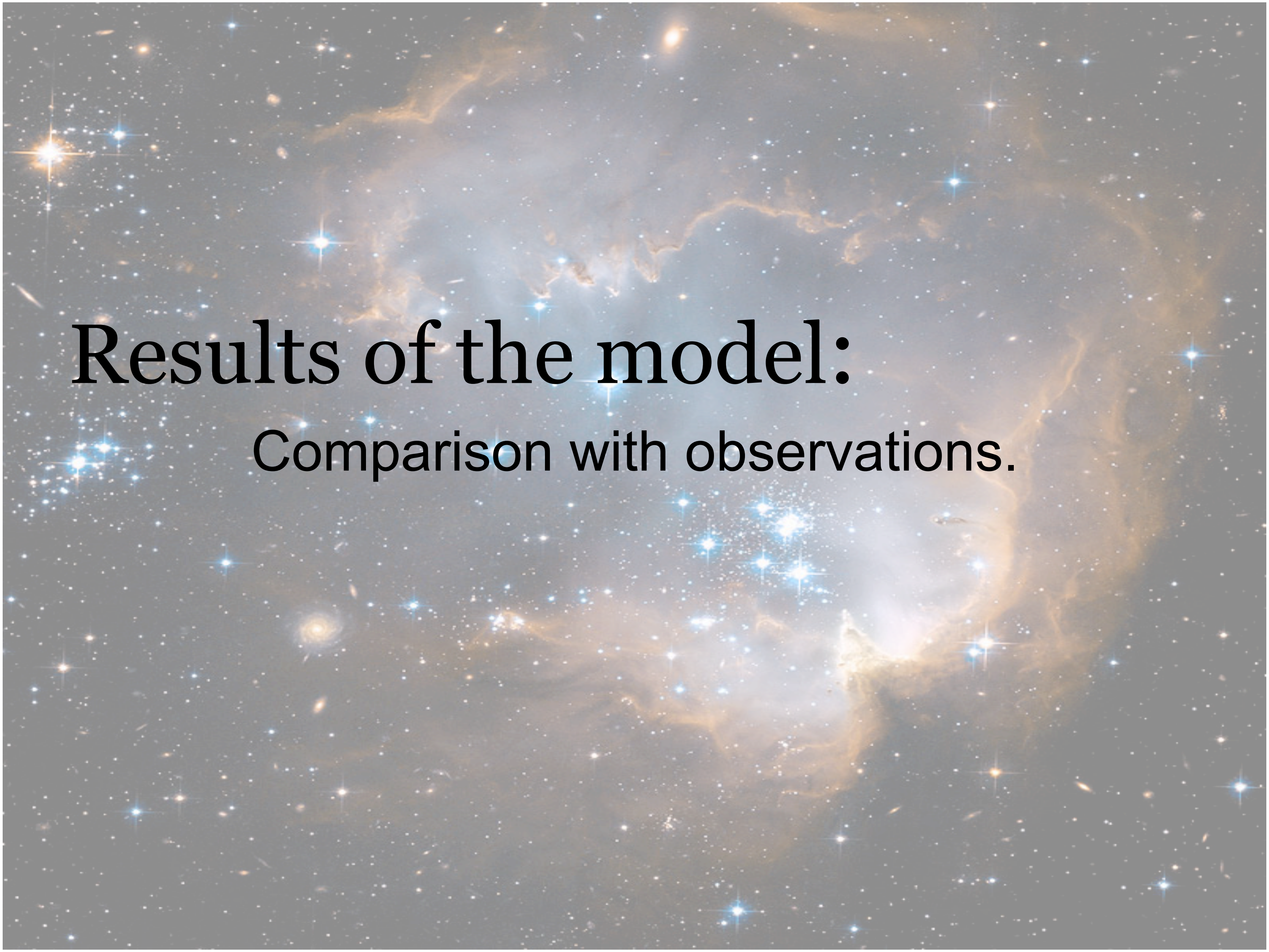
Main controlling parameter is ***cloud's mass***

controlled by inflow radius in the model.

Model is naturally ***evolutionary***.

Other existing models (e.g., Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011) are time-stationary.

SFR increases in time.



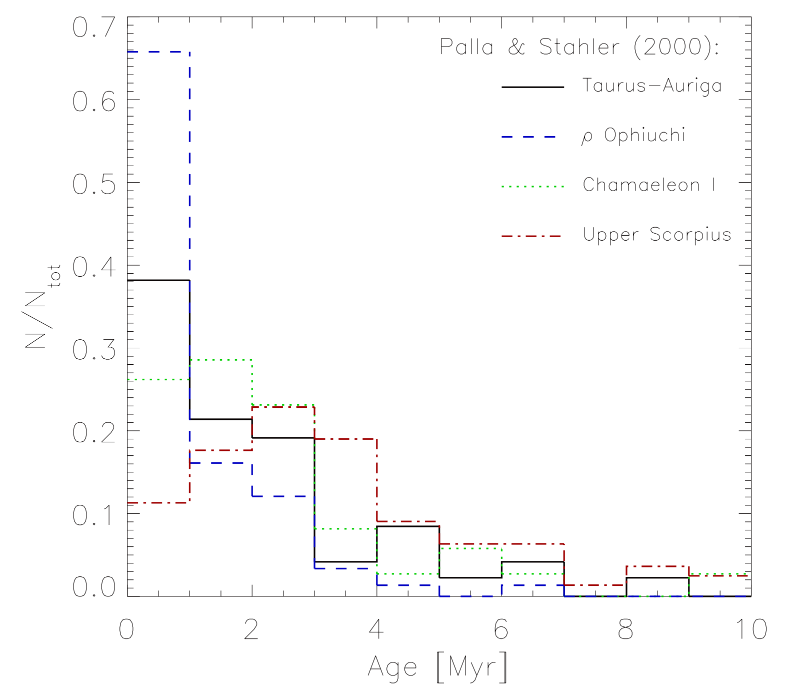
Results of the model:

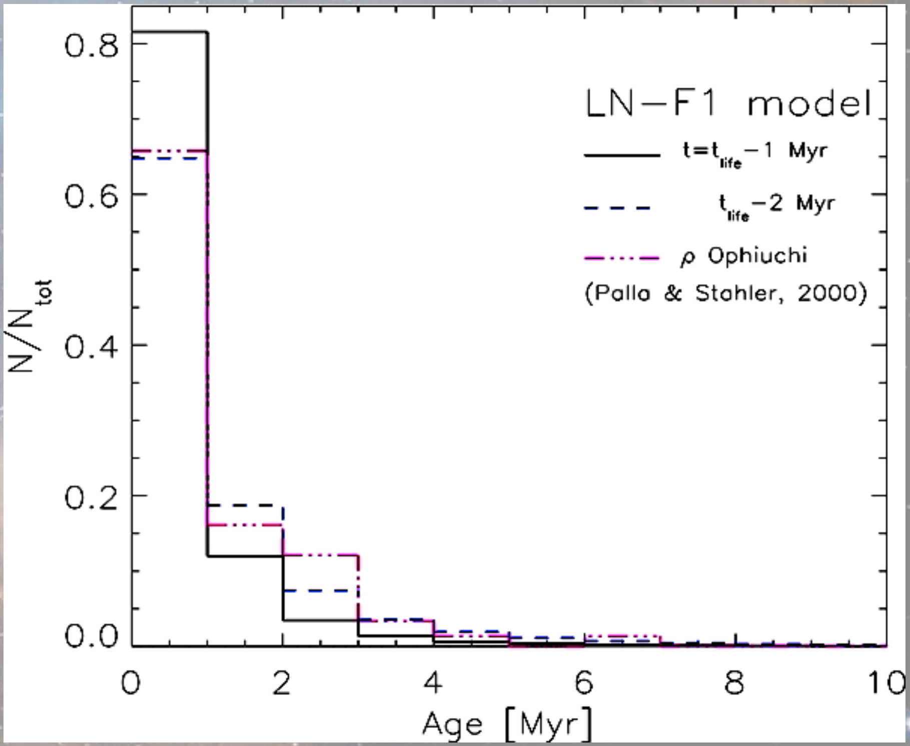
Comparison with observations.

Stellar age distributions

Model with M_{max} ~ 2000 $M_\odot$

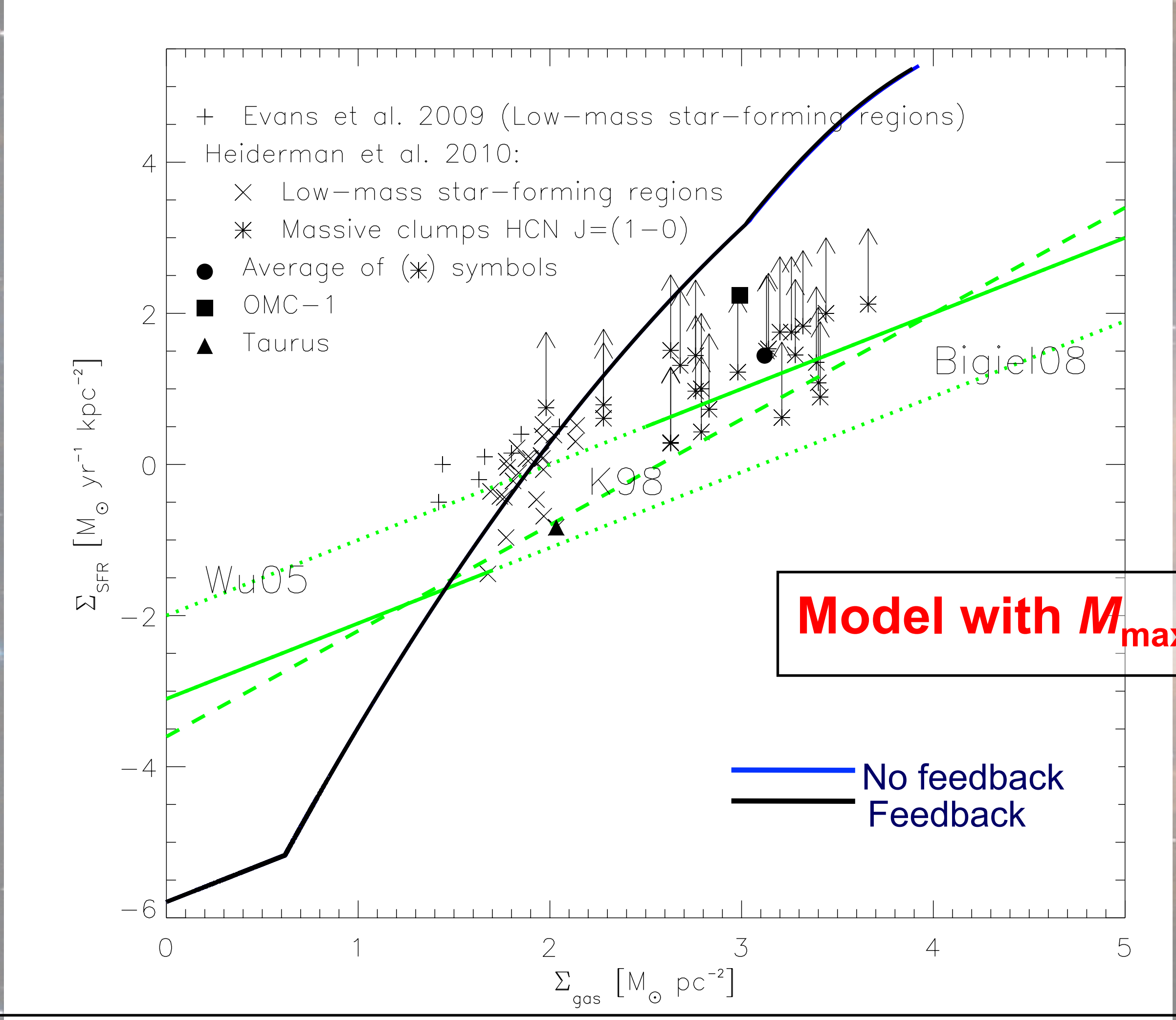
Recall: SFR increases over time!!!





The stellar age histogram 2 Myr before the end of our model’s life resembles those of Palla & Stahler (2000).

Kennicutt-Schmidt relation

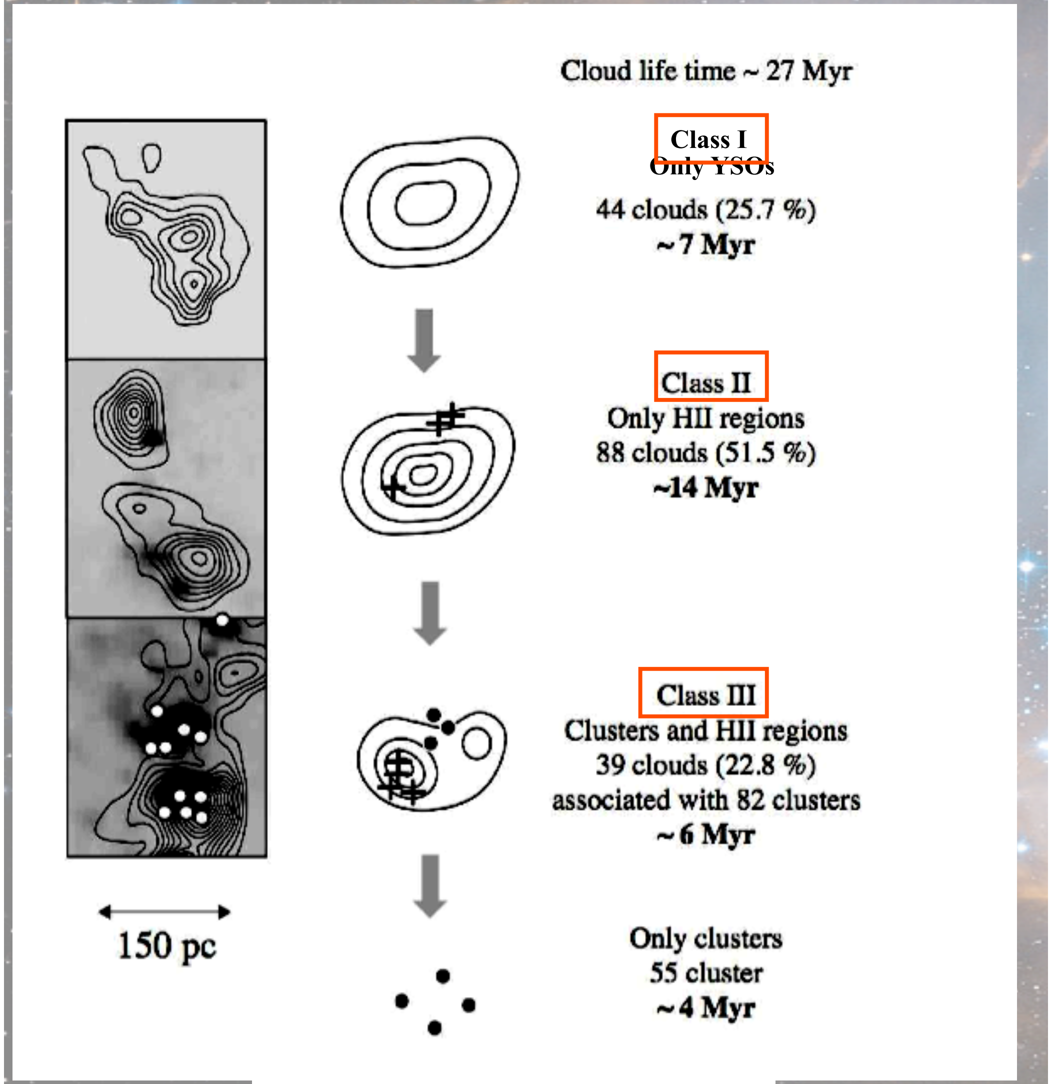


Model with M_{max} ~ 2000 $M_\odot$

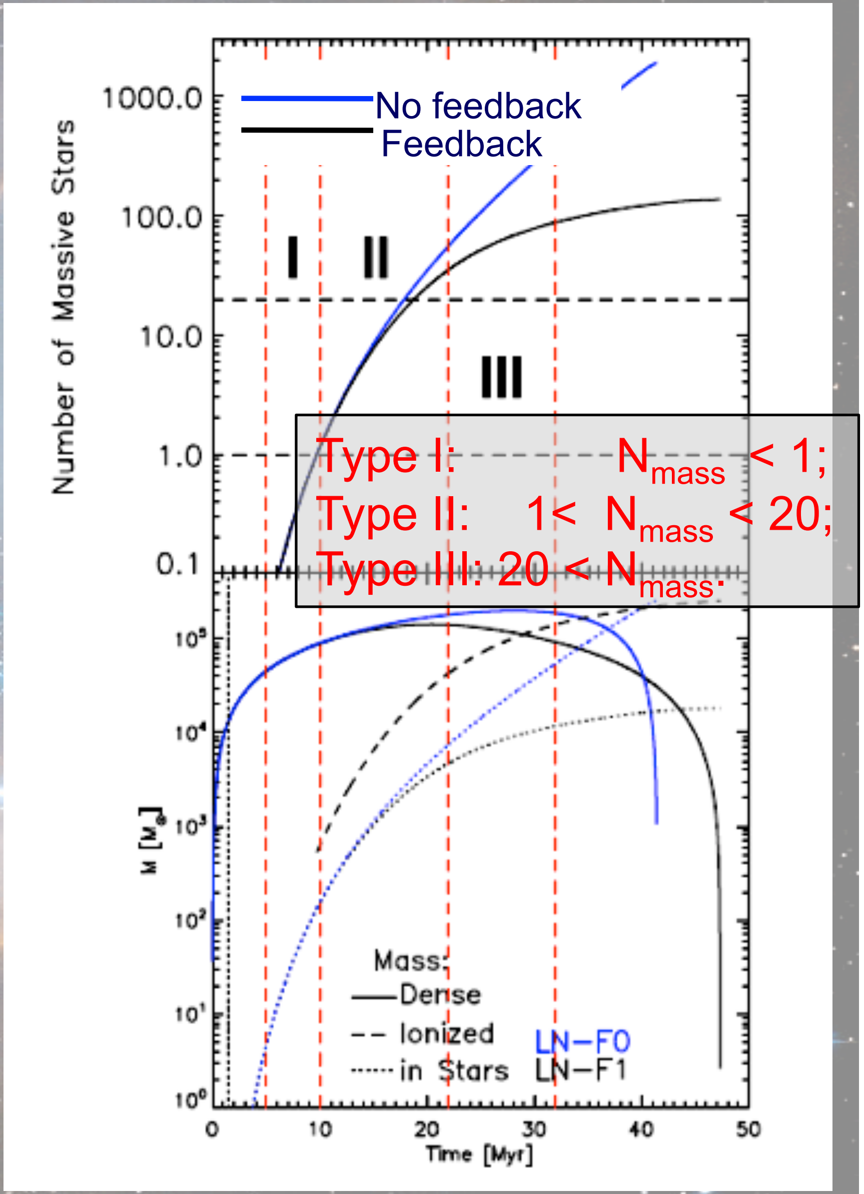
The model (thick solid line) evolves from low to high values of both Σ_{gas} and Σ_{SFR}.

Evolution of stellar content for GMCs

Model with $M_{max} \sim 10^5\ M_{\odot}$



Kawamura+2009



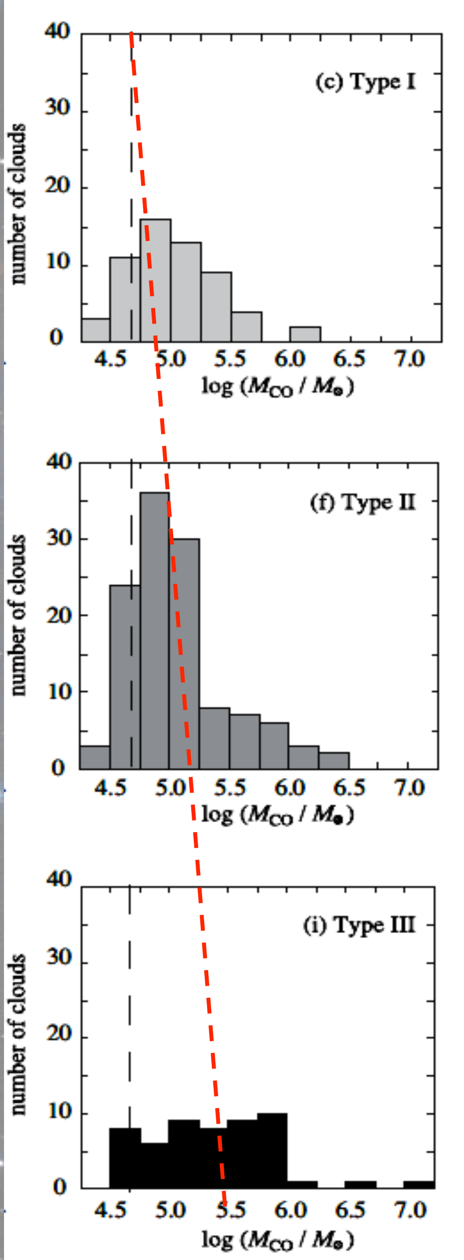
Type I: $N_{mass} < 1$;

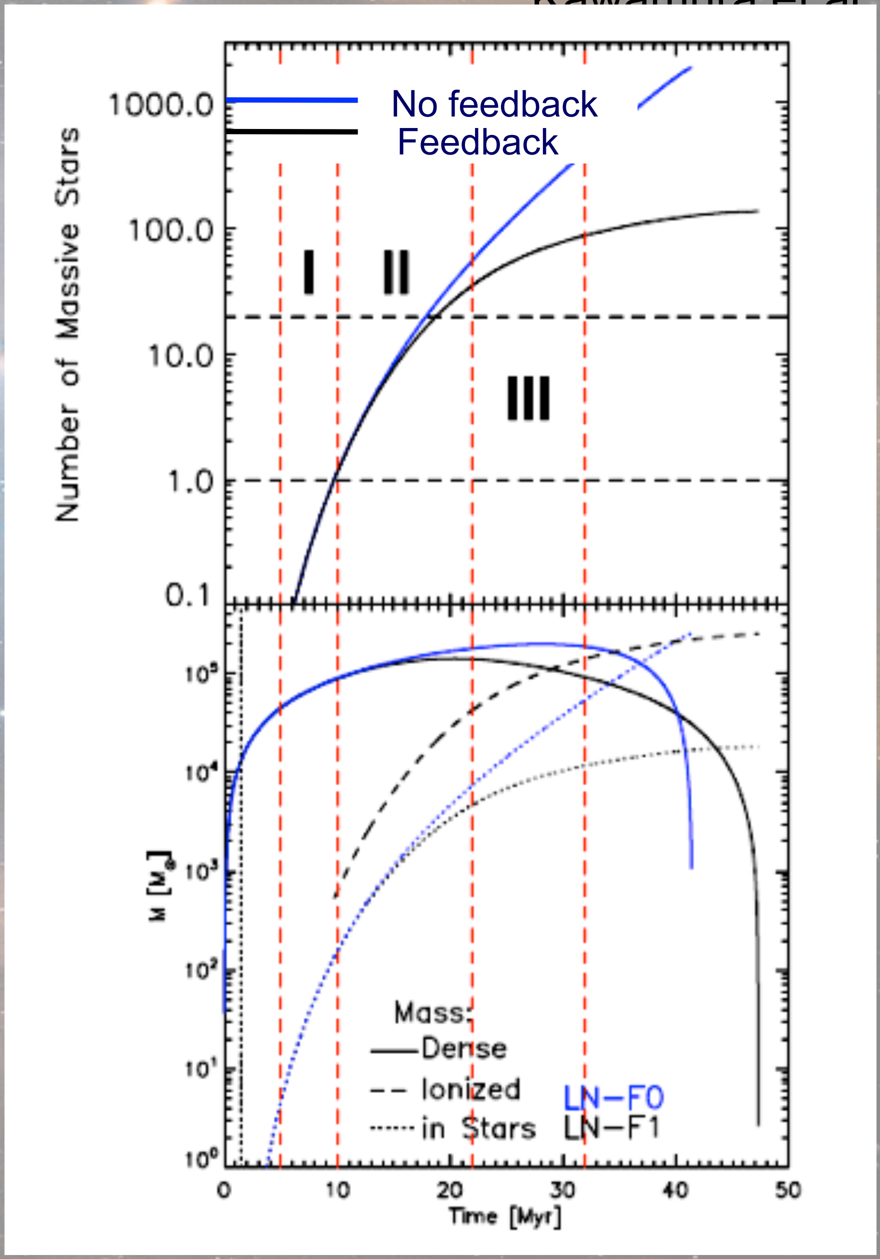
Type II: $1 < N_{mass} < 20$;

Type III: $20 < N_{mass}$.

Mass evolution of the **fiducial GMC model**

Kawamura et al. (2009)





For each class, we have consistency in both mass and time!

Applications:

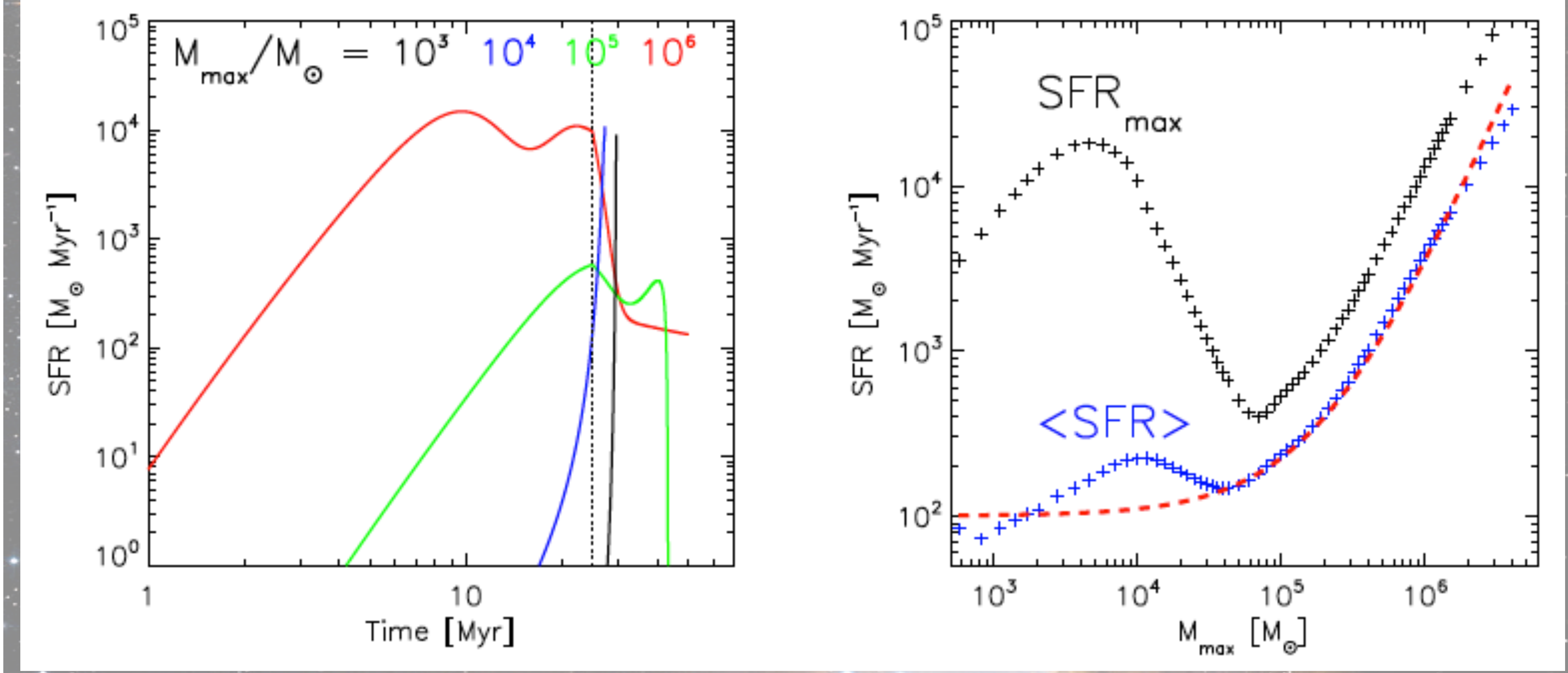
Parameter variation

(Zamora-Avilés & Vázquez-Semadeni, 2013; Submitted)

Dependence on the maximum mass:

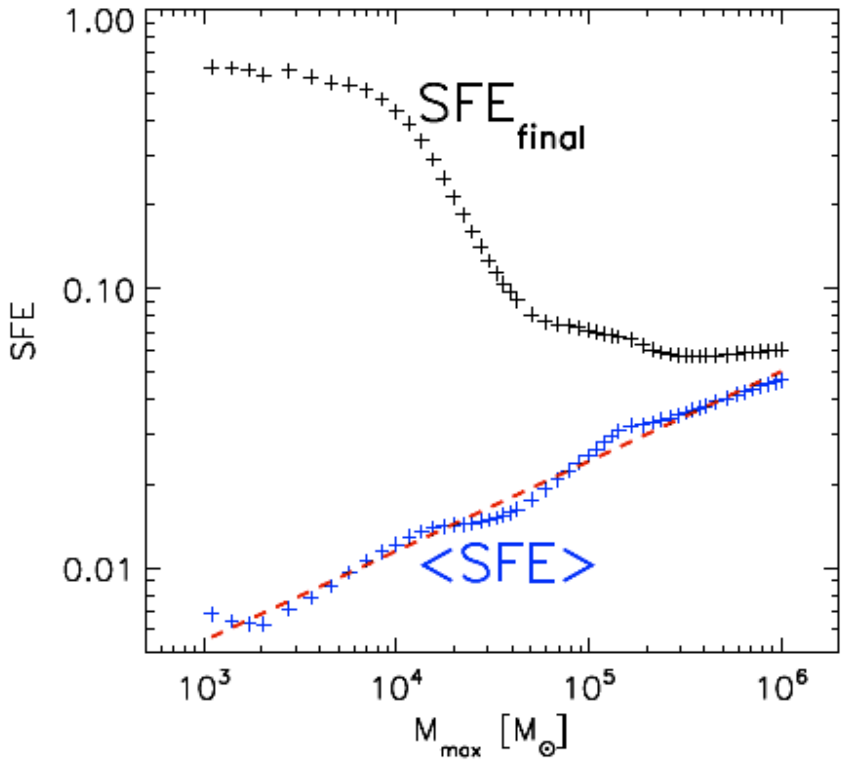
- The accretion lasts 25 Myr
- Predictions about the rate and efficiency can be used to implement recipes of star formation in simulations (cosmological) on a galactic scale.

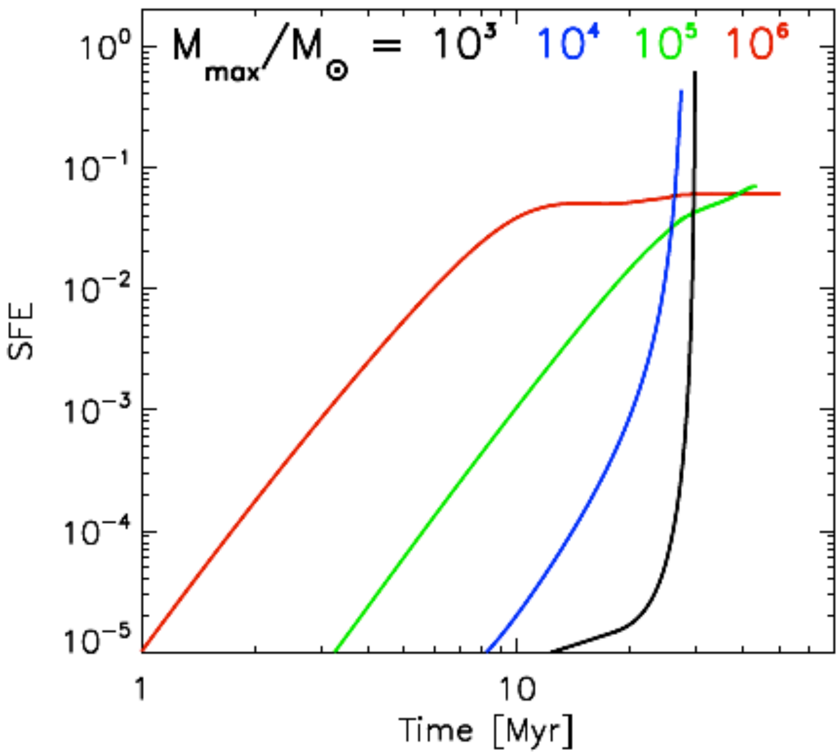
SFR



$$\langle \mathrm{SFR} \rangle \approx 100 \left(1 + \frac{M_{\mathrm{max}}}{2 \times 10^5\,\mathrm{M}_\odot}\right)^2 \mathrm{M}_\odot\,\mathrm{Myr}^{-1},$$

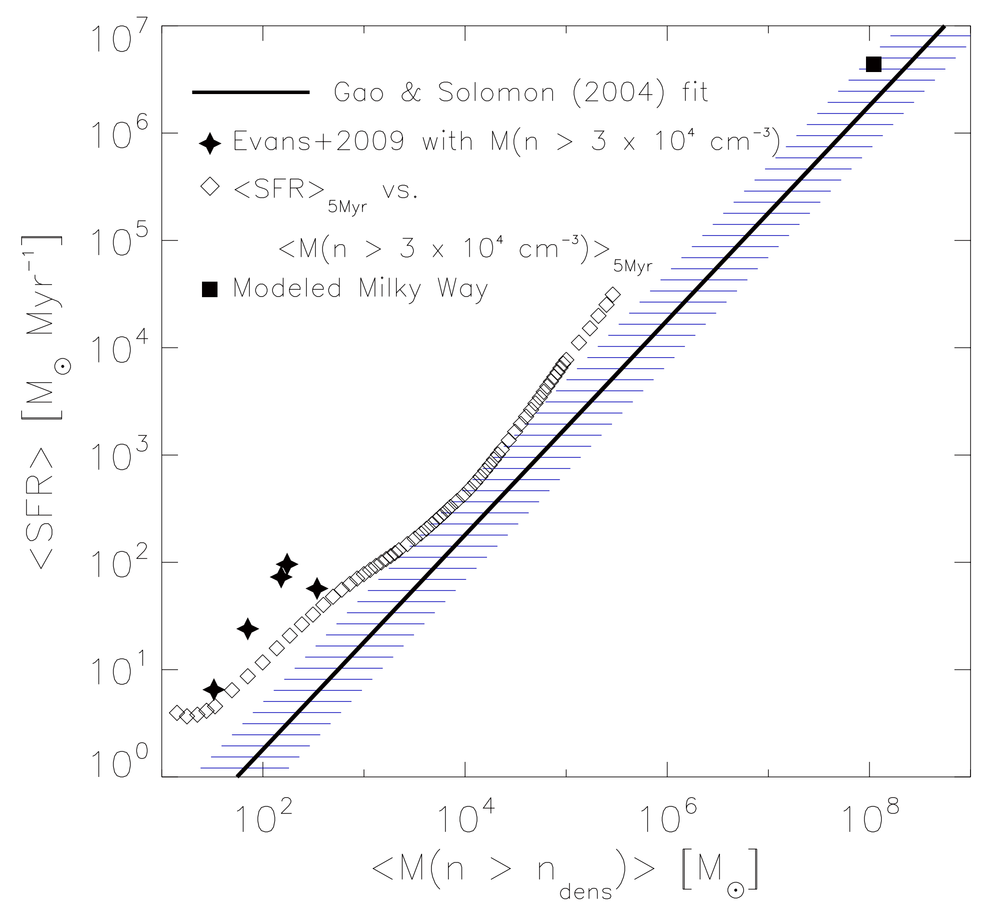
SFE



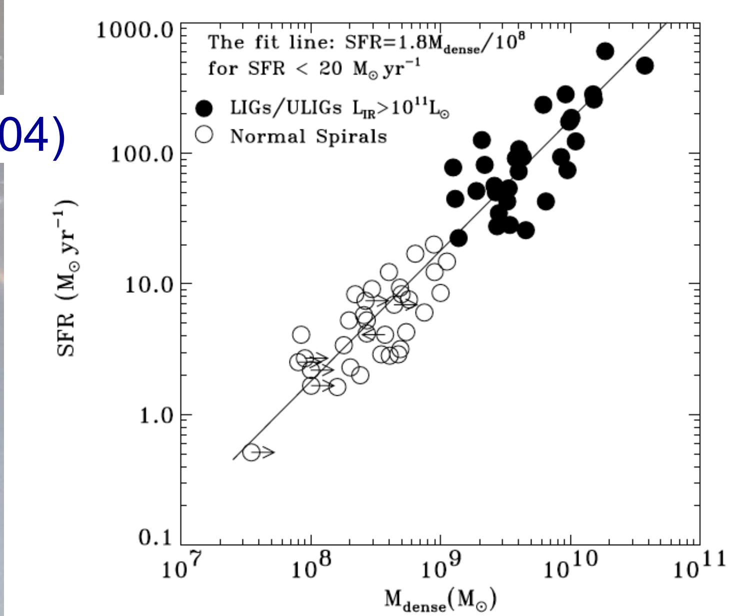


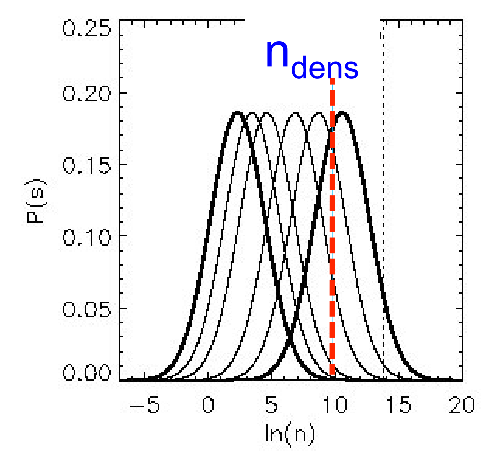
$$< SFE >= 0.02\left(\frac{M_{\rm max}}{10^5\,{\rm M}_\odot}\right)^{0.3}$$

SFR-M_{dens} Diagram



Gao and Solomon (2004)

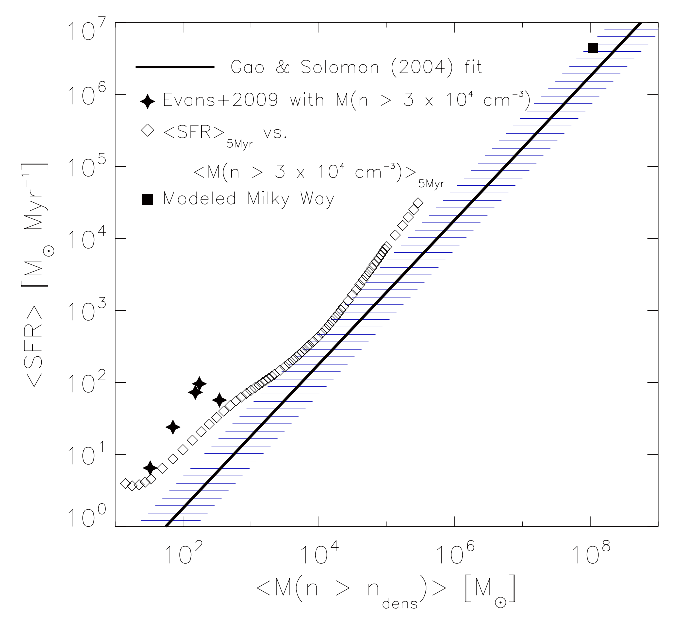




$< M_{dens} >$

$$M_{dens} = M_{cloud}(n > n_{dens}) = M_{cloud} \int_{n_{dens}}^{\infty} p(s) e^{s} ds$$

SFR-M_{dens} Diagram



+

Mass distribution of MCs in the Galaxy

$$\frac{d\mathcal{N}_c}{d\ln M} = \mathcal{N}_{cu}\left(\frac{M_u}{M}\right)^{\alpha} \quad (M \le M_u),$$

$$\mathcal{N}_{cu} = 63,\ \alpha = 0.6$$

$$M_u = 6 \times 10^6\ M_\odot$$

Williams & McKee (1997)

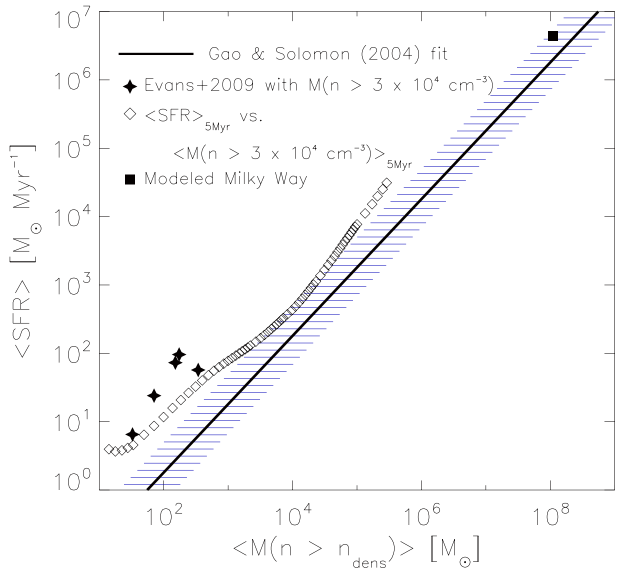
=

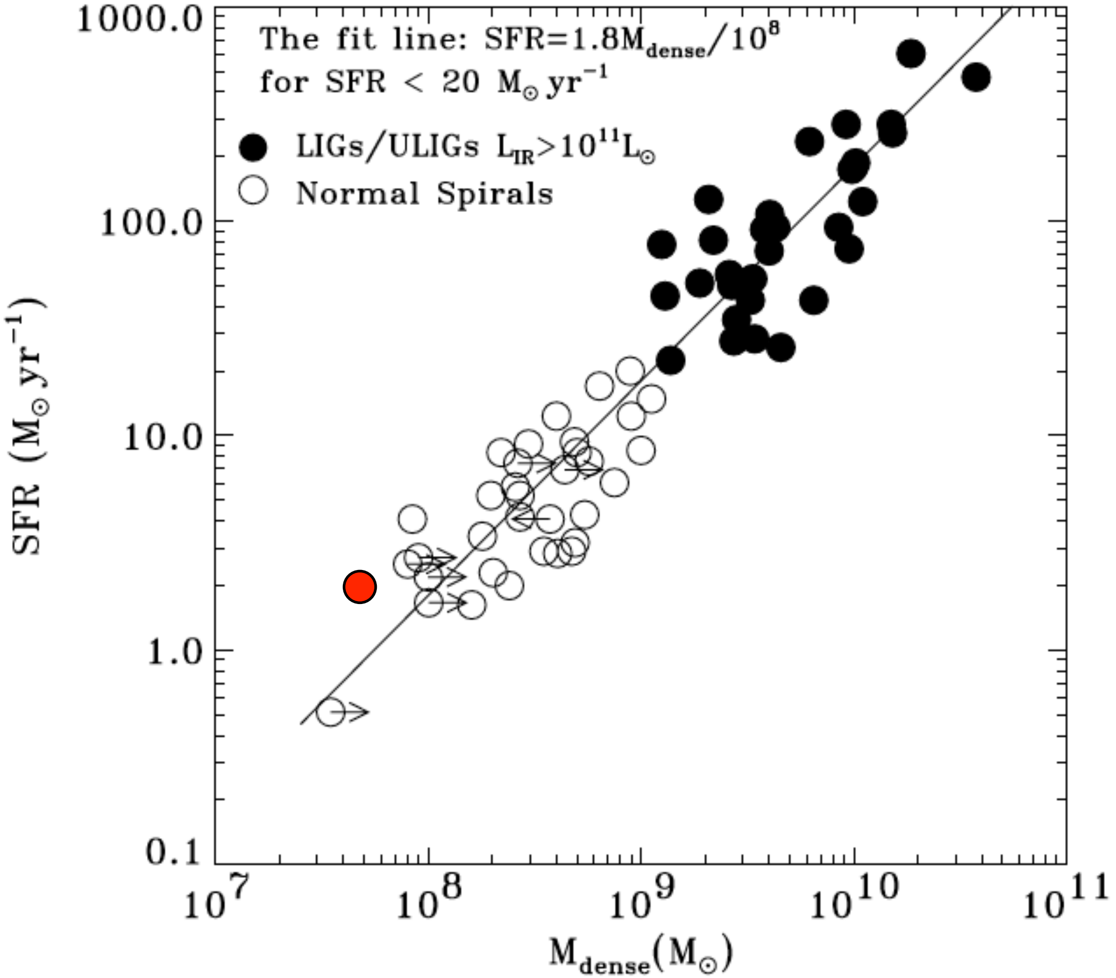
$$M_{\mathrm{dens}} = 1.1 \times 10^8\,\mathrm{M}_\odot$$

SFR= $4.4\,\mathrm{M}_\odot\mathrm{yr}^{-1}$

$n_{\mathrm{dens}} = 3 \times 10^4\ \mathrm{cm}^{-3}$

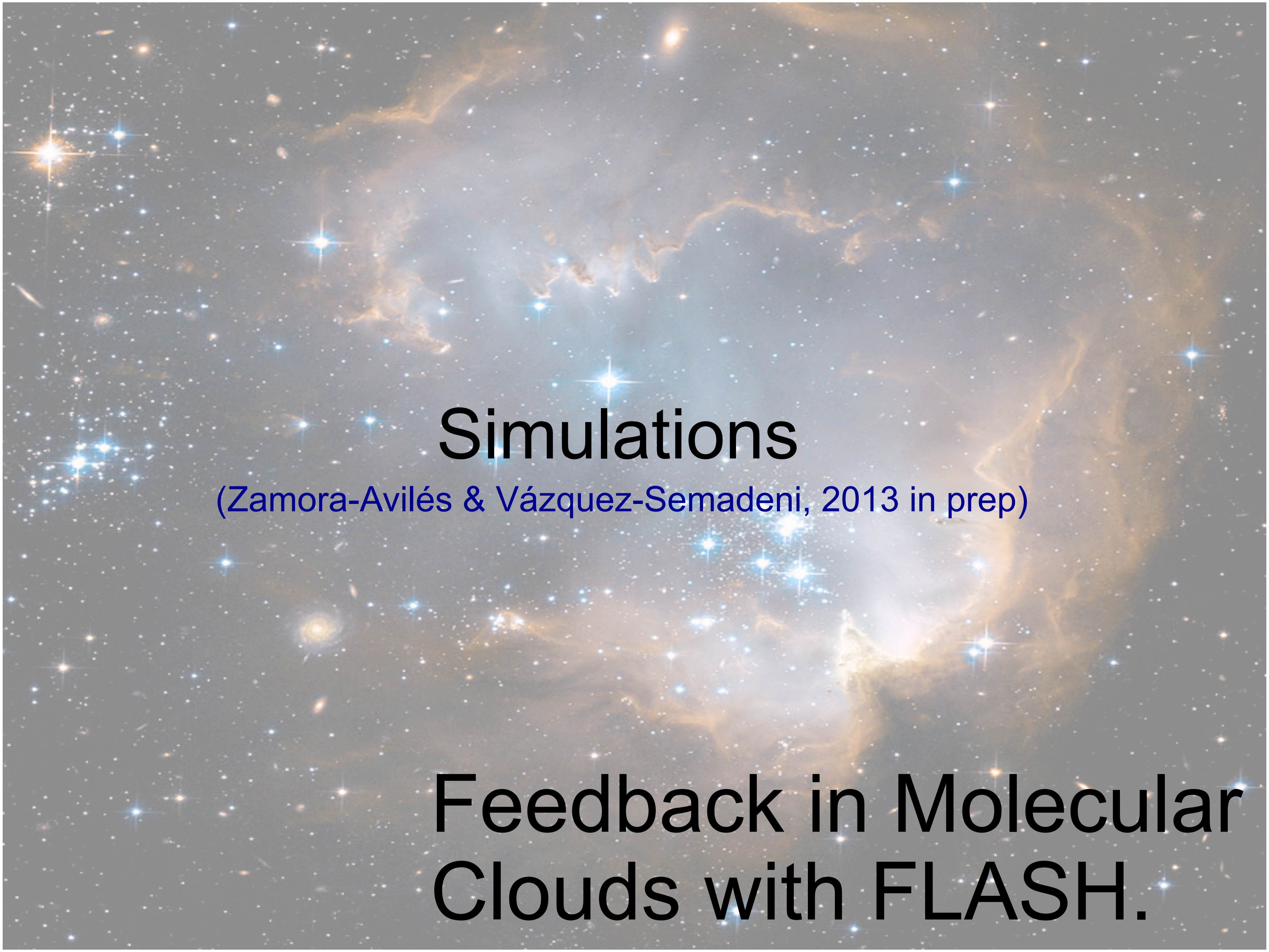
SFR-M_{dens} Diagram





SFR= $4.4\,M_\odot yr^{-1}$

$n_{dens} = 3 \times 10^4\ cm^{-3}$

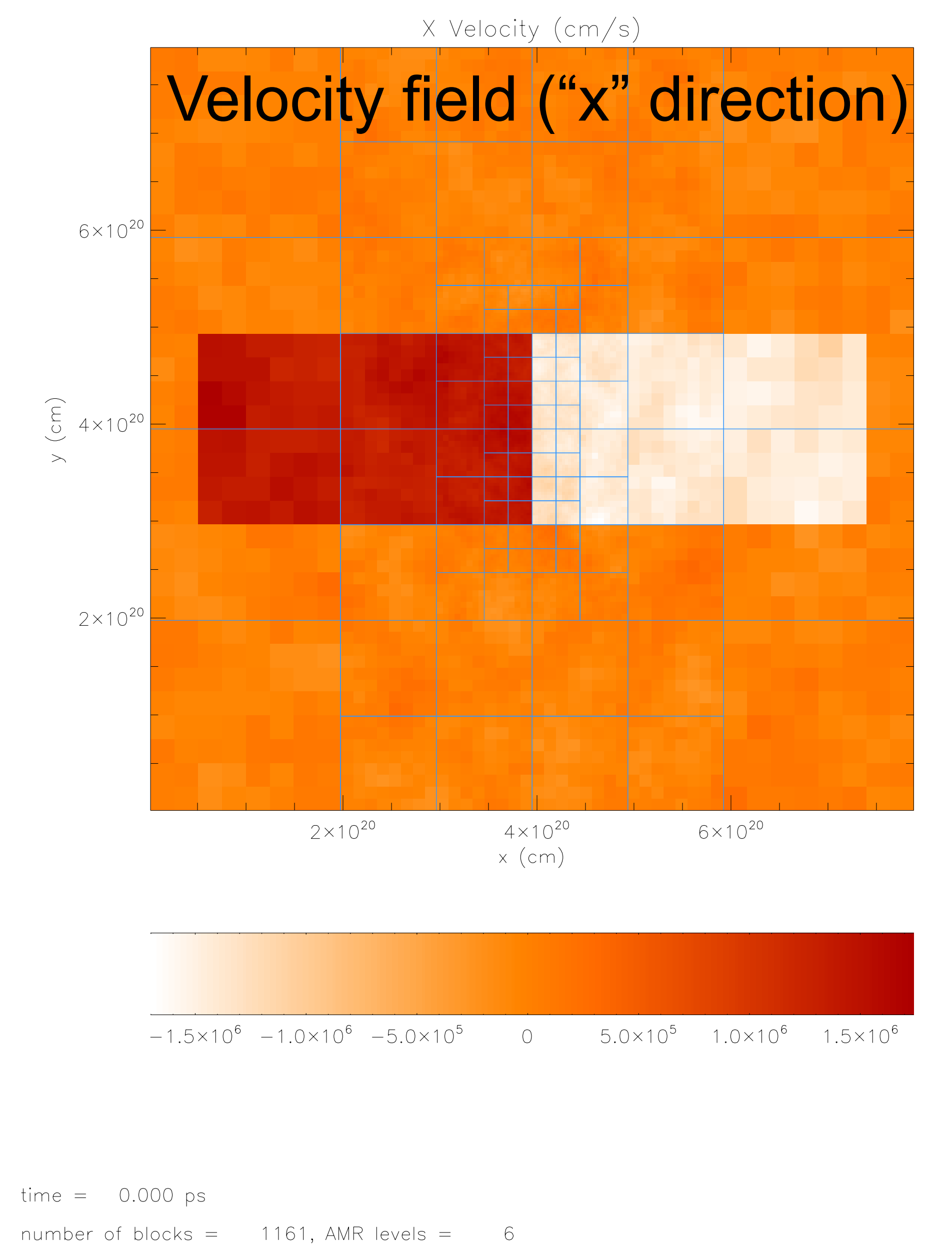


Simulations

(Zamora-Avilés & Vázquez-Semadeni, 2013 in prep)

Feedback in Molecular Clouds with FLASH.

FLASF setup…


Velocity field (“x” direction)

•The FLASH (AMR) code Includes:

- Magnetic Field
- Self gravity
- Radiative cooling and heating
- Stellar feedback (UV)

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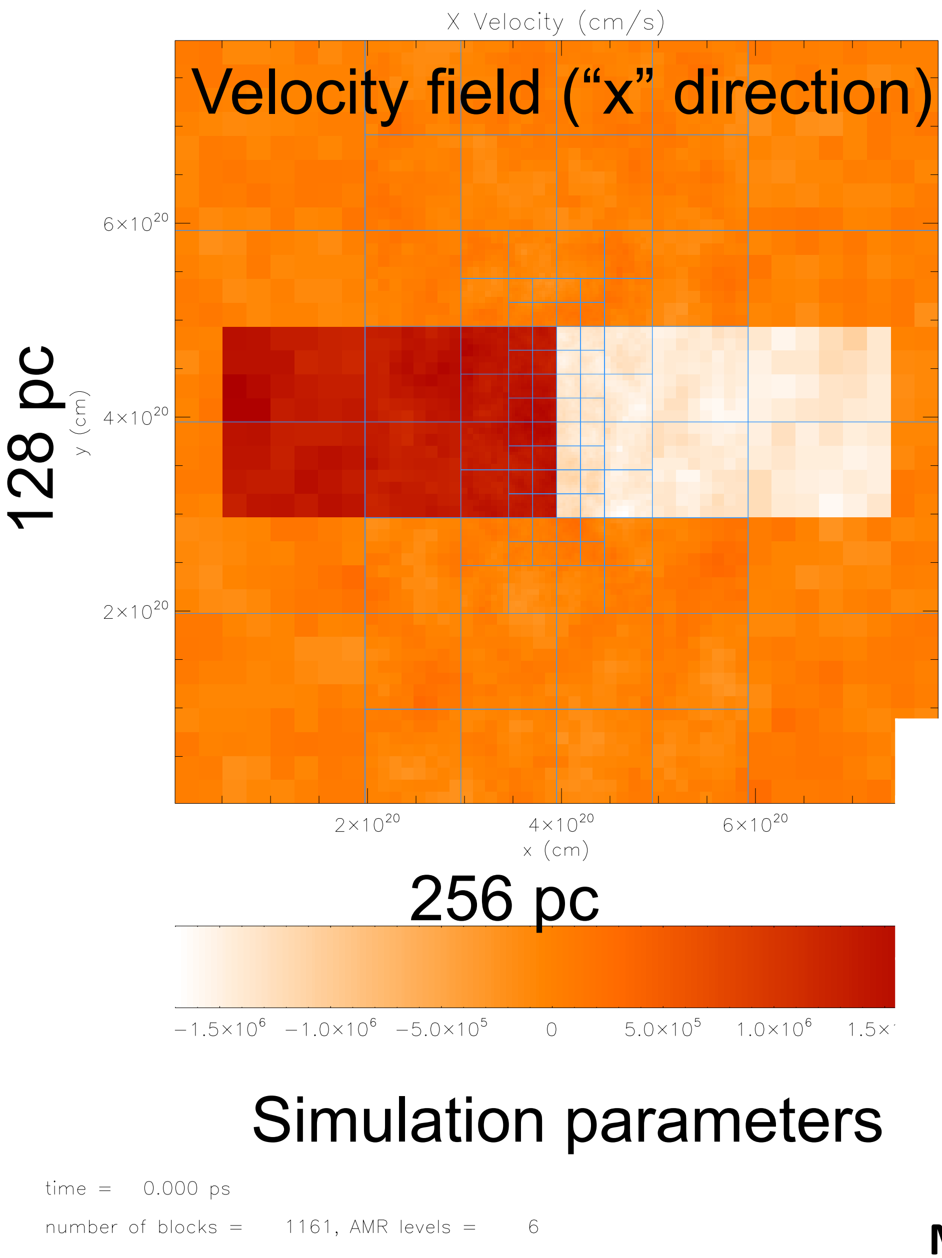
Box size	256 x 128^2 pc^3
Levels	10
Resolution	0.03 pc



Simulation parameters

Inflow number density	2 cm^{-3}
Inflow Mach number	2.44
Inflow radius	32 pc
Inflow length	112 pc
Initial rms Mach number	0.7
Sink formation threshold	4 x 10^6 cm^{-3}
Magnetic Field (x direction)	3 μG

Star formation prescription

Jeans criterion ⟹

(Truelove,1997)

$$\lambda_J/\Delta x \geqslant 4$$

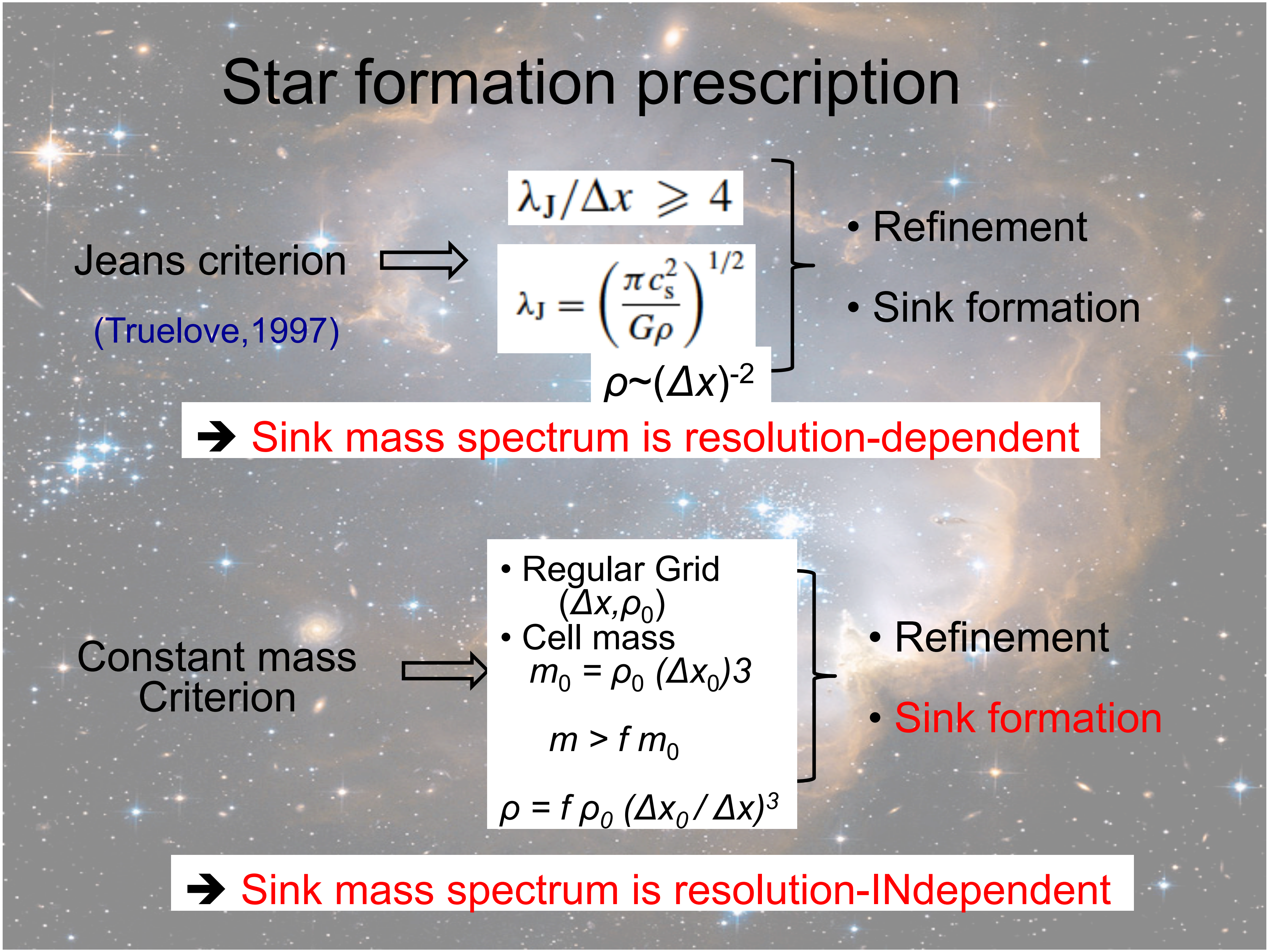
$$\lambda_J = \left(\frac{\pi c_s^2}{G\rho}\right)^{1/2}$$

$\rho \sim (\Delta x)^{-2}$

- Refinement
- Sink formation

➔ Sink mass spectrum is resolution-dependent

Star formation prescription



Jeans criterion ⇨

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➔ Sink mass spectrum is resolution-dependent

Constant mass Criterion ⇨

- Regular Grid $(\Delta x, \rho_0)$
- Cell mass $m_0 = \rho_0 (\Delta x_0)3$

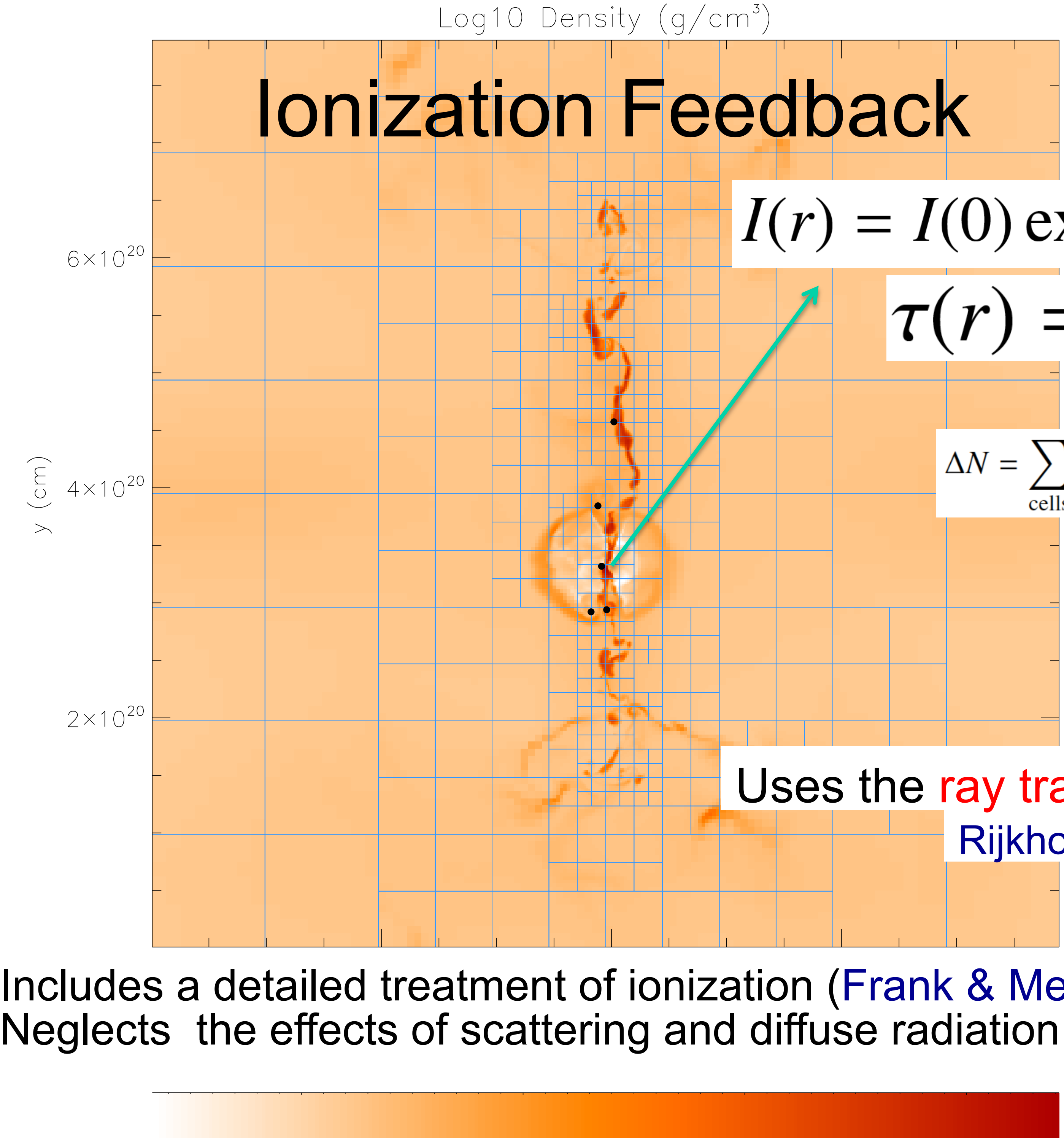
$m > f\, m_0$

$\rho = f\, \rho_0\, (\Delta x_0 / \Delta x)^3$

- Refinement
- Sink formation

➔ Sink mass spectrum is resolution-INdependent

Ionization Feedback



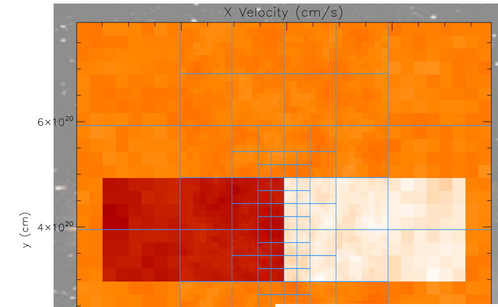
$$I(r) = I(0)\exp(-\tau(r))$$

$$\tau(r) = a_0 N(r)$$

$$\Delta N = \sum_{\text{cells}} x(\text{HI})n(\text{H})\Delta s,$$

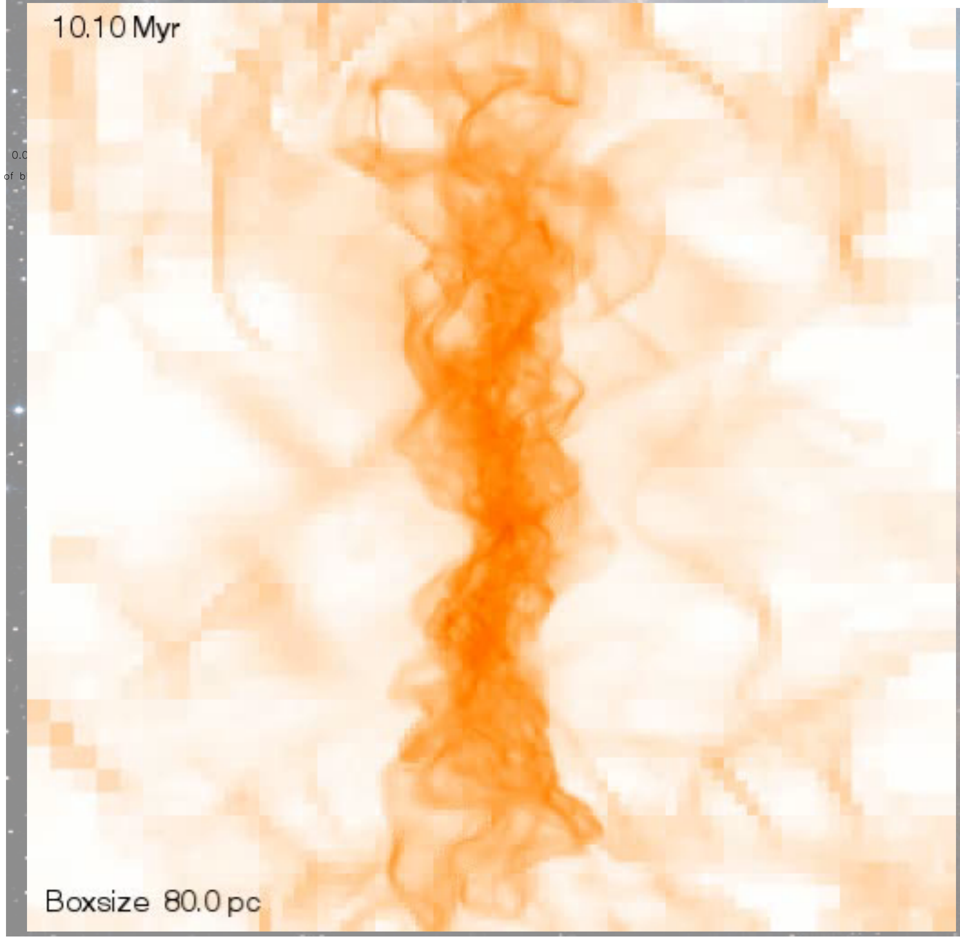
Uses the ray tracing method
Rijkhorst et al. (2006)

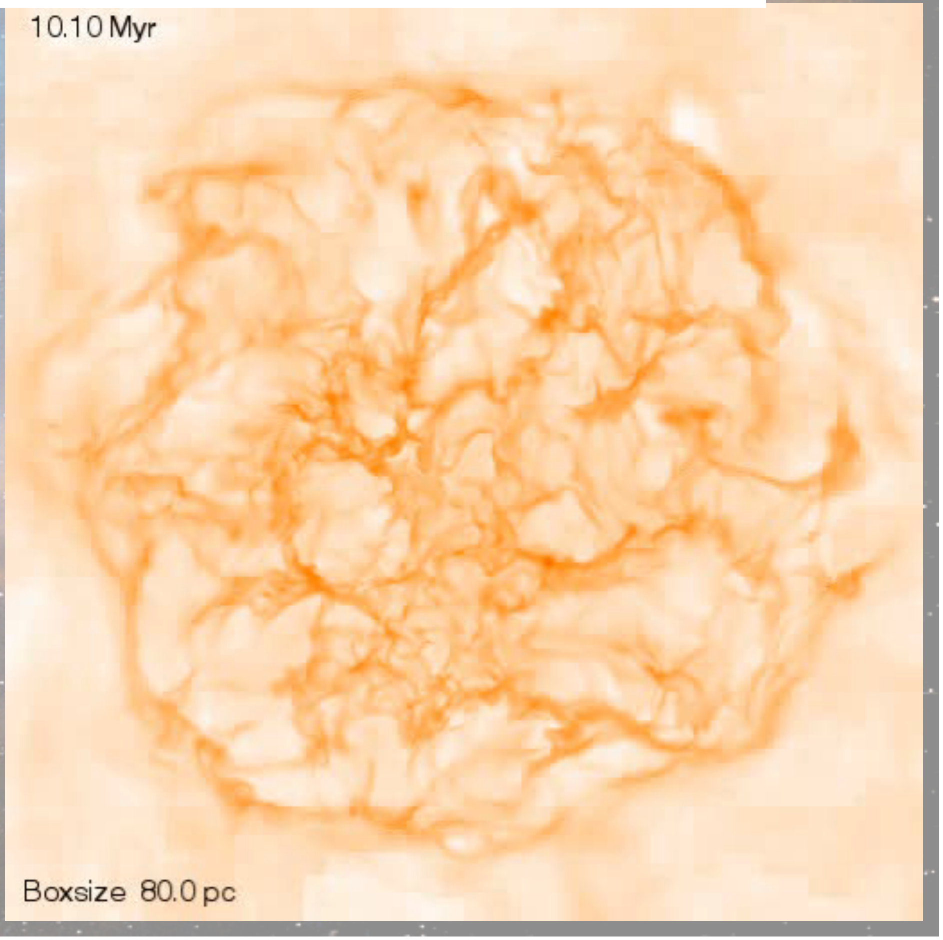
-Includes a detailed treatment of ionization (Frank & Mellema, 1994)
-Neglects the effects of scattering and diffuse radiation.



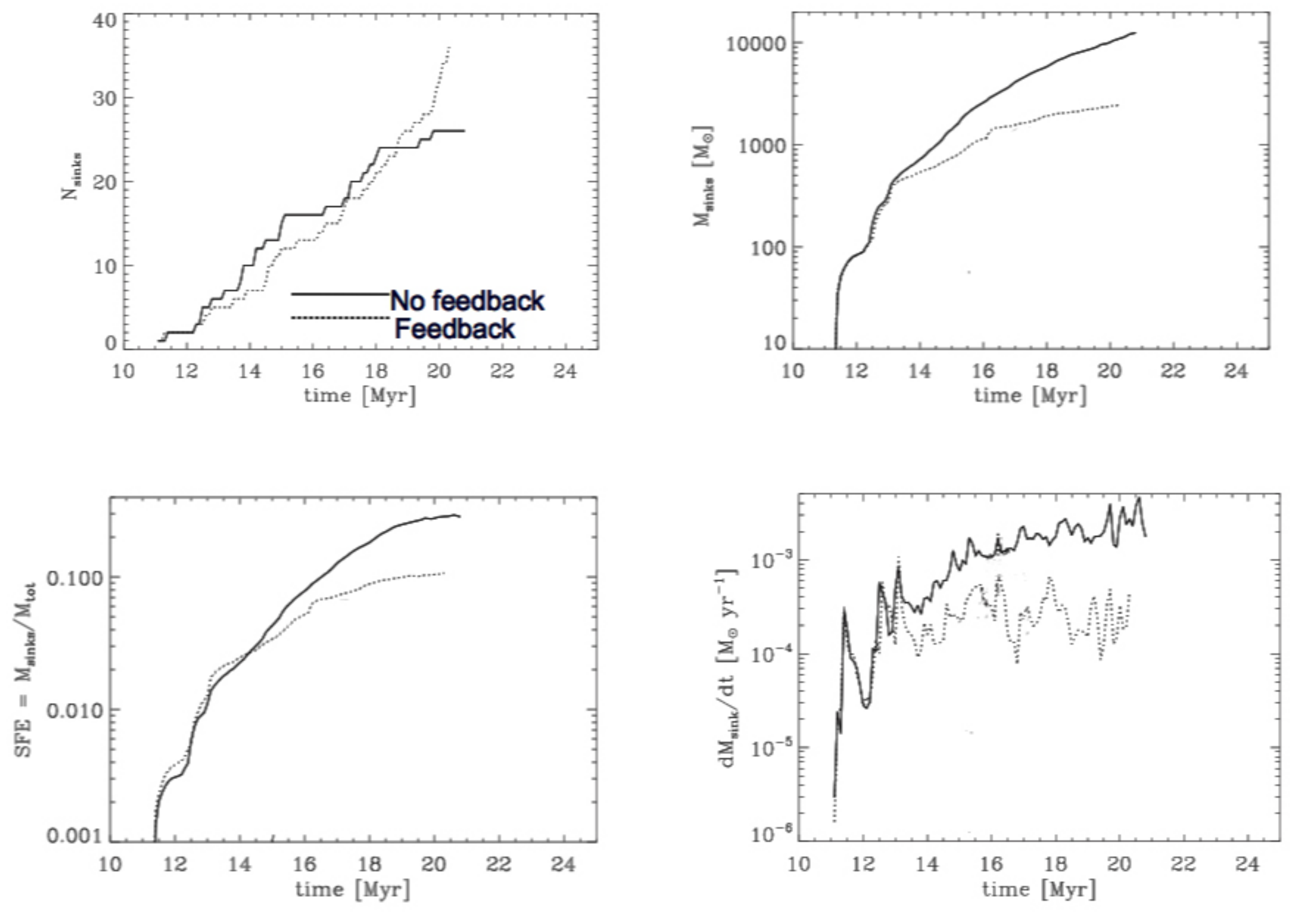
Box size	256x128^2 pc^3
Levels	10
Resolution	0.03 pc

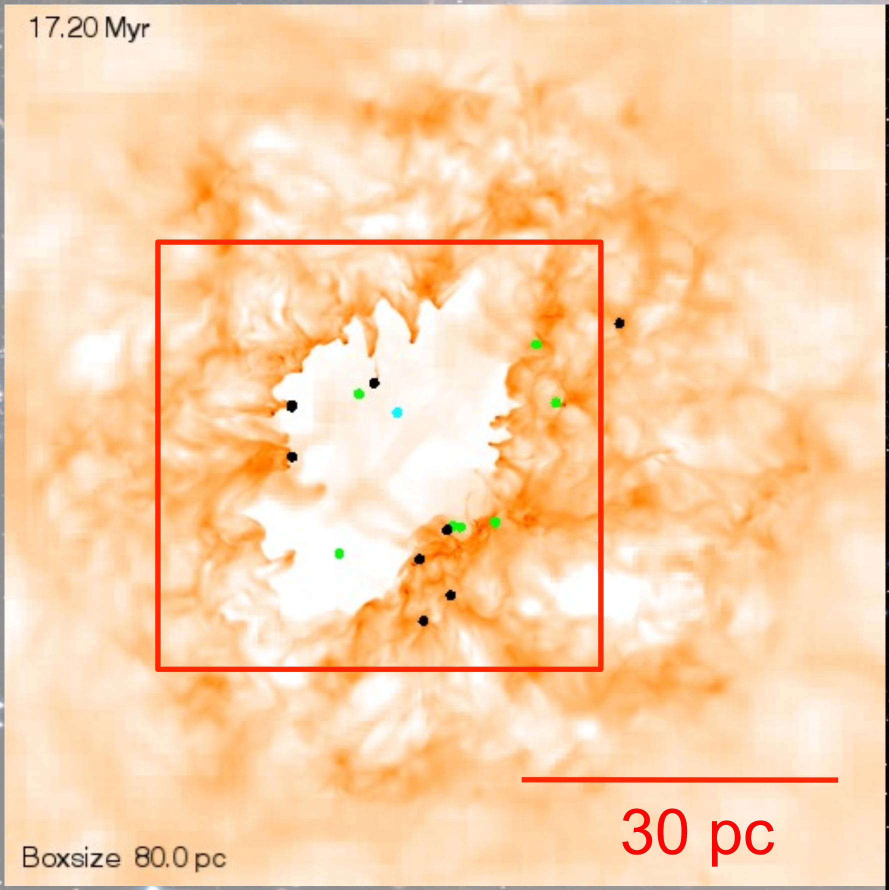
Inflow number density/Temp	2 cm^{-3} / 1450 K
Inflow Mach number	2.44
Inflow radius	32 pc
Inflow length	112 pc
Initial rms Mach number	0.7
Sink formation threshold	4 x 10^6 cm^{-3}
Magnetic Field (x direction)	3 μG



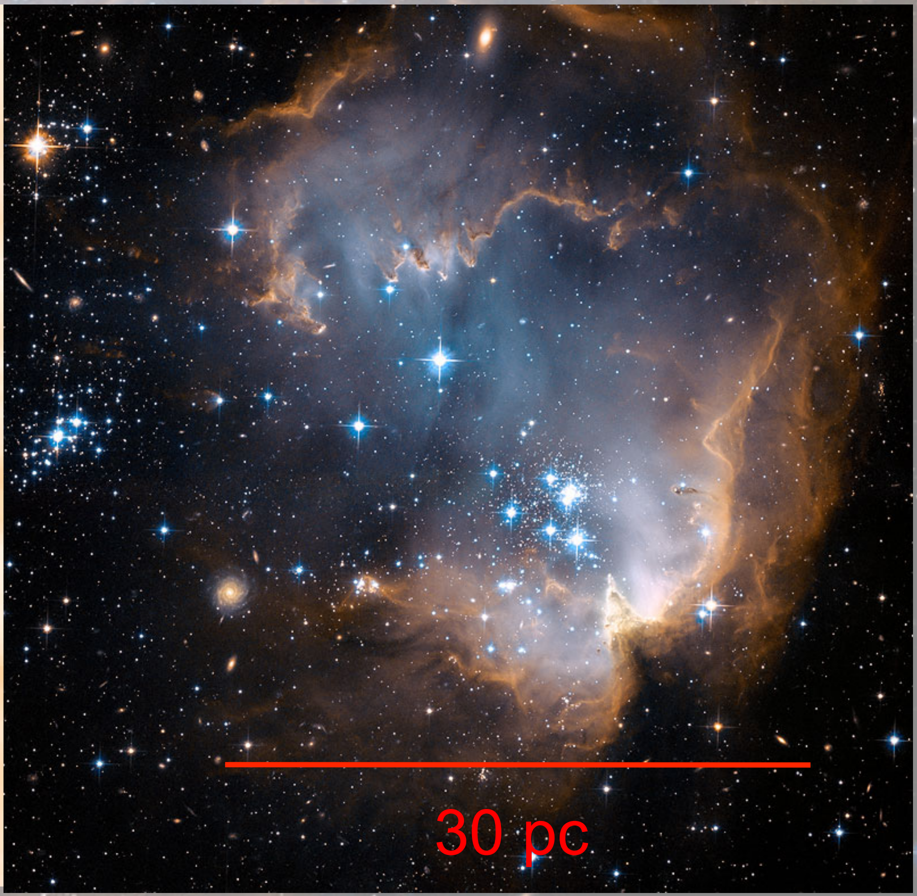


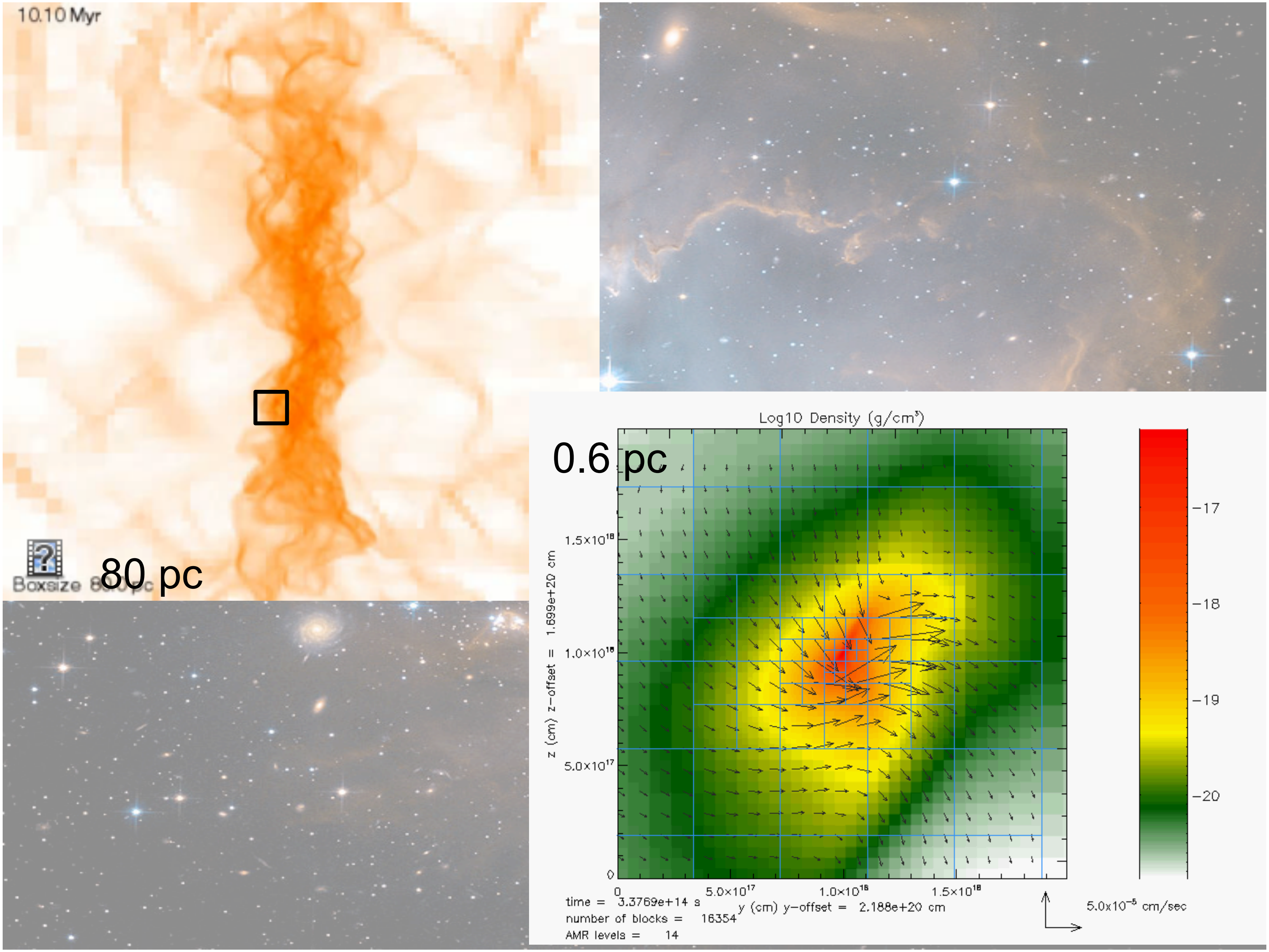
The feedback regulates the SFR and the sink MF





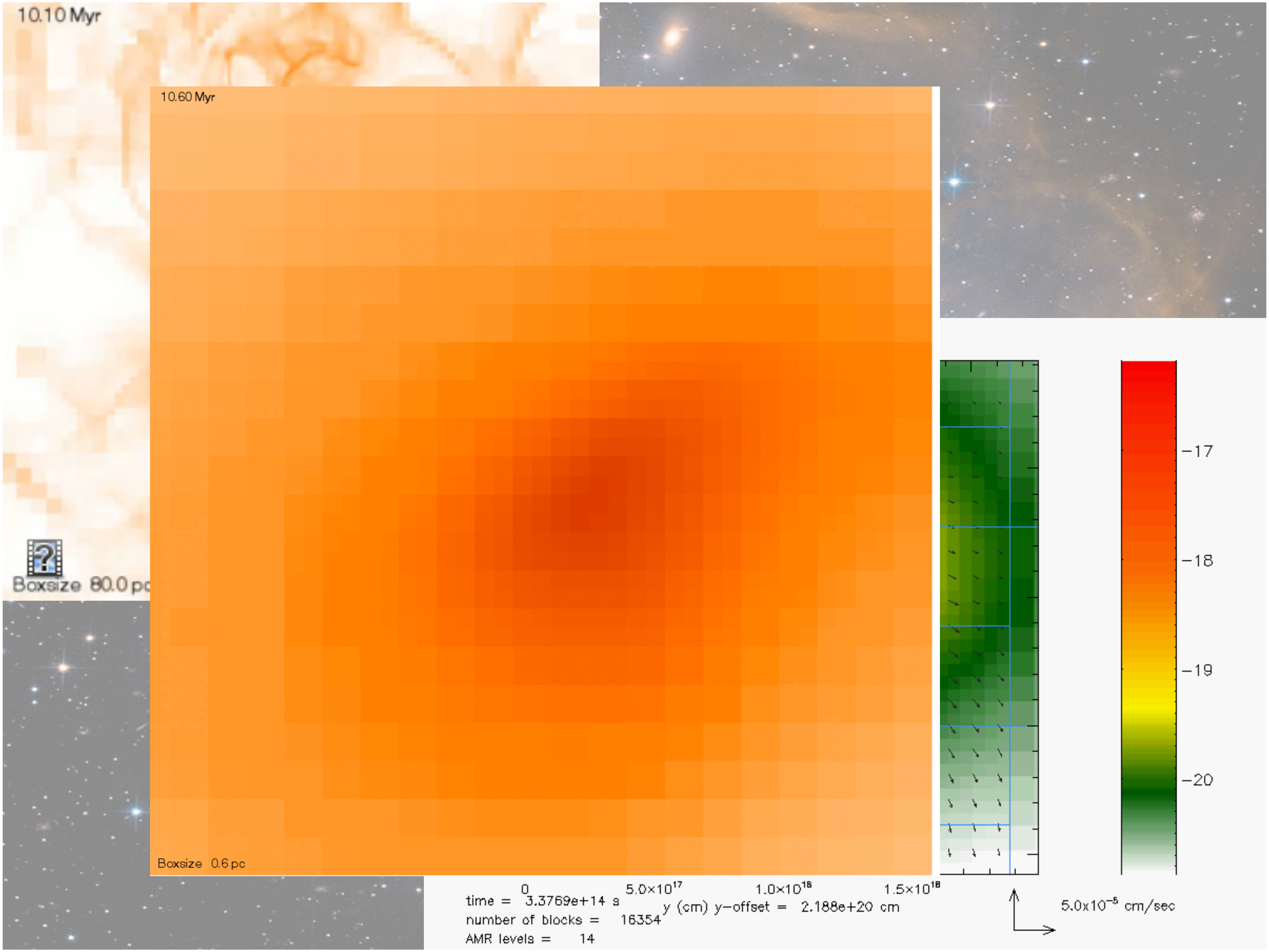
NGC 602 / N90

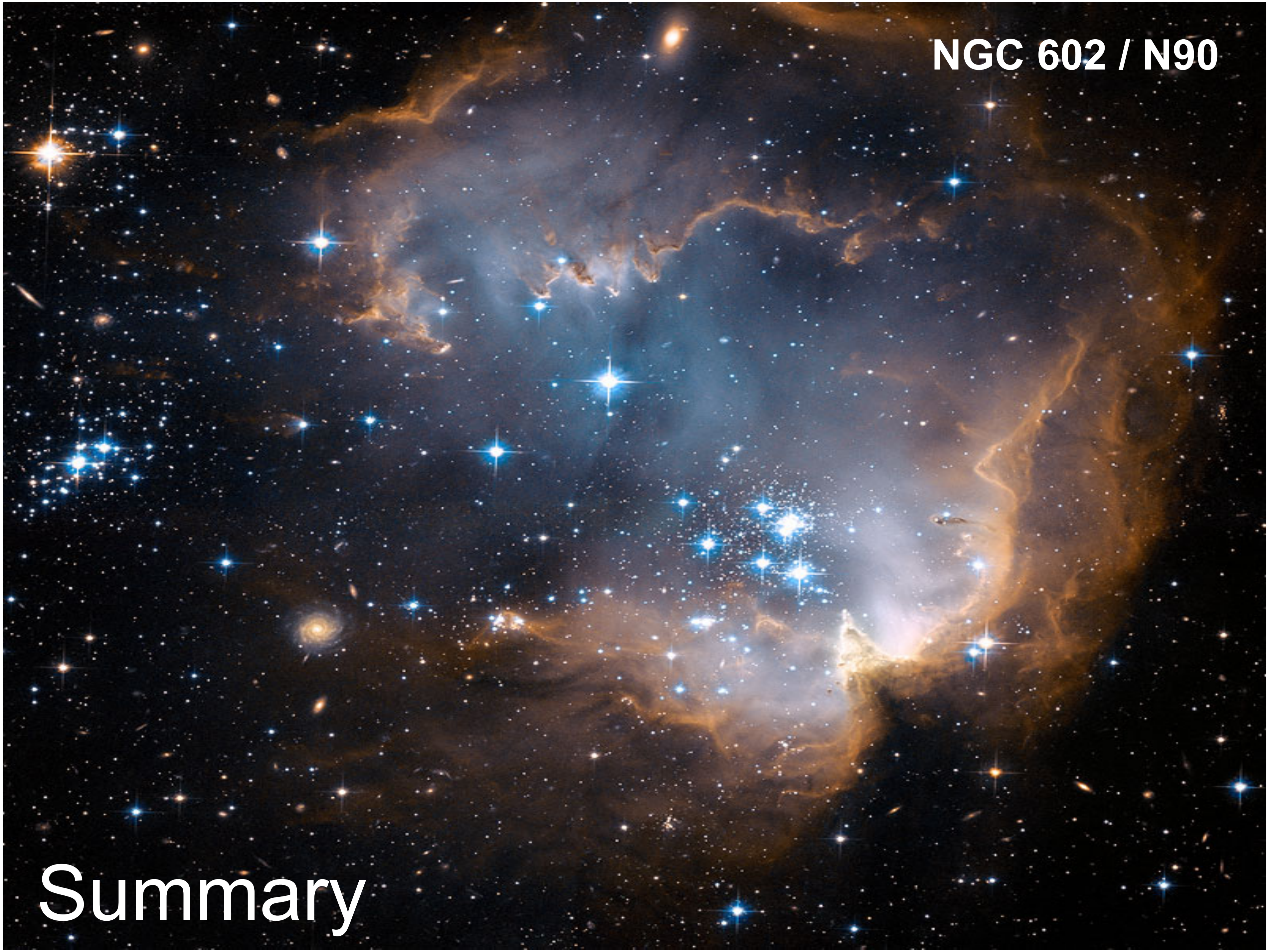



10.10 Myr
Boxsize
Log10 Density (g/cm³)
1.5×10¹⁸
1.0×10¹⁸
5.0×10¹⁷
0
z (cm) z−offset = 1.699e+20 cm
0
5.0×10¹⁷
1.0×10¹⁸
1.5×10¹⁸
y (cm) y−offset = 2.188e+20 cm
−17
−18
−19
−20
5.0x10⁻⁵ cm/sec
time = 3.3769e+14 s
number of blocks = 16354
AMR levels = 14

80 pc

0.6 pc


10.10 Myr
Boxsize 80.0 pc
10.60 Myr
Boxsize 0.6 pc
−17
−18
−19
−20
0
5.0×10^{17}
1.0×10^{18}
1.5×10^{18}
time = 3.3769e+14 s
number of blocks = 16354
AMR levels = 14
y (cm) y−offset = 2.188e+20 cm
5.0×10^{-5} cm/sec



Summary

-The isolated-cloud model evolves, first resembling low-mass star-forming clouds, and later high-mass star forming regions.

- The SFR accelerates over time.
- The majority of massive stars are formed in the last few Myr, at which point the model resembles massive star-forming regions.

-Our models are consistent with the stellar age distributions presented by Palla & Stahler (2000) for various clusters and associations.

-Our models agree with the evolutionary GMC scenario for GMCs recently proposed by Kawamura et al. (2009).

-Our models occupy the locus of individual low- to intermediate-mass observed clouds in the Kennicutt-Schmidt diagram.

- Like observed individual clouds, they lie higher in the diagram than spatially-averaged (galaxy-scale or kpc-scale) regions (Kennicutt 98, Bigiel+ 08, Leroy+08)
    - ==> large-scale averages include much non-star-forming gas.

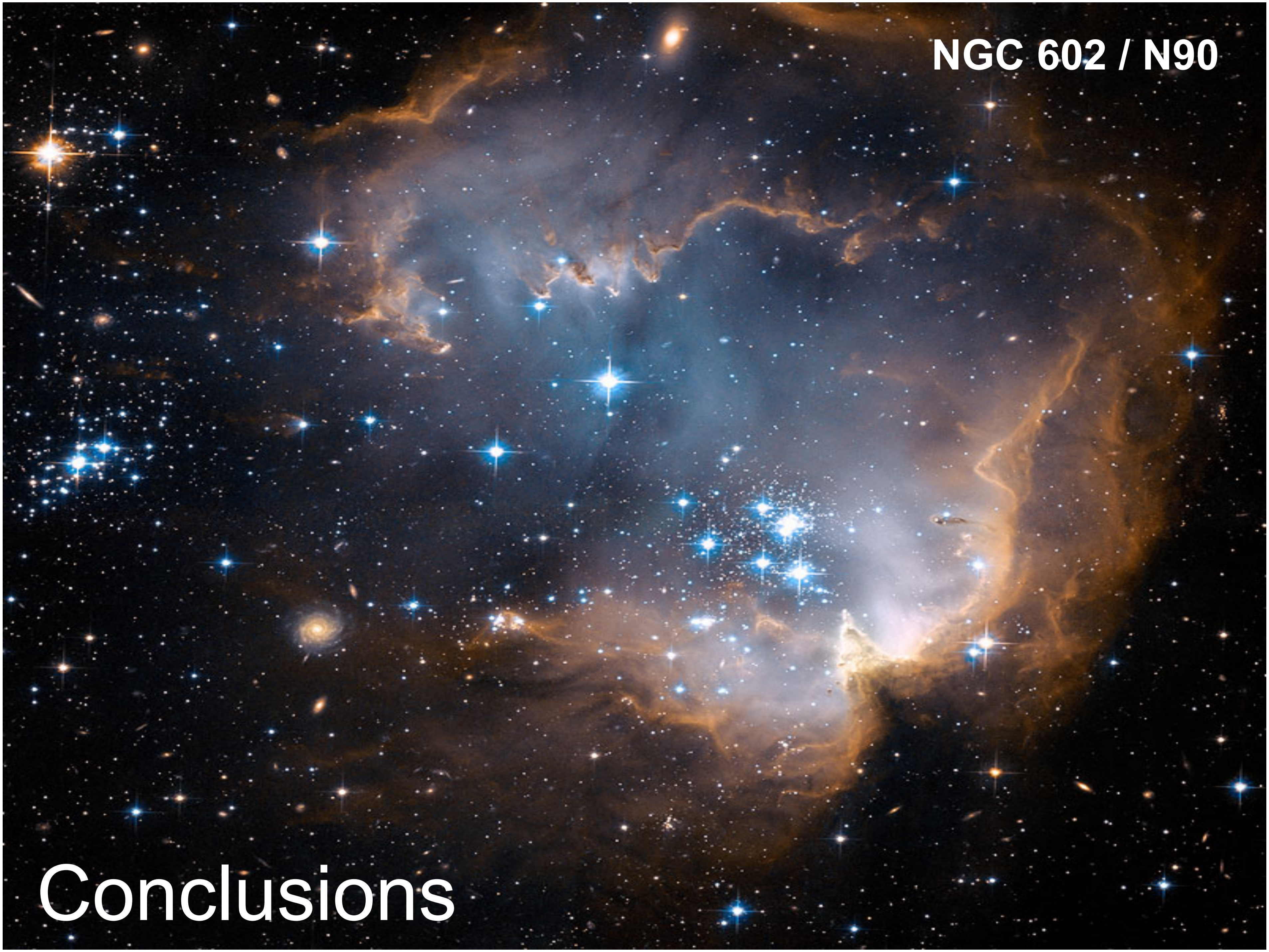
- The *SFR* and the dense gas mas (M_{dens}) averages follows the Gao and Solomon (2004) relationship.
- The models show the relations

$$\langle \mathrm{SFR} \rangle \approx 100 \left(1 + \frac{M_{\max}}{2 \times 10^5 \, \mathrm{M}_\odot}\right)^2 \mathrm{M}_\odot \, \mathrm{Myr}^{-1},$$

$$< SFE >= 0.02 \left(\frac{M_{\max}}{10^5 \, \mathrm{M}_\odot}\right)^{0.3}$$

About the simulations…

- The feedback:
  - Regulates the SFR and the sink MF
  - … by disrupting the cloud and terminating the local SF burst.



Conclusions

- The proposed resolution to the SFR conundrum is that the early collapses produce enough massive stars to eventually disrupt the cloud long before all of its mass is consumed.
- We have obtained realistic MC properties. This suggests that the scenario of global cloud collapse, with the SFR and SFE regulated by massive star-feedback is plausible.

Thank you.