The SFR of MCs in SN-Driven Turbulence

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Four papers on SN-driven turbulence at 250 pc scale:

Supernova Driving. IV. The Star-formation Rate of Molecular Clouds
Padoan et al. 2017, ApJ 840, 48

Supernova Driving. III. Synthetic Molecular Cloud Observations
Padoan et al. 2016, ApJ 826, 140

Supernova Driving. II. Compressive Ratio in Molecular-Cloud Turbulence
Pan et al. 2016, ApJ 825, 30

Supernova Driving. I. The Origin of Molecular Cloud Turbulence
Padoan et al. 2016, ApJ 822, 11

A physical SFR law

- Gravitational energy
- Kinetic energy
- Thermal energy
- Magnetic energy

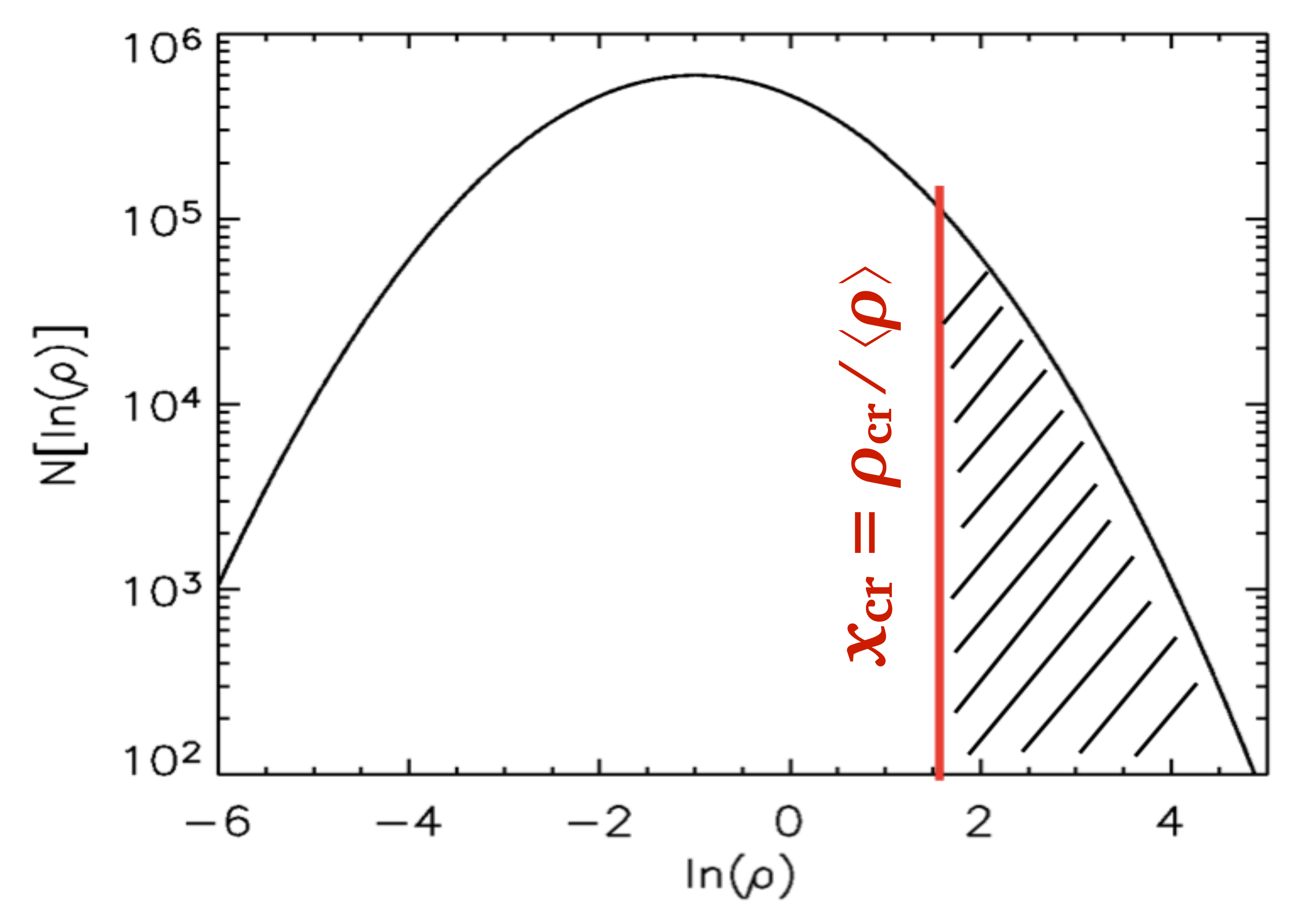
$\longrightarrow$ Three non-dimensional parameters: $\alpha_{\rm vir}$, $\mathscr{M}_{\rm S}$, β

$$\boxed{\mathbf{SFR = f\,(\,\alpha_{vir},\ \mathscr{M}_S,\ \beta,\ \chi\,)}}$$

But what matters is the compressible fraction of the Mach number, $\chi\,/\,(\,1+\chi\,)\,\mathscr{M}_{\rm S}$, where $\boldsymbol{\chi} = \langle u_c^2\rangle/\langle u_s^2\rangle$ is the compressive ratio

The SFR in the turbulent fragmentation model

Turbulence helps: $$p(x)dx = \frac{x^{-1}}{(2\pi\sigma^2)^{1/2}} \exp\left[-\frac{(\ln x + \sigma^2/2)^2}{2\,\sigma^2}\right] dx \qquad x = \rho / \langle\rho\rangle$$



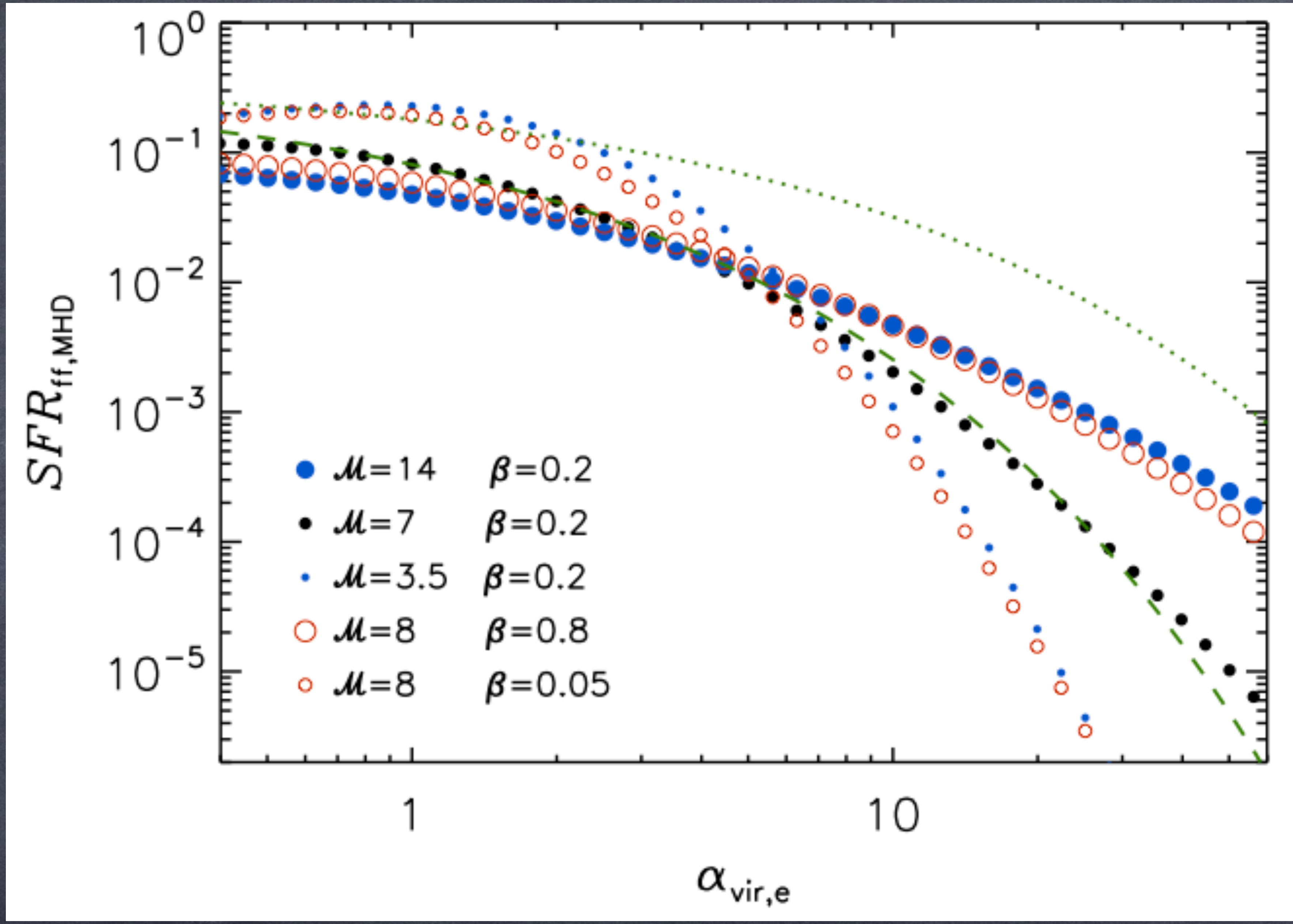
The SFR is the integral of the PDF above a critivcal density, divided by a timescale:

$$SFR \equiv \int_{x_{cr}}^{\infty} x\, p(x)\, dx \;/\; \tau$$

The crux of the model:

- critical density, x_{cr}
- timescale, τ

Non-dimensional SFR: $SFR_{ff} = SFR \times t_{ff} / M$

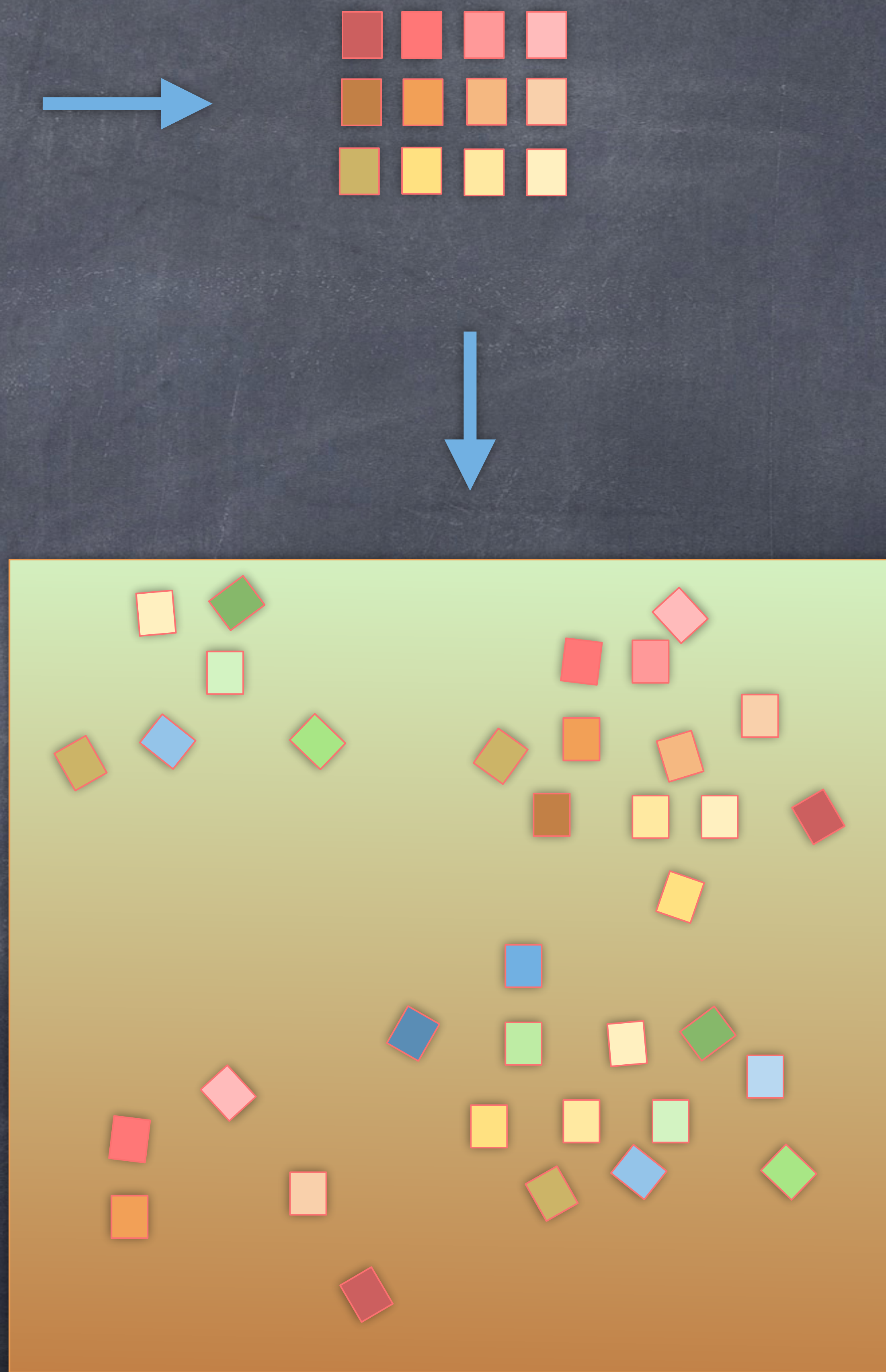


$$SFR_{ff}\,(a_{vir}) = 0.4\,\exp(-1.6\,a_{vir}^{1/2})$$

Numerical tests of the SFR law

Previously

Parameter studies with idealized simulations (*Padoan and Nordlund 2011, Federrath and Klessen 2012, Padoan et al. 2012*)



Caveats:

- isothermal, randomly-driven, no larger-scale context
- initialization and time evolution of SF are somwehat artificial
- no idea about realistic distributions of parameters
- no prediction for the scatter in the SFR

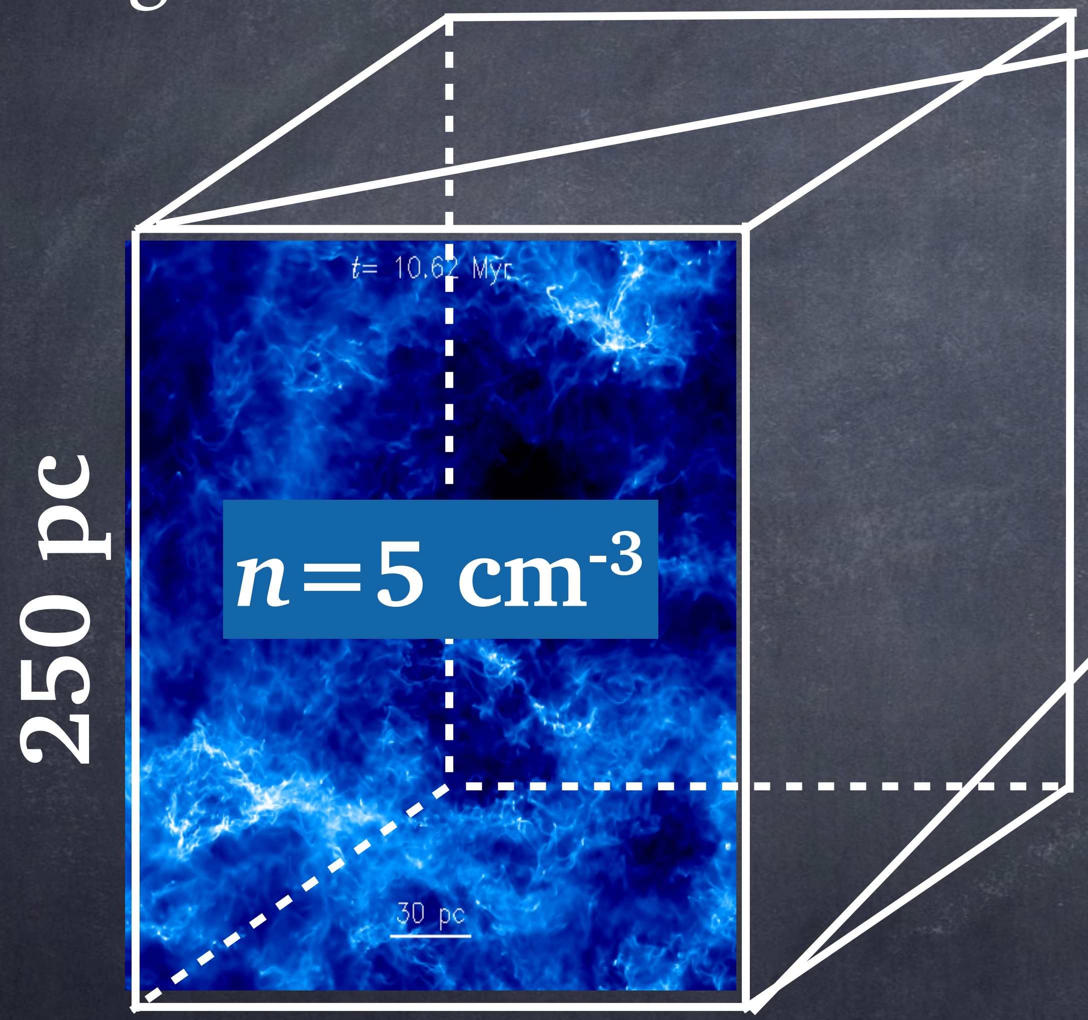
<u>Better approach:</u>

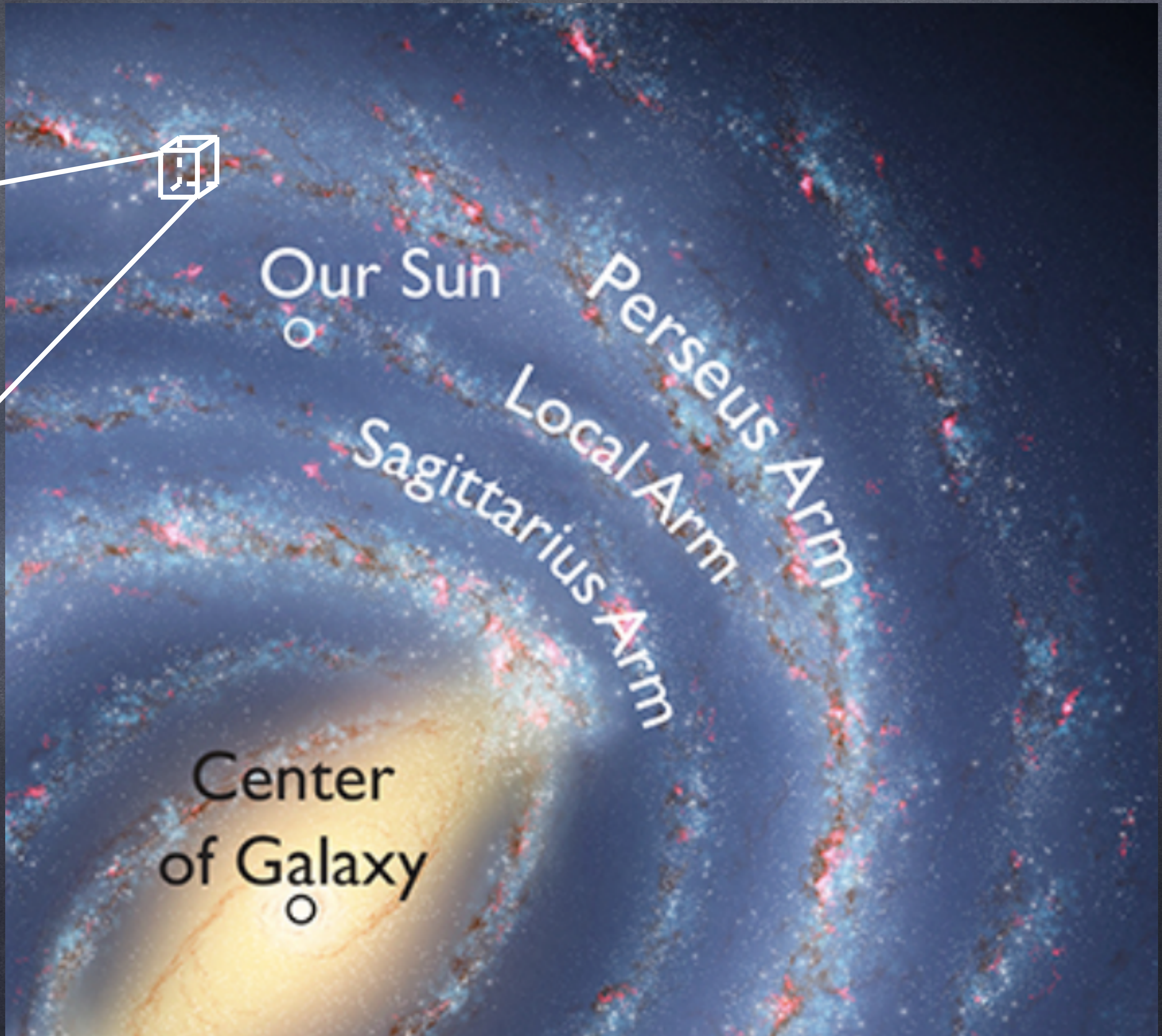
*A single simulation of a much-larger scale (**5 pc —> 250 pc**) and much-longer integration time (**2 Myr —> 100 Myr**), with realistic driving (e.g. SNe).*

Then we obtain hundreds of star-forming regions formed ab initio, with realistic distributions of ICs and BCs.

We simulate a 250 pc (*periodic*) 2.e6 $M_\odot$ chunk of a spiral arm

Outer scale ≲ 100 pc, so going much above 250 pc is a waste of dynamic range.





First random SNe, ~6 SNe/Myr

<u>Then **real SNe** from resolved stars</u>

Model Setup (*Ramses*):

- **Physics:** 3D MHD equations, parametrized cooling and heating, individual SNe (thermal energy with exponential profile)

- **Resolution:** dx=0.0076 pc (512^3 root grid + 6 AMR levels), $\boldsymbol{r_{SN}}$**=3dx=0.02 pc**, 2.5e8 tracers
- **AMR criteria:** pressure and density *gradients,* density levels (dx / λ_J = const)

- **Initial conditions:** Uniform n=5 cm^{-3}, uniform B=4.6 muG

- **Total time:** 45 Myr with random SNe + 32 Myr with self-gravity, SF and **real SNe**

A huge sample of stars and clouds formed ab initio:

hundreds of SNe and MCs and ~7,000 stars to date

BIG DATA:

$\sim$100 M core hours, 1 yr wall-clock time, 200 TB of data to analyze

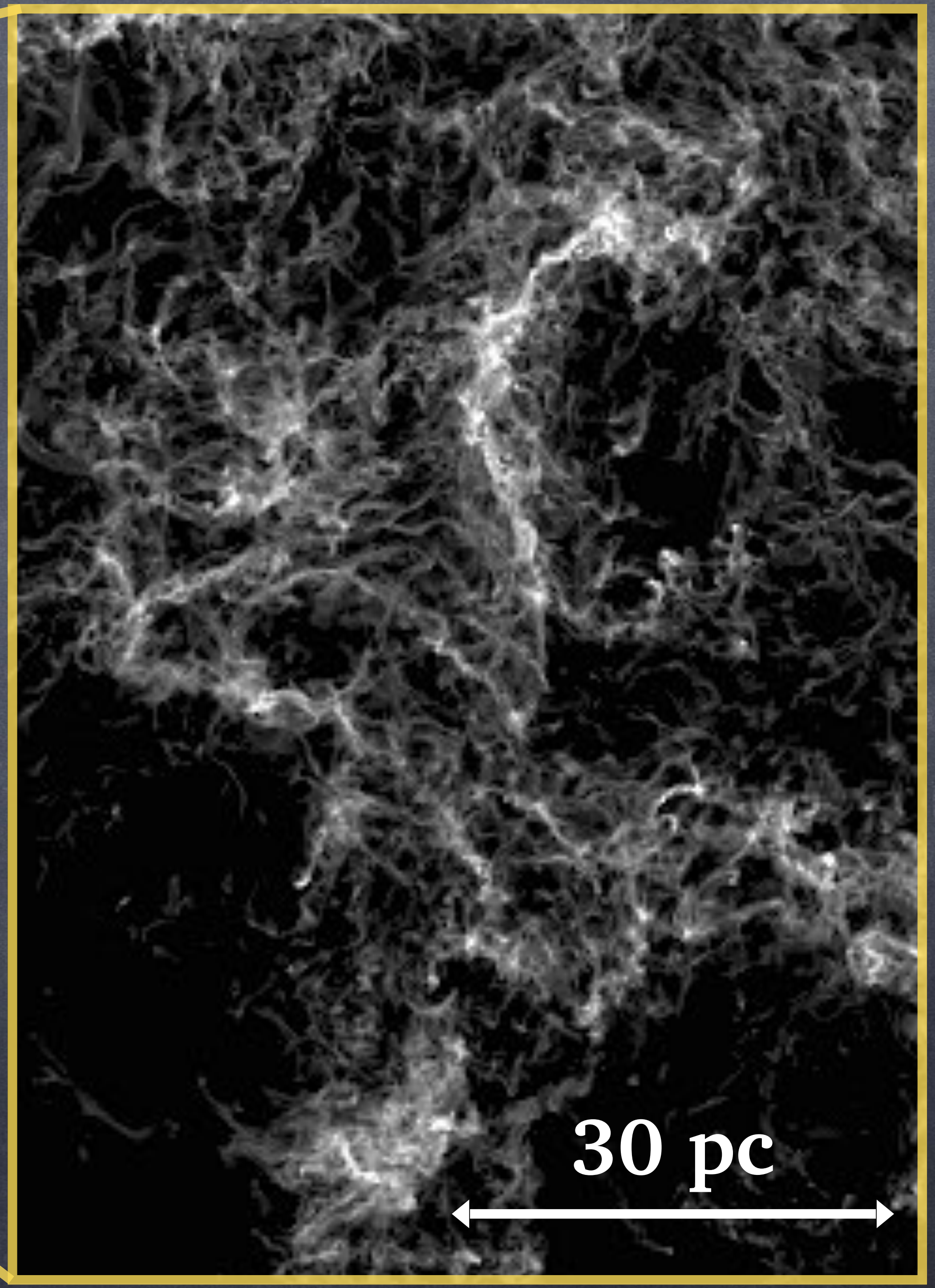
(*NASA High-End Computing, Pleiades+Electra)*

CAVEATS:

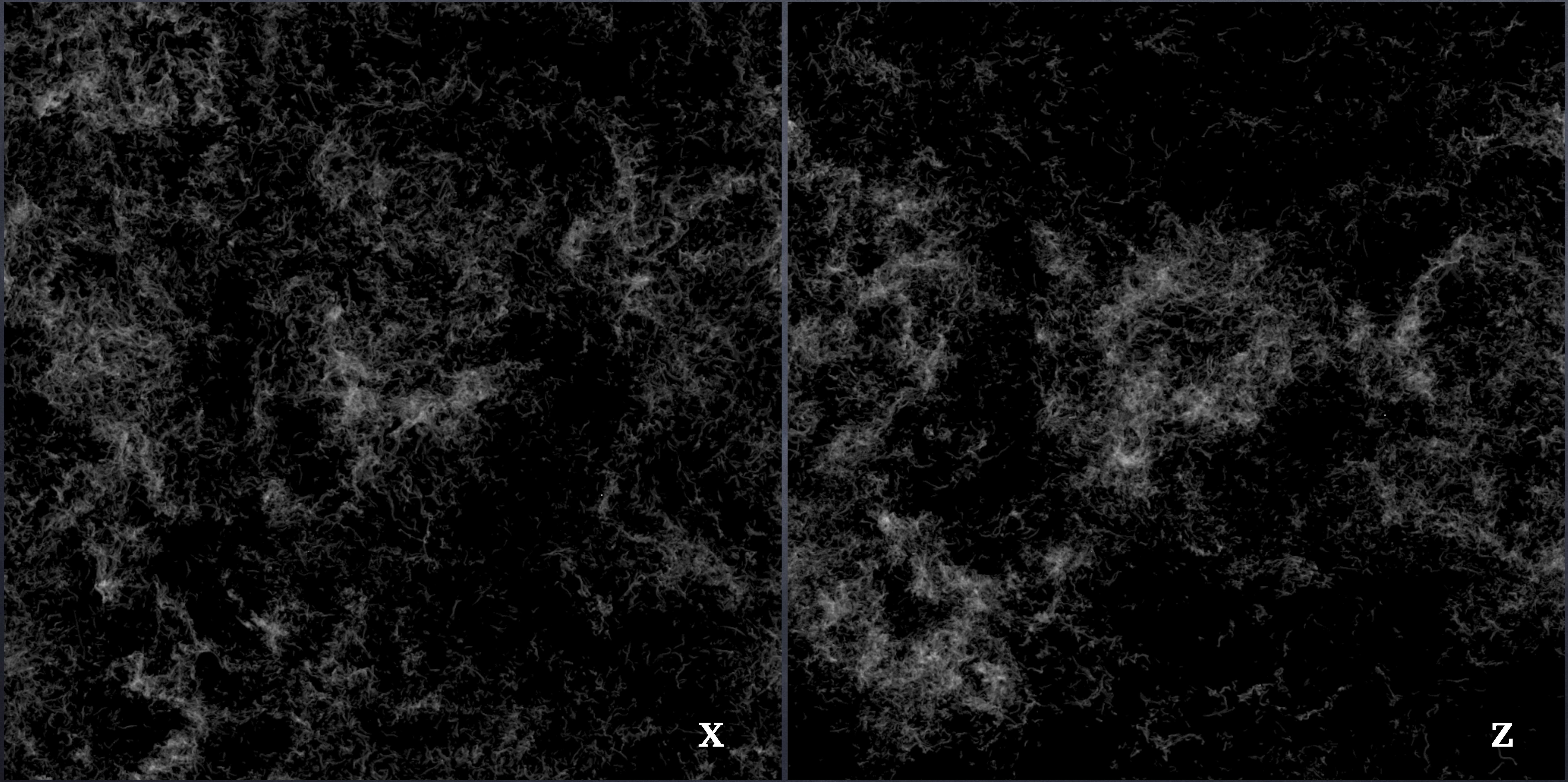
- No chemistry (H2 and CO formation)
- No escape of hot gas
- No parameter study for the largest scale

Although the mean density is fixed at 250 pc, we have a huge sample on MC scales, much better than any ad hoc parameter study of MCs.

Very filamentary, but also hundreds of clumps:



Projected density + sinks over ~30 Myr with selfgravity and “real” SNe




100 parsecs
5.27 Myr

Results from the simulation so far:

1) The simulation resolves well the turbulent cascade, from the SN energy injection scale of ~70 pc to ~1 pc within dense clouds (power-law velocity structure functions)

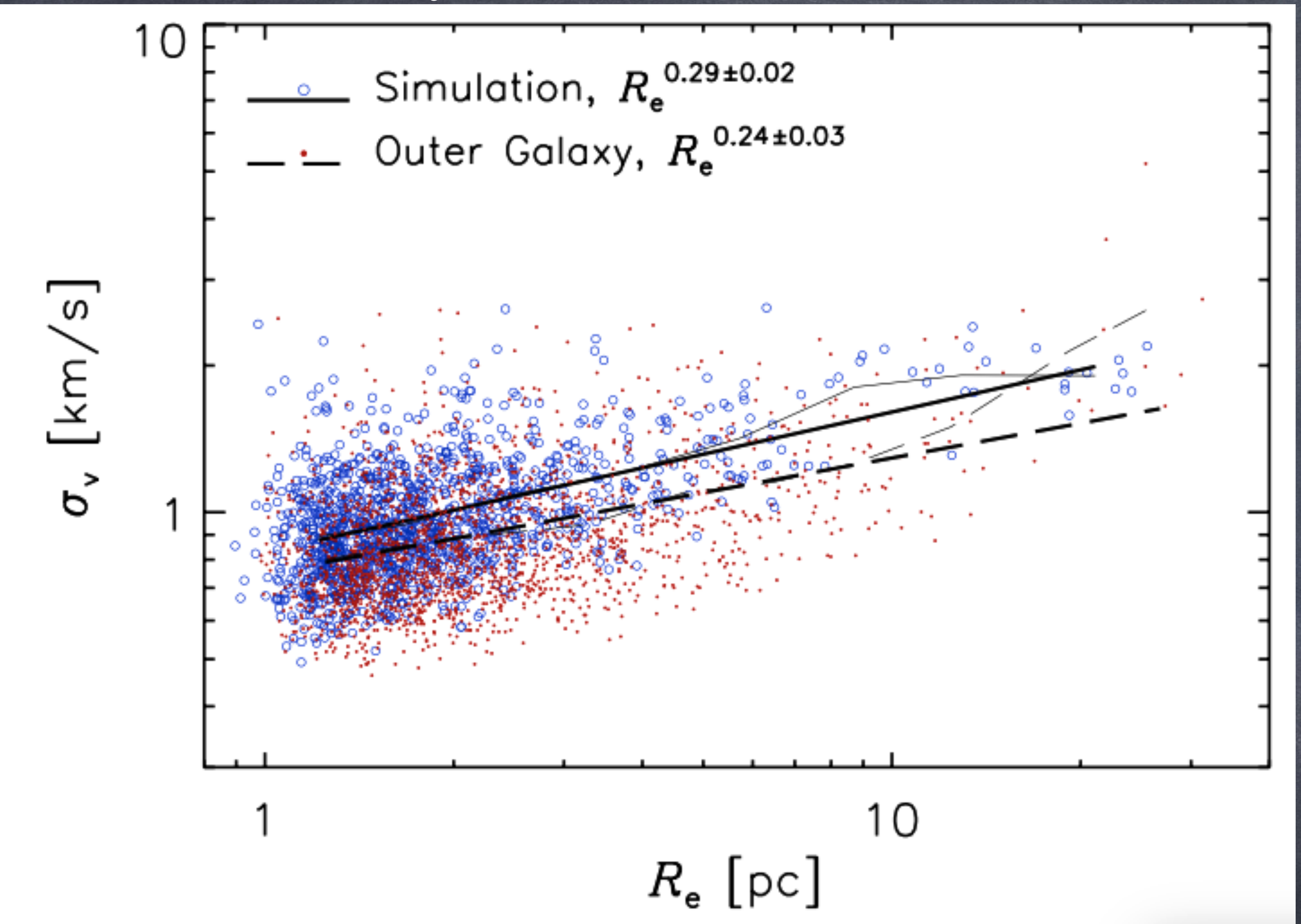
2) The clouds in the simulation reproduce the observed properties of MCs:
   - Larson relations
   - Mass and size distributions

3) Several predictions for MC properties that cannot be observed directly:
   - Virial parameter
   - Lifetime
   - Alfvénic Mach number
   - Compressive ratio
   - PDF of gas density

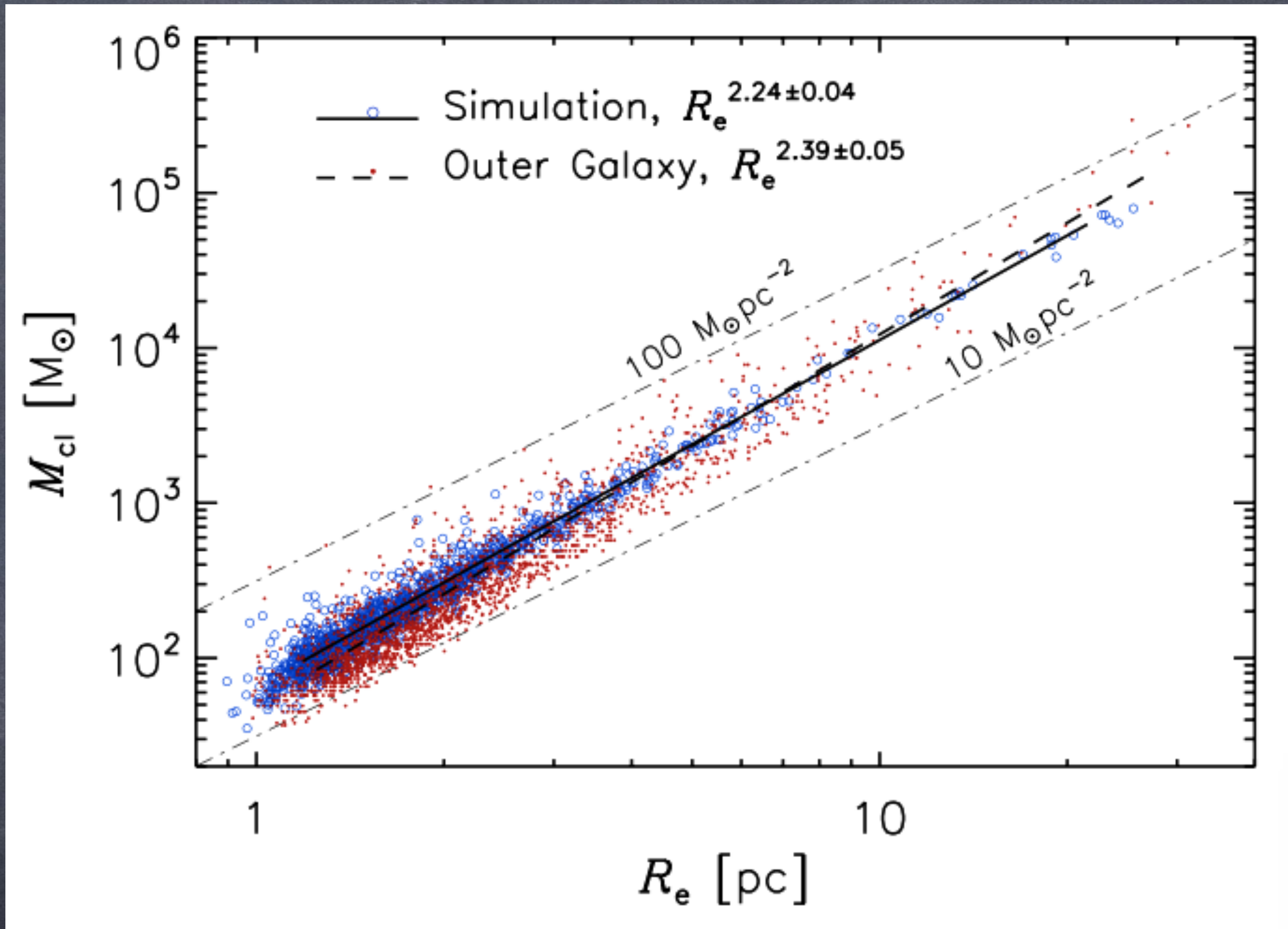
4) SFR (this talk)

Larson Relations from synthetic CO observations

Velocity-size relations



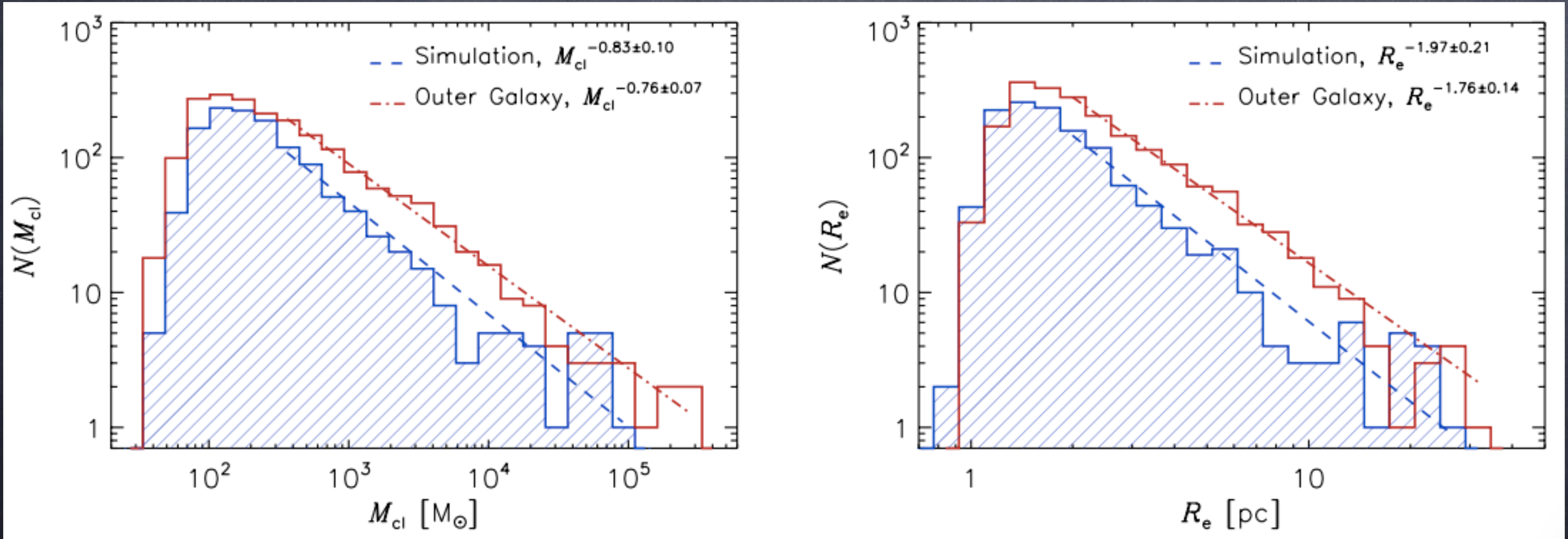
Mass-size relation



- **The relations are the same before and after gravity**
- The slope of the relation is independent of the threshold for MC selection
- Same vertical scatter and slope as in the observations

Probability distributions of MC mass and size

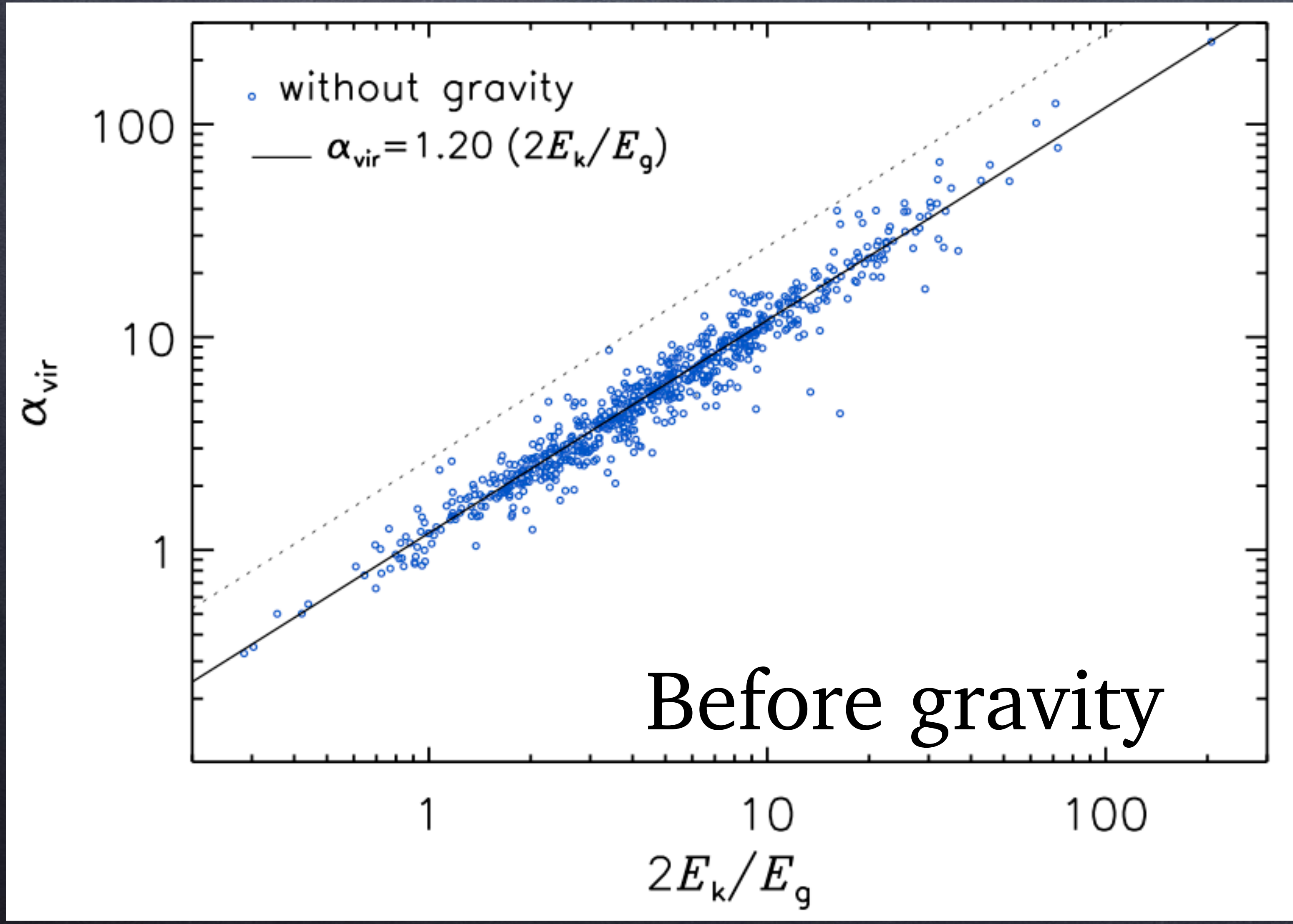
- The slopes of the relations are independent of the brightness threshold of MC selection

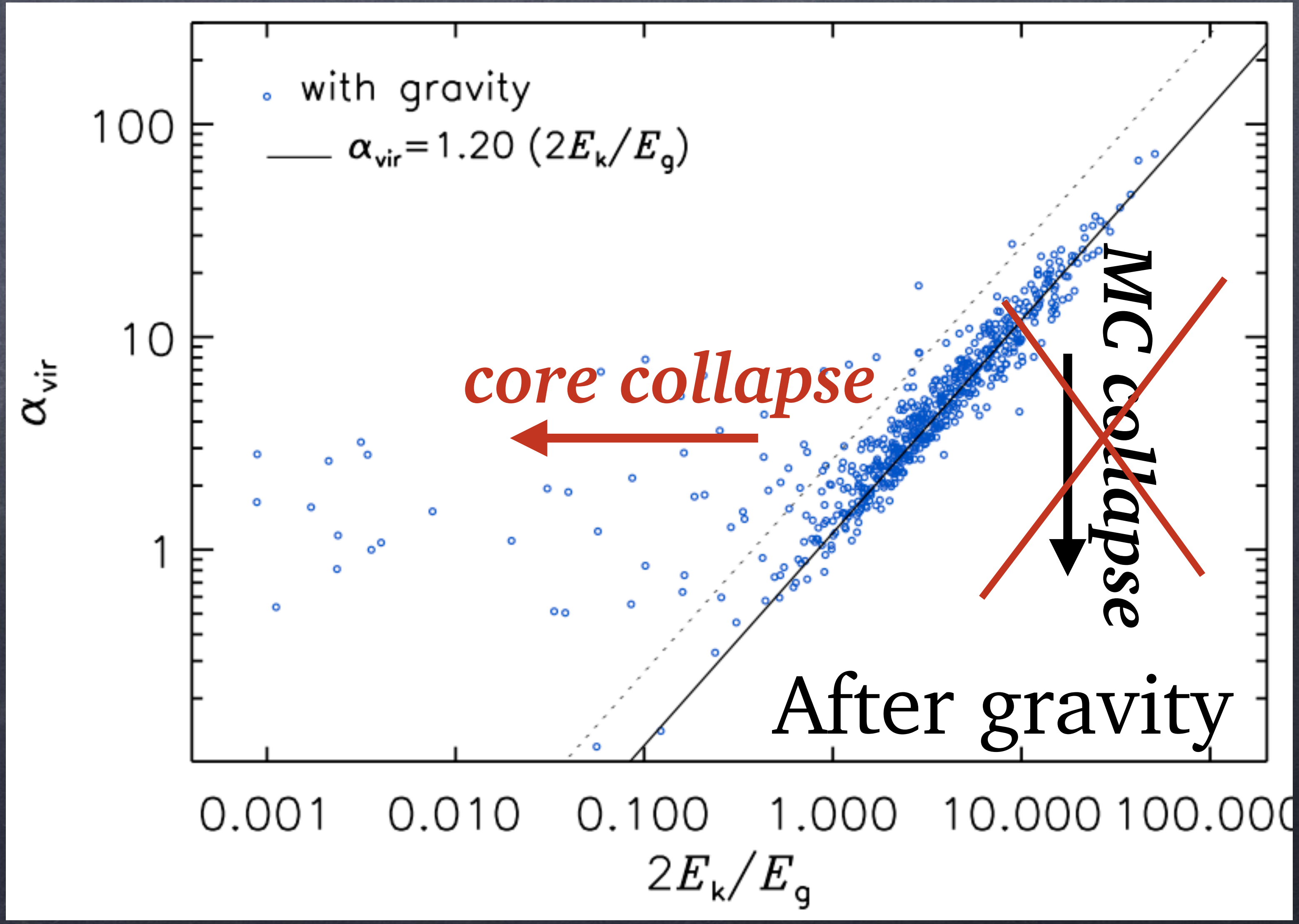


Virial Parameter

$$\alpha_{\rm vir} \equiv \frac{5\sigma_{\rm v}^2 R_{\rm cl}}{G M_{\rm cl}} = \frac{40}{3\pi^2}\left(\frac{t_{\rm ff}}{t_{\rm dyn}}\right)^2 \sim \frac{2E_{\rm k}}{E_{\rm g}}$$

- $\alpha_{\rm vir} \sim 2\, E_{\rm k}/E_{\rm g}$ over 3 orders of magnitude in $E_{\rm k}/E_{\rm g}$
- This ratio is independent of GMC mass (scale-free fractal structure of GMCs)
- $\alpha_{\rm vir}$ is the same before and after gravity, while $E_{\rm k}/E_{\rm g}$ drops in clouds with collapsing cores

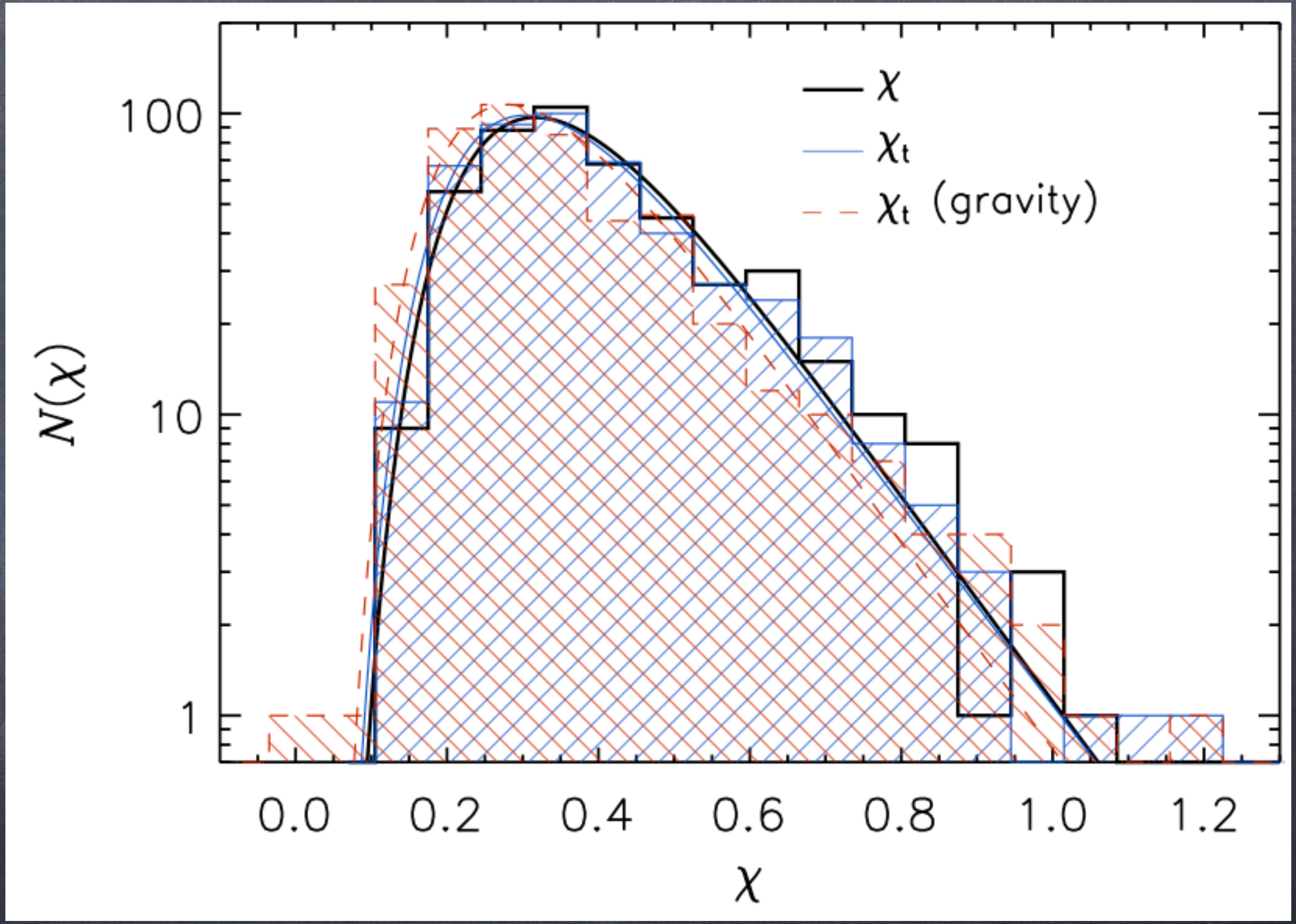




Compressive ratio of MC turbulence

$$\chi \equiv \langle \boldsymbol{v}_{\mathrm{c}}^2 \rangle / \langle \boldsymbol{v}_{\mathrm{s}}^2 \rangle \qquad \chi_{\mathrm{t}} \equiv [\langle \boldsymbol{v}_{\mathrm{c}}^2 \rangle - V_{\mathrm{e}}^2] / [\langle \boldsymbol{v}_{\mathrm{s}}^2 \rangle - V_{\mathrm{r}}^2]$$

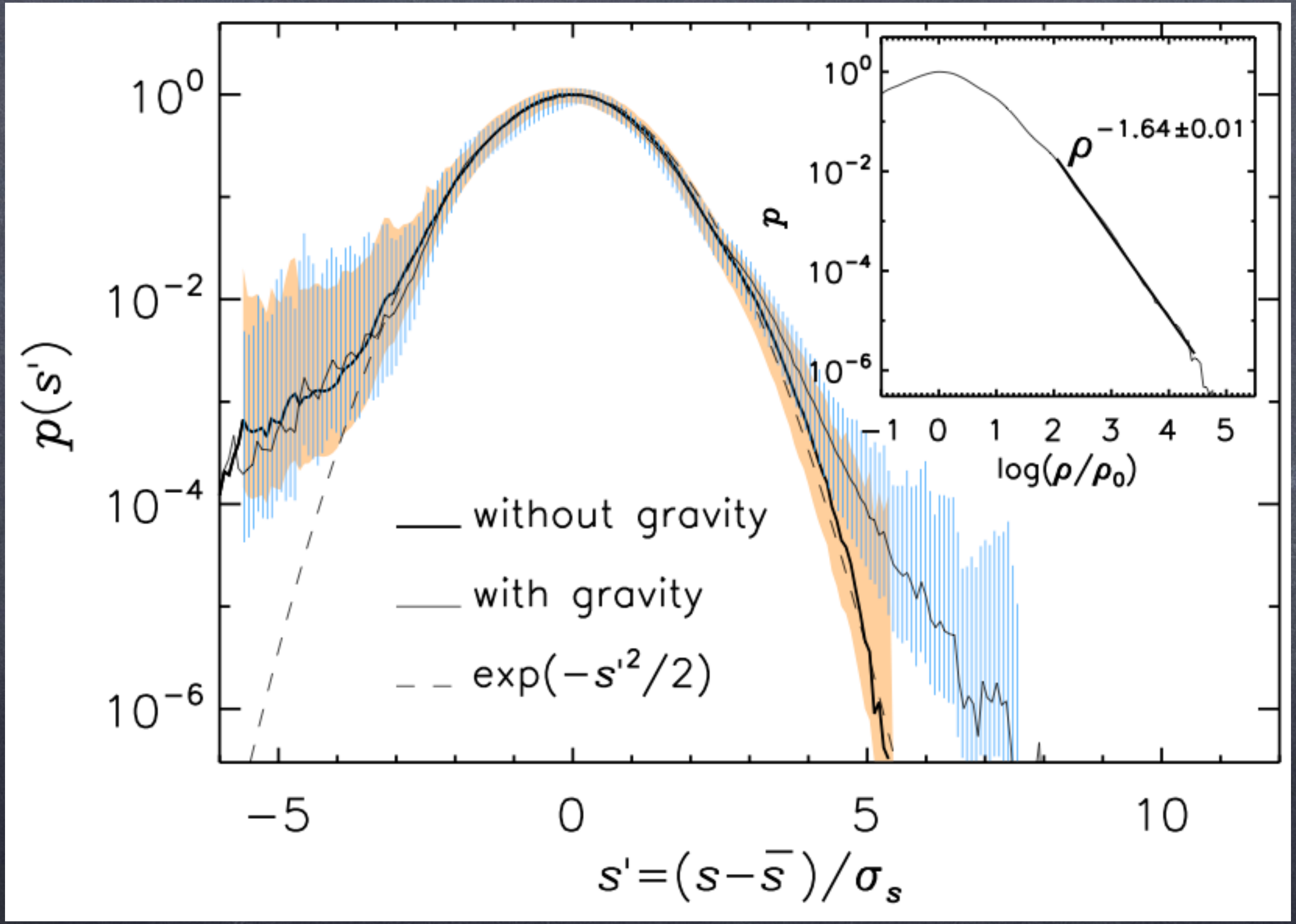
- Broad lognormal distribution of the compressive ratio
- $\langle \chi_{\mathrm{t}} \rangle \simeq \langle \chi \rangle \simeq 0.3 \pm 0.2$
- Same results with gravity



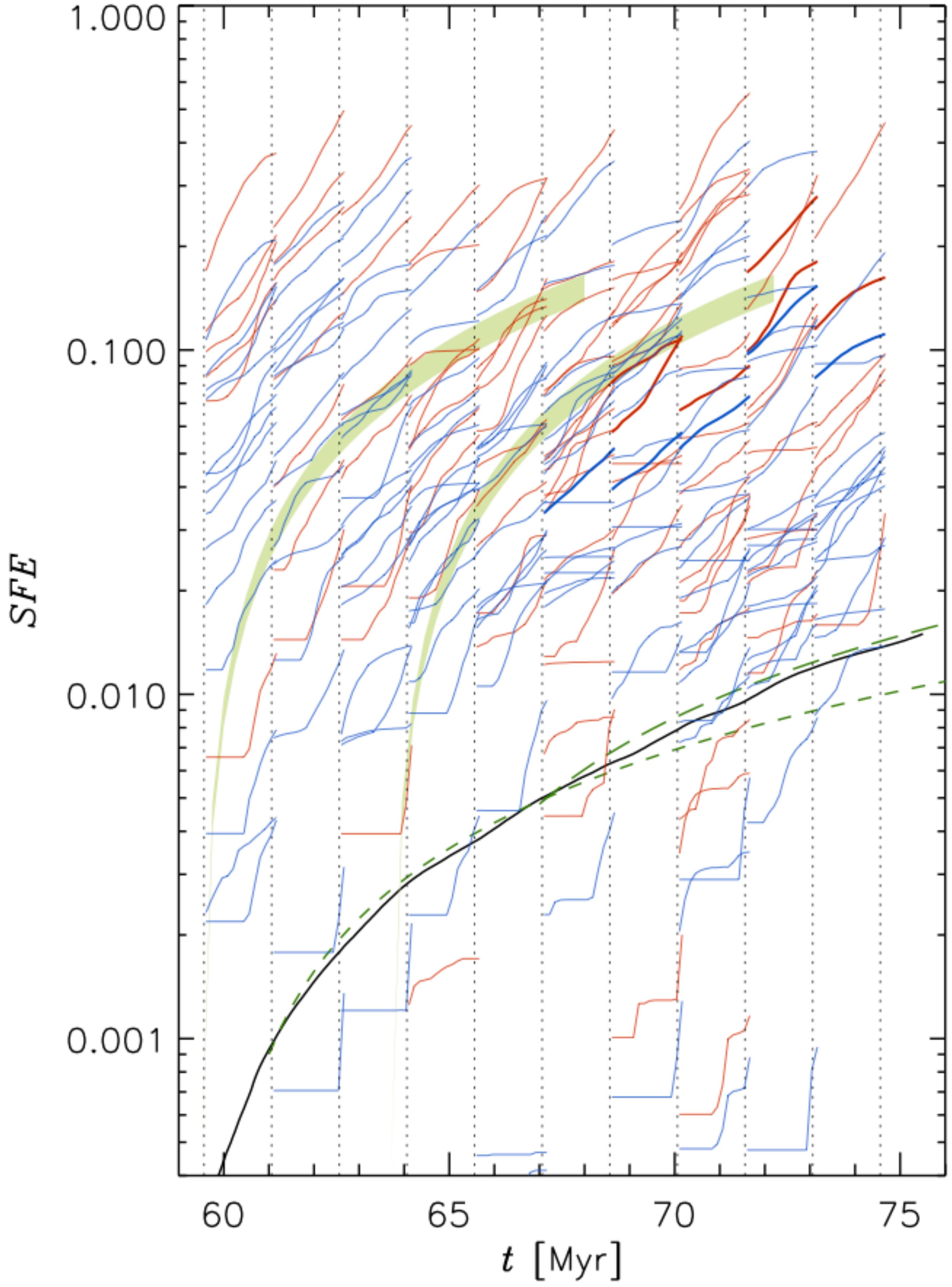
SF models should account for this distribution.

Density PDF of MCs

- Indivdual cloud PDFs are well approximated by lognormal distributions.
- The composite PDF of all clouds is lognormal over 6 orders of magnitude in $p(s)$
- Power law tail with self-gravity



Results on the SFR



Time evolution of the SFE

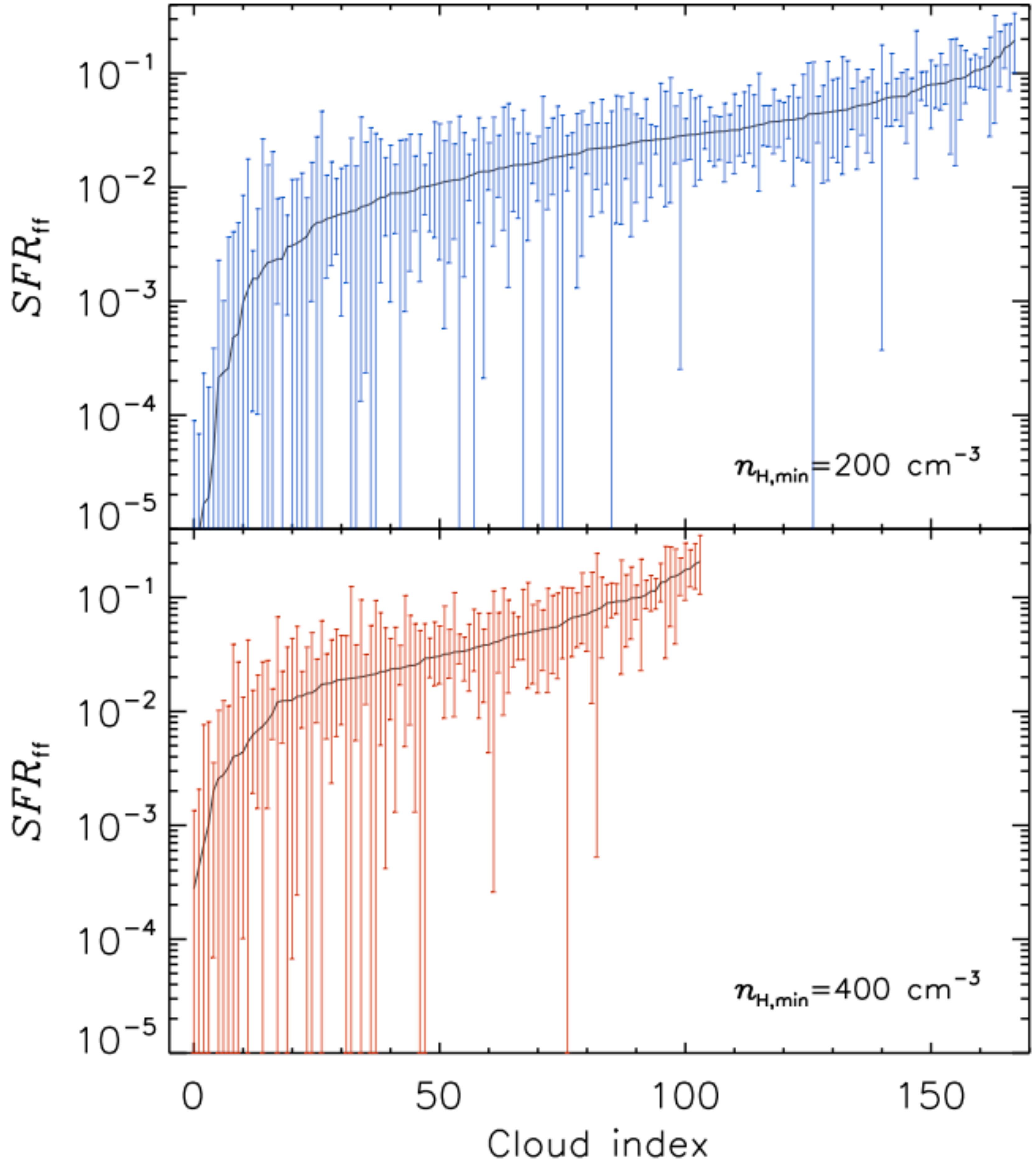
Using 10 snapshots at intervals of 1.5 Myr, we select 313 clouds with Mc>10^3 M$_\odot$, with two density thresholds:

$n_{\mathrm{H,min}}$=200 cm^{-3} **$n_{\mathrm{H,min}}$=400 cm^{-3}**

Global depletion time ~1 Gyr

MC depletion time ~0.05 Gyr

Then we compute SFR$_{\mathrm{ff}}$ in MCs as an average over 1.7 Myr (in the future).

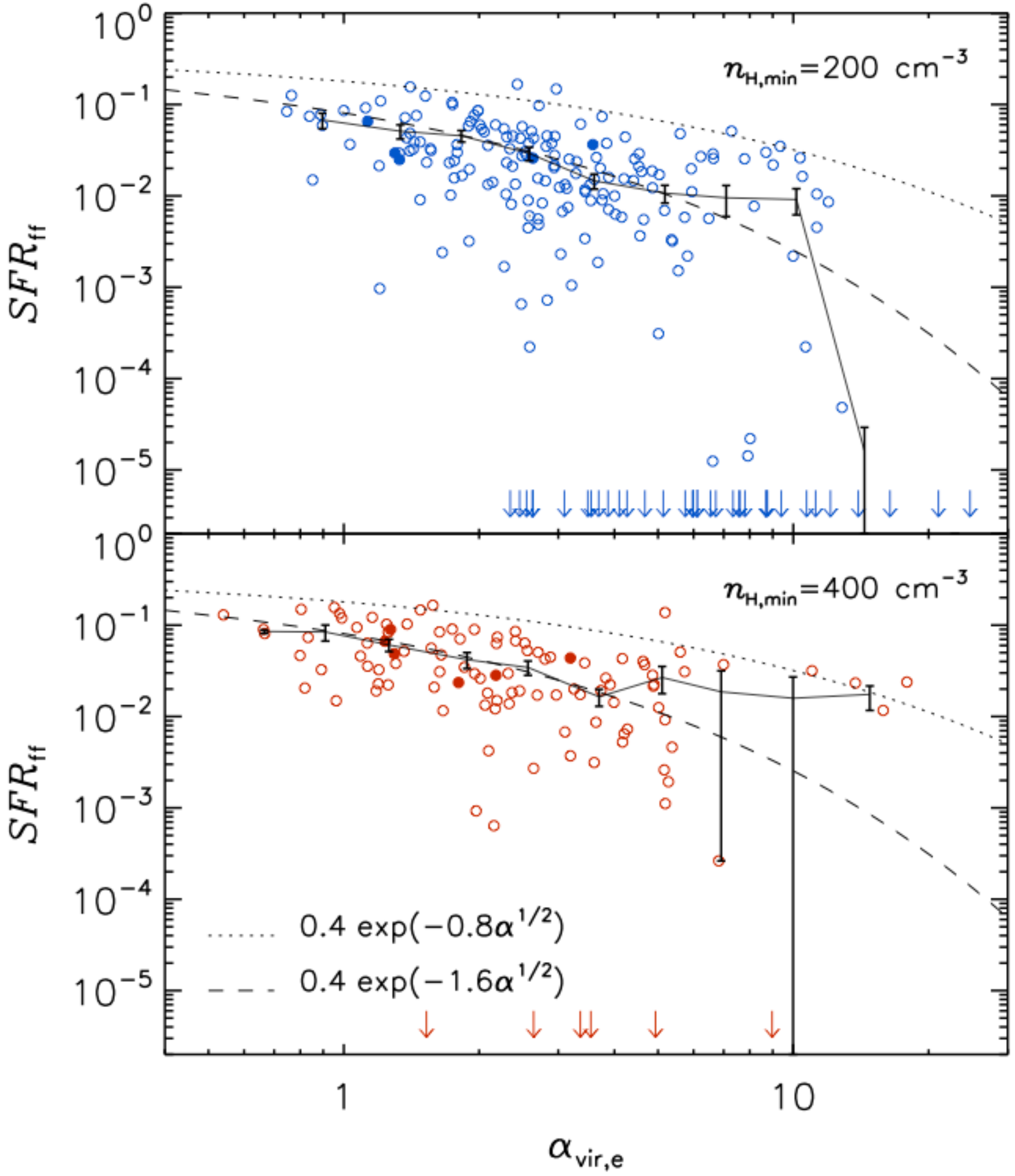


The SFR per free-fall time

To study its variations, we also average SFR_{ff} over a smaller interval of 0.12 Myr.

Large time variations of SFR_{ff} within a cloud and large variations from cloud to cloud.

Such variations are to be expected: clouds are not idealized turbulent boxes, perfectly relaxed and in steady state! They are transient, they are formed and dispersed by the SNe.



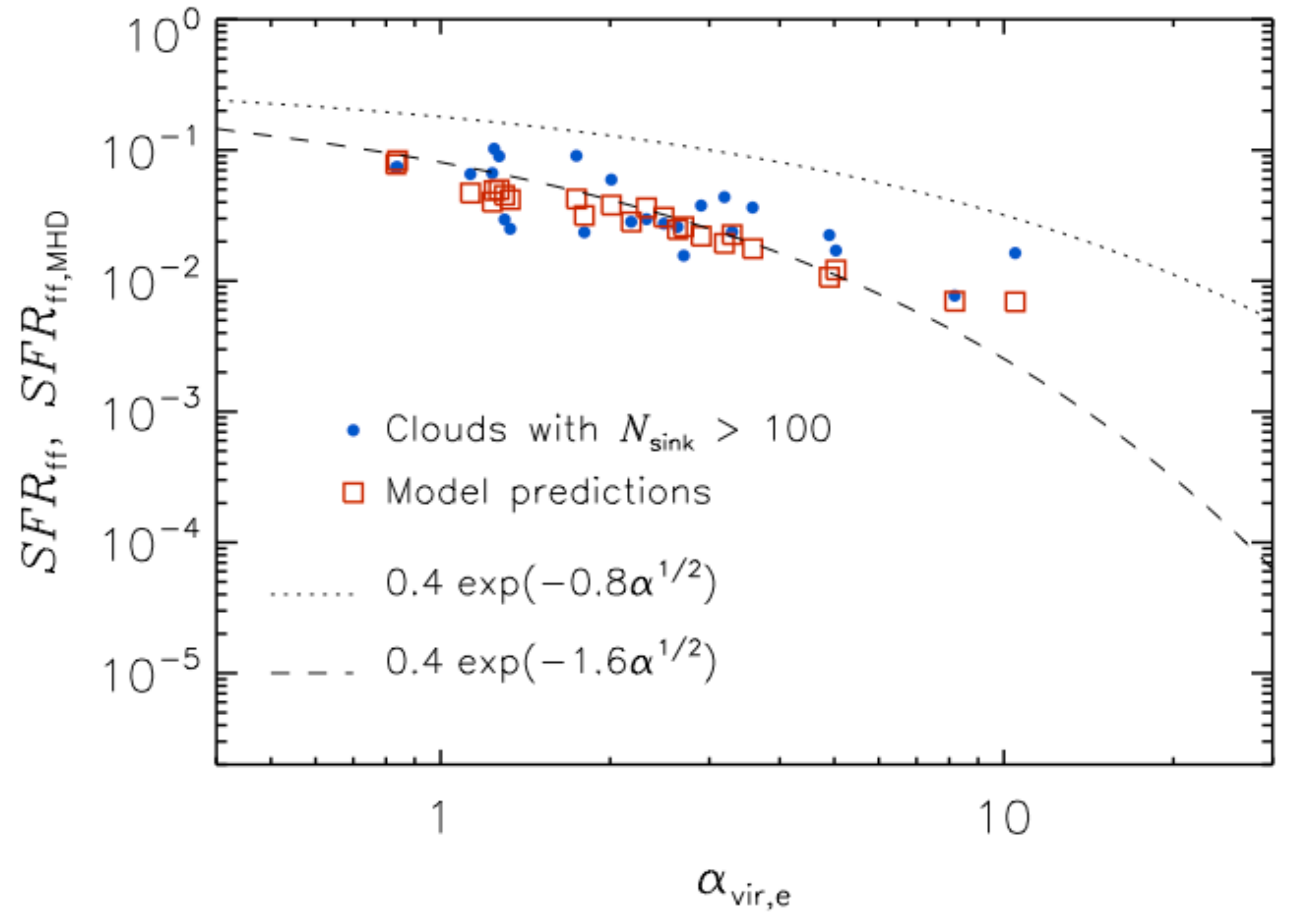
SFR_{ff} versus virial parameter

Large scatter, but consistent with the model prediction of decreasing SFR_{ff} with increasing α_{vir} on average.

The scatter is not explained by variations of $\mathcal{M}_S$, β, χ. It is mostly due to:

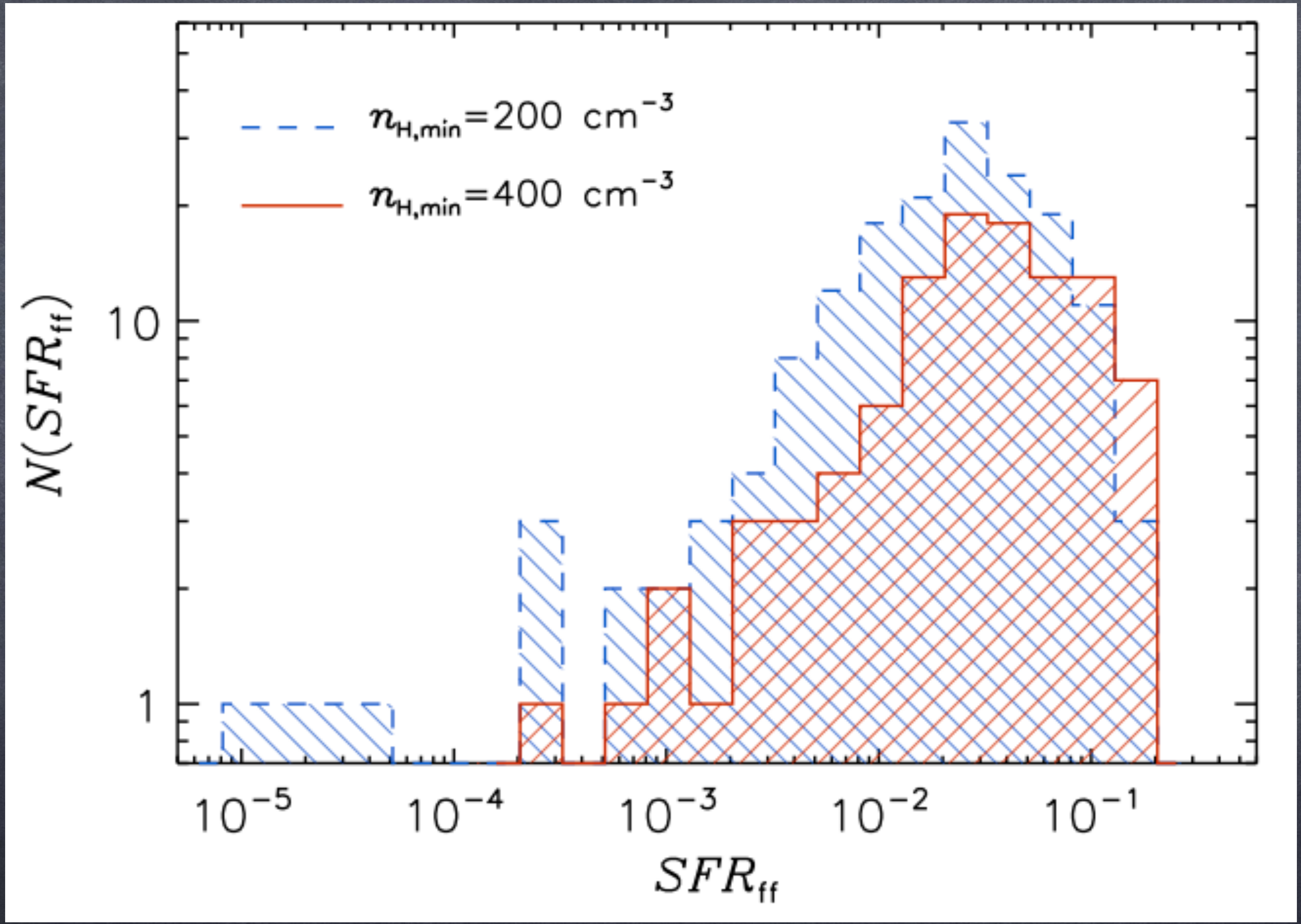
- time variations in the high-density tail of the gas density PDF
- random fluctuations of SFR_{ff} in clouds with a low number of sink particles
- lack of statistical equilibrium of the MC turbulence, due to the transient nature of MCs.

Very little scatter for clouds with **Nsink > 100**

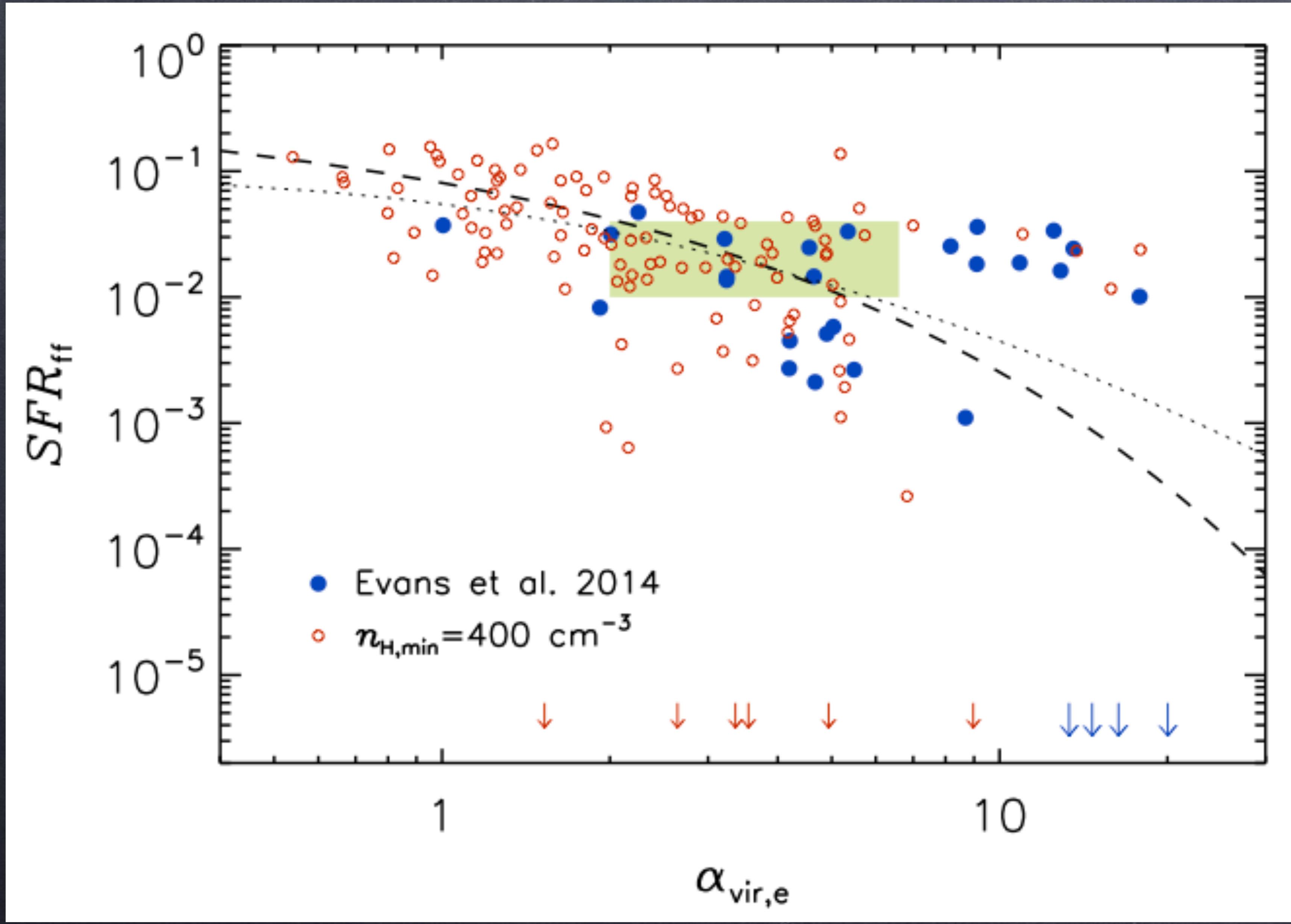


The deviations from the model are less than a factor of two !

Broad distribution of SFR_{ff}, with an average value of ~0.025 and a maximum of ~0.2:



$SFR_{ff} \sim 2\%$ is consistent with protostellar counts in nearby MCs (*Evans et al. 2014*)
Global $t_{dep} \sim 1$ Gyr is consistent with disk galaxies (*Bigiel et al. 2011*).



The scatter of SFR_{ff} in the observations (protostellar counts in nearby clouds) is large and increases towards larger values of a_{vir}, like in the simulation.

The SFR_{ff} in the CMZ, derived from the physical properties of the “Brick” cloud and an orbital model of the CMZ clouds, is also consistent with our numerical and theoretical predictions (*Barnes et al. 2017*).

Conclusions

SIMULATION:

- Broad distribution of $\mathrm{SFR_{ff}}$, with a mean of $\sim$0.025 and a maximum of $\sim$0.2.
- On average, $\mathrm{SFR_{ff}}$ decreases with increasing $\alpha_{\rm vir}$, but with a large scatter, due to random fluctuations in low-SFE clouds ($N_{\rm sink} < 100$) and to the transient nature of the clouds.
- The model does not account for the transient nature of MCs and so it predicts a small scatter in $\mathrm{SFR_{ff}}$ as a function of $\alpha_{\rm vir}$, and is fit well by the relation $\mathbf{SFR_{ff}\,(\alpha_{vir}) = 0.4\,exp(-1.6\,\alpha_{vir}{}^{1/2})}$.
- The values of $\mathrm{SFR_{ff}}$, averaged in intervals of $\alpha_{\rm vir}$, follow the model closely. Individual clouds with $N_{\rm sink} > 100$ follow the model closely as well.

OBSERVATIONS:

- $\mathrm{SFR_{ff}}$ measured in nearby MCs from direct counts of protostars is consistent with the simulation and the model.
- As in the simulation, the scatter of $\mathrm{SFR_{ff}}$ from the observations is large and increases towards larger values of $a_{\rm vir}$
- $\mathrm{SFR_{ff}}$ in the CMZ is also consistent with the numerical and theoretical predictions.

SUMMARY and CONCLUSIONS

The SFR depends on four non-dimensional parameters: α_{vir}, $\mathcal{M}_S$, β, χ

We have a large sample of turbulent clouds formed *ab initio* in the SN-driven turbulence (realistic ICs and BCs) —> study the SFR as function of environment.

Main Predictions:

- On average, $\mathbf{SFR_{ff}}$ decreases with α_{vir} : $\mathbf{SFR_{ff}(\alpha_{vir}) = 0.4 \exp(-1.6\, \alpha_{vir}^{1/2})}$
- The scatter in $\mathbf{SFR_{ff}}$ is large and increases with increasing α_{vir}.
- Broad distribution of $\mathbf{SFR_{ff}}$, with a mean of 0.025 and a maximum of 0.2.
- $\mathbf{SFR_{ff}}$ in nearby MCs and in the CMZ are consistent with these predictions.

THANKS