Turbulence in the interstellar medium: from intermediate galactic scales to self-gravitating cores

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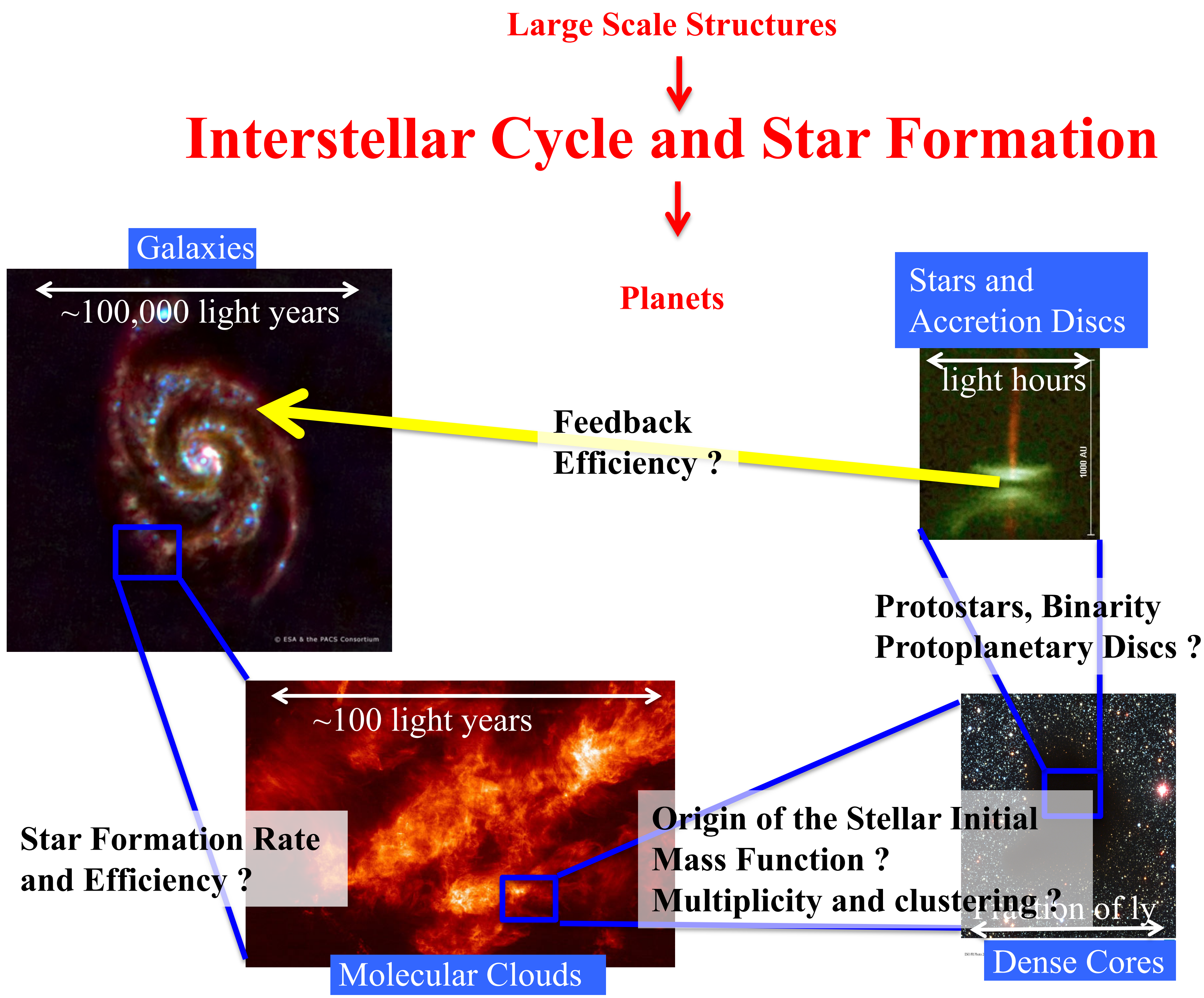

Large Scale Structures
Interstellar Cycle and Star Formation
Planets
Galaxies
~100,000 light years
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Stars and
Accretion Discs
light hours
1000 AU
Feedback
Efficiency ?
Protostars, Binarity
Protoplanetary Discs ?
~100 light years
Star Formation Rate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

simplicity

Supersonic turbulence in a periodic box

Comparison with polarization Planck data

Semi-global models: toward self-consistent energy injection

Zooming-in: getting the core mass function from turbulent fluctuations

Need for large scale turbulent driving

realism

simplicity

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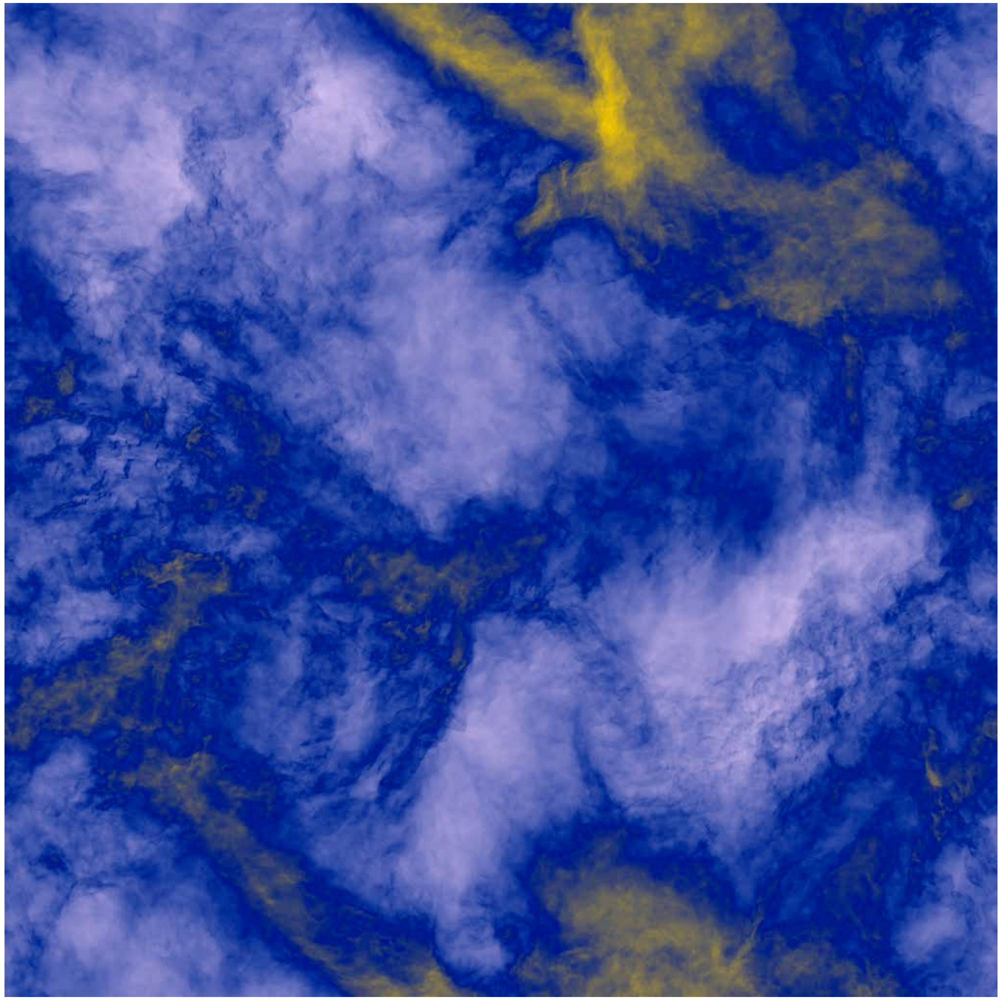
The cold gas is experiencing super-sonic highly compressible turbulence

~10 light years



3D simulation of supersonic isothermal turbulence with AMR

Periodic boxes
Random solenoidal forcing is applied at large scales ensuring constant rms velocity.

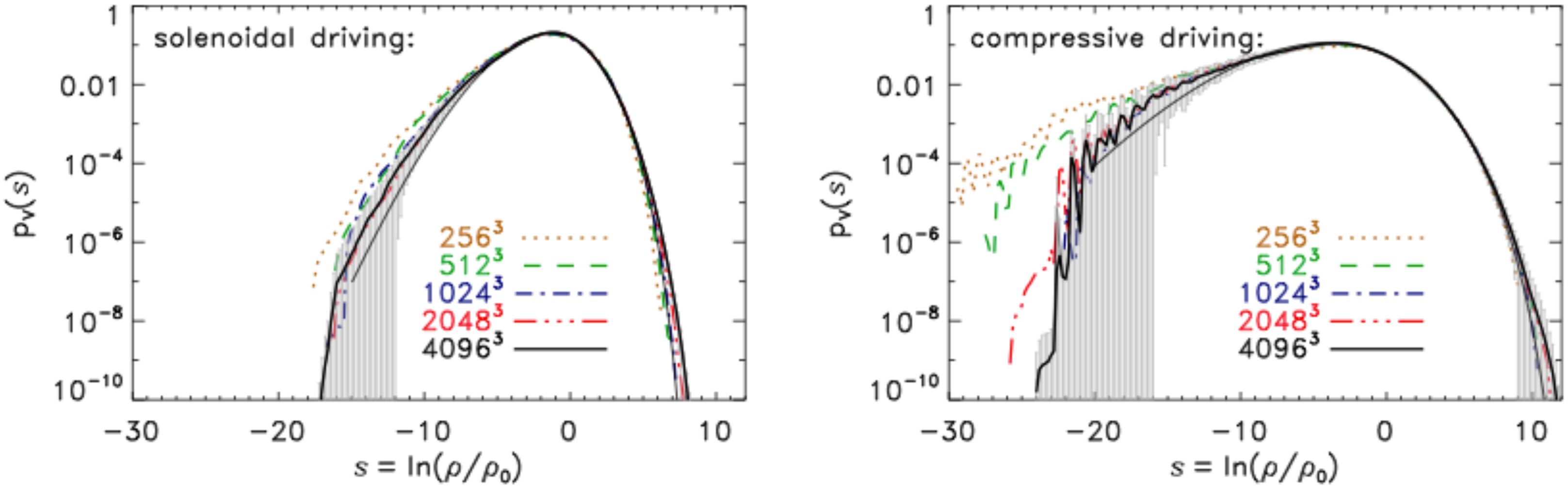
Typical Mach number: 6-10

Effective Reynolds number: $\sim 10^4$
(intrinsic limitation should be $\sim 10^7$)

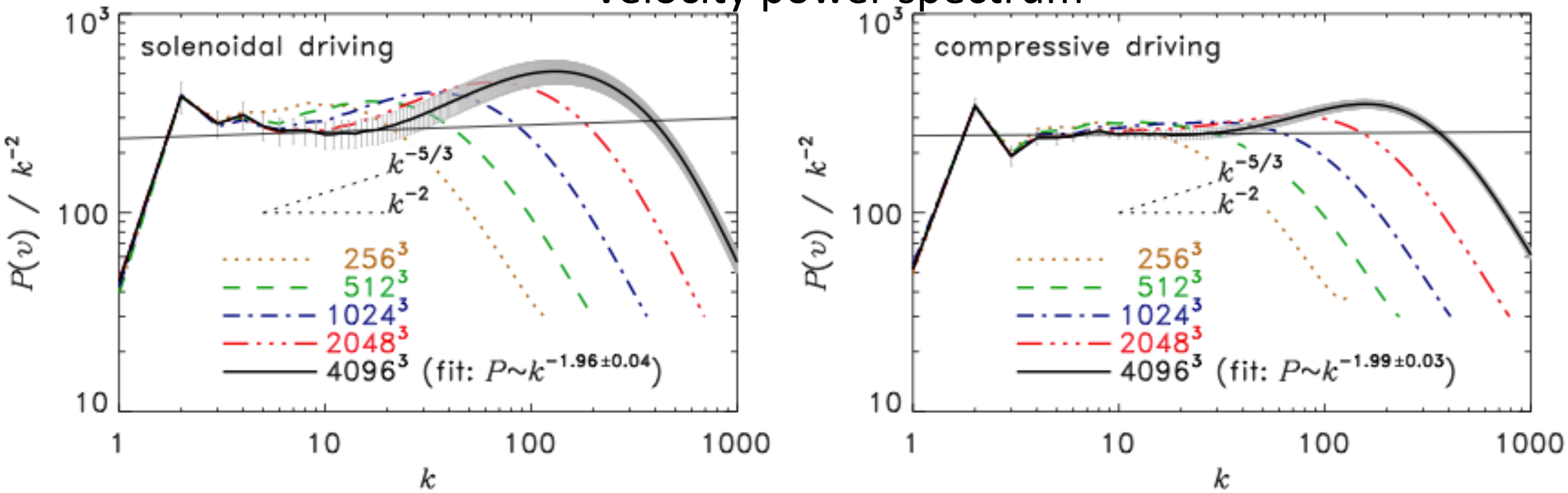
Kritsuk+2007

Some statistics of super-sonic highly compressible turbulence

Distribution of density field



Velocity power spectrum



Federrath 2013

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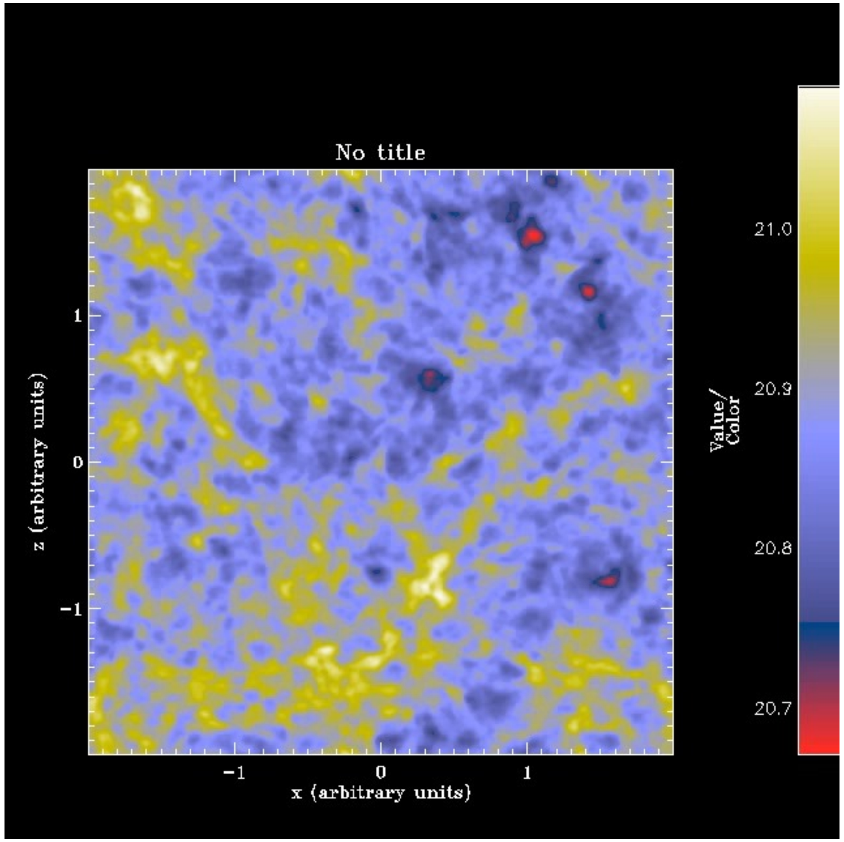
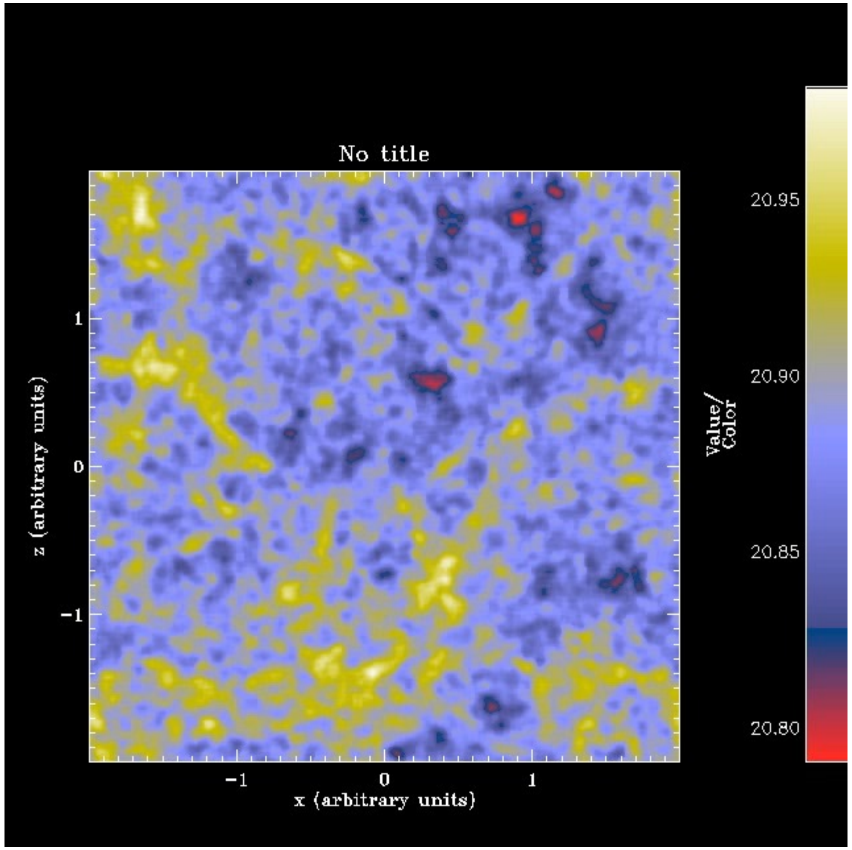
Decaying turbulence in a two-phase magnetized interstellar medium

Hydrodynamics



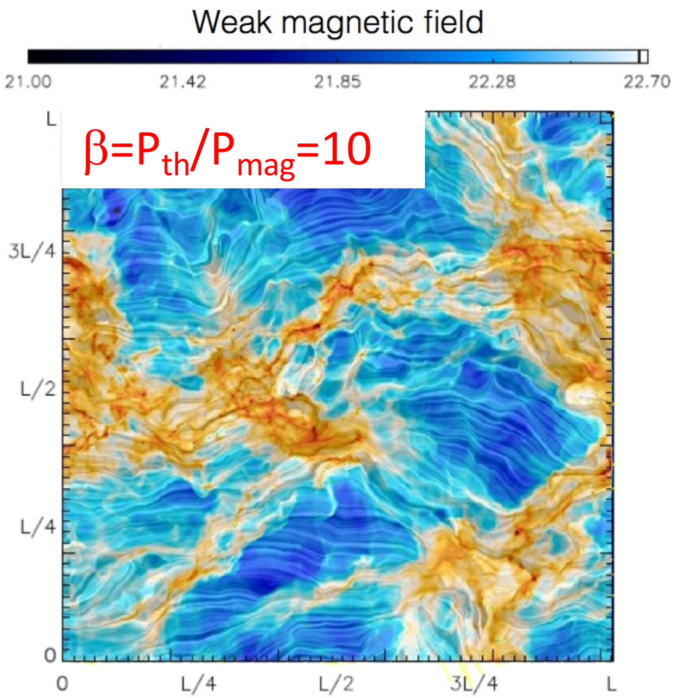
Magneto-hydrodynamics

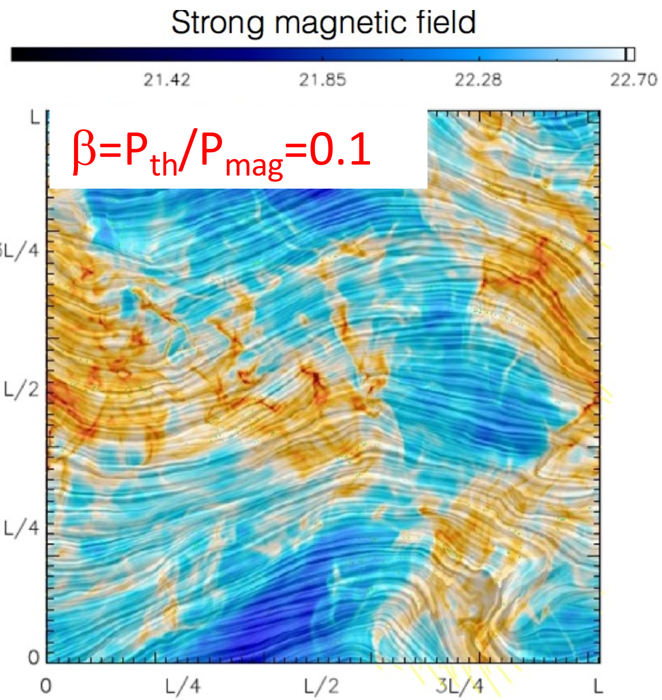


H 2013

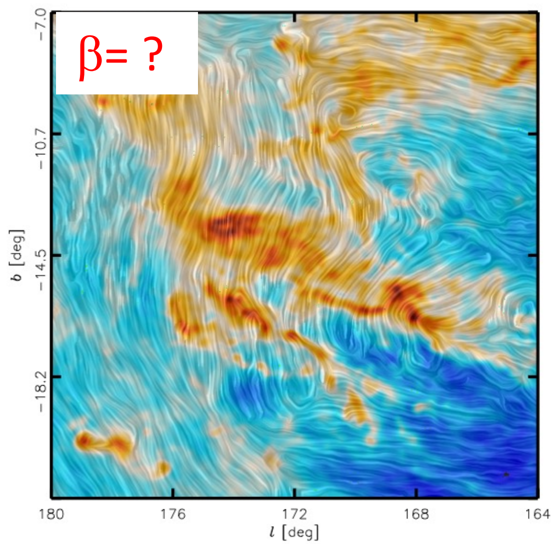
Integrated column density and magnetic field lines as seen by PLANCK

Simulations of molecular clouds: decaying turbulence, gravity, magnetic field





Planck collab 2015



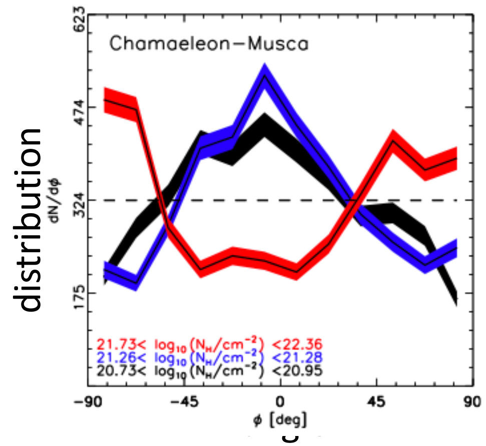
Soler+2013
Soler & H 2017

Simulations

Observations

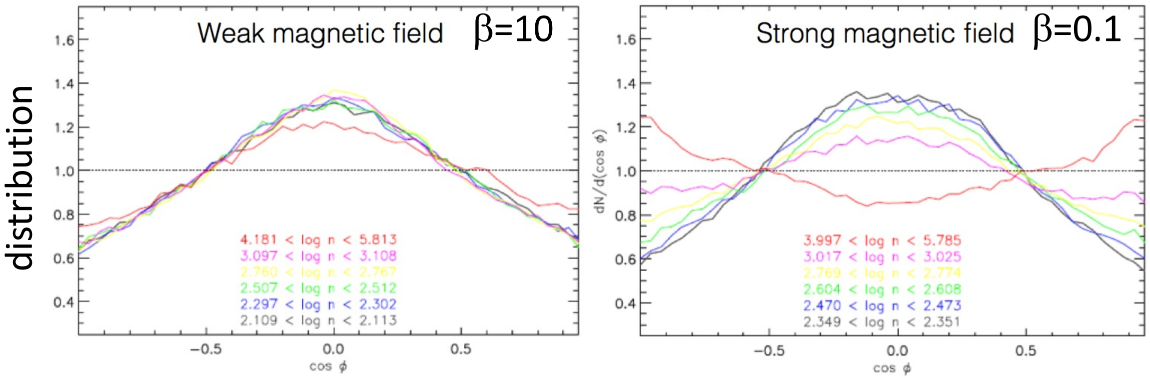
Two preferential orientations: A *predicted* behaviour

Observed distribution of angle between B and column density isocontour



Planck collab 2015

Simulations: distribution of $\cos\phi = \frac{\nabla\rho \cdot \boldsymbol{B}}{|\nabla\rho|\,|\boldsymbol{B}|}$



Soler+2013

A theoretical explanation

$$\frac{\mathrm{d}(\cos\phi)}{\mathrm{d}t} = \frac{\partial_i(\partial_j v_j)}{(R_k R_k)^{1/2}}[-b_i + r_i\cos\phi] + (\partial_i v_j)[r_i r_j - b_i b_j]\cos\phi,$$

Soler & H 2017

simplicity

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Model for star forming interstellar medium

RAMSES code is used (Teyssier 2002, Fromang+2006, Bleuler & Teyssier 2013)

MHD equations

External gravity due to stars and dark matter
Self-gravity, MHD turbulence, standard ISM cooling

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} - \boldsymbol{B}\boldsymbol{B}) + \nabla P = -\rho \nabla \Phi + \rho \boldsymbol{f},$$

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + P)\boldsymbol{v} - \boldsymbol{B}(\boldsymbol{B}\boldsymbol{v})] = -\rho \boldsymbol{v} \cdot \nabla \Phi + \rho \boldsymbol{f} \cdot \boldsymbol{v} - \rho \mathcal{L},$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + \nabla \cdot (\boldsymbol{v}\boldsymbol{B} - \boldsymbol{B}\boldsymbol{v}) = 0,$$

Sink particles mimics star formation. Given the typical resolution their mass is typically 10^3-10^5 Ms => they represent clusters
Each time 120 Ms is accreted, a massive star forms and therefore its feedback is applied.
Mass distribution follows Salpeter.

When a massive star forms:
-the **supernovae** momentum is injected after a time that corresponds to the stellar age and at a distance proportional to its age.
-**ionising radiation** is treated (M1 method) and applies 4 Myr after the formation of the massive star.
-the **UV heating** is proportional to the star formation rate

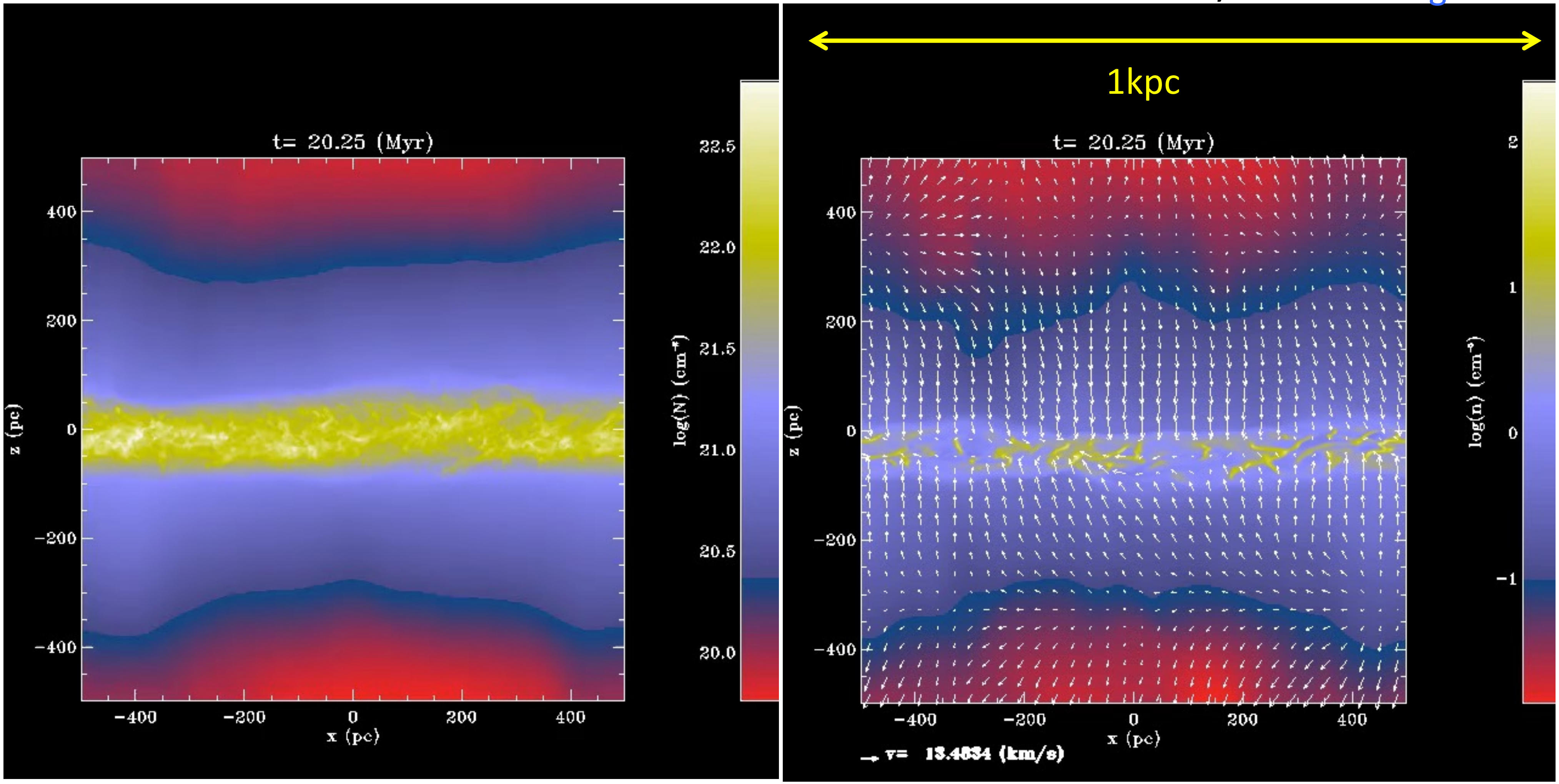
Series of kpc simulations:
- -resolution from 1-2 to 0.004 pc
- -variations of physical and numerical parameters

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, 2017, H & Iffrig 2014, Gatto et al. 2014, Walch et al. ….)

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

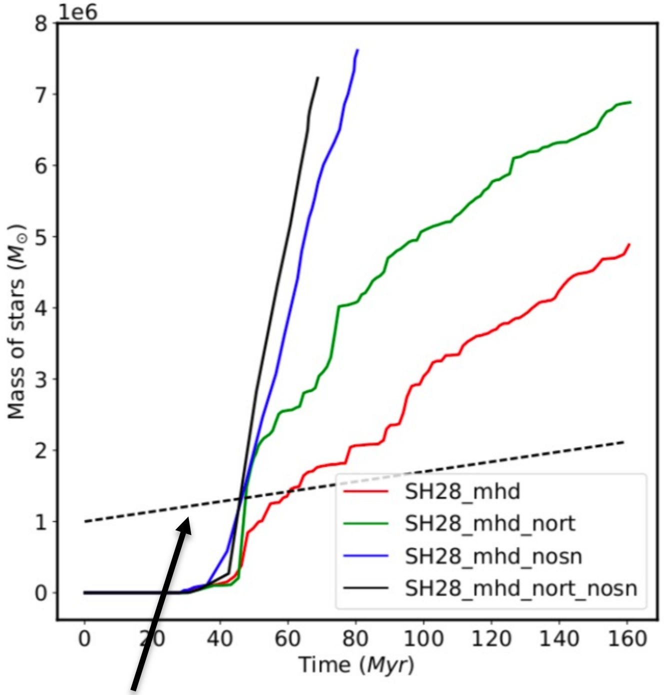
Column density density H&Iffrig 2014



Influence of various processes on the SFR

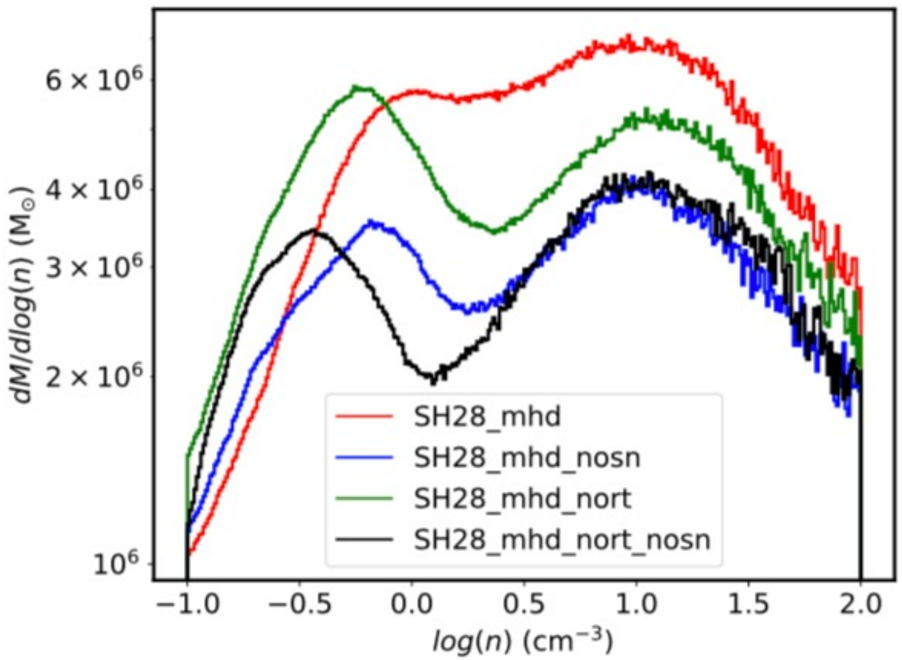
Hydro No feedback | MHD No feedback | MHD SN feedback | MHD SN and HII

Total mass of stars



Expected SFR from SK relation

Density PDF



More feedback =>
more intermediate density gas

When all source of stellar feedback are included (plus shear), the star formation rate for a MW type galaxy is *reasonably* reproduced (possibly a bit too high).

Colling+2018

simplicity

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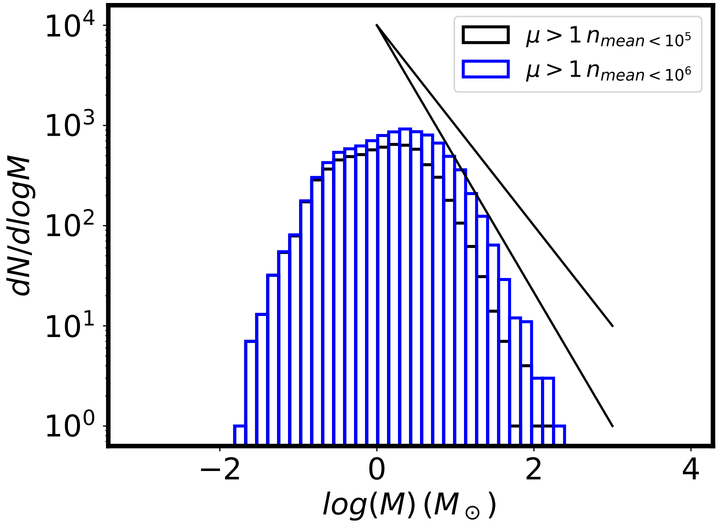
FRIGG : From Intermediate Galactic scales to self-Gravitating cores

--Spinning the clouds—

Goal : obtain a self-consistent description from few 100pc to less than 0.1 pc (spatial numerical resolution of 0.004/0.002 pc)

H 2018

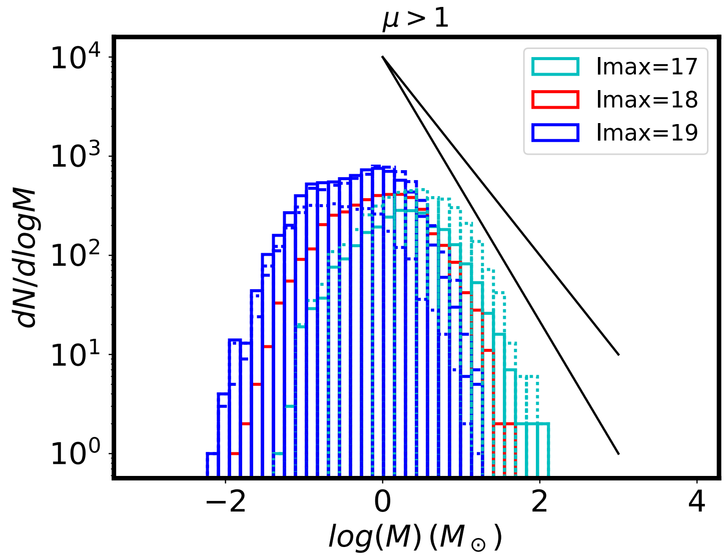
Getting the "core" mass function from zooming-in simulations



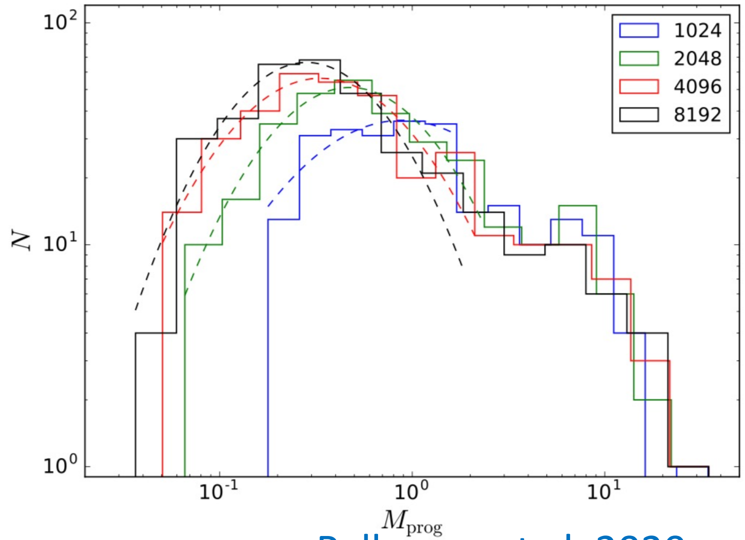
The slope is about "right", close to Salpeter values but:

The peak of the core mass function is resolution dependent!

(see also Pelkonen et al. 2020, Louvet et al. 2021)



H 2018



Pelkonen et al. 2020

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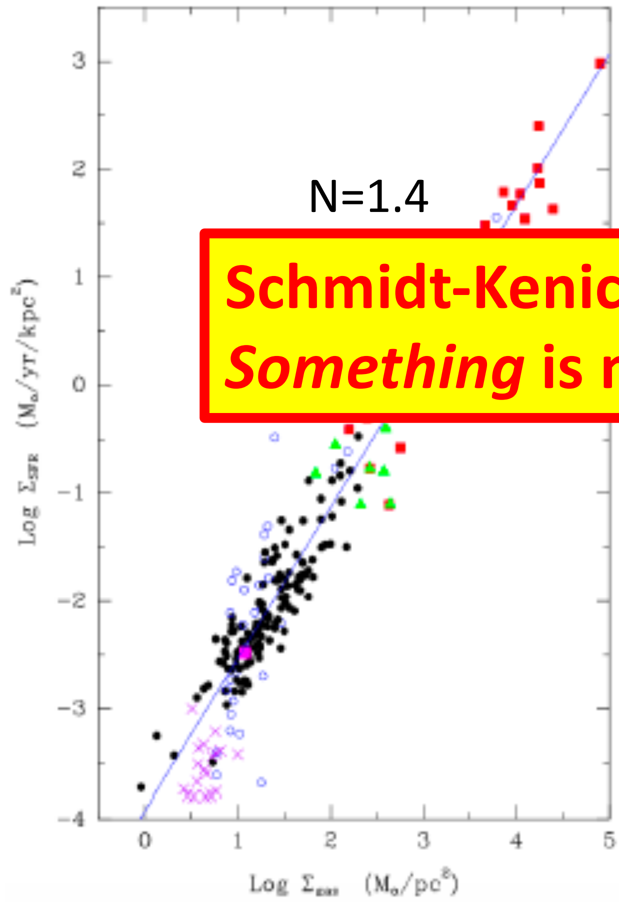
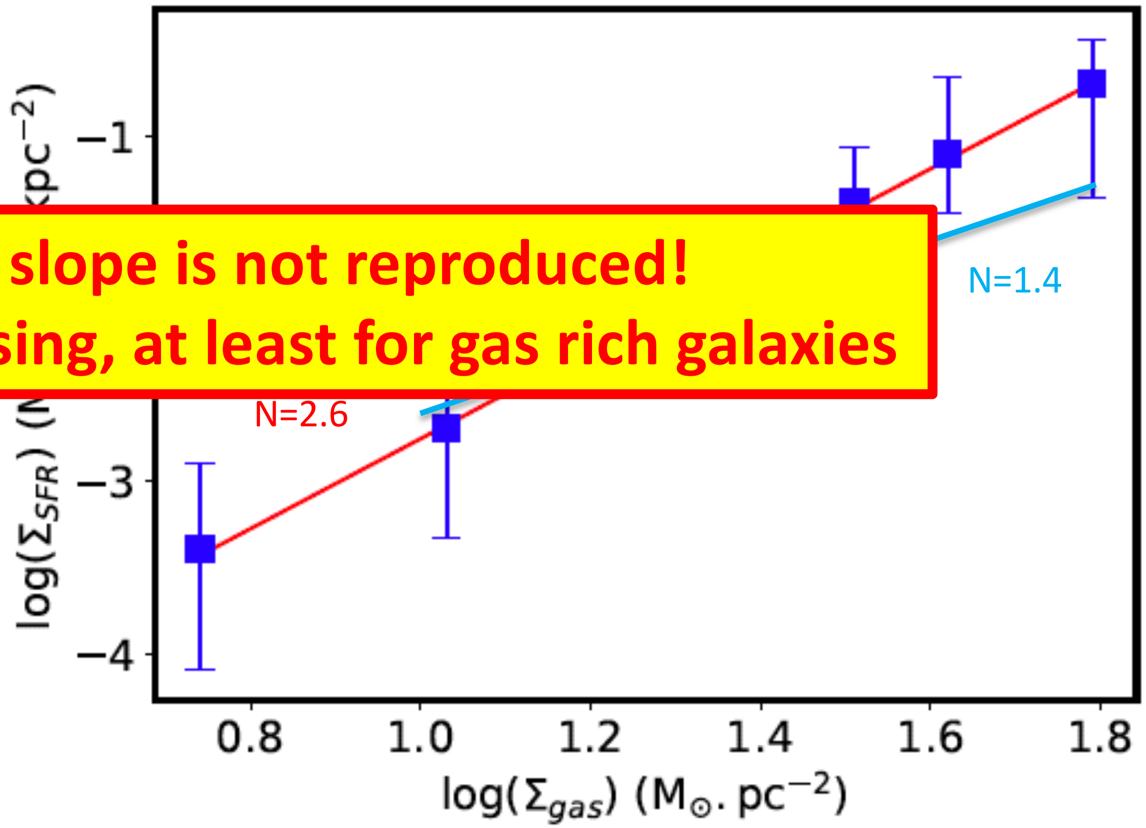
Trying to reproduce Schmidt-Kenicutt relation

Dependence of the SFR on the mean column density



Schmidt-Kenicutt slope is not reproduced!

Something **is missing, at least for gas rich galaxies**



Colling PhD
Brucy+2020

The role of externally driven turbulence

What sources of turbulence do we foresee?

The gas orbital energy of the galaxy which is tapped by gravitational instabilities (Bournaud et al. 2010, Krumholz et al. 2018)

Maximum ε ? $\varepsilon \sim V_{rot}^3/R$ => enormous source of free energy

How do we drive?

$$d\hat{\boldsymbol{f}}(\boldsymbol{k},t) = -\hat{\boldsymbol{f}}(\boldsymbol{k},t)\frac{dt}{T} + F_0(\boldsymbol{k})\boldsymbol{P}_\zeta\left(\begin{pmatrix} k_x \\ k_y \\ 0 \end{pmatrix}\right)\cdot d\boldsymbol{W}_t$$

(Schmidt+2006,2009)

75% solenoidal modes – compressible forcing change our conclusion quantitatively

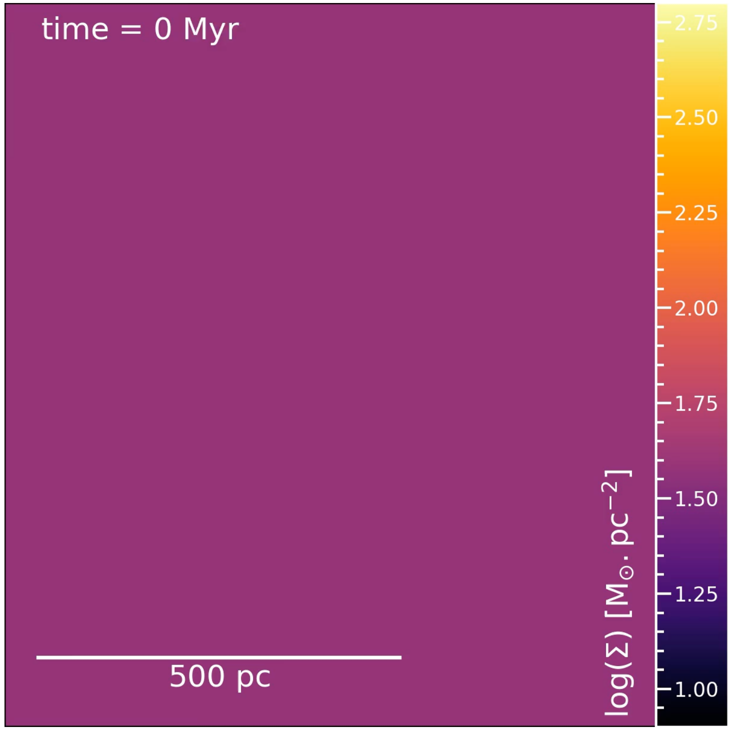
How intensively do we drive?

$$\epsilon \sim \frac{v_l^3}{l} \propto \sigma^3 \qquad Q = \frac{c_s\kappa}{\pi\Sigma G} \propto \frac{\sigma\kappa}{\Sigma} \qquad \epsilon \propto \Sigma^3. \qquad P_{\rm inj} \propto \Sigma^4.$$

(incidently note that feedback provides “only” $P_{inj} \propto \Sigma^{1.4}$)

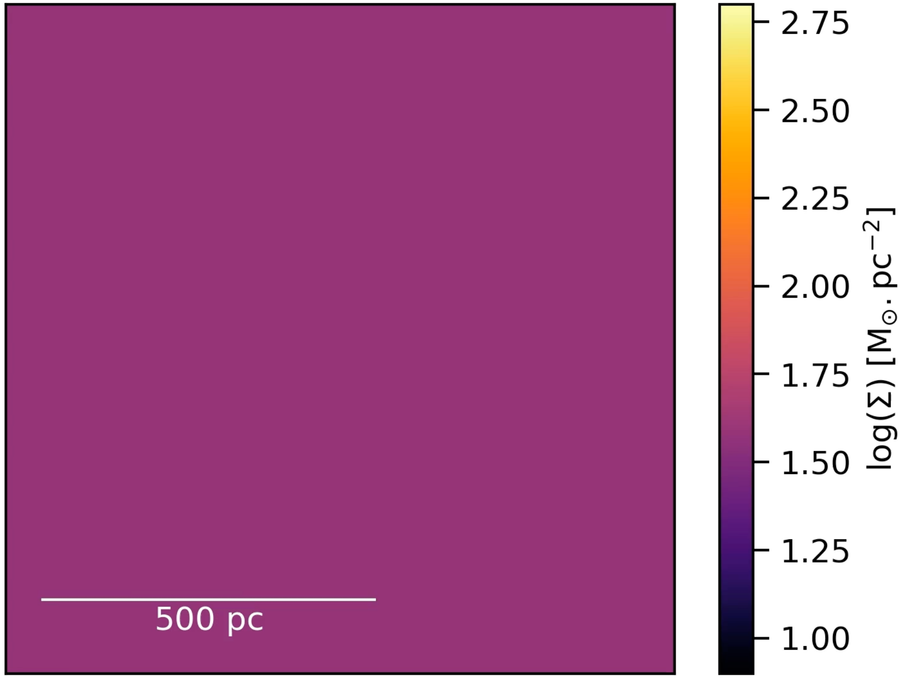
Brucy+ApJ 2020

Without driving



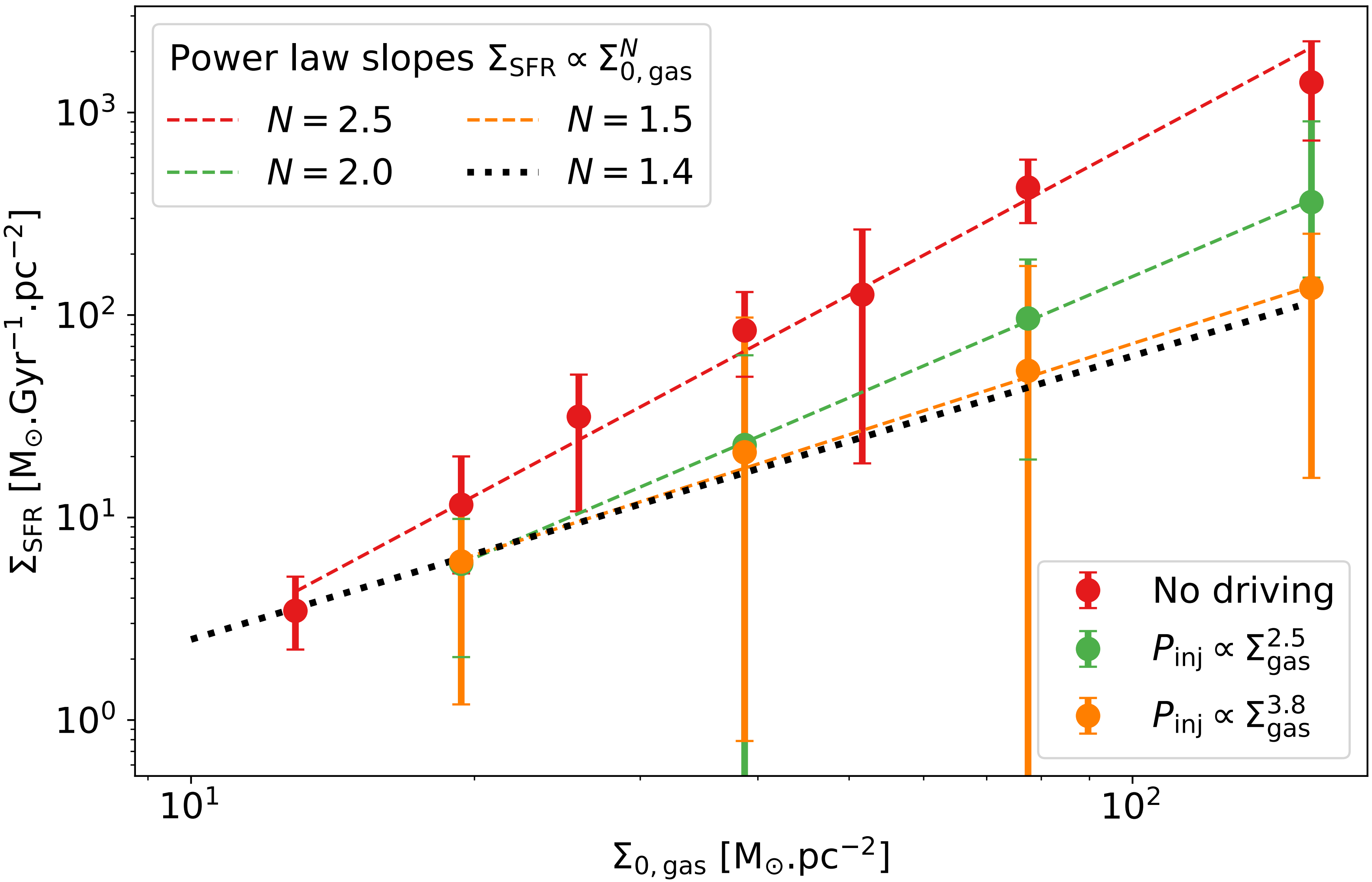
With driving

0 Myr



Brucy+ApJ 2020

Evidence for large scale driven turbulence I:
Externally driven turbulence can explain Schmidt-Kunnicutt relation



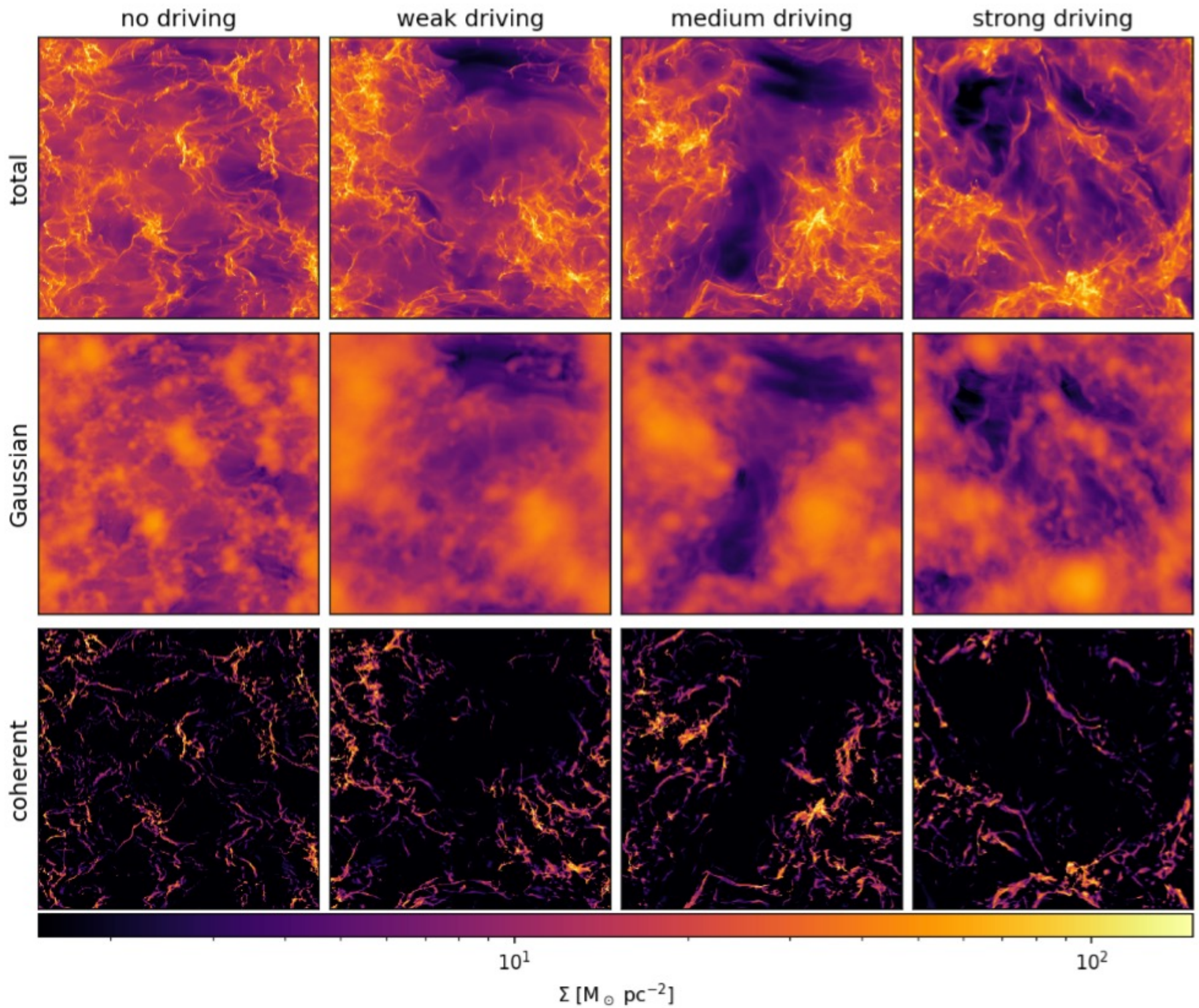
Brucy+2020

Evidence for large scale driven turbulence II: Coherent density structure power-spectrum

Separating coherent structure and Gaussian background

Power-spectra of complete images are usually not very discriminant.

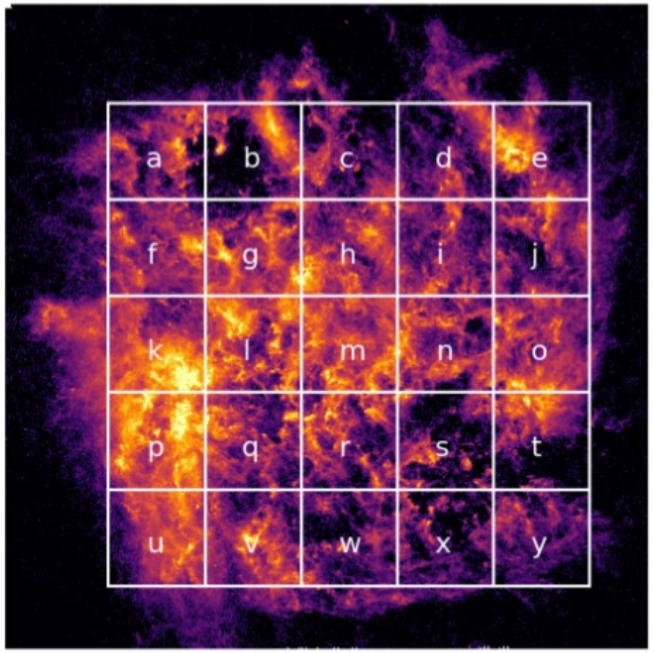
A wavelet based techniques is applied to separate the coherent structures from the Gaussian background (Robitaille+2014, 2019).



Colman+2022

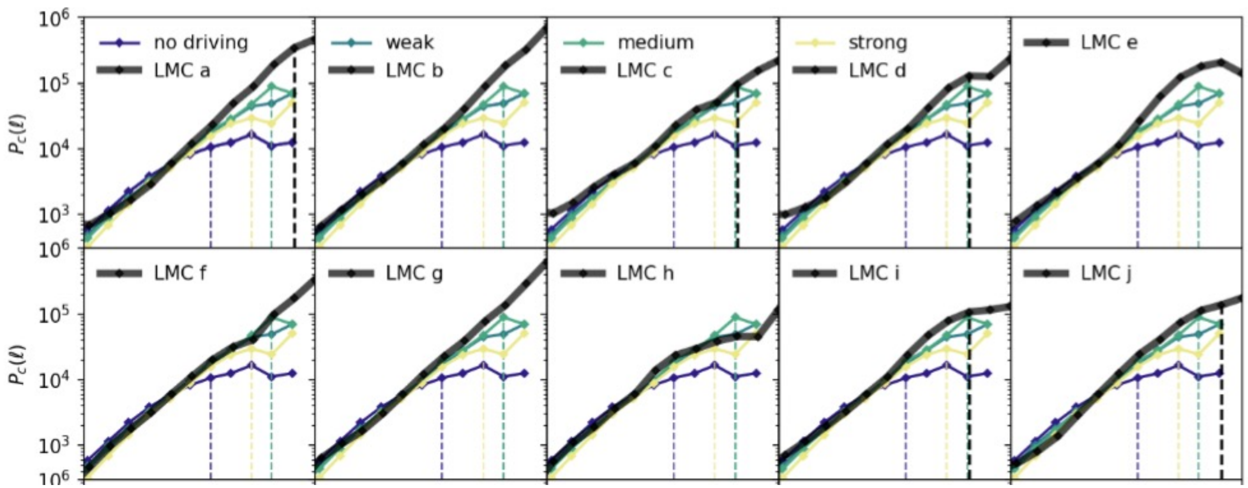
Evidence for large scale driven turbulence II: Coherent density structure power-spectrum

Comparisons between various forcing and LMC data



The power-spectrum of the coherent structures is different for simulations with and without forcing.

Comparison with LMC data reveals that large scale turbulent forcing is needed.



Colman+2022

Conclusions

-multi-scale and self-consistent ISM model is on the way

-kpc box start producing reasonable self-consistent regulated ISM for MW type column densities

-Feedback does not seem to be strong enough to reproduce the Schmidt-Kennicutt relation.

-Turbulent forcing coming from large galactic scales seems requested for this.

http://www.galactica-simulations.eu/db

GALACTICA : Download / Upload / postprocess (ISM) simulations

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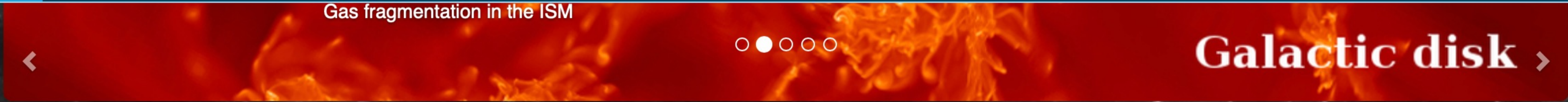

The Galactica simulation database

The **Galactica** database results of heavy numerical simulations computed in various fields of computational astrophysics (solar magnetohydrodynamics, star-planet interactions, star formation, galaxy formation, galaxy mergers). The **Galactica** project gives observers and computational astrophysicists access to the results of these numerical simulations, which could be useful to help prepare or analyze observations or compare with other numerical studies.

The contributors of this database will provide a wide range of reduced data but will also give authenticated users the possibility to run online post-processing requests on the raw simulation data to fulfill one's specific needs.

Star-planet interactions

Project	Description
Fragdisk	Fragmentation of self-gravitating disks

Star formation

Project	Description
ORION	This project aims at providing a self-consistently description of molecular cloud fragmentation and evolution including the prestellar cores and up to the formation of dense fragments inside them (sink particles representing the stars)
LS	This project aims at modelling self-consistently a 1kpc piece of galaxy including star formation and stellar feedback.
FRIG	This project aims at providing a self-consistently description from a 1kpc piece of galaxy to the prestellar cores
DustyCollapses	Dusty collapse calculations

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OPEN DATA

http://www.galactica-simulations.eu/db