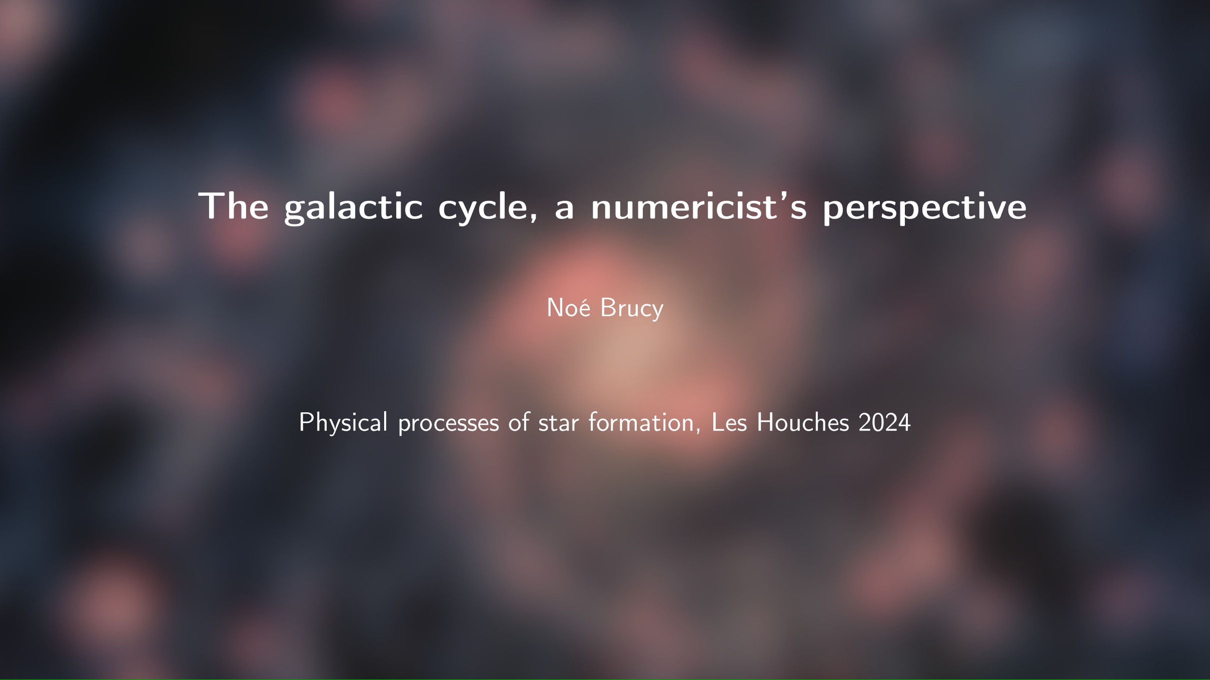

The galactic cycle, a numericist's perspective

Noé Brucy

Physical processes of star formation, Les Houches 2024

Aims

- When and how the galactic environement affect star formation?
- What are the different simulation techniques available and how to use them?

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- What are the different simulation techniques available and how to use them?

Disclaimer

This talk

- is biased towards my small experience of galactic simulations
- contains ~~stolen~~ borrowed ideas & material from
  - Philipp Girichidis
  - Florent Renaud
  - Rowan Smith
- contains "in prep" ECOGAL material

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Scales

Large: > 100 kpc

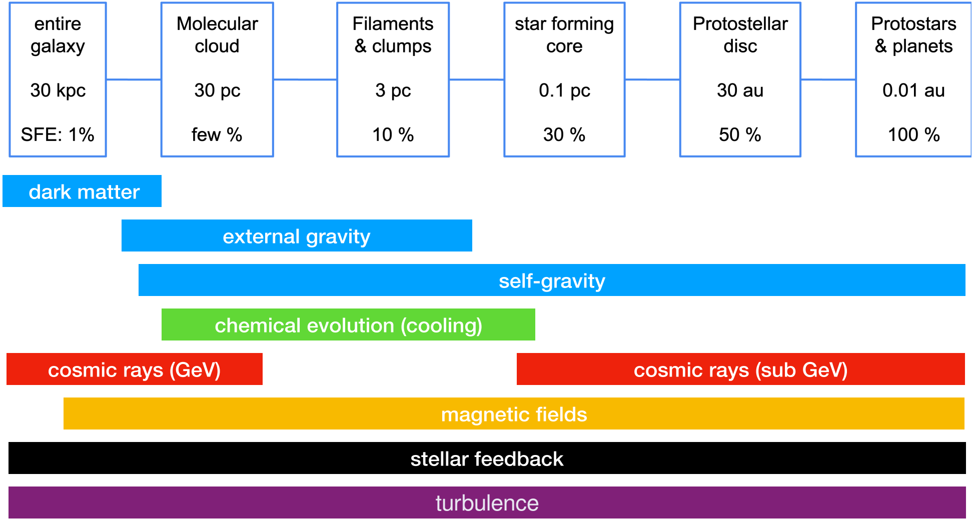
- $\oint$ Galaxy: 10^4 pc
- $\boxed{\oint}$ Intergalactic medium: 10^6 pc
- ∞ Universe: 10^9 pc

Medium: 1 pc to 1 kpc

- $\otimes$ HII regions: 10 pc
- $\circledast$ SN shells: 100 pc
- ☁ Molecular clouds: 100 pc

Small: < 10 pc

- $\cdot$ Atoms: 10^{-25} pc
- $\star$ Stars: 10^{-8} to 10^{-5} pc
- $\bowtie$ Protoplanetary disks: 10^{-4} pc
- ● Star clusters: 1 pc



entire galaxy	Molecular cloud	Filaments & clumps	star forming core	Protostellar disc	Protostars & planets
30 kpc	30 pc	3 pc	0.1 pc	30 au	0.01 au
SFE: 1%	few %	10 %	30 %	50 %	100 %

dark matter

external gravity

self-gravity

chemical evolution (cooling)

cosmic rays (GeV)

cosmic rays (sub GeV)

magnetic fields

stellar feedback

turbulence

Slide courtesy P. Girichidis

Outline

- Simulation of galaxies
- Structure of galaxies
- Regulation of star formation
- Conclusion

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What astrophysics hydrodynamical simulations codes do?

Task 1: solve the equations of (Magneto-)Hydrodynamics (M)HD

$$\begin{aligned}
\frac{\partial \rho}{\partial t} + \boldsymbol{\nabla} \cdot (\rho \boldsymbol{v}) &= 0 \\
\rho \left(\frac{\partial \boldsymbol{v}}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) \boldsymbol{v} \right) &= -\boldsymbol{\nabla} P + \frac{(\boldsymbol{\nabla} \times \boldsymbol{B}) \times \boldsymbol{B}}{4\pi} + \rho \boldsymbol{g} \\
\rho \left(\frac{\partial e}{\partial t} + (\boldsymbol{v} \cdot \boldsymbol{\nabla}) e \right) &= -P (\nabla \cdot \boldsymbol{v}) - \rho \mathcal{L} \\
\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) &= 0
\end{aligned}$$

What astrophysics hydrodynamical simulations codes do?

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\frac{\partial \boldsymbol{B}}{\partial t} - \boldsymbol{\nabla} \times (\boldsymbol{v} \times \boldsymbol{B}) &= 0
\end{aligned}$$

But you need

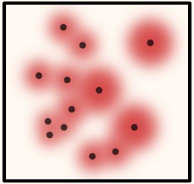
- to do it over many scales
- include (sometimes) star formation, radiative transfer, dust, chemistry, cosmic rays, stellar feedback.
- be able to run in less of a lifetime: complex parralellisation and domain decomposition challenge.

Families of simulations code for MHD

Lagrangian & Pseudo-Lagrangian

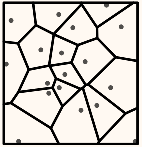
SPH

Smoothed Particle Hydrodynamics



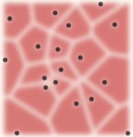
Phantom, Gadget, Shamrock

Moving Mesh



Arepo

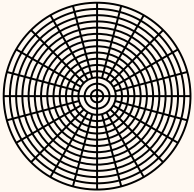
Meshless



GIZMO

Eulerian

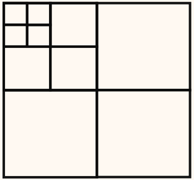
Fixed grid



Idefix, Pluto, Fargo

AMR

Adaptive Mesh Refinement



Ramses, Flash, Enzo, Athena++

Simulation of galaxies

What do you need to check when reading a simulation paper?

Simulation of galaxies

What do you need to check when reading a simulation paper?

Things to check

- **Methods** Code used, Resolution, Refinement scheme, Initial conditions, Physics included AND used method, subgrid models.
- **Diagnostics** Phase plots, Star formation rate

Simulation of galaxies

What do you need to check when reading a simulation paper?

Things to check

- **Methods** Code used, Resolution, Refinement scheme, Initial conditions, Physics included AND used method, subgrid models.
- **Diagnostics** Phase plots, Star formation rate

Some reminders

- Simulations are numerical experiments : ~~The simulation is right / wrong~~
- The are many kind of simulations: ~~Simulations say that ...~~
- Simulations outputs are sometimes as hard to interpret as observations

The numericist's jargon (1)

- **Subgrid model**: A way to modelize unresolved phenomena.
    - **Supernova** *Energy* and/or *Kinetic energy* injected.
    - **Early feedback: HII regions, winds, jets** Simple approximation (Strömgren sphere), radiative transfer
    - **Star formation**: conversion of gas into particle (which kind? which criterion?)

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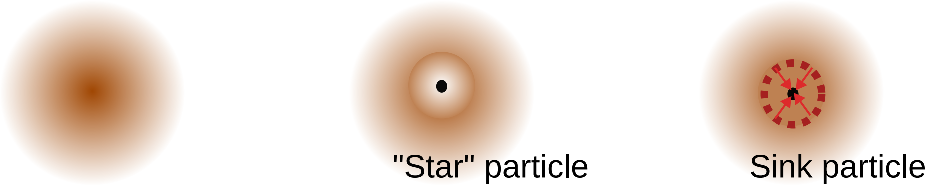
  - **Star formation**: conversion of gas into particle (which kind? which criterion?)
- **Particles**: non gas elements (stars, black hole, colisionless dark matter, stellar cluster, ...). Simulation with subgrid model for star formation use
  - **Star (normal) particle** An object with fixed mass,
  - **Sink particle** An object that can accrete gas over time

  Warning: SFR = mass of gas converted into particle over time.



The numericist's jargon (2): witchcraft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"We switch off gravity": We have full control on what physical model are included in the simulation. We can remove some to see if they are important for the evolution of the system.

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"We switch off gravity": We have full control on what physical model are included in the simulation. We can remove some to see if they are important for the evolution of the system.

"We drive turbulence": Turbulence plays a major role in astrophysical processes, but can't always be self-consistently generated. Its effects can be mimicked via an "extra force" that generates random motions.

The numericist's jargon (2): witchcraft

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"We clean $\vec{\nabla}\vec{B}$": Some MHD numerical scheme (such as SPH) do not ensure that $\vec{\nabla}\vec{B} = 0$ and the divergence of the magnetic field should be removed. This is not the case for the numerical scheme of Ramses.

The numericist's jargon (2): witchcraft


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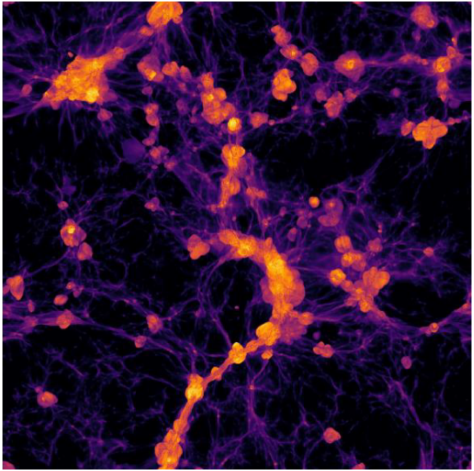
And you, what is the numericist's jargon you would like to understand?

Cosmological simulation

size: > 10 Mpc, res.: $\sim$100-500 pc

Full cosmological volume



Extreme Horizons (Dubois+ 2021)

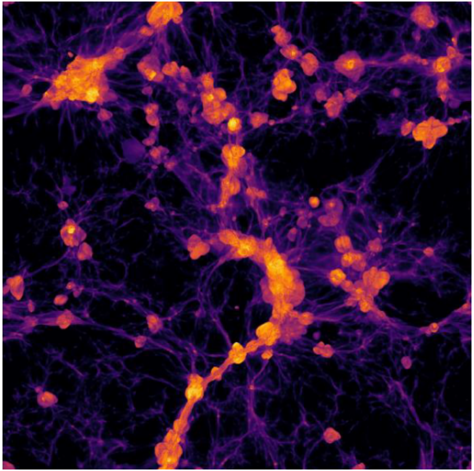
Cosmological simulation

size: > 10 Mpc, res.: $\sim$100-500 pc

Full cosmological volume

Advantages

- CMB initial conditions
- Statistics on galaxy population



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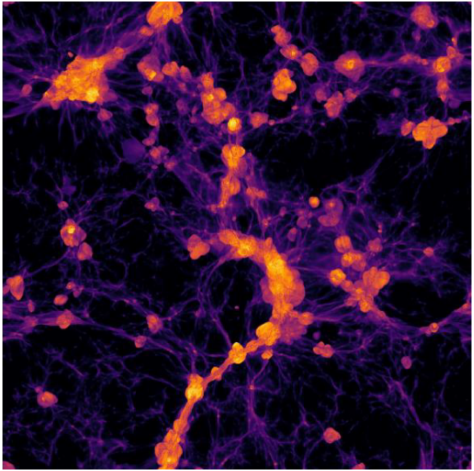
Full cosmological volume

Advantages

- CMB initial conditions
- Statistics on galaxy population

Drawbacks

- Galaxies resolved by only a few cell
- No description of the ISM (or as a subgrid model)



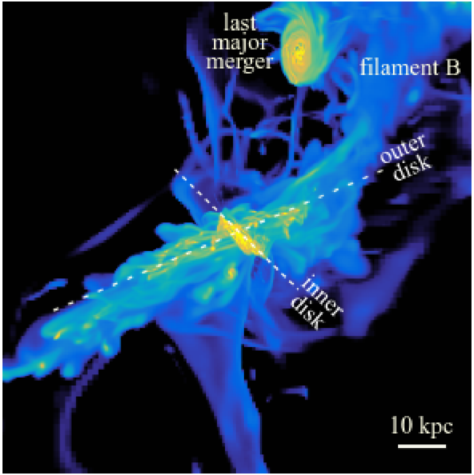
Extreme Horizons (Dubois+ 2021)

Cosmological zoom-in

size: ∼ 1 Mpc, res.: ∼10-100 pc

Advantages

- CMB initial conditions
- Galaxies in their environnent



Vintergatan (Agertz+2021)

Cosmological zoom-in

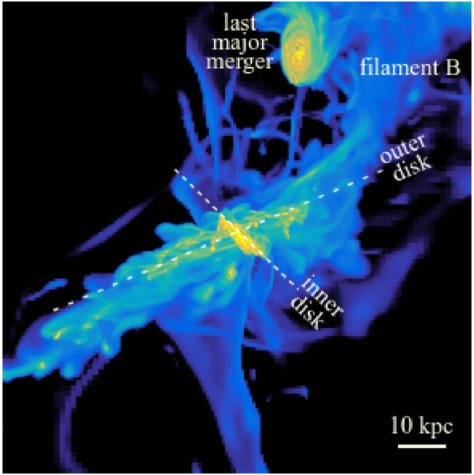
size: $\sim$ 1 Mpc, res.: $\sim$10-100 pc

Advantages

- CMB initial conditions
- Galaxies in their environnent

Drawbacks

- Poor ISM description
- Heavy to run

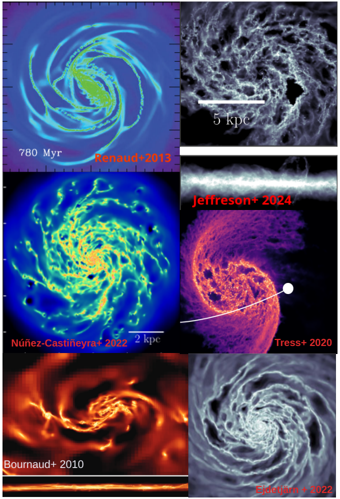


Vintergatan (Agertz+2021)

Galactic scale simulations

size: ∼100 kpc res.: ∼1-10 pc

Isolated or with idealised interactions. Many dwarf galaxies simulations.



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size: ∼100 kpc res.: ∼1-10 pc

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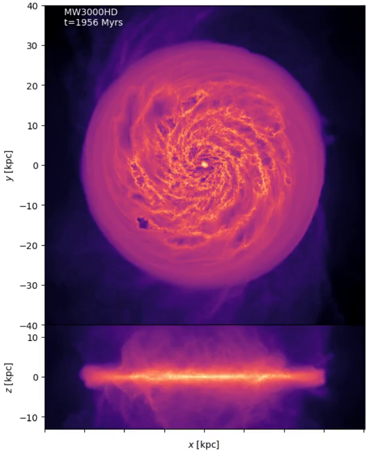
Advantages

- Possible to model ISM
- Disk dynamics
- Control on the parameters



Göller + ECOGAL in prep

Galactic scale simulations

size: ∼100 kpc res.: ∼1-10 pc

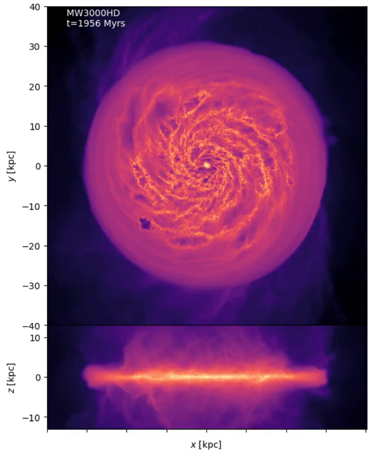
Isolated or with idealised interactions. Many dwarf galaxies simulations.

Advantages

- Possible to model ISM
- Disk dynamics
- Control on the parameters

Drawbacks

- Initial condition from analytical formula
    - Dark matter halo, bulge, stellar and gas disks



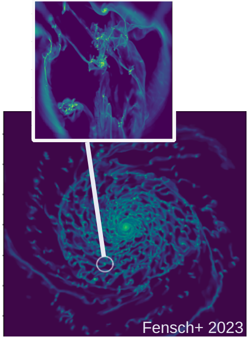
Göller + ECOGAL in prep

Galactic Zoom-in

size: ∼100 kpc res.: ∼ 0.1 pc

A region of the disk is refined and is followed as it rotates.

- Further refine the zone of interrest (Fensch+ 2023)

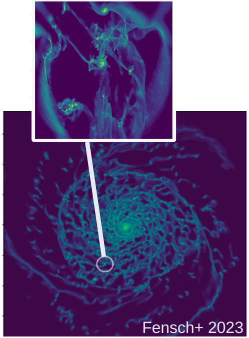


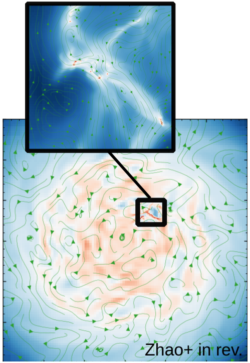
Galactic Zoom-in

size: ∼100 kpc res.: ∼ 0.1 pc

A region of the disk is refined and is followed as it rotates.

- Further refine the zone of interrest (Fensch+ 2023)
- Also decrease the resolution outside (Zhao+ in rev.)



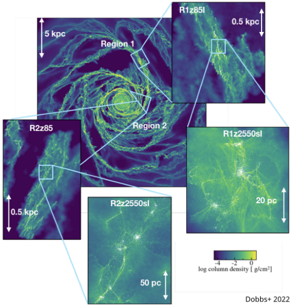


Galactic Zoom-in

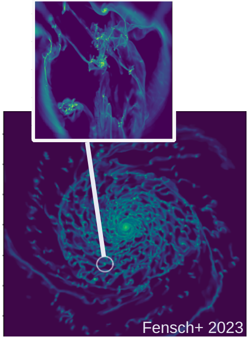
size: ∼100 kpc res.: ∼ 0.1 pc

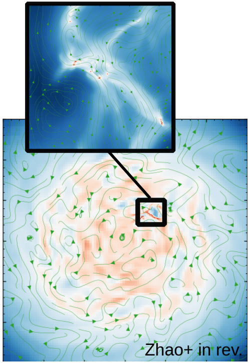
A region of the disk is refined and is followed as it rotates.

- Further refine the zone of interrest (Fensch+ 2023)
- Also decrease the resolution outside (Zhao+ in rev.)
- Isolate the region of interest (Dobbs+ 2022)



Dobbs+ 2022


Fensch+ 2023

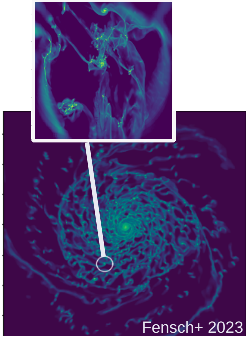

Zhao+ in rev.

Galactic Zoom-in

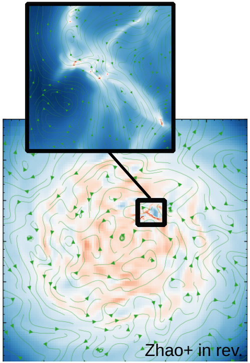
size: ∼100 kpc res.: ∼ 0.1 pc

Advantages

- Conserve galactic environement information (intiallly or live)
- Allow to probe properties on many scales



Fensch+ 2023



Zhao+ in rev.

Galactic Zoom-in

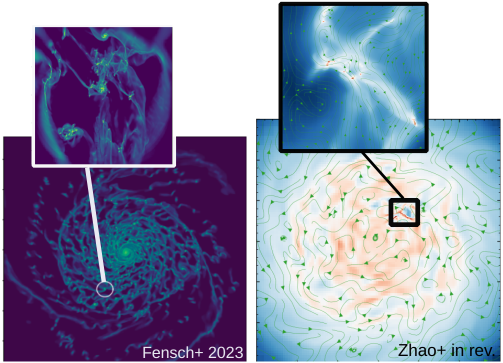
size: ∼100 kpc res.: ∼ 0.1 pc

Advantages

- Conserve galactic environement information (intiallly or live)
- Allow to probe properties on many scales

Drawbacks

- Very computation-expensive
- Difficulty at the boundary of the zoomed regions
- Need to have different subgrid models

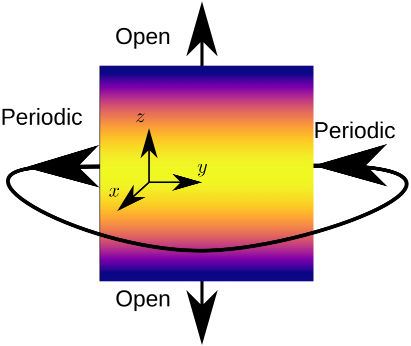


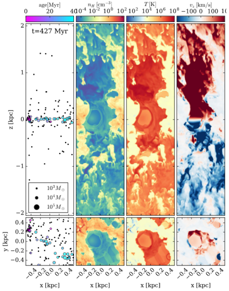
Fensch+ 2023

Zhao+ in rev.

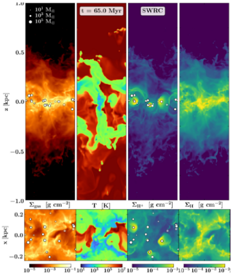
Stratified ISM patches

size: 0.2 - 1 kpc res.: 0.1-10pc

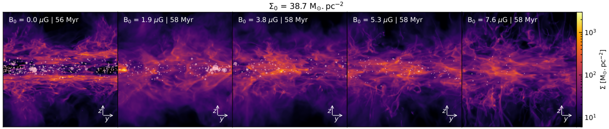




TIGRESS (Kim+ 2017)



SILCC (Walch+2015)



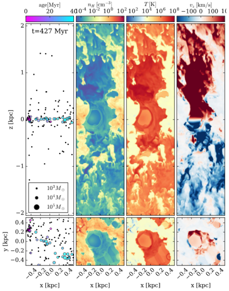
(Colling+ 2018, Brucy+ 2020,2023 - Colman+ 2022)

Stratified ISM patches

size: 0.2 - 1 kpc res.: 0.1-10pc

Advantages (pick one)

- Allow the use of more computationaly expensive models
- Better resolution
- Parameter study



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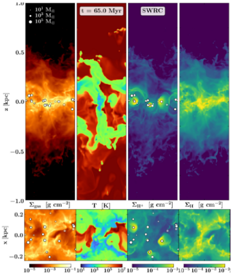

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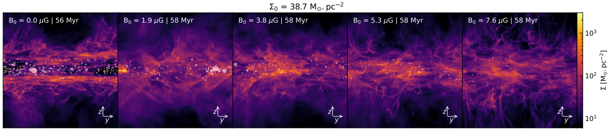


(Colling+ 2018, Brucy+ 2020,2023 - Colman+ 2022)

Stratified ISM patches

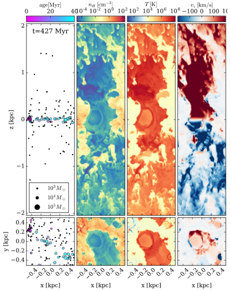
size: 0.2 - 1 kpc res.: 0.1-10pc

Advantages (pick one)

- Allow the use of more computationaly expensive models
- Better resolution
- Parameter study

Drawbacks

- Analytical initial conditions
- No (self-consistent) description of galactic dynamics



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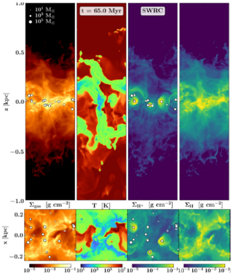

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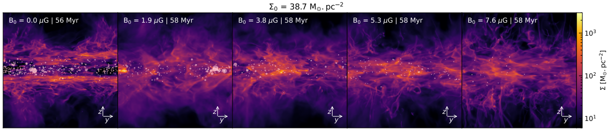
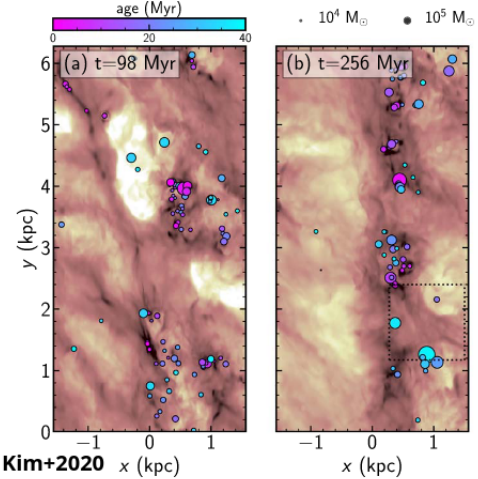
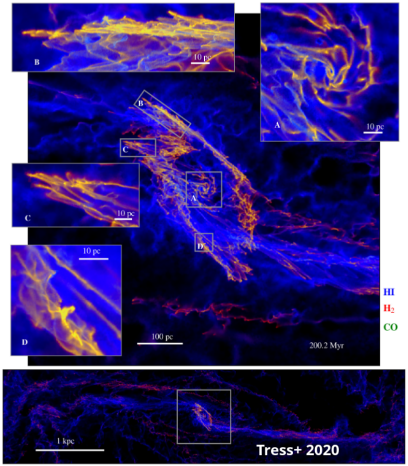


(Colling+ 2018, Brucy+ 2020,2023 - Colman+ 2022)

Special region simulations



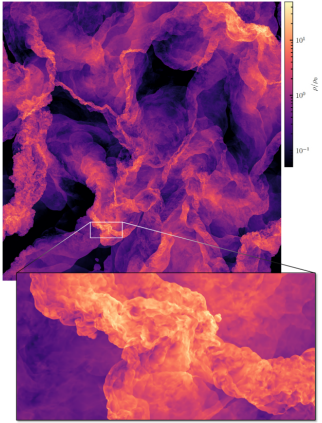


Local simulation of a spiral arm (Kim, Kim & Ostriker 2020)

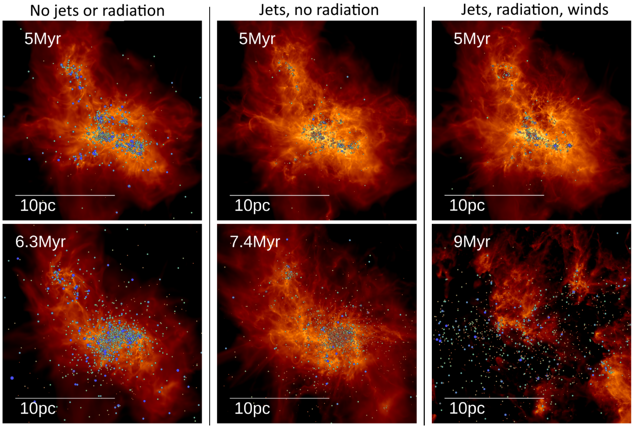
Simulation of the Galactic center (Tress+ 2020)

ISM boxes - Clouds simulation

Nice for simplified experiment (turbulent boxes), or to include even more physics

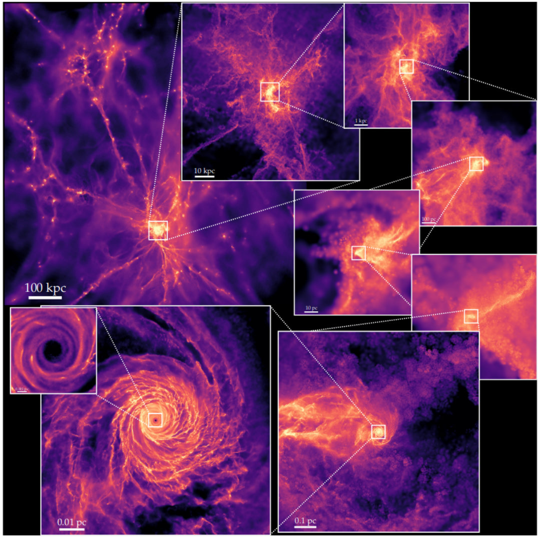


Federrath+ 2021 (10000^3 turbulent box simulation)



StarForge (Grudic+ 2021)

All in one simulation?

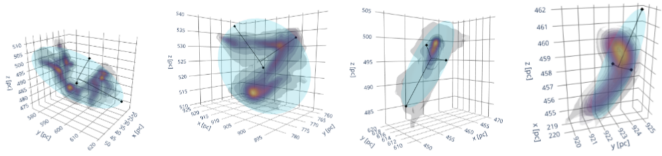


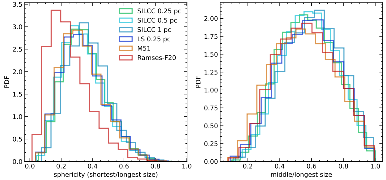
Hopkins et al. 2023.

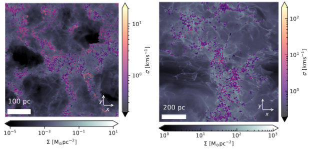
- Simulation over 8 orders of magnitude
- From Intergalactic medium (IGM) to the black hole accretion disk
- Different models for IGM/ISM with where star formation and feedback properties are averaged and smaller scales were indivual (proto)stars are tracked.

Comparison between stratified boxes and isolated galaxies

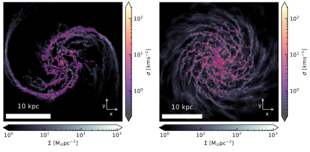
Clouds properties - Colman + ECOGAL (in rev)



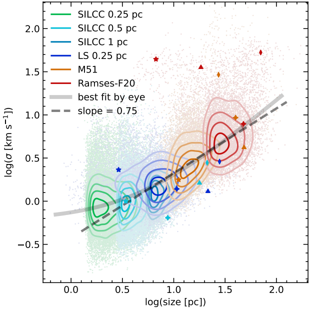




(a) SILCC-0.5pc-3μG simulation (b) LS simulation (weak driving)



(c) M51 simulation (d) Ramses-F20 simulation

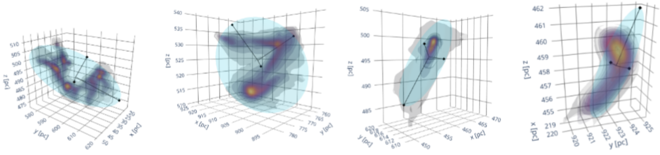


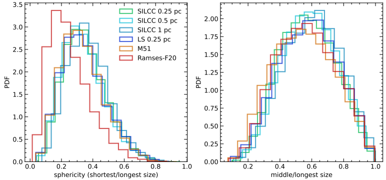
Comparison between 4 sets of simulations (stratified boxes and full galaxies, with/without magnetic field, isolated and interacting).

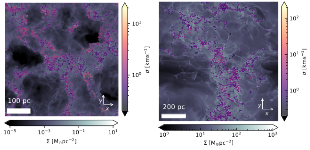
Consistent size-mass, size-velocity dispersion relations and similar shape distribution. Variations linked to resolution.

Comparison between stratified boxes and isolated galaxies

Clouds properties - Colman + ECOGAL (in rev)







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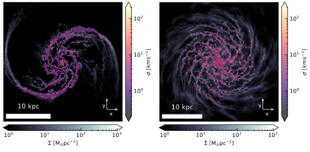

(c) M51 simulation

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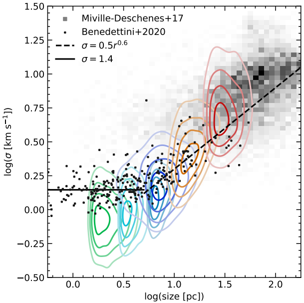

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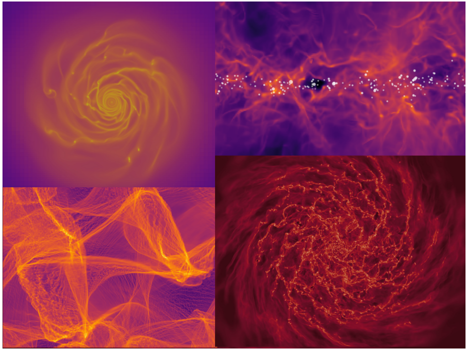
Summary: Types of galaxy simulation



The simulation setup should be chosen the same way as a lab experiment, with a hypothesis to prove or infirm, as well as the limits of the methods.

CC-BY-SA David Revoy

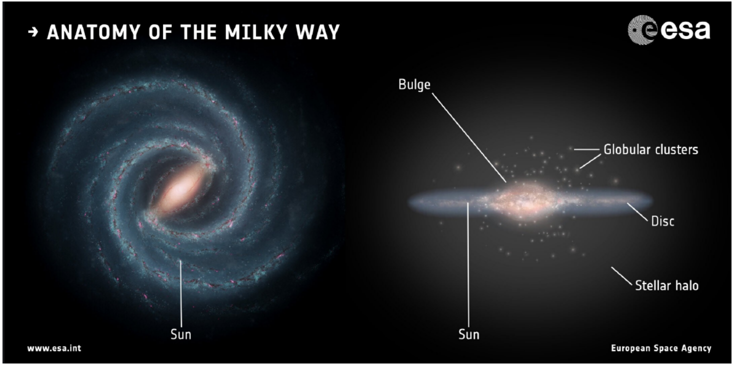
Outline

Simulation of galaxies

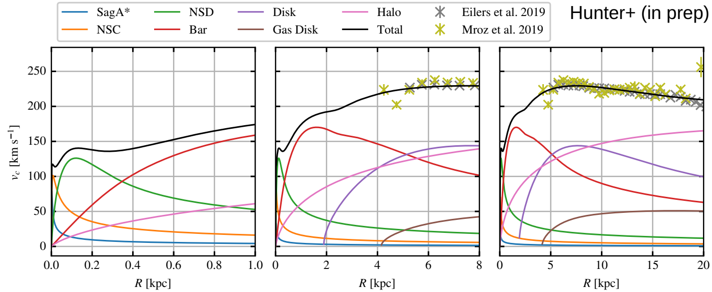
Structure of galaxies
- The galactic potential
- Spiral arms
- The Bar

Regulation of star formation

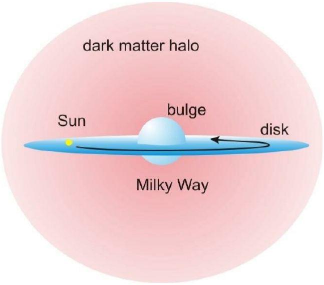
Conclusion



Galactic potential (for the Milky Way)

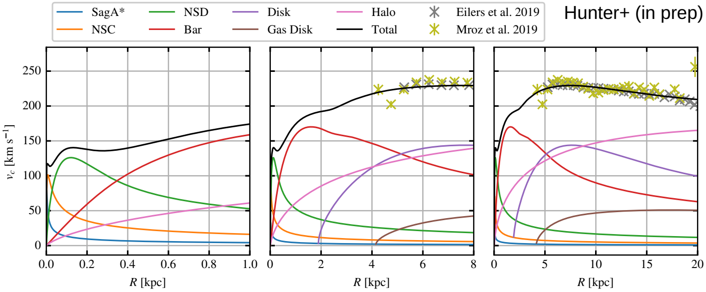


Hunter+ (in prep)



- **Central zone: the bulge**: Sag A*, Nuclear stellar cluster (NSC), Nuclear stellar disk (NSD)

Galactic potential (for the Milky Way)



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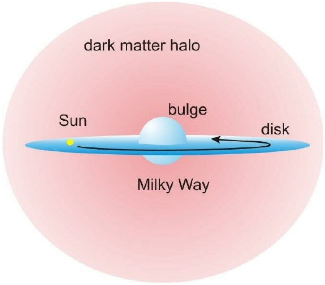

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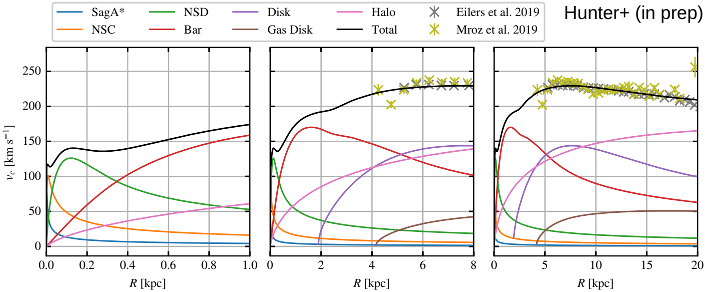

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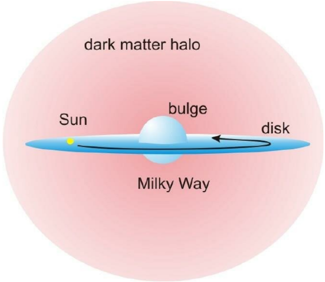

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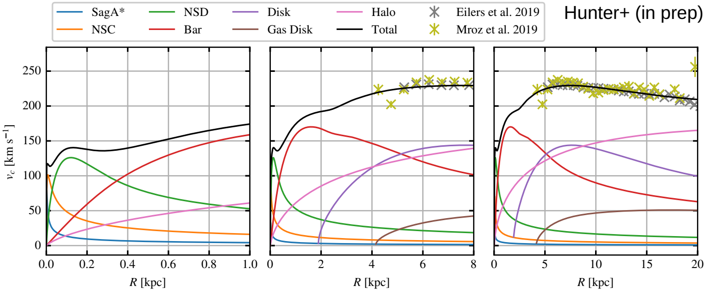

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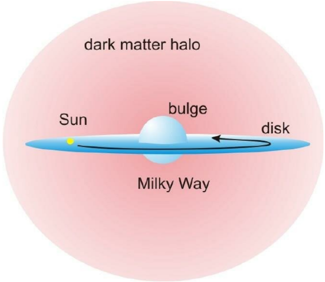


- **Central zone: the bulge**: Sag A*, Nuclear stellar cluster (NSC), Nuclear stellar disk (NSD)
- Thin and thick stellar disk, gas disks (HI and H_2)
- Dark matter halo
- **Non axisymmetric components** Bar & Spiral arm

Spiral Arms

What are they?

A material structure created by differential rotation?

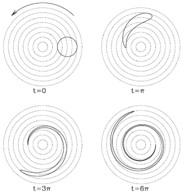


Fig. 11.4. The creation of a spiral arm. A circular patch at $t = 0$ is sheared into a spiral arm due to the differential rotation in the direction indicated by the arrow.

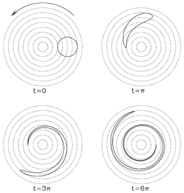
Mo 2010. Video credits: CC-BY-SA Ingo Berg

Spiral Arms

What are they?

A material structure created by differential rotation?

→ No, because of the winding up problem (derivation on the board - Binney 2008).



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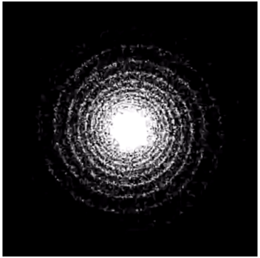

Mo 2010. Video credits: CC-BY-SA Ingo Berg

Spiral Arms

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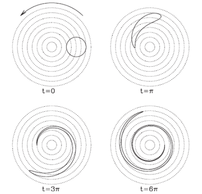
→ No, because of the winding up problem (derivation on the board - Binney 2008).

Lin-Shu theory: spiral arms are **density waves** in solid rotation with $\Omega_p \neq \Omega$ except at the corotation radius.



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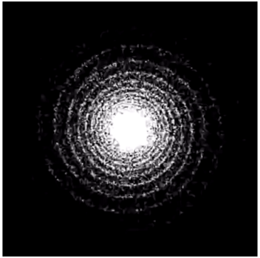

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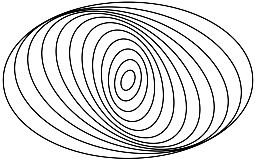
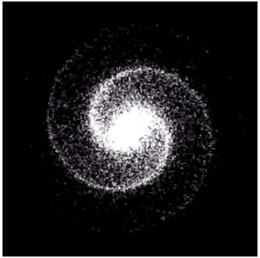
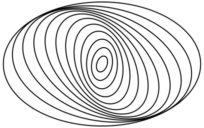
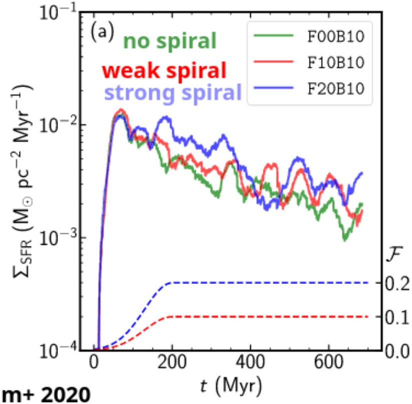




Spiral Arms & Star formation

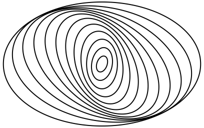




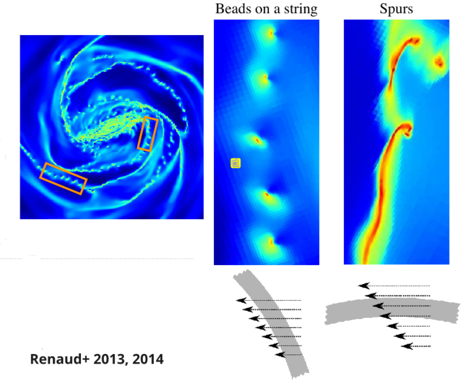
Kim+ 2020

- Spiral arms are the galactic traffic jams: molecular clouds are preferentially found there,
- this is where most of the star formation occurs (but not more efficiently with respect to the available gas mass)

Spiral Arms & Star formation



- Spiral arms are the galactic traffic jams: molecular clouds are preferentially found there,
- this is where most of the star formation occurs (but not more efficiently with respect to the available gas mass)
- A diversity of structures, that may depend on the pitch angle
  - high pitch angle (radial spiral) → weak shear → "beads on a string" fragmentation
  - small pitch angle (azymuthal spiral) → strong shear → "beads on a string" fragmentation



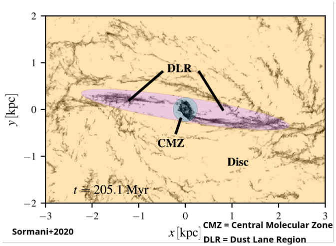
Renaud+ 2013, 2014

The Bar and the Central Molecular Zone (CMZ)

Bar channels matter towards the galactic center.
x1 orbits: elliptic trajectories alongside the bar
x2 orbits: perpendicular to the bar

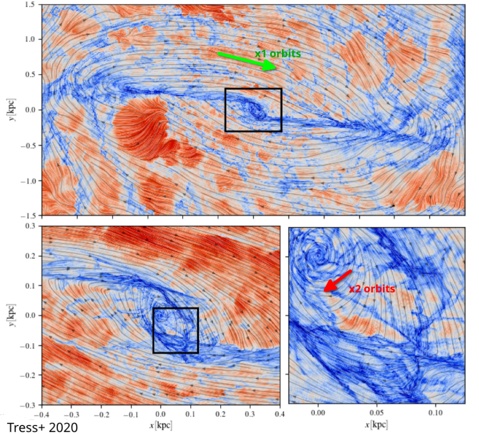
Consequences

- High column denisty in the central zone
- High shear and velocity dispersion
- Low star formation rate efficiency



Sormani+2020

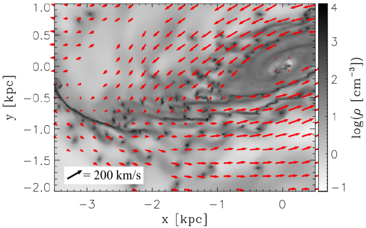
CMZ = Central Molecular Zone
DLR = Dust Lane Region



Tress+ 2020

The Bar

Tips of the bar Another traffic jam area.
Increased cloud collision rate.
Also linked with the start of the spiral arms → more traffic jam.



The Bar

Tips of the bar Another traffic jam area.
Increased cloud collision rate.
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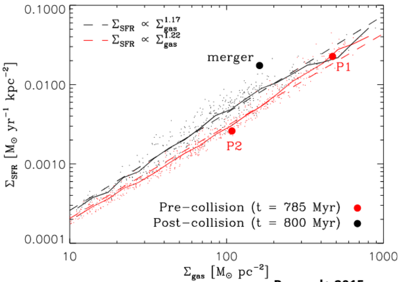
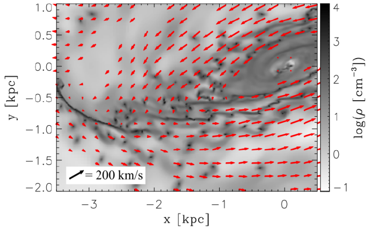
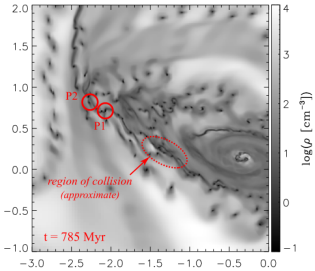
Cloud-Cloud collisions increase the star formation efficiency (Renaud+ 2015, Hunter+2023).



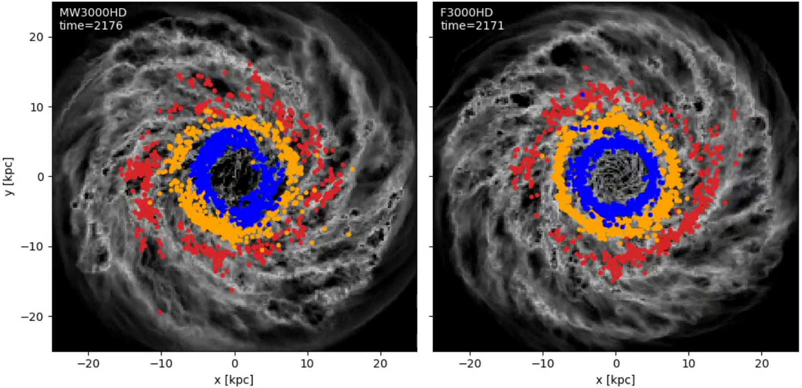
Renaud+ 2015





Renaud+2015

Effect of the bar on stellar migration



Movie. Göller + ECOGAL in prep

Left: imposed bar & spiral arm potential.
Right: flat constant rotation curve potential
Dots: stars born at 4 kpc, 8 kpc, 12 kpc.

Outline

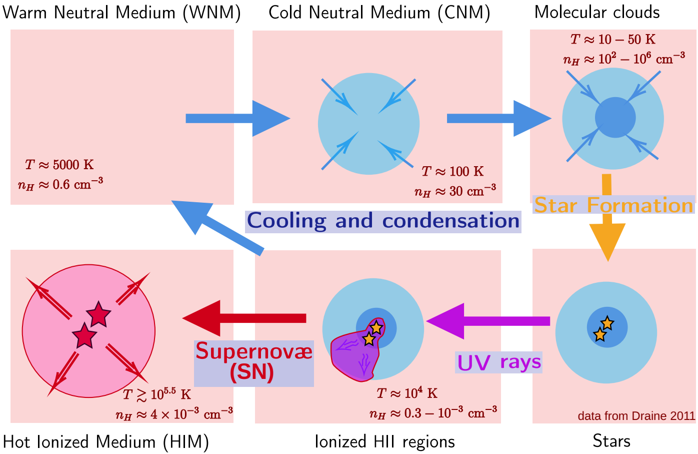
Simulation of galaxies

Structure of galaxies

Regulation of star formation
- Need for regulation
- Disk stability
- Feedback processes
- Magnetic field
- Turbulence

Conclusion

Gas cycle & star formation rate (**SFR**)



Warm Neutral Medium (WNM)

$T \approx 5000$ K
$n_H \approx 0.6$ cm^{-3}

Cold Neutral Medium (CNM)

$T \approx 100$ K
$n_H \approx 30$ cm^{-3}

Molecular clouds

$T \approx 10 - 50$ K
$n_H \approx 10^2 - 10^6$ cm^{-3}

Cooling and condensation

Star Formation

Hot Ionized Medium (HIM)

$T \gtrsim 10^{5.5}$ K
$n_H \approx 4 \times 10^{-3}$ cm^{-3}

Supernovæ (SN)

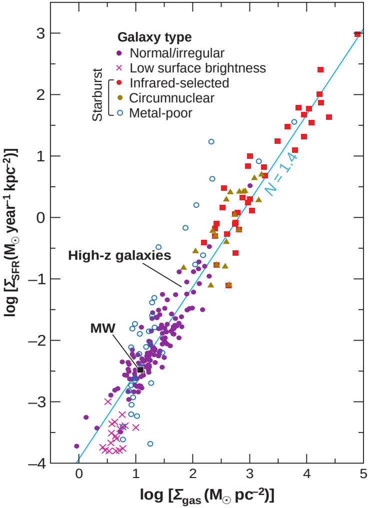
Ionized HII regions

$T \approx 10^4$ K
$n_H \approx 0.3 - 10^{-3}$ cm^{-3}

UV rays

Stars

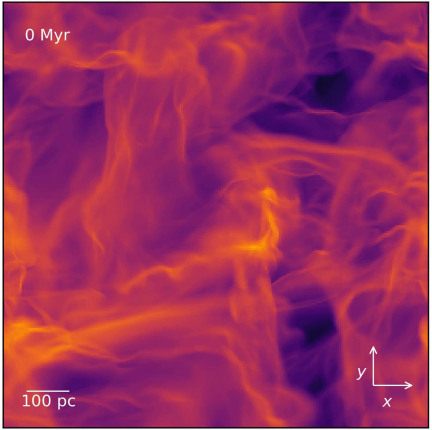
data from Draine 2011



Kennicutt+ 2012

What ~~triggers~~ stops star formation?

because gravity would consume all the gas quickly



$$SFR_{\mathrm{grav}} \approx \frac{M_{\mathrm{dense}}}{t_{\mathrm{free-fall}}} \approx 460\ \mathrm{M}_\odot \cdot \mathrm{yr}^{-1}$$

$$\gg SFR_{\mathrm{obs}} \approx 2\ \mathrm{M}_\odot \cdot \mathrm{yr}^{-1}$$

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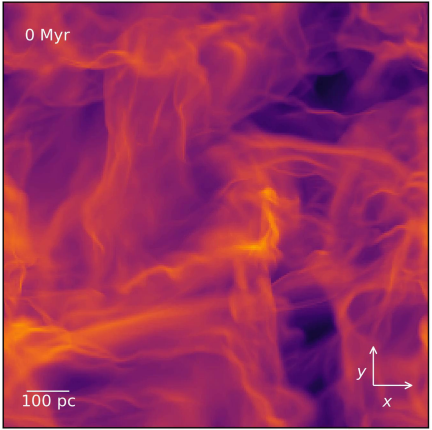

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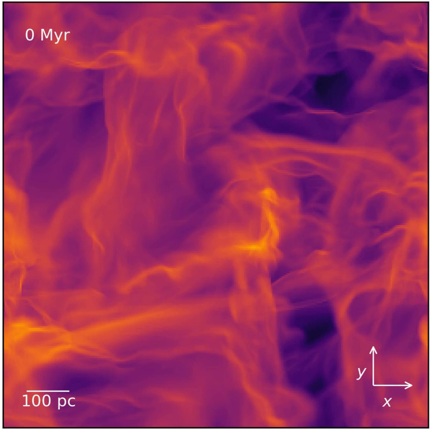

$$SFR_{\mathrm{grav}} \approx \frac{M_{\mathrm{dense}}}{t_{\mathrm{free-fall}}} \approx 460\ \mathrm{M}_{\odot} \cdot \mathrm{yr}^{-1}$$

$$\gg SFR_{\mathrm{obs}} \approx 2\ \mathrm{M}_{\odot} \cdot \mathrm{yr}^{-1}$$

There should be a regulation mecanism

I will give some insights from simulation ... → for analytical models, see Blakesley Buckart's slides .

Stability parameter for disks

Local instability criterion for an axisymmetric thin disk.

Toomre parameter for a gaseous disk

$$Q_g := \frac{\kappa \sigma_g}{\pi G \Sigma_0} > 1$$

Toomre parameter for a stellar disk

$$Q_\star := \frac{\kappa \sigma_\star}{3.36 G \Sigma_0} > 1$$

But what about a multifluid disk?

Stability parameter for multifluid disks

Idea: the instability is given by the most unstable fluid

Stability parameter for multifluid disks

Idea: the instability is given by the most unstable fluid

Wang & Silk (1994) parameter

$$Q_{\mathrm{WS}} := \left(\frac{1}{Q_\star} + \frac{1}{Q_g} \right)^{-1}$$

Stability parameter for multifluid disks

Idea: the instability is given by the most unstable fluid

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Issues

- Fluids can have different weights
- Fluids can be more or less coupled

Stability parameter for multifluid disks

Idea: the instability is given by the most unstable fluid

Wang & Silk (1994) parameter

$$Q_{\mathrm{WS}} := \left(\frac{1}{Q_\star} + \frac{1}{Q_g} \right)^{-1}$$

Issues

- Fluids can have different weights
- Fluids can be more or less coupled

Romeo & Falstad (2013) parameter

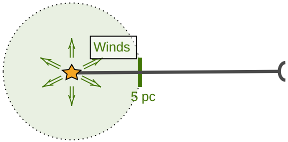
$$Q_{\mathrm{RF}} := \left(\sum_i \frac{1}{Q_i} \frac{W_i}{T_i} \right)^{-1}$$

Stellar feedback

See Fabian Schneider's lecture

Feedback processes we think has a significant impact on the SFR

- **Stellar winds**



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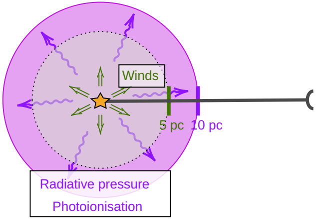
- **(Radiative pressure)**



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Feedback processes we think has a significant impact on the SFR

- **Stellar winds**
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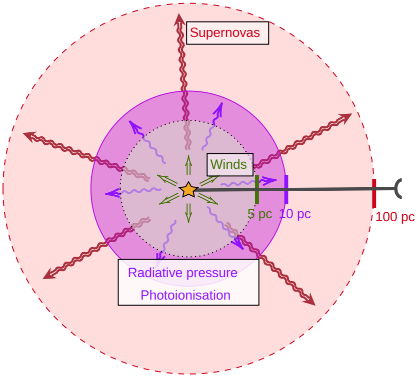
- **Photoionization**
- **Supernovae**



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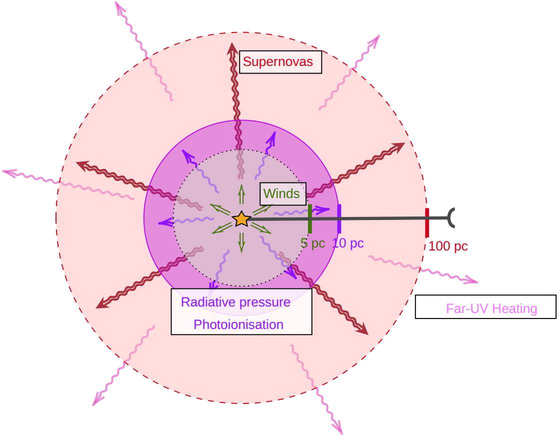

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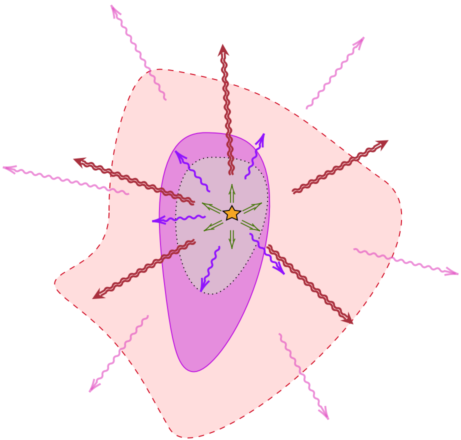
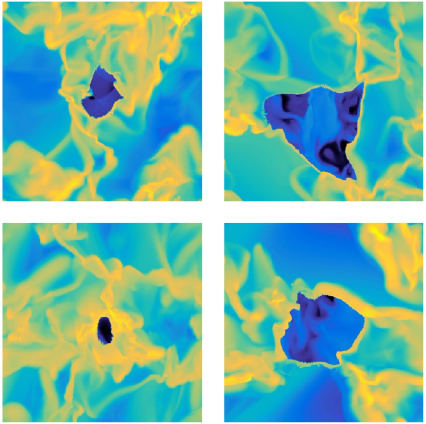
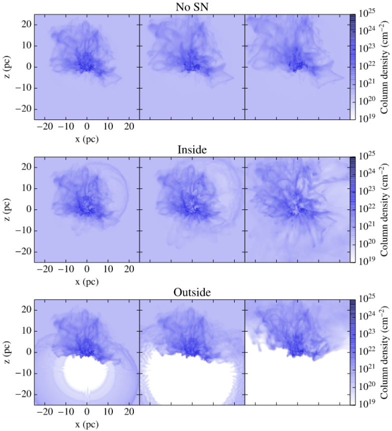


Where the supernova explodes matters

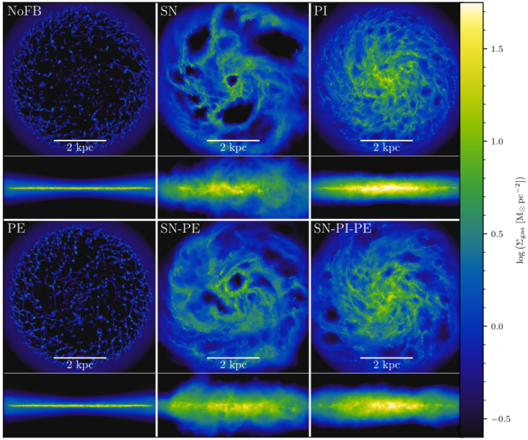


Ohlin+ 2019: Explosion of a supernova in different realisation of turbulence

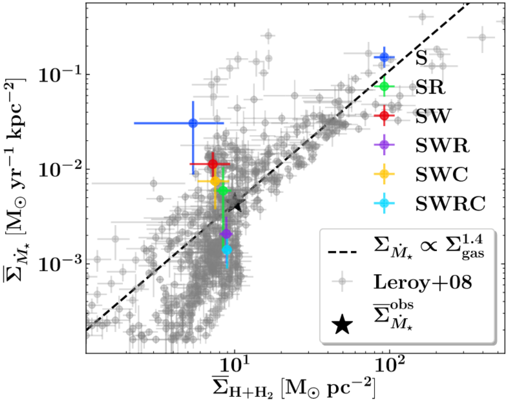


Iffrig+ 2015: Explosion at different position relative to a molecular clouds

Different feedback effects interact non-linearly



Smith+ 2021. SN = Supernova, PI = Photoinization, PE = Photo-electric heating

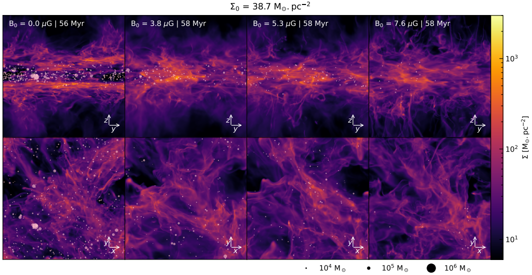


Rathjen+ 2021. S = Supernova, R = Photoinization, W = Winds, C = Cosmic rays

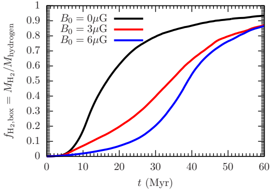
Magnetic field and Star Formation

Remarkable effects of magnetic on Star formation at the galactic scale

- Magnetic pressure increases the scale height of the disk

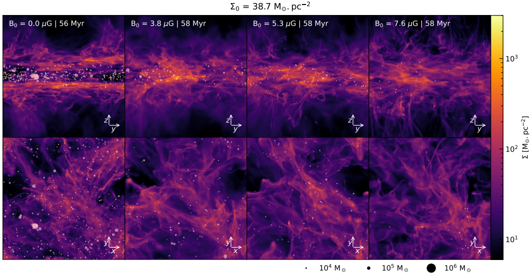


Magnetic field and Star Formation



Remarkable effects of magnetic on Star formation at the galactic scale

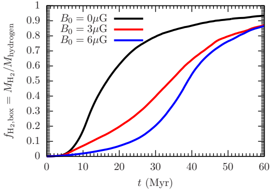
- Magnetic pressure increases the scale height of the disk
- Delayed formation of H_2.

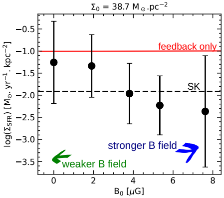


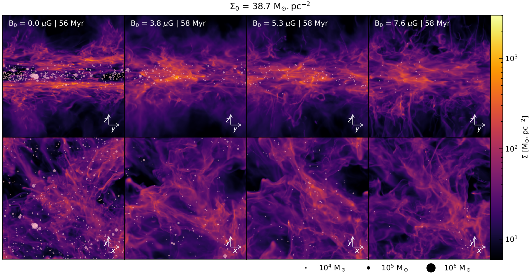
Magnetic field and Star Formation

Remarkable effects of magnetic on Star formation at the galactic scale

- Magnetic pressure increases the scale height of the disk
- Delayed formation of H_2.
- Reduced star formation Rate

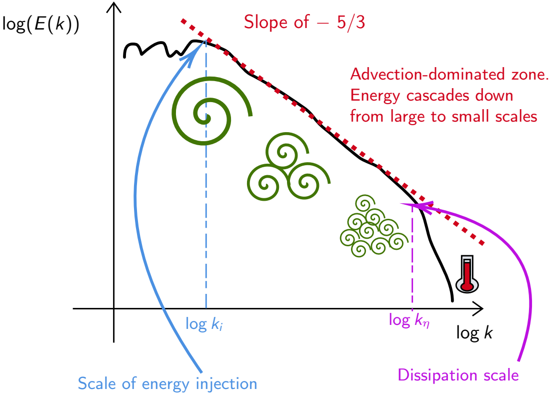






Turbulence

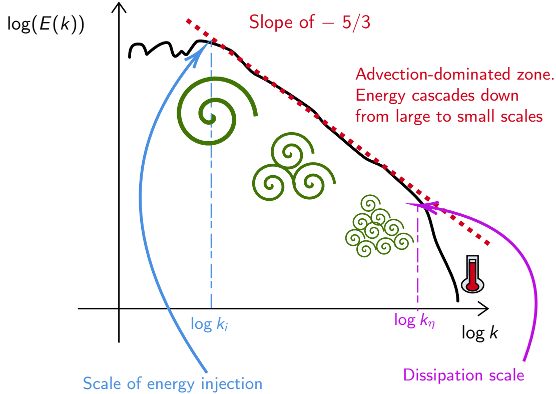
see Sebastien Galtier's & Blakesley Buckart's lectures



Richardson cascade for incompressible turbulence
(**but ISM is compressible**)

Turbulence

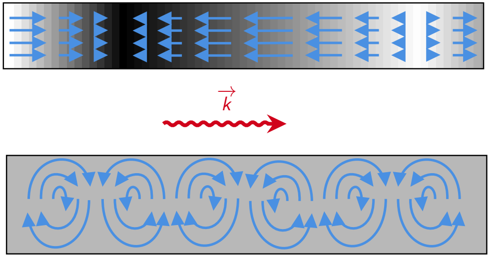
see Sebastien Galtier's & Blakesley Buckart's lectures



Richardson cascade for incompressible turbulence
(**but ISM is compressible**)

Turbulence can be composed of

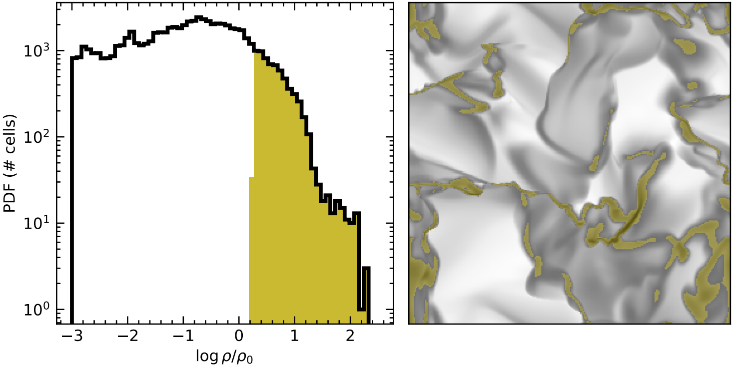
- compressive modes



- or solenoidal modes

Single-Freefall models

Krumholz & McKee 2005 (KM), Padoan & Nordlund 2011/17 (PN)

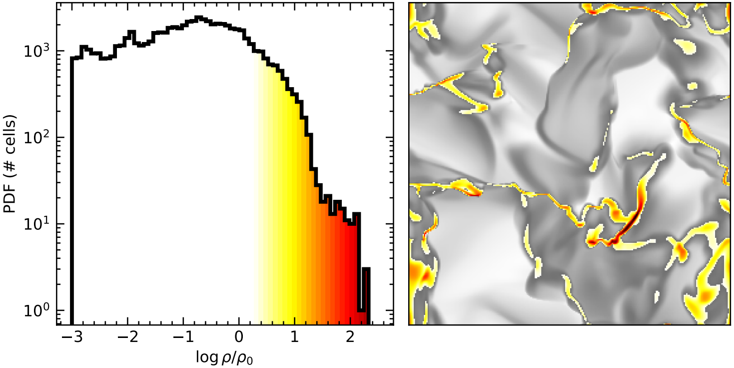


$$SFR_{ff} = \epsilon \frac{\tau_{ff}^{0}}{\tau_{ff,cr}\phi_t} \int_{\ln \widetilde{\rho}_{crit}}^{\infty} \widetilde{\rho} \mathcal{P}(\delta) d\widetilde{\delta}, \qquad (1)$$

Note: $\widetilde{\rho}_{crit}$ usually does not consider turbulent disruption.

Multi-freefall models

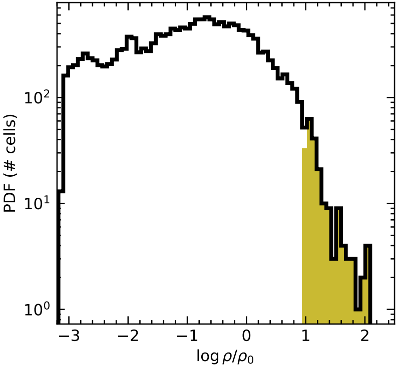
Hennebelle & Chabrier 2011/13 (simplified), Federrath & Klessen 2012

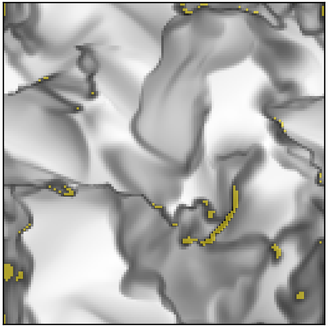


$$SFR_{ff}^{c} = \epsilon \int_{\delta_{crit}}^{\infty} \frac{\tau_{ff}^{0}}{\tau_{ff}(\rho)\phi_t} \widetilde{\rho} \mathcal{P}(\delta) d\delta$$

The Hennebelle & Chabrier (HC) theory

Hennebelle & Chabrier 2011/13

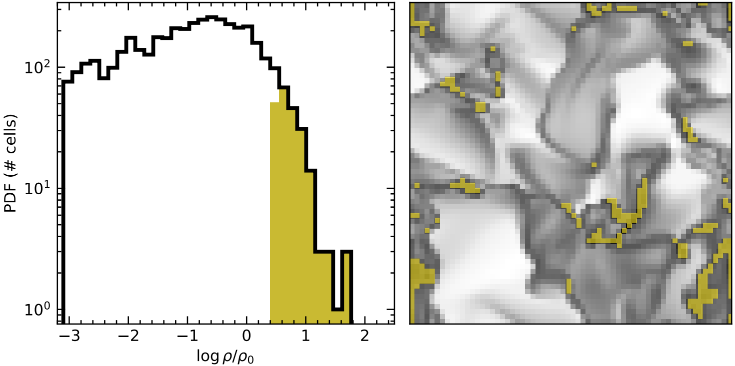




$$\widetilde{SFR} = \int_0^{\widetilde{M_{\rm cut}}} \frac{\tilde{\mathcal{N}}(\tilde{M})\tilde{M}}{\tilde{\tau}_{\rm freefall}(R)} d\tilde{M}. \tag{2}$$

The Hennebelle & Chabrier (HC) theory

Hennebelle & Chabrier 2011/13



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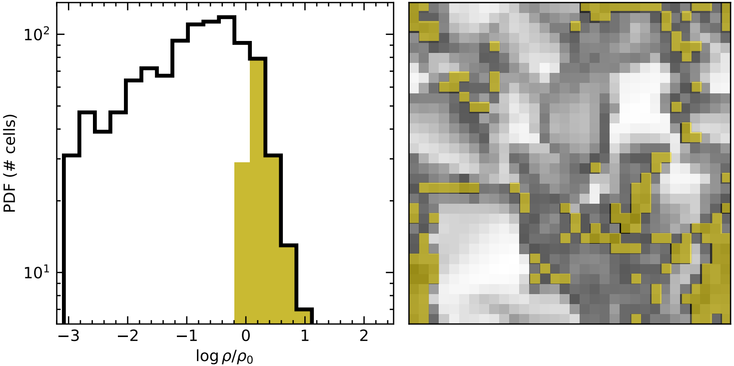

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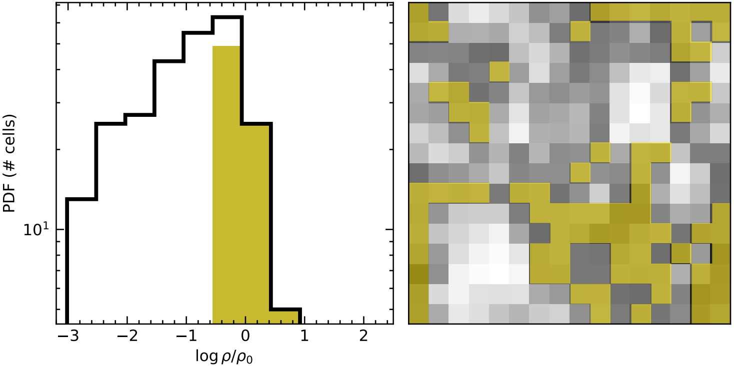

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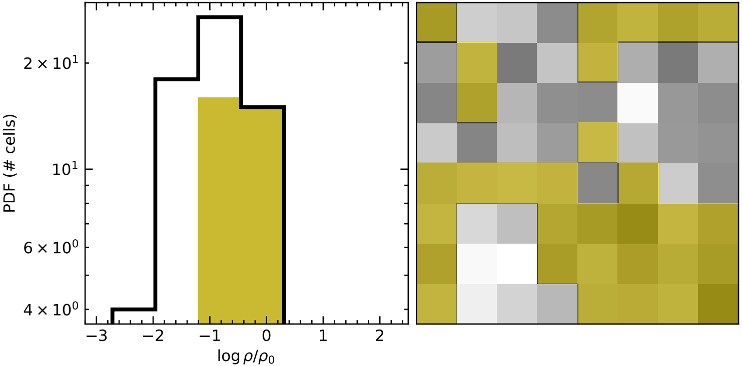

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Driving turbulence in simulation

- Self-consistent driving
    - Cosmologic context
    - Disc dynamics
    - Stellar feedback

Driving turbulence in simulation

- Self-consistent driving
  - Cosmologic context
  - Disc dynamics
  - Stellar feedback
- Modelized turbulence
  - Decaying turbulence
  - **Driven turbulence**

Driven turbulence: Ornstein-Uhlenbeck process (Schmidt+ 2006). We add a "new force" $\boldsymbol{f}$ of strength f_{rms} defined by its Fourier components $\hat{\boldsymbol{f}}$

$$\boldsymbol{f}(\boldsymbol{x}, t) = g(\zeta) f_{\mathrm{rms}} \int \hat{\boldsymbol{f}}(\boldsymbol{k}, t) e^{i\boldsymbol{k}\cdot x} \mathrm{d}^3\boldsymbol{k}$$

The components are evolved over time (decaying part with correlation time T + new infenitesimal random seed $d\boldsymbol{W}_t$)

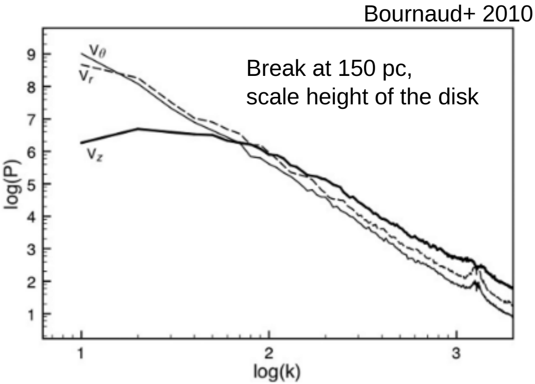
$$\mathrm{d}\hat{\boldsymbol{f}}(\boldsymbol{k}, t) = -\hat{\boldsymbol{f}}(\boldsymbol{k}, t)\frac{\mathrm{d}t}{T} + F_0(\boldsymbol{k})\boldsymbol{P}_\zeta(\boldsymbol{k})\,\mathrm{d}\boldsymbol{W}_t.$$

The solenoidal fraction is given by ζ. $g(\zeta)$ is a normalizing coefficient.

$$\boldsymbol{P}_\zeta(\boldsymbol{k}) = \zeta\boldsymbol{P}^{\perp}(\boldsymbol{k}) + (1-\zeta)\boldsymbol{P}^{\parallel}(\boldsymbol{k})$$

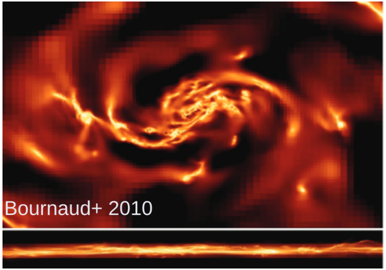
$F_0(\boldsymbol{k})$ weights the wavenumbers on which the driving is done.

Velocity power spectrum in galactic scale simulations



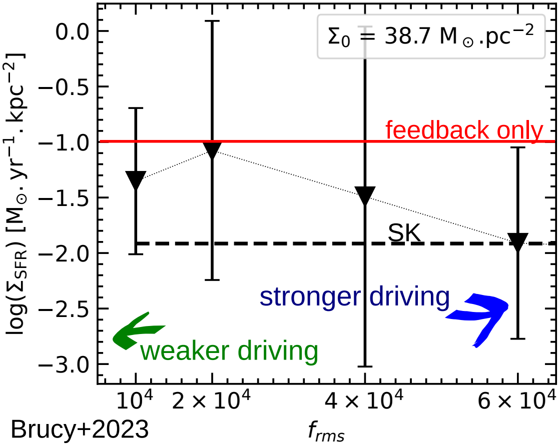
Break at 150 pc,
scale height of the disk

Transition from 3D to 2D turbulence at the scale height of the disk.

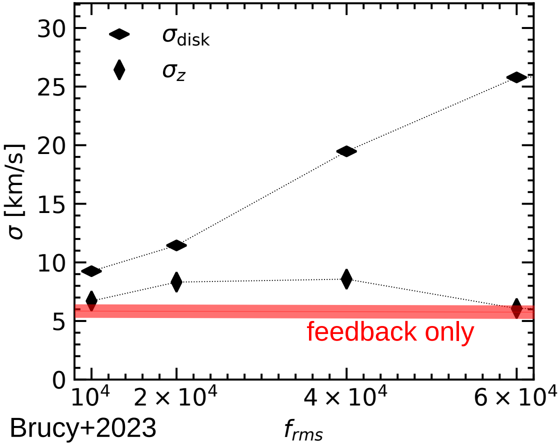


Influence the driving strength

Study of the influence of strength of the turbulent driving f_{rms}.



Brucy+2023

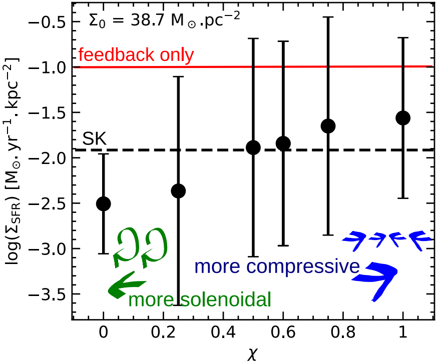


Brucy+2023

2D large scale turbulent driving reduce SFR and generates strong anisotropic velocities.

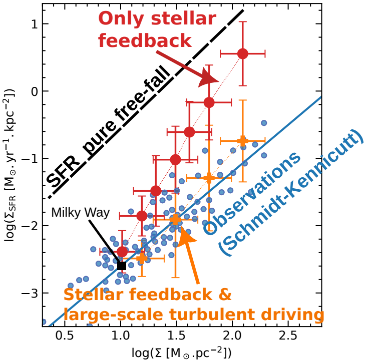
Influence of the compressibility

Study of the influence of the compressive forcing fraction χ.

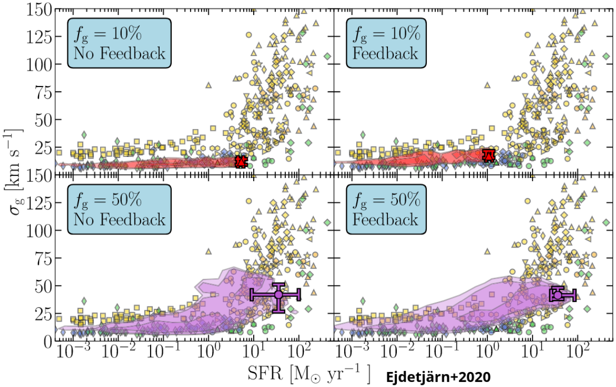


Solenoidal driving is more efficient at quenching SFR by a factor 10.

Large-scale turbulence may also be needed to explain SFR and velocity dispersion in gas rich galaxies



Brucy+ 2023. See also Rathjen+ 2023 which match SK with high magnetic fields and more feedback included.



Galactic-scales simulation. High velocity dispersion in the galaxy are not feedback driven but originate from galactic dynamics. They however do not match observed values.

What I hope you learned

Simulations code

- There are many families of simulation codes
- Good subgrid modeling is key
- Simulations are numerical experiments

Galactic structure

- Disks dynamics are determined by the differents components of the Galactic potential,
- Bar and spiral arms create traffic jam where density is increased,
- Shear plays an important role in shaping structure and star formation.

Regulation of star formation

- Magnetic fields, stellar feedback, and large scale turbulence all contribute to reduce star formation
- Which process dominates depends on where you are in the galaxy and in the gas content.