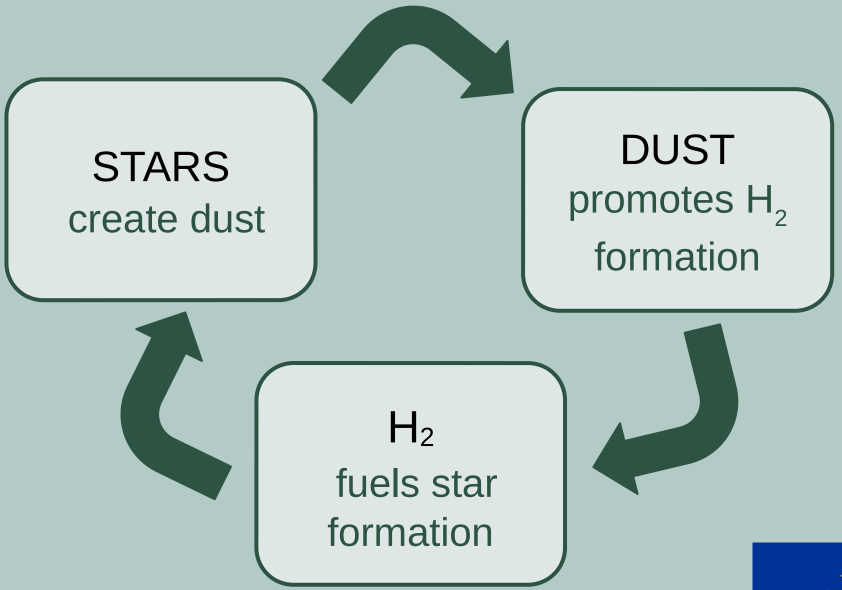
Intertwined Formation of H_2, Stars, and Dust in Cosmological Simulations

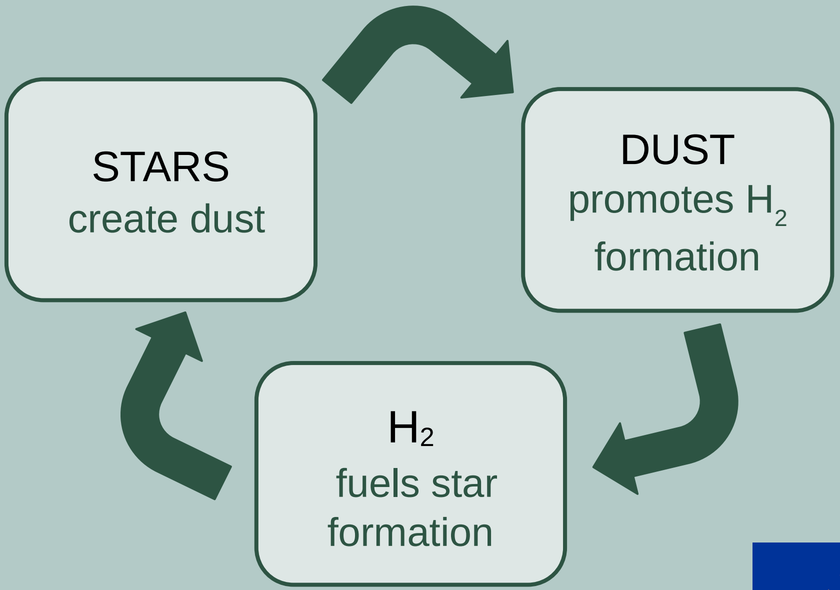
Cinthia Ragone-Figueroa
Also starring...
GL Granato, M. Parente,
G. Murante, M. Valentini
S. Borgani, U. Maio



cinthia.ragone@unc.edu.ar Ljubljana-2024

Intertwined Formation of H_2, Stars, and Dust in Cosmological Simulations

Cinthia Ragone-Figueroa
Also starring...
GL Granato, M. Parente,
G. Murante, M. Valentini
S. Borgani, U. Maio



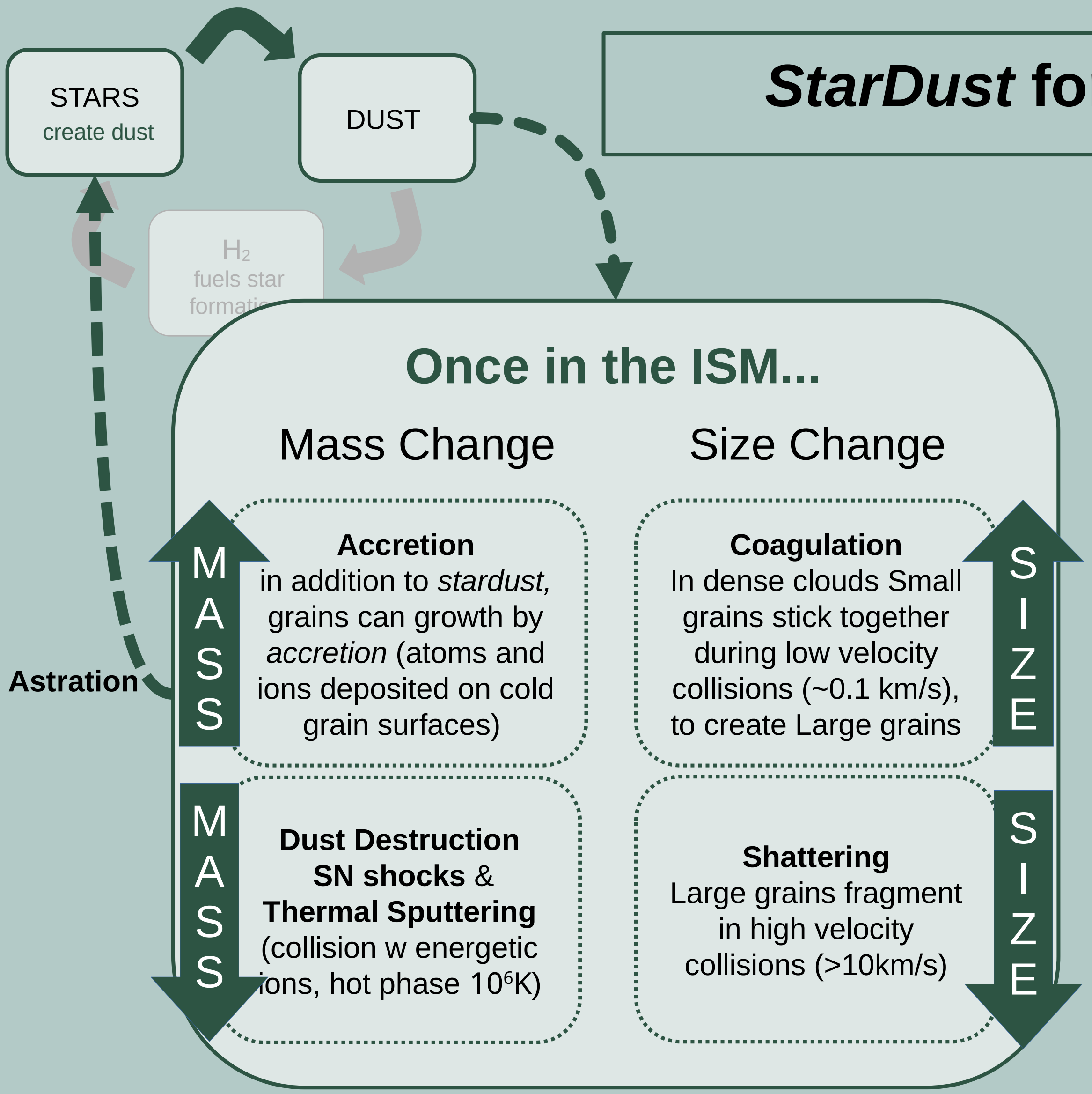
Disclaimer:
No `OpenGADGET3` here,
`P-GADGET+MUPPI` instead

cinthia.ragone@unc.edu.ar

Ljubljana-2024

***StarDust* formed in Stellar Outflows**

The ejected material from stars (AGBs & SNe), enriched with heavy elements like C, Si, O, and Fe, cools and condenses into solid particles: ***StarDust***

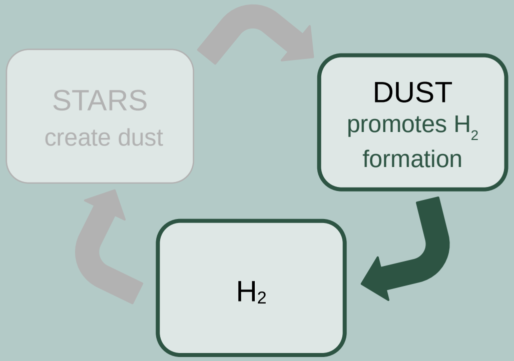


Dust is a very active element in the ISM

- ✔ Modifies the radiation field
- ✔ Enhances radiative pressure
- ✔ Contributes to hot gas (>10^6K) cooling

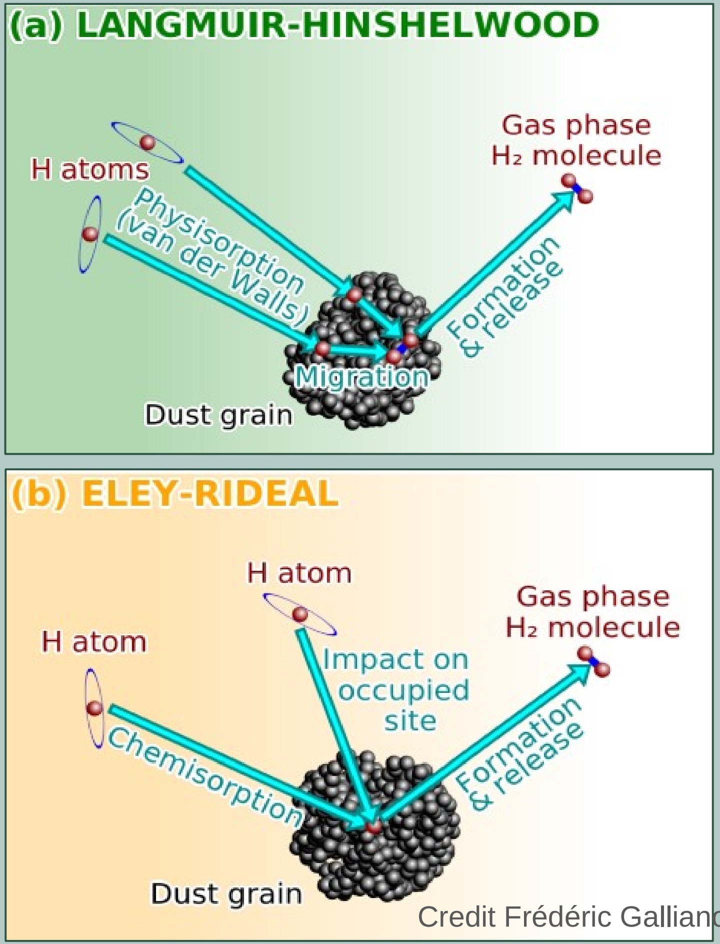
...

✔ Catalyzes **H_2 formation**



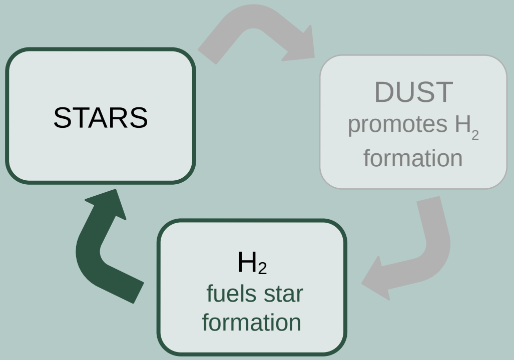
Dust Promotes H_2 Formation

- Direct H_2 formation in gas very inefficient due to H_2 molecule difficulty to radiate away the excess energy. Relevant only in primordial conditions.
- When H atoms meet and form H_2 on a grain, the grain structure absorbs the excess energy and the molecule stabilizes.
- It takes place primarily on small grains.
- The most abundant molecule in the Universe is H_2.
  Molecular Clouds are made of H_2+He+a few % metals (gas and dust)



Credit Frédéric Galliano

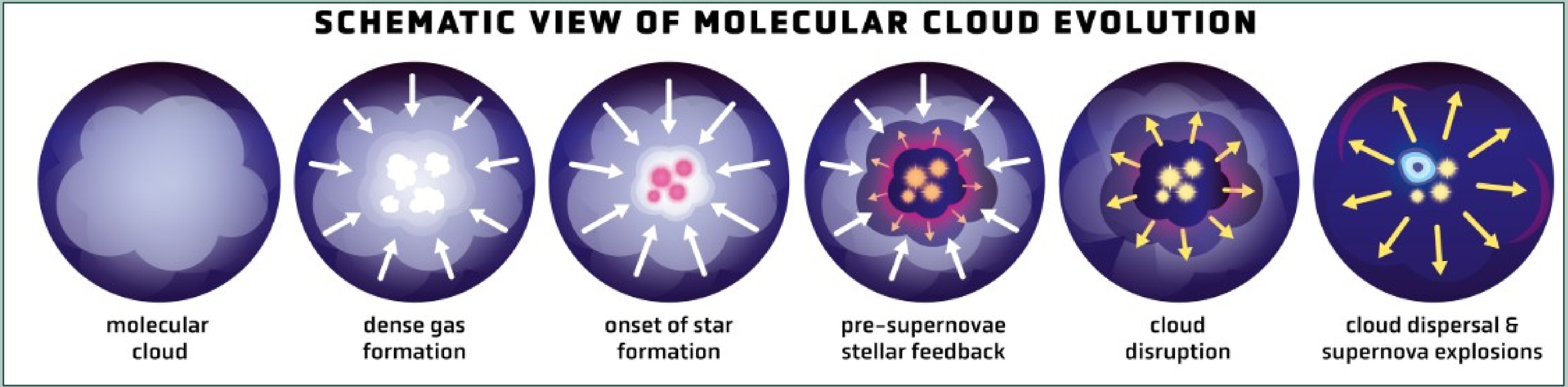
cinthia.ragone@unc.edu.ar



Molecular Clouds as Bricks for Star Formation

Timescales:
5-20Myr before the onset of intense high-mass SF
Fast <5Myr clearing of gas before the first SNe
Lifetime: 20-40Myr for M33, Miura+ (2012)
Lifetime: (27 +/- 12) Myr for MW, Murray (2011)

Schinnerer & Leroy 2024



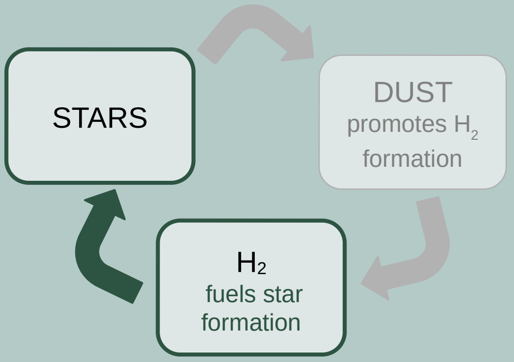
cloud begins as an over-density of cold gas (predominantly H2)

A subset of the gas achieves high column and volume densities

Stars form from this dense material.

pre-SN: gas clearing by winds, radiation, and thermal gas pressure

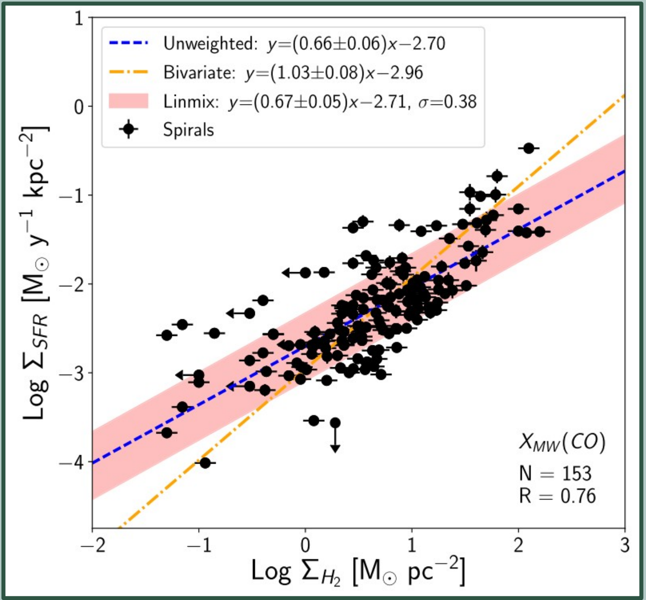
Newly formed massive stars rapidly impact their surrounding birth material via radiation and winds, reshaping or even disrupting the cloud



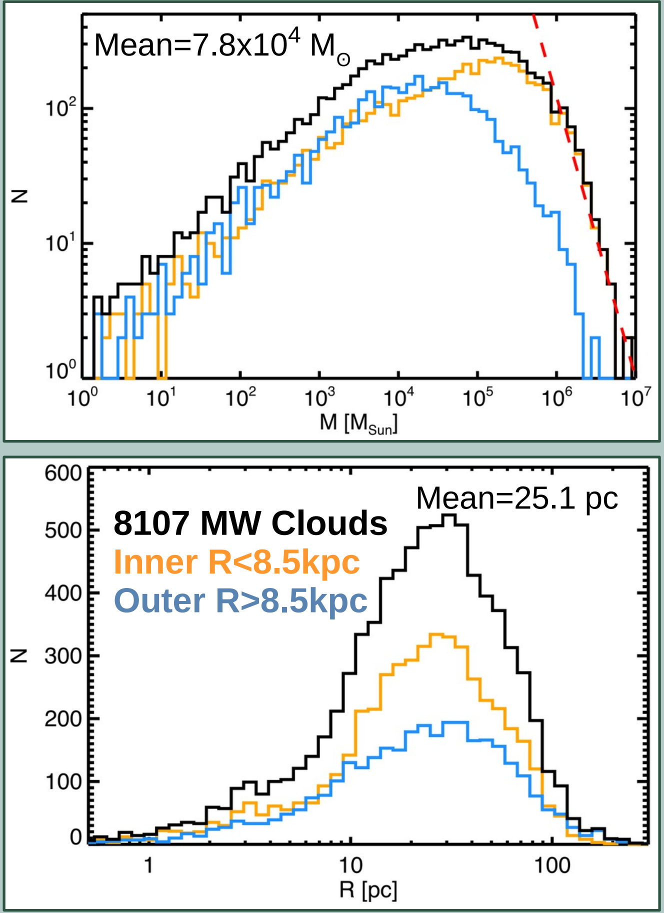
Molecular Clouds as Bricks for Star Formation

H_2 is the Main constituent of Molecular Clouds

- ✔ MCs are the densest and coldest component of the ISM
- ✔ Very complex entities
  - Gravitation
  - Magnetic fields
  - Heating & Cooling
  - Turbulence & Shocks



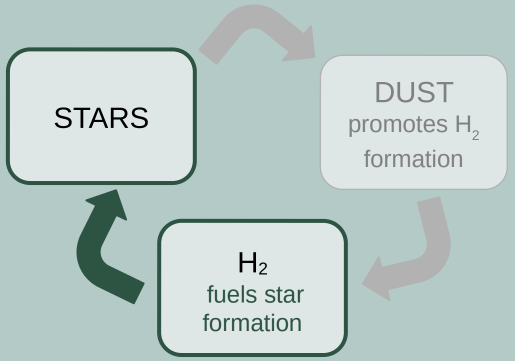
De los Reyes & Kennicutt (2019)



cinthia.ragone@unc.edu.ar

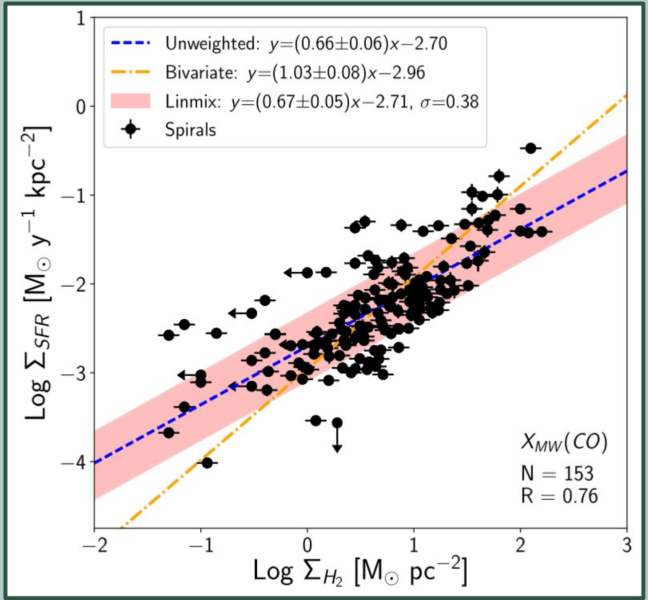
Miville-Deschenes, Murray & Lee, 2017

Molecular Clouds as Bricks for Star Formation

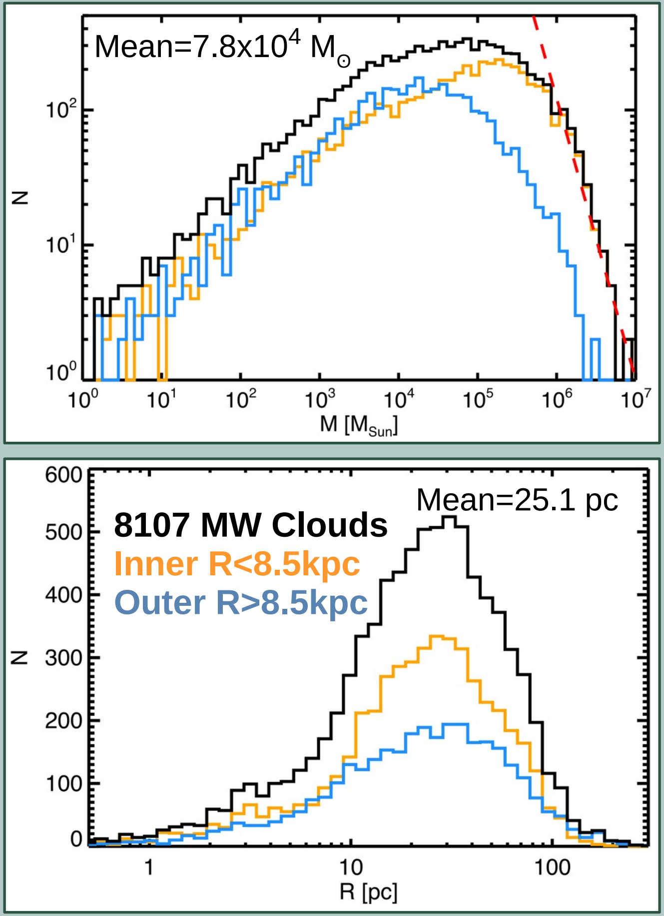


H_2 is the Main constituent of Molecular Clouds

- ✔ MCs are the densest and coldest component of the ISM
- ✔ Very complex entities
  - Gravitation
  - Magnetic fields
  - Heating & Cooling
  - Turbulence & Shocks



De los Reyes & Kennicutt (2019) INTEGRATED



Miville-Deschenes, Murray & Lee, 2017

Typical Masses: 10^4 - 10^5 $M_\odot$
Typical Sizes: 20 - 30 pc

Not Resolved in Cosmological Simulations

Cosmological simulations cover a volume of at least a few (tens of) Mpc

SF modeling from first principle is impossible in this context due to complex physical mechanisms across vast scale range (> 10 orders of magnitude in size).

Mass and energy transfers between phases in MP particles regulated by simple differential equations describing cooling, star formation and feedback”s”. SAM-like

Murante+10,15

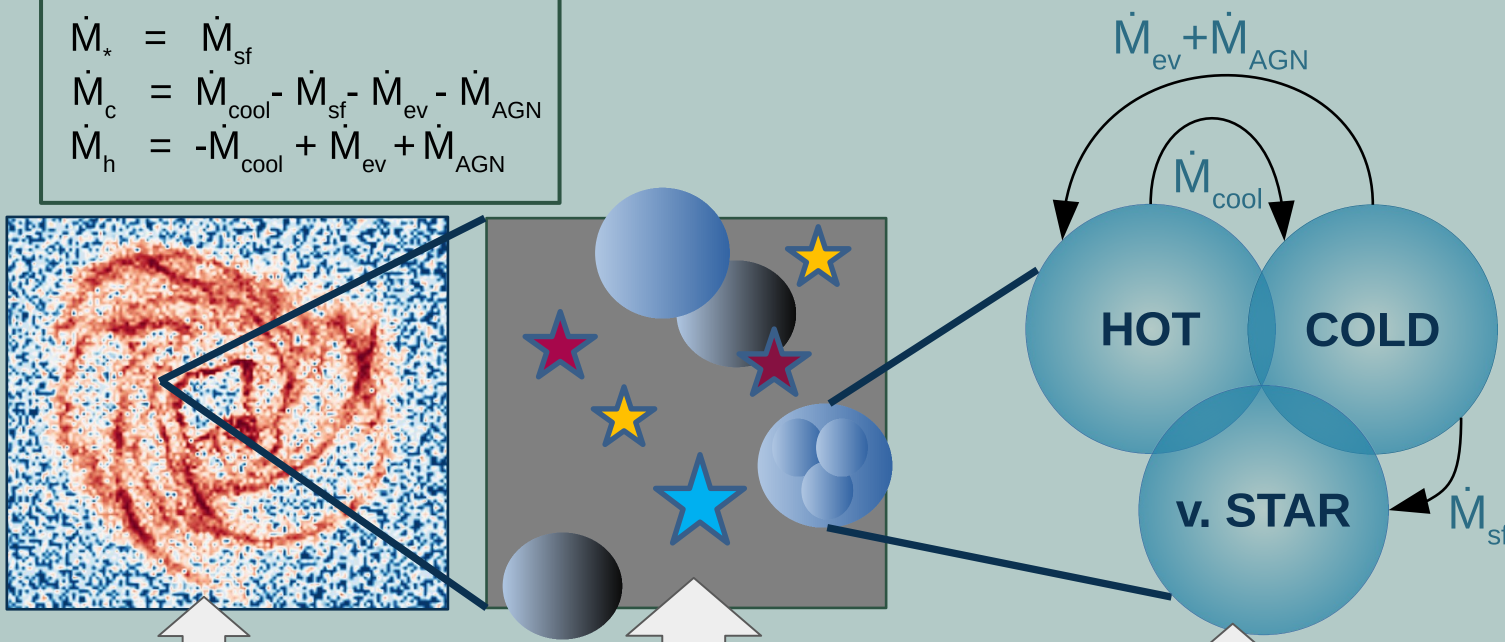
MUPPI (MUlti Phase Particle Integrator)

A subgrid model for Star Formation and Feedback”s”

AGN, Valentini+20

MUPPI mass flows differential equations:

$$\dot{M}_* = \dot{M}_{sf}$$
$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$
$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$



A simulated galaxy

a bunch of particles
DM, starts, gas

A Multi-Phase gas particle
$n > 0.01 cm^{-3}$
$T < 5x10^{4}K$

$SFR = \varepsilon \times M_{MOL} / t_{dyn,c}$

ORIGINAL MUPPI

MUPPI (MUlti Phase Particle Integrator)

Murante+10,15

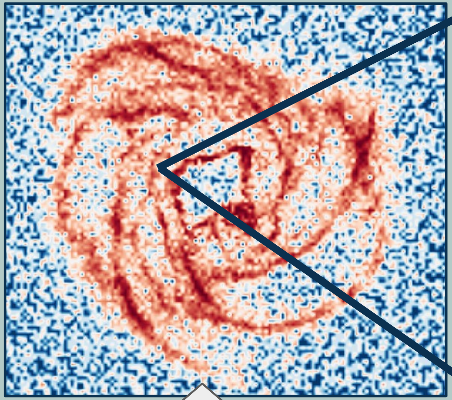
A subgrid model for Star Formation and Feedback"s"

AGN, Valentini+20

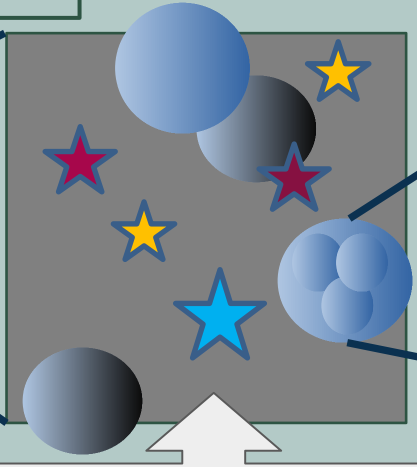
Mass and energy transfers between phases in MP particles regulated by simple differential equations describing cooling, star formation and feedback"s". SAM-like

MUPPI mass flows differential equations:

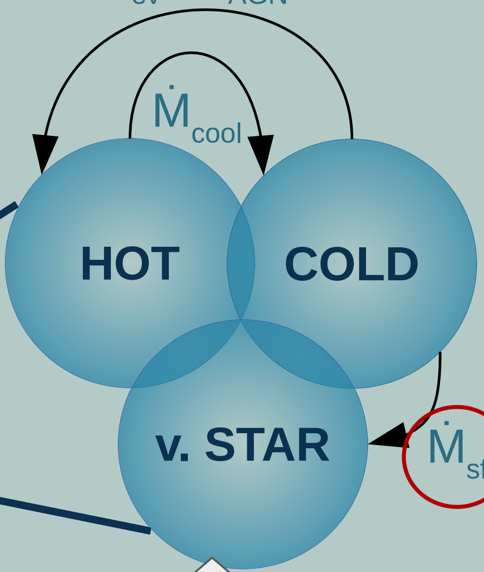
$$\dot{M}_* = \dot{M}_{sf}$$
$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$
$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$



A simulated galaxy



a bunch of particles DM, starts, gas



A Multi-Phase gas particle
$n > 0.01 cm^{-3}$
$T < 5x10^4 K$

$$SFR = \varepsilon \times M_{MOL} / t_{dyn,c}$$

ORIGINAL MUPPI

Mass and energy transfers between phases in MP particles regulated by simple differential equations describing cooling, star formation and feedback"s". SAM-like

MUPPI (MUlti Phase Particle Integrator)

Murante+10,15

A subgrid model for Star Formation and Feedback"s"

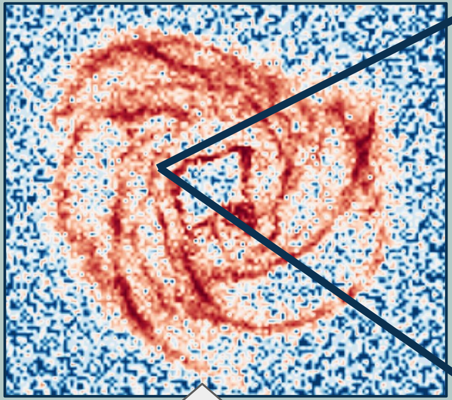
AGN, Valentini+20

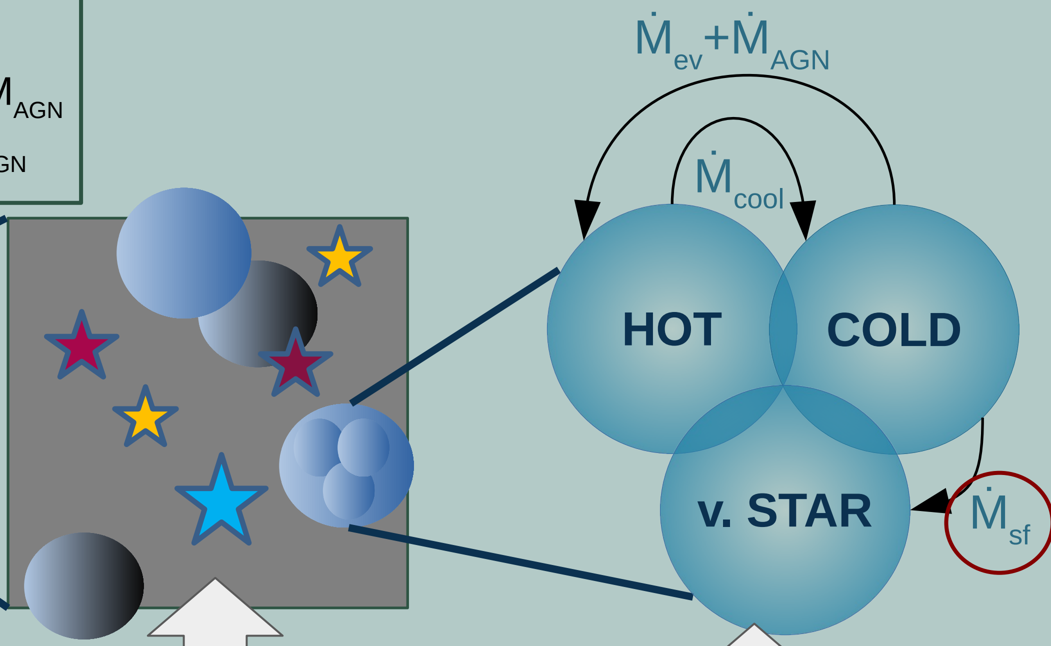
MUPPI mass flows differential equations:

$$\dot{M}_* = \dot{M}_{sf}$$

$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$

$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$





?

$$SFR = \varepsilon \times M_{MOL} / t_{dyn,c}$$

A simulated galaxy

a bunch of particles
DM, starts, gas

A Multi-Phase gas particle
$n > 0.01 cm^{-3}$
$T < 5 \times 10^4 K$

ORIGINAL MUPPI

Mass and energy transfers between phases in MP particles regulated by simple differential equations describing cooling, star formation and feedback"s". SAM-like

MUPPI (MUlti Phase Particle Integrator)

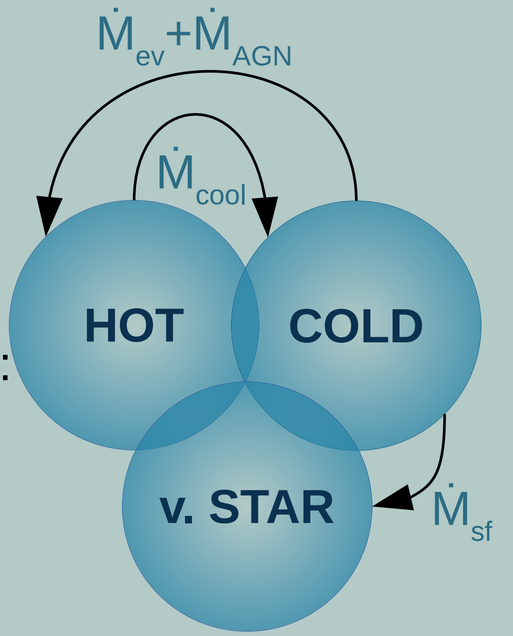
Murante+10,15

A subgrid model for Star Formation and Feedback"s"

AGN, Valentini+20

MUPPI mass flows differential equations:

$$\dot{M}_* = \dot{M}_{sf}$$
$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$
$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$



?

SFR = ε x M_{MOL} / $t_{dyn,c}$

fmol := M_{MOL} / M_{COLD} estimated by a prescription:

$$f_{mol} = \frac{1}{1 + P_0/P},$$

fmol = fmol(P) "inspired" by Blitz, Rosolowsky+ works (calibrated with **LOCAL** observations)

Alternatively, fmol = fmol(Z, Σ) Krumholz+ theoretical works

ORIGINAL MUPPI

Mass and energy transfers between phases in MP particles regulated by simple differential equations describing cooling, star formation and feedback"s". SAM-like

Murante+10,15

MUPPI (MUlti Phase Particle Integrator)

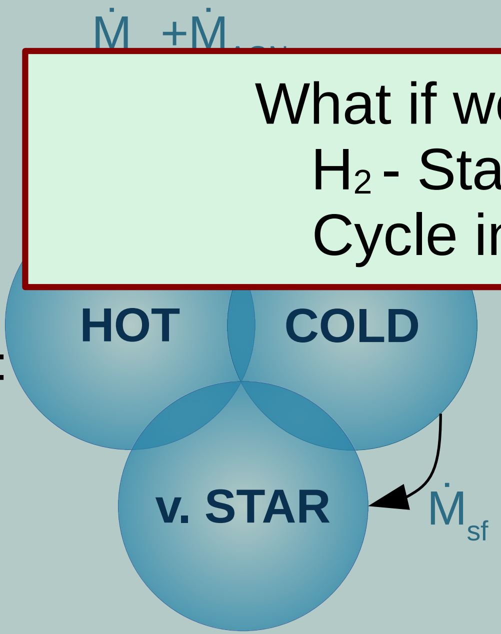
A subgrid model for Star Formation and Feedback"s"

AGN, Valentini+20

MUPPI mass flows differential equations:

$$\dot{M}_* = \dot{M}_{sf}$$
$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$
$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$

What if we use the H_2 - Star - Dust Cycle instead?



?

SFR = ε x M_{MOL} / $t_{dyn,c}$

fmol := M_{MOL} / M_{COLD} estimated by a prescription:

$$f_{\rm mol} = \frac{1}{1 + P_0/P},$$

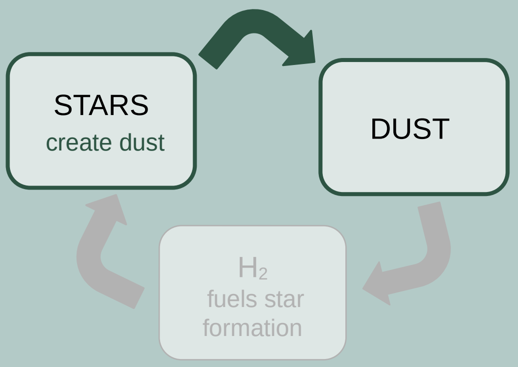
fmol = fmol(P) "inspired" by Blitz, Rosolowsky+ works (calibrated with **LOCAL** observations)

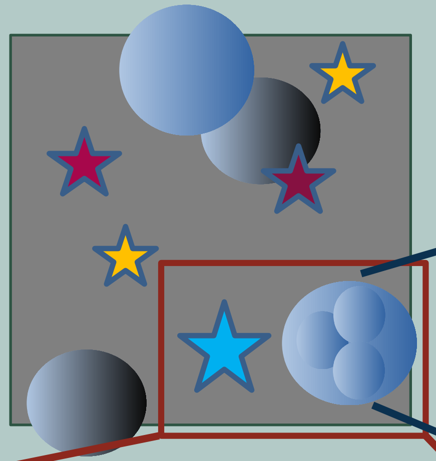
Alternatively, fmol = fmol(Z, Σ) Krumholz+ theoretical works

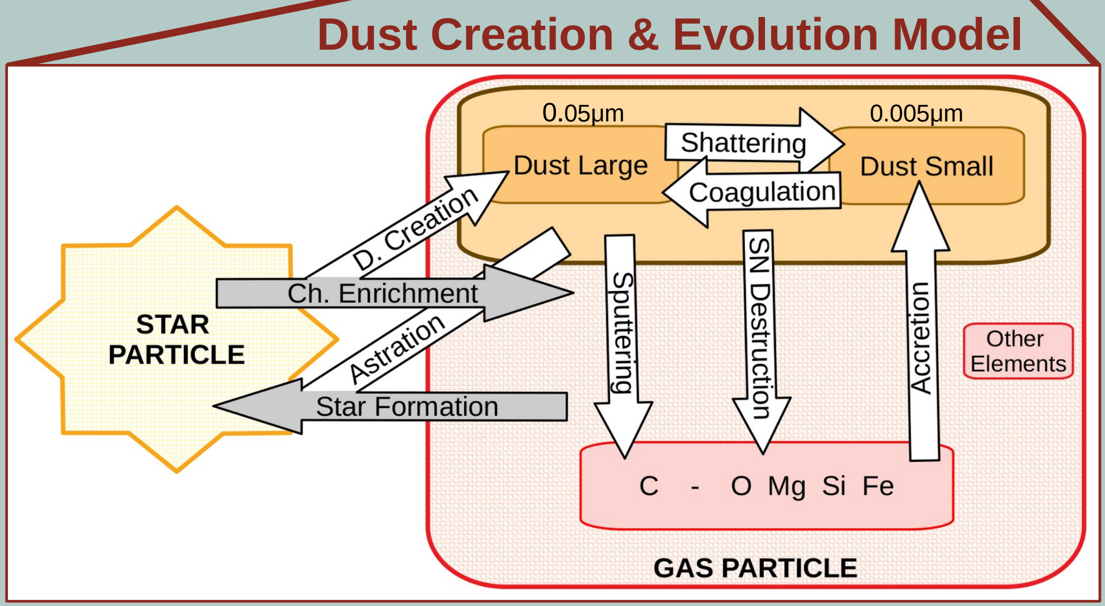
ORIGINAL MUPPI

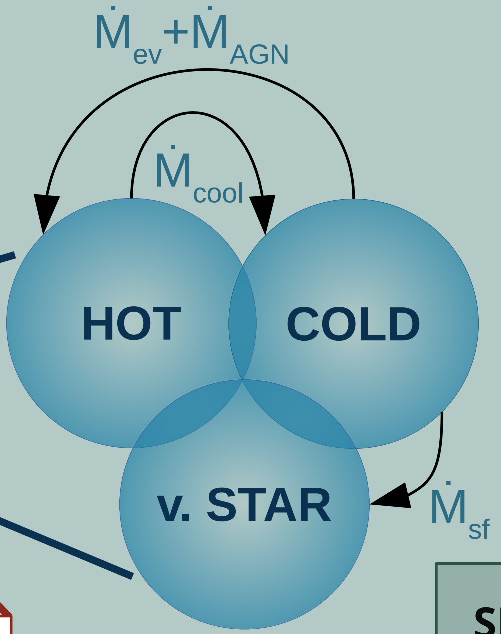
MUPPI + DUST

Granato+21



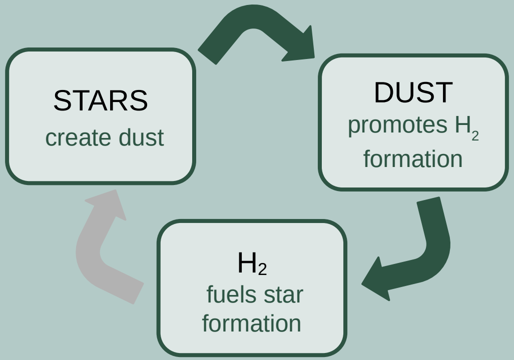






$$SFR = \varepsilon \times M_{MOL} / t_{dyn,c}$$

- ➔ Galaxy Clusters (not MUPPI), Gjergo+18
- ➔ MW-like Galaxies (MUPPI), Granato+21
- ➔ BOX (MUPPI), Parente+22
- ➔ Currently in Open-Gadget (2023, before Sesto)



Dust promoted H_2 CREATION implemented in MUPPI

Rate of H_2 formation on dust grains

Hollenbach & Salpeter (1970-71)

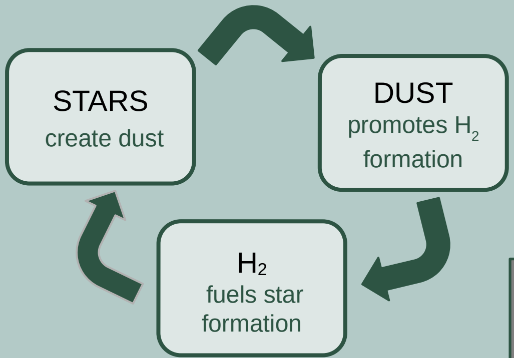
$$R_G = \frac{1}{2} \gamma \langle v_H \rangle n_H n_{gr} \langle \sigma_{gr} \rangle$$

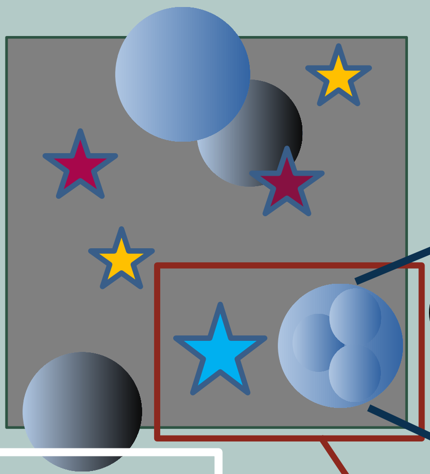
- γ: fraction of HI atoms that stick, combine on the surface of dust grains, and detach from it as H_2
- $\langle \sigma_{gr} \rangle$: Dust grains mean geometric cross-section
- $\langle v_H \rangle$: Mean velocity of HI atoms
- n_H: Number density of HI atoms
- n_{gr}: Number density of dust grains

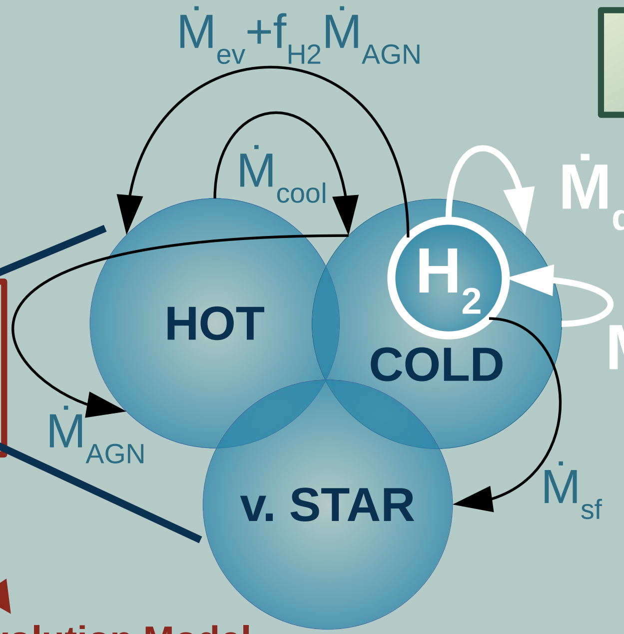
Different Rates for SMALL and LARGE grains

cinthia.ragone@unc.edu.ar

… and Finally we close the cycle







MUPPI + DUST + H_2

Ragone-Figueroa+24

$$R_G = \frac{1}{2}\gamma \langle v_H \rangle n_H n_{gr} \langle \sigma_{gr} \rangle$$

SFR = ε x M_{MOL} / $t_{dyn,c}$

MUPPI mass flows differential equations:

$$\dot{M}_* = \dot{M}_{sf}$$

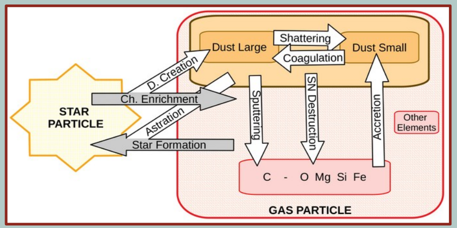
$$\dot{M}_c = \dot{M}_{cool} - \dot{M}_{sf} - \dot{M}_{ev} - \dot{M}_{AGN}$$

$$\dot{M}_h = -\dot{M}_{cool} + \dot{M}_{ev} + \dot{M}_{AGN}$$

+

$$\dot{M}_{H2} = \dot{M}_{formH2} - \dot{M}_{destH2} - \dot{M}_{sf} - \dot{M}_{ev} - f\dot{M}_{AGN}$$

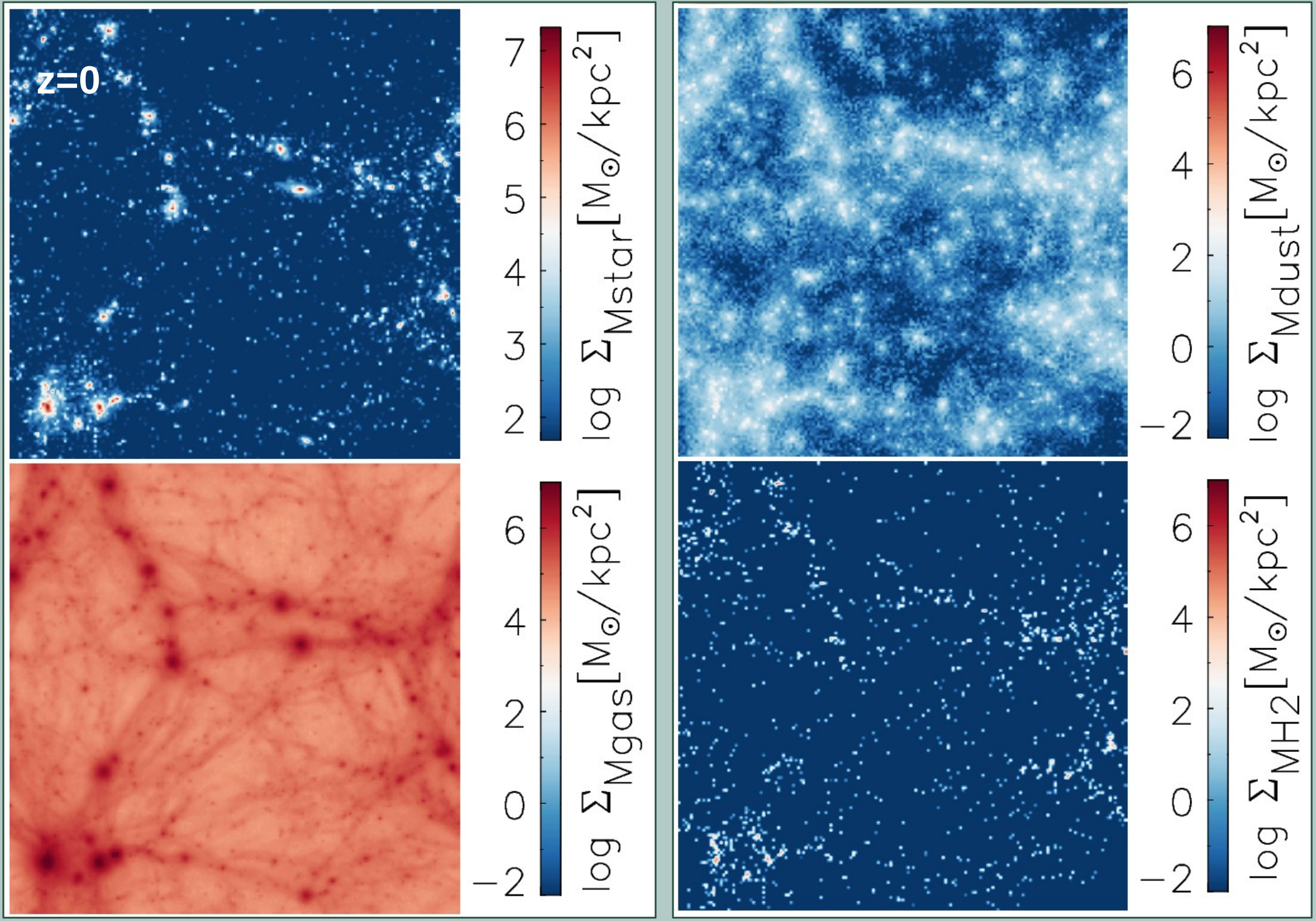
Dust Evolution Model



Granato+21 & Parente+22

✔ Now M_{MOL} "self consistently" predicted taking into account H + H → H_2 on grains

A Visual Inspection: we run 5 boxes like this:

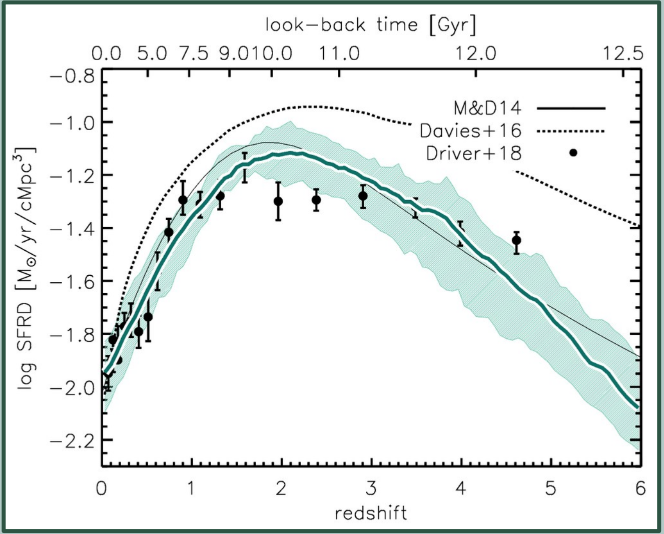


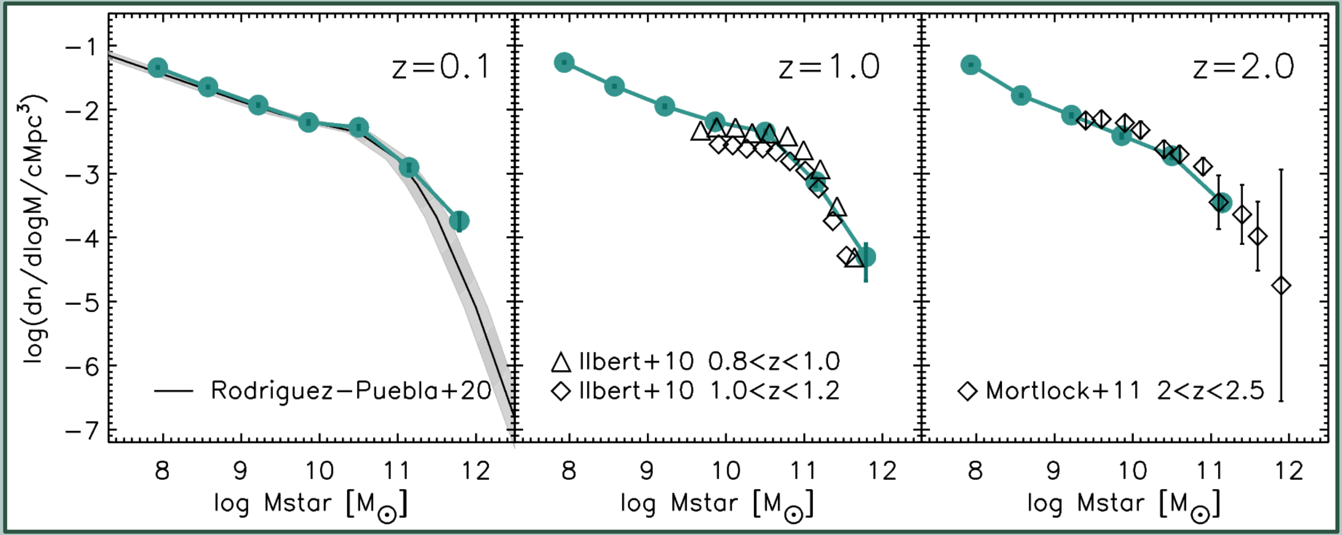
26Mpc

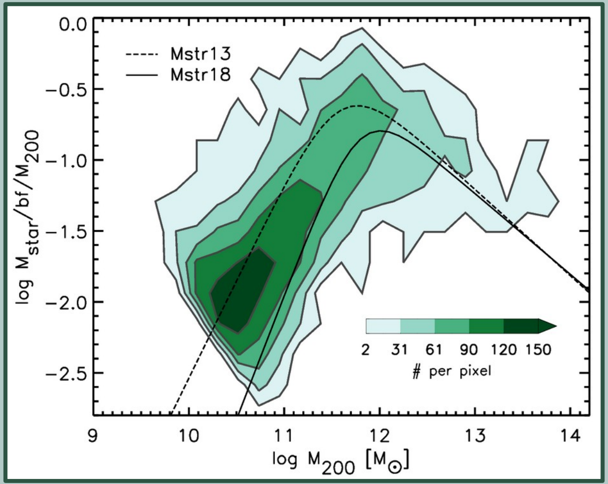
P-GADGET3 + MUPPI

LBox = 26 Mpc
DM = 3.7 x 10^7 $M_\odot$
Gas = 6.9x10^6 $M_\odot$
SoftDM = 960 pc
Softgas = 960 pc

“Calibration Quantities”





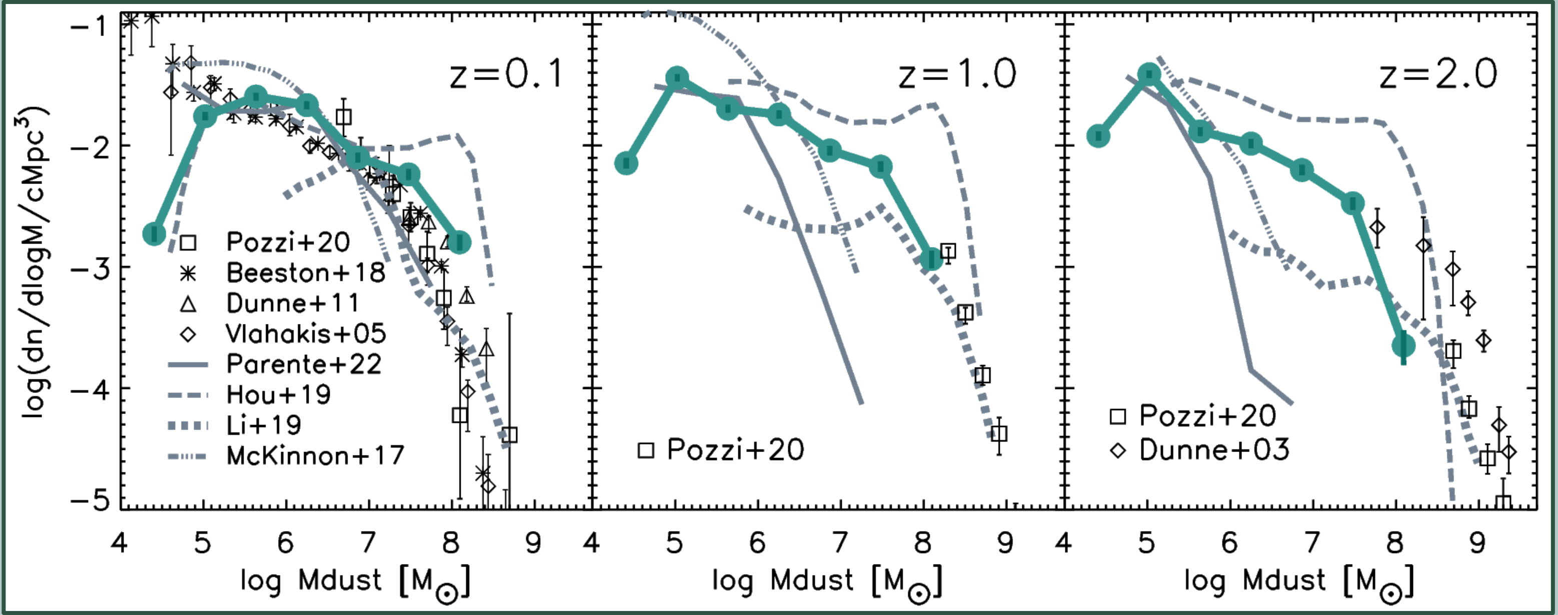


Calibration done using:

- ✔ SFRD
- ✔ Stellar Mass Function @ z=0
- ✔ Stellar-Halo Mass @ z=0

cinthia.ragone@unc.edu.ar

“Predicted Quantities”: Dust Mass Functions



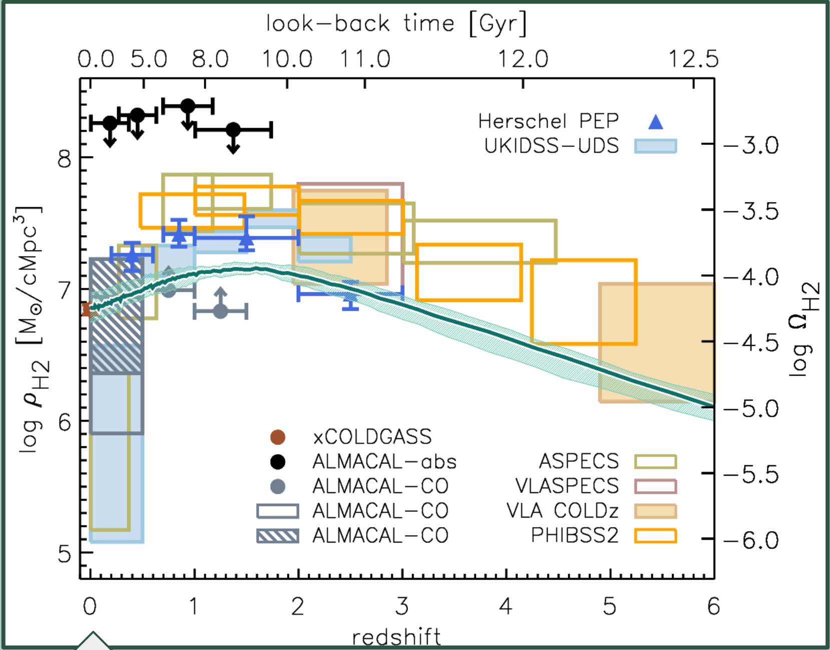
Accurately probing redshifts z = 1 and z = 2 presents some challenges:

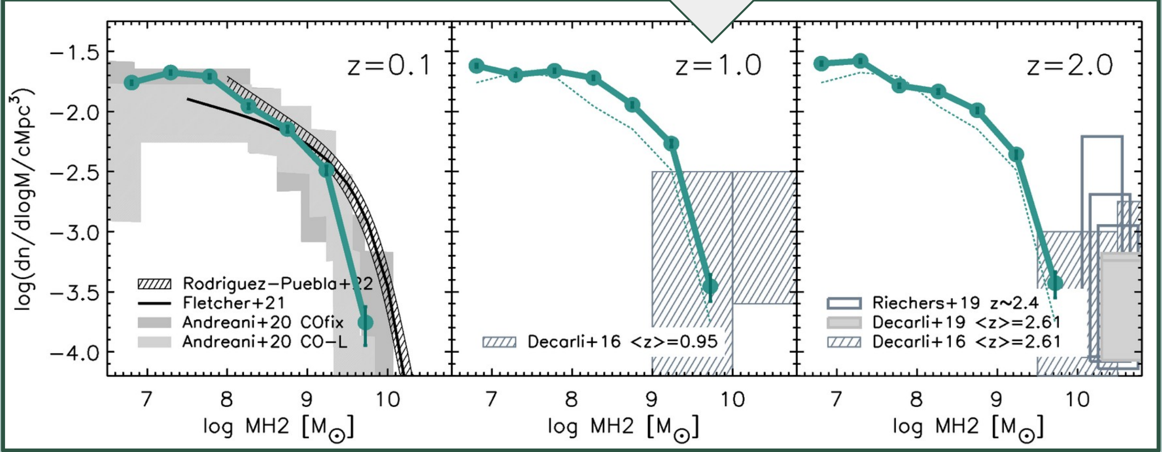
- Observations lack coverage of the small dust masses range that our simulations do sample.
- Conversely, the limited volume of our simulations could lead to an inability to capture the high masses observed in real data, consequently resulting in an under-prediction at the highest dust mass bin.

“Predicted Quantities”: H_2

H_2 Mass Functions @ z=0, 1, 2

H_2 is NOT directly observed! (estimated from CO or dust)





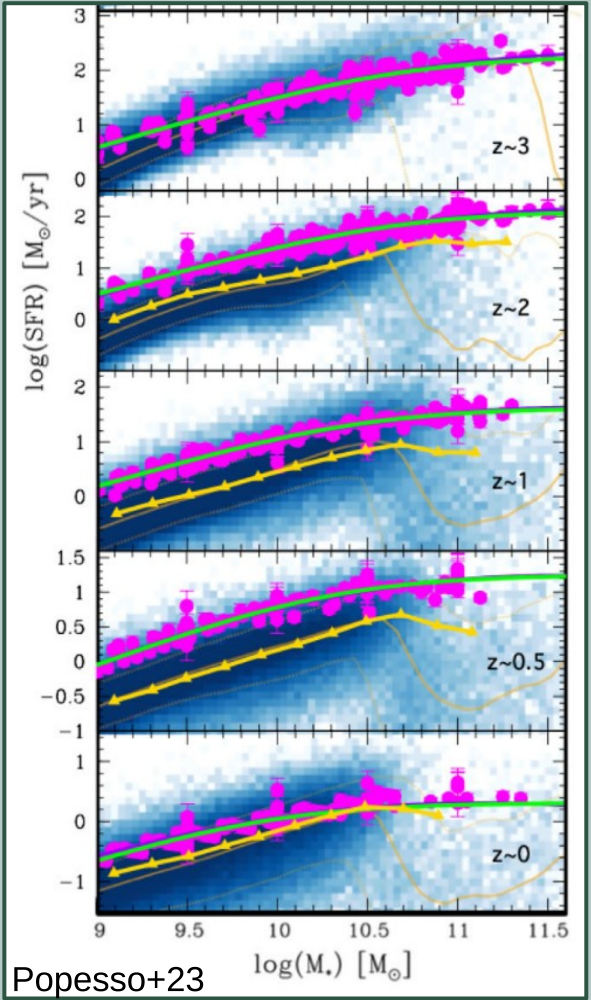
H2MF shows **little evolution** from z=2 to 0, contrasting with observations (Riechers et al. & Decarli et al., 2019) which report a shift of the characteristic CO luminosity towards lower values of one order of magnitude in the same z range.

H_2 Cosmic Density

CO-, dust-based methods and our model predict a peak at z∼1.5 and a decline over the last ∼ 9 Gyrs.

Decarli et al. (2019) found that the decline of ρH2 by a factor of approximately 6 from its peak at z ∼ 1.5 to the present would reduce to a factor 3 if they had halved the CO-to-H2 conversion factor for a galaxies at z>1

“Predicted Quantities”: the Main Sequence



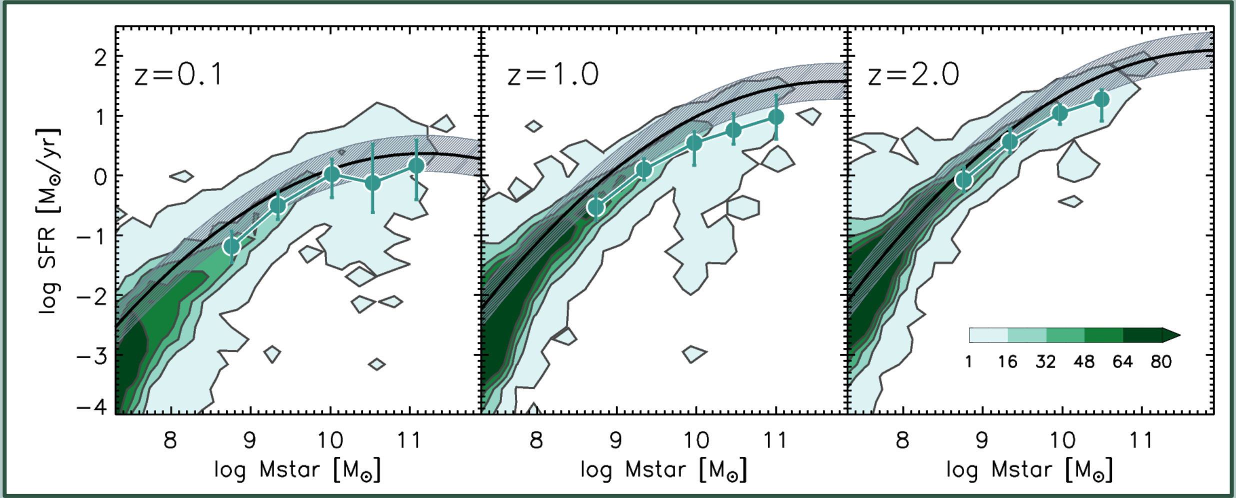
Popesso+23
Observational
Compilation since 2014

Illustris-TNG 300

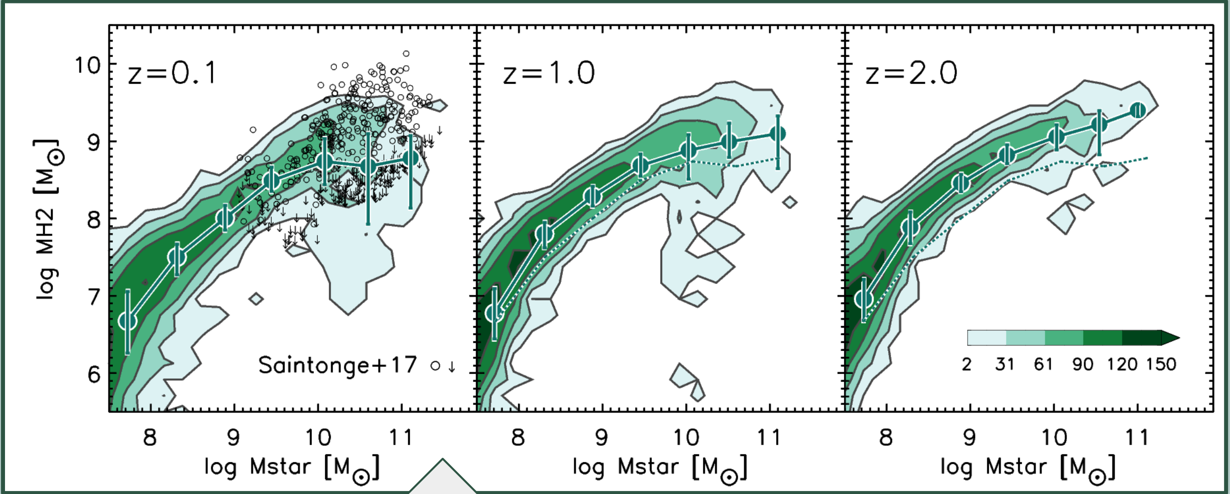
Median
Donnari+19 limited to UVJ selected galaxies

Solid black line: Popesso+23: The MS bends at high masses.

Green dots: Model Main Sequence
We reproduce the MS bending



“Predicted Quantities”: H_2 scaling relation & the Main Sequence

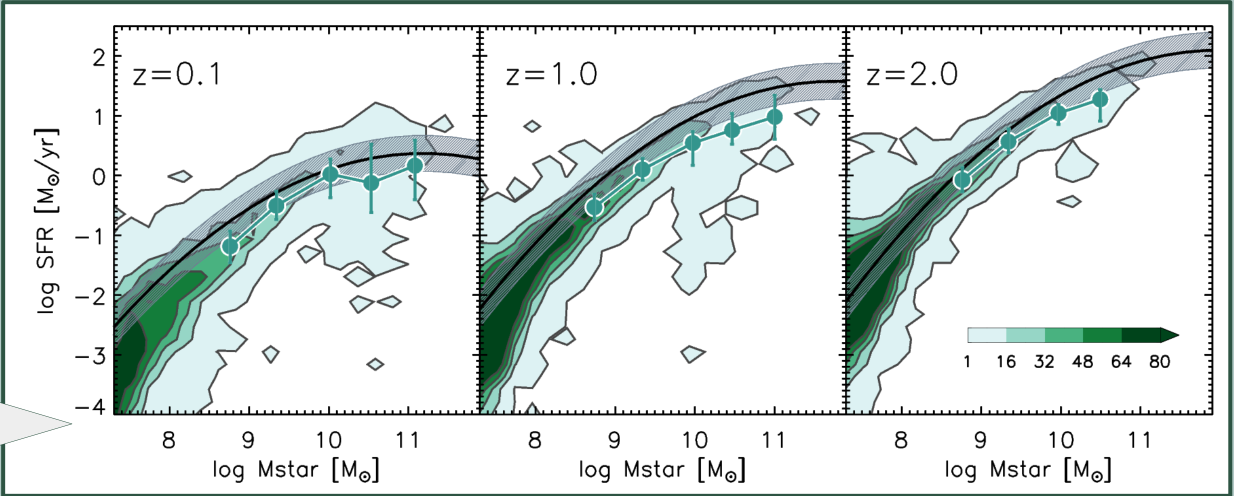


P23:The MS bends at high masses. We reproduce the MS bending.

A similar bending also present in the MH2-Mstar relation.

Since H2 is the fuel for SF, the latter implies that the bending of the MS is mainly driven by a relative lack of H2 in the most massive galaxies.

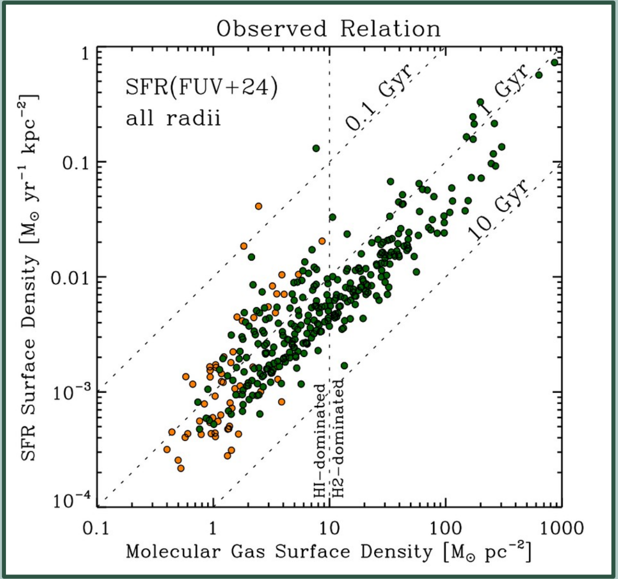
Mstar vs H_2 mass (contours and points with dispersion bars are model)



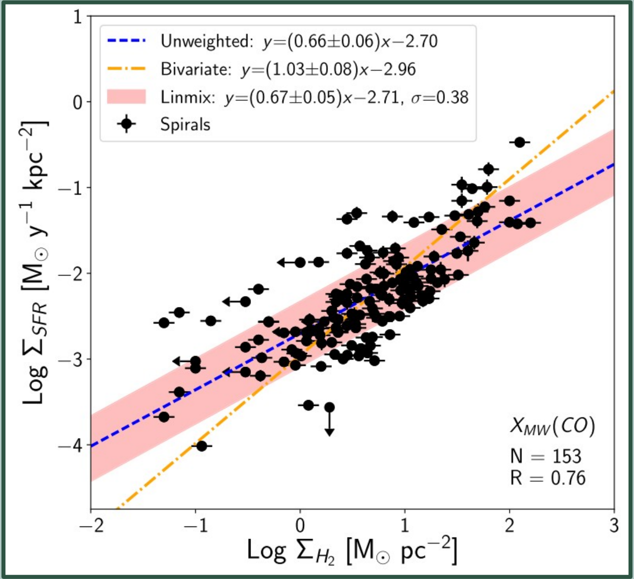
Solid black line: Popesso+23 MS (compilation since 2014)
Green dots: Model MS

The Molecular Kennicutt-Schmidt Relation

Astronomers have been exploring scaling relationships between gas and star formation since Schmidt's work in 1959.
The question remains:
which gas surface density should be employed?



Schruba et al. (2011) RADIAL



De los Reyes & Kennicutt (2019) INTEGRATED
They compile 114 publications

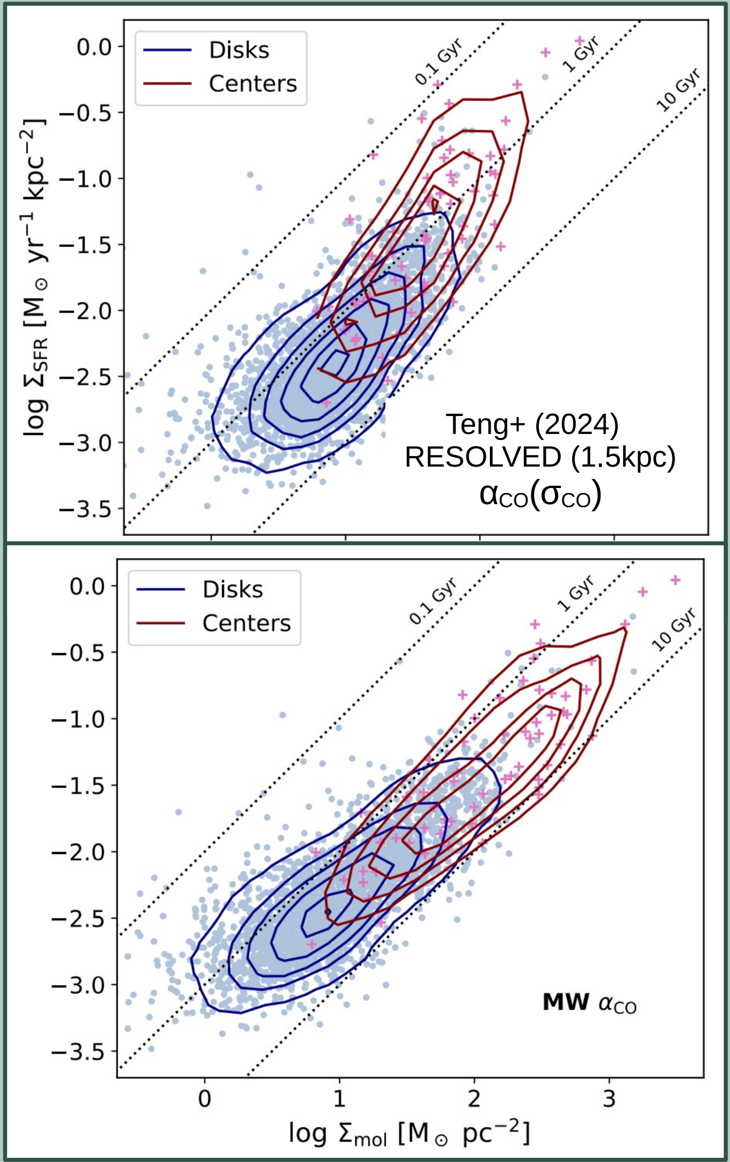
Σ_{H2}

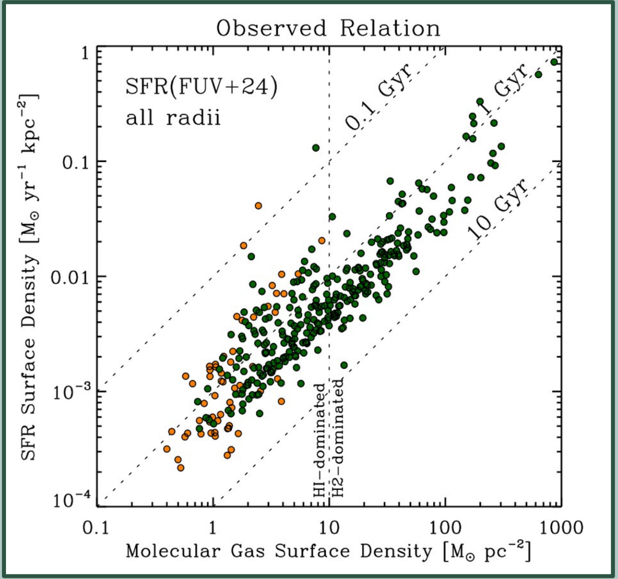
Wong &Blitz (2002), Kennicutt et al. (2007), Bigiel et al. (2008), Leroy et al. (2008), Wilson et al. (2008), Blanc et al. (2009), Bigiel et al. (2011), de los Reyes & Kennicutt (2019)...

H_2 is NOT directly observed! (estimated from CO or dust)

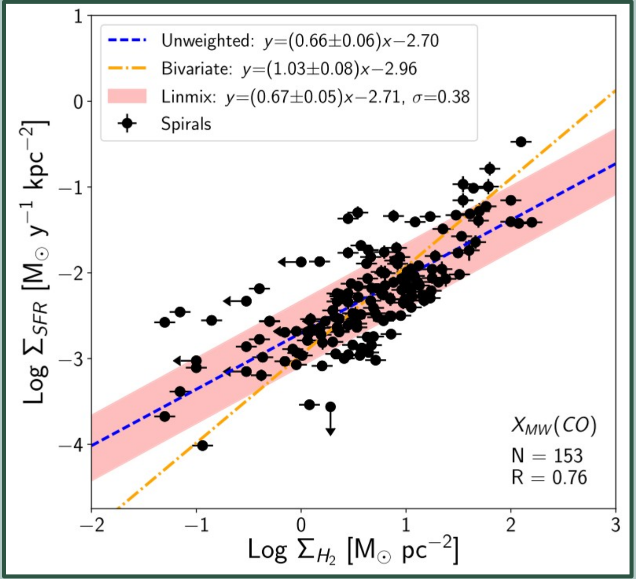
The Molecular Kennicutt-Schmidt Relation

Teng+ (2024): At high Σ_{H2}, the mKS relation steepens, a phenomenon that goes undetected when a fixed CO-to-H2 conversion factor is used





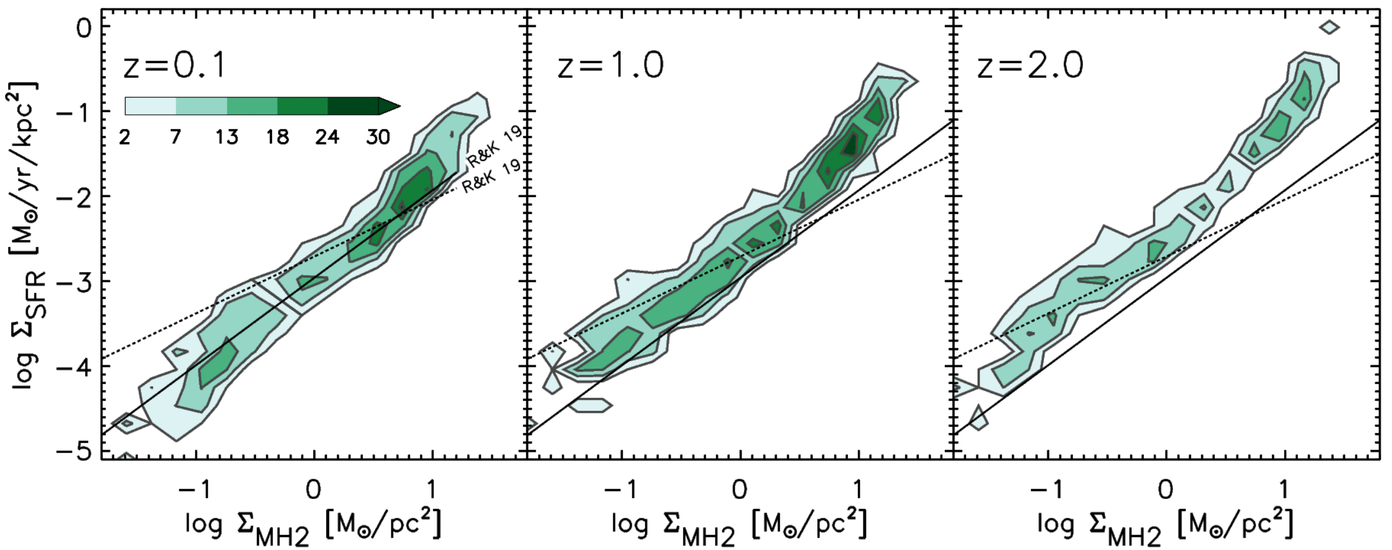
Schruba et al. (2011) RADIAL

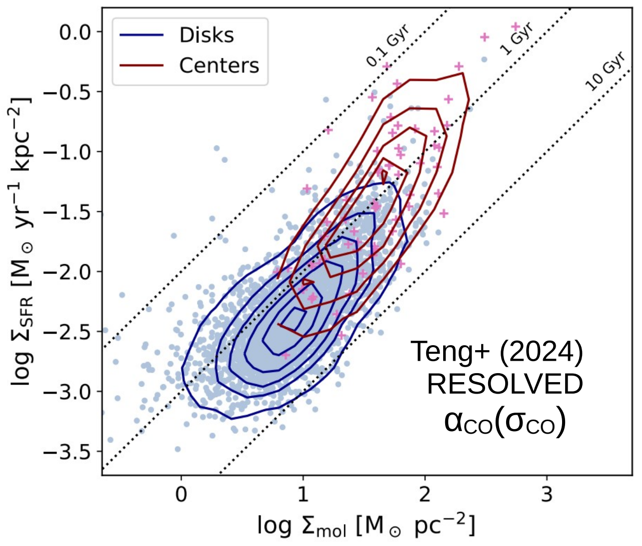


De los Reyes & Kennicutt (2019) INTEGRATED
They compile 114 publications

H_2 is NOT directly observed! (estimated from CO or dust)

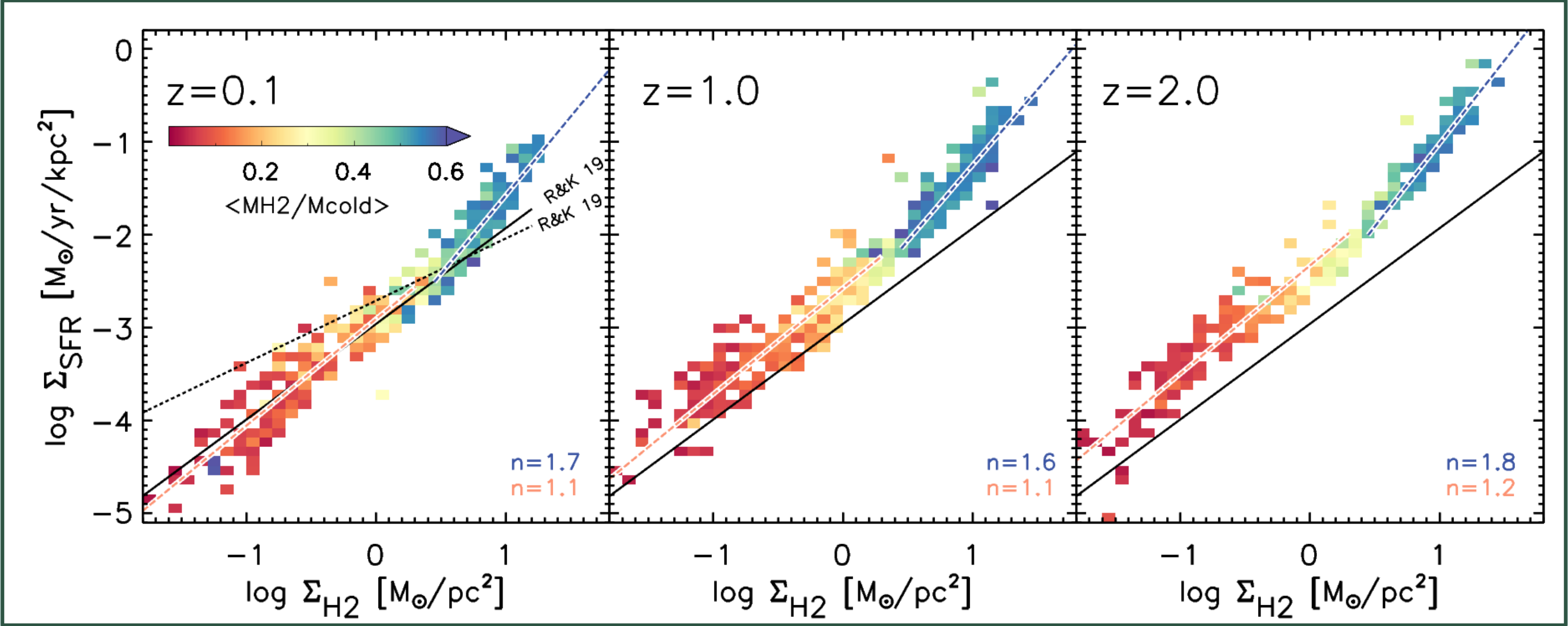
The Molecular Kennicutt-Schmidt Relation





- ✔ The integrated molecular Kennicutt-Schmidt relation is evident in our model galaxies as early as redshift 2, although with a higher normalization than at redshift 0.
- ✔ The slope remains close to unity across the examined redshifts for surf densities below Σ_{H2} ~5 $M_{\odot}/pc^2$…
- ✔ However, at higher surface densities, we observe a steeper slope.

The Molecular Kennicutt-Schmidt Relation



$$\dot{M}_{\rm sf} = f_* \frac{M_{\rm H2}}{(1-Y)t_{\rm dyn}}$$

$$t_{\rm dyn} \propto \rho_{\rm c}^{-0.5}$$

At high densities

$$\Sigma_{\rm SFR} \propto \Sigma_{\rm H2}^{1.5}$$

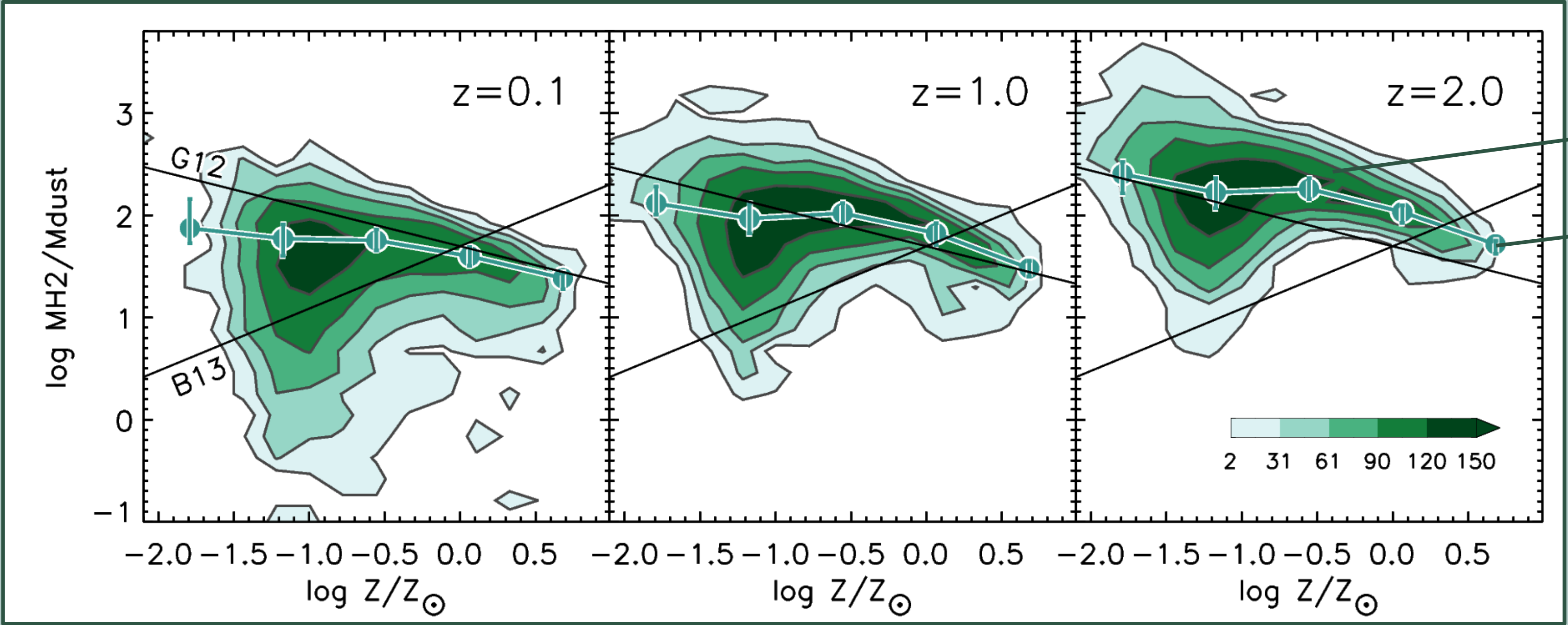
H_2 mass determination from dust: A complex task

$$\chi_{G12}(Z) = 10^{-1.27(12+\log(O/H)-8.67)},$$

$$\chi_{B13}(Z) = 0.67 \times \exp\left(0.36 \times 10^{-(12+\log(O/H)-8.67)}\right).$$

The evaluation of molecular mass in galaxies is limited to indirect methods.
Bertemes+18 derived (z<0.2) a formula to obtain Molecular Mass from Dust Mass:
G12: Using Genzel+12 CO-to-H2 conversion factor
B13: Using Bolatto+13 CO-to-H2 conversion factor

G12 sample: MS SF glxs z>1
+ 5 local group glxs,
$-0.9<\log(Z/Z_\odot)<0.3$



All galaxies

MS galaxies

H_2-to-dust

	Low M_*	High M_*
z=2	160	65
z=0	50	30

- ✔ Galaxies with higher Z (or Mstar) exhibit smaller H2-to-dust ratios at all redshifts
- ✔ Higher H2-to-dust dispersion at lower Z (or Mstar).
- ✔ Higher normalization associated at higher redshift.

- ✔ G12 determination preferred

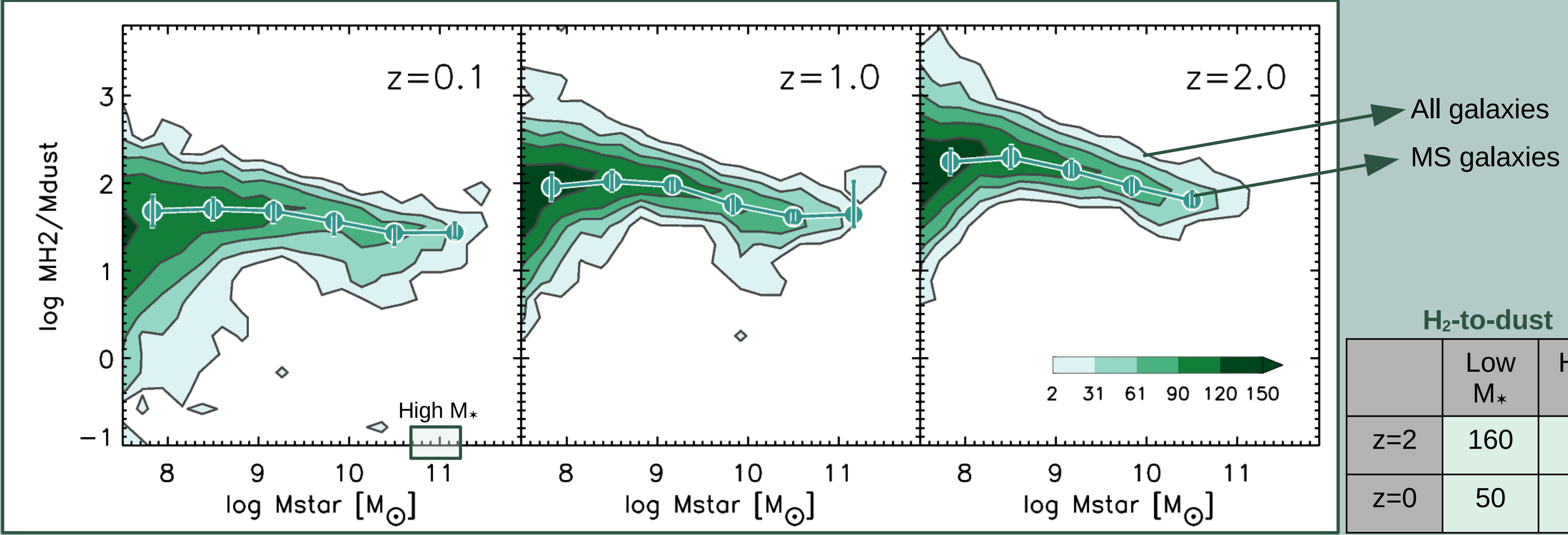
H_2 mass determination from dust: A complex task

$$\chi_{G12}(Z) = 10^{-1.27(12+\log(O/H)-8.67)},$$

$$\chi_{B13}(Z) = 0.67 \times \exp\left(0.36 \times 10^{-(12+\log(O/H)-8.67)}\right).$$

The evaluation of molecular mass in galaxies is limited to indirect methods.
Bertemes+18 derived (z<0.2) a formula to obtain Molecular Mass from Dust Mass:
G12: Using Genzel+12 CO-to-H2 conversion factor
B13: Using Bolatto+13 CO-to-H2 conversion factor

G12 sample: MS SF glxs z>1 + 5 local group glxs, $-0.9<\log(Z/Z_\odot)<0.3$



H_2-to-dust

	Low M_*	High M_*
z=2	160	65
z=0	50	30

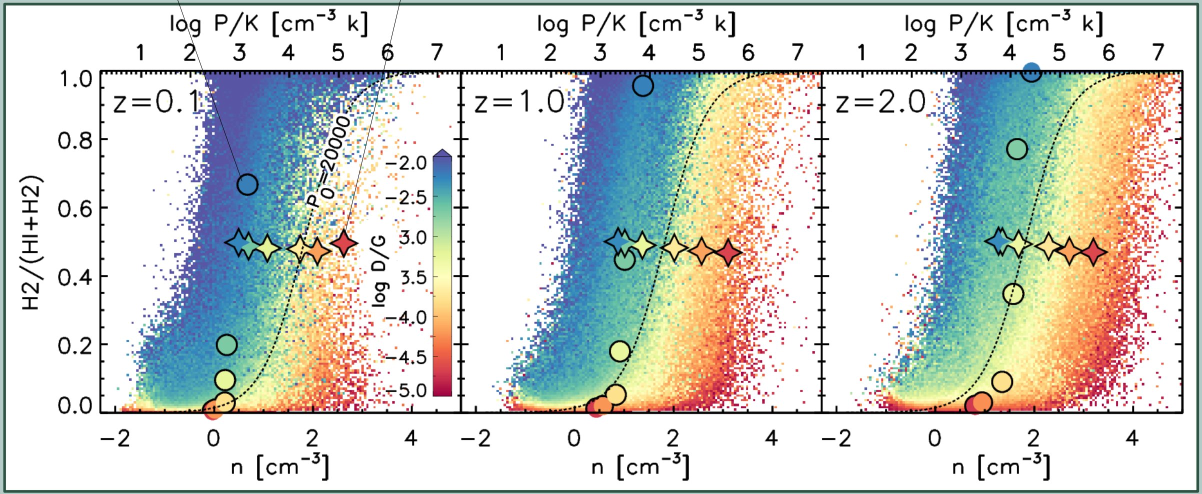
- ✔ Galaxies with higher Z (or Mstar) exhibit smaller H2-to-dust ratios at all redshifts
- ✔ Higher H2-to-dust dispersion at lower Z (or Mstar).
- ✔ Higher normalization associated at higher redshift.

- ✔ G12 determination preferred

The atomic to molecular transition

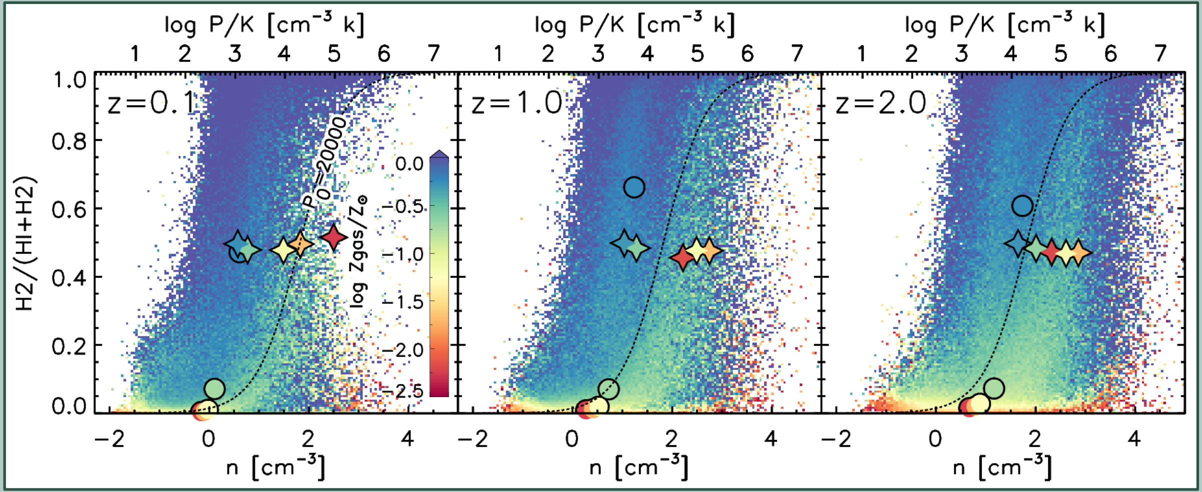
Median values

The molecular transition



Dust/Gas

At lower D/G the molecular transition occurs at higher densities.
For a given D/G ratio, we recover the B&R "shape".
Can this prescription be improved?.



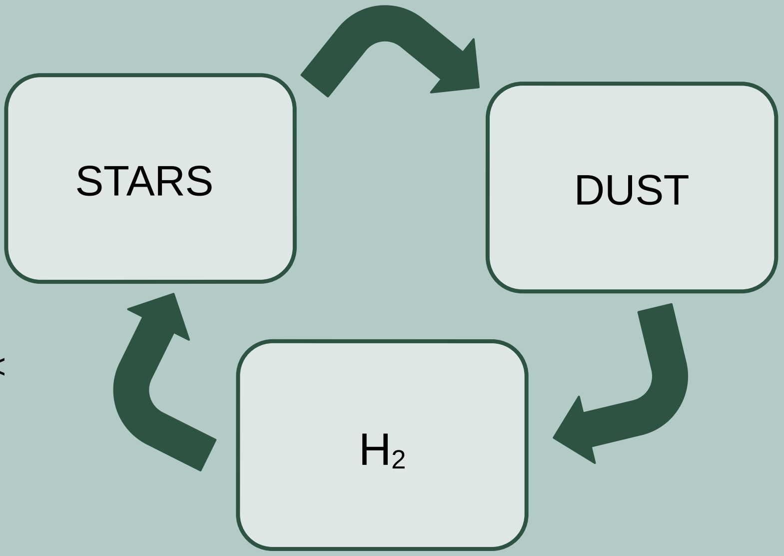
Metallicity

The atomic to molecular transition is not that clear when using metallicity.

Dust & Metallicity: it is not the same thing

Summary

- In the Universe, Star Formation, Dust pollution and Molecular Gas are intertwined. Now also in these simulations
- MUPPI **Star Formation law is now linked to the dust-promoted H_2 content, which in turn is produced from stellar ejecta and evolves in the ISM**
- We find good agreement with several observational constraints in the range $0 < z < 2$
- The integrated molecular Kennicutt-Schmidt relation emerges as early as redshift $z \sim 2$, although with a higher normalization than at $z=0$.
- Can we improve prescriptions to estimate molecular mass in galaxy formation models, when dust and/or H2 modeling is not performed



cinthia.ragone@unc.edu.ar