The interstellar medium in nearby galaxies

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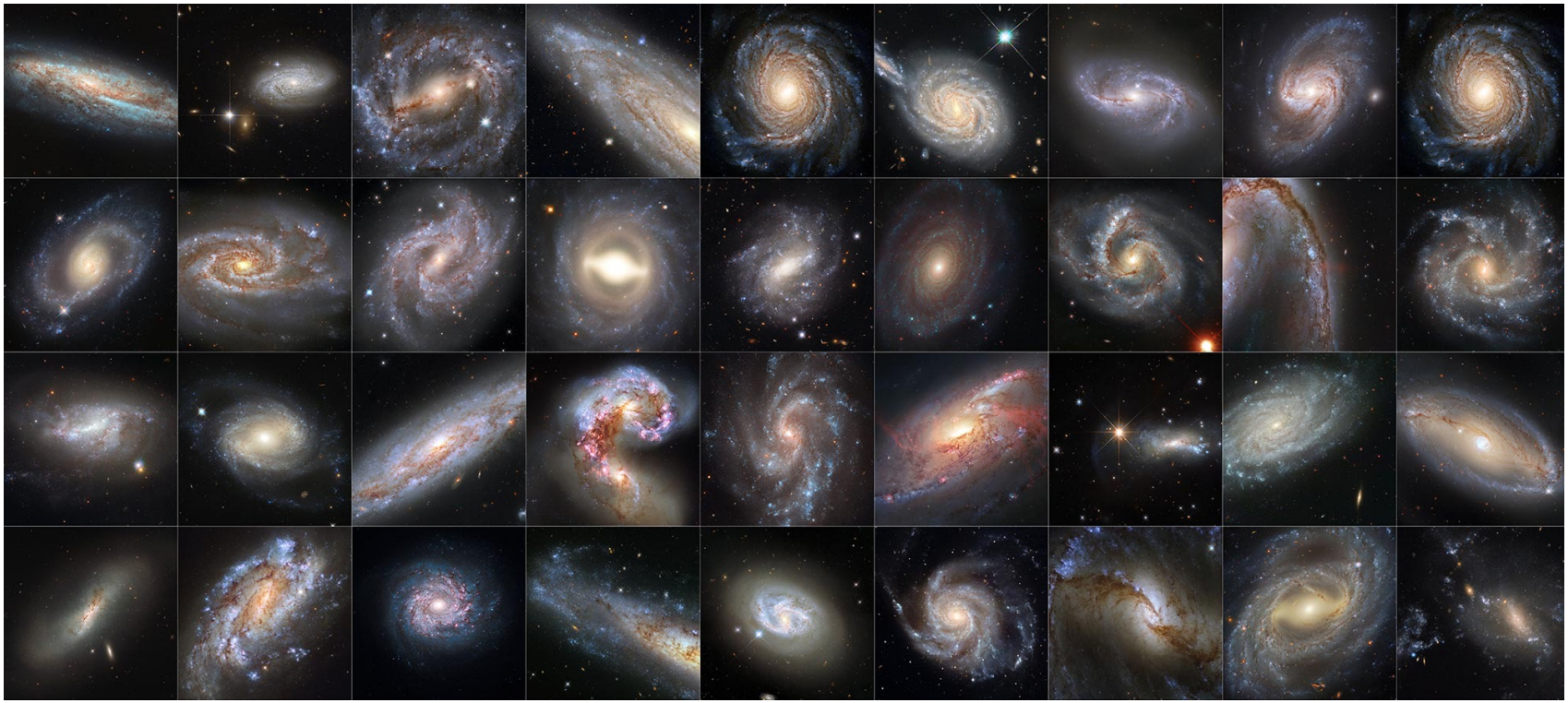


Credits: NASA, ESA, ADAM G. RIESS (STSCI, JHU)

Outline of my review

- **ISM**: Components, life, role
- **Surveys** on the **ISM** in **nearby galaxies**
- The **ISM** **distribution** in **nearby galaxies**
- The **ISM** global and spatially resolved **scaling relations** in **nearby galaxies**
- Example of **ongoing/future** **ISM** **applications**

The ISM: Components

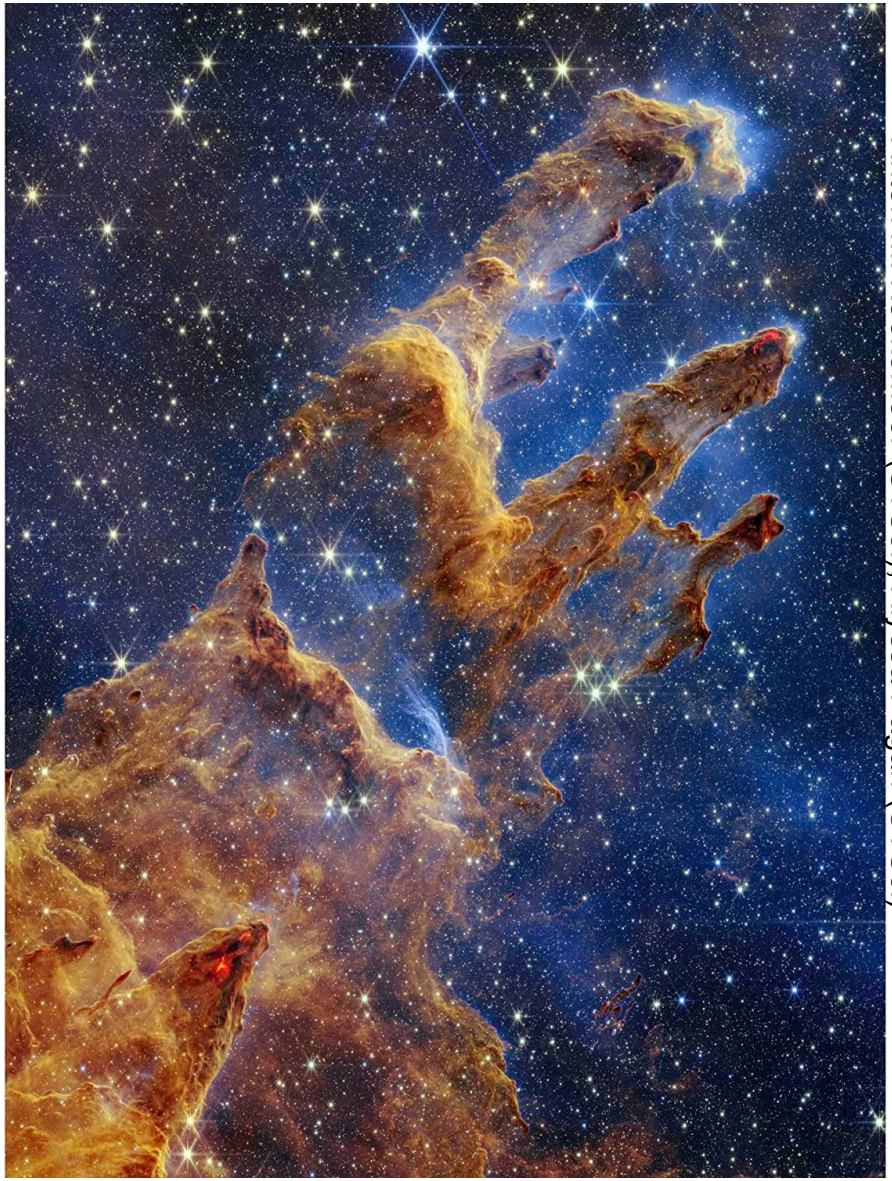
The ISM spans a wide range of densities and temperatures, components/phases:

1. The **hot ionised medium**:
   $T \gtrsim 10^5$ K, $n \lesssim 0.01$ cm^{-3}

2. The **warm medium**
   (neutral + ionized):
   $T \sim$ several 10^3 K, $n \sim 0.1 - 1$ cm^{-3}

3. The **cold neutral gas**:
   $T \lesssim 100$ K, $n \gtrsim 10$ cm^{-3}

The Pillars of Creation - JWST



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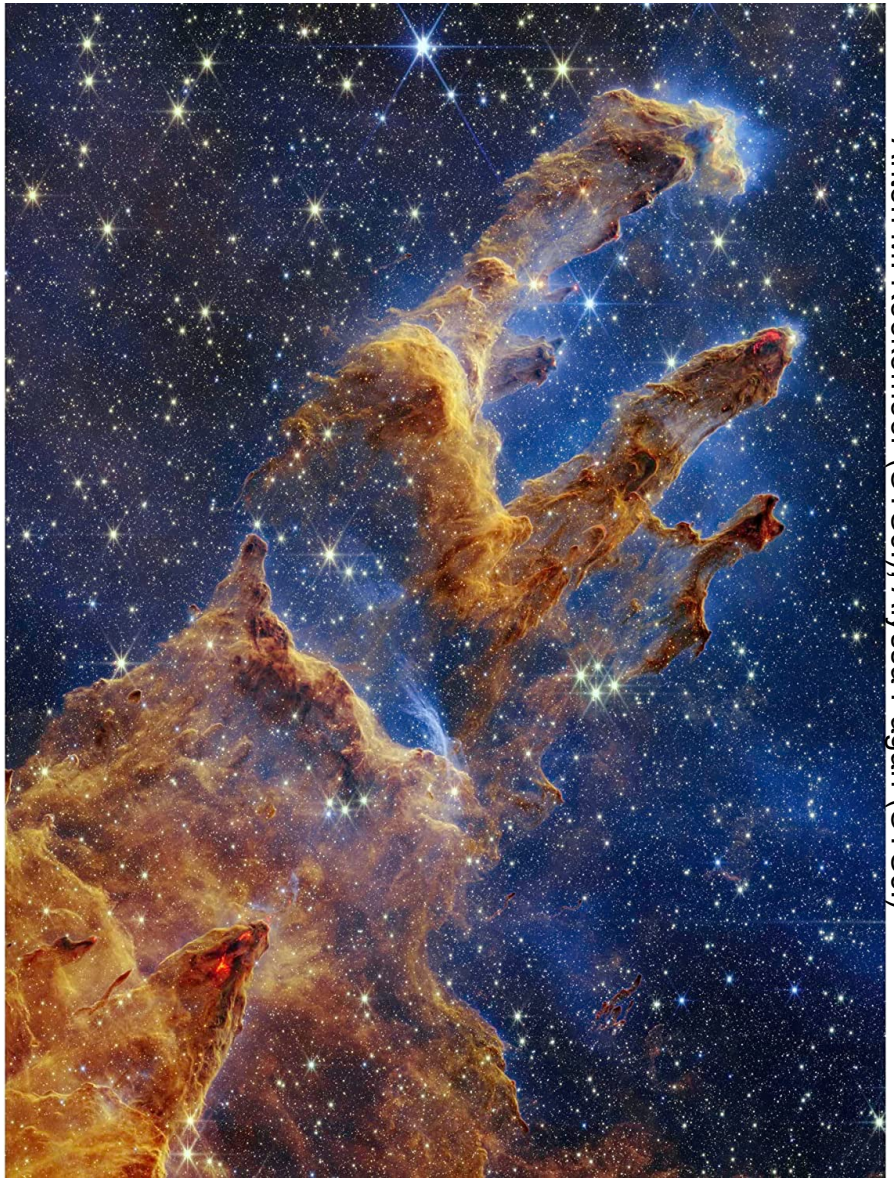

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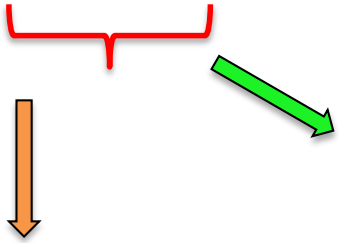
The cold ISM: Mass

The mass of the cold ISM is composed of:

- **gas** for ~99%: ~74% H, ~25% He, ~1% heavier elements ("metals")



~25% by molecular gas:
T ~ 10 – 100 K, $n \sim 10^3$ - 10^6 cm^{-3}

~75% by atomic gas (HI):

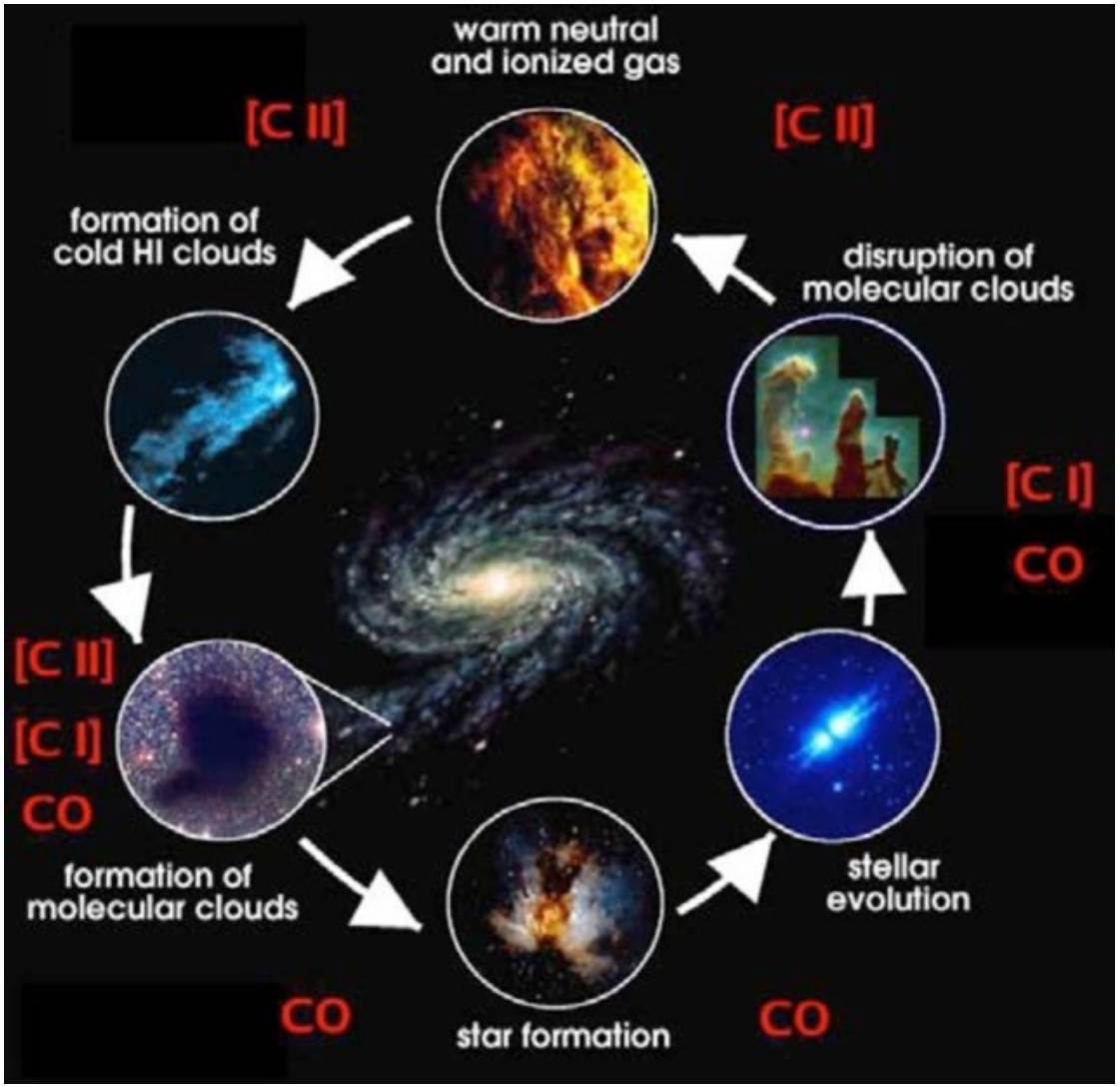
1. warm and diffuse
   T ~ 5000 K, $n \sim 0.6$ cm^{-3}

2. cold and dense
   T ~ 100 K, $n \sim 30$ cm^{-3}

- **dust** for ~1%, mixed in with atomic and molecular gas

The life of the ISM

From the Milky Way to high-*z* galaxies



1. **Transformation** of neutral, molecular clouds into star and star cluster (SF)
2. **Interaction** of the ISM with the young stars
3. **Return** of enriched stellar material to the ISM, eventually to form new stars

Groppi et al. (2009)

The role of the cold ISM

The cold **ISM** plays a central role in the **galaxy evolution**: driver of SF, fuel for galaxy growth.

The ISM is also a main **tracer** of **internal** and **external processes** affecting entire galaxies (e.g., AGN activities, galaxy/environment interaction).

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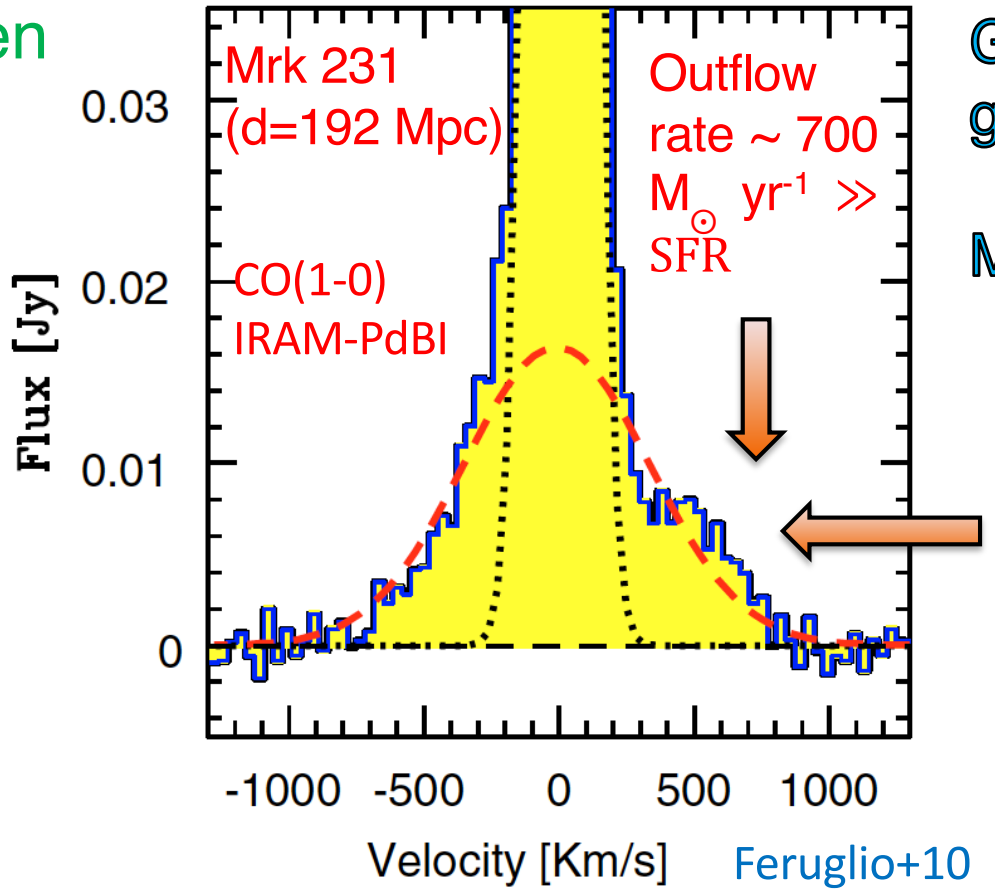
Quasar-driven outflow



Giant molecular gas outflow!

$M(H_2)_{out} \sim 6 \times 10^8 M_\odot$

velocities up to 750 km/s

Expelling gas in 10^7 yr, stopping SF

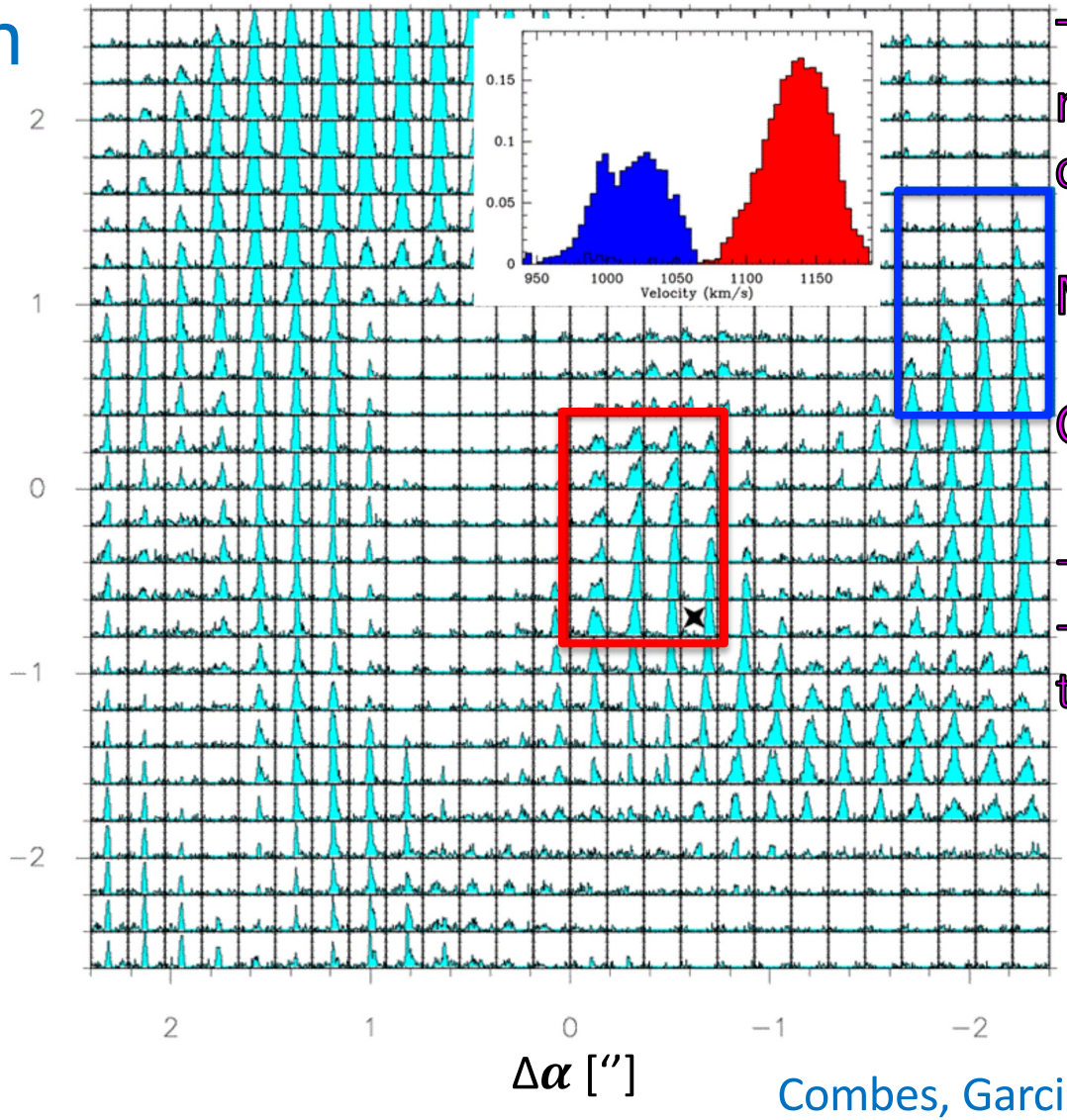
The role of the cold ISM

NGC 1433, Seyfert 2 (d = 9.9 Mpc)

AGN-driven outflow

ALMA CO(3-2) spectra r < 2.5" of the center

1" = 48 pc



The smallest molecular gas outflow in galaxies!

$M(H_2)_{out} \sim 4 \times 10^6 M_\odot$

Out rate ~ 7 $M_\odot$/yr

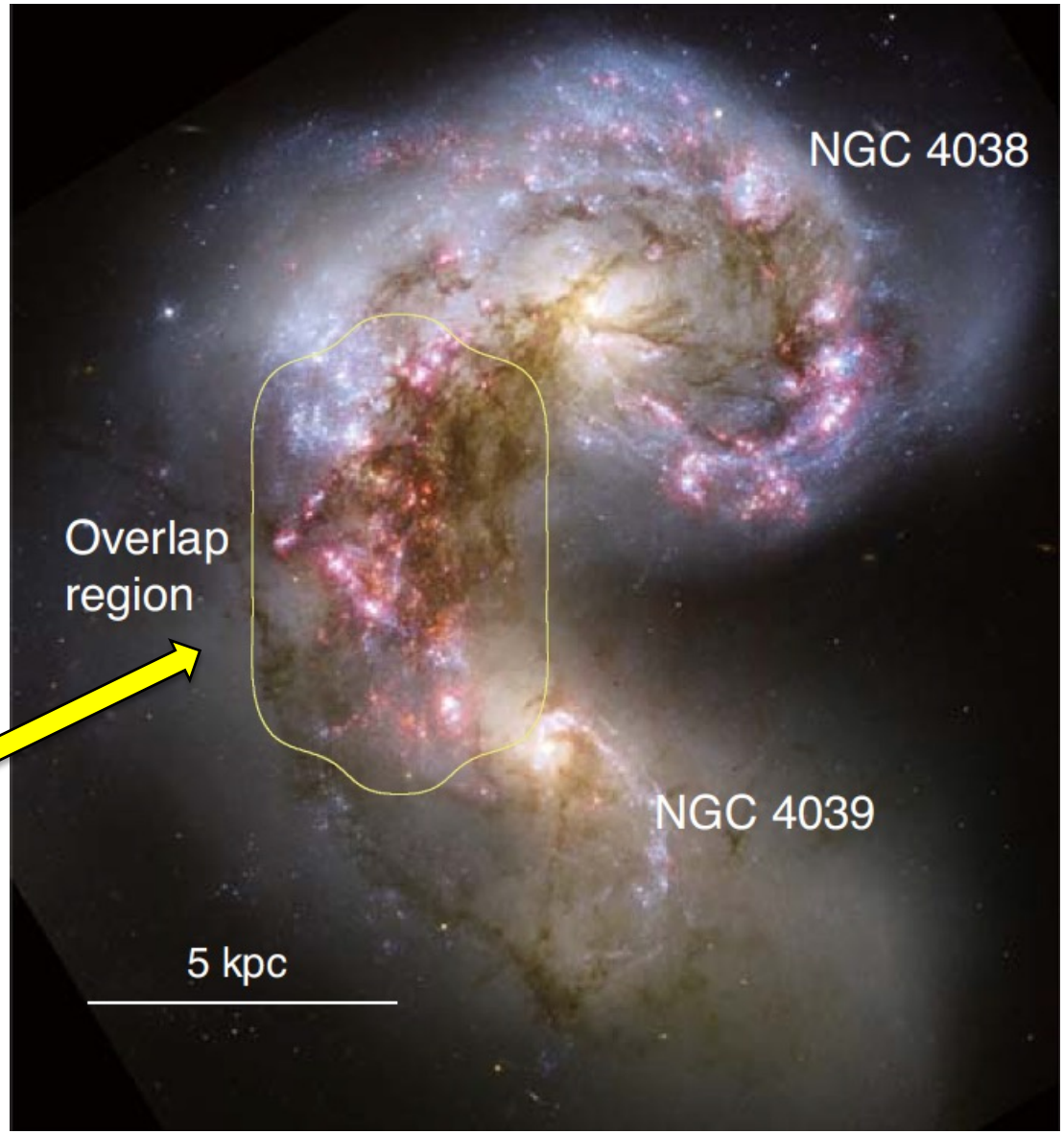
- Able to stop SF
- Able to regulate the growth of bulges

Combes, Garcia-Burillo, Casasola+13

The role of the ISM

HST:
B-band
V-band
I-band + Hα

The Antennae: Interacting galaxies (d = 22 Mpc)



ALMA CO(3-2)
0.5" ~ 50 pc

$M(H_2) \sim 2 \times 10^{10}\ M_\odot$
(Gao+01, Wilson+03)

Interacting galaxies have a higher gas content than normal ones (e.g., Combes+94, Casasola+04, Violino+18, Lisenfeld+19)

Withmore+14, Tsuge+20

The role of the ISM

HST:
B-band
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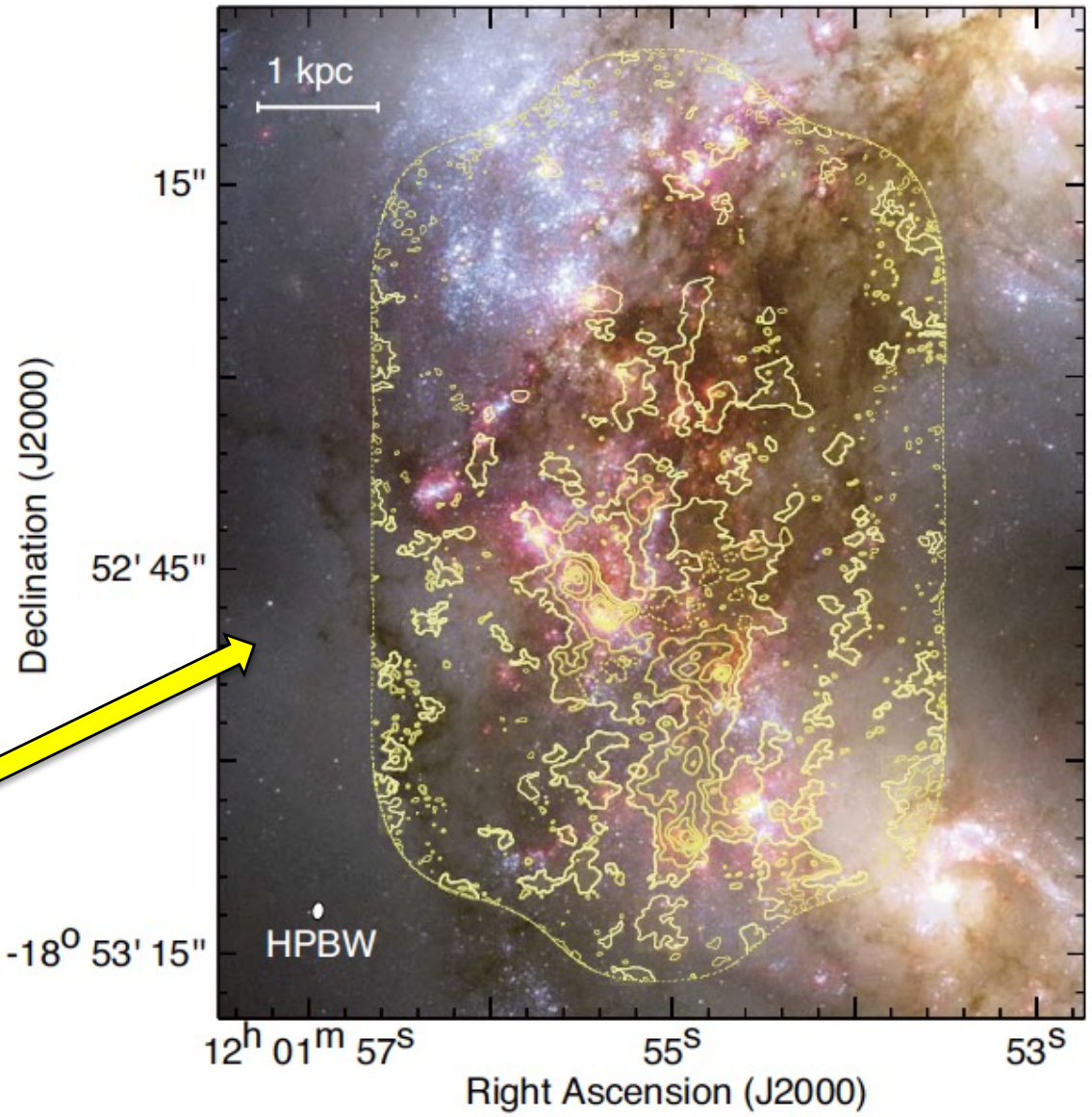

ALMA CO(3-2)
0.5" ~ 50 pc

CO in the overlap region:
A long (3 kpc) and thin filament of molecular gas with ~10 individual knots

cloud-cloud collision able to trigger the formation of young massive clusters

Withmore+14, Tsuge+20

mm-ISM Surveys in the Local Universe

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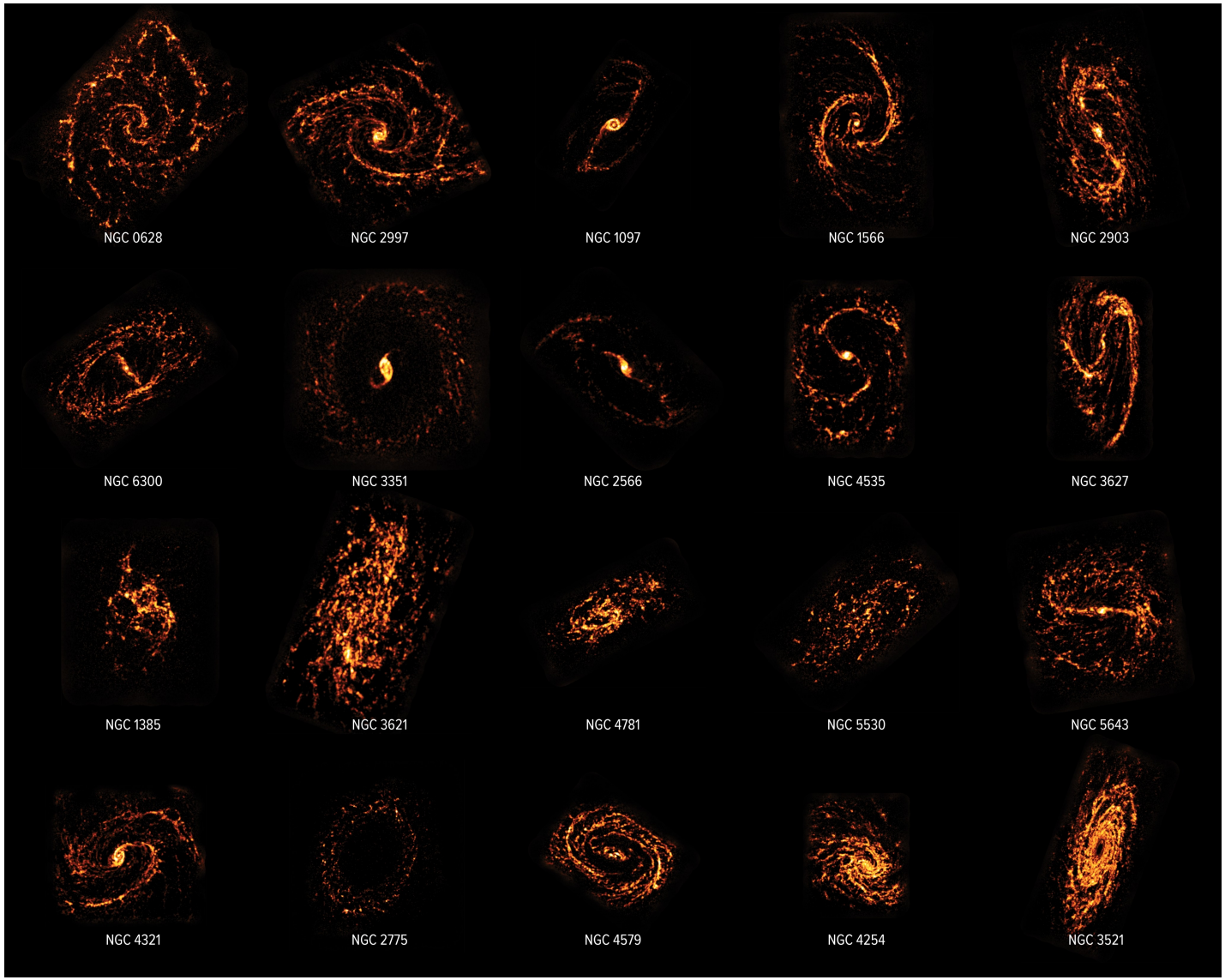
PHANGS-ALMA (Physics at High Angular Resolution in Nearby GalaxieS)



Credits: ALMA (ESO/NAOJ/NRAO)/S. Dagnello (NRAO)

CO(2-1) survey
1'' ~ 100 pc
(GMC scale)
90 nearby
(z ~ 0, d $\lesssim$ 20 Mpc)
galaxies

Follow-up in other bands, such as
PHANGS-MUSE
PHANGS-JWST

To connect molecular gas with other ISM/galaxy properties

PIs: Schinnerer, Blanc, Hughes, Leroy, Rosolowsky, Schruba

Leroy+21a,b

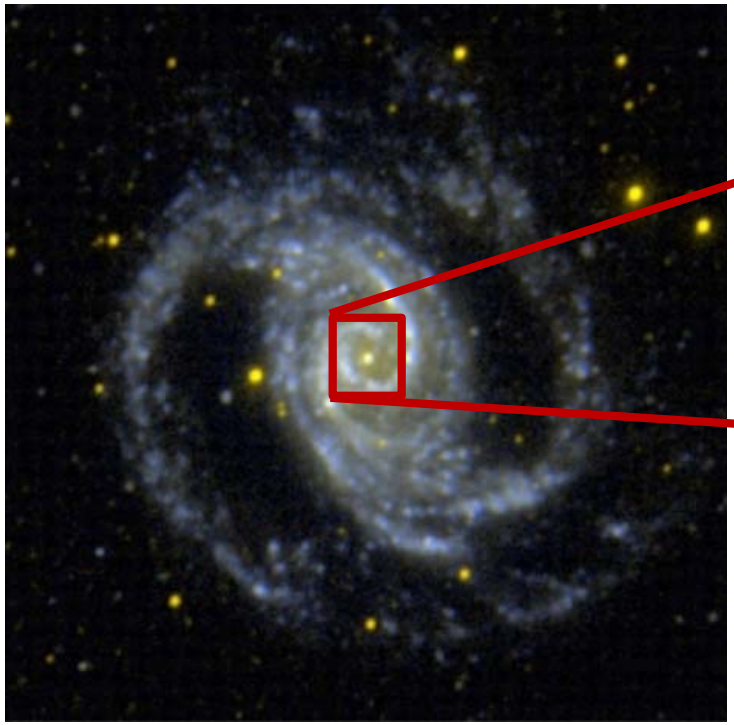
mm-ISM Surveys in the Local Universe

AGN & Tori

mm-ISM Surveys in the Local Universe

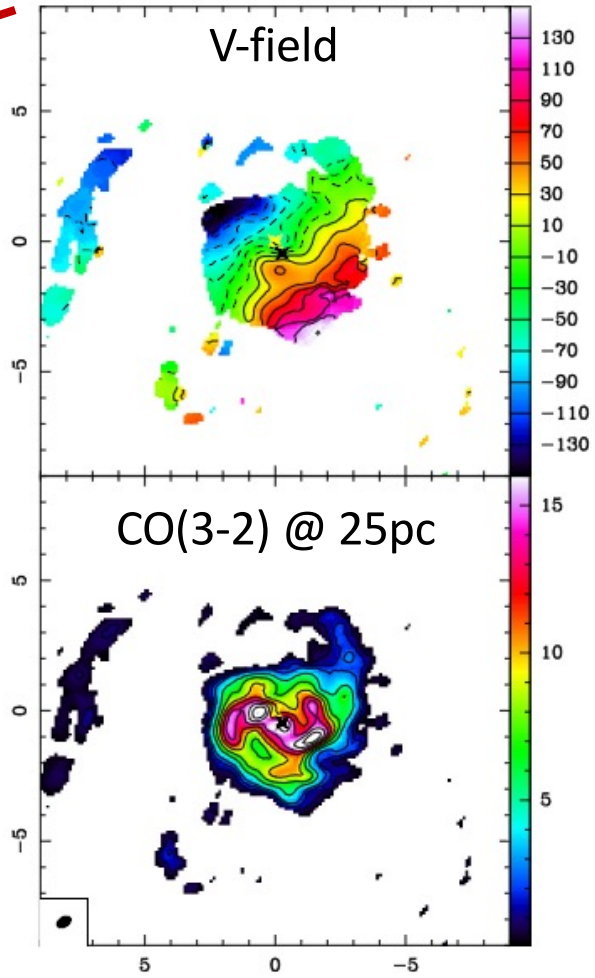
AGN & Tori

The NGC 1566 barred Seyfert 1: AGN feeding phase



12’

ALMA: mapping the gas inside the nuclear ring, the gas is fueling the nucleus



FOV=18’’ ~ 900 pc

Combes, Garcia-Burillo, Casasola+14

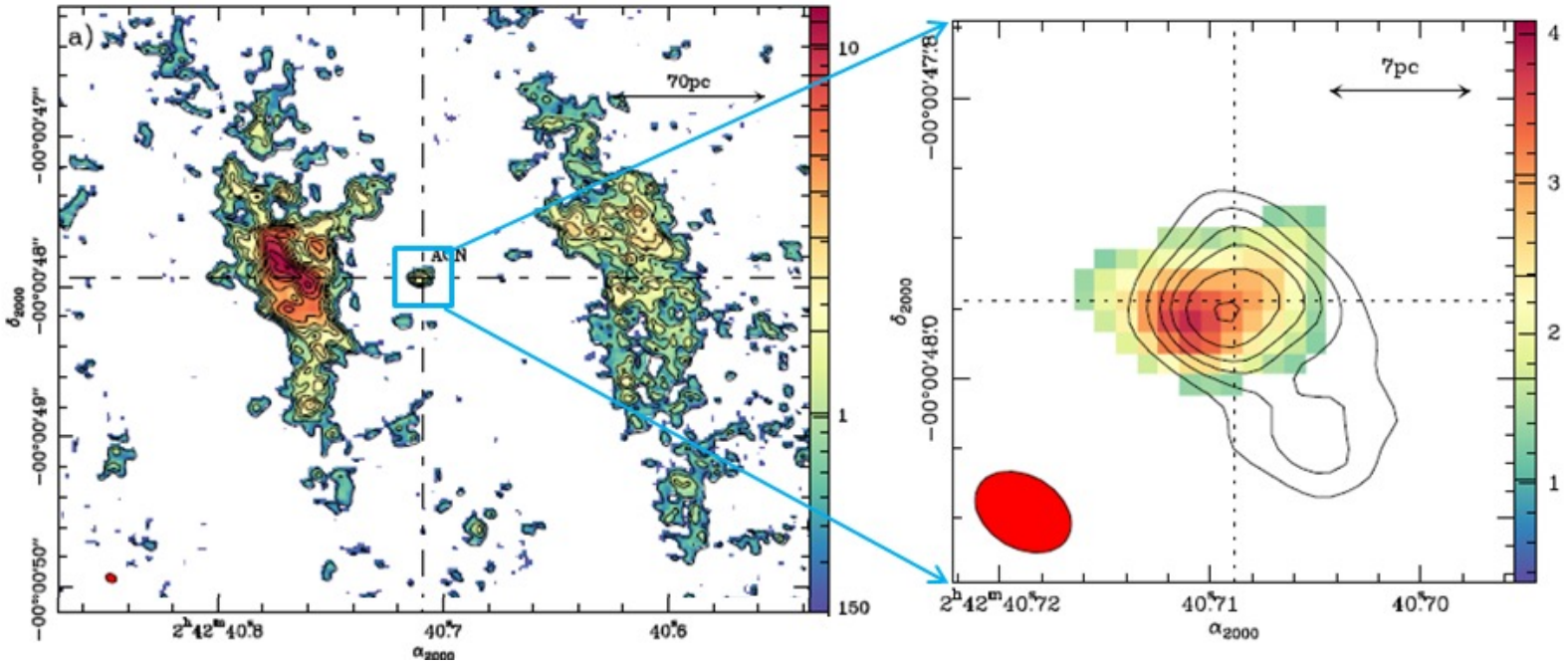
Slide modified from Francoise Combes, with permission

mm-ISM Surveys in the Local Universe

AGN & Tori

Detection of molecular Tori

The Seyfert 2 galaxy NGC 1068 (d = 14 Mpc)



CO(6-5) @ ~3.4 pc

432 µm dust emission @ ~3.4 pc

M_{gas} (torus) = (1 ± 0.3) x 10^5 $M_\odot$, R(torus) = (3.5 ± 0.5) pc (CLUMPY Torus model, Nenkova+08a,b)

Garcia-Burillo+16, see also Garcia-Burillo+19, Combes+19

cm-ISM Surveys in the Local Universe

21 cm – Atomic gas

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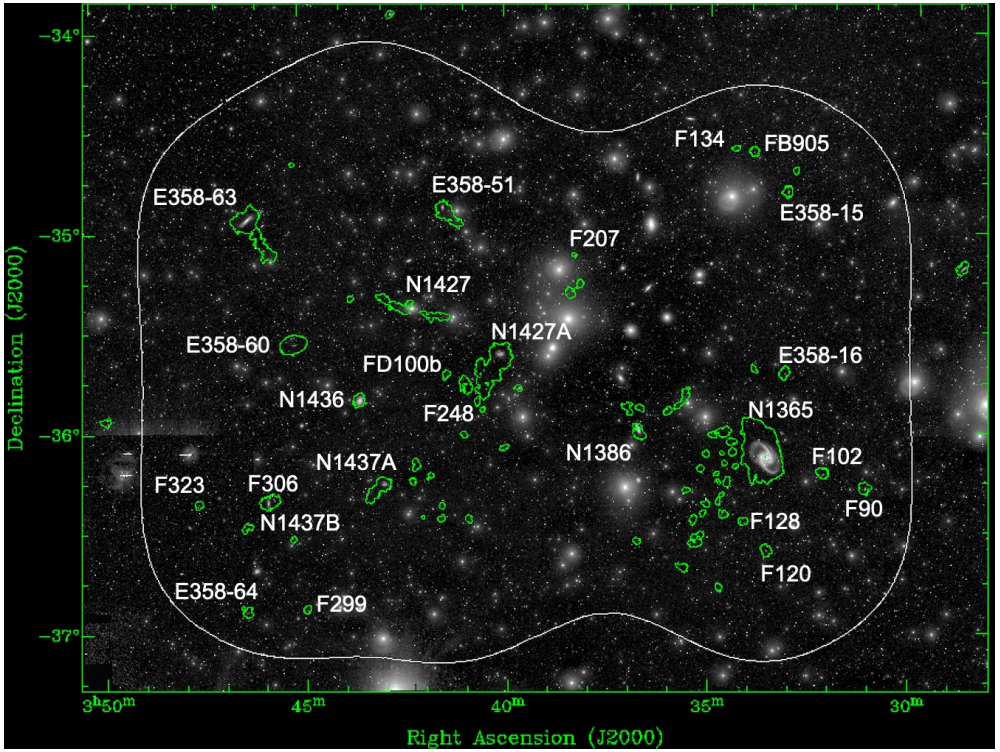
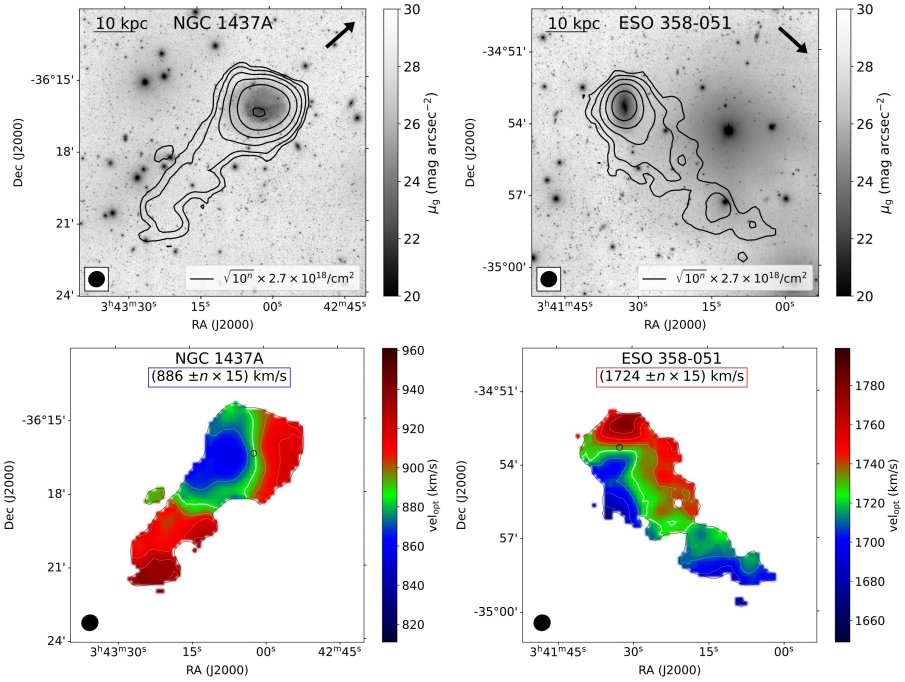
21 cm – Atomic gas

MeerKAT Fornax Survey (PI: P. Serra)

- HI imaging out to $2R_{vir}$ (12 deg^2) and down to 5x10^{19} - 8x10^{17} cm^{-2} at resolution 1 - 10 kpc
- Observations 70% complete, all data processed, first papers coming out
- Ram pressure stripping, HI depletion and quenching in dwarf and S0 galaxies





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Serra+23, se also Kleiner+23, Loni+23

DustPedia - A Definitive Study of Cosmic Dust in the Local Universe (FP7-SPACE proj. 606847)
PI: Jon Davies. 6 European nodes, INAF is 1/6

A legacy database of 875 galaxies observed by *Herschel* (HRS, KINGFISH, HeViCS...).
D_{25}> 1', z < 0.01, multiwavelength coverage from UV to submm (up to 42 bands/ galaxy)

DustPedia Database:
http://dustpedia.astro.noa.gr/

Davies et al. (2017)

Clark et al. (2018)

The ISM distribution in nearby galaxies

In a typical **star-forming late-type galaxy**:

the cold ISM is ~10-20% of the total baryonic mass (gas + stars)

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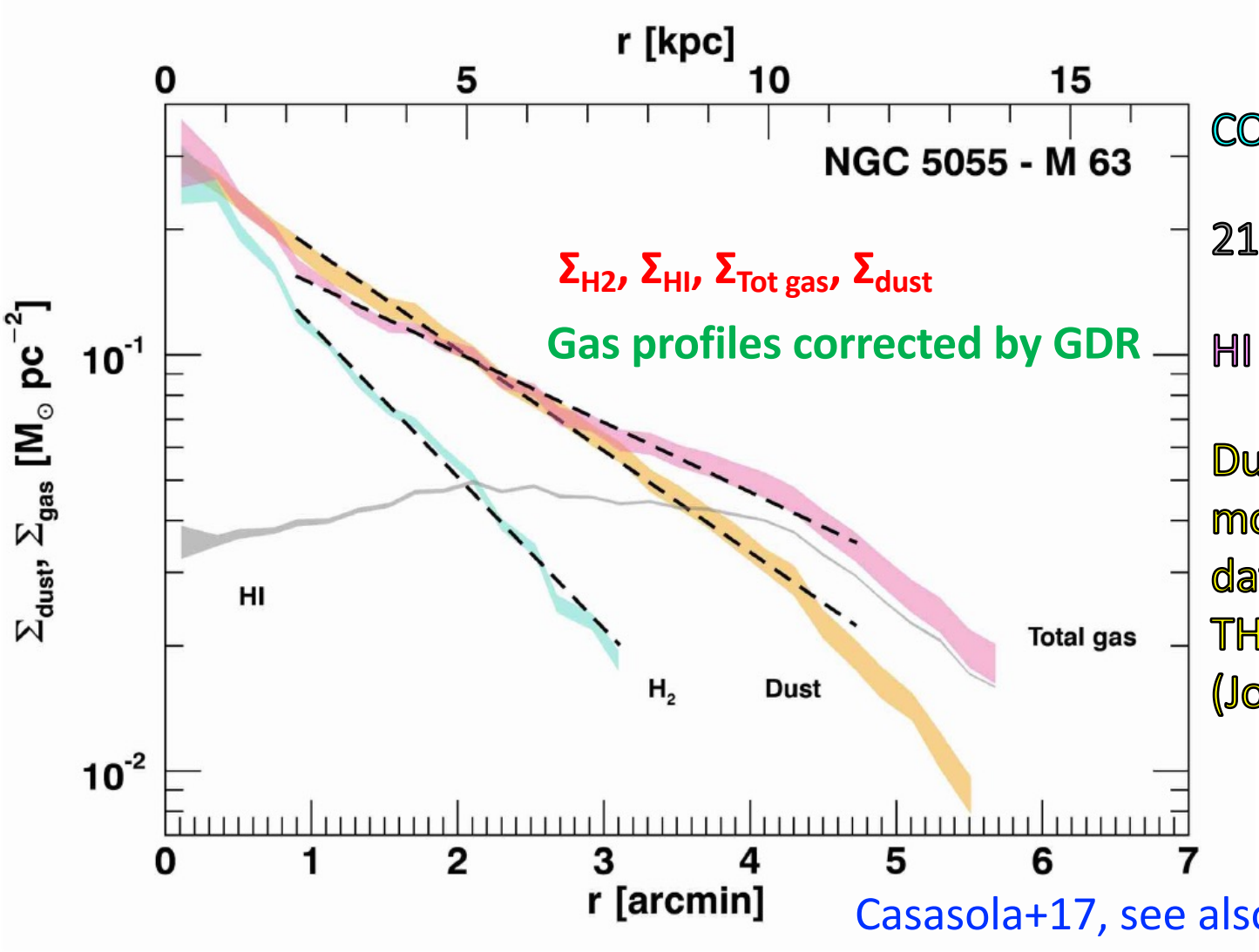


CO + fixed α_{CO} → H_2

21 cm → HI

HI + H_2 = Total gas

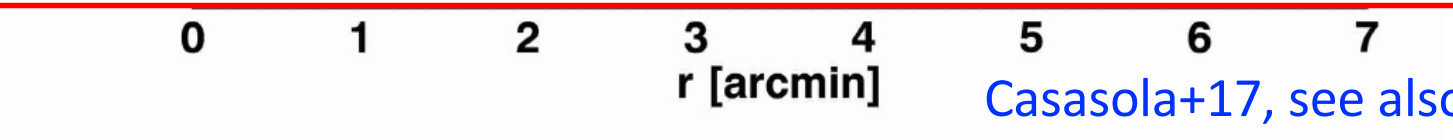
Dust = Comparing a modelled SED with data
THEMIS dust model (Jones+13, +17)

Casasola+17, see also Bigiel & Blitz 2012

The ISM distribution in nearby galaxies

In a typical **star-forming late-type galaxy**:
the cold ISM is ~10-20% of the total baryonic mass (gas + stars)

Common trend but all possibilities observed
including a central gas hole, both in CO and HI:
Milky Way (Misiriotis+06), M 31 (Nieten+06),
M 81 & NGC 3147 (Casasola+07, +08)
+ some PHANGS galaxies



Casasola+17, see also Bigiel & Blitz 2012

The ISM distribution in nearby galaxies

In a typical **early-type galaxy**:

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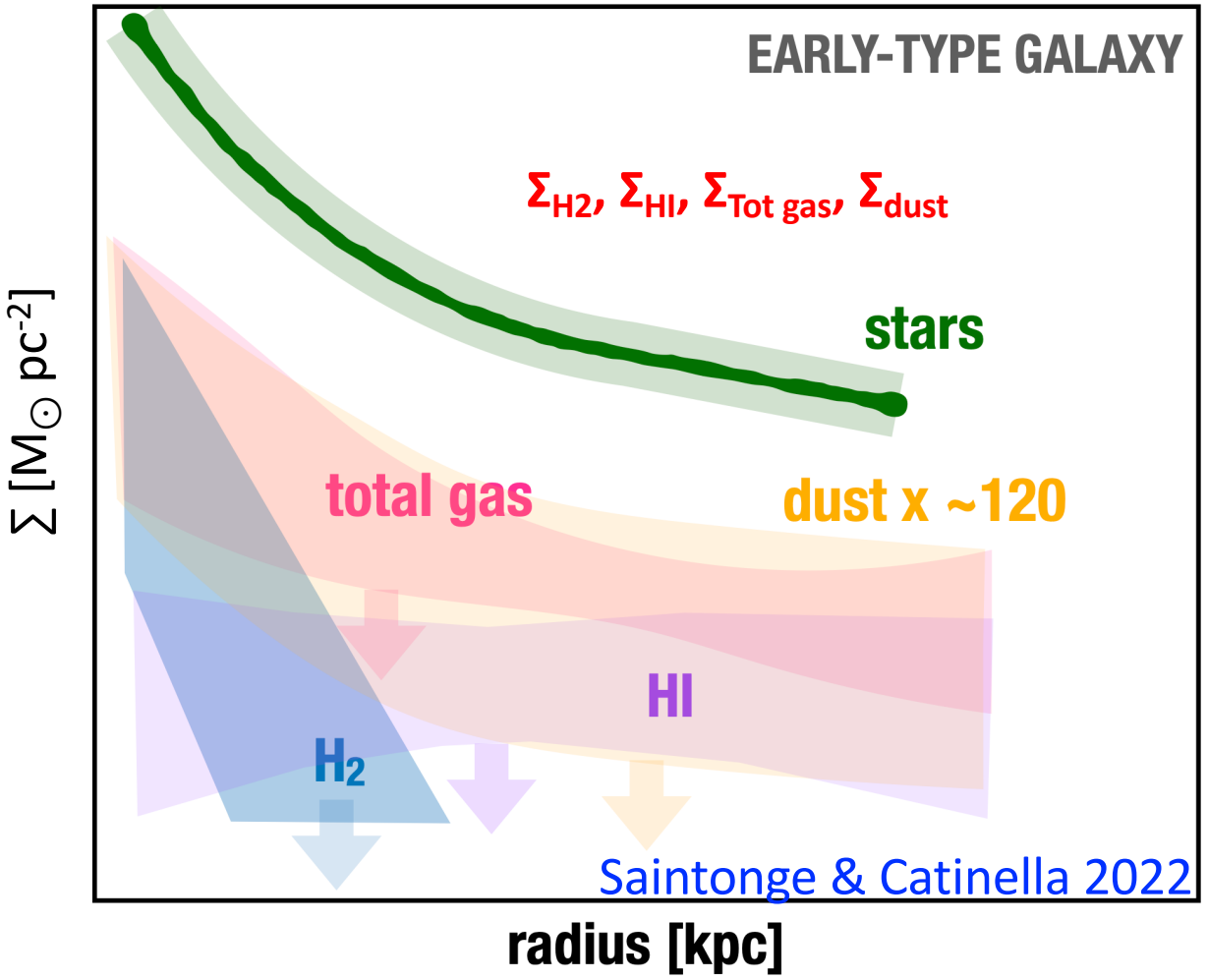

Molecular gas, if present, centrally concentrated with ∑ that can be similar to spirals (Davis+13)

HI: huge range of morphologies (Serra+12)

The global ISM scaling relations (SRs) in nearby late-type galaxies

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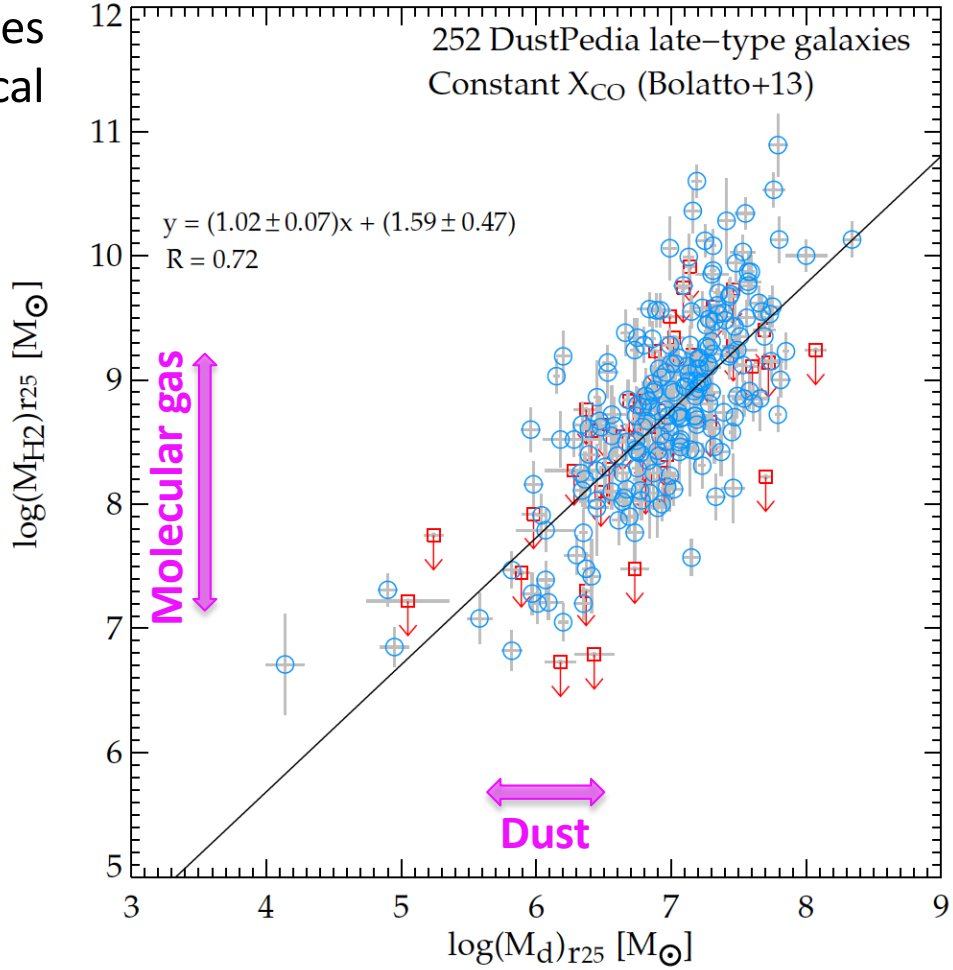
Dust and gas components (CO→H_2, HI, HI+H_2)

Both dust and gas masses are referred to the optical disk (r_{25})



Dust and molecular gas correlated

Consistent with SF process

No improvement with X_{CO} depending on metallicity (e.g., Sandstrom+13; Hunt+15; Amorin+16)

Casasola+20

The global ISM SRs in nearby late-type galaxies

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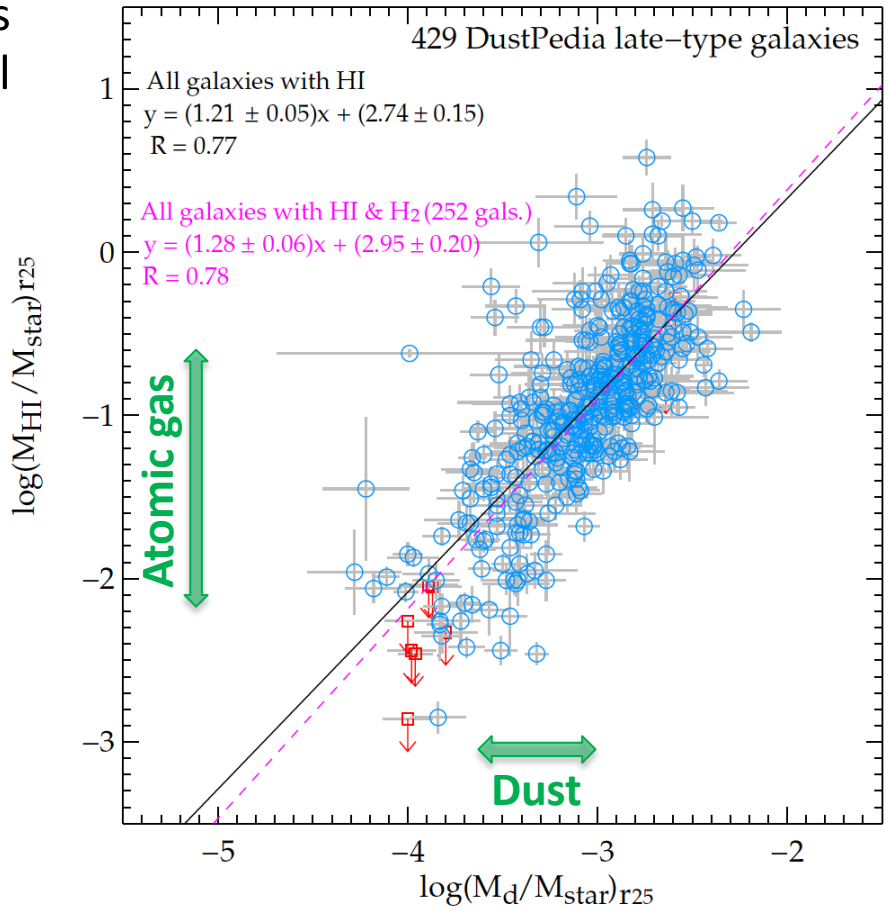

Dust and HI are better correlated than dust and molecular gas

Casasola+20

The global ISM SRs in nearby late-type galaxies

Dust and gas components (CO→H_2, HI, HI+H_2)

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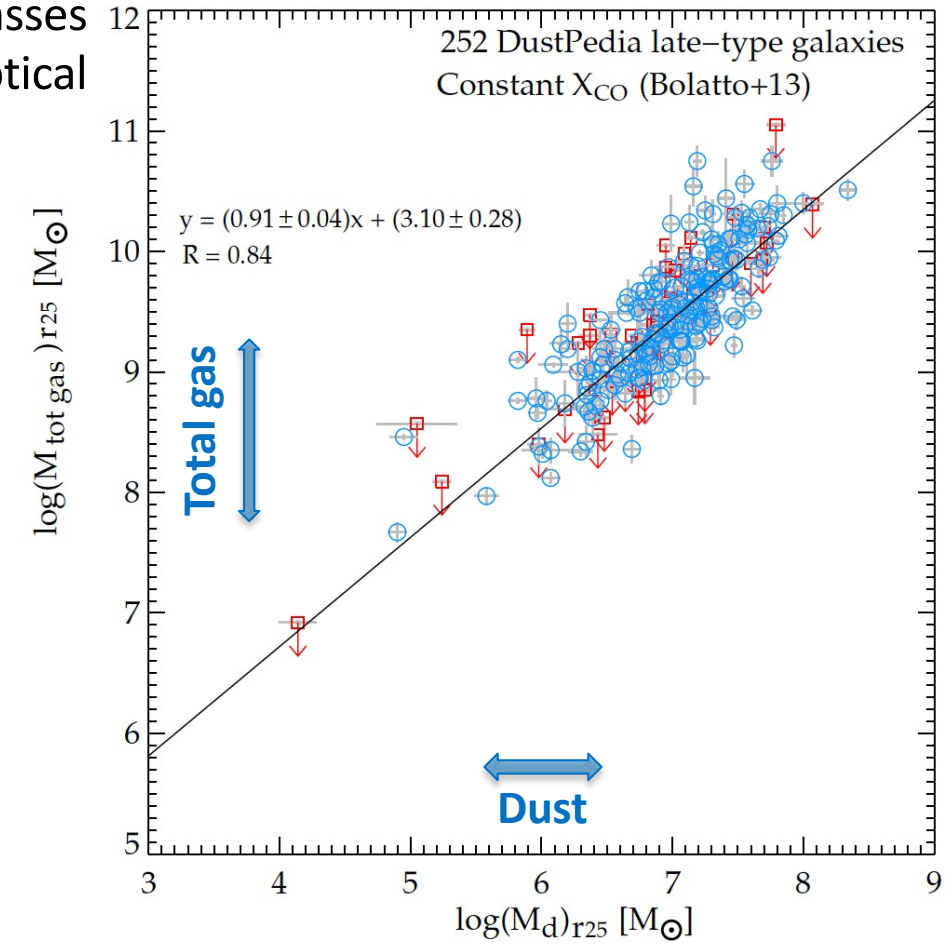


Dust and total gas is the best correlation

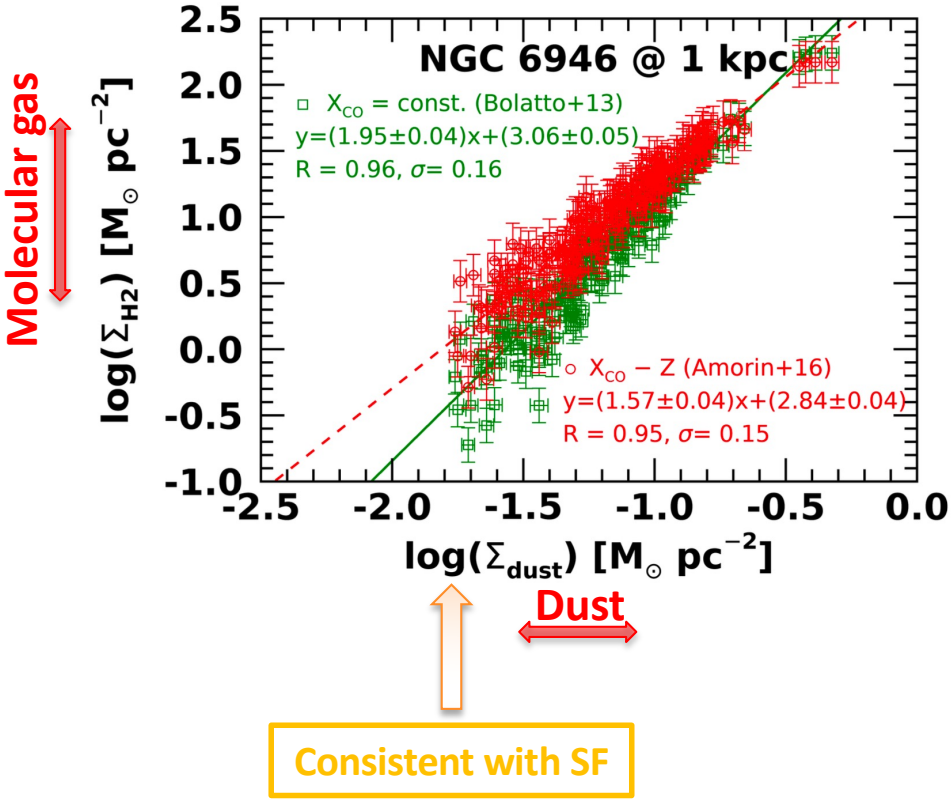
Scaling relations tested with a large and homogenous sample and under different physical assumptions.

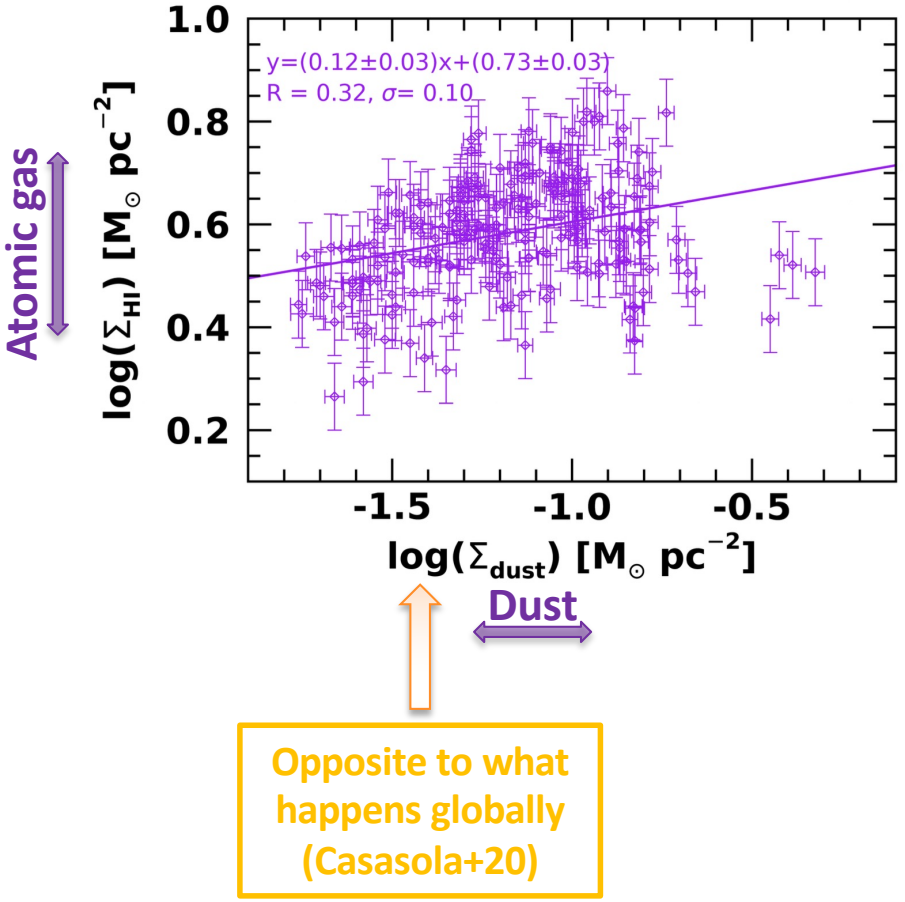
Casasola+20

What happens at small scales?

What happens at small scales galaxy-by-galaxy?

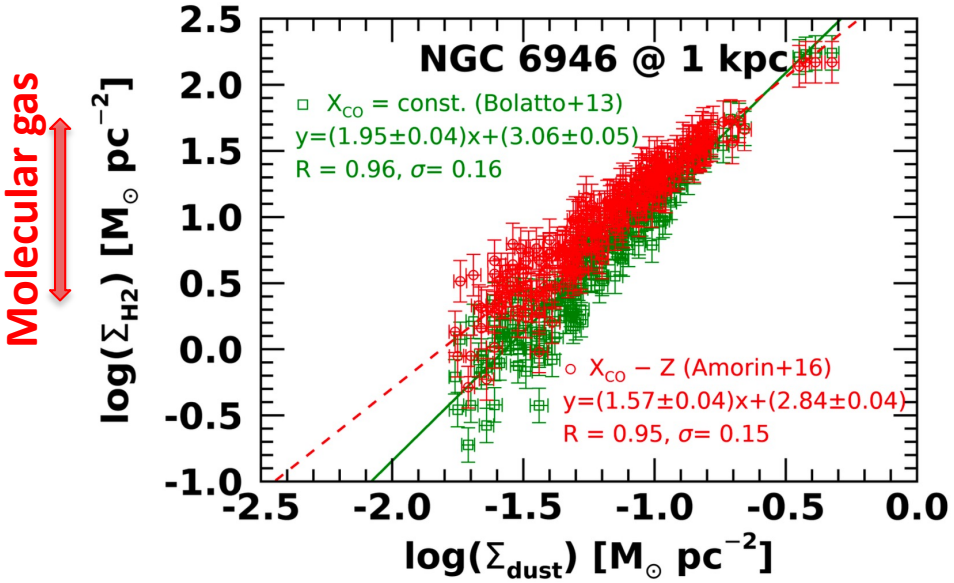
The spatially resolved ISM SRs in nearby late-type galaxies

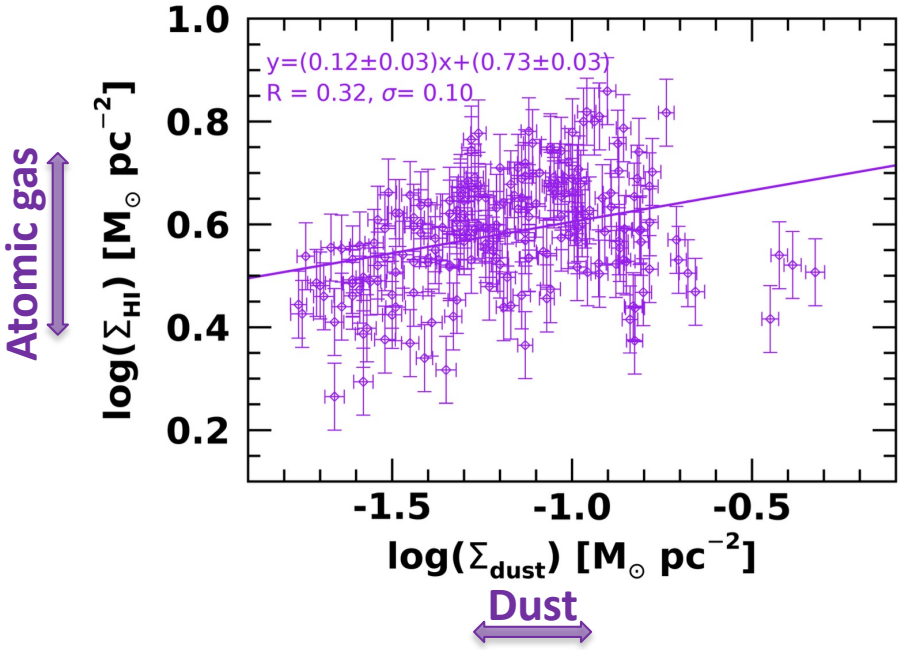


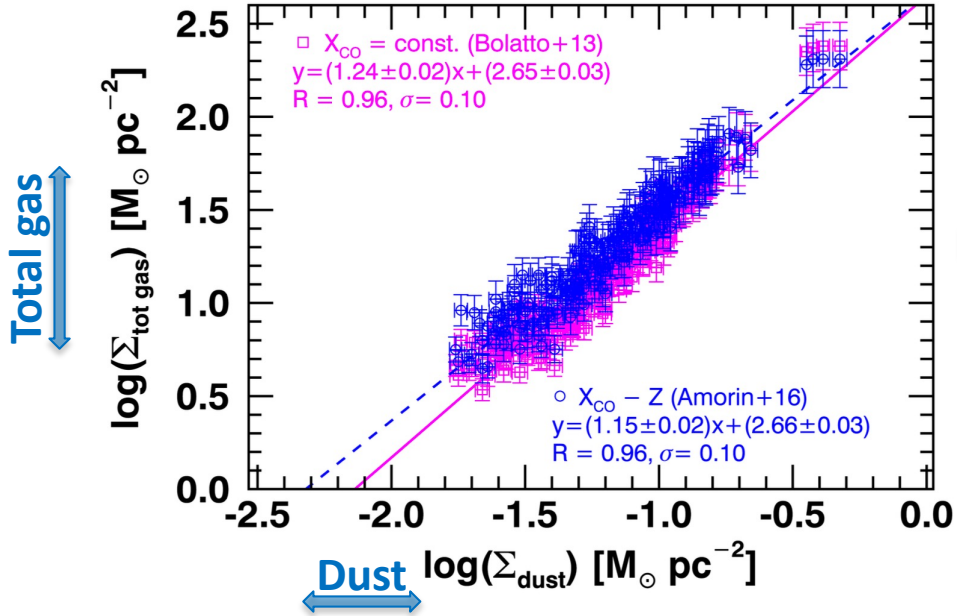


Casasola+22

The spatially resolved ISM SRs in nearby late-type galaxies







Dust–total gas:
the best correlation @ SMALL and GLOBAL scales

Casasola+22

The spatially resolved ISM SRs in nearby late-type galaxies

Common trends but each galaxy has distinct ISM SRs @ sub-kpc/kpc scales: Not universal correlations!

- SRs affected by local processes and galaxy peculiarities
- SRs holds from 300 pc (including M_{star}, SFR, M_{bar})
- Agreement between kpc and global scales: processes regulating galaxy properties occur locally
- dust-total gas good @ all scales, dust-H_2 good @ small scales, dust-HI good @ global scales

Casasola+22

The spatially resolved ISM SRs in nearby late-type galaxies

Common trends but each galaxy has distinct ISM SRs
@ sub-kpc/kpc scales: Not universal correlations!

- SRs affected by local processes and galaxy peculiarities

Heterogeneity of galaxy properties

Importance of resolved studies on local galaxies in the context of galaxy evolution

- dust-total gas good @ all scales, dust-H_2 good @ small scales, dust-HI good @ global scales

- Sub-galactic ratios (DGR, dust-to-metal, dust-to-star) consistent with whole galaxies, from low to high-z ($z \sim 5$): Ratios set by local processes

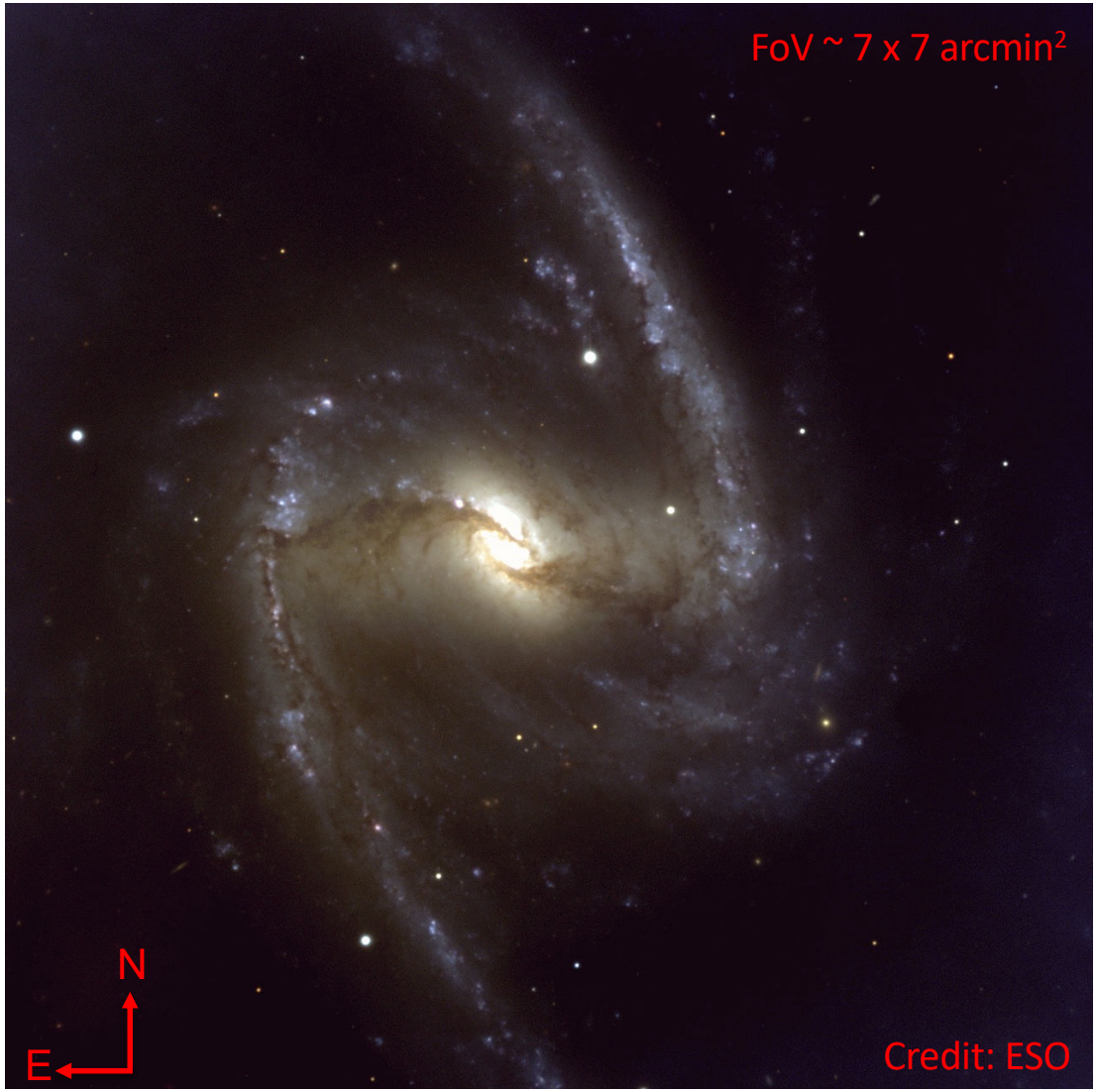
Casasola+22

Focus on NGC 1365

NGC 1365

VLT: B (blue), V (green), R (red)

SB(s)b
Dist. = 17.7 Mpc
D_{25} = 12 arcmin
Seyfert 1.8

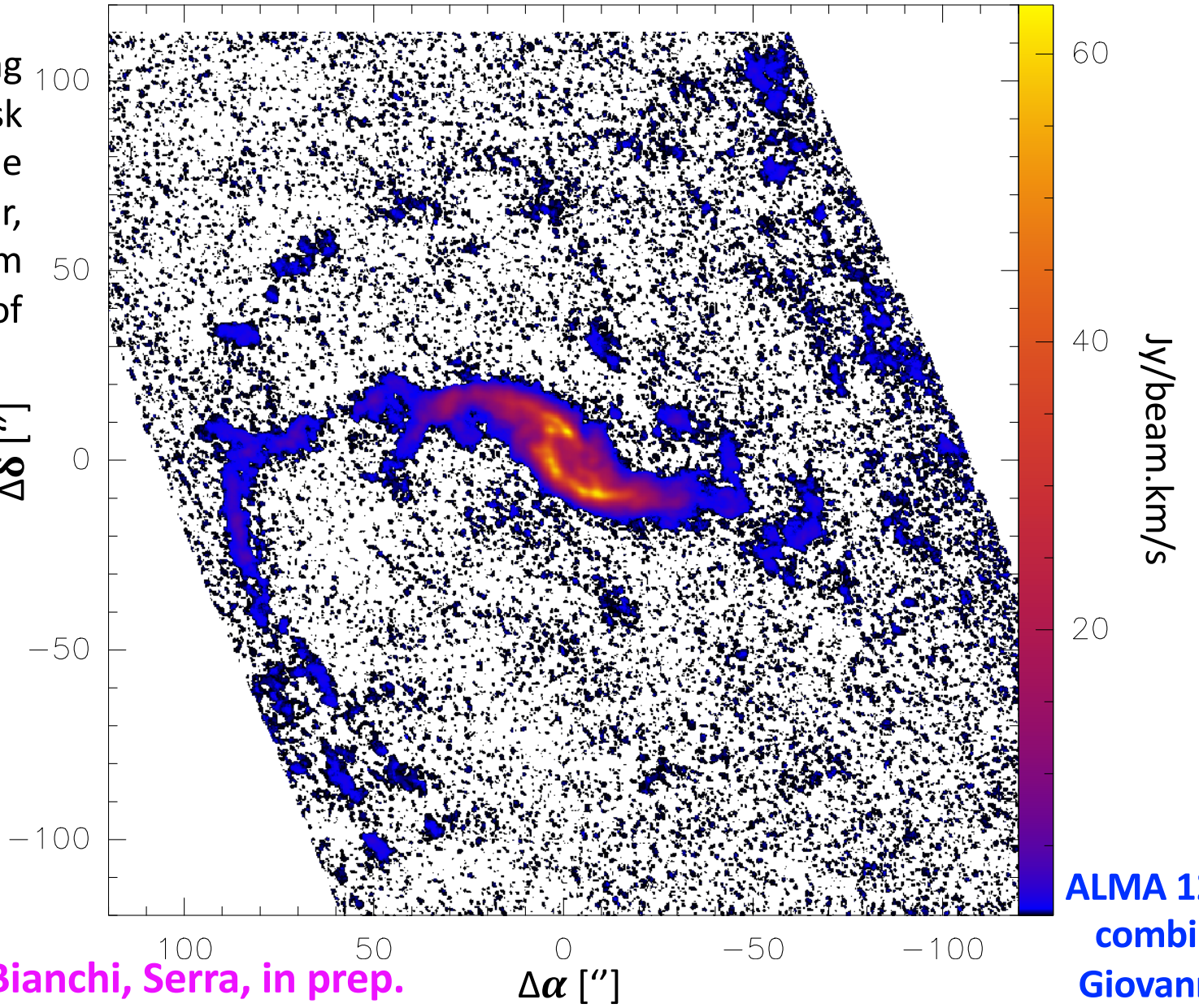


A DustPedia galaxy with 31 available band images: FUV-submm

NGC 1365

CO(2-1) @ 2'' (~170 pc) - ALMA PHANGS

FoV = 2' x 3'
Not covering the entire disk but the center, bar, and bar–arm transition of this galaxy



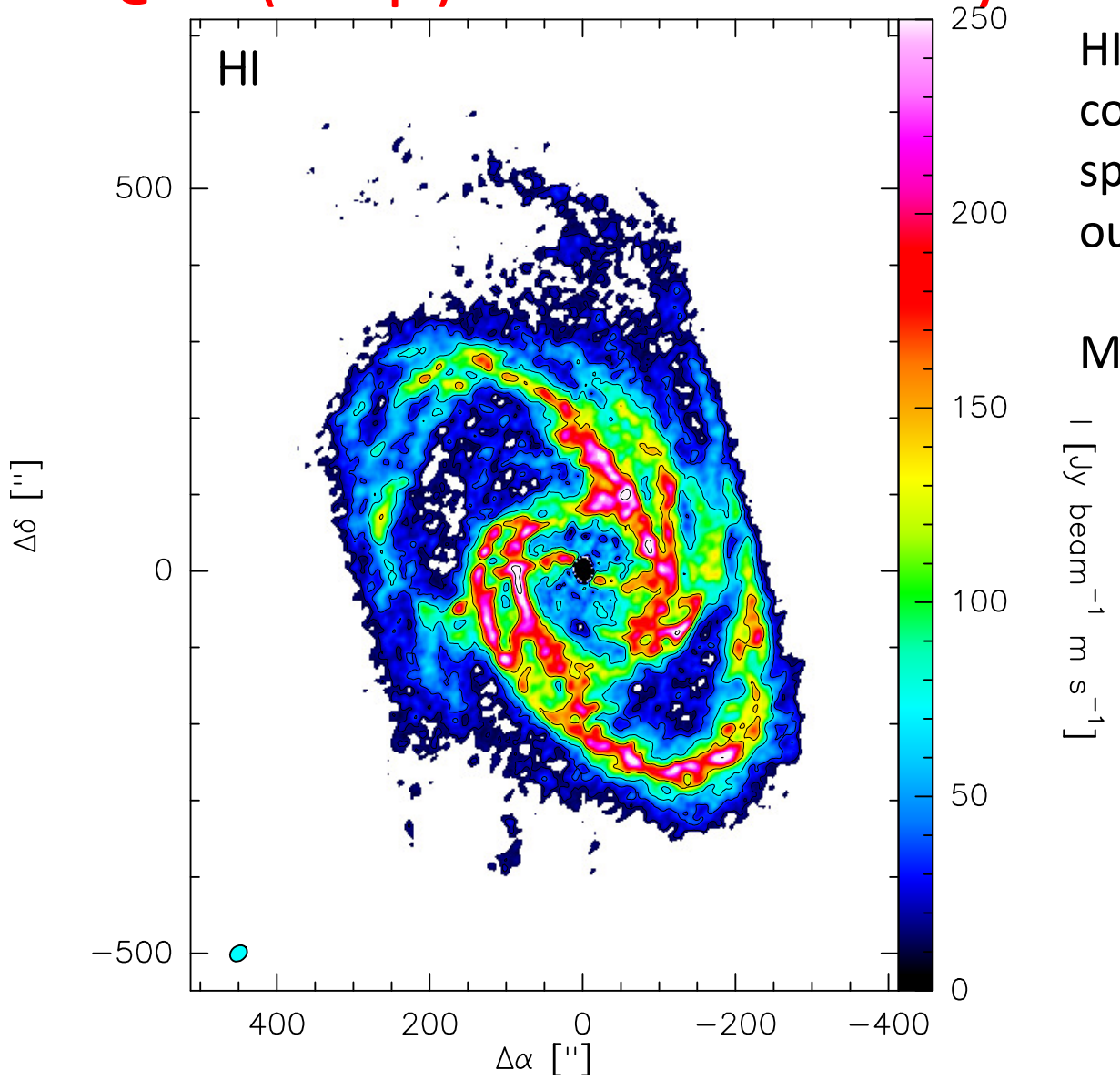
Work in progress

Casasola, Bianchi, Serra, in prep.

ALMA 12m+7m+TP combination by Giovanni Sabatini

NGC 1365

HI @ 11'' (~945 pc) – MeerKAT Fornax Survey



HI mostly concentrated in spiral arms and outside the bar

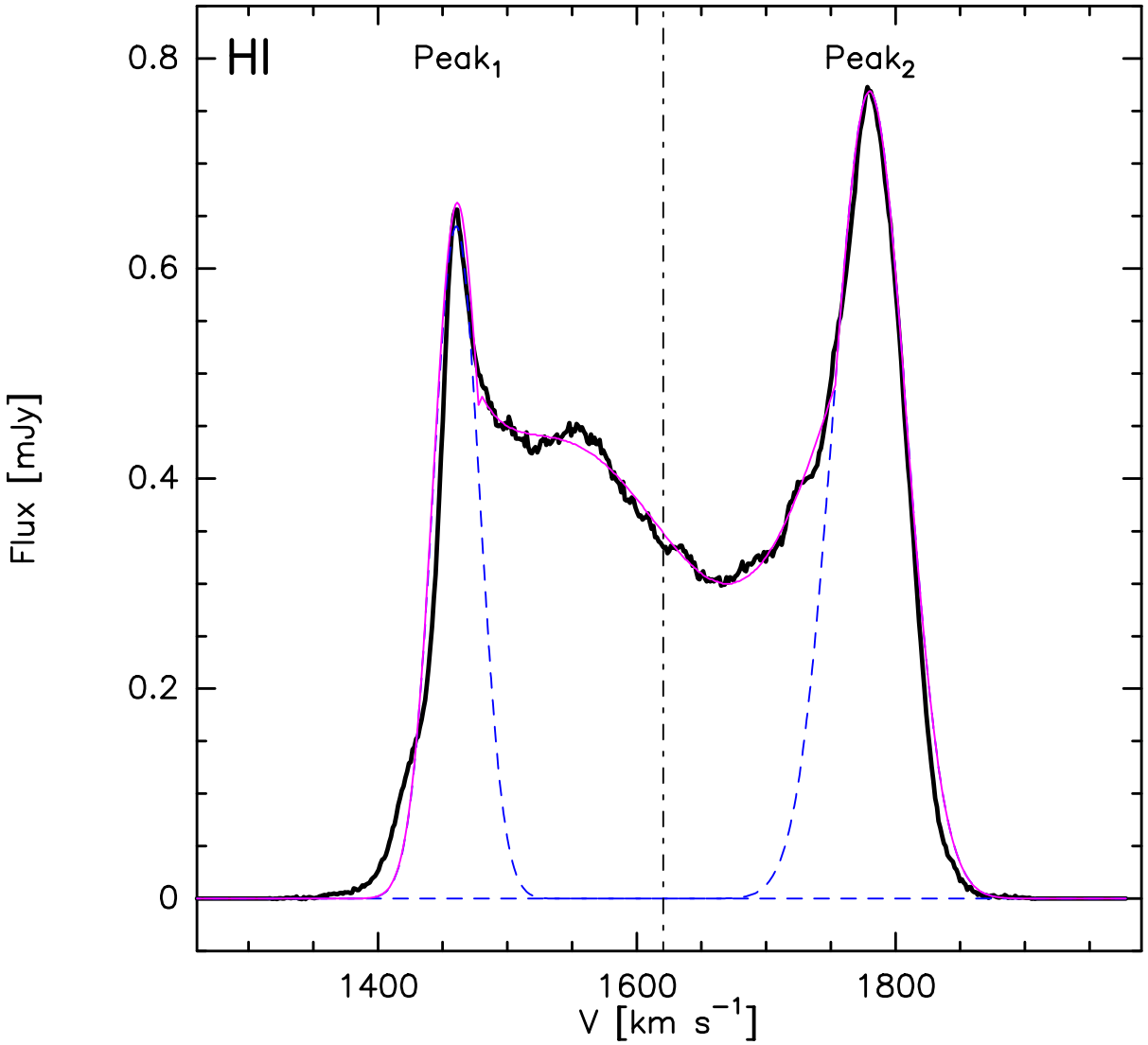
$M_{HI} = 1 \times 10^{10} M_{\odot}$

Work in progress

Casasola, Bianchi, Serra, in prep.

NGC 1365

HI @ 6 km/s velocity resolution – MeerKAT Fornax Survey



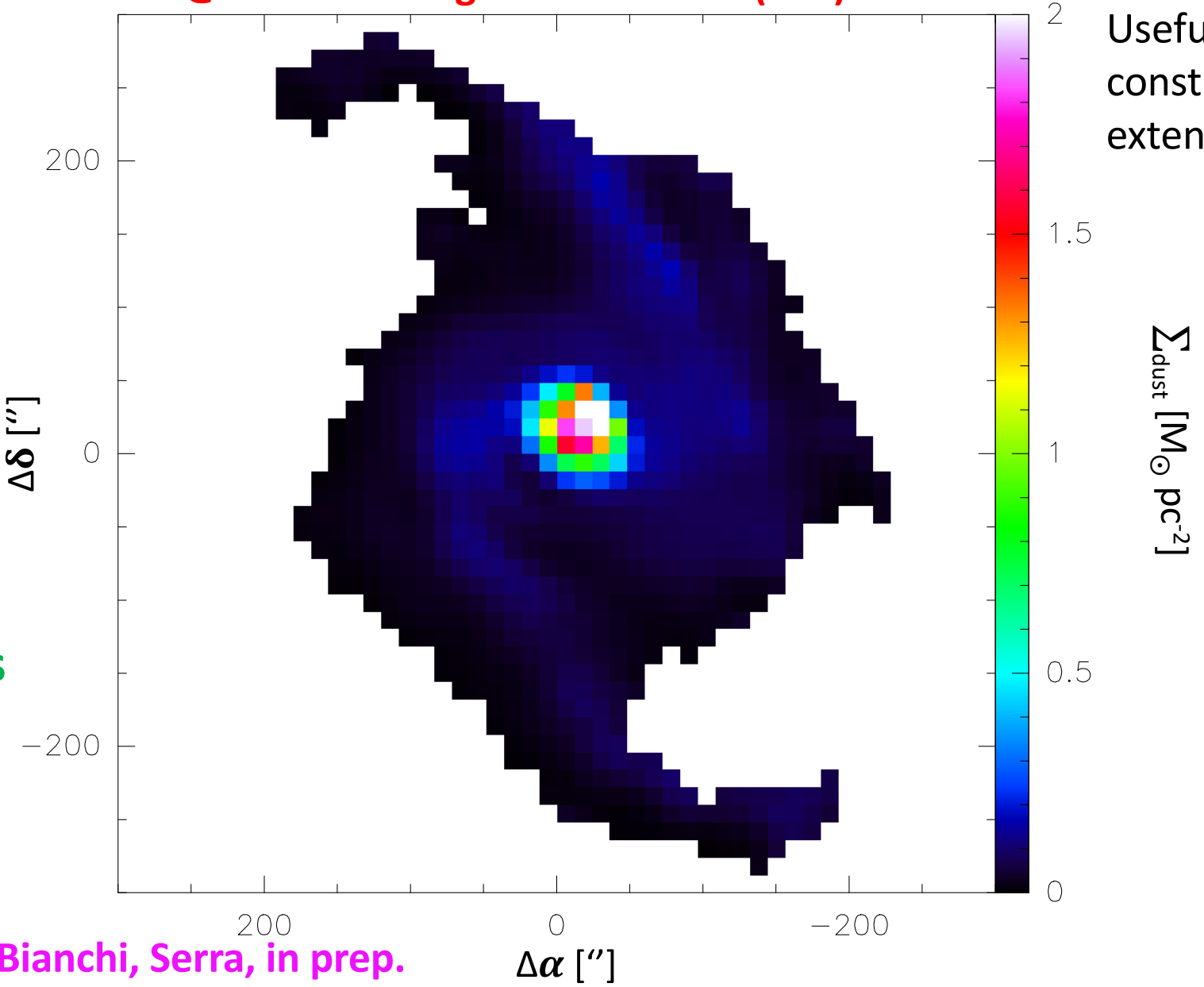
Double-horn profile: rather regularly rotating disc

Work in progress

Casasola, Bianchi, Serra, in prep.

NGC 1365

Dust @ MeerKAT angular resolution (11'') – DustPedia



Useful to constrain CO extension

Work in progress

Casasola, Bianchi, Serra, in prep.

Conclusions

- The **ISM** drives the **Galaxy Evolution**
- **Nearby galaxies**: link between Milky Way and high-*z* Universe
- **Nearby galaxies**: **new observational constraints** for theoretical models of galaxy evolution and a reference for high-*z* studies
- There are **NO UNIVERSAL** distributions/correlations between ISM components (and other galaxy properties) at sub-galactic scales
- **Local physical processes and galaxy peculiarities** drive global properties
- **Available surveys/projects/telescopes** allow us to perform very detailed analysis of the ISM in nearby galaxies

Thanks for your attention

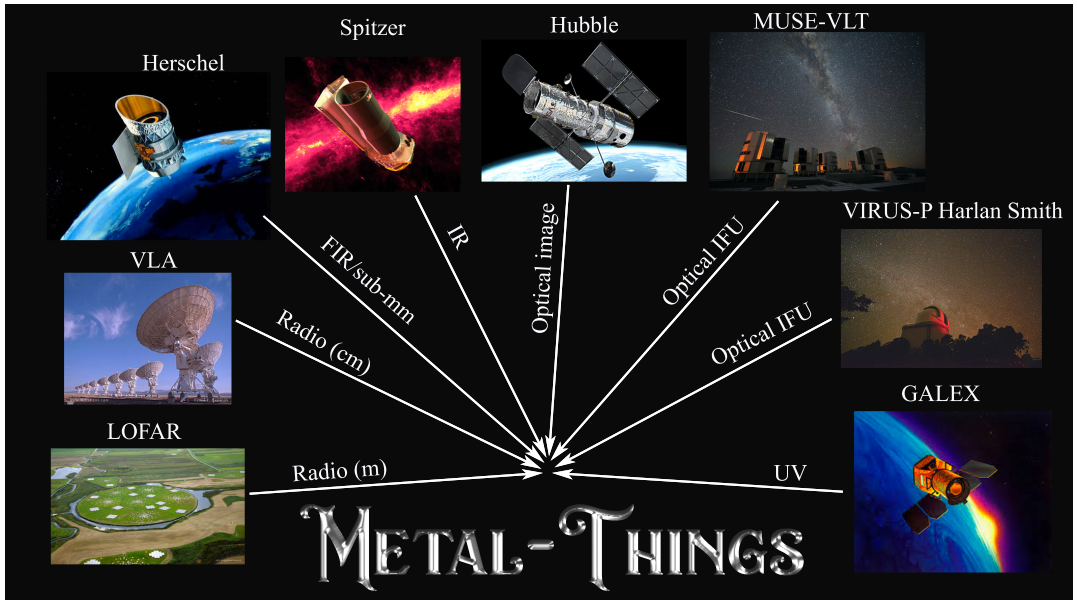
and

Enjoy next talks!

Additional slides

METAL-THINGS

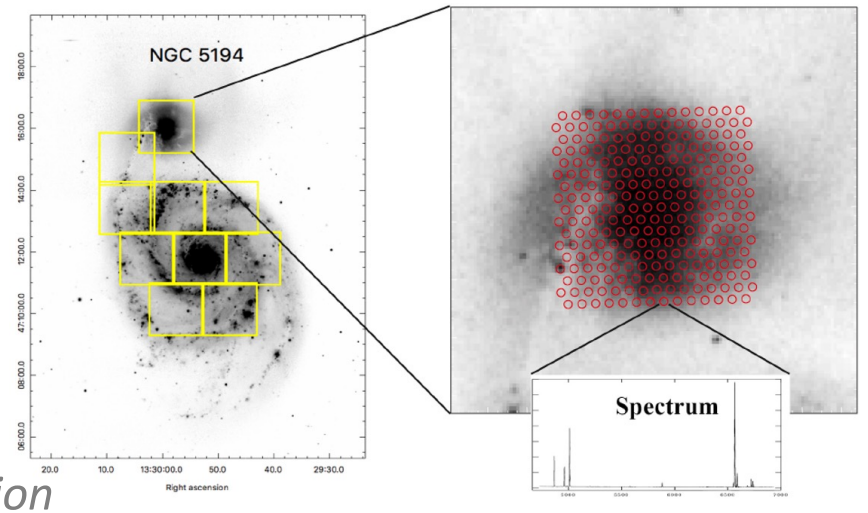
PI: Maritza Lara-López



A panchromatic survey!

- 34 Nearby Galaxy with IFU (VIRUS-P and MUSE)
- VLA HI information from the THINGS survey (all galaxies)
- 26/34 are DustPedia galaxies
- 8/34 are PHANGS galaxies
- Magnetic fields through Radio (m) by the LOFAR survey (Shimwell et al. 2017)

-Garuño et al. (2023, submitted)
-Lara-López et al. (2023)
-Comerón et al. (2023)
-Lara-López et al. (2021)



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mm-ISM Surveys in the Local Universe

AGN & Tori

Frequency of molecular Tori: 7/8

Galaxy	Radius (pc)	$M(H_2)^a$ 10^7 $M_\odot$	inc(°) torus	inc(°)^b gal
NGC 613	14±3	3.9±1.4	46±7	36
NGC 1326	21±5	0.95±0.1	60±5	53
NGC 1365	26±3	0.74±0.2	27±10	63
NGC 1433	–	–	–	67
NGC 1566	24±5	0.88±0.1	12±12	48
NGC 1672	27±7	2.5±0.3	66±5	28
NGC 1808	6±2	0.94±0.1	64±7	84
NGC 1068	3.5±0.5	0.01	80	24

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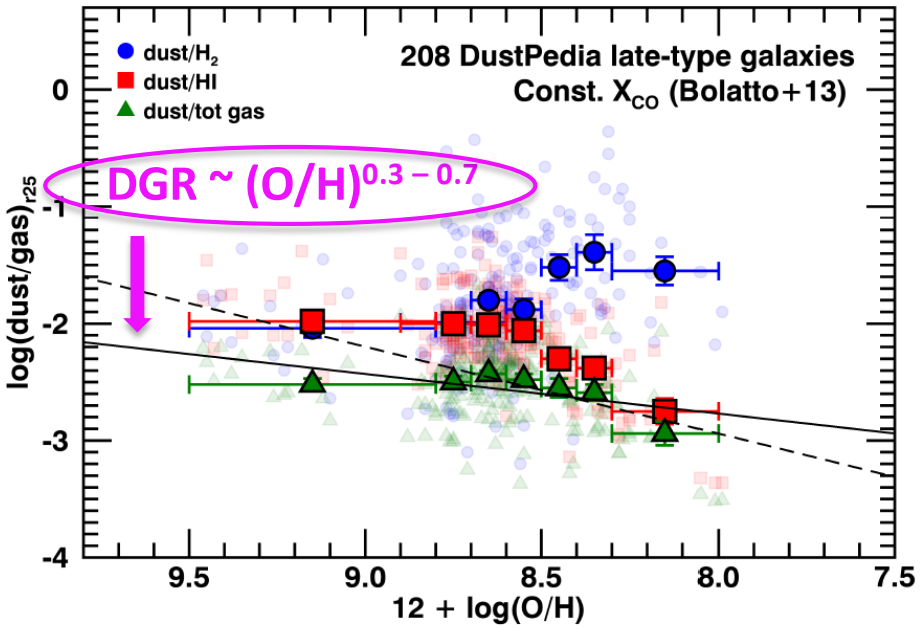
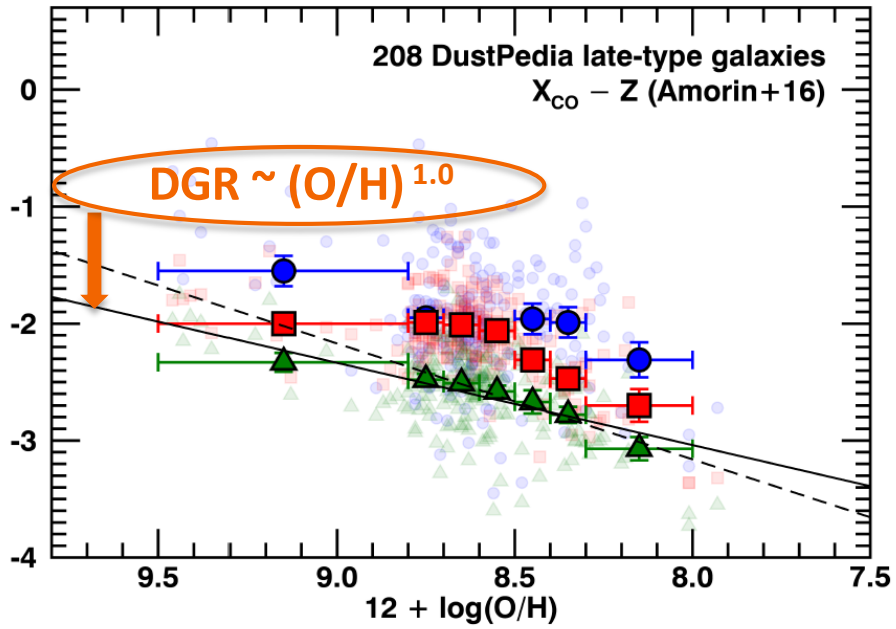
Combes+19

Dust-to-gas mass ratio (DGR) vs. metallicity
Global measurements

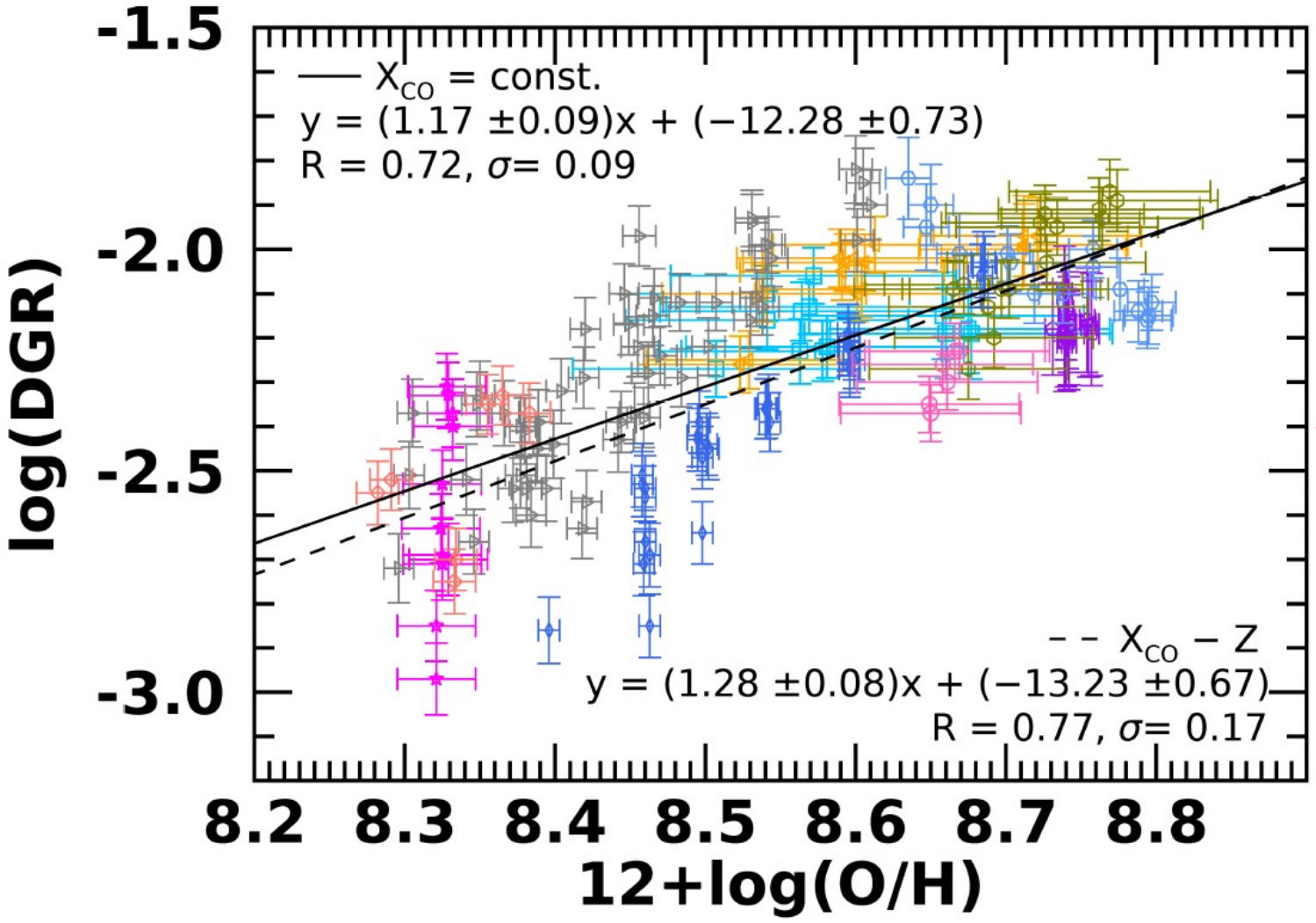




- D/H_2 is the most affected by X_{co}: D/H_2 increases for low O/H with constant X_{co}, while X_{co} – Z realigns D/H_2 with D/HI and D/tot gas
- **With X_{co} – Z, DGR ~ $O/H^{1.0}$ consistent with theoretical expectations (models neglecting dust grain growth, with a constant dust-to-metal ratio)**

Casasola+20

Dust-to-gas mass ratio (DGR) vs. metallicity
Spatially-resolved measurements



Spatially resolved data of galaxies at 3.4kpc

Sub-galactic DGR consistent with global DGR

Little evolution of DGR-O/H at *z* = 0-6 (e.g., Popping & Peroux 2022, Li+19)

Casasola+22