Molecular Cloud Scale "Micro-physics" as Drivers of the Baryon Cycle and Galaxy Evolution

NASA Hubble Fellowship Program

Jiayi Sun

Hubble Fellow @ Princeton University

NHFP Symposium | September 19, 2024

PRINCETON UNIVERSITY

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Phangs

MAUVE

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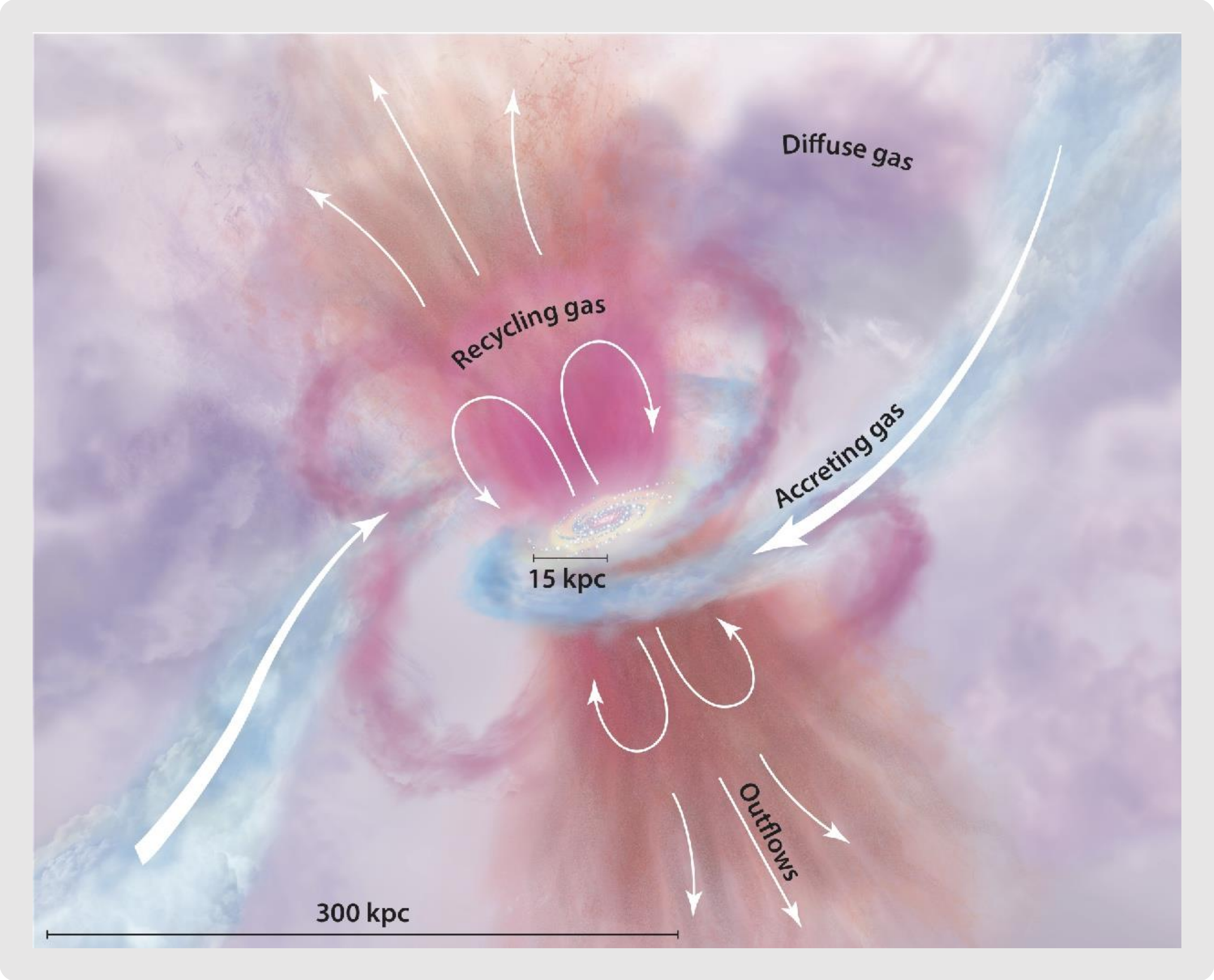
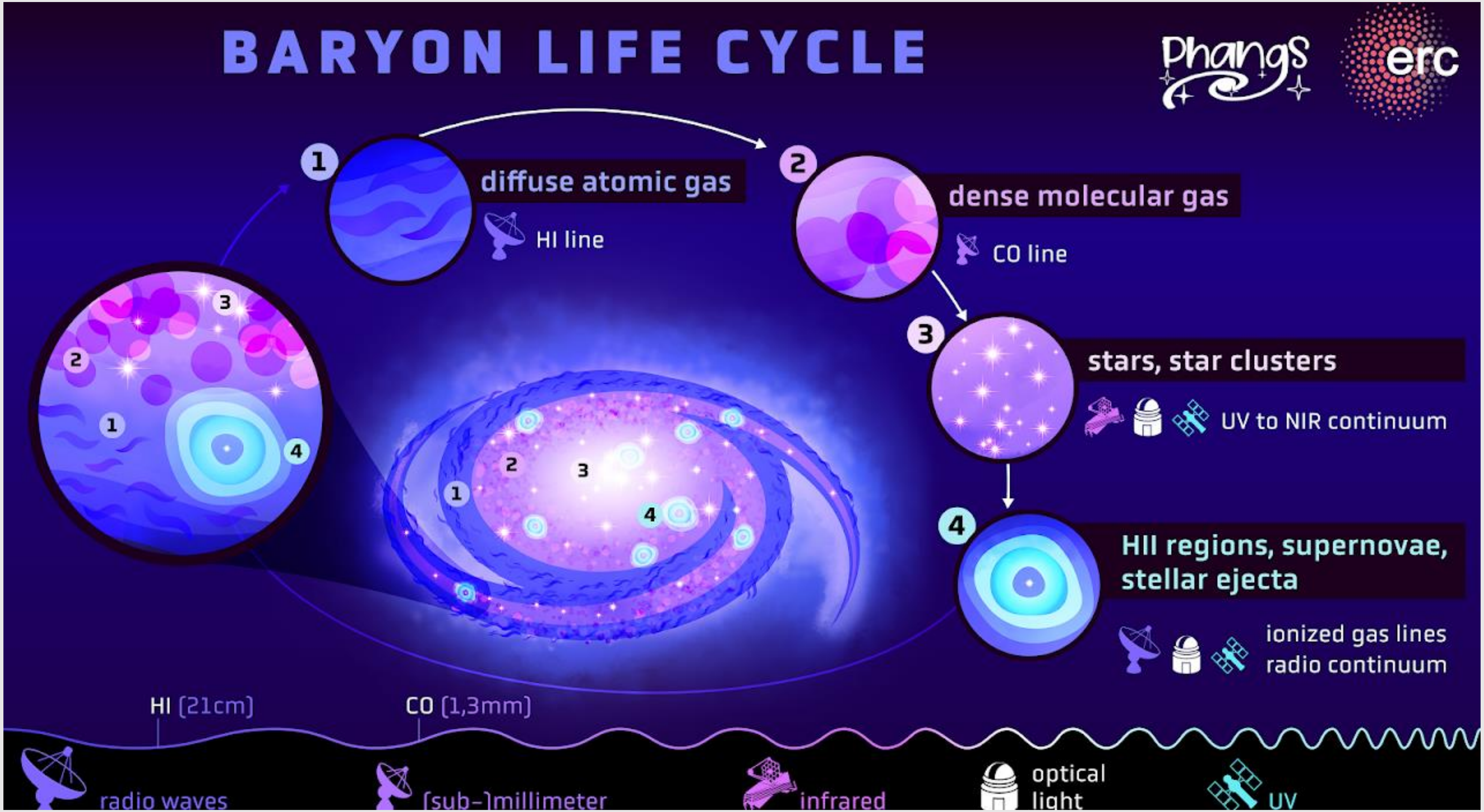
The “Global” Baryon Life Cycle in the Context of Galaxy Evolution



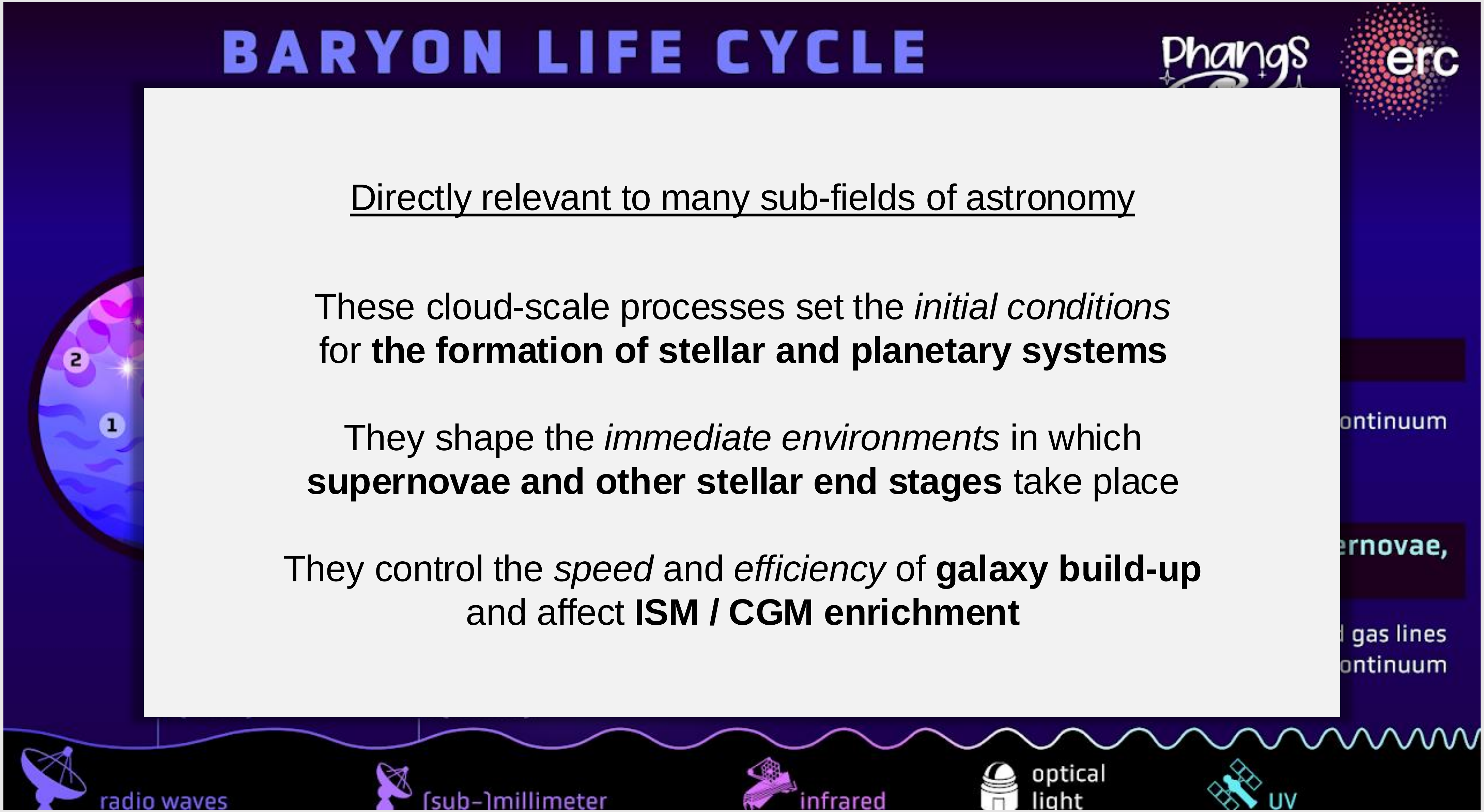
Tumlinson+ (2017)

The Baryon Life Cycle on Individual Star-forming Region Scales



Credit: ERC / E. Schinnerer / PHANGS

The Baryon Life Cycle on Individual Star-forming Region Scales



<u>Directly relevant to many sub-fields of astronomy</u>

These cloud-scale processes set the *initial conditions* for **the formation of stellar and planetary systems**

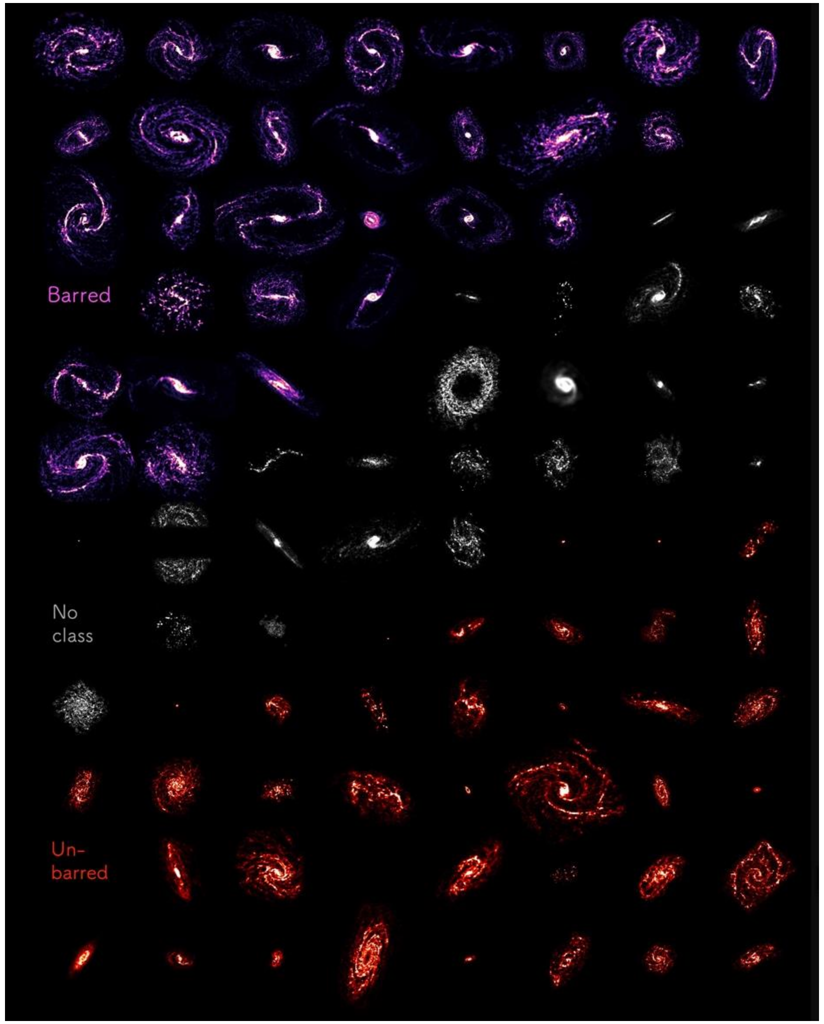
They shape the *immediate environments* in which **supernovae and other stellar end stages** take place

They control the *speed* and *efficiency* of **galaxy build-up** and affect **ISM / CGM enrichment**

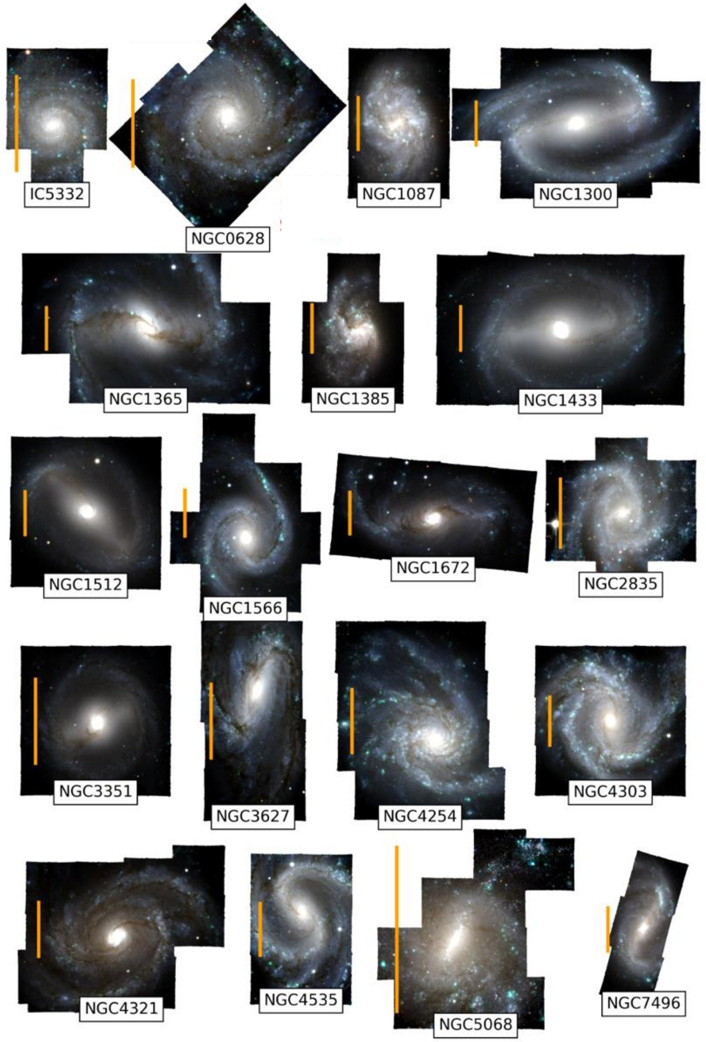
Credit: ERC / E. Schinnerer / PHANGS

The PHANGS* Multiwavelength Surveys (* Physics at High Angular resolution in Nearby GalaxieS)

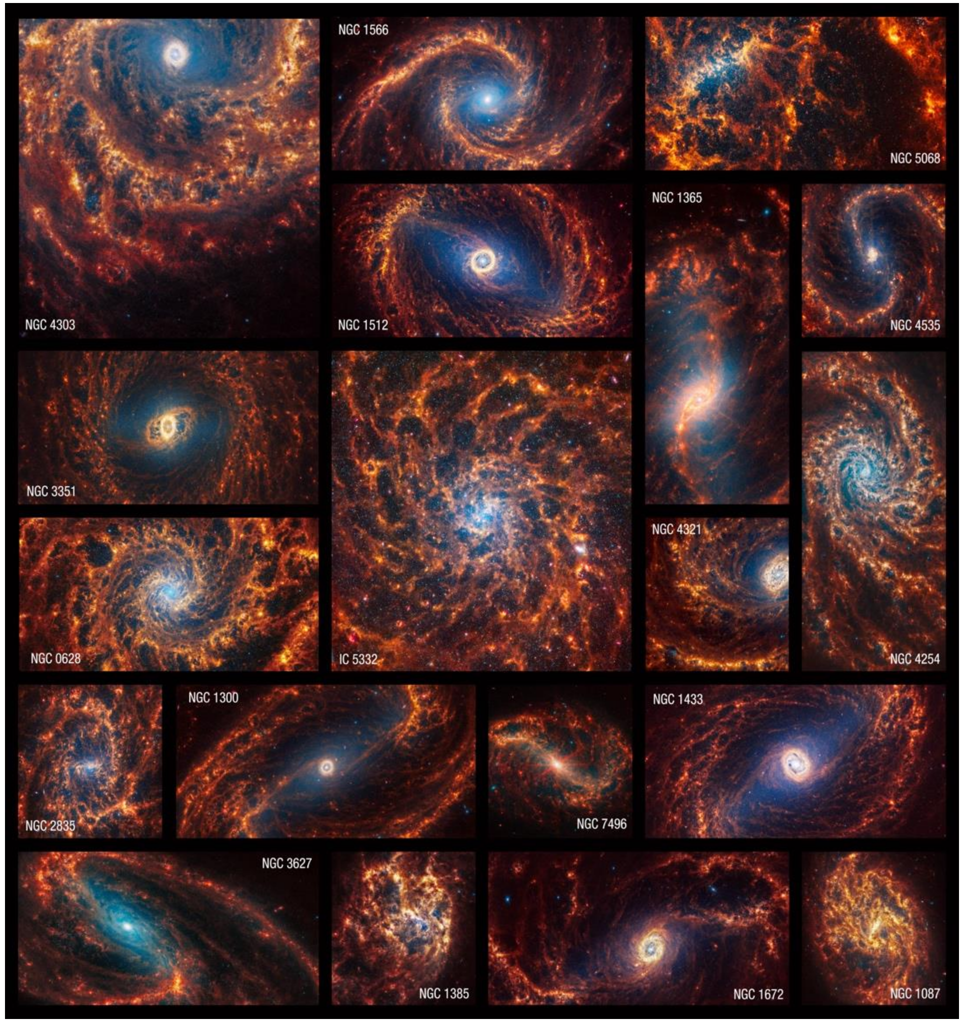
Team PI: Eva Schinnerer (MPIA). Myself as a science working group leader and builder of several key datasets.



PHANGS-ALMA: ~90 galaxies
Leroy+ (2021a,b)



PHANGS-MUSE: ~20 galaxies
Emsellem+ (2022)



PHANGS-HST & JWST: ~50-70 galaxies
Lee+ (2022, 2023)

How Fast Do Star-forming Regions Evolve?

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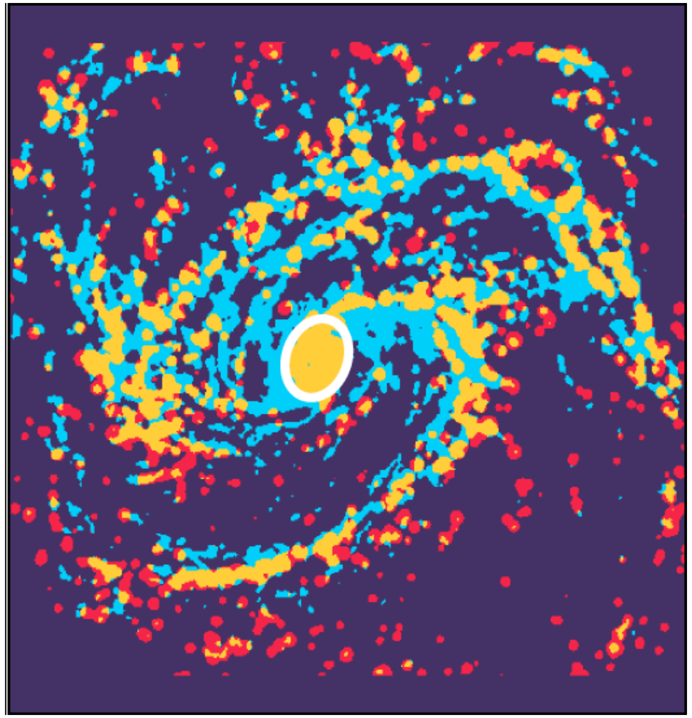
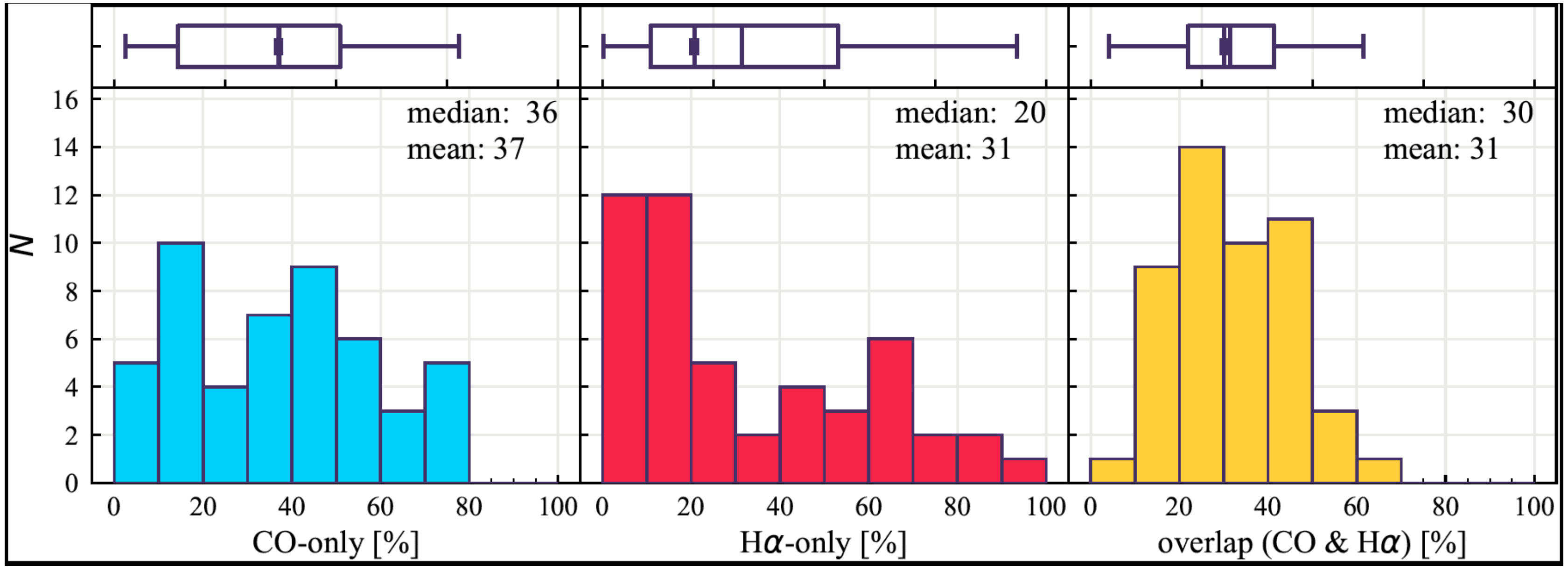
Tracers of cold gas (e.g., CO) and massive star formation (e.g., Hα) do not perfectly overlap on individual star-forming region scales, suggesting **rapid evolution on ~< 5 Myr**.

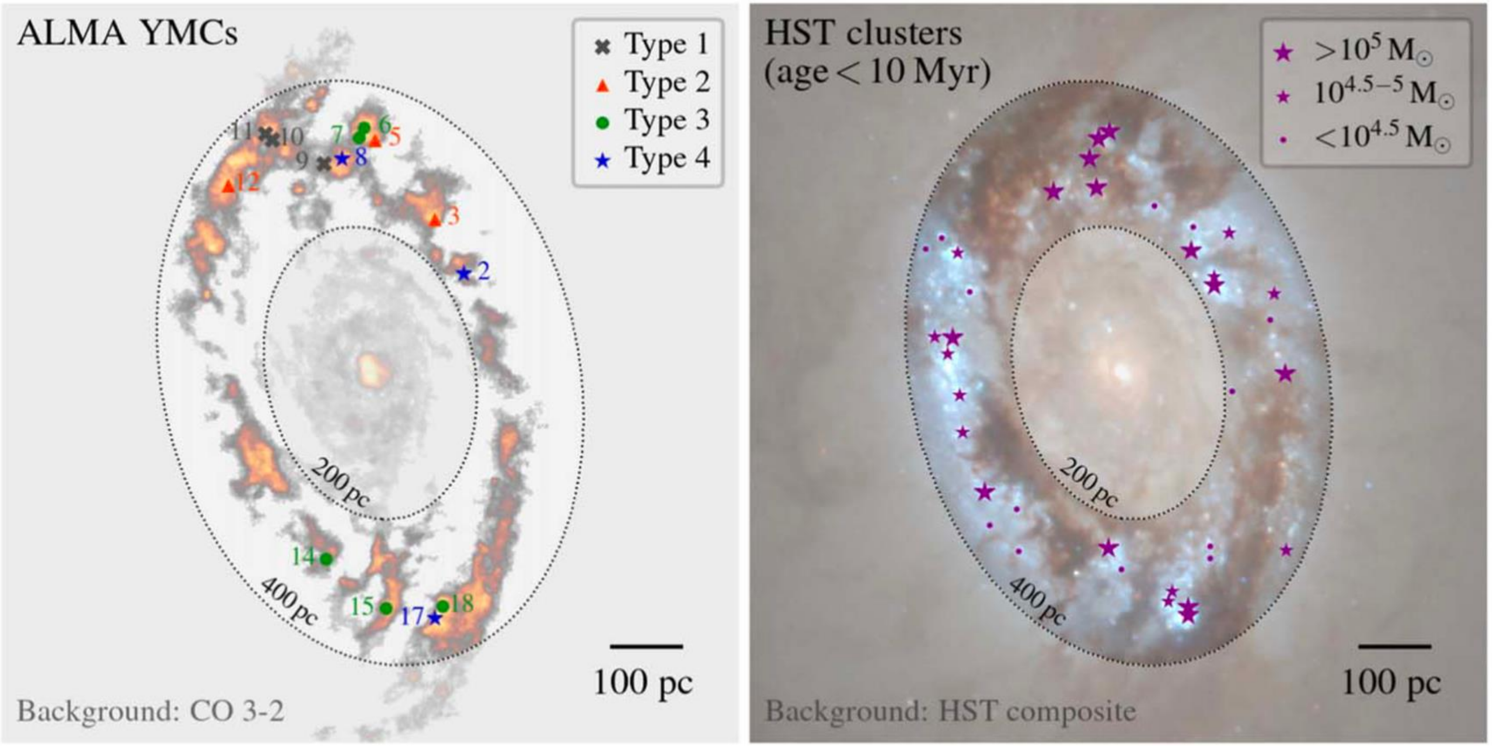




Fraction of regions with bright CO, bright Ha, or both across 50+ galaxies

Schinnerer+ (2019); Chevance+ (2020); Kim+ (2022); Pan+ (2022)

How Fast Do Star-forming Regions Evolve?



Direct detection and matching of young star clusters with their immediate progenitors

PhD & undergrad students involved

J. Sun, ***H. He***, ***K. Batschkun***, *et al. (2024)*

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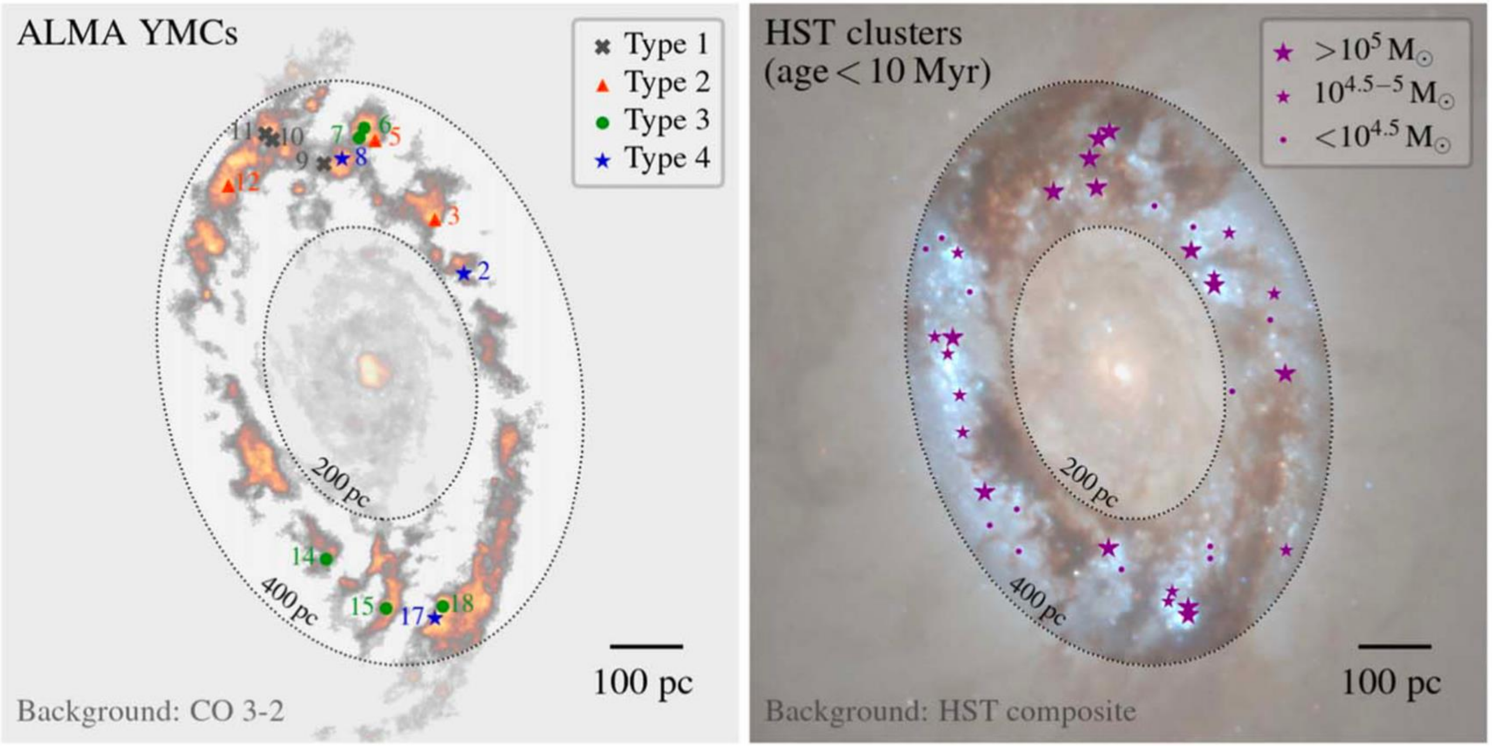

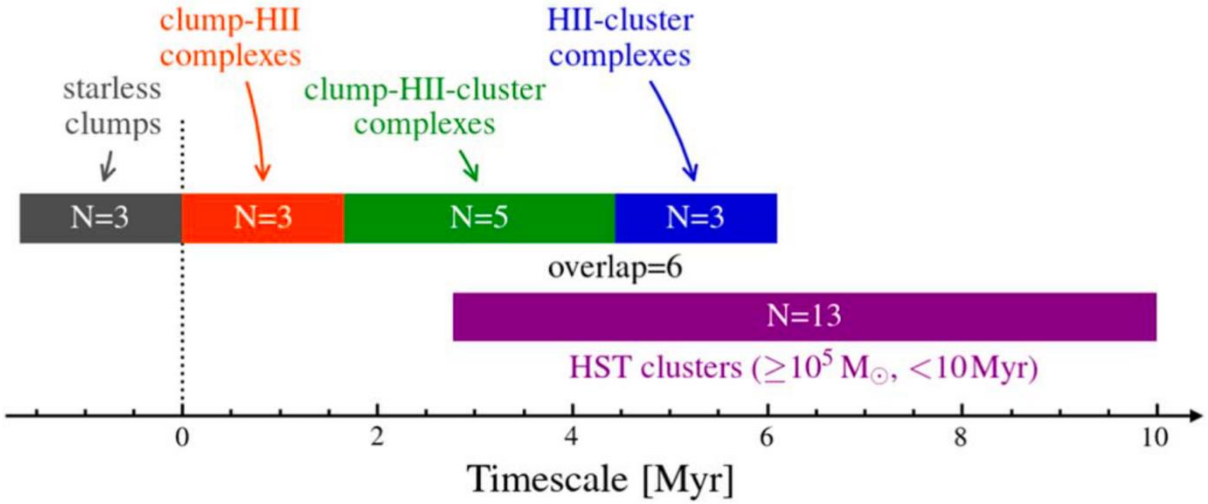

Direct detection and matching of young star clusters with their immediate progenitors offer independent evidence for **rapid formation and cluster-gas decoupling timescales**.

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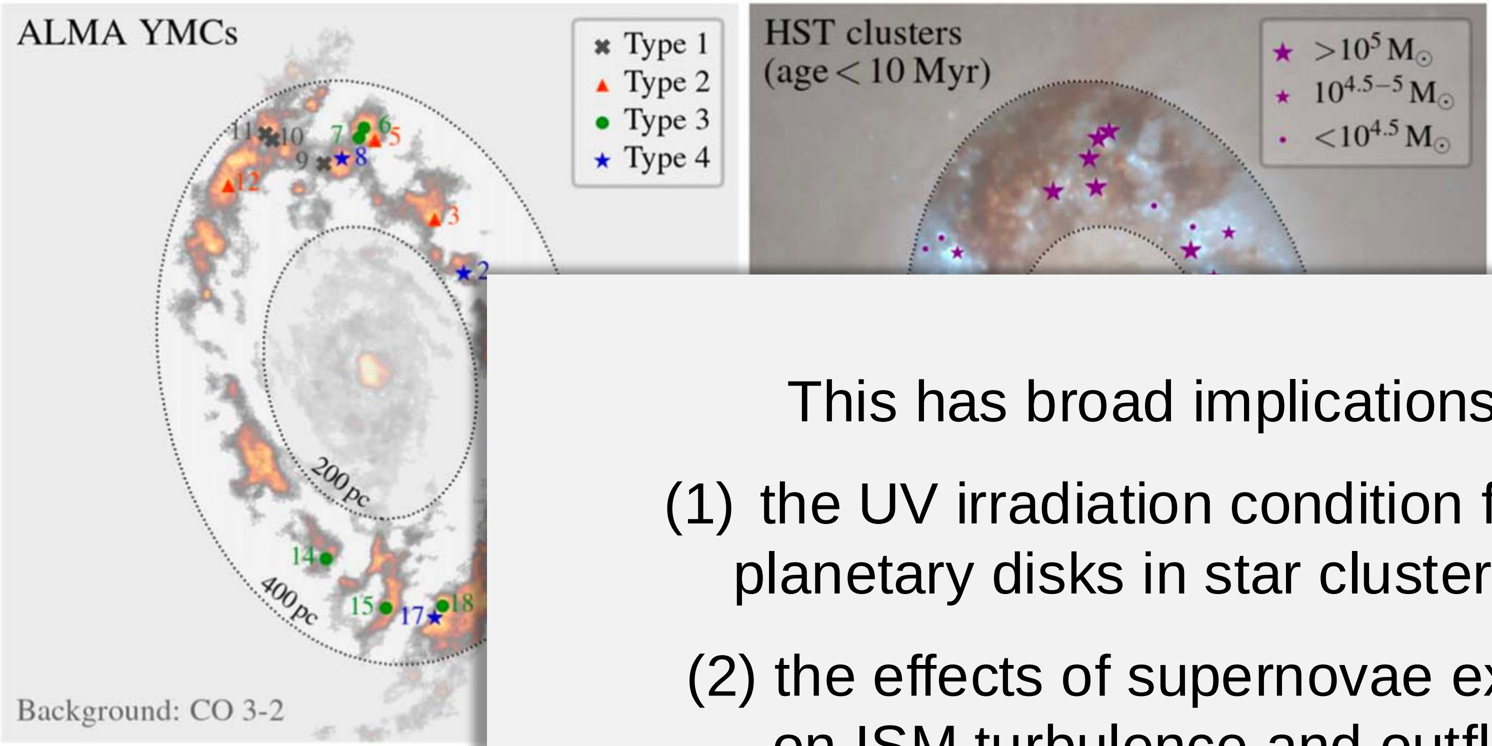
How Fast Do Star-forming Regions Evolve?

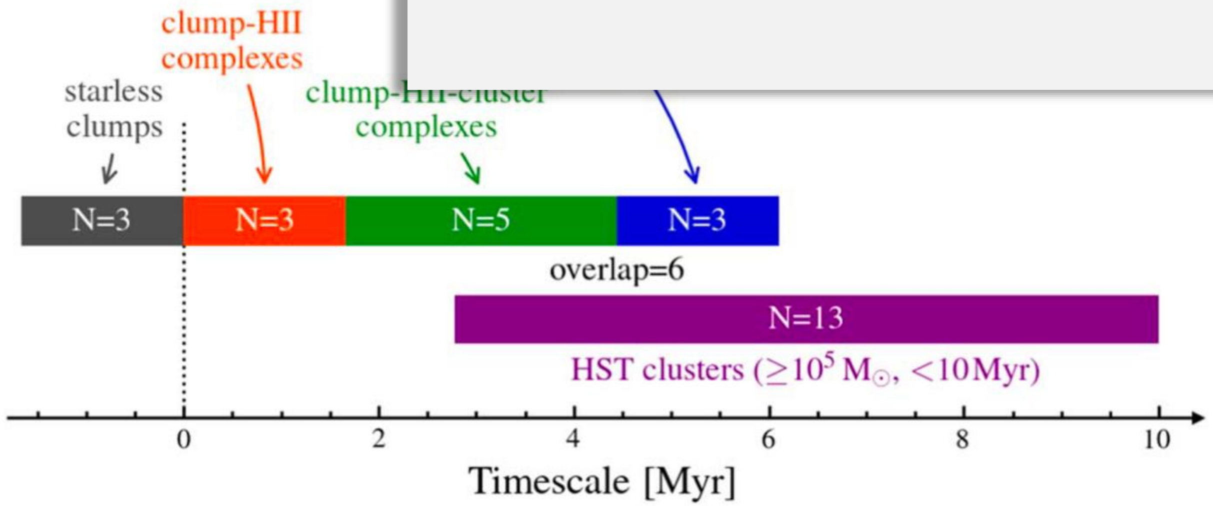


This has broad implications on:

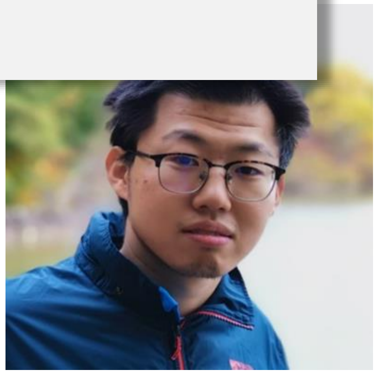
(1) the UV irradiation condition for proto-planetary disks in star clusters, and

(2) the effects of supernovae explosion on ISM turbulence and outflows.

Direct detection and matching of young star clusters with their immediate progenitors offer t evidence for **rapid** **nd cluster-gas** **timescales**.



rad students involved



J. Sun, H. He, K. Batschkun, et al. (2024)

How Efficient Do These Star-forming Regions Form Stars?

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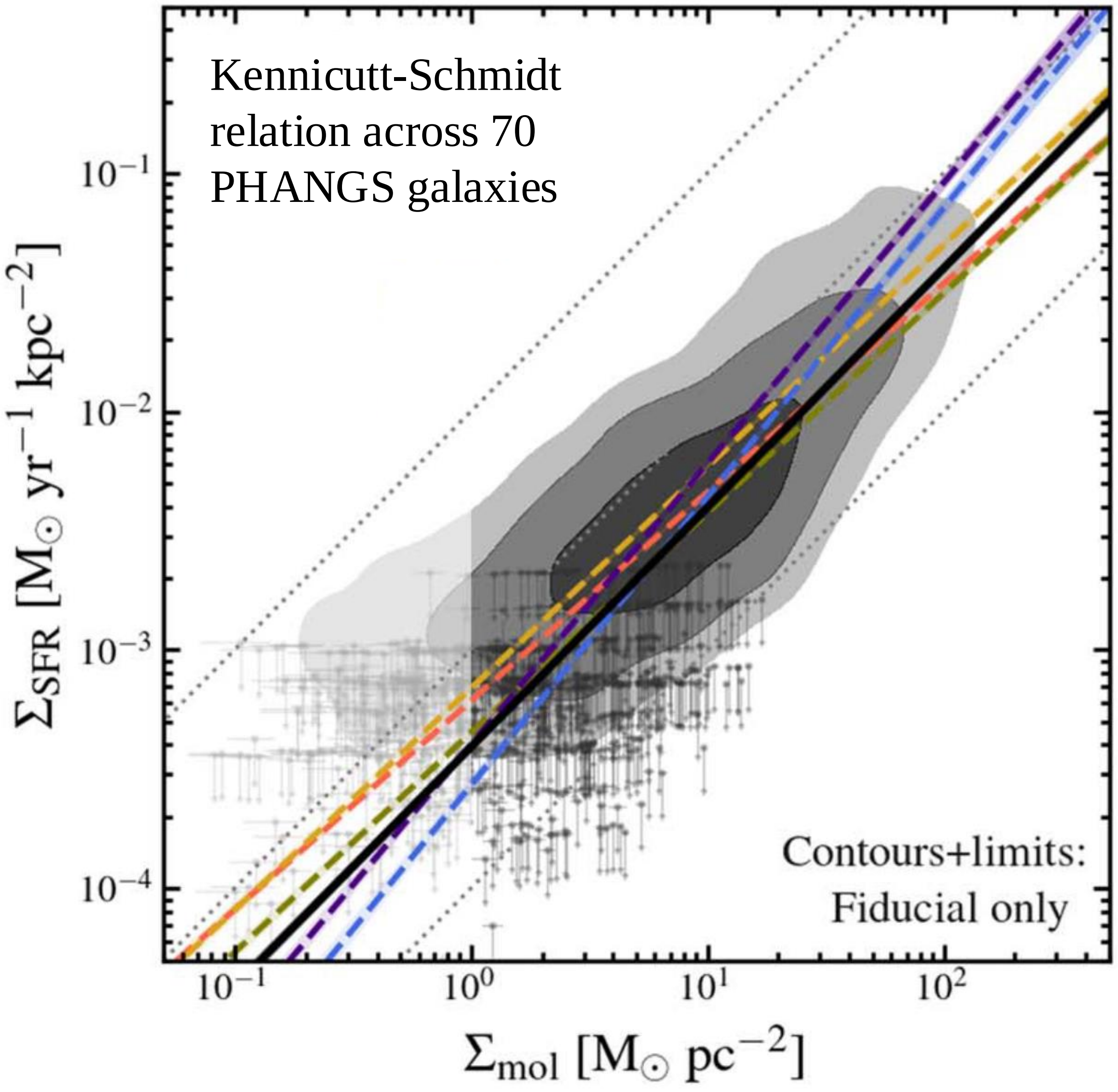
This is sometimes quantified by the **gas depletion time**, with *short depletion time* equated to *high efficiency of star formation*.

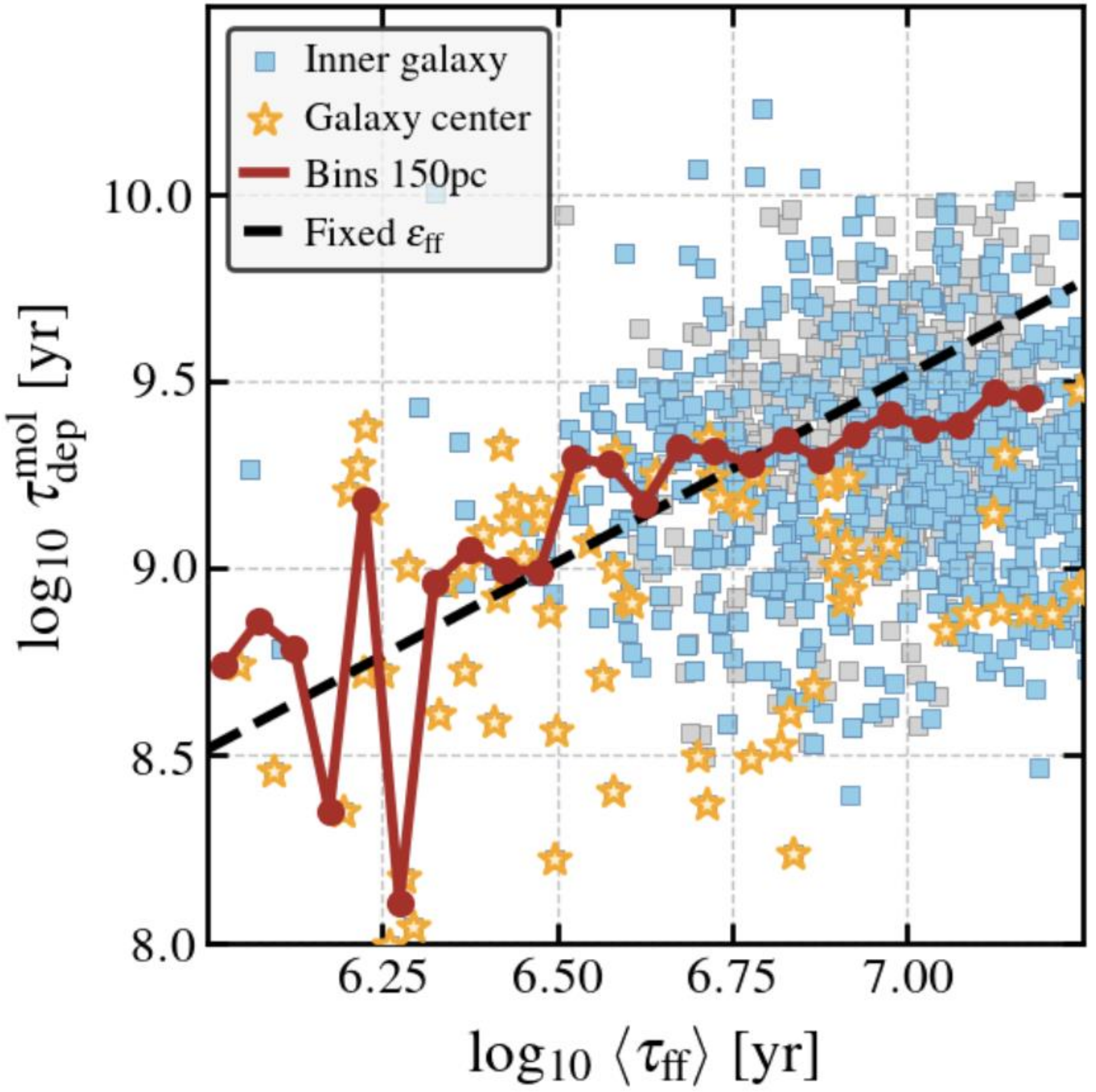


***J. Sun**+ (2023); also see Kennicutt & de los Reyes (2021)*

How Efficient Do These Star-forming Regions Form Stars?

This is sometimes quantified by the **gas depletion time**, with *short depletion time* equated to *high efficiency of star formation*.

But a more physical parameterization is the **dimensionless efficiency per free-fall time**. We find regions with shorter depletion time tend to host clouds with shorter free-fall time, which means *the efficiency per free-fall time is roughly constant, ~0.4%.*



*Leroy, **JS**+ (2024, in prep); also see Utomo, **JS**+ (2018); **J. Sun**+ (2023)*

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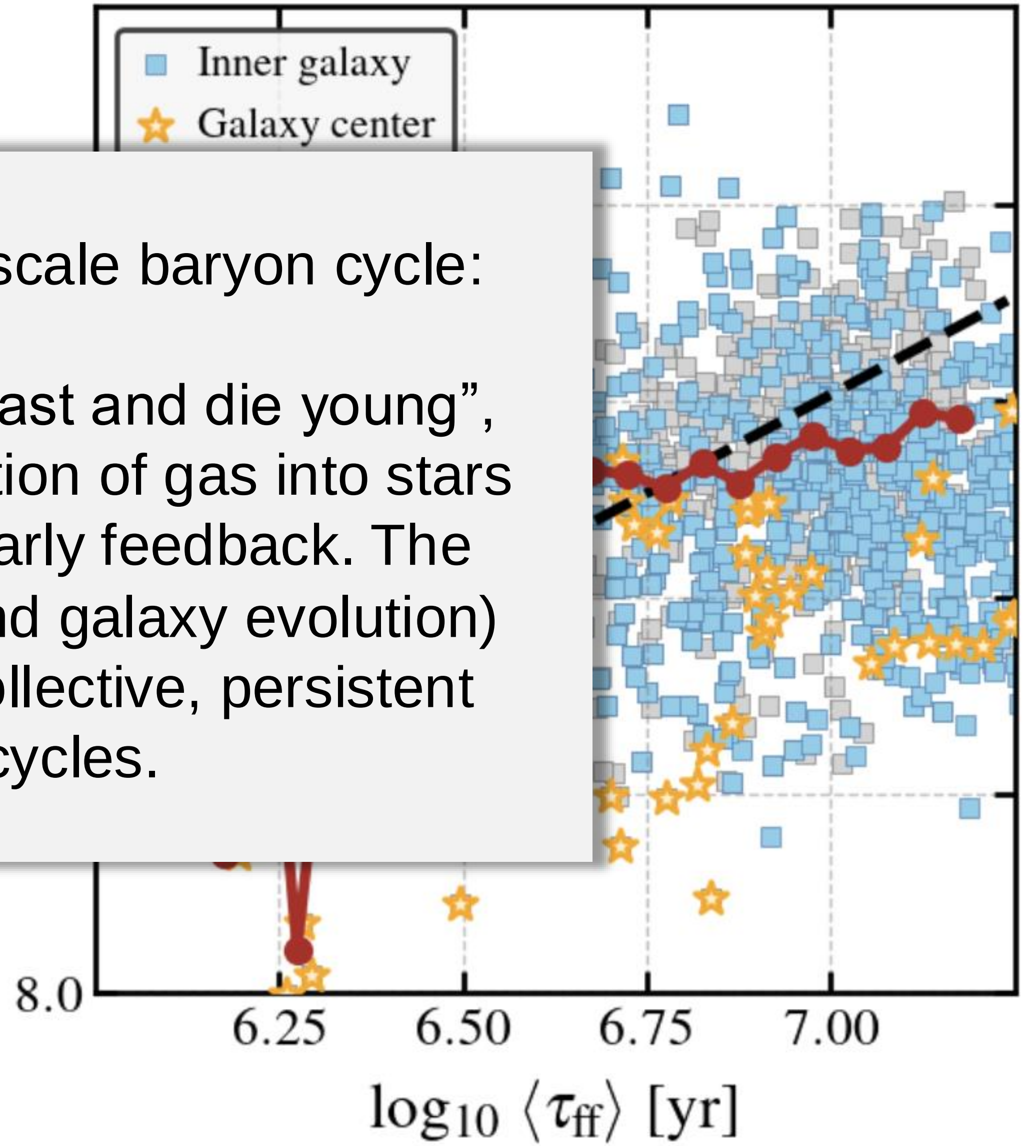
The emerging picture of cloud-scale baryon cycle:

Most star-forming regions "live fast and die young", only able to convert a small fraction of gas into stars before they are dispersed by early feedback. The build-up of stellar population (and galaxy evolution) is realized only through their collective, persistent efforts over many cycles.



*Leroy, **JS**+ (2024, in prep); also see Utomo, **JS**+ (2018); **J. Sun**+ (2023)*

How Do These New Knowledge Help Us Understand Galaxy Evolution?

The MAUVE* Project (*MUSE and ALMA Unveiling the Virgo Environment)

A **VLT/MUSE Large Program** *(PIs: Catinella & Cortese)* and a **400h+ ALMA program** *(PI: **J. Sun**, 12m + ACA)* targeting 40 disk galaxies in the Virgo cluster

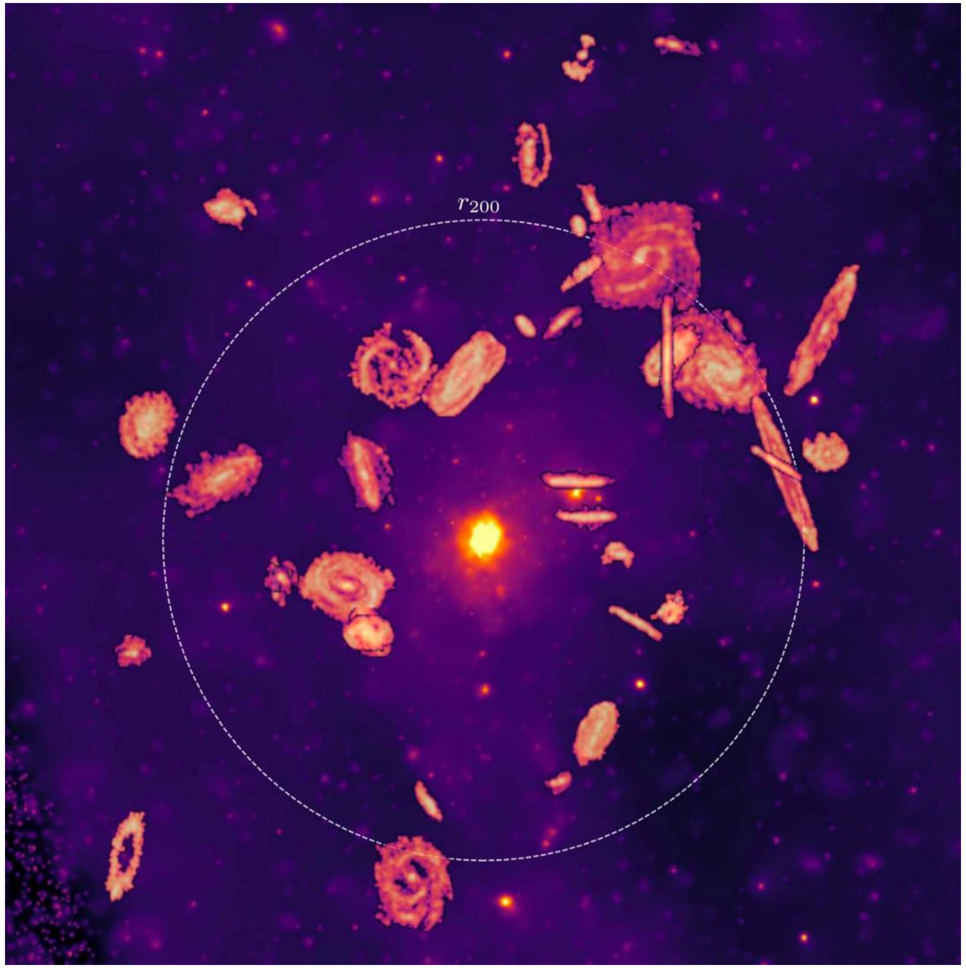


Image credit: Brown+ (2021)

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- ✓ Samples galaxies across *all infall stage* and experiencing *various environmental processes*
- ➢ Pinpoints when and how fast galaxies lose their gas and become quenched over the course of their infall
- ➢ Reveals variations in the cloud populations and if they become more/less efficient in forming stars
- ➢ Constraints multi-phase gas outflows and how much they influence the gas budget

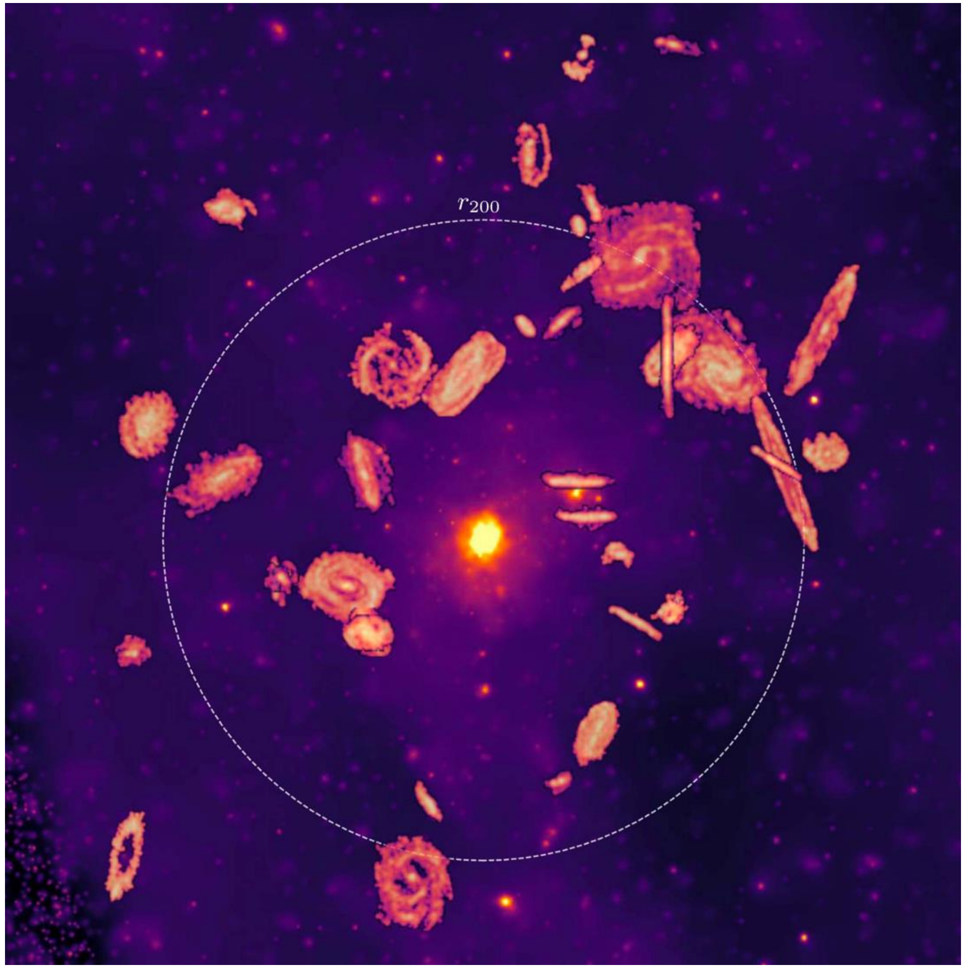
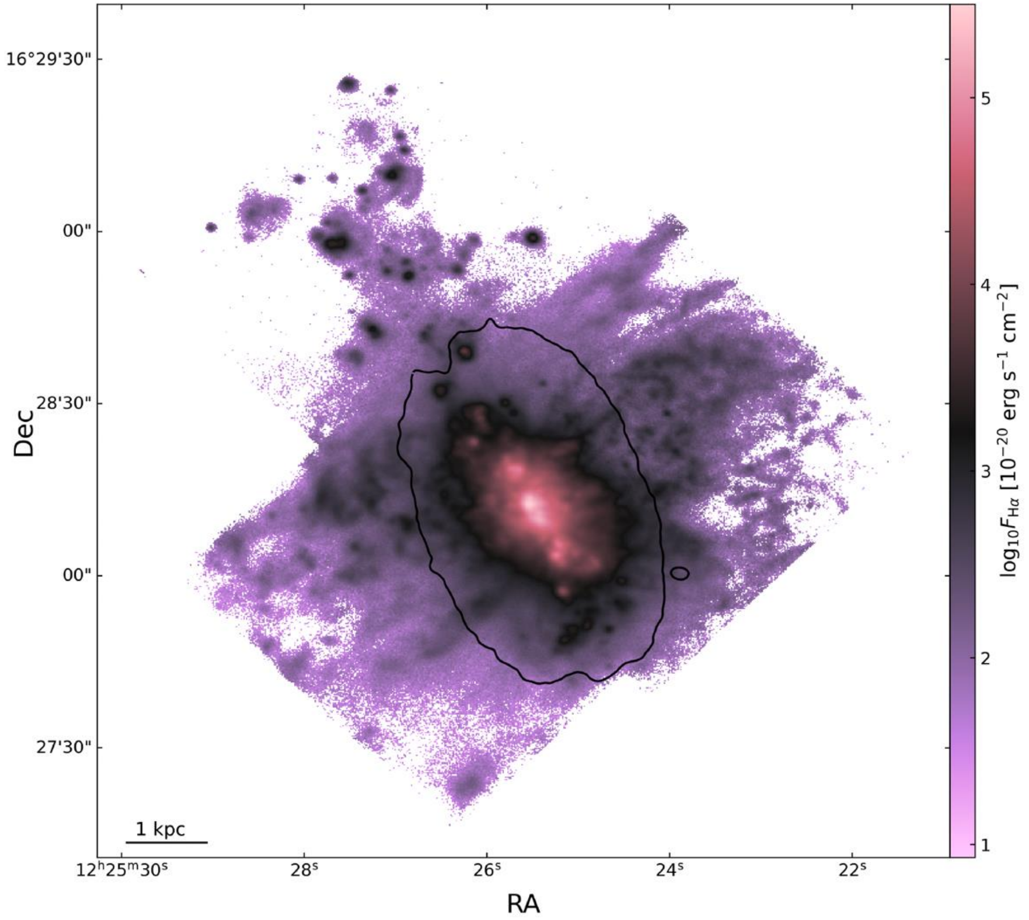


Image credit: Brown+ (2021)

First MUSE and ALMA Observations Already Give Surprises

Kpc-scale ionized gas outflows in a recent infaller

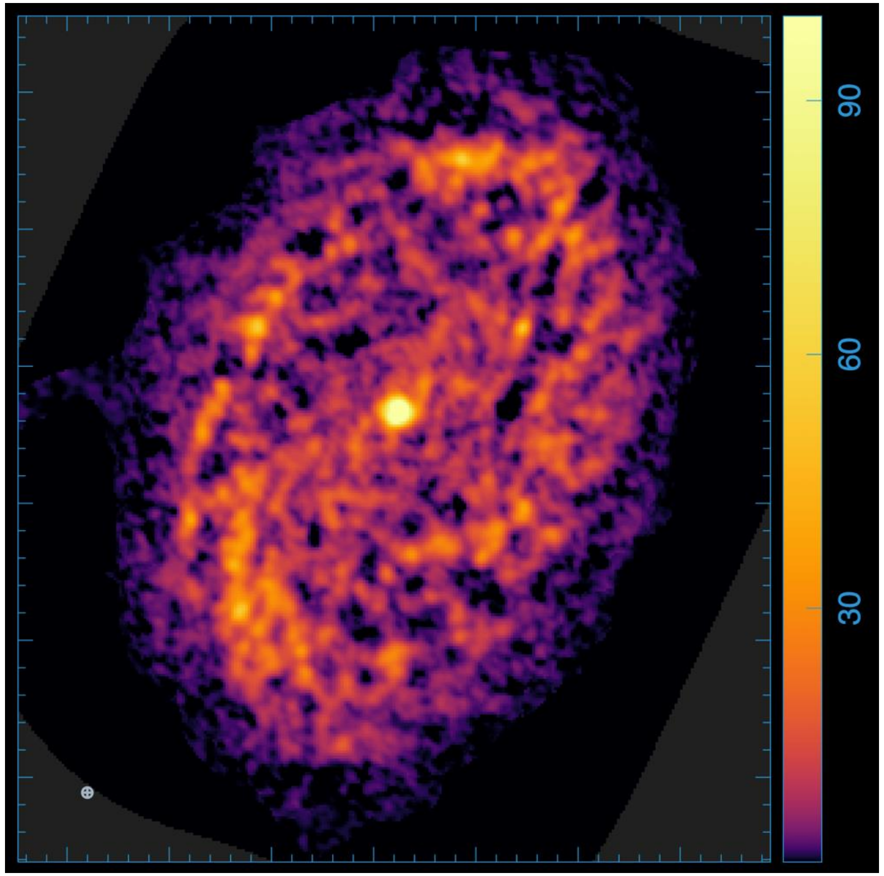
NGC 4383 – MUSE Hα



Watts+ (2024, 1st MAUVE-MUSE paper)

Abundance diffuse gas in a truncated disk

NGC 4580 – ALMA CO



***J. Sun**+ (in prep, MAUVE-ALMA survey paper)*

Take Home Messages

I hope you agree with me that:

- The baryon cycle on cloud scales is fundamentally relevant to many sub-fields of astronomy

With the PHANGS team, we have learnt that:

- The units of the small-scale baryon cycle are environment-aware, short-lived, and inefficient in forming stars per dynamical time

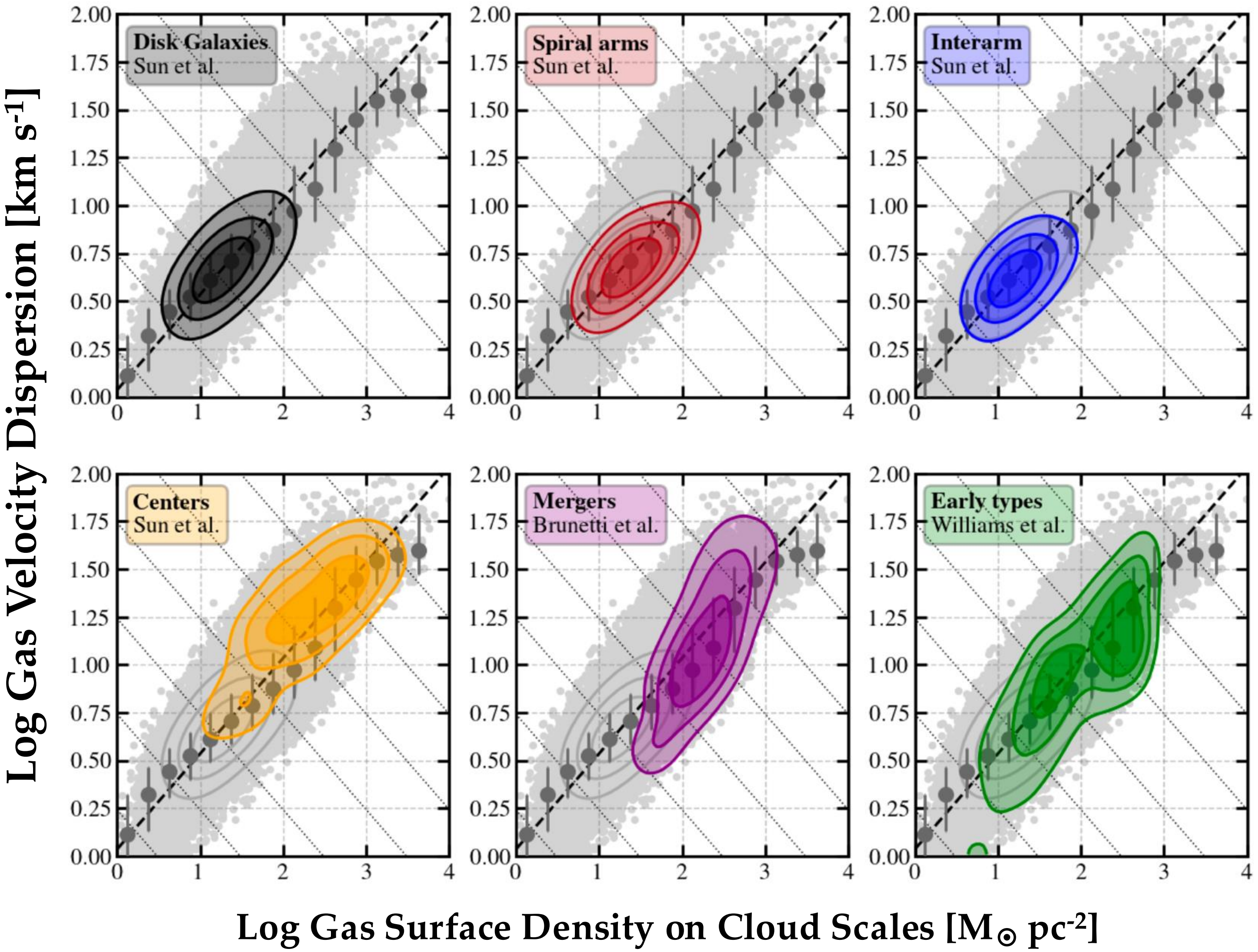
With the MAUVE team, we will show how:

- The cloud-scale physics can help us understand when and how galaxies become quenched in dense cosmic environments

Do Star-Forming Regions Have Similar Properties Across Galaxies?

Molecular clouds (traced by CO line emission) tend to be denser and more turbulent towards galaxy centers and in gas-rich merger systems.

Similar trends are found for HII regions and star clusters (traced by their optical and IR emission).



J. Sun+ (2018, 2020b, 2022), Brunetti+ (2021), Williams+ (2023), Schinnerer & Leroy (2024, ARA&A)

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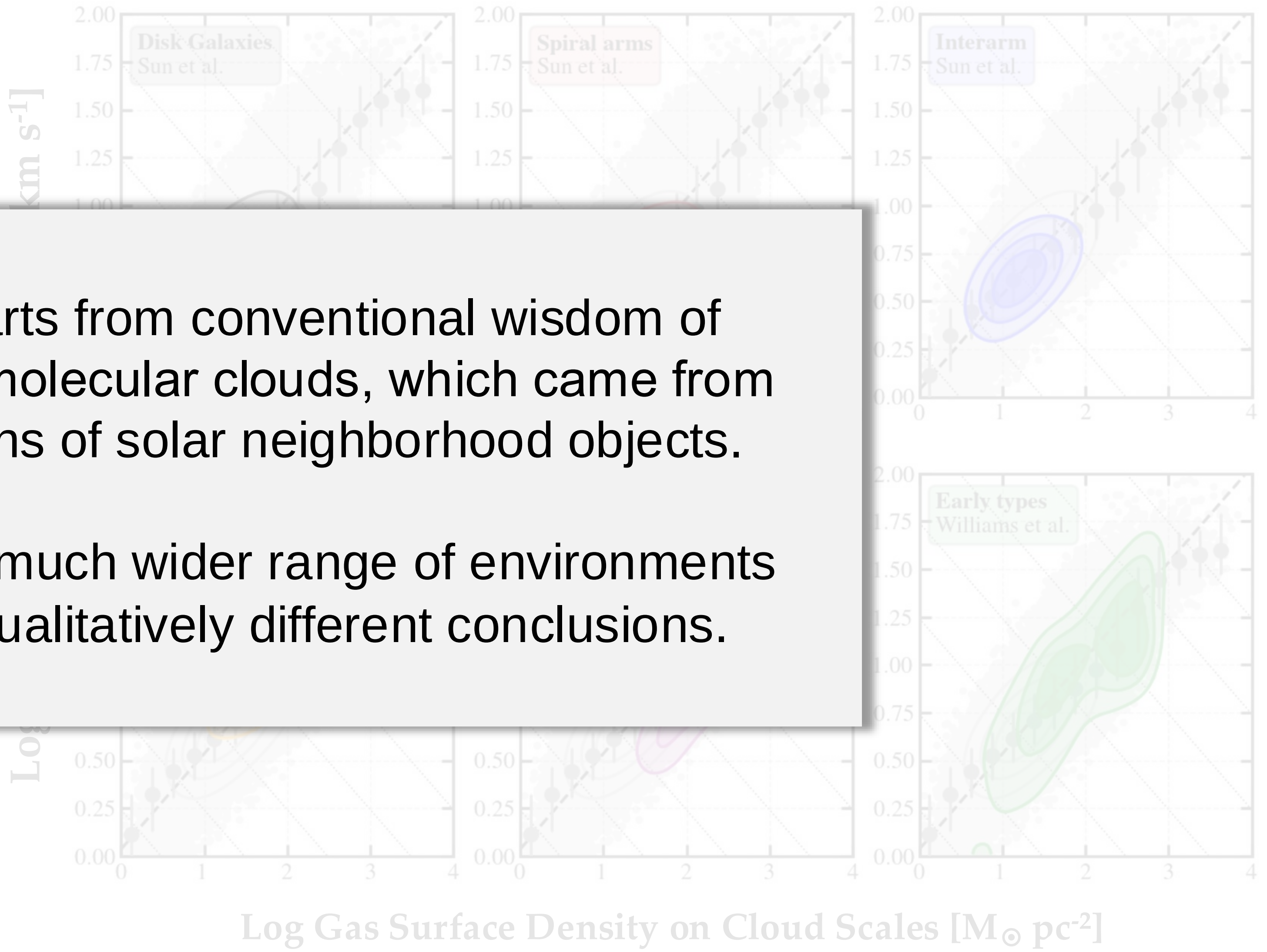


This departs from conventional wisdom of "universal" molecular clouds, which came from observations of solar neighborhood objects.

Sampling a much wider range of environments leads to qualitatively different conclusions.

J. Sun+ (2018, 2020b, 2022), Brunetti+ (2021), Williams+ (2023), Schinnerer & Leroy (2024, ARA&A)

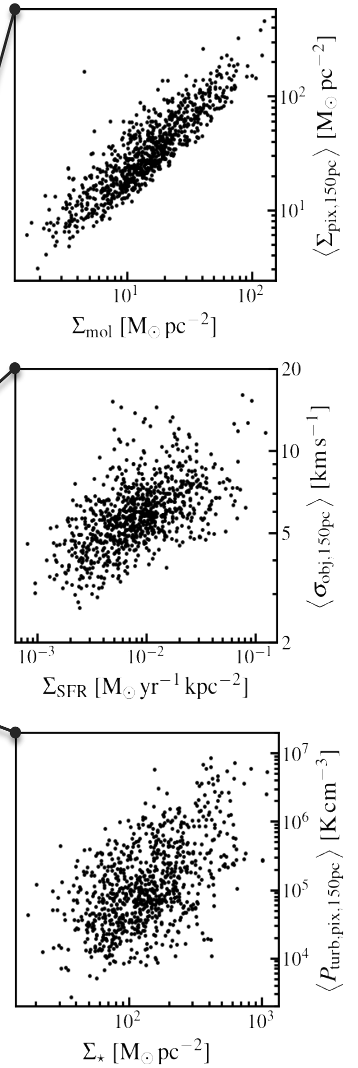
Units of Baryon Cycle are Strongly Environment-Dependent

Wide-spread correlations between the average properties of molecular cloud populations (y-axis) vs host galaxies (x-axis) over **thousands of kpc-scale sub-galactic region**

The fundamental units of baryon cycle <u>behave differently</u> depending on where they are in a galaxy and what kind of galaxy it is

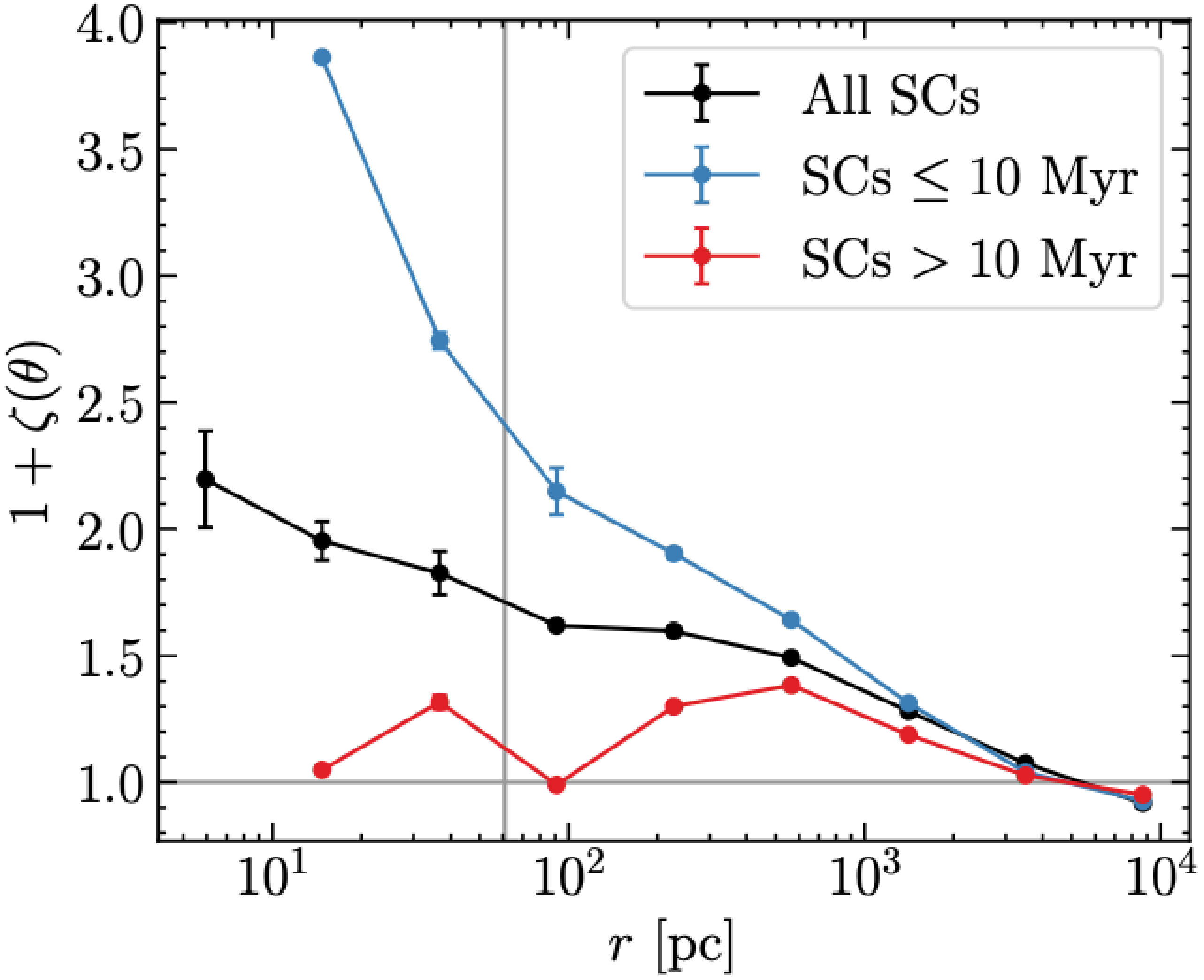
Properties of Host Galaxies

Properties of Cloud Populations	local environmental metrics							global galaxy properties				
	r_{gal}	Σ_{mol}	Σ_{atom}	$\Sigma_\star$	Σ_{SFR}	Ω_{circ}	A_{Oort}	r_{disk}	M_{mol}	M_{atom}	$M_\star$	SFR
$\langle M_{obj,\,150pc}\rangle$	-0.10	0.78	0.30	0.42	0.62	0.18	0.13	-0.01	0.33	0.03	0.19	0.24
$\langle R_{obj,\,150pc}\rangle$	0.02	-0.25	-0.15	-0.06	-0.29	-0.07	-0.14	0.04	-0.19	-0.07	0.04	-0.06
$\langle \Sigma_{obj,\,150pc}\rangle$	-0.11	0.87	0.35	0.42	0.76	0.22	0.24	-0.05	0.42	0.07	0.13	0.26
$\langle \Sigma_{pix,\,150pc}\rangle$	-0.16	0.92	0.32	0.46	0.81	0.26	0.27	-0.02	0.46	0.09	0.16	0.32
$\langle \sigma_{obj,\,150pc}\rangle$	-0.23	0.57	0.16	0.36	0.57	0.39	0.40	0.06	0.29	0.14	0.15	0.29
$\langle \sigma_{pix,\,150pc}\rangle$	-0.25	0.79	0.20	0.52	0.74	0.38	0.37	0.09	0.40	0.12	0.21	0.34
$\langle P_{turb,\,obj,\,150pc}\rangle$	-0.19	0.84	0.31	0.48	0.77	0.33	0.33	0.02	0.40	0.12	0.17	0.31
$\langle P_{turb,\,pix,\,150pc}\rangle$	-0.20	0.85	0.29	0.53	0.78	0.31	0.28	0.05	0.41	0.09	0.21	0.32
$\langle \alpha_{vir,\,obj,\,150pc}\rangle$	-0.17	-0.35	-0.25	-0.05	-0.21	0.24	0.26	0.12	-0.17	0.08	-0.01	-0.00
$\langle \alpha_{vir,\,pix,\,150pc}\rangle$	-0.29	-0.09	-0.29	0.10	0.01	0.38	0.39	0.15	-0.06	0.16	0.01	0.07



J. Sun+ (2018, 2020b, 2022), Rosolowsky+ (incl. JS, 2021)

We Get Similar Answers from Cloud-cluster Correlation Analysis



Cross-correlation of molecular clouds in PHANGS-ALMA and star clusters in PHANGS-HST:

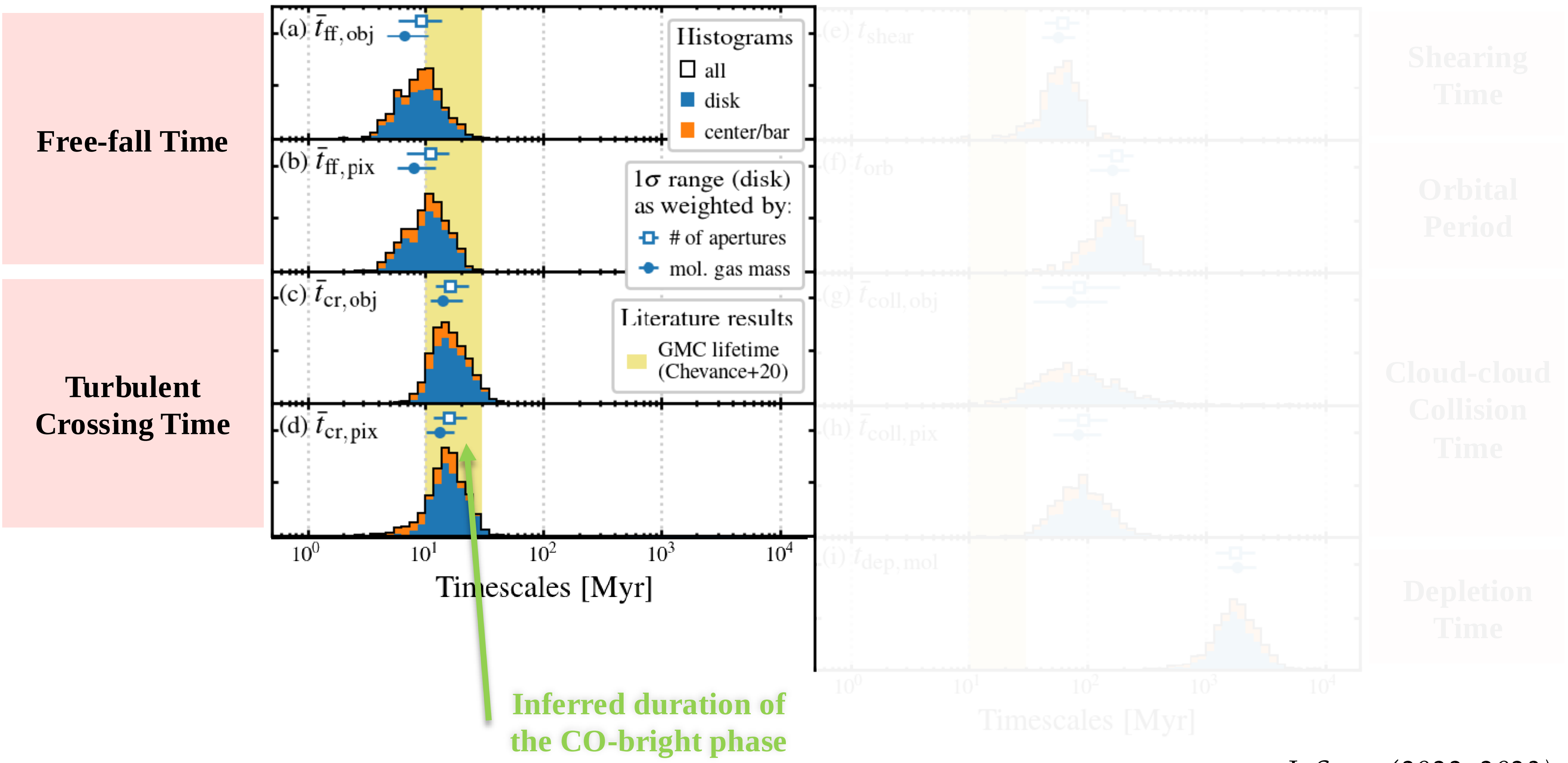
Star clusters with age < 10 Myr show clear spatial correlation with molecular clouds over ~10-100 pc scales.

This is *not* the case for older star clusters.

Turner+ (2022); also see Grasha+ (2018, 2019)

The Baryon Cycle Timeline in Contexts: Short-lived Molecular Clouds

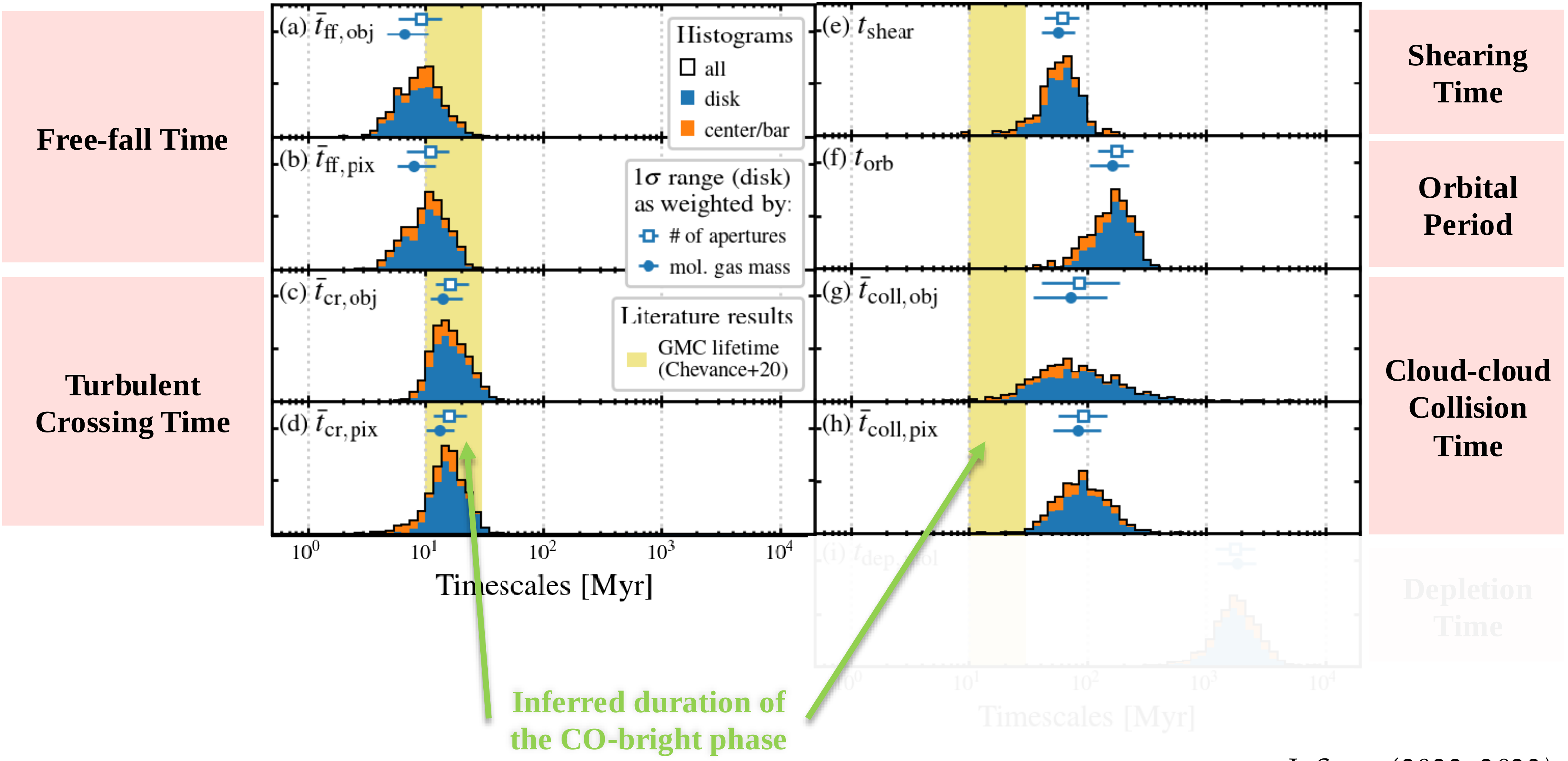
Duration of the molecular cloud phase is comparable to their free-fall time or crossing time…



J. Sun+ (2022, 2023)

The Baryon Cycle Timeline in Contexts: Rapid Cycling w.r.t. Galaxy Dynamics

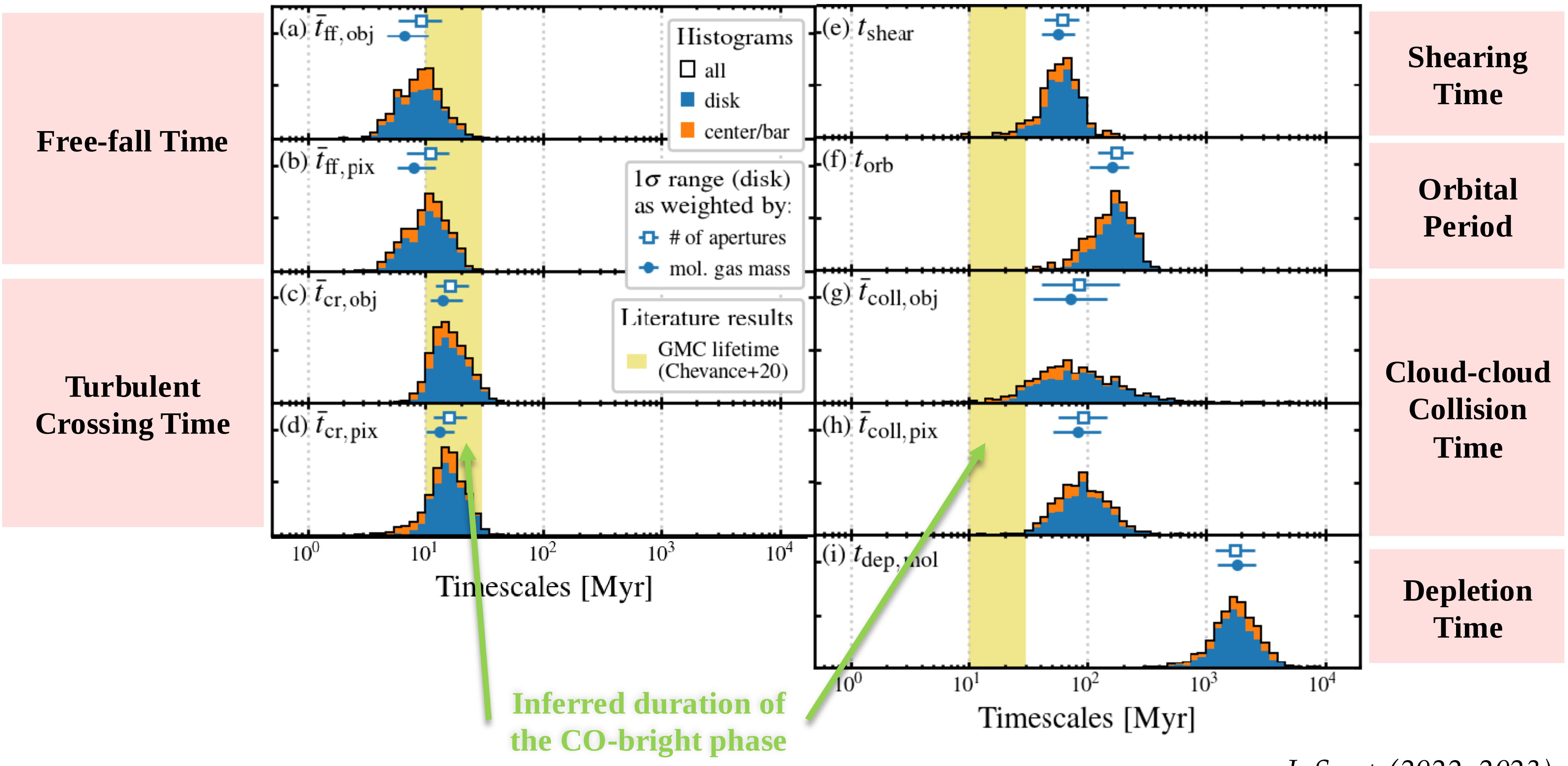
Most galactic-scale dynamical processes have slower timescales by up to an order of magnitude.



J. Sun+ (2022, 2023)

The Baryon Cycle Timeline in Contexts: Very Low "Yield" (i.e. Star Formation)

The time it takes to deplete all gas by star formation is the longest, on the order of Gigayears.



J. Sun+ (2022, 2023)

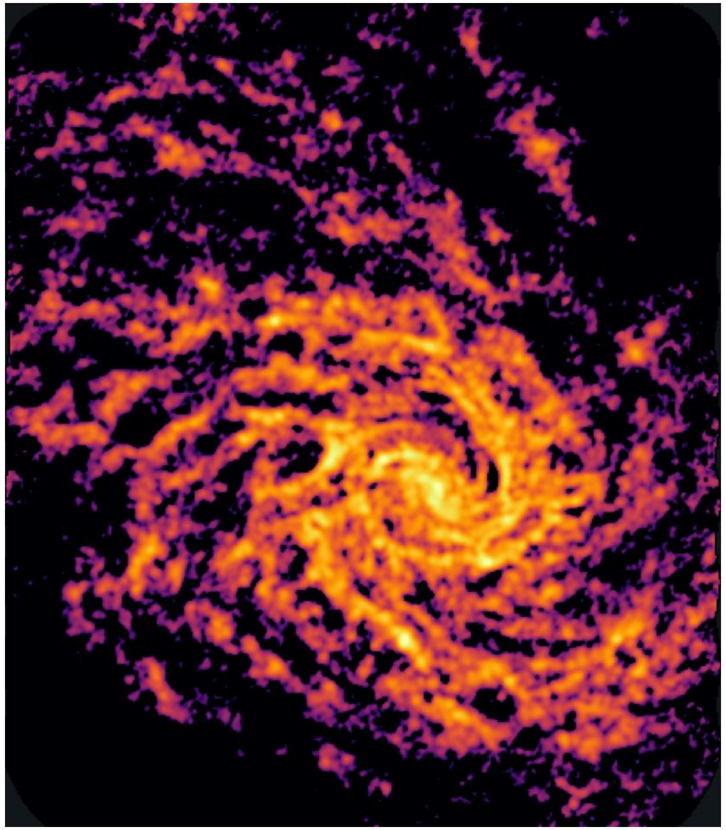
New ALMA Observations Are Coming As We Speak!

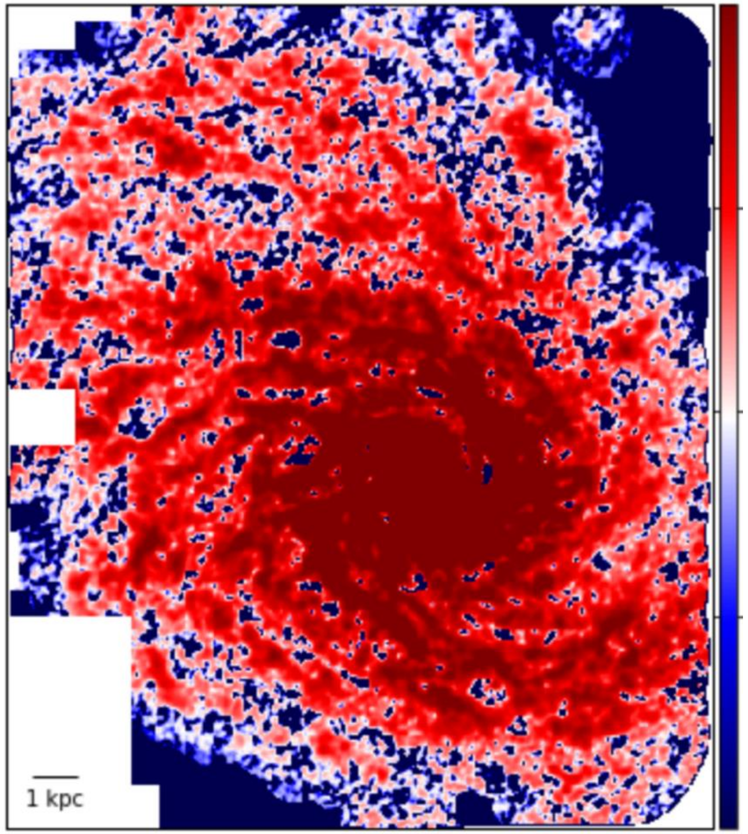
ALMA CO data will probe the density structures and kinematics of the cold molecular gas, which:

- can provide reliable kinematics to separate gas in disk vs outflow and constrain outflow strengths
- can be combined with MUSE data to probe the baryon cycle timescale and star formation efficiency
- is critical for modeling the gas “sinks” of such system, especially ram pressure stripping

ALMA CO map for NGC 4254, a Virgo galaxy experiencing ram pressure stripping

J. Sun+ (2018)





Ram pressure modeling yields *resolved* maps of “strip-ability”: gas in the blue regions will likely be stripped

Celine Greis, *JS+ (in prep.)*