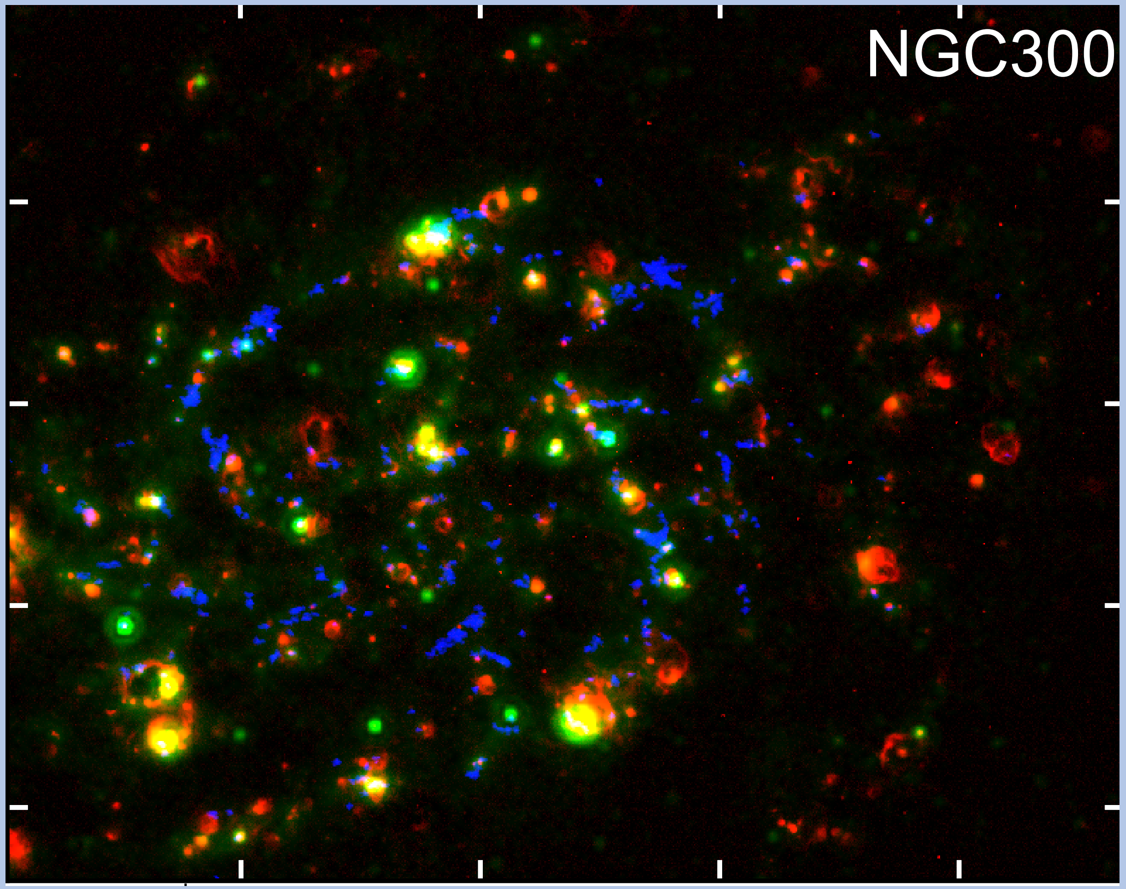
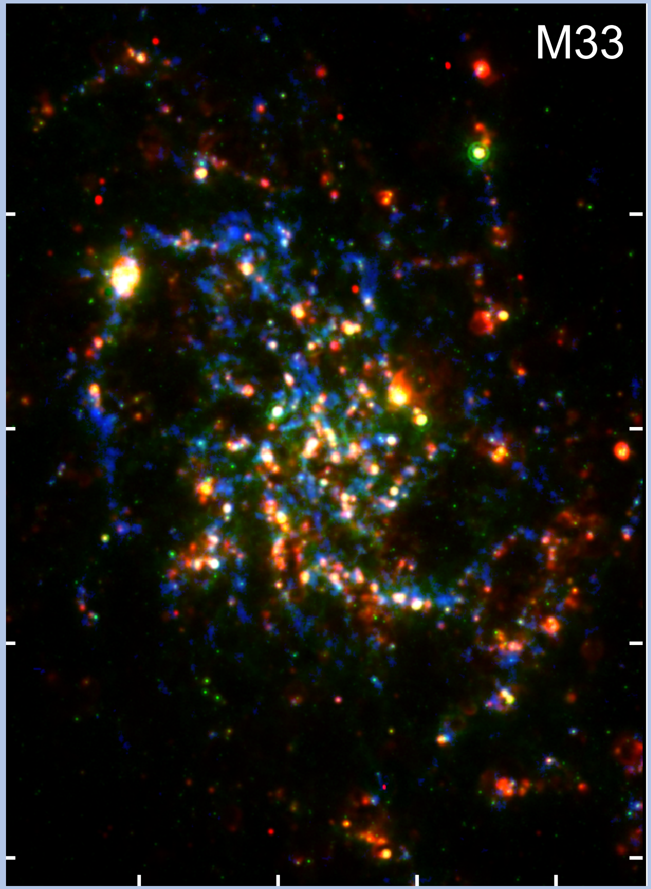
Constraining the detailed evolutionary timeline of star formation from cloud assembly to embedded stars and HII regions





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Mélanie Chevance
Diederik Kruijssen
Andreas Schruba
Jake Ward
Karin Sandstrom
And the *PHANGS* collaboration

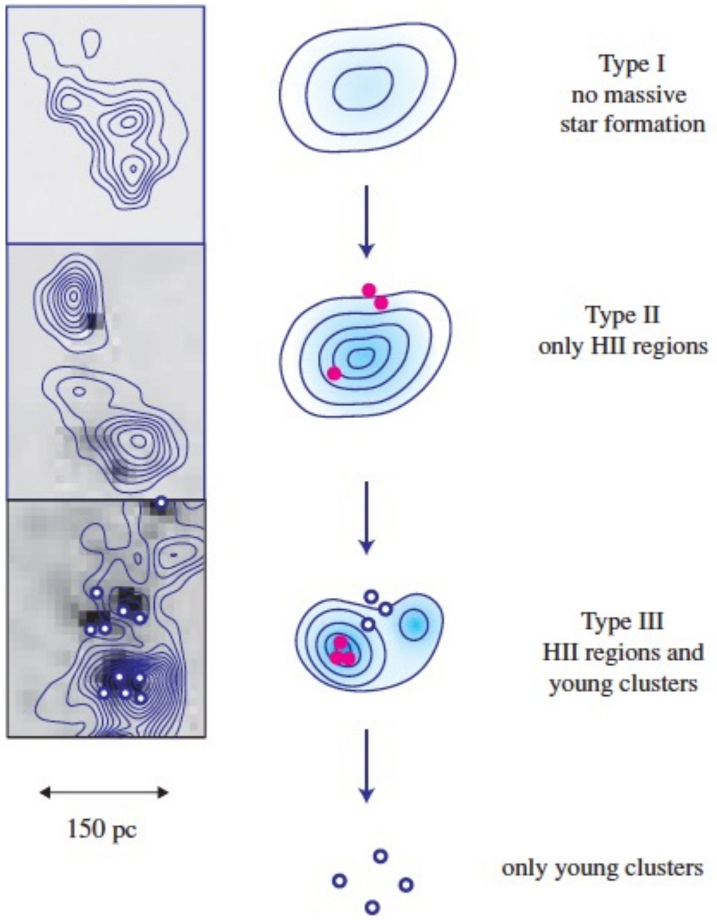
Massive star feedback

- Creates HII regions
- Alters the structure of the ISM
- Disperses molecular clouds terminating further star formation (Krumholz 2014; Dale 2015; J.-G. Kim et al. 2020)

Image credit: F. Santoro

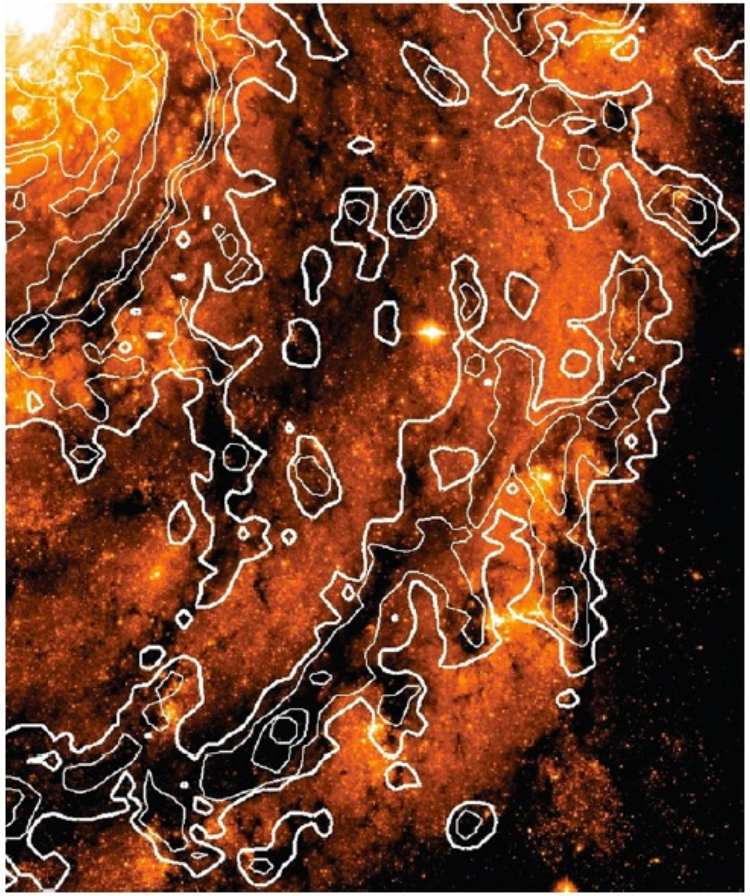
Are clouds transient objects?

Classification of cloud 'types' based on SF activity gives 10 - 20 Myr



Kawamura+09

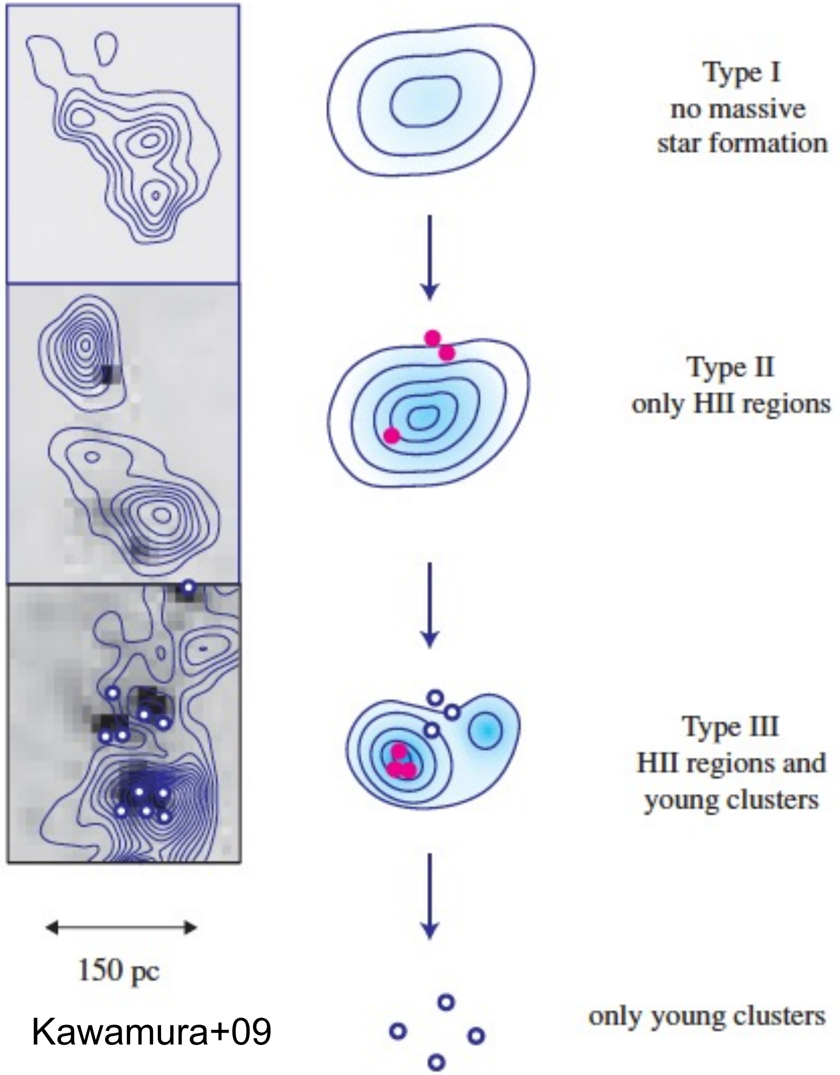
GMCs survive for a substantial fraction of galactic rotation period: 10^8 yr



Koda+2009
Scoville & Hersh 1979

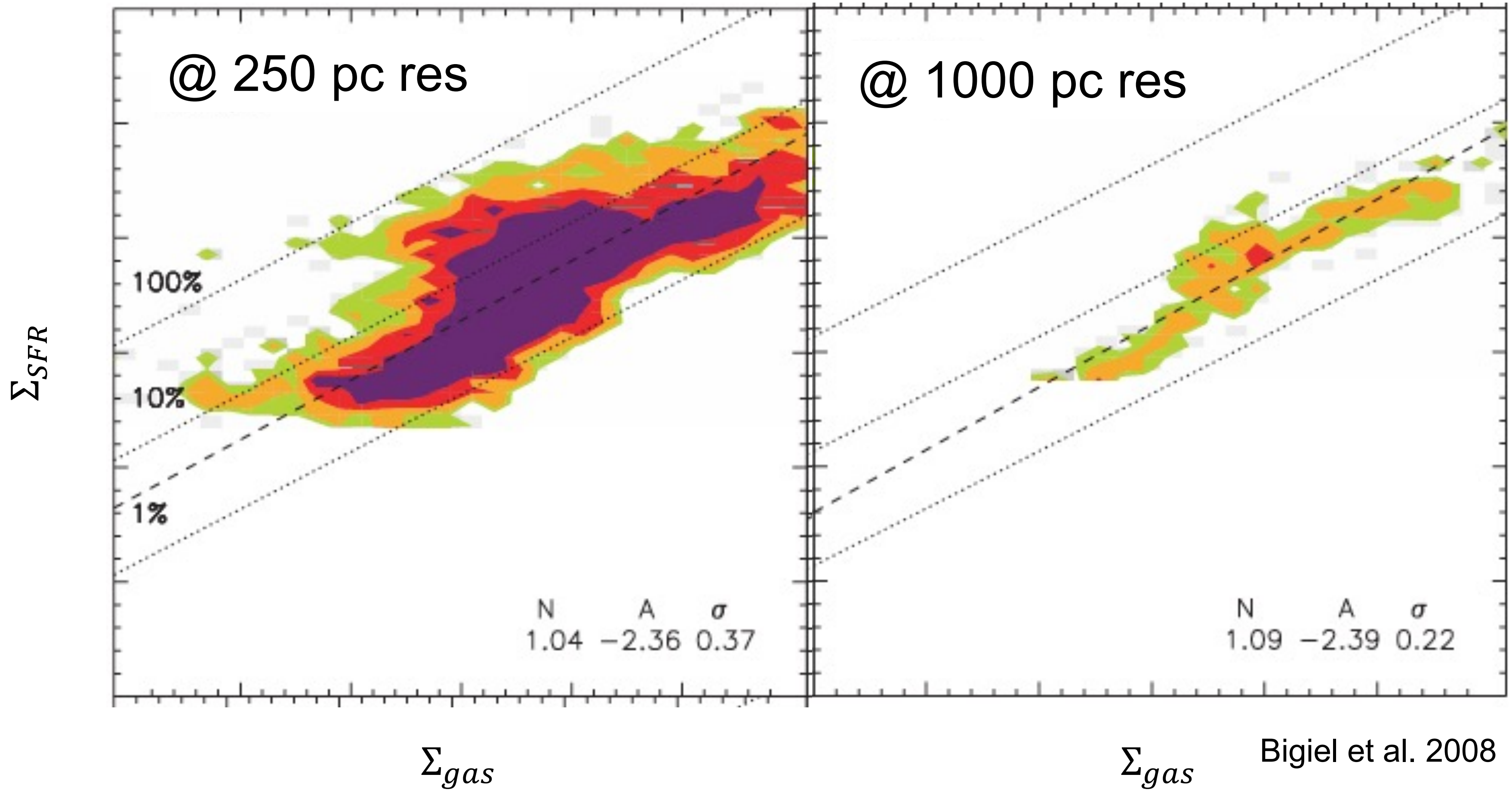
Limitations of previous methods

- Require individual star-forming regions to be resolved (10-50 pc).
- Use optical and UV as SFR tracers.
- Based on visual inspection.



Kawamura+09

Spatial decorrelation between gas and SFR at small scales

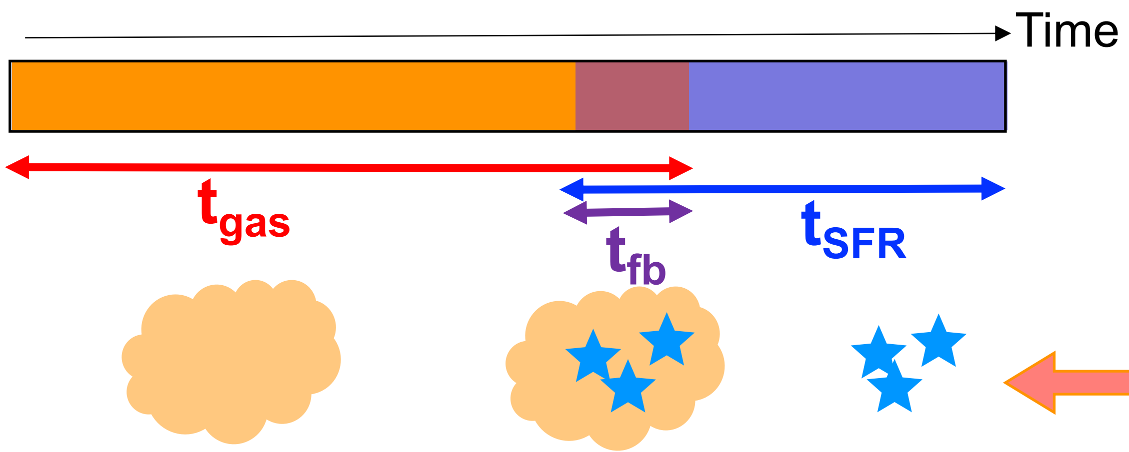


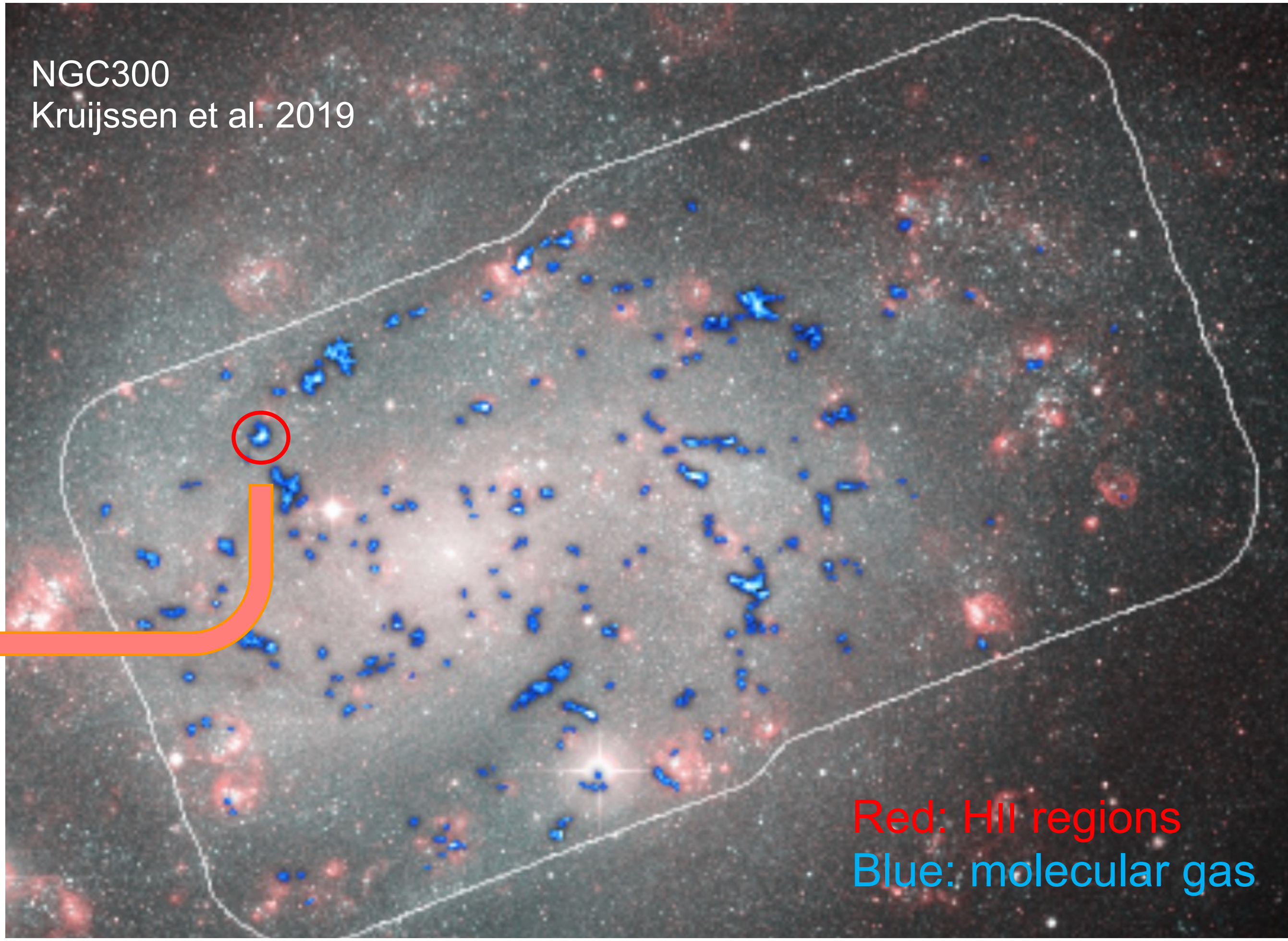
Bigiel et al. 2008

- Breakdown of SF relation at small scales (Bigiel et al. 2008; Onodera et al. 2010; Schruba et al. 2010; Leroy et al. 2013)

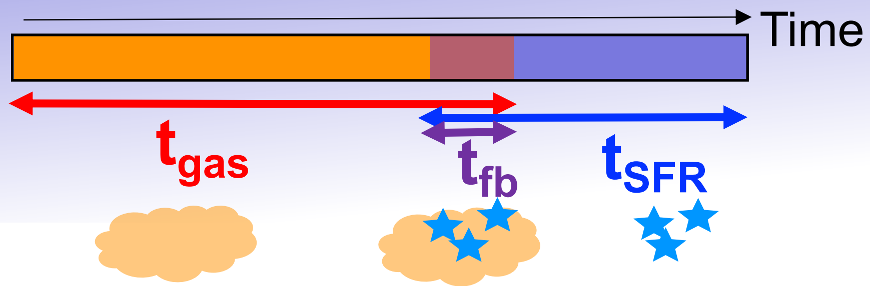
Spatial decorrelation is linked to the evolutionary cycling between gas and stars

Kruijssen & Longmore 2014
Kruijssen et al. 2018

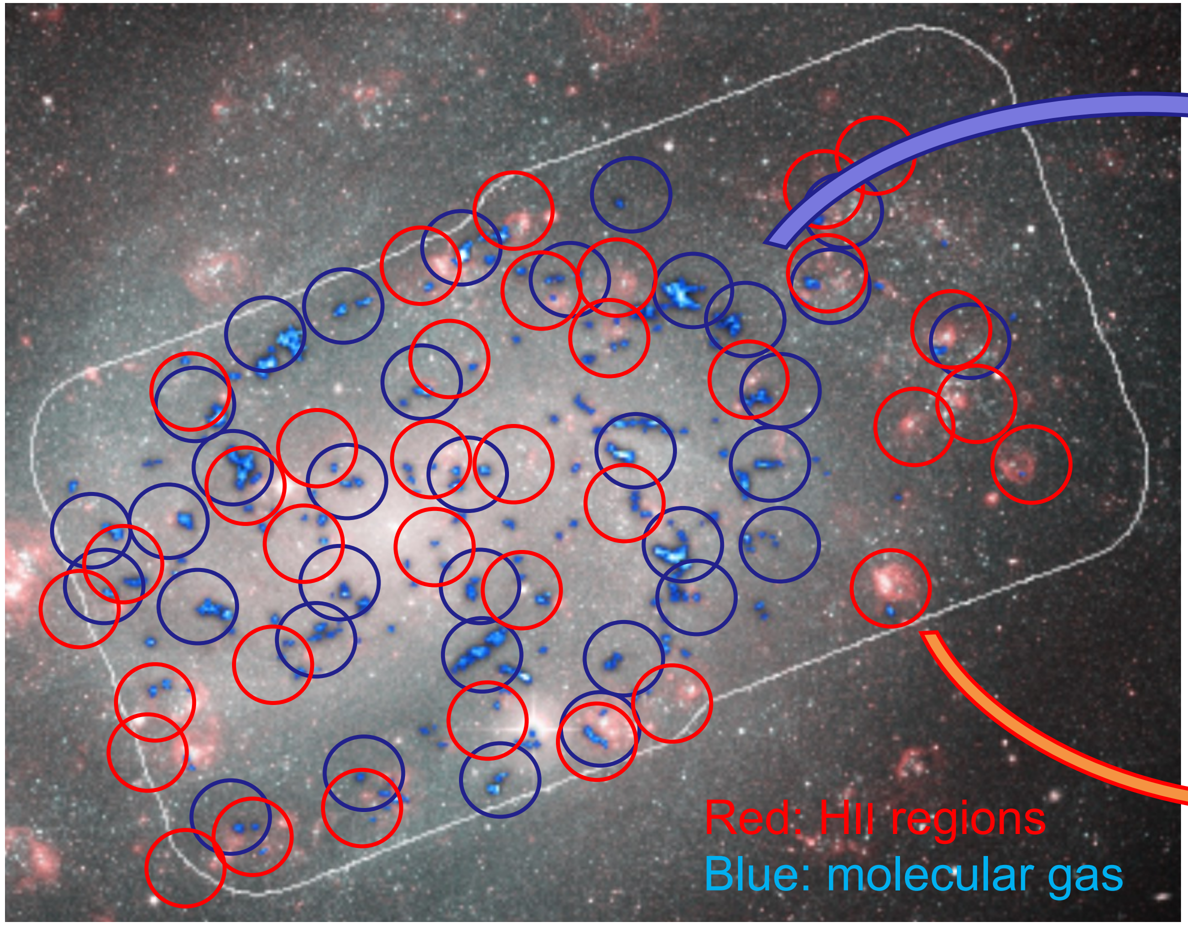


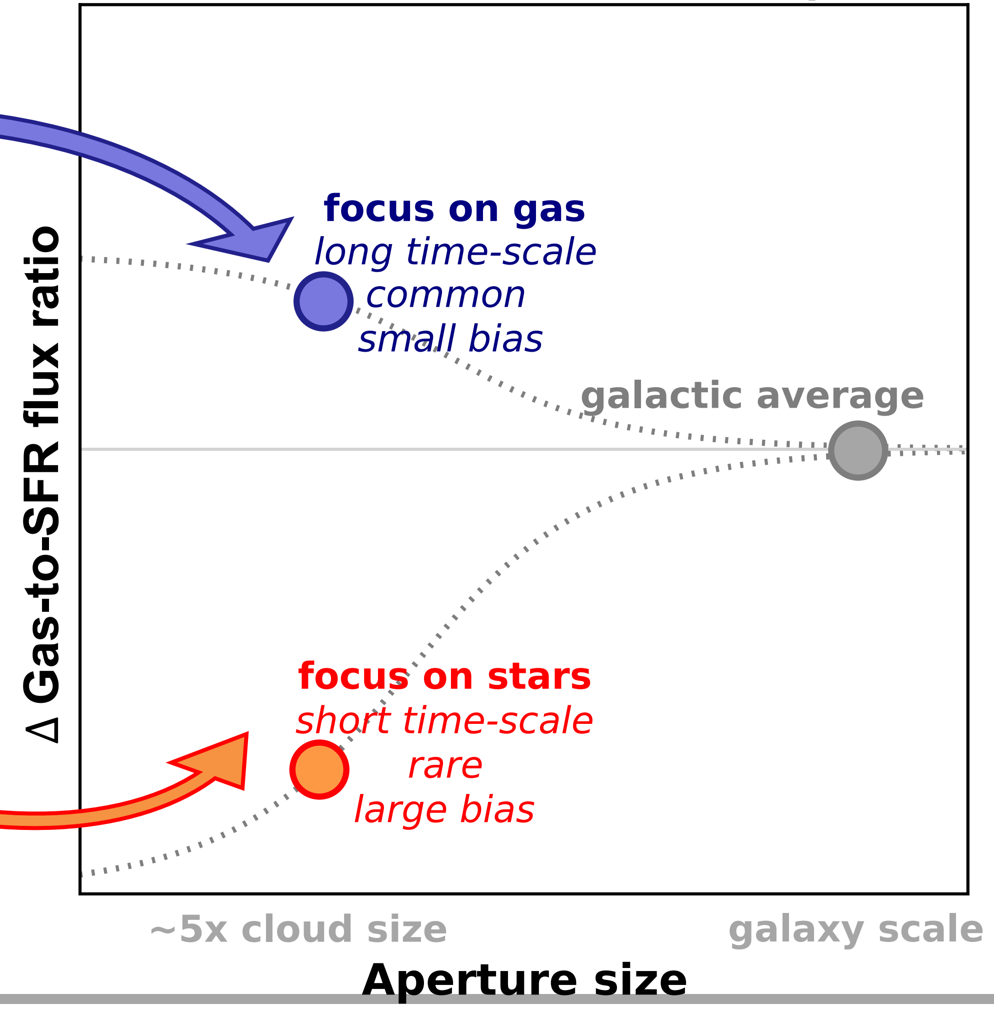


Spatial decorrelation translated into underlying timeline



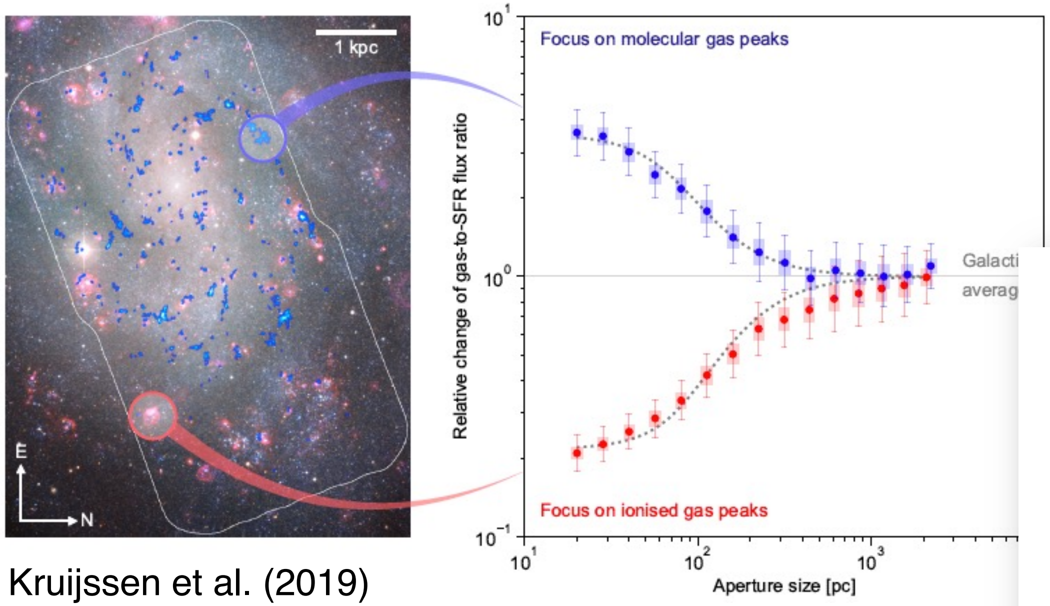
Kruijssen & Longmore 2014
Kruijssen et al. 2018



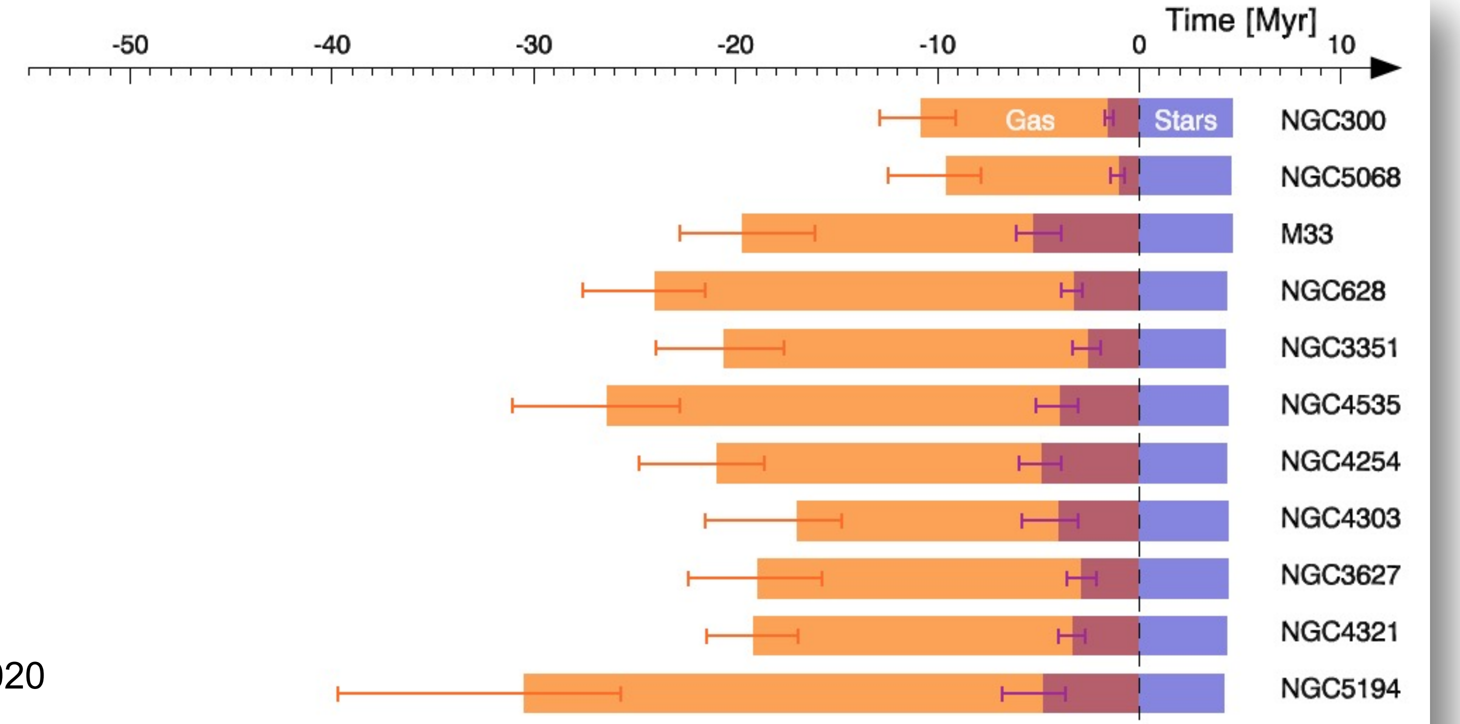


Evolutionary sequence of GMCs constrained using our method

- GMCs live for 10 - 30 Myr and are destroyed quickly within 1 - 5 Myr after Hα becomes visible
- Pre-SN feedback mainly drives feedback process.



Kruijssen et al. (2019)

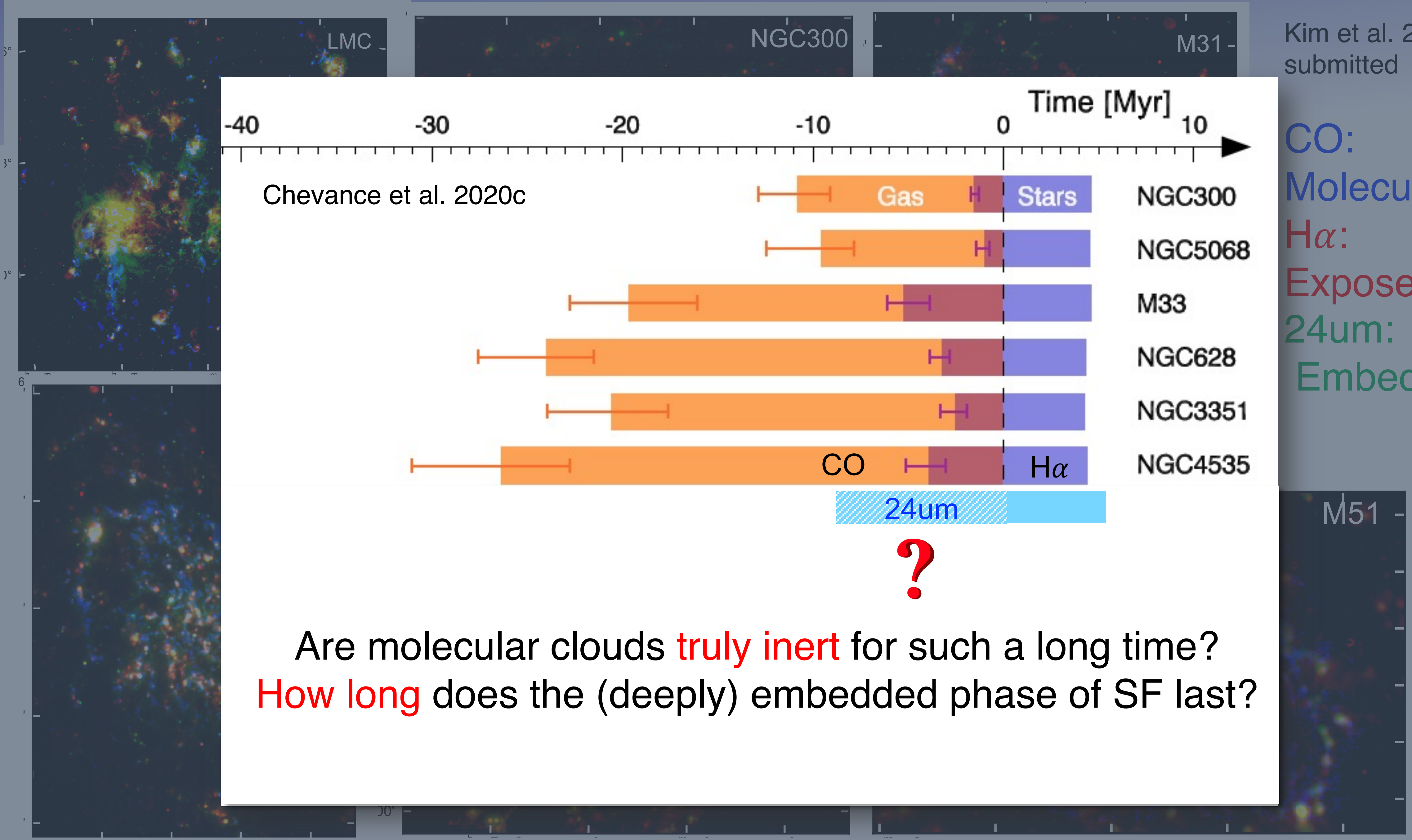


Chevance et al. 2020c

- Molecular gas tracer: CO
- Exposed SF tracer: Hα

NGC300: Kruijssen et al. 2019; M33: Hygate PhD thesis
LMC : Ward et al. 2020; nine disc galaxies: Chevance et al. 2020
Kim et al. 2021

Kim et al. 2020 submitted



CO: Molecular gas

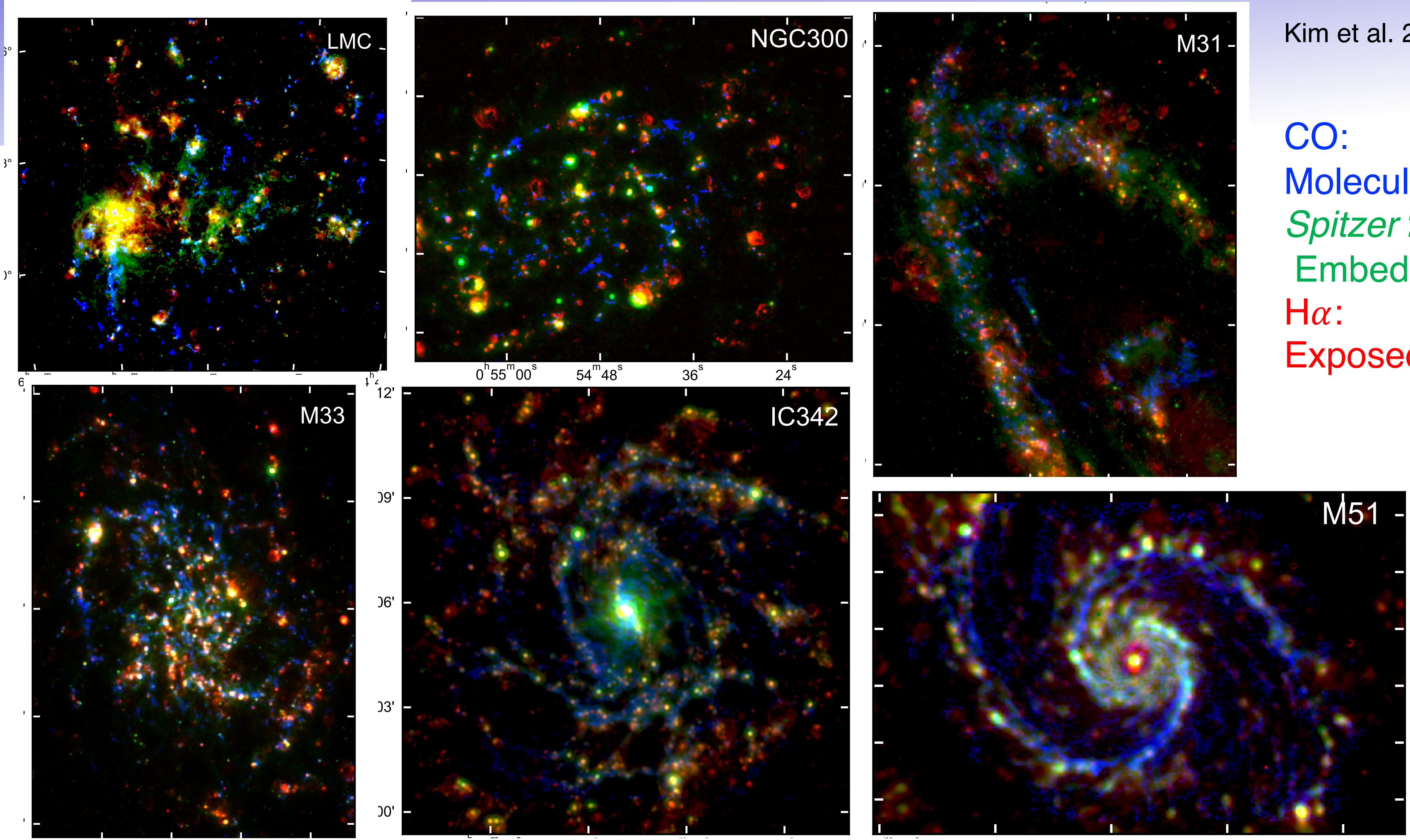
Hα: Exposed SF

24um: Embedded SF

Are molecular clouds truly inert for such a long time?

How long does the (deeply) embedded phase of SF last?

Kim et al. 2021



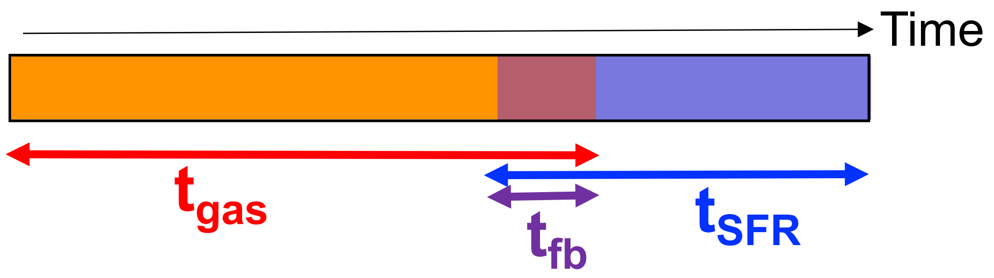
CO:
Molecular gas

Spitzer 24um:
Embedded SF

Hα:
Exposed SF

Duration of the embedded phase of SF (overlapping CO & 24um)

Galaxy	CO vs 24 μm				ϵ_{sf}
	t_{CO} [Myr]	$t_{fb,24\,\mu m}$ [Myr]	$t_{24\,\mu m}$ [Myr]	λ [pc]	[per cent]
IC 342	$20.0^{+2.0}_{-2.3}$	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$1.9^{+1.4}_{-0.8}$
LMC	$11.1^{+1.6}_{-1.7}$	$5.0^{+1.6}_{-2.0}$	$13.6^{+3.7}_{-4.8}$	73^{+38}_{-26}	$6.8^{+4.9}_{-3.0}$
M31	$14.0^{+2.1}_{-1.9}$	$2.4^{+1.4}_{-0.8}$	$4.2^{+1.5}_{-0.7}$	128^{+97}_{-23}	$0.7^{+0.2}_{-0.2}$
M33	$14.5^{+1.6}_{-1.5}$	$6.8^{+2.1}_{-2.0}$	$11.9^{+2.9}_{-2.1}$	119^{+60}_{-35}	$3.5^{+2.5}_{-1.5}$
M51	$30.7^{+8.7}_{-4.9}$	< 4.0	$3.6^{+1.2}_{-0.9}$	< 136	$3.3^{+2.9}_{-1.4}$
NGC 300	$10.8^{+2.2}_{-1.6}$	$4.9^{+1.2}_{-1.9}$	$7.9^{+1.5}_{-2.1}$	178^{+125}_{-75}	$3.3^{+2.6}_{-1.4}$



- Embedded phase of SF lasts for 2 - 7 Myr (20 - 50% of the cloud lifetime).

Kim et al. 2021

Duration of the embedded phase of SF (overlapping CO & 24um)

Galaxy	t_{CO} [Myr]	$t_{fb, 24\,\mu m}$ [Myr]	$t_{24\,\mu m}$ [Myr]	λ [pc]	ϵ_{sf} [per cent]
	CO vs 24 μm				
IC 342	$20.0^{+2.0}_{-2.3}$	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$1.9^{+1.4}_{-0.8}$
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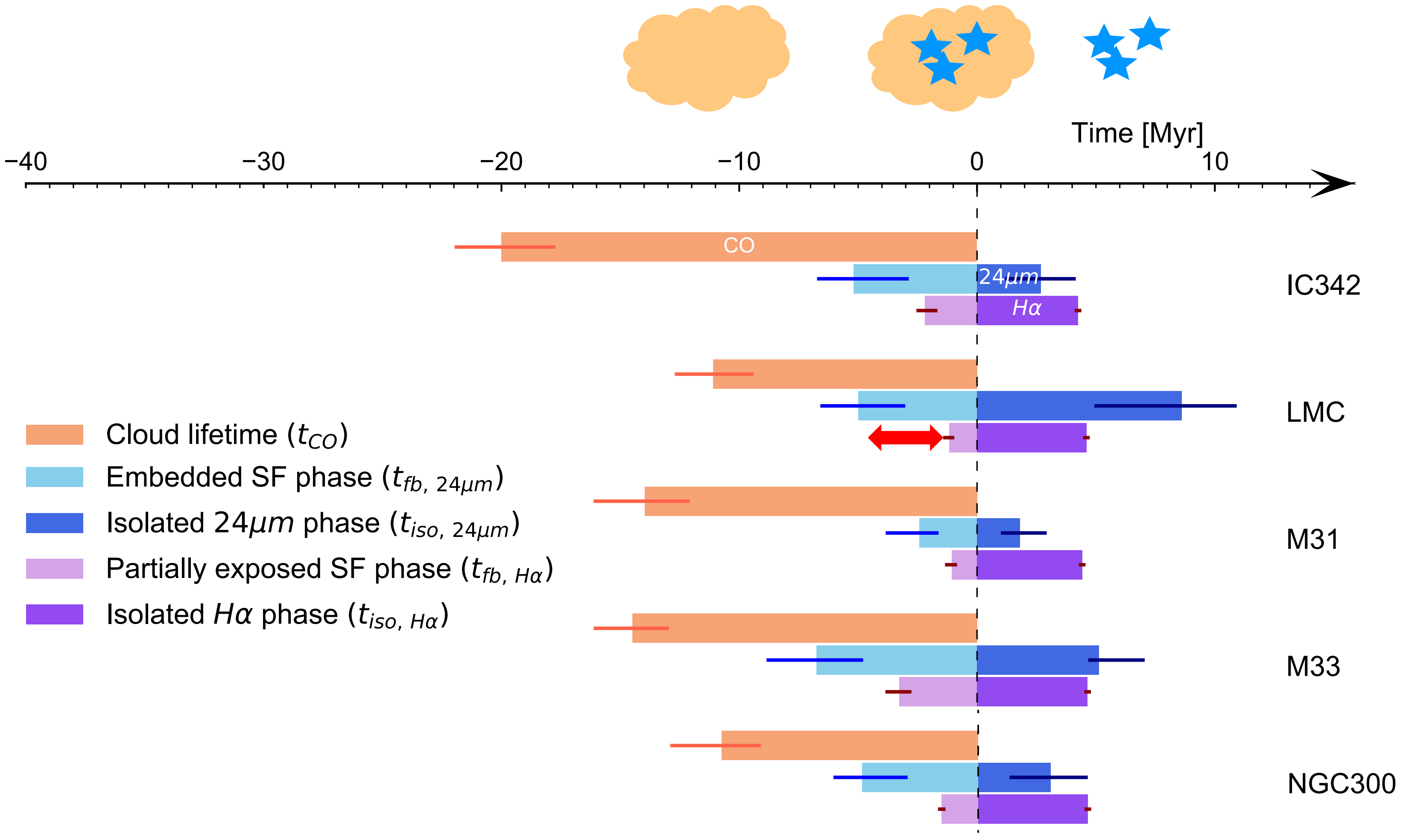
Kim et al. 2021

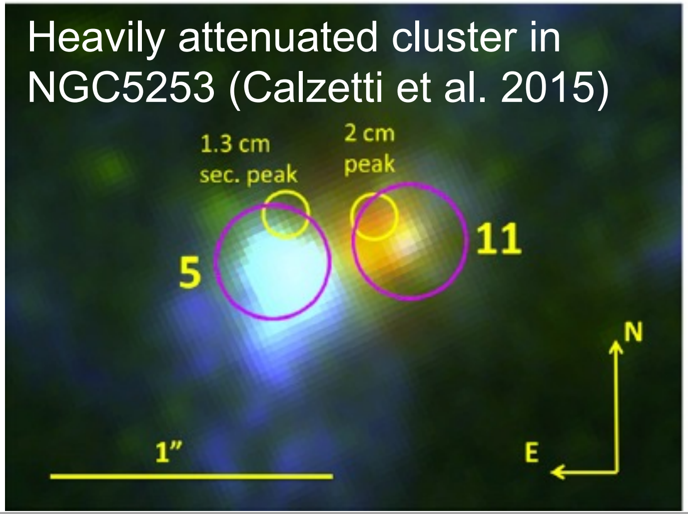
- Pre-SN feedback is mostly responsible for molecular cloud dispersal.
- Similar to age of star clusters when they stop being associated with natal GMC (Whitmore+14; Hollyhead+15; Grasha+18,19).
- For M33, similar duration of embedded phase has been measured by Corbelli et al. (2017).
- Similar to duration of SF (4 – 8 Myr) from RMHD simulation of GMC (J.-G. Kim+20).

Duration of the heavily obscured phase of SF (CO & 24um, w/o Hα)



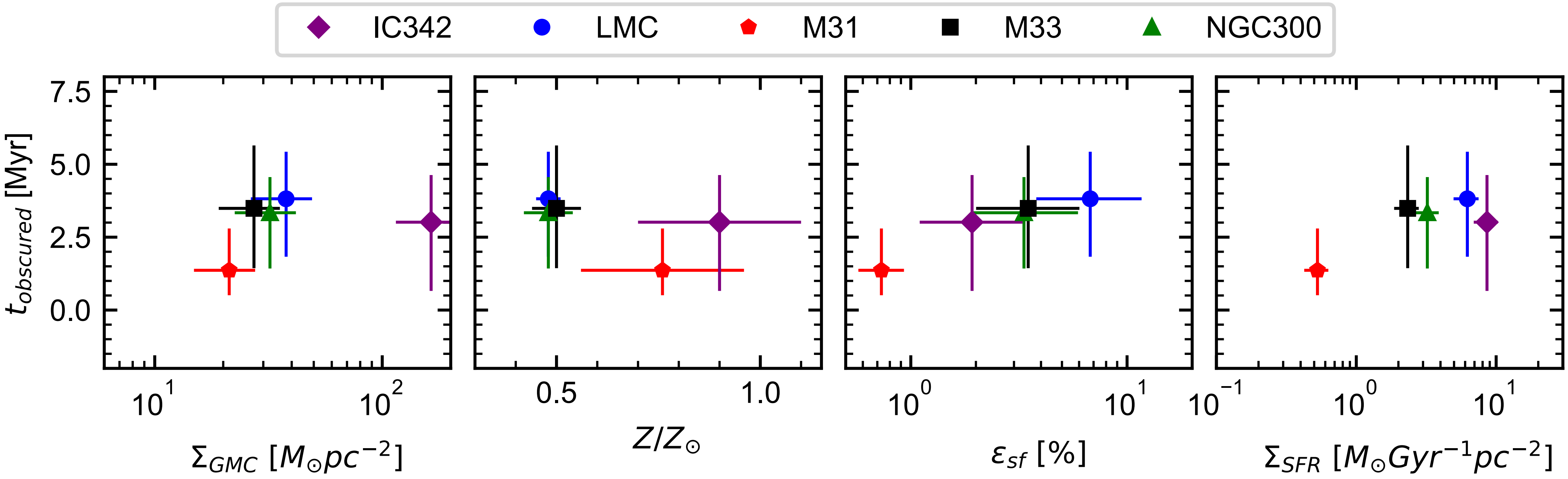
Kim et al. 2021

- 1.4-3.8 Myr
- Similar duration measured using different method (Whitmore+14; Calzetti et al. 2015; Corbelli+2017; Elmegreen & Elmegreen 2019, 2020).



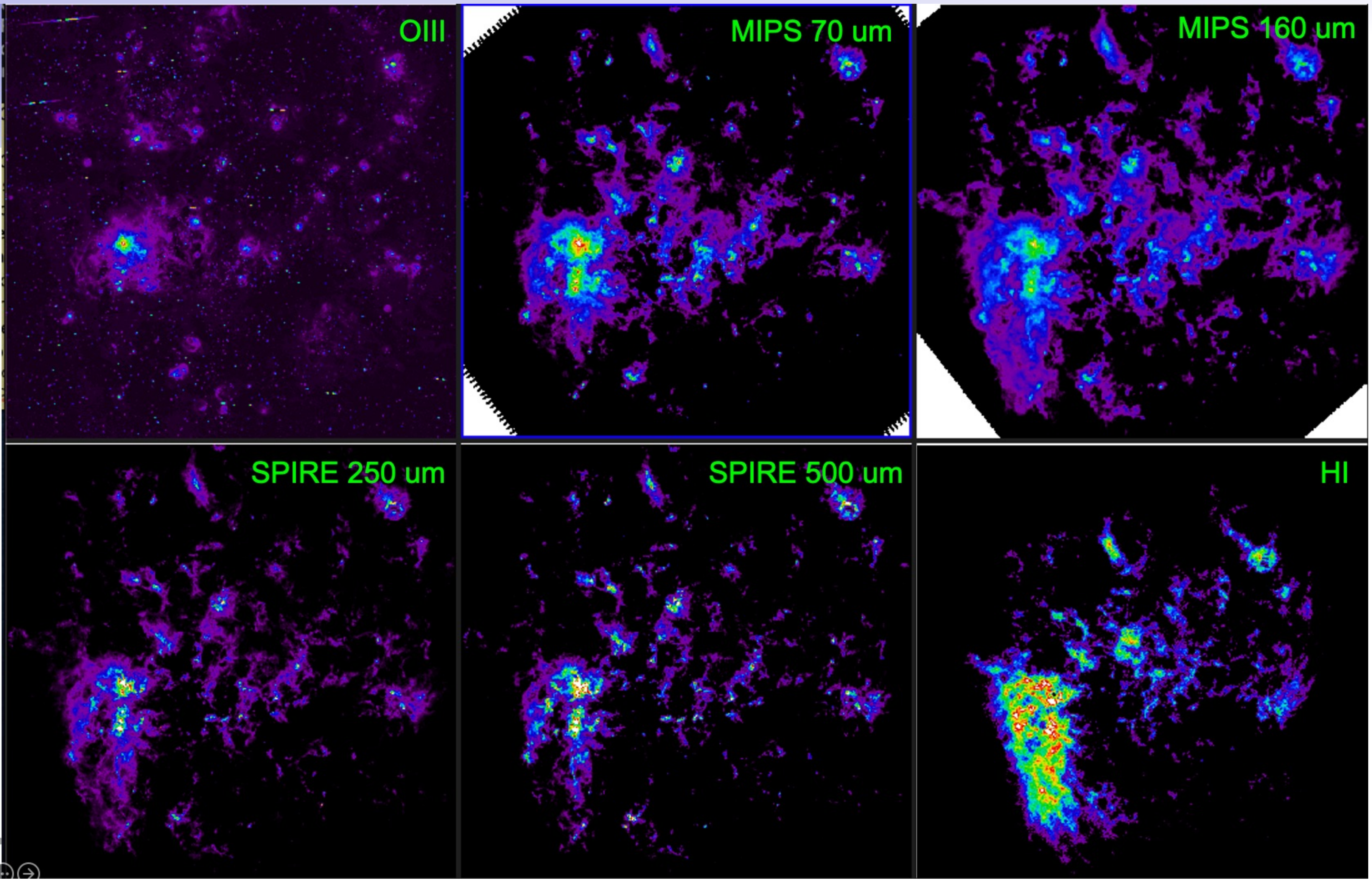
Heavily attenuated cluster in NGC5253 (Calzetti et al. 2015)

Measured phases as a function of galactic properties



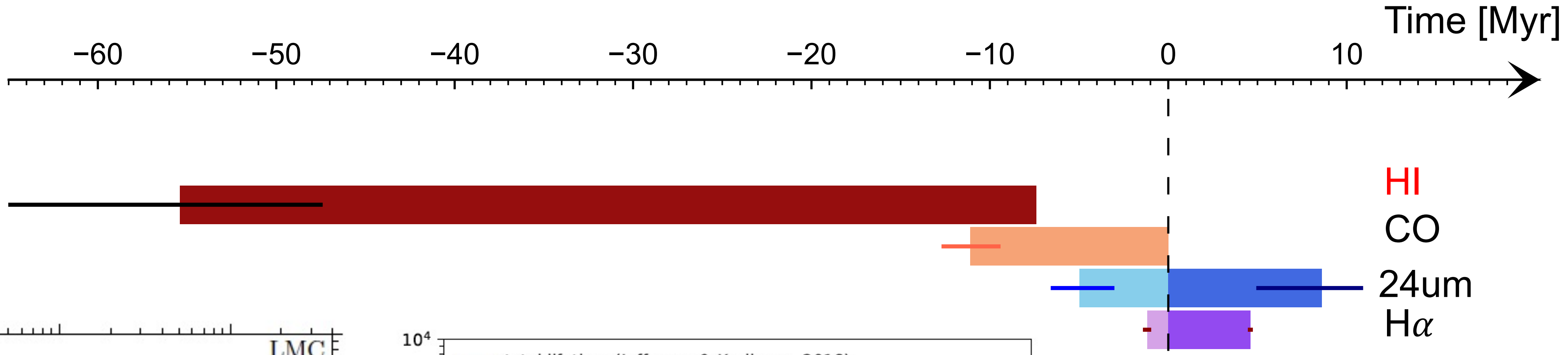
Kim et al. 2021

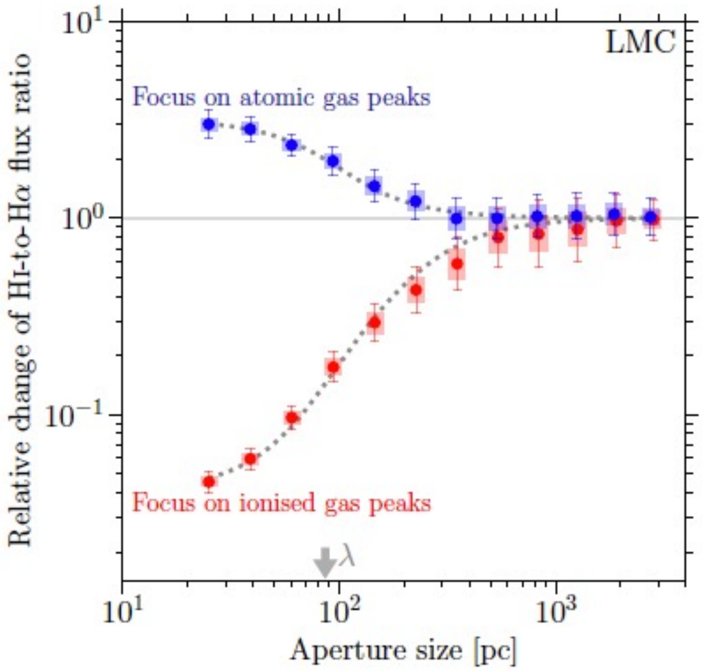
Multi-tracer timeline of star formation in the LMC

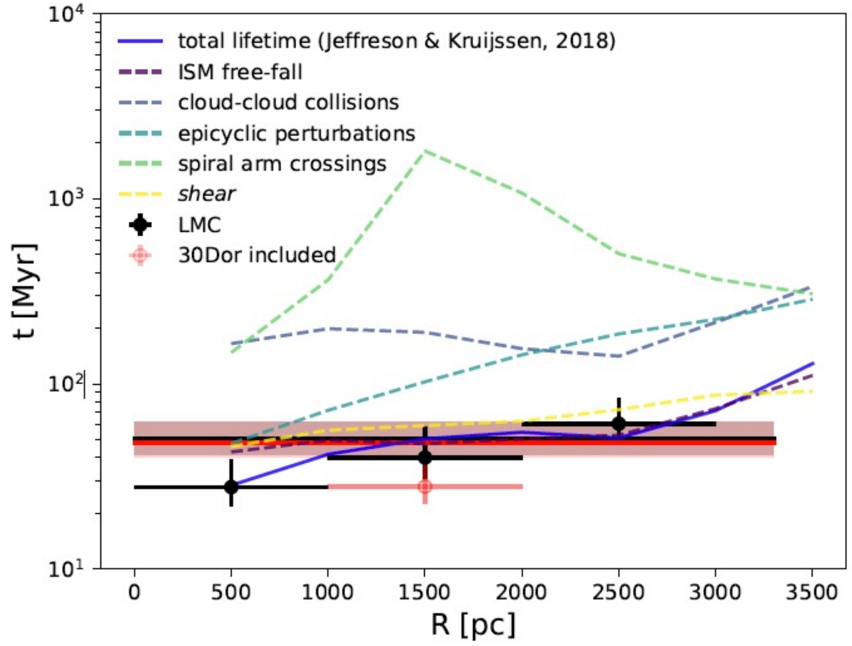


Atomic Gas (HI)	ATCA+Parkes
Molecular gas (CO)	MAGMA
Cold dust	HERITAGE (500-250 μm)
Warm dust	SAGE (160 μm)
Hot dust	SAGE (24-60 μm)
Protostars	SAGE (3-8 μm)
Ha +/- continuum	MCELS
Ha - continuum	SHASSA
[S II]	MCELS
[O III]	MCELS

Lifetimes of HI clouds in the LMC



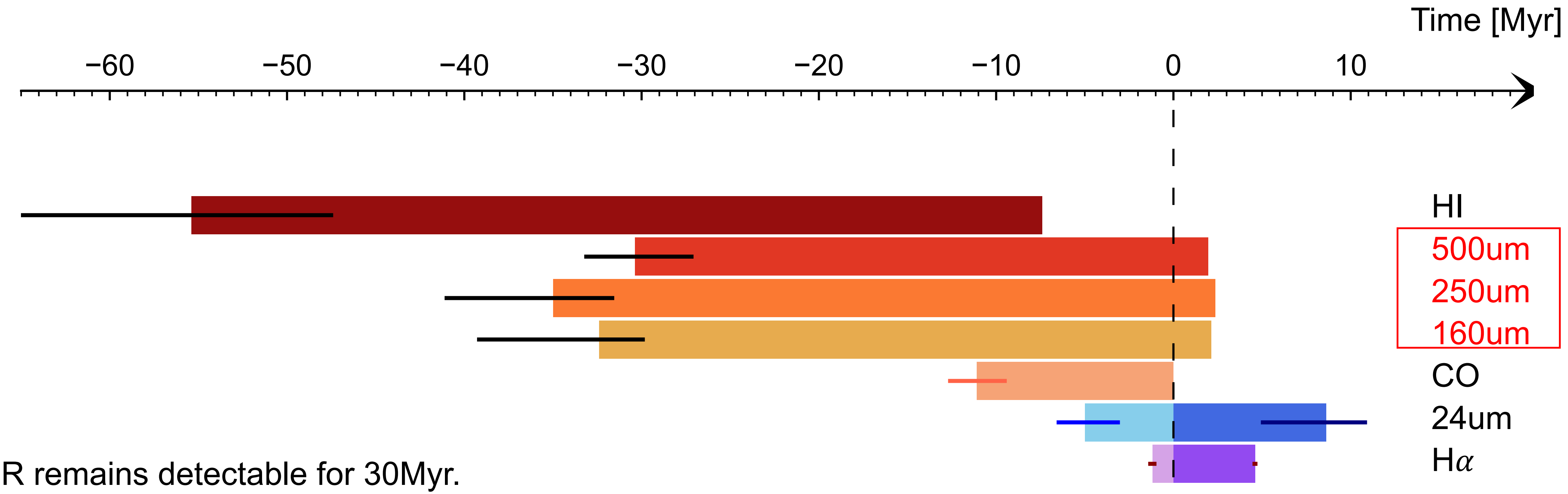




- t_{HI} = 50Myr, with 4Myr overlap with CO.
- Rapid conversion from HI to H_2

Ward et al. 2020

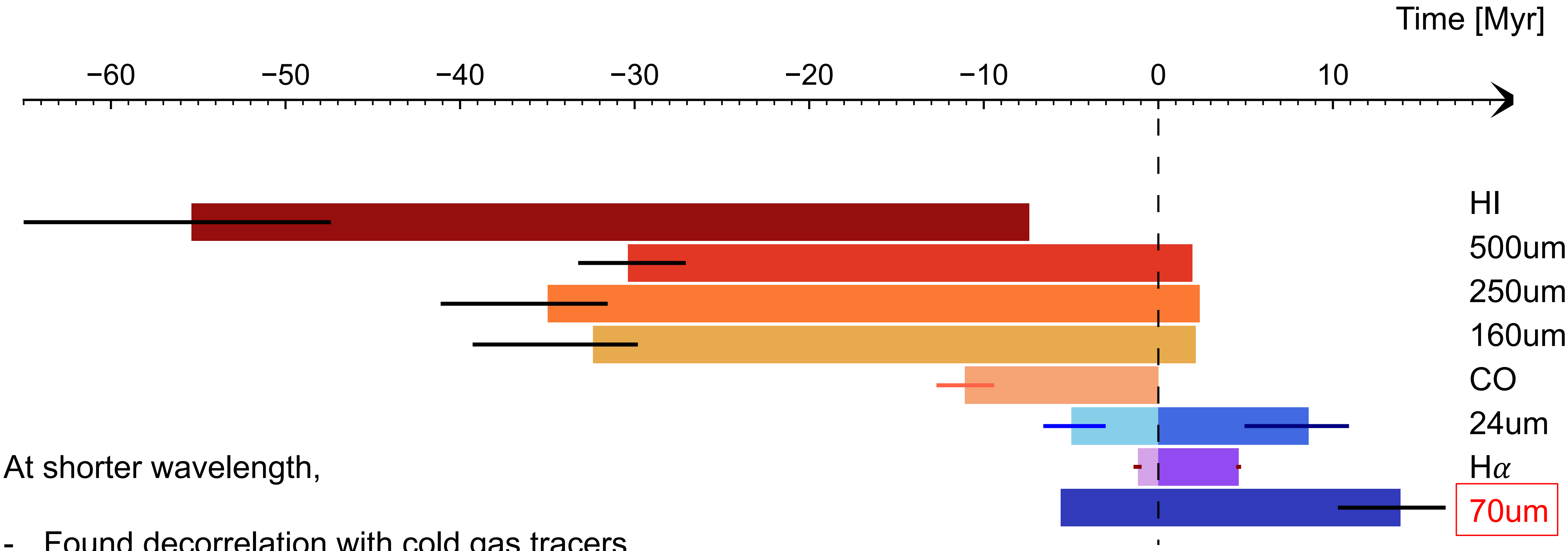
Lifetimes of cold/warm dust overdensities (500, 250, 160um)



- FIR remains detectable for 30Myr.
- Cold dust over densities become detected earlier than CO emission, tracing cold gas component not detected in CO (formation of CO molecules on dust grain surfaces?).
- Over densities of FIR emission does not fully correlate with HI but fully covers CO emission.
- Cold dust seems to be less easily destroyed by feedback

Kim et al. in prep

Lifetimes of hot dust overdensities (70 um)



At shorter wavelength,

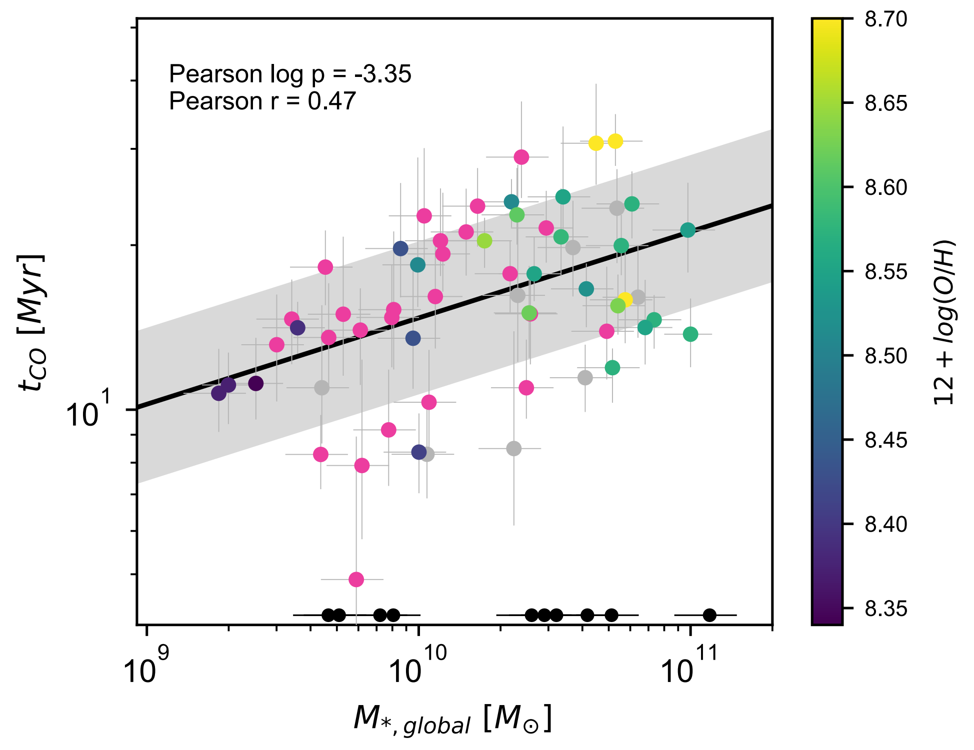
- Found decorrelation with cold gas tracers.
- 70um seems to trace what 24um is tracing

Kim et al. in prep

Constraining the detailed evolutionary timeline of star formation from cloud assembly to embedded stars and HII regions

- We characterized the evolutionary timeline from molecular cloud phases to young stellar regions in six nearby galaxies.
- Embedded phase of SF lasts for 2-7 Myr (17 - 47 % of the cloud lifetime).
- Heavily obscured phase of SF lasts for about 1.4 - 3.8 Myr.
- With MIRI (*JWST*), the method can be applied to 19 galaxies located out to 20 Mpc
- We obtained the full evolutionary timeline of star-forming regions in the LMC from atomic gas to HII regions (Ward et al. 2020; Kim et al. in prep a).
- HI phase lasts for 50 Myr, which is set by the midplane ISM free-fall timescale.
- FIR (500-160um) emission stays visible for 30 Myr, with significant overlap with HI, while encompassing the duration of CO emission.
- 70um emission traces embedded star formation traced by 24um.

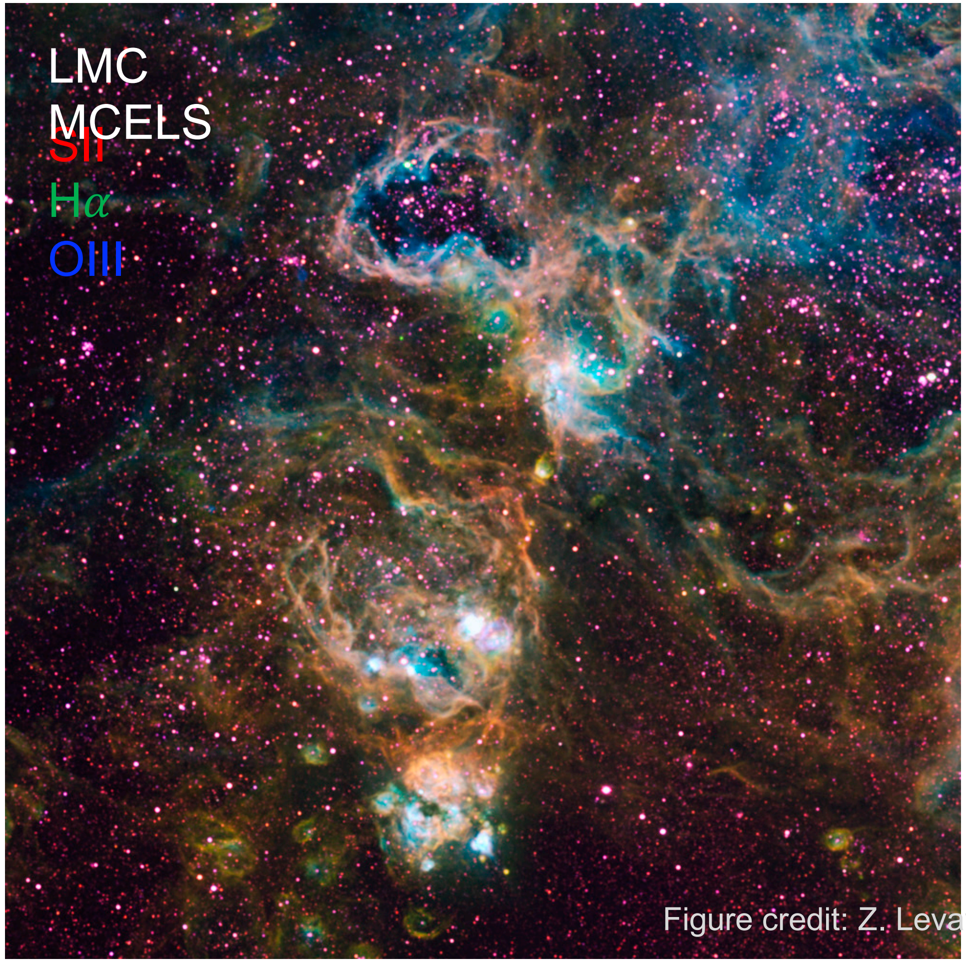
Envrionmental dependence of GMC lifecycle in 54 PHANGS galaxies



Kim et al. (in prep. b)

Work in progress

Phangs

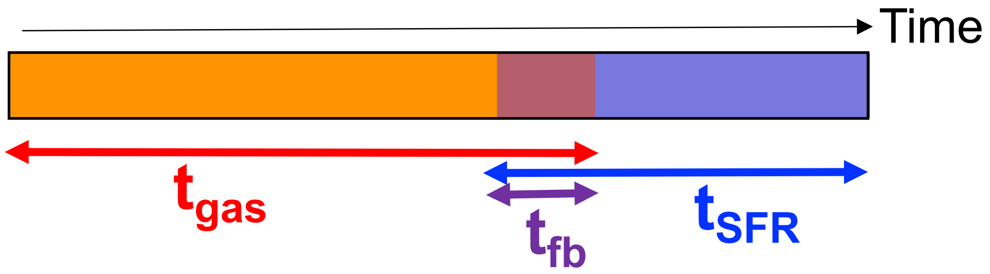


Kim et al. in prep a

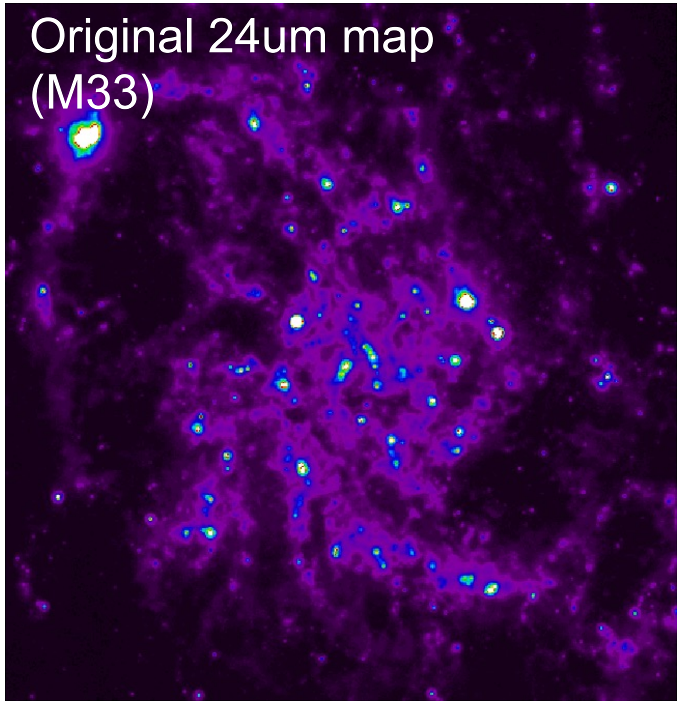
Kim et al. in prep b

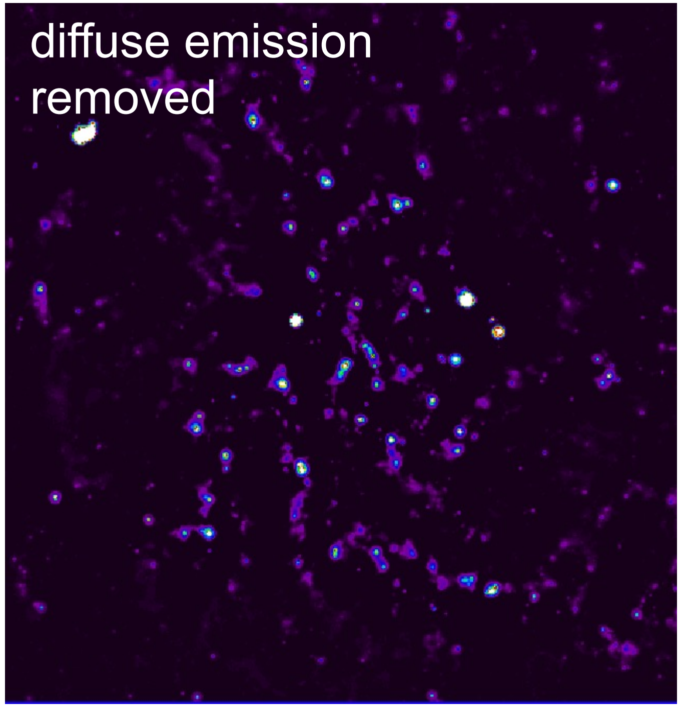
Assumptions

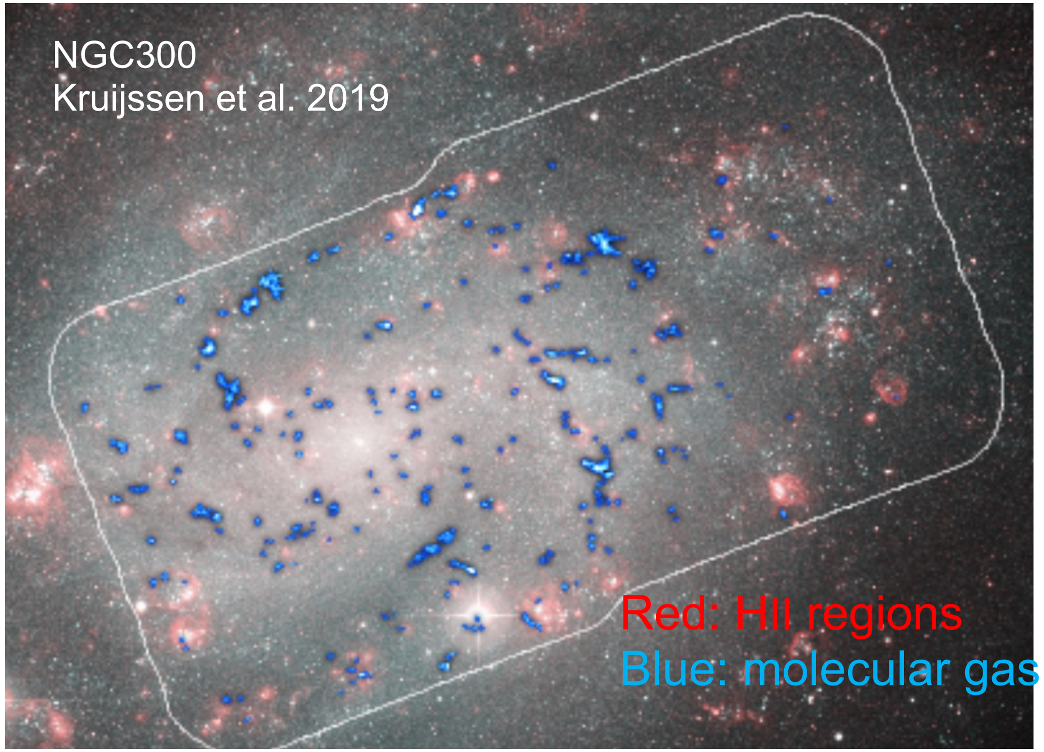
Kruijssen & Longmore 2014
Kruijssen et al. 2018
Hygate et al. 2020



1. Individual star-forming regions should be located somewhere on an evolutionary timeline.

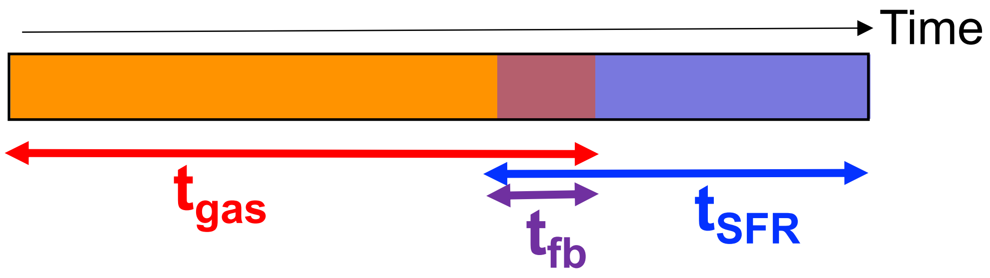






Assumptions

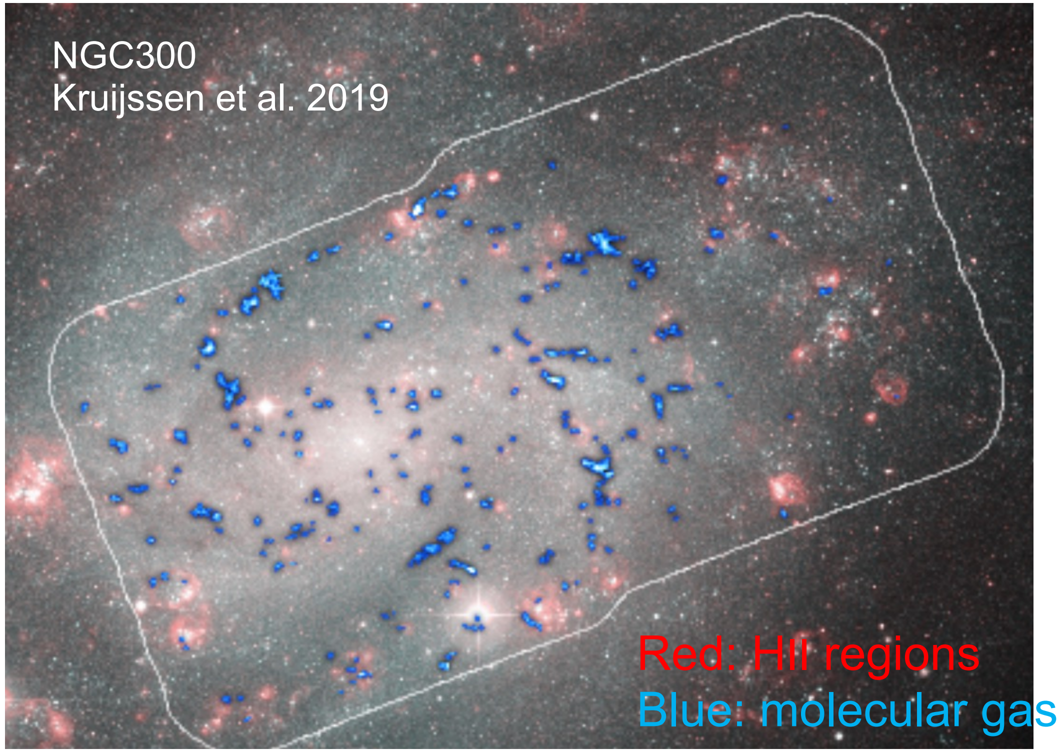
Kruijssen & Longmore 2014
Kruijssen et al. 2018



1. Individual star-forming regions should be located somewhere on an evolutionary timeline.

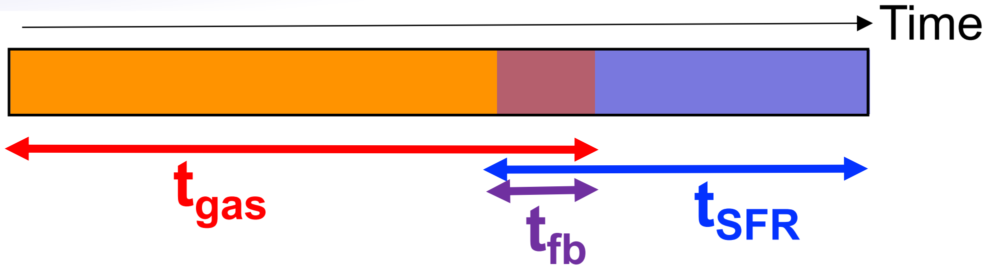
2. Regions are distributed randomly in a galaxy on scales of ~500-1000 pc.

3. Reference timescale required to obtain the absolute duration of each phase (e.g. 4.3 Myr at solar metallicity for Halpha from SLUG2 by Haydon et al. 2020).

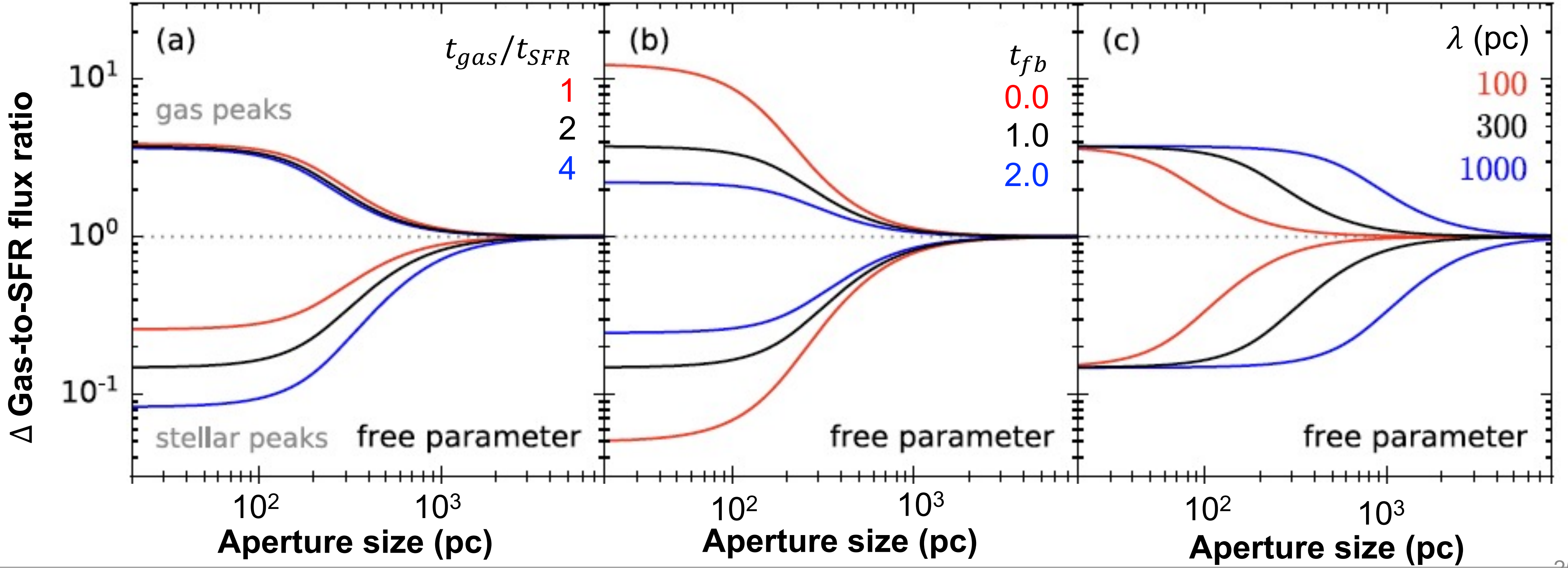


Constrained quantities

Kruijssen & Longmore 2014
Kruijssen et al. 2018



- Analytic fit to the data is described by :
  t_{gas} (or t_{star}), t_{fb}, λ



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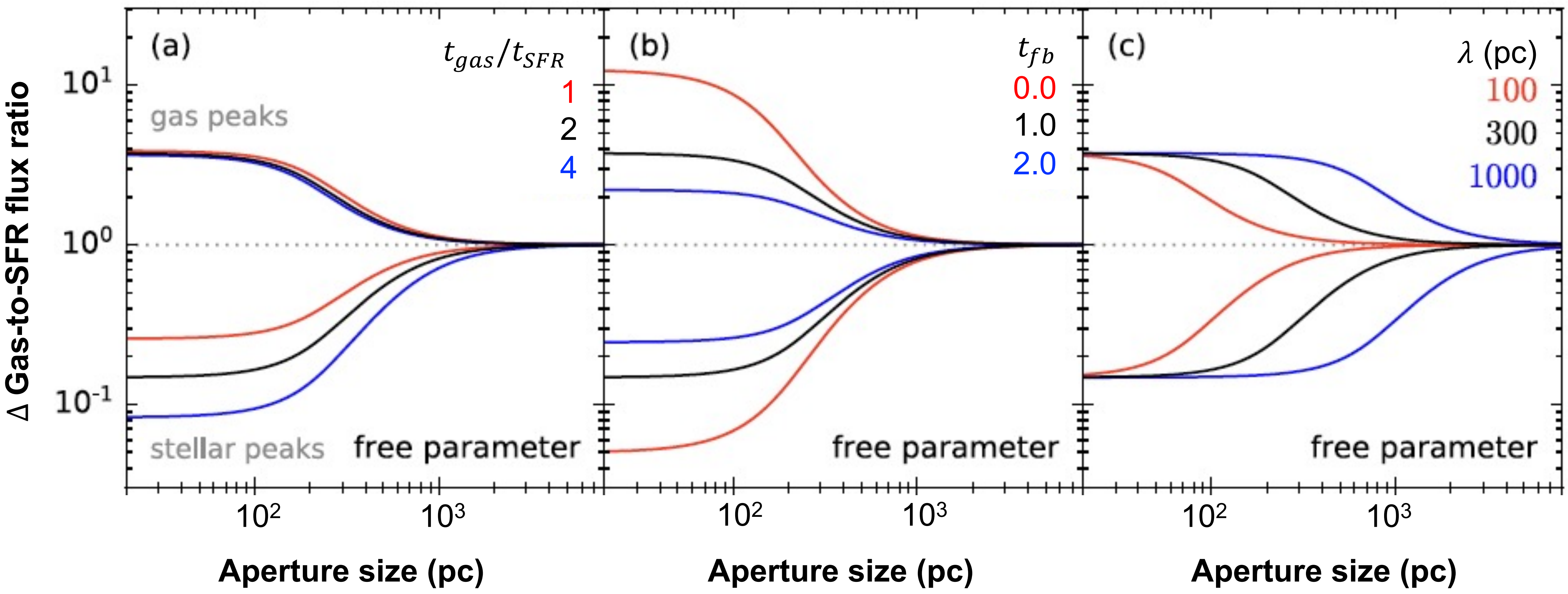
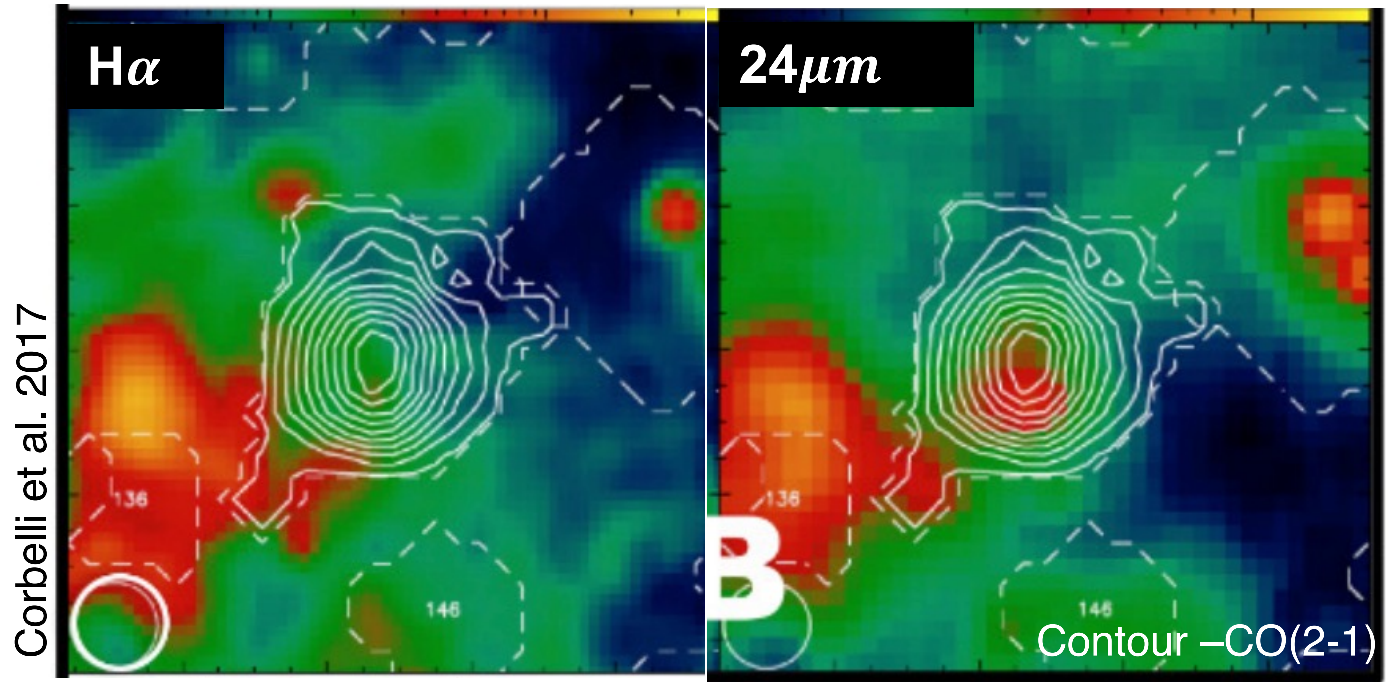
Spatial decorrelation translated into underlying timeline



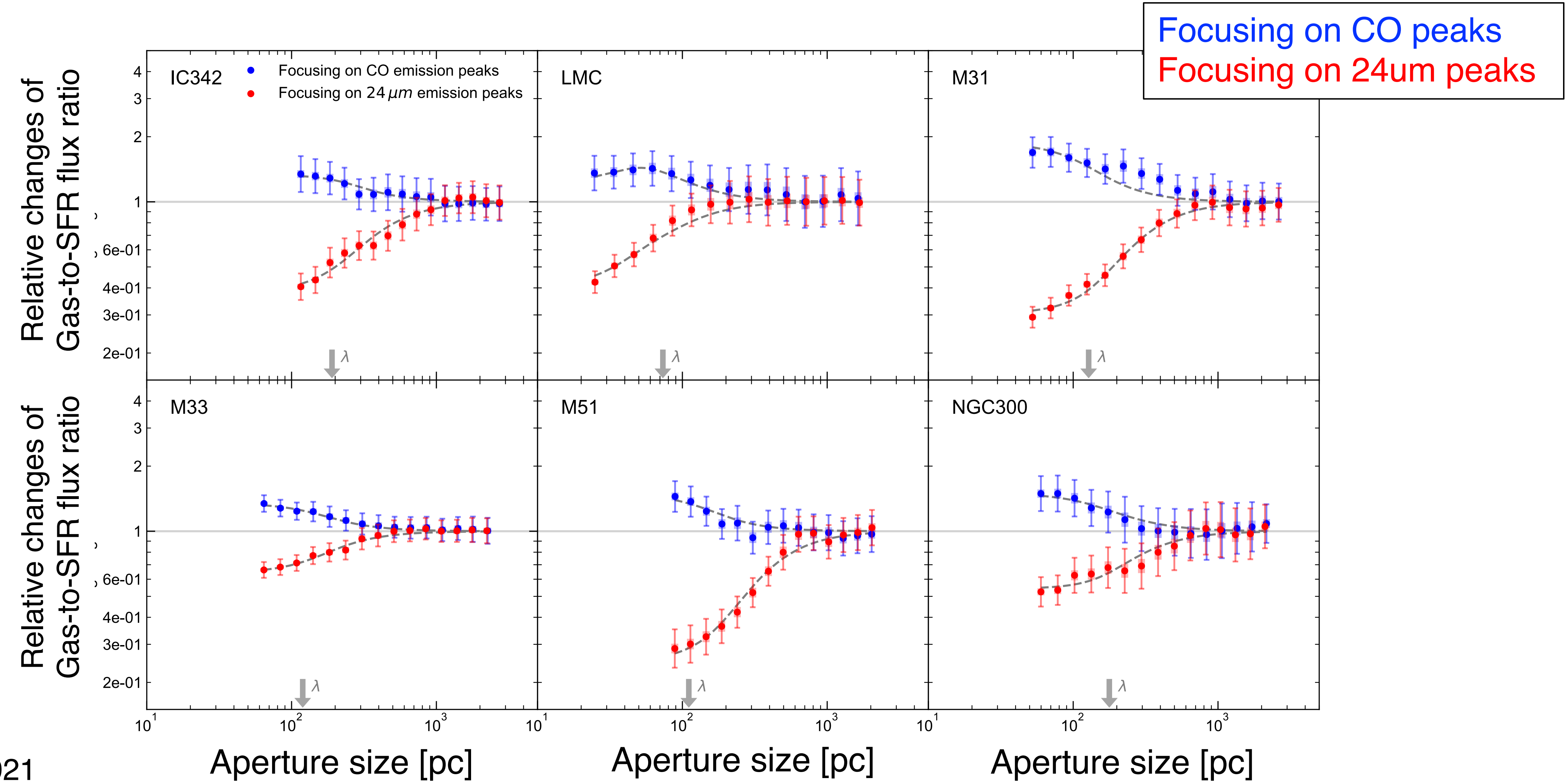
Kruijssen et al. 2018

Result 1: How long is the embedded phase of SF?



- MIR emission (e.g. *Spitzer* MIPS 24 μm) traces embedded star formation (Kennicutt & Evans 2012).
- Originates from excitation of small dust grains.
- However, older stars (< 100 Myr) also contribute to the dust heating (Draine & Li 2007; Verley et al. 2009; Leroy et al. 2012).

Spatial decorrelation between gas and embedded SF on sub-kpc scales



Kim et al. 2021

Constrained best-fitting values

Galaxy	CO vs Hα				CO vs 24 μm				
	t_{CO} [Myr]	$t_{fb, H\alpha}$ [Myr]	$t_{H\alpha}$ [Myr]	λ [pc]	$t_{fb, 24\,\mu m}$ [Myr]	$t_{24\,\mu m}$ [Myr]	λ [pc]	v_{fb} [km s^{-1}]	ϵ_{sf} [per cent]
IC 342	$20.0^{+2.0}_{-2.3}$	$2.2^{+0.4}_{-0.5}$	$6.4^{+0.5}_{-0.6}$	120^{+10}_{-10}	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$14.3^{+4.0}_{-1.8}$	$1.9^{+1.4}_{-0.8}$
LMC	$11.1^{+1.6}_{-1.7}$	$1.2^{+0.2}_{-0.2}$	$5.8^{+0.4}_{-0.4}$	71^{+13}_{-8}	$5.0^{+1.6}_{-2.0}$	$13.6^{+3.7}_{-4.8}$	73^{+38}_{-26}	$10.0^{+2.1}_{-1.7}$	$6.8^{+4.9}_{-3.0}$
M31	$14.0^{+2.1}_{-1.9}$	$1.1^{+0.3}_{-0.2}$	$5.5^{+0.4}_{-0.3}$	181^{+28}_{-19}	$2.4^{+1.4}_{-0.8}$	$4.2^{+1.5}_{-0.7}$	128^{+97}_{-23}	$29.5^{+6.9}_{-5.3}$	$0.7^{+0.2}_{-0.2}$
M33	$14.5^{+1.6}_{-1.5}$	$3.3^{+0.6}_{-0.5}$	$7.9^{+0.7}_{-0.6}$	155^{+30}_{-24}	$6.8^{+2.1}_{-2.0}$	$11.9^{+2.9}_{-2.1}$	119^{+60}_{-35}	$10.3^{+1.5}_{-1.3}$	$3.5^{+2.5}_{-1.5}$
M51	$30.7^{+8.7}_{-4.9}$	$4.7^{+2.0}_{-1.1}$	$8.9^{+2.0}_{-1.2}$	140^{+25}_{-17}	< 4.0	$3.6^{+1.2}_{-0.9}$	< 136	$7.9^{+2.0}_{-2.1}$	$3.3^{+2.9}_{-1.4}$
NGC 300	$10.8^{+2.2}_{-1.6}$	$1.5^{+0.2}_{-0.2}$	$6.1^{+0.2}_{-0.2}$	104^{+22}_{-18}	$4.9^{+1.2}_{-1.9}$	$7.9^{+1.5}_{-2.1}$	178^{+125}_{-75}	$9.4^{+0.8}_{-0.7}$	$3.3^{+2.6}_{-1.4}$

Kim et al. 2021

Duration of the 24um emitting timescale: t_{24um}

Galaxy	t_{CO} [Myr]	$t_{fb,\,24\,\mu m}$ [Myr]	$t_{24\,\mu m}$ [Myr]	λ [pc]	ϵ_{sf} [per cent]
	CO vs 24 μm				
IC 342	$20.0^{+2.0}_{-2.3}$	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$1.9^{+1.4}_{-0.8}$
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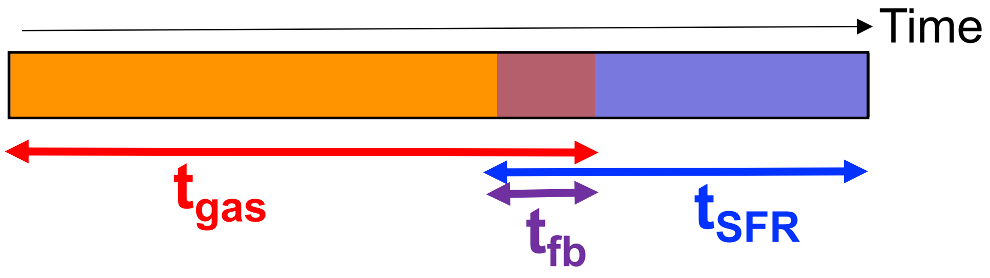


- 24um emission phase lasts for 4 – 14 Myr.
- For M33, similar to 10 Myr measured in Corbelli et al. (2017).

Kim et al. 2021

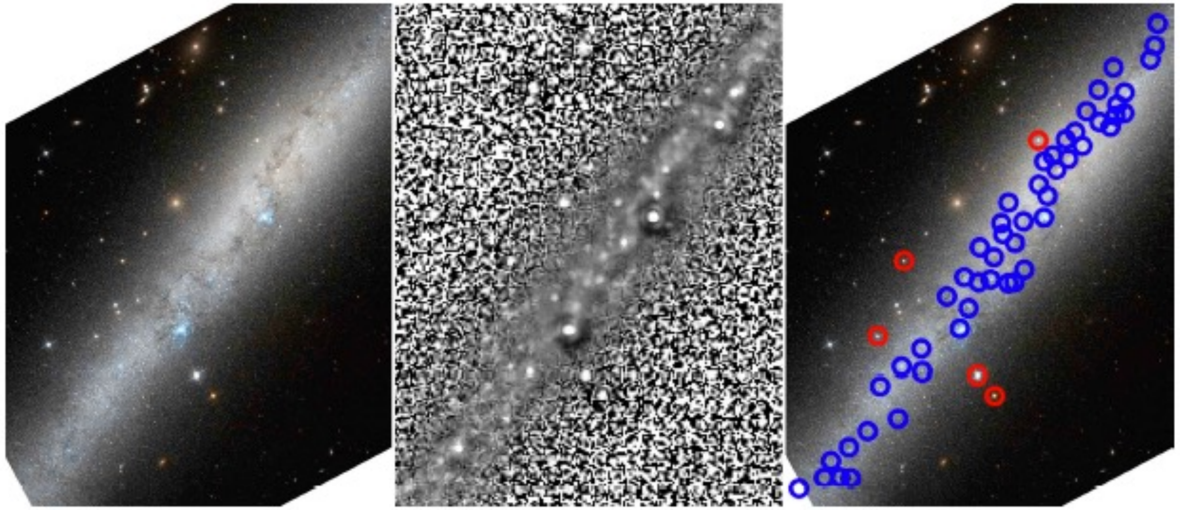
Separation length between regions: λ

Galaxy	CO vs 24 μm				
	t_{CO} [Myr]	$t_{fb,24\mu m}$ [Myr]	$t_{24\mu m}$ [Myr]	λ [pc]	ϵ_{sf} [per cent]
IC 342	$20.0^{+2.0}_{-2.3}$	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$1.9^{+1.4}_{-0.8}$
LMC	$11.1^{+1.6}_{-1.7}$	$5.0^{+1.6}_{-2.0}$	$13.6^{+3.7}_{-4.8}$	73^{+38}_{-26}	$6.8^{+4.9}_{-3.0}$
M31	$14.0^{+2.1}_{-1.9}$	$2.4^{+1.4}_{-0.8}$	$4.2^{+1.5}_{-0.7}$	128^{+97}_{-23}	$0.7^{+0.2}_{-0.2}$
M33	$14.5^{+1.6}_{-1.5}$	$6.8^{+2.1}_{-2.0}$	$11.9^{+2.9}_{-2.1}$	119^{+60}_{-35}	$3.5^{+2.5}_{-1.5}$
M51	$30.7^{+8.7}_{-4.9}$	< 4.0	$3.6^{+1.2}_{-0.9}$	< 136	$3.3^{+2.9}_{-1.4}$
NGC 300	$10.8^{+2.2}_{-1.6}$	$4.9^{+1.2}_{-1.9}$	$7.9^{+1.5}_{-2.1}$	178^{+125}_{-75}	$3.3^{+2.6}_{-1.4}$

Kim et al. 2021

- Separation length is 70-190 pc
- Similar to the gas disc scale height, thickness of vertical distribution of star-forming regions, thickness of molecular gas disc.

Elmegreen & Elmegreen 2020



Time-averaged star formation efficiency

Galaxy	CO vs 24 μm				ϵ_{sf} [per cent]
	t_{CO} [Myr]	$t_{fb, 24\,\mu m}$ [Myr]	$t_{24\,\mu m}$ [Myr]	λ [pc]	
IC 342	$20.0^{+2.0}_{-2.3}$	$5.2^{+1.5}_{-2.3}$	$7.9^{+1.8}_{-2.2}$	190^{+59}_{-62}	$1.9^{+1.4}_{-0.8}$
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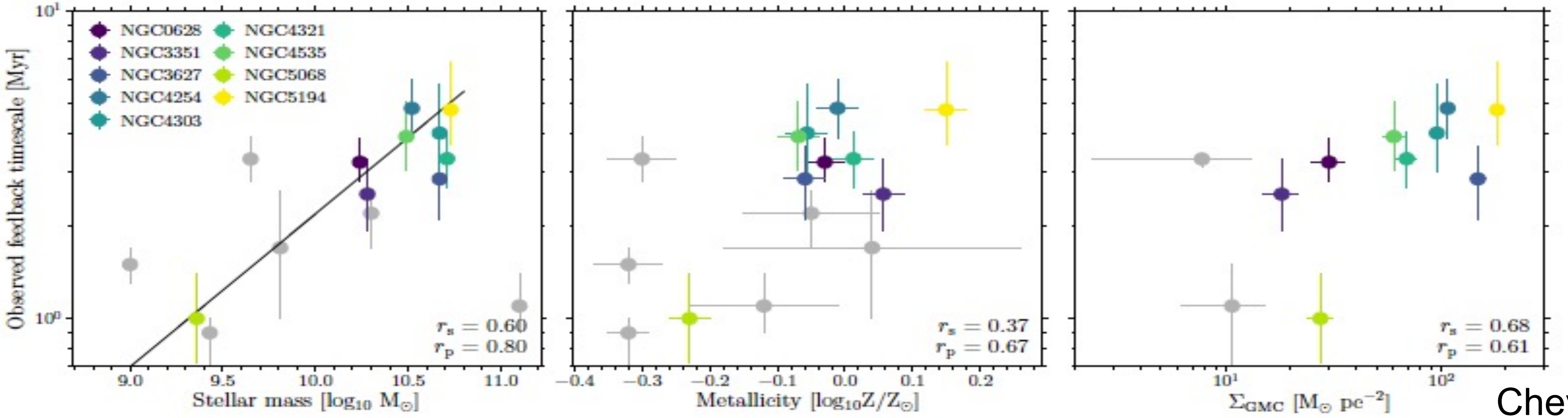
$$\epsilon_{sf} = \frac{\Sigma_{SFR}}{\Sigma_{gas}/t_{CO}}$$

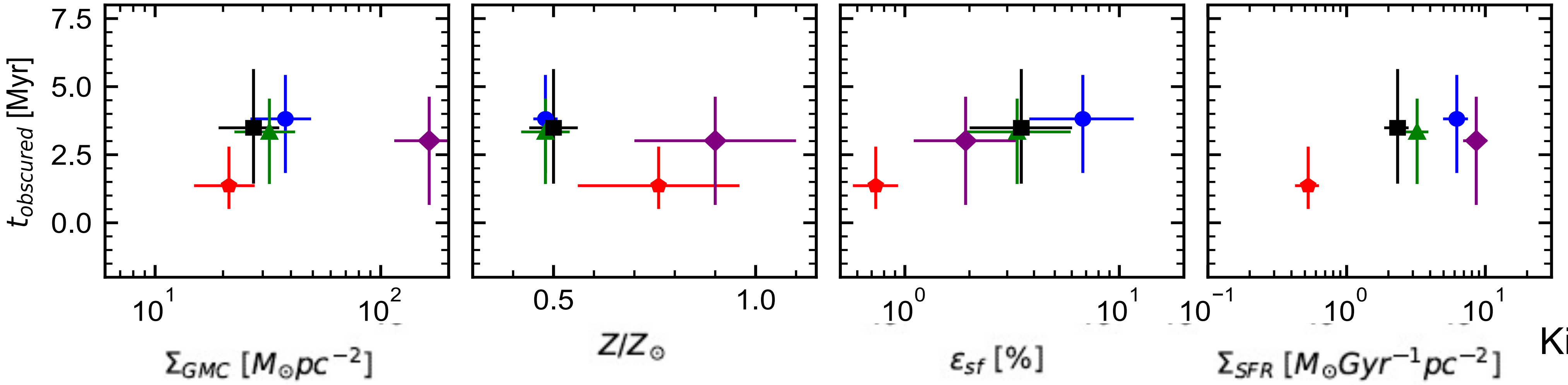
- We measure a low efficiency with ϵ_{sf} = 0.7-6.8 %

Kim et al. 2021

Environmental dependence?



Chevance+2021

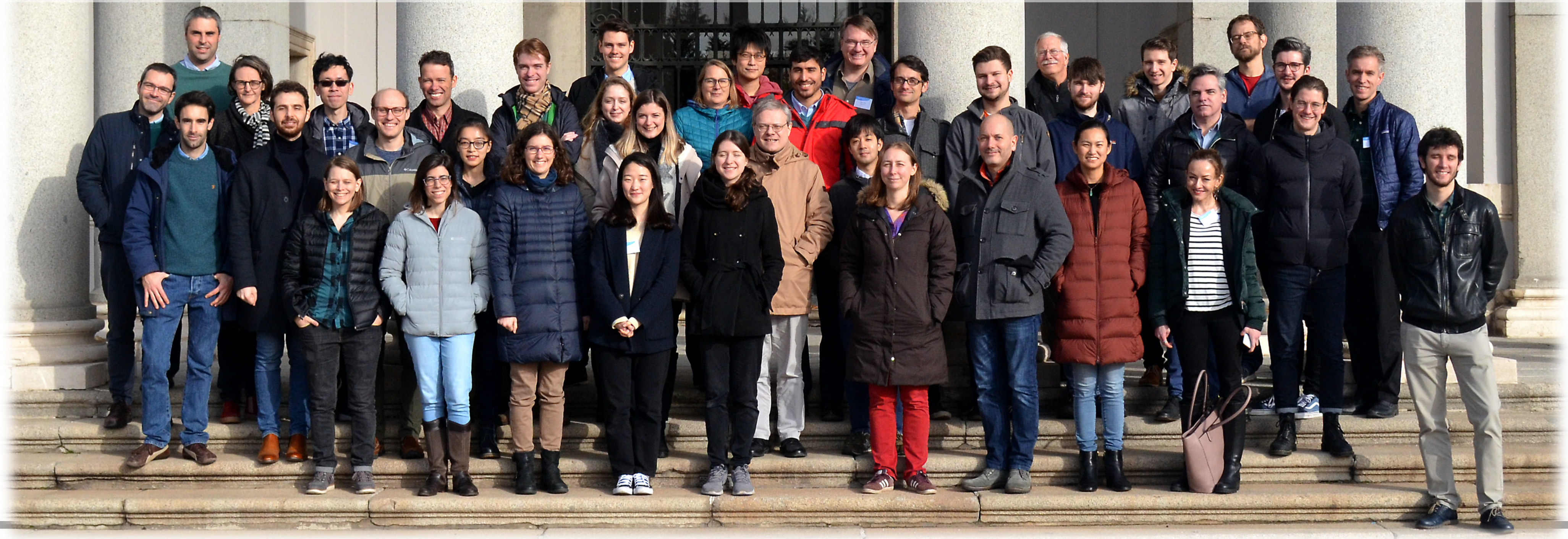


Kim+2021

PHANGS

Physics at **H**igh **A**ngular resolution in **N**earby **G**alaxie**S**

Bigiel, Blanc, Emsellem, Escala, Groves, Hughes, Kreckel, Kruijssen, Lee, Leroy, Meidt, Querejeta, Pety, Rosolowsky, Sanchez-Blazquez, Sandstrom, Schinnerer, Schruba, Usero, Anand, Barnes, Belfiori, Benincasa, Bešlić, Boquien, den Brok, Cao, Chandar, Chastenet, Chevance, Congiu, Dale, Deger, Diaz-Fernandez, Eibensteiner, Faesi, Gallagher, Garcia-Rodriguez, Glover, Grasha, Henshaw, Herrera, Jeffreson, Jimenez-Donaire, Kessler, Kim, Klessen, Koch, Larson, Lazar, Le Reste, Liu, Machado, Mayker, McElroy, Mok, Neuman, Ostriker, Pan, Pessa, Puschnig, Razza, Saito, Santoro, Sardone, Sormani, Scheuermann, Stuber, Sun, Thilker, Turner, Ubeda, Utreras, Utomo, Van Dyk, Vjesnica, Watkins, Whitmore, Williams, Chiang, Choubani, Farahanim, Kang, Lopez, Murphy, Teng



Phangs

Samples

- face-on
- main seq.
- < 17 Mpc

(res 100-200pc)

ALMA +

HST

74 (+26)

Nearest, massive, star-forming galaxies "representative of where stars form in z=0"

38

muse

multi unit spectroscopic explorer

19 +

+

Leroy et al. 2021
Leroy et al. 2021
Lee et al. 2021
Emsellem et al. in press
Razza et al. in prep.

+

ASTROSat
FUV
16 Galaxies

WFI, duPont
Hα
74 Galaxies

VLA HI
50 Galaxies

Spitzer NIR
74 Galaxies

- We systemeatically study the connection between young stars and cold molecular gas
- Sample covers large range of galaxy properties

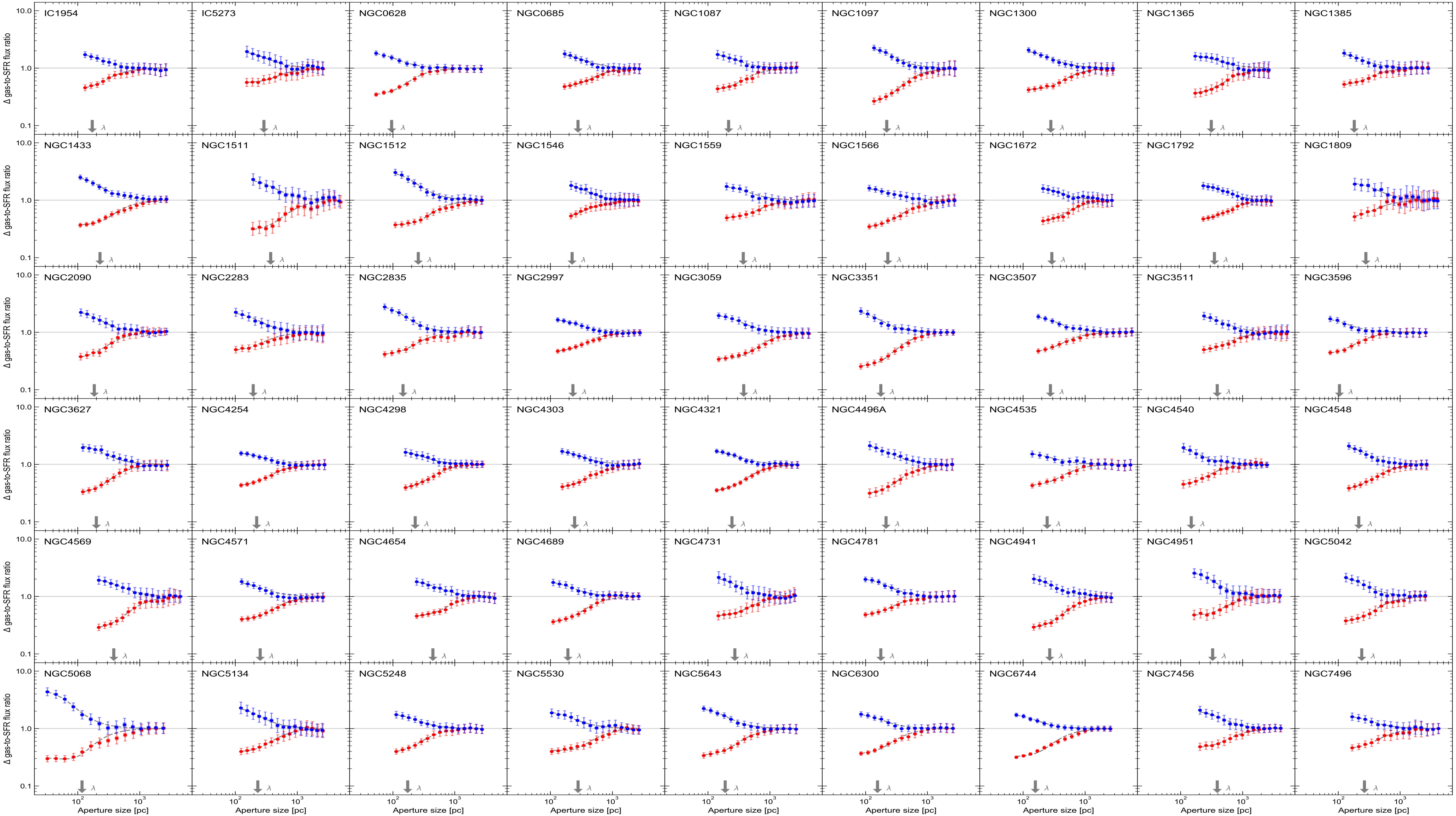
+

WFI, duPont Hα
74 Galaxies

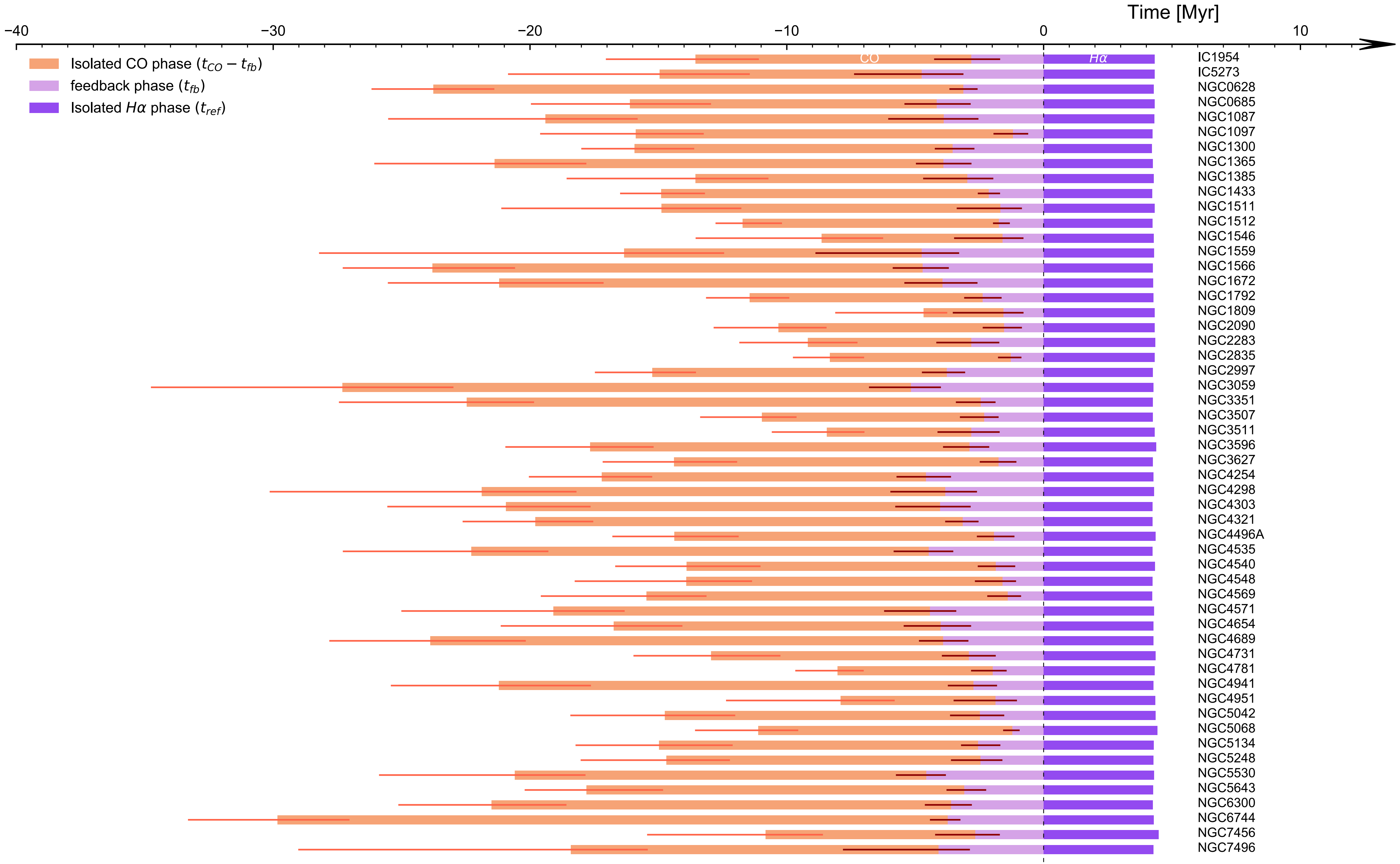
: by Kruijssen et al. (2019)

: by Chevance et al. (2020)

Universal decorrelation between gas and HII regions

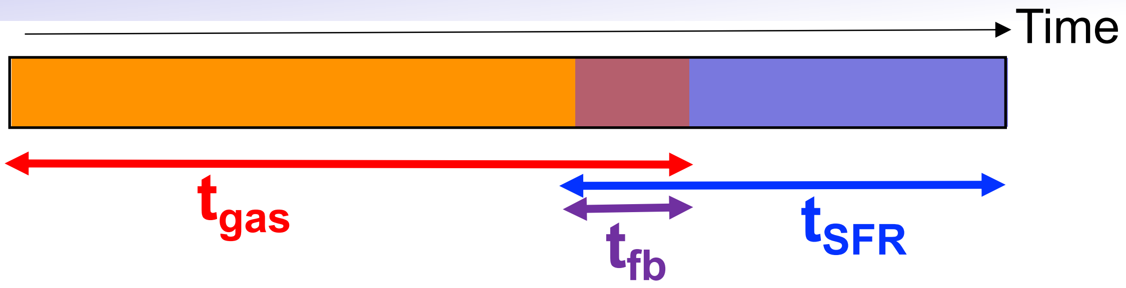


Kim et al. in prep a


Time [Myr]
−40
−30
−20
−10
0
10
Isolated CO phase ($t_{CO} - t_{fb}$)
feedback phase (t_{fb})
Isolated $H\alpha$ phase (t_{ref})
CO
$H\alpha$
IC1954
IC5273
NGC0628
NGC0685
NGC1087
NGC1097
NGC1300
NGC1365
NGC1385
NGC1433
NGC1511
NGC1512
NGC1546
NGC1559
NGC1566
NGC1672
NGC1792
NGC1809
NGC2090
NGC2283
NGC2835
NGC2997
NGC3059
NGC3351
NGC3507
NGC3511
NGC3596
NGC3627
NGC4254
NGC4298
NGC4303
NGC4321
NGC4496A
NGC4535
NGC4540
NGC4548
NGC4569
NGC4571
NGC4654
NGC4689
NGC4731
NGC4781
NGC4941
NGC4951
NGC5042
NGC5068
NGC5134
NGC5248
NGC5530
NGC5643
NGC6300
NGC6744
NGC7456
NGC7496

Distribution of our measurements of 54 MS galaxies

Kim et al. in prep

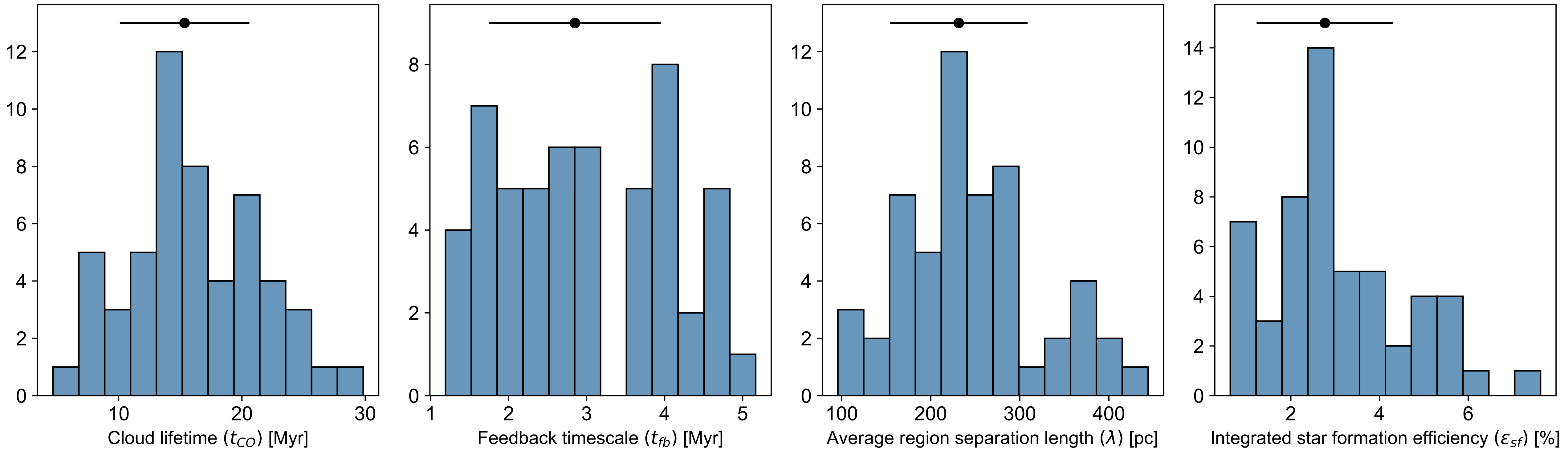


$< t_{CO} >= 15 \pm 5$ Myr

$< t_{fb} >= 2.8 \pm 1.1$ Myr

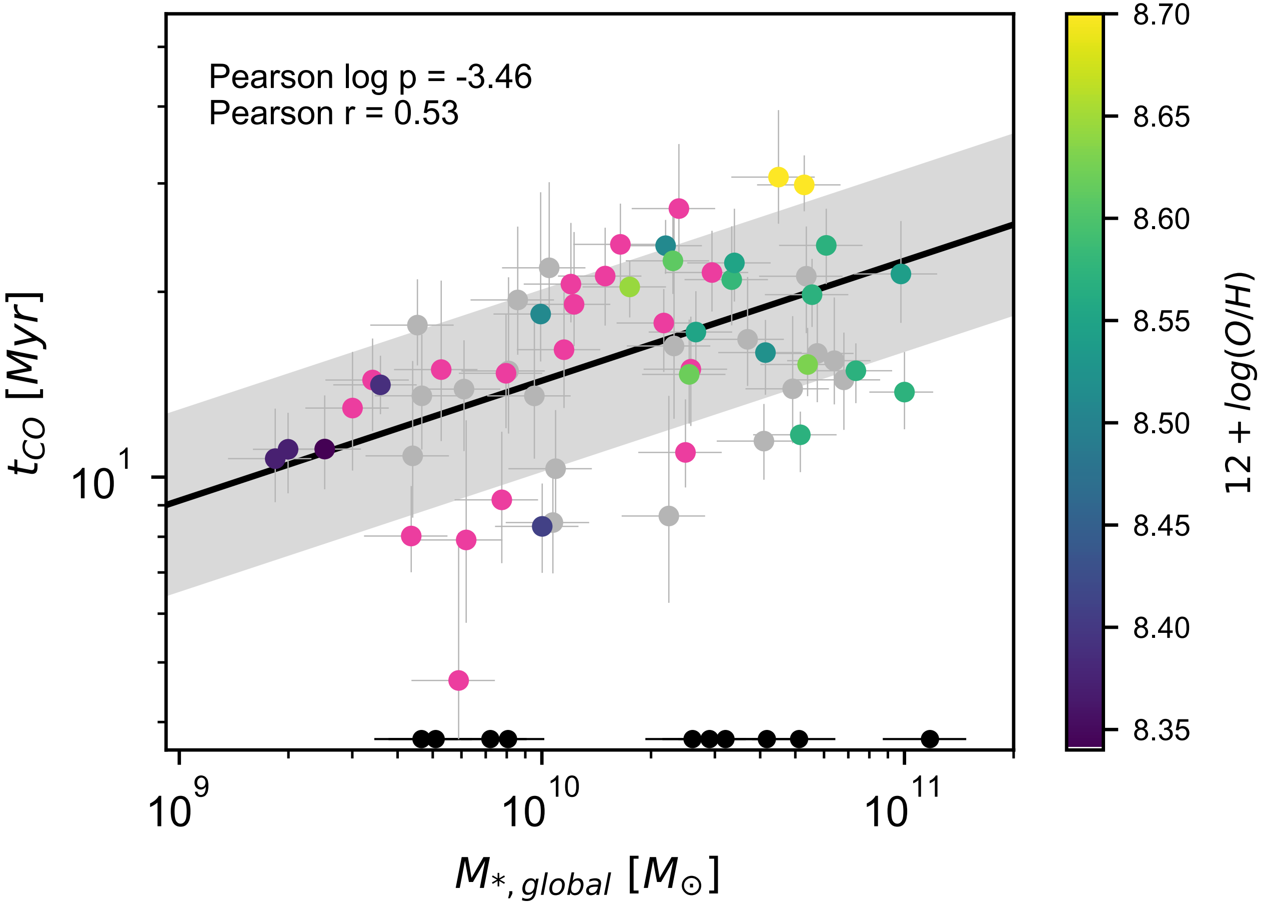
$< \lambda >= 231 \pm 77$ pc

$< \varepsilon_{sf} \geq 2.8 \pm 1.5$ %

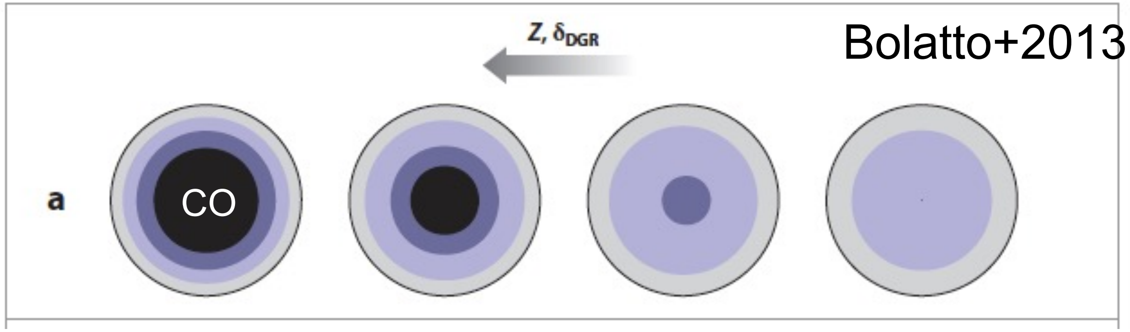


Strong correlations with measured cloud lifetime

Kim et al. in prep a



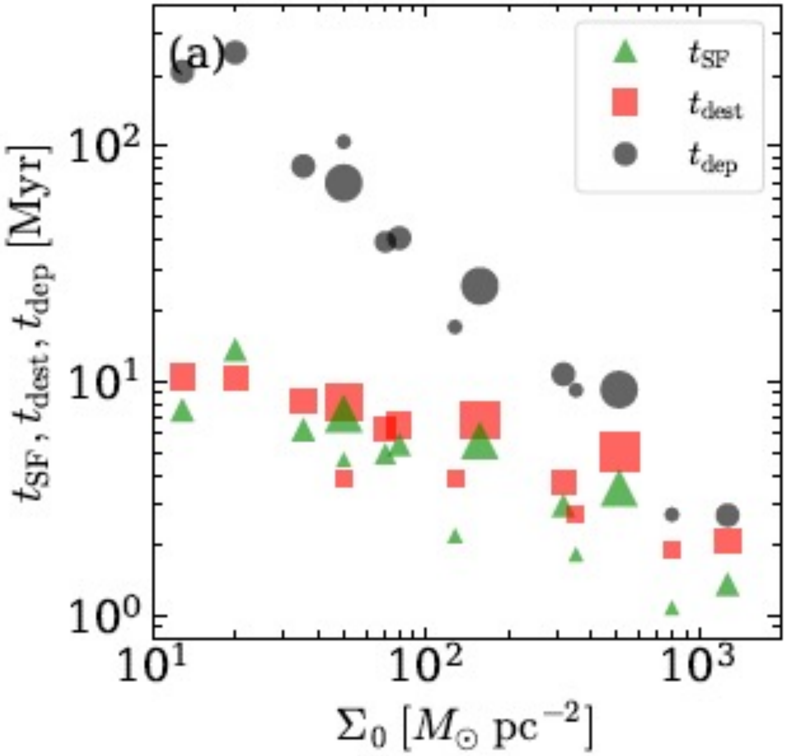
Low metal → less dust → higher column density is required to shield CO from photodissociating



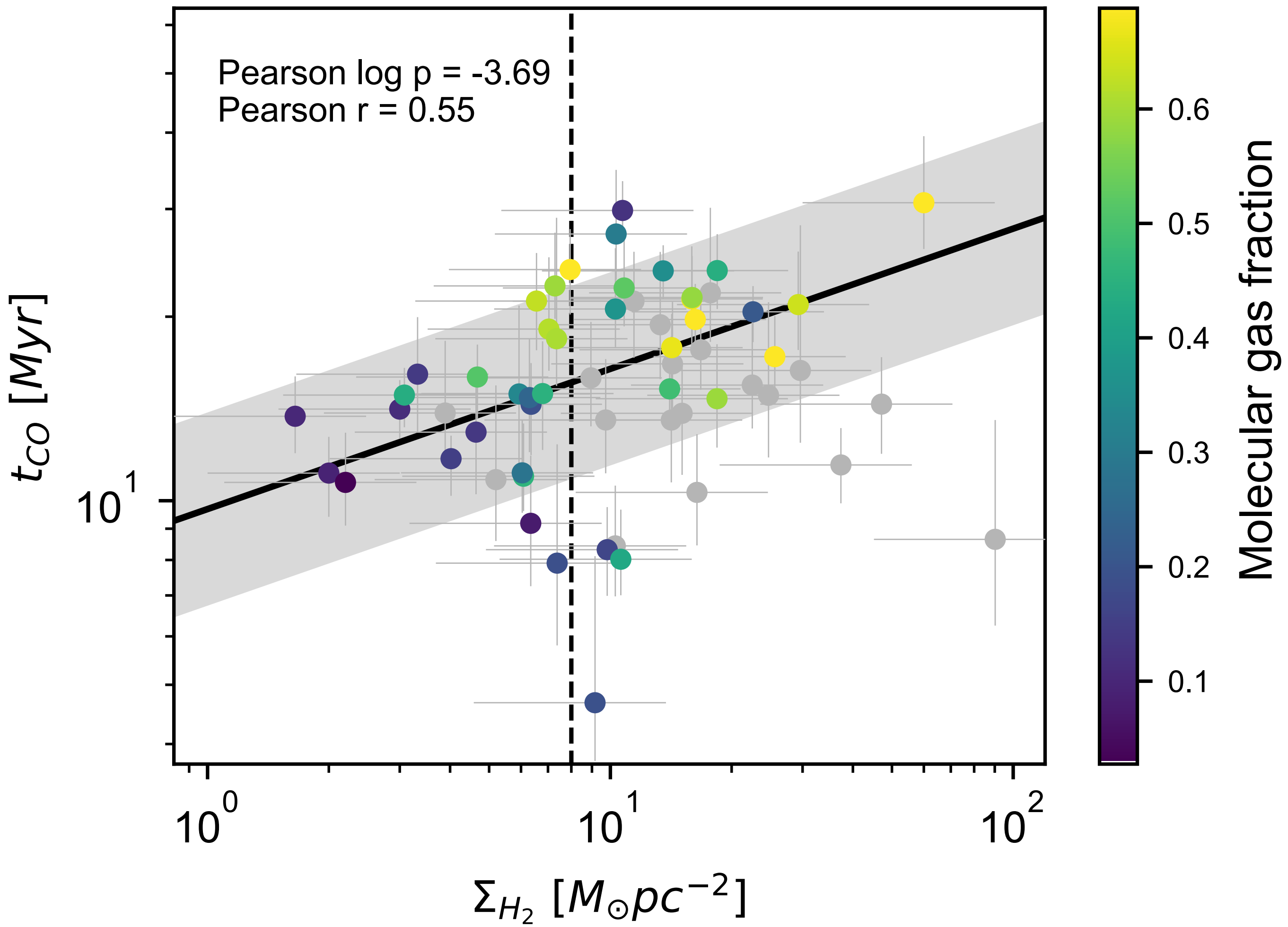
1) CO-dark phase in the beginning of cloud assembly is missed in our measured cloud lifetime
2) Higher mass → higher pressure → makes CO visible relatively early from the beginning
3) Observational biase: we miss more low mass GMCs in low mass galaxies

Strong correlations with measured cloud lifetime

Kim et al. in prep a



MHD sim by Kim+2018

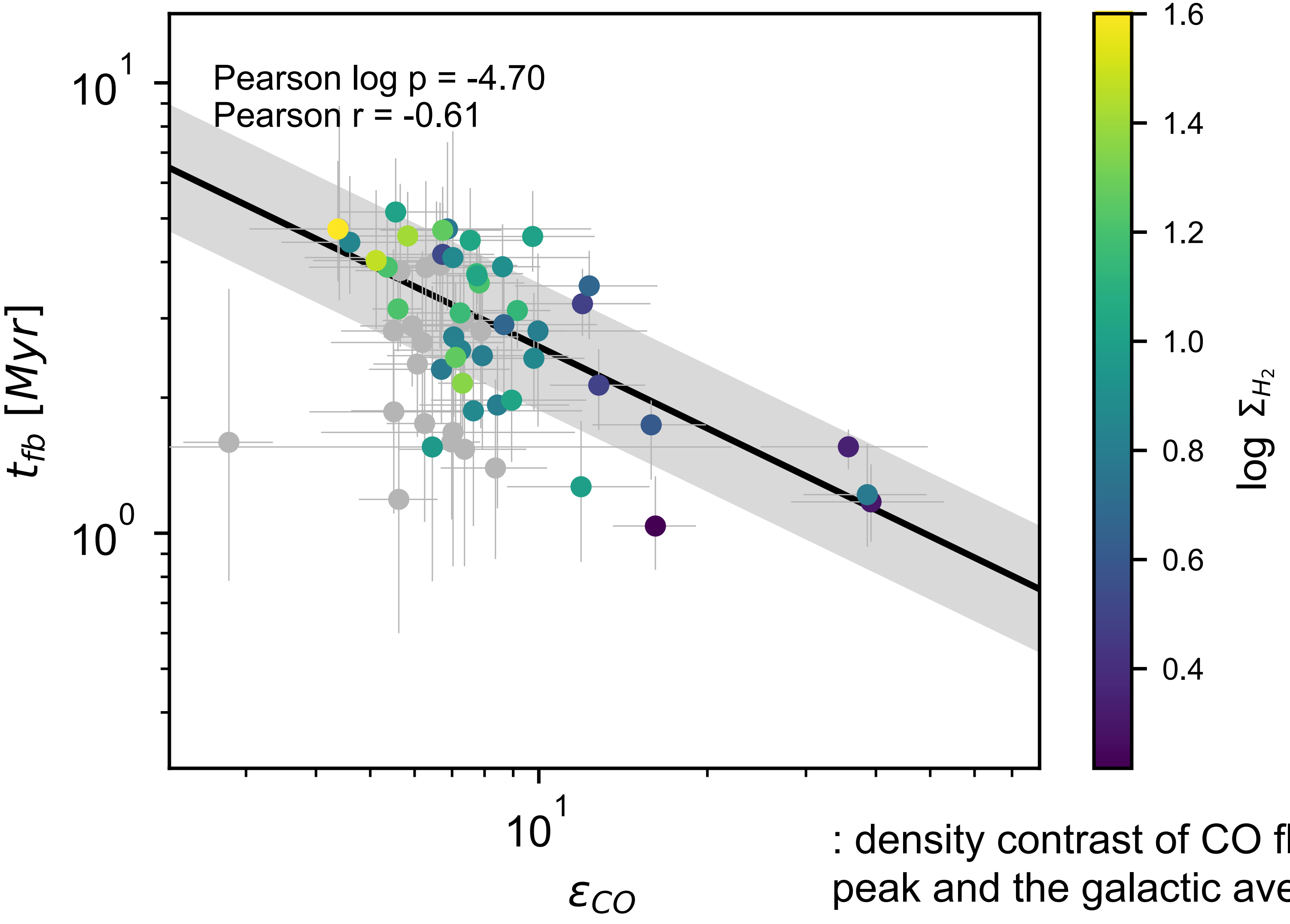


At low density (atomic gas dominated),

1) CO only emitted only in the central region
2) Spends longer time in CO-dark and atomic gas phase

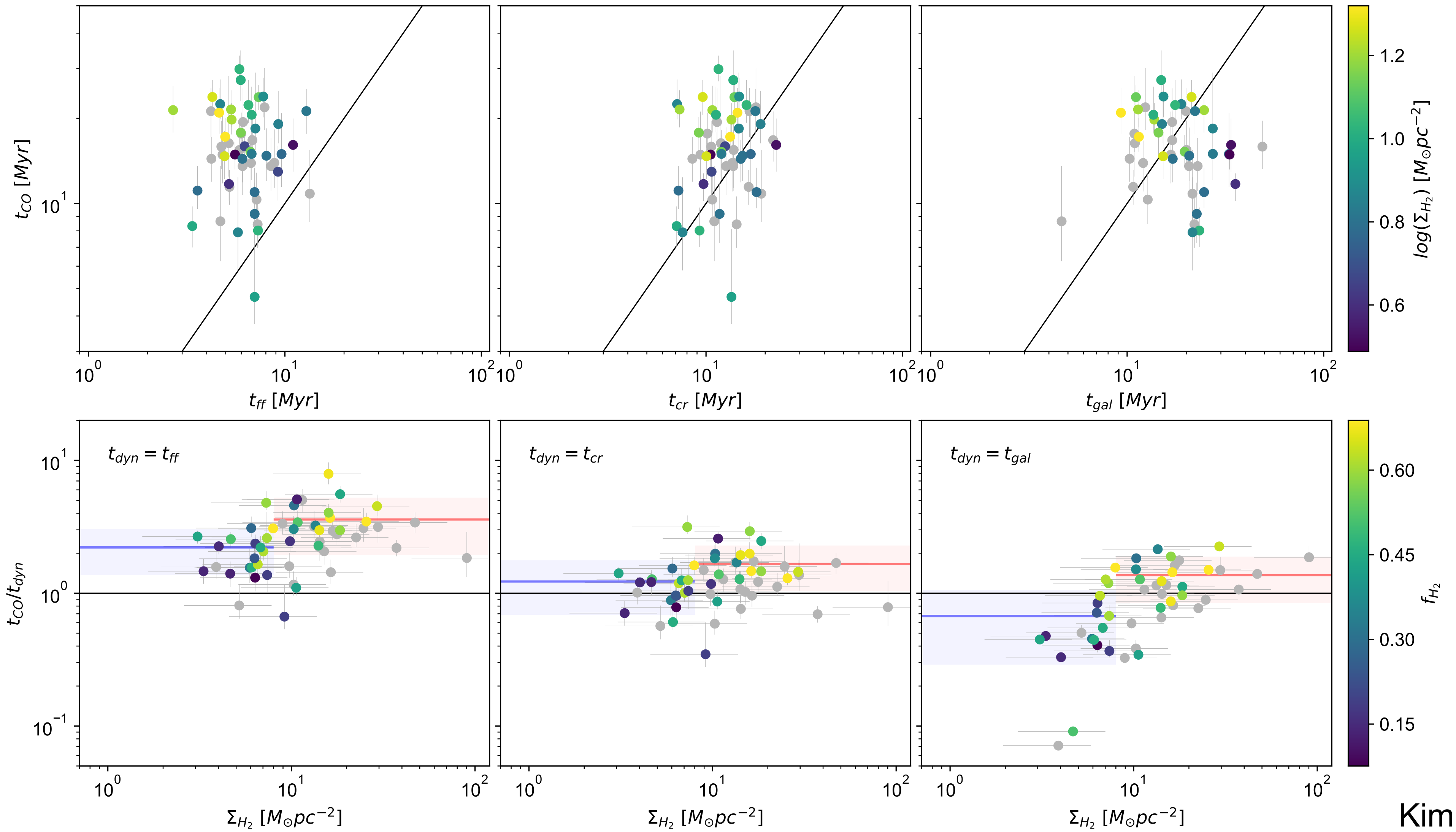
Strong correlations with our measurements

Kim et al. in prep a



: density contrast of CO flux between the peak and the galactic average

Comparison with analytical predictions (t_{ff}, t_{cr}, and t_{gal})



Kim et al. in prep a

Environmental dependence of the matter cycle from cloud evolution to star formation and feedback in 54 main sequence galaxies

- We characterize the evolutionary timeline from molecular cloud phases to exposed young stellar regions in 54 molecular gas-rich main sequence galaxies.
- We find that clouds live for about 5 - 30 Myr and are efficiently dispersed by stellar feedback within 1.2 - 5.1 Myr after the star-forming region has become partially exposed.
- Cloud lifetime increases with increasing stellar mass and molecular gas surface density.
- Feedback timescale decreases with increasing density contrast of molecular gas surface density between the emission peak and the galactic average
- At low density regime, cloud lifetime is set by internal dynamics (cloud crossing timescale), whereas at high density, cloud lifetime is governed by galactic dynamics.