ISM & Star Formation in Extreme Environments

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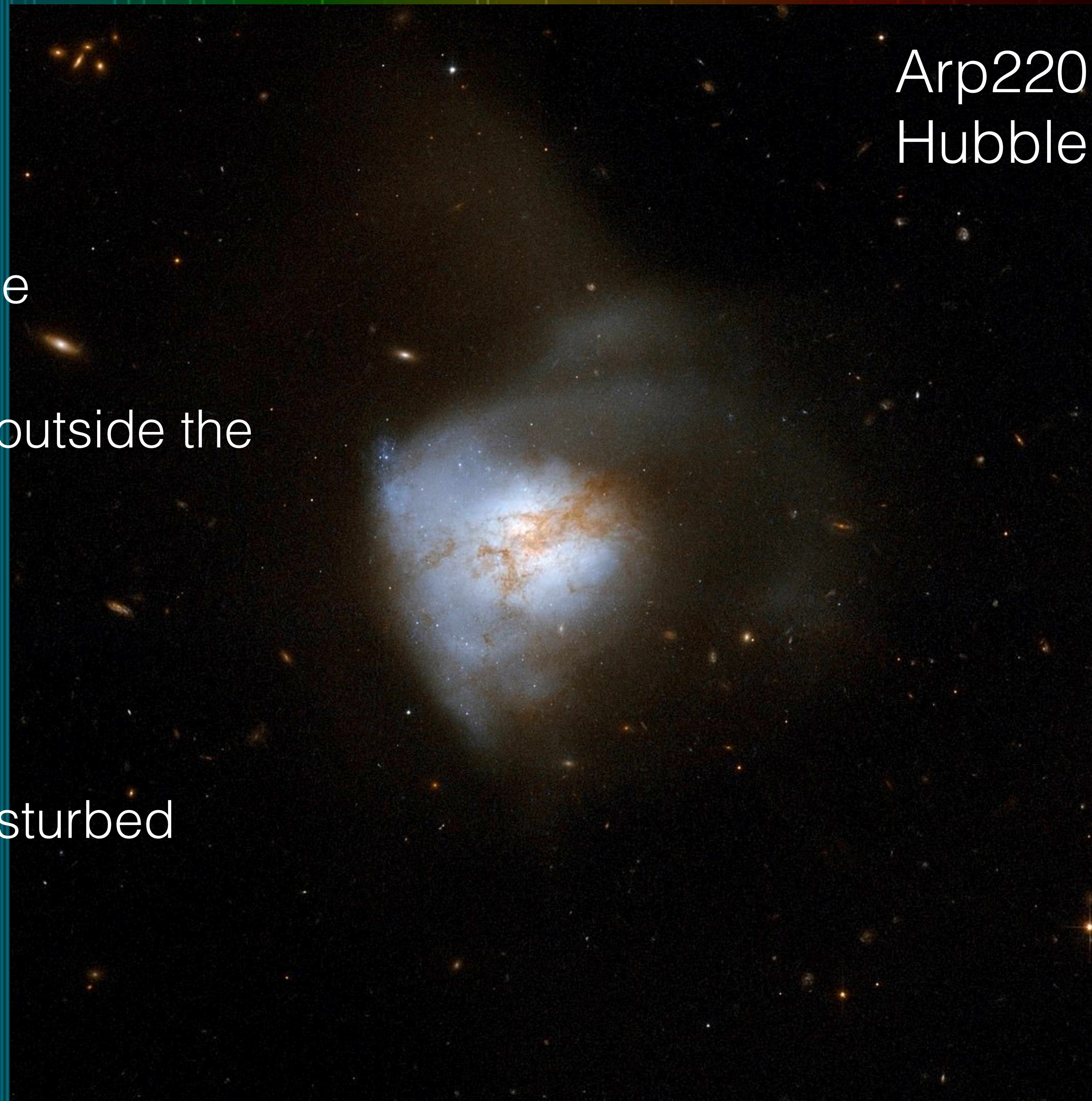
Why Extreme?

- Most star formation in Universe appears to follow simple rules
- However in extreme environments, these rules are either altered or harder to determine
- Star formation in these environments therefore give clues on the underlying physics of star formation
- At their core, it is the physics of the ISM diving these differences

- DISCLAIMER!! - this is a rapid view with biases, there is much more out there!

Extreme Environments?



- What are extreme environments?
  - Environments outside the norm
- ULIRGs
- Starbursts
- AGN
- Kinematically disturbed regimes

Overview

- ULIRGs (a historical perspective & recent update)
- Starbursts
- Kennicutt-Schmidt relation
- The ISM of Starbursts/ULIRGS
- AGN & their ISM
- Outflows
- Star formation & ISM in kinematically disturbed regions

ULIRGS

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Extremely bright

- Since the advent of IR, some galaxies found to emit more in IR than optical (Riecke & Lebofsky 1979)
- Some were known quasars or clear AGN
- Others were found to host a remarkable amount of star-formation activity
- These are the first "Starbursts"

Image courtesy NASA

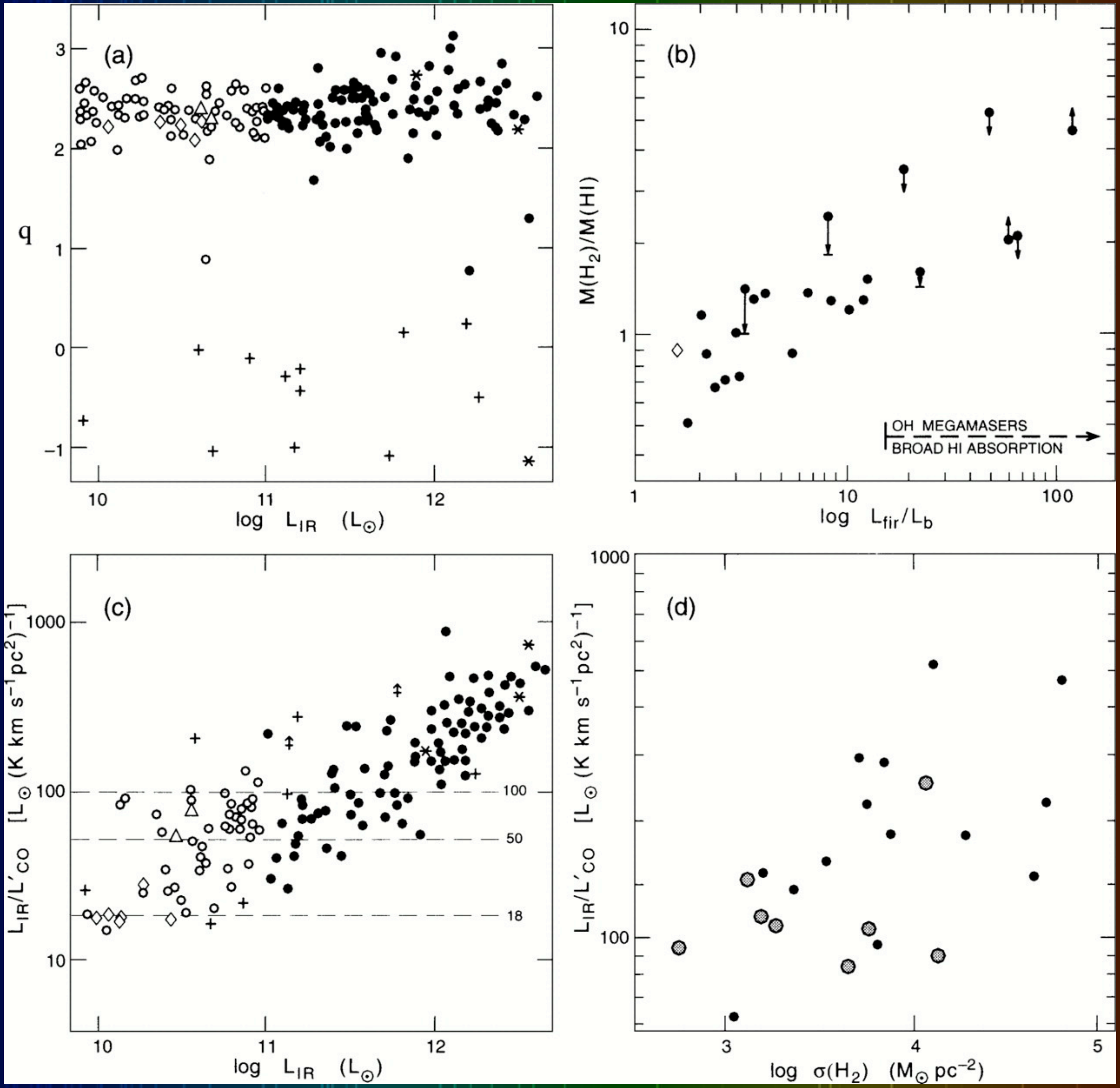
ULIRGS

Credit: NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

- Ultra Luminous InfraRed Galaxies (ULIRGs): $L_{IR} > 10^{12}$ $L_{\odot}$ (LIRGS > 10^{11} $L_{\odot}$, HyLIRGS > 10^{13} $L_{\odot}$, SMGs…)
- Locally found earlier (Riecke & Lebofsky 1979) but many found with advent of IRAS (Houck et al. 1985)
- Most Luminous (non-transient) sources in Universe
- See early review of ULIRGs Sanders & Mirabel (1996)

Physics of ULIRGs

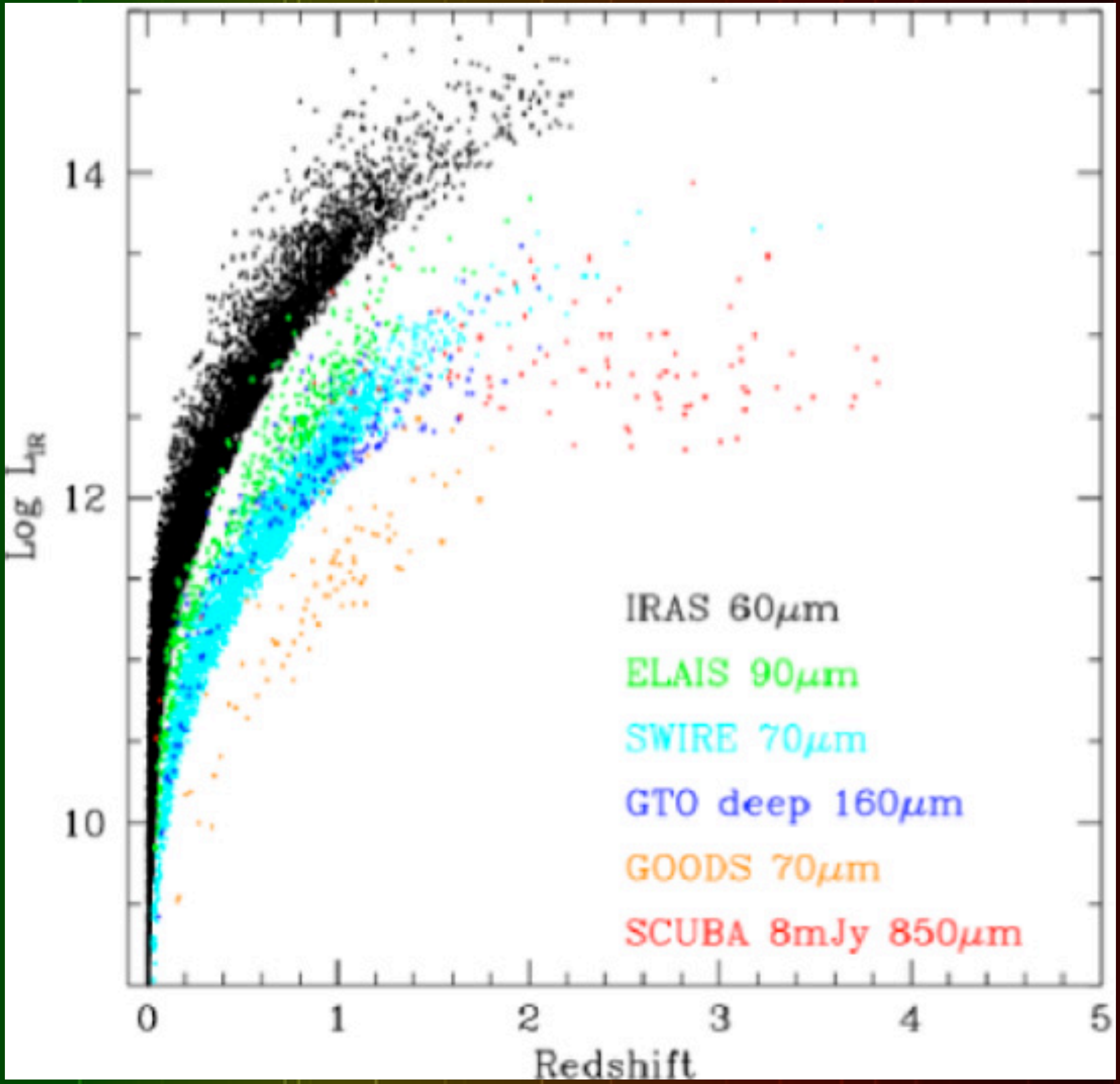
IR/1.4 GHz



Sanders & Mirabel+1996

ULIRGs

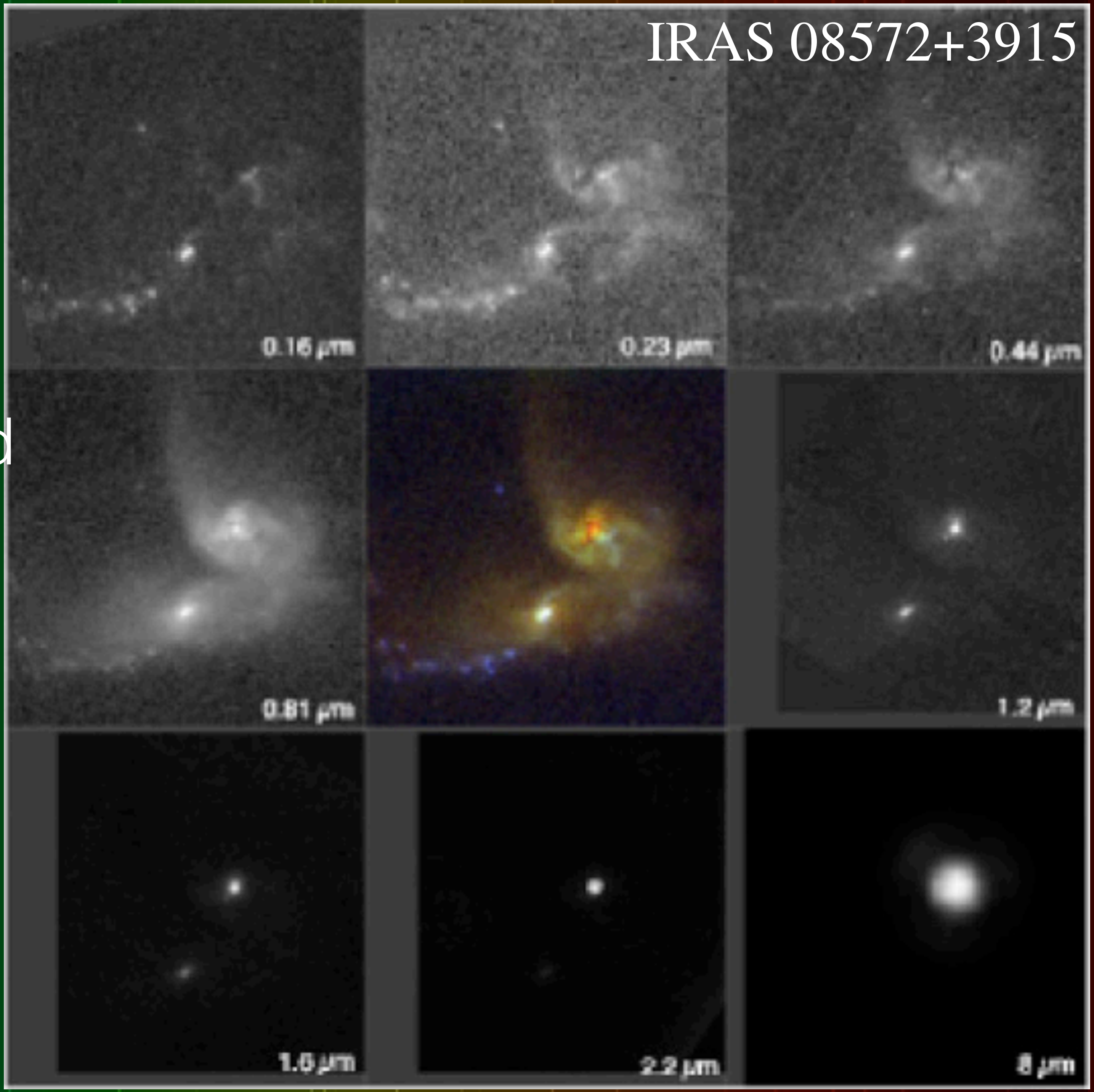
- Locally most ULIRGs are mergers or interactions
- At higher z, evolution of typical SFR means some non-merger ULIRGs found
- Strong evolution with redshift ($L_{IR} \sim (1+z)^4$), but linked to evolution of star formation rate
- While bright, they are rare; only ~3% of total energy density (6% IR energy density; Lonsdale, Farrah & Smith 2006)
- At high z see review Casey, Narayanan, Cooray, 2014.



Lonsdale, Farrah, Smith (2006)

ULIRGs

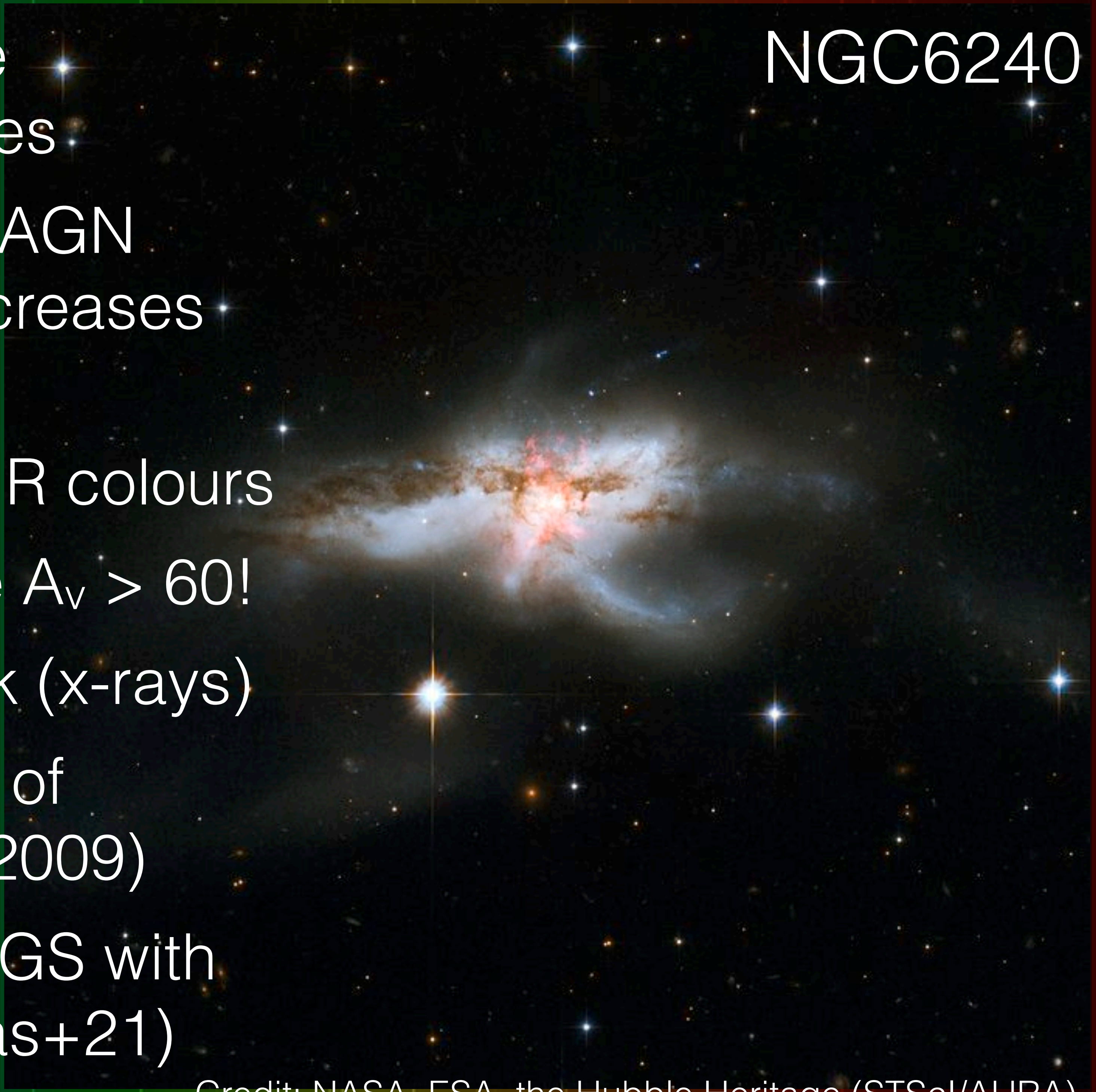
- Locally most ULIRGs are mergers or interactions
- At higher z, evolution of typical SFR means some non-merger ULIRGs found
- Issues are optical depth
- UV originates different sites
- ID heating mechanism hard



Lonsdale, Farrah, Smith (2006)

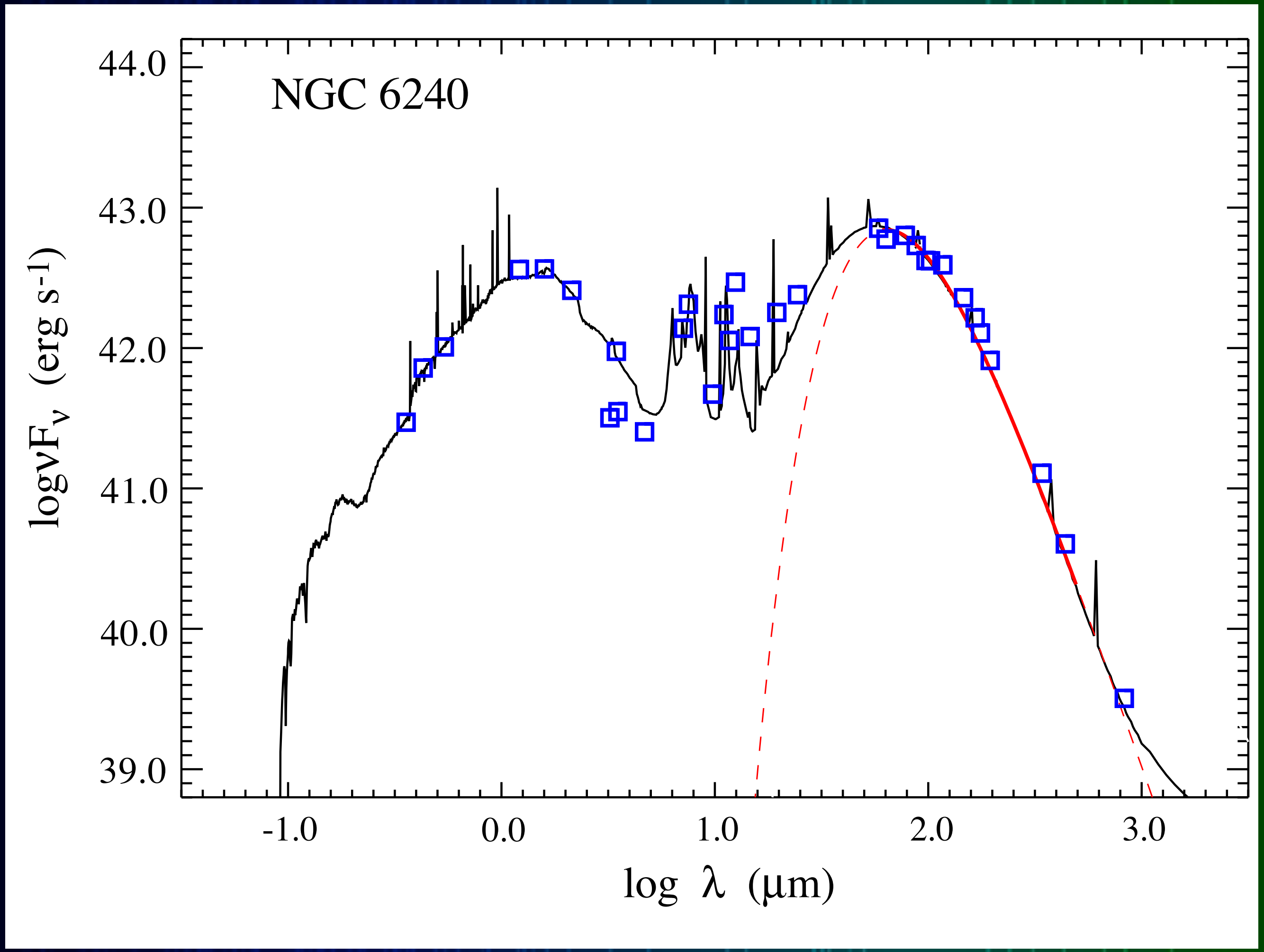
Heating the monsters

- Most ULIRGs heating can be identified with optical/NIR lines
- All have significant SFR, but AGN fraction high (> 25%) and increases with L_{IR}
- AGN also have warmer mid-IR colours
- However some ULIRGs have A_V > 60!
- Can even be Thompson thick (x-rays)
- GOALS survey has overview of identifying ULIRGs (Armus+2009)
- Next PUMA: Physics of ULIRGS with MUSE & ALMA (Perna,Arribas+21)



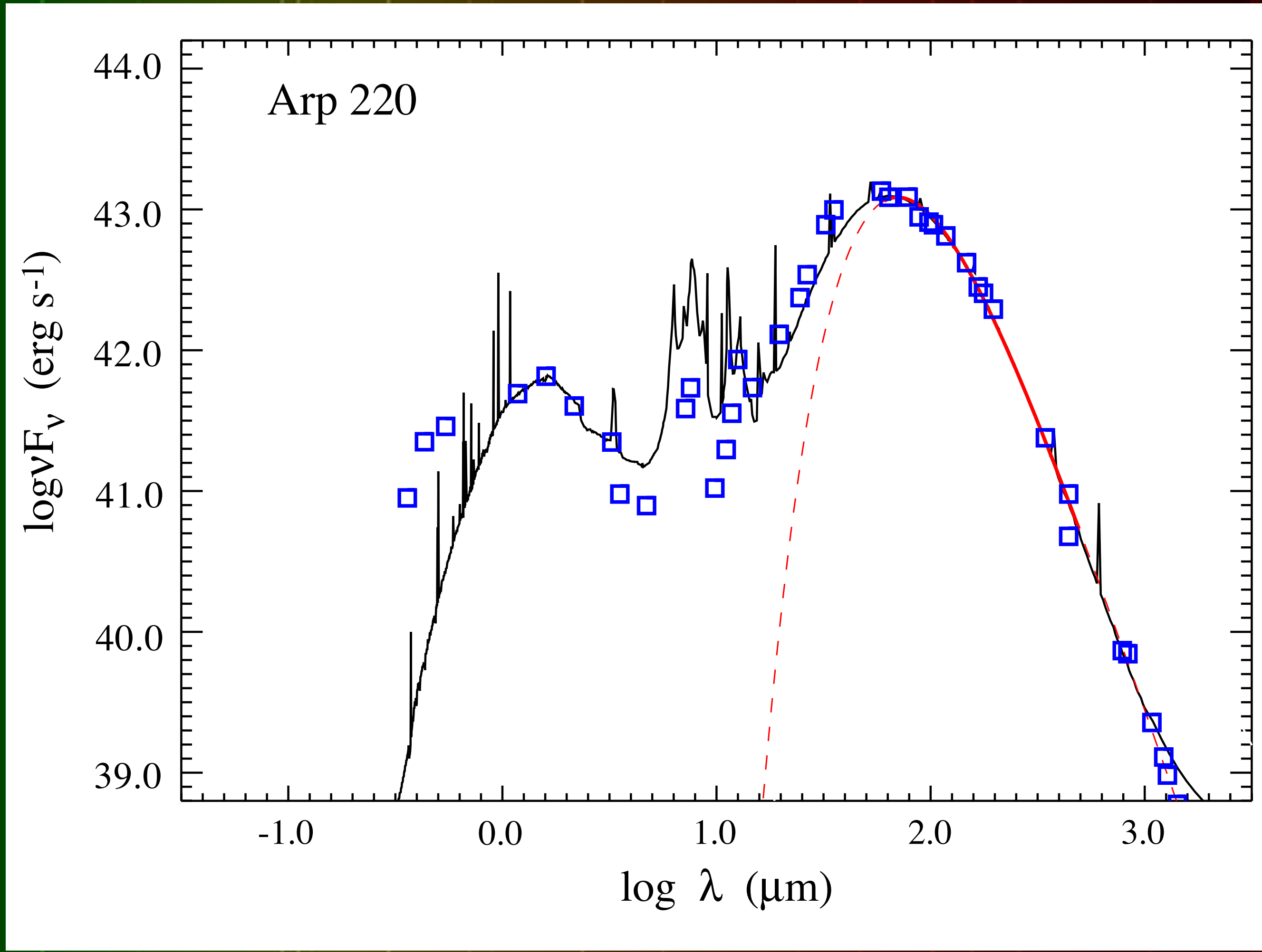
Credit: NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University)

Measuring SFR in ULIRGs



- SFRs in ULIRGs are easy & hard
- Basically perfect bolometers
- L_{IR} ~ SFR

Groves+2008

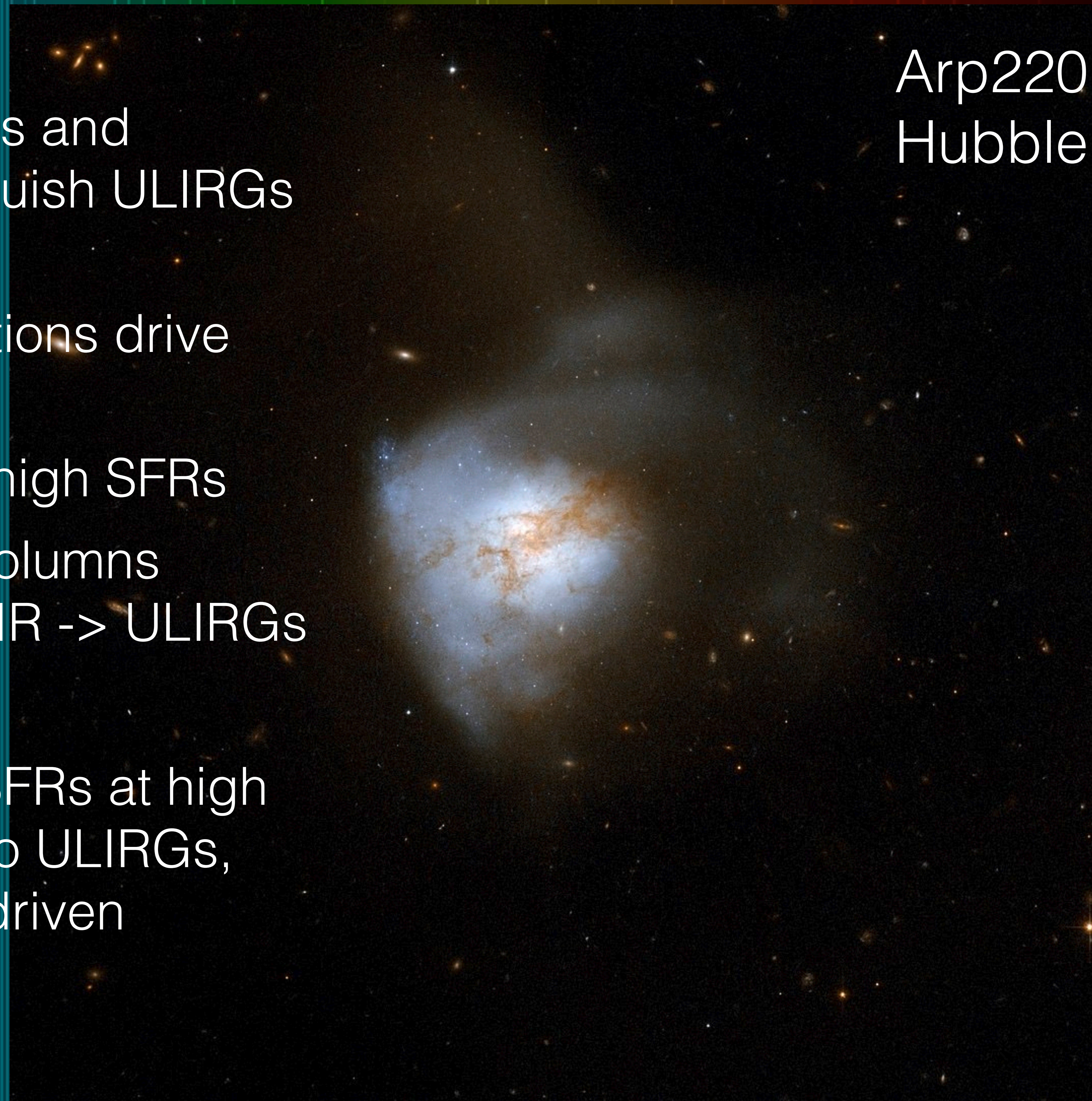


- Main issue - what fraction of heating by stars or AGN?

Drivers?

- High gas masses and densities distinguish ULIRGs (mostly H_2)
- Mergers/interactions drive gas to centres
- Lead to AGN & high SFRs
- High gas/dust columns process light to IR -> ULIRGs

- At high z, high SFRs at high mass can lead to ULIRGs, but not merger driven



Arp220
Hubble

Why ULIRGs?

- Extreme monsters
- High gas densities & High SFRs (> 1000 $M_\odot$/yr!)
- Warm H2 (NIR lines observed)
- Shocks ([FeII] and H_2 observed in NIR, strong gas flows)
- AGN
- Compact (high surface brightness)
- High optical depths (even to IR!)
- Luminosity means visible across cosmic time (plus negative k-correction)

Why not ULIRGs?

- Extreme monsters (limited number)
- Huge optical depths make diagnostics hard
- Shocks, high densities, AGN & obscuration mean Xco & densities uncertain
- Fractional contribution of AGN mean SFR uncertain
- How to study star formation when its hard to see?

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- ULIRGs are complex & rare
- While part of the next discussion I'll split these into Starbursts and AGN, but remember that ULIRGs will be in both

Starbursts

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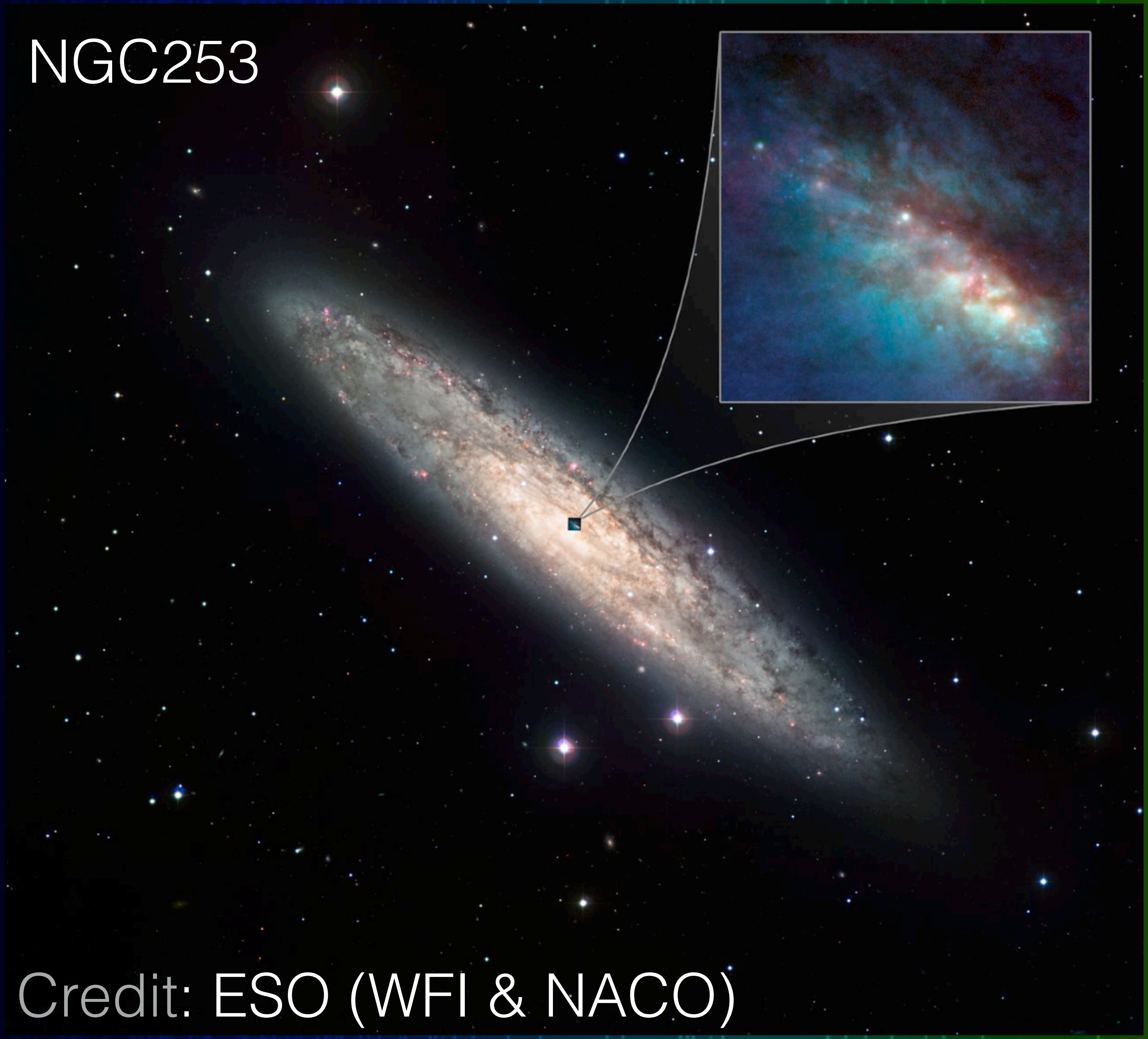
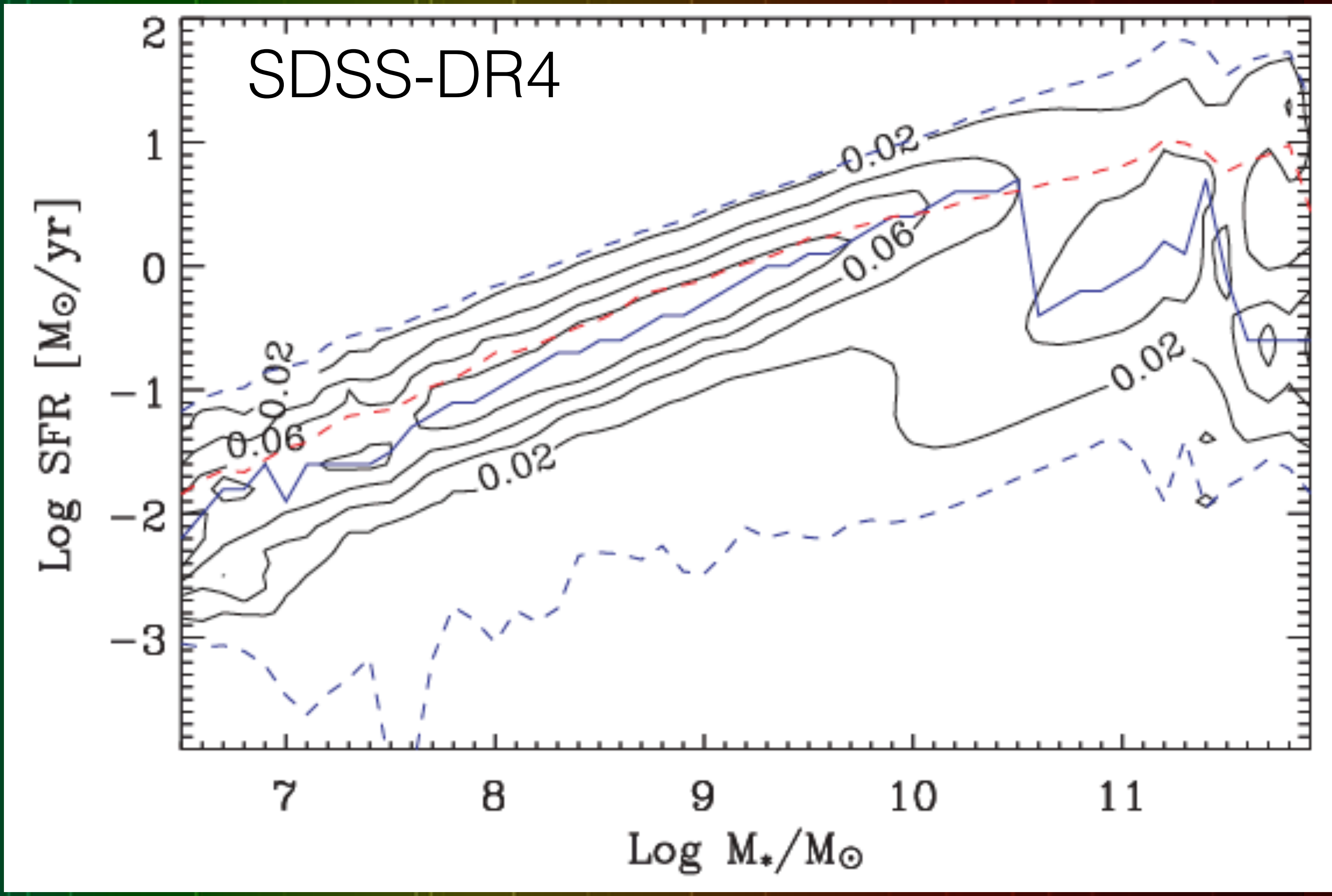
Starbursts



- Starbursts are places with excessive star formation
- This can either be global or as density
- In nearby galaxies typically manifests as circumnuclear rings or starbursts
- But what's "excessive"?

Starbursts

- Most star-forming galaxies follow a relation between $M_\star$ and SFR ("Main-Sequence")

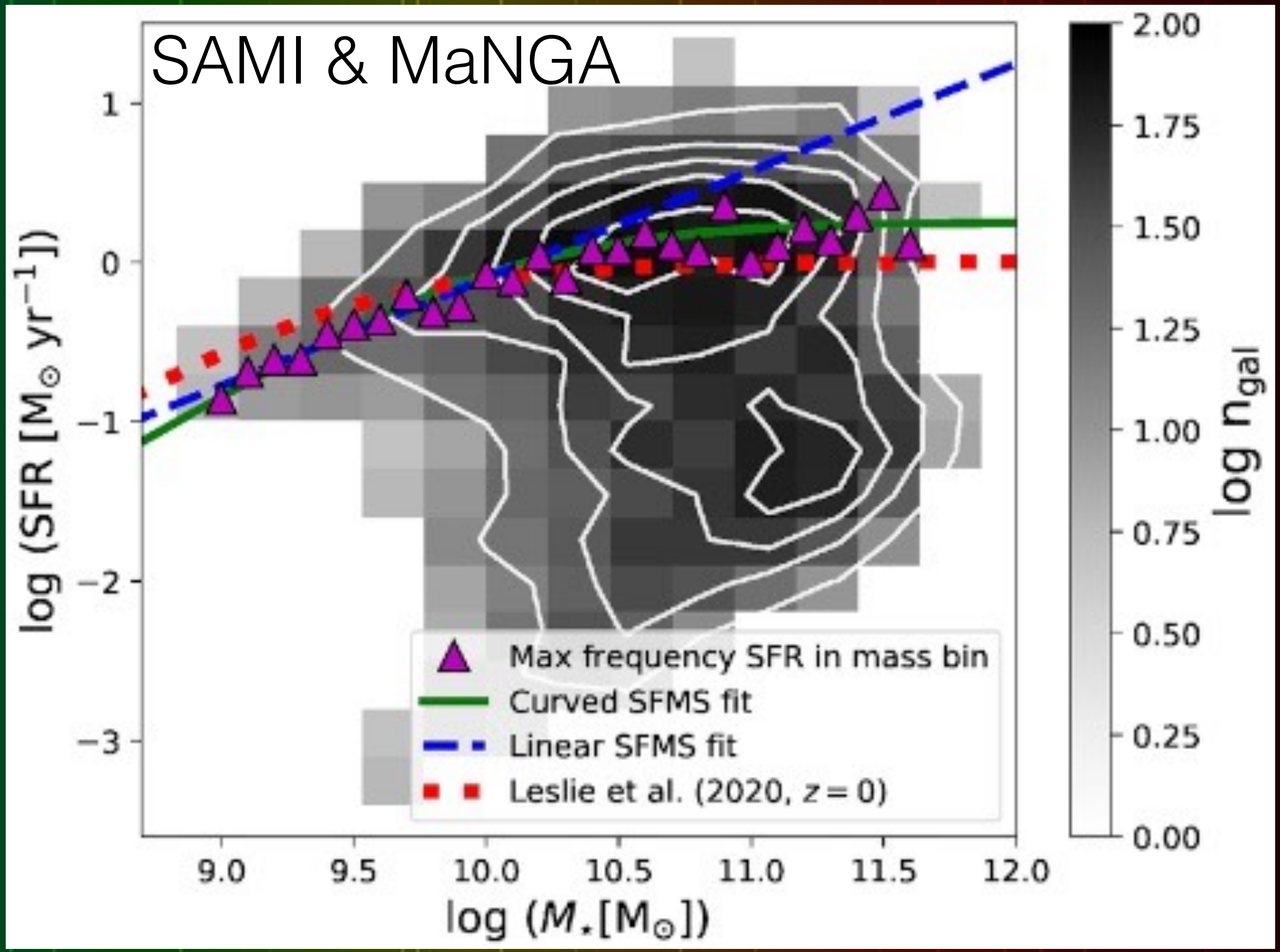


Brinchmann+2004

D. Dale talk yesterday

Starbursts

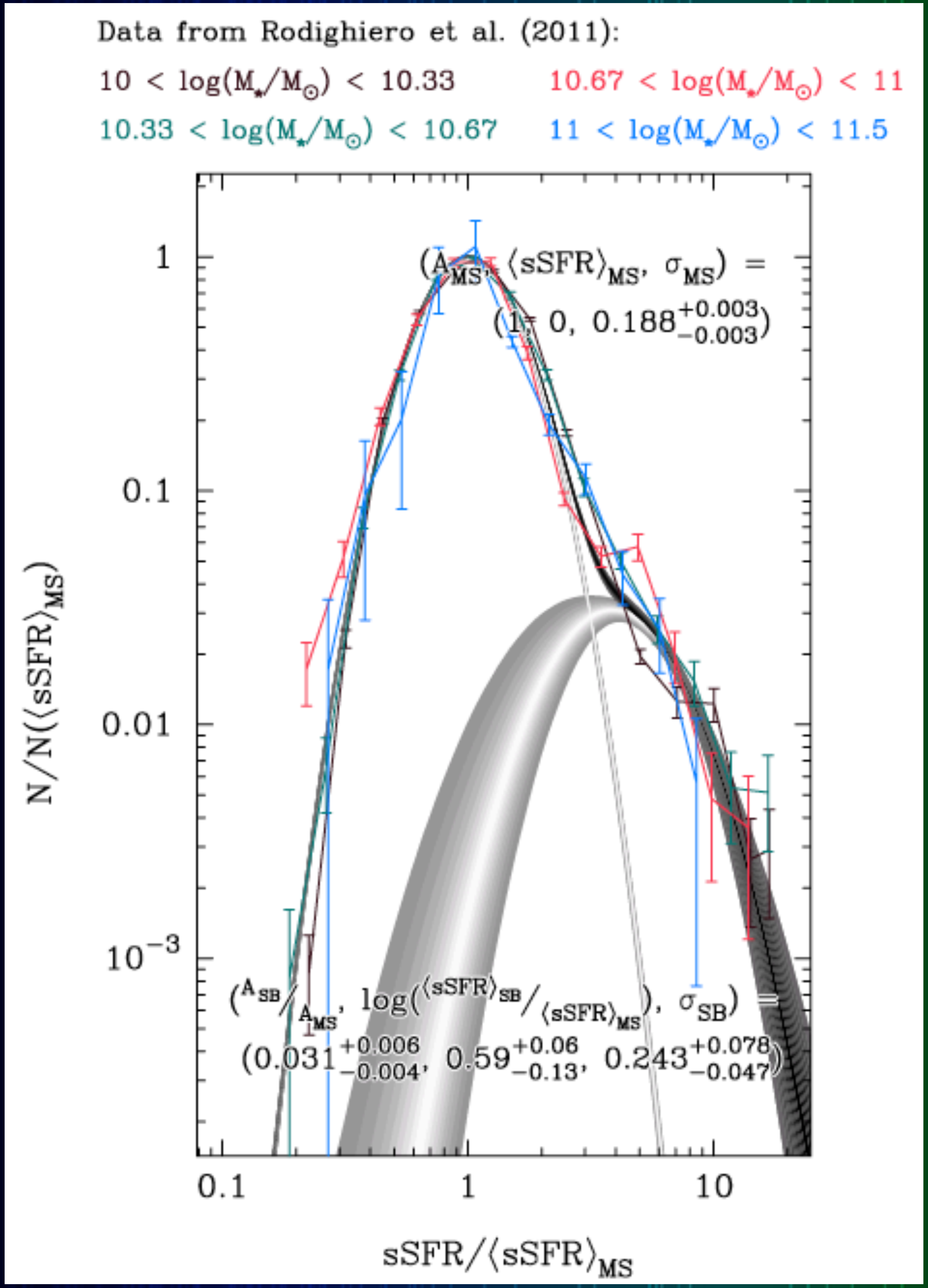
- Most star-forming galaxies follow a relation between M⋆ and SFR (“Main-Sequence”)
- Many fall below this (Passive/Quenched)
- But some have much higher star formation
- These are Starbursts



Fraser-McKelvie+2021

D. Dale talk yesterday

Starbursts

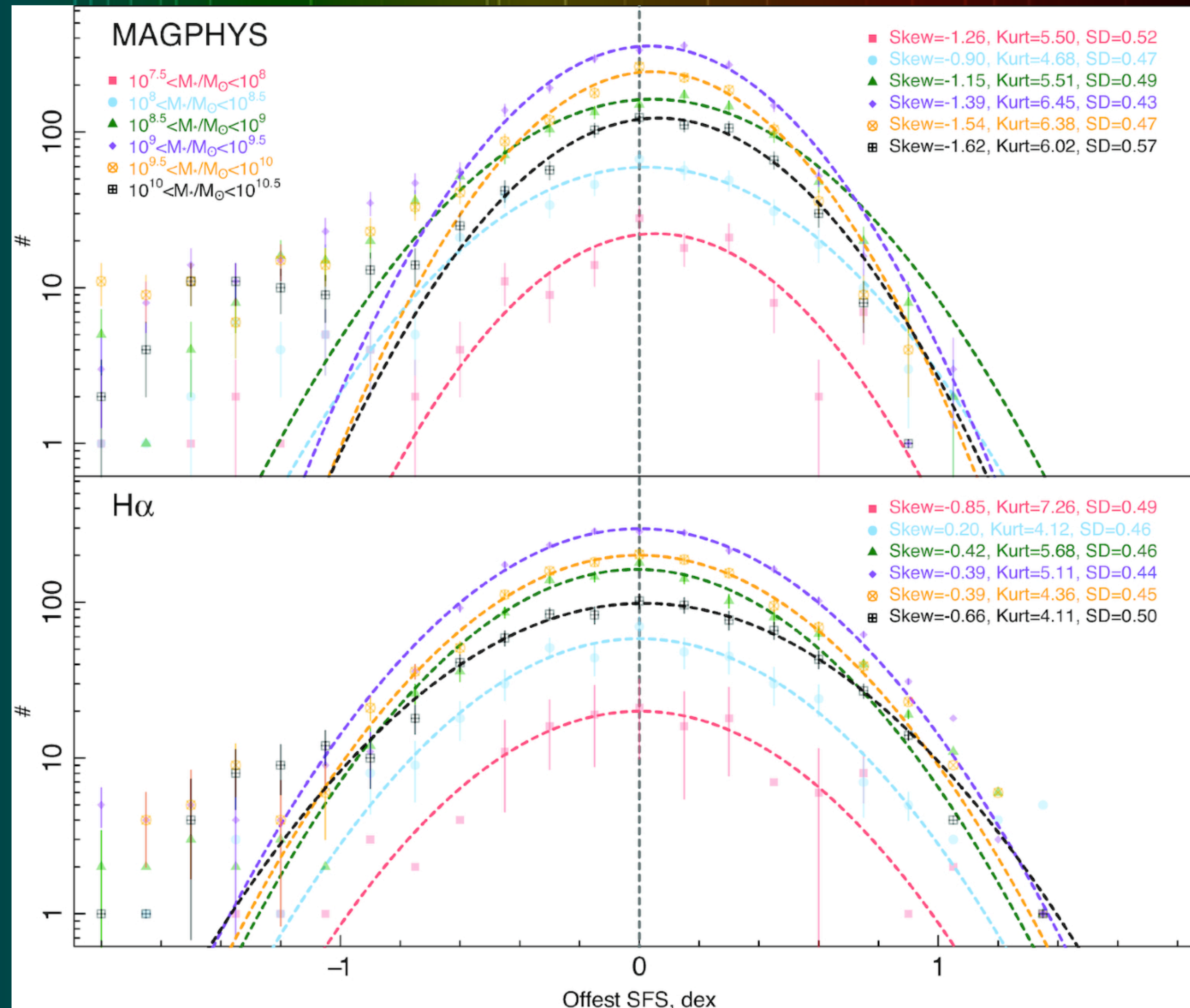


Sargent+2012

- Simplistically, Starbursts have excessive SFR (either as a function of mass or $\Sigma_{M\star}$)
- A few % relative to MS galaxies
- Are gas rich & increased extinction

Variation in the main-sequence

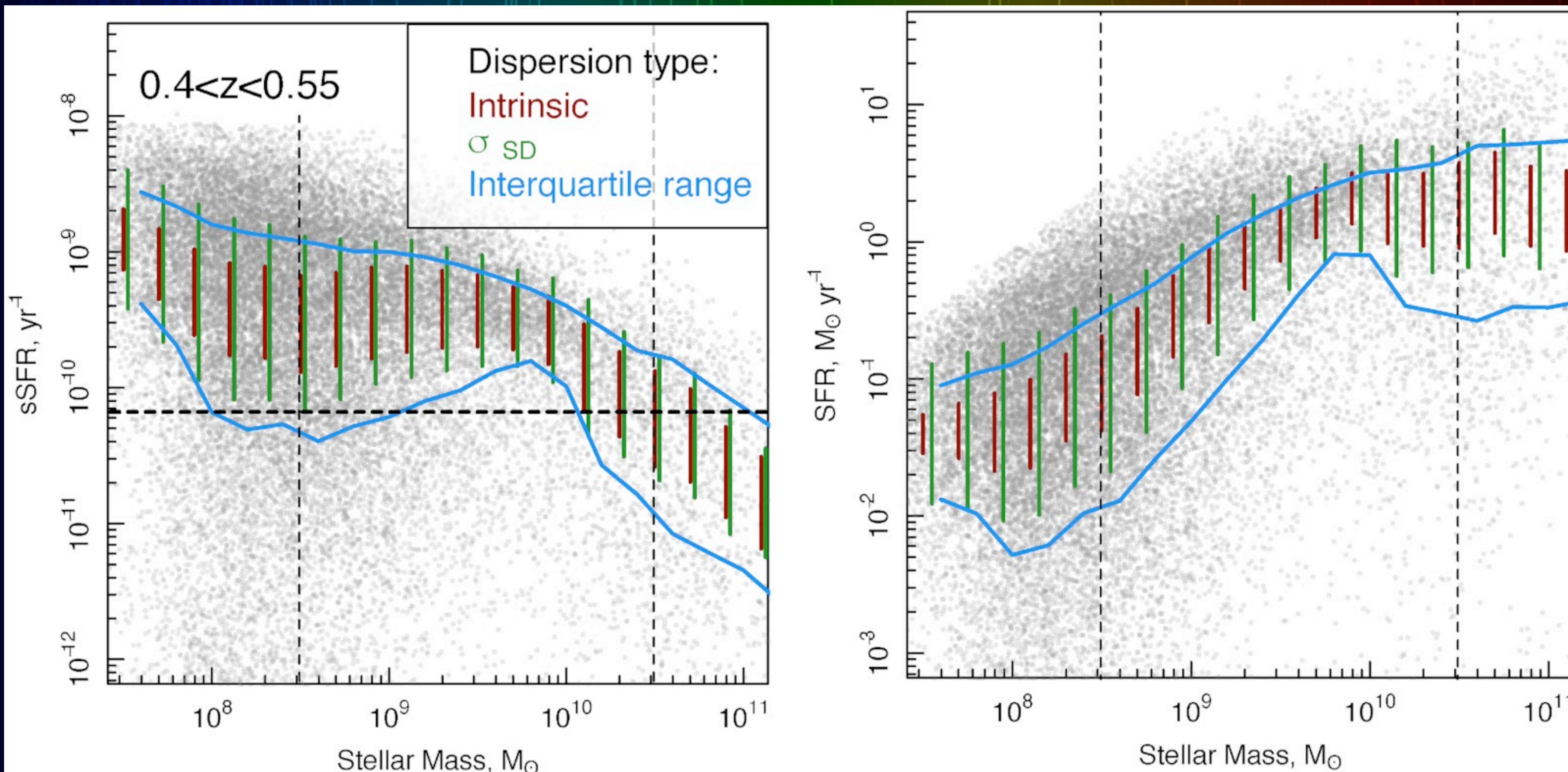
- Given uncertainty with MS and dispersion exact definition of SBs malleable



GAMA/DEVILS sample

Davies+2019

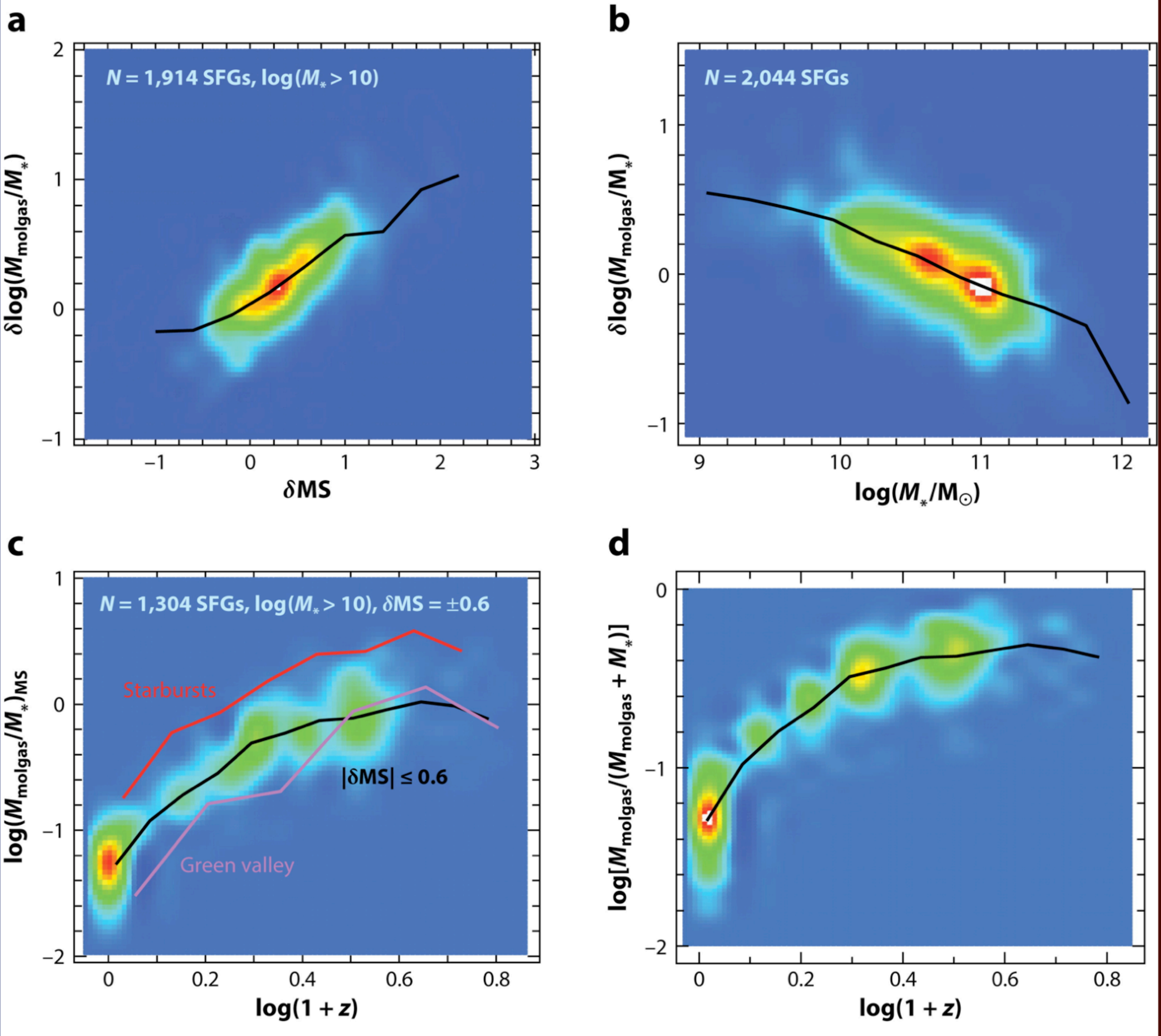
Variation in the main-sequence



GAMA/DEVILS sample

Davies+2022

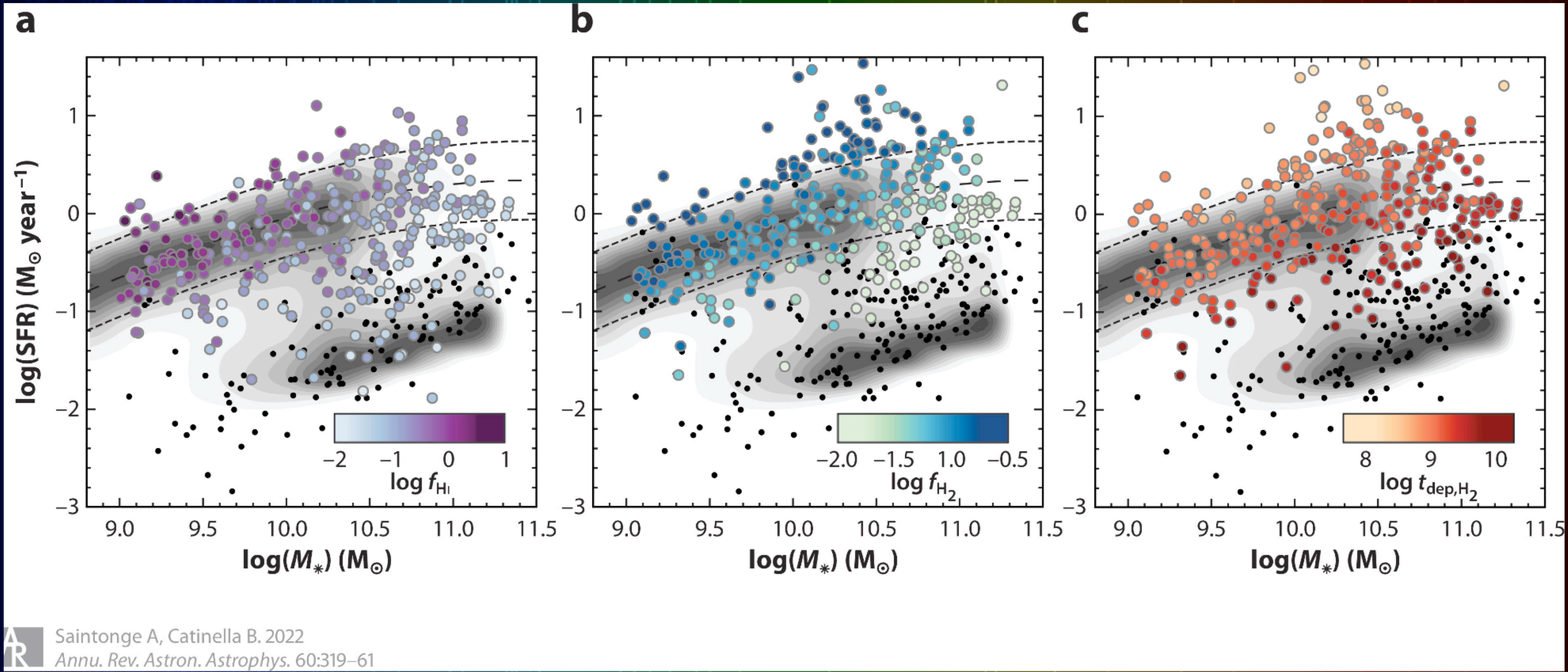
Excess SFR varies with z



Tacconi LJ, et al. 2020.
Annu. Rev. Astron. Astrophys. 58:157–203

Variation of Gas over MS

- Globally we see $f_{HI}=M_{HI}/M_\star$ decrease with increasing $M_\star$

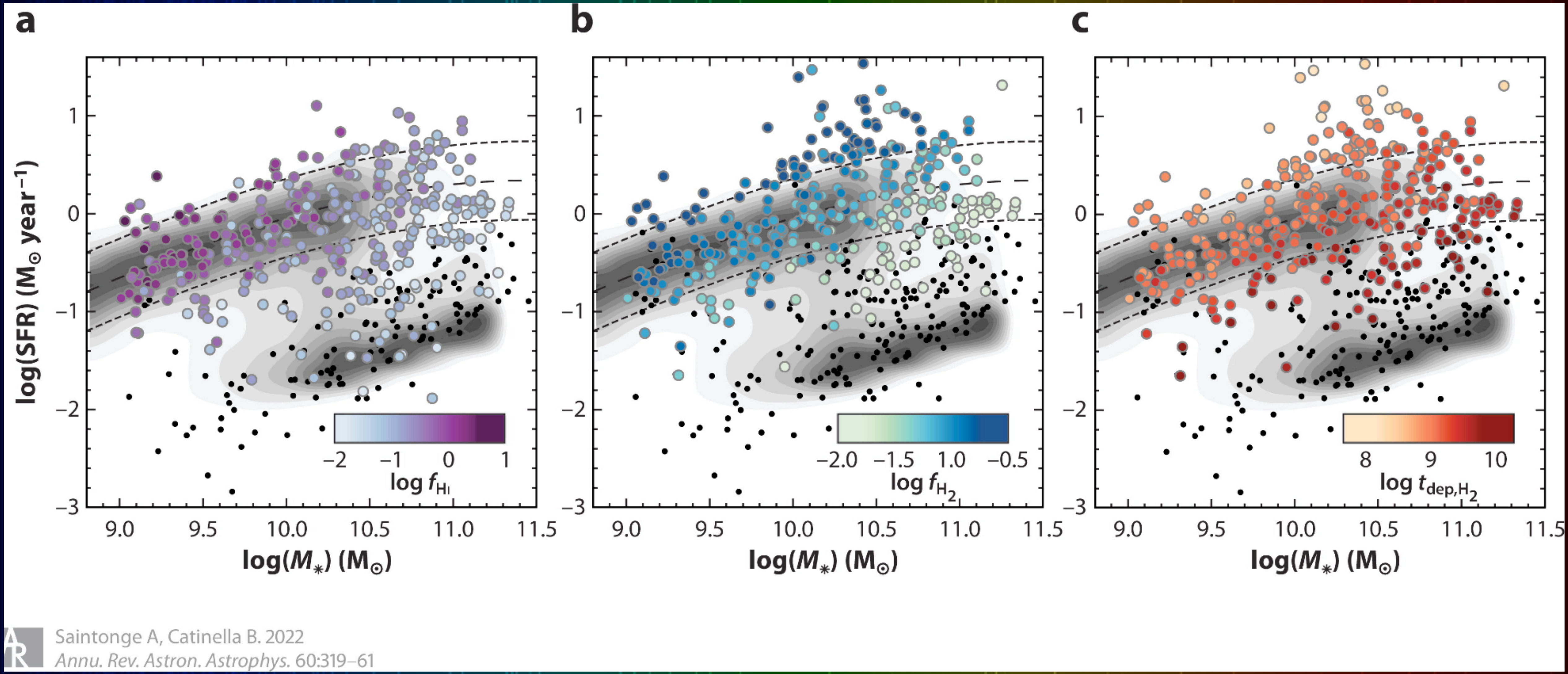


xCOLDGASS

Saintonge, Catinella+ (2022)

Variation of Gas over MS

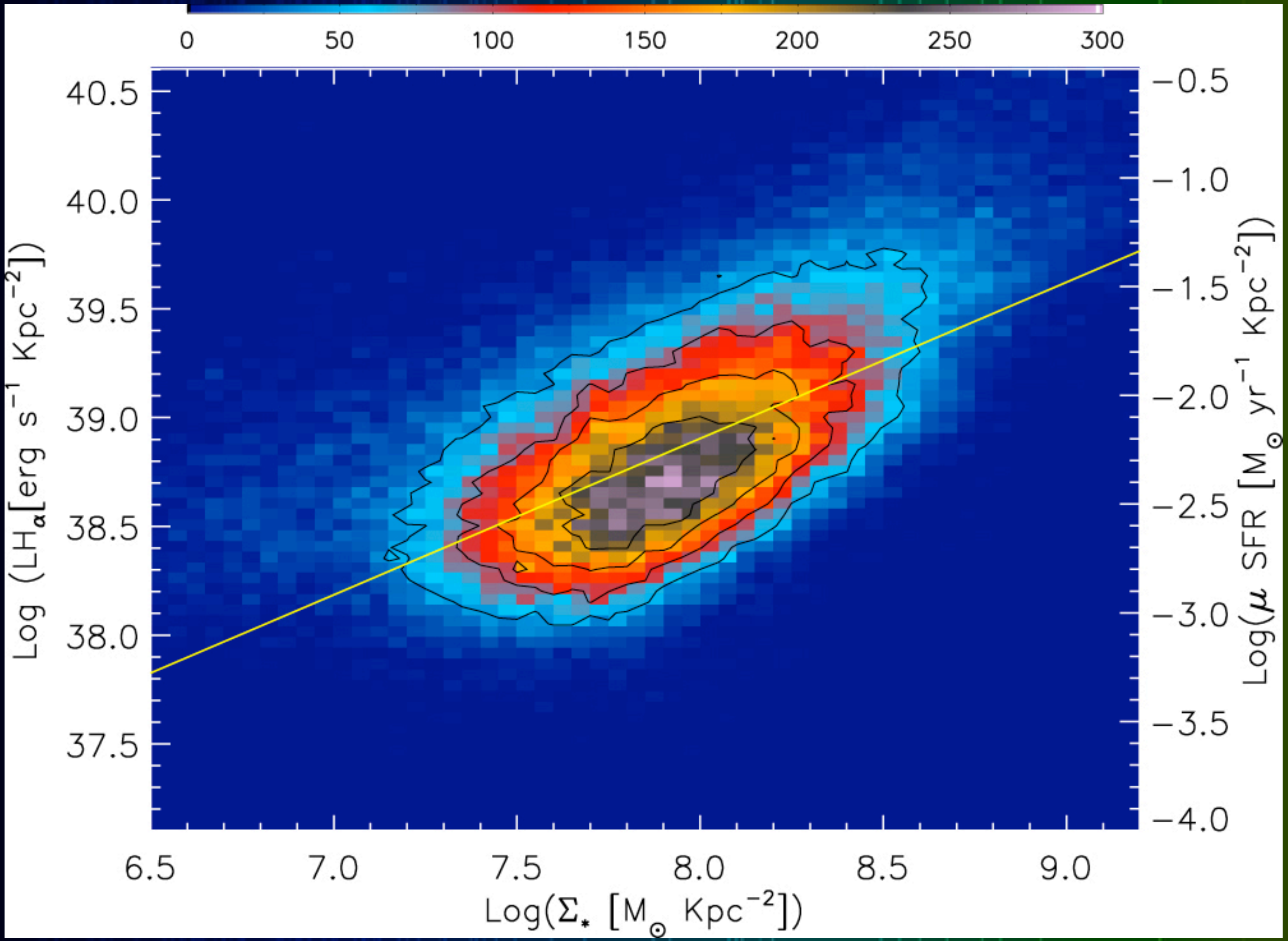
- Globally we see $f_{HI}=M_{HI}/M_\star$ decrease with increasing $M_\star$
- But $f_{H2}=M_{H2}/M_\star$ increasing with increasing SFR at same $M_\star$



xCOLDGASS

Saintonge, Catinella+ (2022)

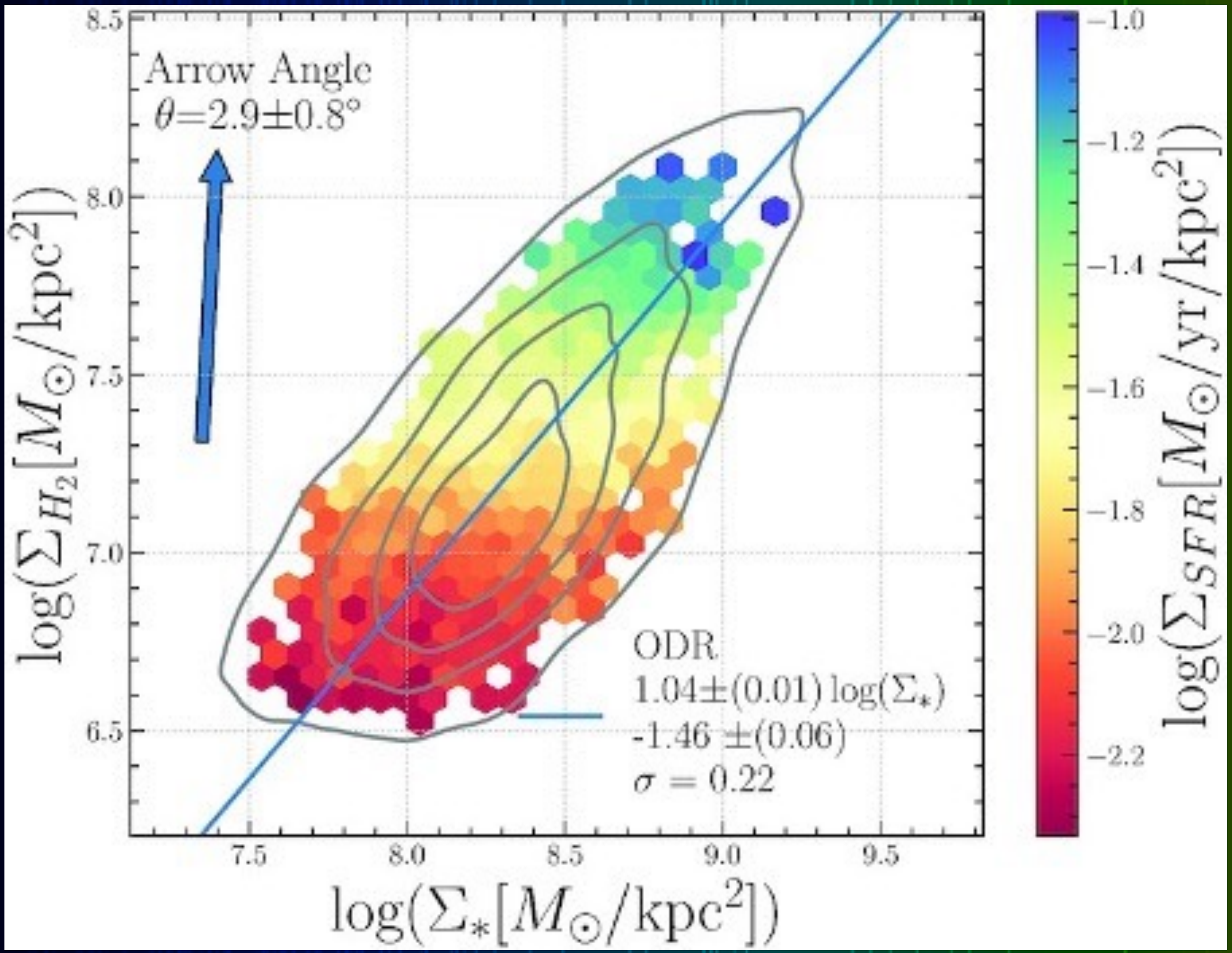
Resolved Main-Sequence



CALIFA: Cano-Díaz+2020

- The star forming main sequence also appears at resolved scales (~kpc)

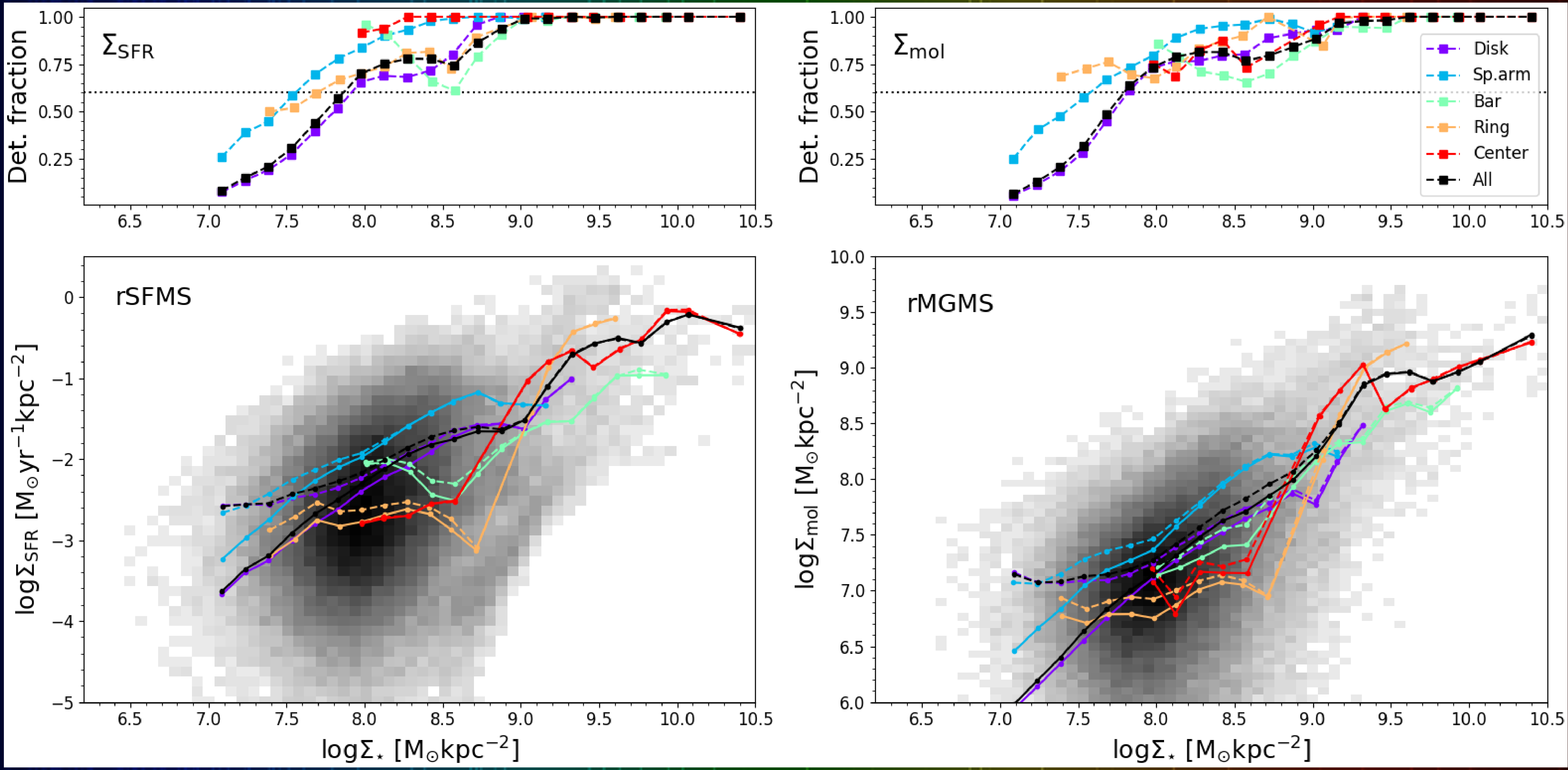
Resolved Main-Sequence



ALMA/MaNGA:Baker+2022

- The star forming main sequence also appears at resolved scales (~kpc)
- However this appears mostly to be driven by the Σ_{H2} -$\Sigma_{\star}$ relation

Resolved Main-Sequence

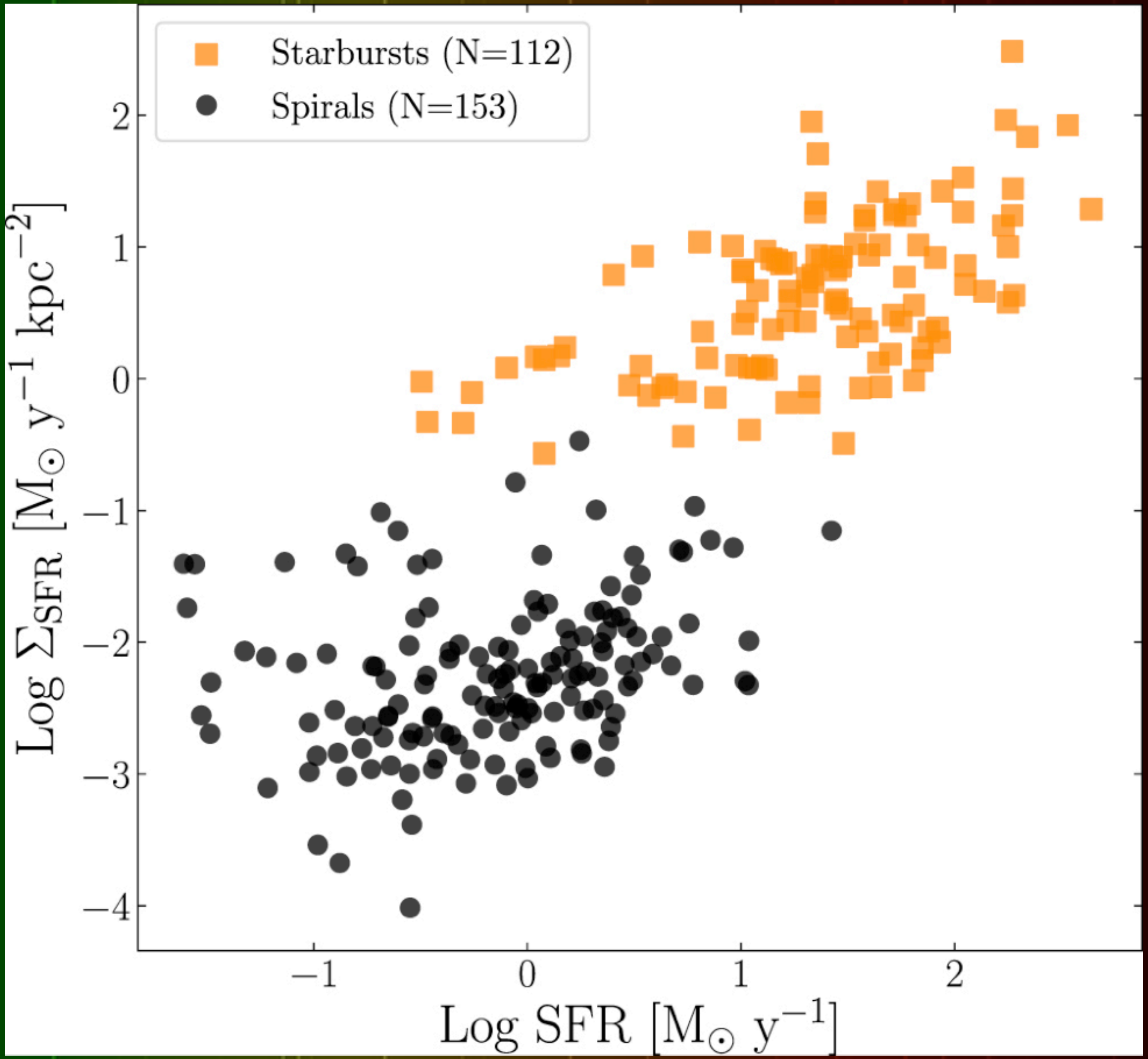


Pessa+ (2022)

- We also start to see variation in these relations as a function of galactic environment

Resolved Starbursts

- Note going forward:
- I tend to interchange global & resolved starbursts
- However generally global == local starburst
- But resolved =/= global
- For nearby galaxies, we're limited by small number of global starbursts



Kennicutt & De Los Reyes (2021)

Resolved Starbursts

- 'Resolved' Starbursts in nearby galaxies tend to be circumnuclear
- Located in barred or interacting galaxies
- Bars or interactions drive gas into centre (e.g. Sormani+2023 for NGC1097)
- Examples are NGC253, M82, NGC1365…
- Also associated with AGN (NGC1365, NGC1068, NGC1097…)

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Kennicutt-Schmidt Relation

OR

Depletion times & SF Efficiencies

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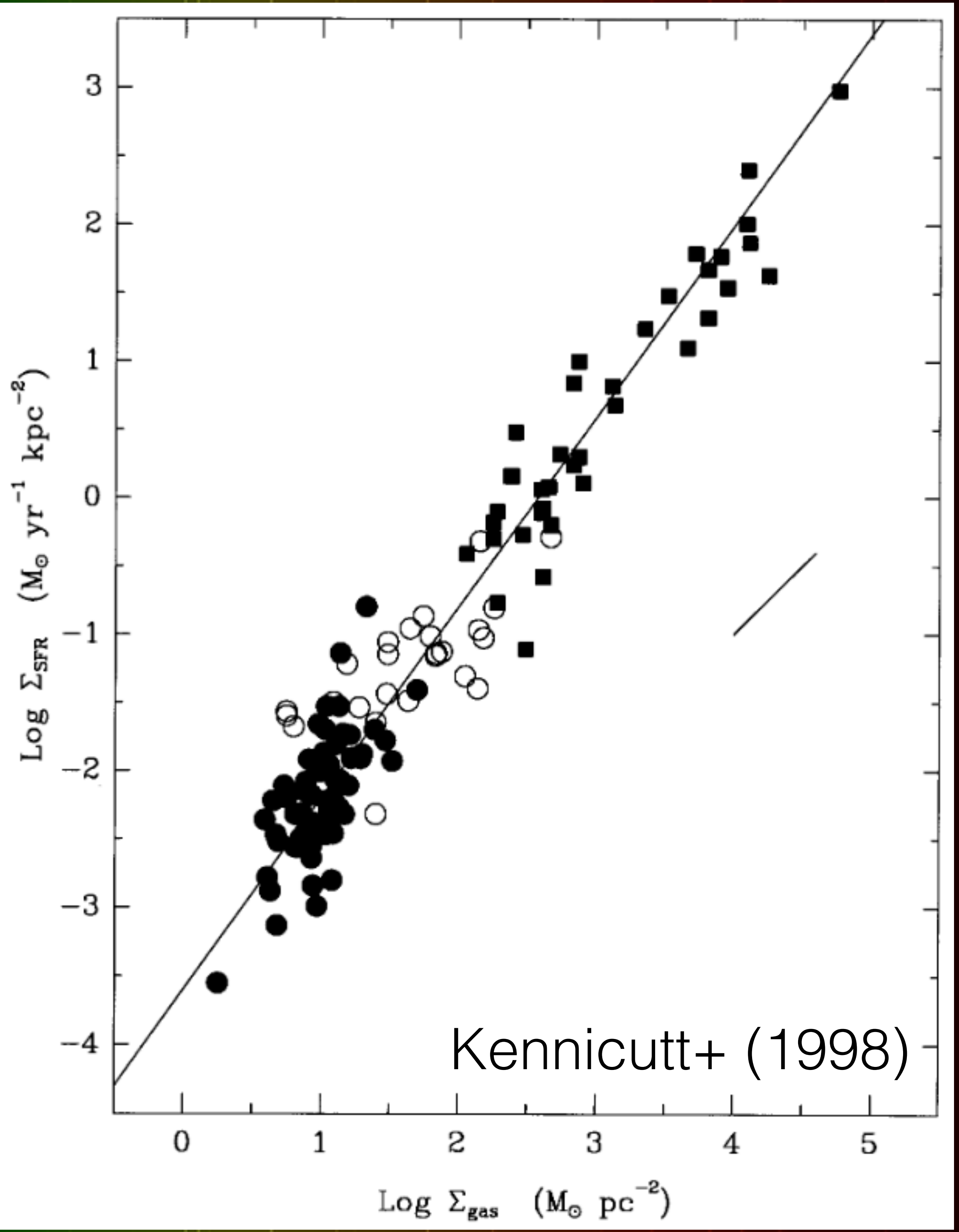
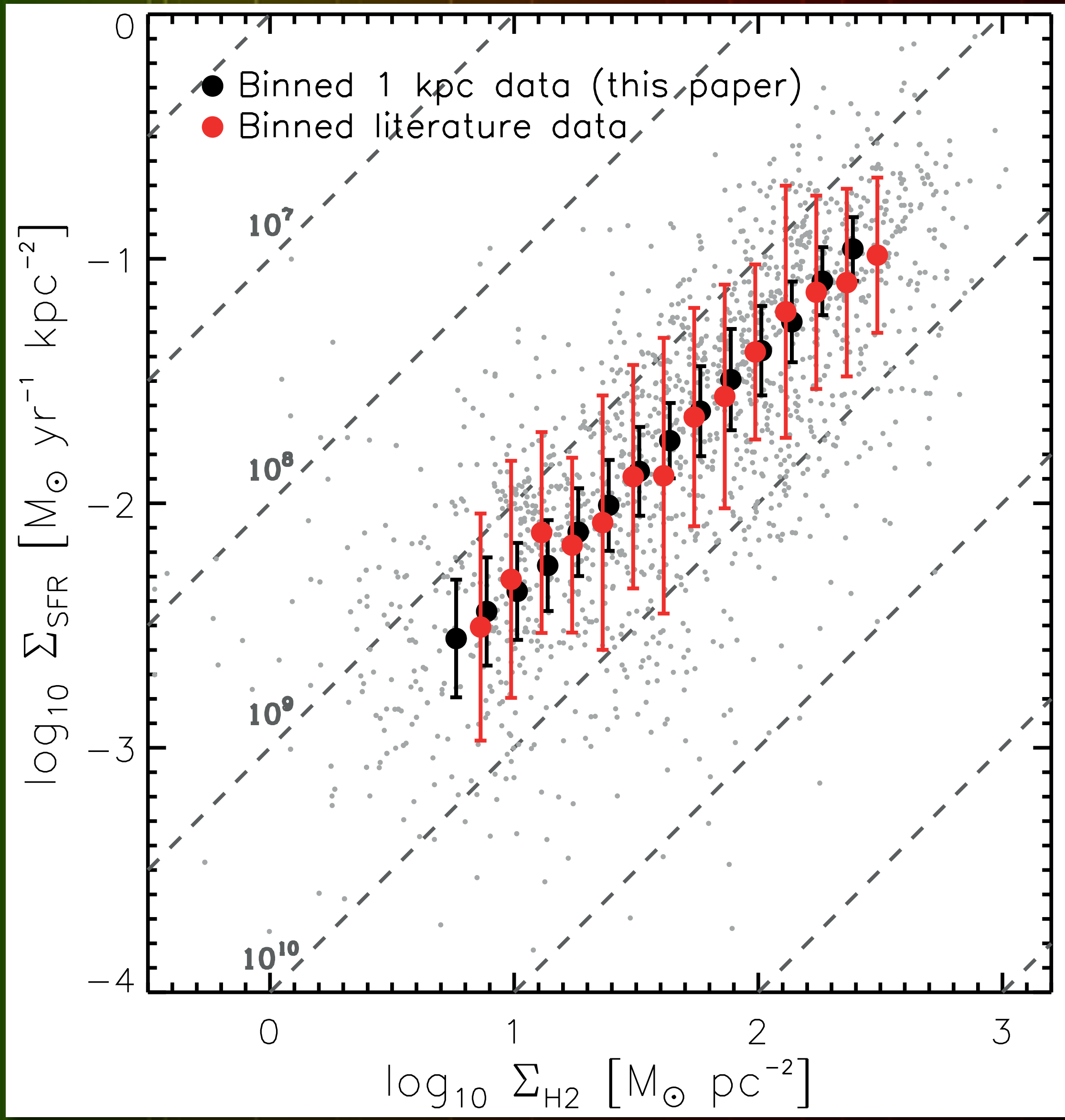
Kennicutt-Schmidt relation

- First put forward by Schmidt (1959) the relation between gas and stars has proven remarkably tight.
- Kennicutt (1998) put it together using nearby galaxies, including (nuclear) starbursts (squares)
- Depletion time τ_{dep}= Gas/SFR
- SF Efficiency = SFR*Δt/Gas



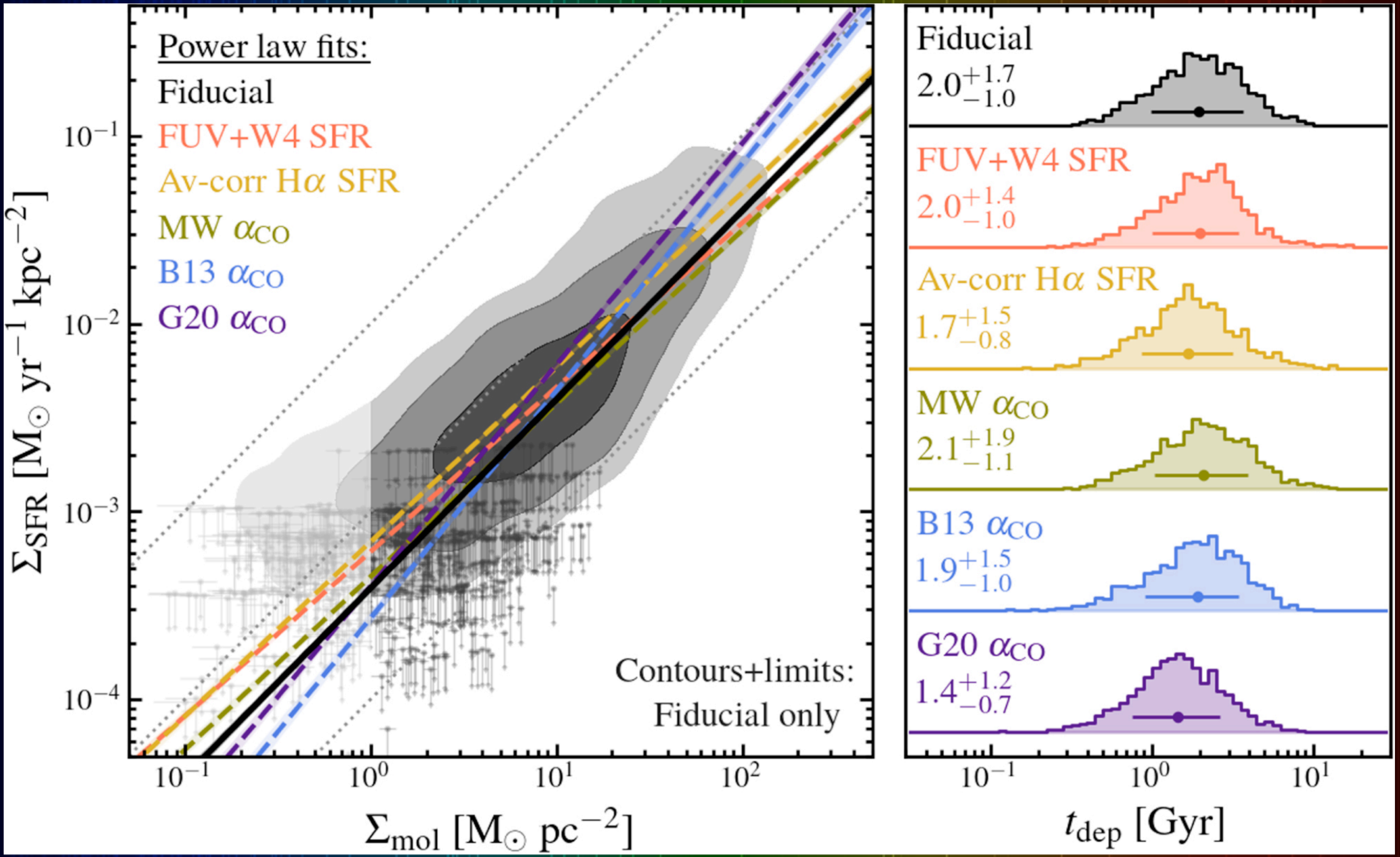
Kennicutt-Schmidt relation

- Heracles pushed this to kpc scales with Bigiel+2008,2011
- Finding a tight relation with constant depletion times of few x 10^9 yr
- PHANGS (Sun+2023 has only confirmed this)



Bigiel+ (2011)

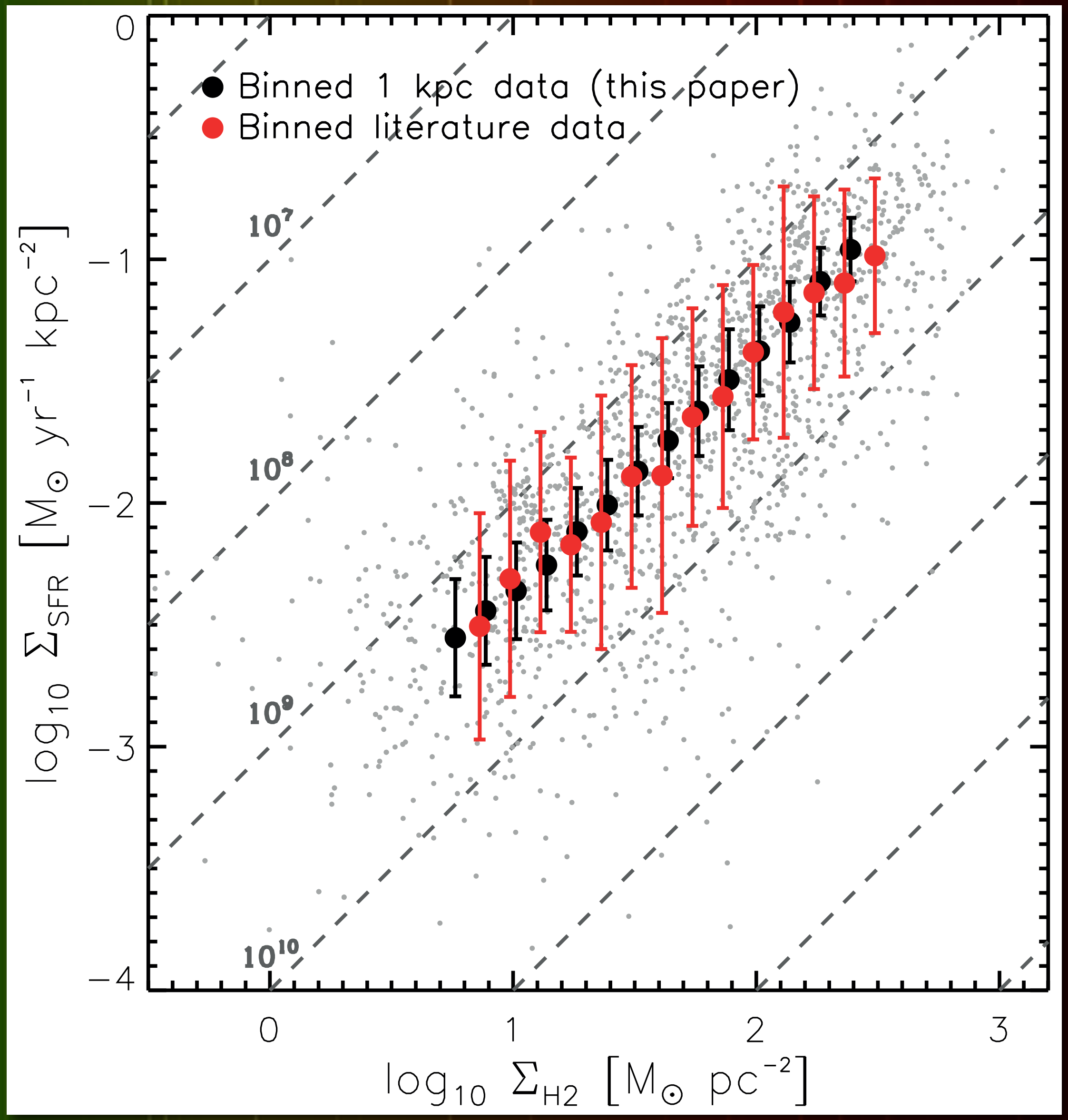
Kennicutt-Schmidt on kpc scales



Sun+ (2023)

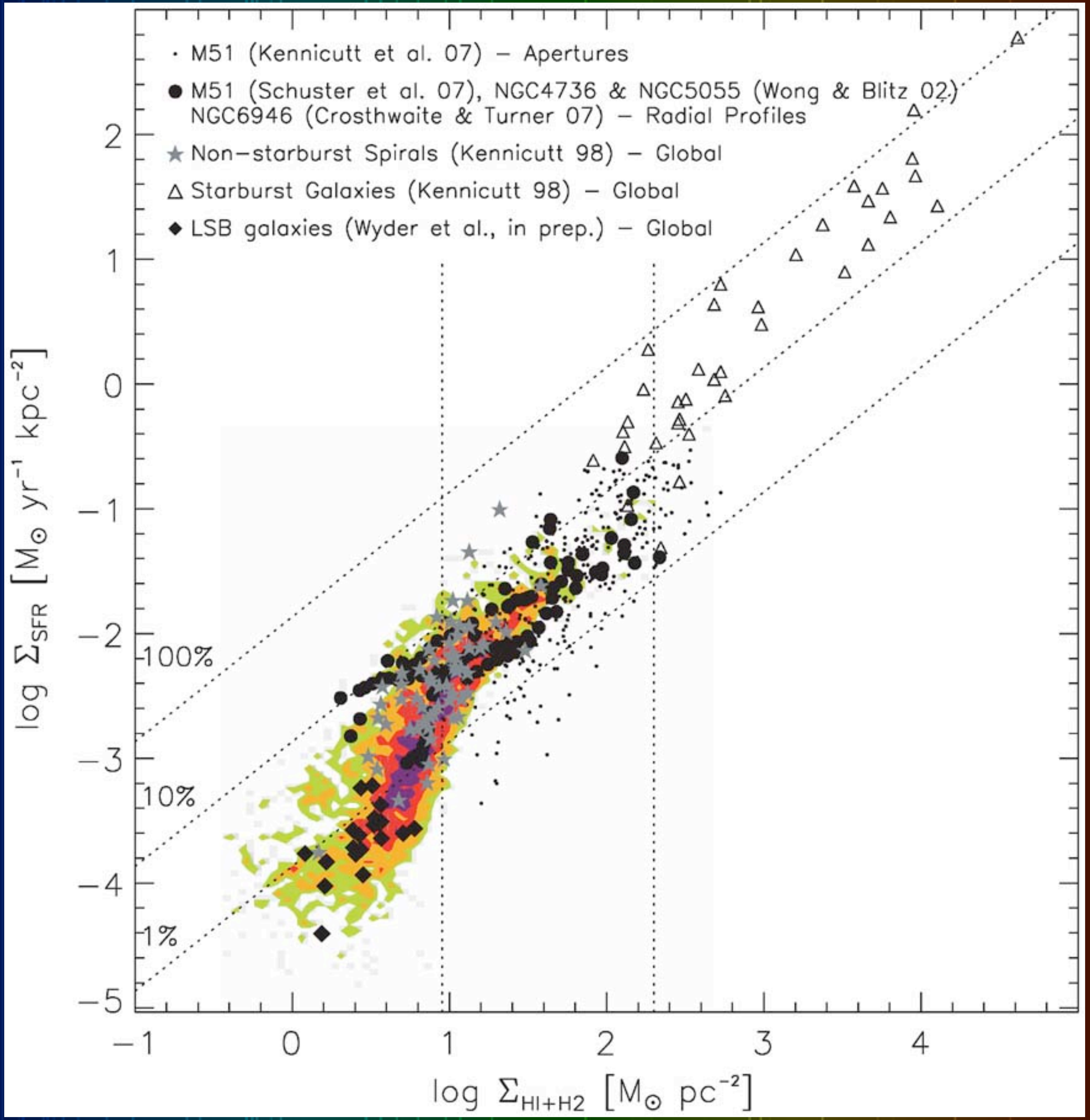
Kennicutt-Schmidt on kpc scales

- Heracles pushed this to kpc scales with Bigiel+2008,2011
- Finding a tight relation with constant depletion times of few x 10^9 yr
- PHANGS (Sun+ has only confirmed this)
- BUT…



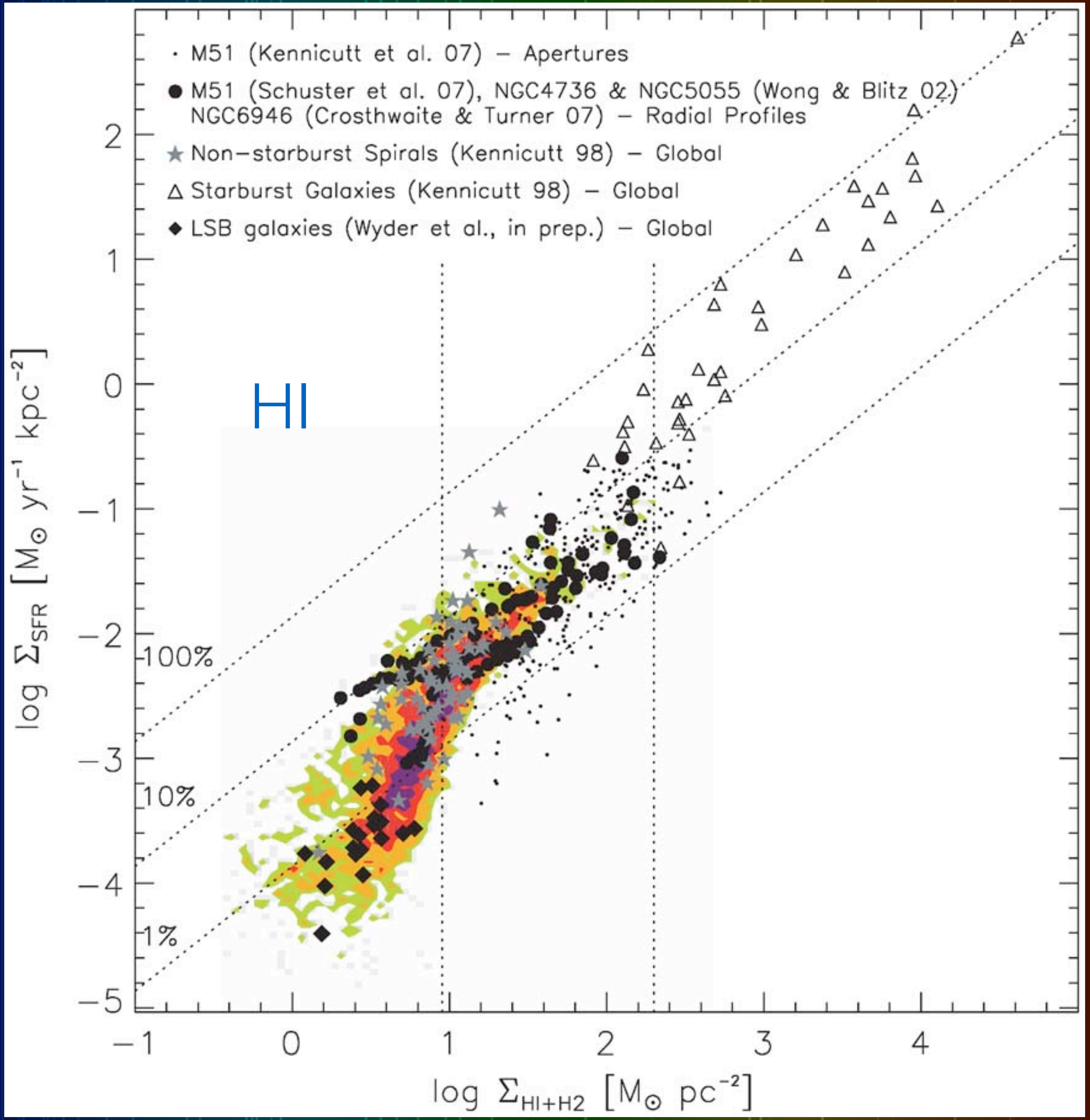
Bigiel+ (2011)

Kennicutt-Schmidt on kpc scales



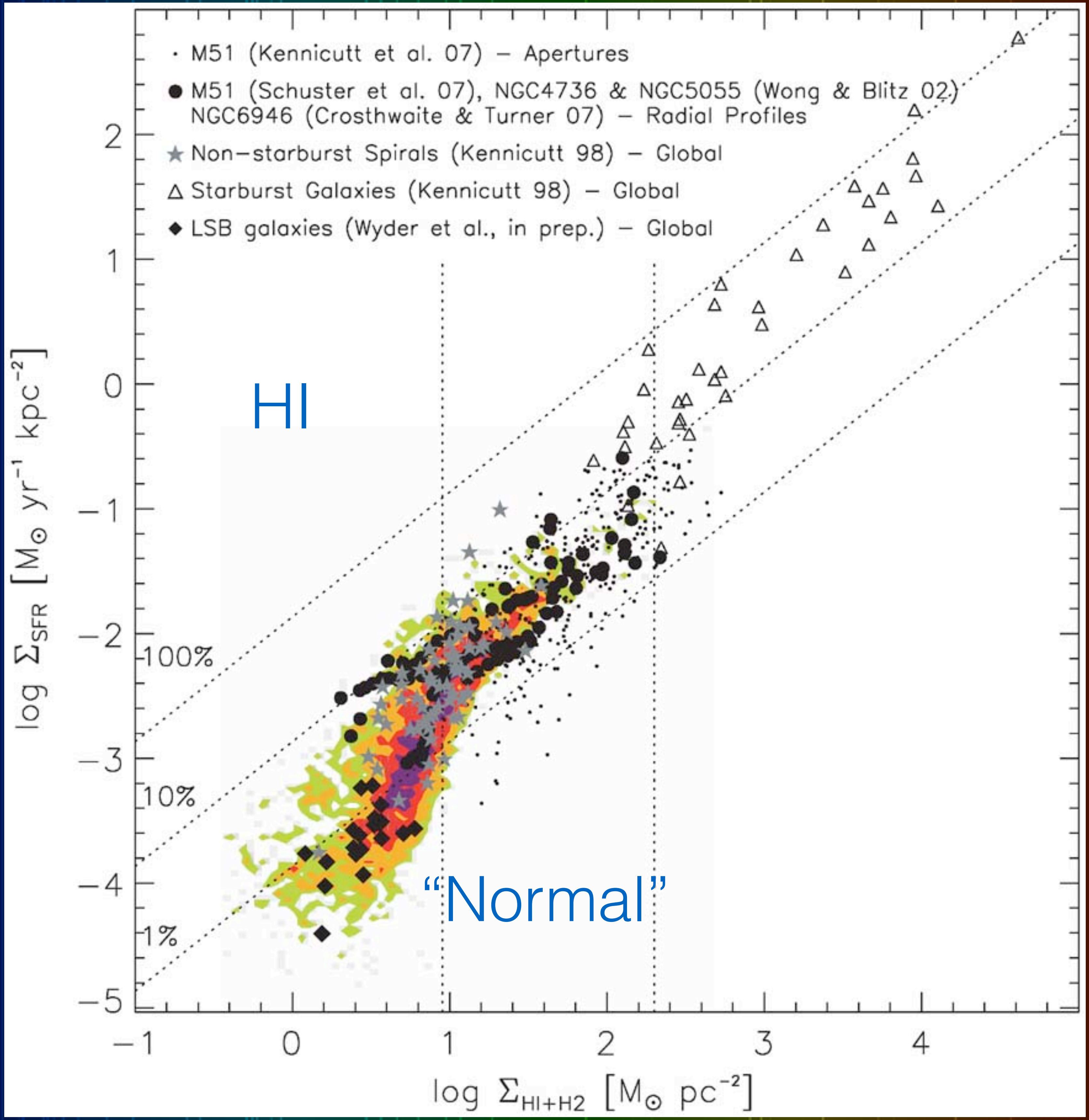
Bigiel+ (2008)

Kennicutt-Schmidt on kpc scales



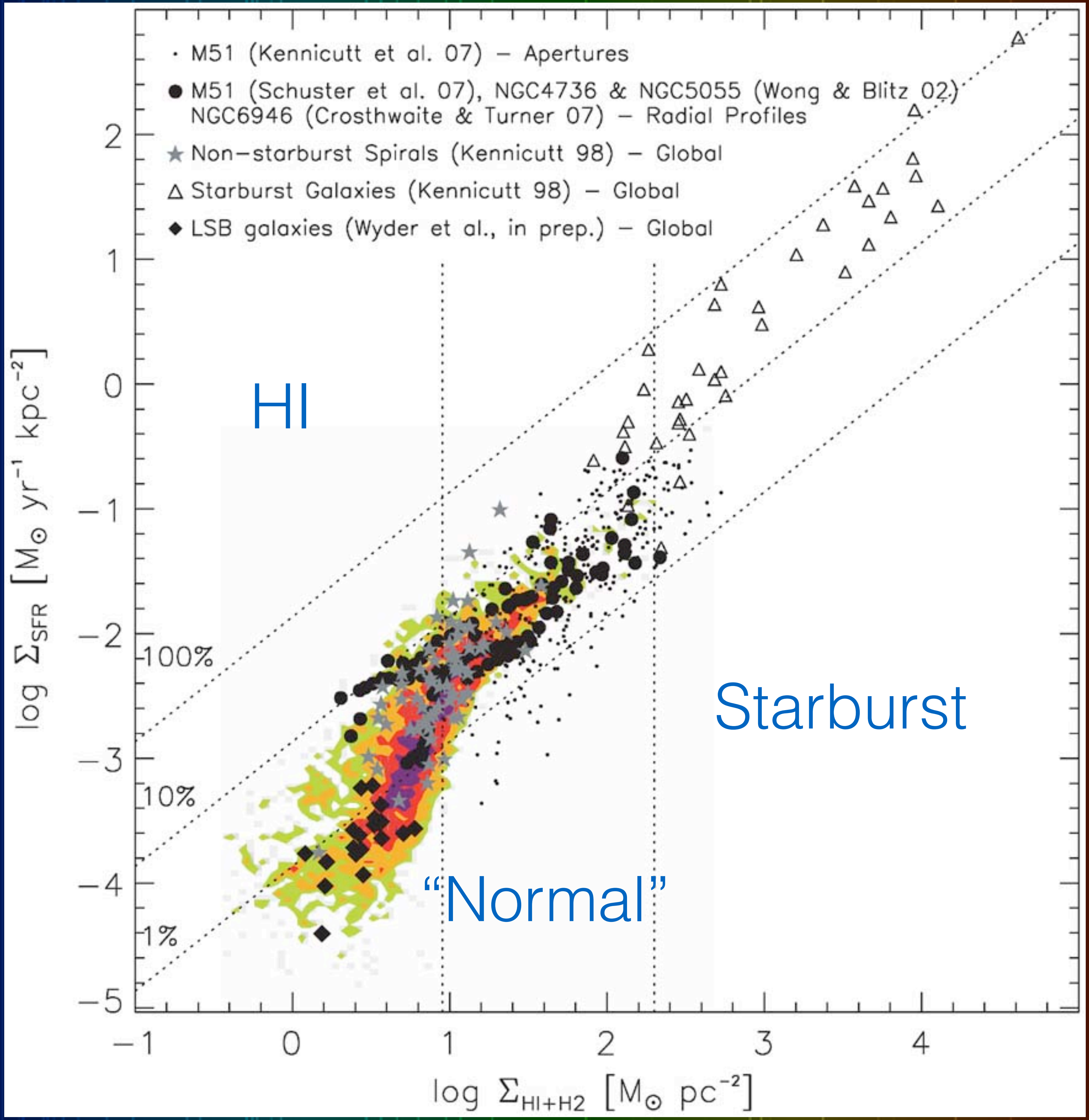
Bigiel+ (2008)

Kennicutt-Schmidt on kpc scales



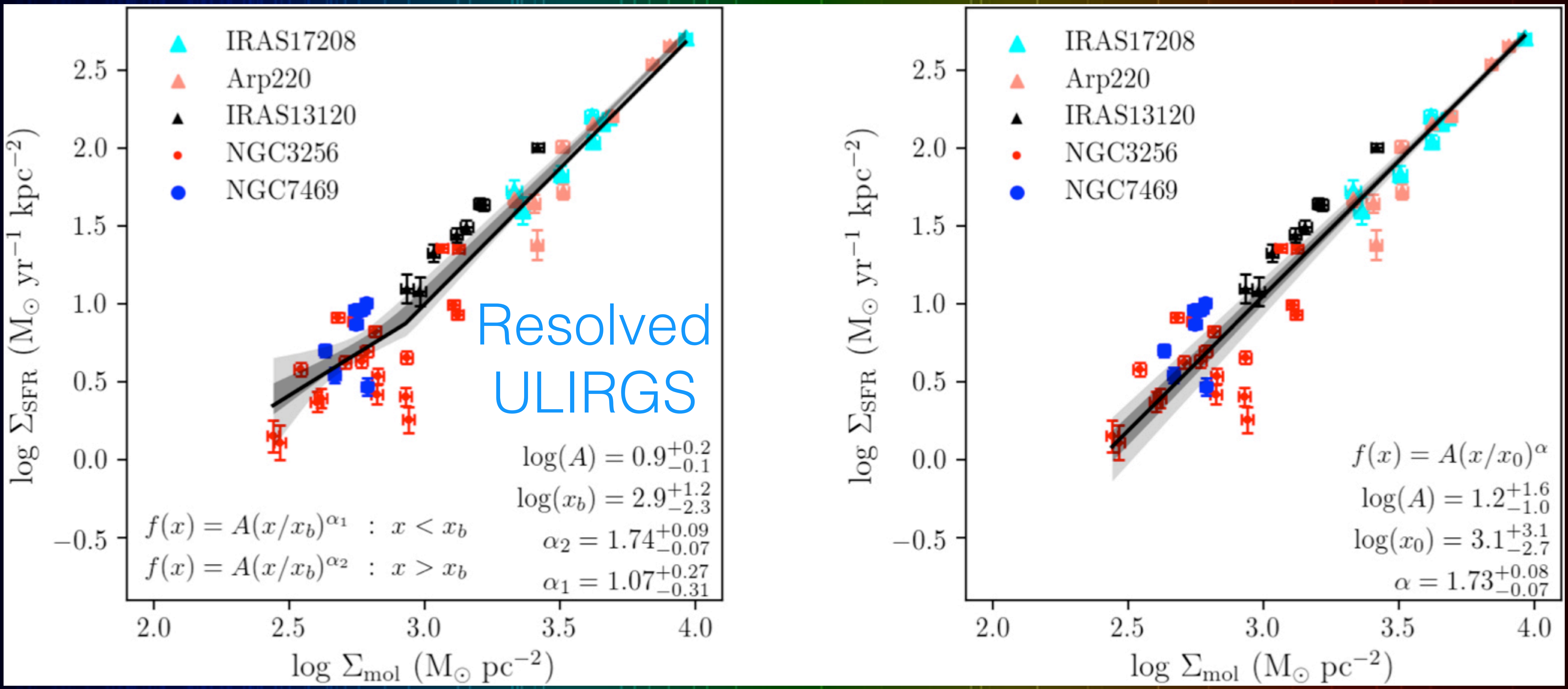
Bigiel+ (2008)

Kennicutt-Schmidt on kpc scales



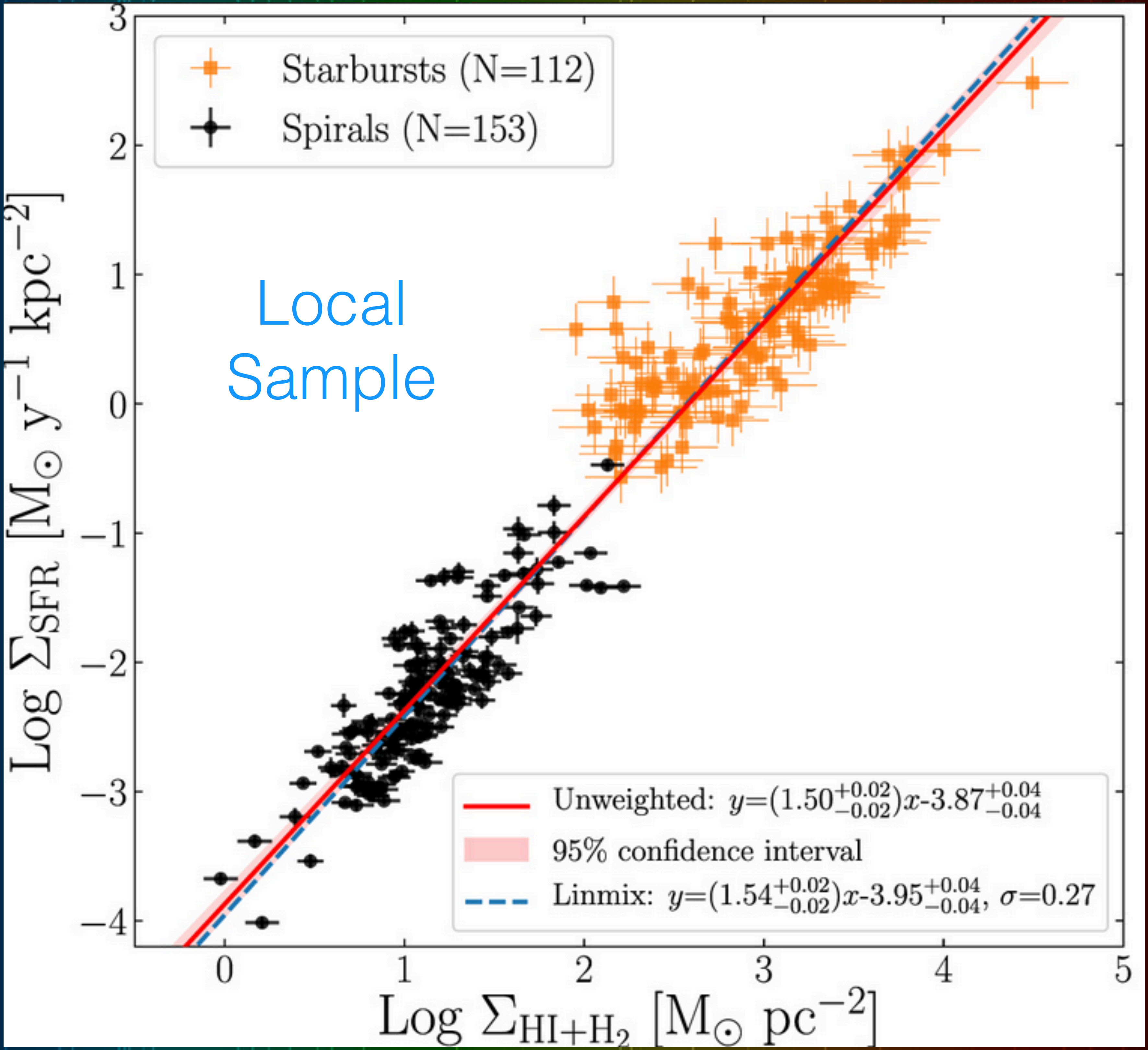
Bigiel+ (2008)

Kennicutt-Schmidt on kpc scales



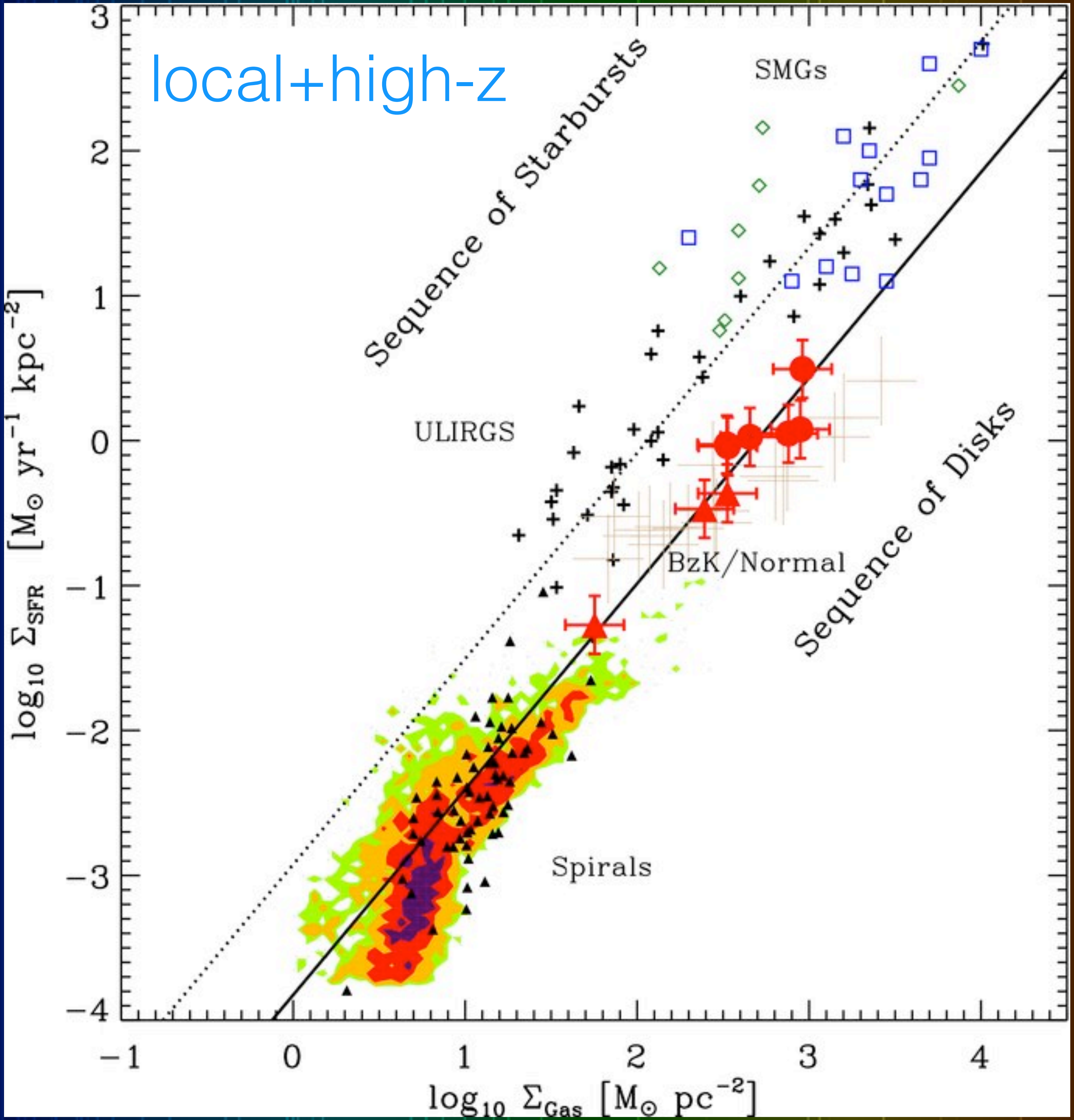
Wilson+ (2019)

Kennicutt-Schmidt on kpc scales



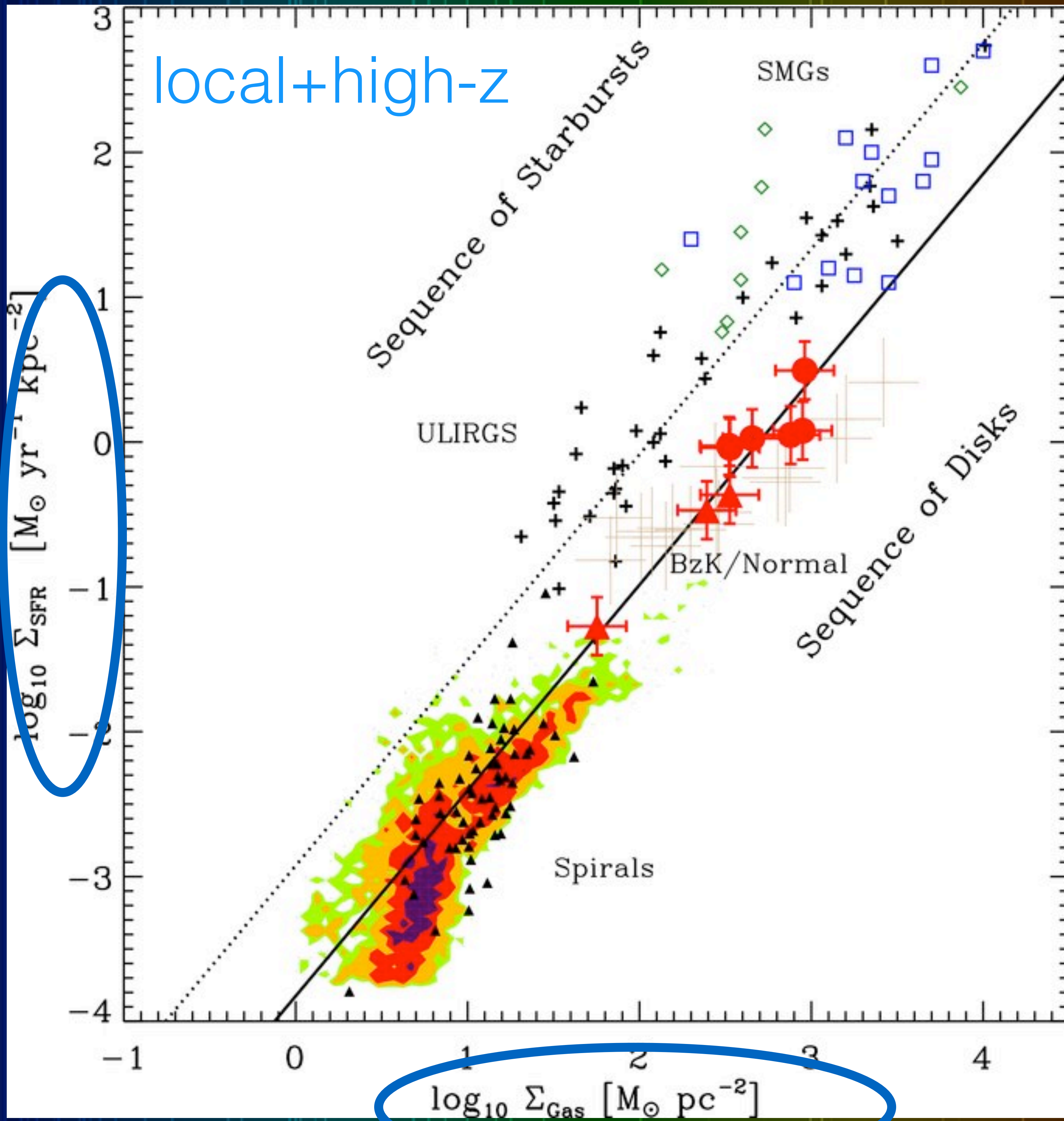
Kennicutt & De Los Reyes (2021)

Kennicutt-Schmidt on kpc scales



Daddi+ (2010)

Kennicutt-Schmidt on kpc scales



Daddi+ (2010)

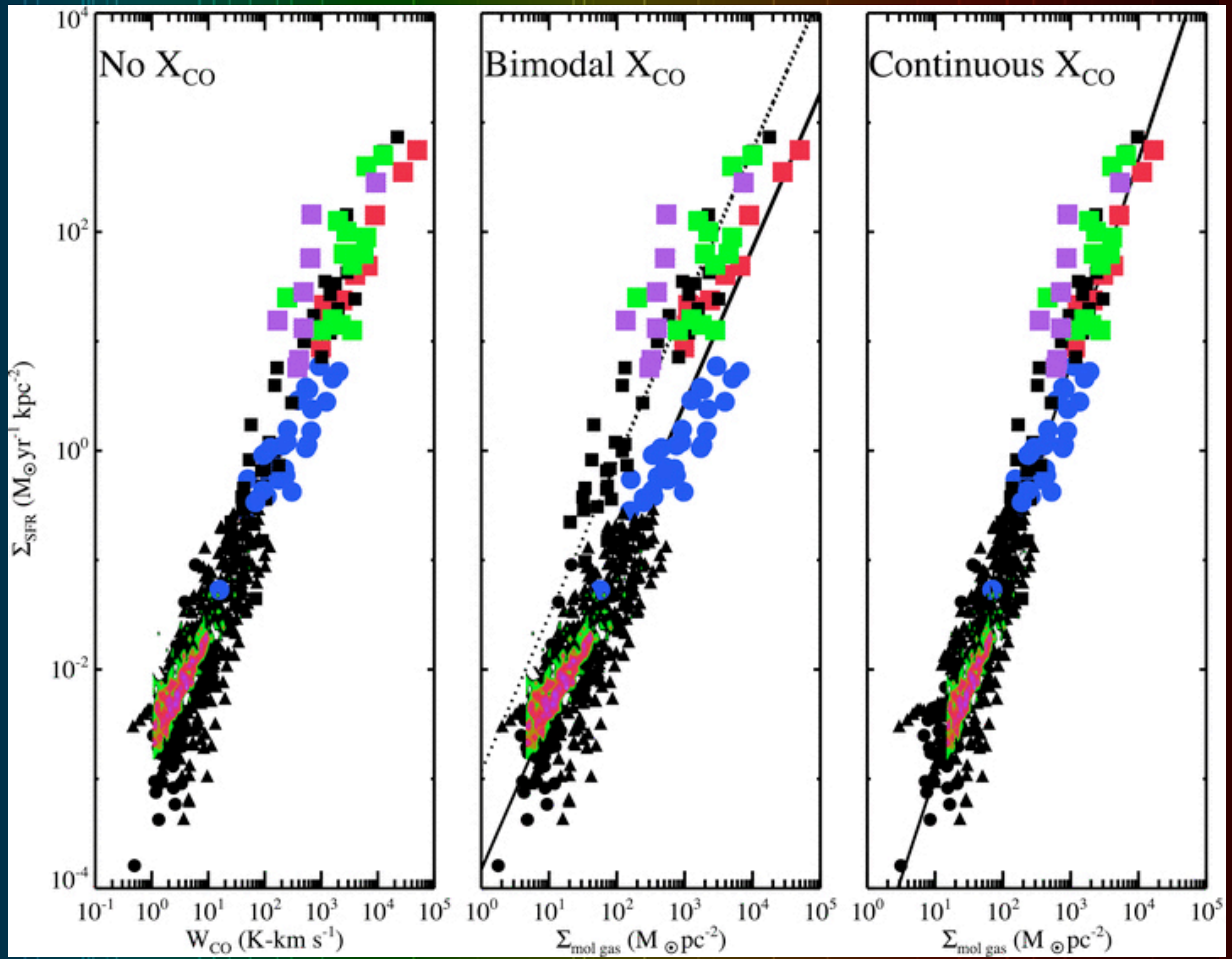
Kennicutt-Schmidt & starbursts

- Kennicutt-Schmit relation: more gas = more stars
- Similar efficiency across normal galaxy disks
- Yet starbursts offset? Steeper relation?

- SFRs are fairly robust in ULIRGs given most comes out in IR (and AGN removed) but still matching normal and burst hard
  - IMF concerns?
- But Gas densities?
- What about Sizes? (Not all are "resolved")
- Kennicutt & De Los Reyes (2021) very good discussion on these issues

Varying α_{CO}

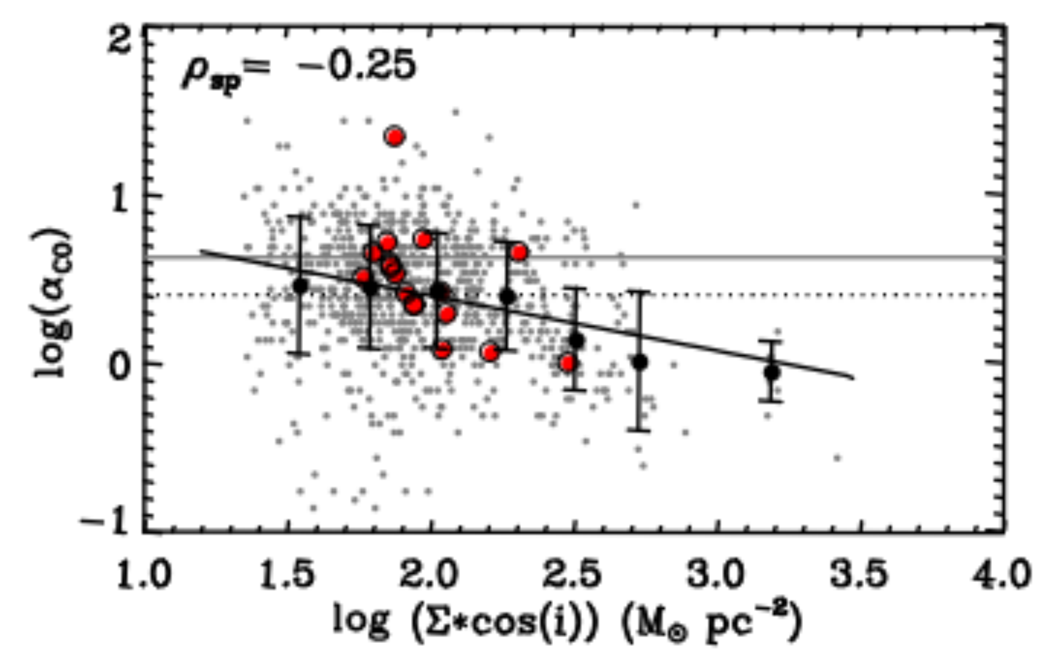
- It's been accepted for a while that relation between CO intensity and H2 column varies in Starbursts
- Must be lower than MW conversion
- See Bolatto+13 for discussion

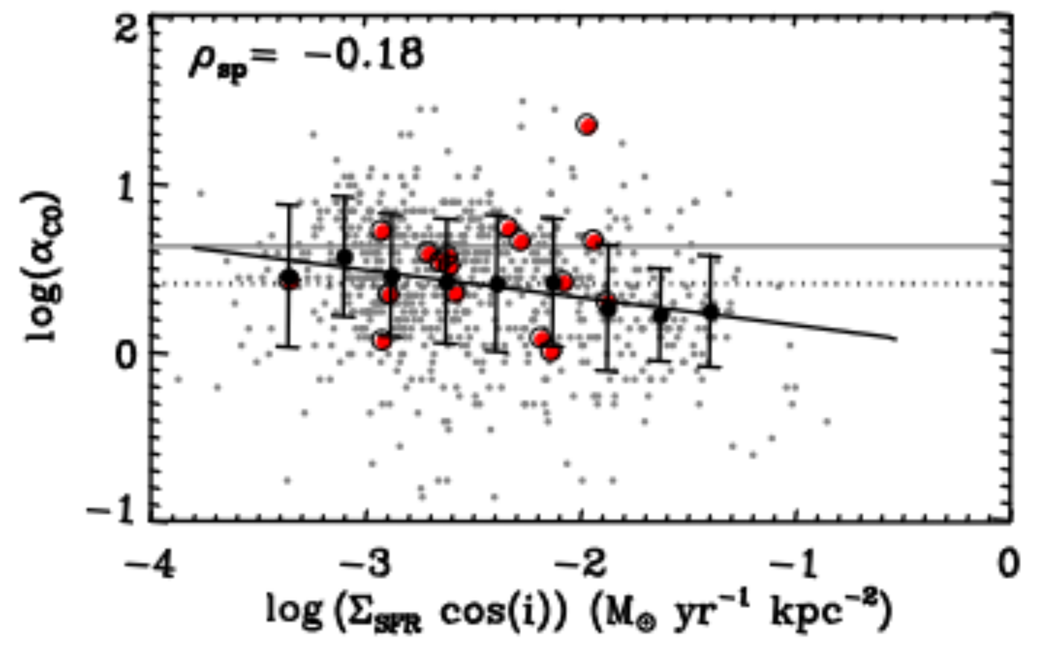


Naranyan+ (2012)

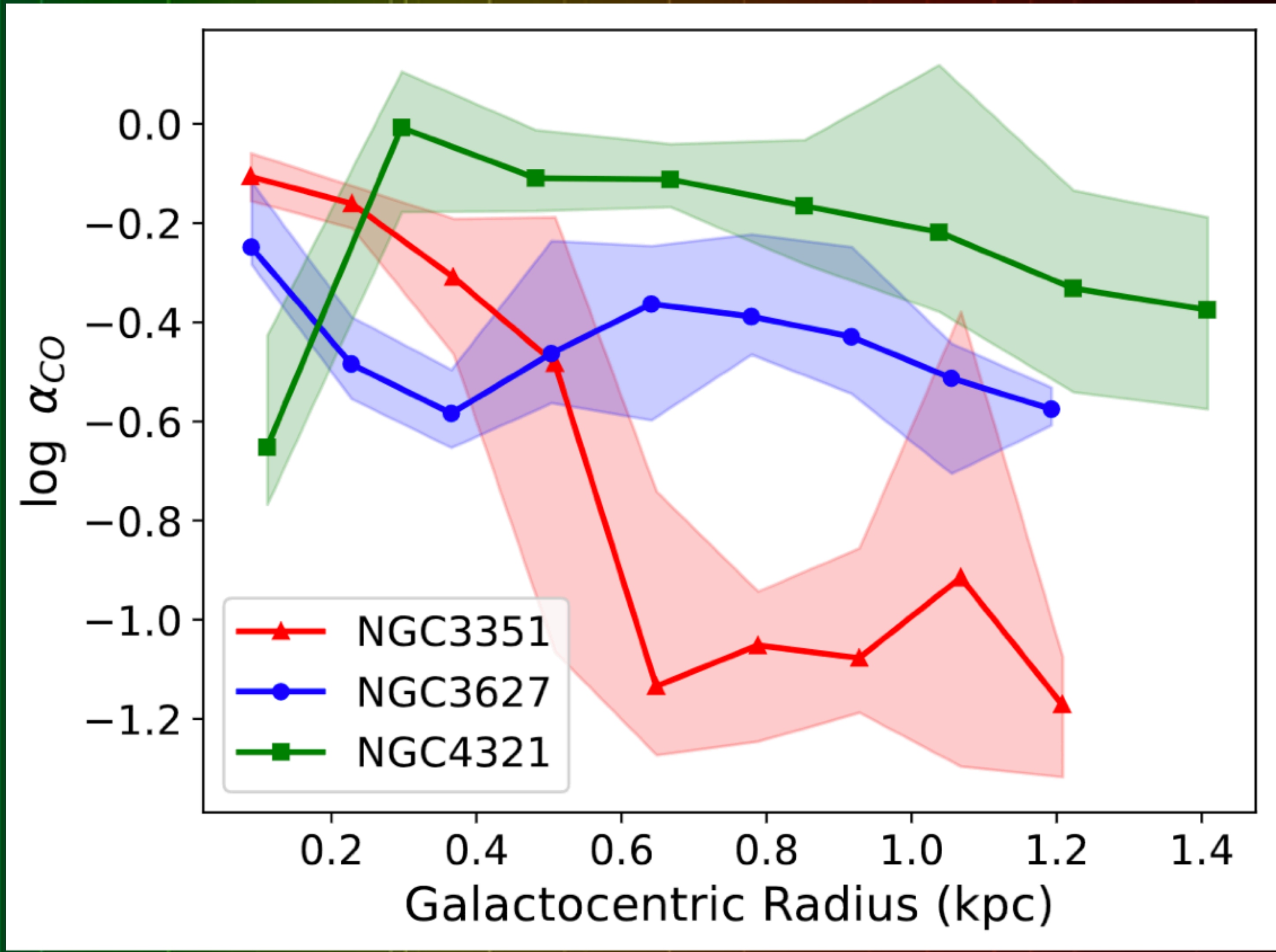
Also J. Roman-Duval talk

Dust -based evidence of α_{CO}



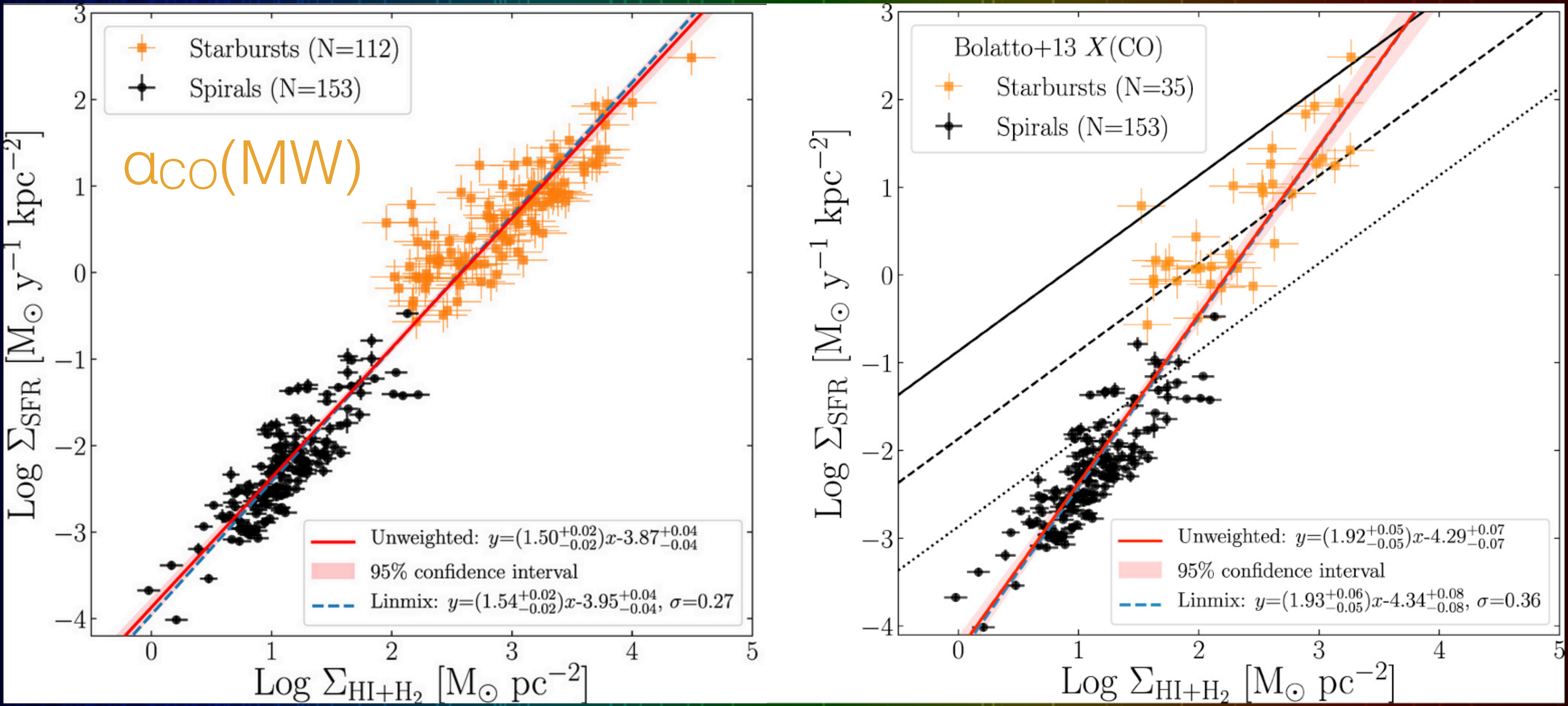


Sandstrom+ (2013)



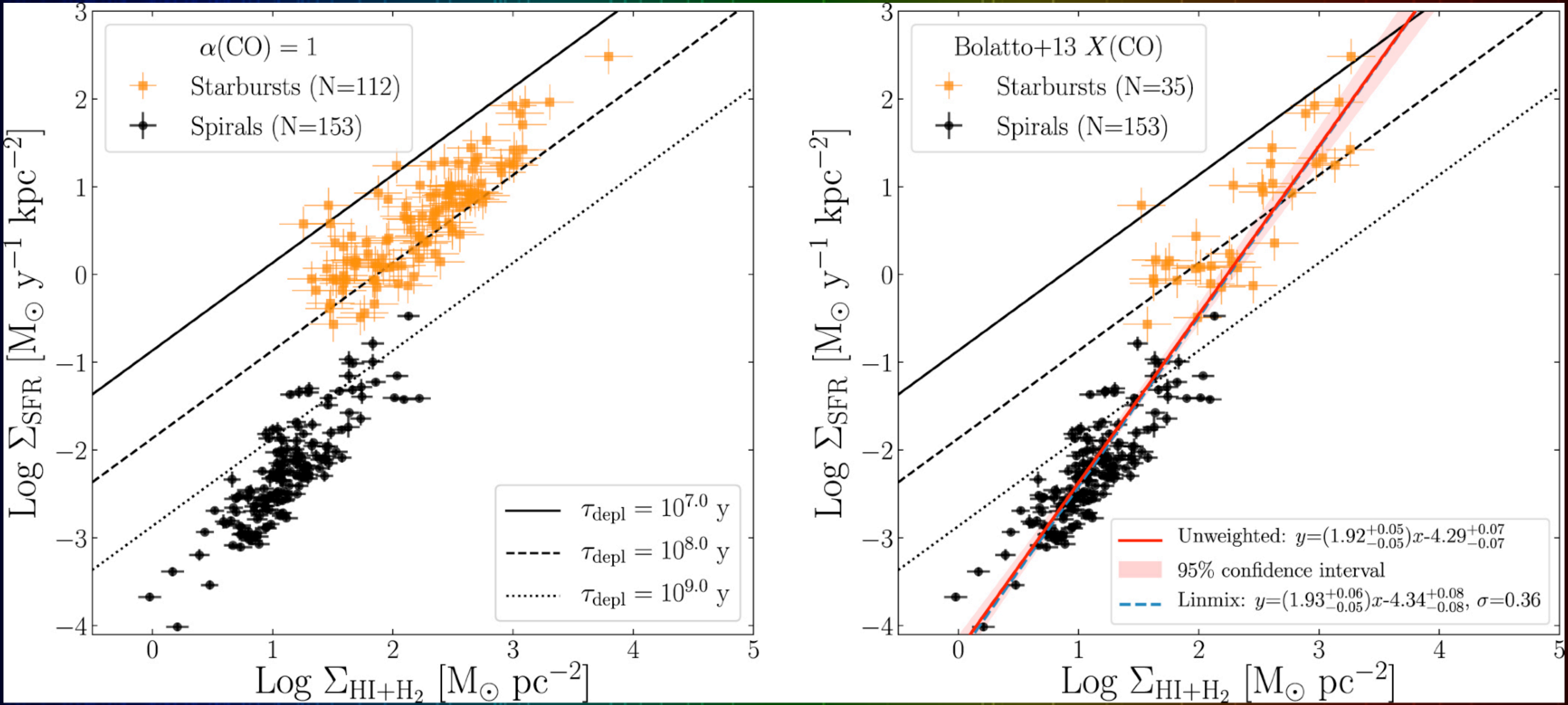
Teng+ (2023)

Varying α_{CO}



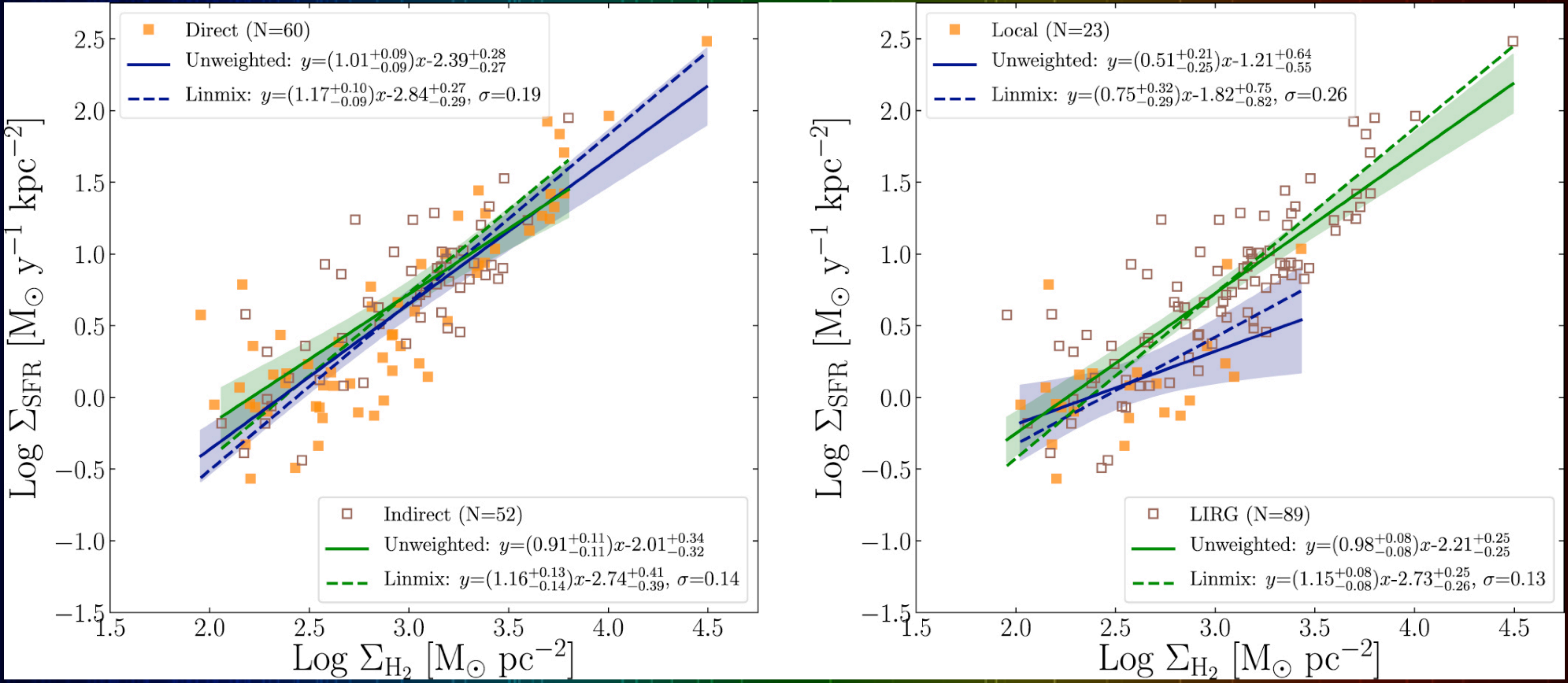
Kennicutt & De Los Reyes (2021)

Varying α_{CO}



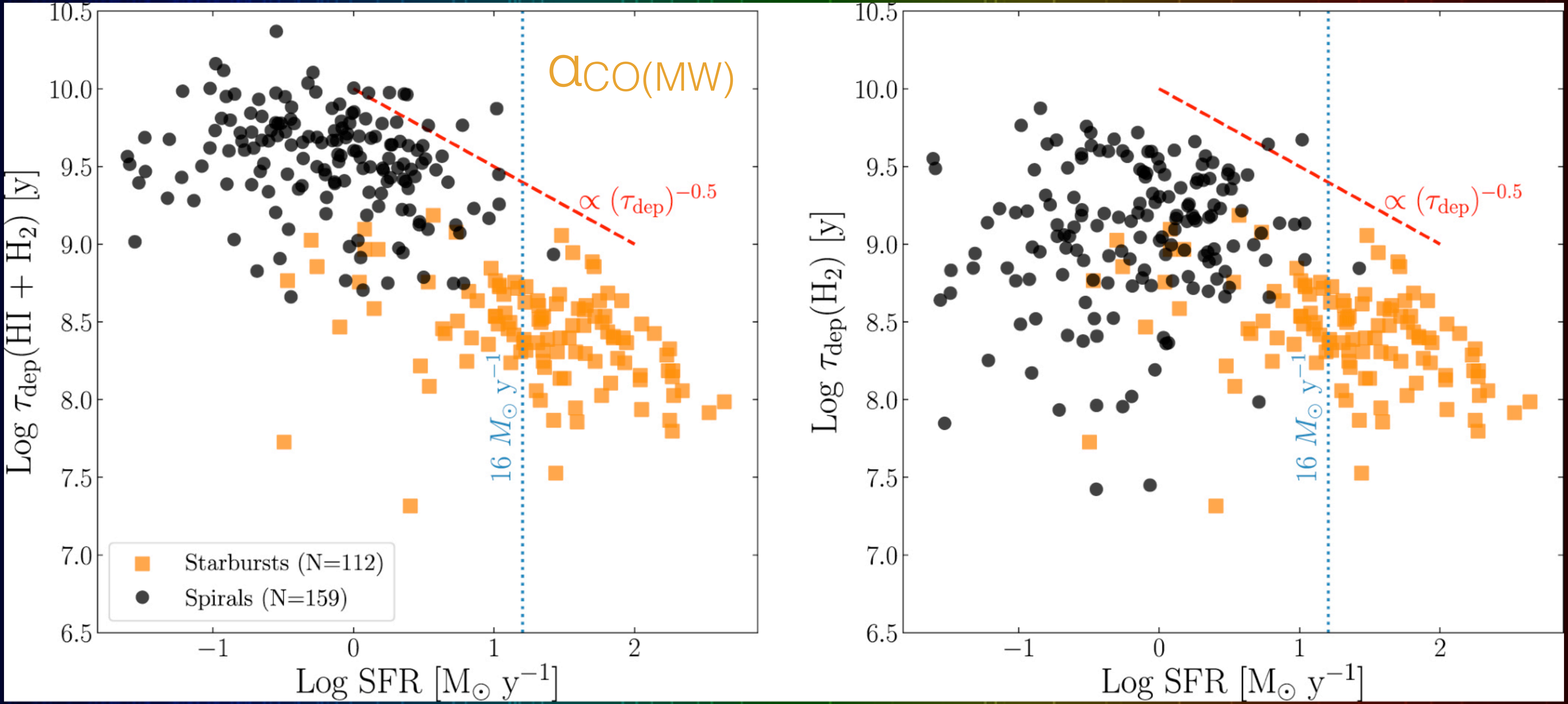
Kennicutt & De Los Reyes (2021)

Resolving the regions



Kennicutt & De Los Reyes (2021)

All evidence suggests ULIRGs more efficient at Star formation

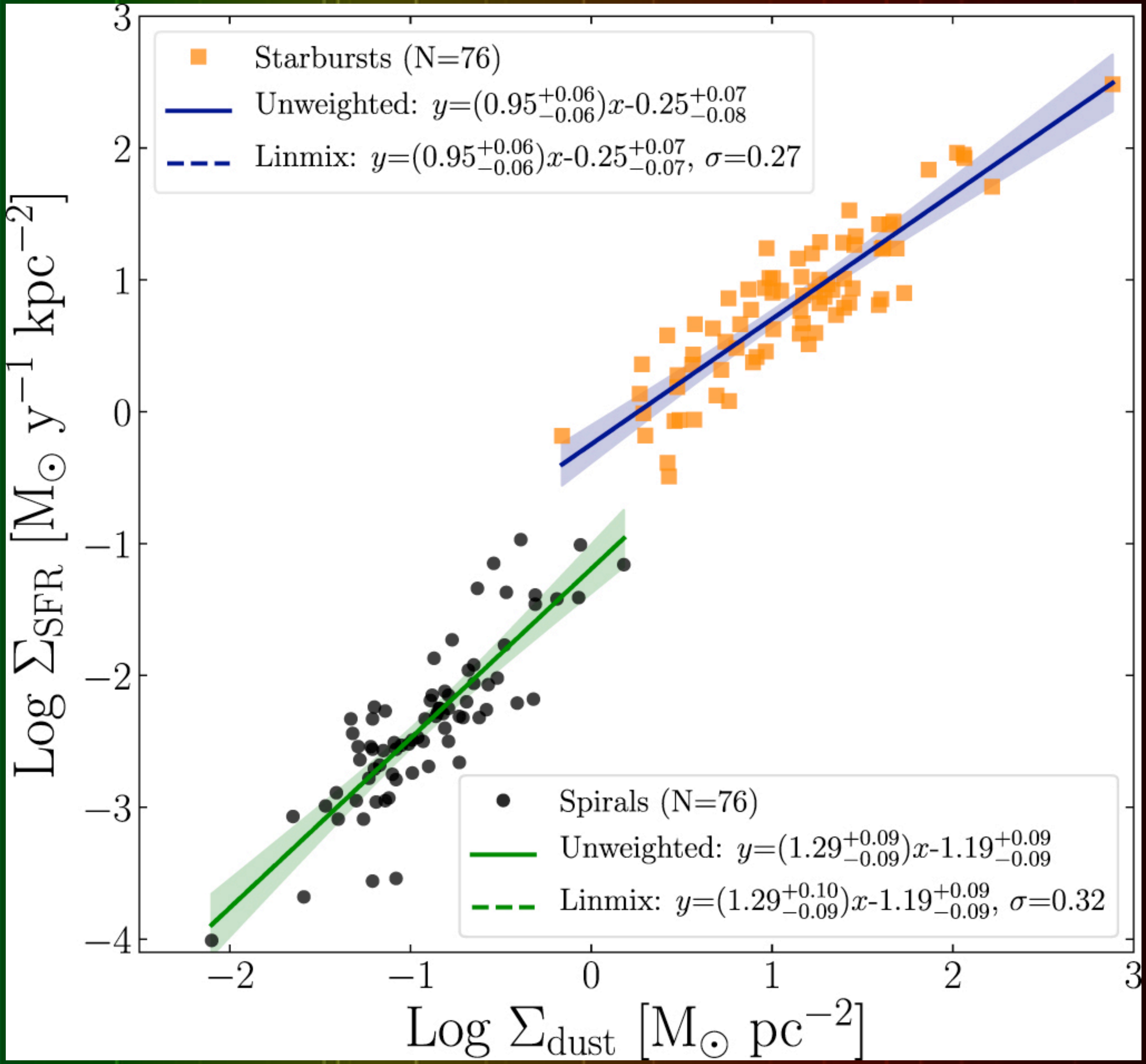


Kennicutt & De Los Reyes (2021)

Even using dust offset seen

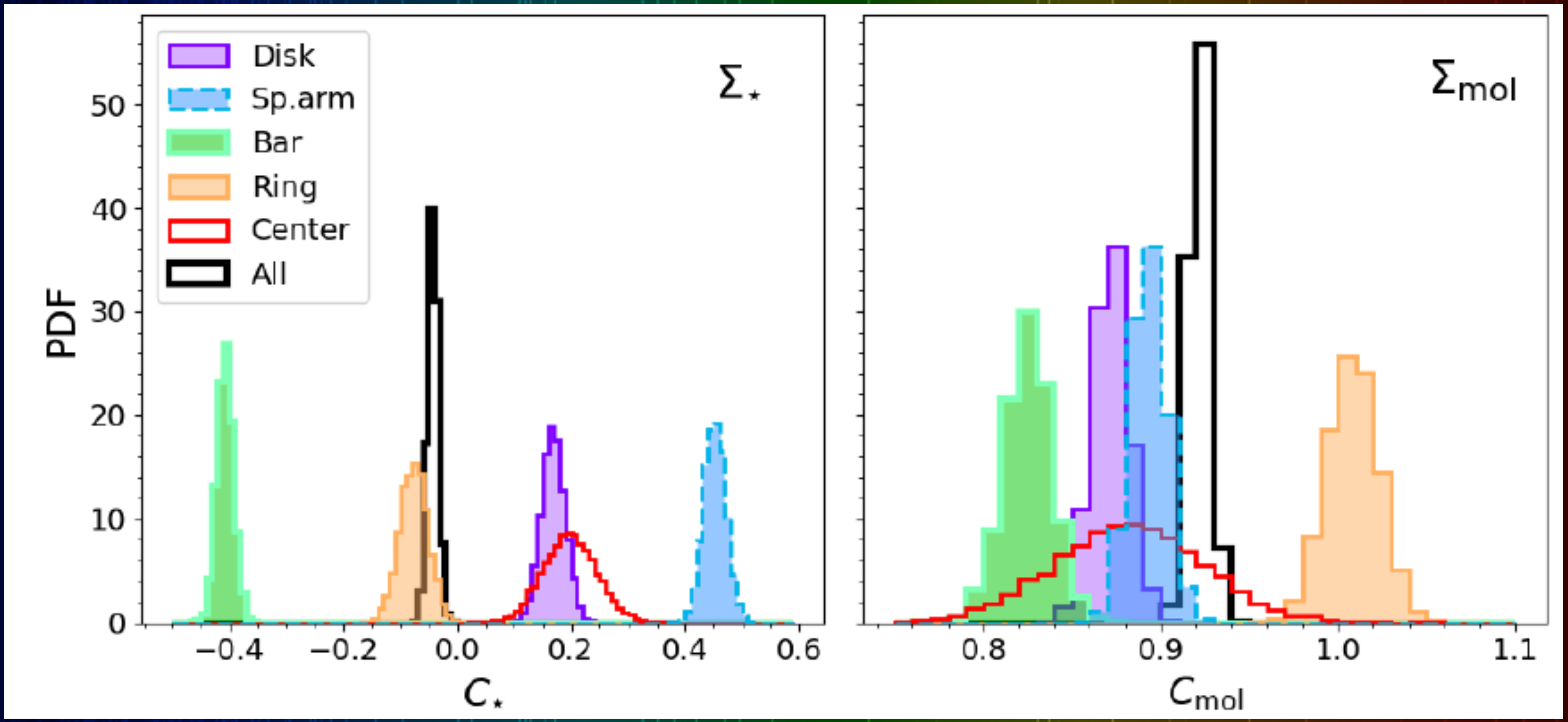
- Clear evidence that α_{CO} varies within and between galaxies
- α_{CO} lower in starbursts
- Offset with Σ_{gas} likely due to HI ->H_2 differences
- Evidence that SF more efficient in ULIRGs ($\tau_{dep}(H_2)$ lower)
- Why?

  see M. Chevance Talk



Kennicutt & De Los Reyes (2021)

Even in 'normal' galaxies, offsets seen



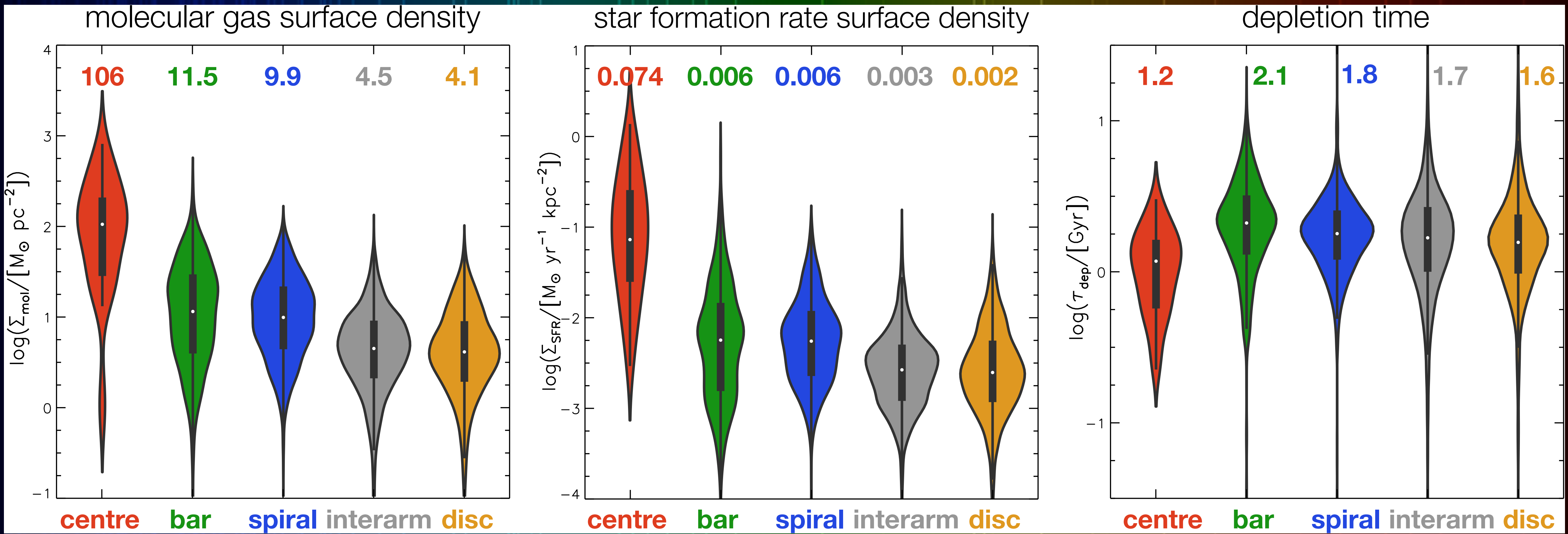
PHANGS: Pessa+ (2022)

$$\log \Sigma_{SFR} - \langle \log \Sigma_{SFR} \rangle = C_\star \Delta \log \Sigma_\star + C_{\rm mol} \Delta \log \Sigma_{\rm mol}$$

- Variation seen within galaxies

- SB rings offset high (as seen)
- BUT Bars offset low?

Even in 'normal' galaxies, offsets seen



PHANGS: Querejeta+ (2021)

- Variation seen within galaxies

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And Stretch!

The ISM of Starbursts/ ULIRGs

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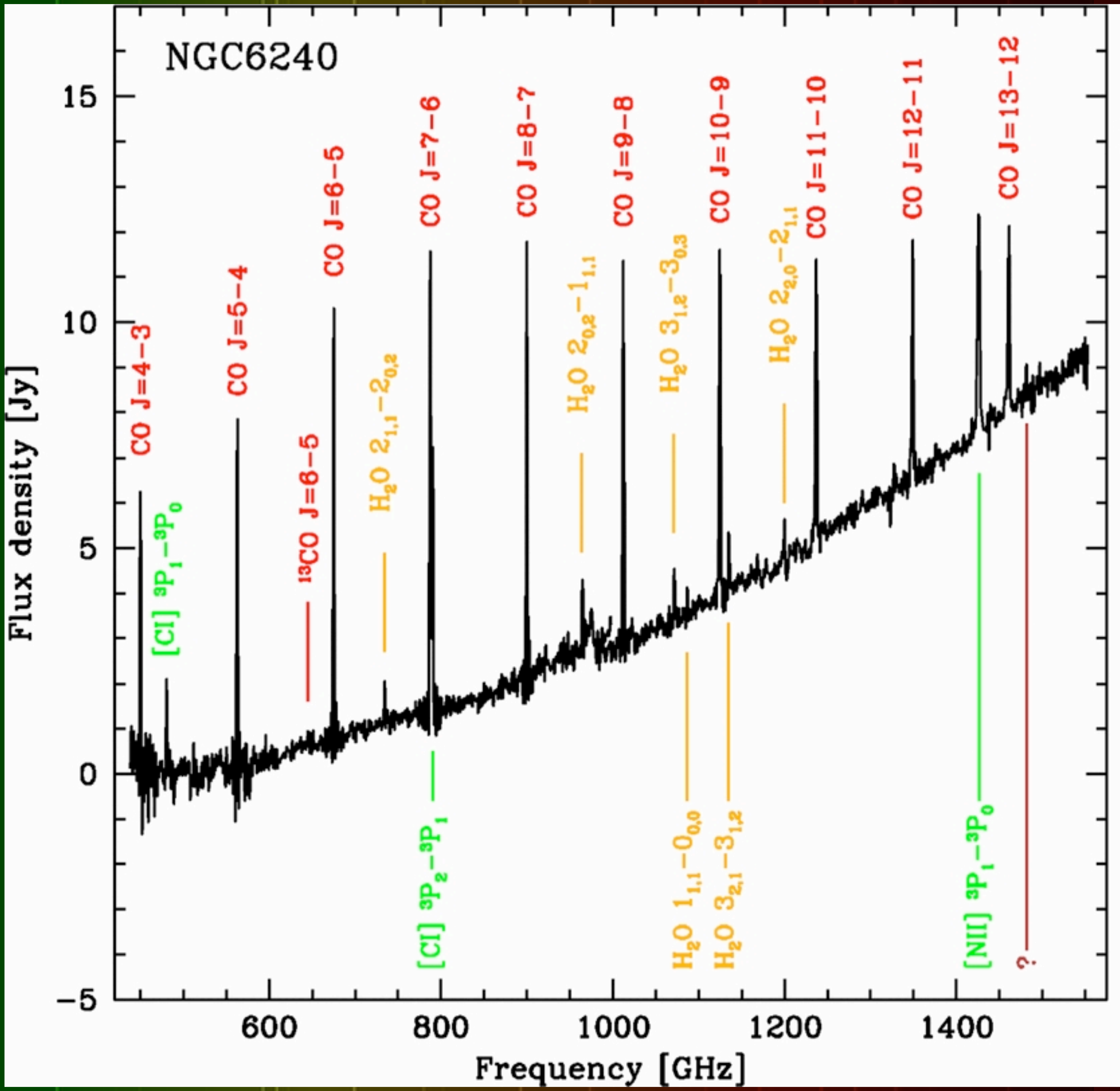
ISM of starbursts & ULIRGs

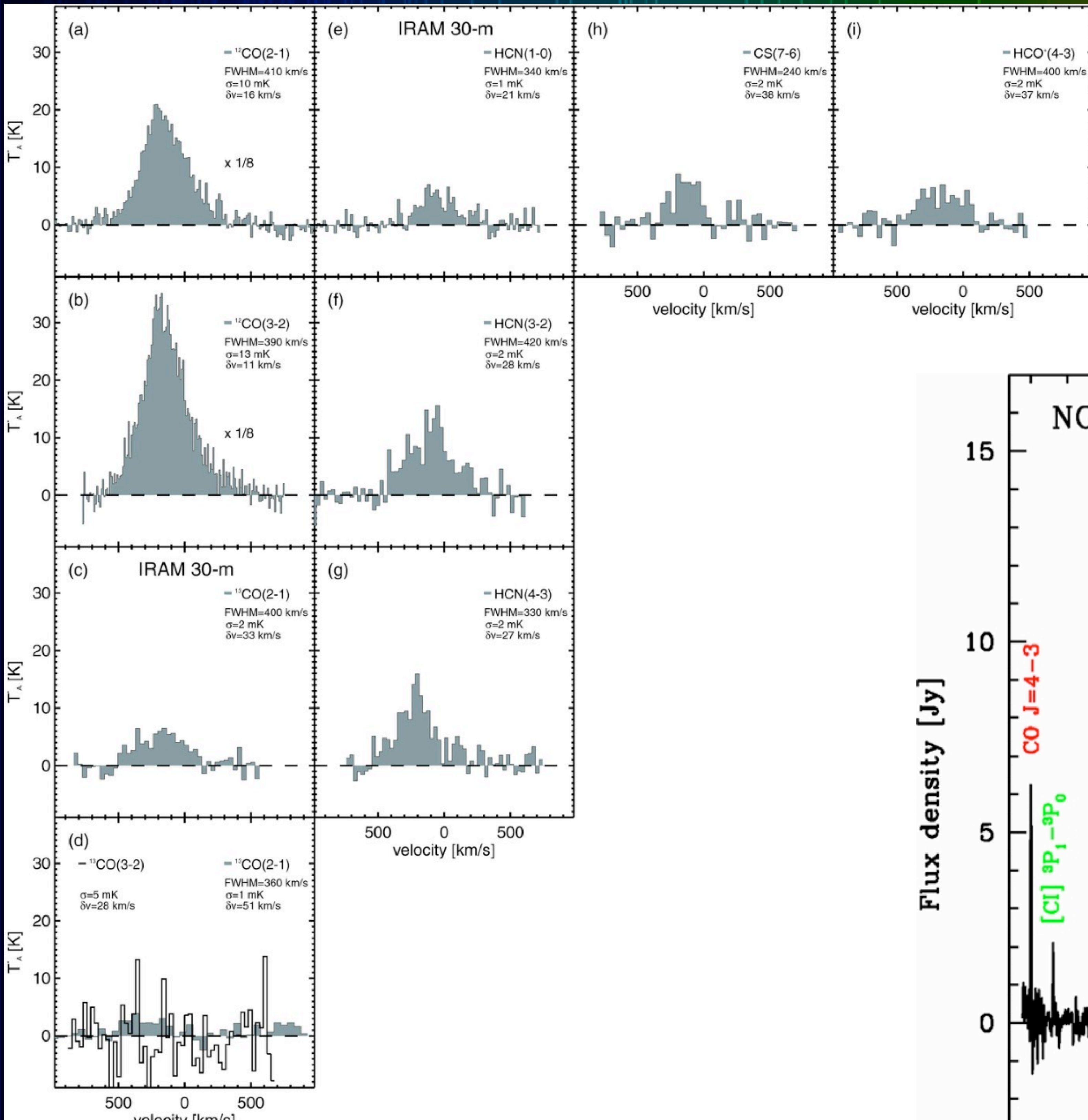
- A lot of it (high $M_{H2}/M_{\star}$)
- Warm (high T, σ_{gas})
- Dense (high Σ_{gas}, n_{gas})

- With high luminosity and molecular abundance, ULIRGs show a suite of easily accessible molecular lines

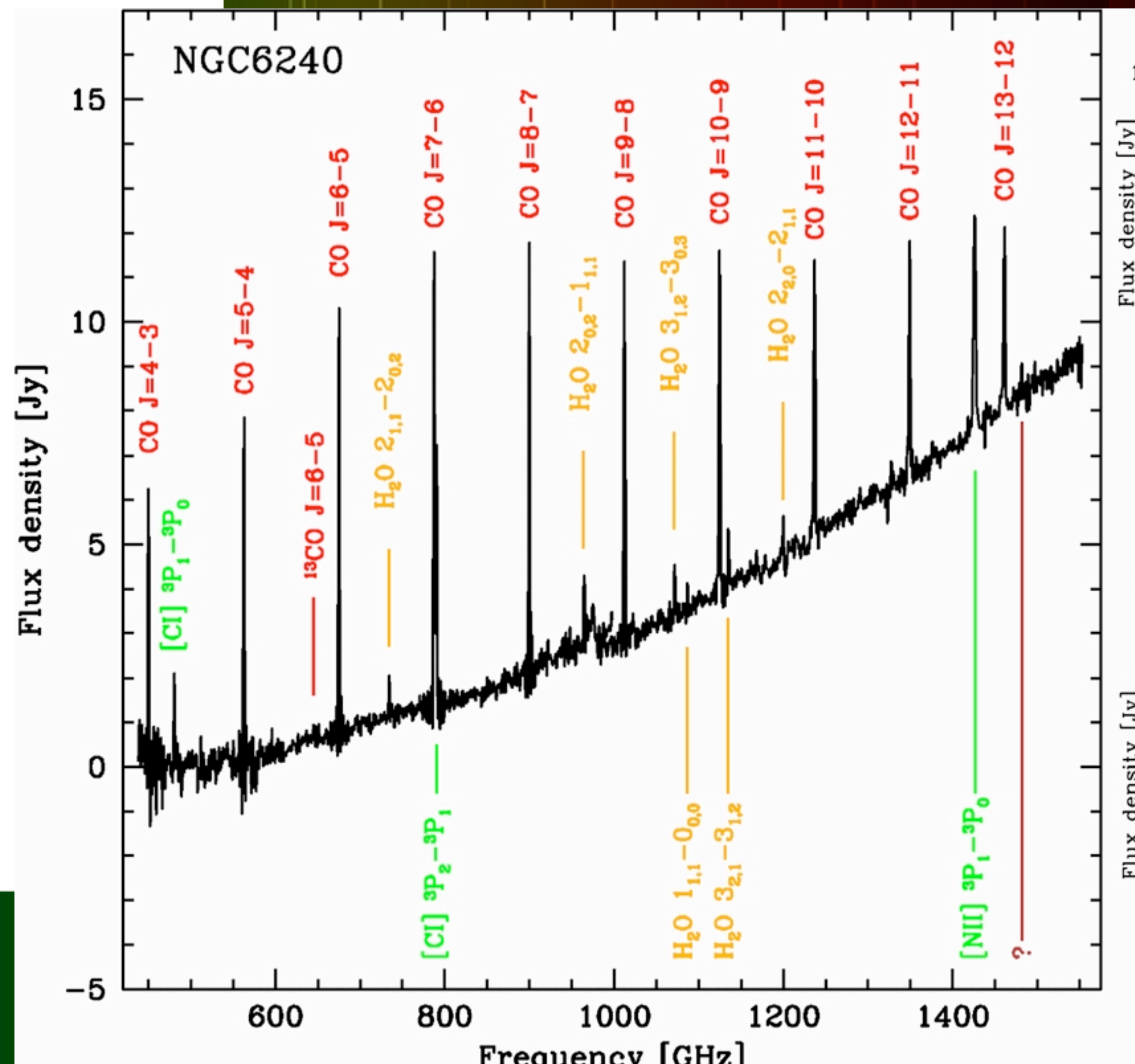


Meijerink+2013

& ULIRGs

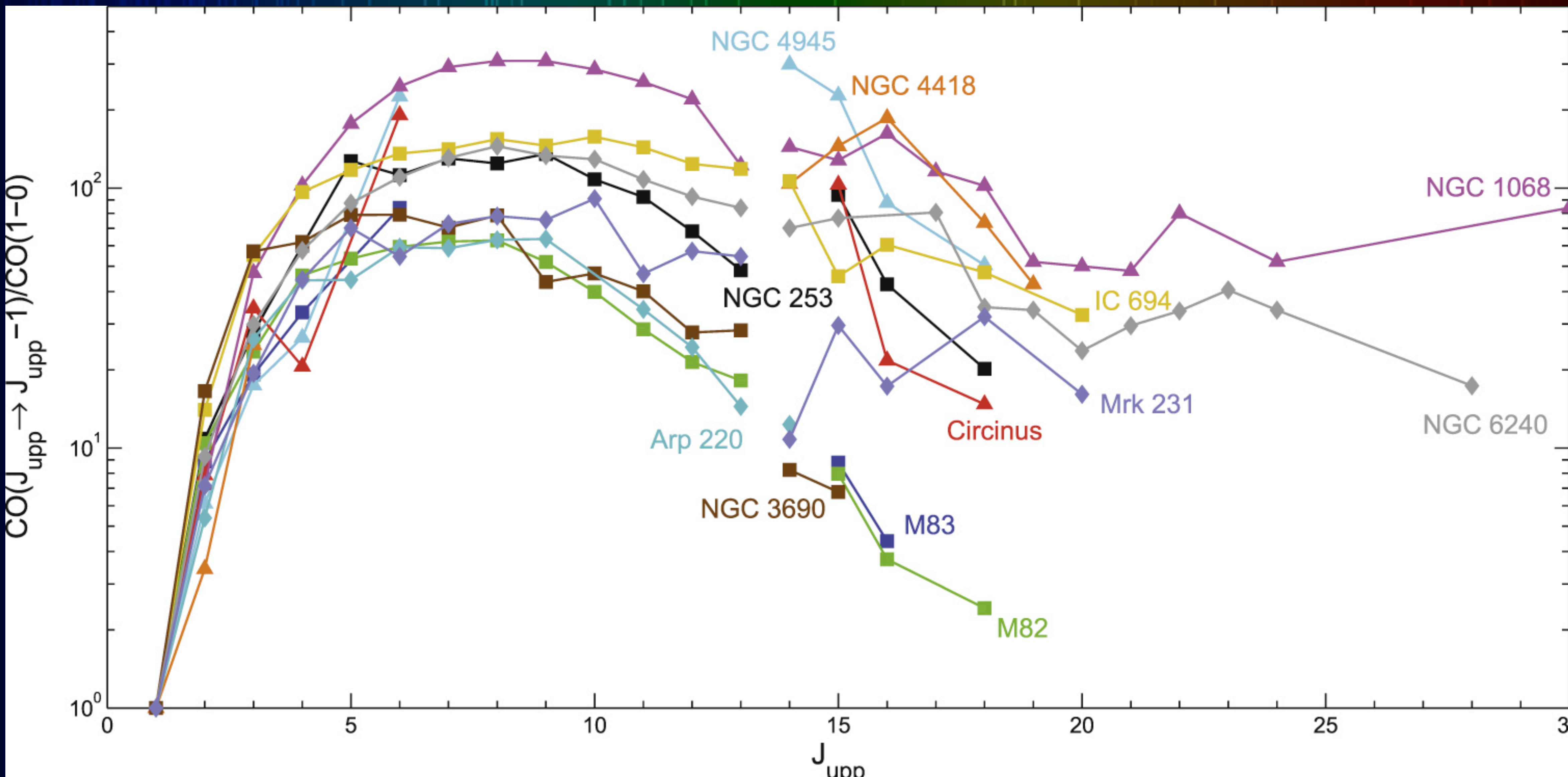


Greve+2009



Meijerink+2013

The Warm ISM - CO ladders

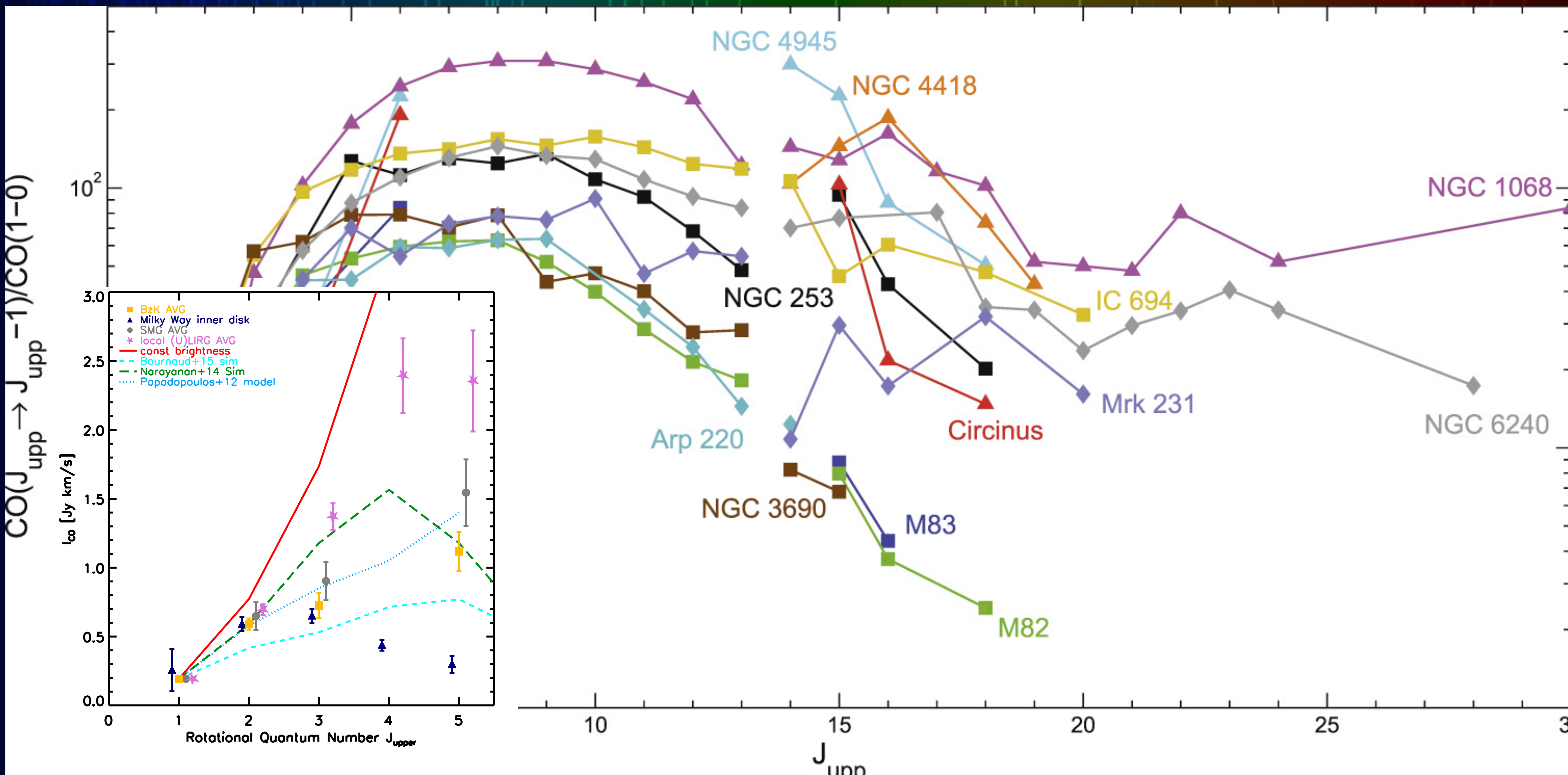


Mashian+2015

- ULIRGs & AGN show high J CO transitions (c.f. Milky Way)
- AGN high, but even starburst (e.g. M82)

See J. Roman-Duval talk

The Warm ISM - CO ladders



Daddi+ (2015) Mashian+2015

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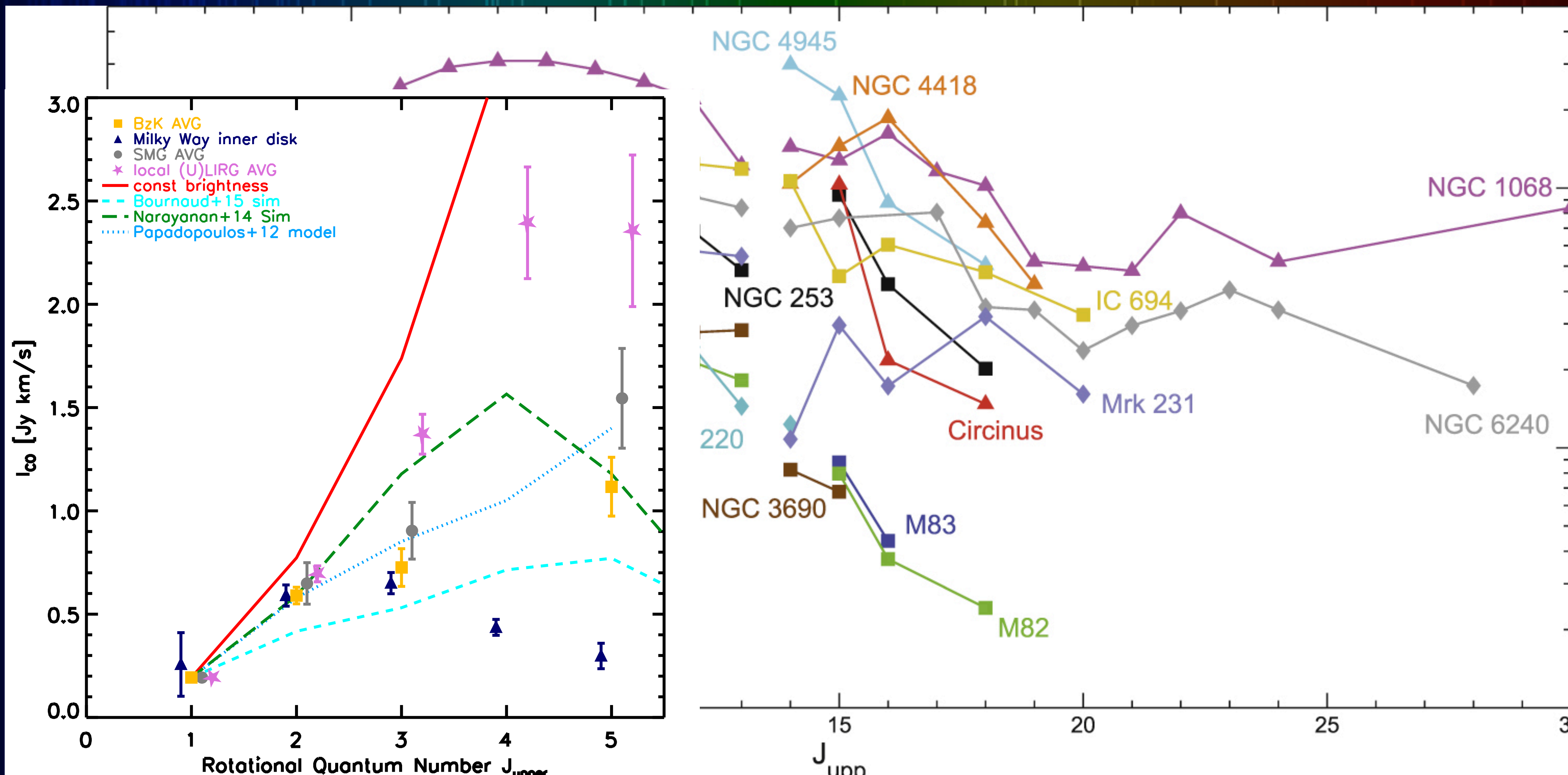


Daddi+ (2015)

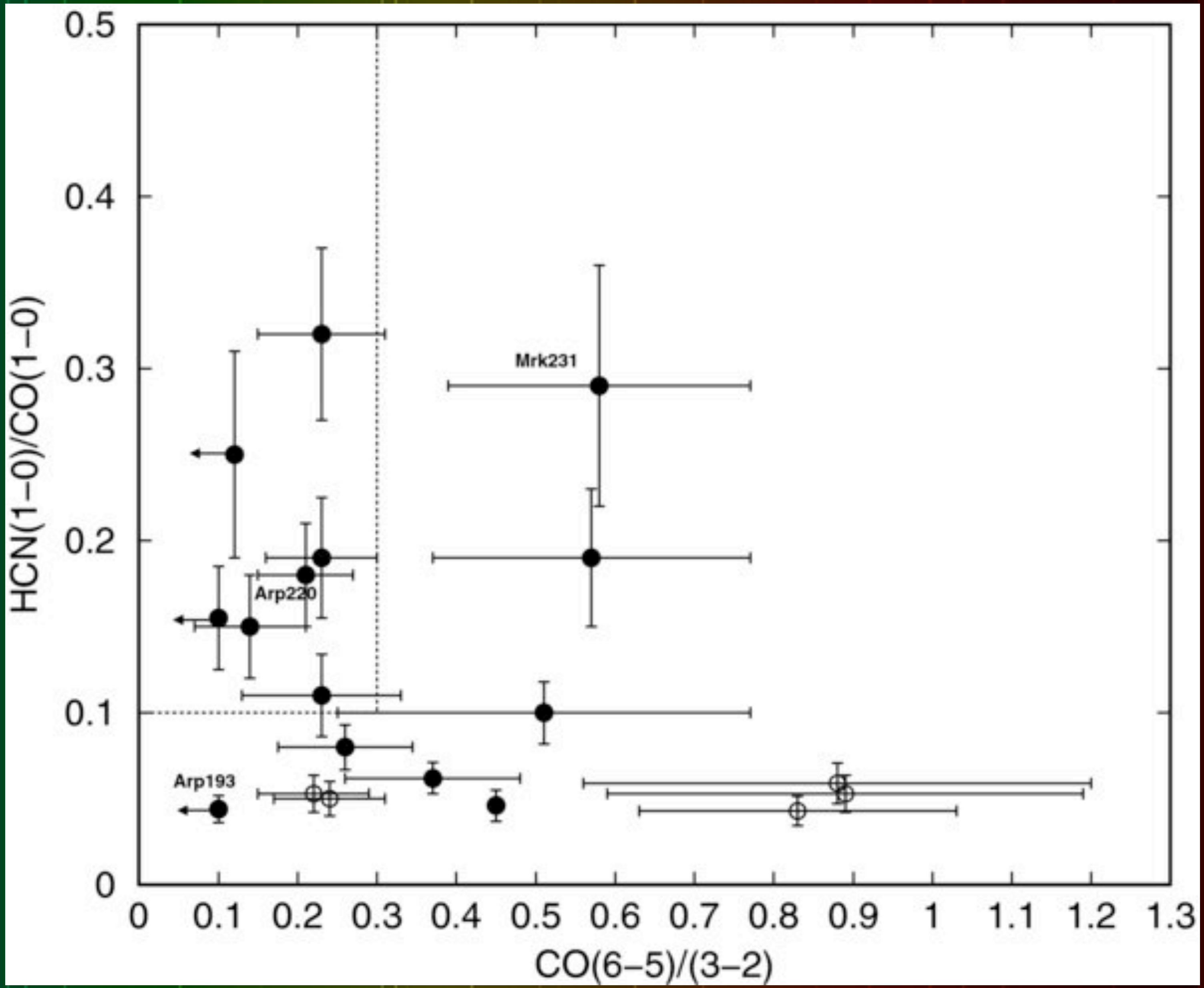
Mashian+2015

- ULIRGs & AGN show high J CO transitions (c.f. Milky Way)
- AGN high, but even starburst (e.g. M82)

See J. Roman-Duval talk

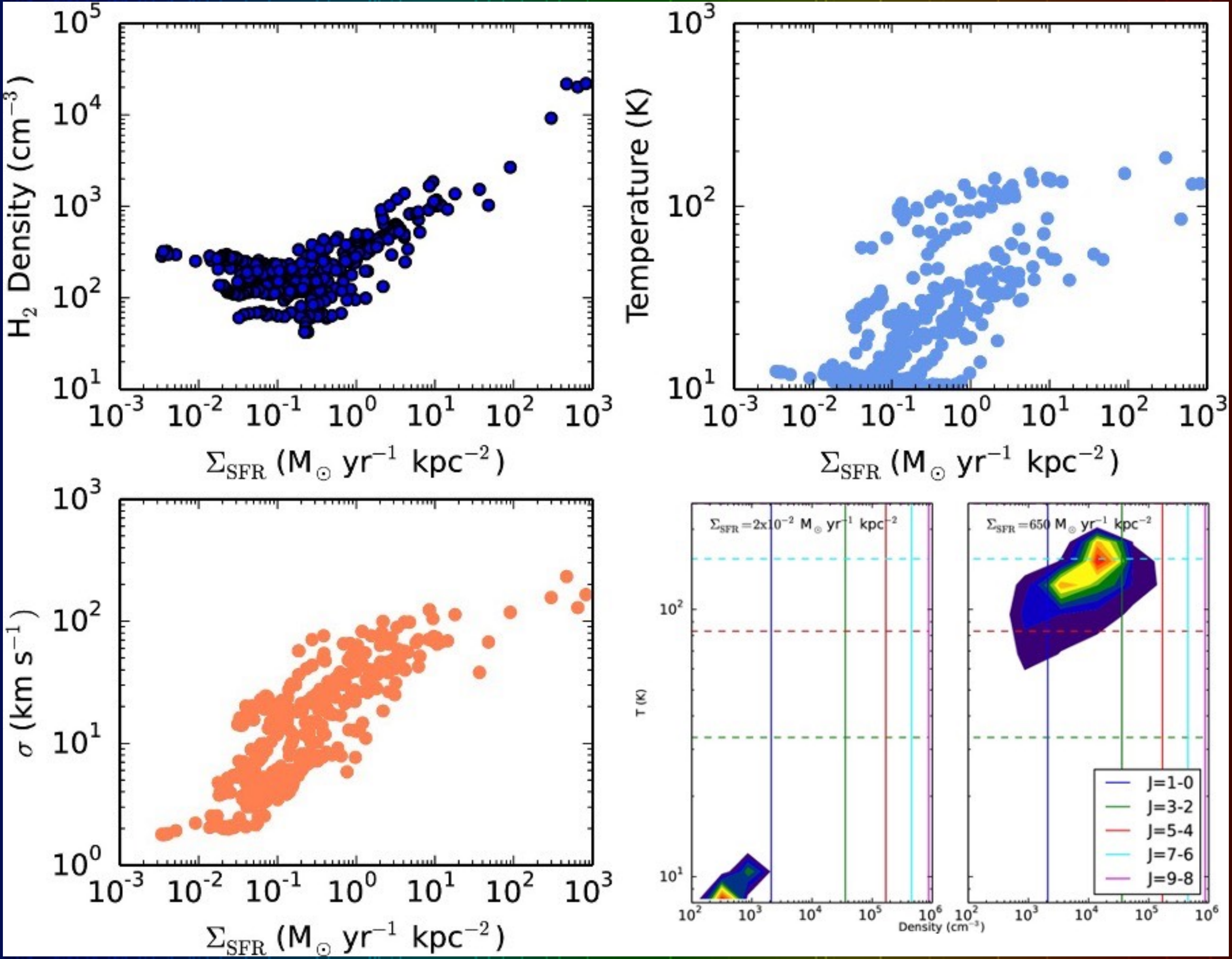
Likely impacted by optical depth

- HCN/CO ratio suggests much denser & warmer gas than CO SLED alone
- High-J transitions obscured!
- Xco difficult in ULIRGs



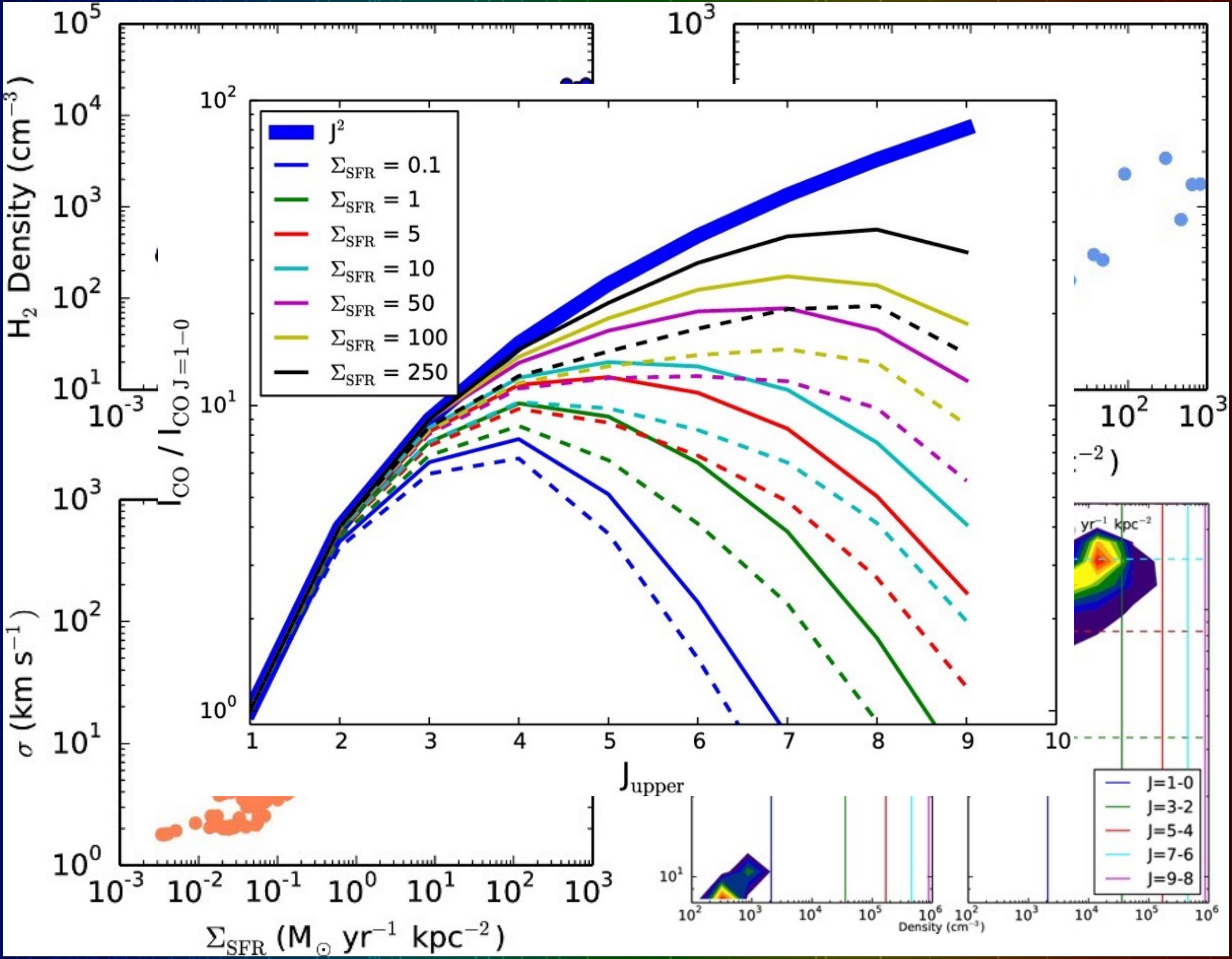
Papdopolous+2010

Underlying physics of α_{CO}



Narayan & Krumholz (2014)

Underlying physics of α_{CO}



Narayan & Krumholz (2014)

Dense gas

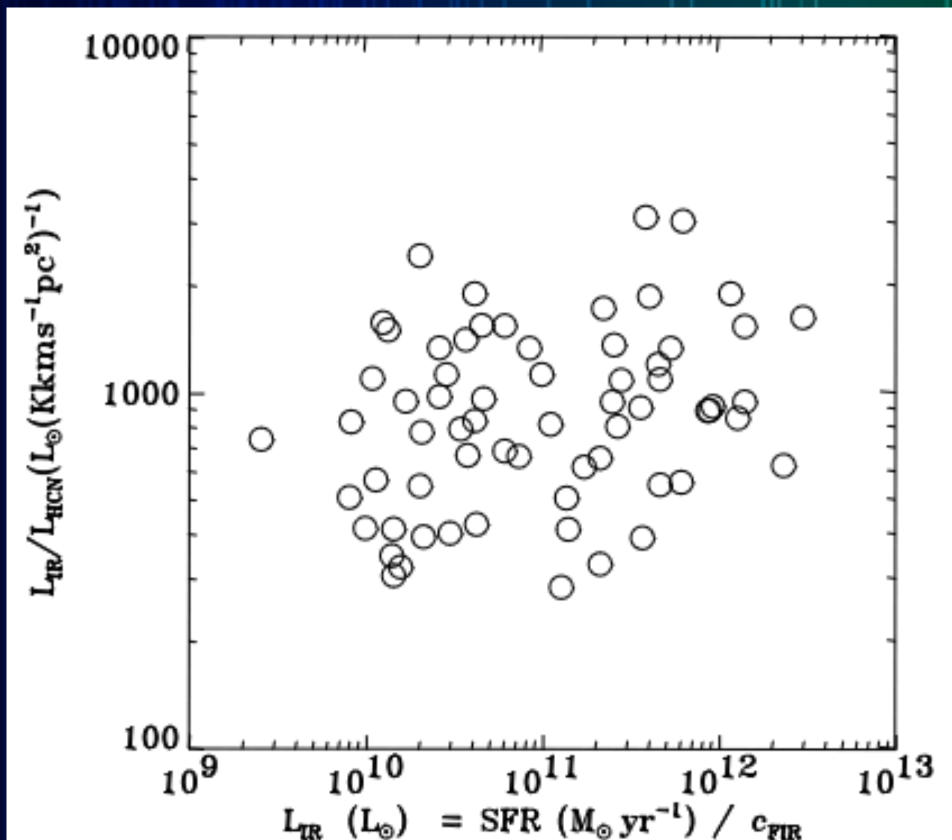
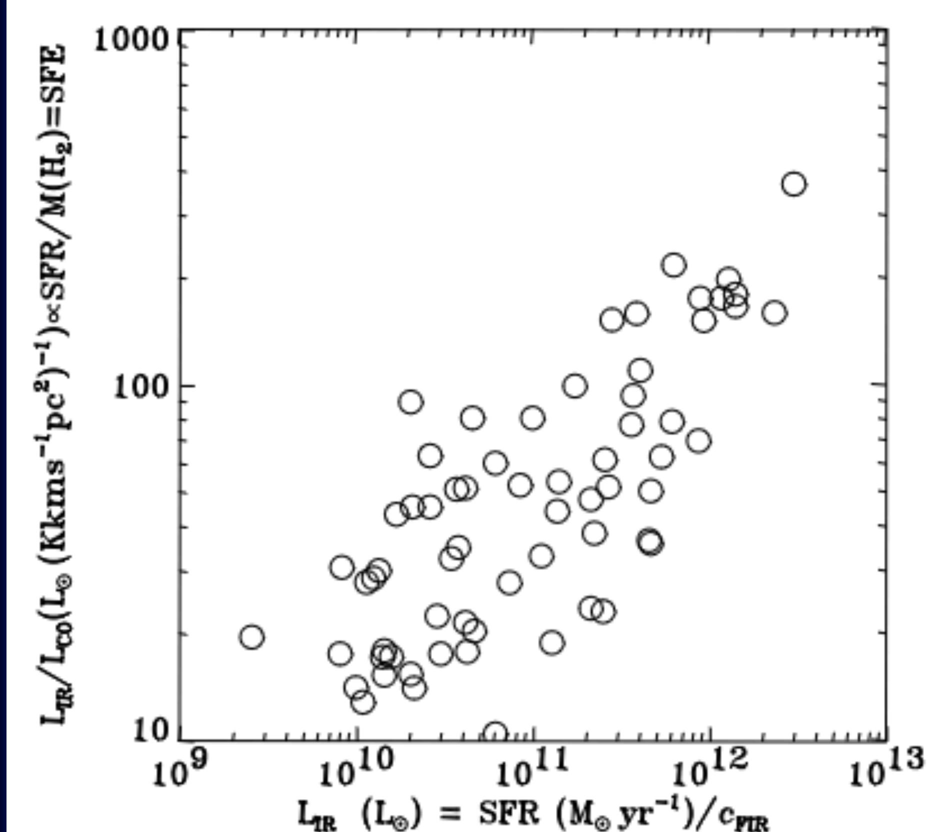
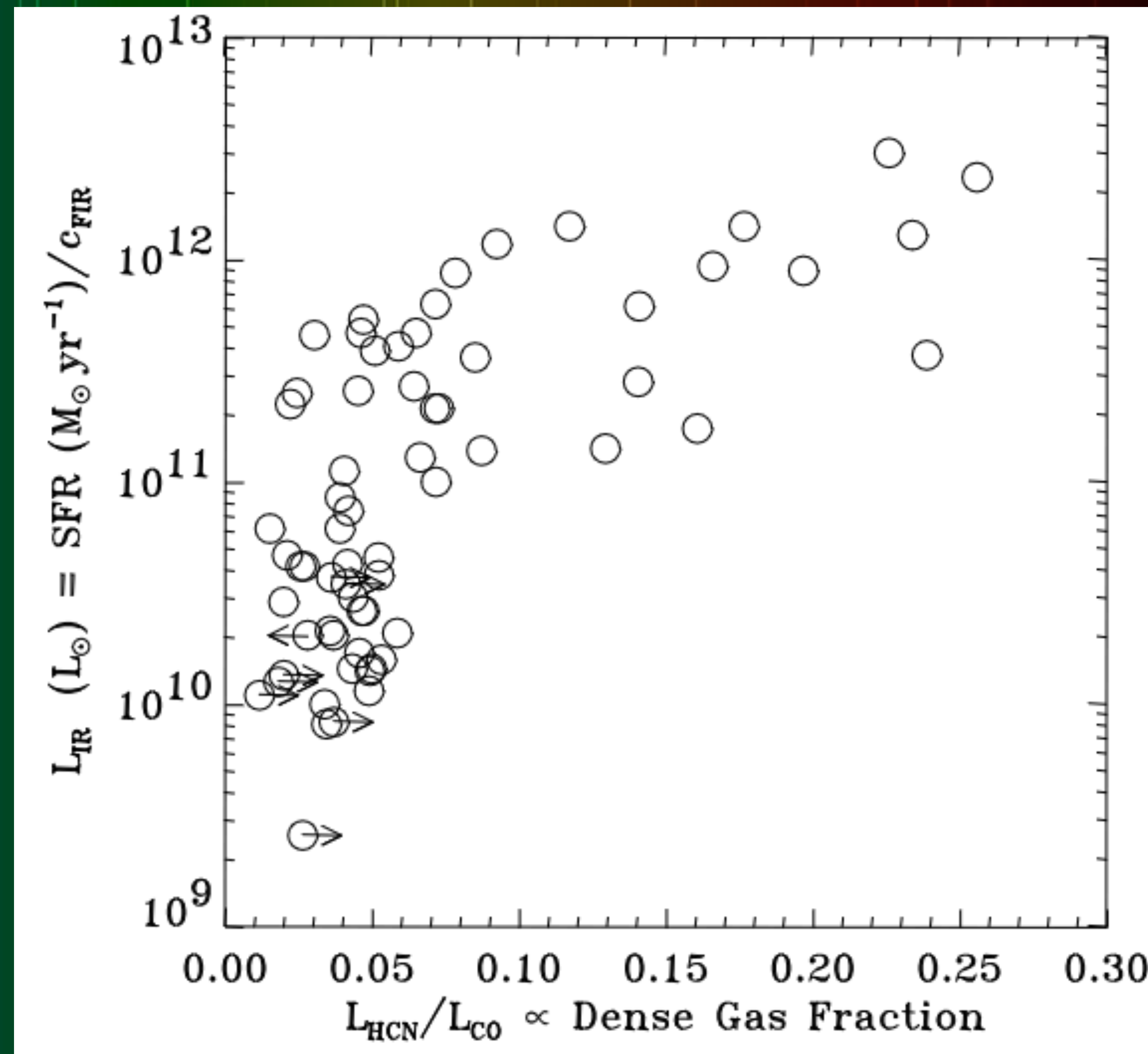
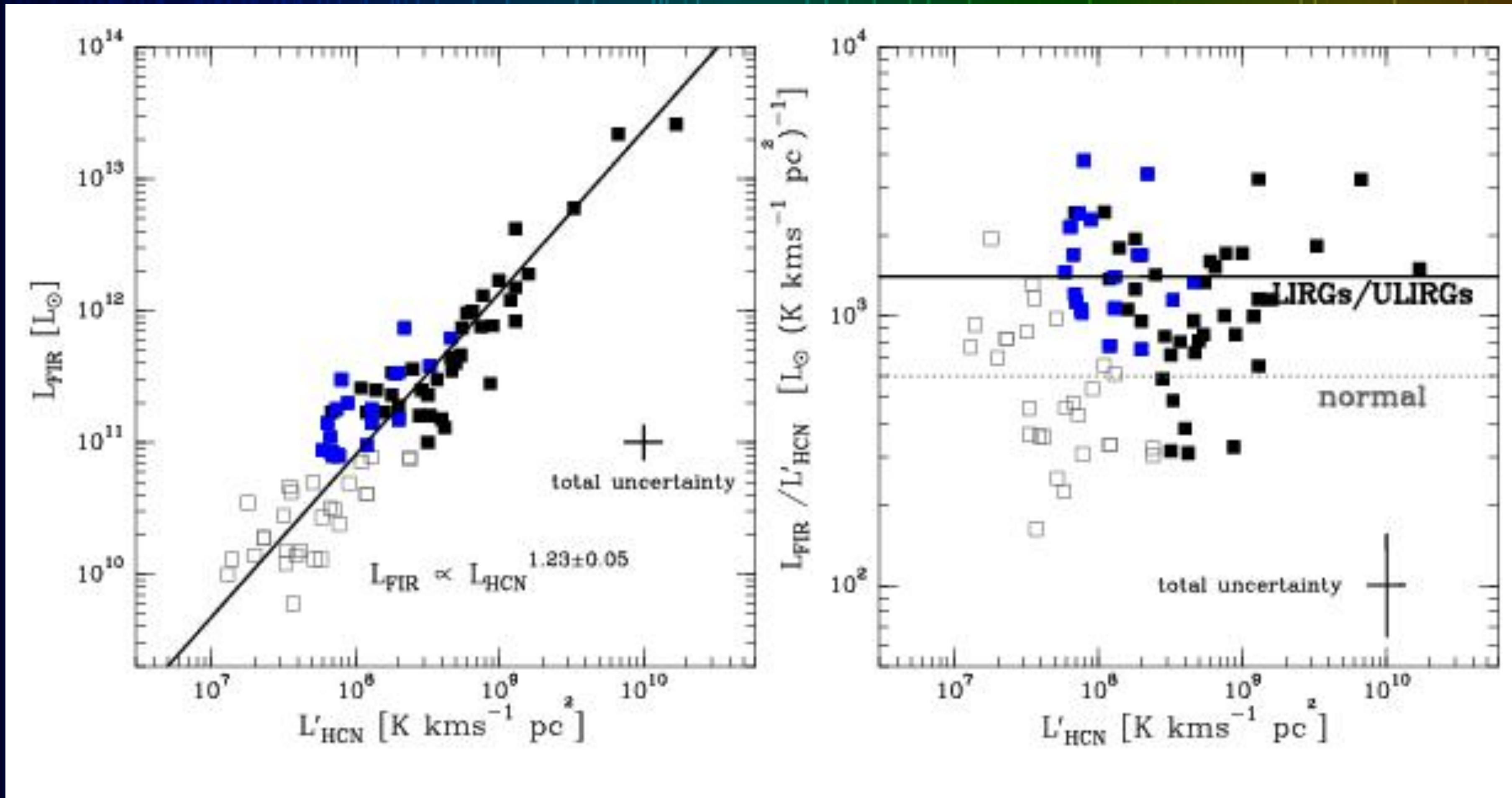


FIG. 2*a*

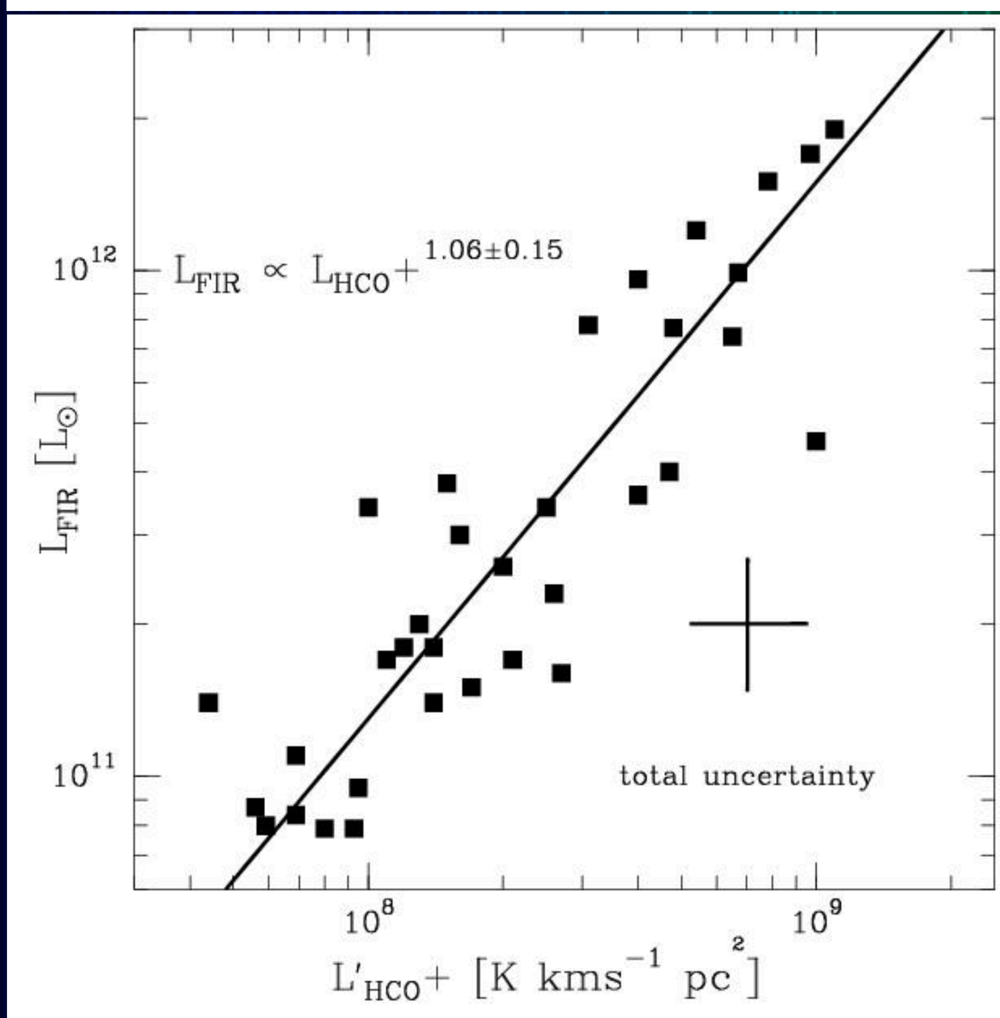




Gao & Solomon (2004)

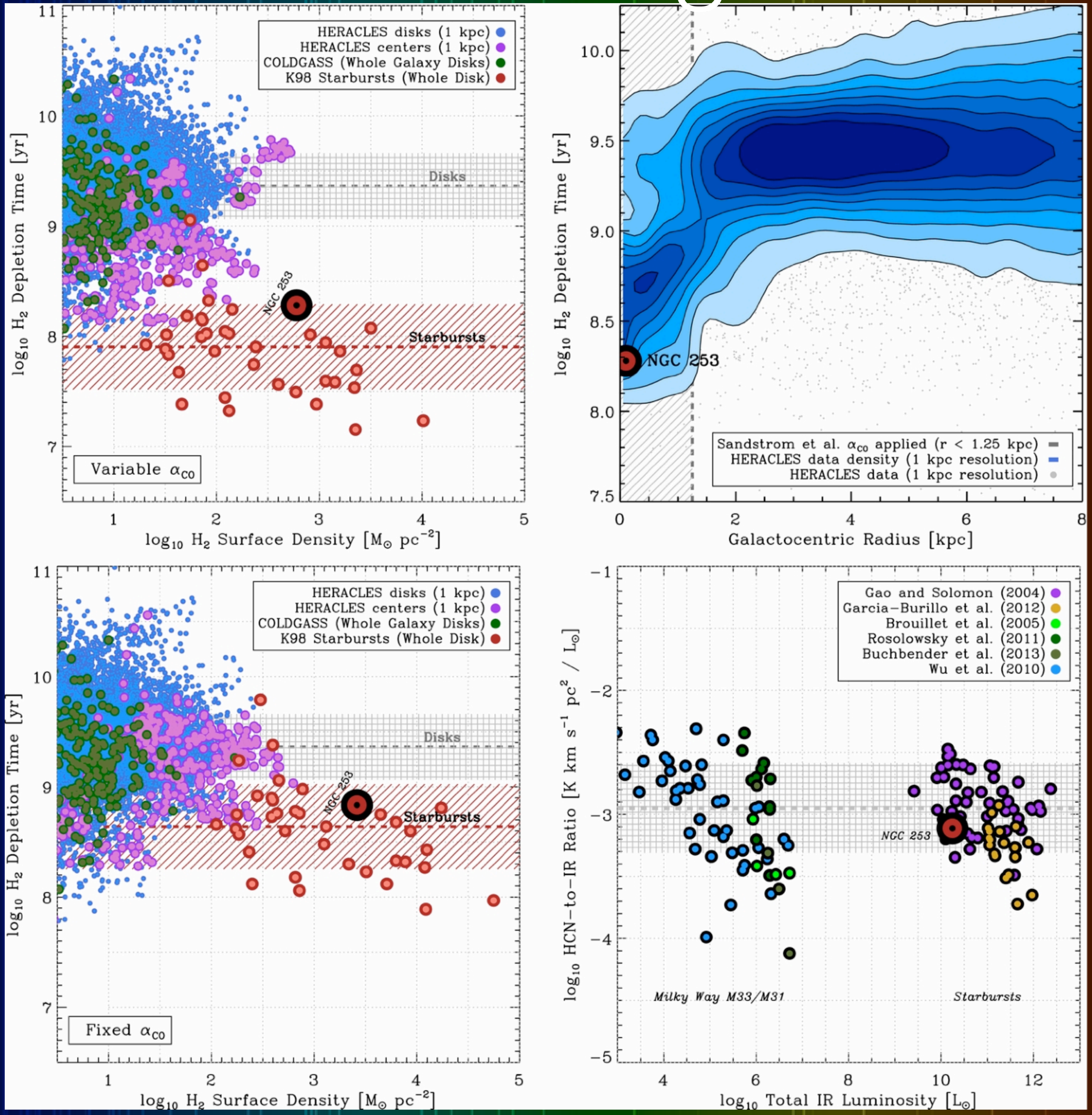


Garcia-Burillo+ (2004)



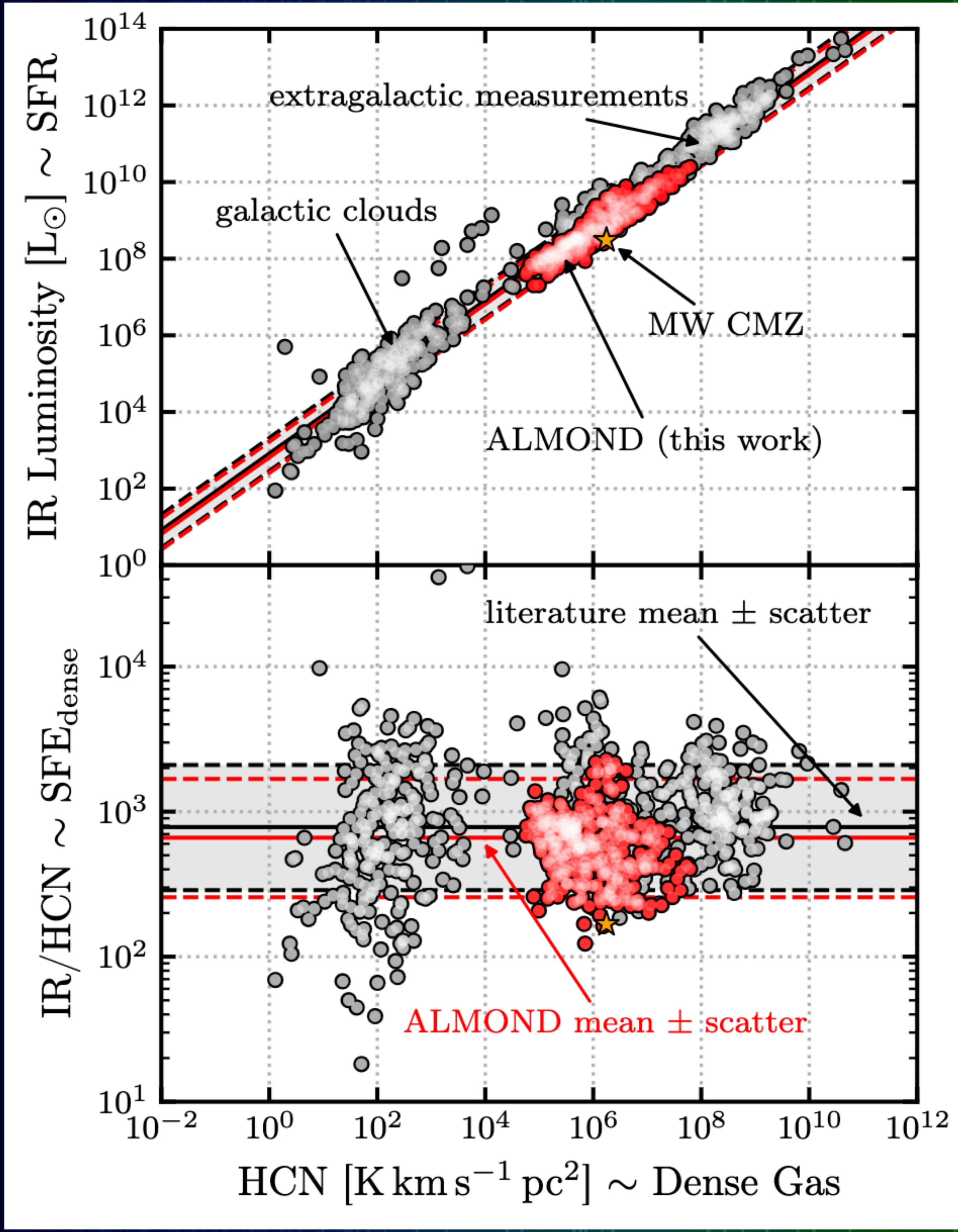
- See more linear correlations with dense gas tracers HCN, HCO^+
- But HCN/HCO^+ impacted by shocks, X-rays (Meijerink+2007,2011)

Dense gas



Leroy+ (2015)

Dense gas

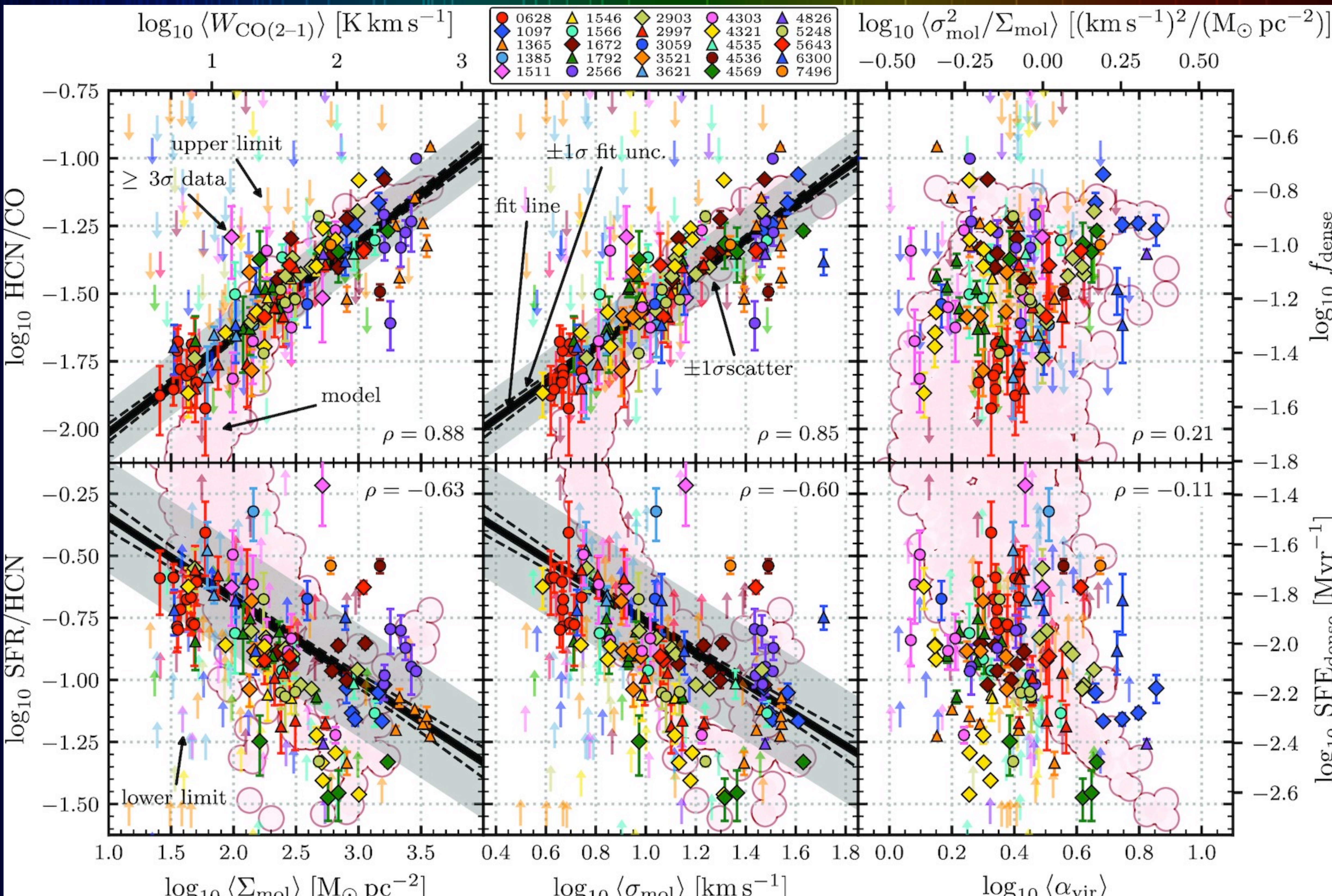


- See more linear correlations with dense gas tracers HCN, HCO^{+}
- This gives a constant τ_{dep}(dense) with ~0.5 dex scatter
- However scatter may be related to cloud properties…

EMPIRE/ALMOND/PHANGS

Neumann+ (2023)

Dense gas



EMPIRE/ALMOND/PHANGS

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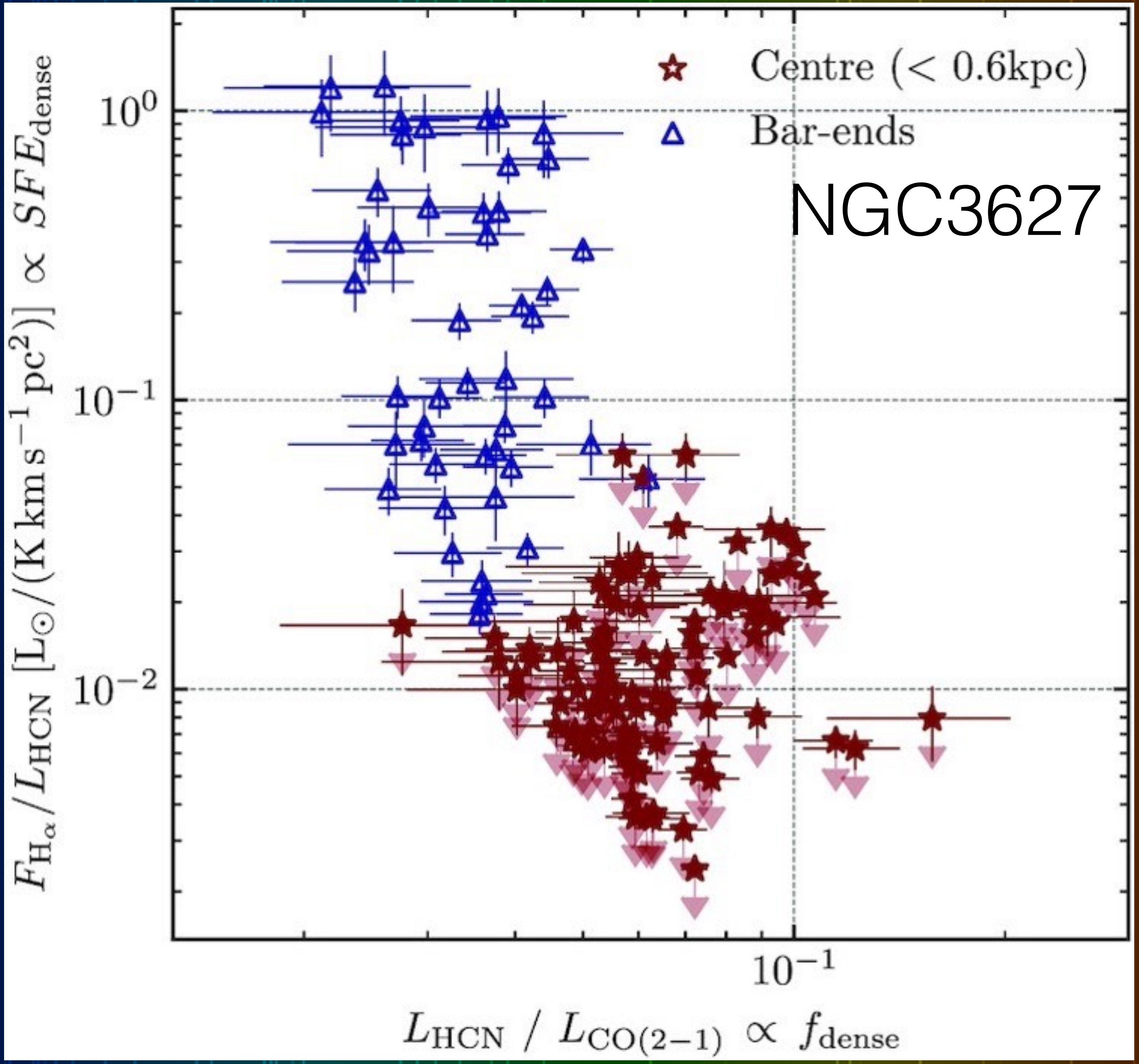
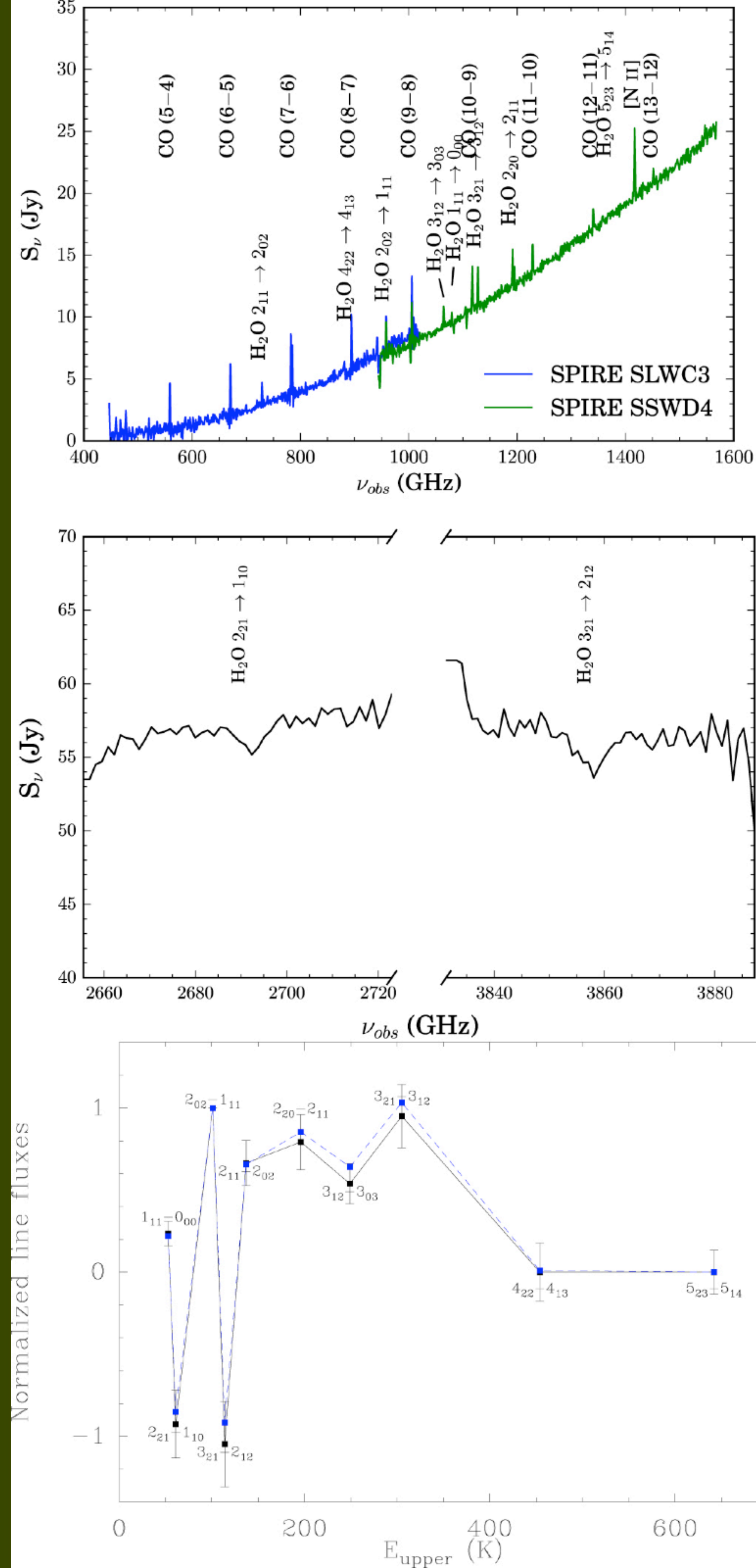


EMPIRE/ALMOND/PHANGS

Bešlić+(2021)

Other molecular lines

- Brightness of ULIRGs allow measurement of transitions of multiple molecules
- Density & Heating in AGN allow for high level transitions (not just in CO)



IRAS 13120–5453

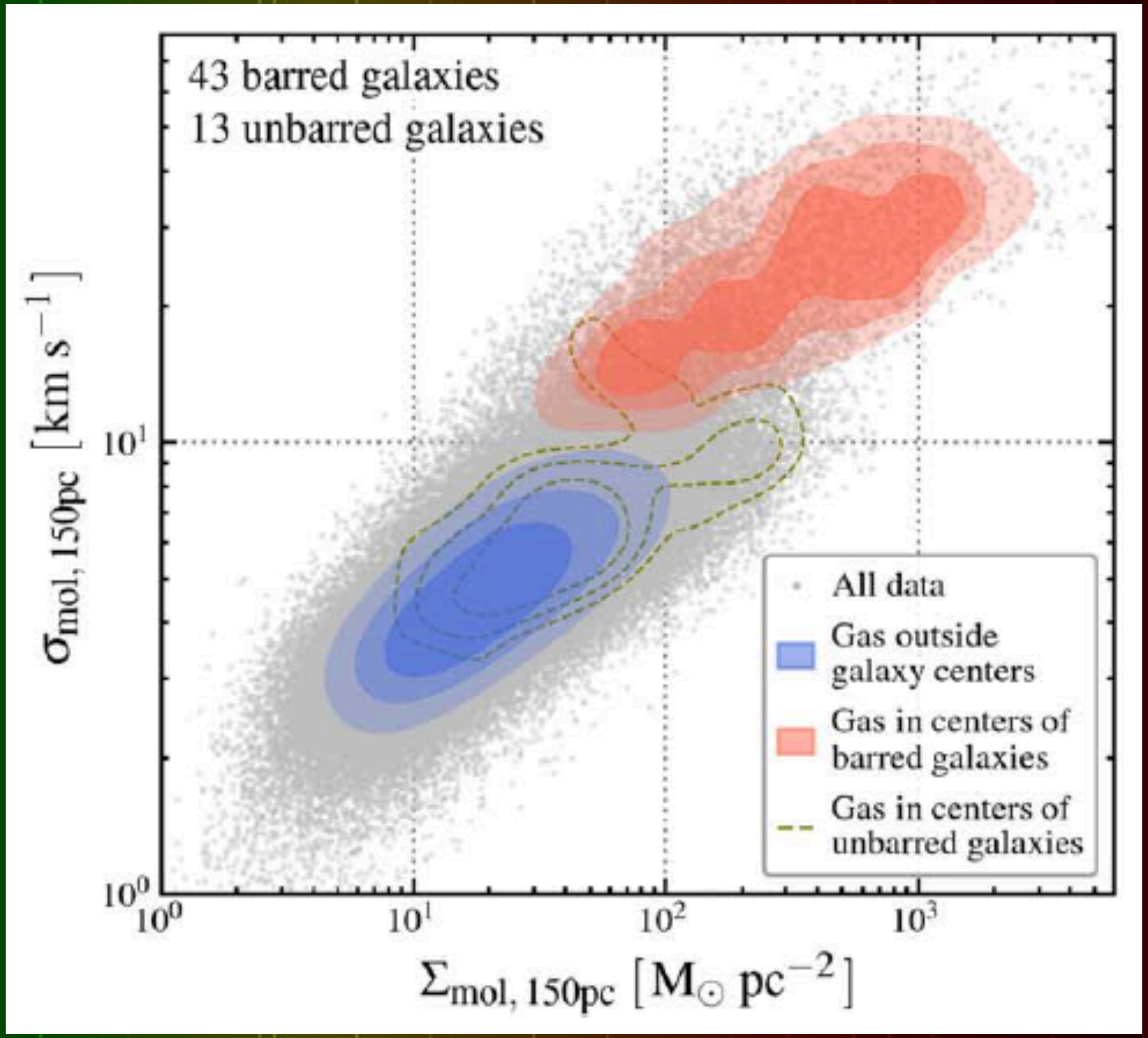
Privon+ (2017)

ISM of ULIRGs

- ULIRGS & Starburst have higher Σ_{gas}, high $f(H_2)$
- Clear evidence of high dense gas fraction (f_{dense} ~HCN/ CO)
- At high density $T_K \sim T_{dust}$ (& warm dust in ULIRGs)
- BUT extra heating sources
  - X-rays (AGN)
  - Cosmic rays
  - shocks (winds & turbulence/high σ_{gas})

Cloud scales

- With ALMA we're now reaching cloud scales in nearby galaxies
- PHANGS show us where typical star-forming galaxies lie
- But even in 'normal', see high values and dispersion in barred galaxy centres



Sun+ (2020)

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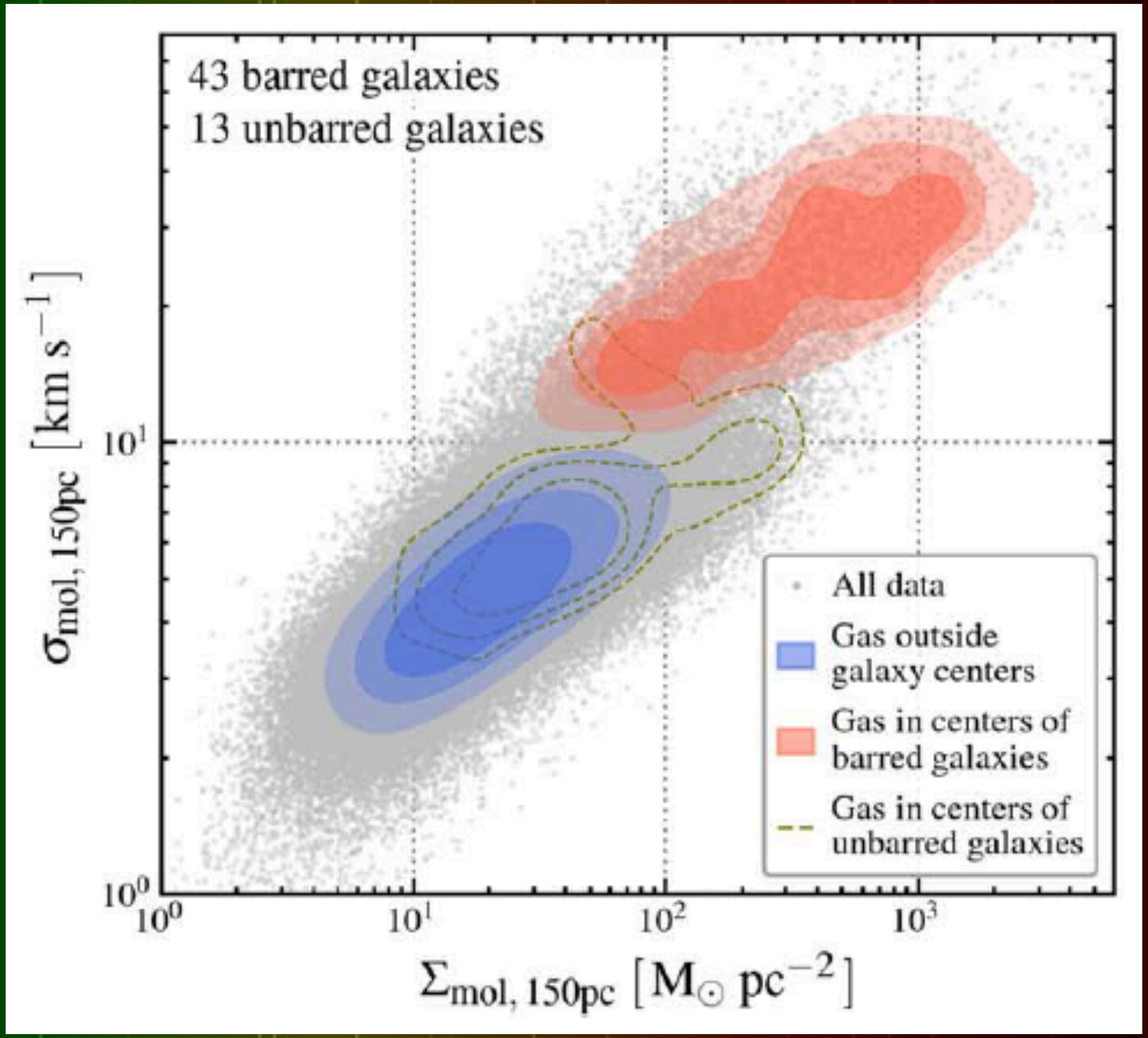

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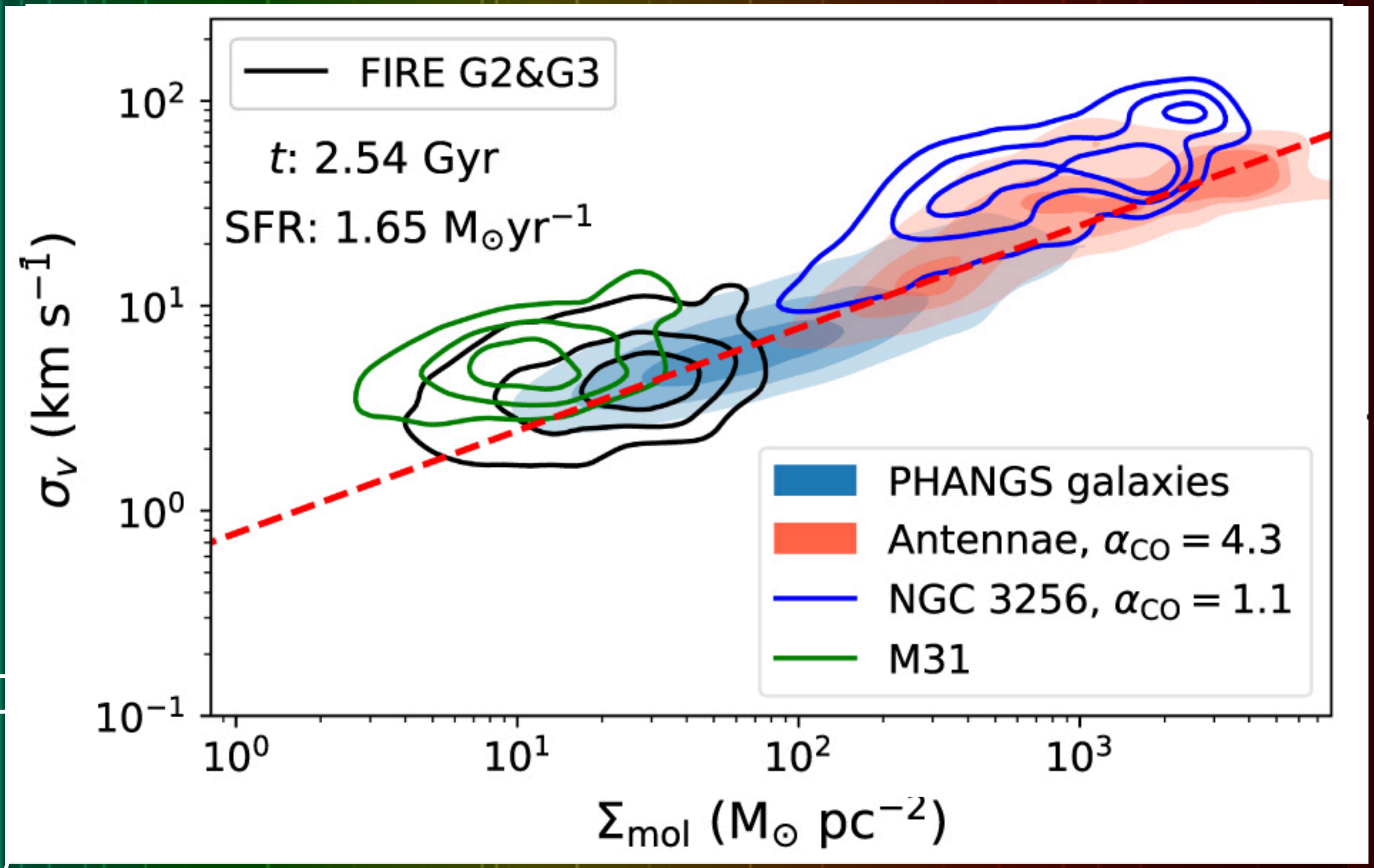

Observations: Brunetti+ (2020,22)
Simulations: He,Bottrell+ (2023)

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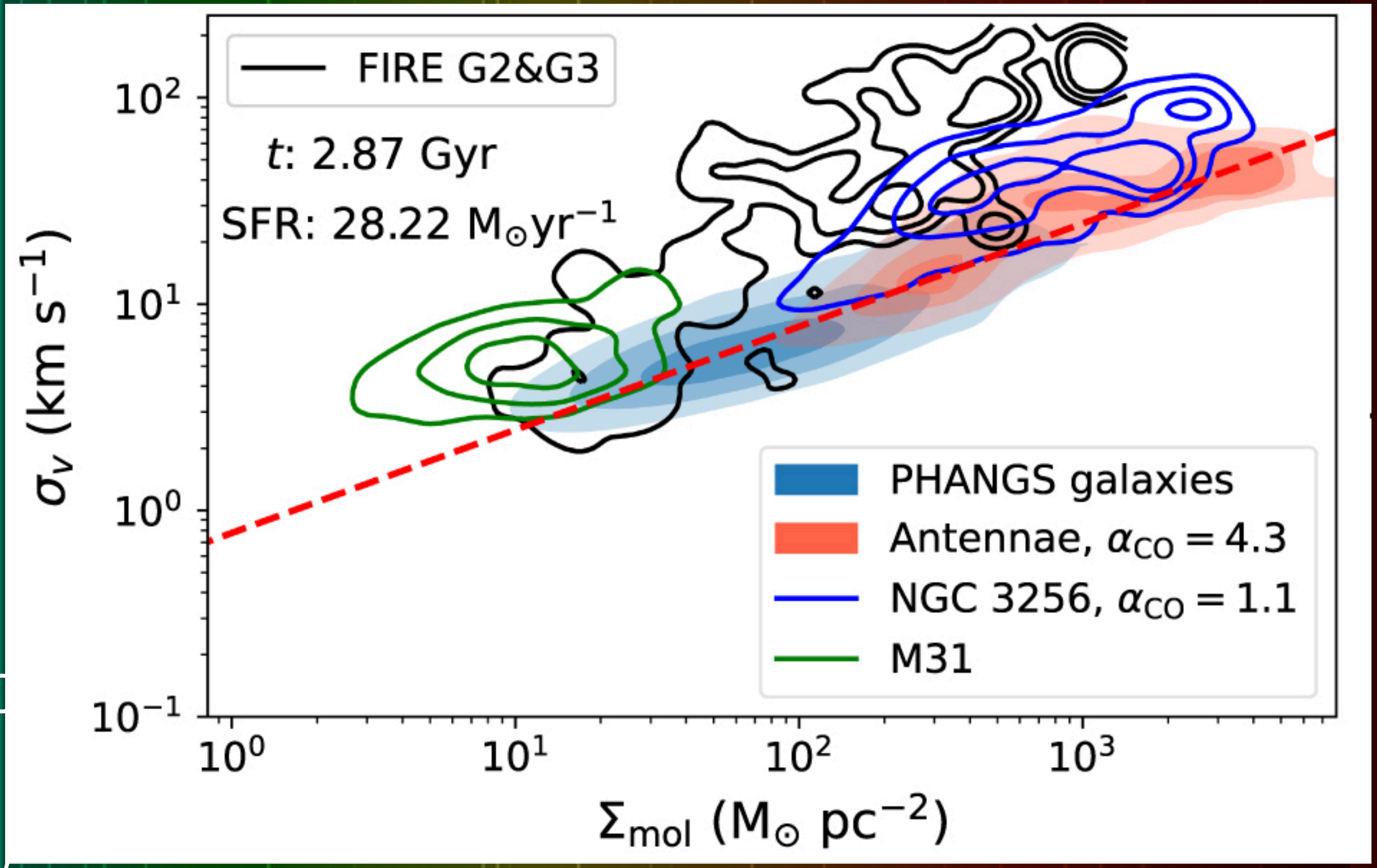

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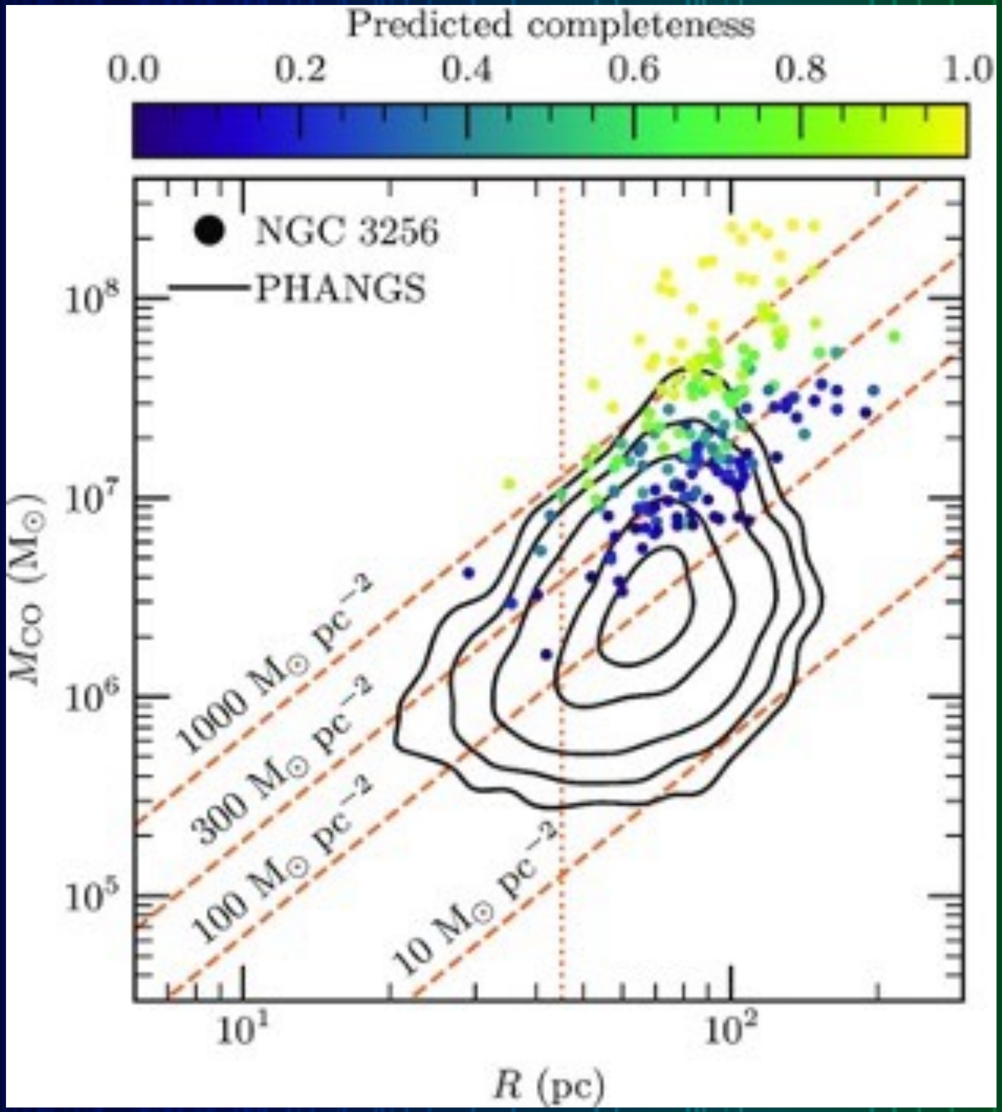
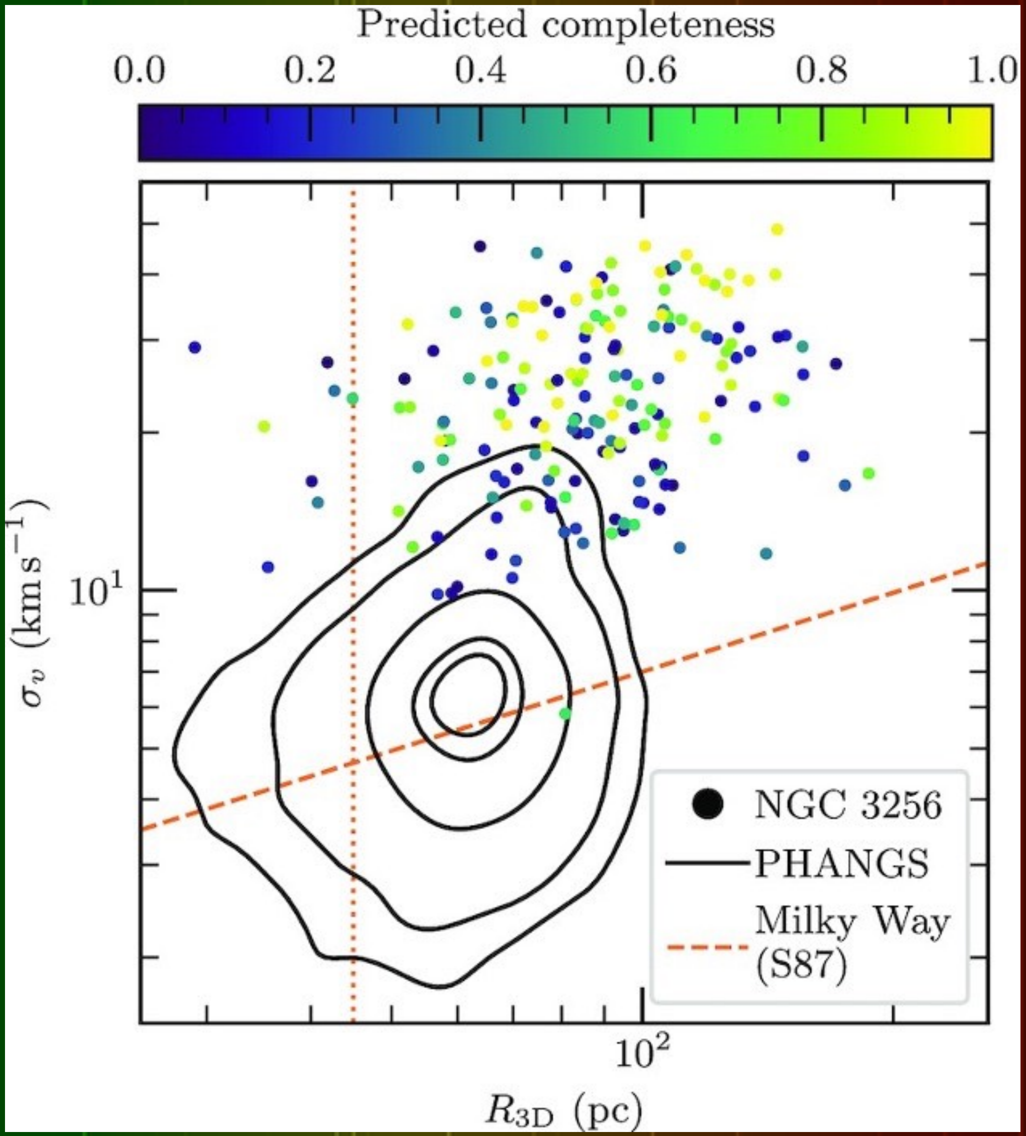
Simulations: He,Bottrell+ (2023)

Cloud scale differences

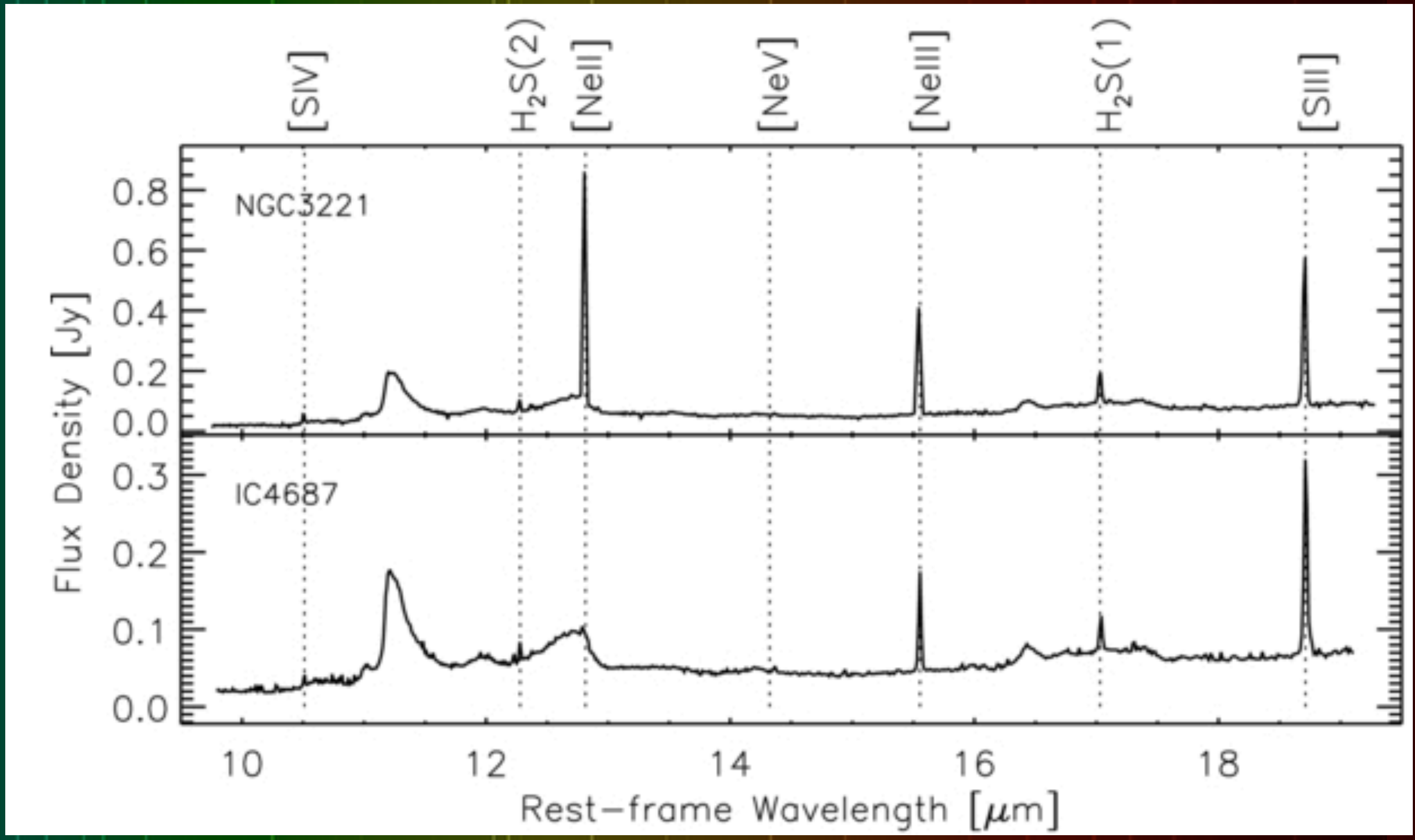




Brunetti & Wilson (2022)

Ionized ISM in ULIRGs

- Typical optical lines from Ionized ISM are heavily obscured in ULIRGs
- However, NIR-FIR lines will not be as obscured
- Can be used to estimate SFRs, ionization states or presence of shocks AGN



Inami+(2013)

GOALS

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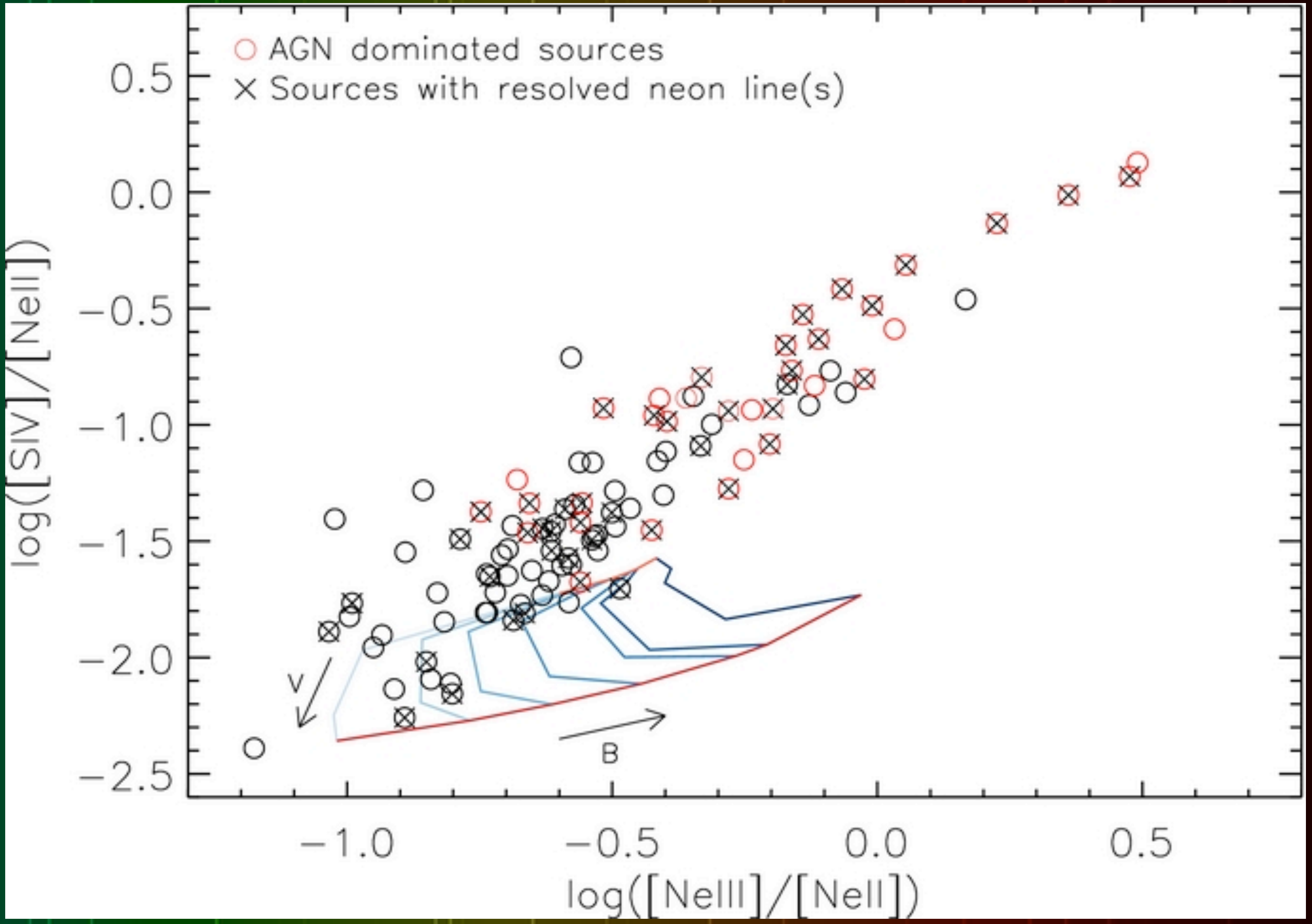

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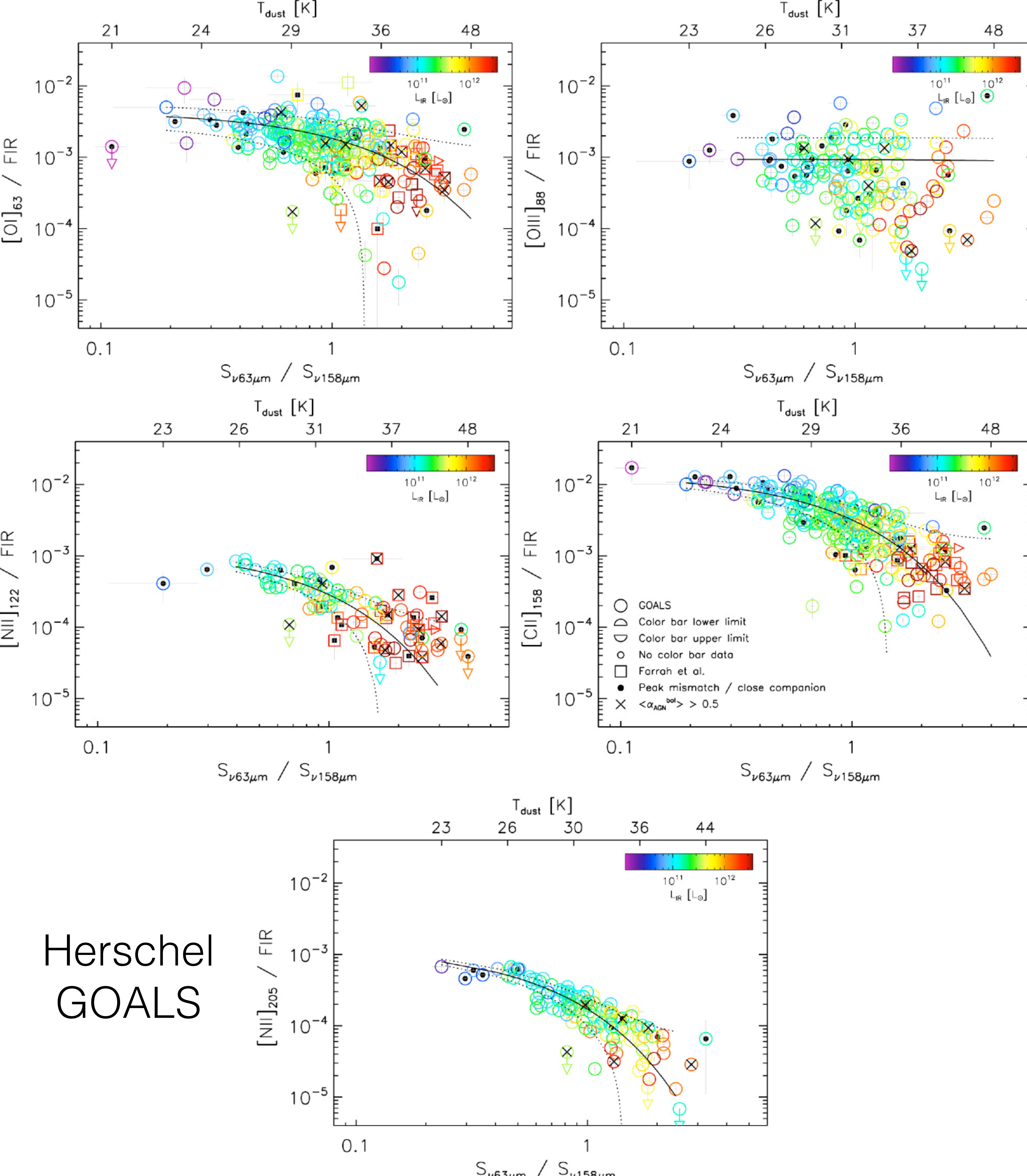
GOALS



Herschel GOALS

- IR lines show "IR-deficit"
- Likely comes from changing ISM physics & increasing 'dust cooling'
- That is dust competing for ionising photons with gas and collisionally heat dust cooling
- Intense radiation fields and compact star forming regions (PDRs) dominate

Diaz-Santos+ (2017)

The ISM & SF in AGN

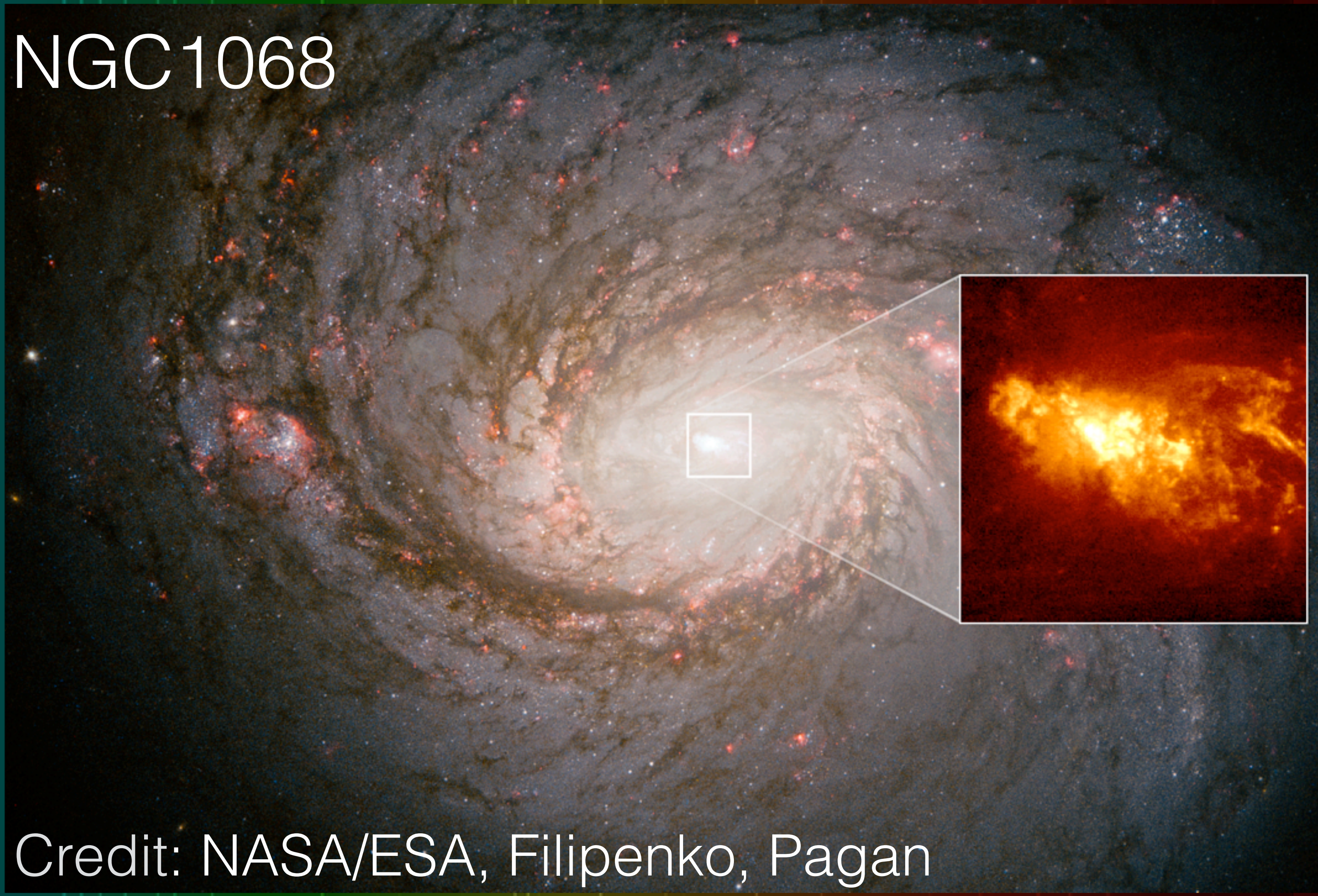
Brent Groves GISM2

THE UNIVERSITY OF WESTERN AUSTRALIA

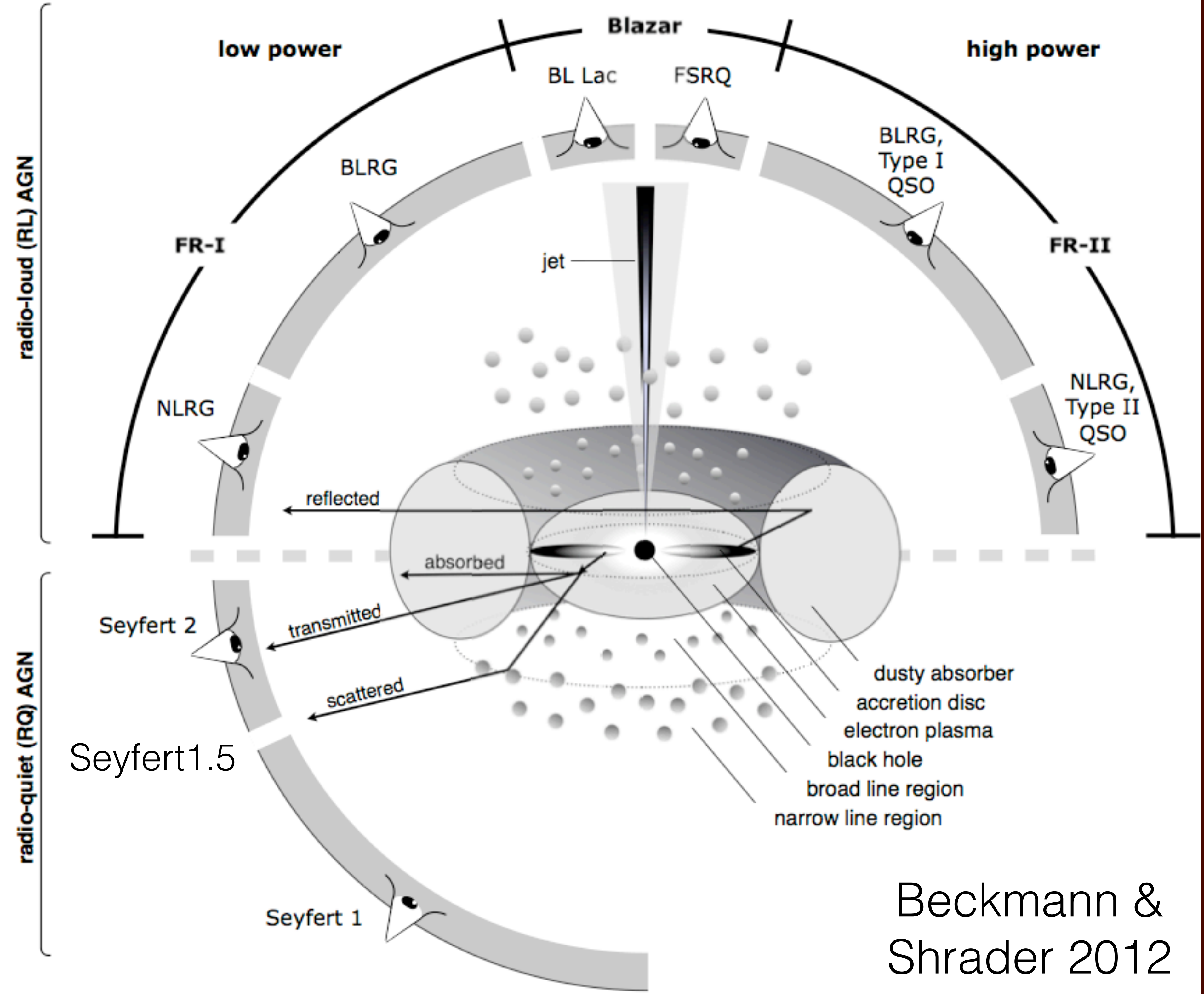
ICRAR

AGN

- AGN: Active galactic Nuclei
- Ongoing accretion onto supermassive black hole
- Strong winds & Jets
- Hard ionising UV& X-ray emission
- Rapid movement of gas towards centre (Broad line region)
- Hot dusty region around nucleus ("torus")



AGN



Beckmann & Shrader 2012

AGN

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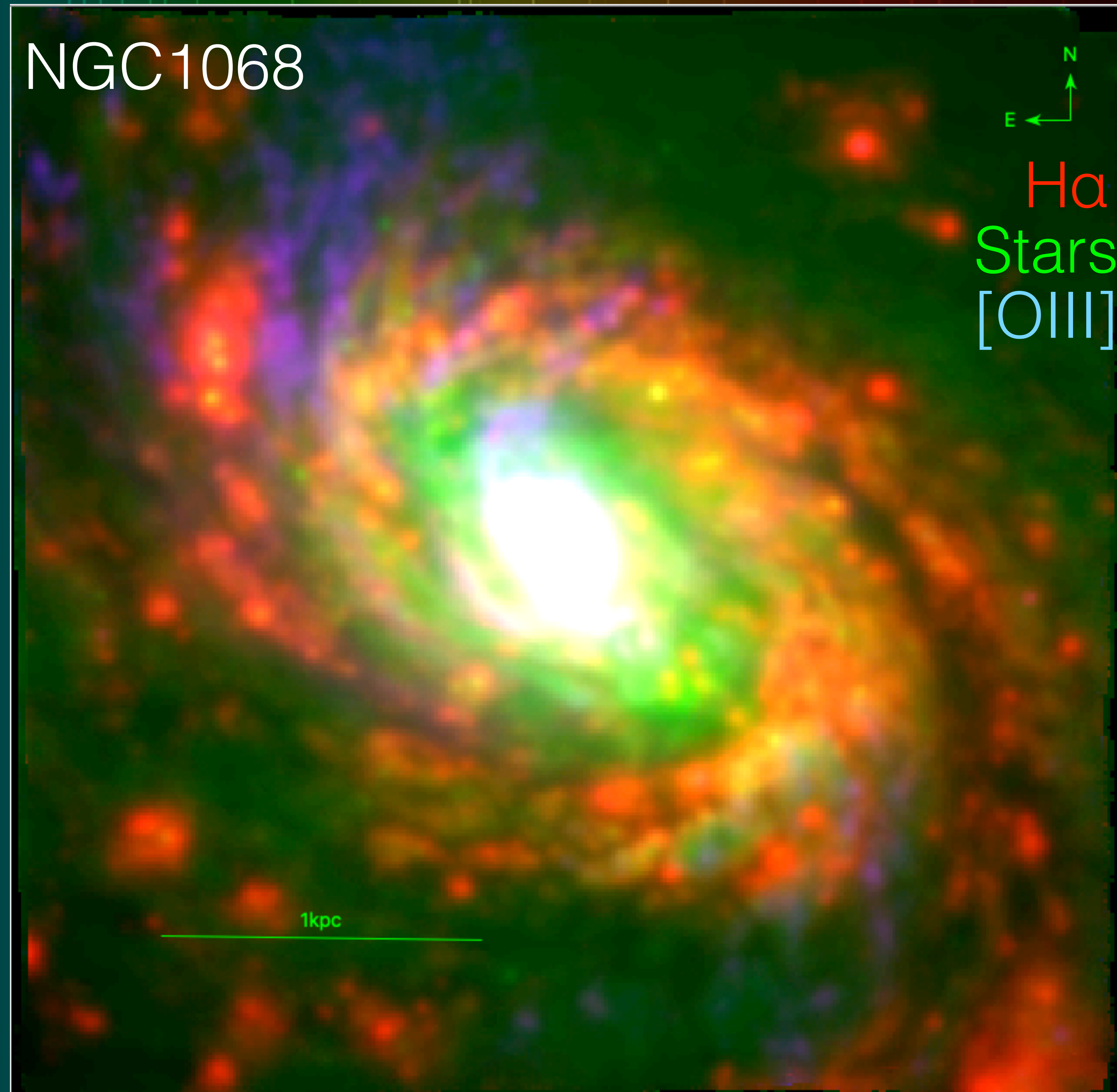

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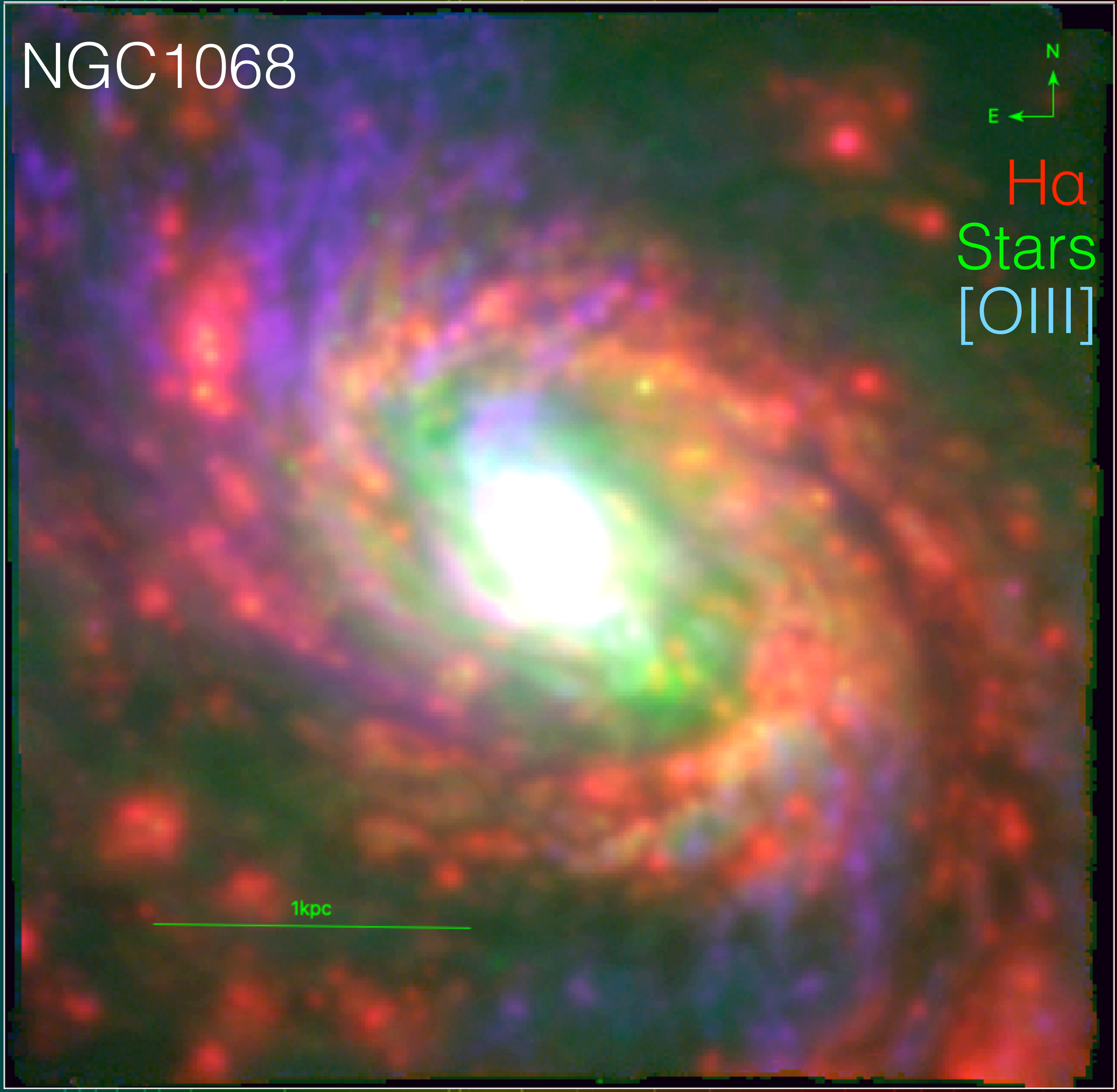
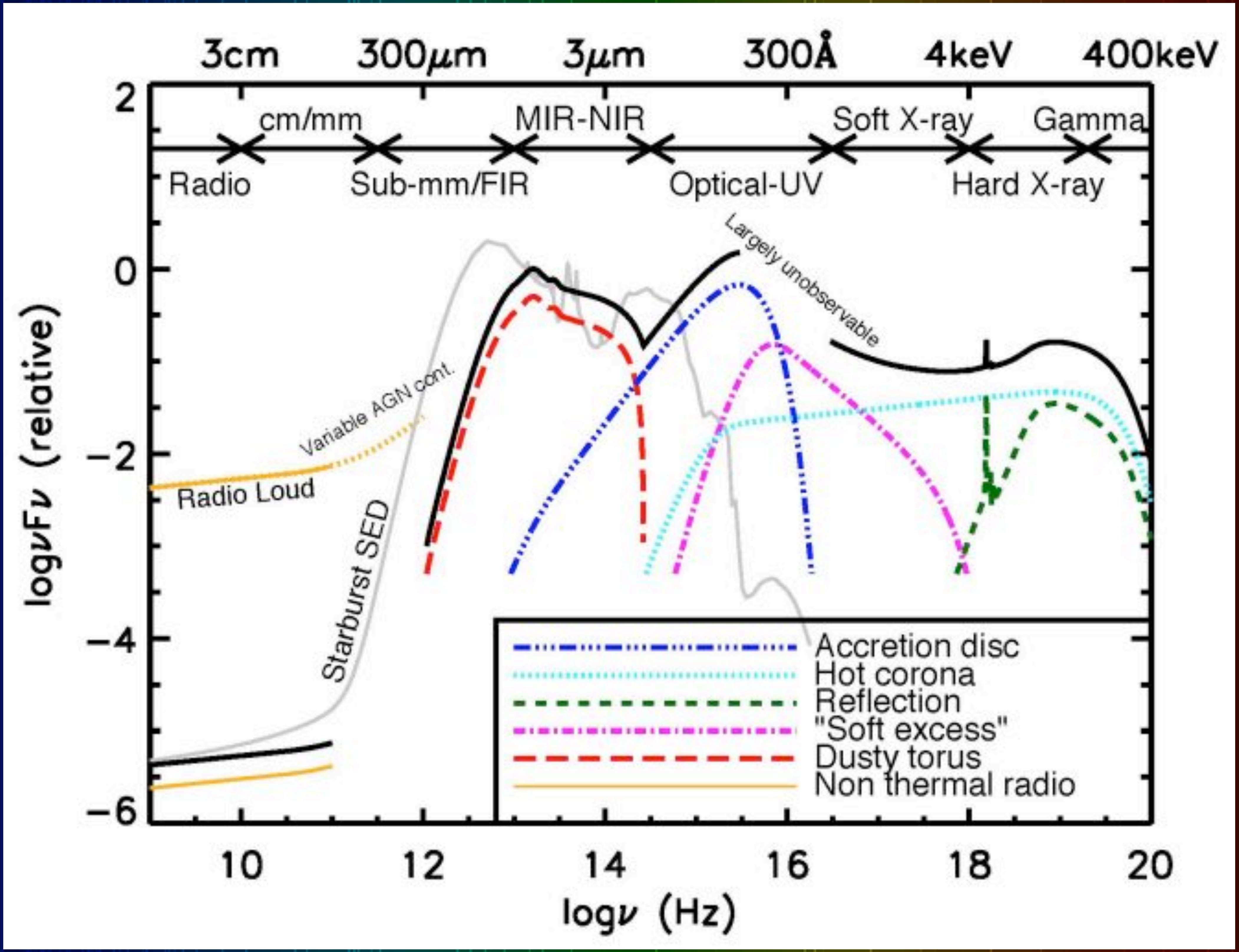


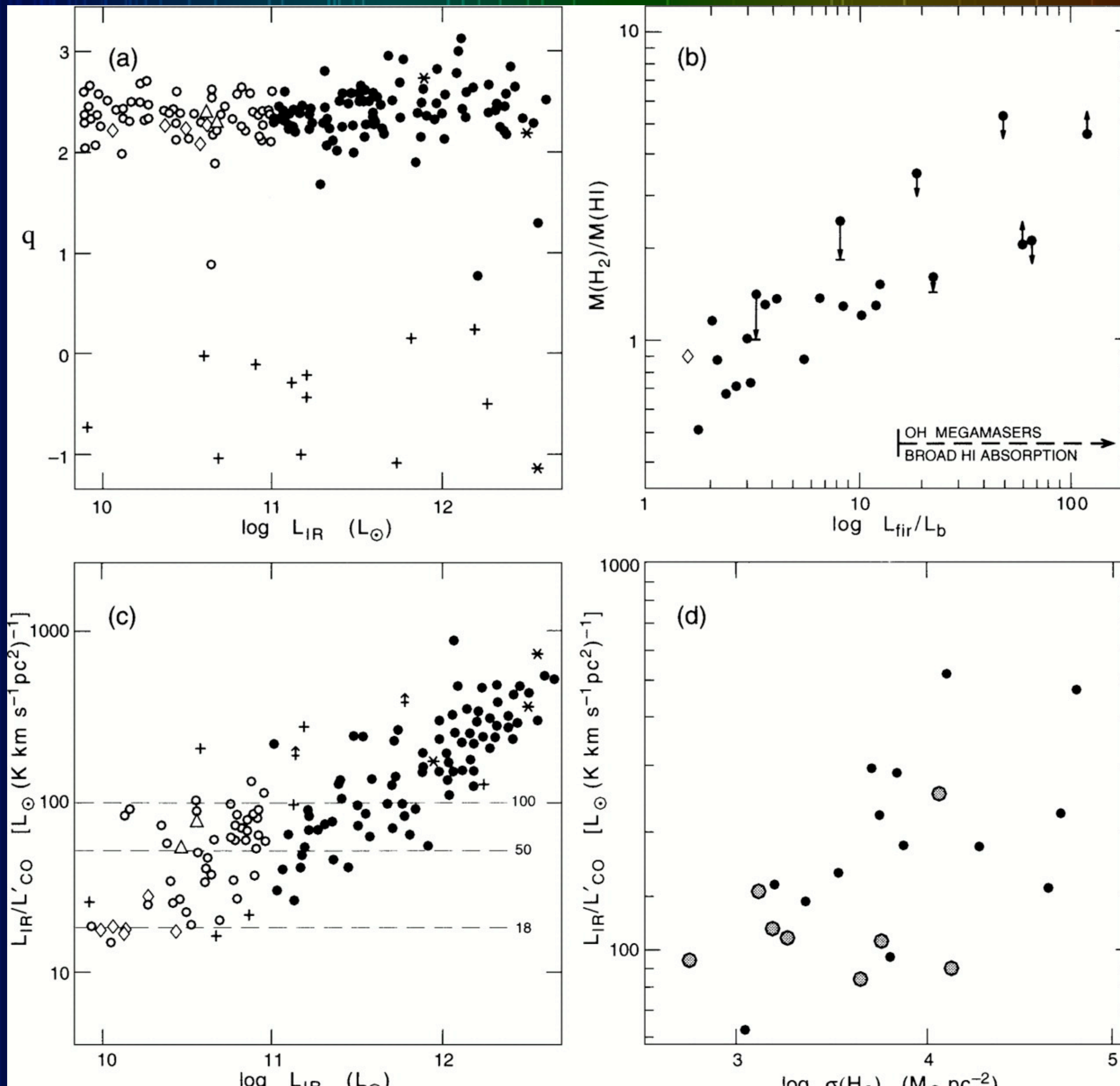
AGN heating



3cm
300μm
3μm
300Å
4keV
400keV
cm/mm
MIR-NIR
Soft X-ray
Gamma
Radio
Sub-mm/FIR
Optical-UV
Hard X-ray
Largely unobservable
Variable AGN cont.
Radio Loud
Starburst SED
logνFν (relative)
logν (Hz)
2
0
−2
−4
−6
10
12
14
16
18
20
Accretion disc
Hot corona
Reflection
"Soft excess"
Dusty torus
Non thermal radio

Physics of ULIRGs

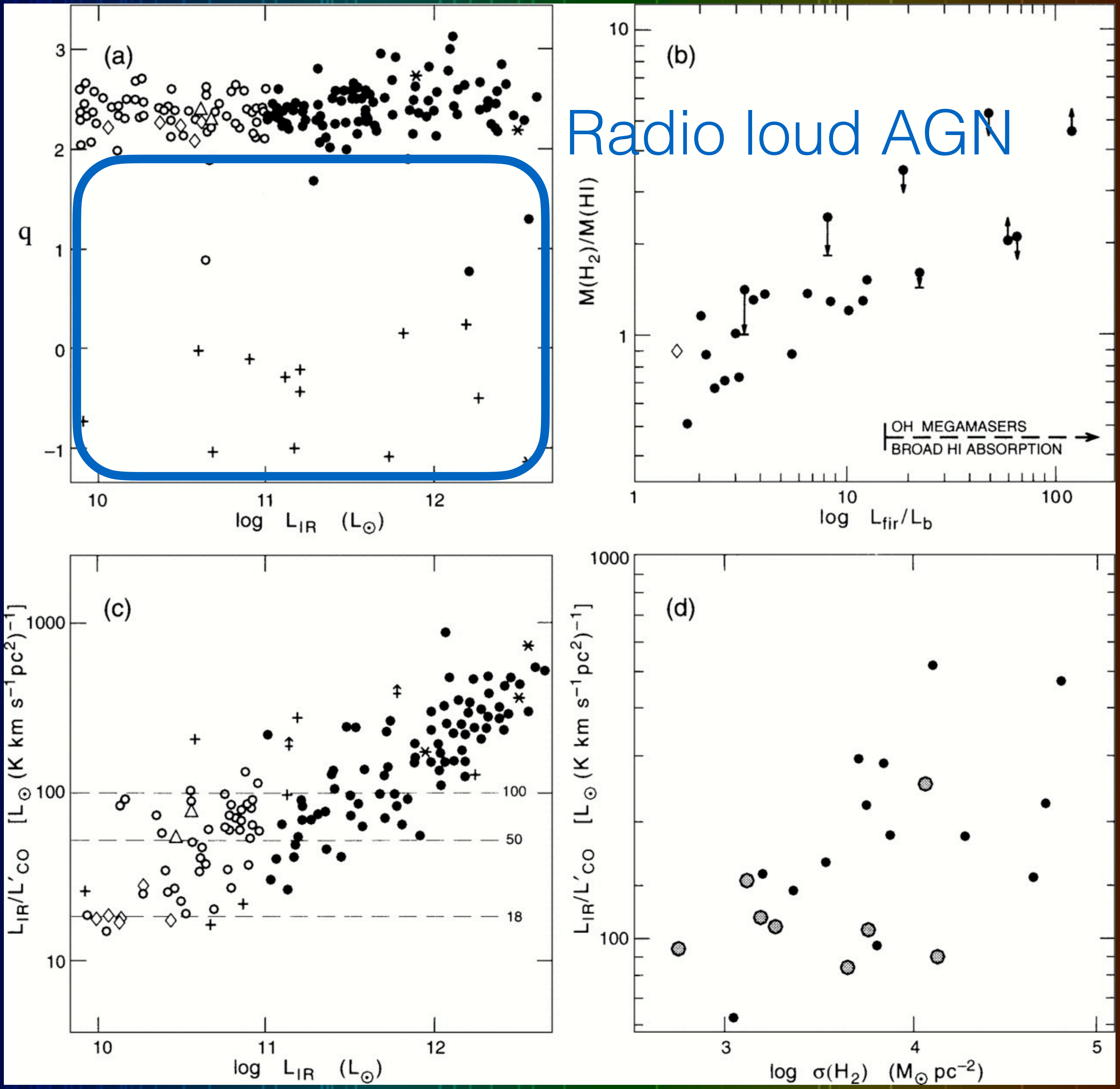
IR/1.4 GHz



Sanders & Mirabel 1996

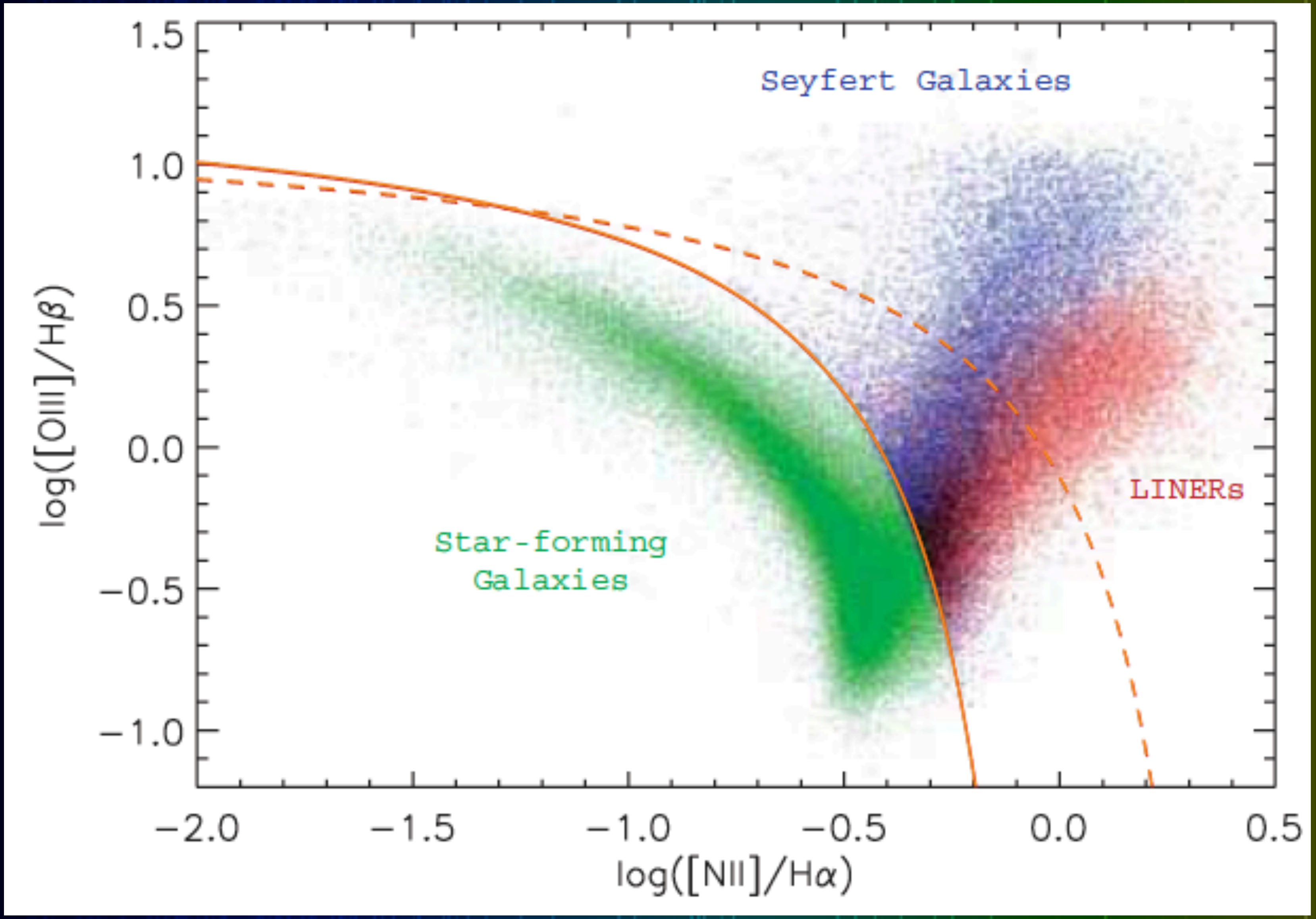
Physics of ULIRGs

IR/1.4 GHz



Sanders & Mirabel 1996

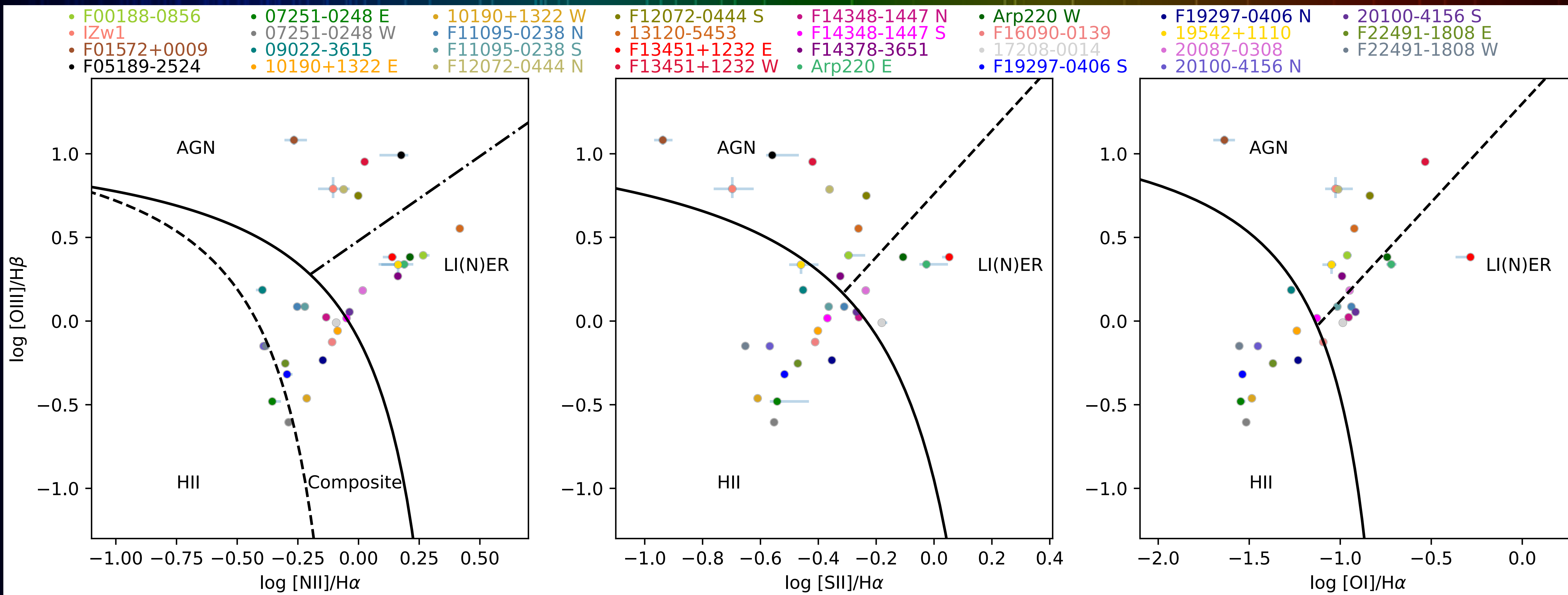
Emission line diagnostics



Groves+2006

- Hard UV & X-ray spectra leads to very different line emission than star formation
- Ionised and molecular show differences

Emission line diagnostics

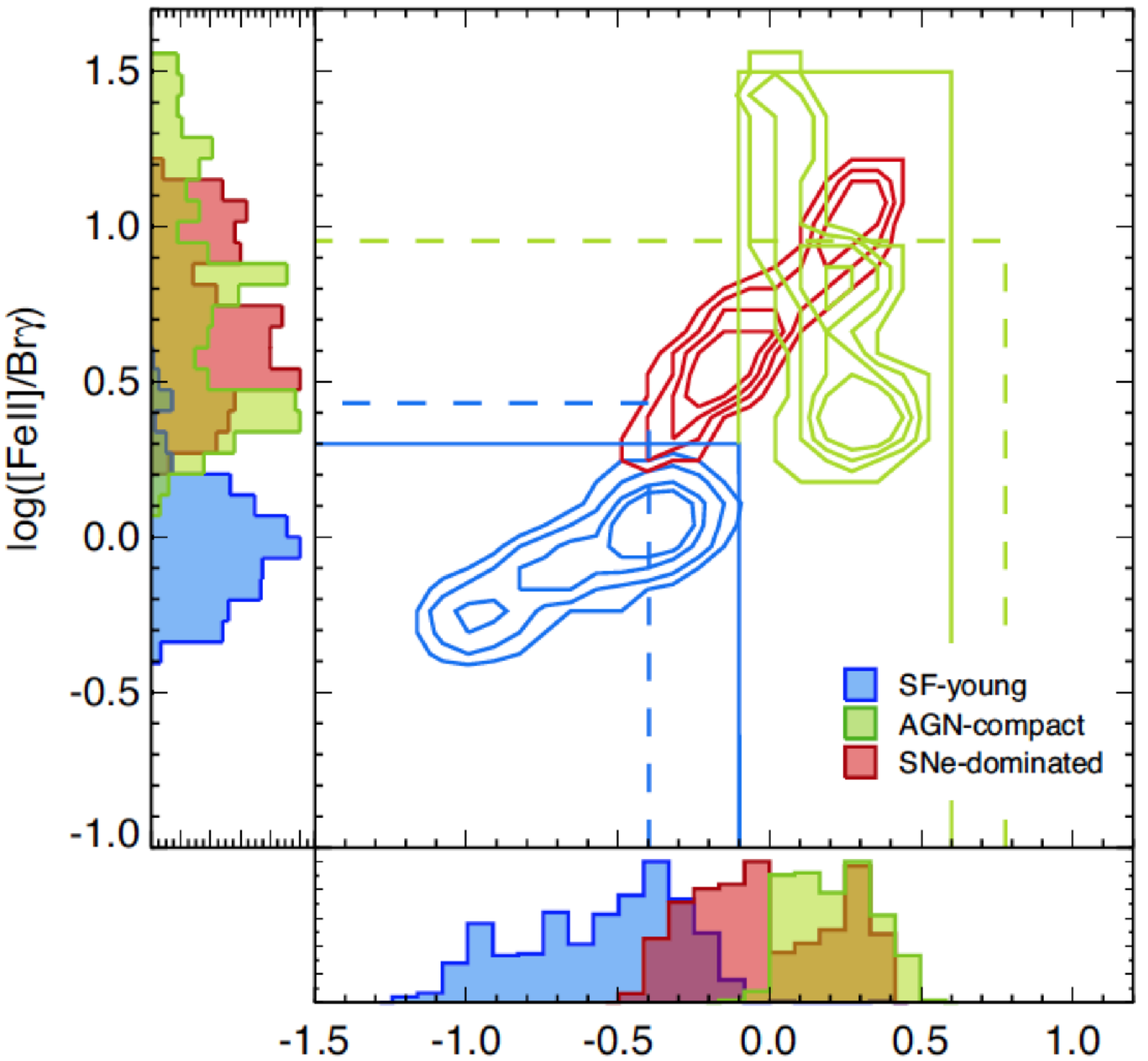


Perna+2021

PUMA: MUSE ULIRGs

Emission line diagnostics

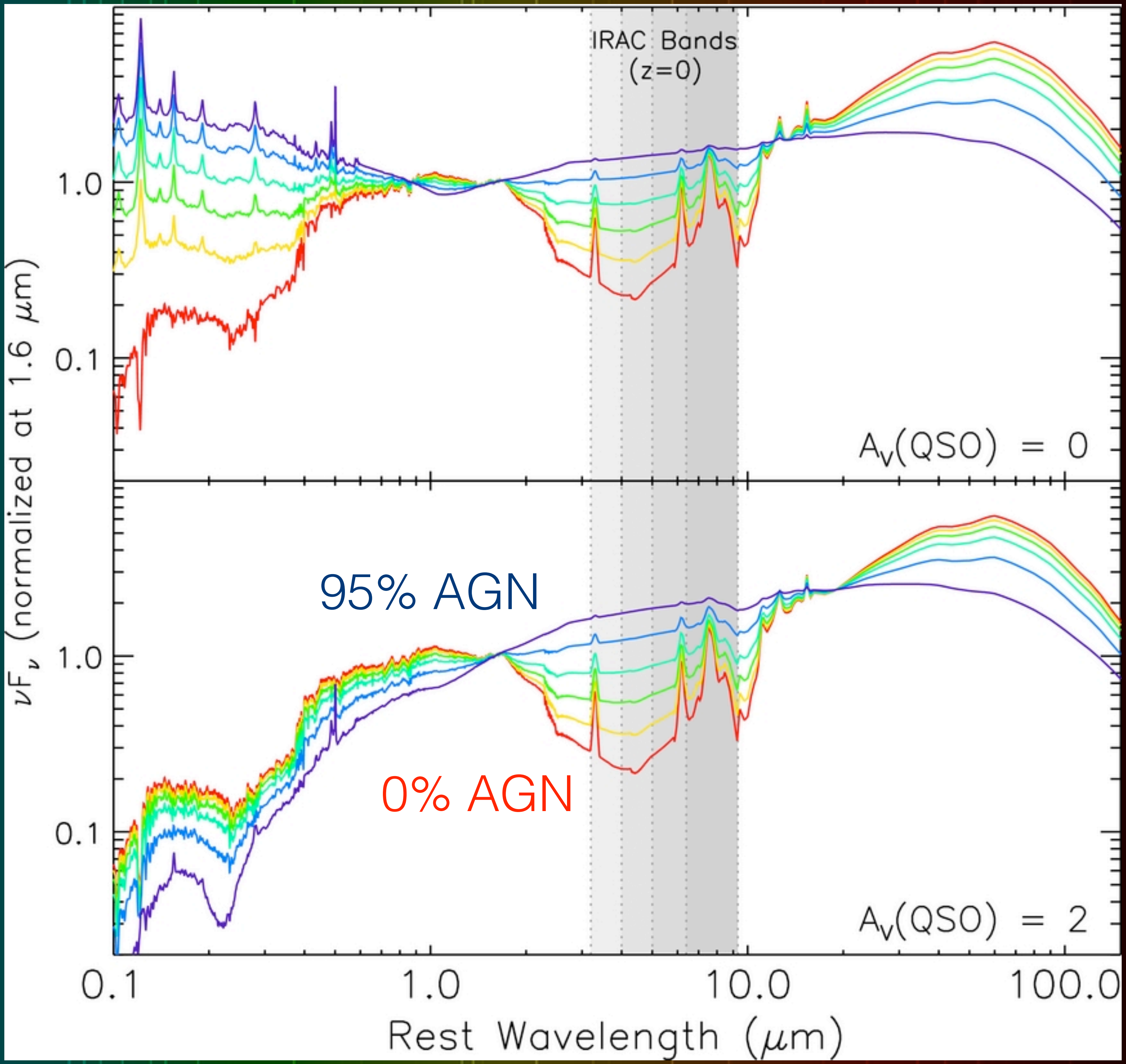
- Diagnostics extend to both UV (but high extinction)
- And NIR & MIR where extinction is less
- Classically used lines in spectral windows
- But with JWST…



Colina et al. (2015)

Mid IR selection

- Warm mid IR emission from torus clear identifier
- Only difficult at highest of Av
-

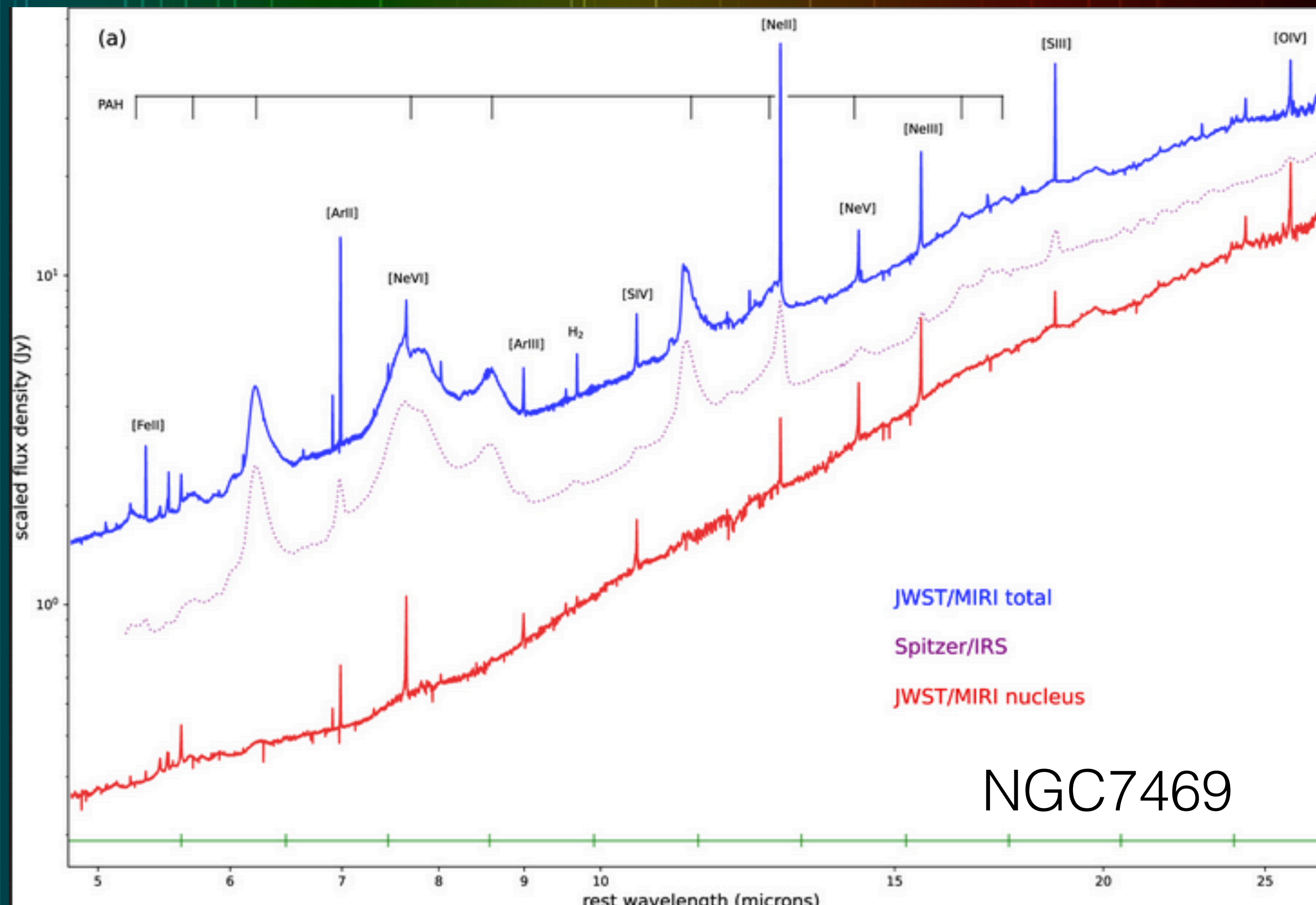


D. Dale talk yesterday

Donley+2012

Mid IR selection

- Warm mid IR emission from torus clear identifier
- Only difficult at highest of Av
- Also in the mid-IR is the [NeV] line - with an IP of 86eV it should only be strong in AGN



GOALS

Armus+2023

D. Dale talk yesterday

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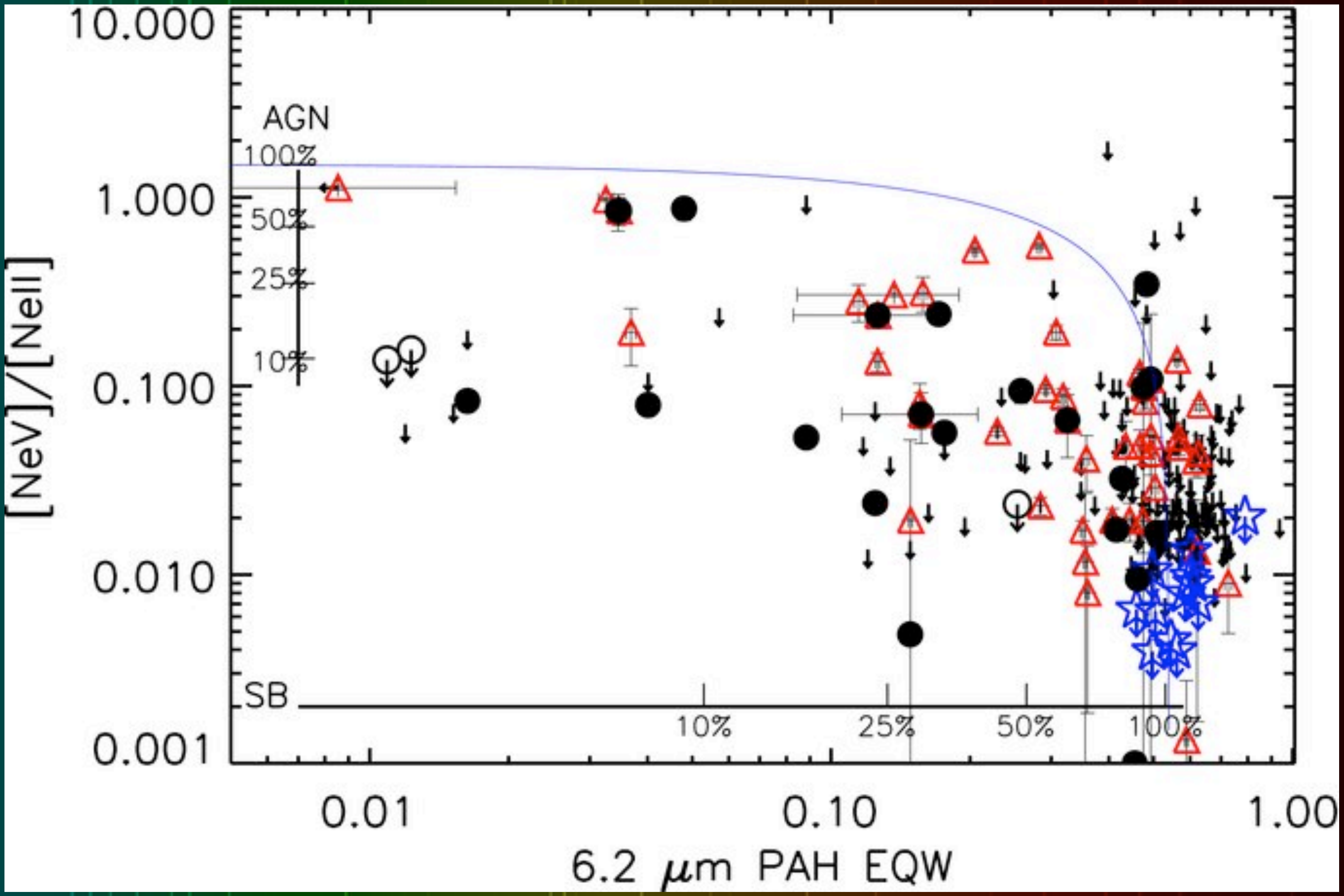
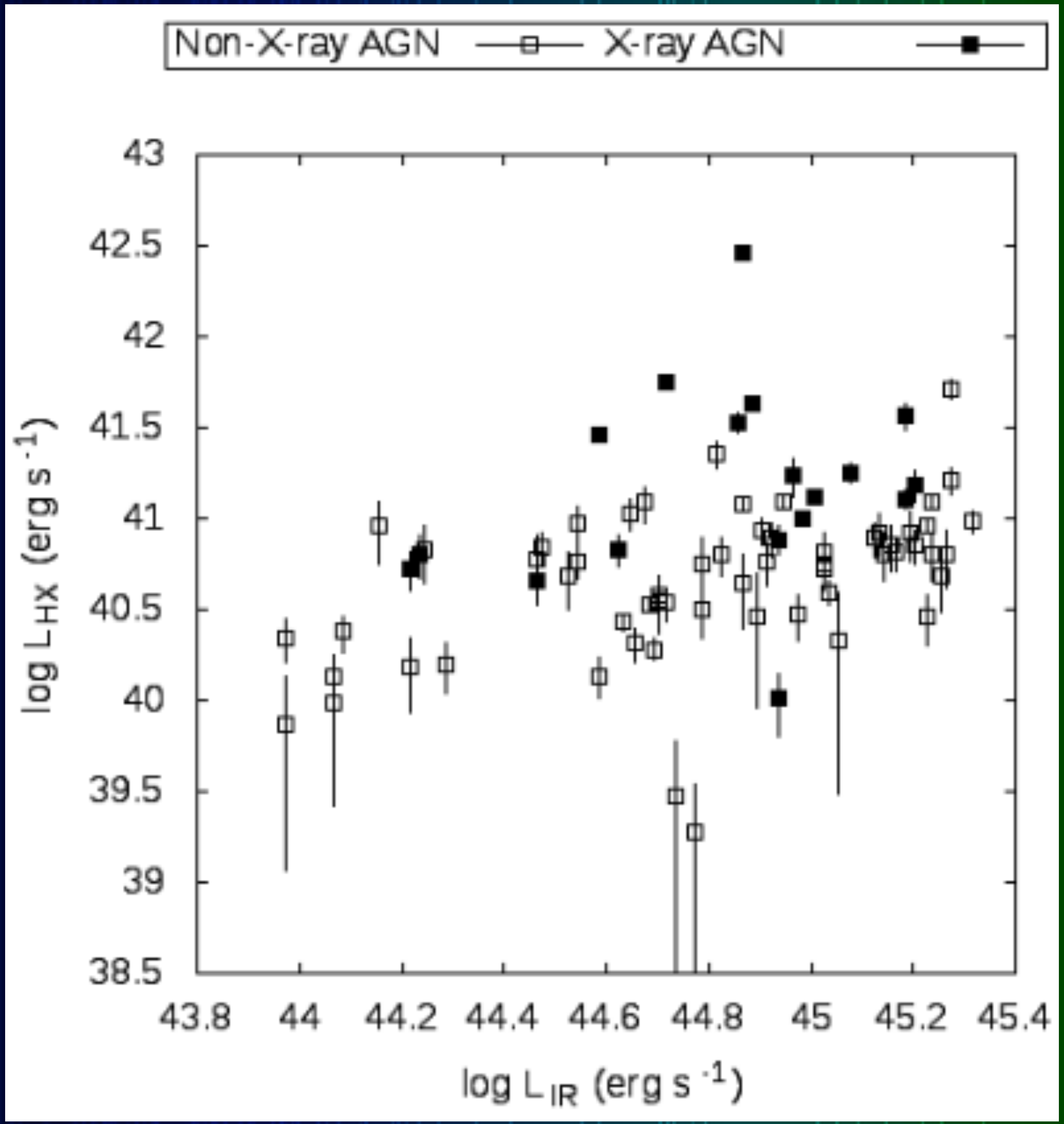


GOALS

Petric+2011

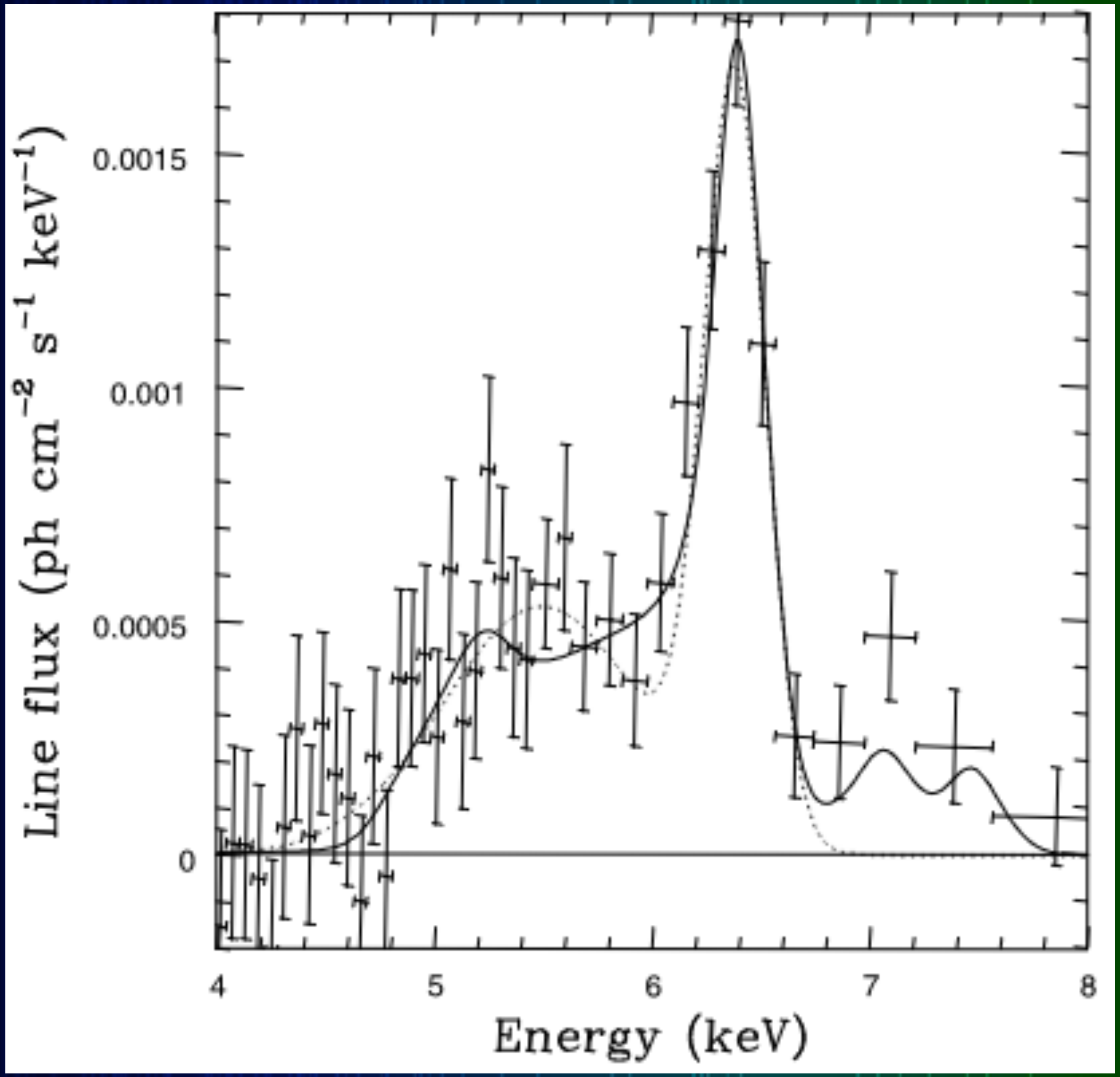
ULIRGs in X-ray



Torres-Alba+2018 C-GOALS

- X-rays are a classic way to detect AGN
- Issues in ULIRGs are absorption and high SFR

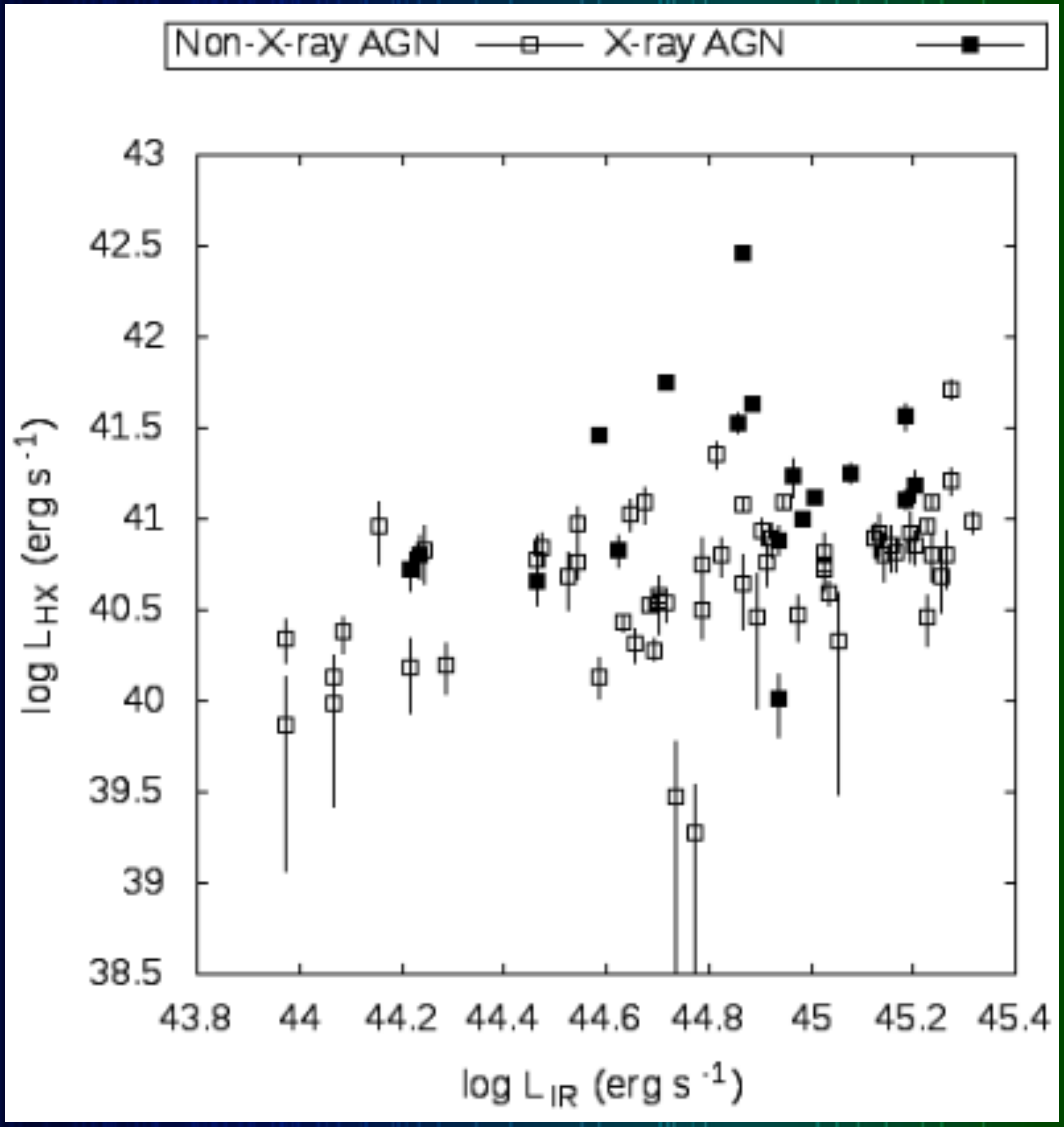
ULIRGs in X-ray



Wang+2001 NGC4151

- X-rays are a classic way to detect AGN
- Issues in ULIRGs are absorption and high SFR
- Also presence of very high ionization lines - Fe Kα at 6.4keV

ULIRGs in X-ray



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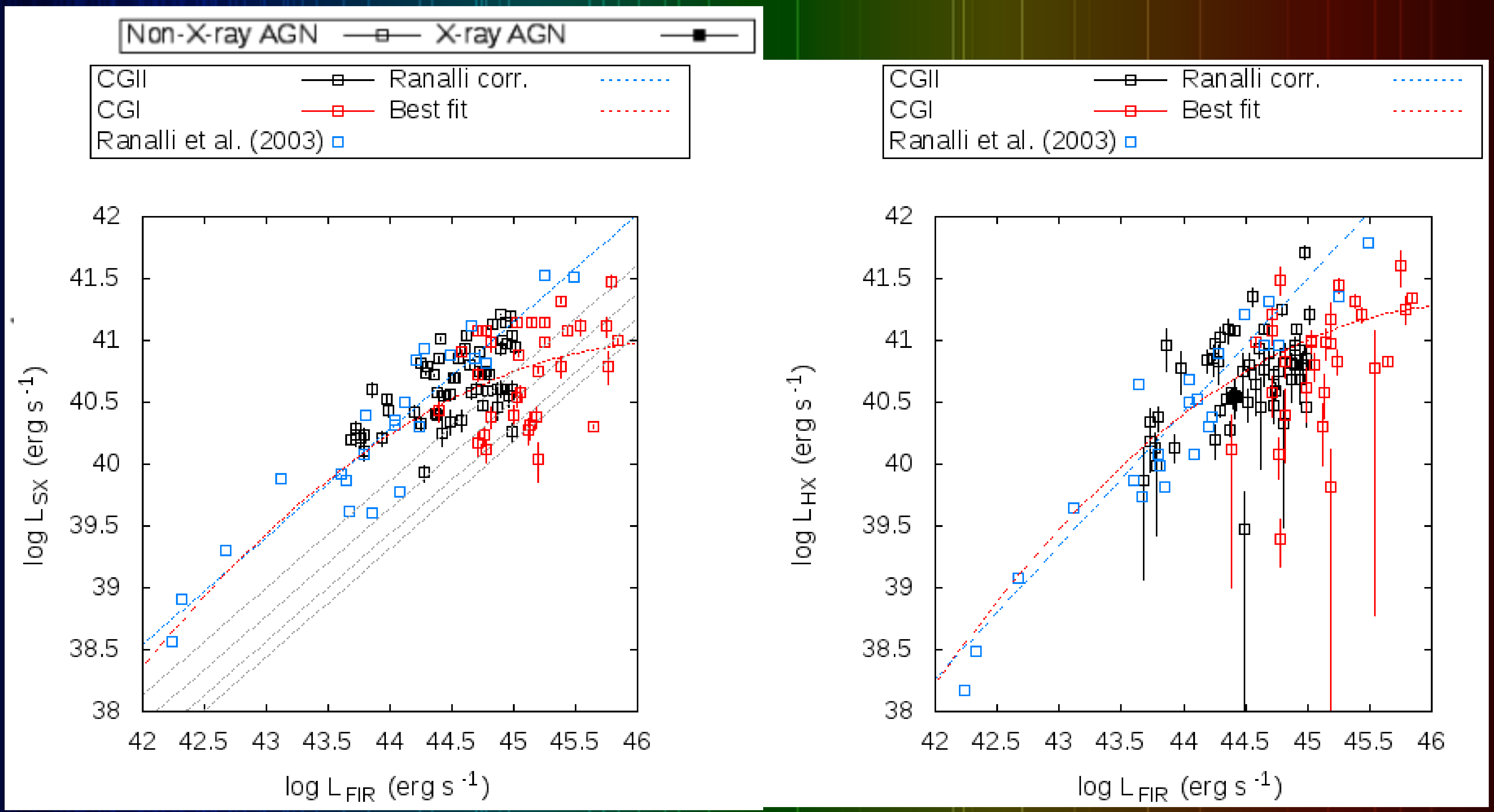
- X-rays are a classic way to detect AGN
- Issues in ULIRGs are absorption and high SFR
- Also presence of very high ionization lines - Fe Kα at 6.4keV
- SFR also has X-rays (X-ray binaries)

ULIRGs in X-ray



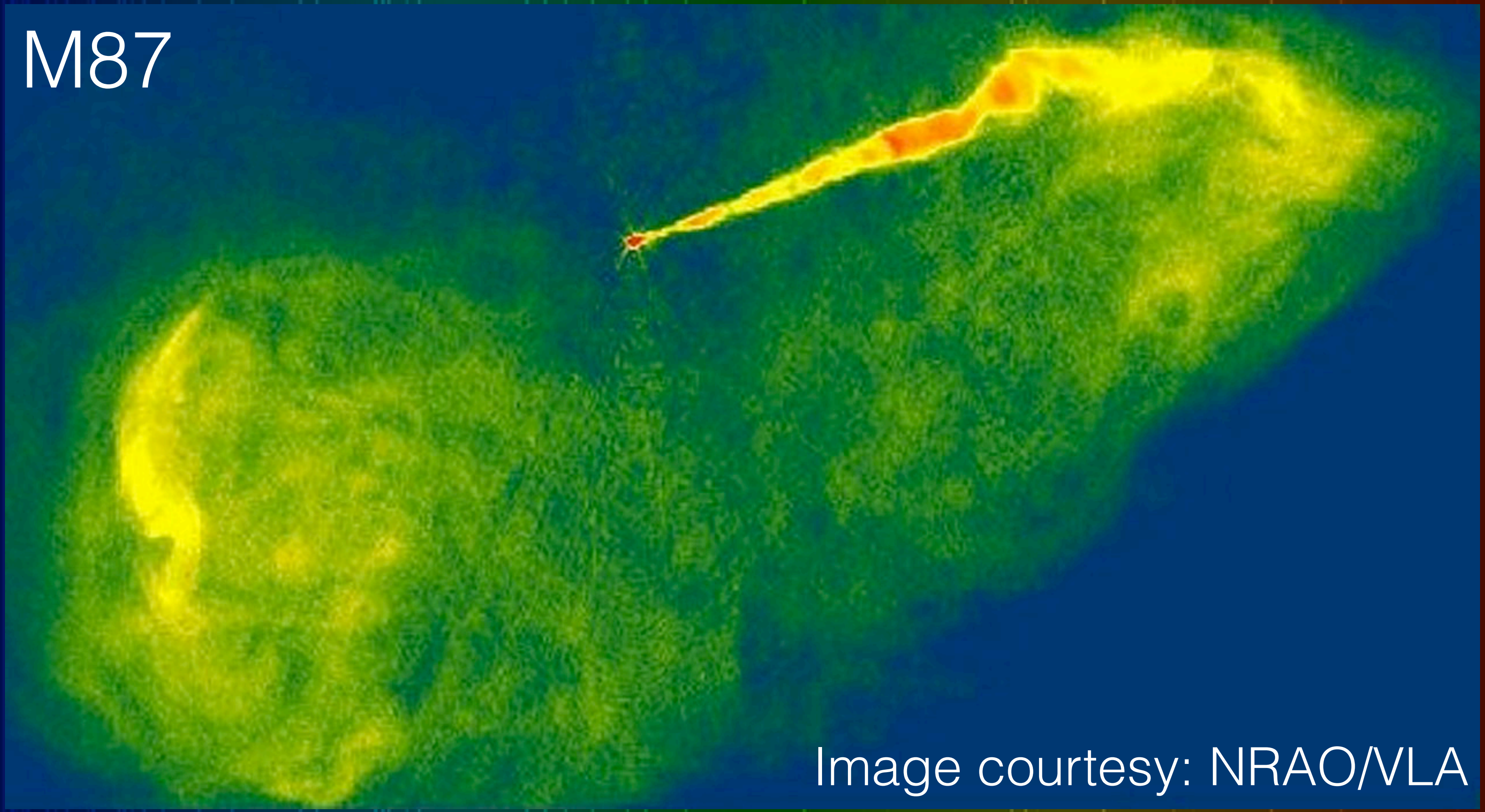
Torres-Alba+2018

C-GOALS

AGN in Radio

- AGN Radio arises from synchrotron emission
- Arising from jets and strong particle emission

- Jets (& outflows) drive material to large radii
- Jets drive shocks into surrounding ISM



AGN in Radio

- Jet lead to shocks in galaxy (both the "drill" and perpendicular
- However, heating of the larger scale diffuse ICM is key to may galaxy evolution models
- Also play a key role in polluting ICM/IGM with metals

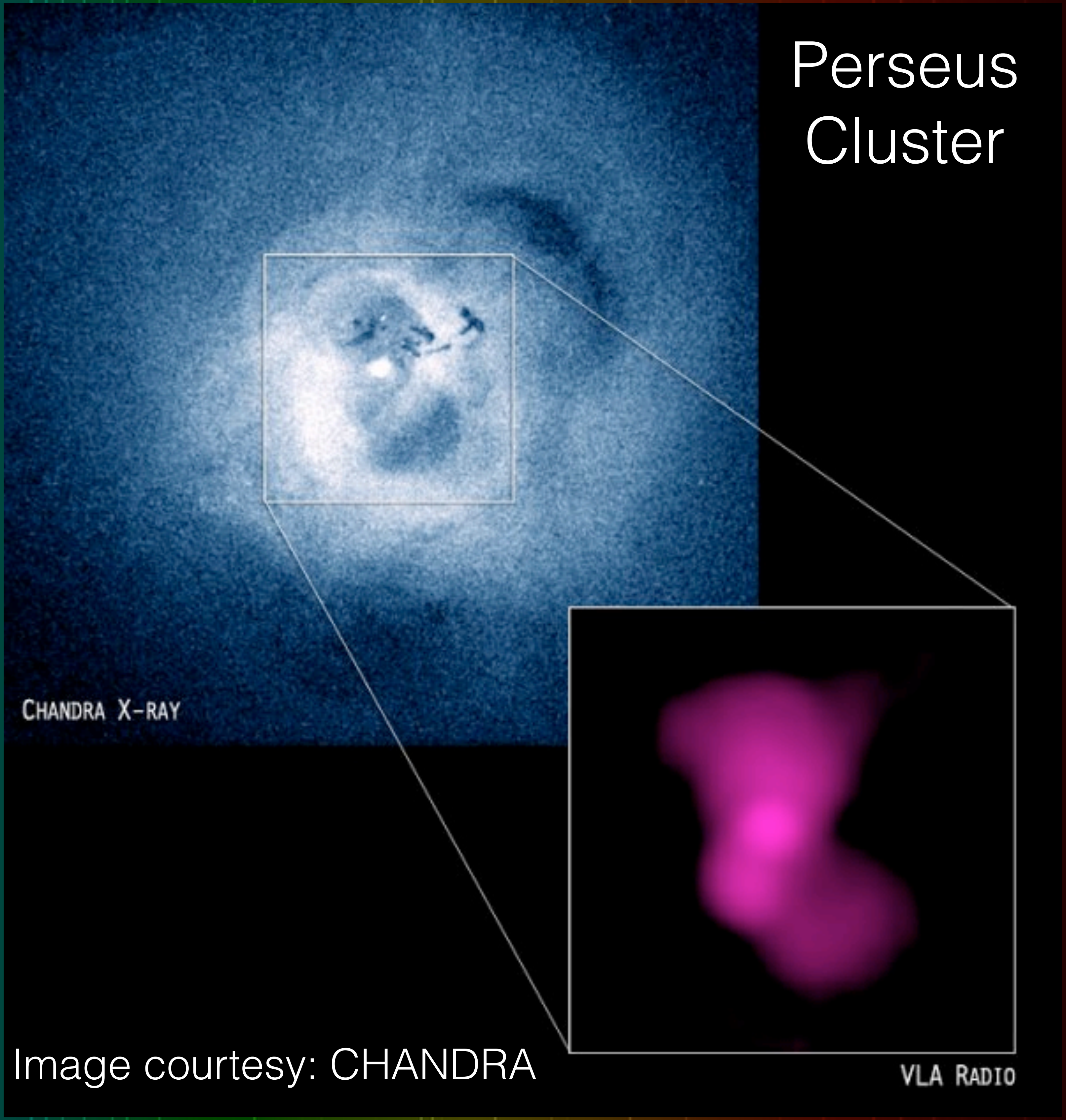
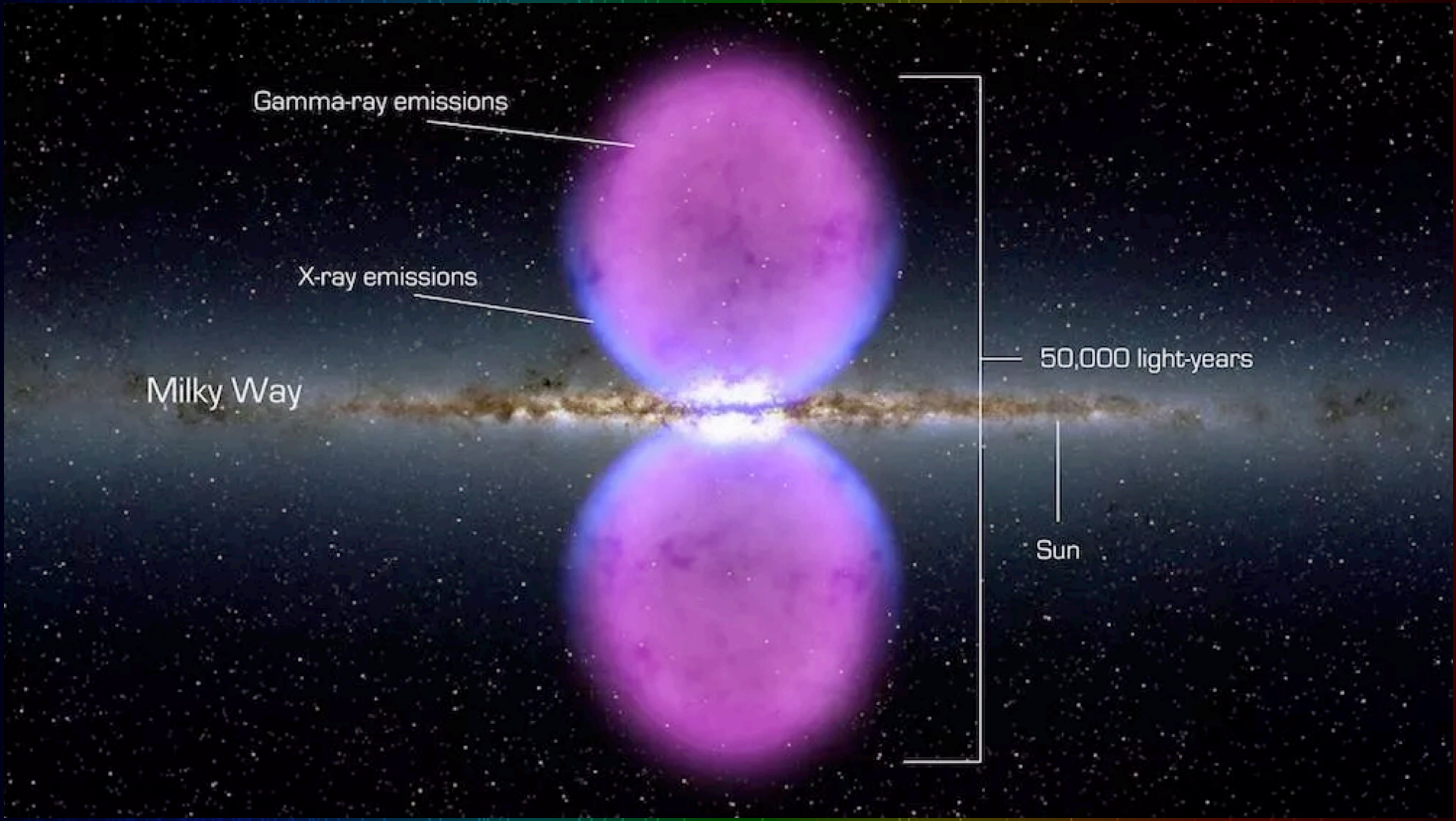


Image courtesy: CHANDRA

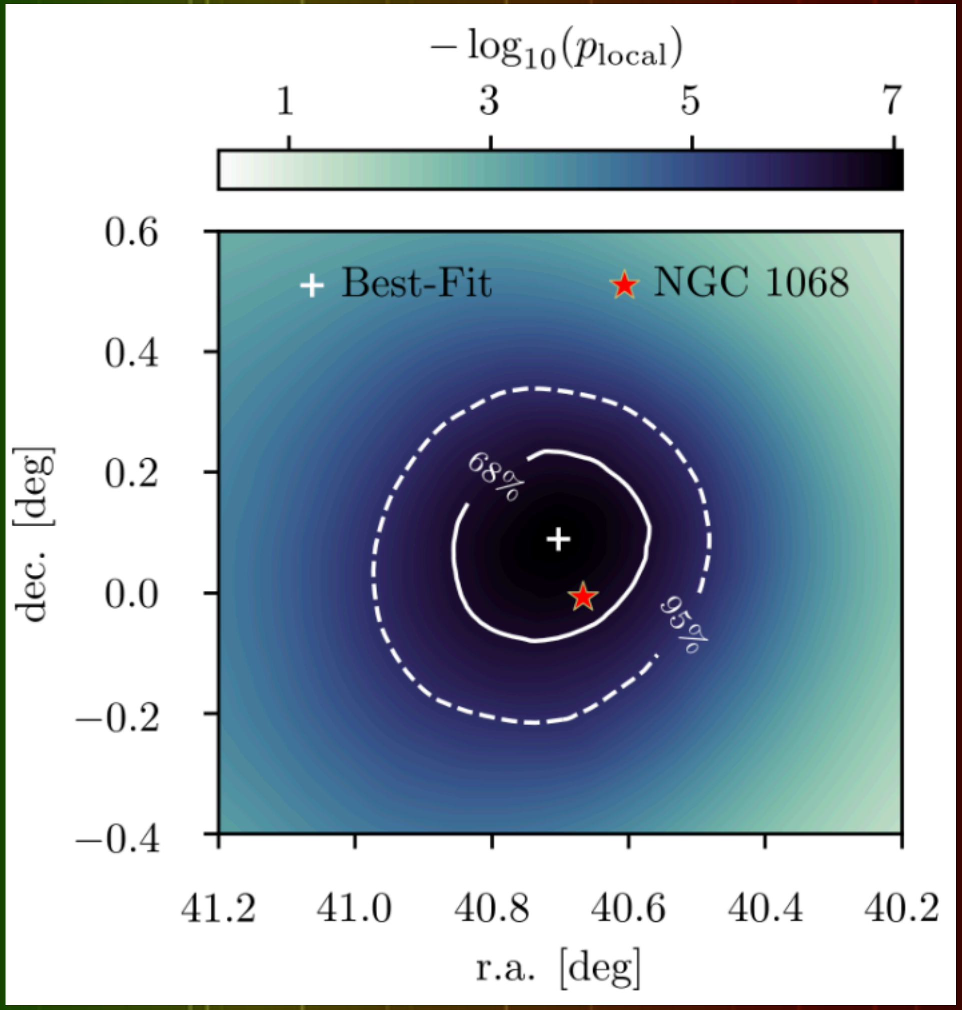
High-energy from AGN



A. Marcowith talk

High-energy from AGN

- AGN with high energy coronae, strong magnetic fields are big sources of high energy emission
- NGC1068 brightest extragalactic source of neutrinos in northern hemisphere
- Cosmic rays can penetrate into & through the deepest molecular cloud



Ice cube collaboration (2022)

High-energy from AGN

- AC
  co
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- NC
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- Co
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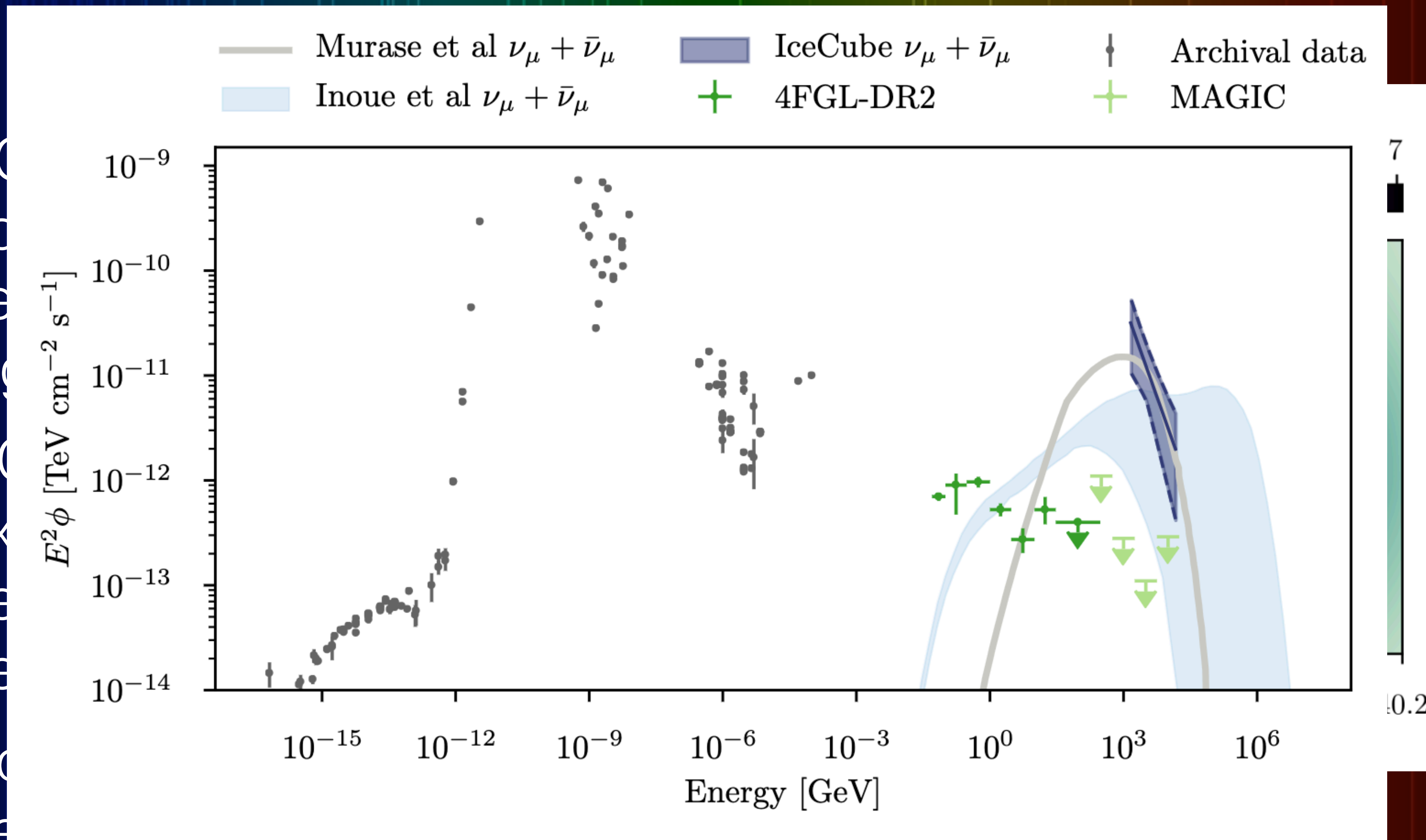
  the deepest molecular
  cloud

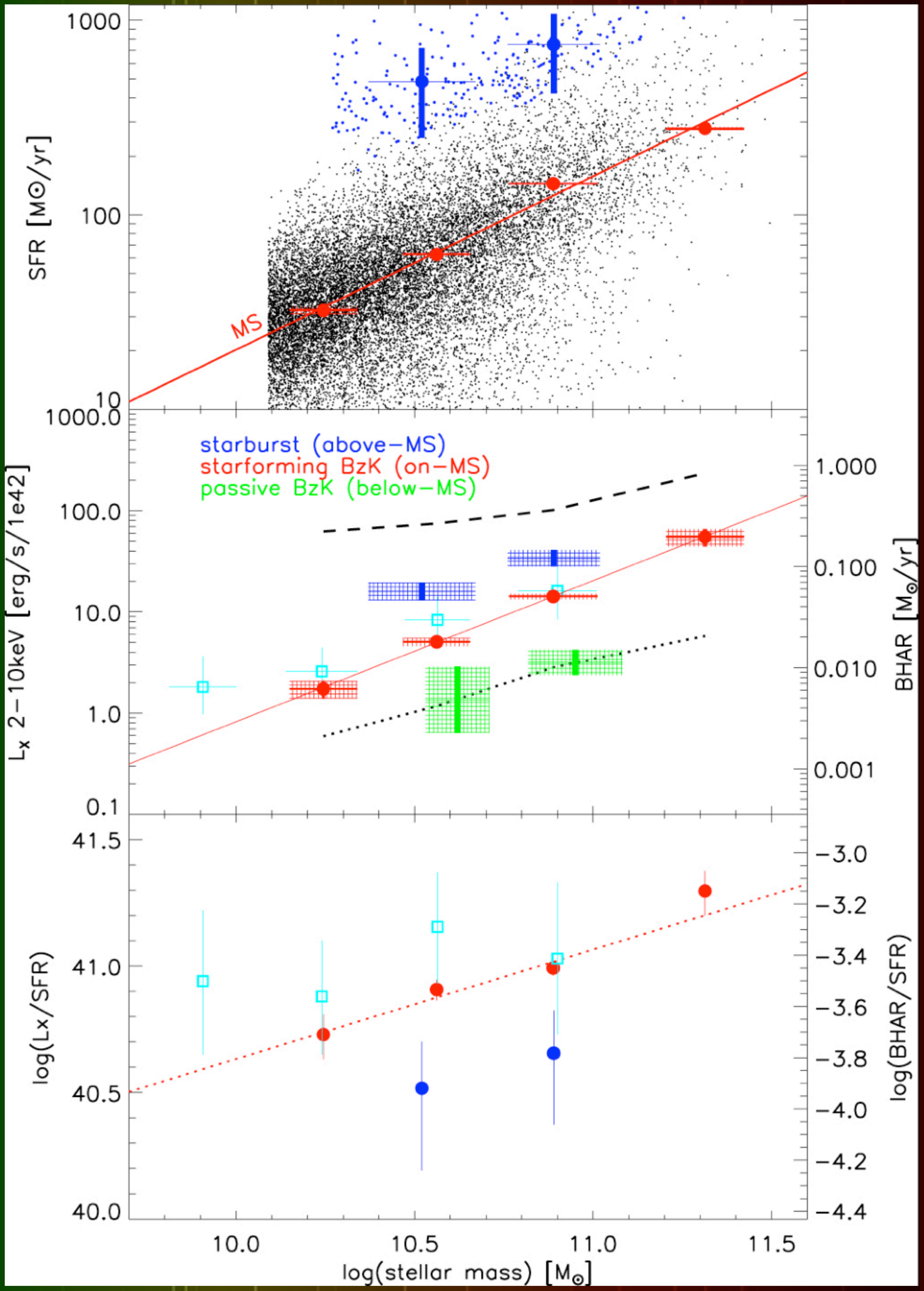


Ice cube collaboration (2022)

AGN in MS & SB galaxies

- Measuring star formation in AGN is about separating AGN heating (spatially/ spectrally)
- What we find in typical EL AGN is star formation suppressed in starbursts with AGN (Masoura+18)

Rodigheiro+ (2015)



ISM in AGN-hosts

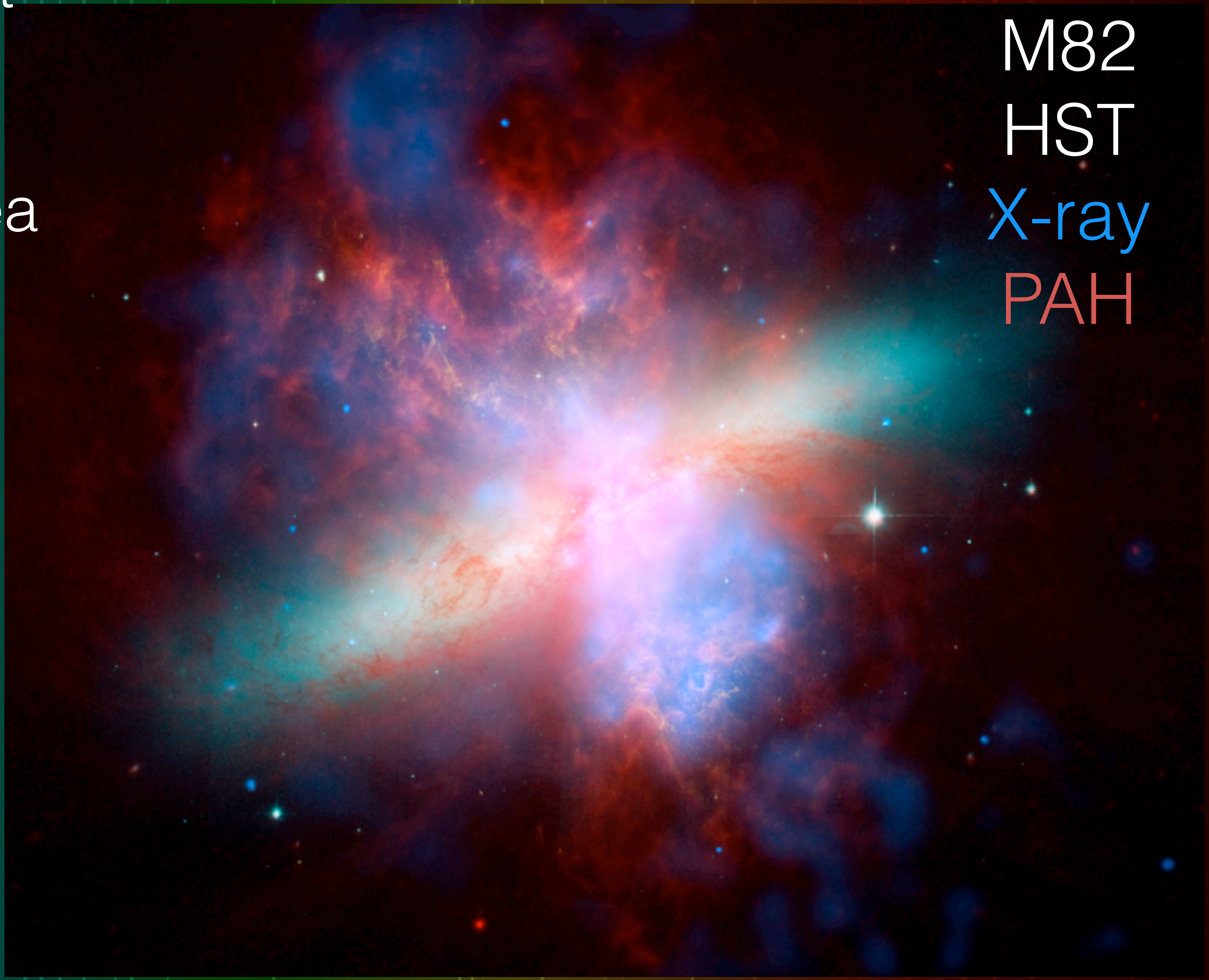
- Strong line (high accretion) AGN correlate with higher central gas densities
- Star formation common in AGN-host galaxies
- AGN act to to further heat ISM
    - Shocks
    - X-rays
    - Turbulence/winds
- But ONLY within zone of influence ionization/wind cones
- Rest of disk like normal galaxies/Starbursts

Outflows

Brent Groves GISM2

Outflows

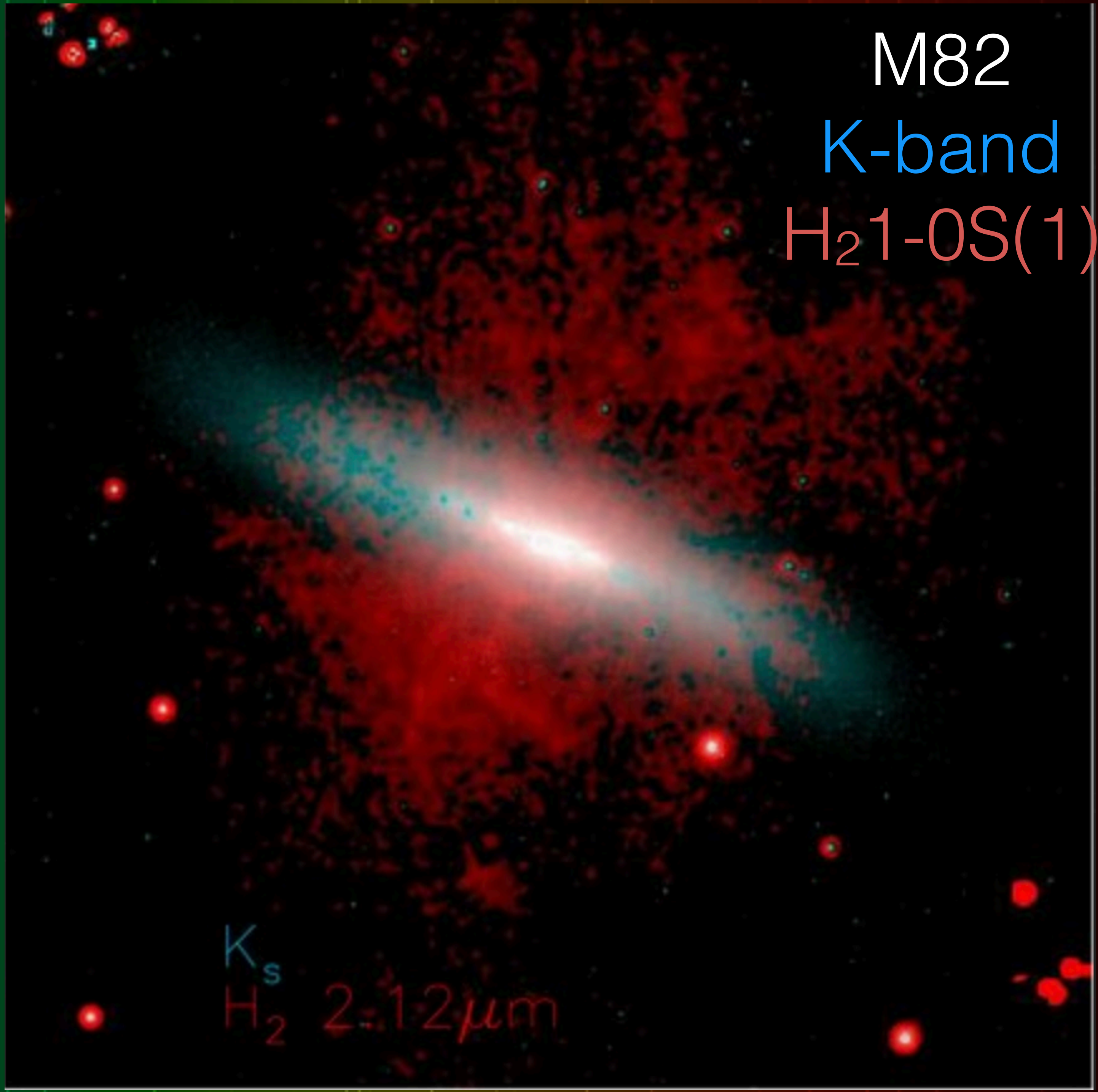
- Starbursts & AGN inject significant momentum (winds & radiation pressure) in a small area
- This drives outflows to large scale heights



Credit: X-ray: NASA/CXC/JHU/D.Strickland;
Optical: NASA/ESA/STScI/AURA/The Hubble Heritage Team;
IR: NASA/JPL-Caltech/Univ. of AZ/C. Engelbracht

Outflows

- Starbursts & AGN inject significant momentum (winds & radiation pressure) in a small area
- This drives outflows to large scale heights
- The outflows can create shocks



Outflows

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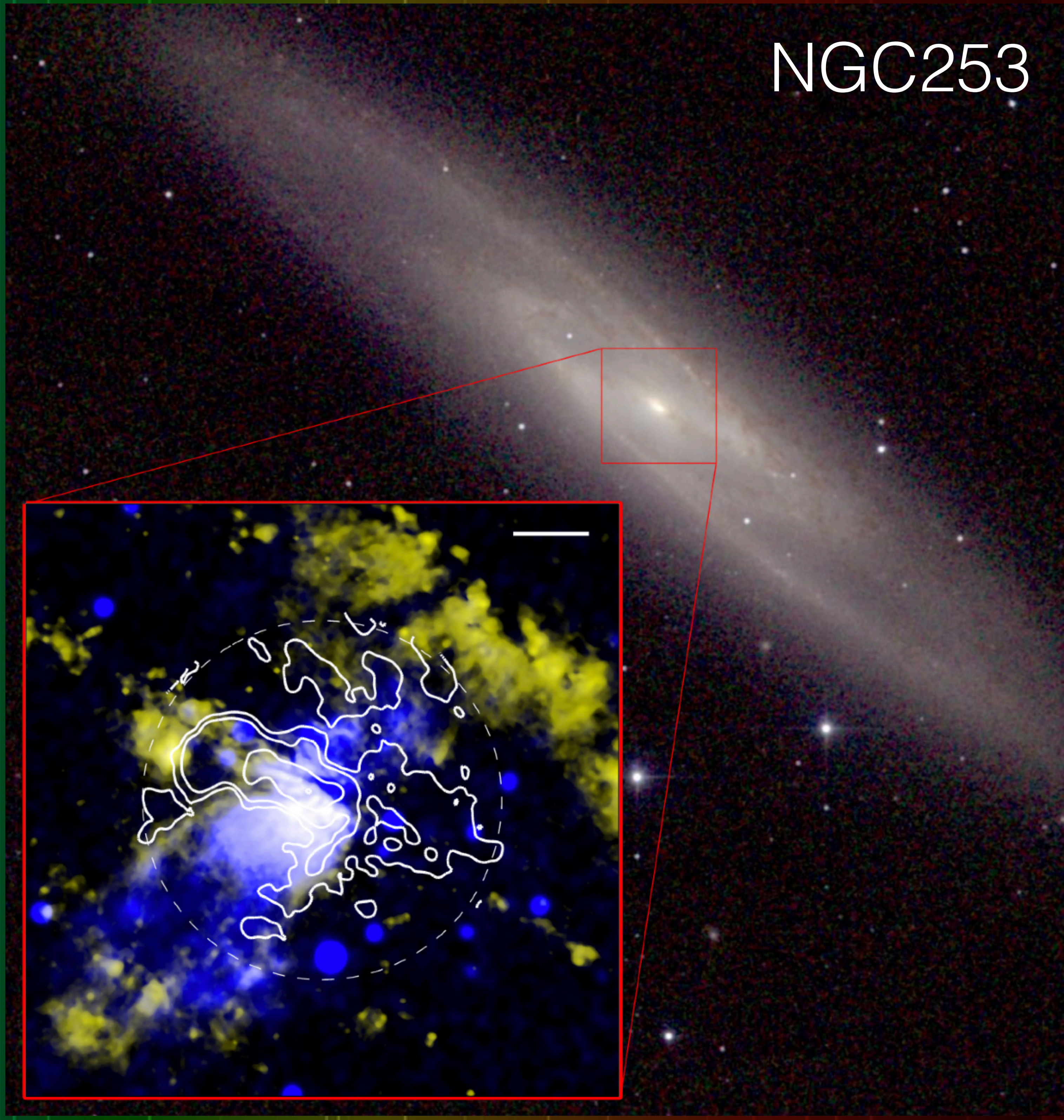
- These outflows can drag molecules & dust with them
- Outflows pollute outer disks and even IGM



Bolatto+2013

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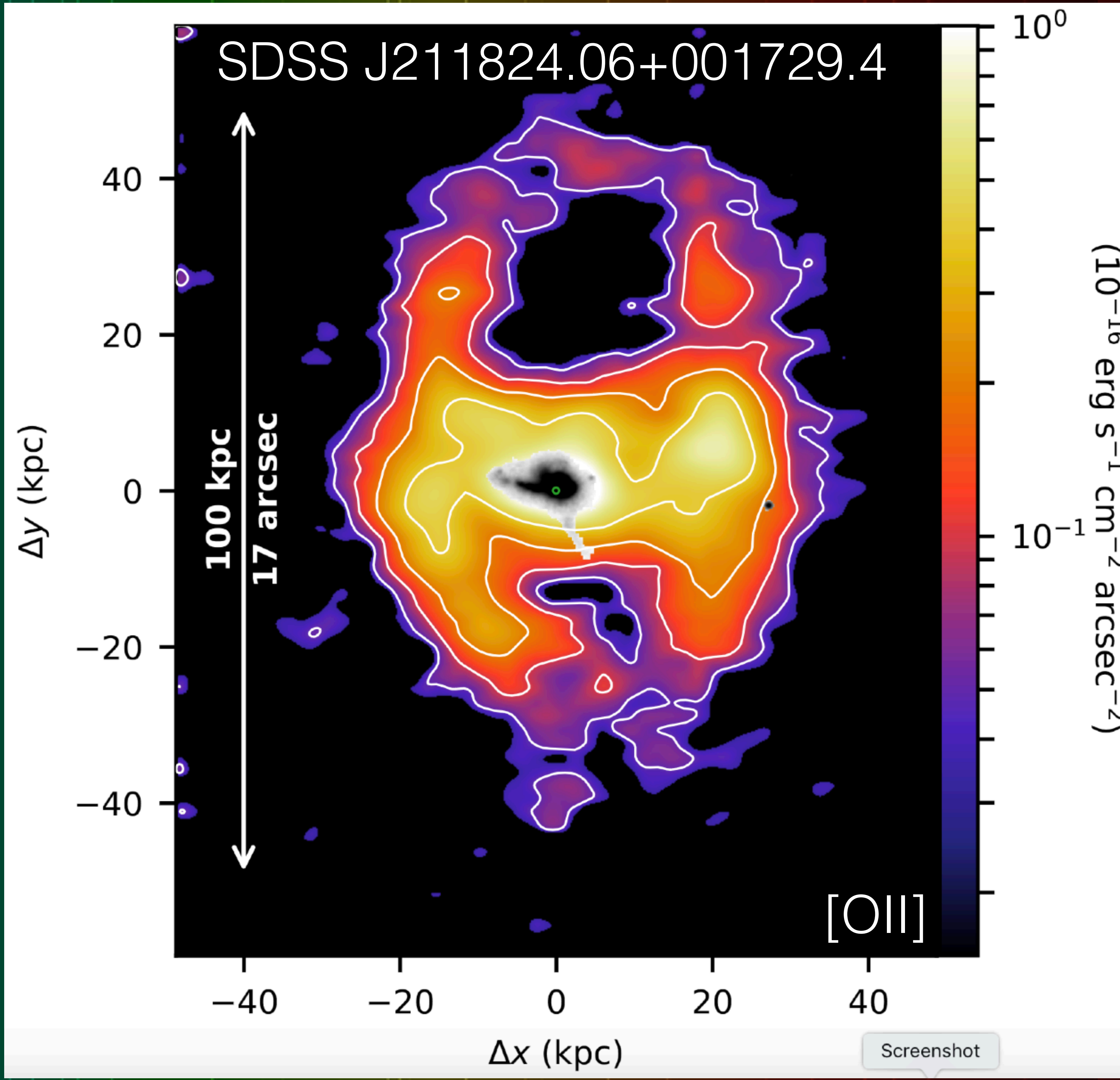
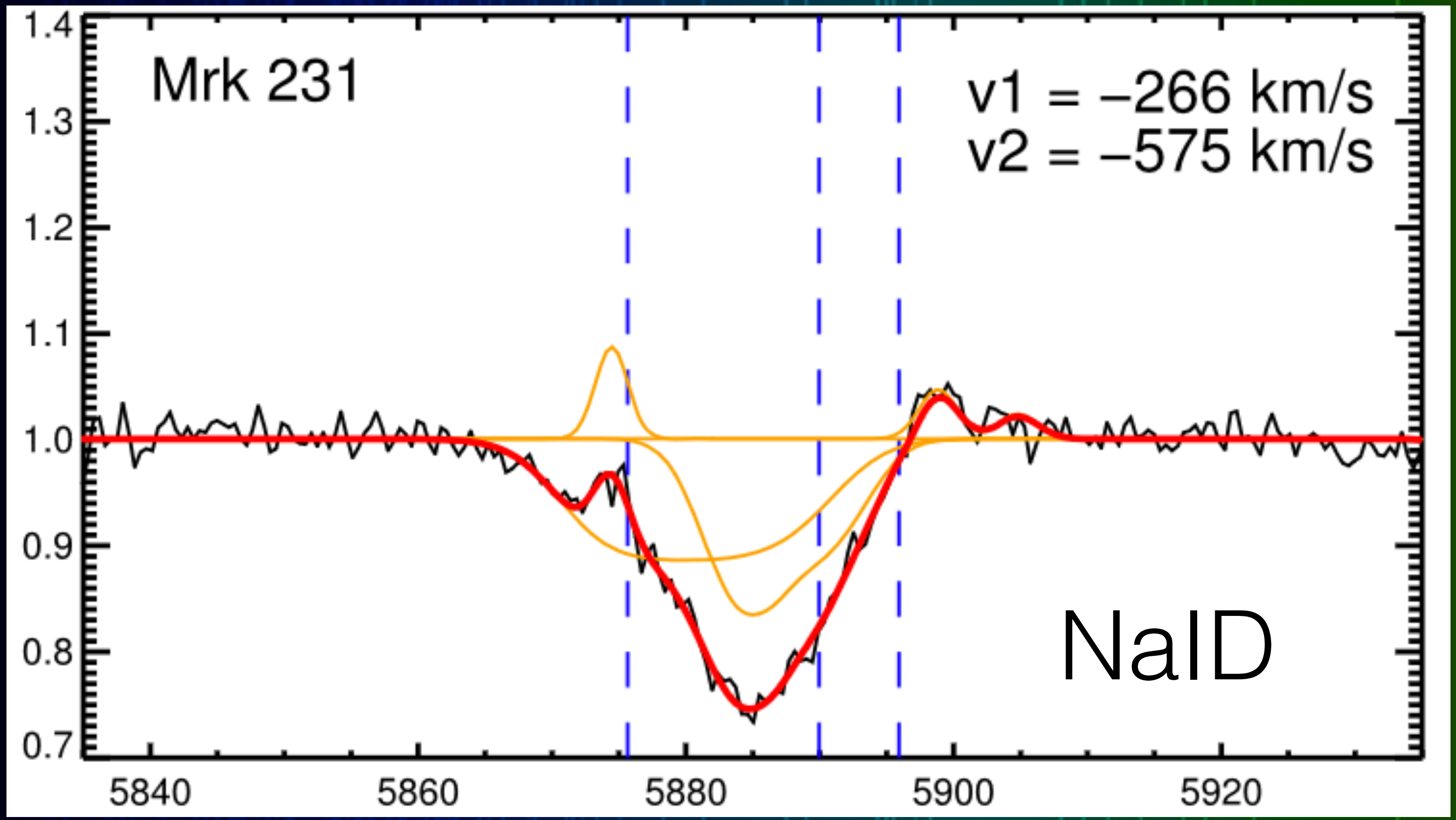


Rupke+2019

Outflows



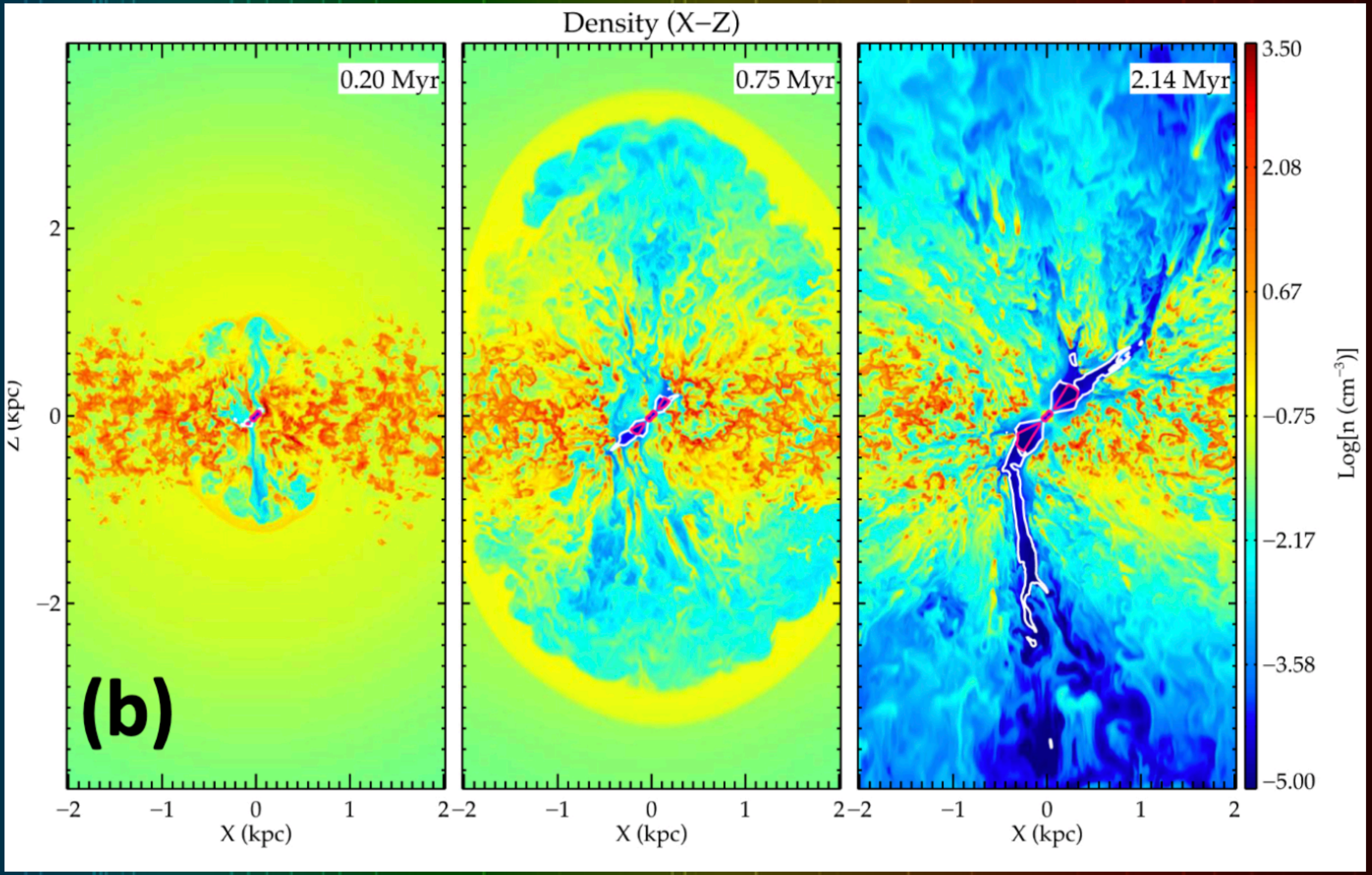
Rupke+2017

- Still open questions on:
  - drivers of outflows
  - On multiphase nature of outflows (how do molecules & dust last in outflows)?
  - Exact mass loading factors (how much material is removed)?
  - See review by Veilleux+2020

AGNJets

- Jets (& outflows) drive material to large radii
- Jets drive shocks into surrounding ISM

- Some Radio Jets observed to Mpc scales!



Mukhajee+2017

Outflows

- Stronger outflows seen in starburst galaxies
- Outflows remove gas locally, limiting further SF
- Most will eventually return, but some mix with CGM
- AGN can drive massive outflows, impacting CGM & IGM
- Outflows are key mechanism for metal removal/mixing and pollution of the IGM

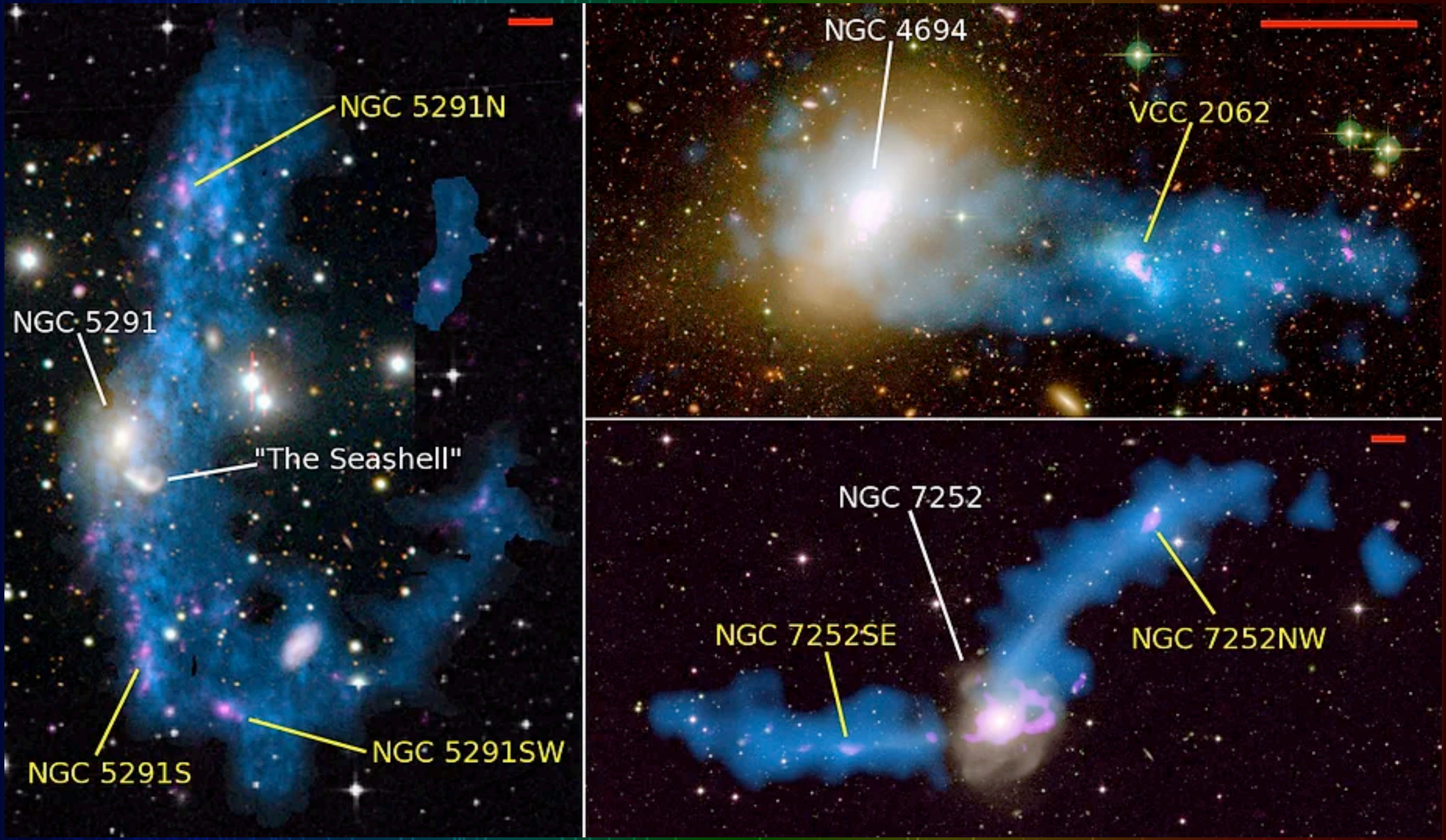
ISM & star formation in dynamic regions

ICRAR

Brent Groves GISM2

THE UNIVERSITY OF WESTERN AUSTRALIA

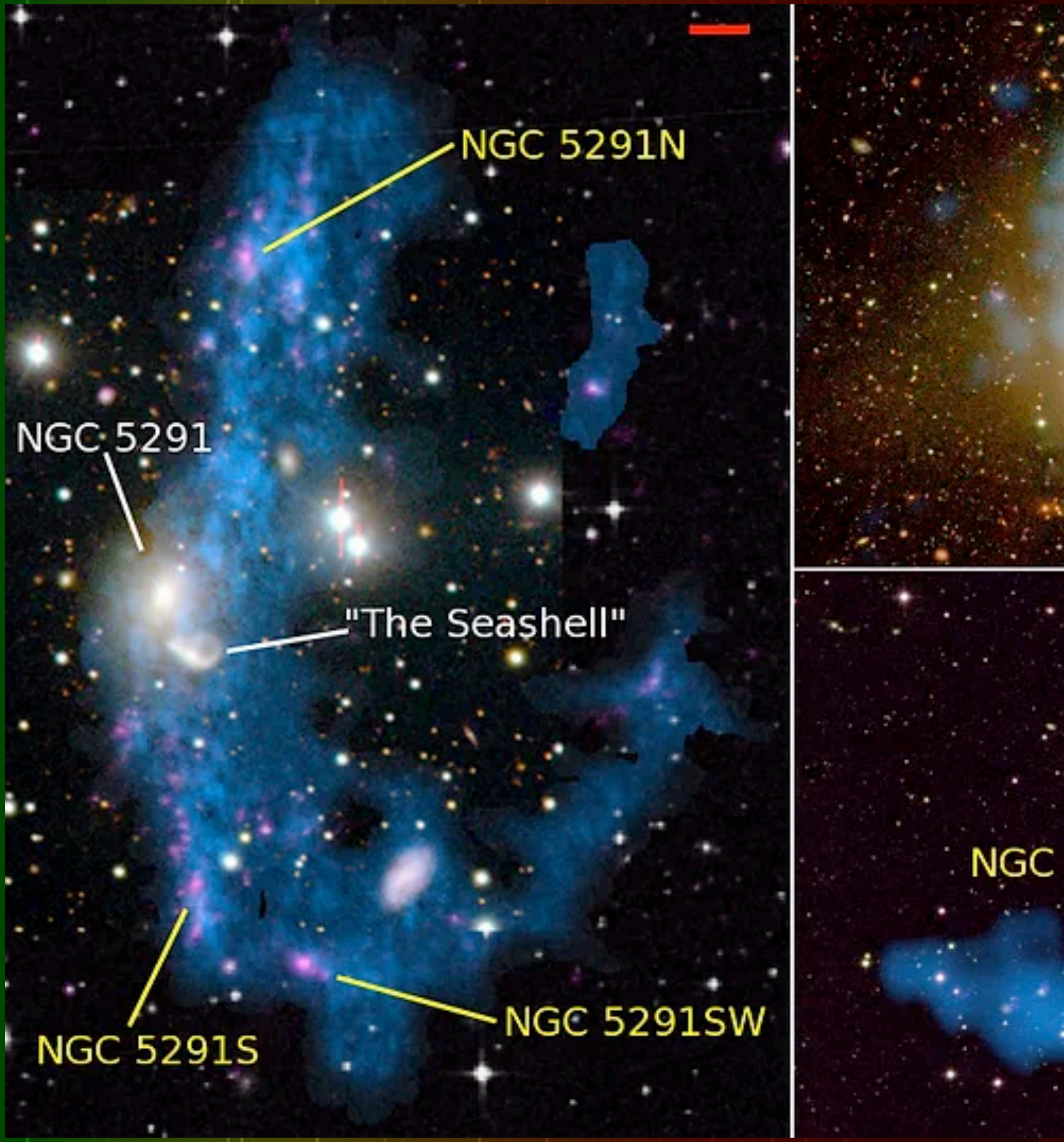
Tidal Dwarfs



Lelli+ (2015)

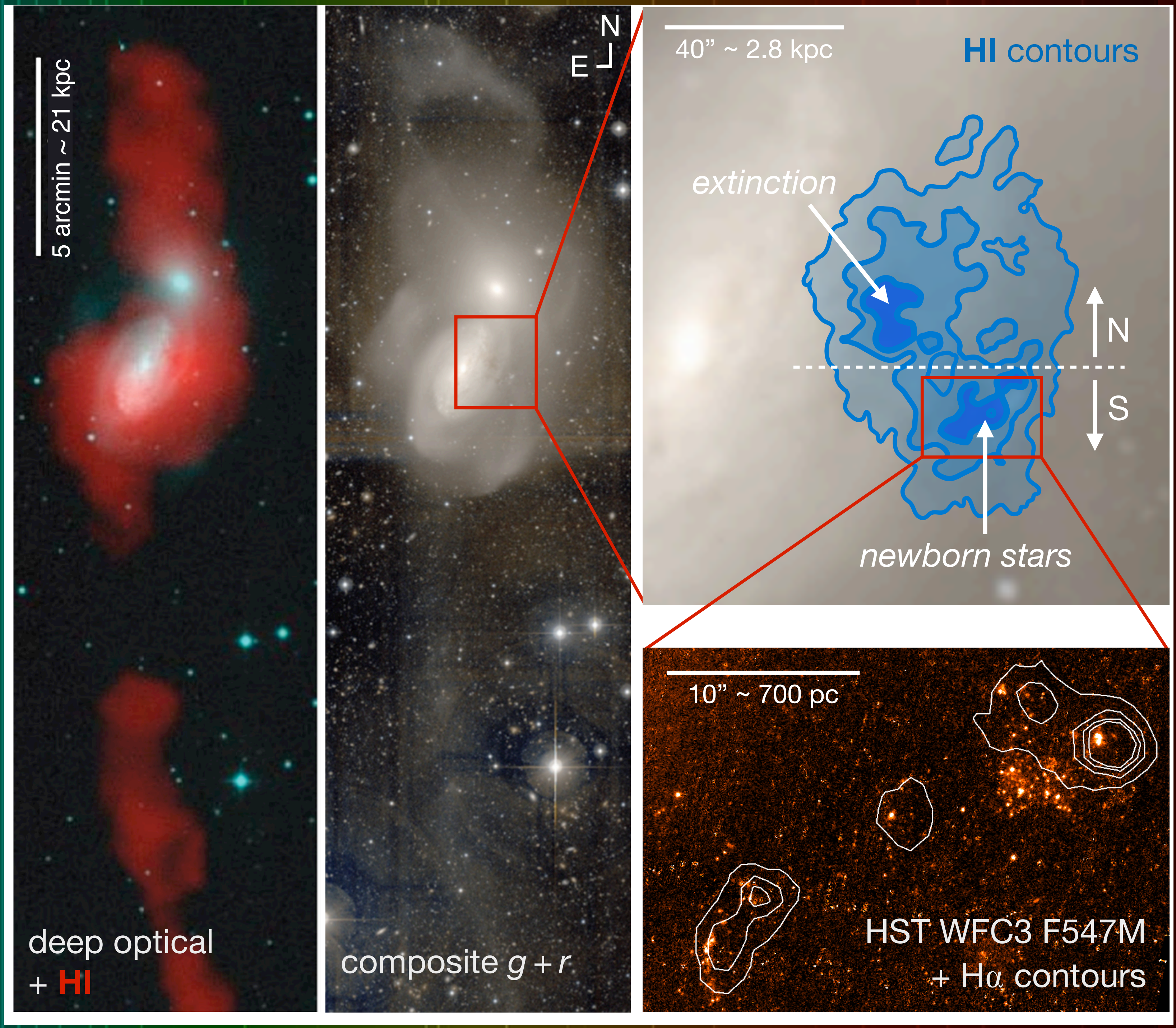
Tidal Dwarfs

- Galaxy collisions can not only lead to ULIRGs but though off material
- This collisional debris can form stars and become tidal dwarf galaxies (TDGs)
- TDGs are interesting that mostly HI and, if rotating, suggest no dark matter.



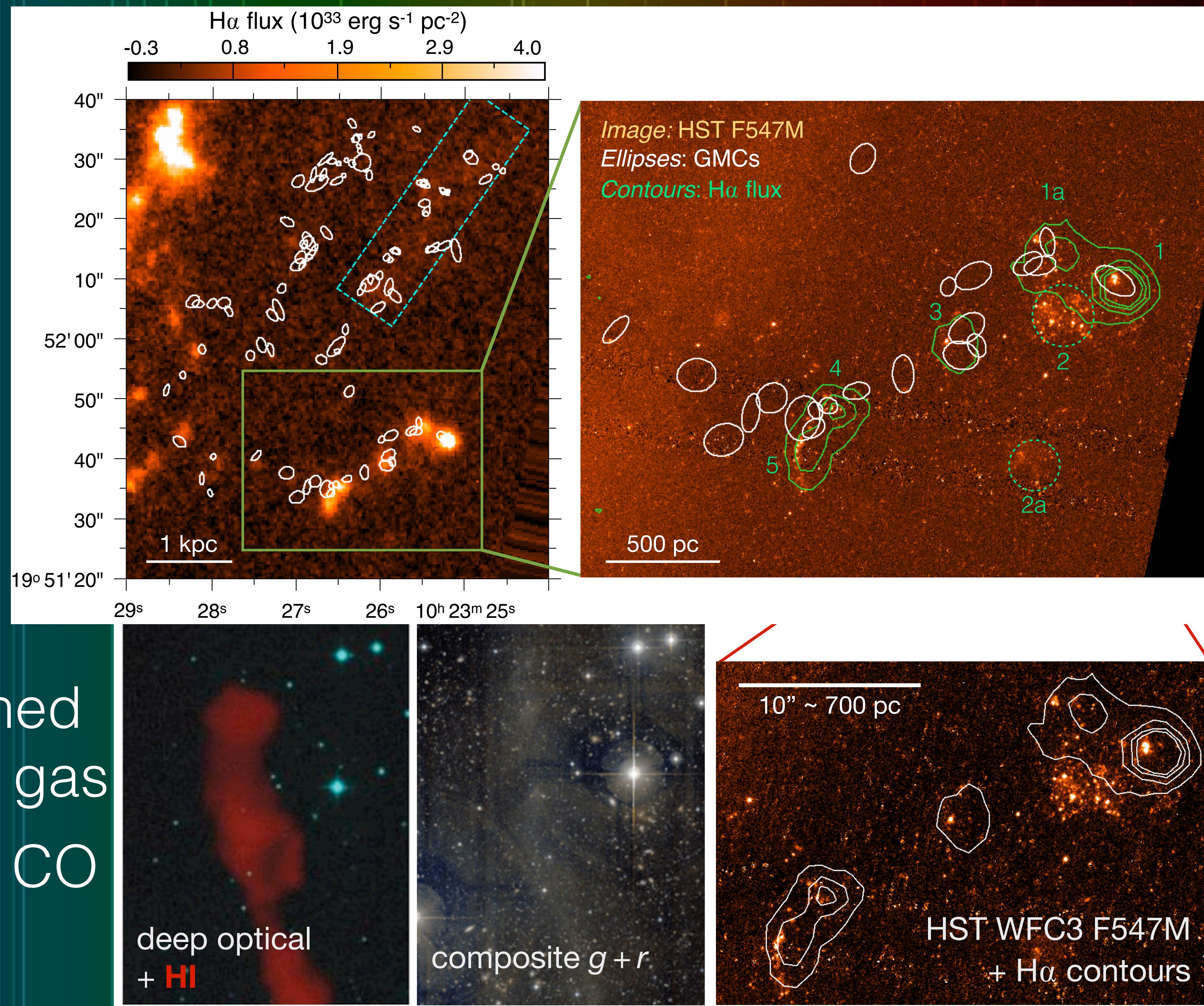
Tidal Dwarfs

- TDGs can be enriched and form molecular gas
- as in other galaxies CO SFR traces CO



Querejeta+2019

Tidal Dwarfs



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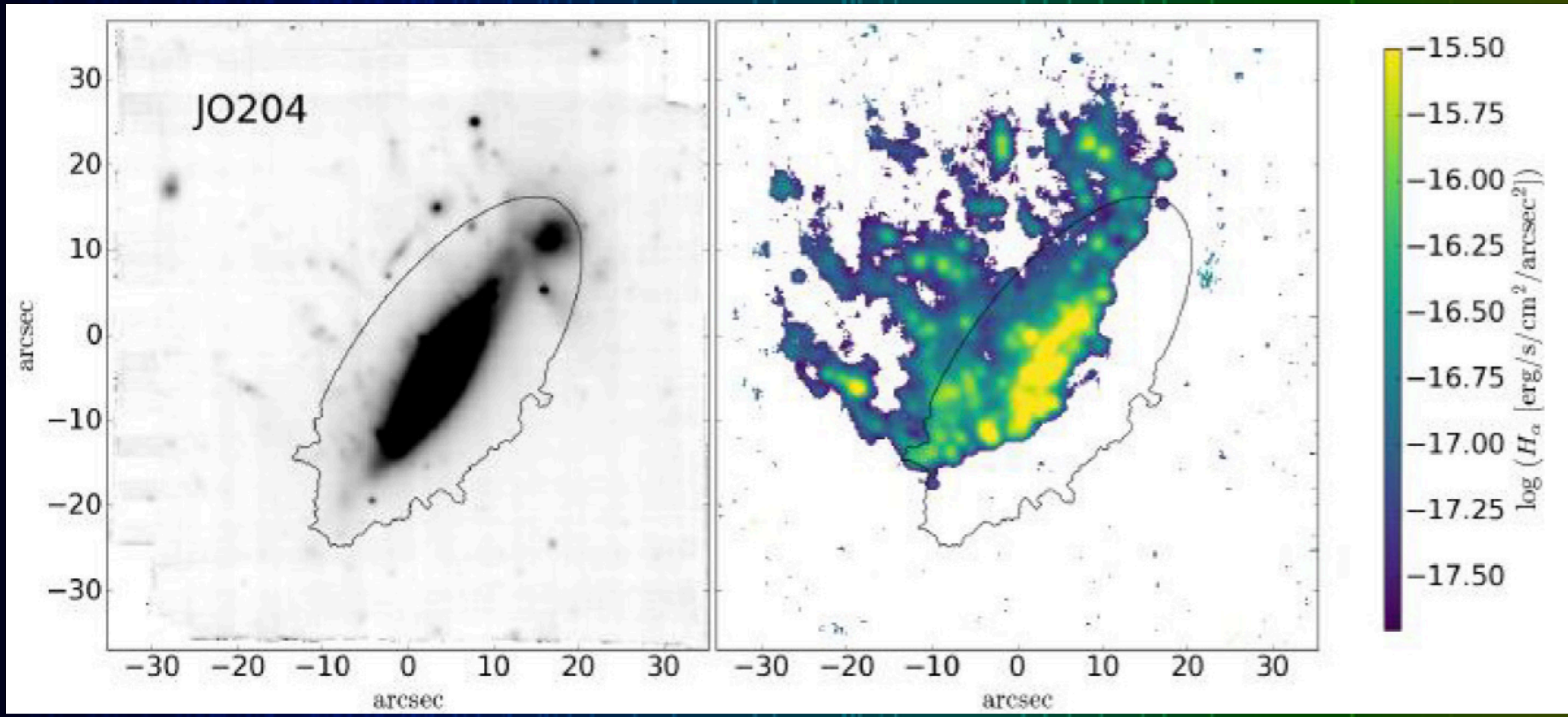
Querejeta+2019

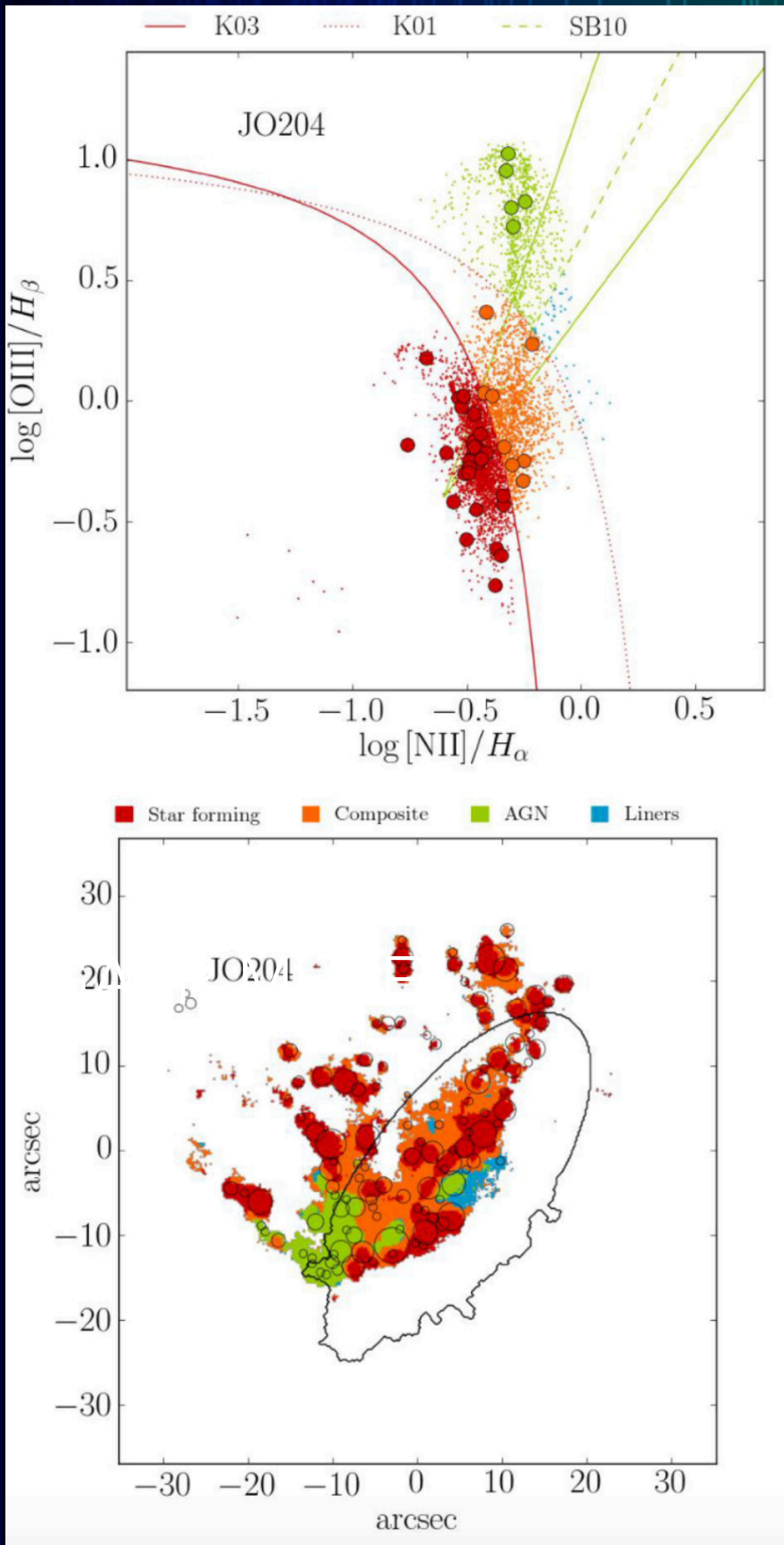
Jellyfish

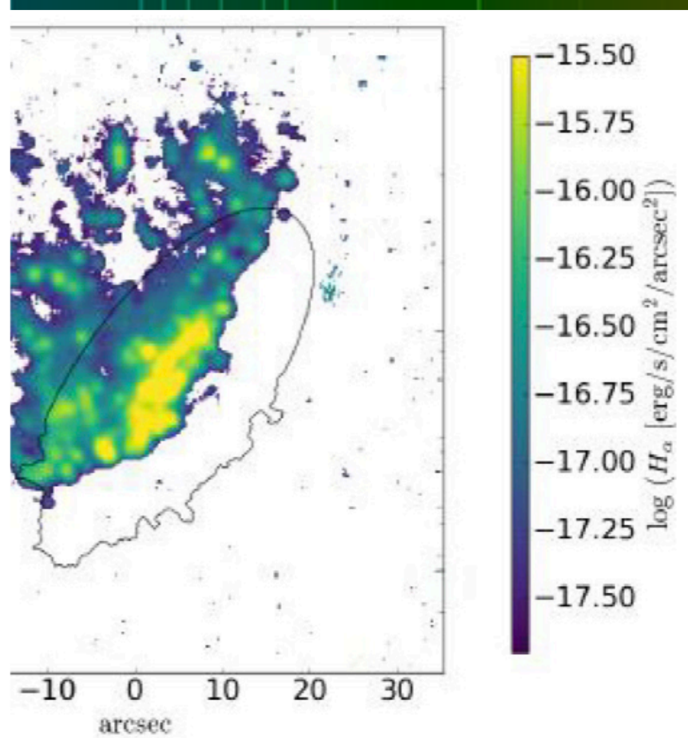


GASP-MUSE Poggianti+2019

- Jellyfish galaxies are galaxies falling into clusters
- Ram pressure & tidal forces stripping gas
- This gas can be shocked but also can form stars!

Jellyfish





Poggianti+2019

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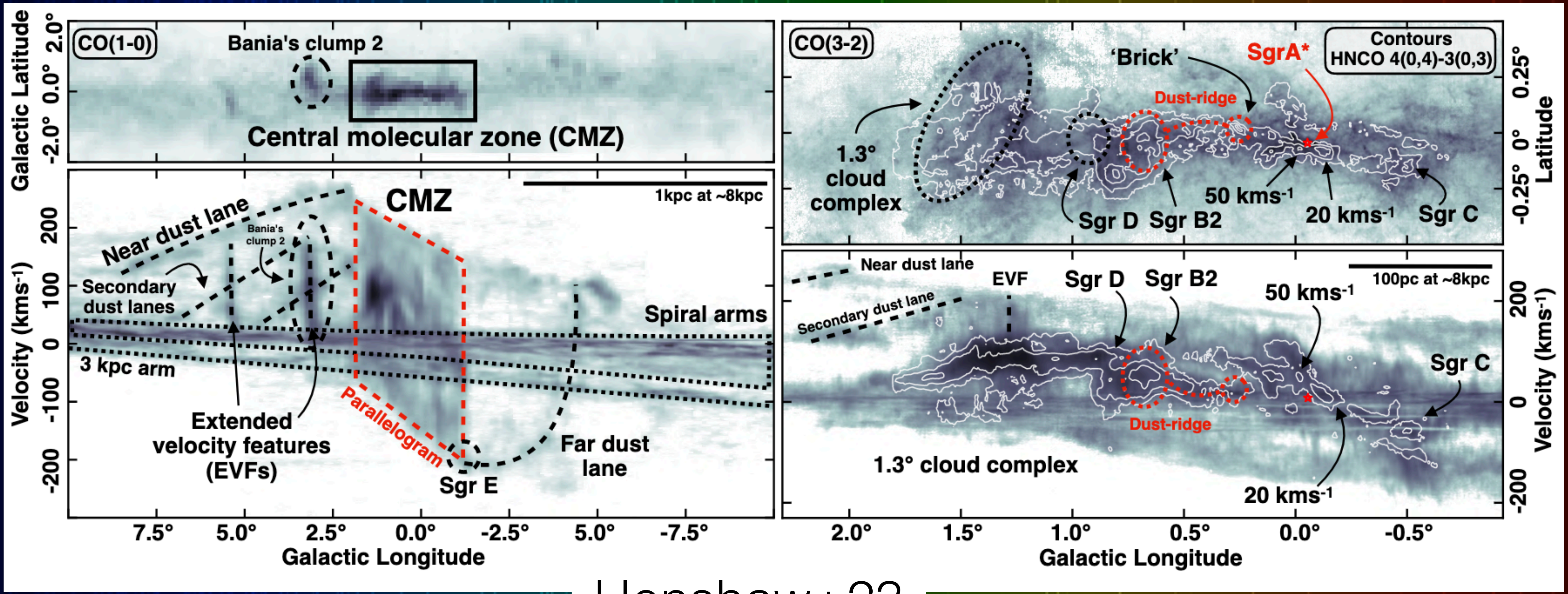
Central Molecular Zones

- Centre of Milky Way shows dense gas
- but SFR depressed
- Likely kinematically disturbed (Shear/turbulence)



Henshaw+23

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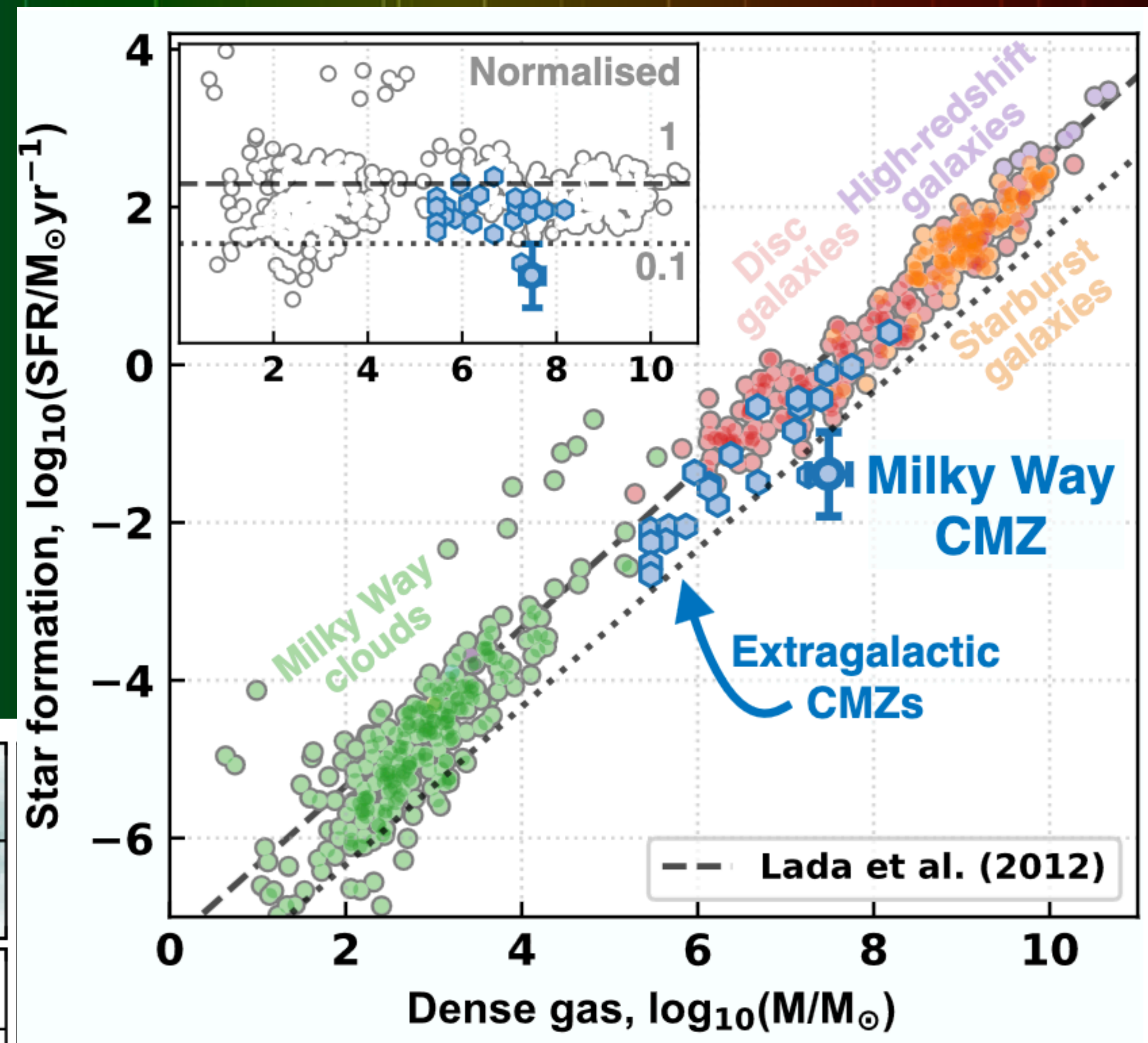

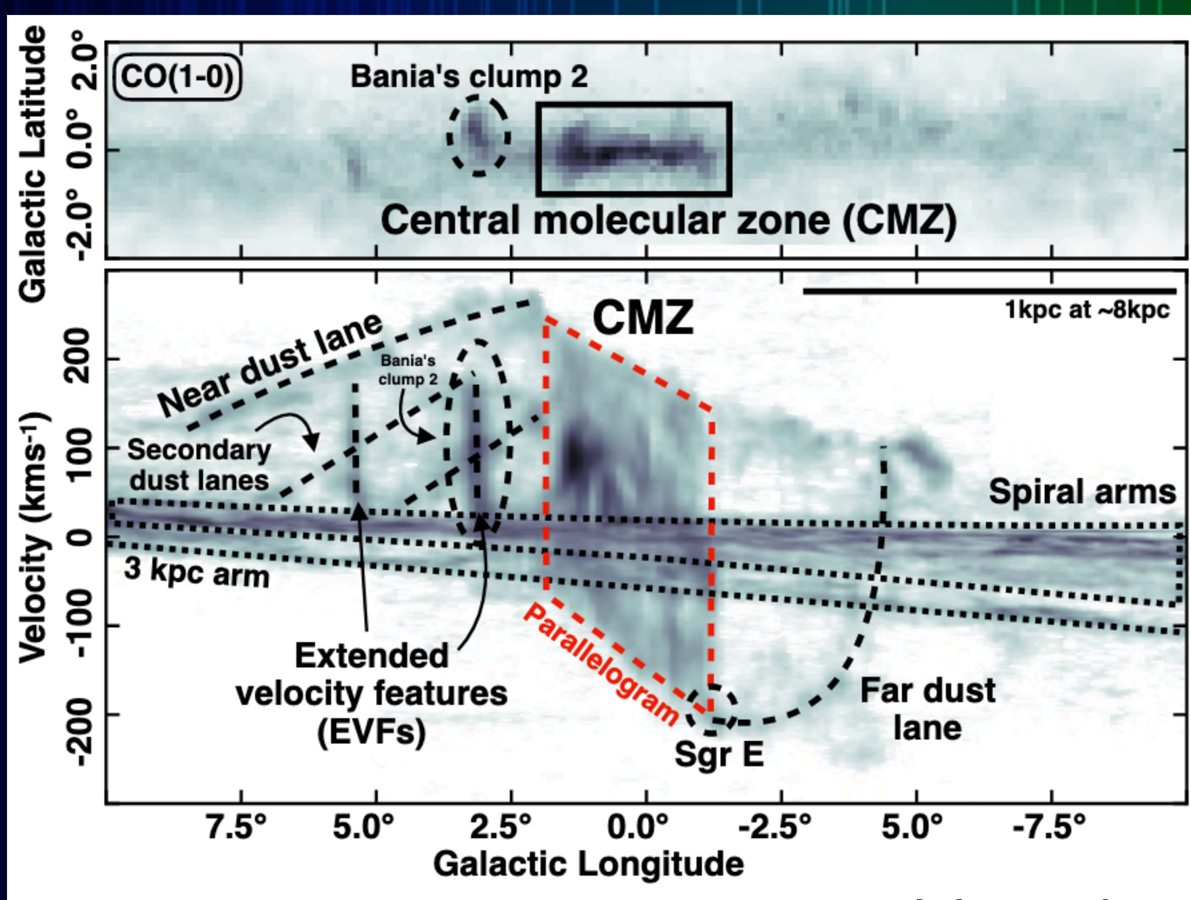

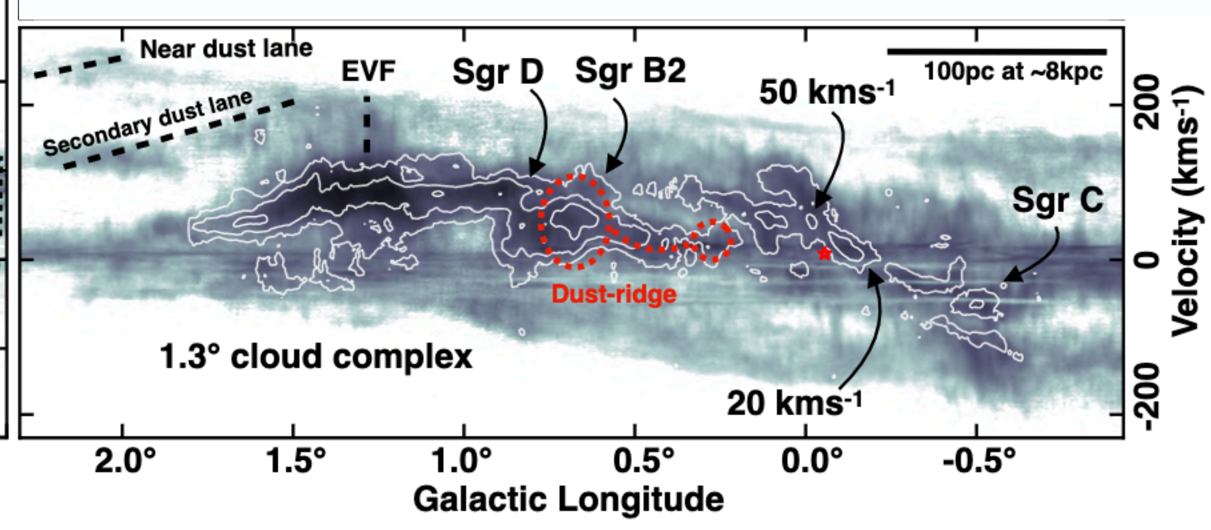

Henshaw+23

Central Molecular Zones

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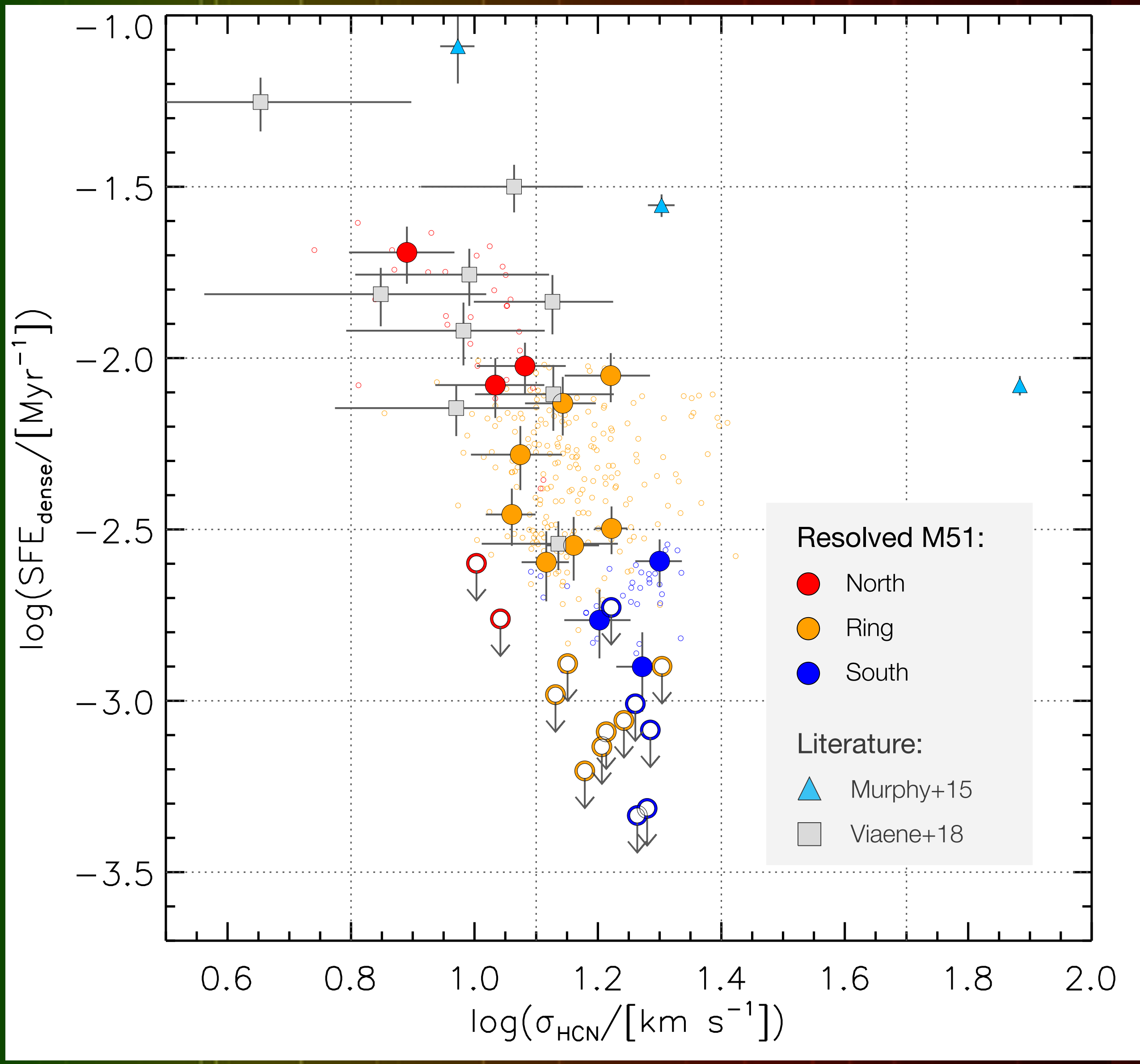
- This is true even with dense gas and in other galaxies' CMZs and kinematically disturbed regions



Querejeta+2019

ISM & Star formation in Extreme Environments

- Rapid overview of starbursts, ULIRGs & AGN
- DEFINITELY missed topics and references
- UV lines, Cosmic Rays, Magnetic Fields, [CI], large scale HI, large scale structure & clusters, low-metallicity starbursts, and more…

ISM & Star formation in Extreme Environments

- ULIRGs locally are highly obscured, merger-driven galaxies, with huge star formation rates and commonly AGN
- However, luminosity cut includes normal galaxies at high-z
- Starburst galaxies are rare, though starburst regions can be found in some galaxies
- Associated with high gas densities and potentially high star formation efficiencies
- Differences are seen even at cloud scales with massive, dense and turbulent clouds
- AGN affect all phases of ISM with strong winds, jets, magnetic fields & UV-γ-ray field
- But AGN only affect within ionization cone

Standard references

- Saintonge & Catinella (2022): “The Cold ISM of Galaxies in the local Universe”
- Tacconi, Genzel & Sternberg: “Evolution of star forming ISM across cosmic time”
- Bolatto, Wolfire & Leroy (2013): “The CO-to-H2 conversion factor”
- Lonsdale, Farrah, & Smith (2006): “ULIRGs”
- Casey, Narayanan, & Hooray (2014): “Dusty star-forming galaxies at high-z”
- Veilleux, Maiolino, Bolatto, & Aalto (2020): “Cool outflows in galaxies and their implications”