Disk-driven galaxy transformation at z~4: insights from spatially resolved ALMA data

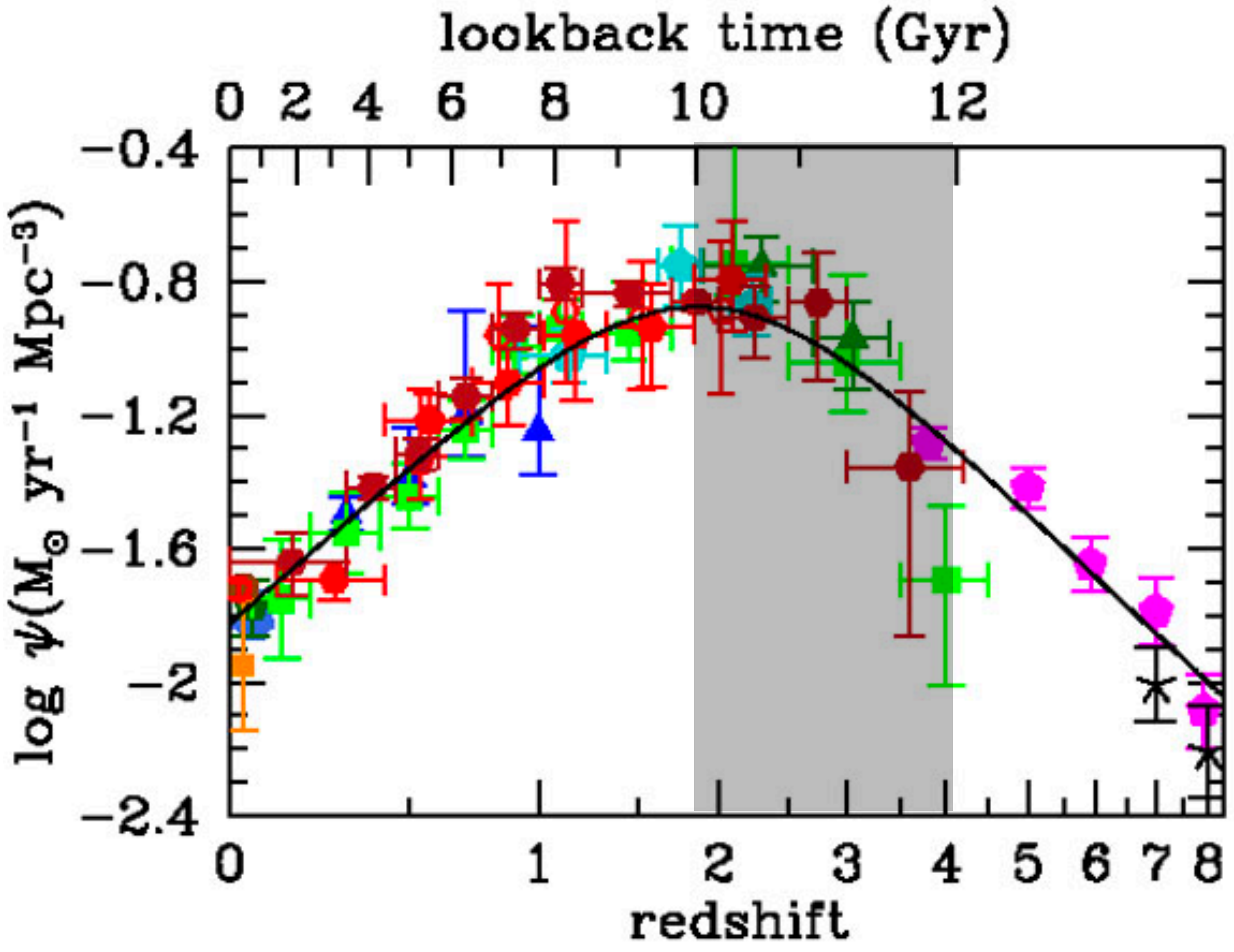
Takafumi Tsukui (Australian National University)

ARC CENTRE OF EXCELLENCE FOR ALL SKY ASTROPHYSICS IN 3 DIMENSIONS

Australian National University

21th Nov 2023 First star first galaxy

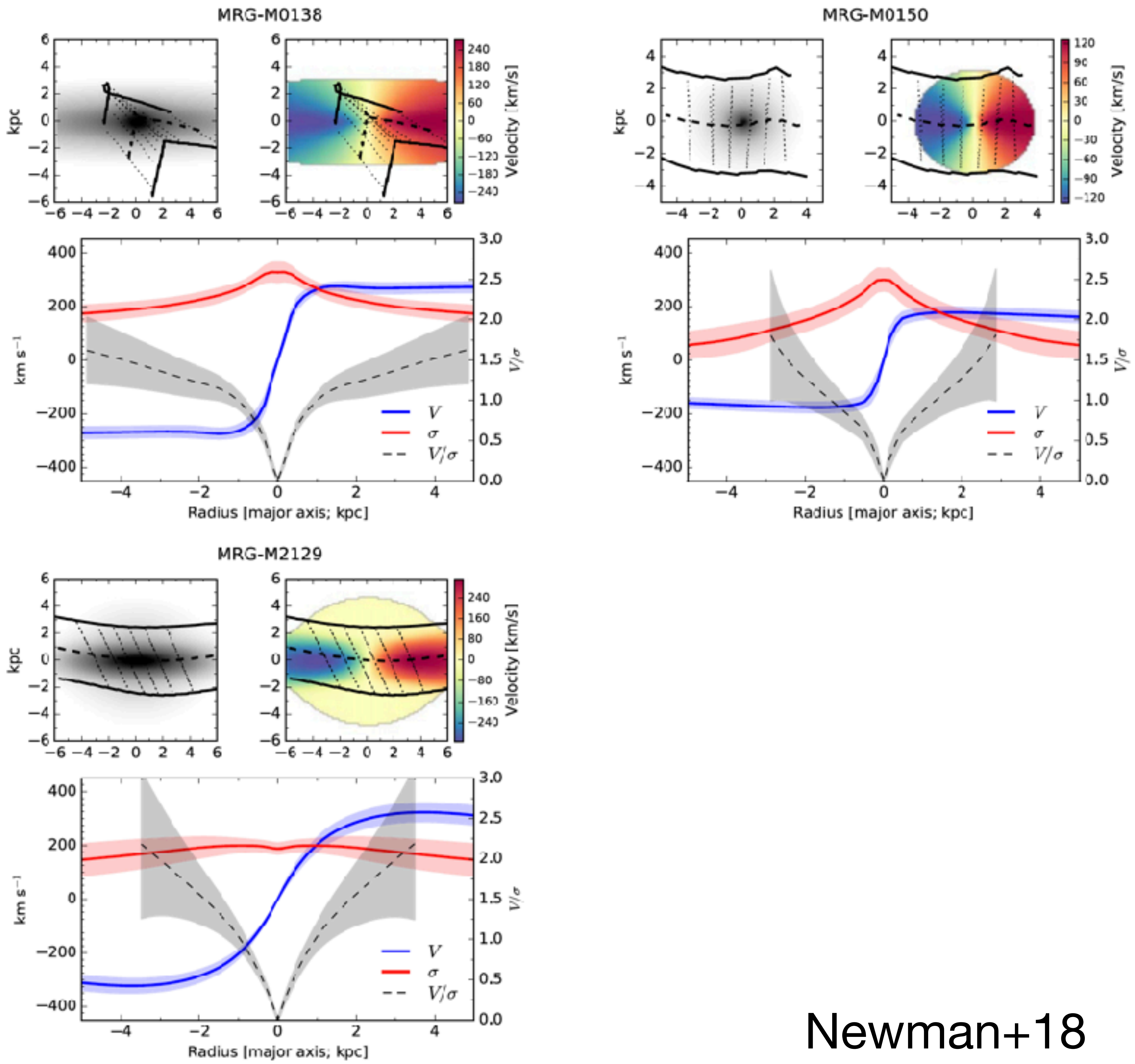
Quenched galaxies already exist less than 2 Gyrs from Big Bang.



Madau+14

Quenched compact massive galaxies ($10^{10} - 10^{11} M_{\odot}$) at z=3 to 4 identified by JWST (e.g., Ito+23, Pérez-González+22)

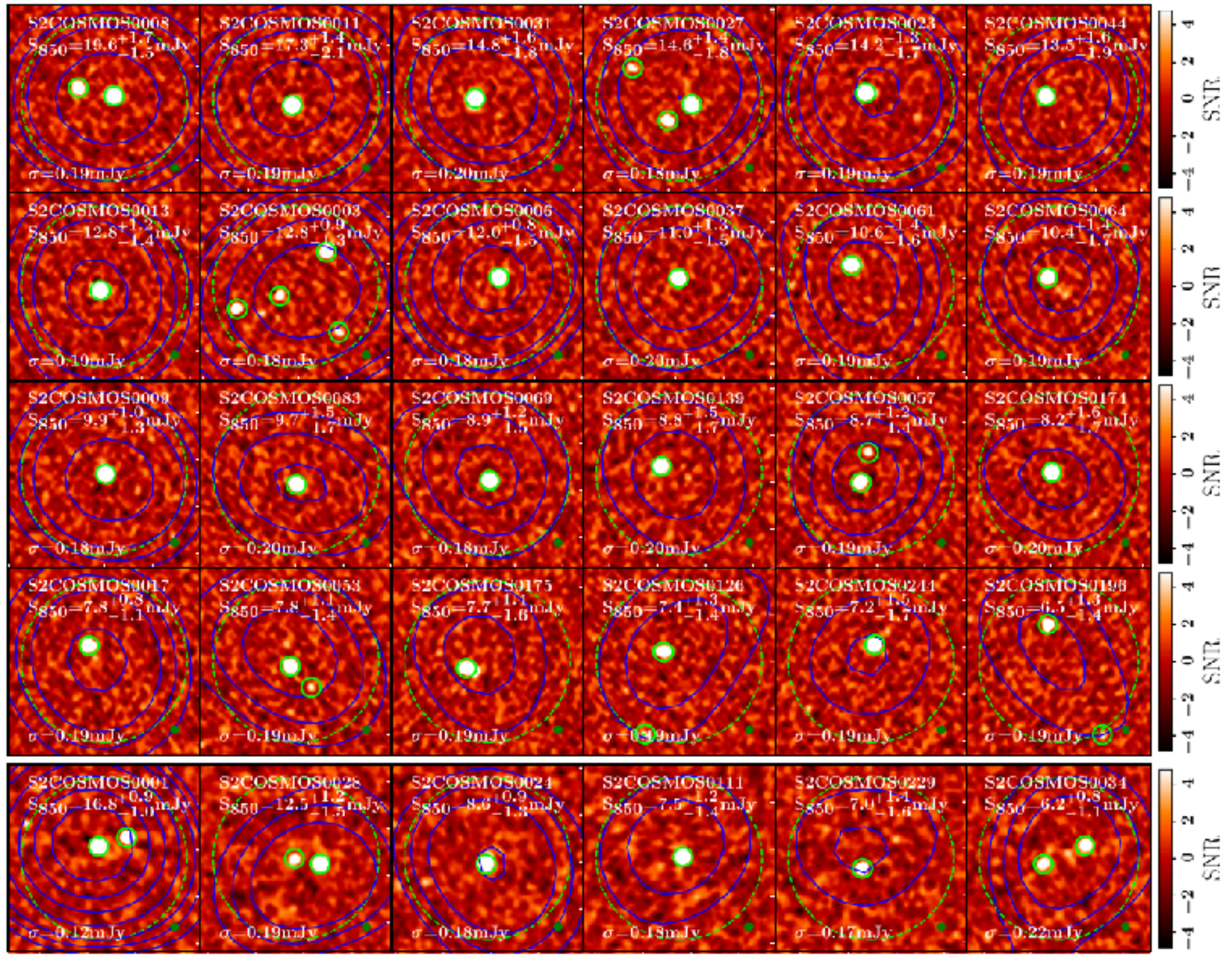
z~2 quenched galaxies show rotating disk (e.g., Newman+18, Toft+17).



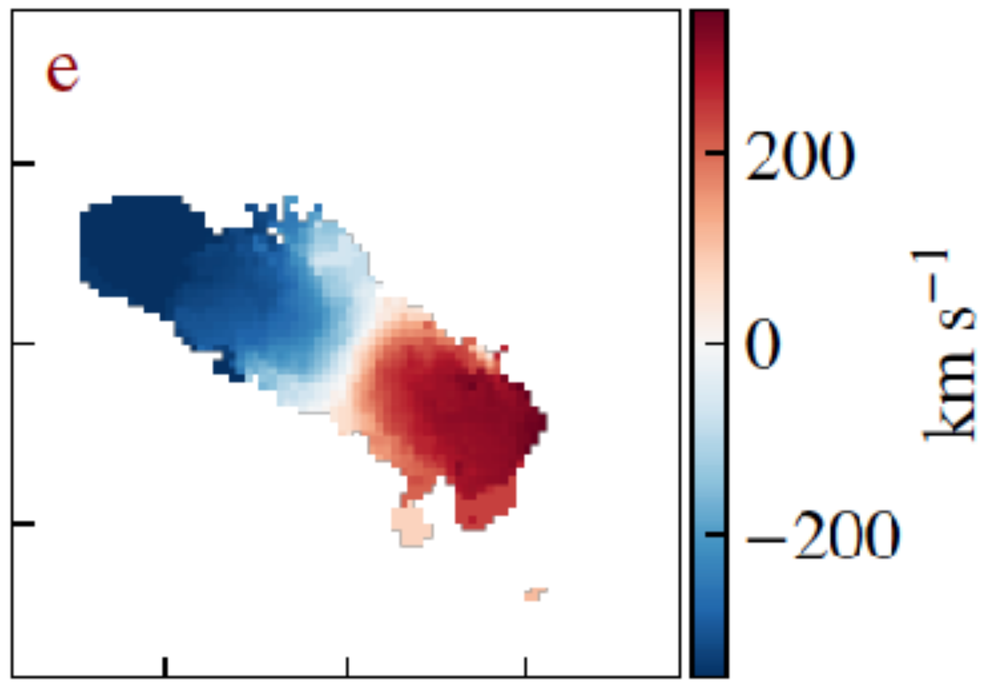
Newman+18

Submillimeter galaxies resolved by ALMA

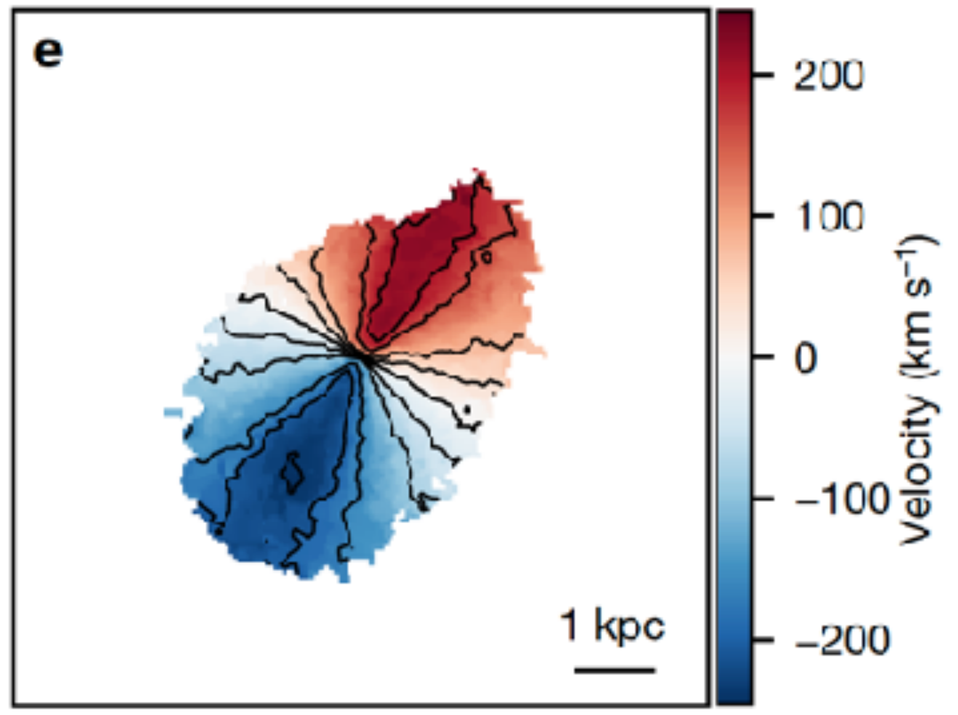
Dusty starburst galaxies form stars at most > 1000 $M_\odot$ yr^{-1}, forming the majority of stars of a massive nearby galaxy in ~ a few 100 Myr (Narayanan+15)



Simpson et al. 2020

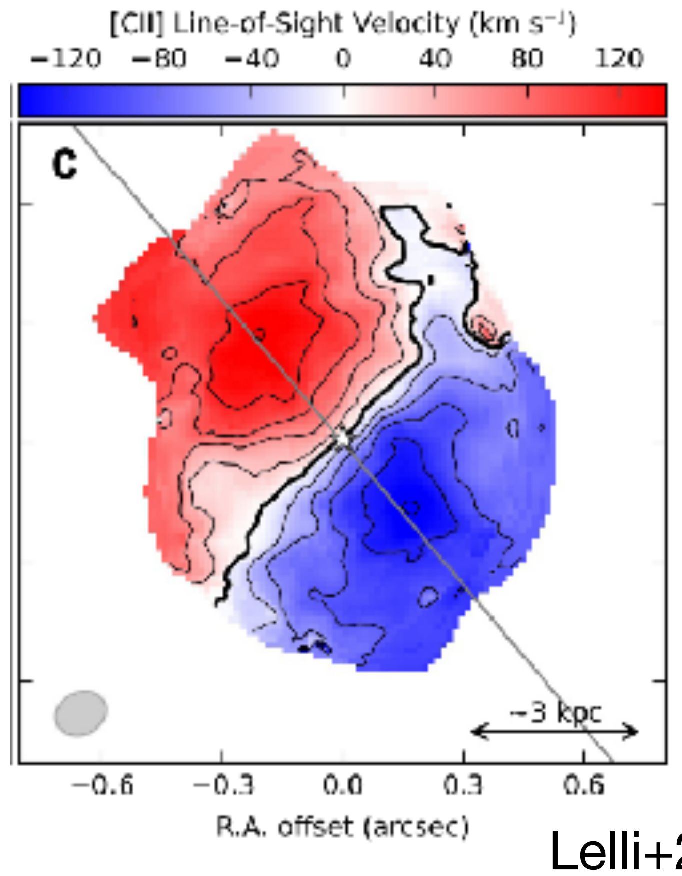


SFR ~ 100 $M_\odot$yr^{-1}
Gas depletion time = ~360Myr



Rizzo+2020

SFR ~ 352 $M_\odot$yr^{-1}
Gas depletion time ~ 40Myr



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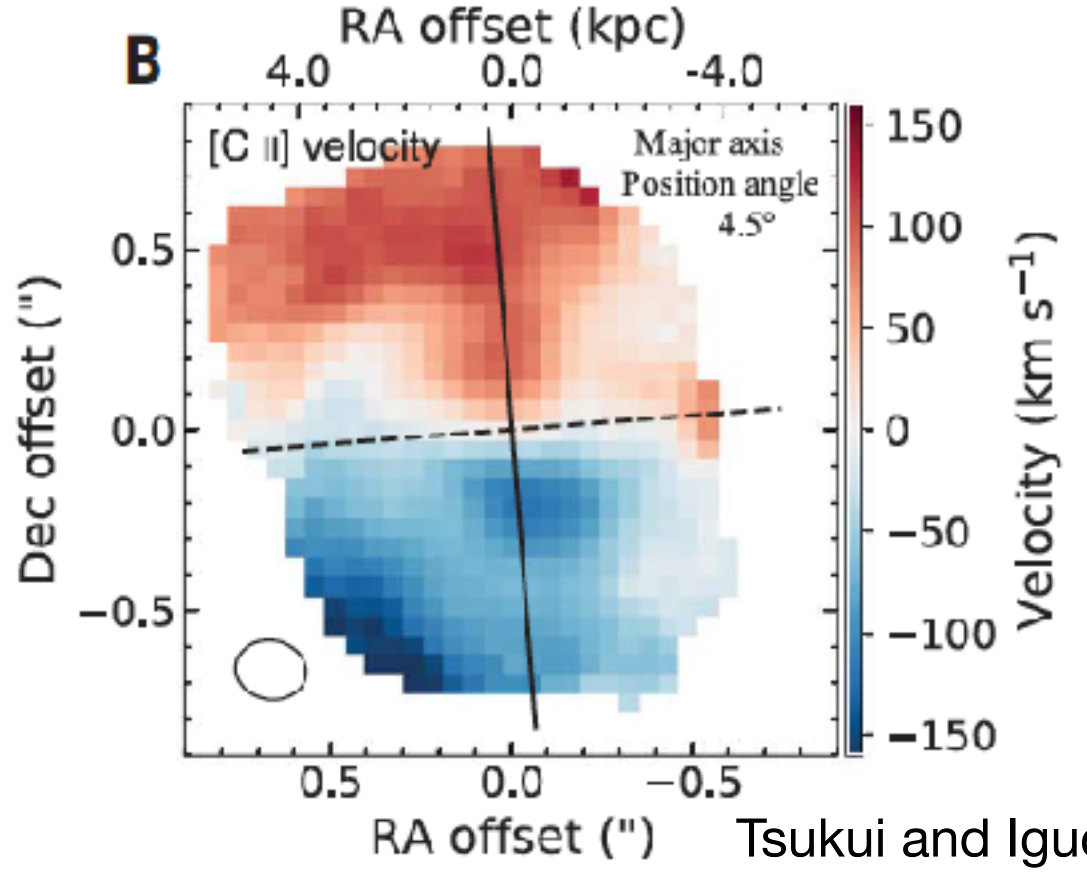
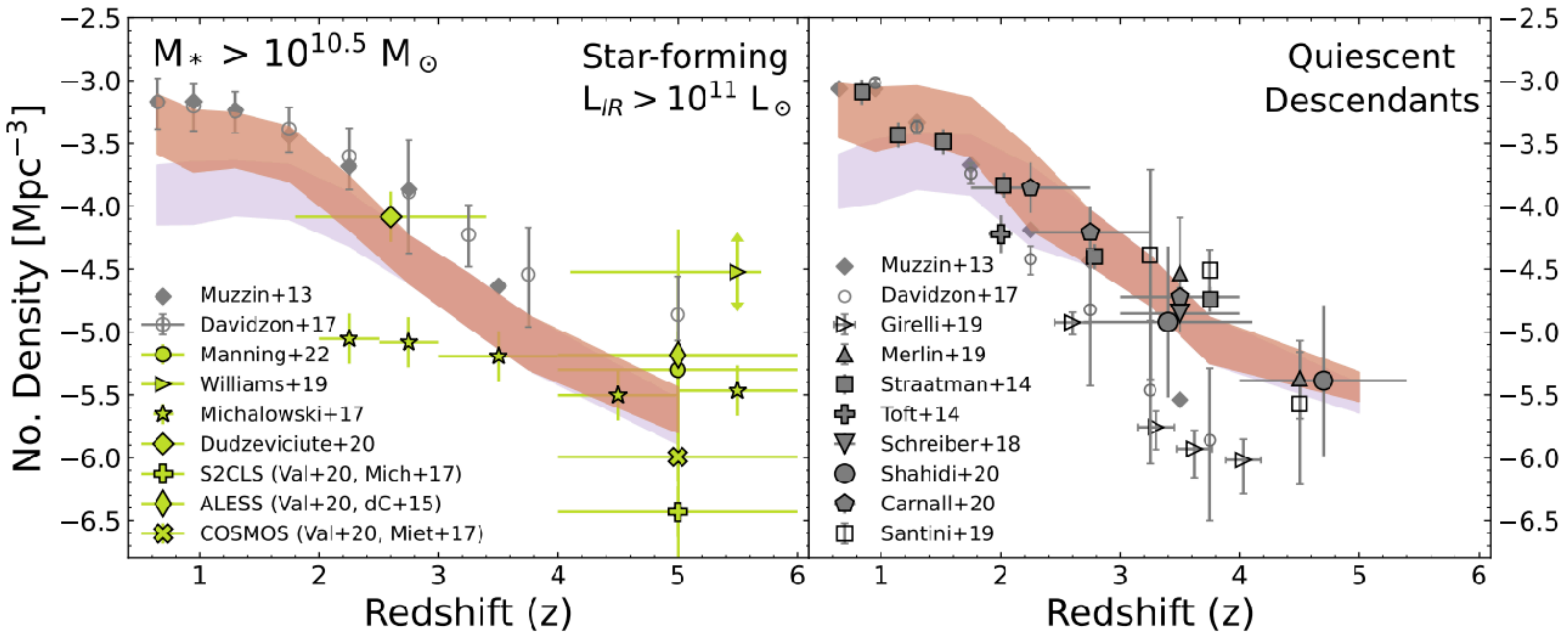


Tsukui and Iguchi 2021

SFR ~5000 $M_\odot$yr^{-1}(?)
Gas depletion time ~ 20Myr

Evolutionally link between two populations

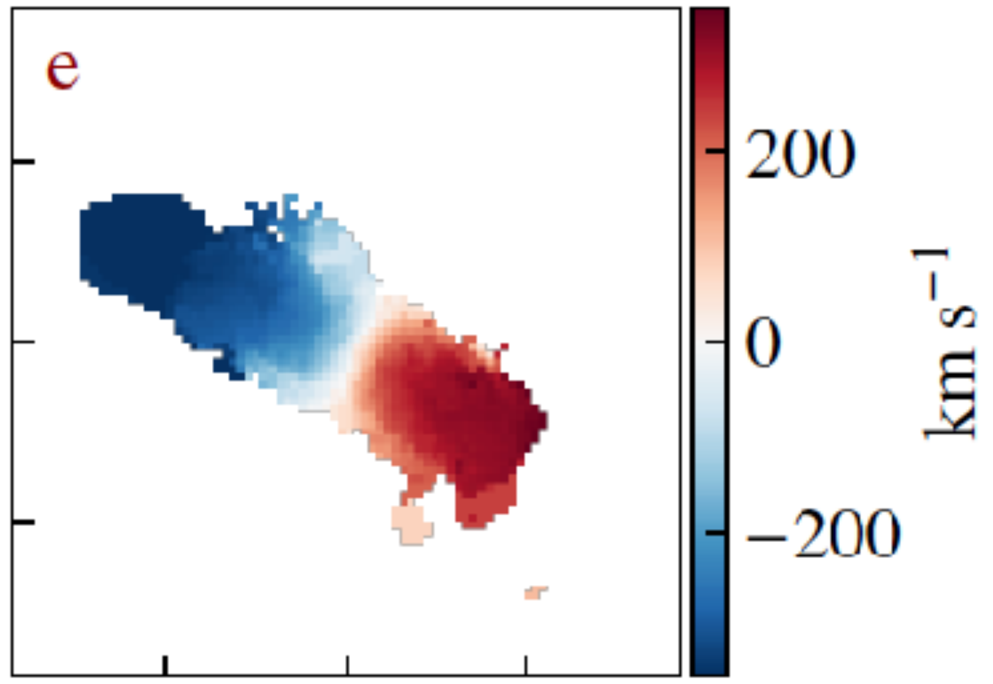
Dusty star-forming galaxies might be
an ancestor of quenched galaxies z>2
(e.g., Barro+2013, Toft+2014)



Long+22

The simple empirical model bridges the two populations.

Evolutionally link between two populations



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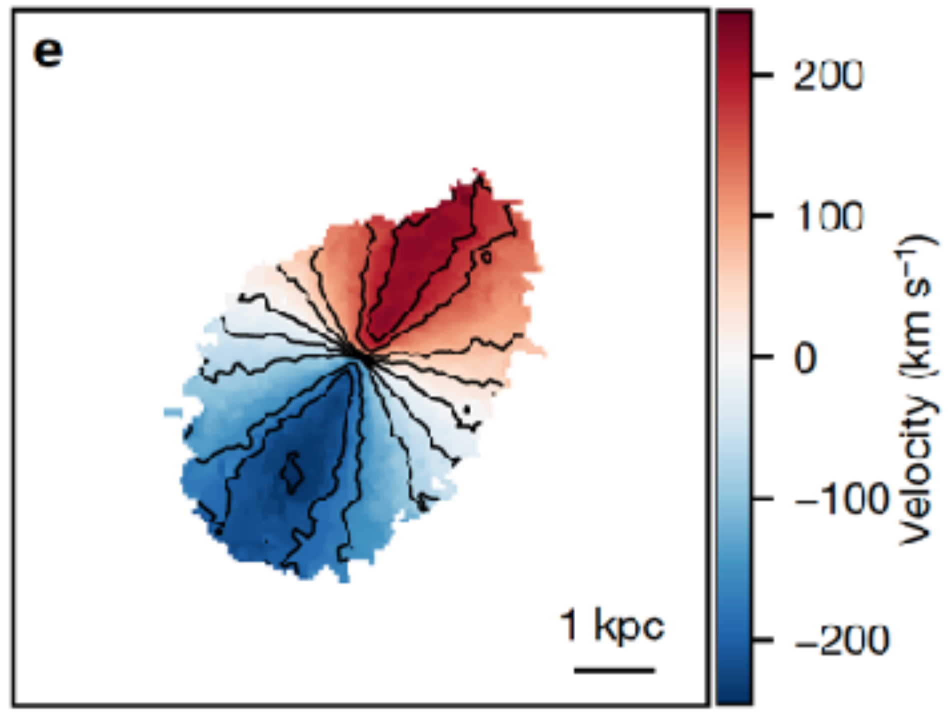

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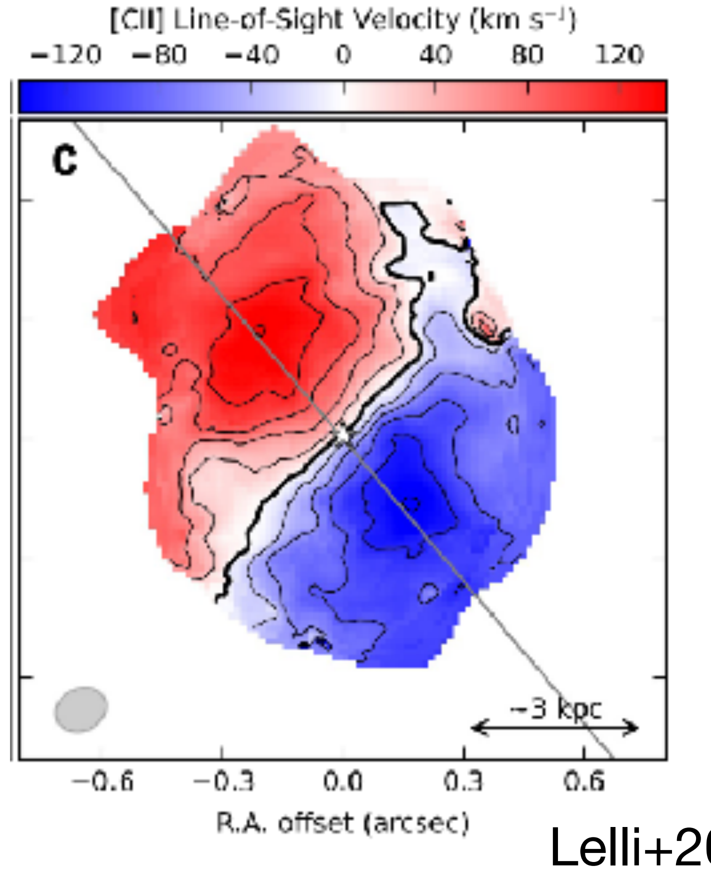

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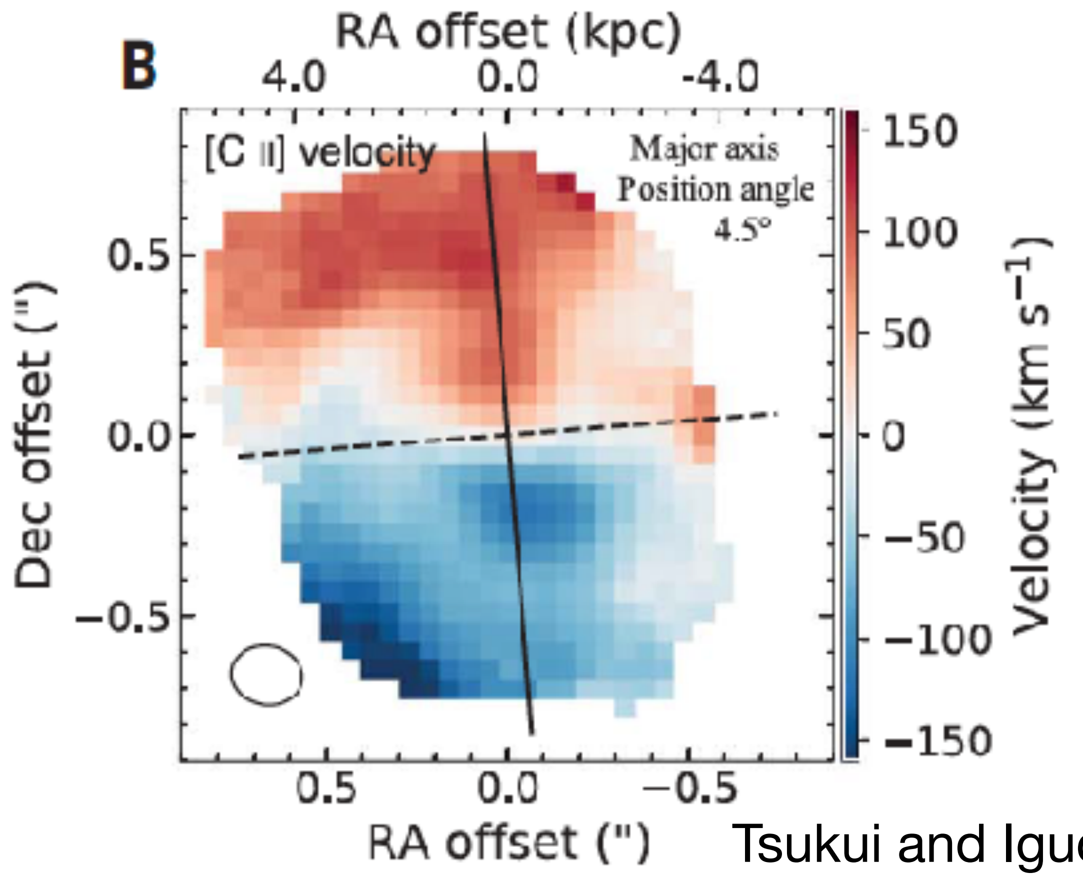

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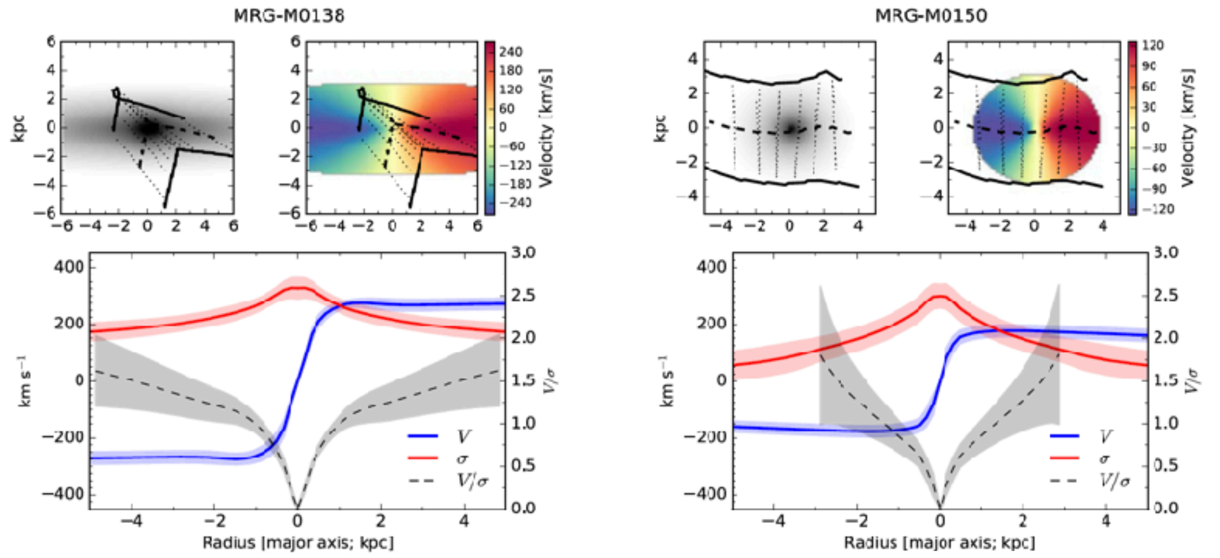
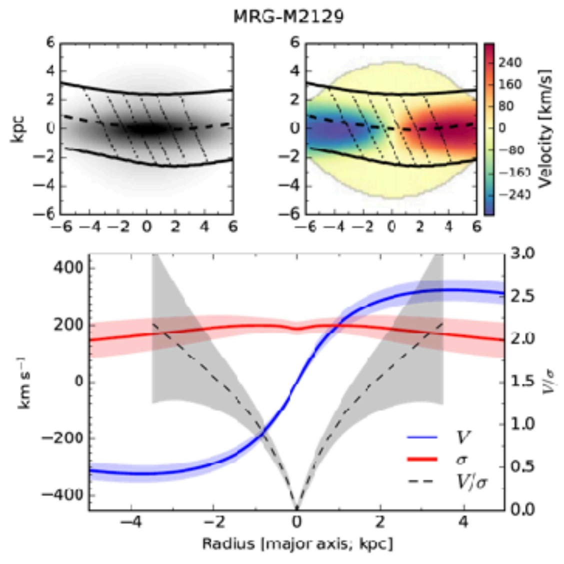
Secular evolution?

Massive compact quiscent?

Newman+17





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Extended quenched spiral?

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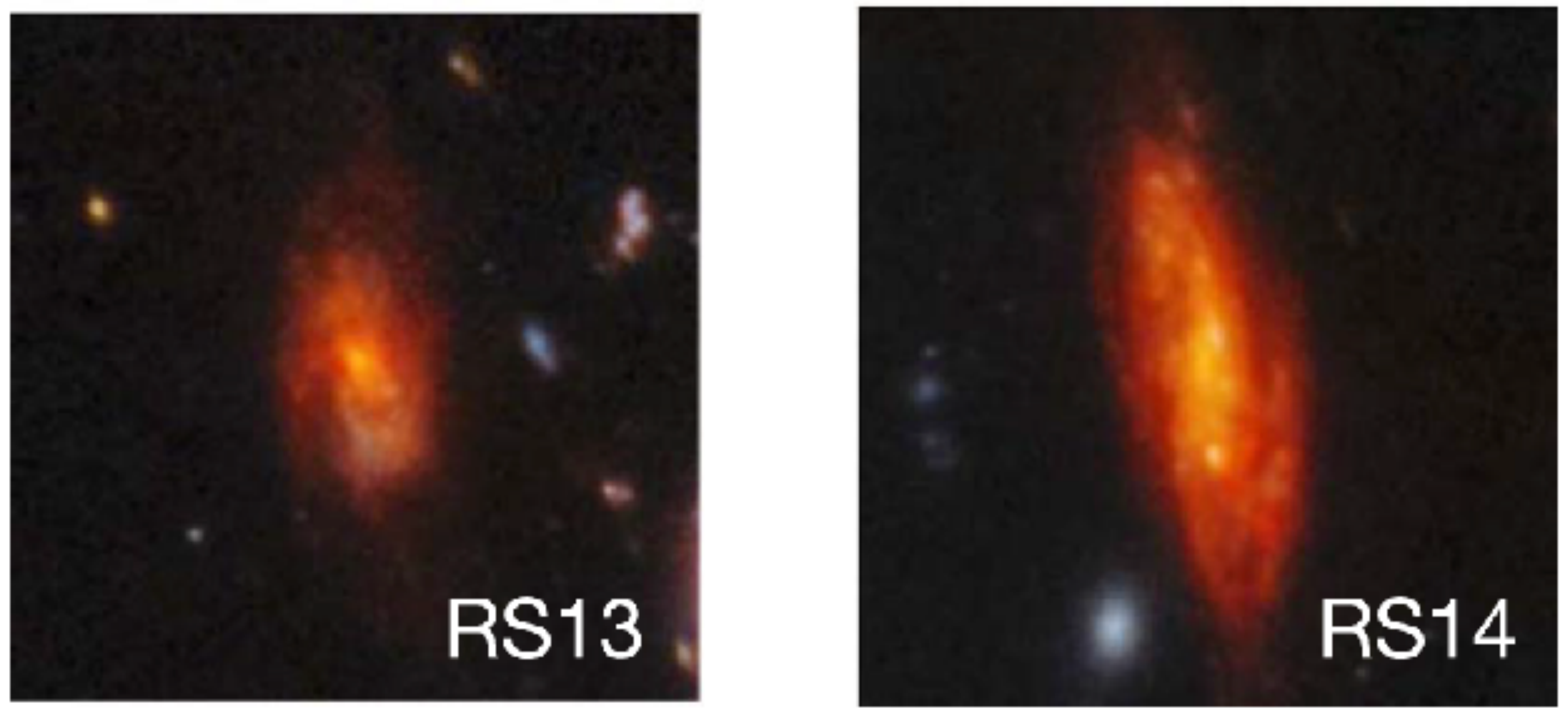

どのような条件でスターバーストが起き、遷移の過程で何が起きているか?

ALMA: ダストを見通し、空間分解した 1) 銀河構造、ダイナミクス and 2) 正確な星形成分布の把握

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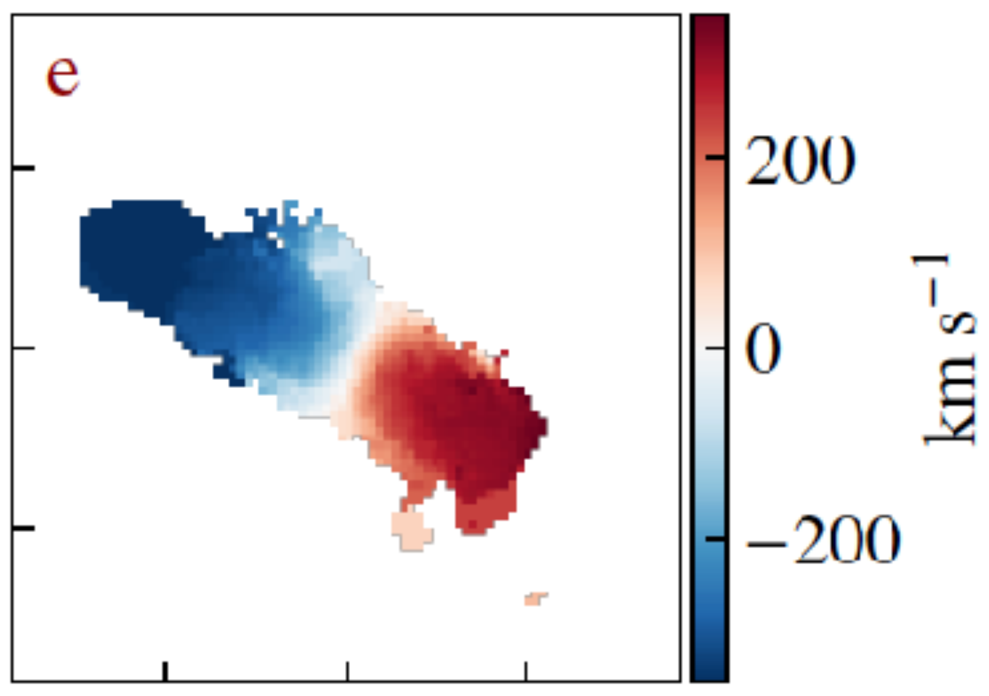

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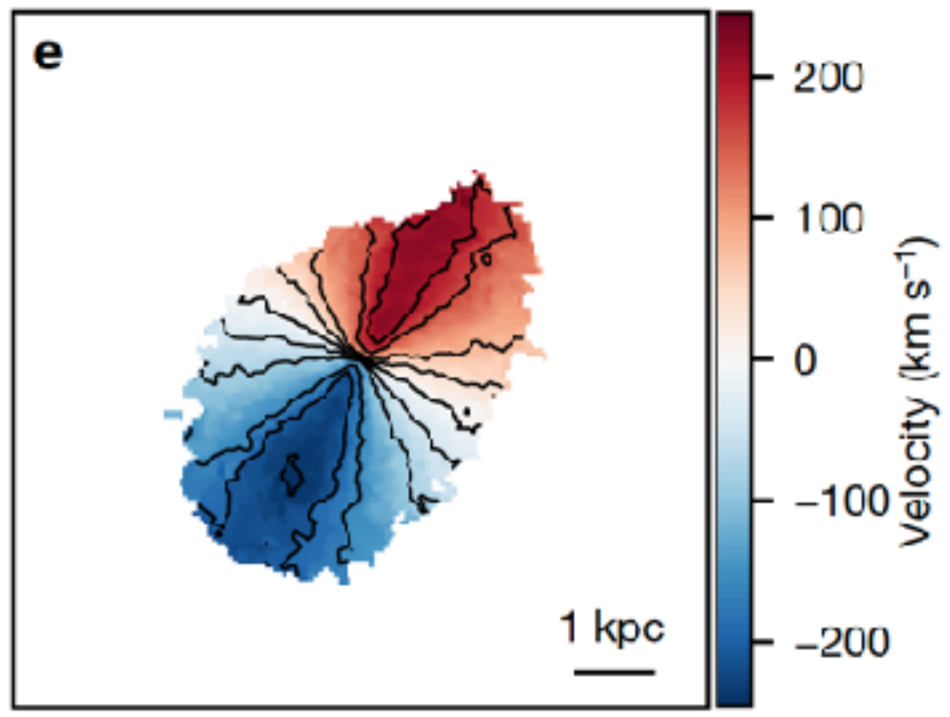

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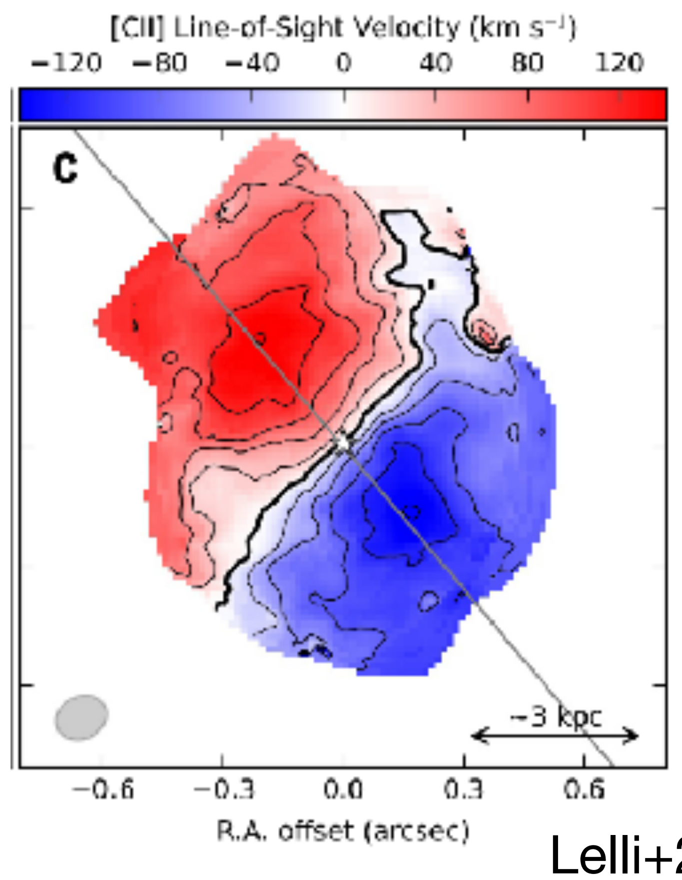

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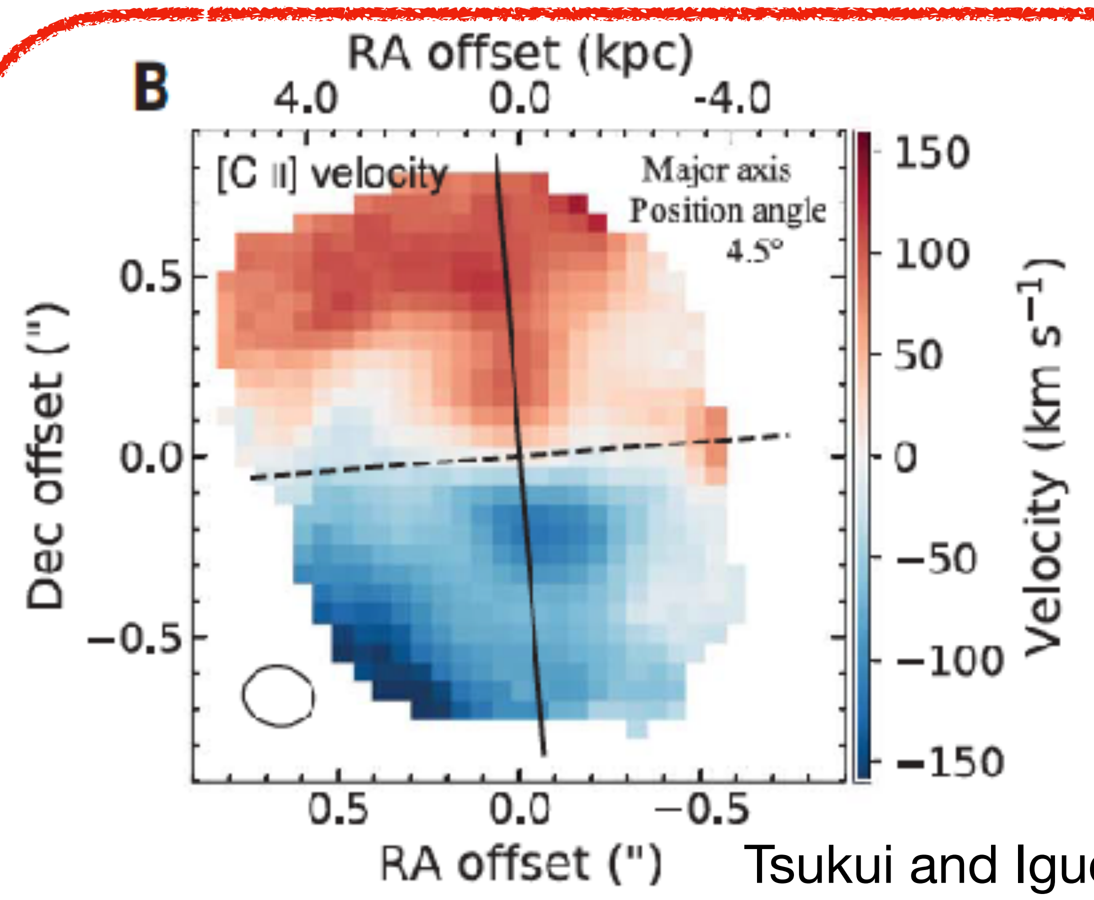

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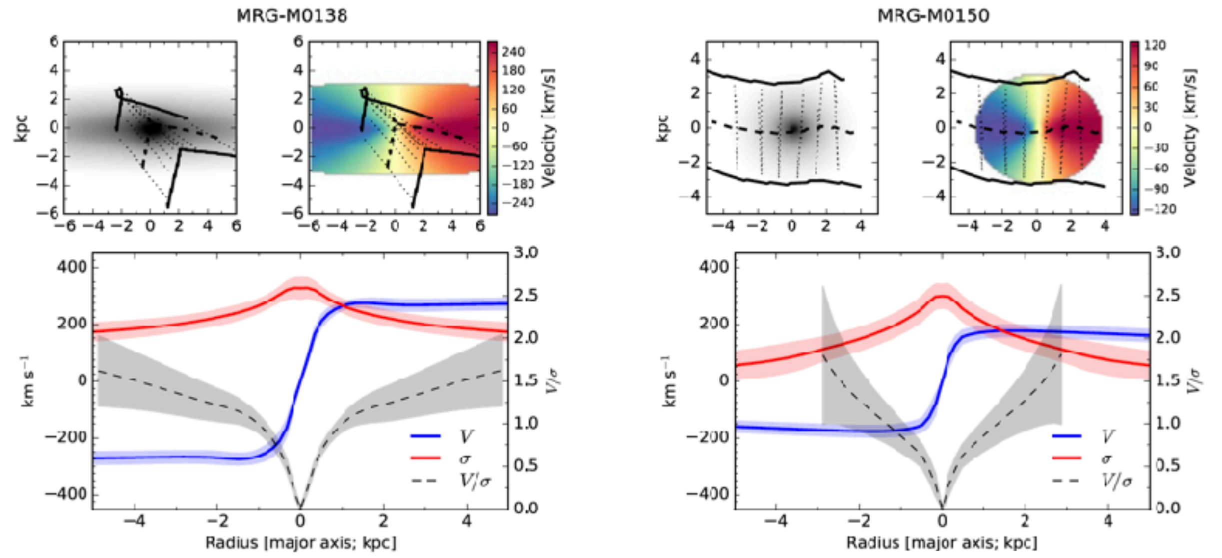

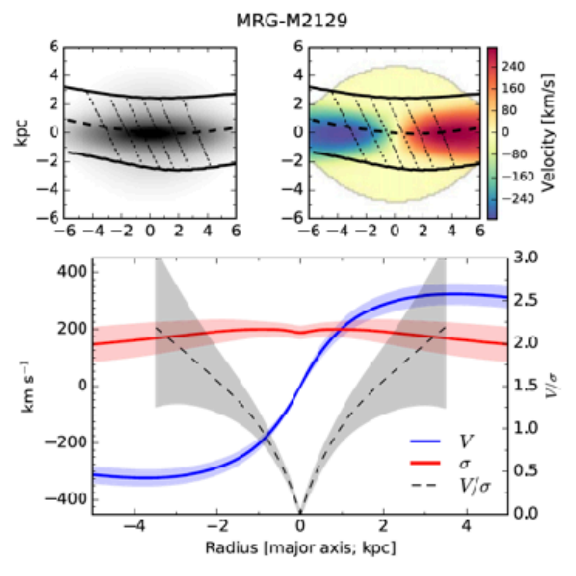

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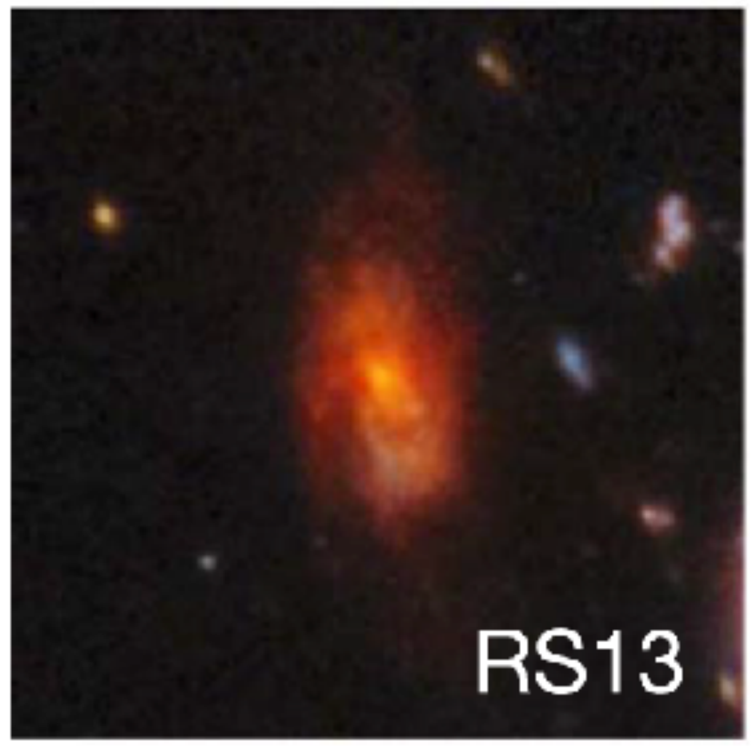

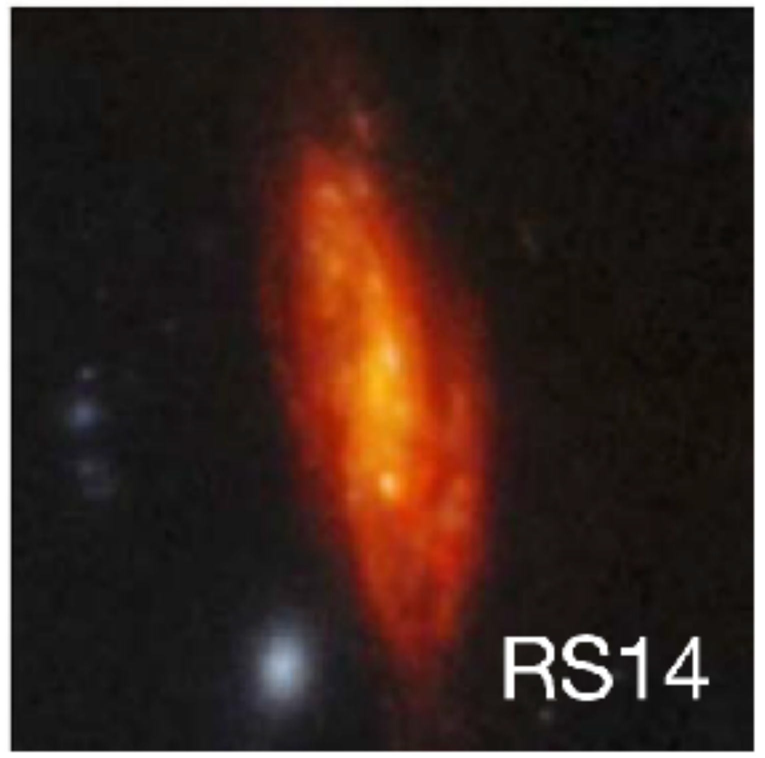

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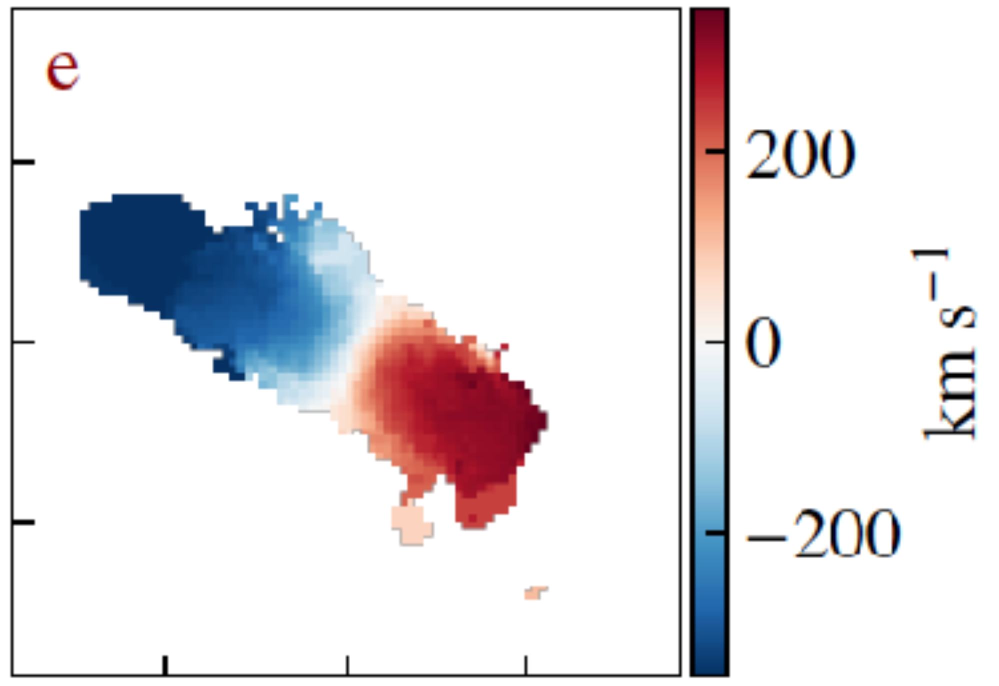

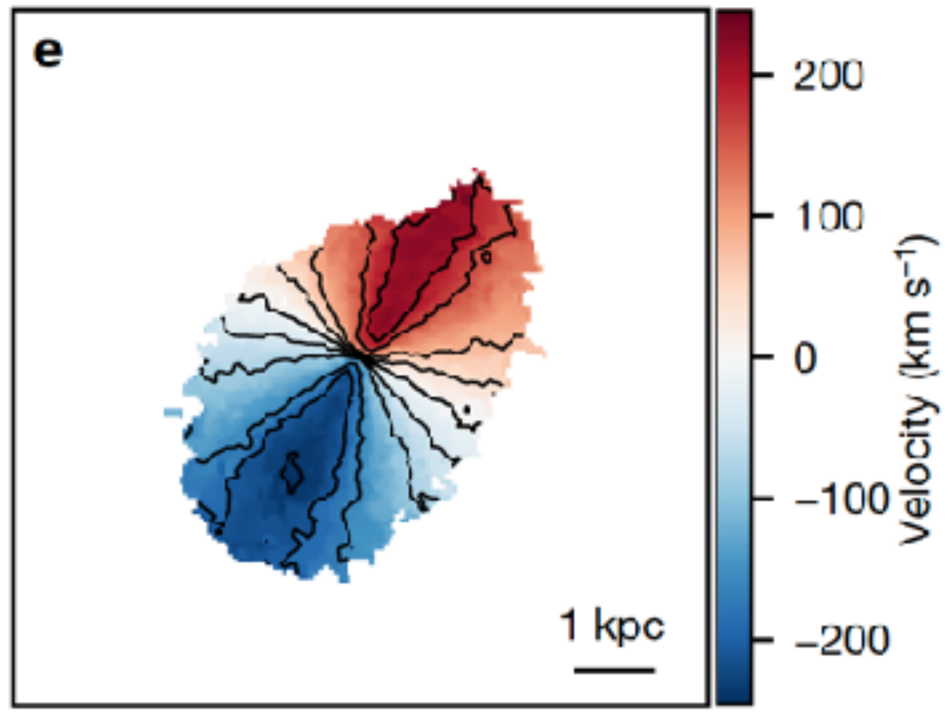

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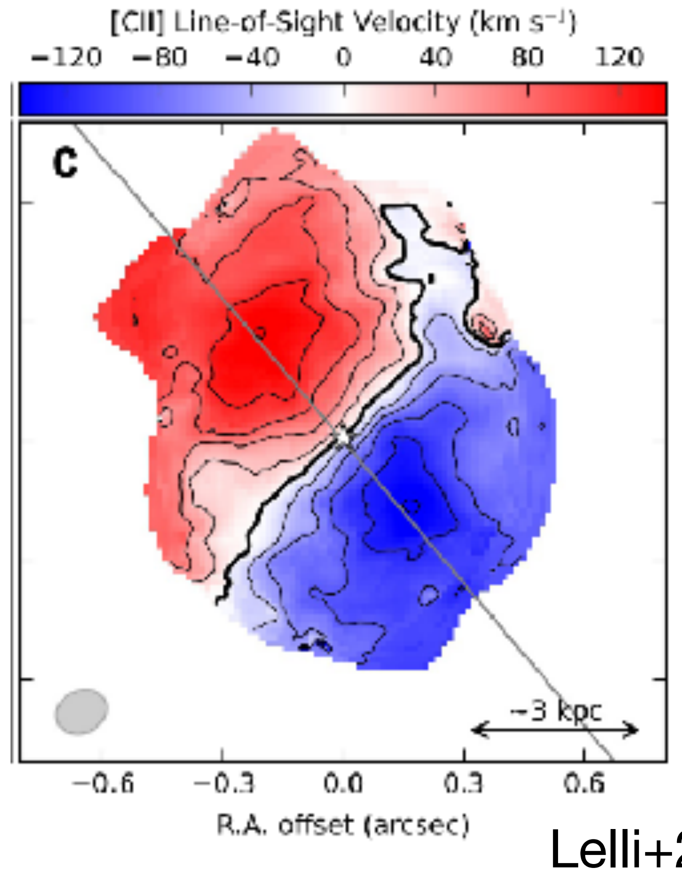

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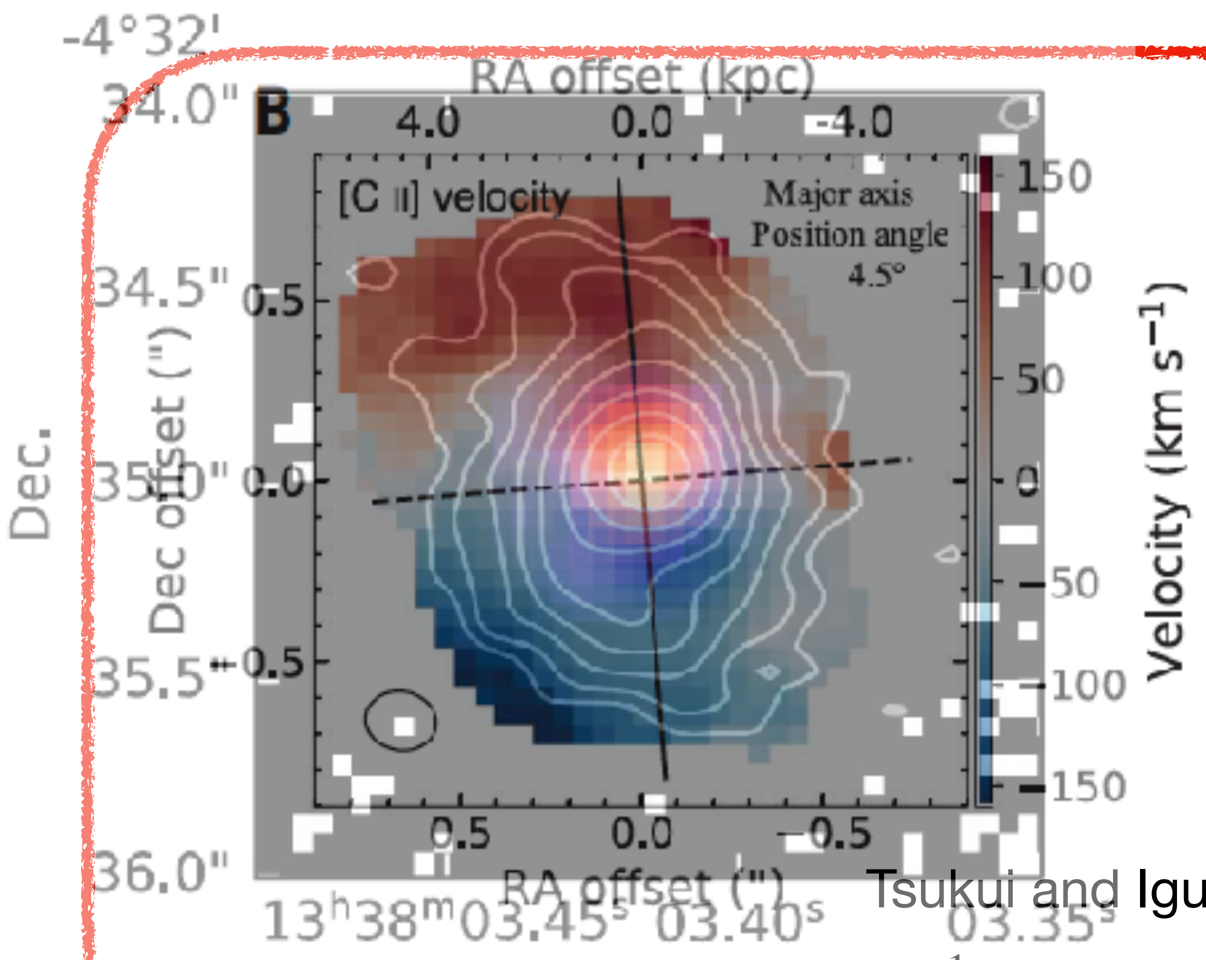

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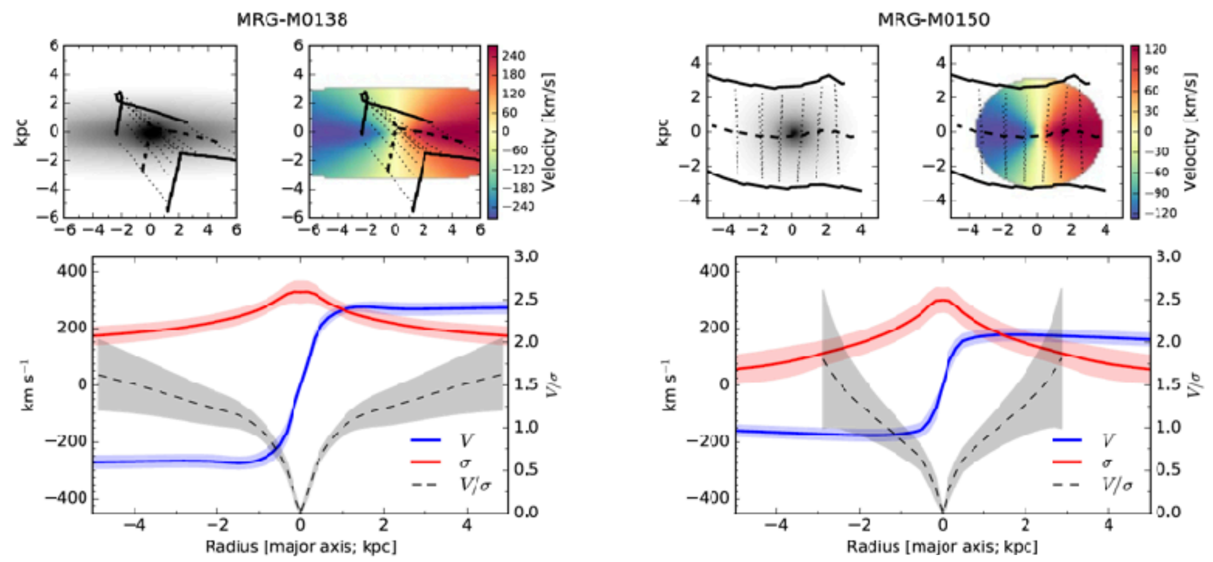

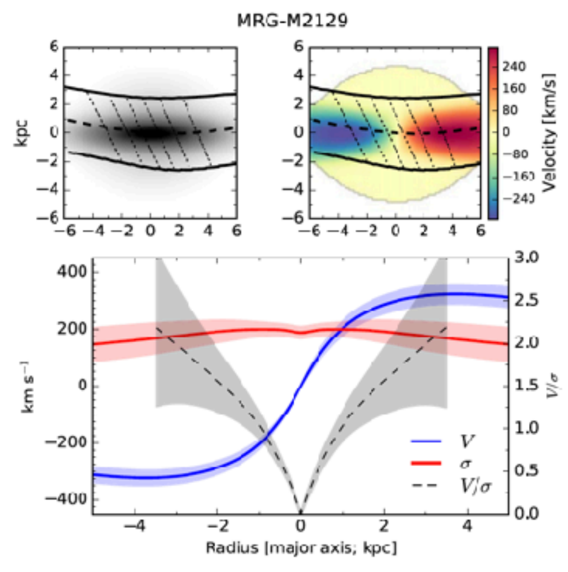

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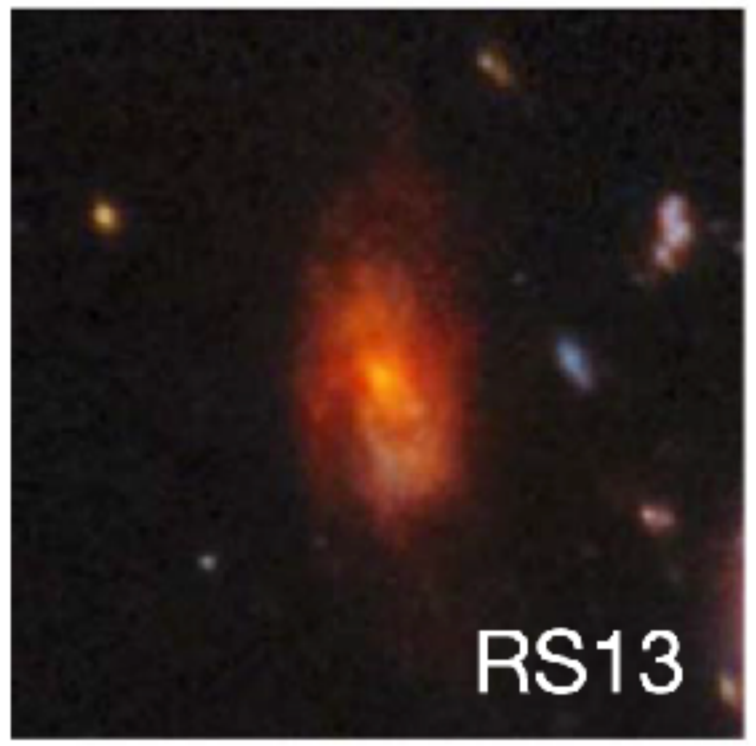

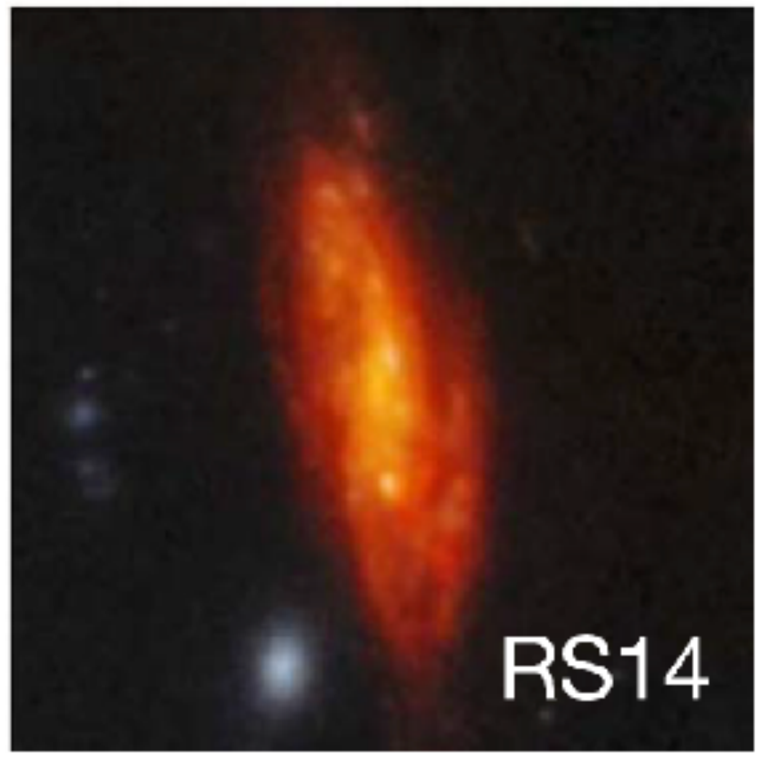

どのような条件で爆発的星形成が起き、遷移の過程で何が起きているか?

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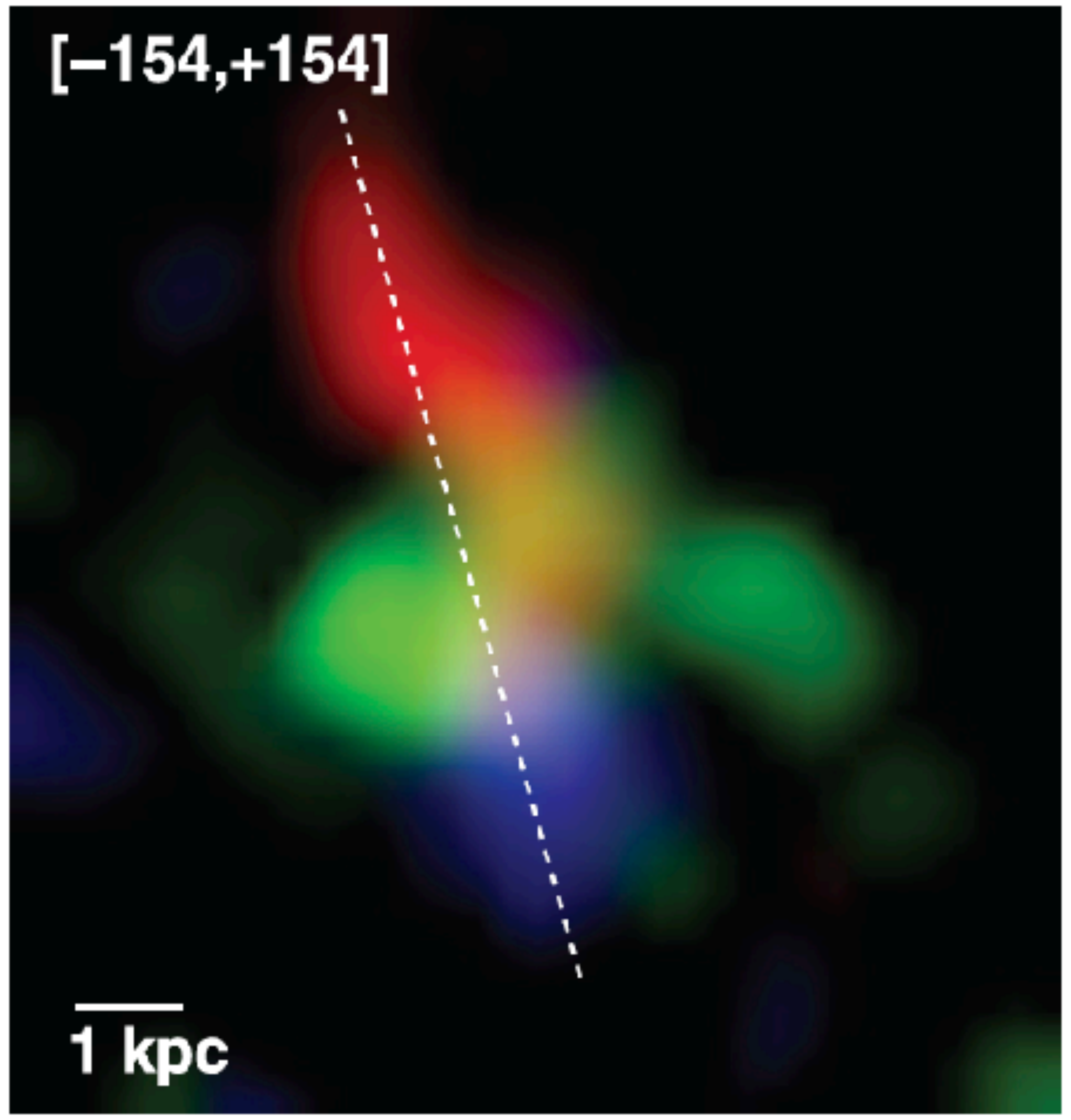
BRI 1335-0417 (z=4.41)

- Quasar-host hyper luminous infrared galaxy $L_{\rm FIR} = 3.1 \times 10^{13}\, L_{\odot}$ (Carilli et al. 1998)
- SFR=$5000 M_{\odot} {\rm yr}^{-1}$ (Dust SED AGNを考慮に入れていない: Wagg et al. 2014)

Tsukui and Iguchi 2021

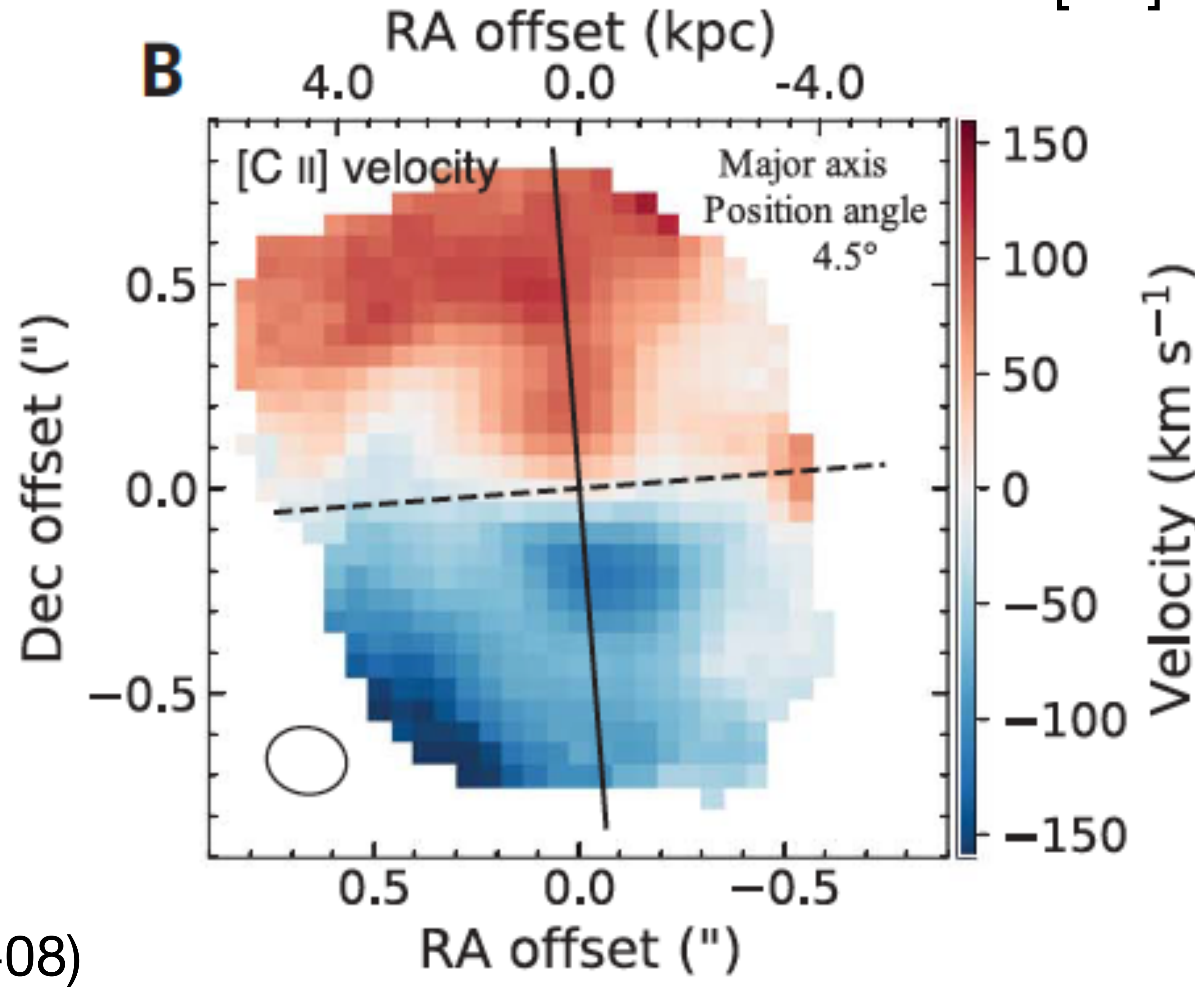
Tsukui + 2023c in press

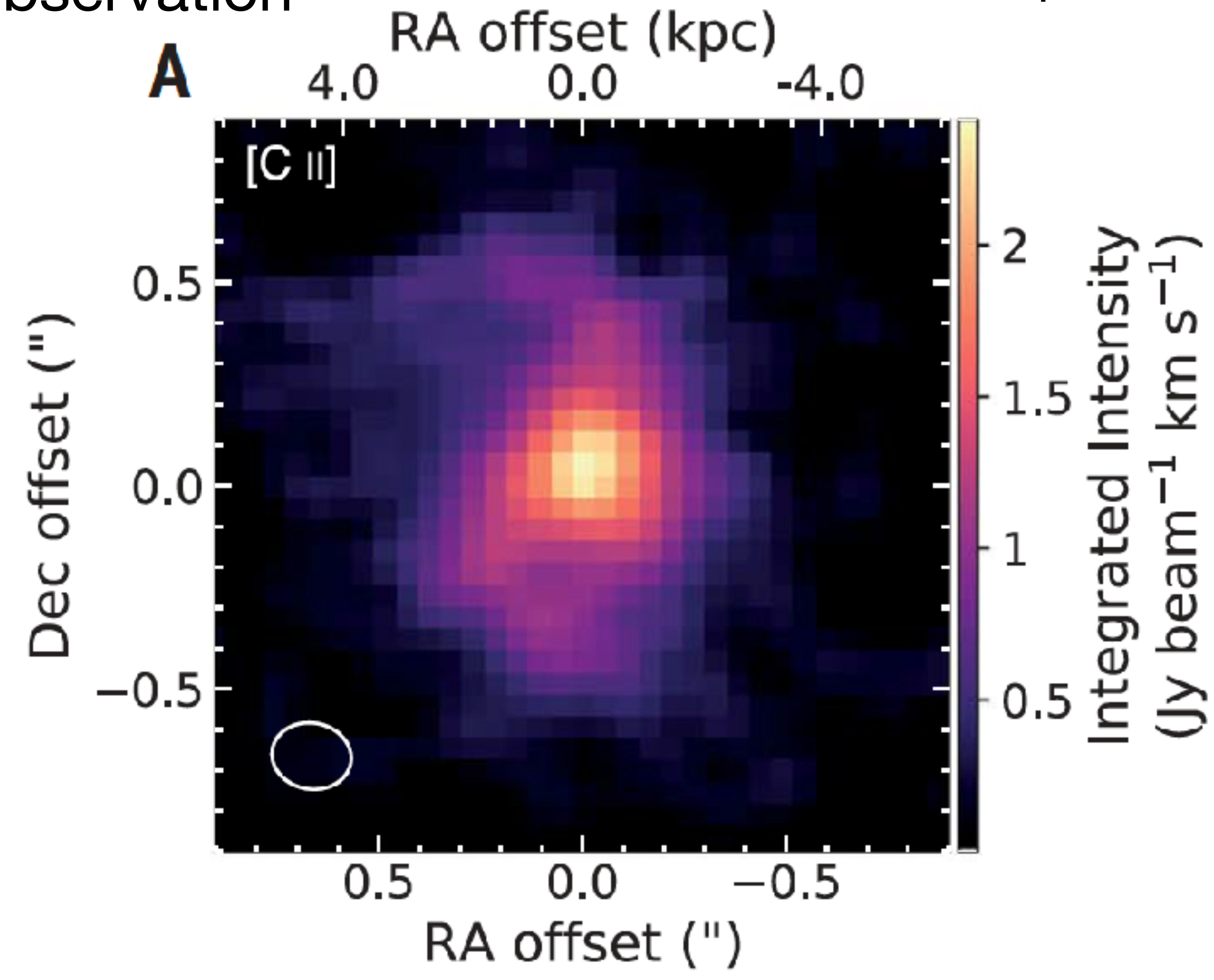
VLA CO (2-1) velocity map



(Riechers+08)

ALMA [CII] observation





- VLAでは不規則な形態と力学 高い星形成率と合わせてmajor mergerだと思われていた。
- ALMAは規則的な円盤(V/sigma~2.6) 渦巻き構造とバー構造。

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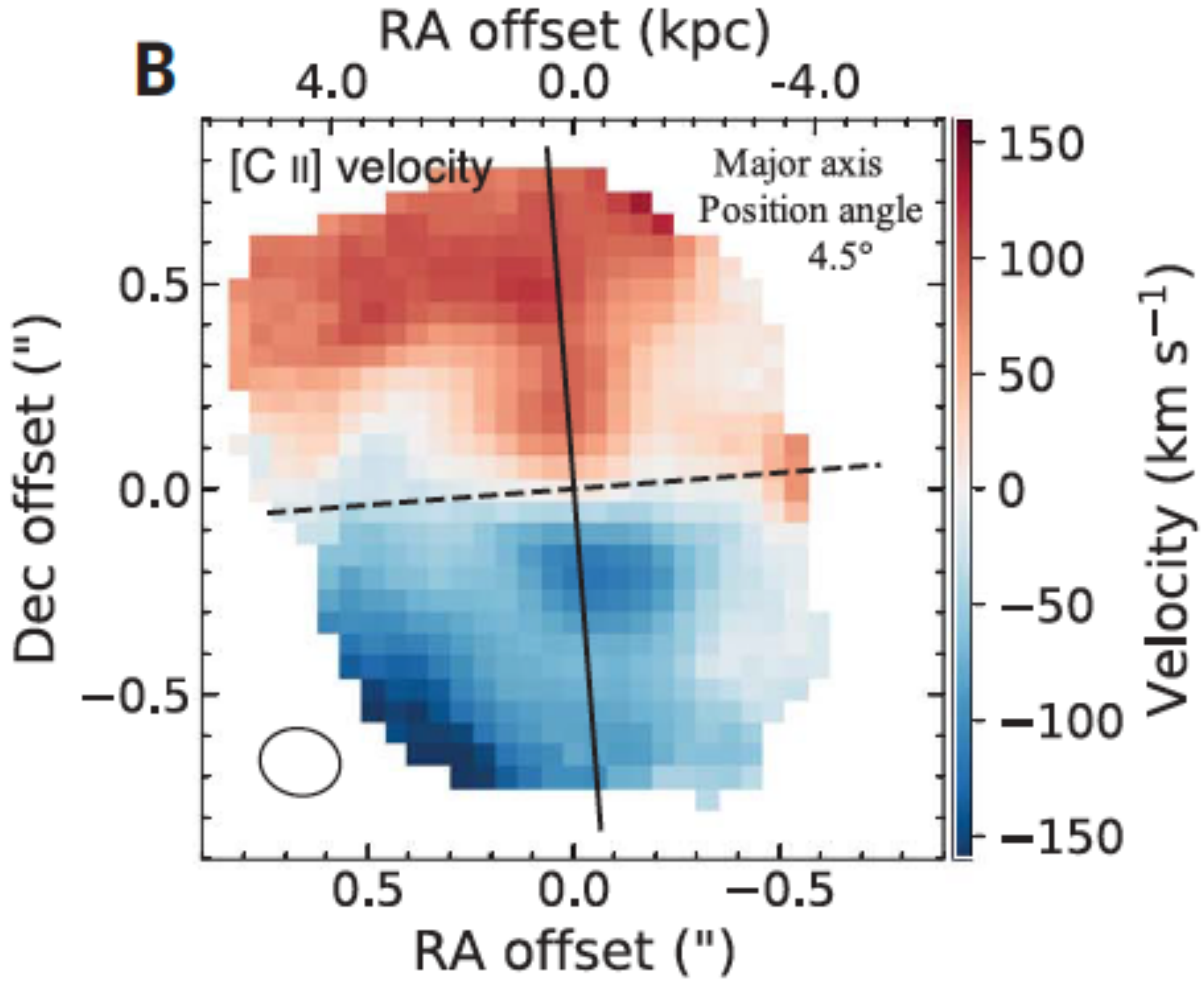

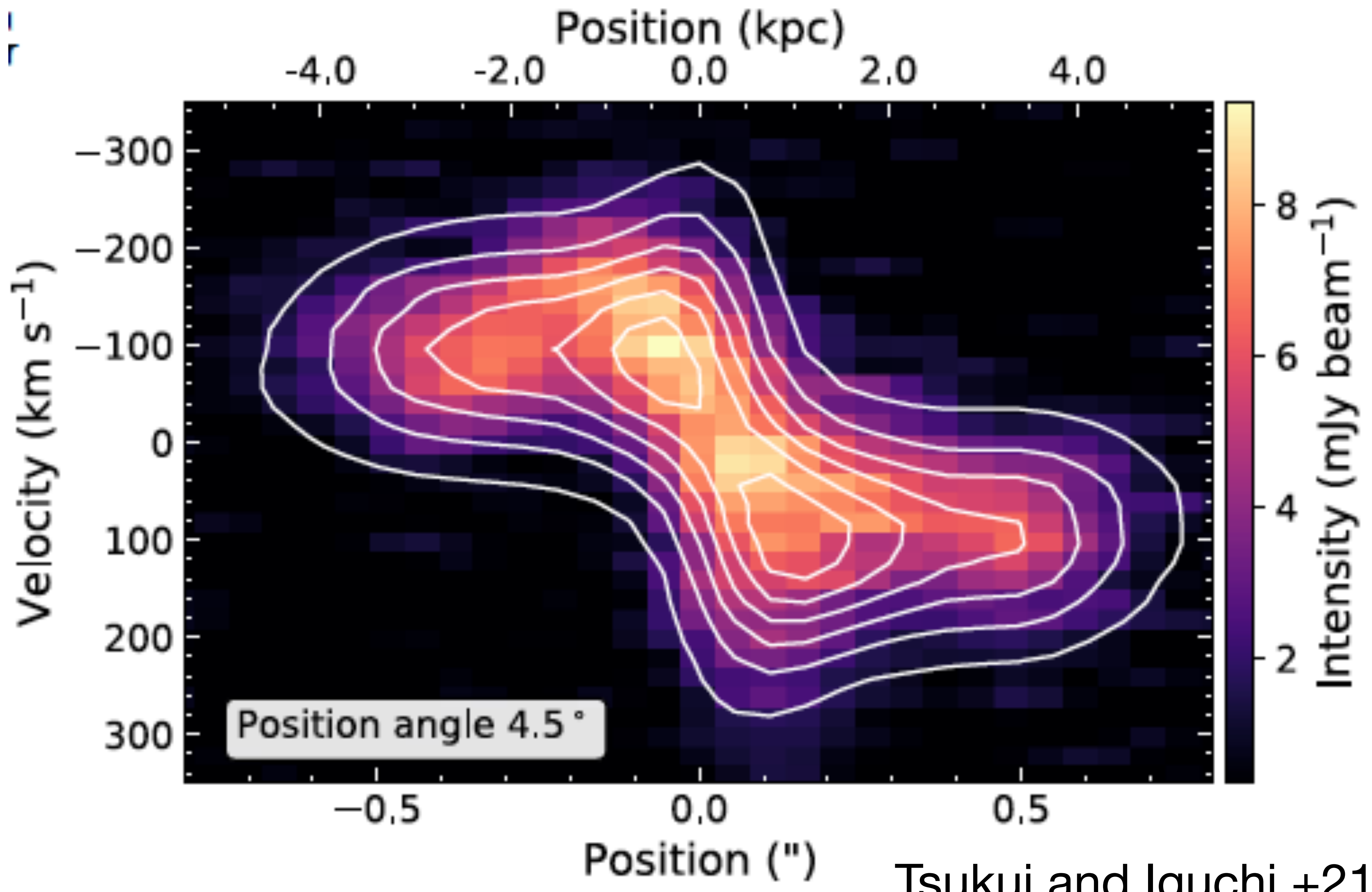

Tsukui and Iguchi +21

Tsukui + 2023c in press

- [CII]輝線力学モデルはバルジの存在を示唆 ($5.2 \times 10^9 M_\odot$<1.3kpc)
- 力学質量 ~ CO輝線から求めた分子ガス質量 -> gas-rich baryon-dominated disk (f_{gas} ~ >73%).

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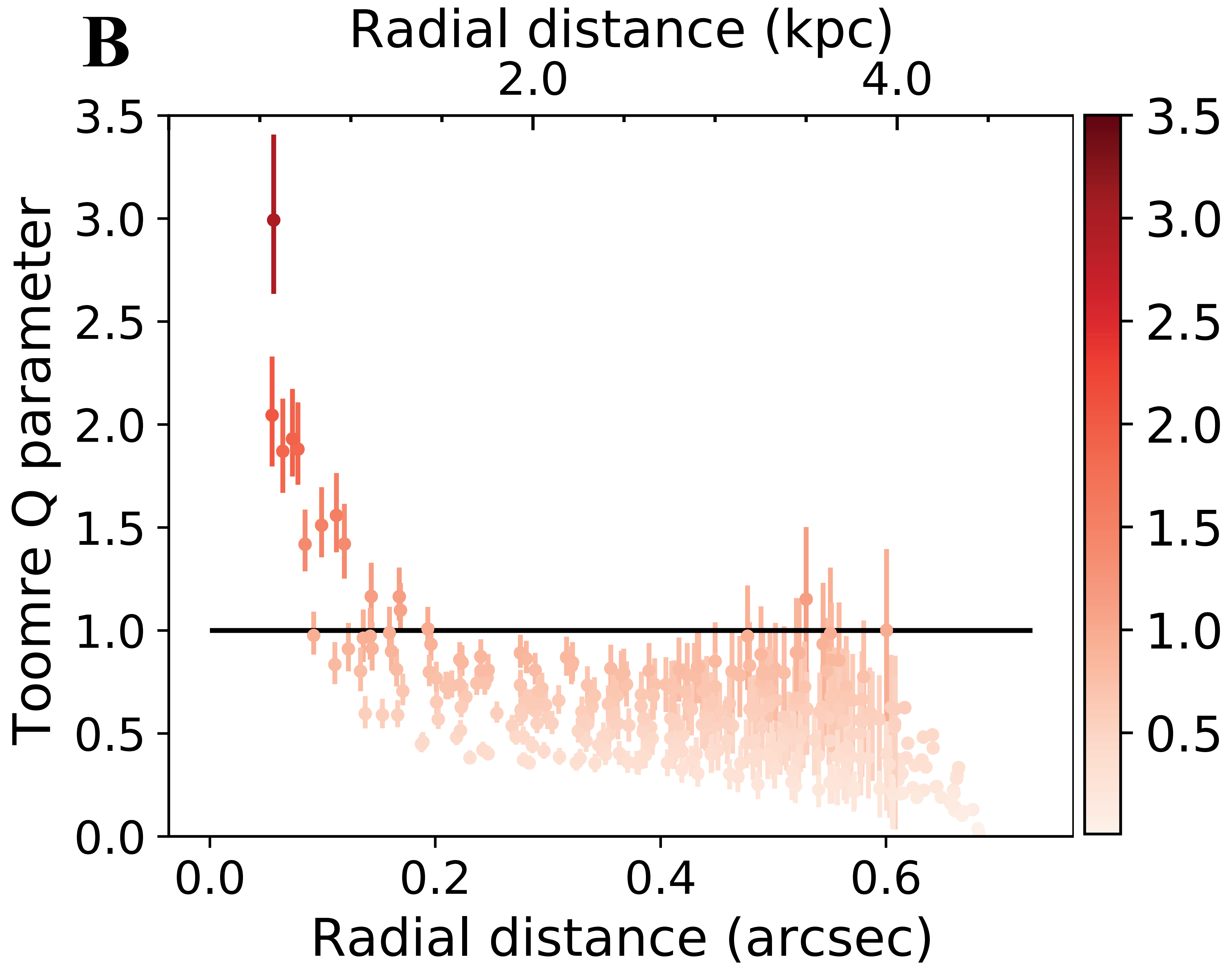
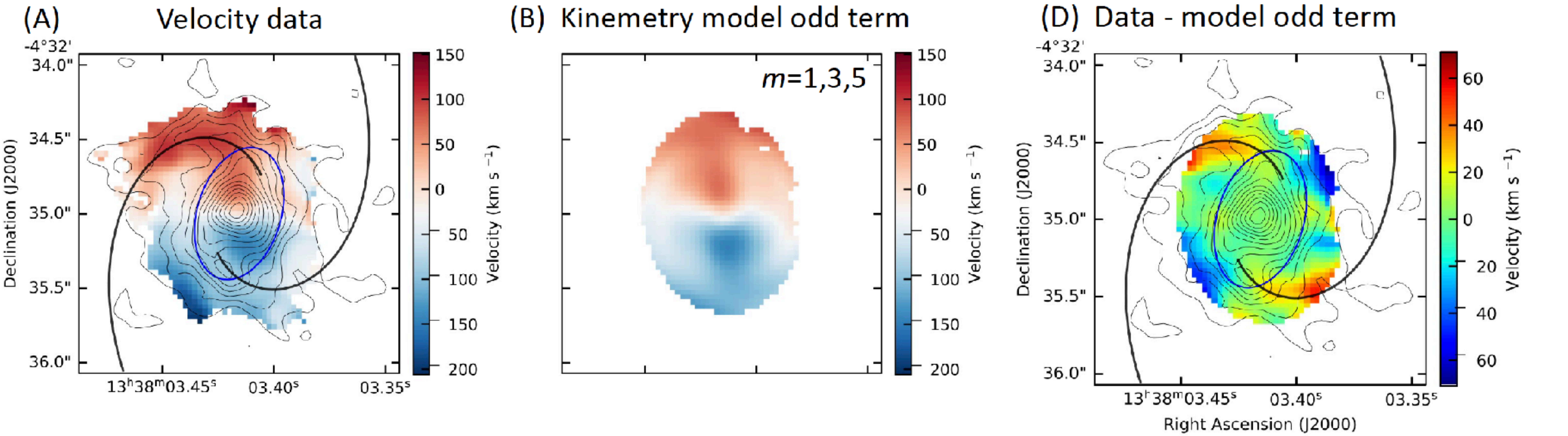


Tsukui and Iguchi +21

- Toomre Q parameterの観点から円盤全体でガス円盤は重力不安定

Higher order kinematics of [CII] emission line



対局的な回転成分を差し引くと速度残差にm=2のパターンが残った.

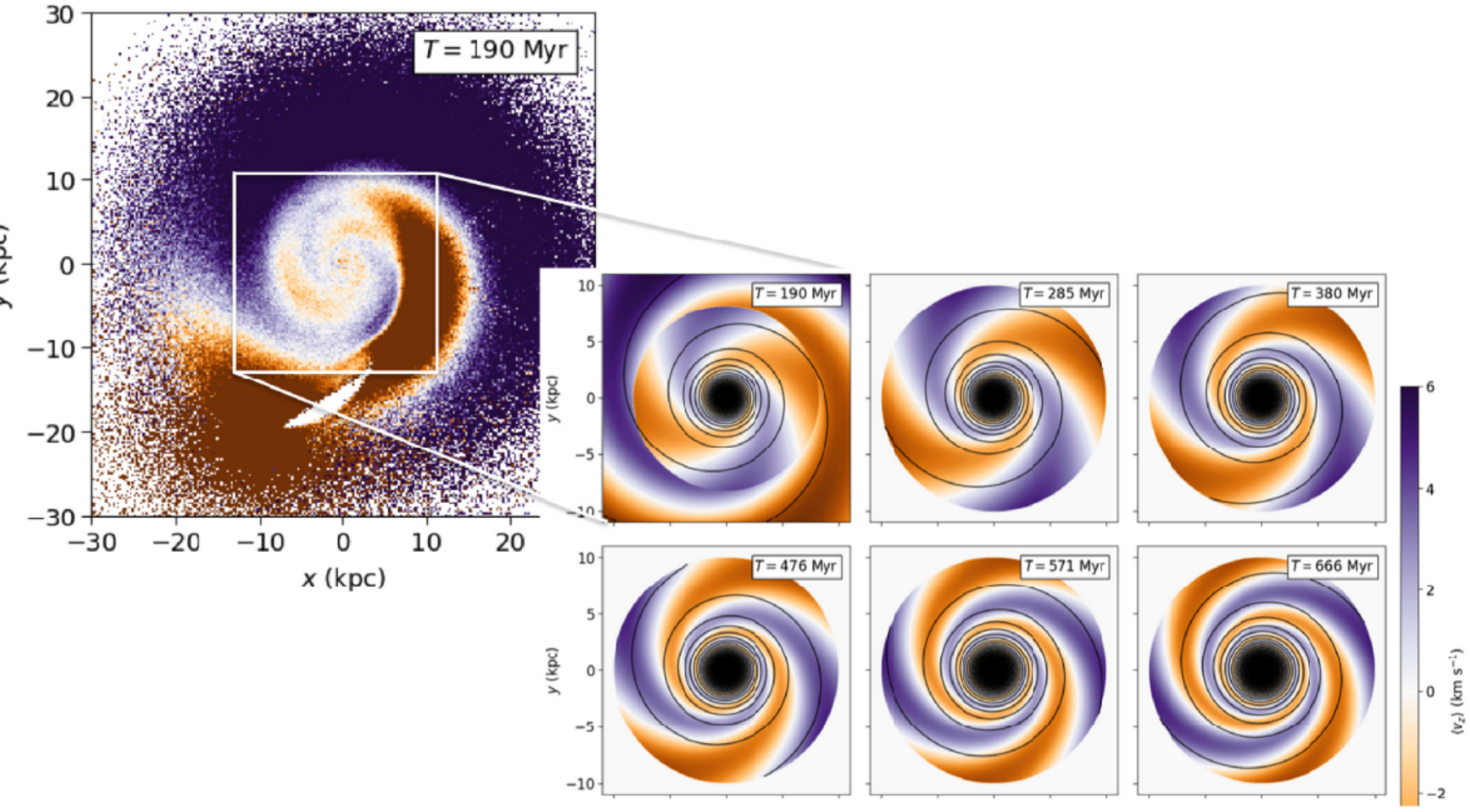
Tsukui + 2023c in press

軸対称なinflow outflowでは対称な位置に反対符号の残差が現れるはず。

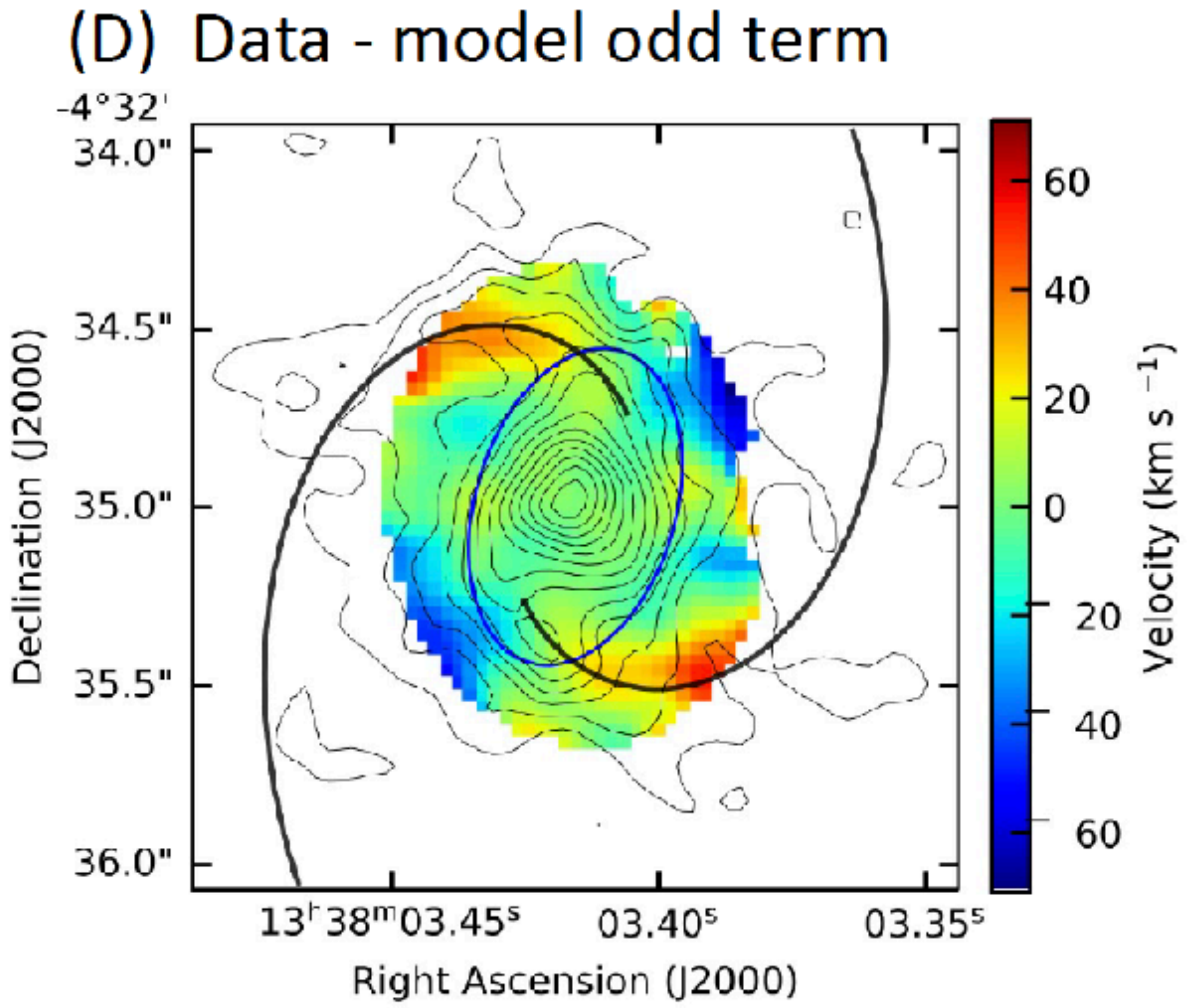
バー、渦巻き構造による非回転運動はm=1 or 3のパターンが現れる。(Schoenmakers+97).

円盤の垂直方向の振動 (disk-bending wave, U-shaped warpping)を見ている。

Disk bending mode caused by interaction/gas accretion



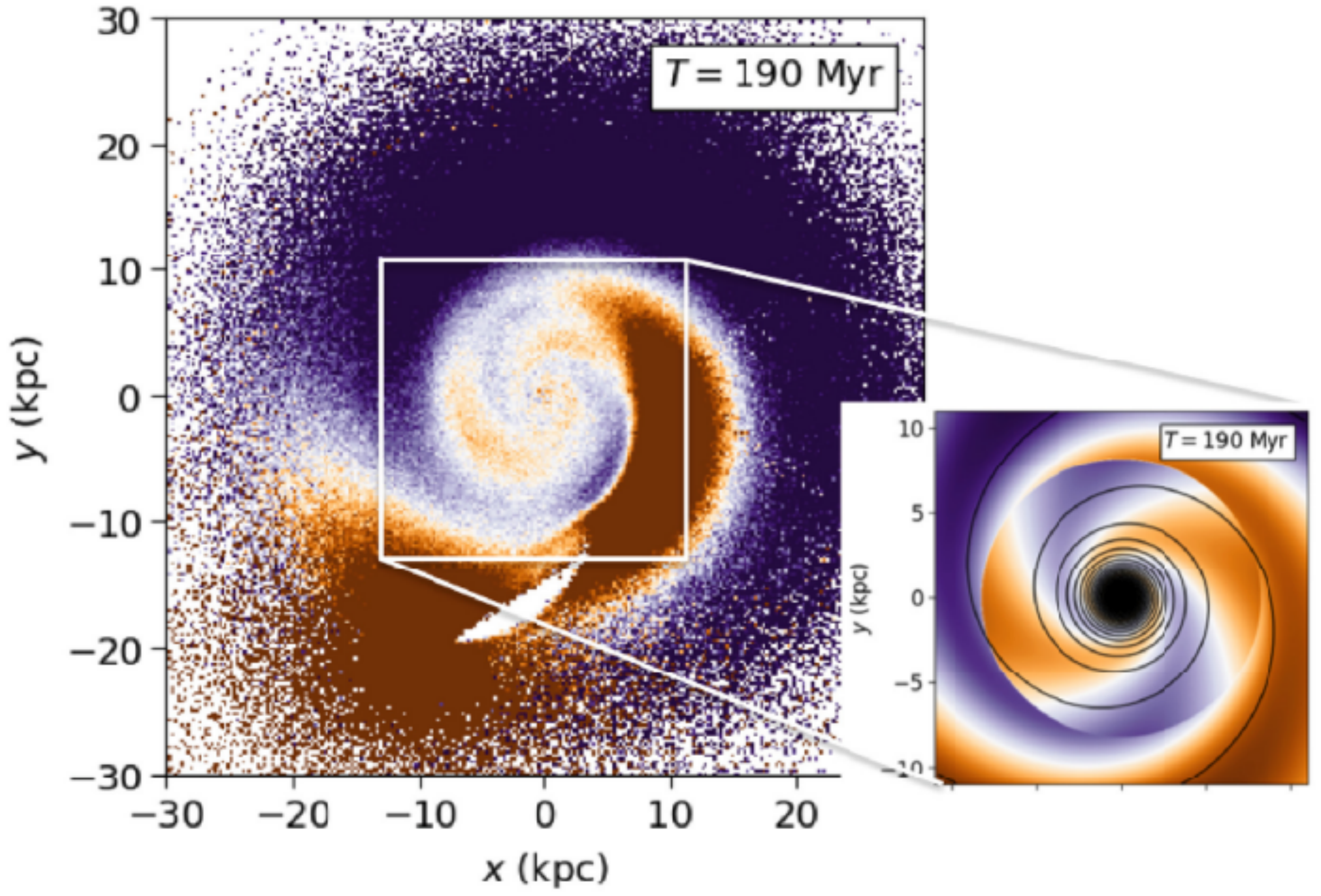
Bland-Hawthorn and Topper-Garcia+21

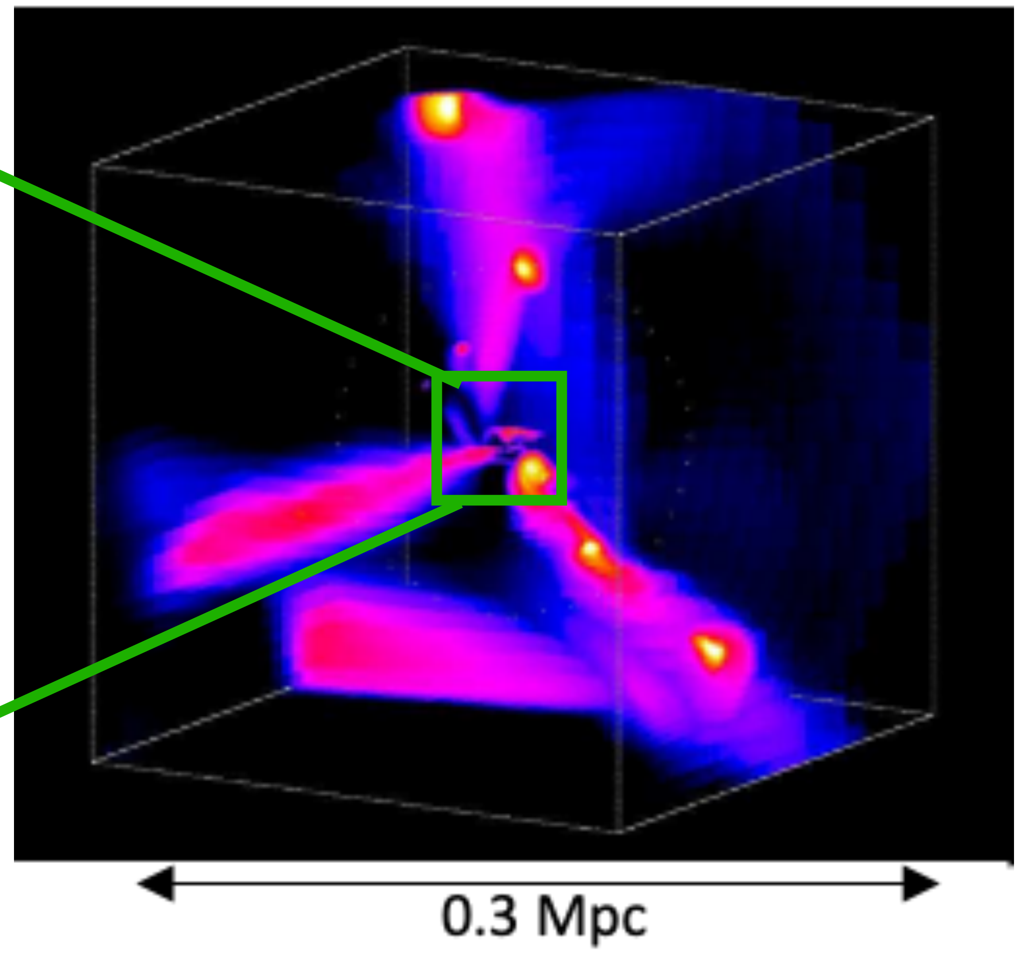


Tsukui + 2023c in press

衛星銀河やガス降着による摂動によって円盤内部にm=2の円盤振動を起動する。振動波は渦巻き腕と位置が一致する。

Galaxy transformation at z=4.4



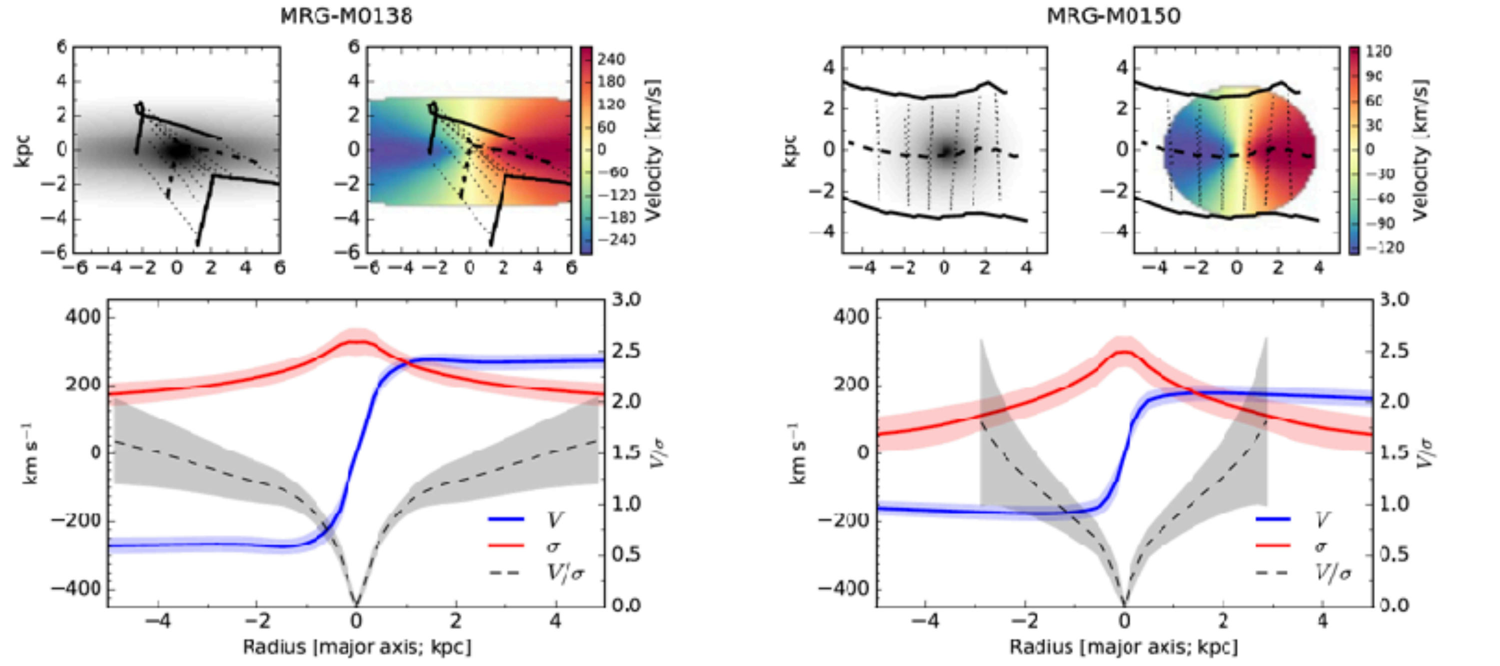


Bland-Hawthorn and Topper-Garcia+21

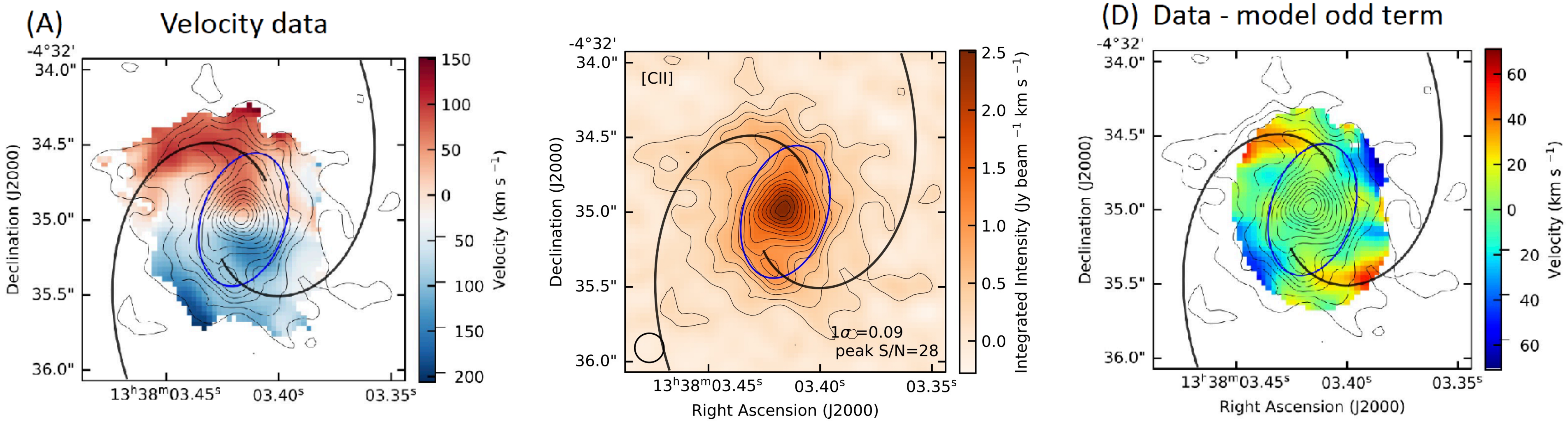
Dekel+09

Massive compact quiscent at z>2

Newman+17

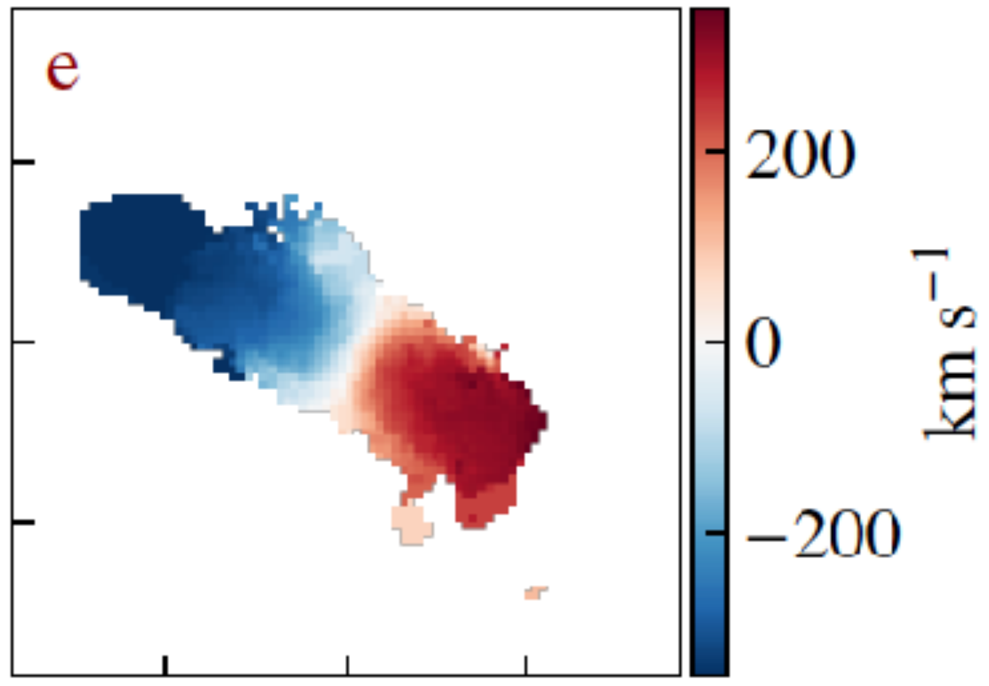


Ito+23



Cold gas/satellite accretion and mergers supply gas in the gas-rich gravitationally unstable disk, causing the seismic ripple of the disk (vertical disk bending wave) and the two-armed spiral. Gas rich disk formed star-forming gaseous bar, subsequently triggering the SF bulge (compact rotating core) and optical quasar.

Evolutionally link between two populations



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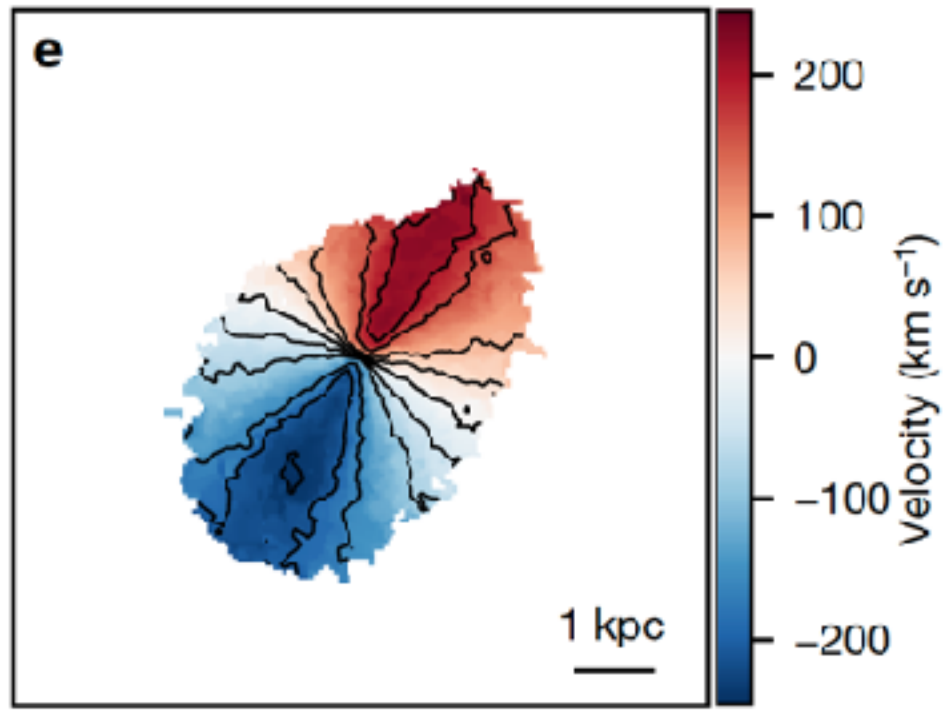

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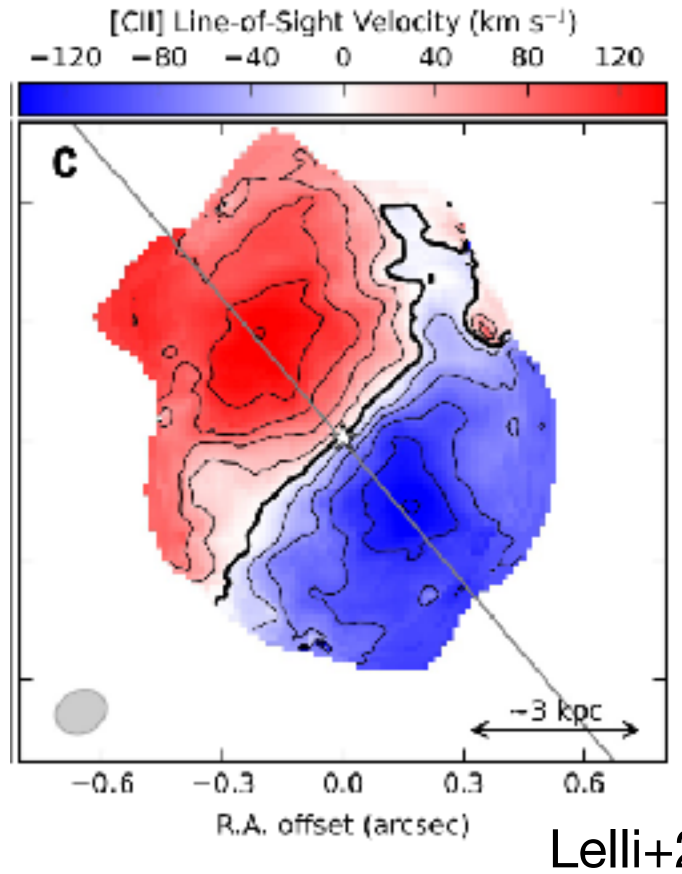

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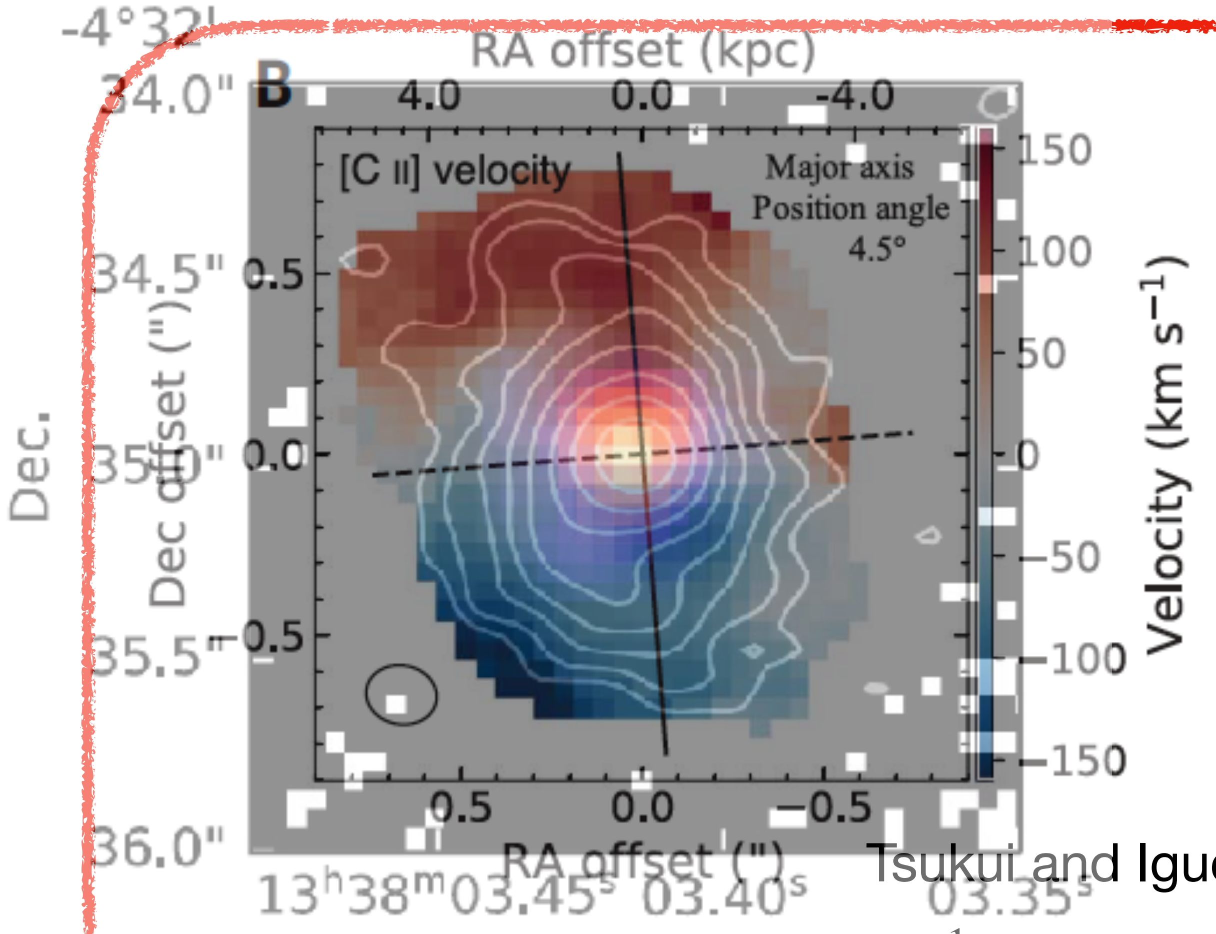

Tsukui and Iguchi 2021

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Compaction?

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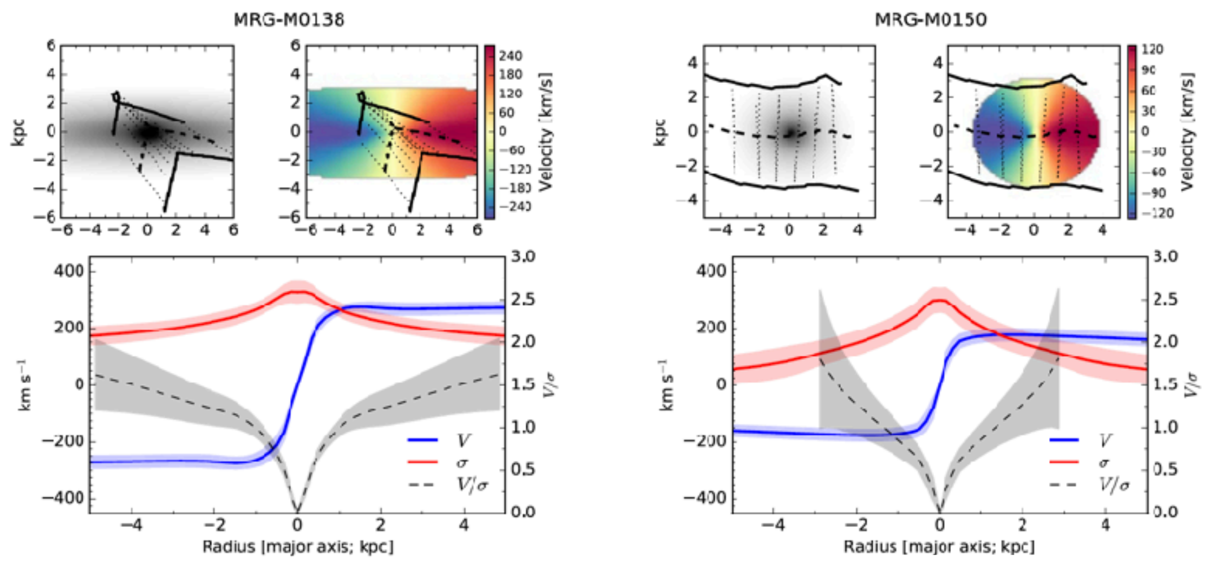

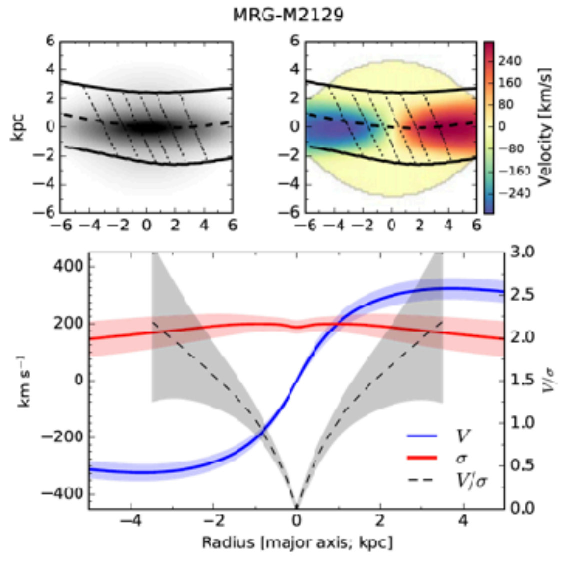

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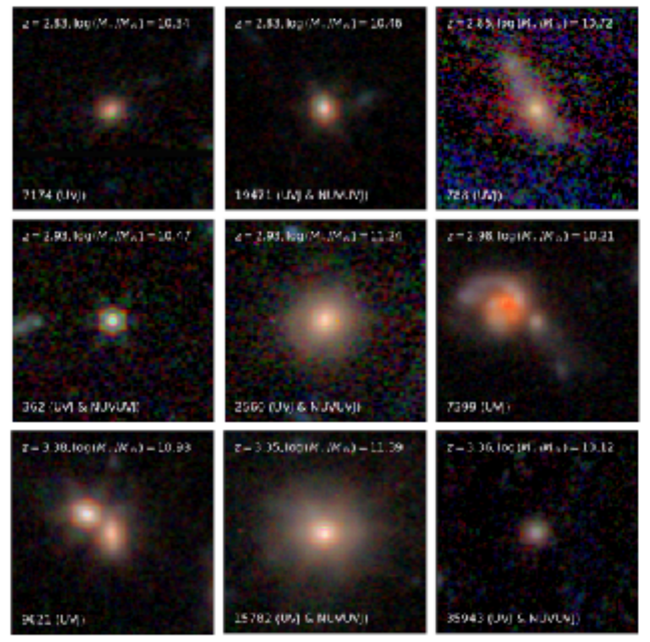

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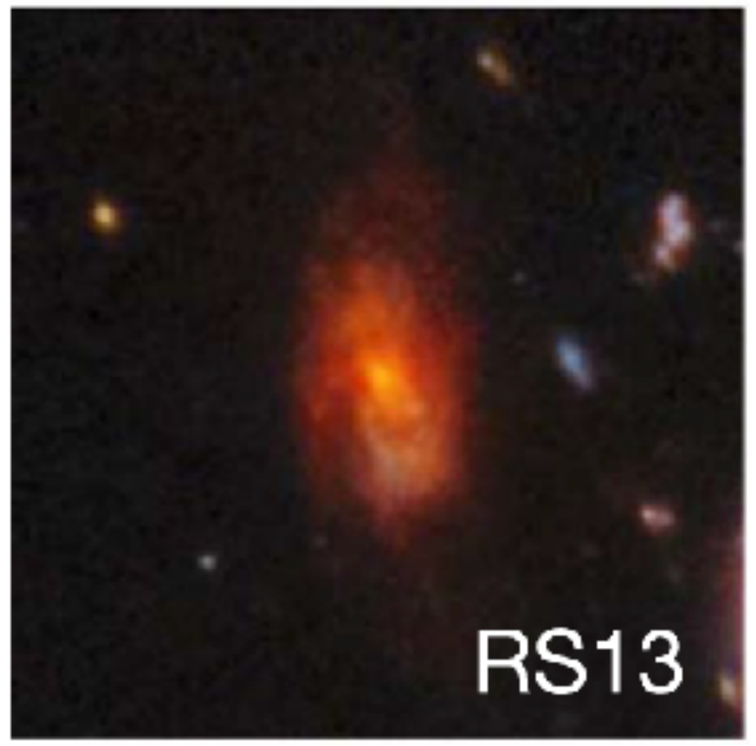
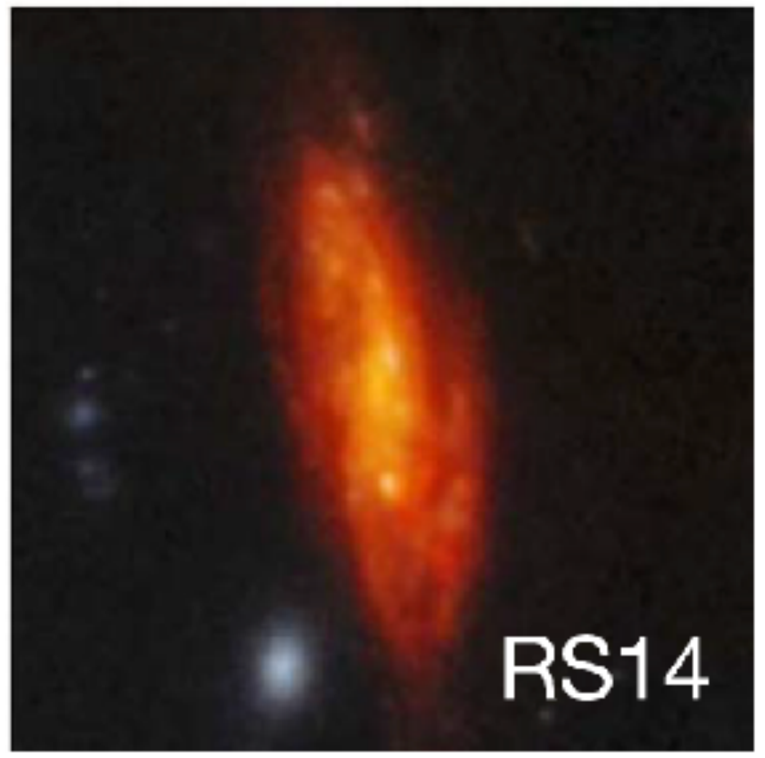
Fudamoto +2022





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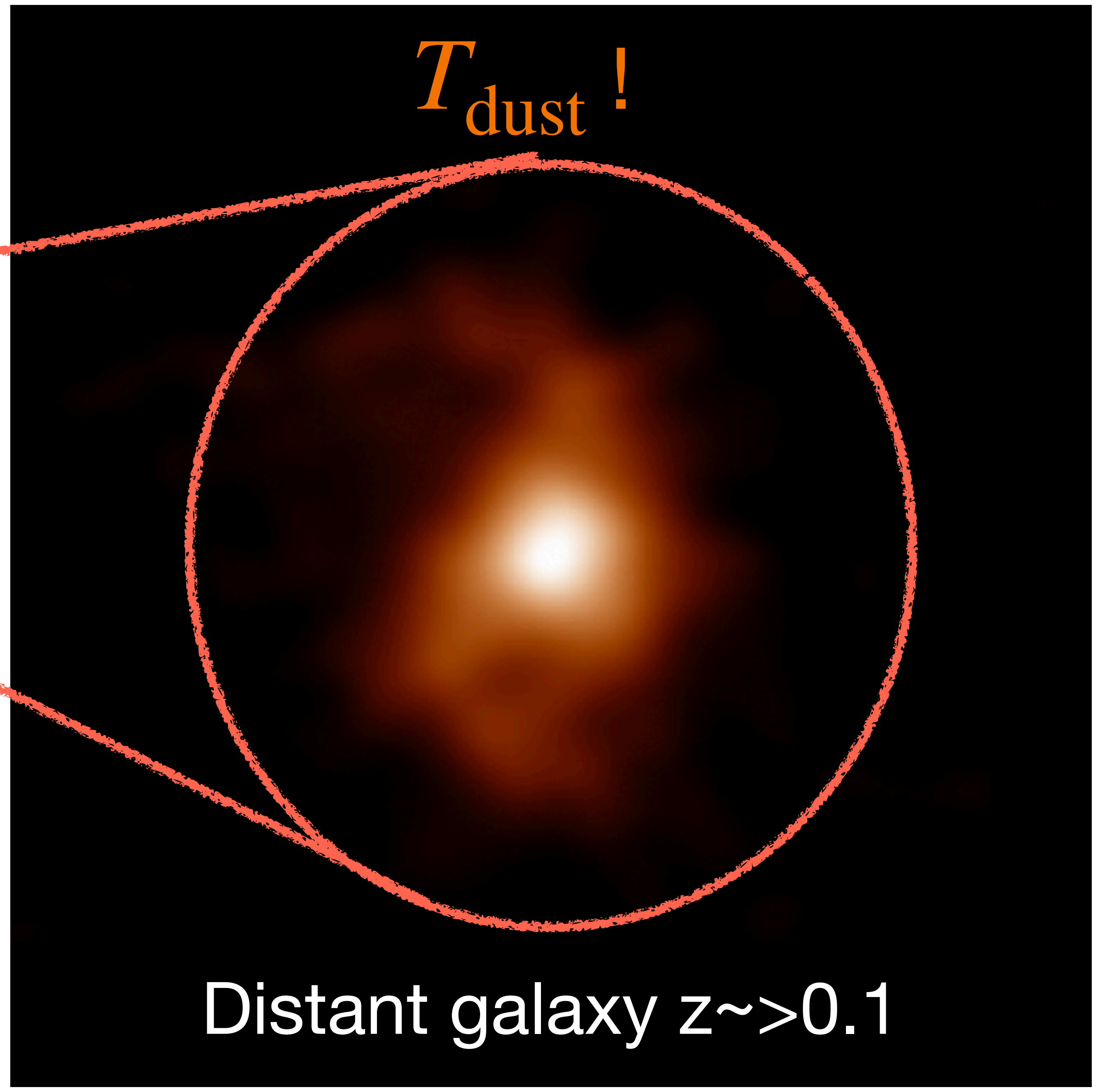
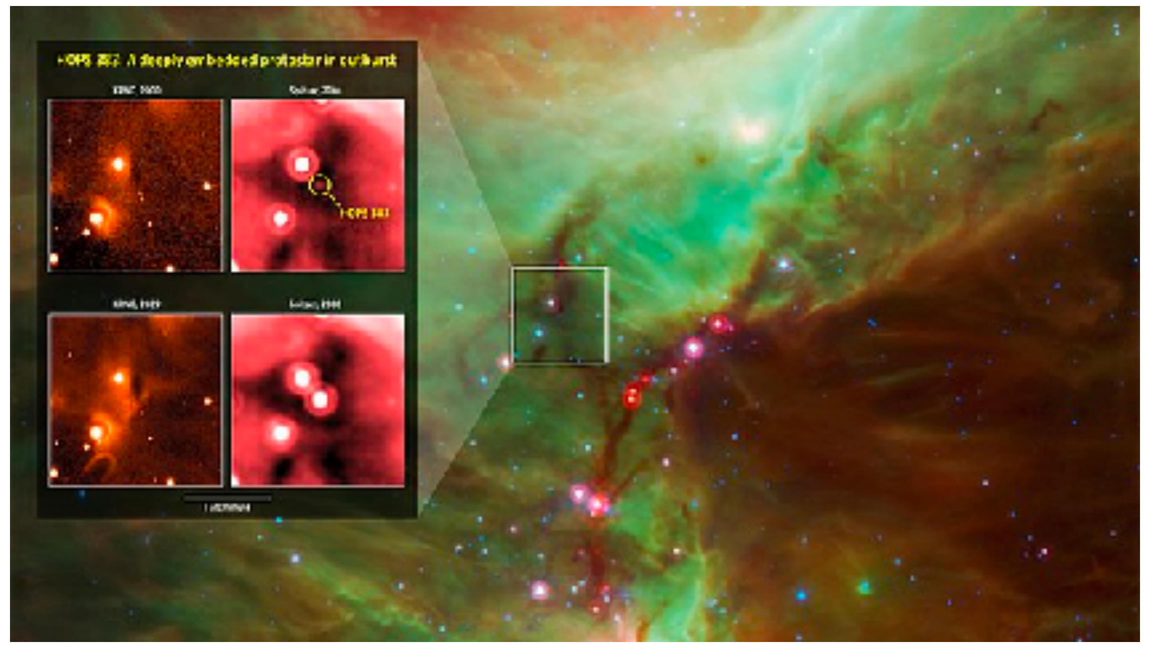
Star formation rate traced by FIR emission

- ダストが主に若い星で加熱されている。
- ダストに隠された星形成率は赤外線高度から見積もられる。 $\mathrm{SFR} \propto L_{IR} \propto T_{\mathrm{dust}}^{\sim 6}$

Herschel / Spitzer etc.



UV light

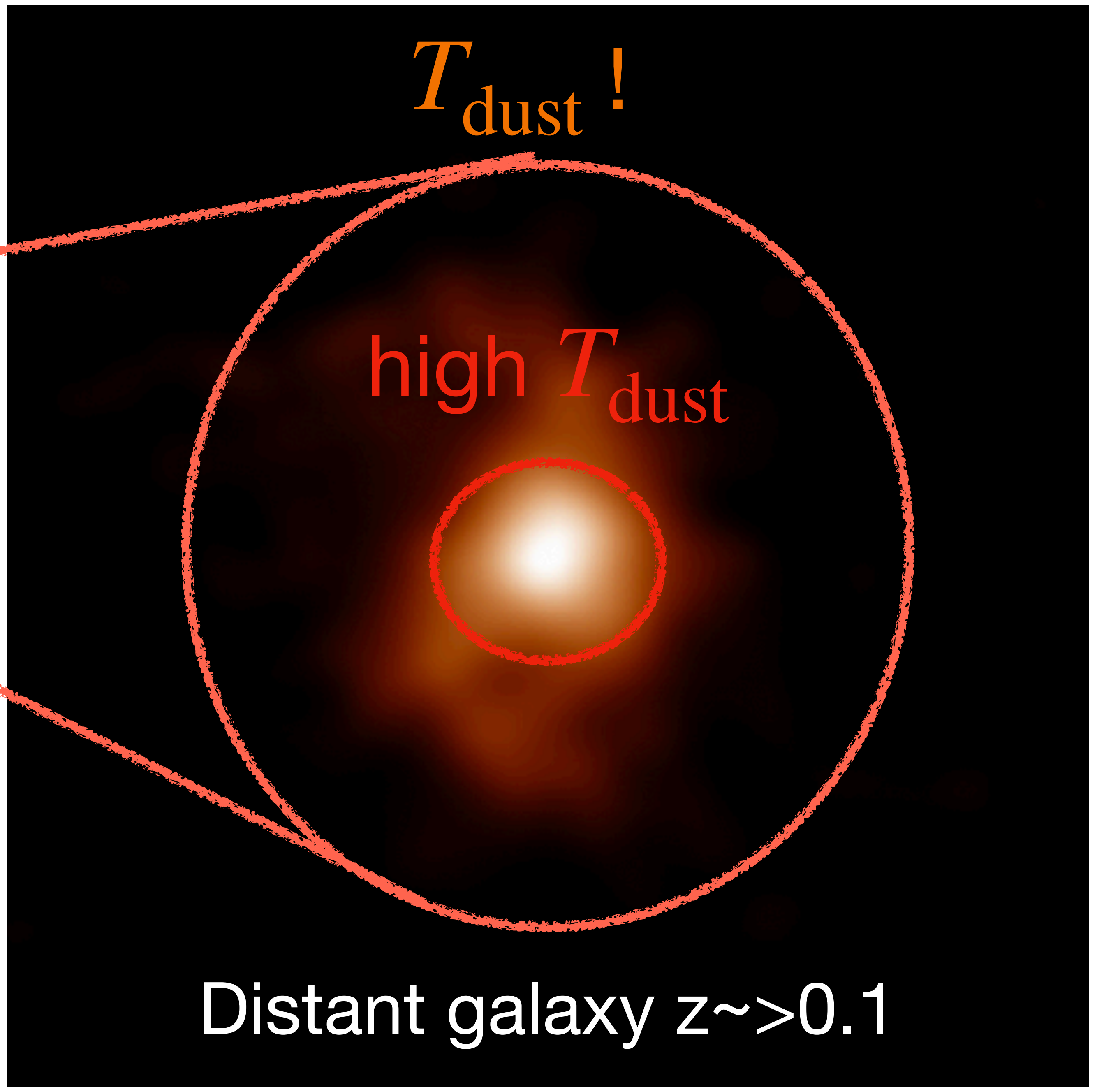


Young massive stars

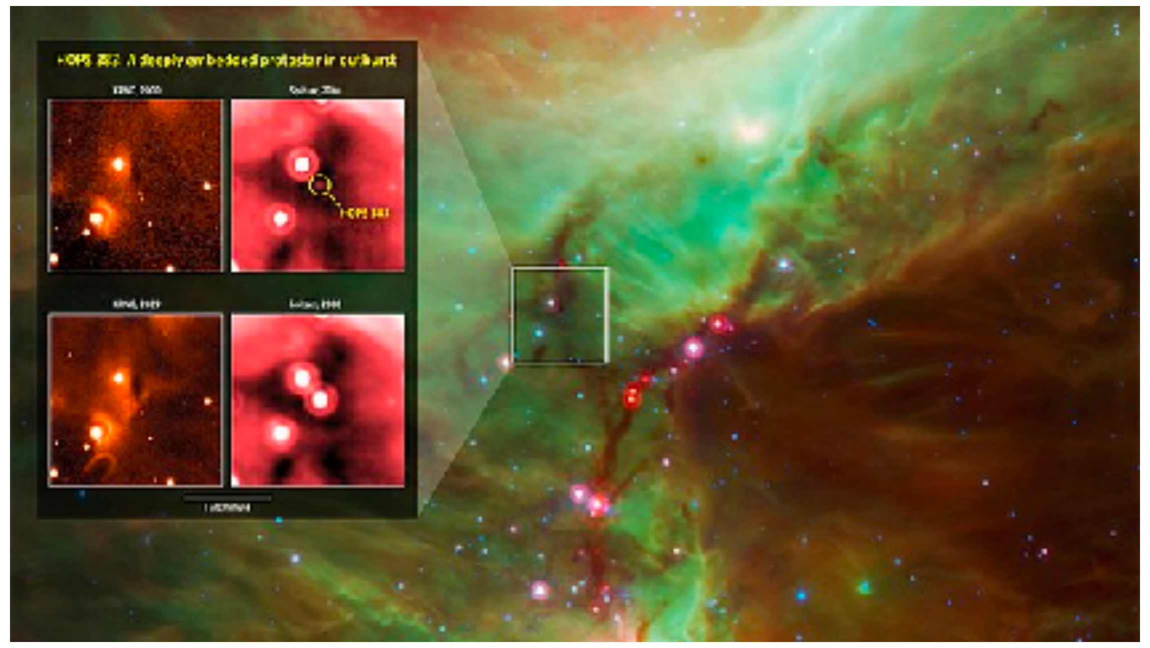
Star formation rate traced by FIR emission

- ダストが主に若い星で加熱されている。
- ダストに隠された星形成率は赤外線高度から見積もられる。 $\mathrm{SFR} \propto L_{IR} \propto T_{\mathrm{dust}}^{\sim 6}$

Herschel / Spitzer etc.



UV light

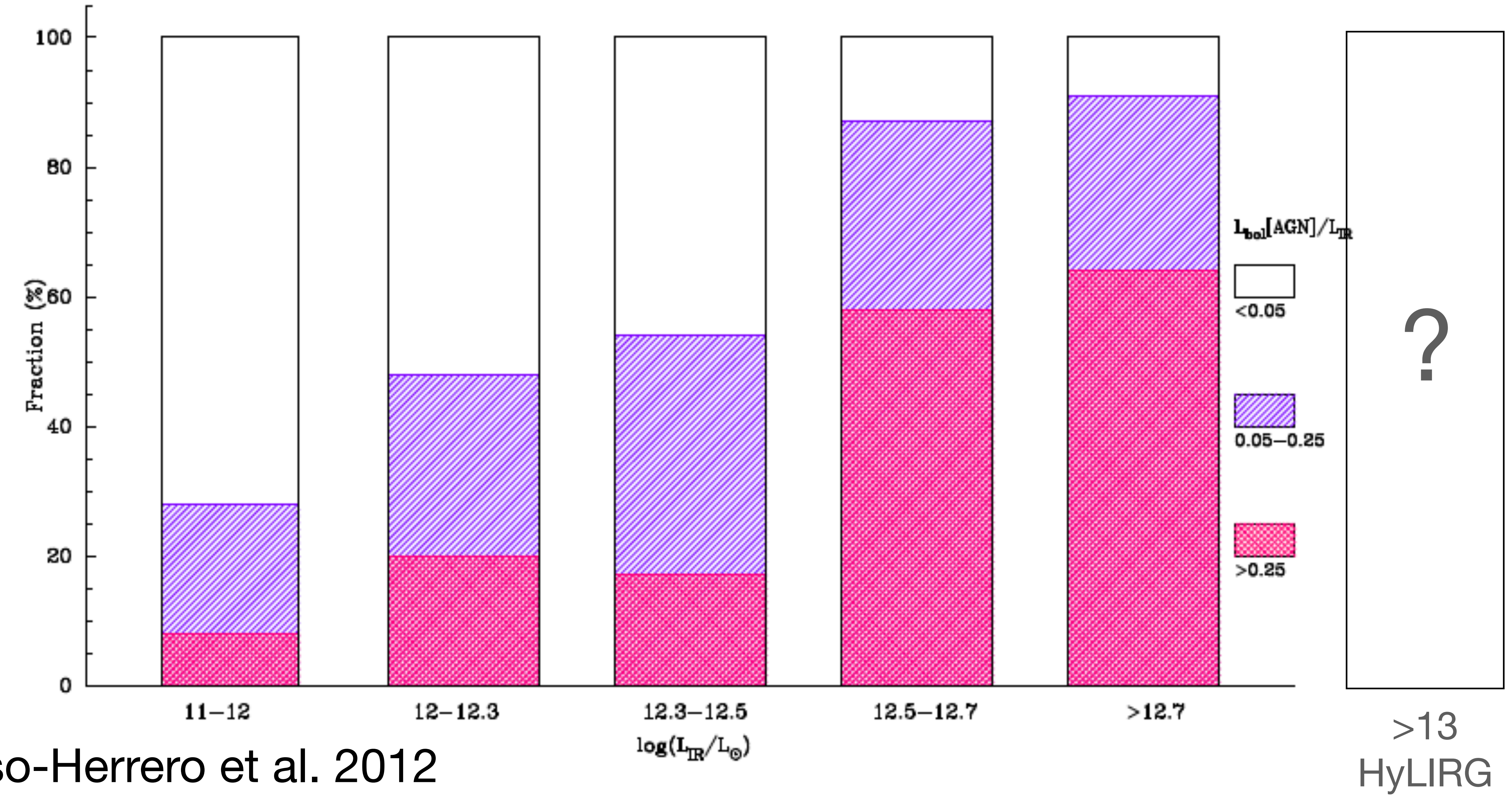


Young massive stars

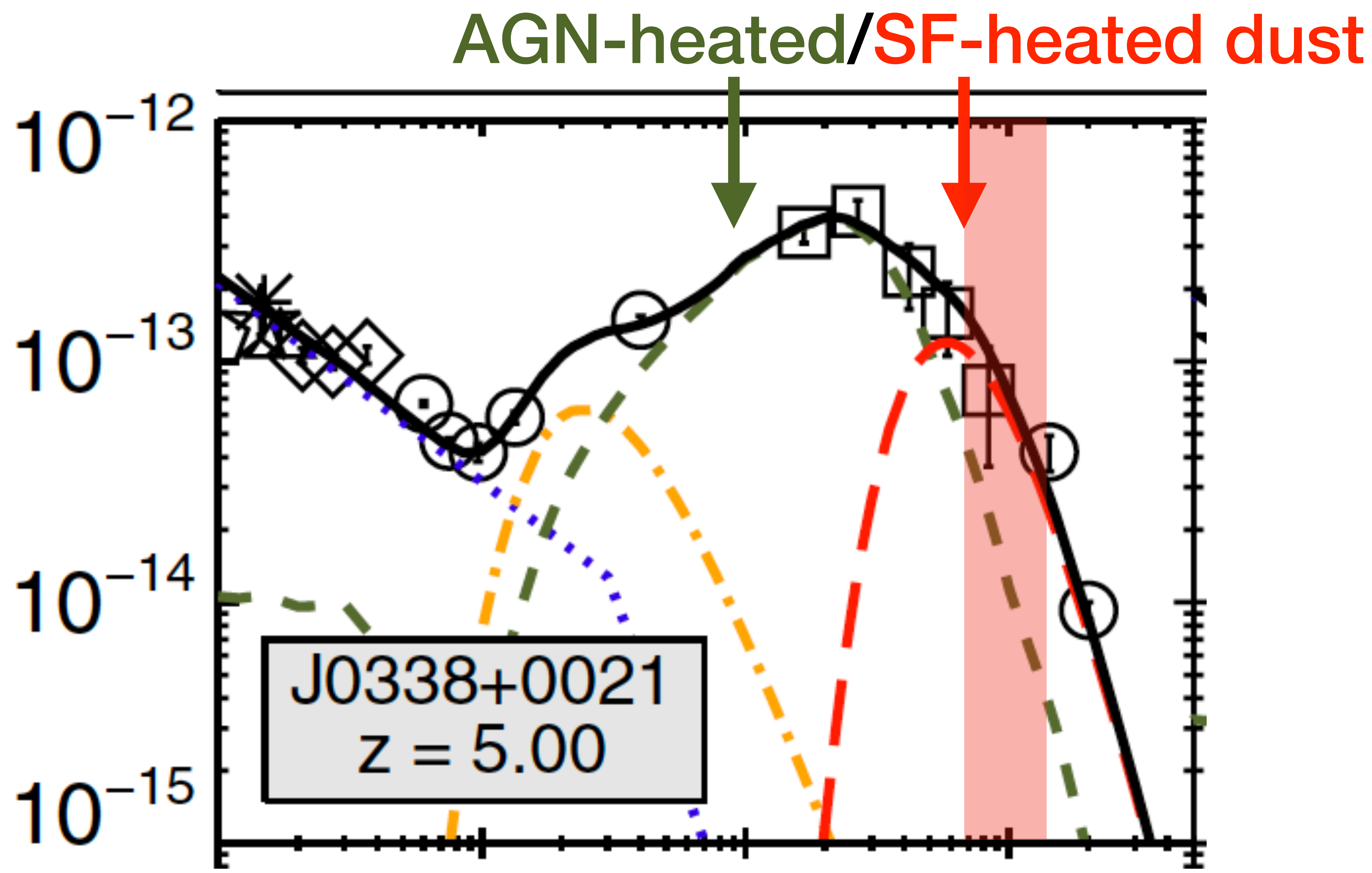
AGN

How much can AGN contribute to IR luminosity?

- 赤外光度が大きくなるほどAGNの赤外線光度に対する寄与は大きくなる(e.g., Alonso-Herrero+12 BPT/MIR spec diagnostics) up to ~100% for the bright source ($L_{\rm IR}$>$10^{13}L_{\odot}$)?(Symeonidis+21)
- AGNと星形成の分離は銀河全体の(空間分解していない)SEDによって行われてきた。
  -> 仮定したテンプレートに依存する。(MIR: AGN torus model etc.).
- 遠赤外線波長 (>~100μm), AGNの寄与は無視できるとされてきた。が、、



Alonso-Herrero et al. 2012



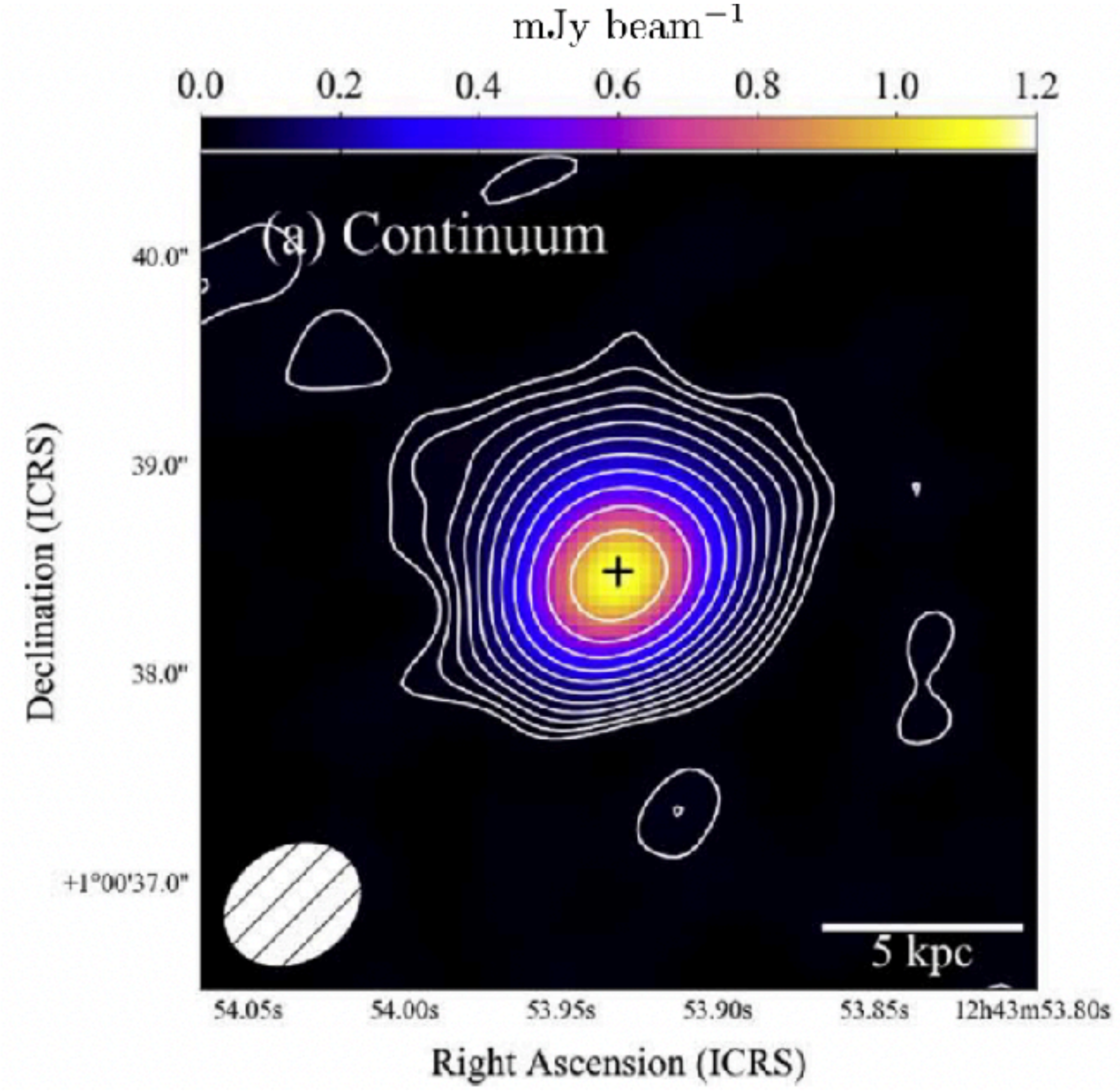
Leipski et al. 2014

AGN contribution in spatially resolved FIR image?

- 近年の高分解能ALMA dataは遠赤外線画像へのAGN寄与を示す。

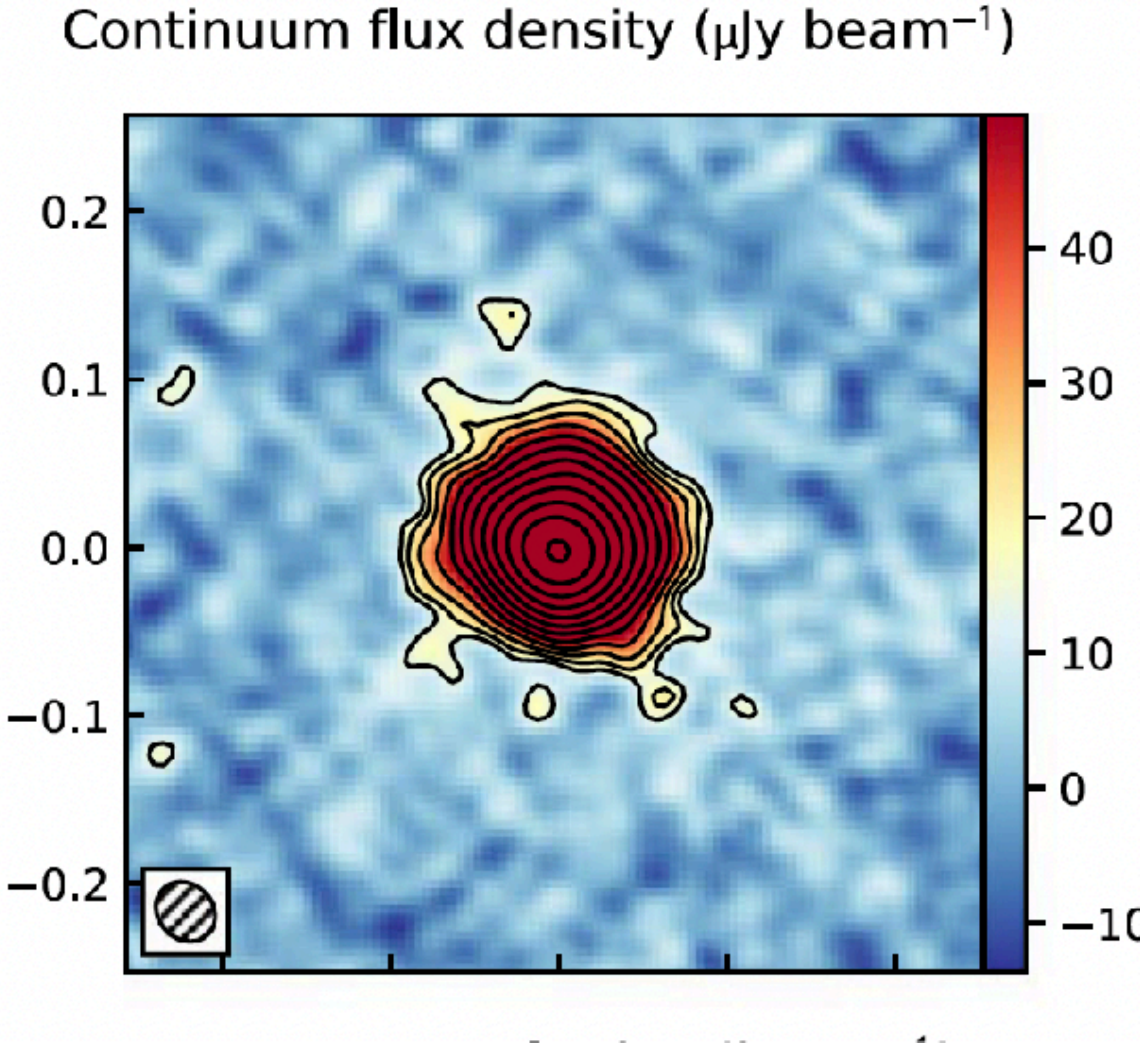
J1243 z=7 3.6kpc resolution (Izumi+21)

compact structure r<<1.54kpc
57% flux



J2348 z=7 200pc resolution (Walter+22)

$T_{\rm dust}$~>200K ?
SFR=970$M_{\odot}{\rm yr}^{-1}$ within r<110 pc?

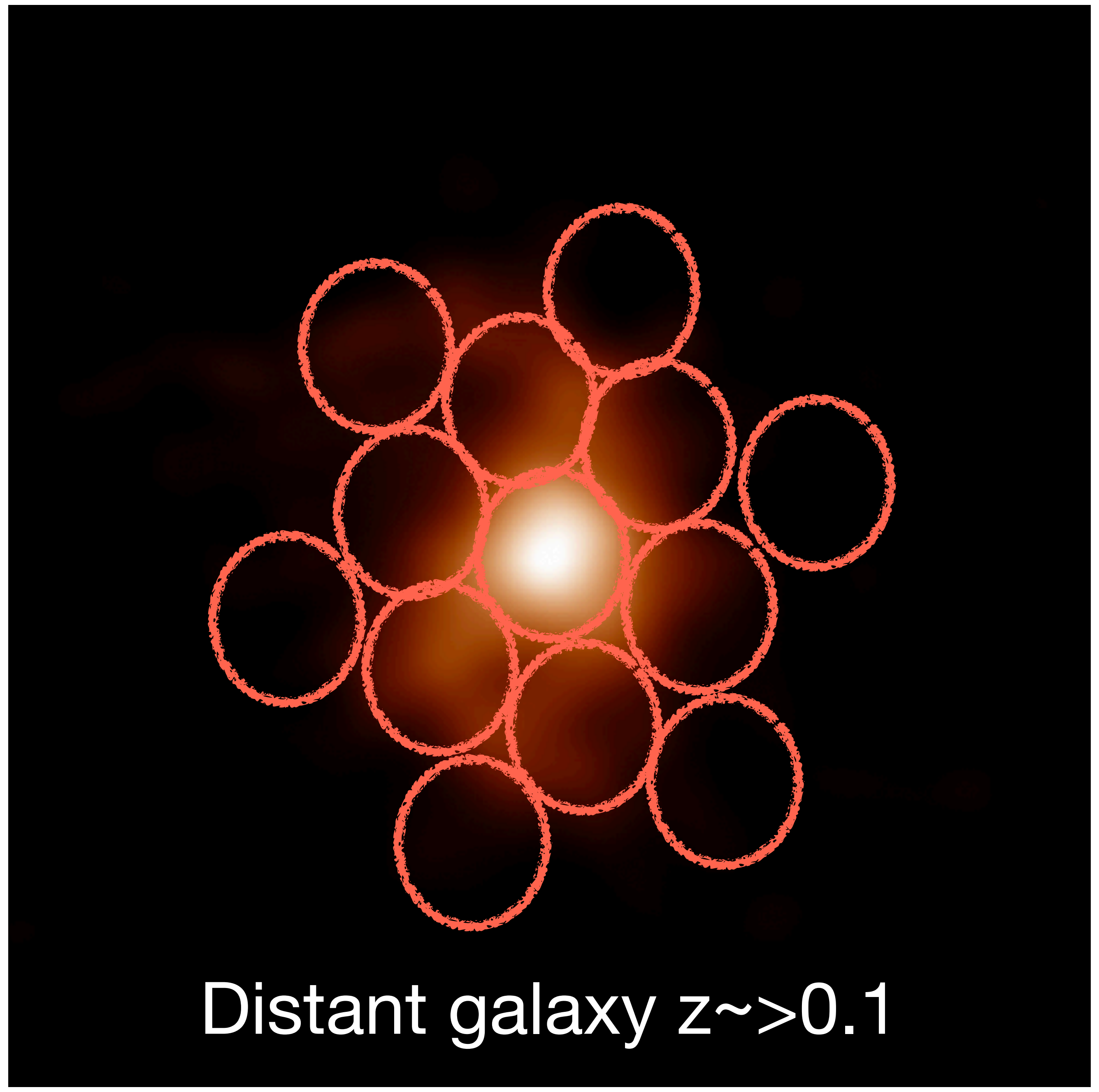


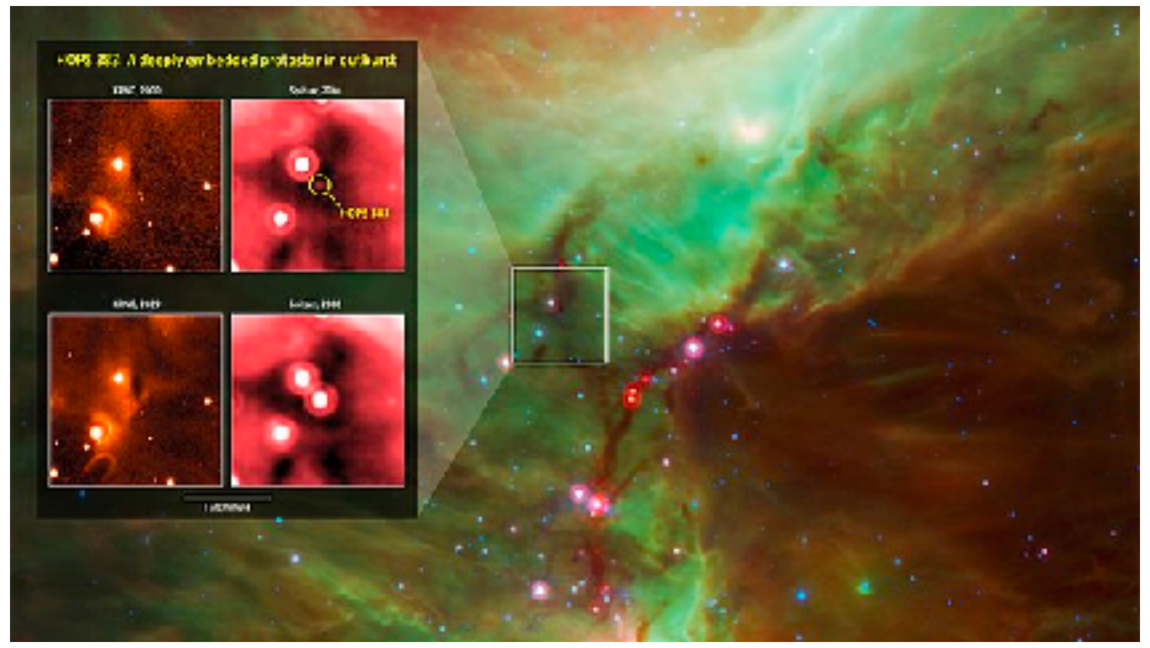
- 1バンド観測のためダストの性質(温度、光学的厚み)に制限をつけることができない。

Star formation rate traced by FIR emission

- 空間分解してダスト温度を測定し、AGNの可能性を検証し、より正確な星形成率の把握を目指す。

ALMA observation



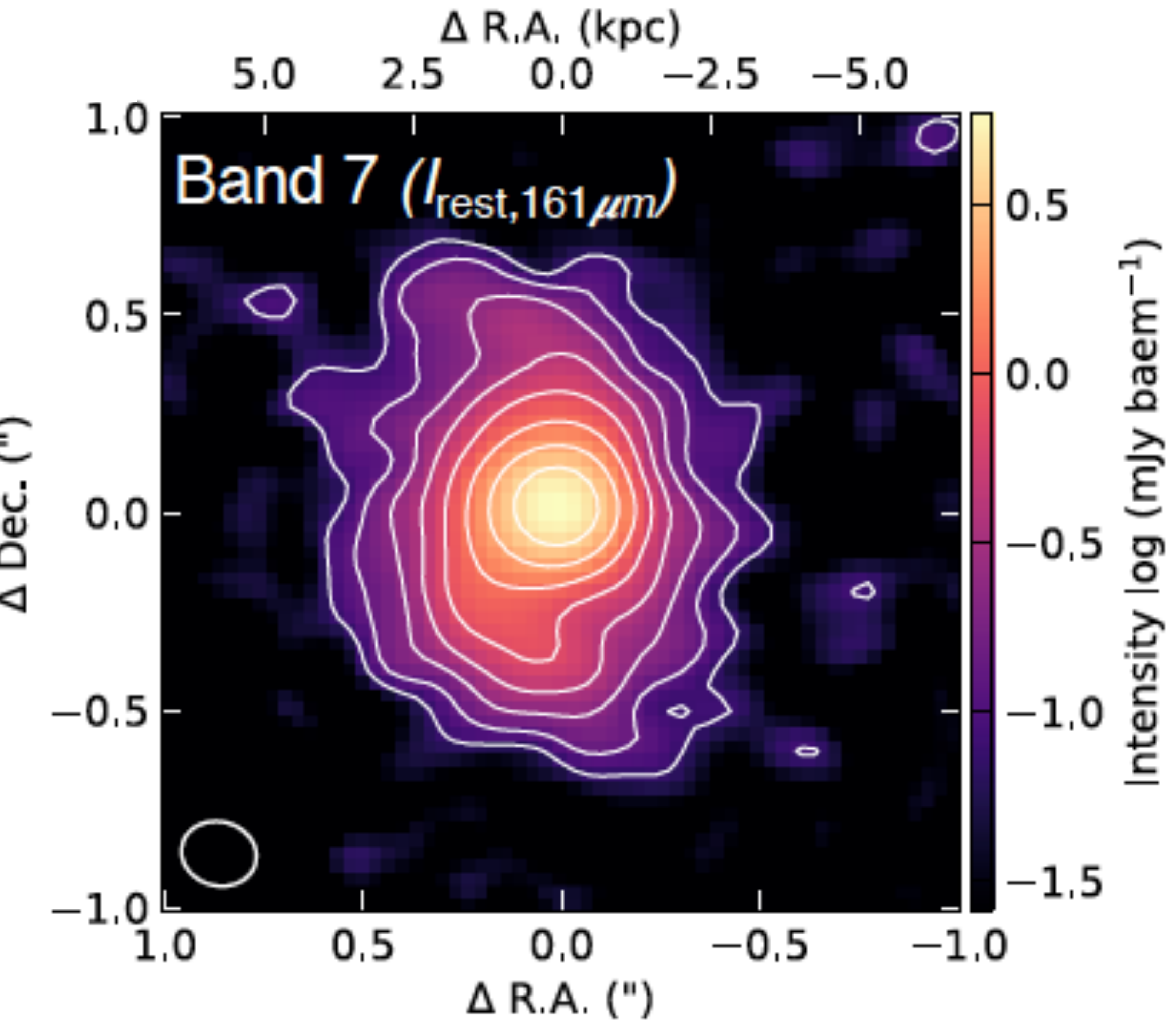


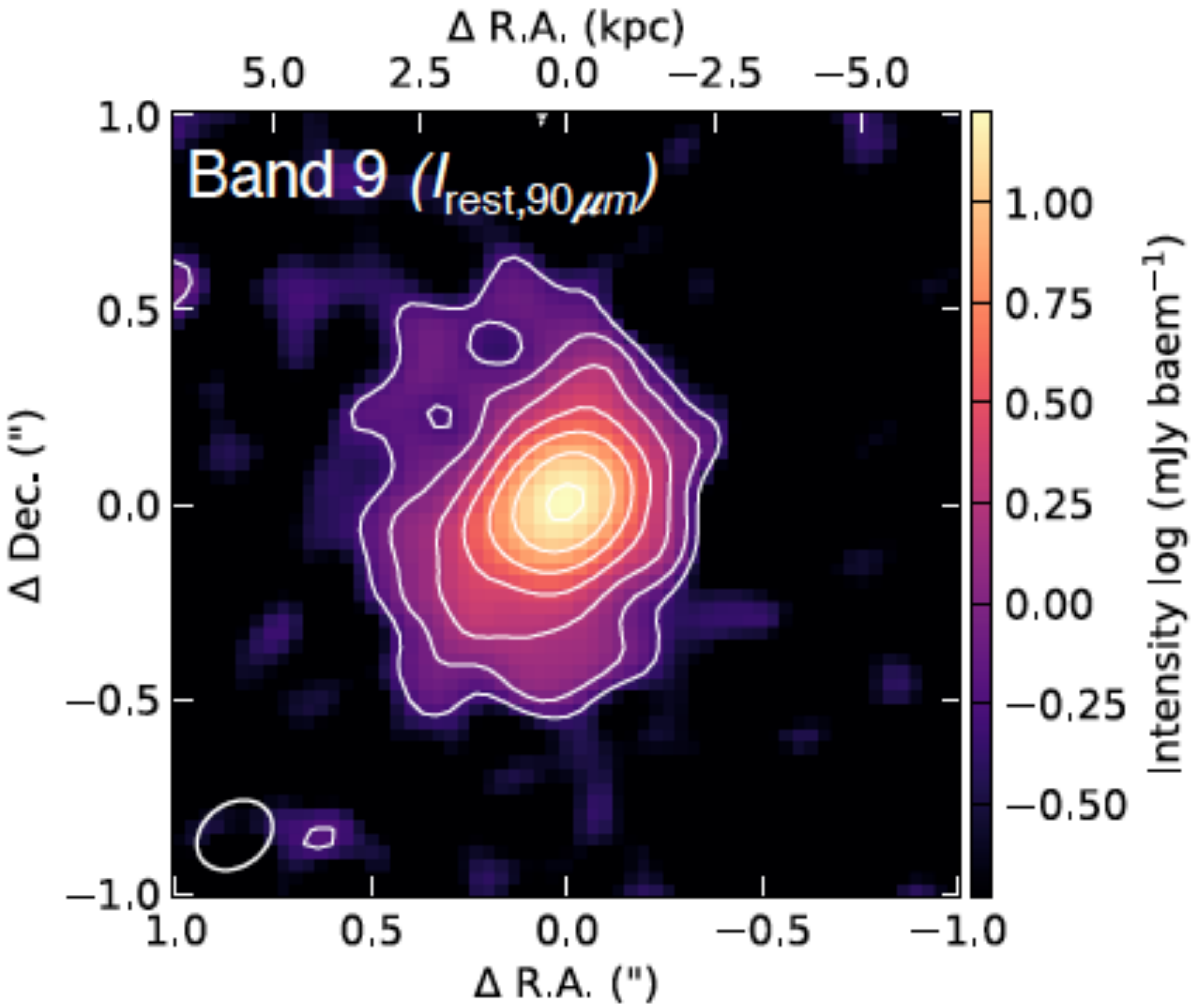
Young massive stars

AGN

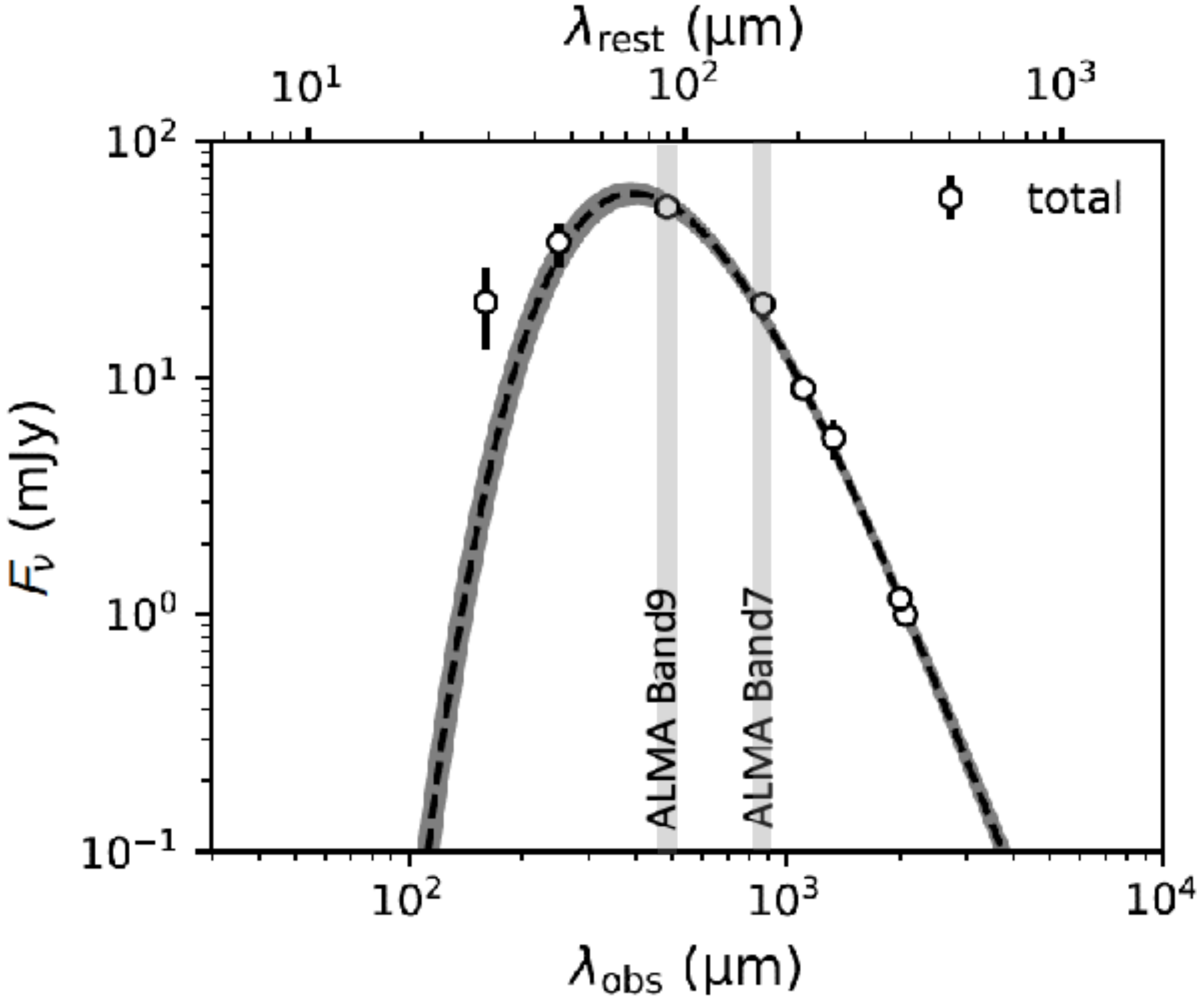
Energetics of the disk interstellar medium

- Rest $161\mu m$ and $90\mu m$ はcoldダストのピークSEDに近い (~40K), フラックス比が温度の制限をつけられる (see also Shao et al. 2022).



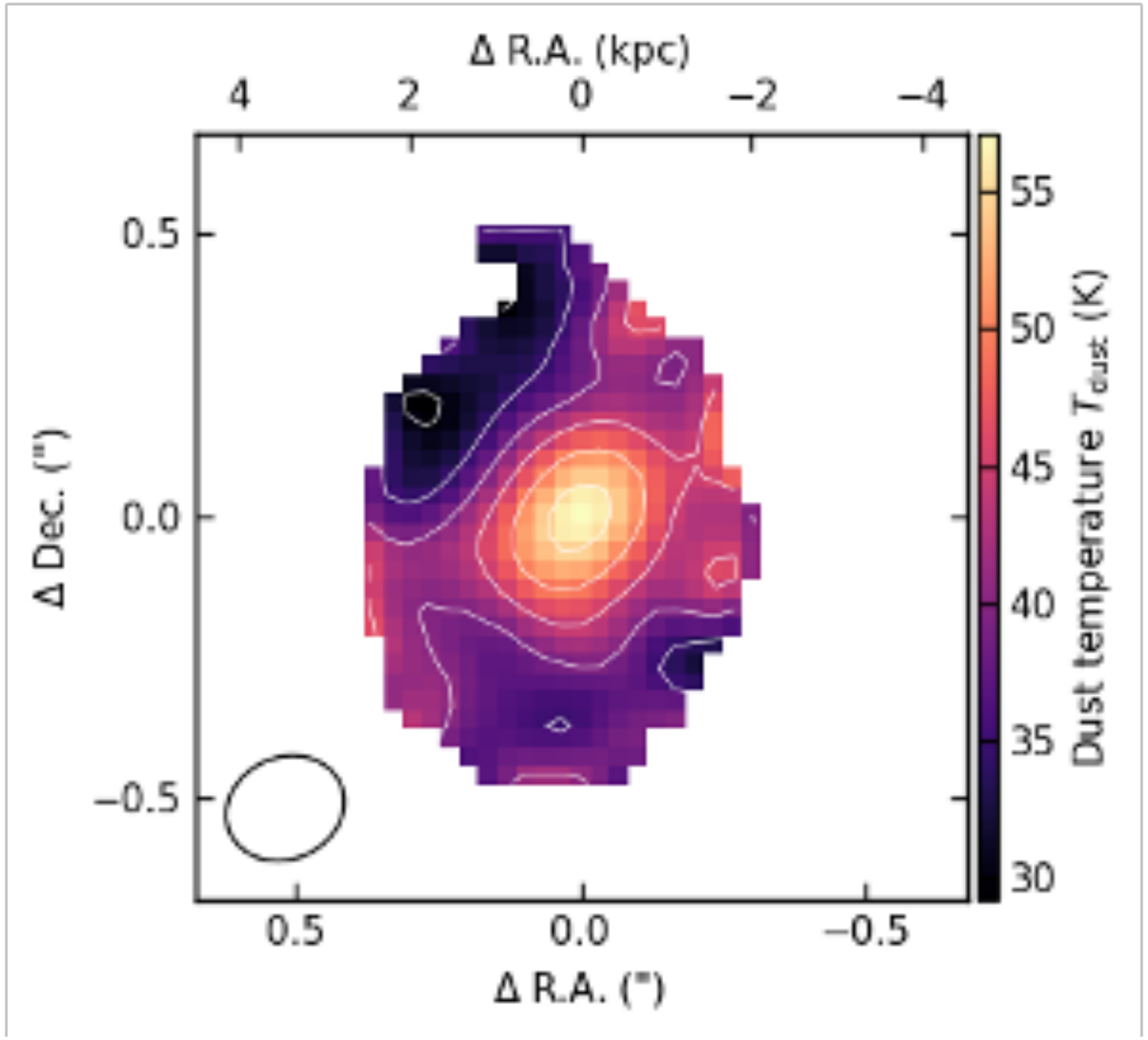


Whole galaxy's SED

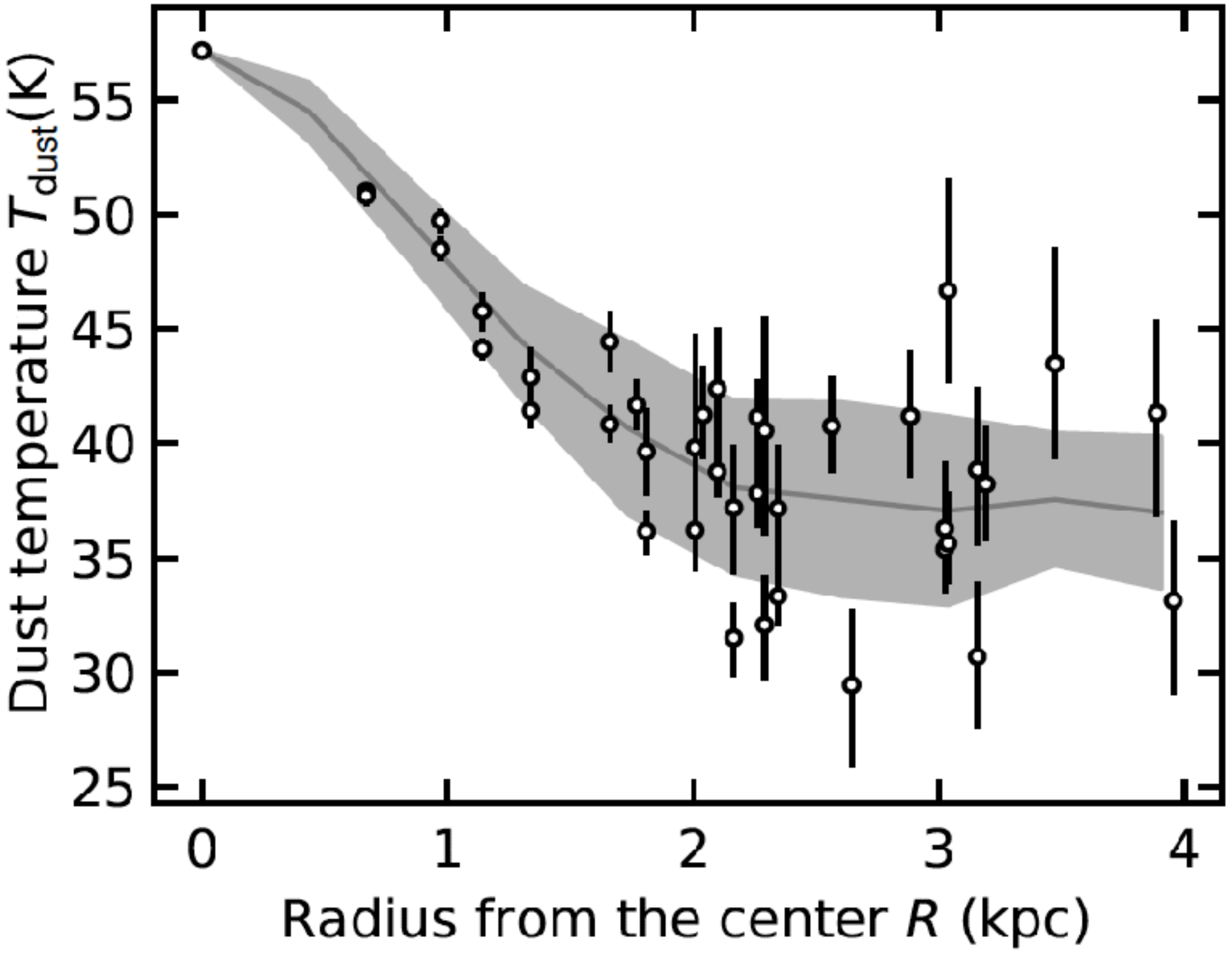


Tsukui + 2023b, MNRAS

Energetics of the disk interstellar medium



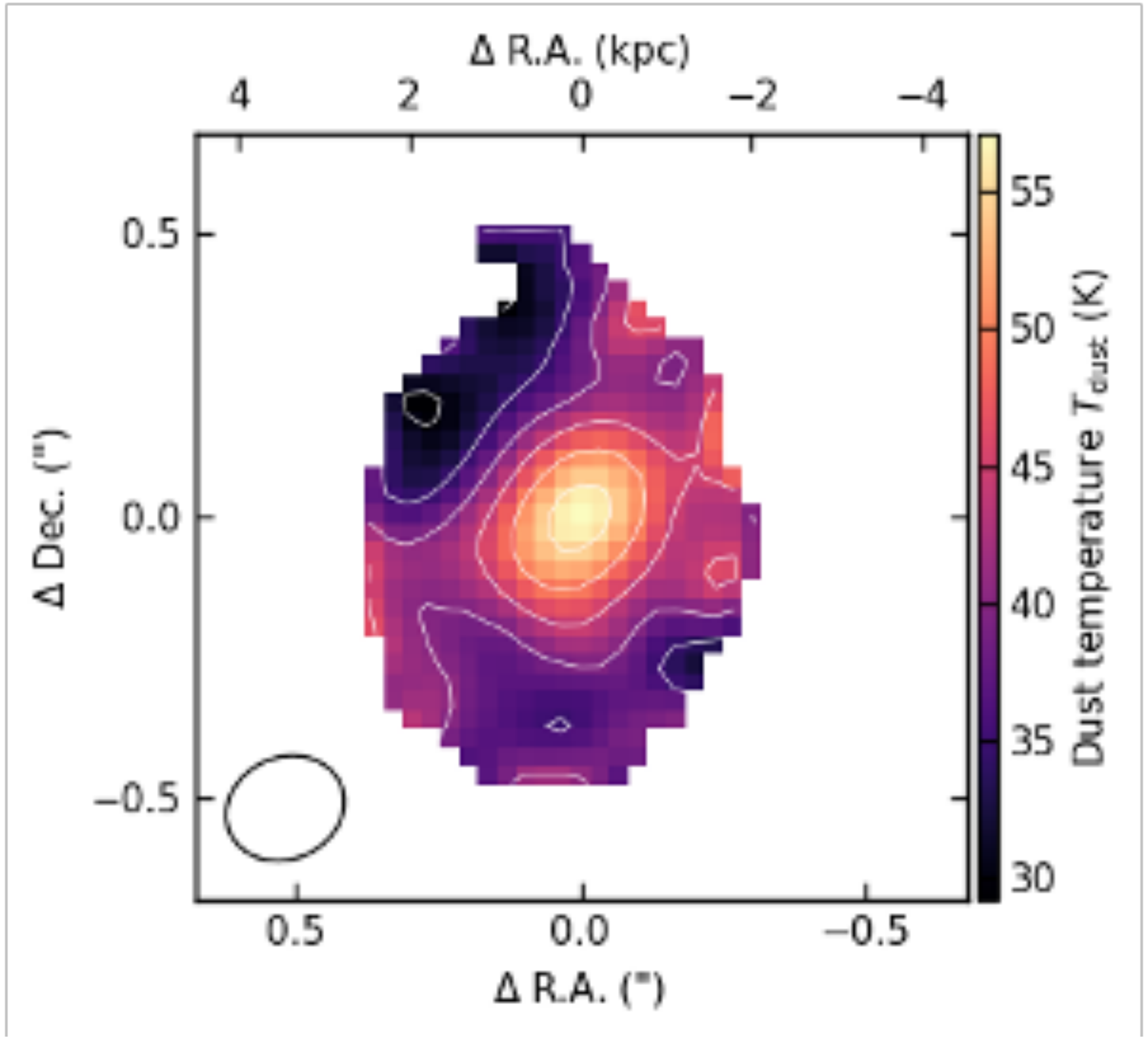
Tsukui + 2023b, MNRAS

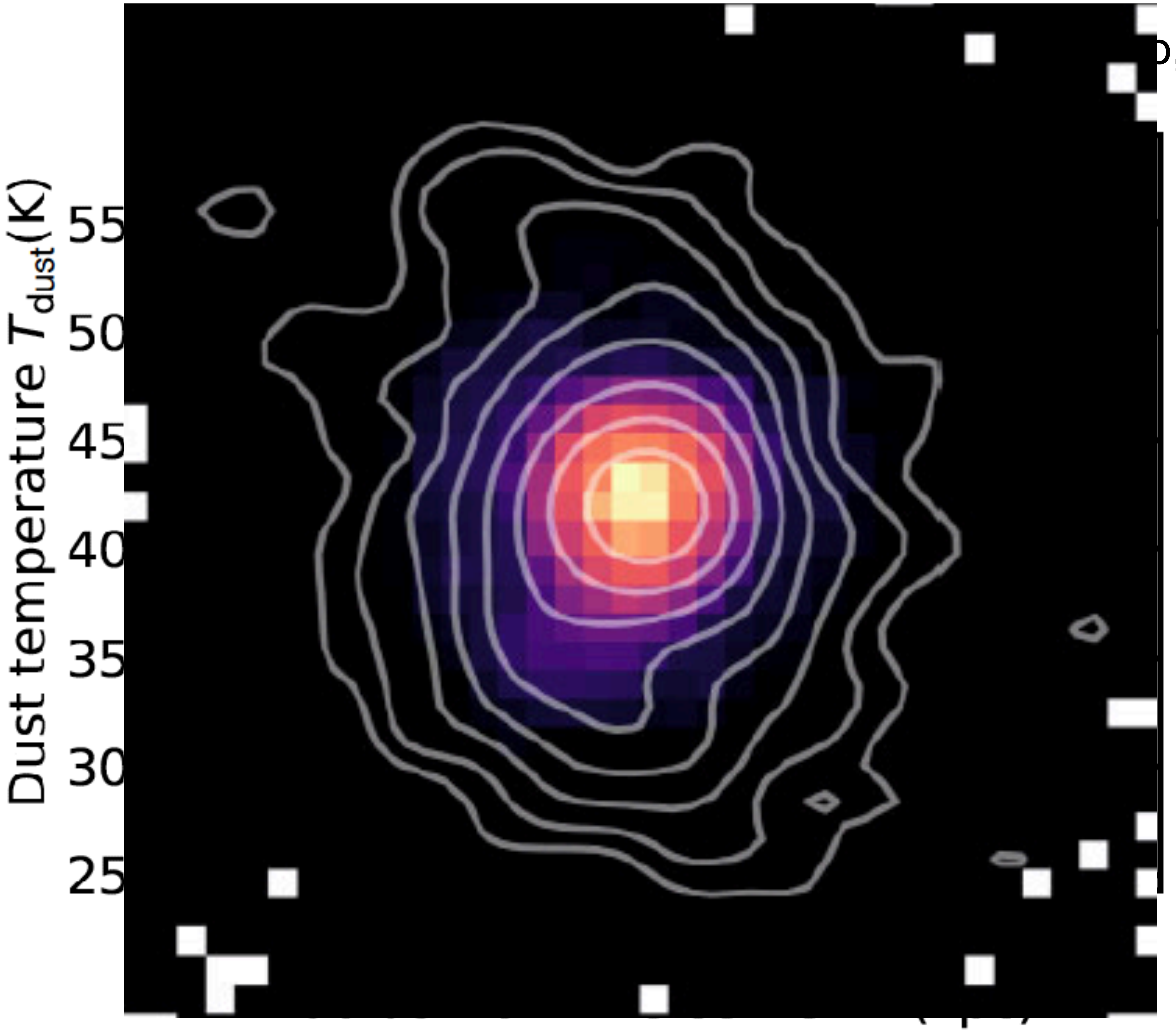


温度ピーク ~ 57 K > 47K (typical quasar) > 40K (typical star-forming galaxy)

温度ピークの位置は可視のクエーサーの位置 + FIR画像に存在する点源に一致する。

Energetics of the disk interstellar medium





, MNRAS

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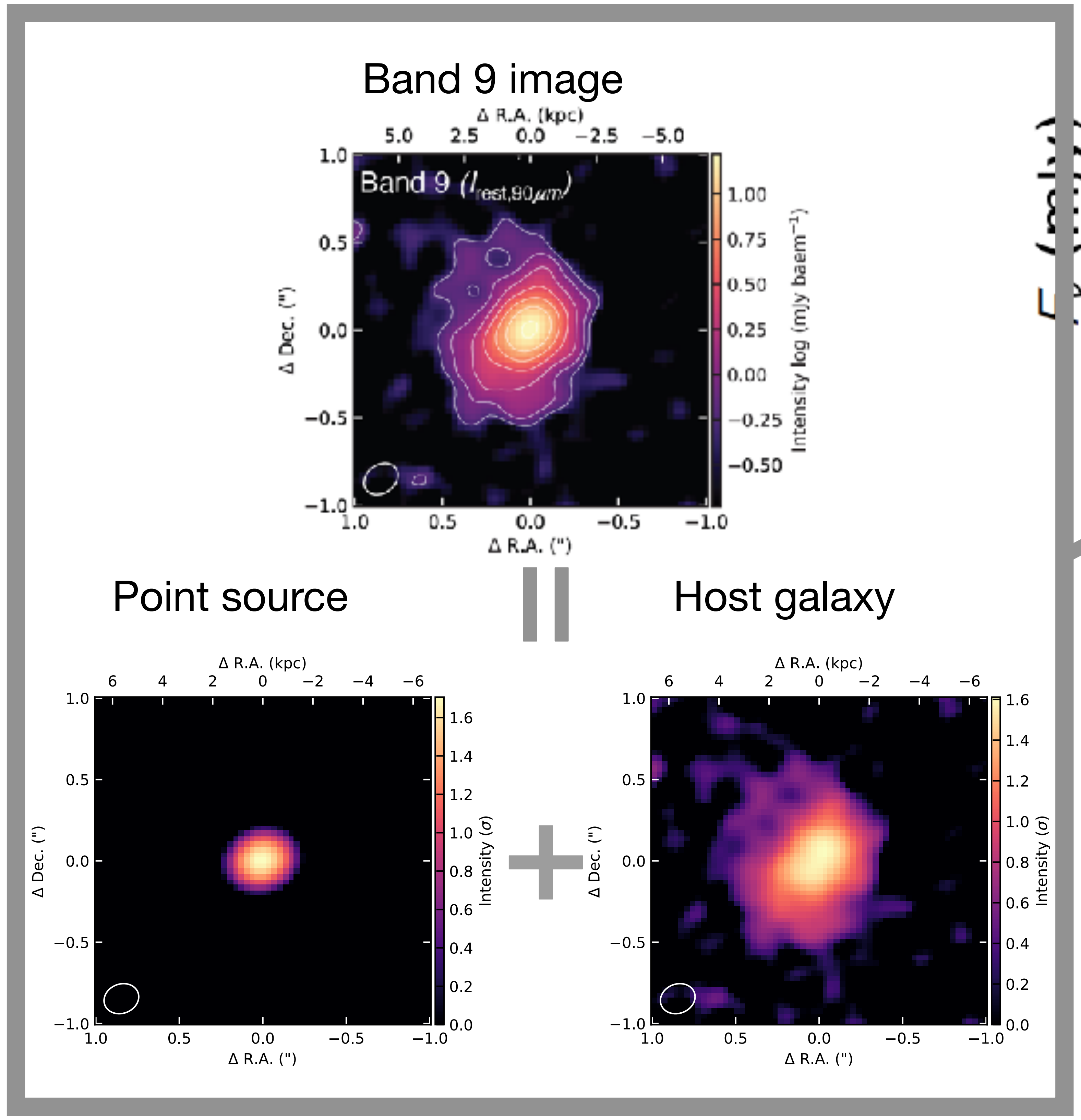
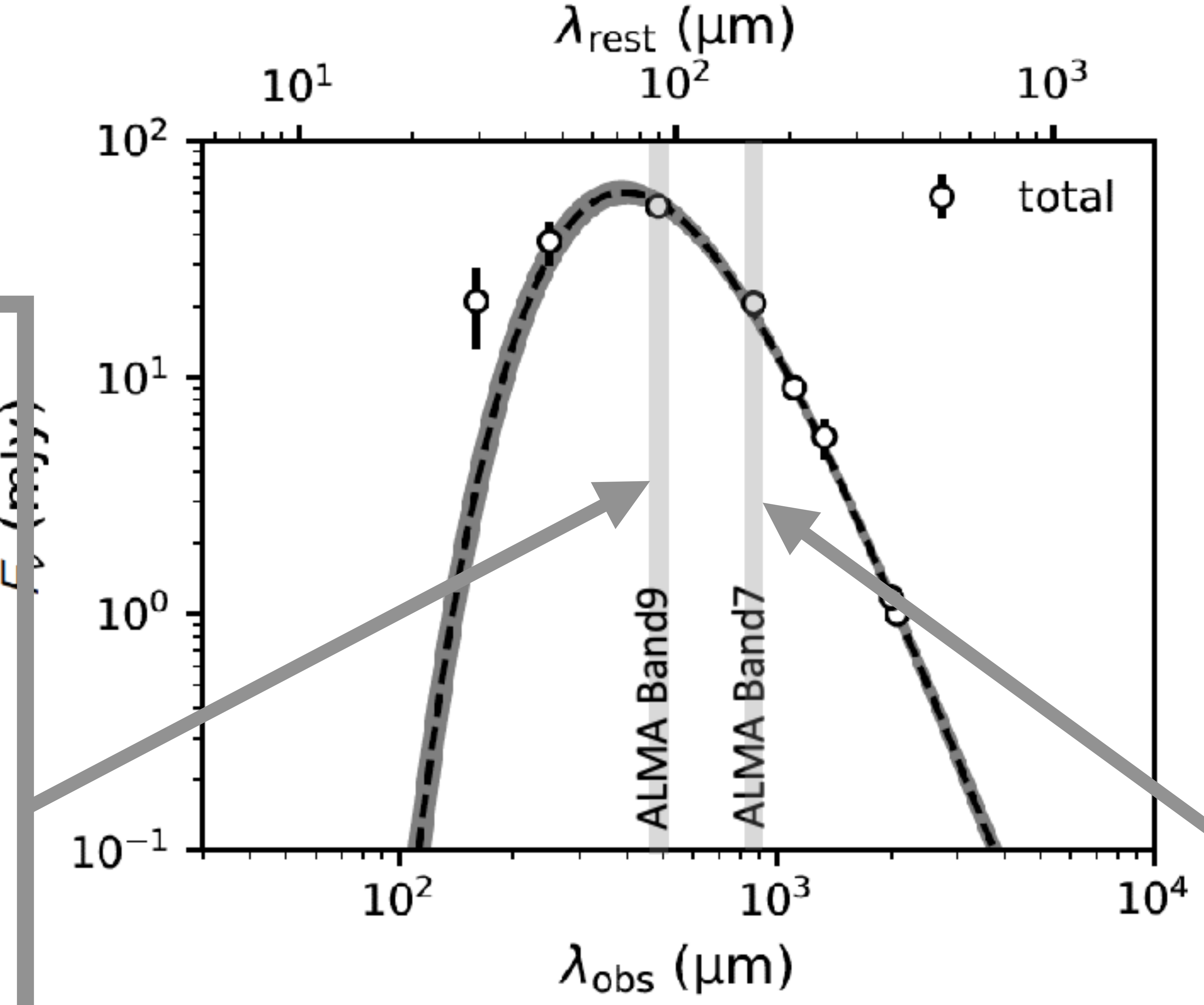
温度ピークの位置は可視のクエーサーの位置 + FIR画像に存在する点源に一致する。

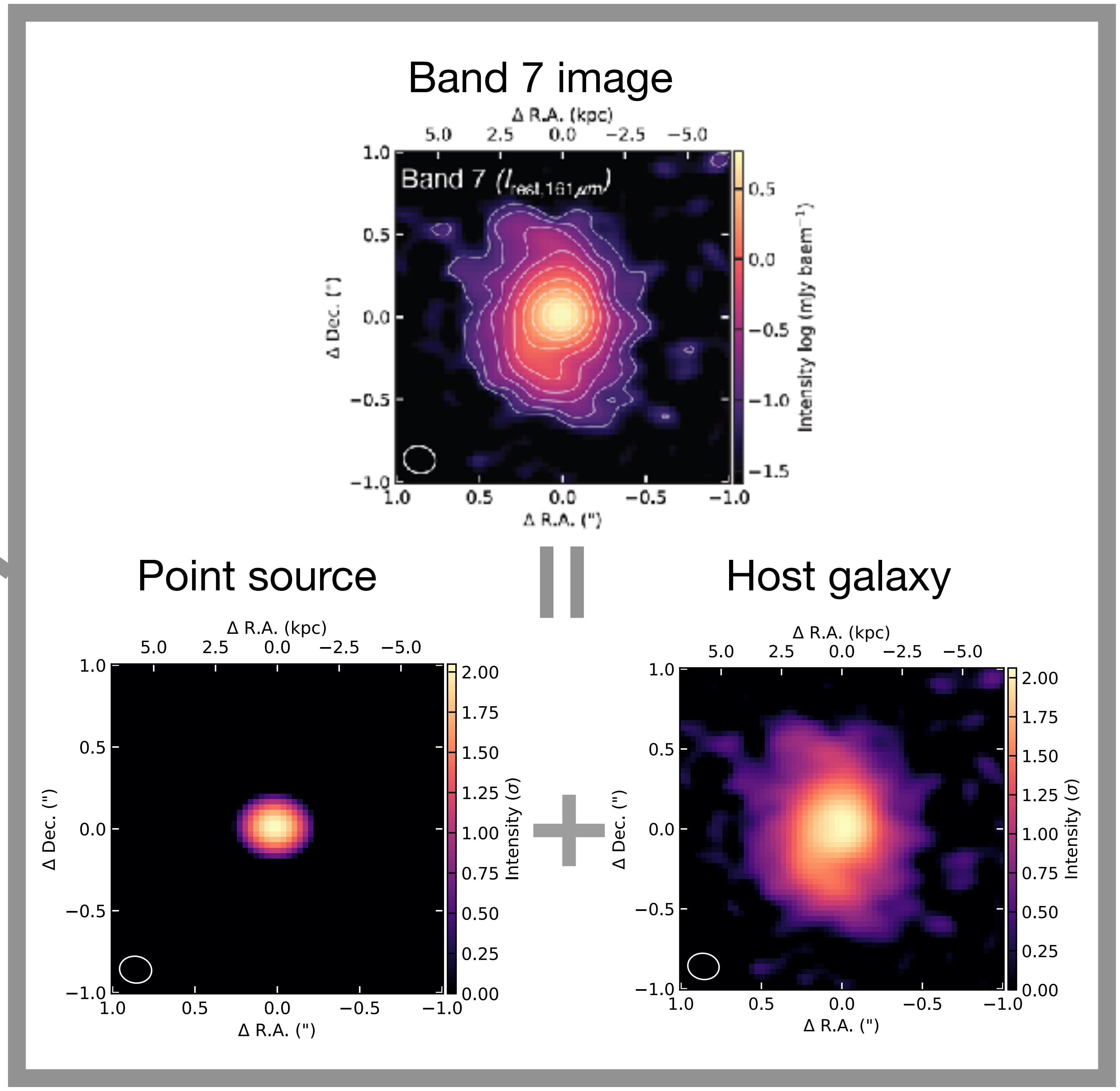
AGN-host galaxy decomposition

Whole galaxy's SED

Tsukui + 2023b, MNRAS

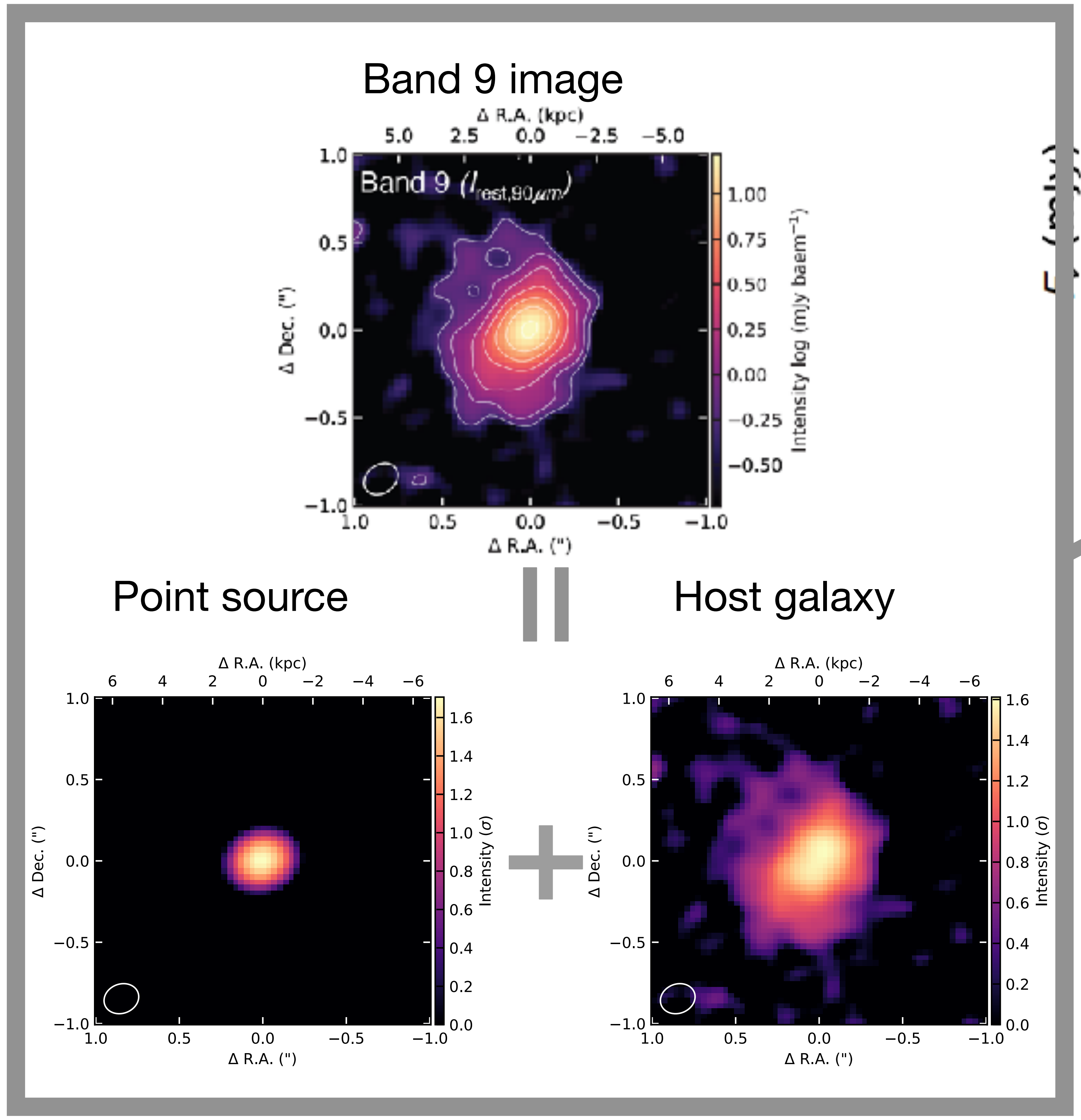




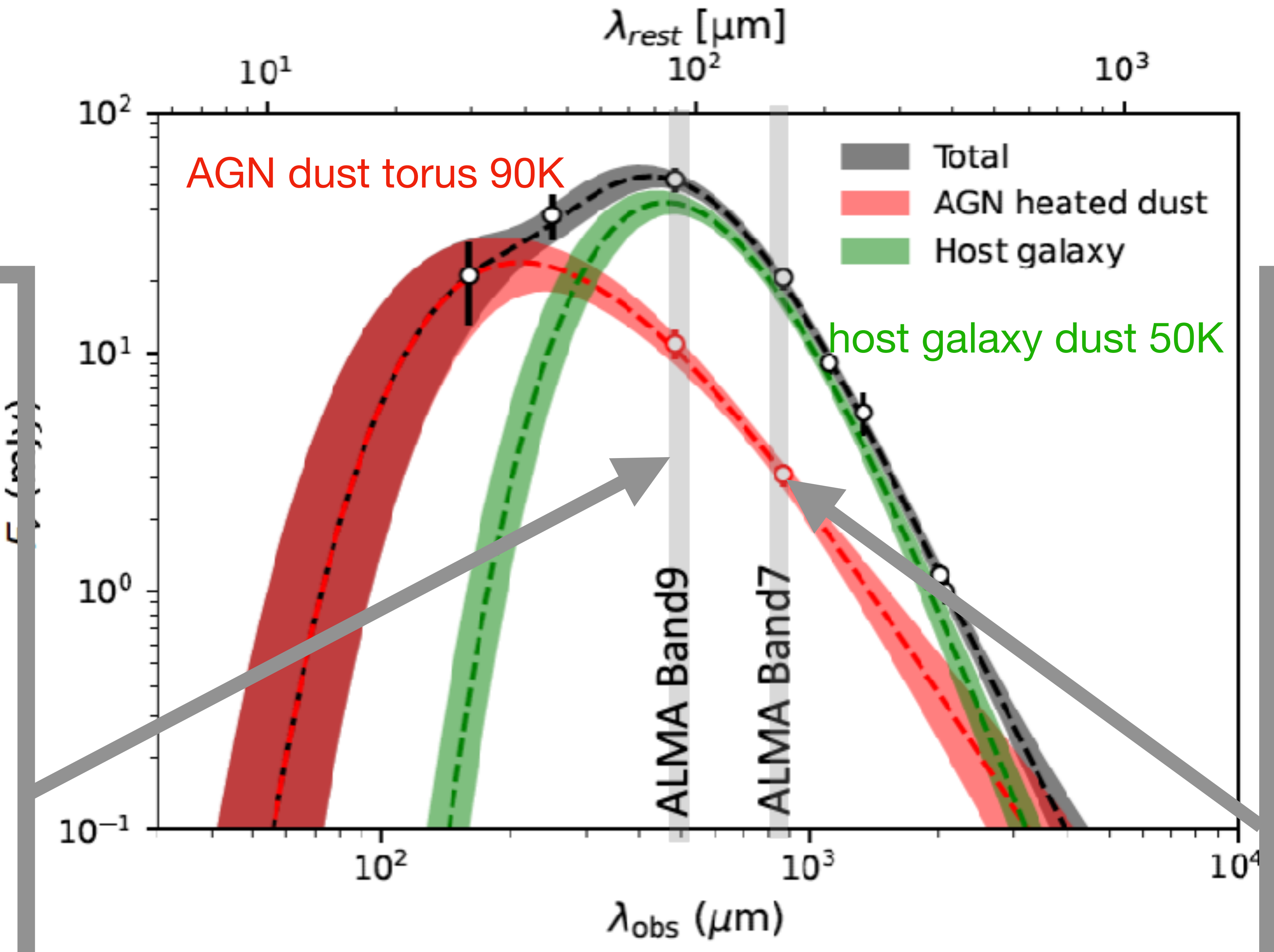


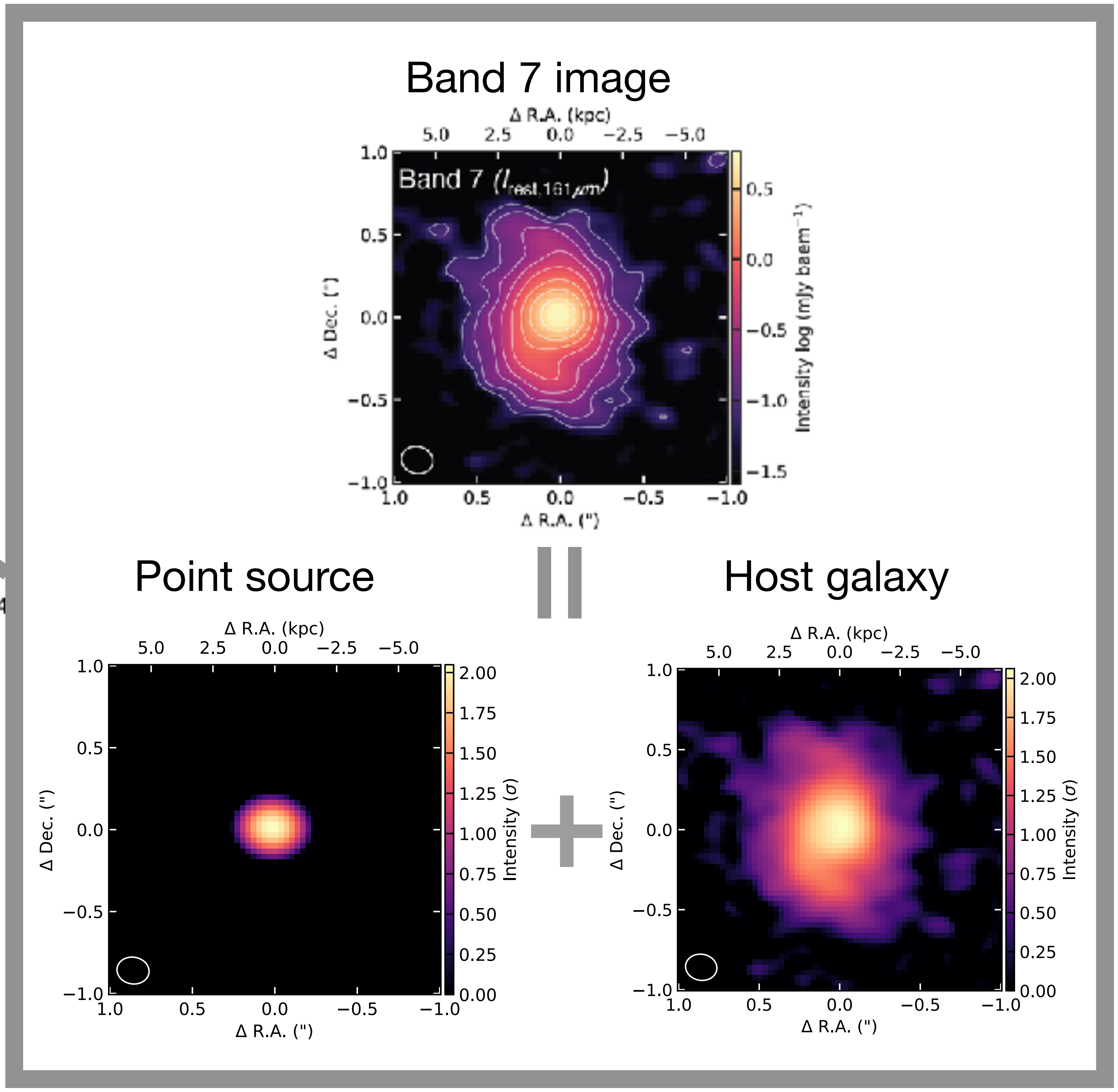
AGN-host galaxy decomposition

Tsukui + 2023b, MNRAS



Whole galaxy's SED



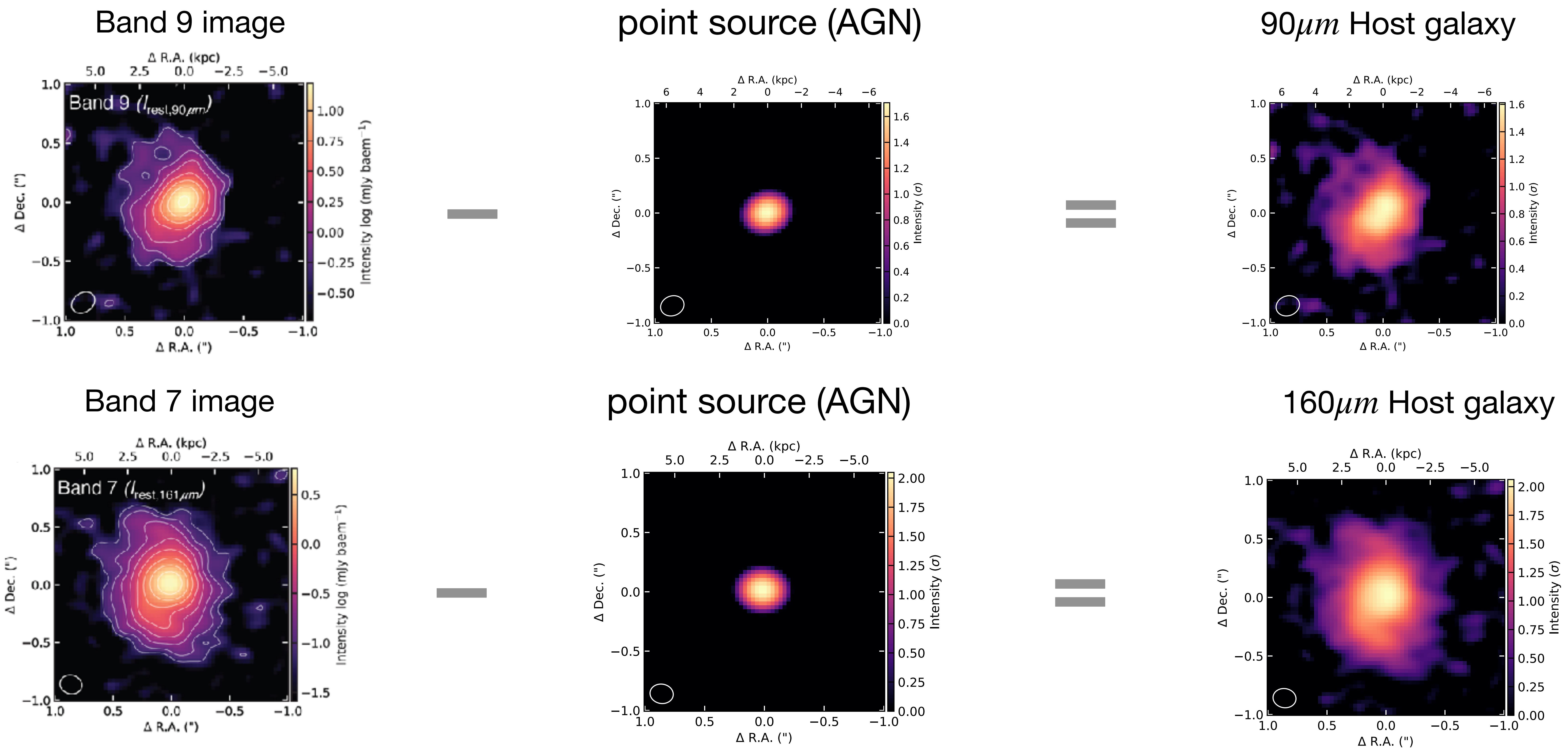


updated SFR $=1700^{+500}_{-400} M_{\odot}\mathrm{yr}^{-1}$

< 3x previous estimate $5000 M_{\odot}\mathrm{yr}^{-1}$

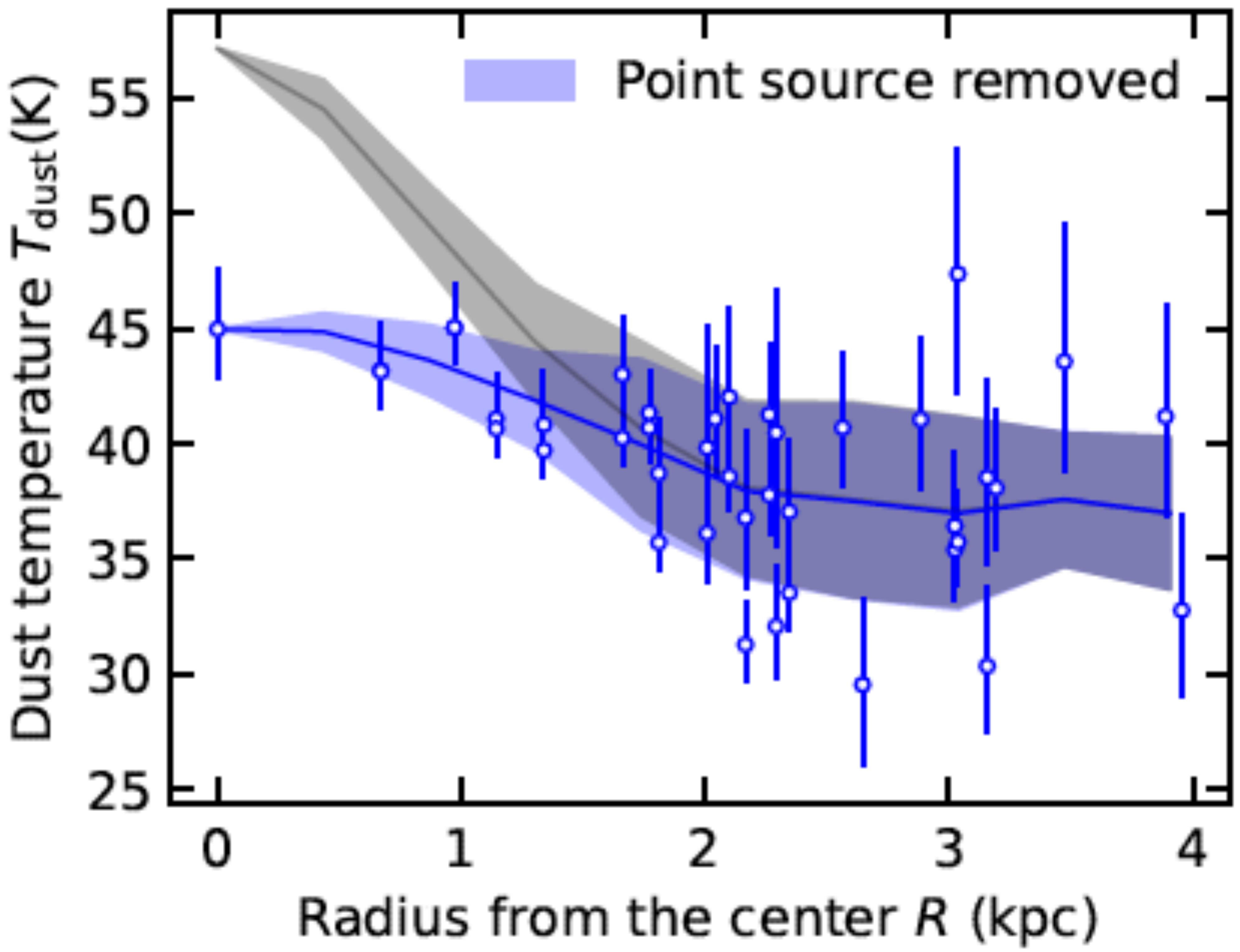
due to a high AGN fraction 53^{+14}_{-15} %

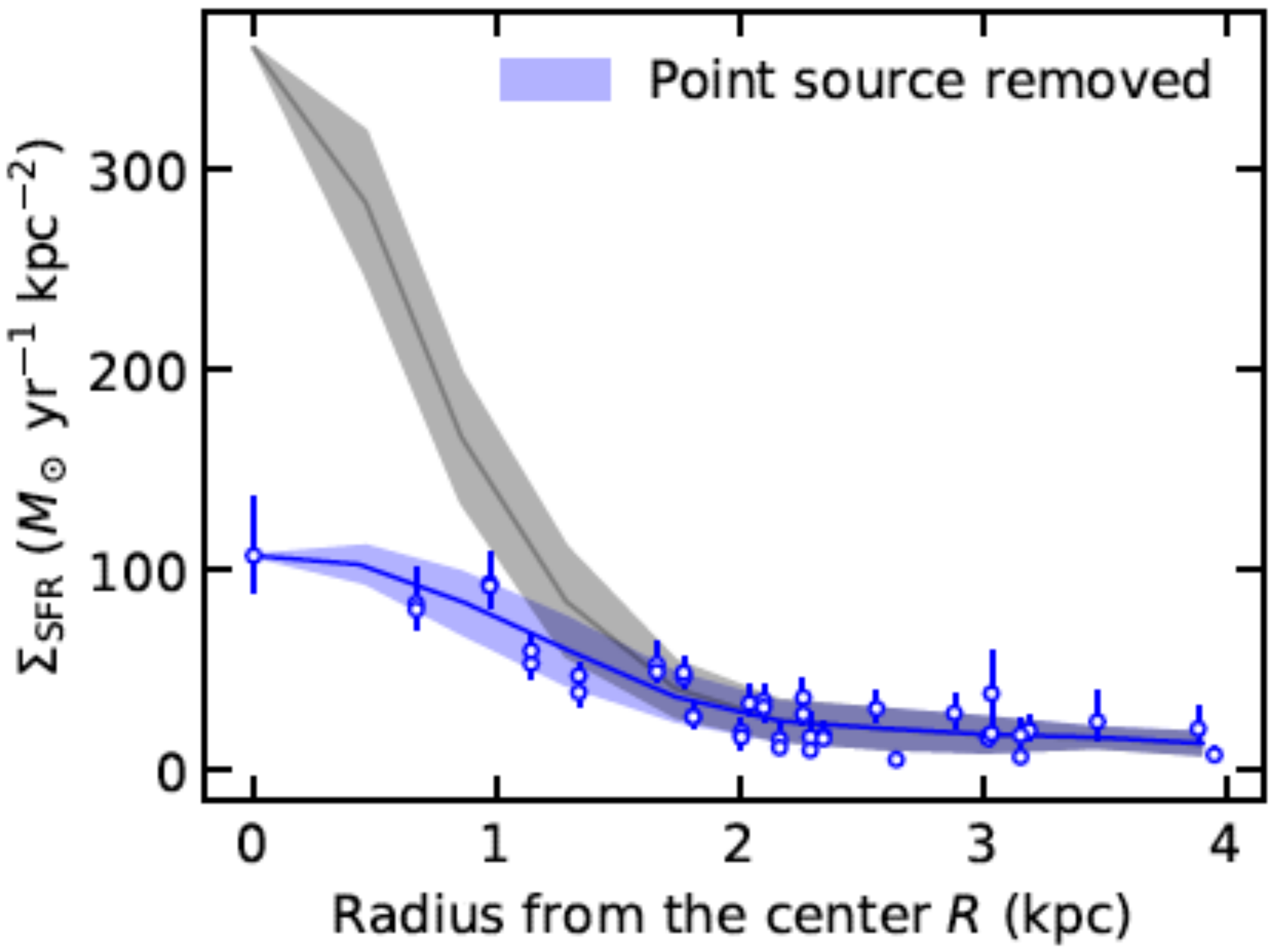
AGN subtracted temperature in image space



Point source contributions to the total flux in the FIR bands are small ~20%, but large ~50% in central pixel.

AGN subtracted temperature in image space

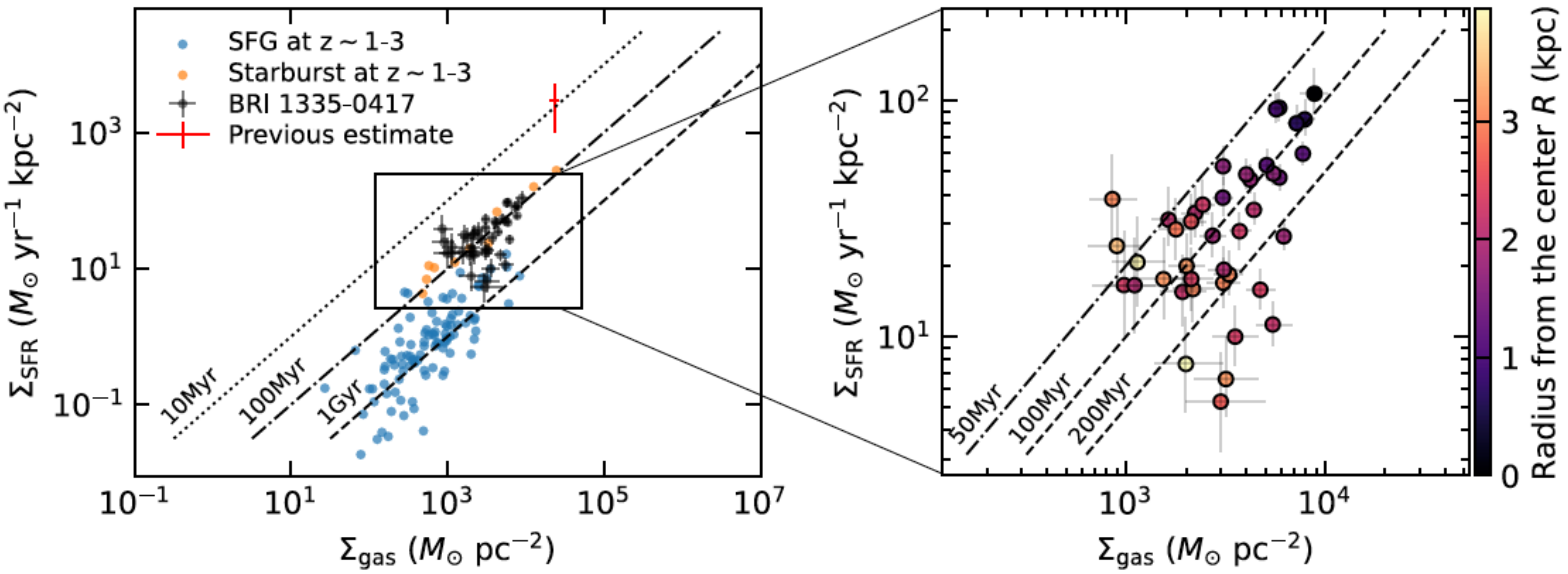




AGN component entirely responsible for the high dust temperature.

We underestimate the size of the SFR distribution if we neglect AGN

Kennicutt–Schmidt diagram



After AGN correction, BRI 1335-0417 is not an outlier
but rather a normal starburst population with a gas depletion time of 100Myr.

Summary

Spatially resolved ALMA data identify bulge, disk, spiral, and bar structure in BRI 1335-0417 at $z=4.4$

Higher order velocity residual in the disk indicates the vertical oscillation of the disk (U-shaped warping).

Gas or satellite accretion likely causes the seismic ripple and spiral arms in the disk.

Bar structure may channel the gas into the central quasar and bulge.

Assuming a single dust temperature over the galaxies leads to a false interpretation of the SFR, its size etc.

Without spatially resolved data, dust optical depth has no physical meaning: we link the opacity with dust mass given the physical beam area.

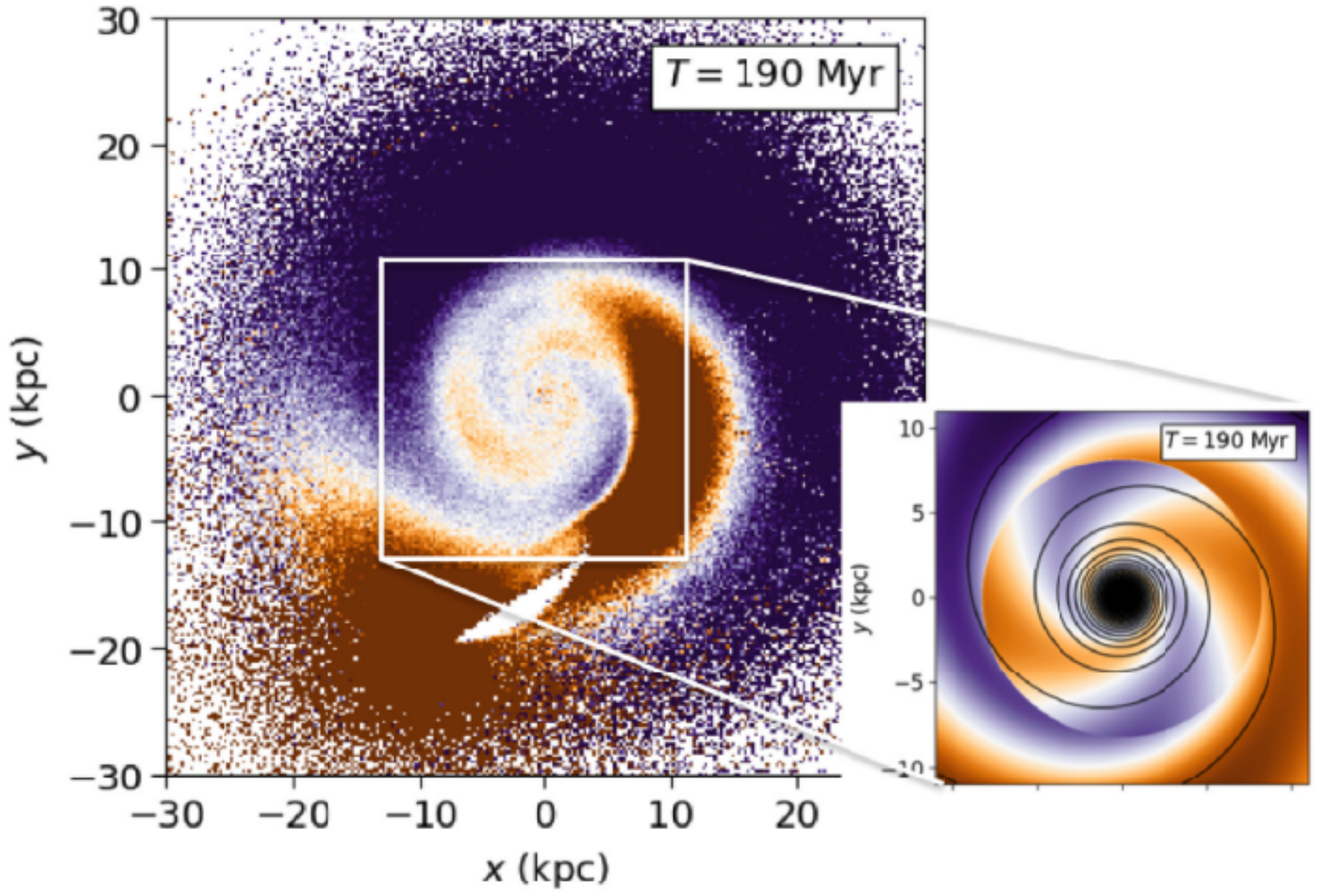
Open question

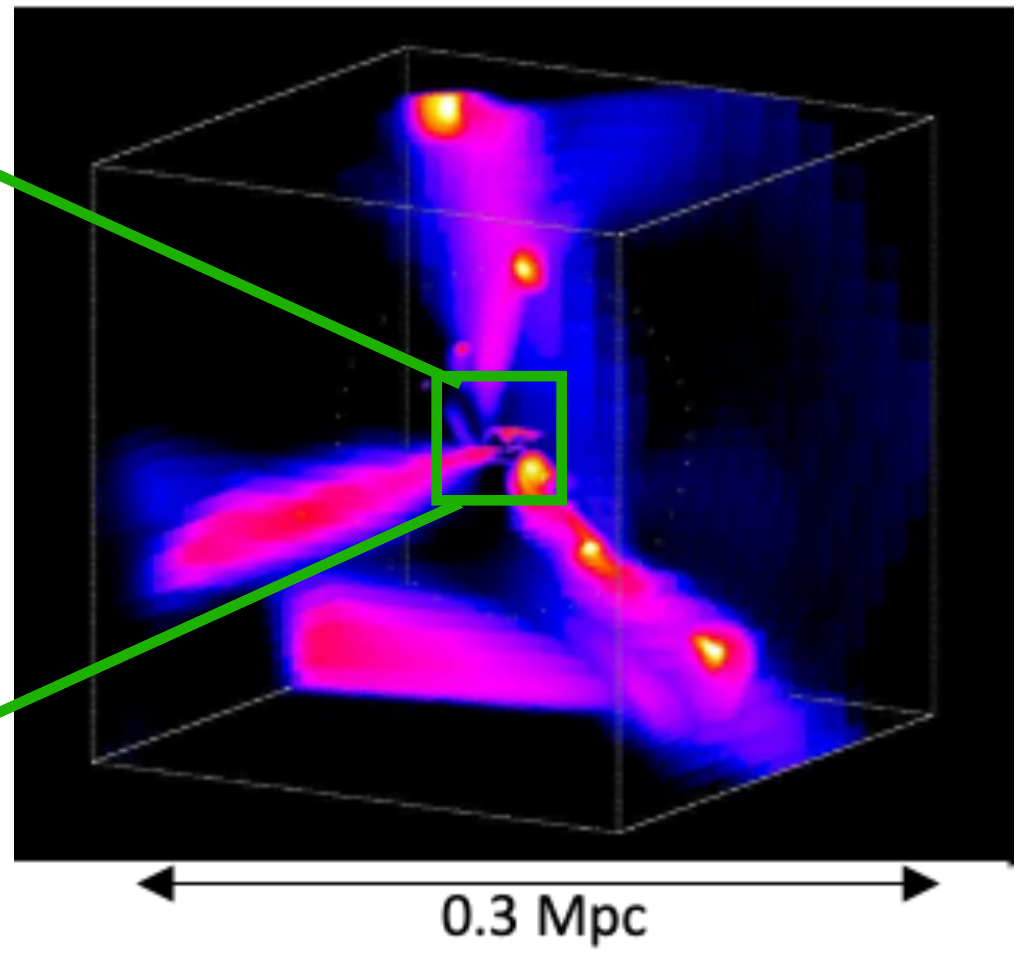
AGN-host decomposition will never be perfect:

AGN optical-UV emission may leak out from the dust torus and heat the extended region of galaxies.

(need more data, sample).

Galaxy transformation at z=4.4



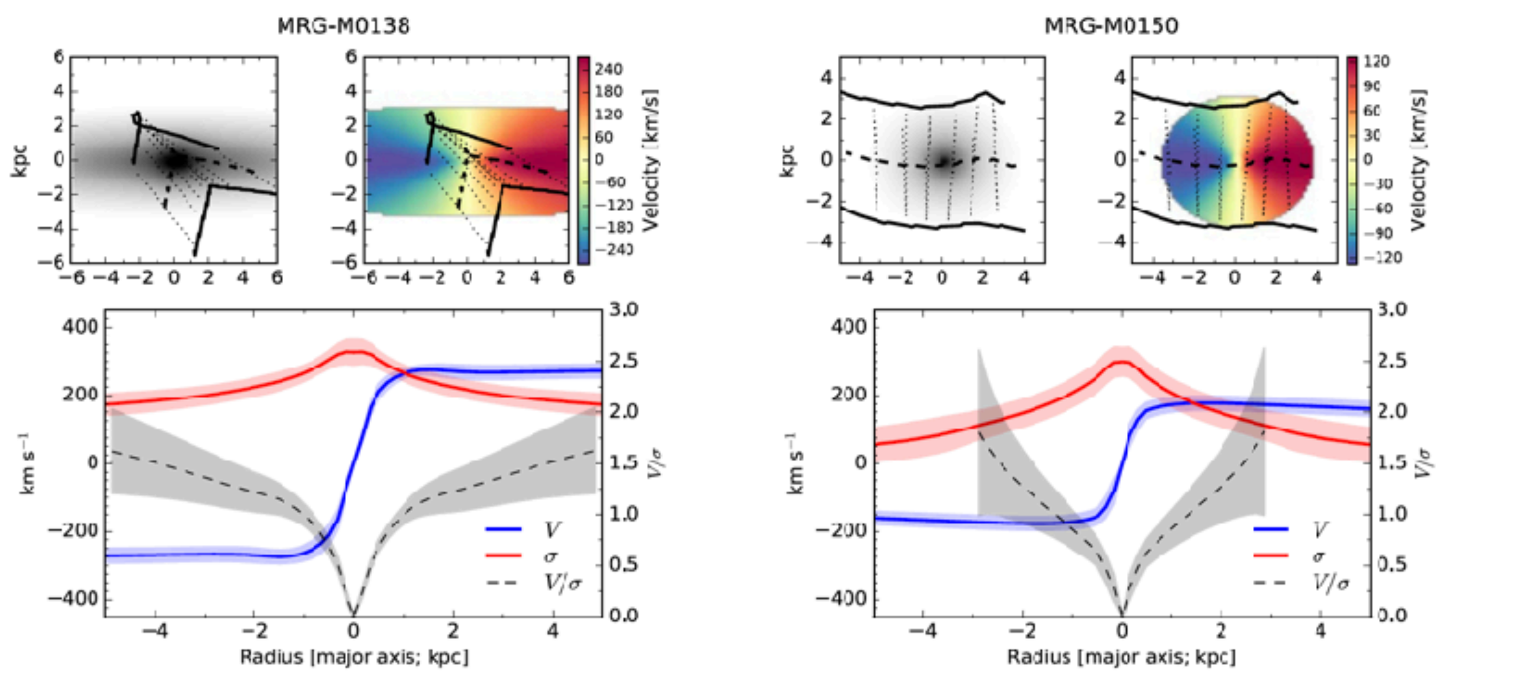


Bland-Hawthorn and Topper-Garcia+21

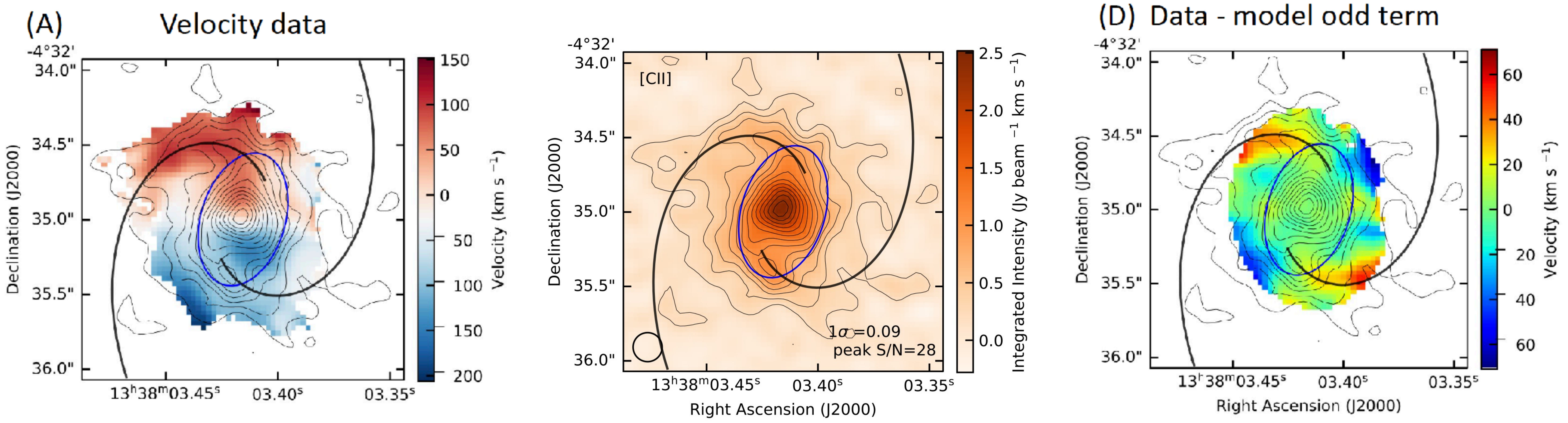
Dekel+09

Massive compact quiscent
at z>2

Newman+17



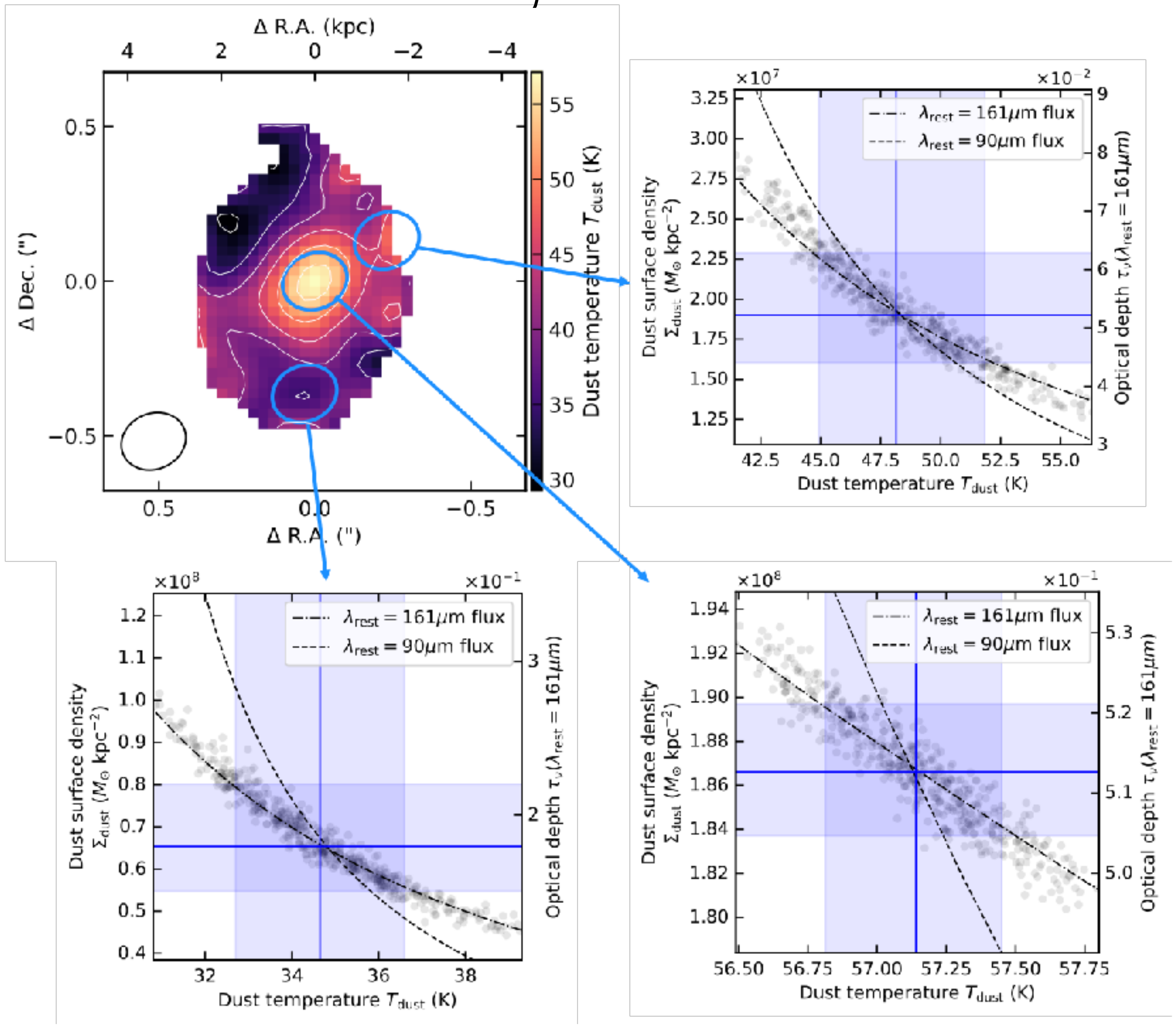
Ito+23



Cold gas/satellite accretion and mergers supply gas in the gas-rich gravitationally unstable disk, causing the seismic ripple of the disk (vertical disk bending wave) and the two-armed spiral. Gas rich disk formed star-forming gaseous bar, subsequently triggering the SF bulge (compact rotating core) and optical quasar.

Fit optically-thick graybody function to each pixel (inc. CMB heating/contrast)

Free Parameters: $T_{\rm dust}$ and $M_{\rm dust}$(or $\tau_{161\mu m}$) with $\beta = 2.14 \pm 0.17$

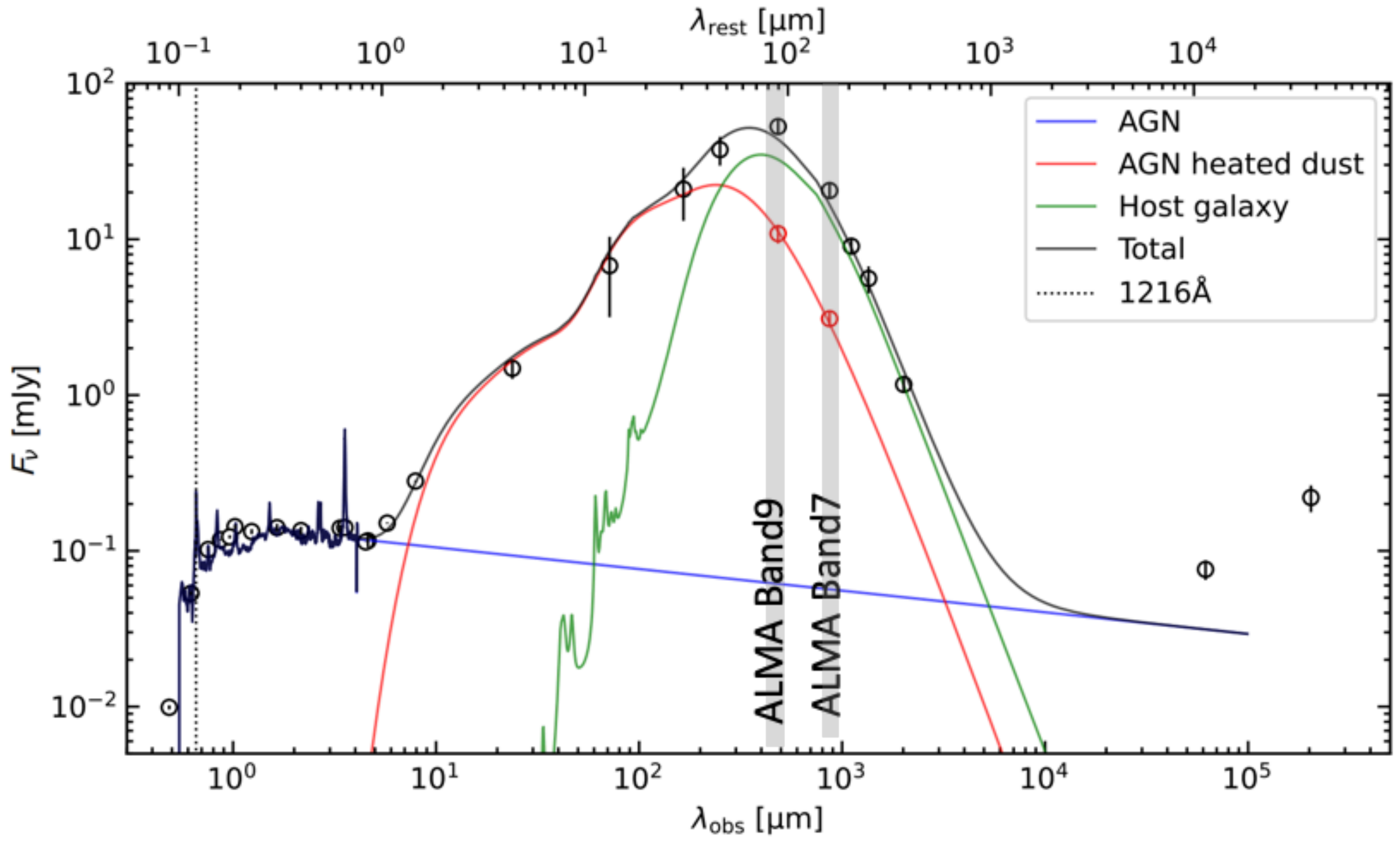


- First 2d temperature map without assuming an optically thin limit: linking dust optical depth with dust masses and physical area subtended by the beam.

AGN-host galaxy decomposition

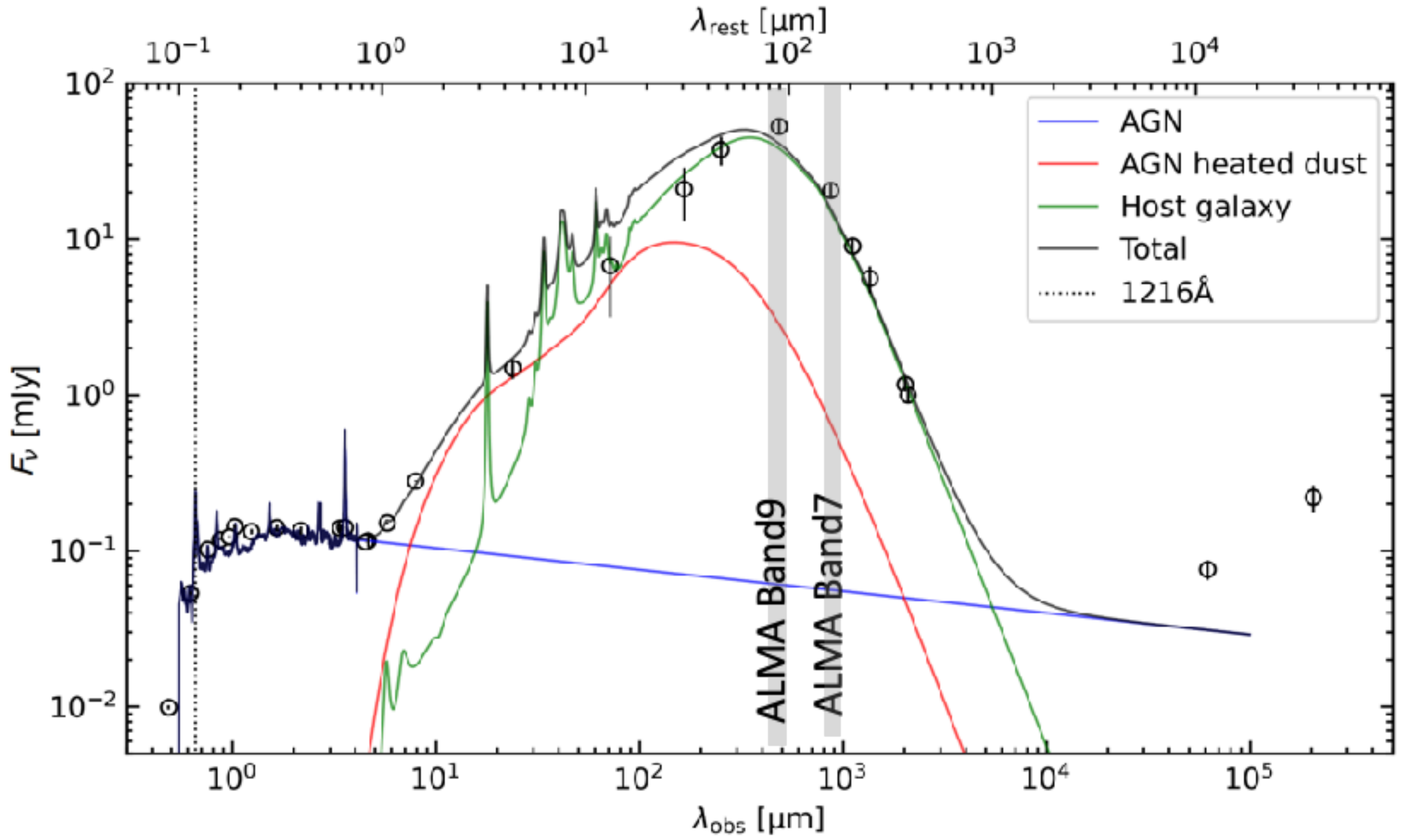
Stardust code (Kokorev 2021), modified to accept point source as AGN constraint

With spatially resolved constraints



SFR~1700 Msun/yr

Without spatially resolved constraints



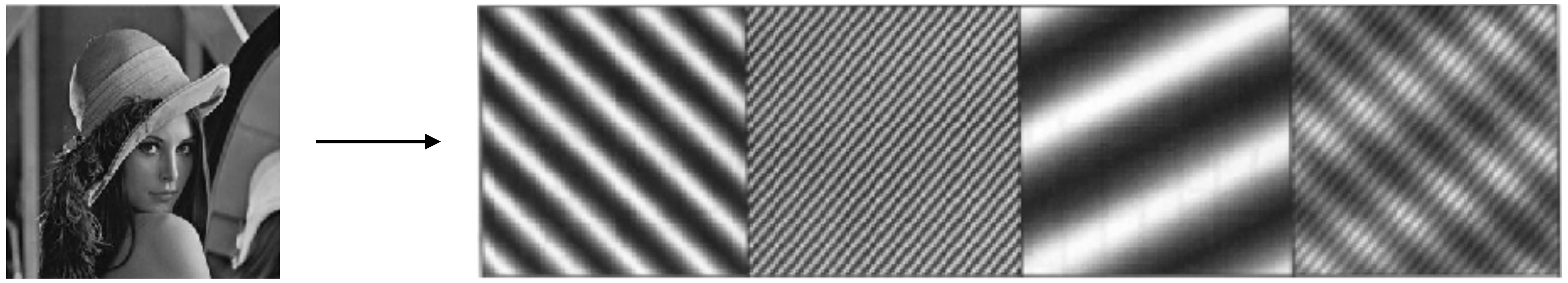
SFR~5260 Msun/yr

The goodness of fit does not change -> Only spatially integrated SED has no power to constrain the AGN fraction.

Identification of the spiral structure

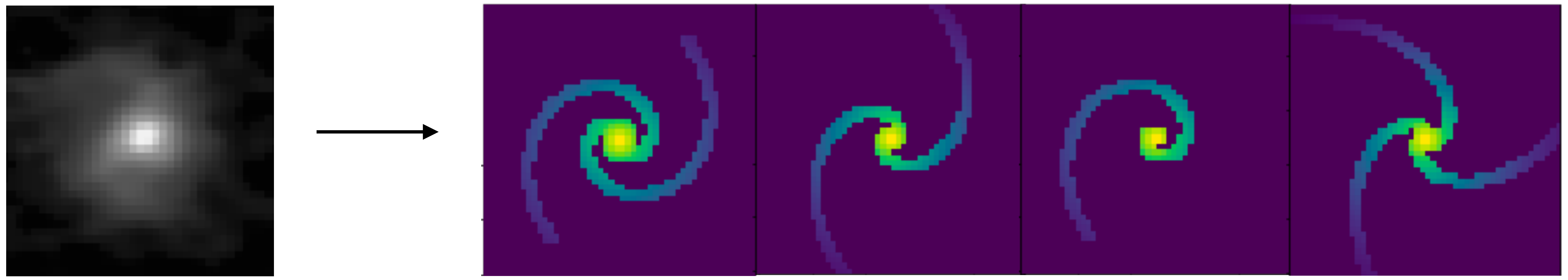
We expand intensity image into logarithmic spiral models with a range of pitch angles (α) and number of arms (m).

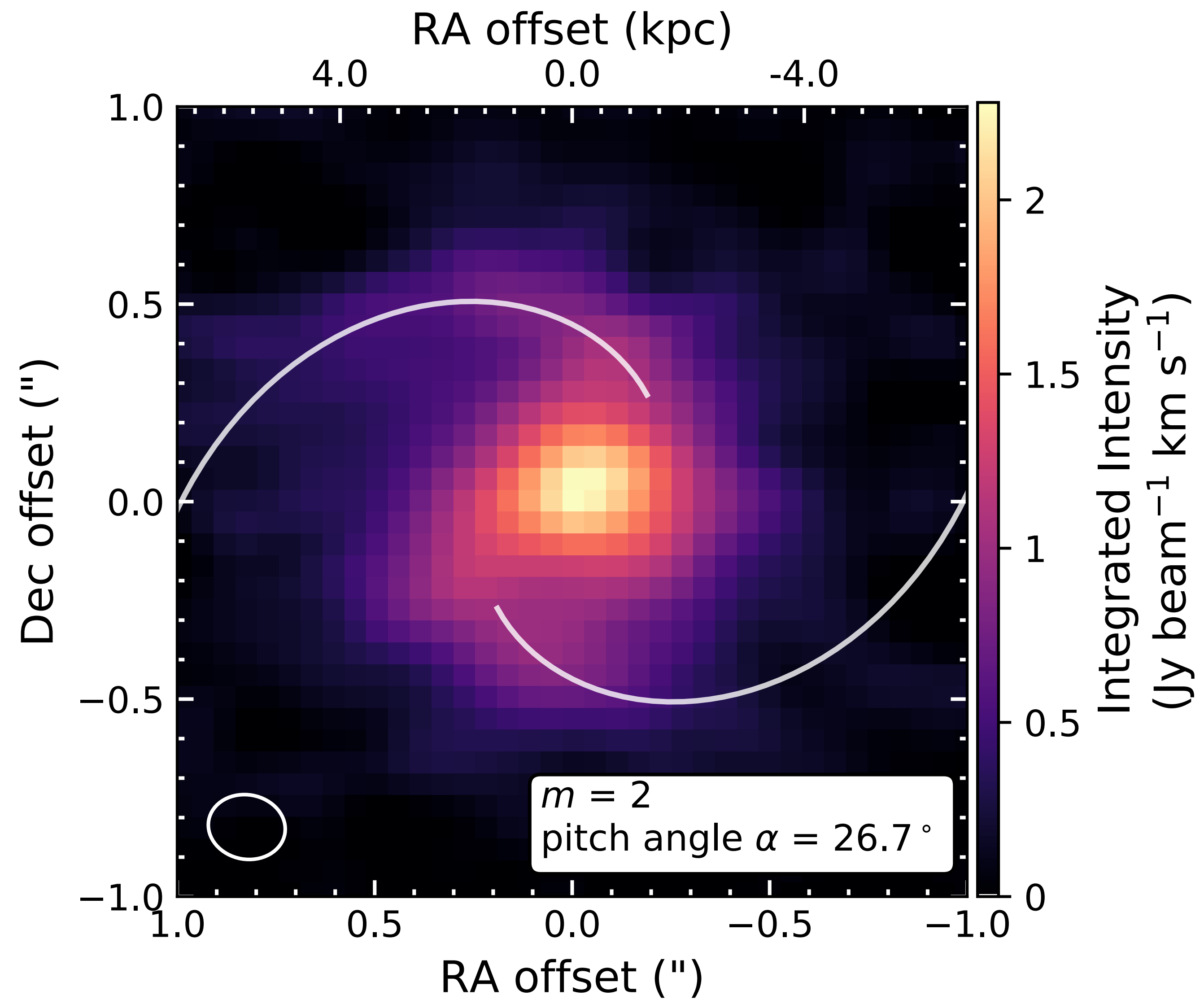
Fourier expansion (basis function: sin cos)

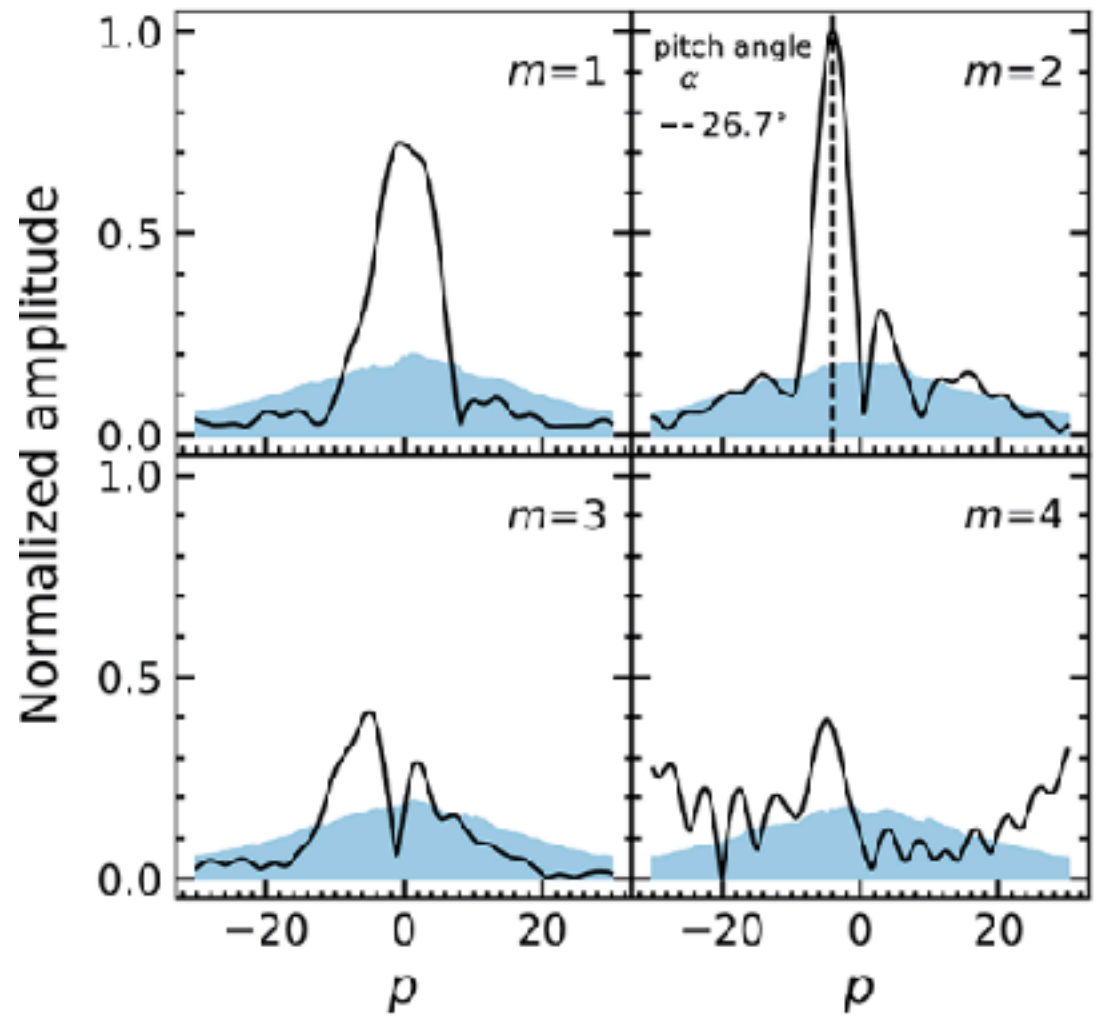


Log spiral expansion (basis function: log spirals)
Puerari and Dottori 1992.

De-projected Intensity image





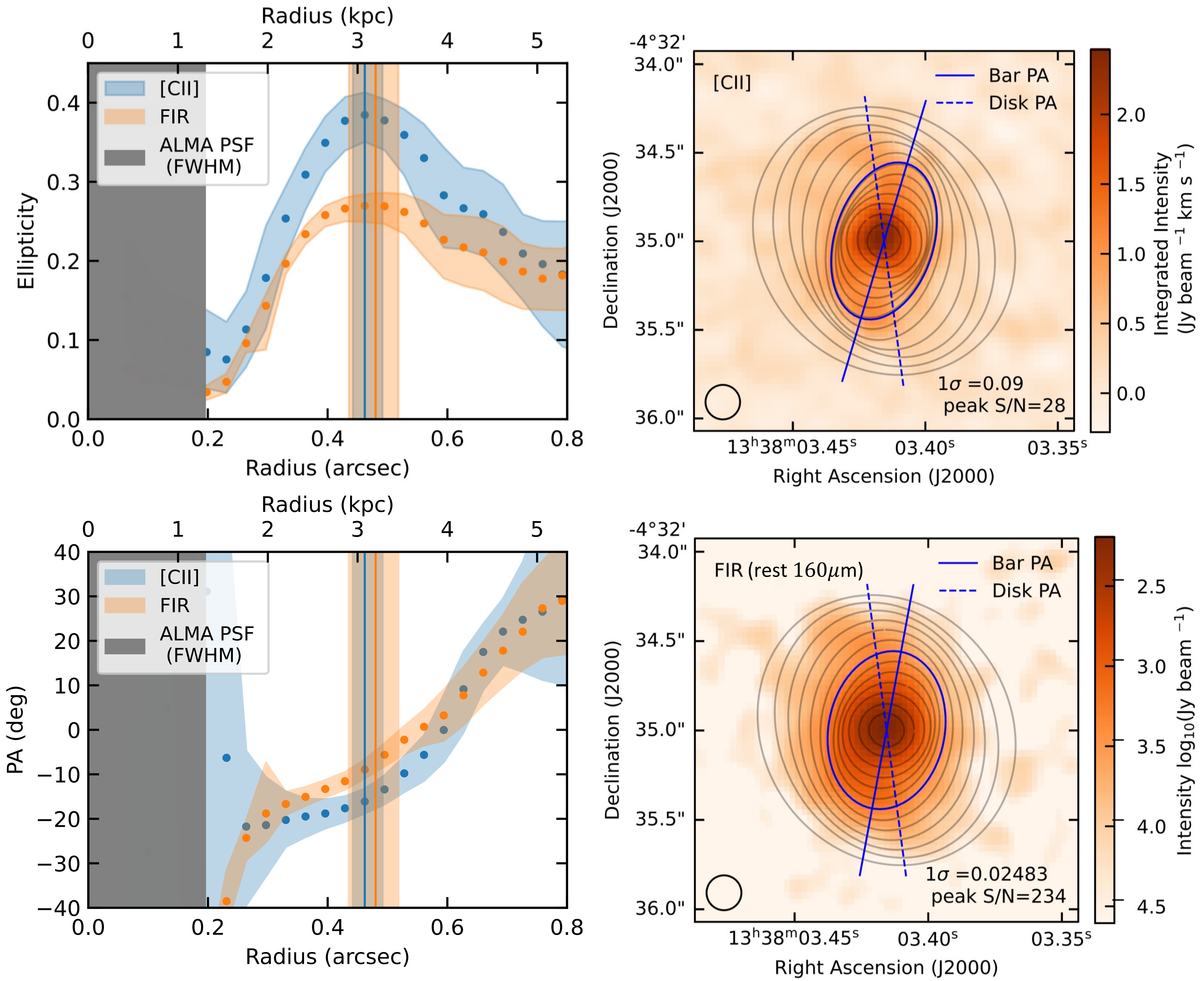


We find that the dominant component is two-arm spirals with a pitch angle of 26.7deg. (still highest-z spiral structure)

m=1 corresponds to the lopsided structure.

Tsukui and Iguchi 21

Identification of bar structure



Tsukui + 2023c in press

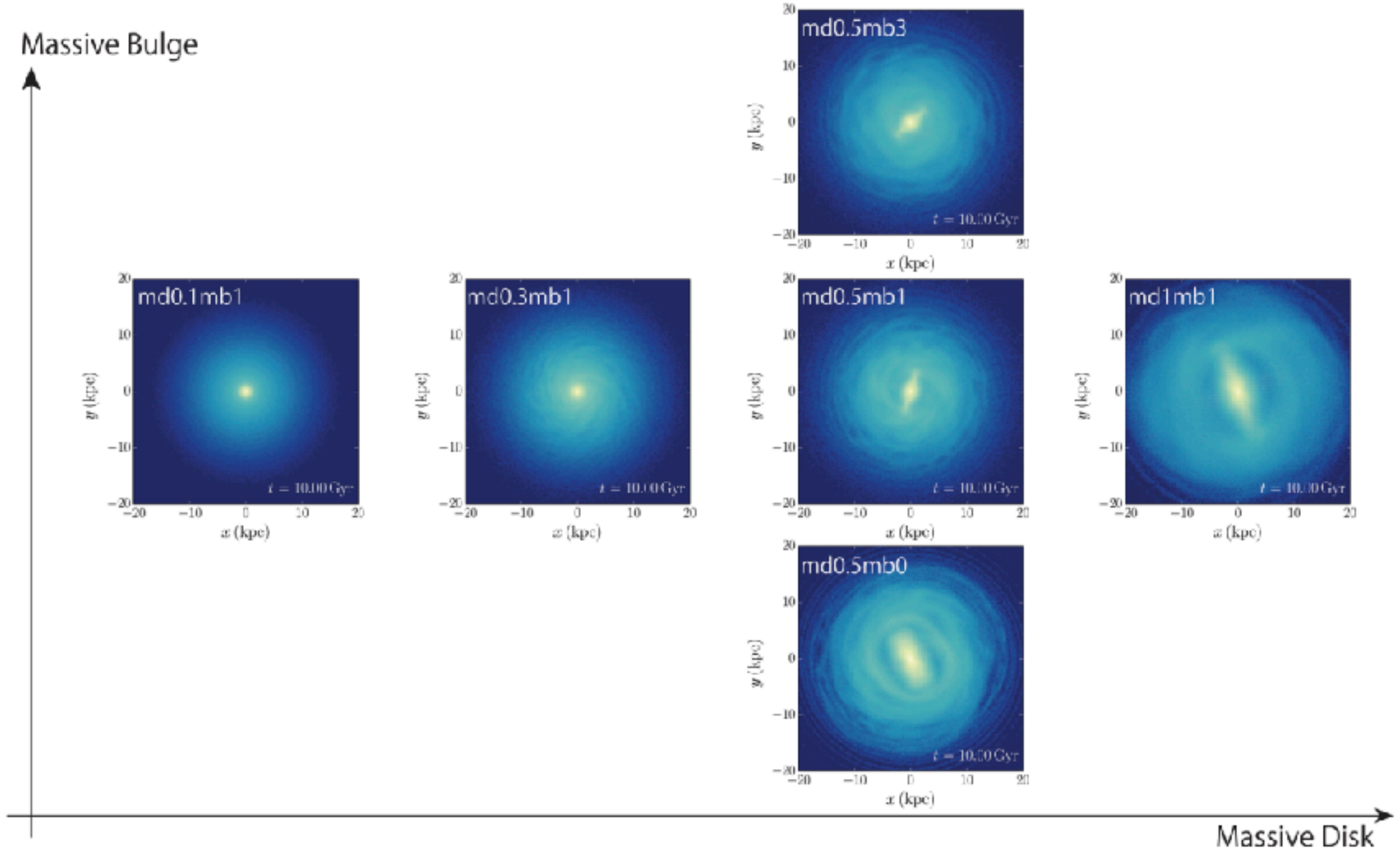
Defining bar length maximum of the ellipticity profile (Wozniak and Pierce 1991)

Bar length $R_{\rm bar} \sim 3.3$ kpc (cf. disk scale R_{disk} ~1.83 kpc) x2 bigger than nearby stellar bar length/disk size ratio.

The presence of a bar in gas-rich disk??

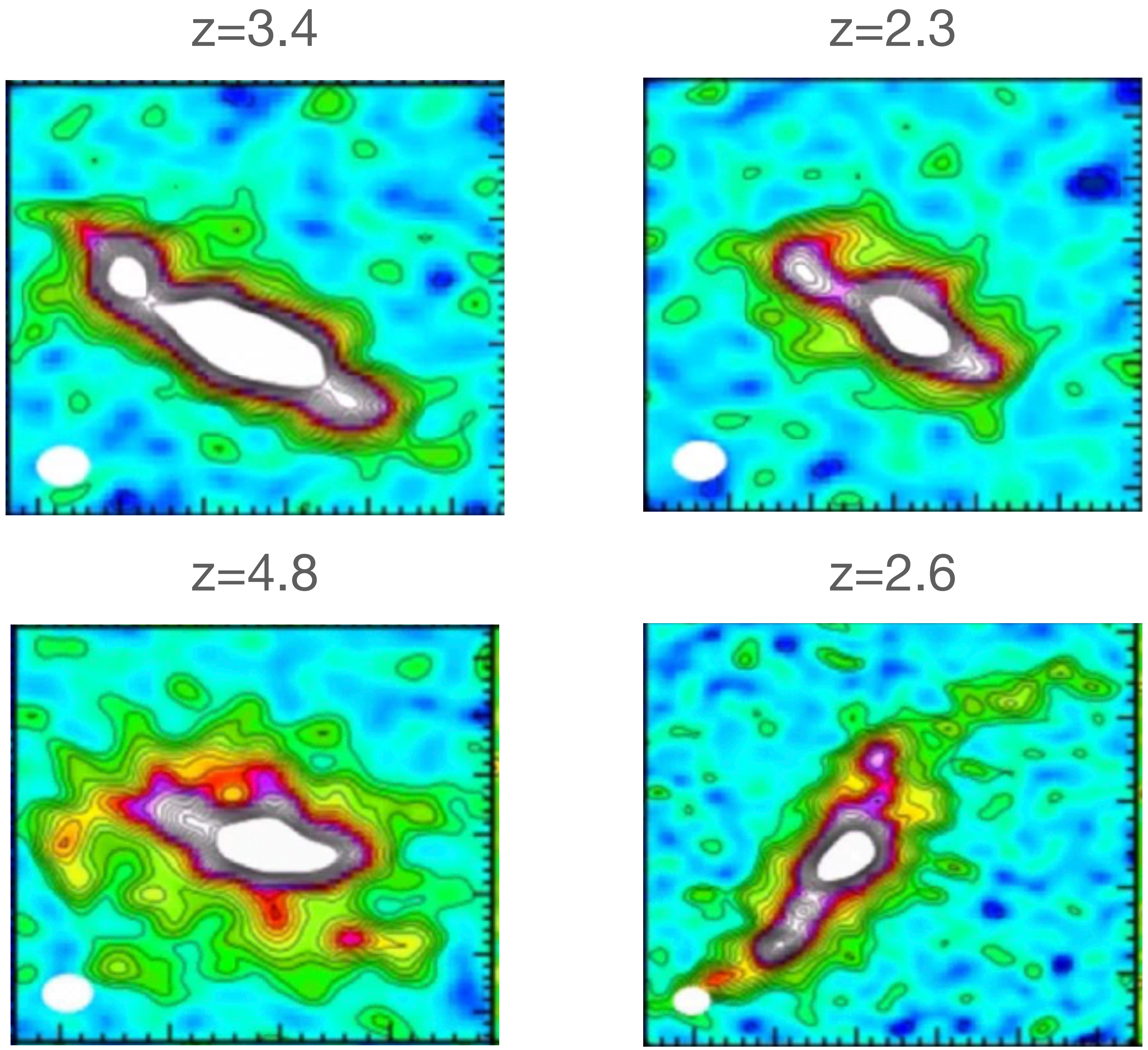
Stellar bar grows faster in a disk-dominated system (Fujii+18).

Gaseous disk may suppress stellar bar formation (Łokas 20; Athanassoula+13).



The experiment is done for isolated / a moderate gas mass fraction of up to 30%.

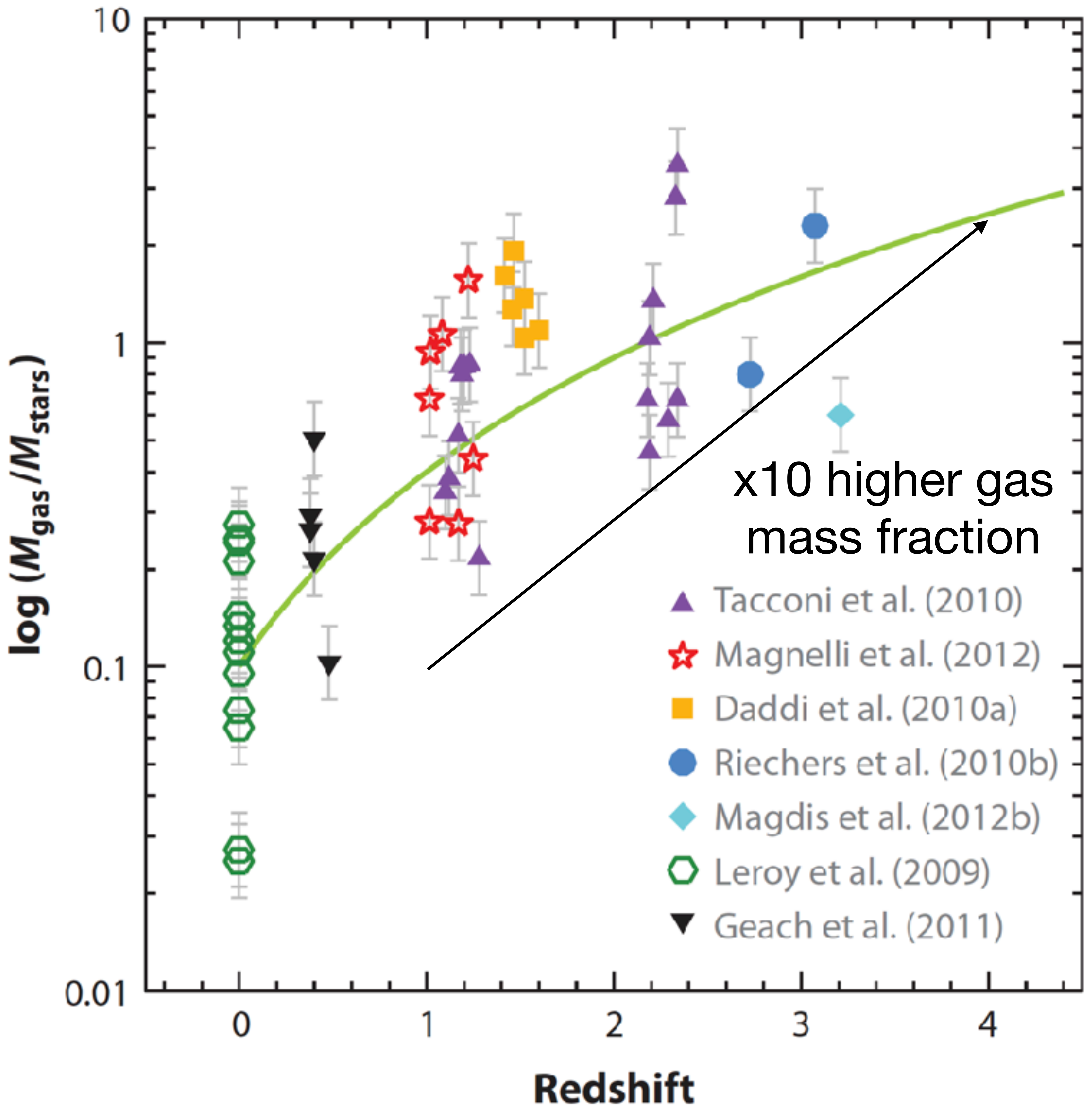
Gaseous bars may be prevalent in the gas-rich high-z universe.



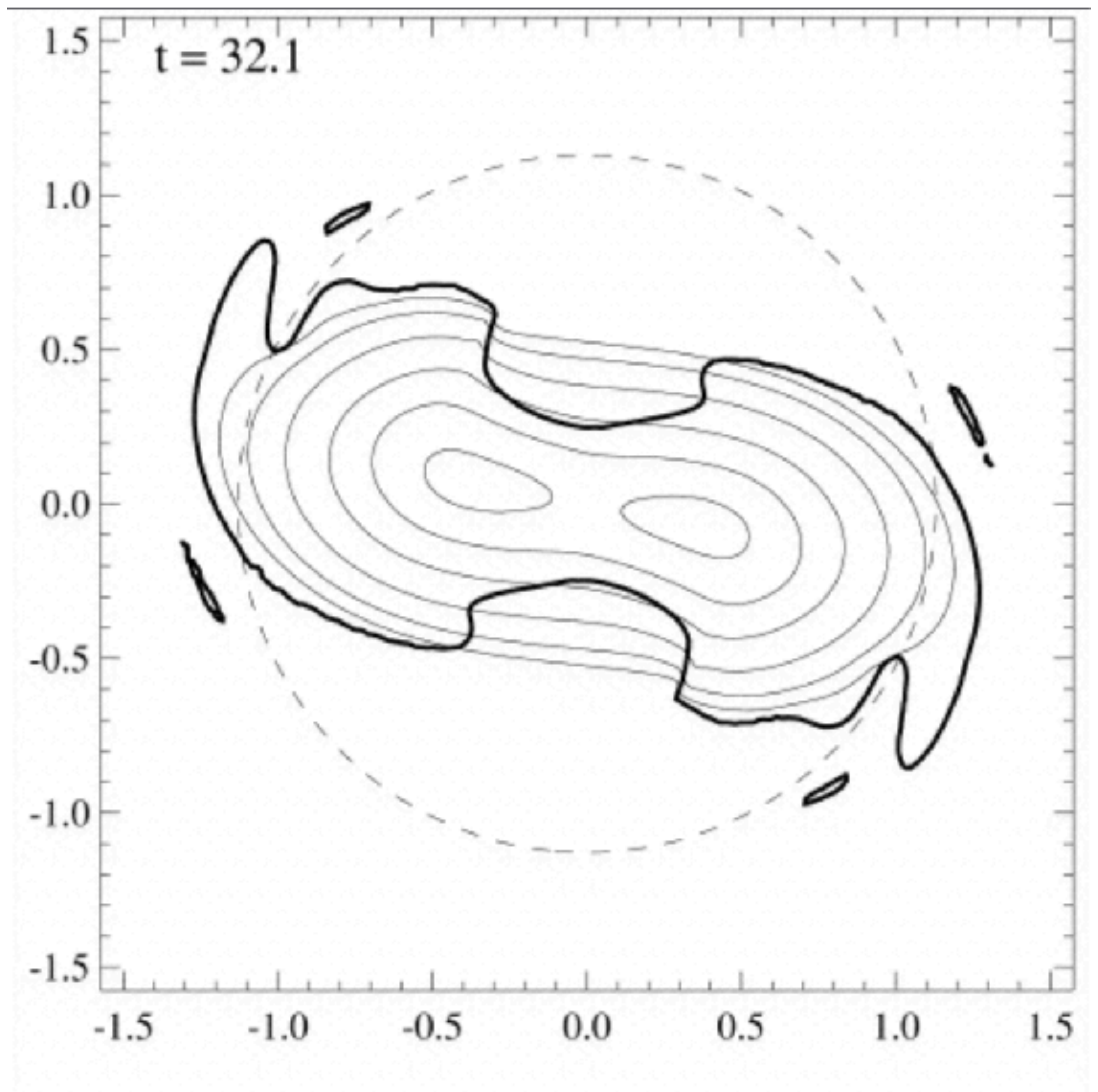
Triaxial bar seen in dust continuum (Hodge+18; Gullberg+18).

The presence of a bar in gas-rich disk??

In gas-rich galaxies being actively supplied with gas, we may need a different perspective:
Gaseous bars form out of gravitationally unstable gas disks.



100% gaseous axisymmetric disk form stable gaseous bar



Cazes and Tohline+1999

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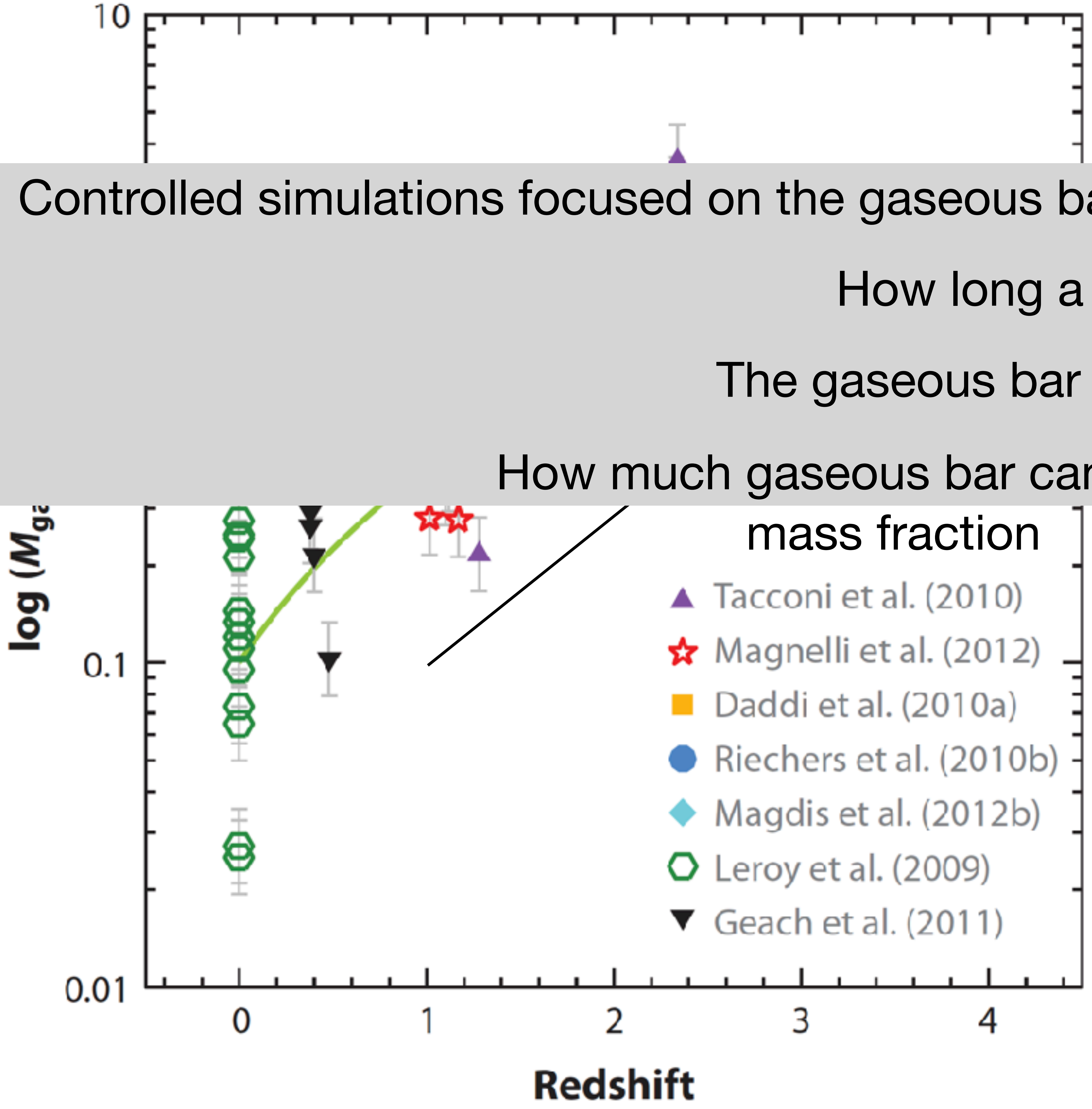


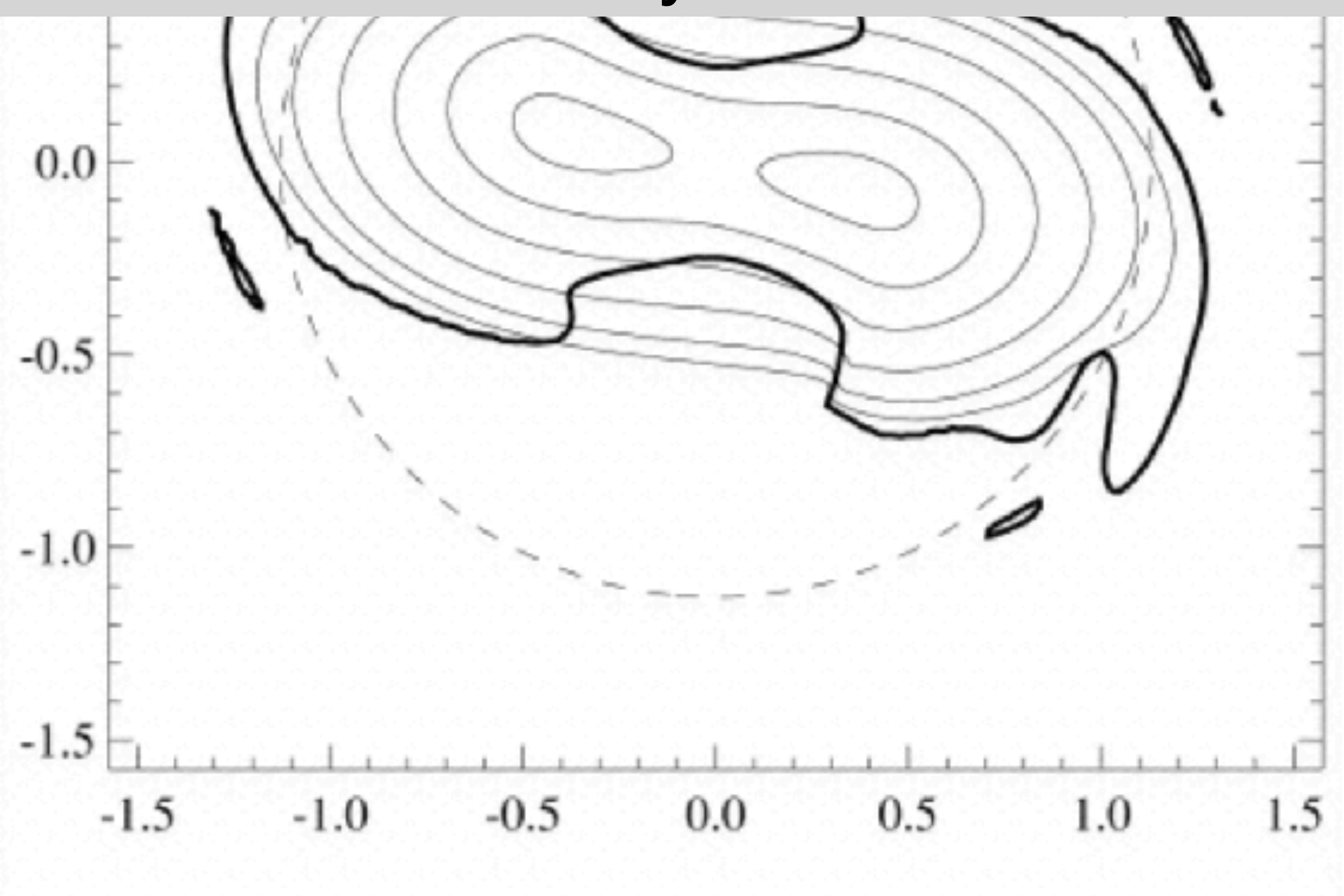
100% gaseous axisymmetric disk form stable gaseous bar

Controlled simulations focused on the gaseous bar with realistic star formation and gas accretion to address:

How long a gaseous bar can live?

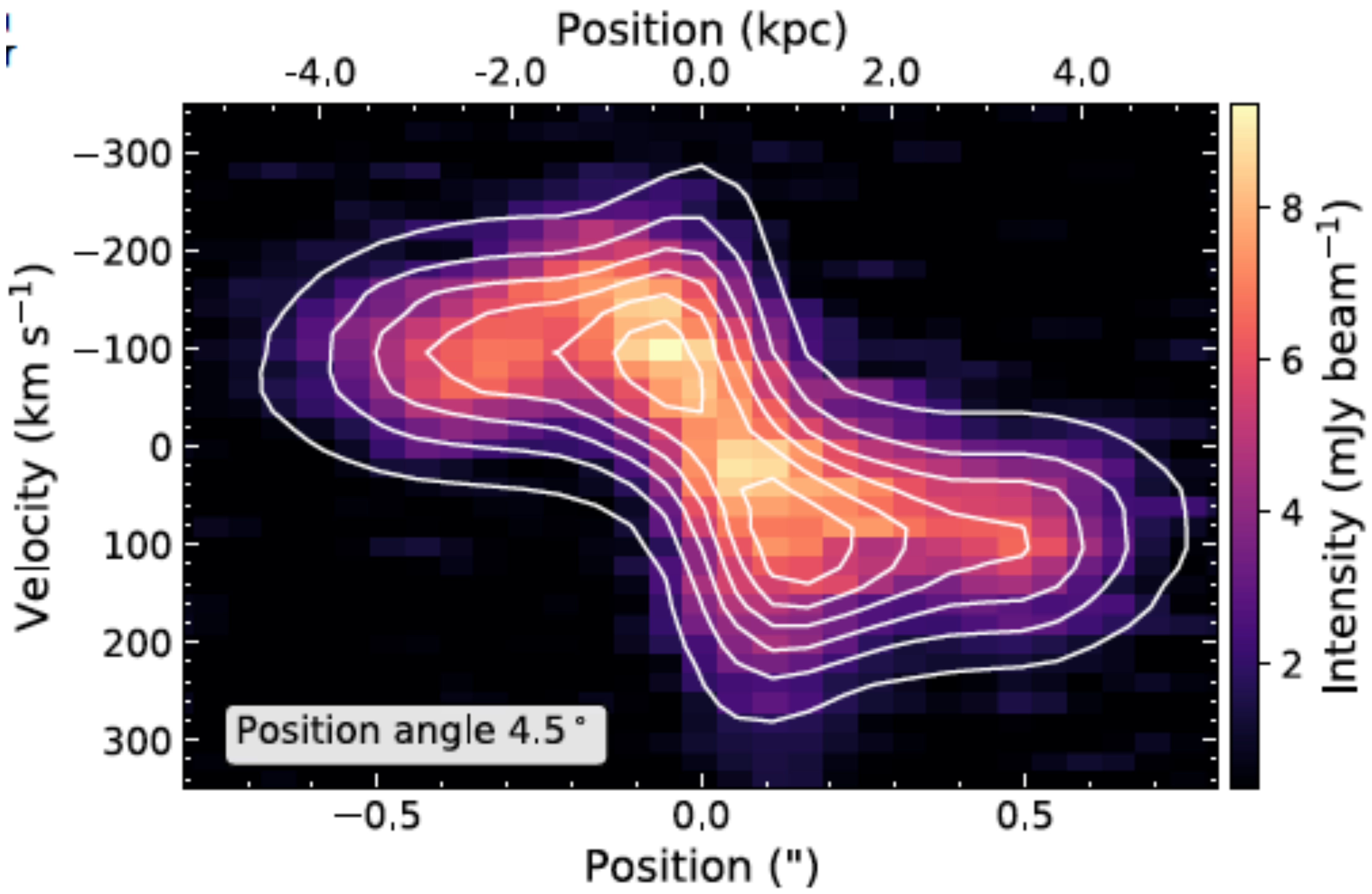
The gaseous bar can yield a stellar bar later?

How much gaseous bar can help the starburst and AGN activity?

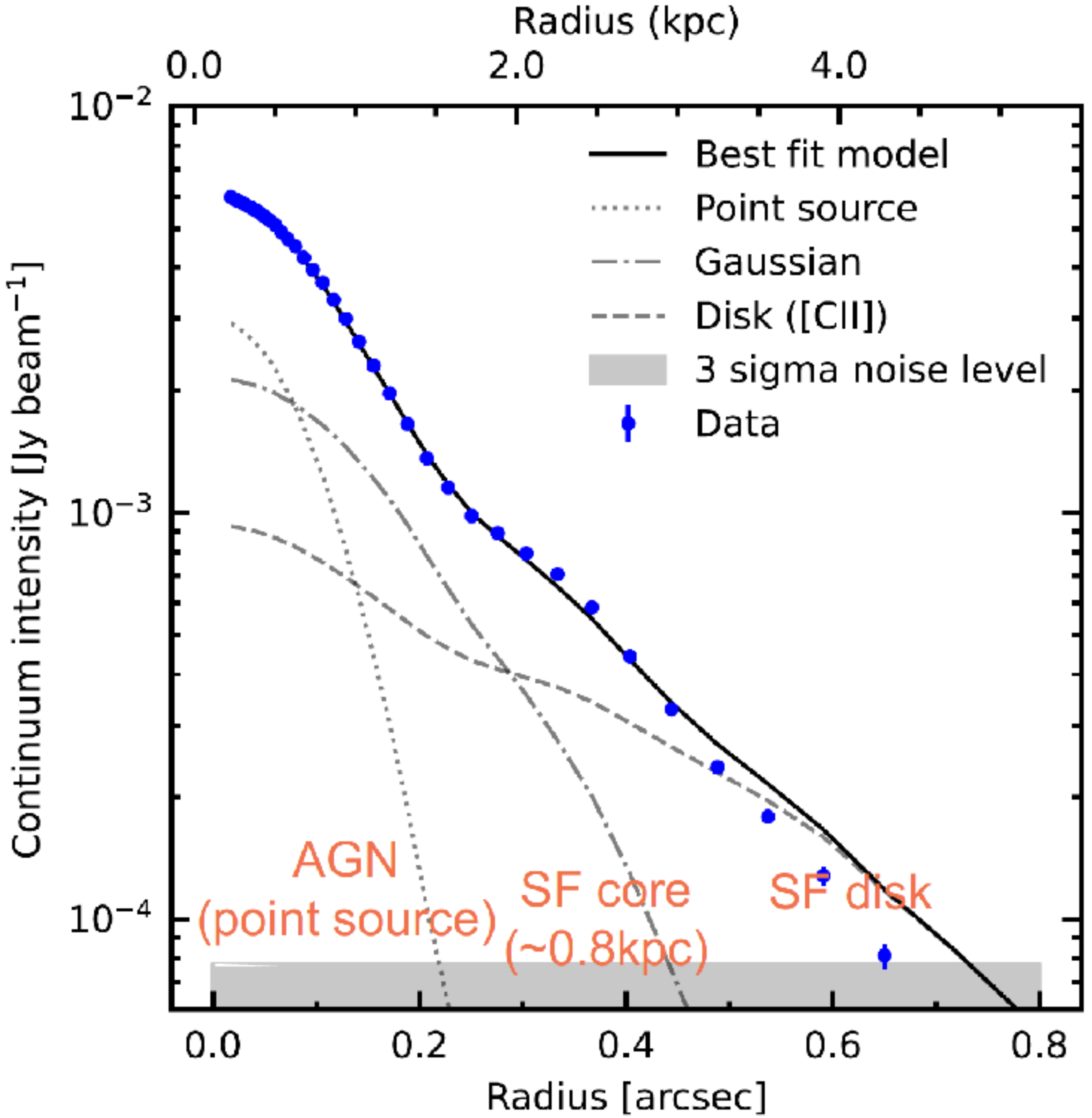


Cazes and Tohline+1999

Starforming bulge



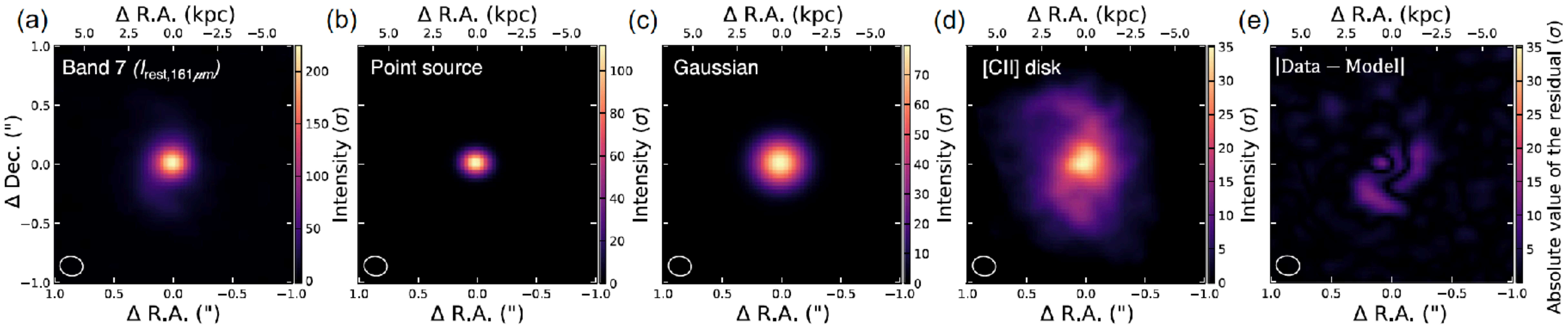
Band7 continuum distribution



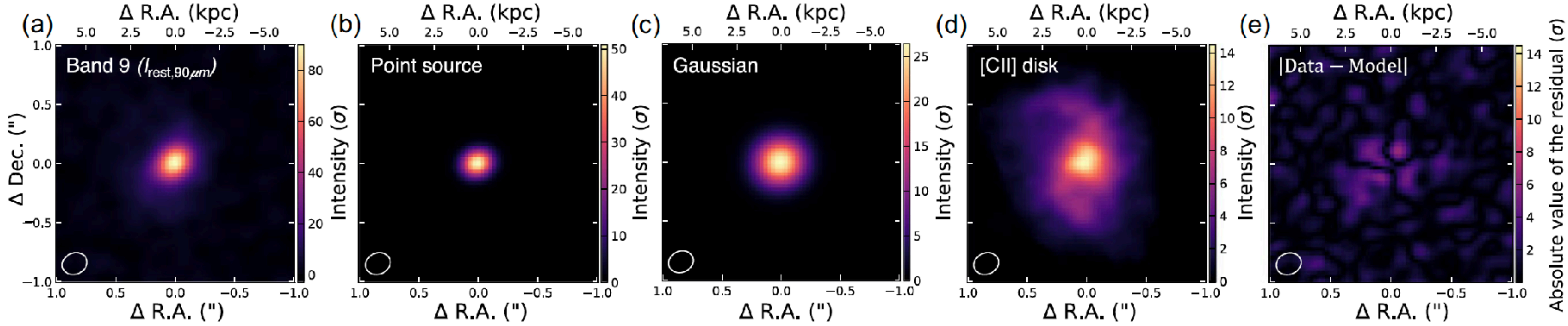
Bulge mass radius <1.3kpc is consistent with the size of the SF core ~800 pc

Image decomposition

- Band 7 image   Point source   Gaussian   [CII] temperate   Residual



- Band 9 image   Point source   Gaussian   [CII] temperate   Residual



A1. Dust temperature correlate with gas velocity dispersion?

- High dust temperature peaks preferentially aligned disk minor axis?
- [CII] velocity dispersion shows the conical enhanced structure.