A brief introduction to interstellar medium (ISM) observations

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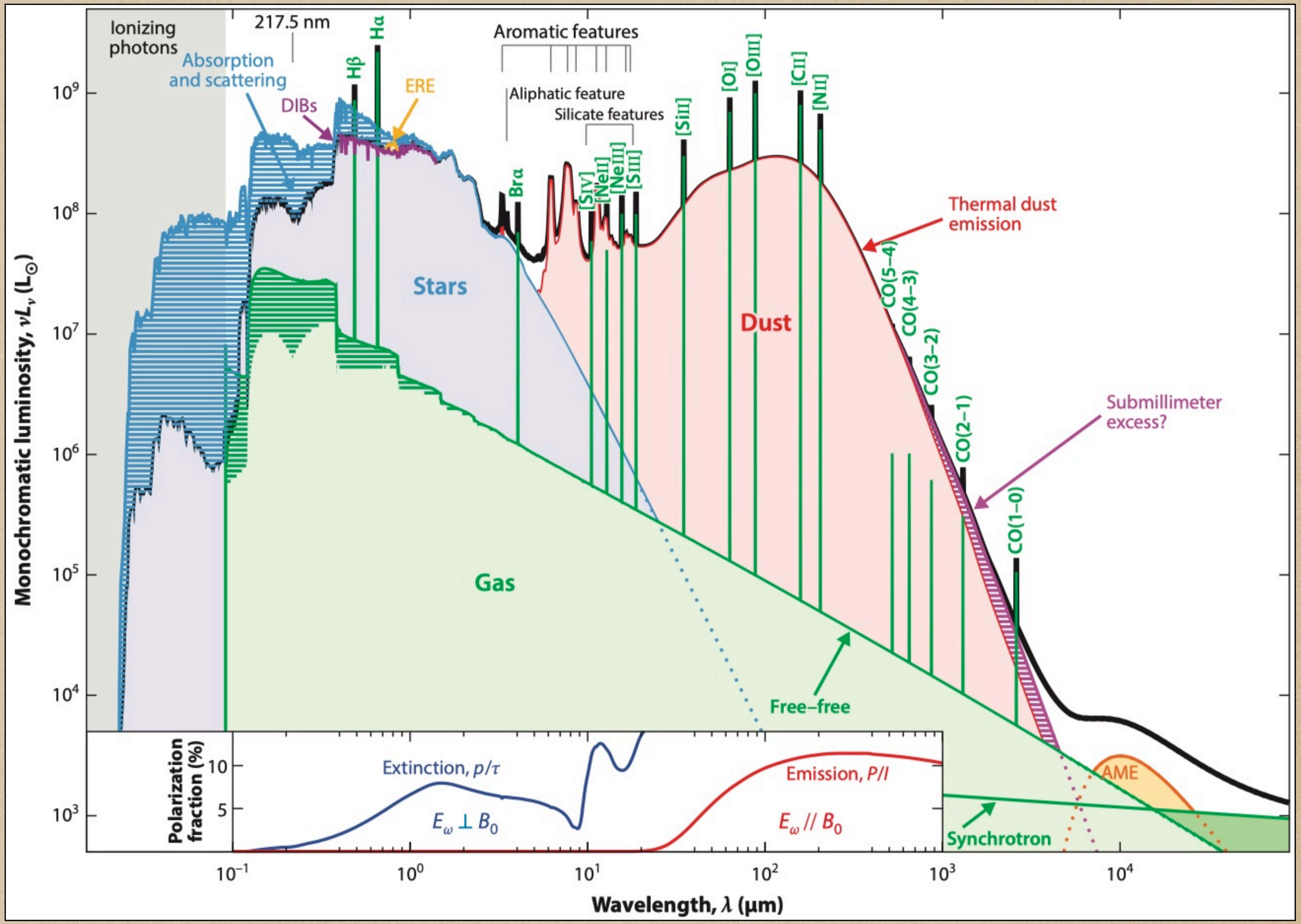
Baryonic component and ISM

Baryonic component:

- Stars, dust, gas, and metals

- Star: emits light mainly from FUV to NIR
- Dust: absorbs the FUV–optical light and reemits from MIR to FIR
- Metal: contribute to the reddening of the SED in the optical–NIR; emission lines
- Gas:
  - Hot gas: X-ray and UV
  - Ionized gas: Hα, Hβ, …
  - Neutral and molecular gas: from submillimeter to radio
  - Synchrotron: radio-loud AGN, radio continuum

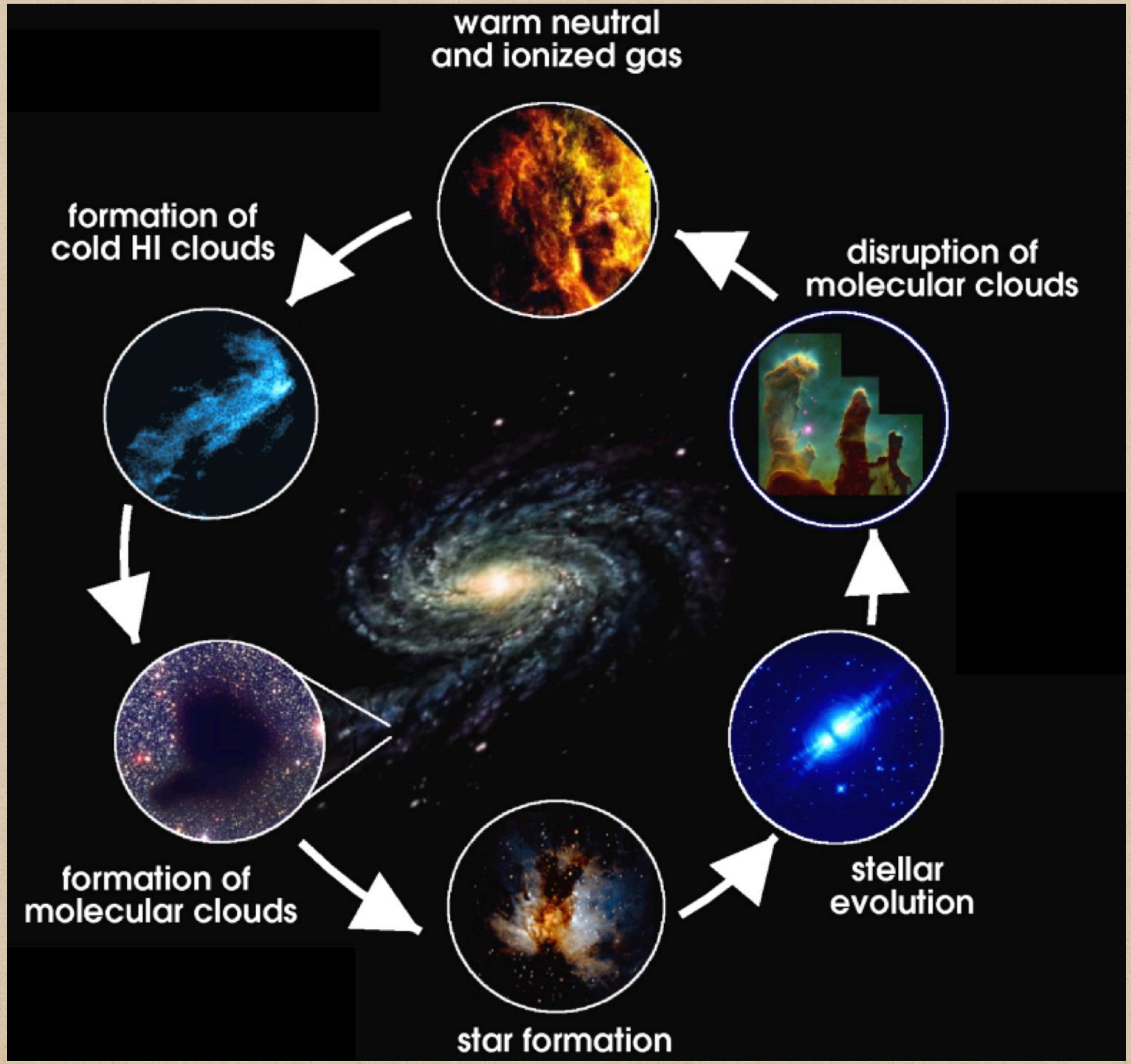


Galliano et al. 2018

Baryon cycle

Gas cool down

Metal enrichment



HI form H2 on the surface of dust grains

Emit gas and dust to galaxies from galactic wind, SN, etc.

Dense H2 gas form stars

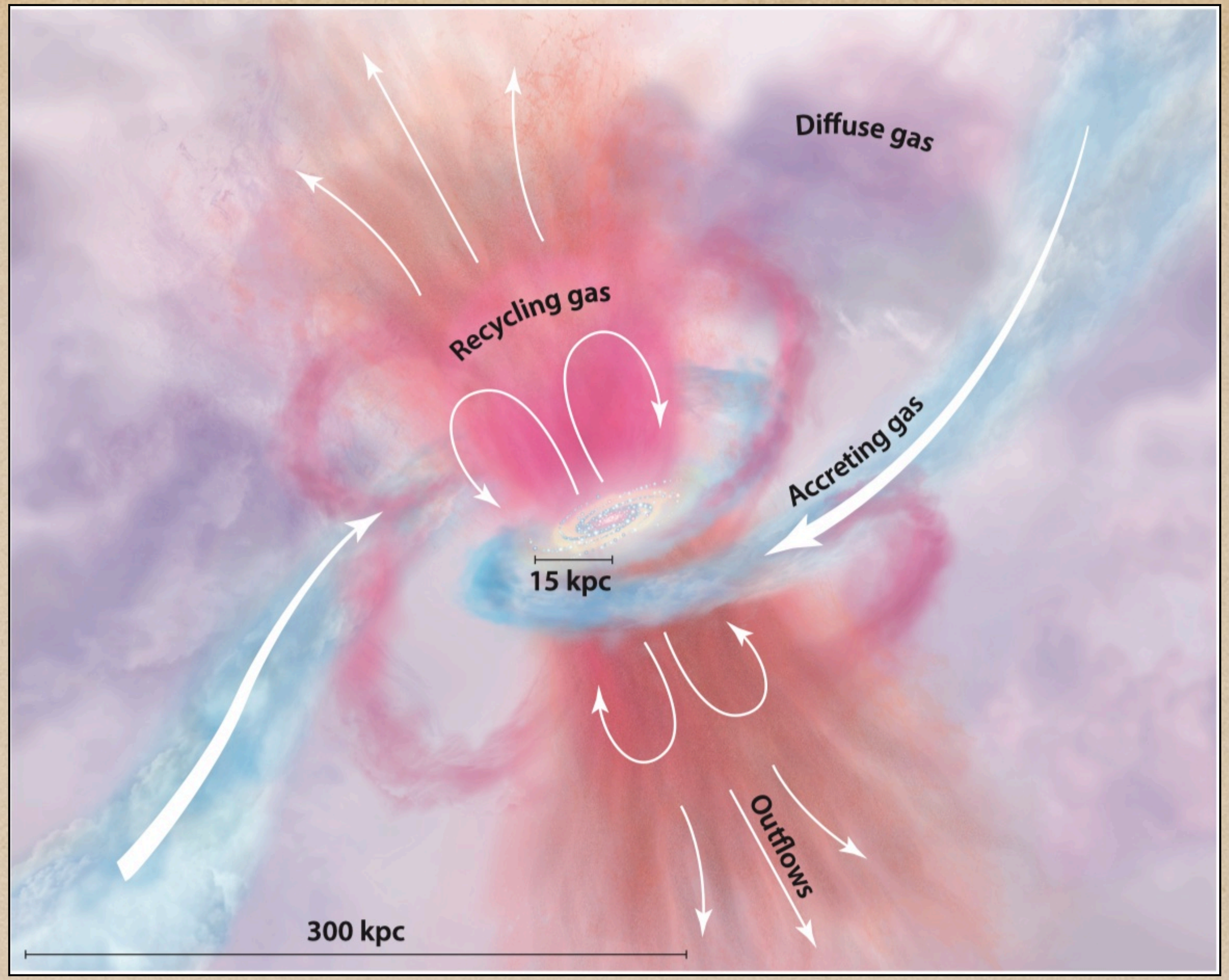
Star formation can be indicated by $H\alpha$ from the ionized HII region

Gas and star formation

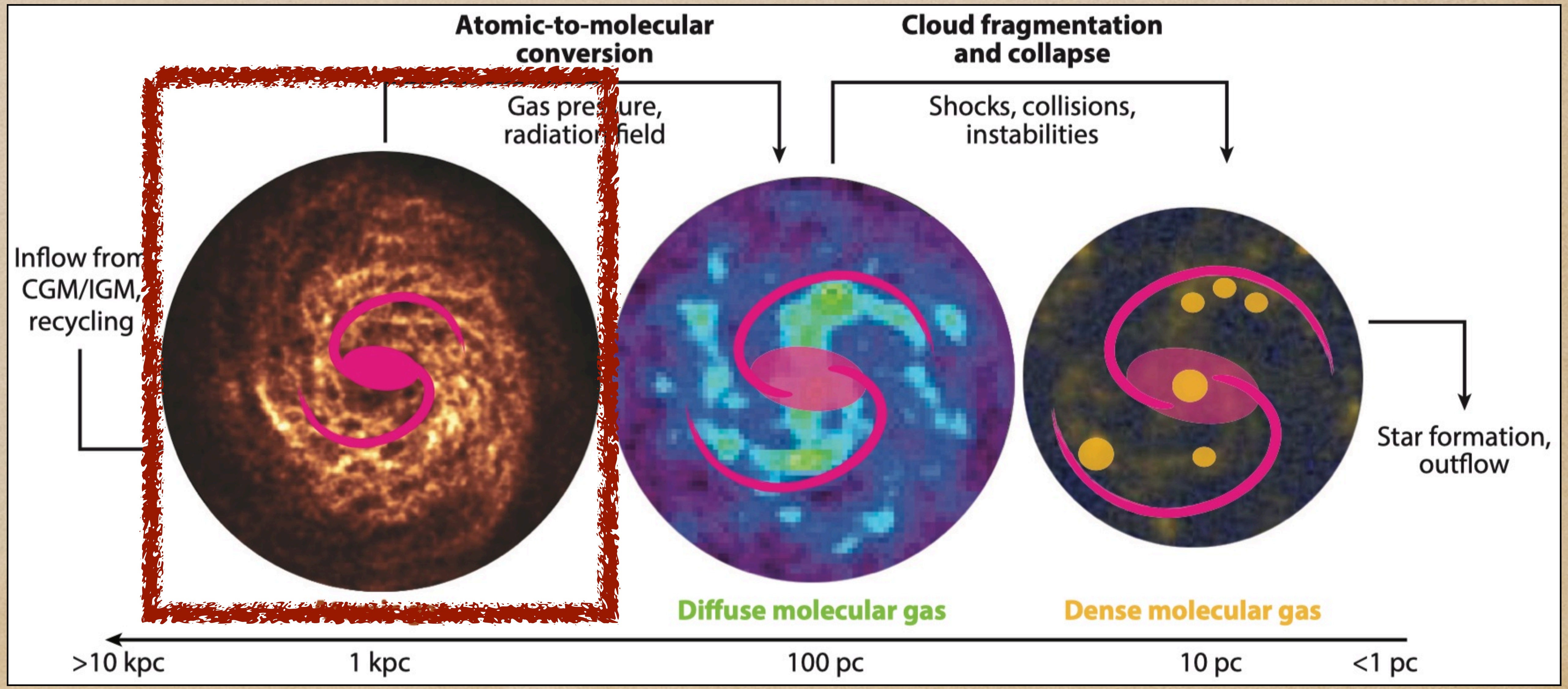
- Gas: A key component of the cosmic baryon cycle
- The fuel of star formation

$$\mathrm{SFR} = \frac{M_{\mathrm{gas}} \cdot \frac{M_{\mathrm{H2}}}{M_{\mathrm{gas}}} \cdot \frac{M_{\mathrm{dense}}}{M_{\mathrm{H2}}}}{t_{\mathrm{dep,dense}}}$$

- HI reservoir is insufficient
- A deep connection M_{gas} with the angular momentum and formation histories of the dark matter halos:
- Gas processes:
  - ✴ HI inflow, Recycling
  - ✴ Outflow (AGN, supernova), tidal stripping, ram pressure, …
- HI disk is more extended than the stellar disk



Tumlinson et al. 2017



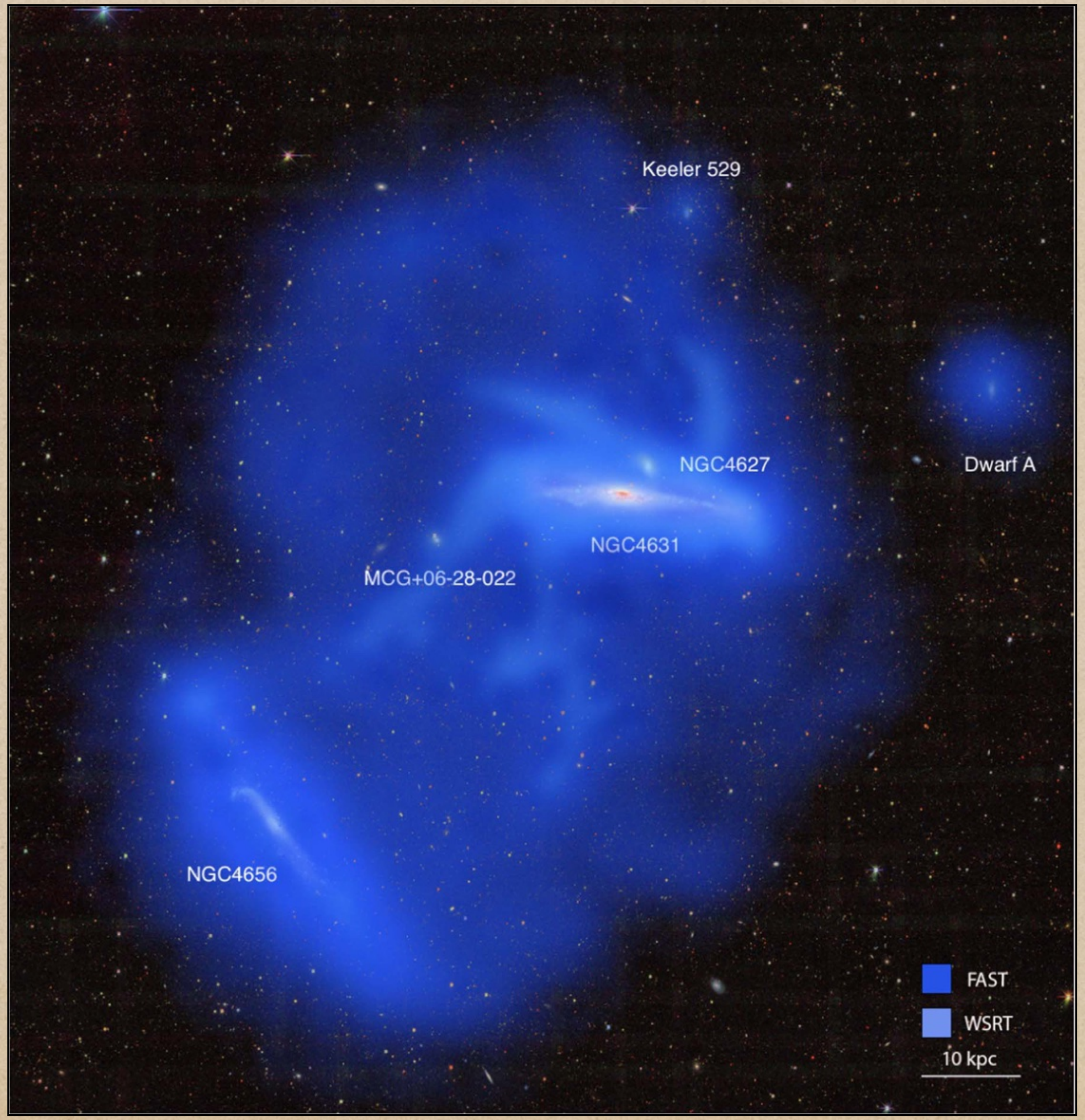
Saintonge and Catinella et al. 2022

Cold gas—— HI gas

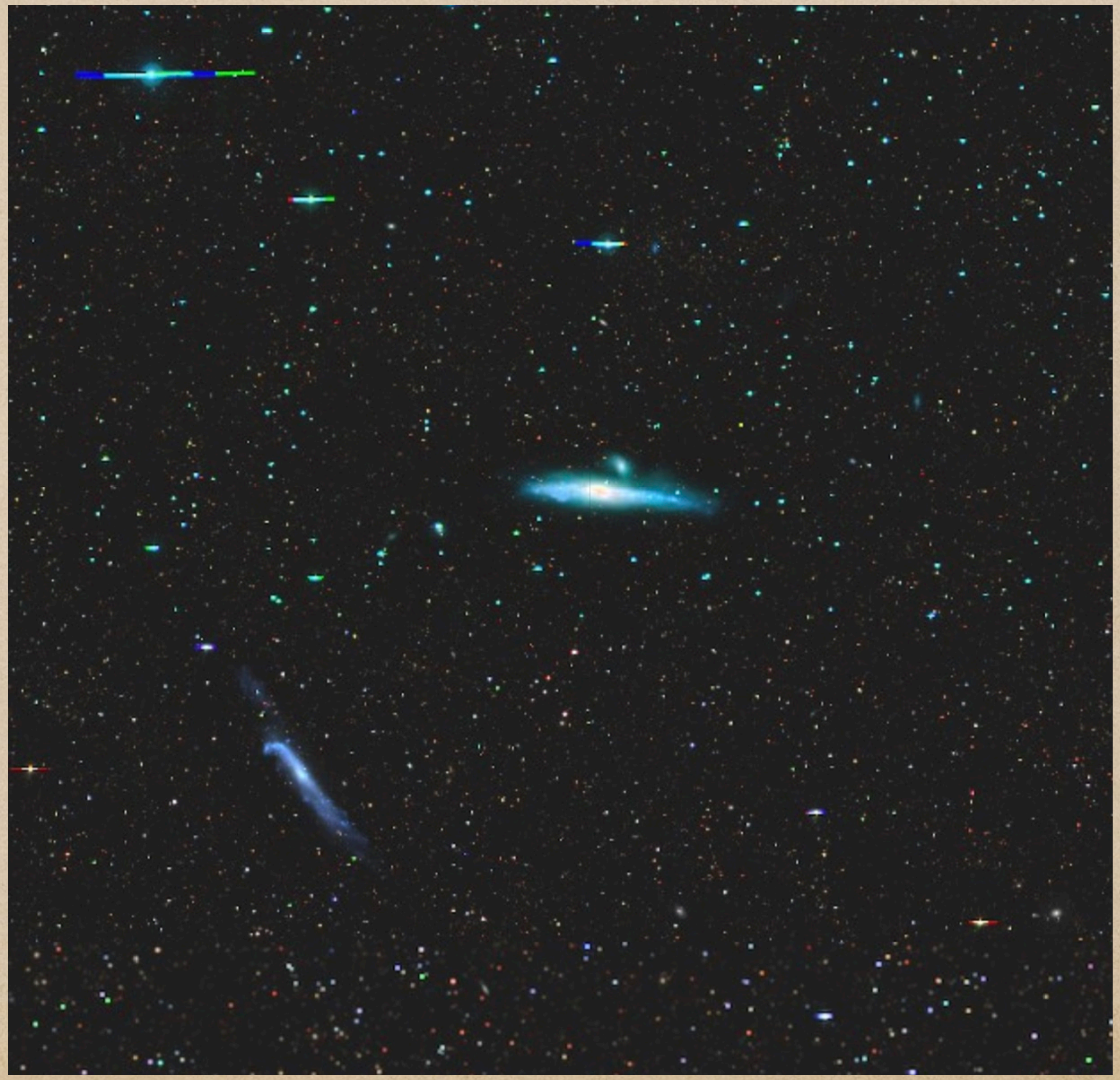
HI distribution:

- Extended
- Can be disturbed by the environment
- Reflect the interaction between galaxies

FAST and WSRT HI observations



DESI optical observations



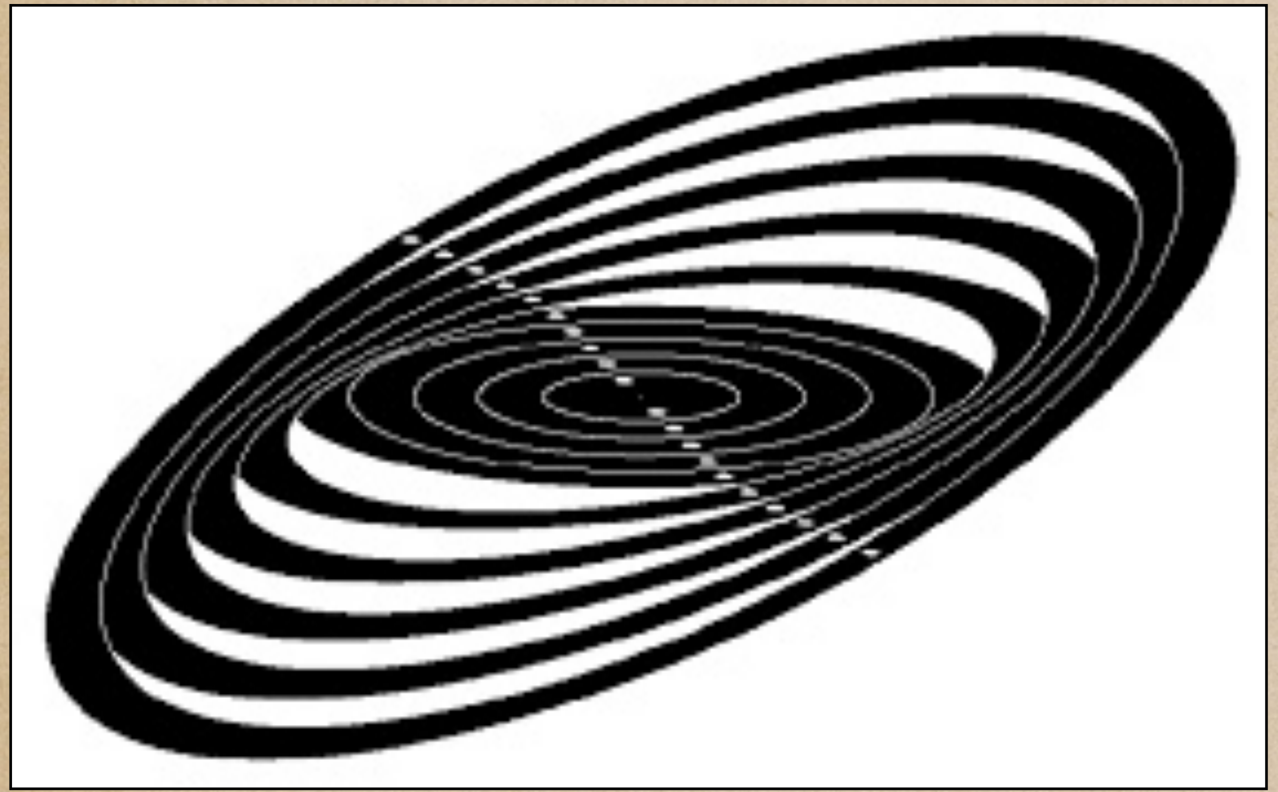
Wang et al. 2023

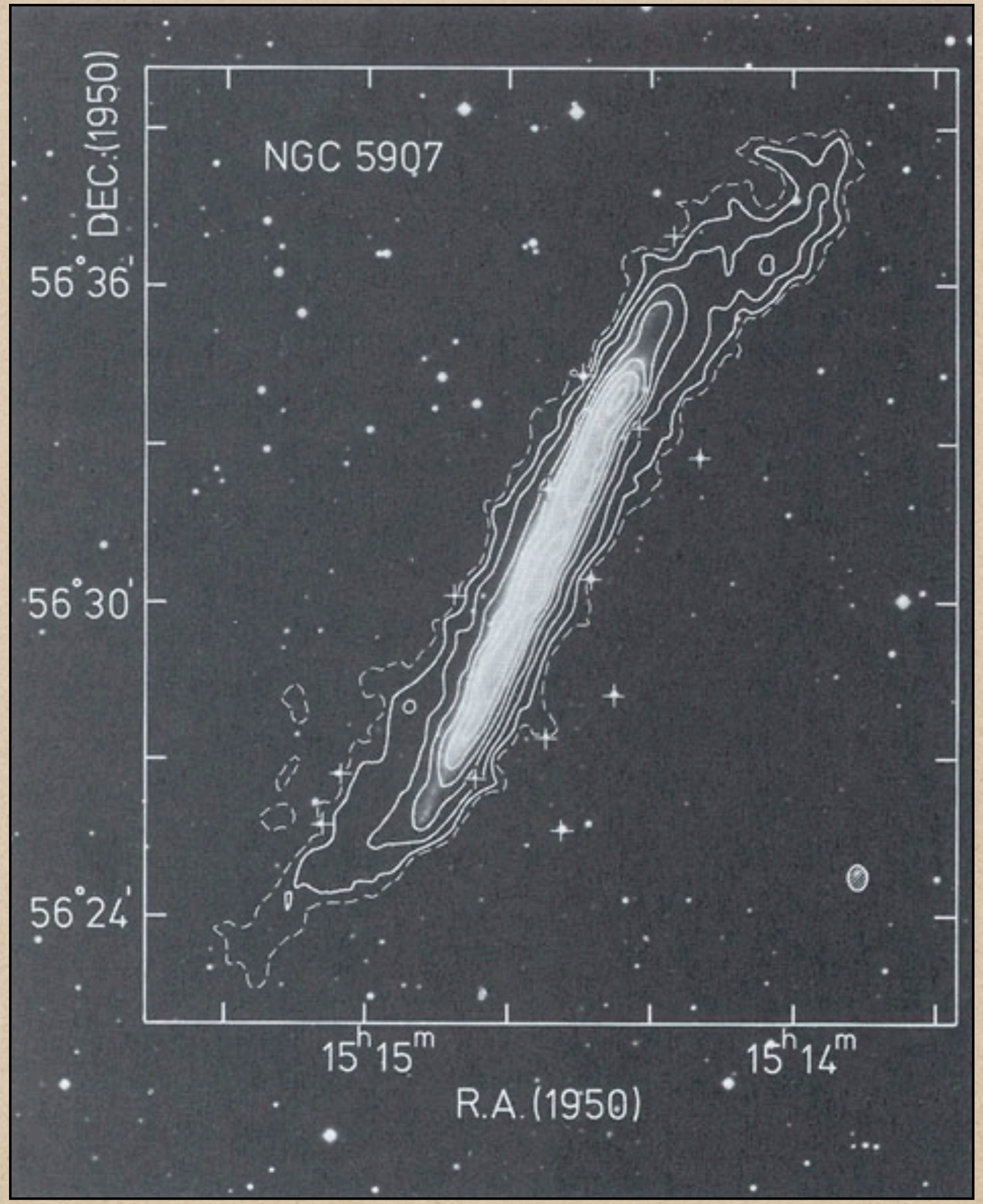
Cold gas ——HI gas

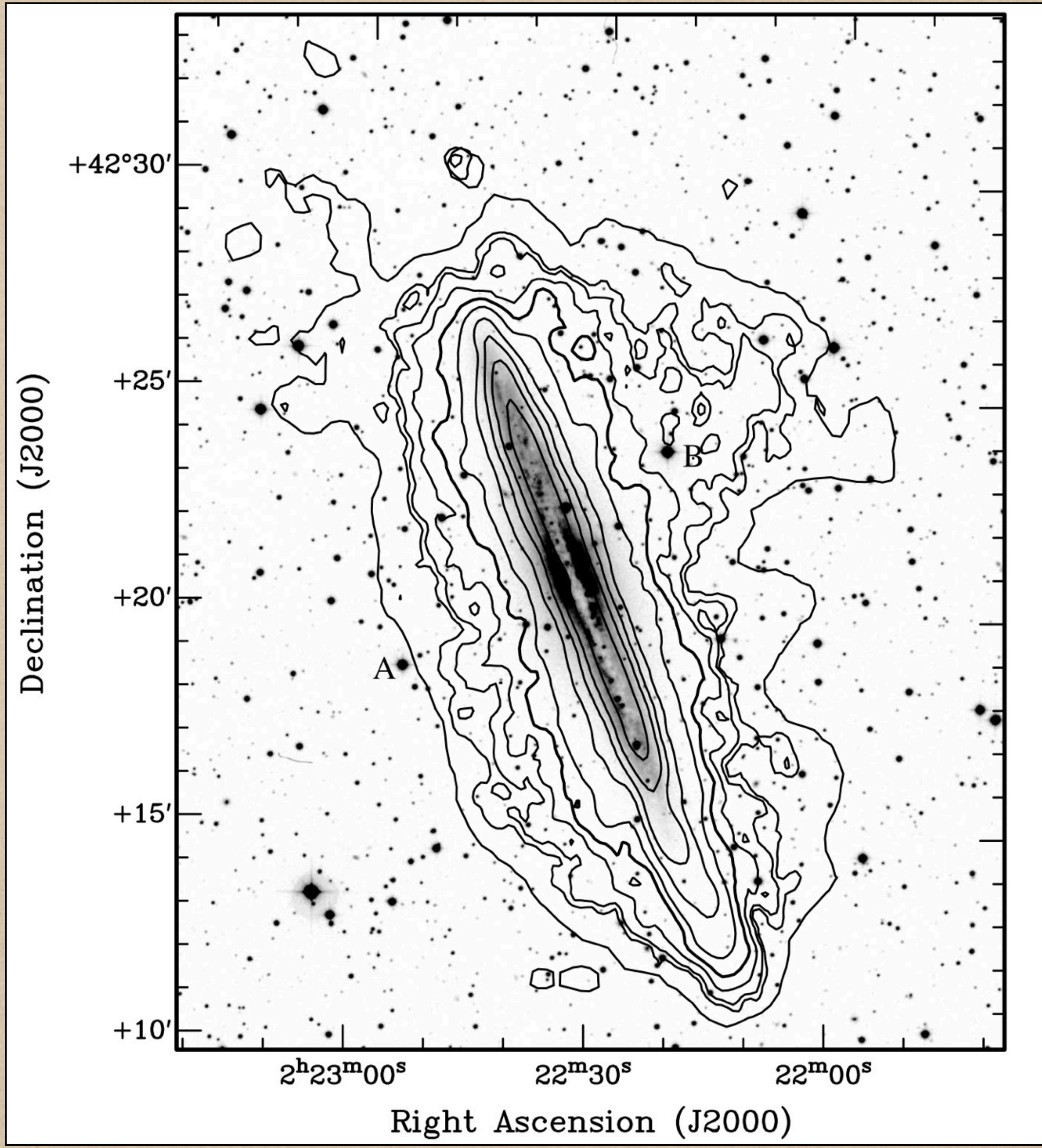
Sancisi & Allen et al. 1977

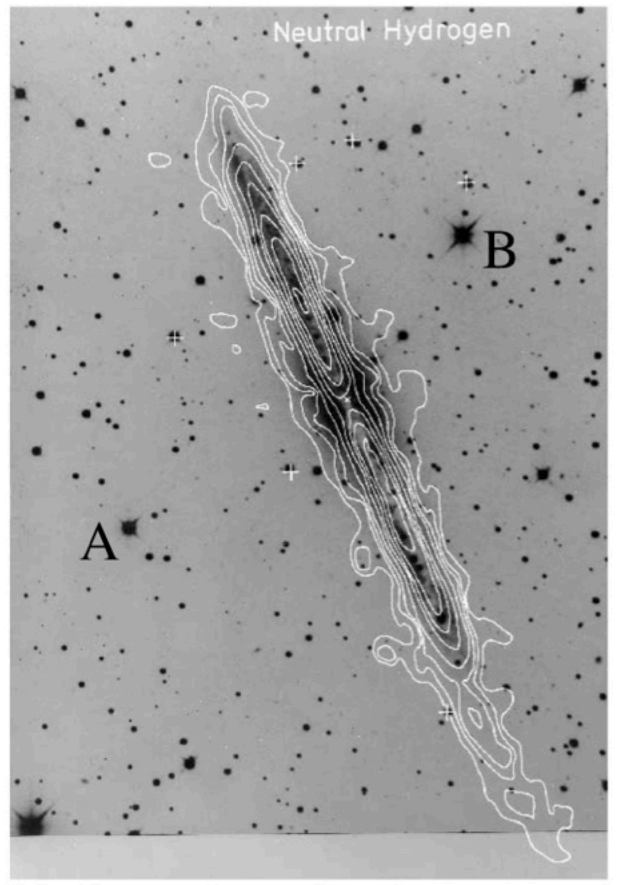
HI distribution:

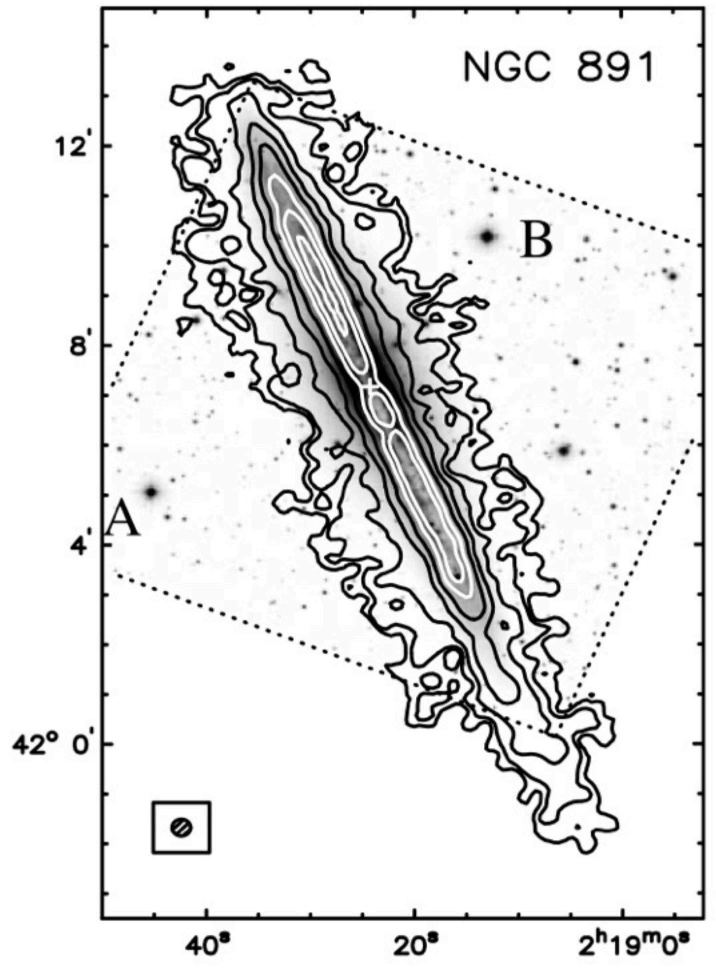
- Large HI halo (diffuse, low density)
- Warps
- Model: Tilted ring











From TiRiFiC

Sancisi et al. 1976

Swaters et al. 2007

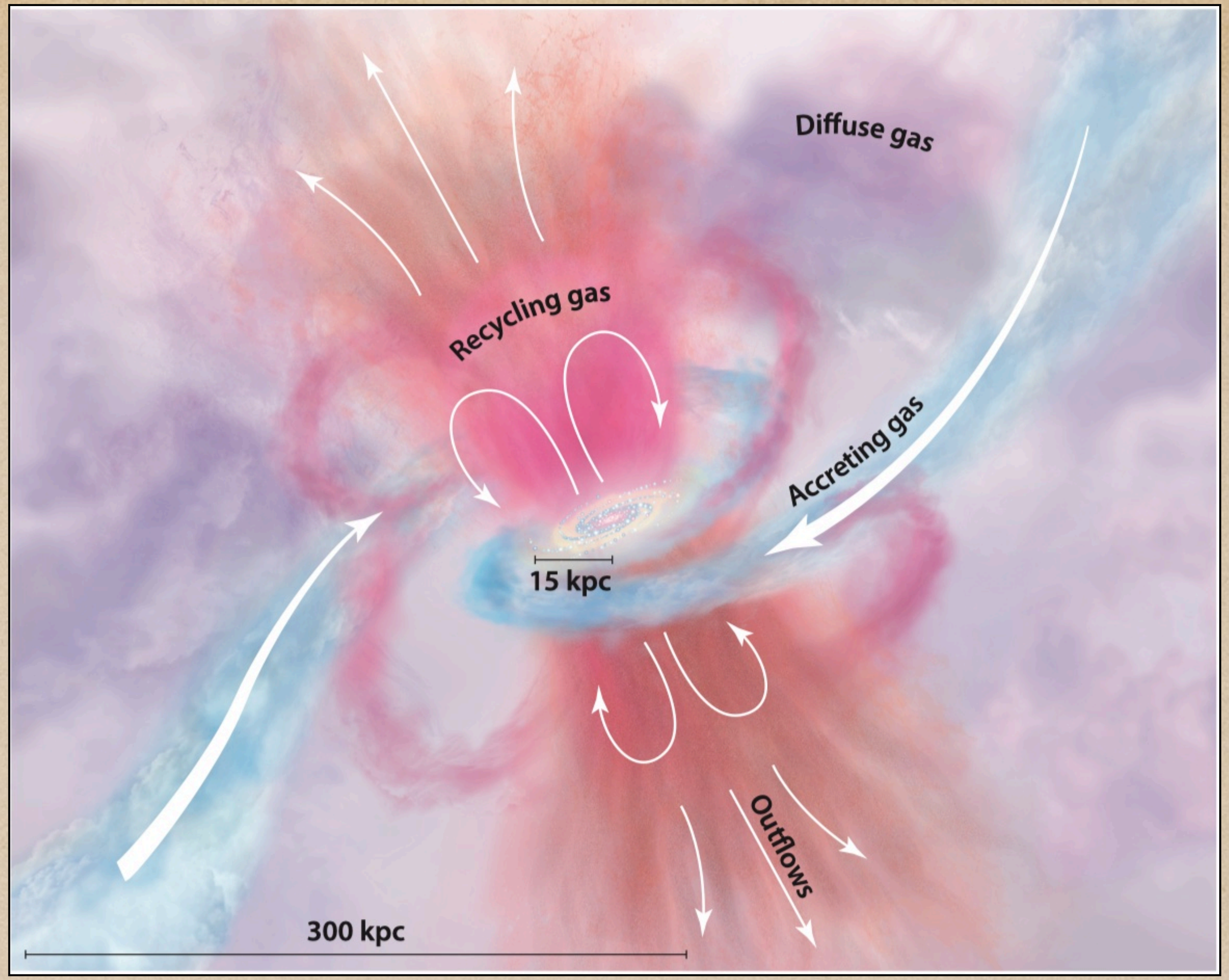
Swaters et al. 1997

Gas and star formation

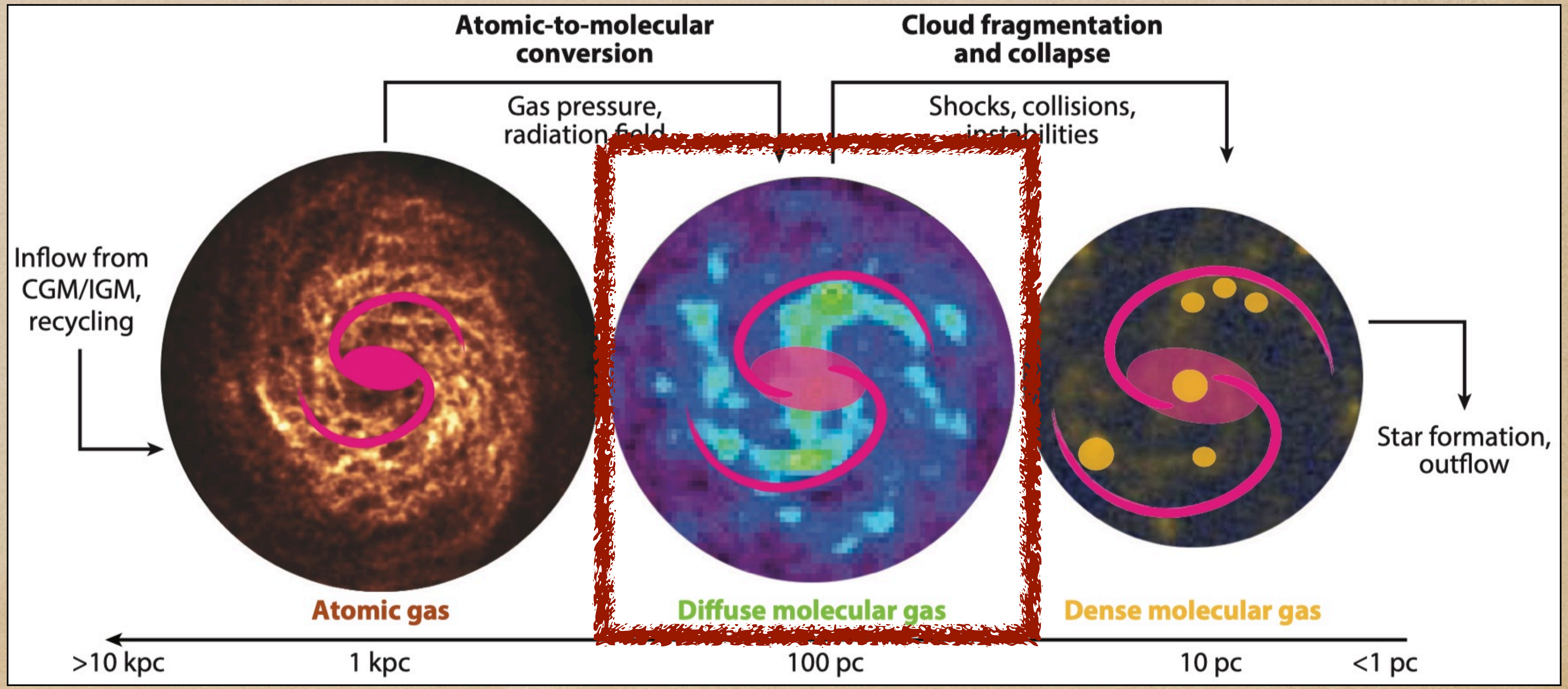
- A key component of the cosmic baryon cycle
- The fuel of star formation

$$\mathrm{SFR} = \frac{M_{\mathrm{gas}} \cdot \frac{M_{\mathrm{H2}}}{M_{\mathrm{gas}}} \cdot \frac{M_{\mathrm{dense}}}{M_{\mathrm{H2}}}}{t_{\mathrm{dep,dense}}}$$

- The molecular ratio ($M_{\mathrm{H2}}/M_{\mathrm{gas}}$):
  * Controlled by the conditions within galactic disks
  * Gas density, the strength of the UV field, temperature, dust, and metallicity



Tumlinson et al. 2017



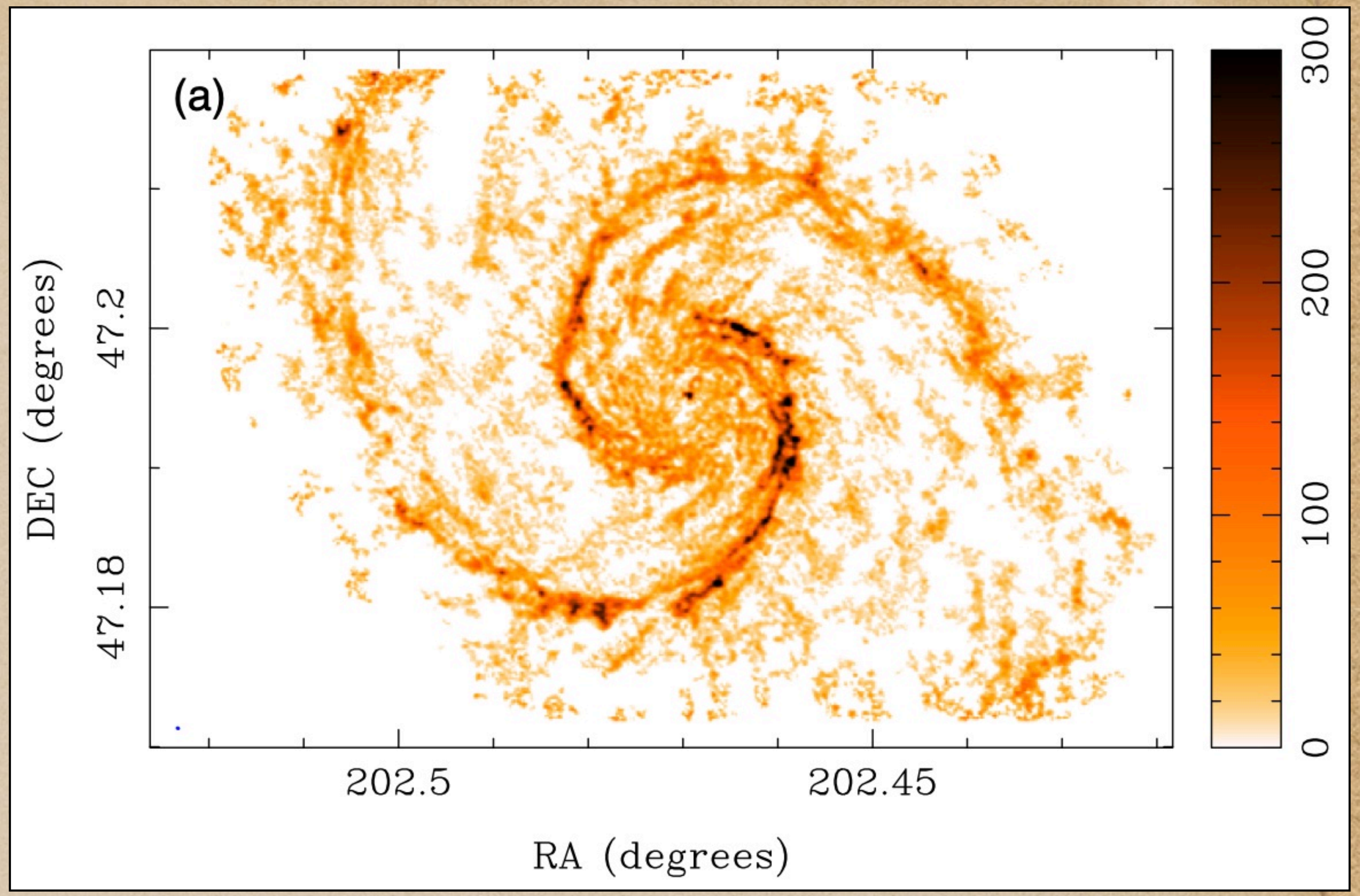
Saintonge and Ctinella et al. 2022

Cold gas —— HI ->H2

H2 distribution:

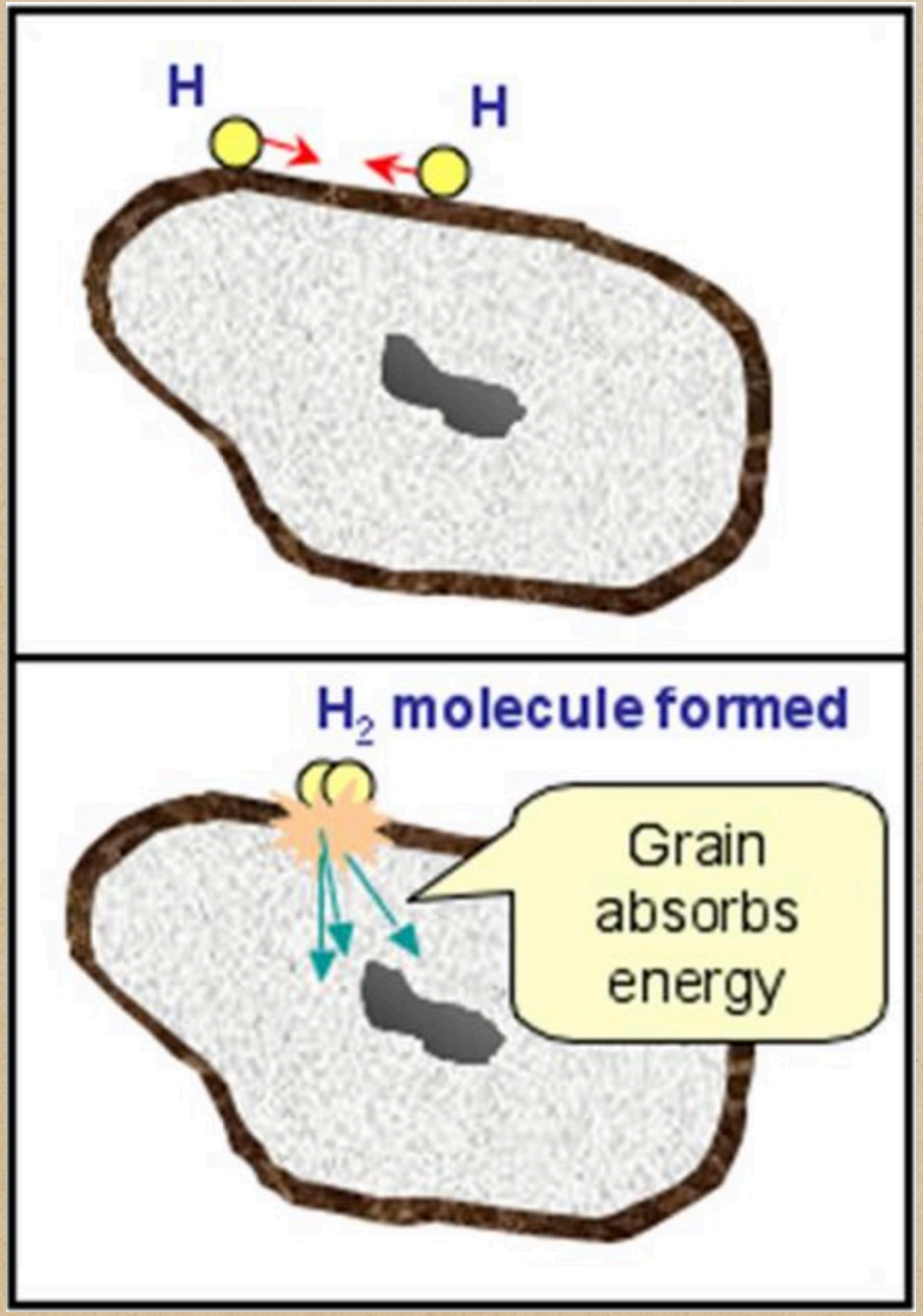
- Denser than HI
- clumpy

M51 CO gas

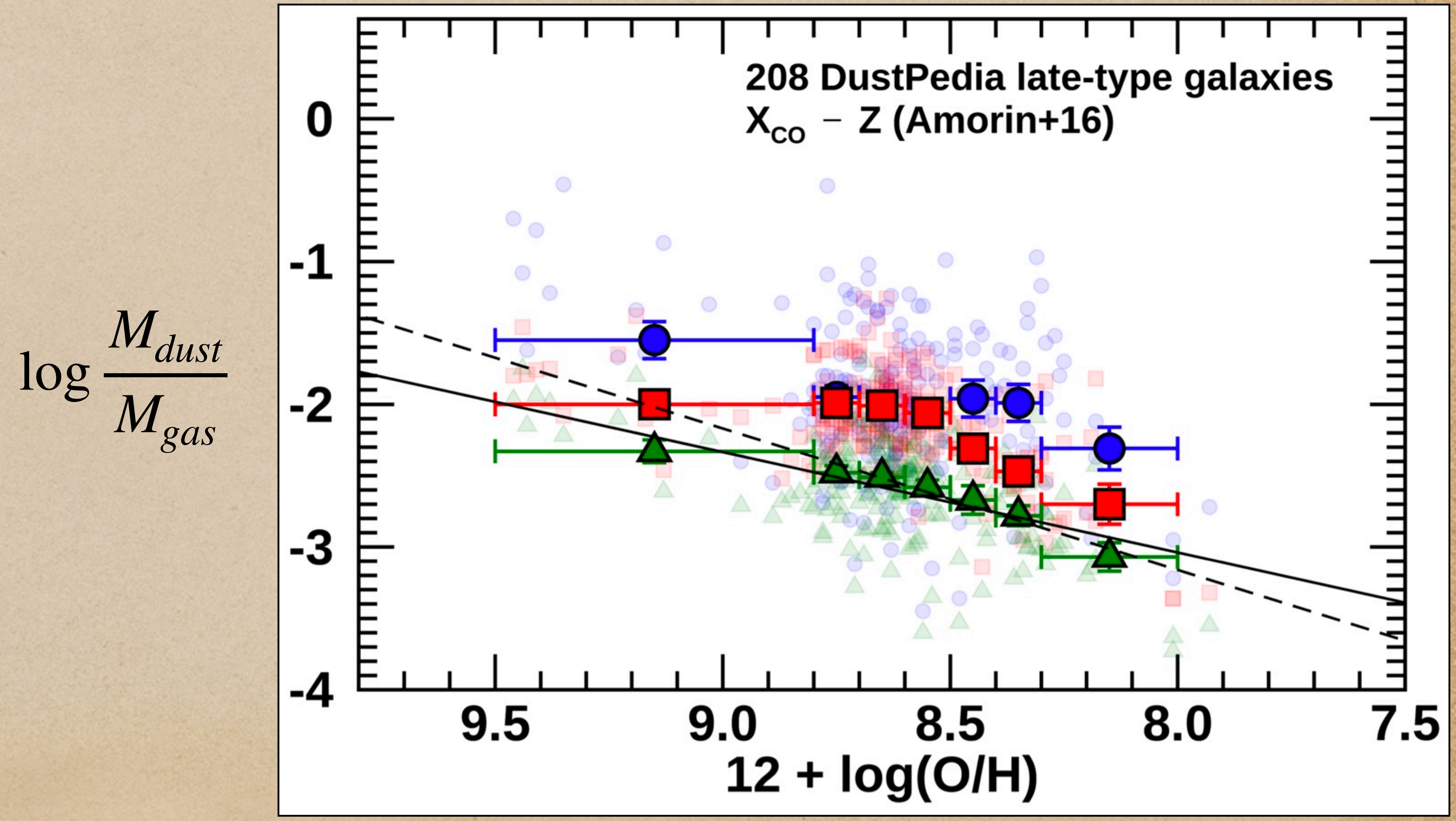


Schinnerer et al. 2013

catalyst (催化剂)



- HI can be absorbed onto dust to form H2
- Connect the dust with gas and star formation!
- Gas-to-dust ratio or dust-to-gas ratio
- Dust-to-gas ratio increases with the gas-phase metallicity



Casasola et al. 2020

Gas and star formation

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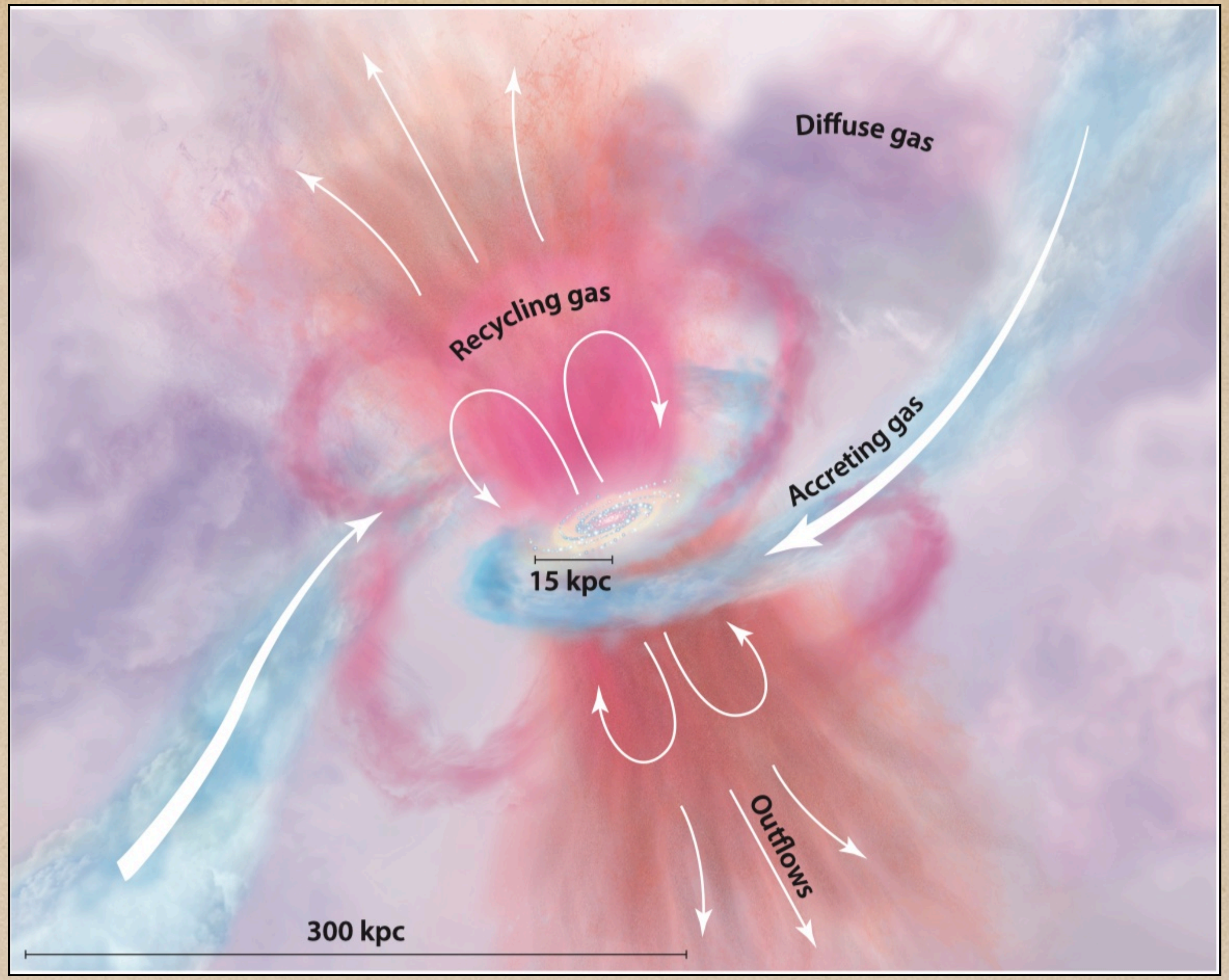
- The dense molecular mass (M_{dense}):
  - Jeans instability:
    - Mass, radiation, angular momentum
  - Toomre Q parameter:
    - Gas and stars



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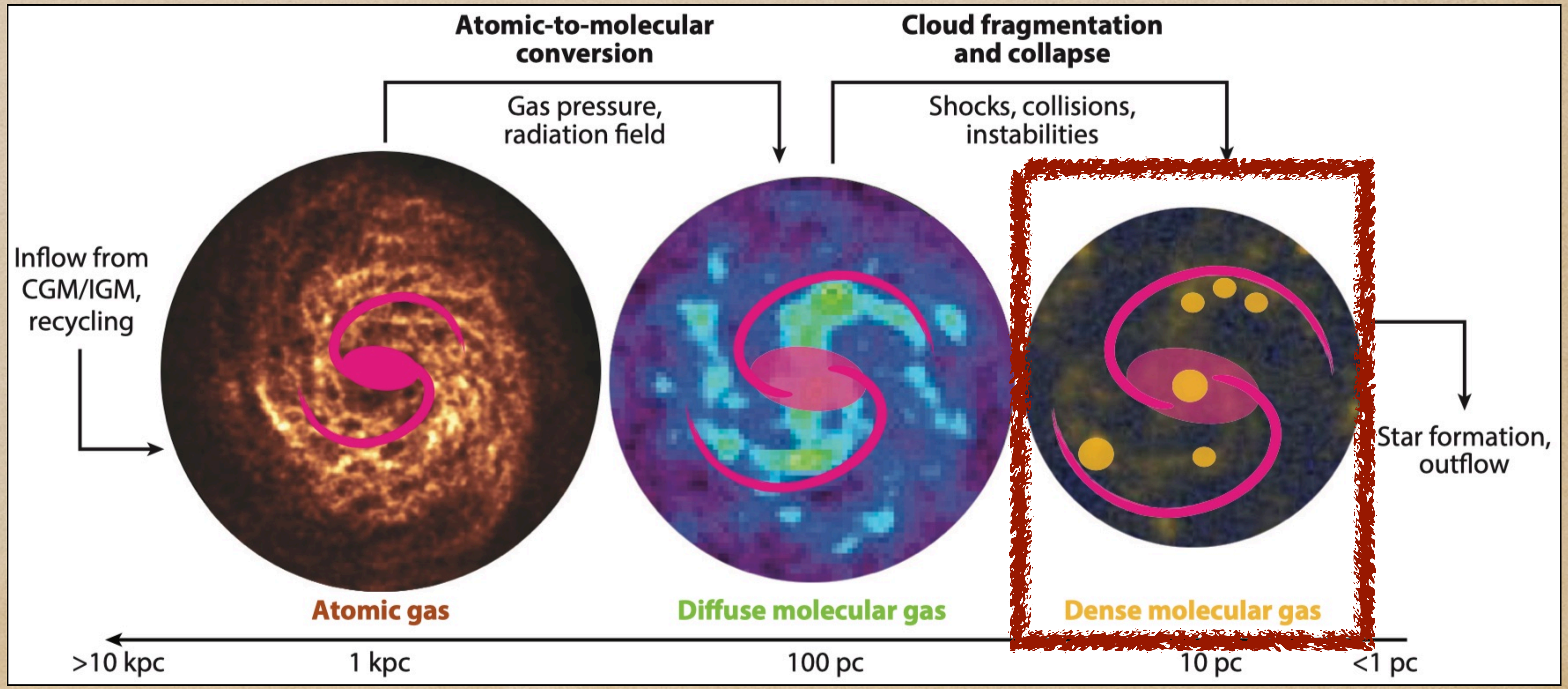
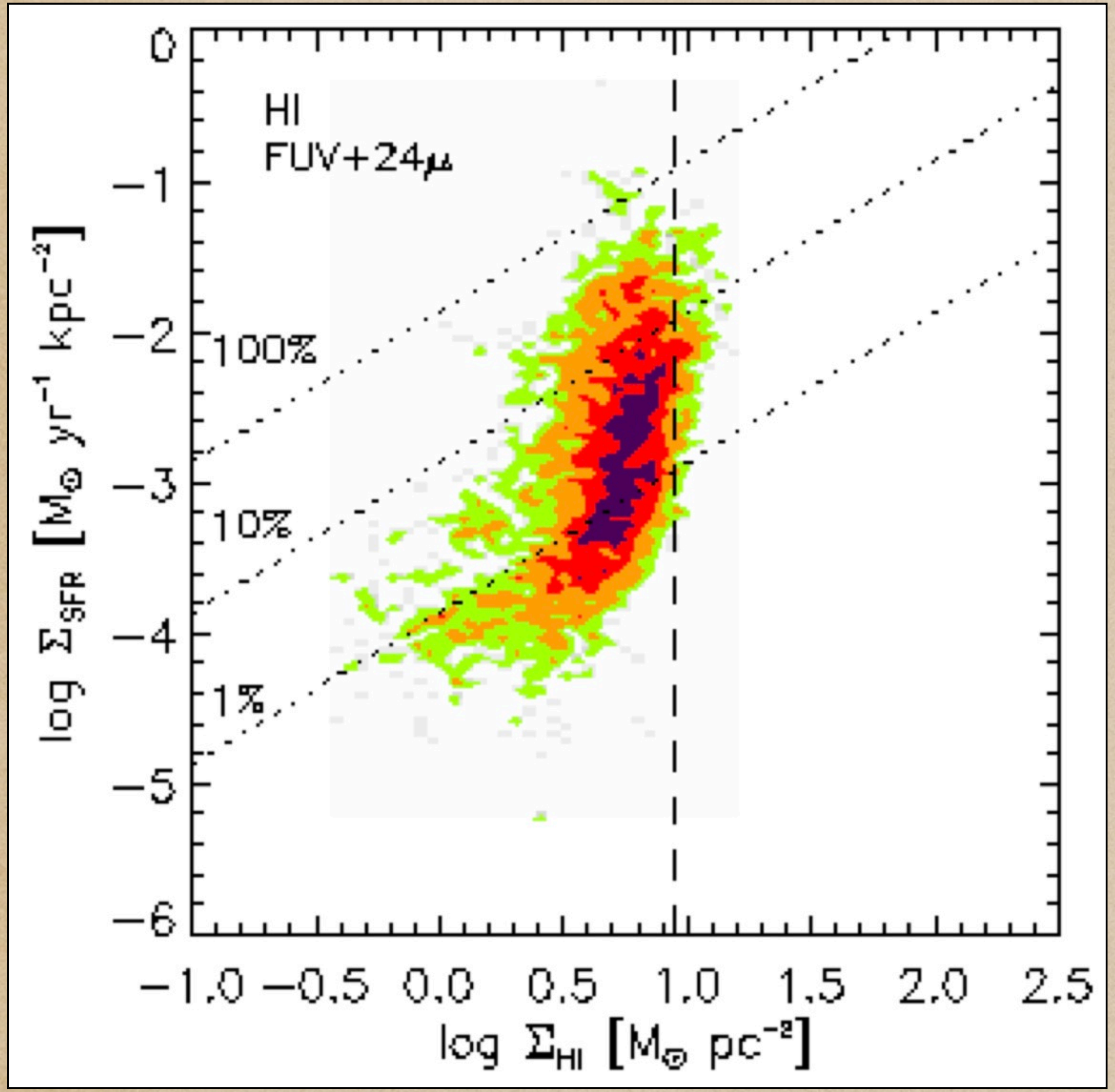
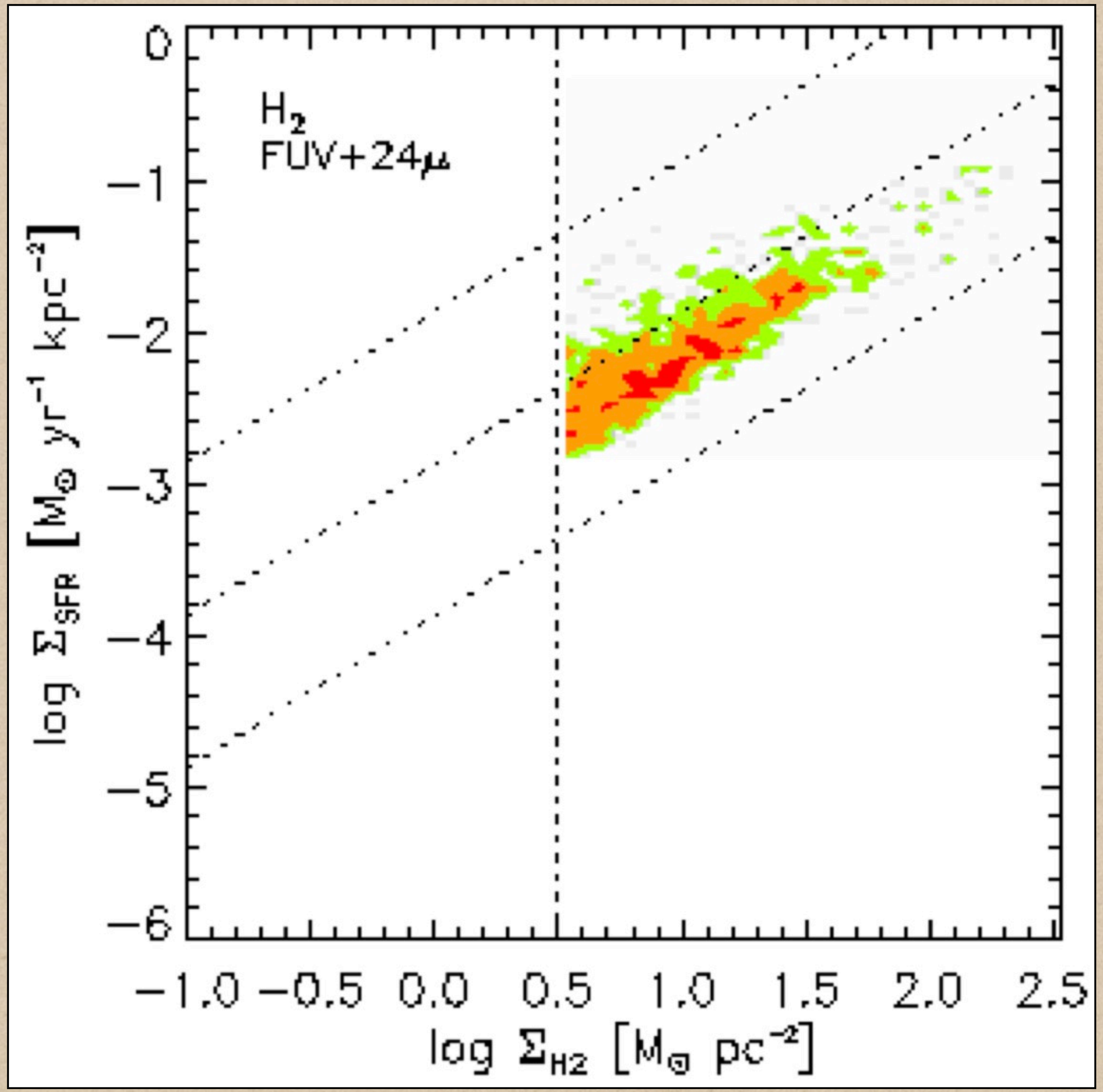


Saintonge and Catinella et al. 2022

Cold gas —— KS law





Bigiel et al. 2009

HI (left panel):

- SFR is not strongly correlated with HI
- Dashed line: HI saturate (9 $M_{\odot}$ pc^{-2})
- < 1 $M_{\odot}$ pc^{-2}: can be easily disturbed by the environmental effects

H2 (right panel):

- H2 form stars at a constant efficiency

Cold gas —— low star formation region

Lower star formation rate in the outer part of galaxies:

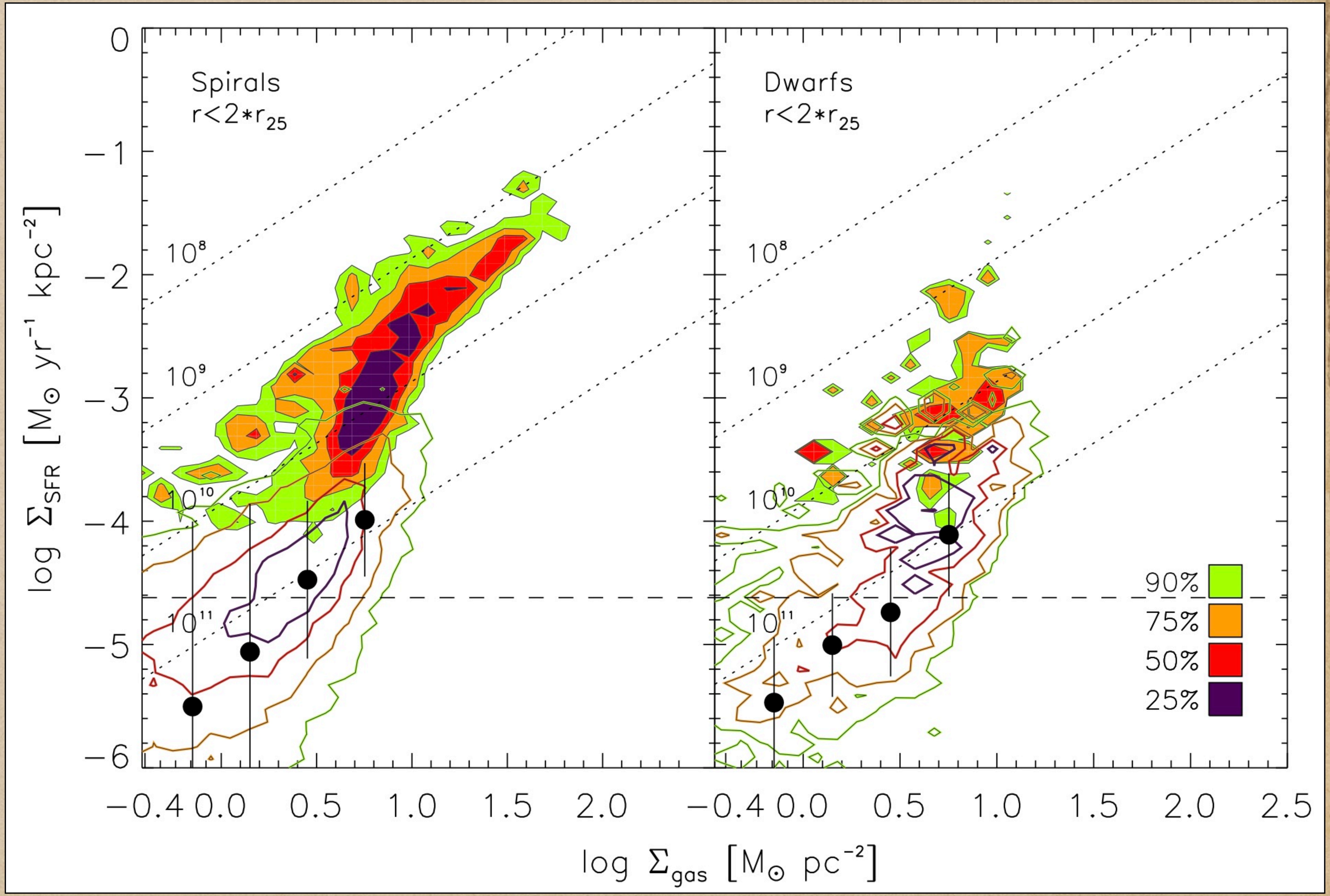
- Low surface density
- Lack of dust or metallicity

Dwarf galaxies show a similar relation with the outer part of spirals:

- Both have low gas surface density and gas-phase metallicity

In the outer part of galaxies:

- SF region shows tight spatial connection with HI



Bigiel et al. 2010

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Optical

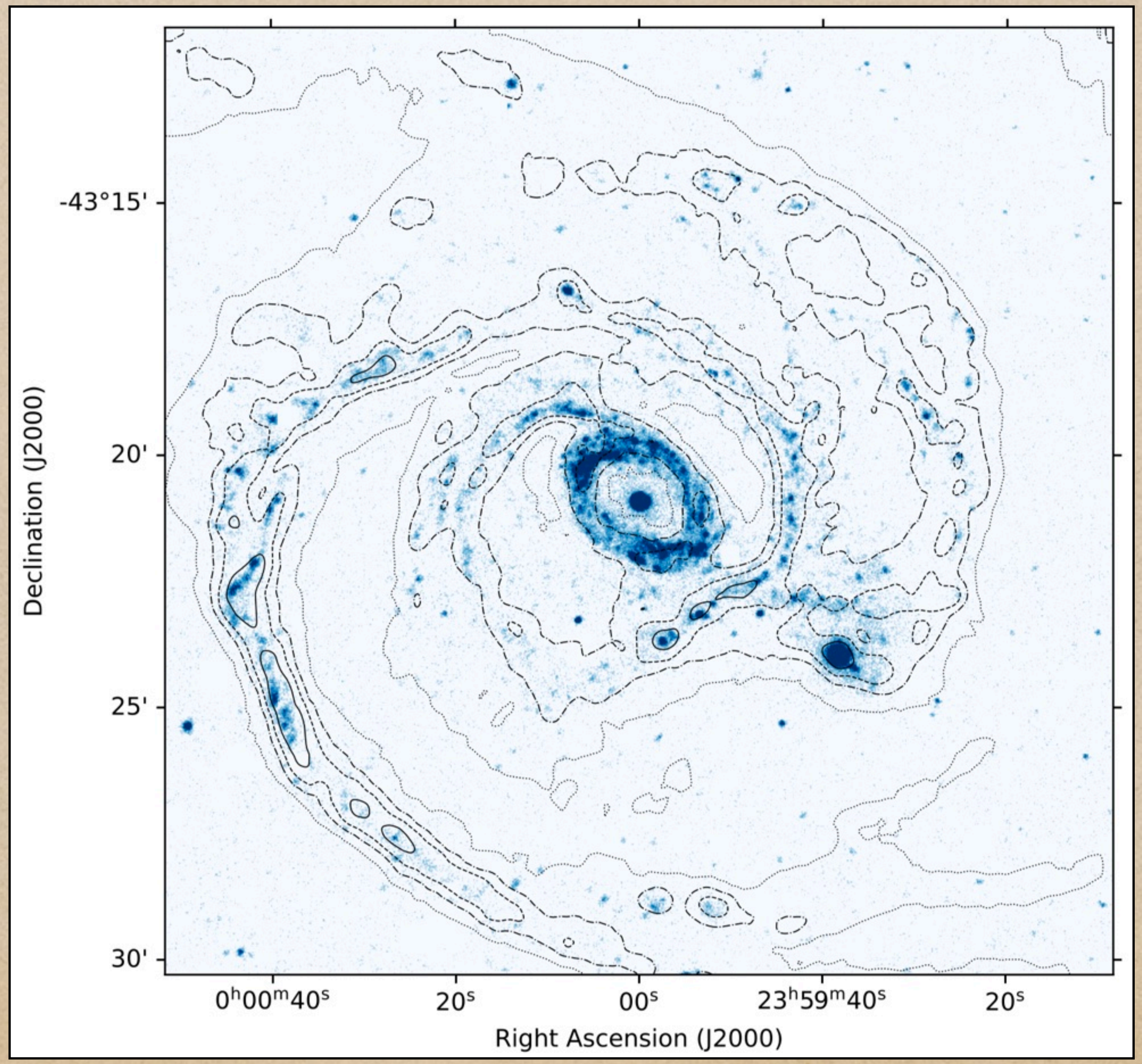


Image: UV

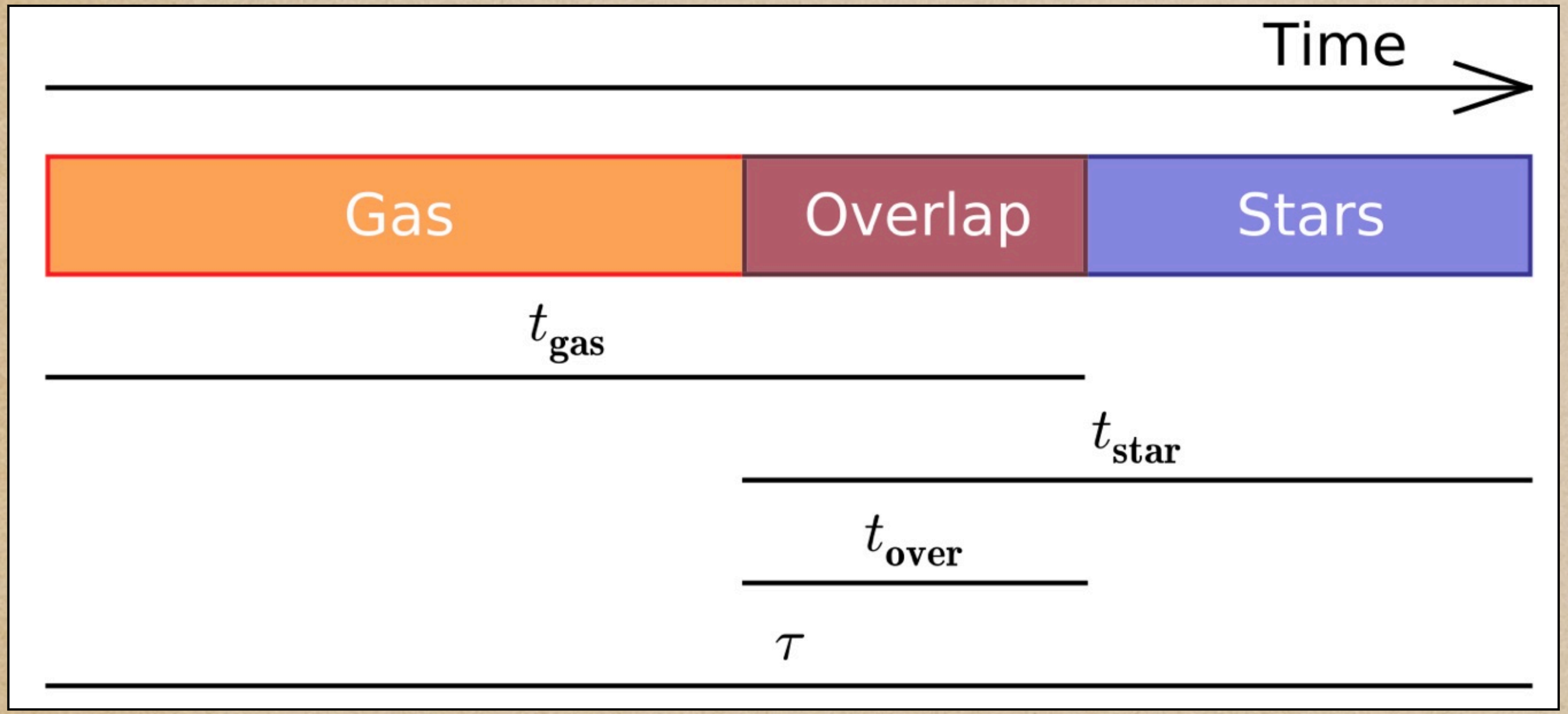
Contours: HI

Elson et al. 2023

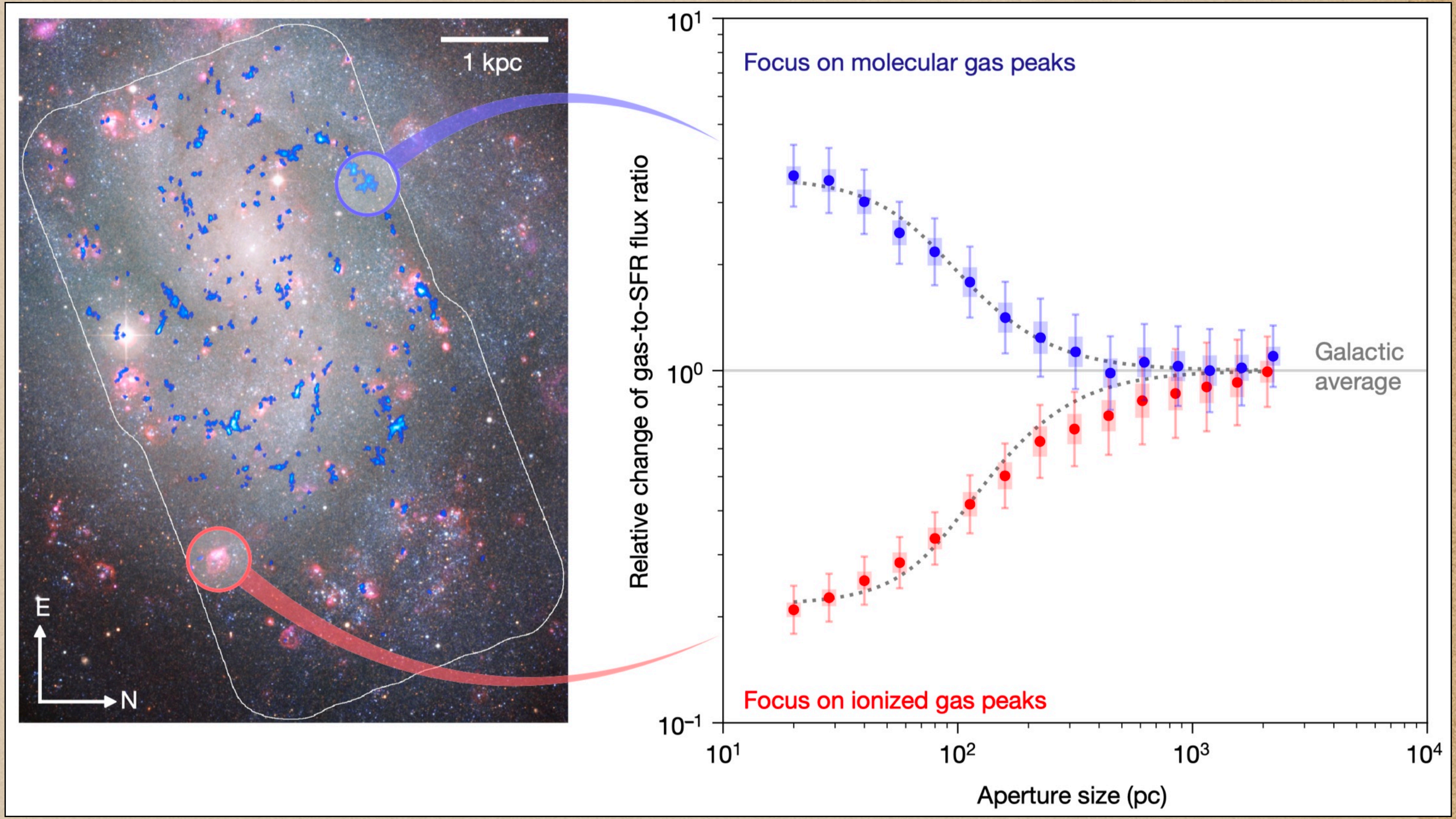
Cold gas —— H2 vs SFR

The H2 gas and star formation:

- Spatially decorrelated on the scale of giant molecular clouds
- Tight correlation on galactic scales



Kruijssen et al. 2018

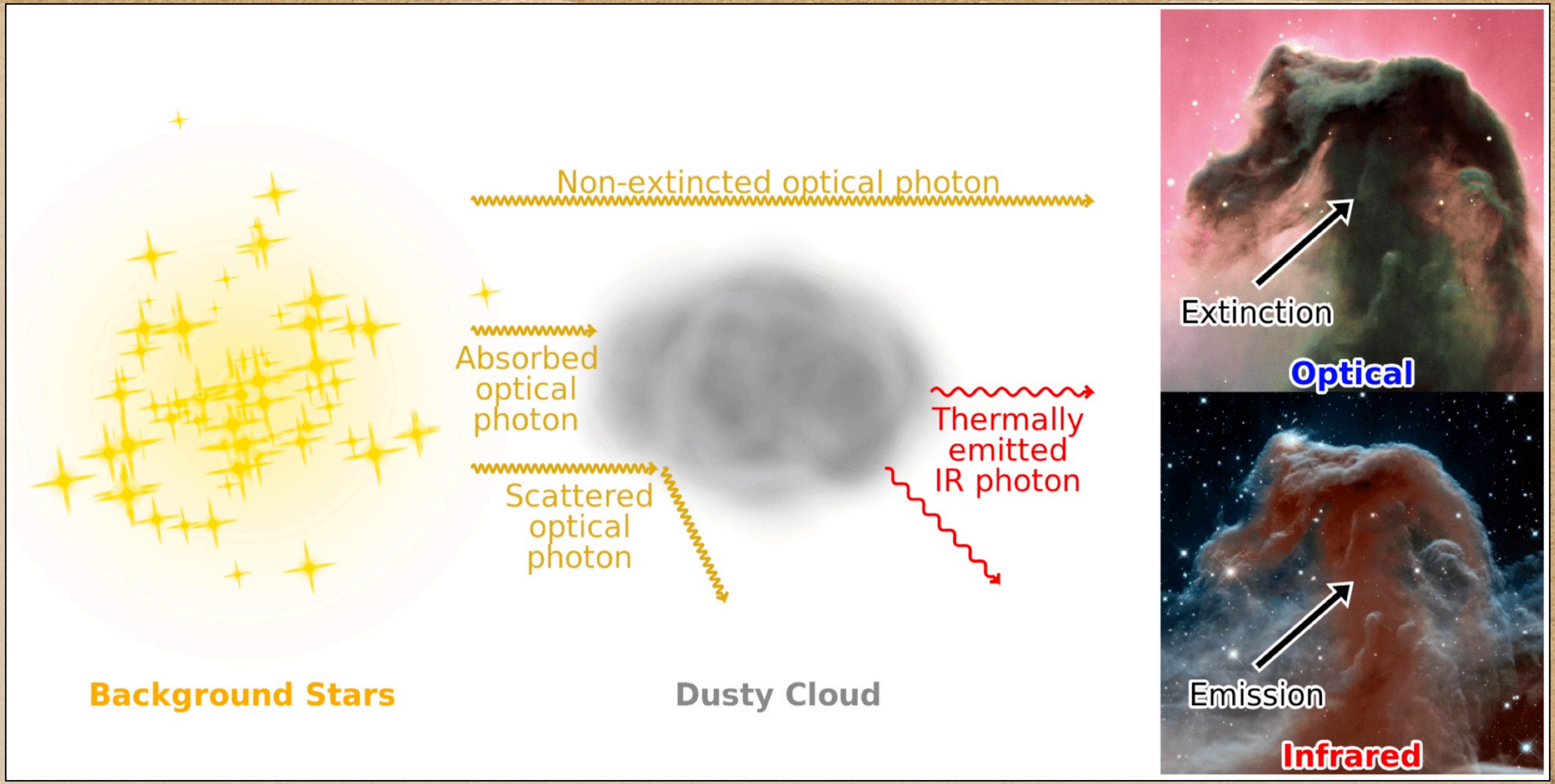


Kruijssen et al. 2019

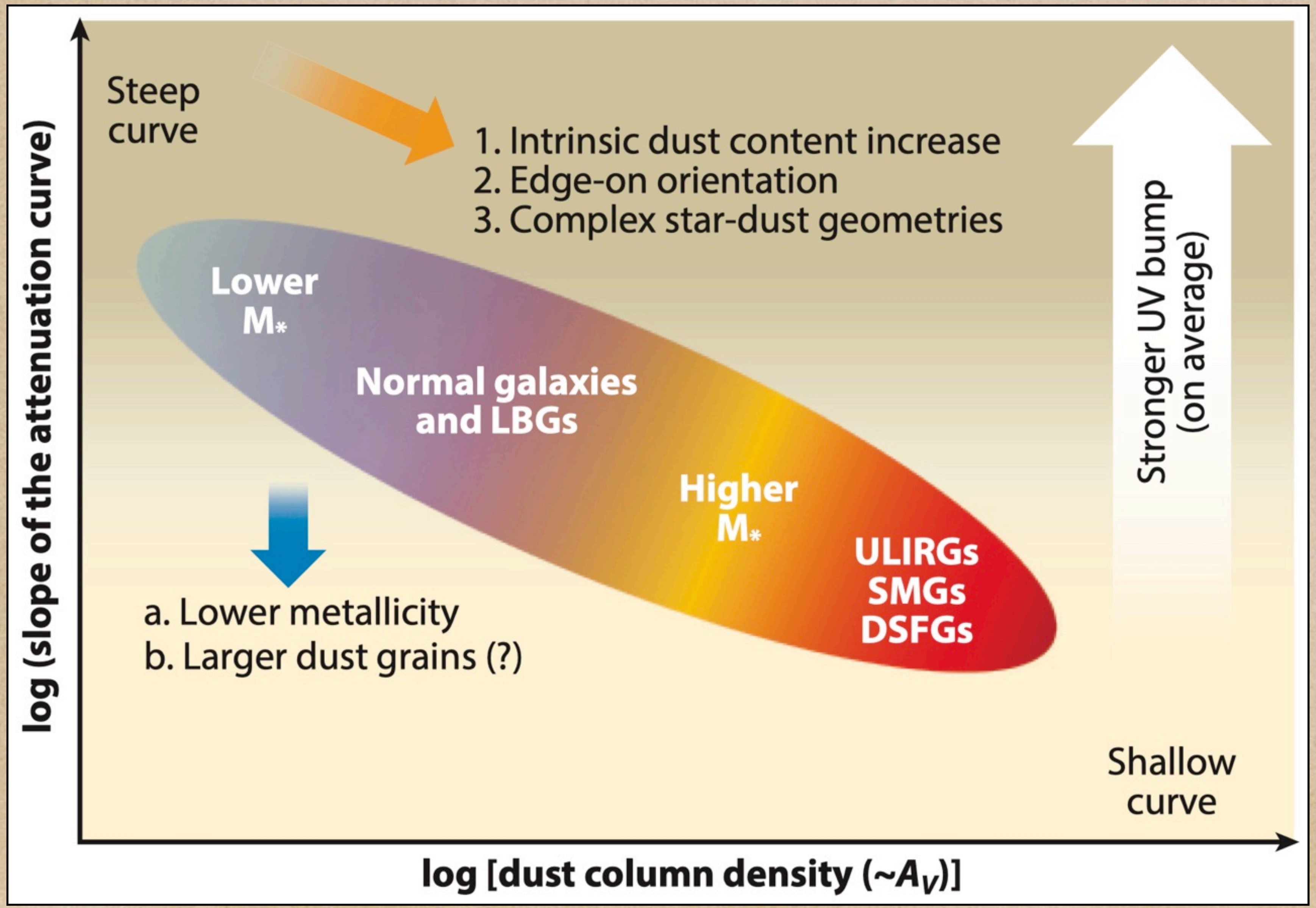
Dust —— Exinction

Extinction:

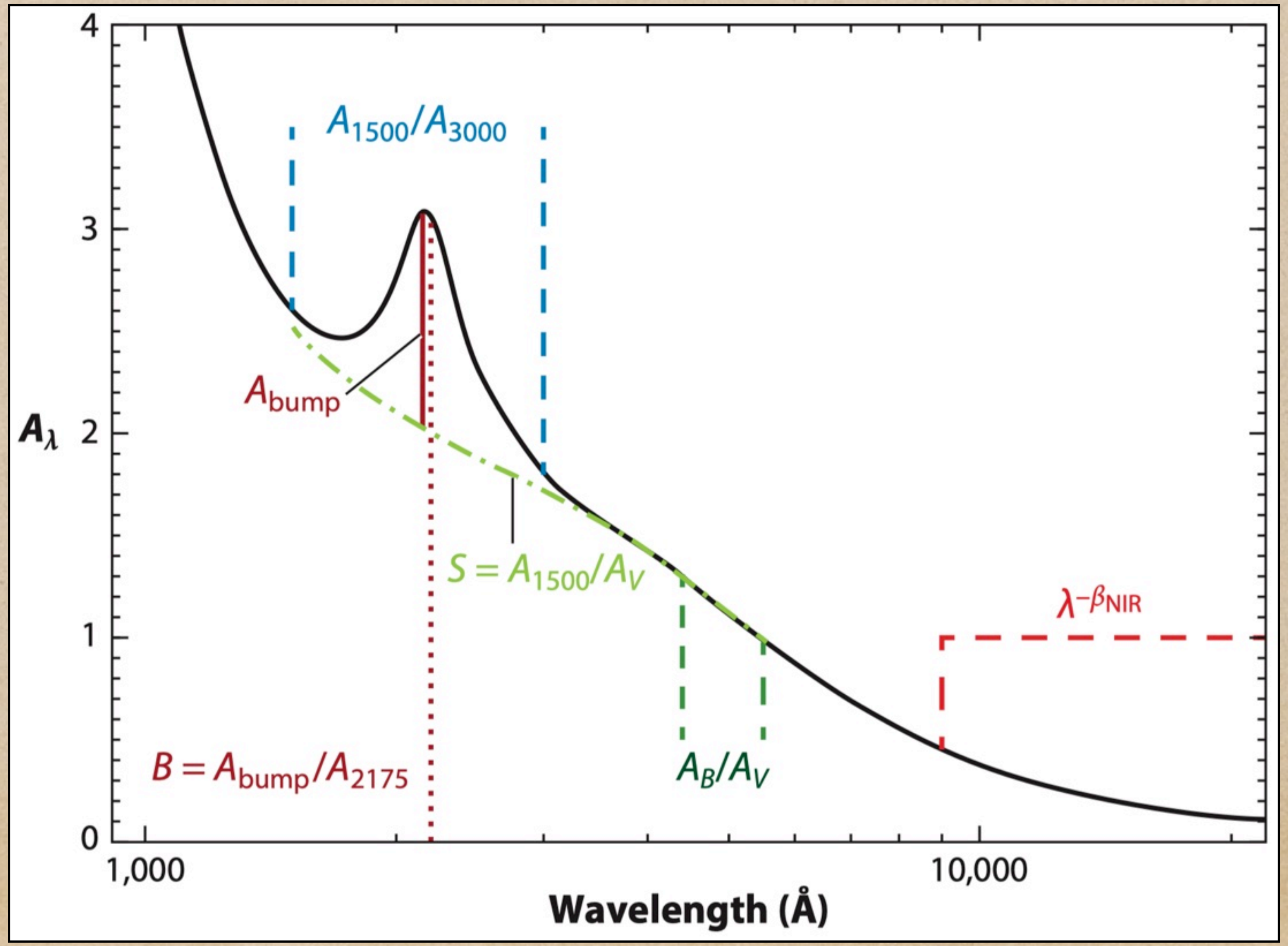
- Absorption: A fraction of the electromagnetic energy is stored in the dust grains
- Scattering: Others are scattered
- Follow extinction curve



Galliano et al. 2022



Salim et al. 2020



Extinction curve

Salim et al. 2020

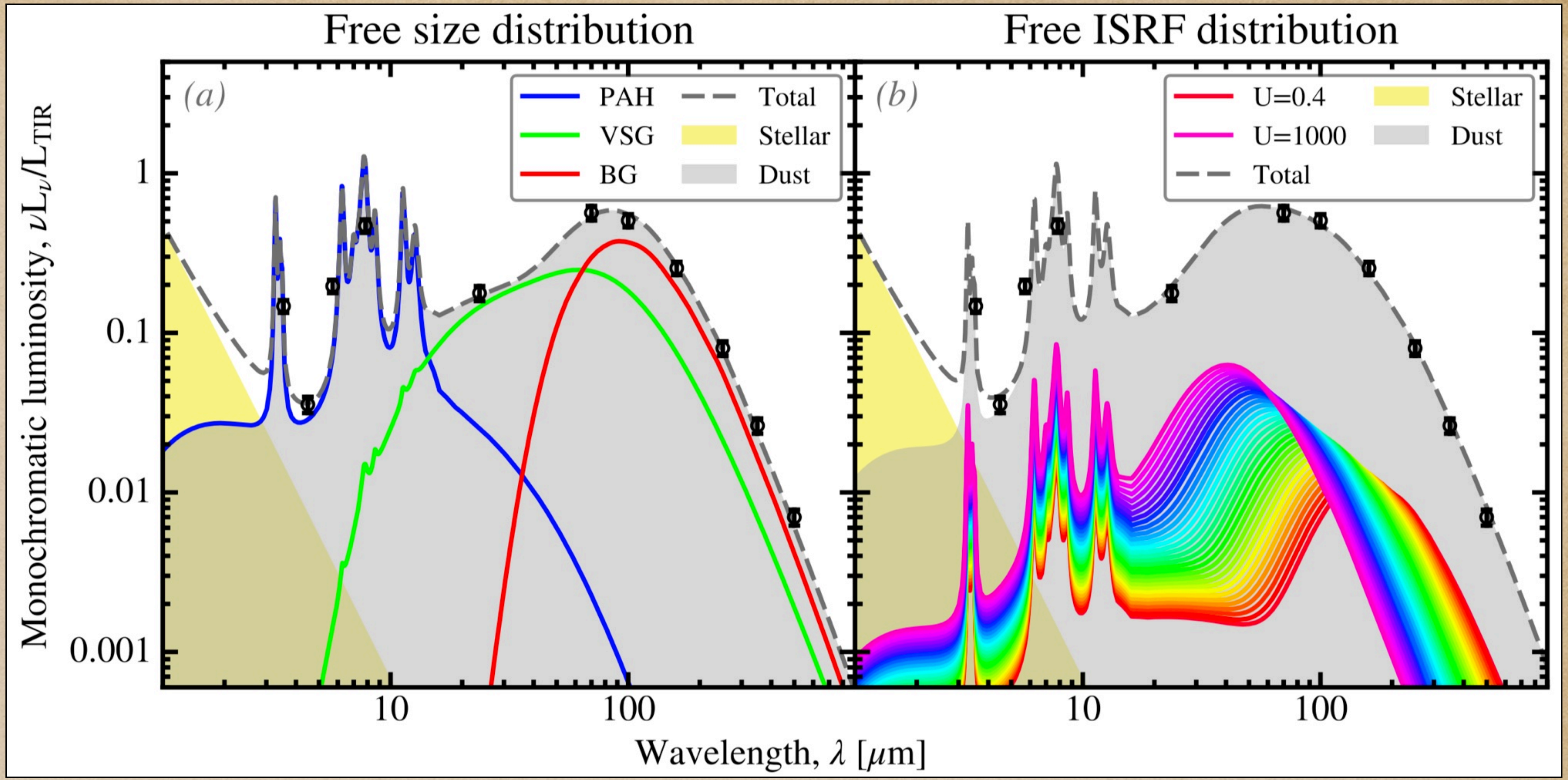
Dust —— Emission

Emission:

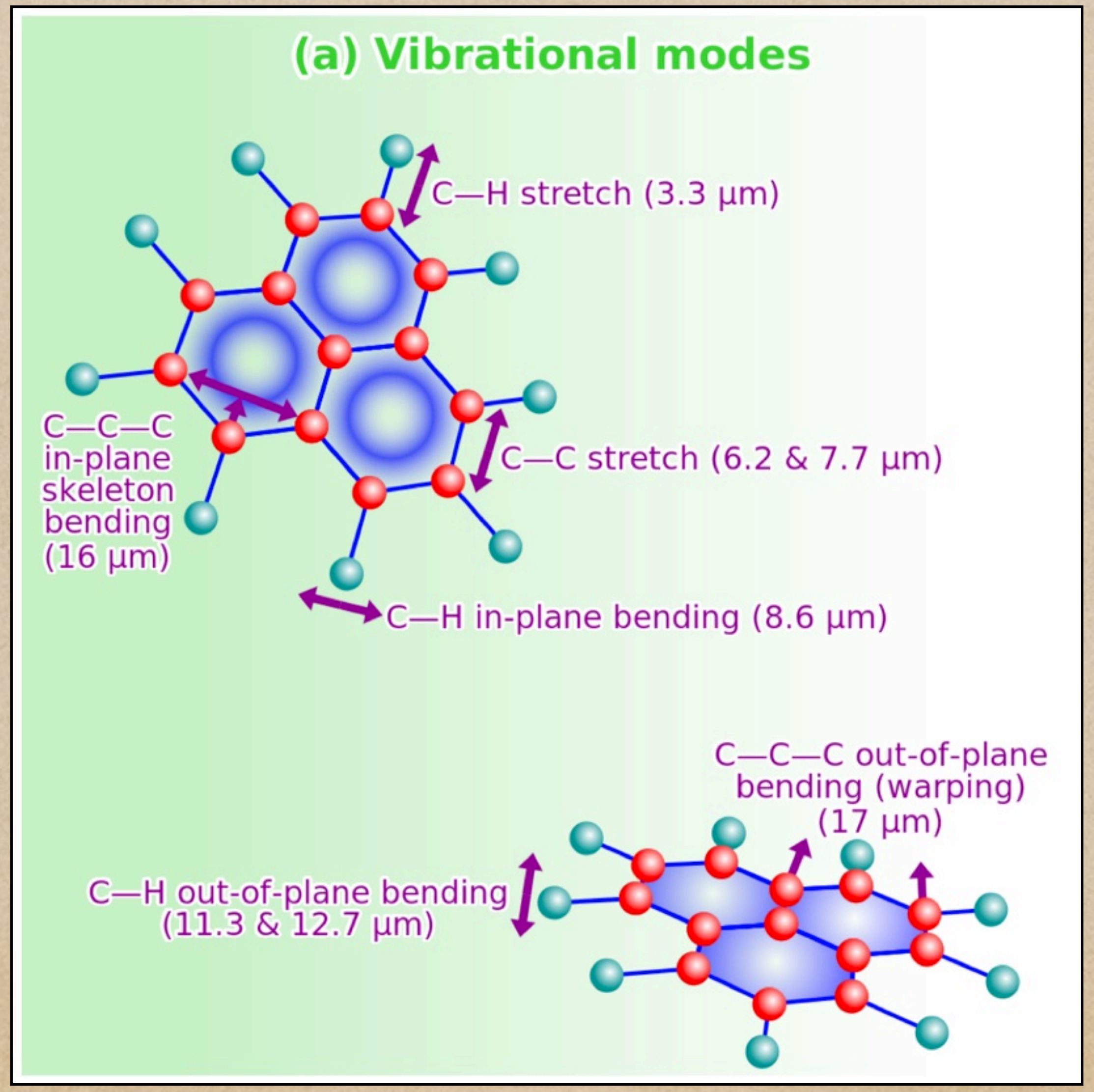
- Thermally emitted IR photon
- Composite Approach:
  - ▸ Grain size:
    - PAH: MIR emission lines
    - VSG: from MIR to FIR
    - BG: FIR, peak
  - ▸ ISRF (InterStellar Radiation Field)

PAH (多环芳香烃):

- The different emission lines come from different C-H structure
- PAH are heated in the photodissociation regions (PDRs)
- L_{PAH} shows a good relation with SFR



Galliano et al. 2022

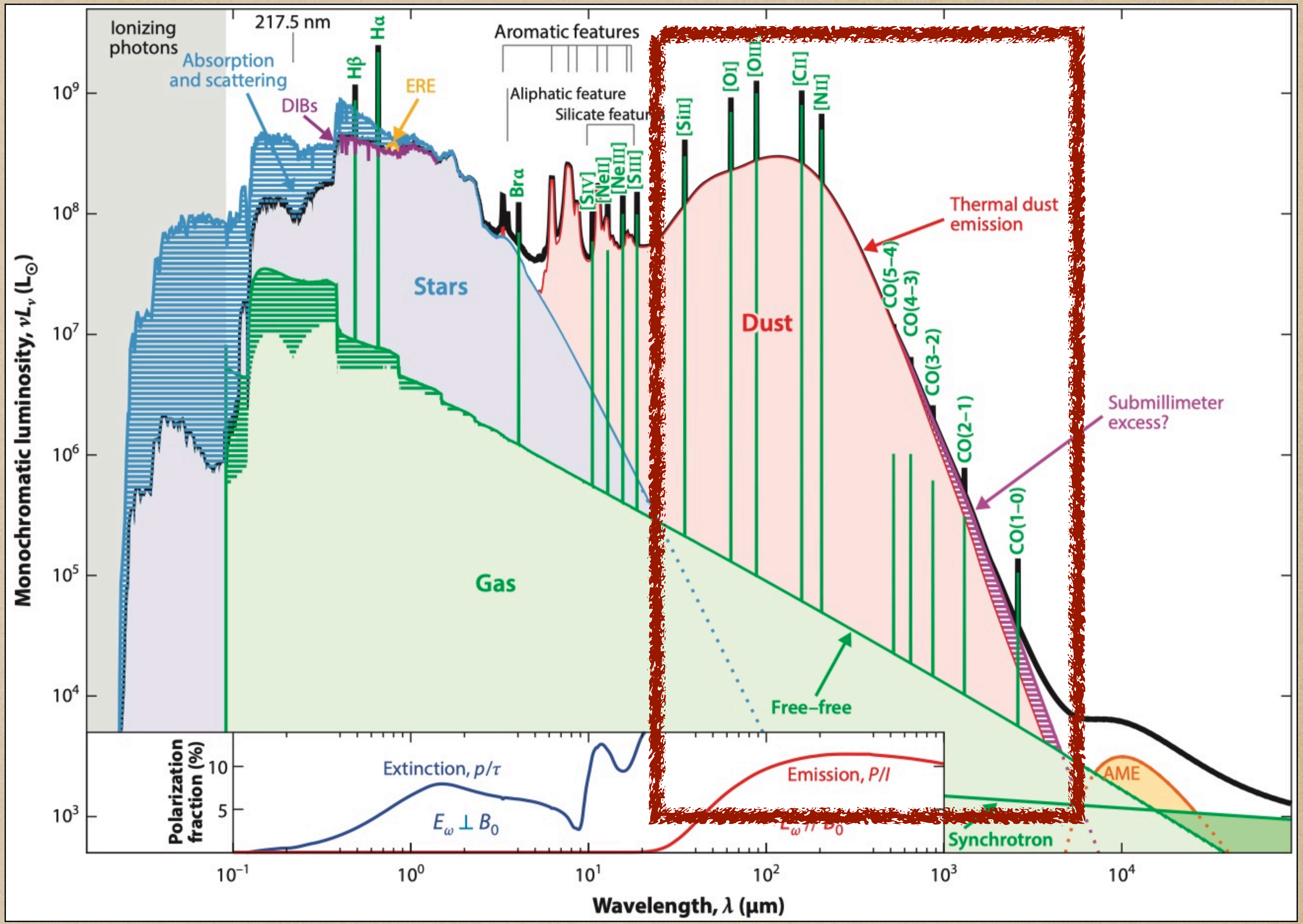


Galliano et al. 2022

Observation

Dust: Infrared (IR):

- FIR:
  - Large-size dust grains
  - Continuum—thermal equilibrium
  - Dust mass, temperature
  - Observations:
    - IRAS 60, 100 μm
    - Spitzer 70, 160 μm
    - Herschel PACS 70, 100, 160 μm
    - Herschel SPIRE 250, 350, 500 μm
    - JCMT SCUBA-2 (ground-based) 850 μm
  - Difficulty:
    - SED fitting: the wavelength corresponding to the peak
    - Can be only be observed from space telescope

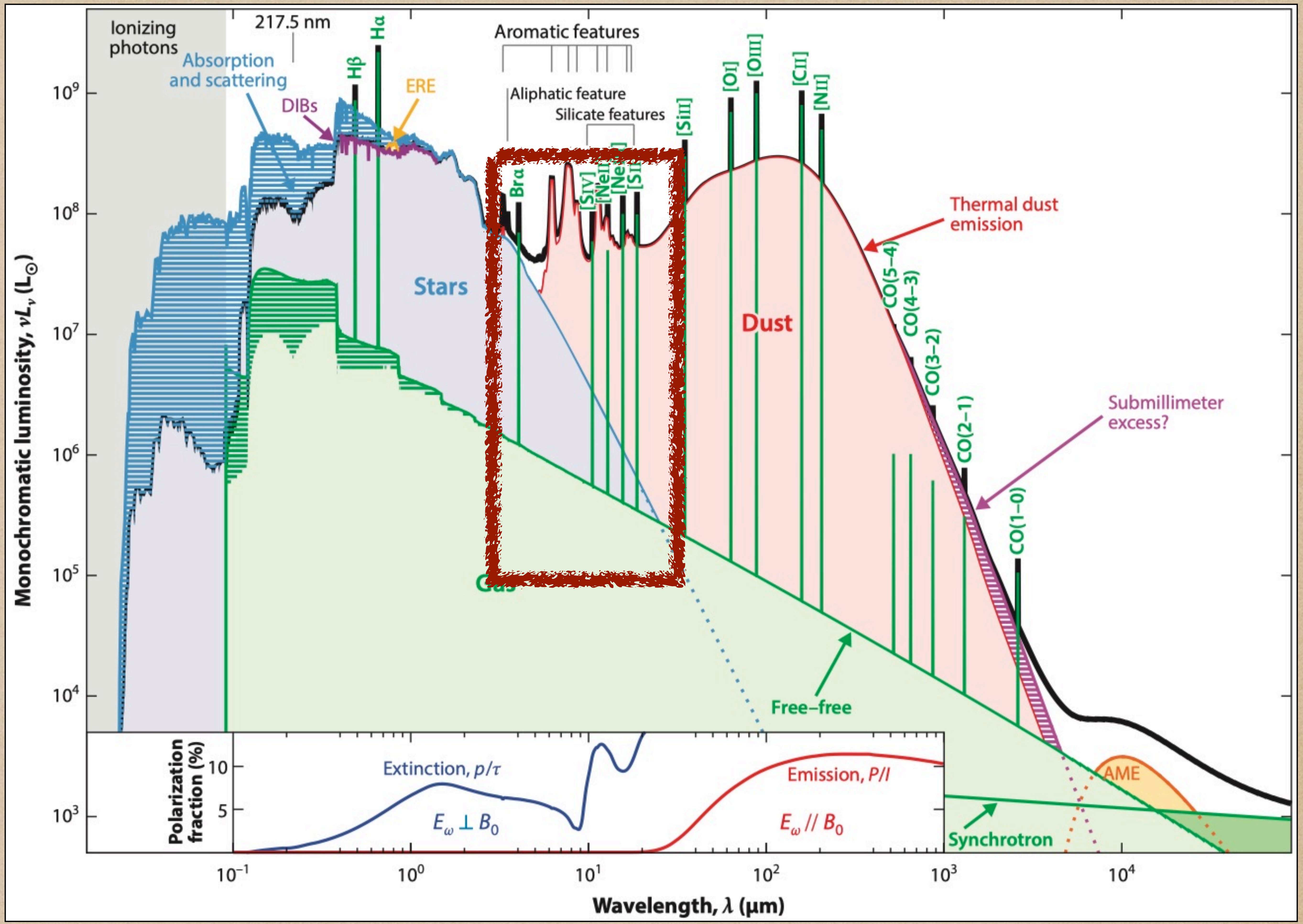


Galliano et al. 2018

Observation

Dust: Infrared (IR):

- MIR:
  - Small-size dust grains
  - Continuum—stochastically heated
  - PAH emission lines
  - Luminosity (from surface area)
  - Observations:
    - WISE 12, 23 μm
    - Spitzer IRAC 8.0 μm
    - Spitzer MIPS 24 μm
    - JWST MIRI 5-27 μm camera and spectrometer
  - Difficulty:
    - Can be only be observed from space telescope



Galliano et al. 2018

Observation

HI gas: 21 cm emission line

- Telescopes:
  - Single dish:
    - Parkes (HIPASS), Arecibo (ALFALFA), FAST (FASHI, CRAFTS)
    - Advantage: large sample, high sensitivity
    - Disadvantage: low spatial resolution: FAST 2.9’
  - Interferometry:
    - WSRT, VLA
    - Advantage: high spatial resolution: less than 1’, the best: VLA ~5”-1’ (depending on the configuration)
    - Disadvantage: small sample, low sensitivity
  - Next Generation:
    - WALLABY: interferometry but with a large sample (spatial resolution: 30”)
    - MeerKAT: interferometry but with deep sensitivity
    - SKA, FASTA

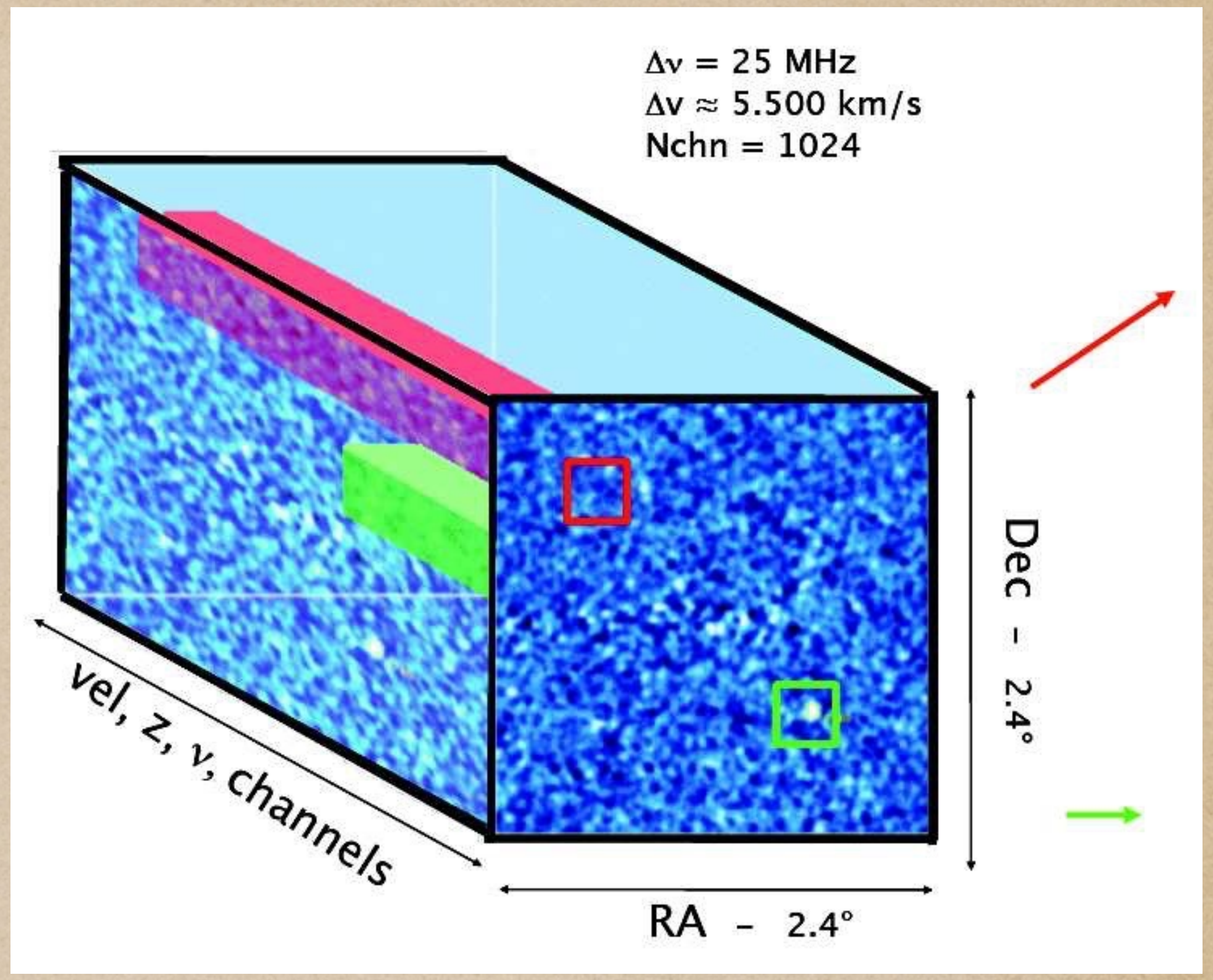
Observation

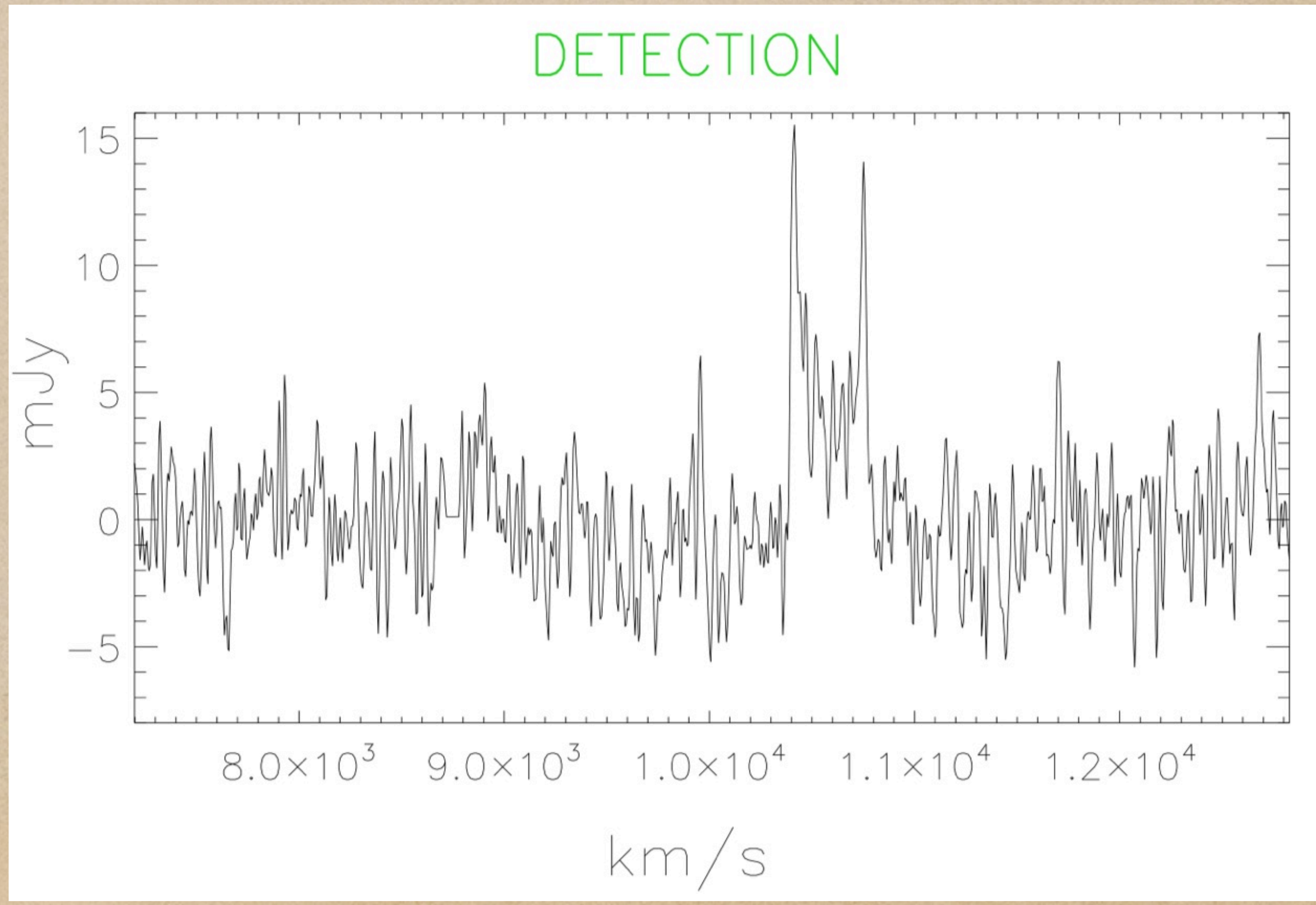
HI observations

- Limitation
  - Weak, low spatial resolution
  - Affected by radio frequency interference (RFI)
- Observation:
  - 21 cm emission line:
    - Only in the local universe (z~0.1, for ALFALFA only 0.05)
  - HI spectra stacking and intensity mapping techniques:
    - Up to z<1
    - Only average HI mass or cosmic HI density
  - Damped Lyα systems (DLA):
    - From background quasar absorption lines
    - z>1.5
    - Only cosmic HI density, need quasar

HI emission lines

- Datacube (3D information)
- HI spectra





Observation

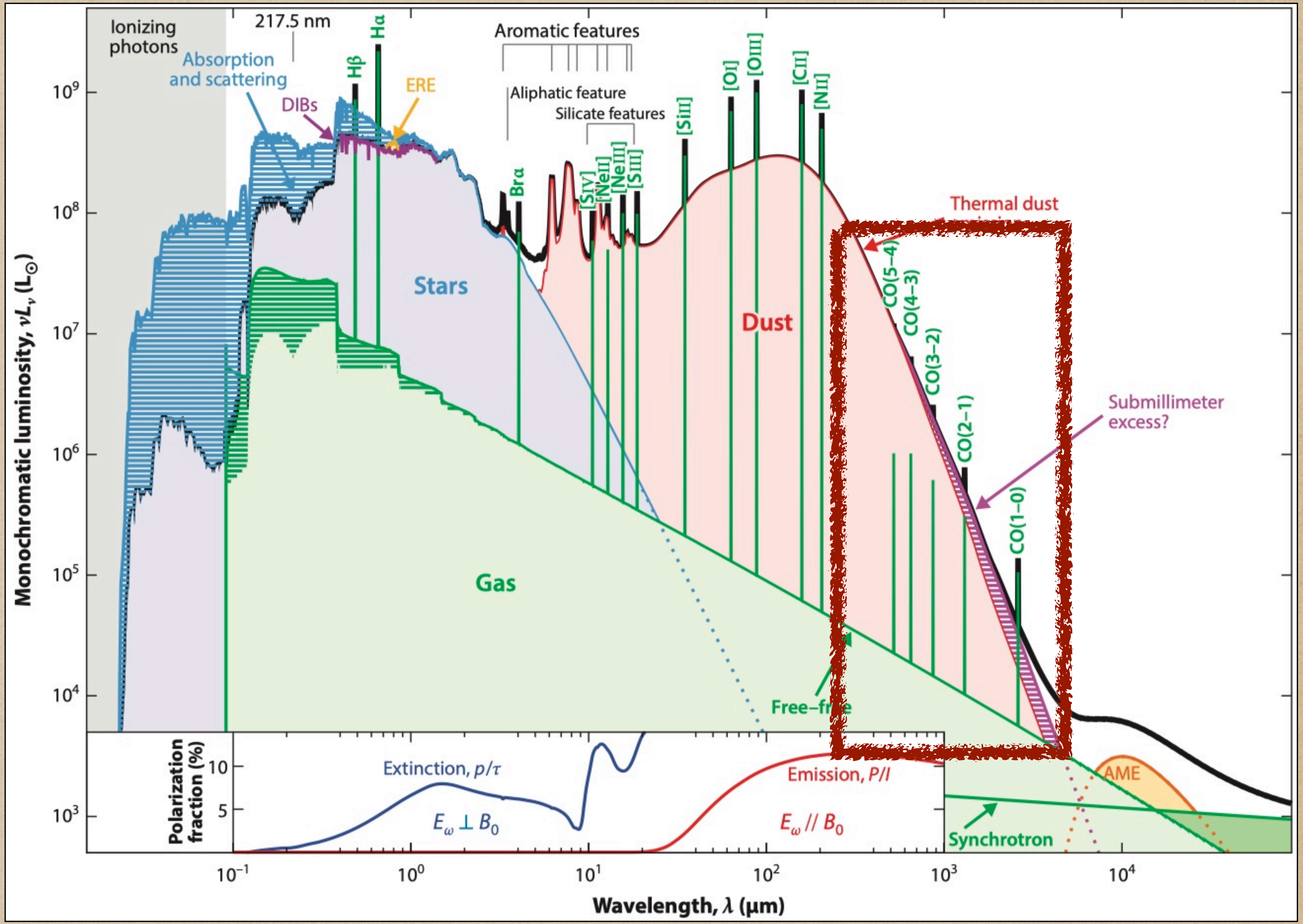
HI gas: 21 cm emission line

- Sample:
  - Large sample:
    - HIPASS (very shallow, South sky), ALFALFA (shallow, North sky, $z<0.05$), FASHI (shallow, North sky, $z<0.08$, may have deeper data in the future), WALLABY (shallow, South sky, $z<0.08$, observations are very slow, ~600 galaxies now, may have deeper data in the future)
  - High spatial resolution:
    - Most are based on VLA, WSRT, GMRT
    - THINGS and LITTLE THINGS (nearby HI-rich galaxies), VIVA (spirals in Virgo), Atlas3D (early-type galaxies), LVHIS and WHISP and FIGGS (not from VLA, low-resolution)
    - The samples are very small!
  - Specific observation:
    - GASS and xGASS:
      1. A mass unbiased sample of $\sim$1179 galaxies covering $9 < \log M_*/M_\odot < 11.5$
      2. A deep observation using the Arecibo telescope
      3. Many works about scaling relations or limitations in simulation are based on this sample!

Observation

H2 gas: using CO emission lines to predict

- H2:
  - Too weak
  - Commonly probed with CO rotational lines (CO 1-0, CO 2-1, …), in submillimeter
  - Telescope: ALMA, JCMT
  - Over a large redshift, but smaller sample size
  - Sample: FCRAO, xCOLD GASS, ASPECS (1<z<3.5), PHIBSS2 (0.48<z<5.25)



Galliano et al. 2018