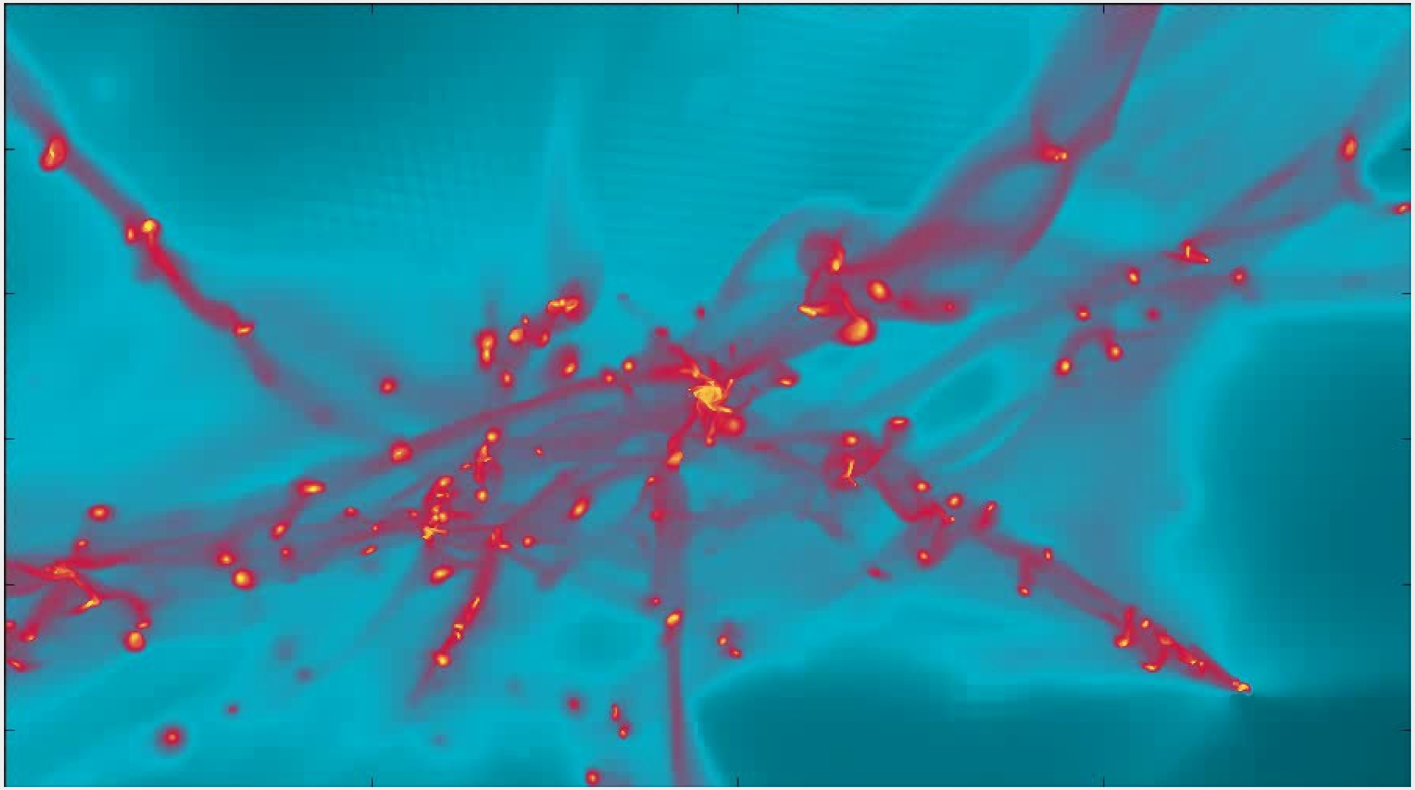
Scientific Data Analysis in Astrophysics:

synthetic spectra from galaxies in cosmological simulations



CENTRO FERMI
MUSEO STORICO DELLA FISICA E CENTRO STUDI E RICERCHE ENRICO FERMI

SCUOLA NORMALE SUPERIORE

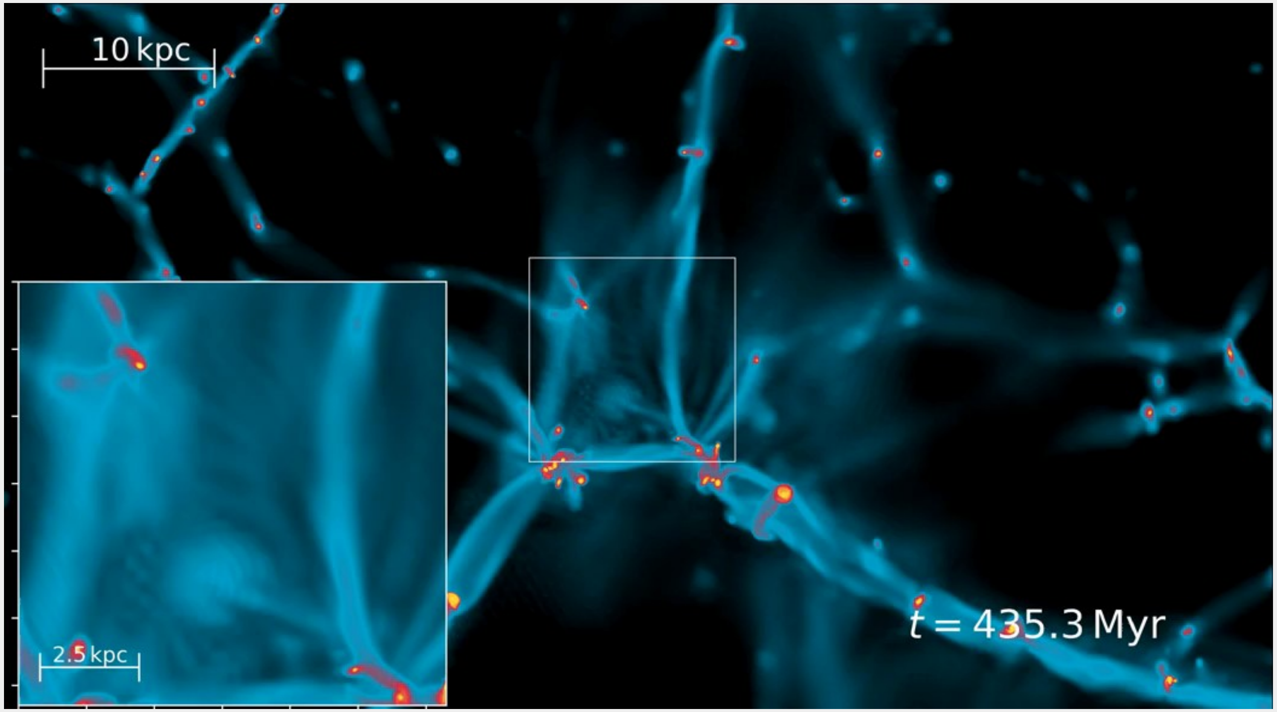
Andrea Pallottini

serra

main references for models used in the lectures: Pallottini+17b, Vallini+18, Kohandel+19
see https://github.com/apallottini/sda_school (already present on your HD)

Galaxy evolution with cosmological simulations: basic ingredients

example: merger of galaxies at at z~9



Gas thermo-dynamics

$$\partial_t \rho + \nabla \rho \mathbf{v} = 0$$

$$\partial_t \rho \mathbf{v} + \nabla (\rho \mathbf{v}\mathbf{v} + P) = -\rho \nabla \Phi$$

$$\partial_t \rho e + \nabla \rho \mathbf{v} (e + P/\rho) = -\rho \mathbf{v} \nabla \Phi + \mathcal{H} - \Lambda$$

Dark Matter evolution

$$\ddot{\mathbf{x}}_{dm} = -\nabla \Phi(\mathbf{x}_{dm})$$

(self)gravity

$$\Delta \Phi = 4\pi G(\rho_{dm} + \rho)$$

cosmological framework

$$\mathrm{d}s^2 = -c^2 \mathrm{d}t^2 + a(t)^2 \mathrm{d}\mathbf{x}^2$$

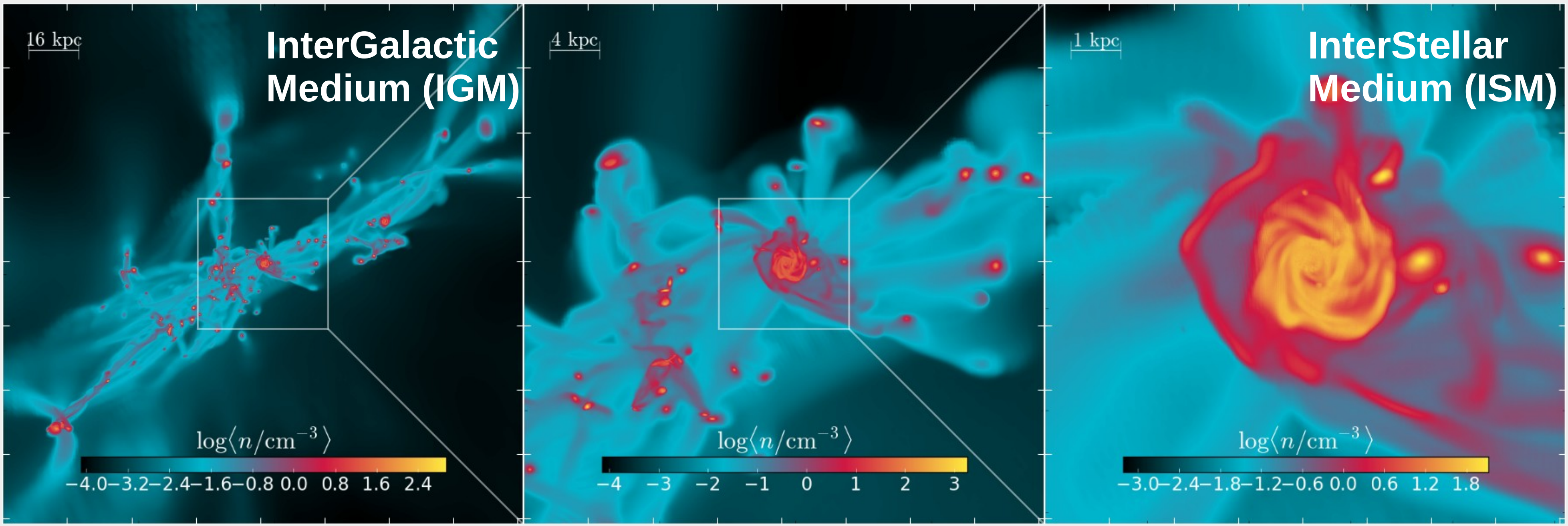
initial conditions generated as perturbations with parameters taken from CMB observations

Pallottini+17b

Zooming-in high-z galaxies

Dahlia

Pallottini+17a



Resolution	
gas mass	$m_g \simeq 10^4\,\mathrm{M}_\odot$
AMR	$\sim 80 - 0.1\,\mathrm{ckpc/h}$
at $z = 6$	$\Delta x \simeq 30\,\mathrm{pc}$

Target LGB characteristics (at z=6)		
dark matter	$M_{\rm dm} \sim 10^{11}\,\mathrm{M}_\odot$	
size	$r_{\rm vir} \simeq 15\,\mathrm{kpc}$	$r_{\rm eff} \simeq 0.5\,\mathrm{kpc}$
stars	$SFR \sim 100\,\mathrm{M}_\odot/\mathrm{yr}$	$M_\star \sim 10^{10}\,\mathrm{M}_\odot$
gas	$M_H \sim 10^{10}\,\mathrm{M}_\odot$	$M_{\rm H2} \sim 10^{8}\,\mathrm{M}_\odot$
metals	$Z \simeq 0.5\,\mathrm{Z}_\odot$	$M_D \sim 10^{7}\,\mathrm{M}_\odot$

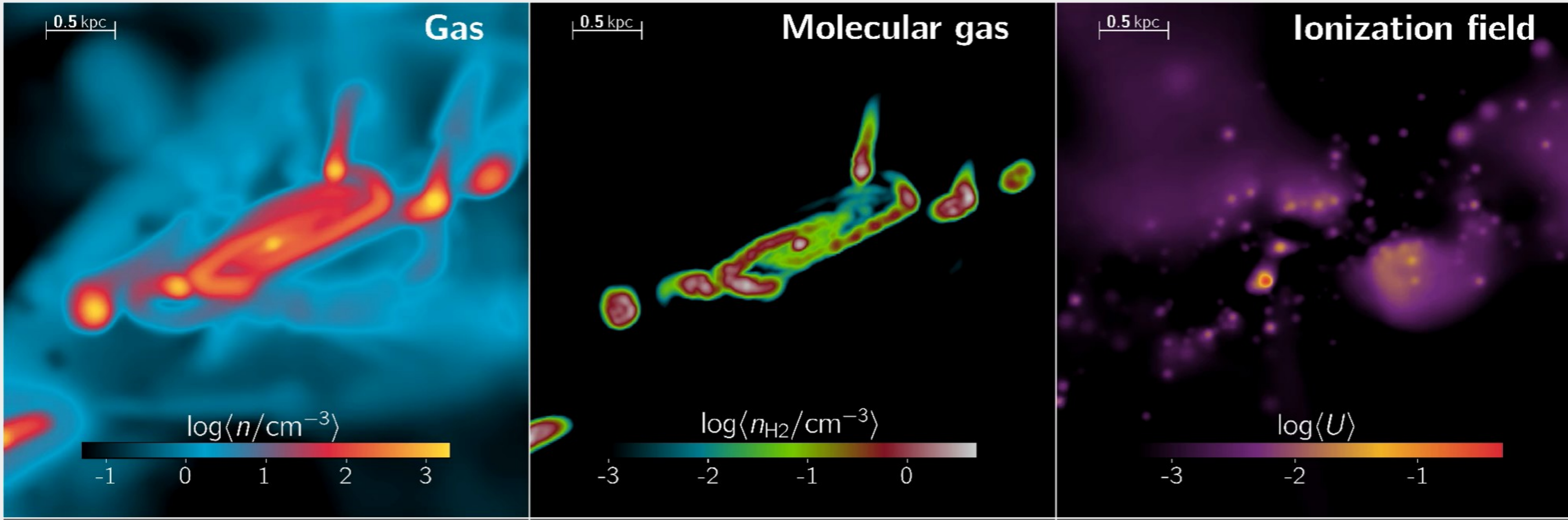
from cosmological to molecular cloud scales

Model main features	
AMR code RAMSES Teyssier 2002	zoom-in IC MUSIC Hahn 2011
H_2 based star formation (SK relation) Krumholz+09	Stellar tracks from STARBURST99 Leitherer+10
Thermal and kinetic energy (e.g. Agertz&Kravtsov 2015)	
GRACKLE 2.1 cooling module Bryan+14	Kinetic energy dissipation Mac Low 1999; Teyssier+13
SN explosions, OB/AGB winds & radiation pressure (e.g. Agertz+13, Hopkins+14)	
Subgrid modelling for blastwaves Ostriker&McKee 1988	

Zooming-in high-z galaxies

Freesia

Pallottini+17a,+19



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serra

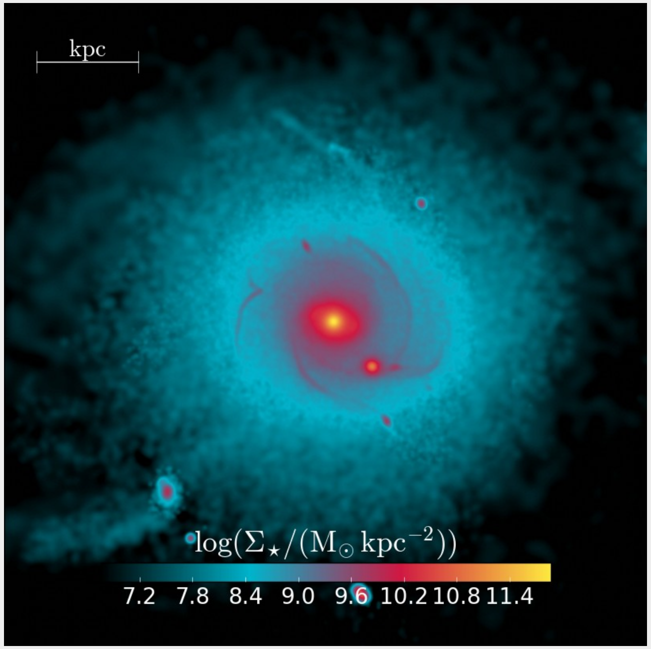
from cosmological to molecular cloud scales

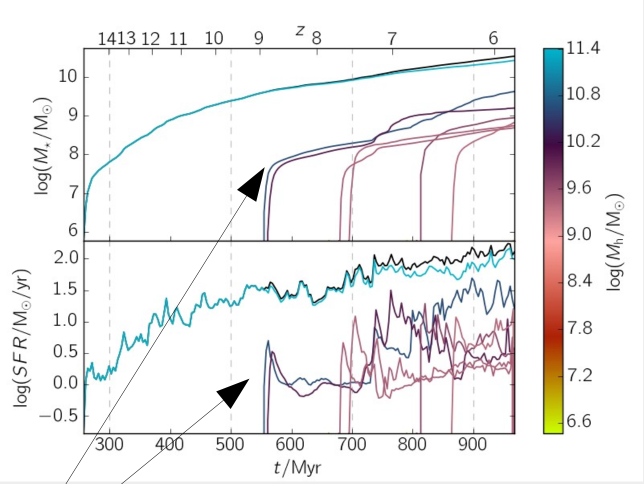
- non-equilibrium chemical networks to form molecular hydrogen and in turn it into stars
- radiation field tracked on the fly to account for ionization and photodissociation effetcs

Stellar component properties

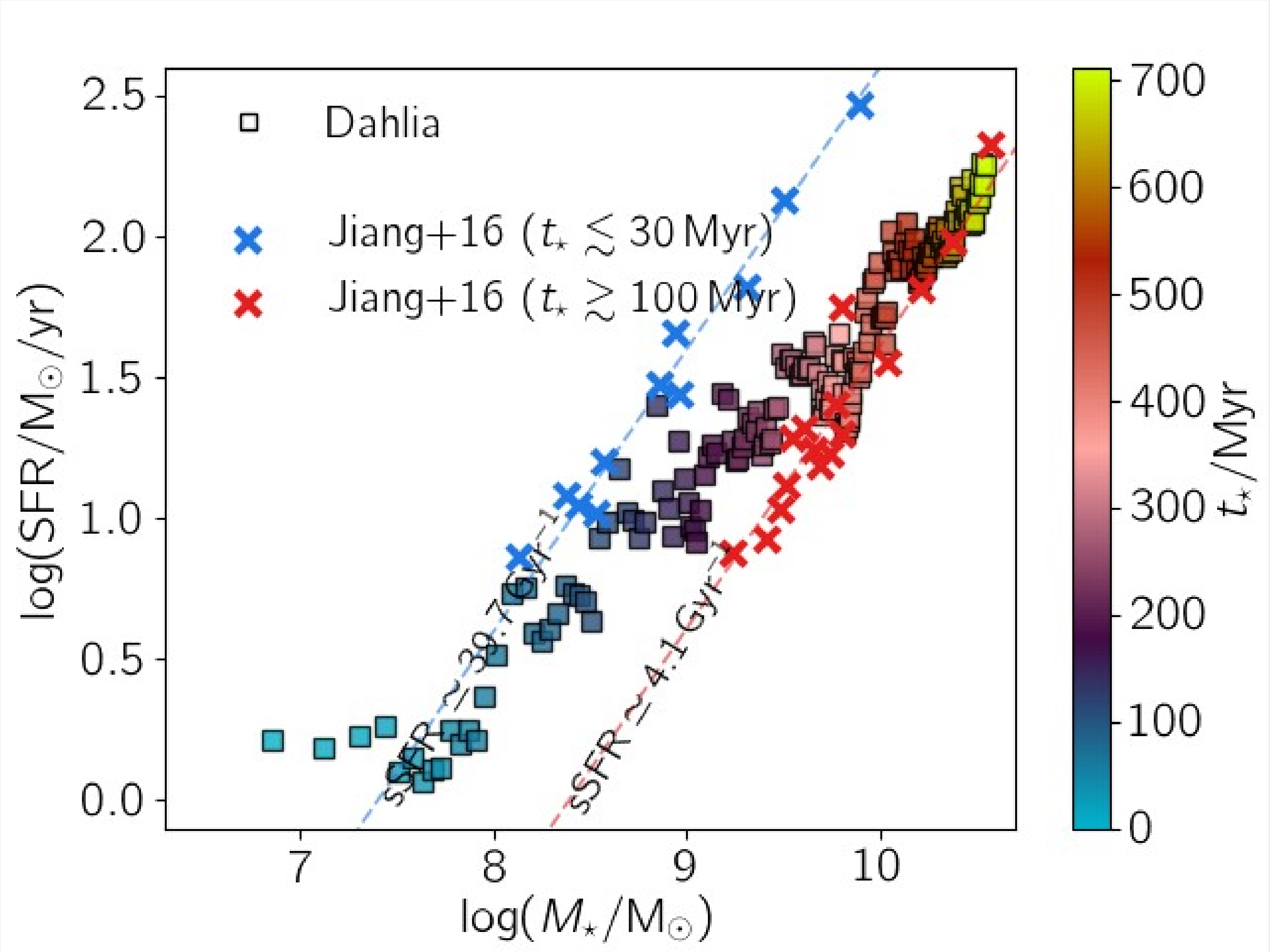
Dahlia

Pallottini+17a,b





other galaxies in the field

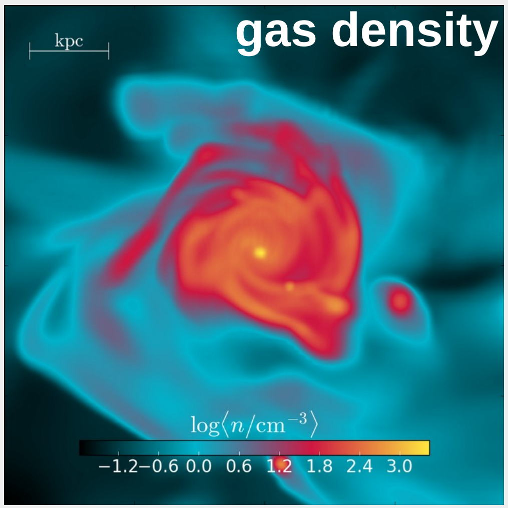


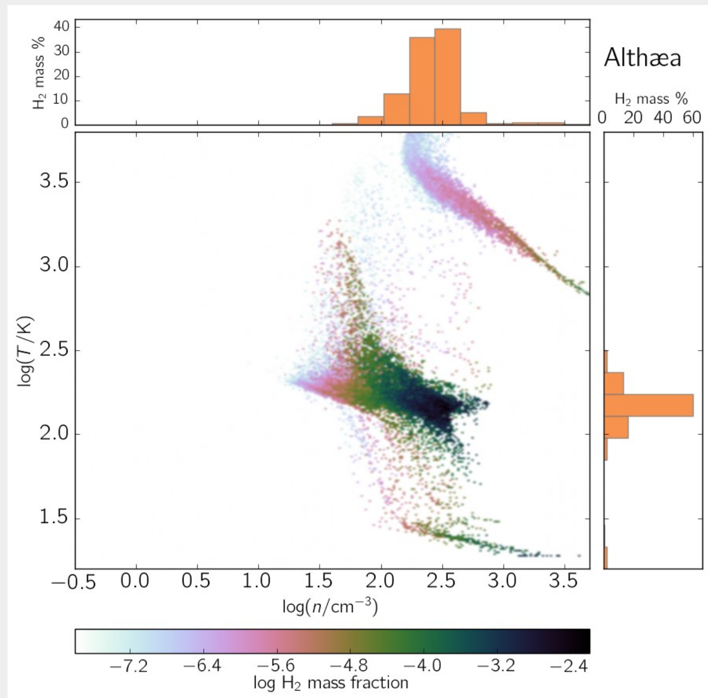
- star formation increasing with time
- frequent induced burst due to merger/gas inflows
- turbulent early life ($sSFR=SFR/M_*$~40/Gyr)
- intense radiation and stellar feedback are expected

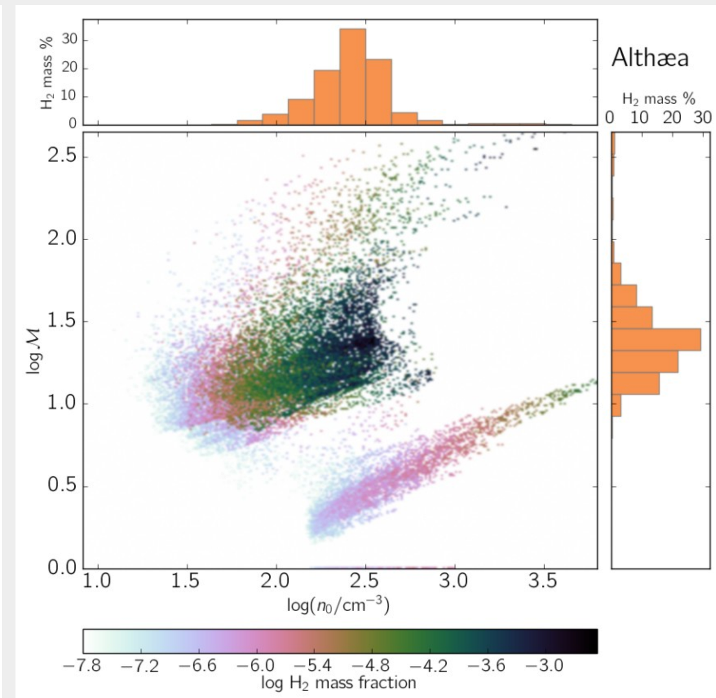
Molecular gas properties

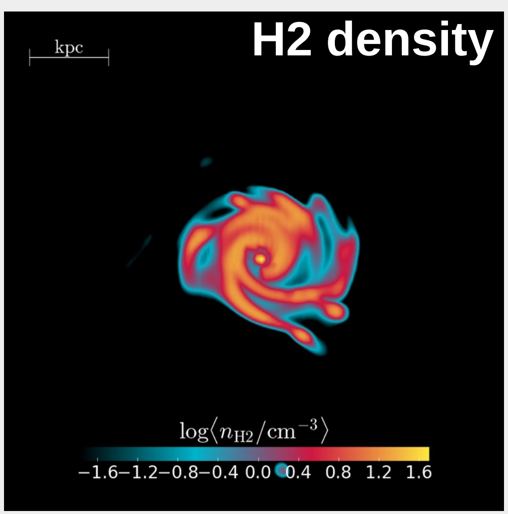
Althæa

Pallottini+17b,Vallini+18









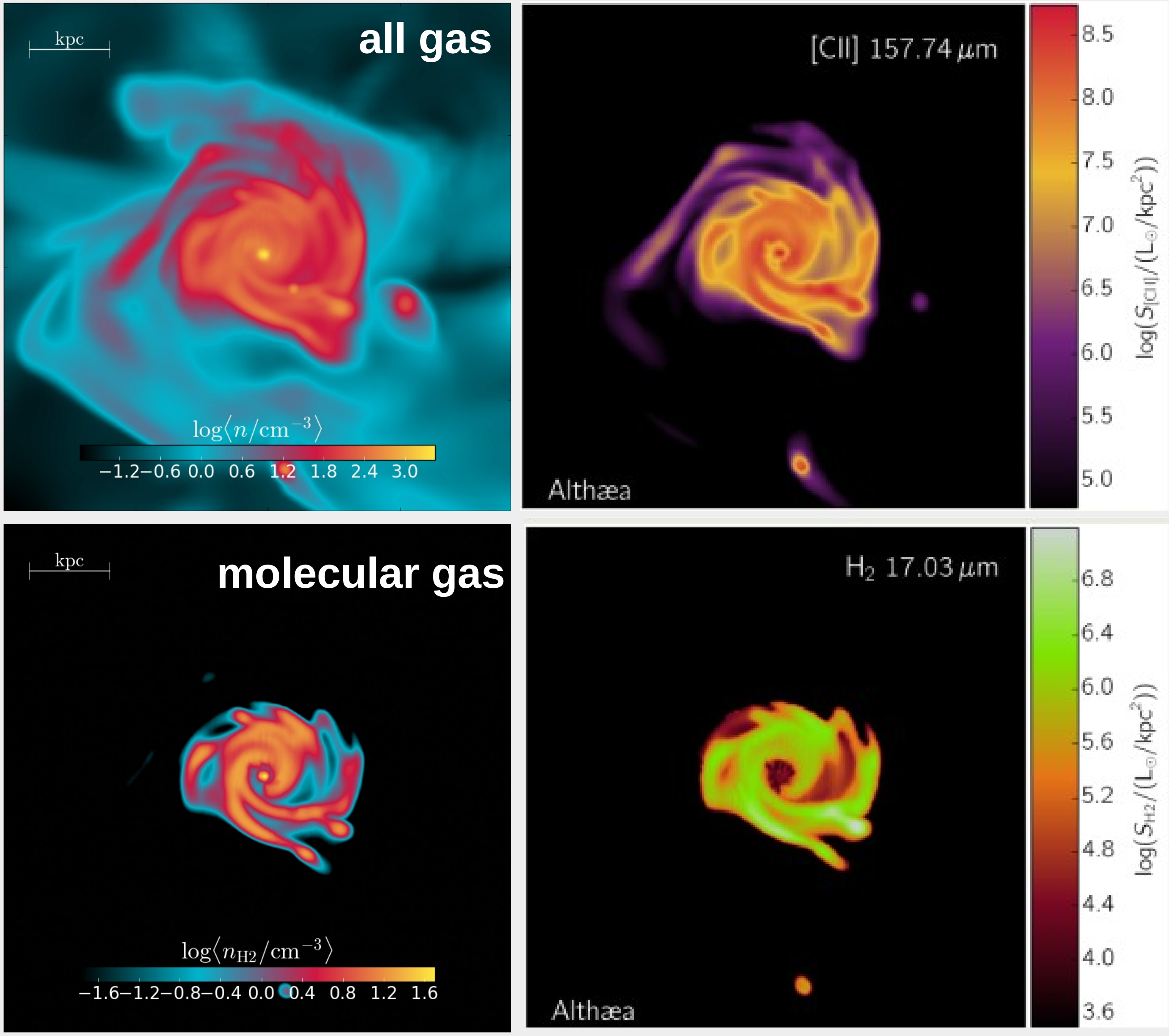
clumpy and concentrated in the galactic disk

relatively denser and hotter wrt the MW

higher turbulence, as a consequence of feedback

Predictions for the gas properties:

line emission and comparison with observations



Far-InfraRed lines to compare with currently available ALMA observations

- different lines traces a variety of ISM conditions
- still C^+ good tracer of dense, molecular gas

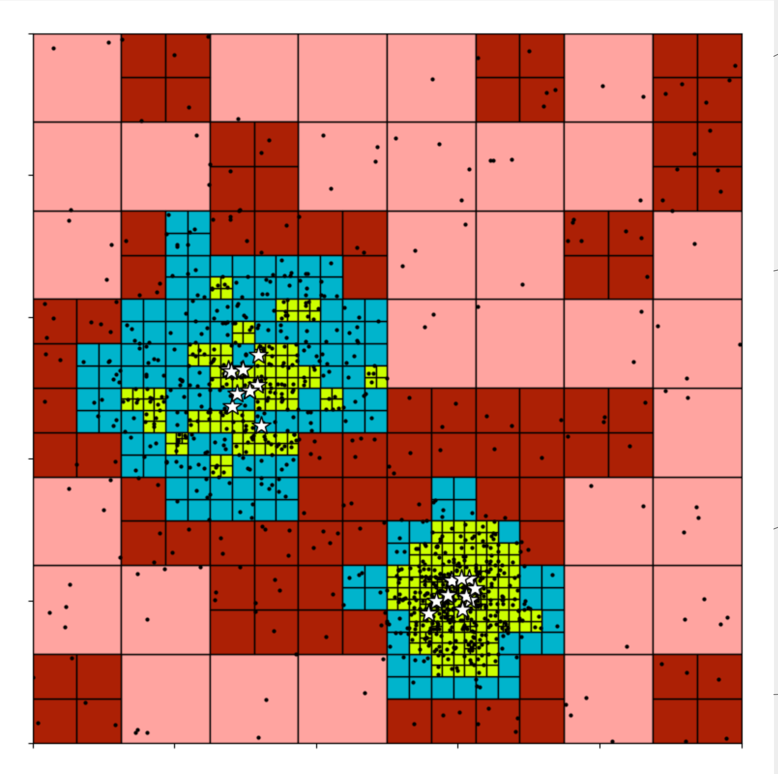
Mid-InfraRed predictions to be tested with SPICA, a proposed instrument

directly probe the molecular gas, by detecting the H_2 component

Vallini+17,Pallottini+17b, Egami+18, Kohandel+19

Data structure of a simulation snapshot

sketch of the structure



DM: $m^i_{dm}, \mathbf{x}^i_{dm}, \mathbf{v}^i_{dm}$

$i = 1, \ldots, N_{dm}$

Stars: $m^j_\star, \mathbf{x}^j_\star, \mathbf{v}^j_\star, t^j_\star$

$j = 1, \ldots, N_\star$

Gas: $\rho^k, \rho^k_{\rm H}, \ldots, \rho^k_{\rm H2}, P^k, \mathbf{x}^k, \Delta x^k, \mathbf{v}^k$

$k = 1, \ldots, N_{\rm cells}$

Radiation field:

$n^k_{\gamma,l}, \mathbf{F}^k_{\gamma,l}$

$k = 1, \ldots, N_{\rm cells};\ l = 1, \ldots, N_{\gamma\, bins}$

Adaptive Mesh Refinement structure:

neighbours, parents, and children information

data available for the hands-on:

gas properties of the ISM of Althæa, a galaxy at high z

$$n[{\rm cm}^{-3}], m[{\rm M}_\odot], T[{\rm K}], Z[{\rm Z}_\odot], \mathbf{x}[{\rm kpc}], \Delta x[{\rm kpc}], \mathbf{v}[{\rm km\,s}^{-1}]$$

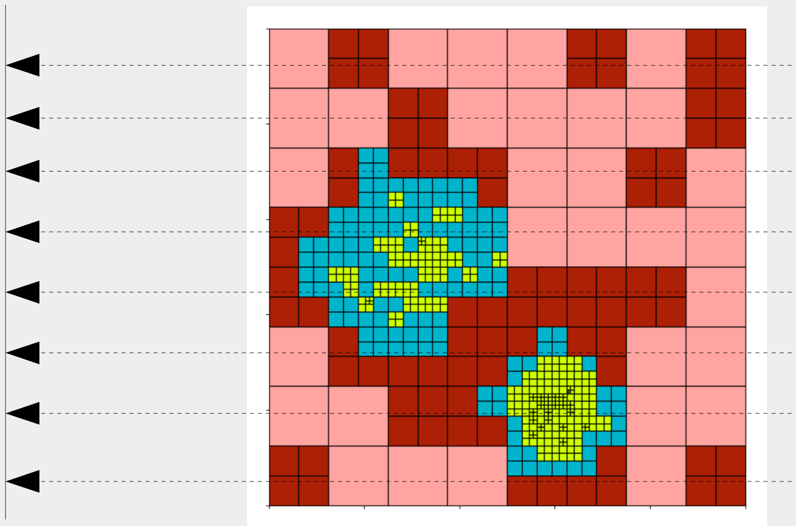
number_density, mass, temperature, metallicity, position, sph_length, velocity

organized as a dictionary of N or Nx3 arrays with explicit units

Pallottini+17b

Visualization of the data structure

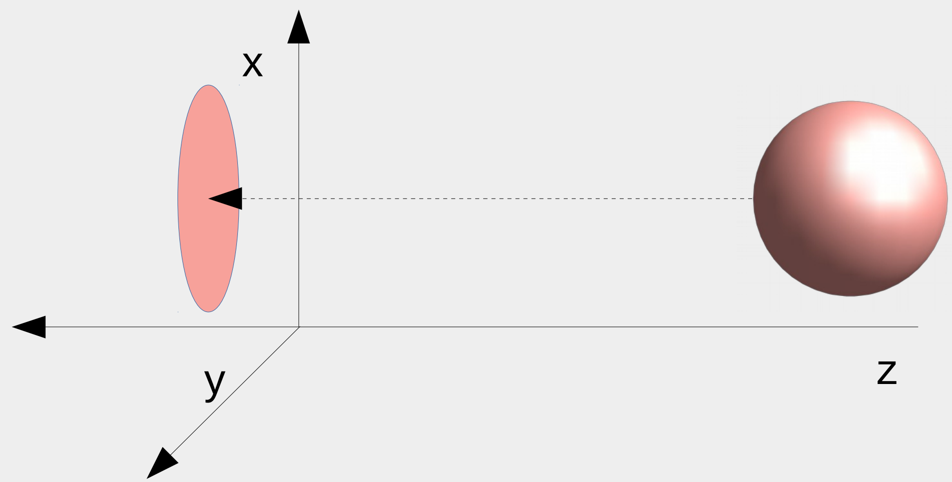
imaging done via kernel splattering



2D image

3D data

imaging of a single gas cell by projecting along z



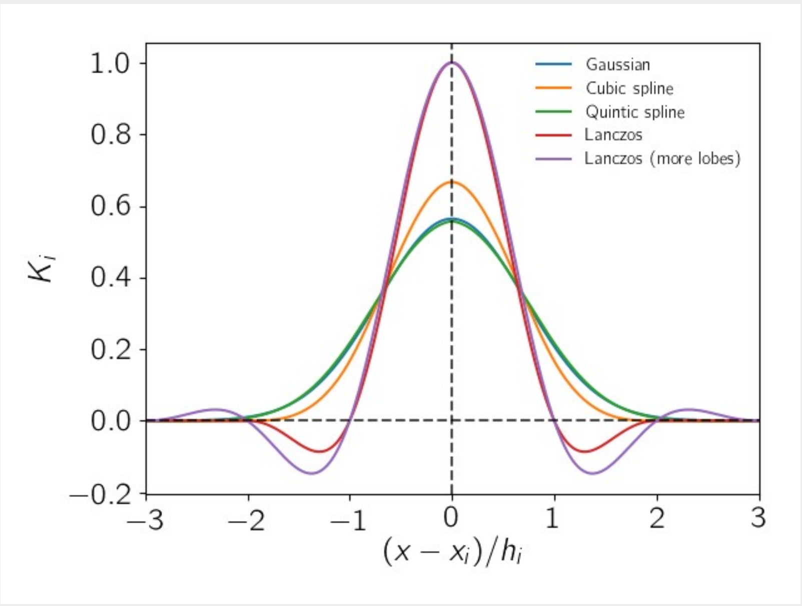
kernel gives the shape of the cell in the transverse direction

averaging along the line of sight: e.g. density

$$\langle n\rangle(x,y) = \frac{\sum_i n_i m_i K(x, x_i, \Delta x_i) K(y - y_i, \Delta x_i)}{\sum_i m_i K(x, x_i, \Delta x_i) K(y - y_i, \Delta x_i)}$$

variable to average

mass weighting



integration along the line of sight: e.g. gas surface density

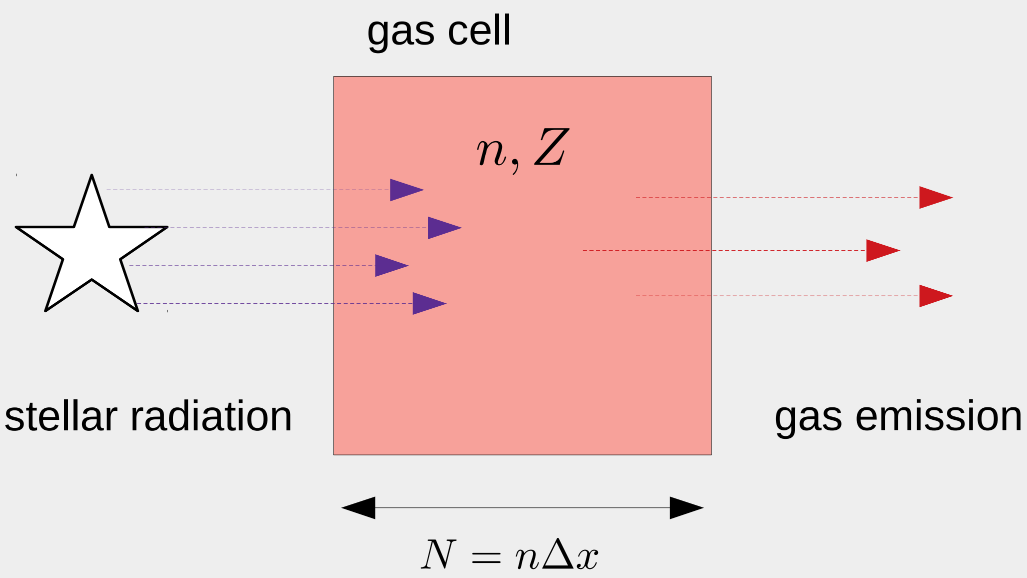
$$\Sigma_g(x,y) = \sum_i m_i K(x, x_i, \Delta x_i) K(y, y_i, \Delta x_i)$$

note that the kernel has dimension of an inverse length

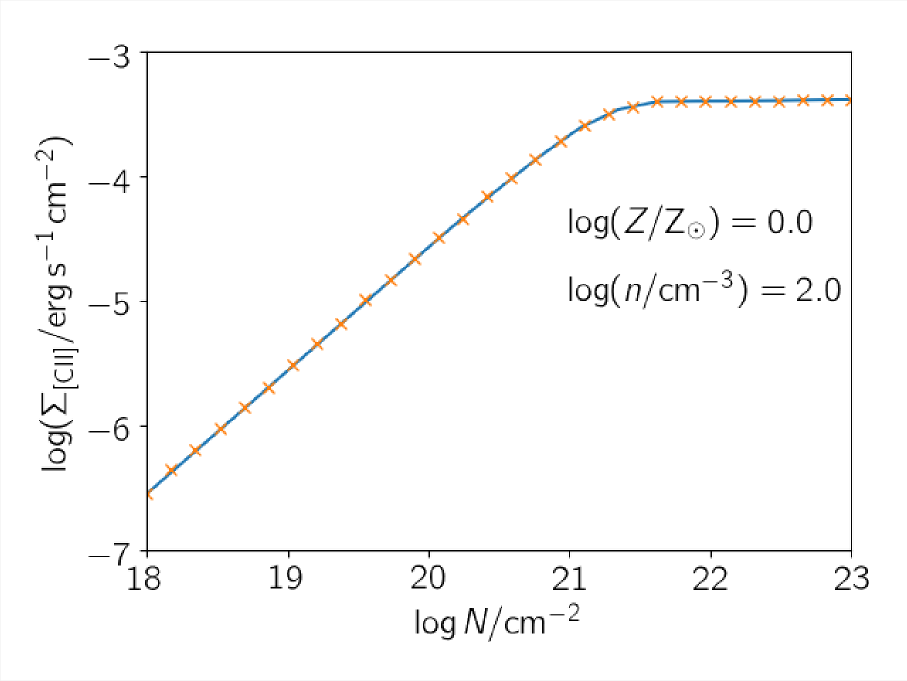
e.g. Labadens+12, Pontzen+13

Line emission calculation

scheme of the CLOUDY setup



emission for a gas cloud as a function of N from CLOUDY



here the radiation field intensity
is fixed to the mean found in Althæa

grid of CLOUDY models, that is interpolated for n, Z, N

$$\begin{cases} \log(n/\mathrm{cm}^{-3}) \in [-2, \ldots, 4.5] & \# = 14 \\ \log(Z/\mathrm{Z}_\odot) \in [-3, \ldots, 0.5] & \# = 8 \\ \log(N/\mathrm{cm}^{-2}) \in [15, \ldots, 23] & \# = 30 \end{cases}$$

from surface brightness to luminosity
for the gas cell of index *i*

$$L^i_{[\mathrm{CII}]} = \Sigma^i_{[\mathrm{CII}]} \Delta x_i^2$$

to compute the surface brightness map

$$\Sigma_{[\mathrm{CII}]}(x, y) = \sum_i L^i_{[\mathrm{CII}]} K(x, x_i, \Delta x_i) K(y, y_i, \Delta x_i)$$

Ferland+13,+17, Vallini+17

Computing spectra

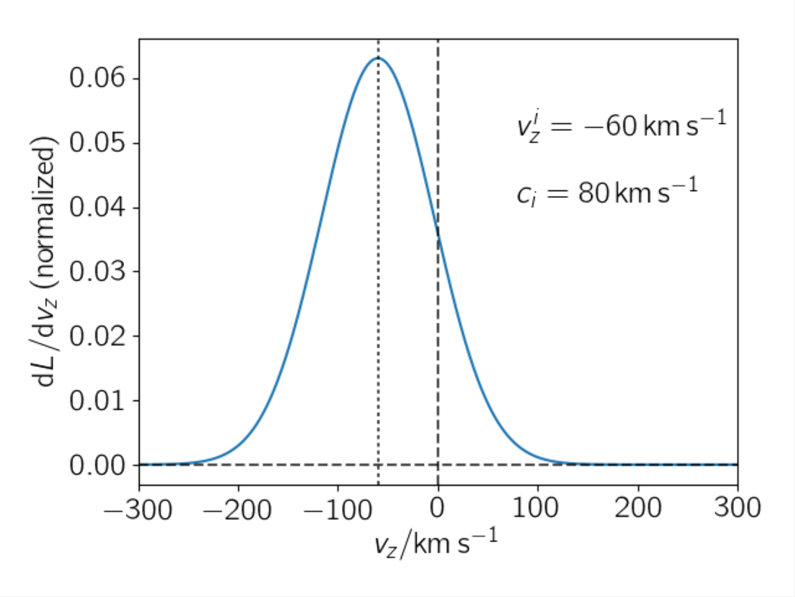
a spectrum depend both on the luminosity and the kinematic structure along the line of sight

$$\frac{\mathrm{d}L}{\mathrm{d}v_z}(v_z) = \sum_i L_i K(v_z, v_z^i, c_i)$$

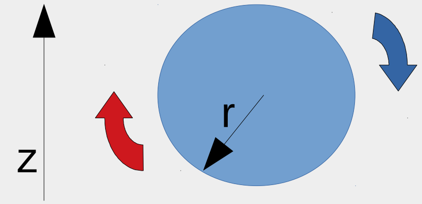
Doppler effect due to proper motion: v_z^i

thermal broadening of the line: $c_i = \gamma\sqrt{\mathrm{K}_b T_i/\mathrm{m}_p}$

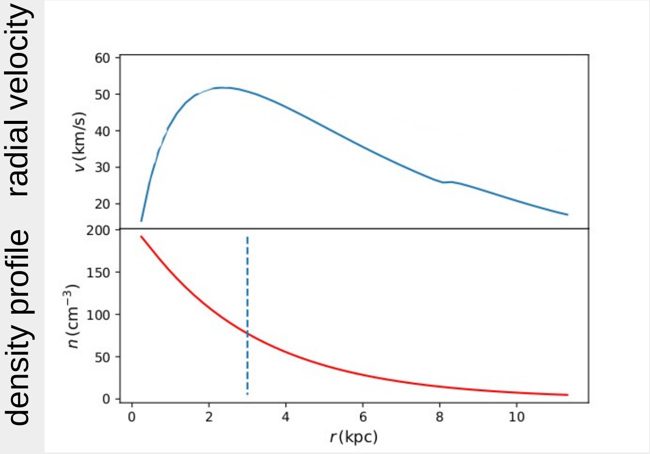
using a Gaussian kernel is physically motivated in this case

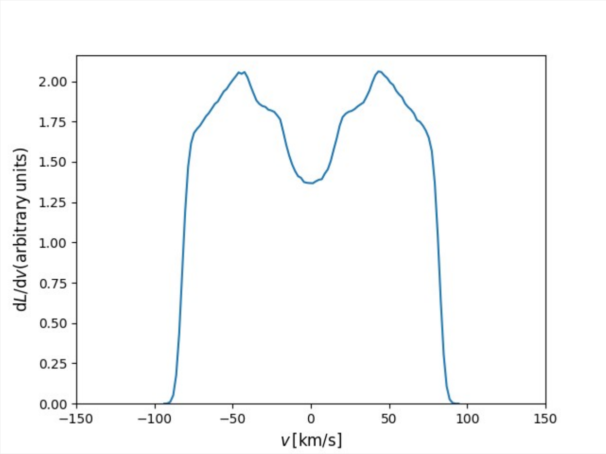


kinematic can be tricky:
e.g. rotating disk seen edge-on



profiles due to a self-gravitating gas disk (no DM here)





resulting profile has a characteristic double horned structure

converting in observed quantities (using astropy)

$$F = \frac{L}{4\pi D_L^2}$$

$$D_L = D_L(z,\ \text{cosmological model})$$

$$F_\nu = \frac{\mathrm{d}F}{\mathrm{d}\nu} = \frac{1}{4\pi D_L^2}\frac{\mathrm{dL}}{\mathrm{d}v_z}\frac{\mathrm{d}v_z}{\mathrm{d}\nu}$$

Kohandel+19