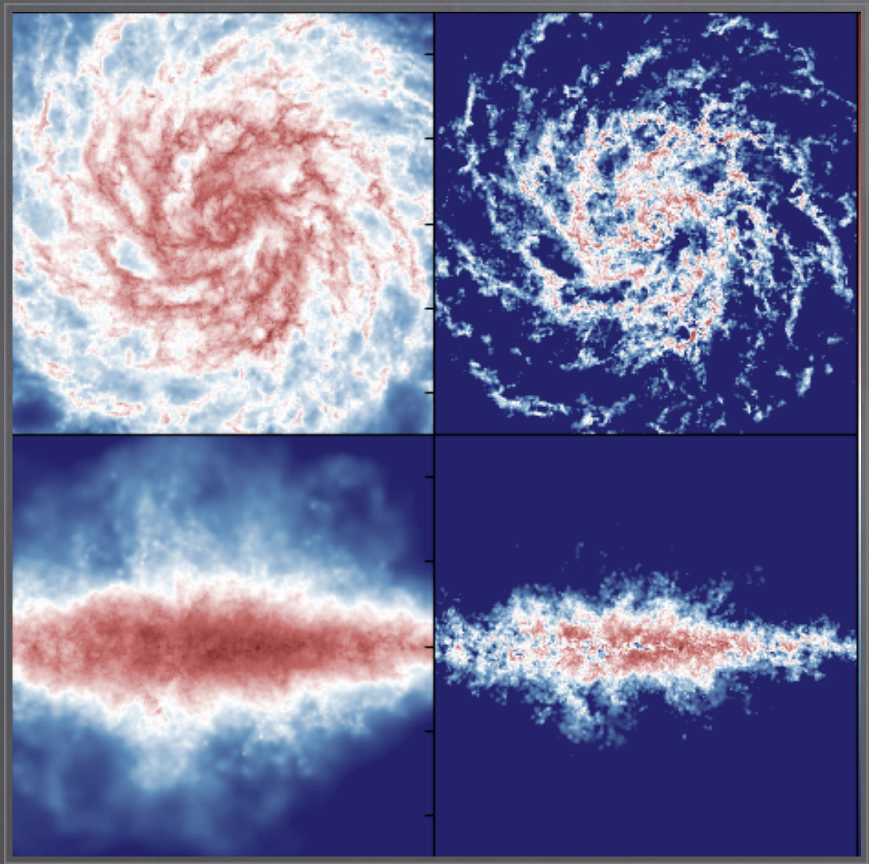
Kinematics and dynamics of molecular gas in galaxies



Alessandro Lupi

(Institut d'Astrophysique de Paris)

DARK MATTERS

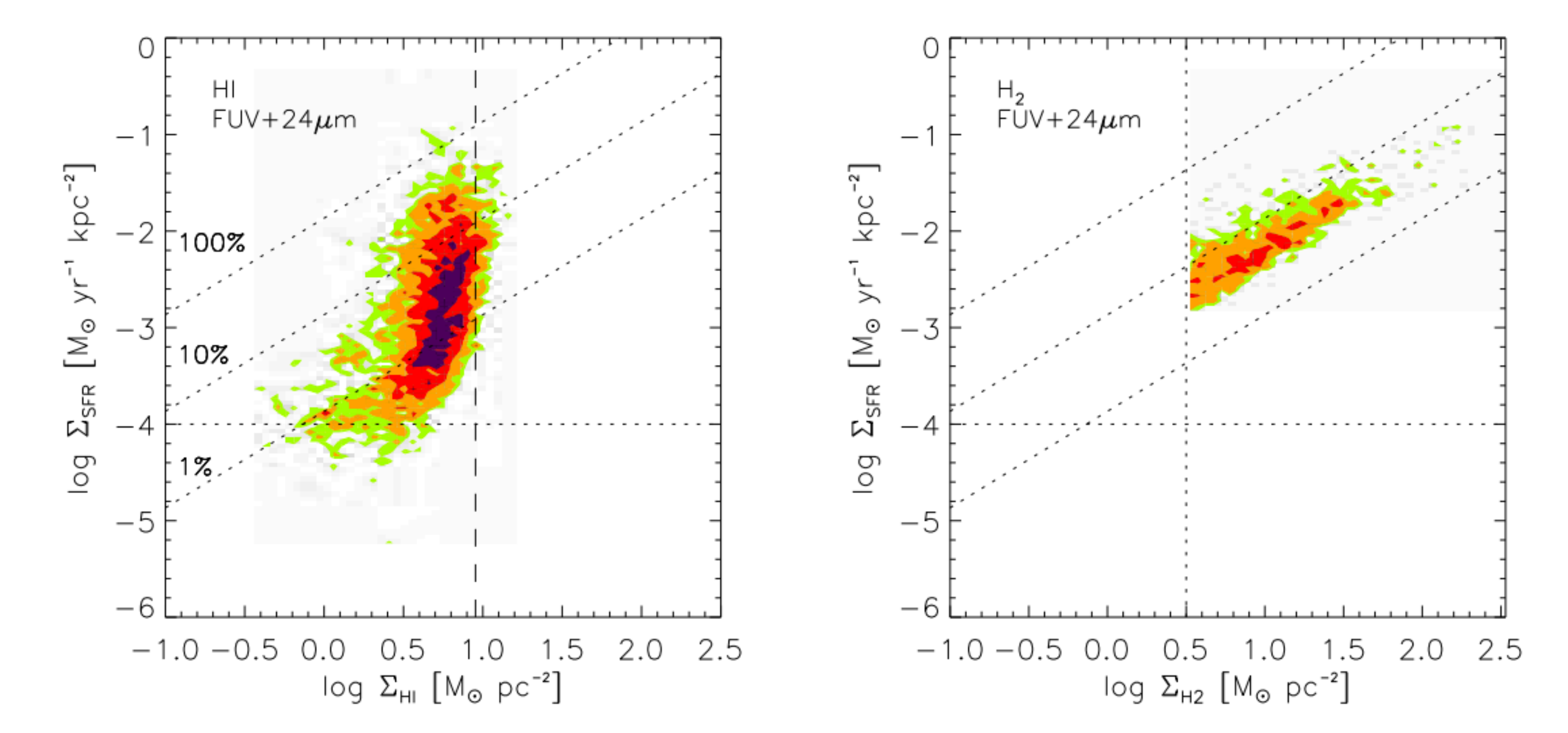
Joe Silk's 75th Birthday

in collaboration with S. Bovino, P. R. Capelo, M. Volonteri, J. Silk

December 11th, 2017

IAP, Paris

The observed KS relation



Bigiel+2008

H2-based star formation

Standard prescription:

$$\dot{\rho}_{\rm SF} = \varepsilon \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

$\rightarrow (T_{\rm g} < T_{\rm g,thr})$

$\rightarrow \rho_{\rm g} > \rho_{\rm g,thr}$

H2-based prescription:

(Gnedin+09, Christensen+12, Hopkins+14, Tomassetti+15, Pallottini+17, Hopkins+17)

$$\dot{\rho}_{\rm SF} = \varepsilon_0 f_{\rm H_2} \frac{\rho_{\rm gas}}{t_{\rm ff}}$$

BUT

Recent theoretical studies have revealed a lack of causal connection between H_2 and SF (Krumholz et al. 2011, Clark et al. 2012).

MORE LIKELY

The formation of H2 is controlled by SF, or, in general, by the gravitational collapse of atomic gas, not vice versa (Mac Low 2016).

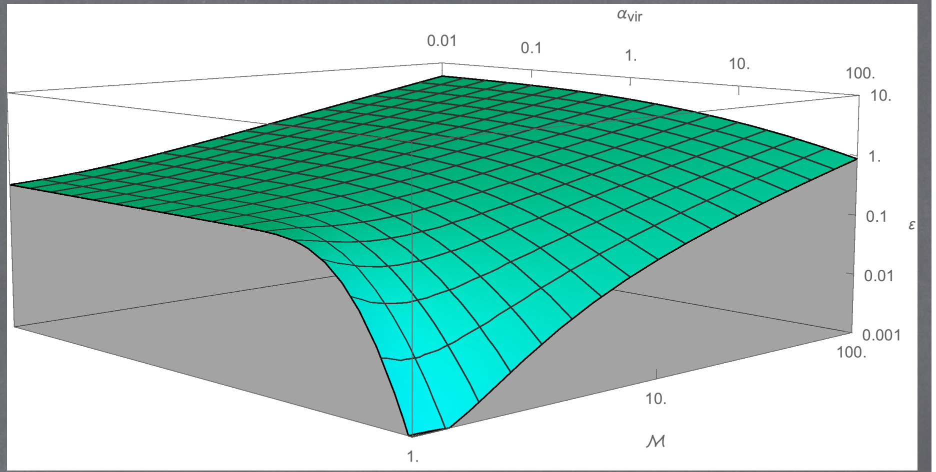
Star formation model

(Turbulent magnetized clouds)

Padoan & Nordlund 2011

$$p_s(s) = \frac{1}{\sqrt{2\pi\sigma_s^2}} \exp[\frac{-(s-s_0)^2}{2\sigma_s^2}]$$

$$\sigma_s^2 = \ln(1 + b^2\mathcal{M}^2)$$



The critical density for SF is related to the magnetic shock jump conditions and to the magnetic critical mass for collapse

$$s_{\rm crit} = \ln\left[0.067\theta^{-2}\alpha_{\rm vir}\mathcal{M}^2\right] \qquad \alpha_{\rm vir} = 5\sigma_{\rm v}^2 L/(6GM_{\rm cloud})$$

$$\varepsilon = \frac{\epsilon_\star}{2\phi_t}\exp(\frac{3}{8}\sigma_s^2)\left[1 + {\rm erf}\left(\frac{\sigma_s^2 - s_{\rm crit}}{\sqrt{2\sigma_s^2}}\right)\right]$$

Federrath & Klessen 2012

Numerical setup

KROME
Non-eq. chemistry
(Photochemistry)

+

GIZMO
mesh-less
finite mass

=

GIZMO-KROME

+

Physically motivated SF

SN feedback + Mass losses from low-mass stars

Interstellar radiation field

Clumping factor

Galaxy with typical z=3 properties

NFW DM halo + exp. decay: $\mathbf{R_{vir} = 45\ kpc}$

$\mathbf{M_{halo} = 2x10^{11}\ M_\odot}$

Stellar + gaseous disc: $\mathbf{R_0 = 1.28\ kpc}$

$\mathbf{M_{star} = 1.6x10^9\ M_\odot\ ;\ M_{gas} = 2.4x10^9\ M_\odot}$

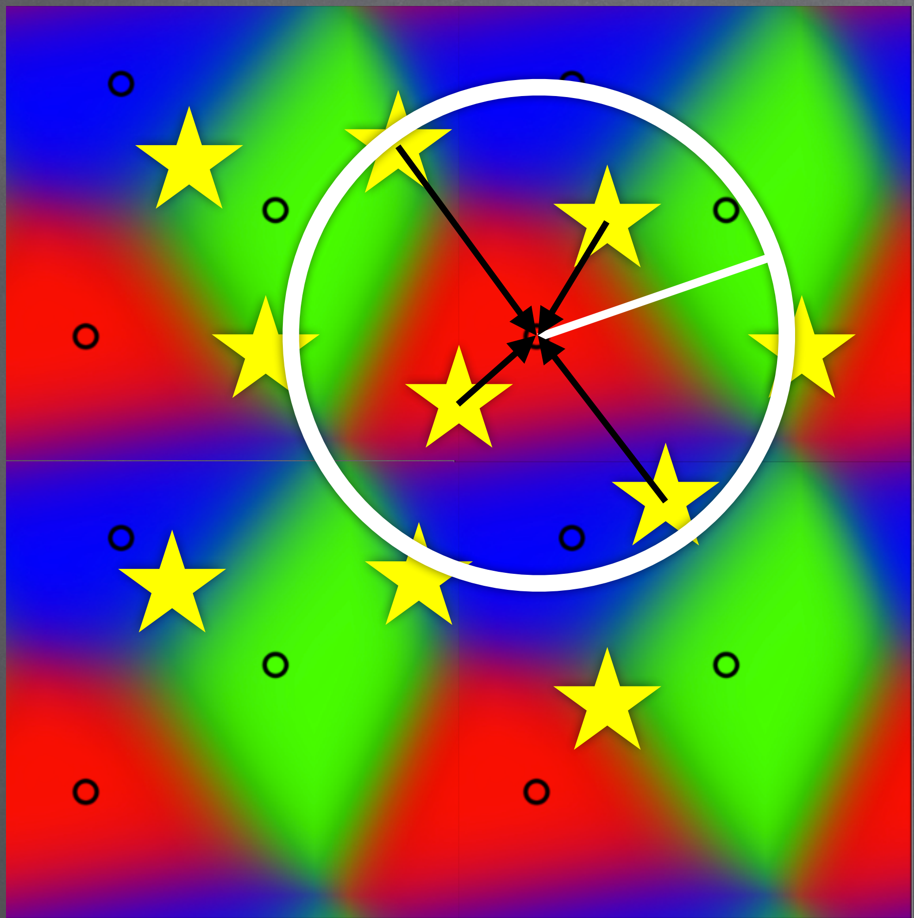
Hernquist stellar bulge: $\mathbf{a = 0.256\ kpc}$

$\mathbf{M_{bulge} = 8x10^8\ M_\odot}$

Evolved for 400 Myr in isolation

The Interstellar radiation field

We implemented two sub-grid models and compared them with a full-RT simulation.



Model ‘S’

$$\tau = \frac{\sigma_{\rm eff}}{m_{\rm H}}(\rho_{\rm g} R_{\rm max} - |\nabla \rho_{\rm g}| R_{\rm max}^2/2)$$

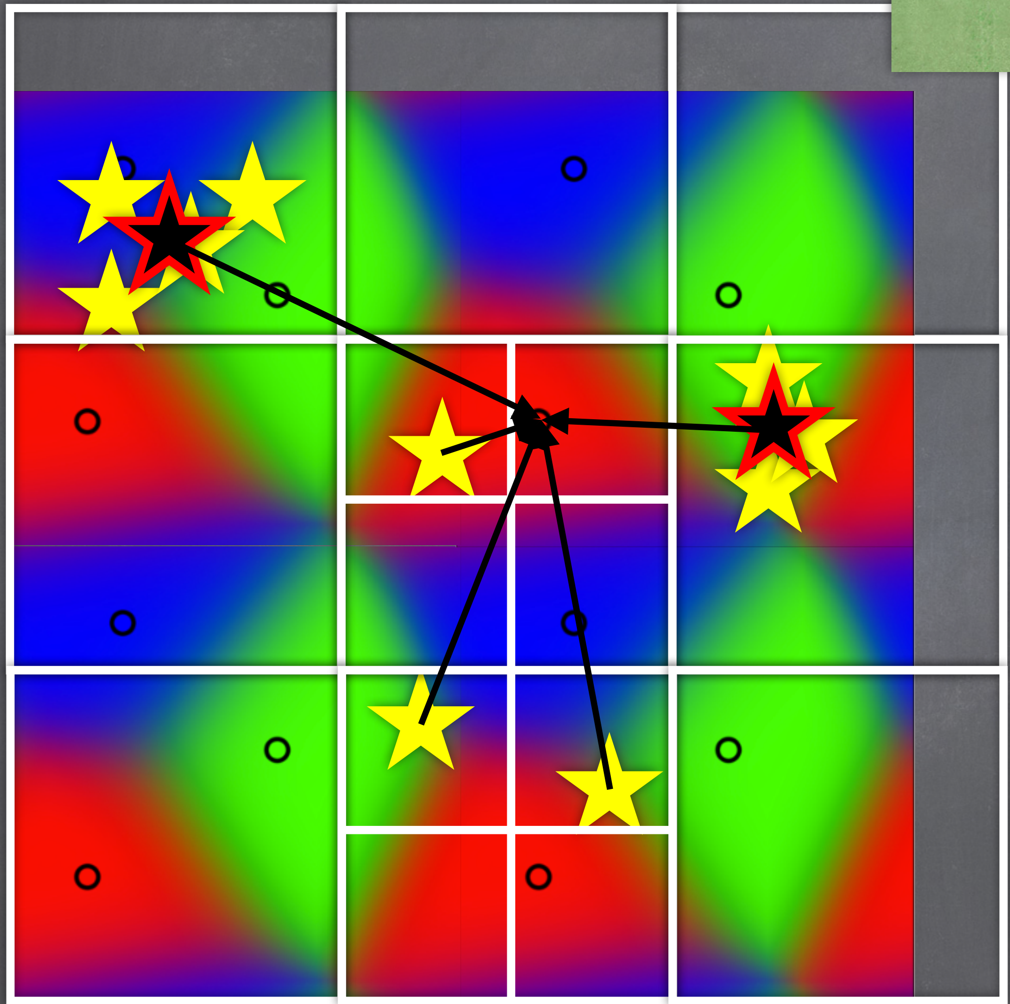
$$F = \sum_i \frac{L_{i,\star}}{4\pi d_i^2} \exp(-\tau_i)$$

$$\tau = \sum_j \sigma_{j,{\rm bin}} n_j \lambda \qquad l_{\rm Sob} = \frac{\rho_{\rm g}}{|\nabla \rho_{\rm g}|}$$

The Interstellar radiation field

Model 'T'

$$F = \left[\sum_i \frac{L_{i,\star}}{4\pi d_i^2} \exp(-\tau_i) \right] \exp(-\tau_\mathrm{g})$$



Around star:

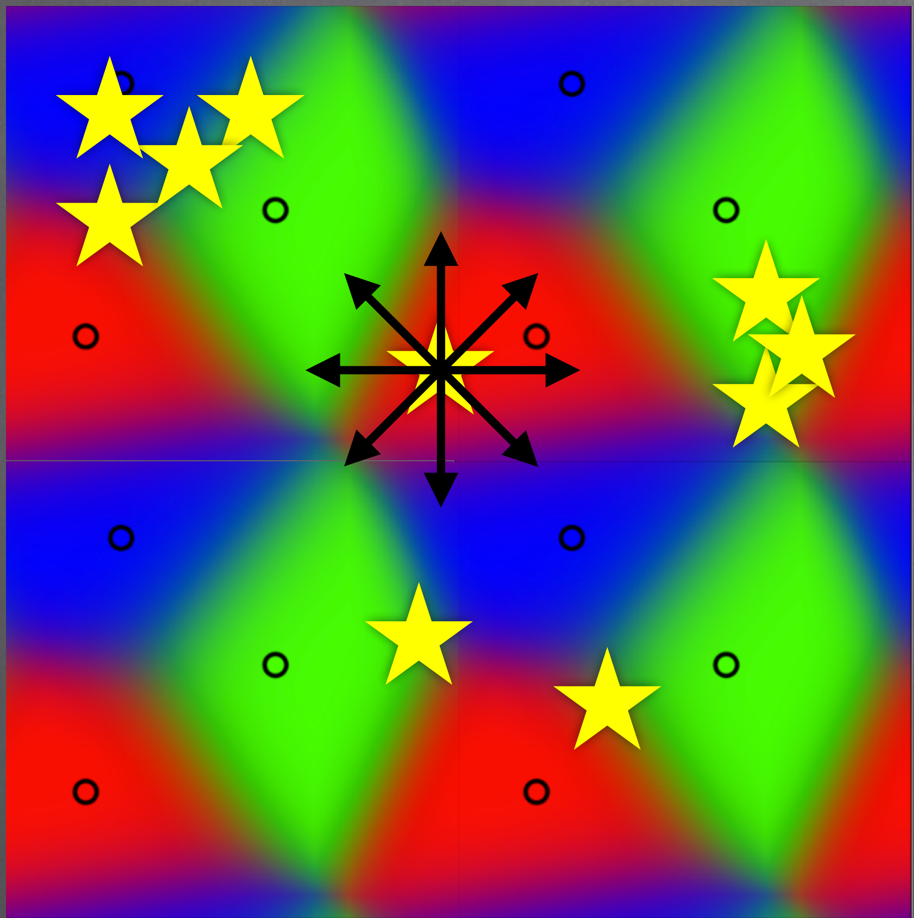
$$l_\mathrm{Sob} = \frac{\rho_\mathrm{g}}{|\nabla \rho_\mathrm{g}|}$$

Around gas:

$$\lambda_\mathrm{J} = \frac{\sqrt{\pi} c_\mathrm{s}}{\sqrt{\mathrm{G}\rho}}$$

RT in GIZMO

Momentum method with M1 closure scheme
(Rosdahl et al. 2013)



$$\frac{1}{c}\frac{\partial I_\nu}{\partial t} + \mathbf{n}\cdot\nabla I_\nu = S_\nu - k_\nu I_\nu$$

$$\begin{cases} \dfrac{\partial N_\nu}{\partial t} + \nabla\cdot\mathbf{F}_\nu = N_\nu^\star - k_\nu c N_\nu \\ \dfrac{\partial \mathbf{F}_\nu}{\partial t} + c^2\nabla\cdot\mathbb{P}_\nu = -k_\nu c\mathbf{F}_\nu \end{cases}$$

Hopkins et al. (in preparation)

The clumping factor

$$R_f(H_2) = 3 \times 10^{-17} n_{\rm H} n_{\rm H_{tot}} Z/Z_\odot \,{\rm cm^{-3} s^{-1}}$$

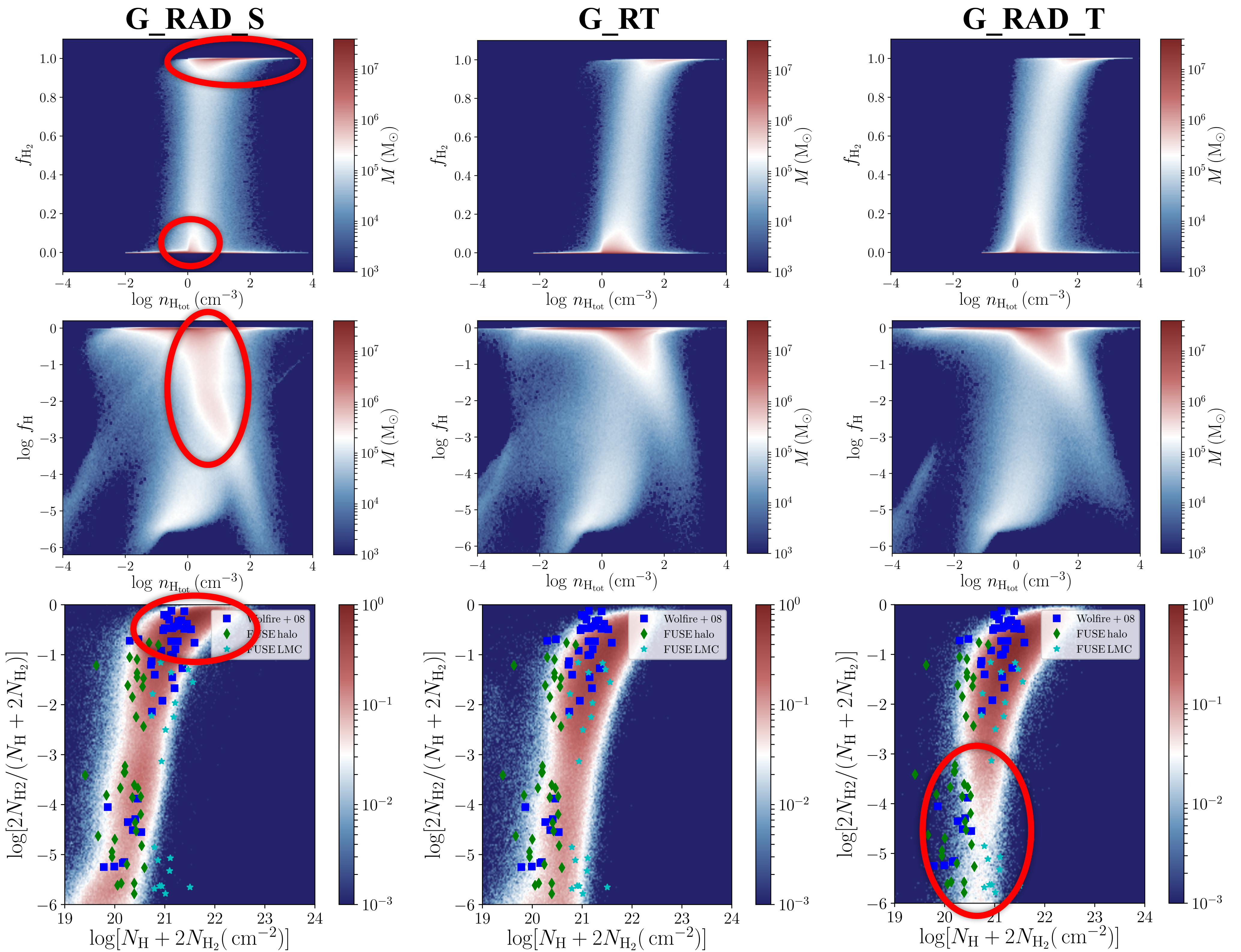
PDF averaged rate

$$\langle R_f(H_2) \rangle = 3 \times 10^{-17} \langle n_{\rm H} n_{\rm H_{tot}} \rangle Z/Z_\odot \,{\rm cm^{-3} s^{-1}}$$

Express using average density

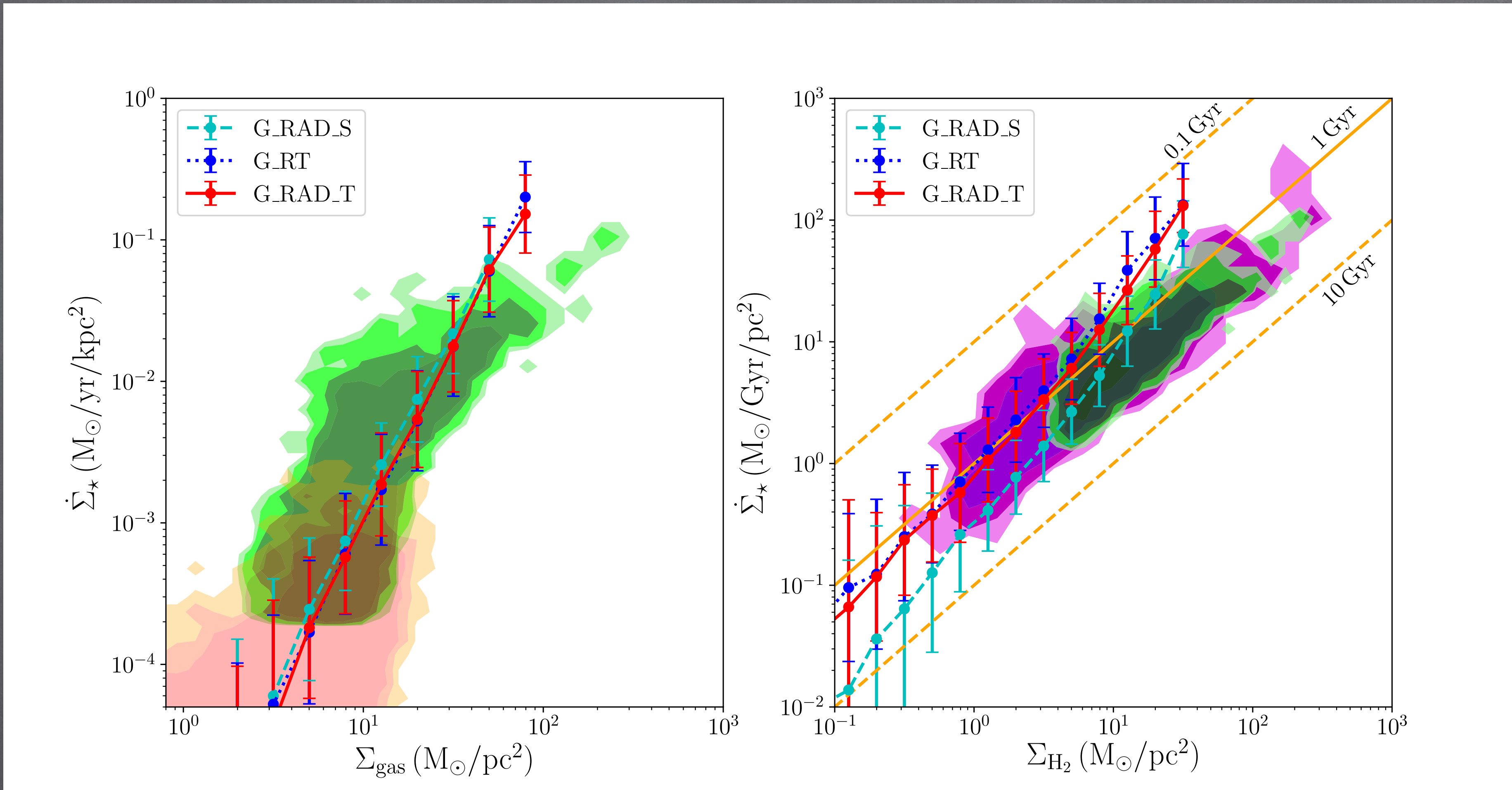
$$\langle R_f(H_2) \rangle = 3 \times 10^{-17} \langle n_{\rm H} \rangle \langle n_{\rm H_{tot}} \rangle C_\rho Z/Z_\odot \,{\rm cm^{-3} s^{-1}}$$

$$C_\rho = \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} = \exp(\sigma_s^2) = 1 + b^2 \mathcal{M}^2$$



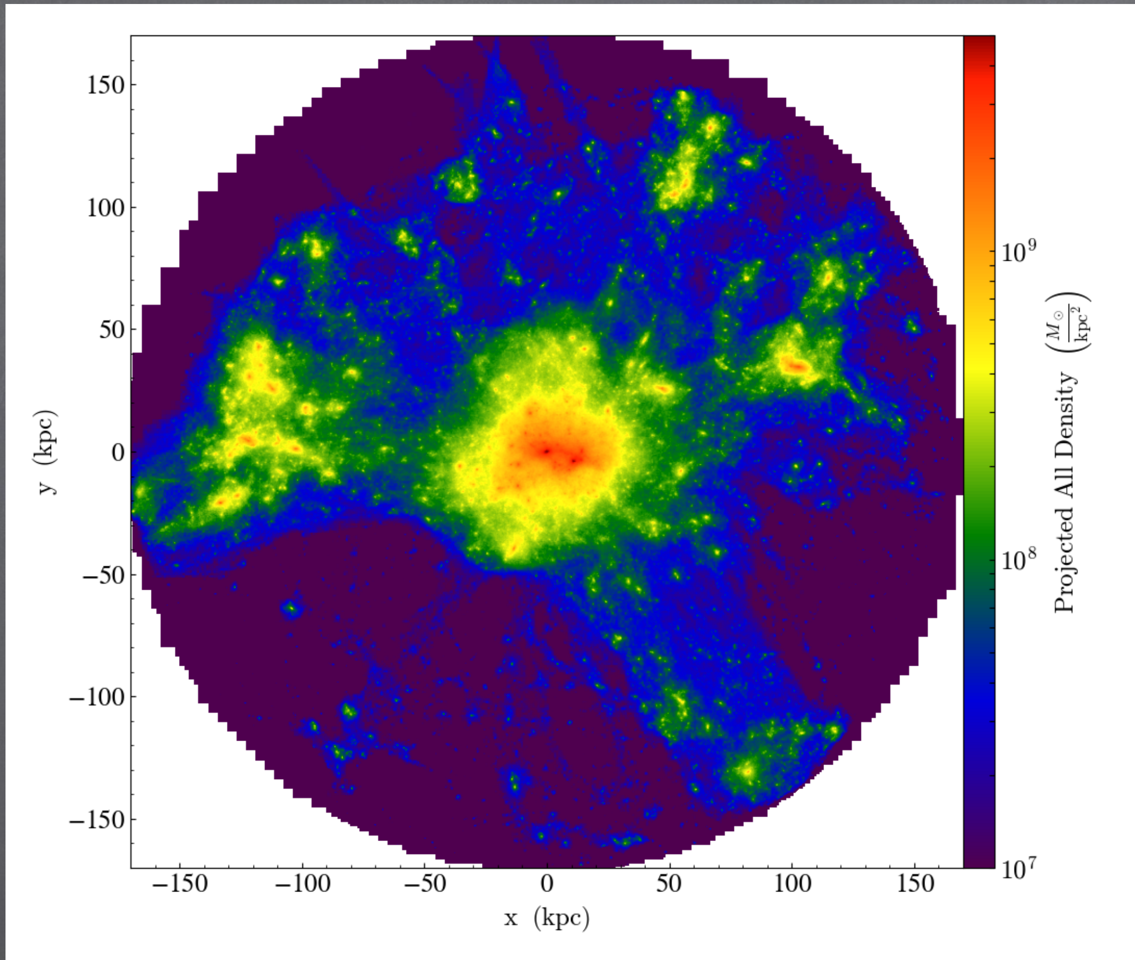
G_RAD_S
G_RT
G_RAD_T
f_{H_2}
$\log n_{H_{tot}}$ (cm^{-3})
$\log f_H$
M (M$_\odot$)
$\log[2N_{H2}/(N_H + 2N_{H_2})]$
$\log[N_H + 2N_{H_2}$(cm^{-2})]
Wolfire + 08
FUSE halo
FUSE LMC

The effect of the interstellar radiation



Model's application

1) Kinematics and dynamics of H_2 in high redshift quasars (Lupi et al. in prep.)



$z_{fin} = 6$
$M_{vir} \sim 2 \times 10^{12}\ M_\odot$

$M_{gas} = \sim 1.5 \times 10^4\ M_\odot$/part
$M_{DM} = \sim 8 \times 10^4\ M_\odot$/part

$N_{gas} = 6.75 \times 10^7$
$N_{DM} = 6.75 \times 10^7$
$N_{DM,low} = 2.2 \times 10^7$

$\epsilon_{gas,min} =$ 80 cpc | 5 pc
$\epsilon_{DM} =$ 640 cpc | 40 pc
$\epsilon_{star} =$ 192 cpc | 12 pc

2) Formation of C^+ in dwarf galaxies, using the network presented in Capelo, Bovino, Lupi et al. 2017 (submitted), which also includes C, O an Si.

Conclusions

Lupi et al. 2018 (MNRAS)

We developed a new model to accurately track H2 in numerical simulations using the package KROME, including photochemistry, SF, SNe, stellar radiation and shielding (gas, dust, H_2).
We tested the model on an idealised setup of an isolated galaxy with typical properties of z=3 galaxies, assessing the effect of the different processes included.

- The correlation between H2 and SF surface densities can be naturally reproduced, if we account for all the most important processes and for a self-consistent clumping factor.

- The correlation is maintained at low H2 surface densities, not yet accessible in observations.

- The model is valid at different resolutions, without any numerical calibration, as long as we can resolve a large fraction of the GMC mass function ($\sim 10^{4-5}\ M_\odot$).

- An H2-dependent SF prescription is not necessary and probably unmotivated.