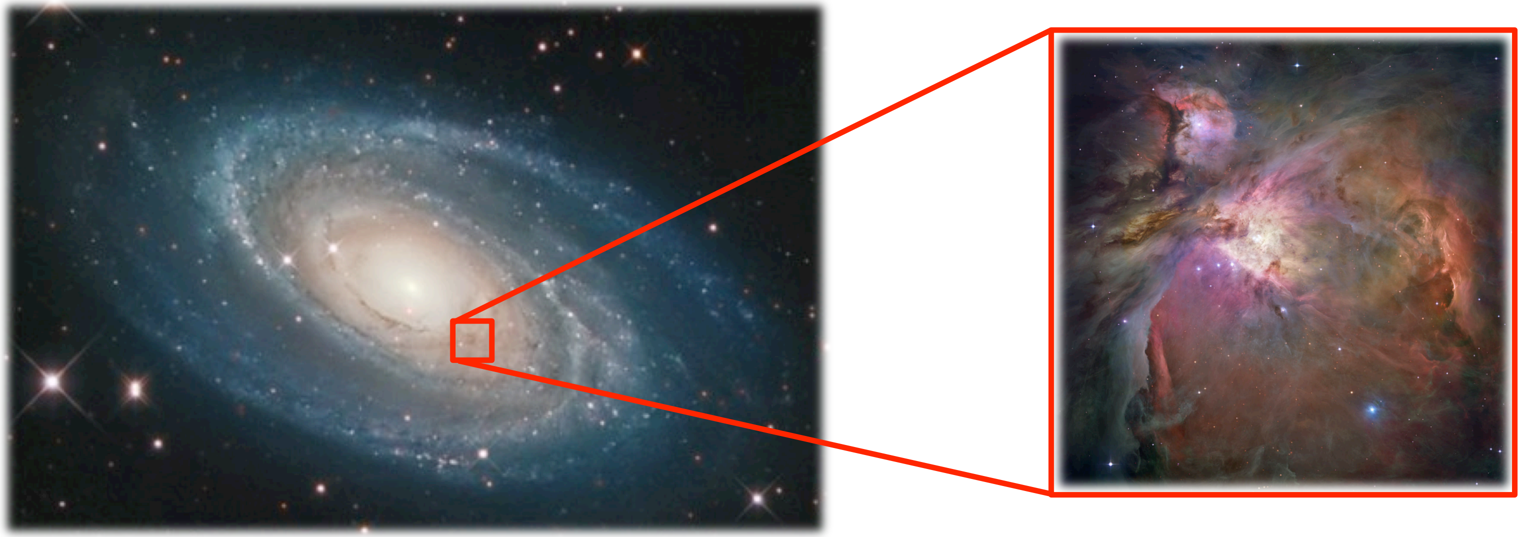
The multi-scale physics of galactic star formation and a solution for the GMC lifetime 'problem'



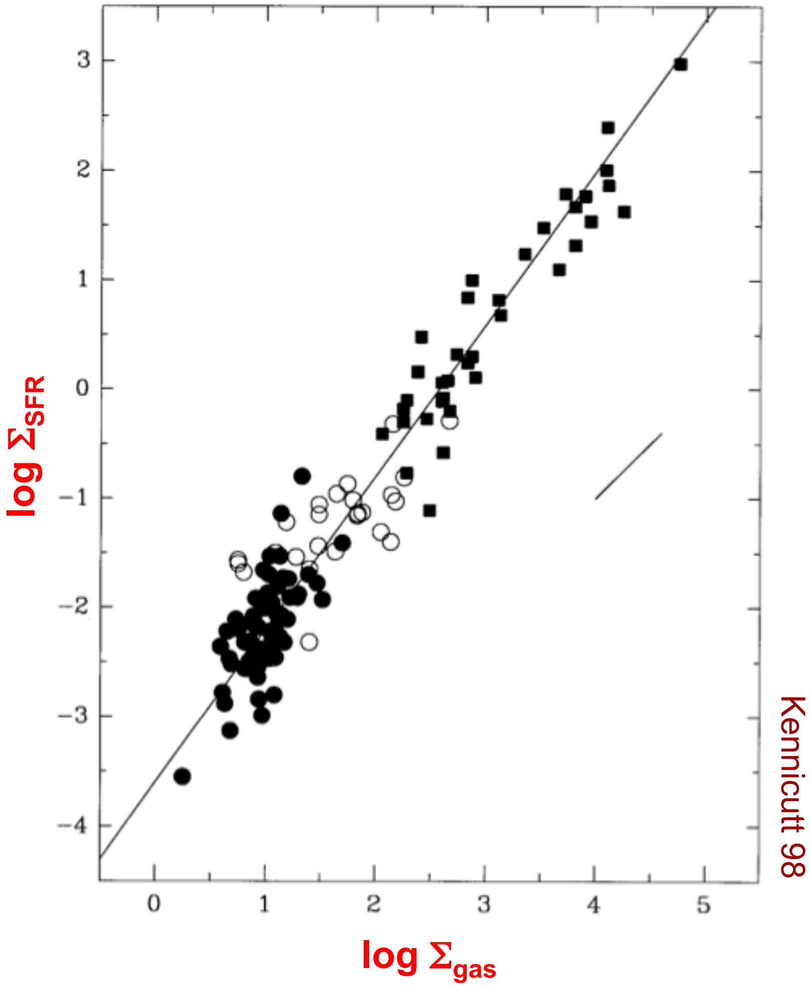
J. M. Diederik Kruijssen
MPA

with Steve Longmore (LJMU), Andreas Schruba (MPE)

Physics and scale dependence of galactic SF relations

J. M. Diederik Kruijssen – Max Planck Institute for Astrophysics

How do galaxies turn their gas into stars?



$$\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^{1.4}$$

Schmidt 59
Kennicutt 98

$$\Sigma_{\rm SFR} \propto \frac{\Sigma_{\rm gas}}{\tau_{\rm dyn}} \propto \Sigma_{\rm gas}\,\Omega_{\rm gas}$$

Elmegreen 97
Silk 97

Star formation occurs in localised events

NGC 300, GALEX

Decomposition of the star formation relation

$$\mathrm{SFR} = \frac{\epsilon}{t_{\mathrm{SF}}} M_{\mathrm{gas}}$$

$$\mathrm{SFR} = \sum_{\mathrm{clouds}} \frac{\epsilon_{\mathrm{cloud}}}{t_{\mathrm{SF,cloud}}} M_{\mathrm{cloud}}$$

Problem #1: need to resolve clouds

Problem #2: how to measure time-scales?

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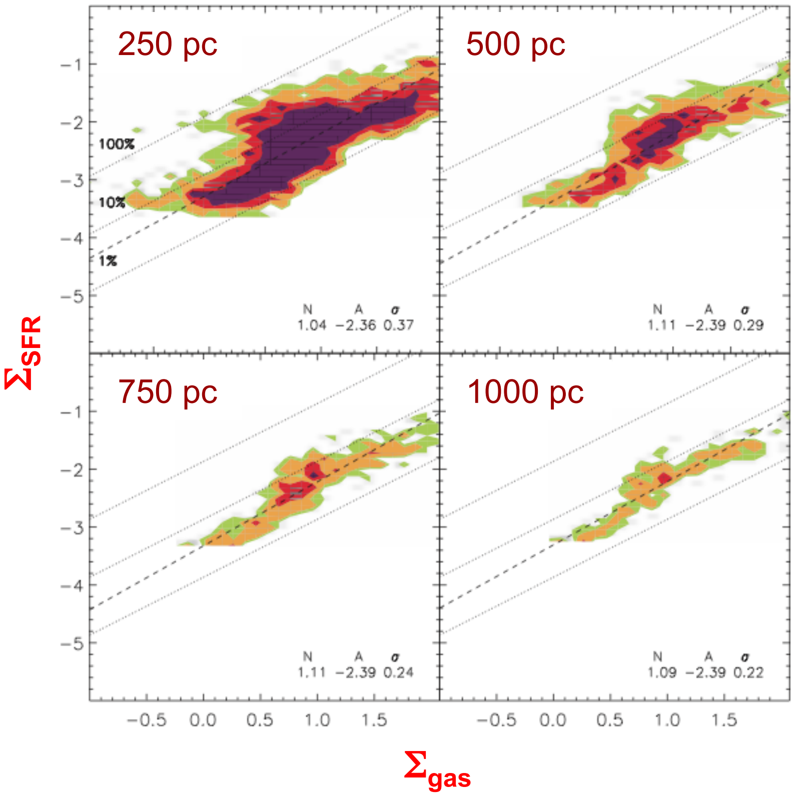
Spatially resolved star formation relations

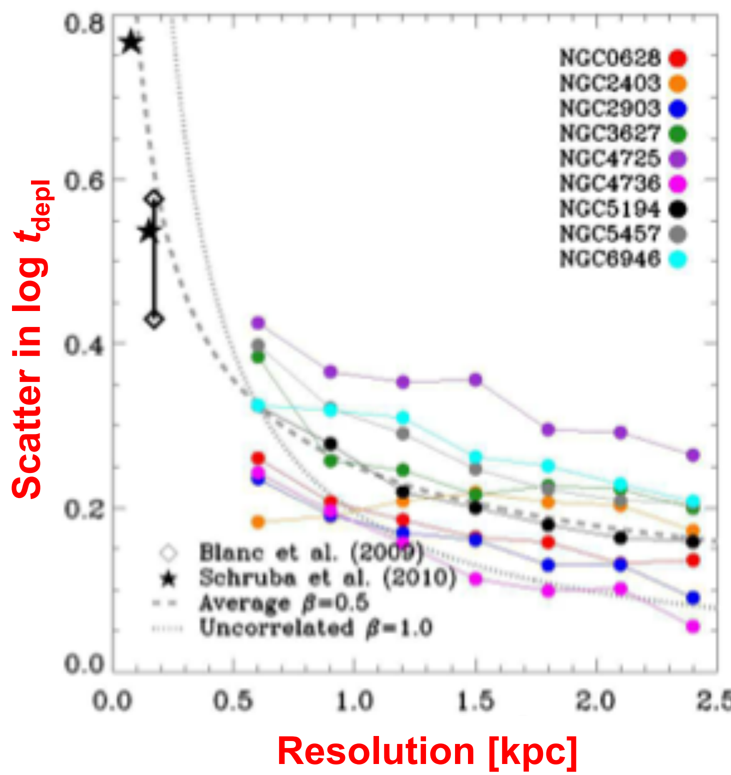
see talk by Gear

✧ Recent observations find increasing *scatter* on smaller scales…

Kennicutt+07, Bigiel+08, Onodera+10, Liu+11, Leroy+13



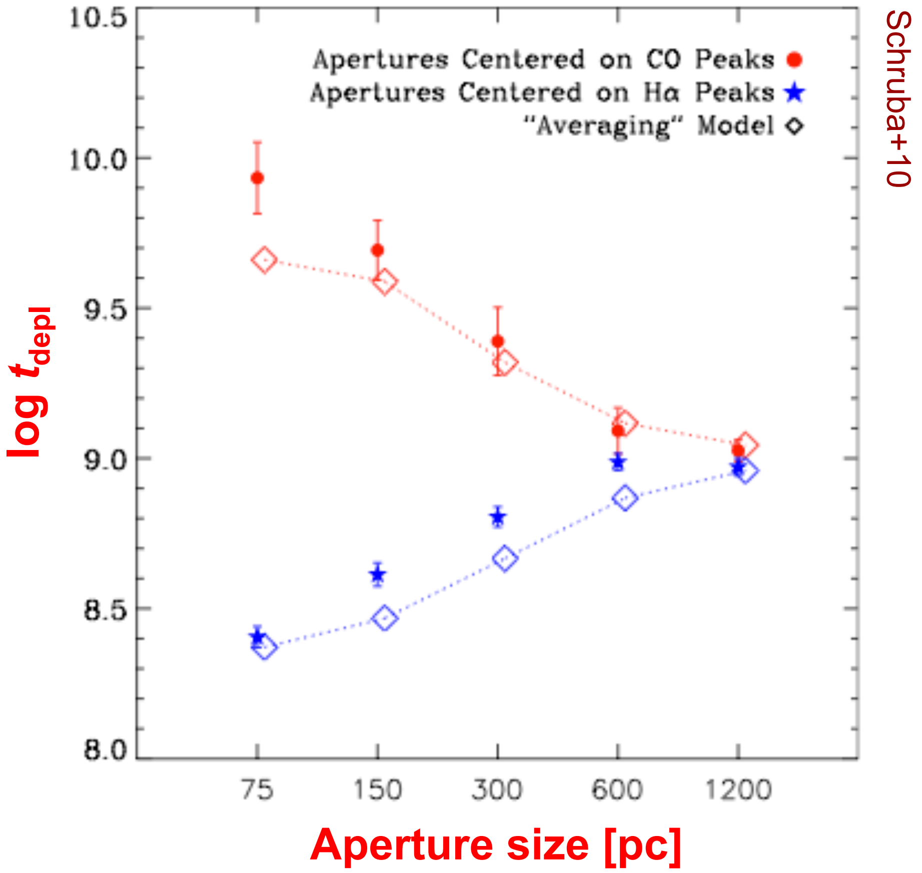
Bigiel+08



Leroy+13

Spatially resolved star formation relations

✧ …or *bias* when focussing apertures on gas or stellar peaks



Centre on:

gas

stars

Spatially resolved star formation relations

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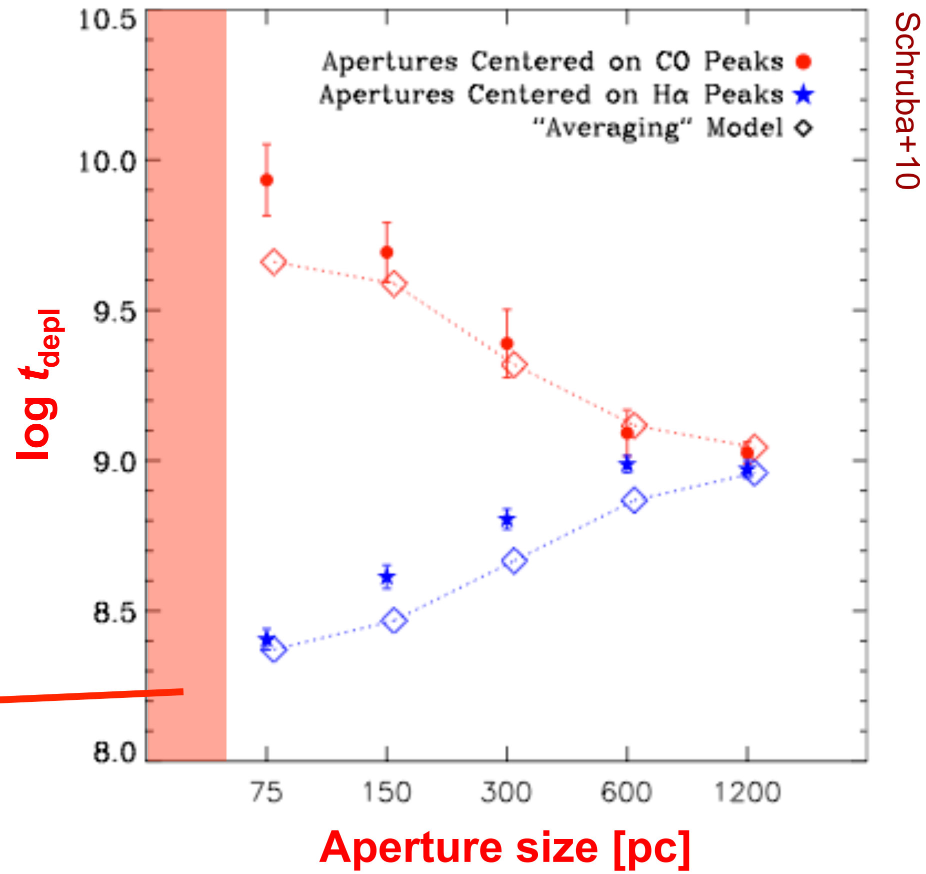

Clouds

Centre on:

gas

stars

The breakdown of galactic SF relations on small scales is *fundamental*

If a macroscopic correlation is caused by a time-evolution, then it *must* break down on small scales because the subsequent phases are resolved.

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The breakdown of galactic SF relations on small scales is *useful*

The *way in which* galactic star formation relations depend on the spatial scale is a direct probe of the physics of star formation on the cloud scale

Decomposition of the star formation relation

$$\mathrm{SFR} = \frac{\epsilon}{t_{\mathrm{SF}}} M_{\mathrm{gas}}$$

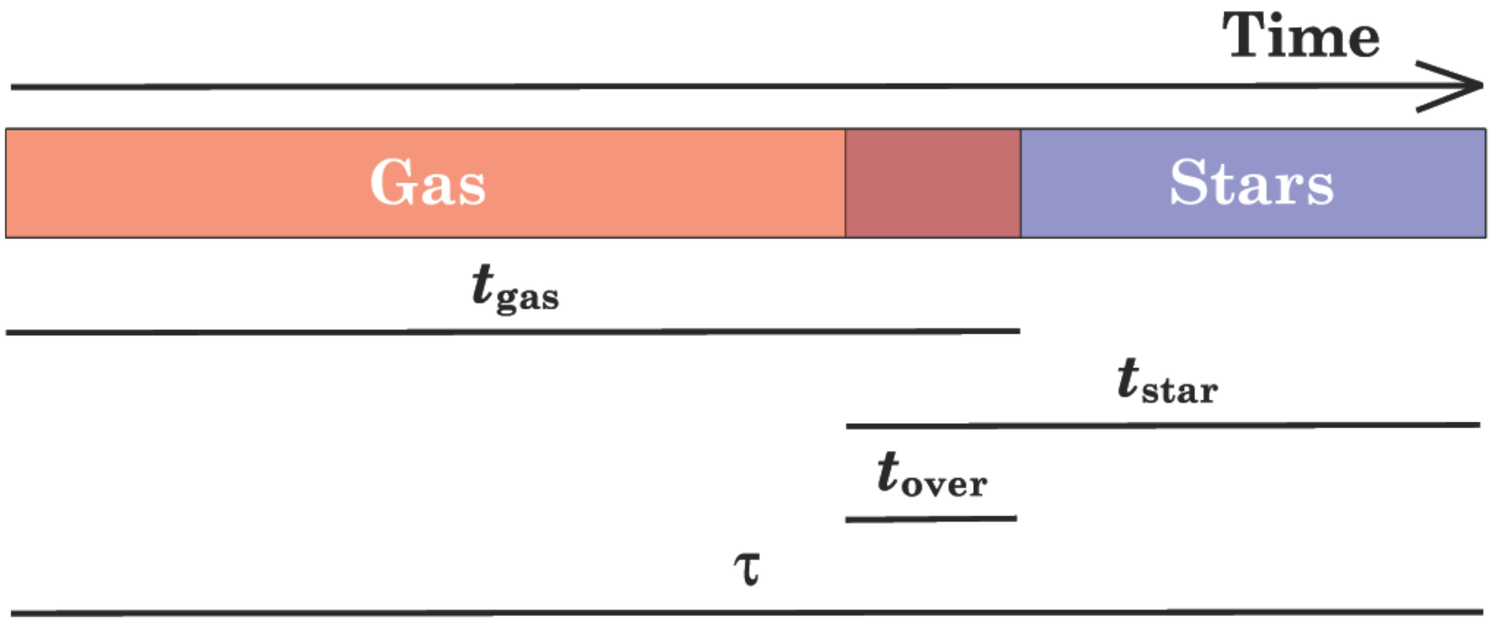
$$\mathrm{SFR} = \sum_{\mathrm{clouds}} \frac{\epsilon_{\mathrm{cloud}}}{t_{\mathrm{SF,cloud}}} M_{\mathrm{cloud}}$$

The multi-scale nature of SF relations provides a way to measure these quantities

1. a toy model

Kruijssen & Longmore 2014, MNRAS 439, 3239

A statistical toy model (1)



✧ Galactic SF relation results from homogeneous sampling of time sequence

✧ Time-integration of single region gives galactic SF relation

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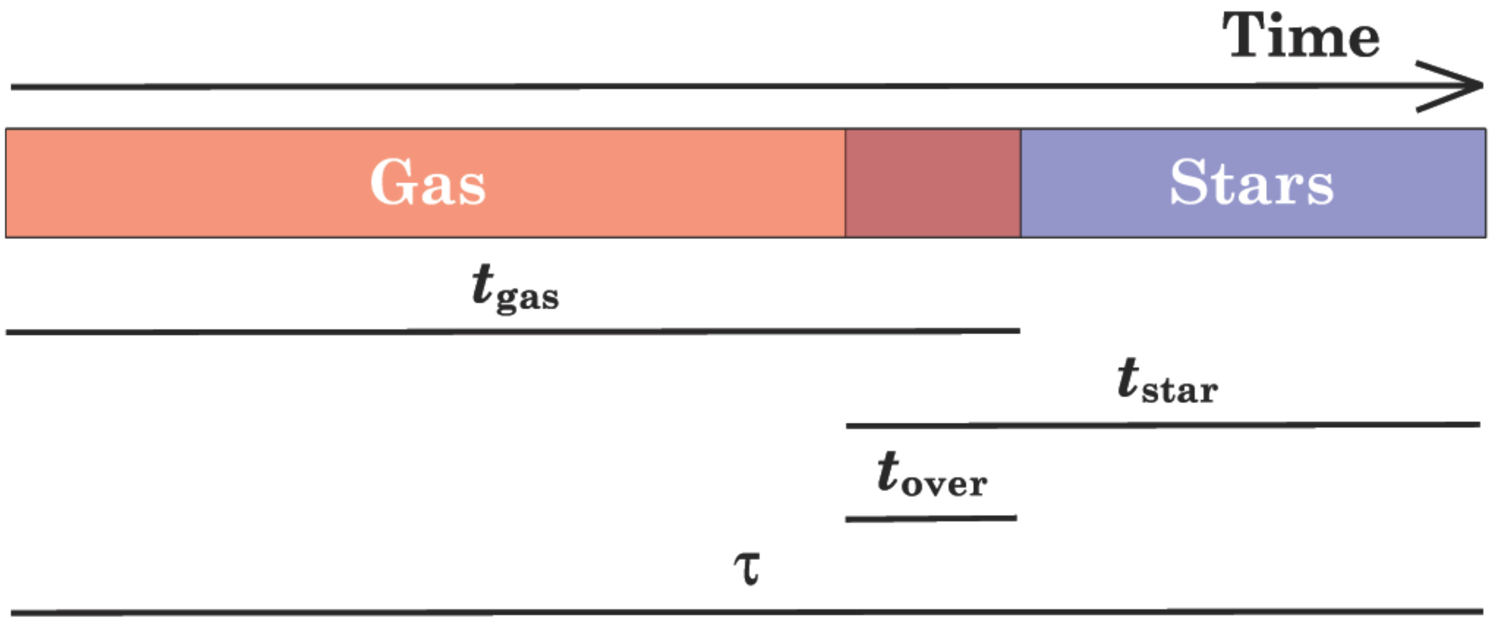
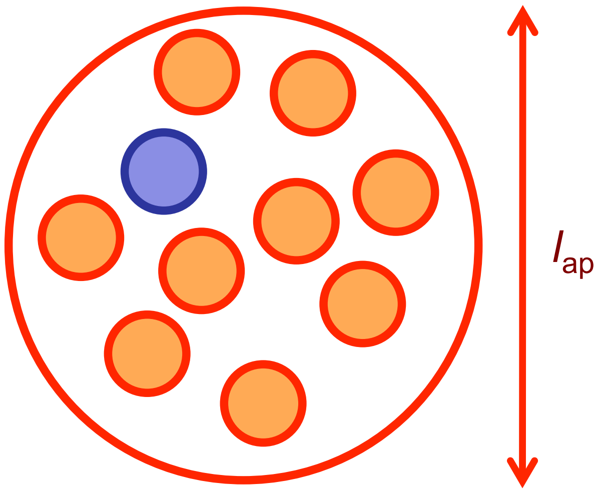
A statistical toy model (2)



- ✧ What does this mean in practice?
- ✧ To retrieve galactic SF relation from observations: need (at least) one region in aperture that contains the "shortest" tracer
- ✧ Example for t_{gas} = 9 x t_{star}



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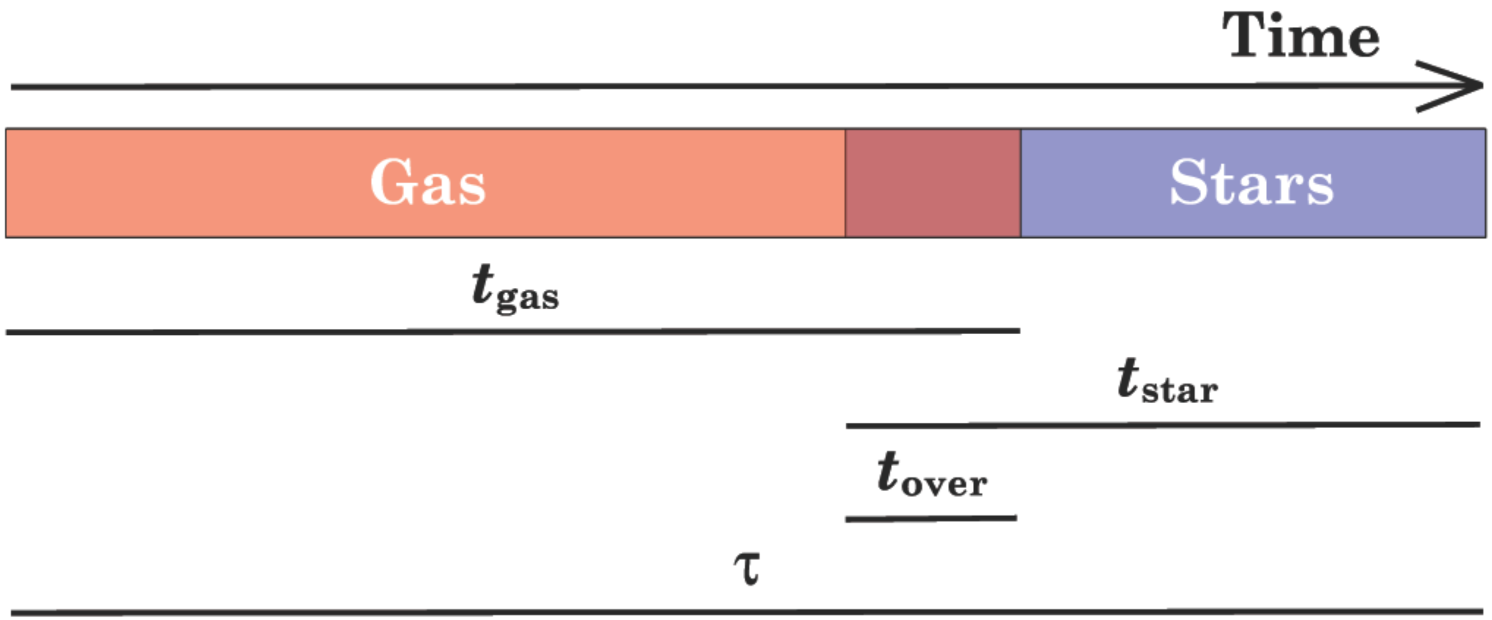

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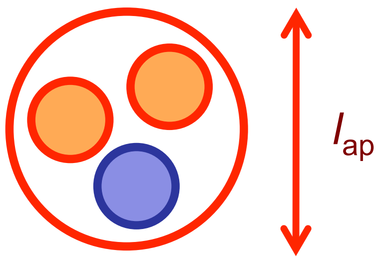


- Example for $t_{\rm gas}$ = 2 x $t_{\rm star}$

An uncertainty principle for star formation

Kruijssen & Longmore 14

$$\Delta x \Delta t^{1/2} \geqslant \lambda \tau^{1/2}$$

Size-scale over which SF relation is spatially averaged

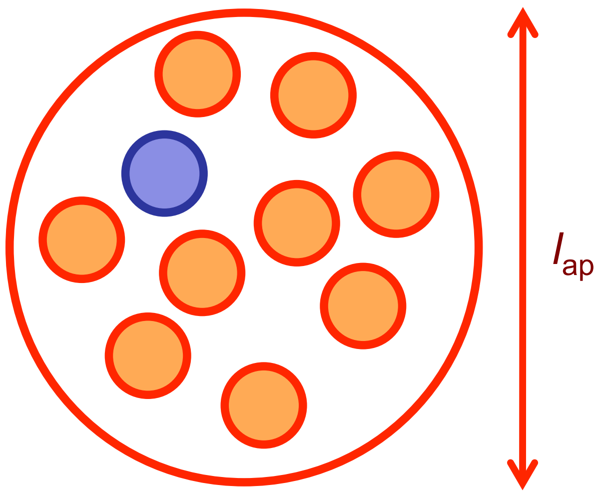
Duration of shortest SF phase

Separation of independent regions

Total duration of the SF process

If this condition is satisfied, the "shortest" tracer should be well-sampled within the aperture

➔ Galactic SF relation is retrieved



An uncertainty principle for star formation

Kruijssen & Longmore 14

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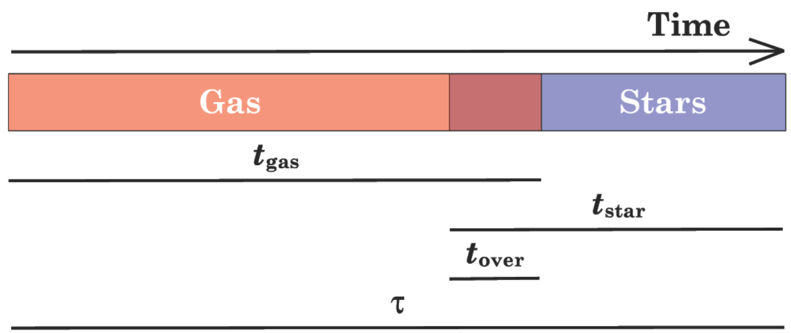
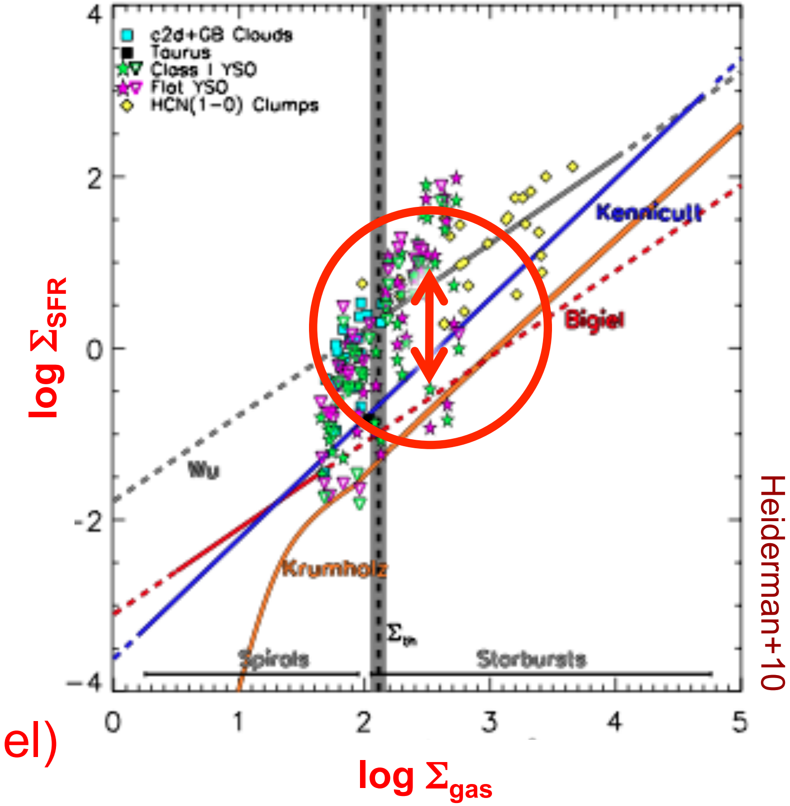


If this condition is not satisfied:

➔ Scatter is large
➔ Time-line may only partially be covered
➔ Depletion time shorter by factor t_{gas}/t_{over} ~ 10–20

(hence Heiderman/Lada vs. Kennicutt/Bigiel)

see talks by Alves, André



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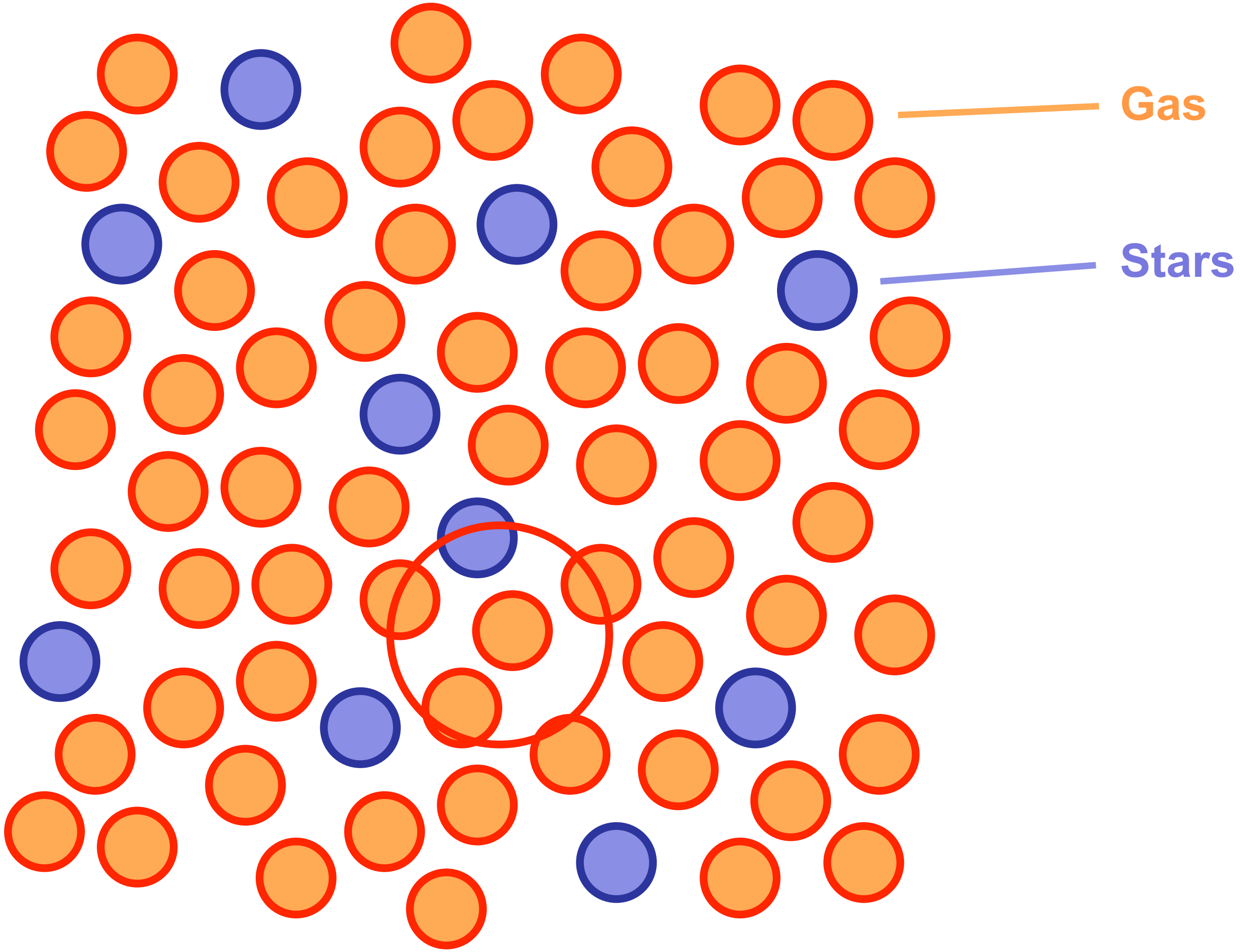
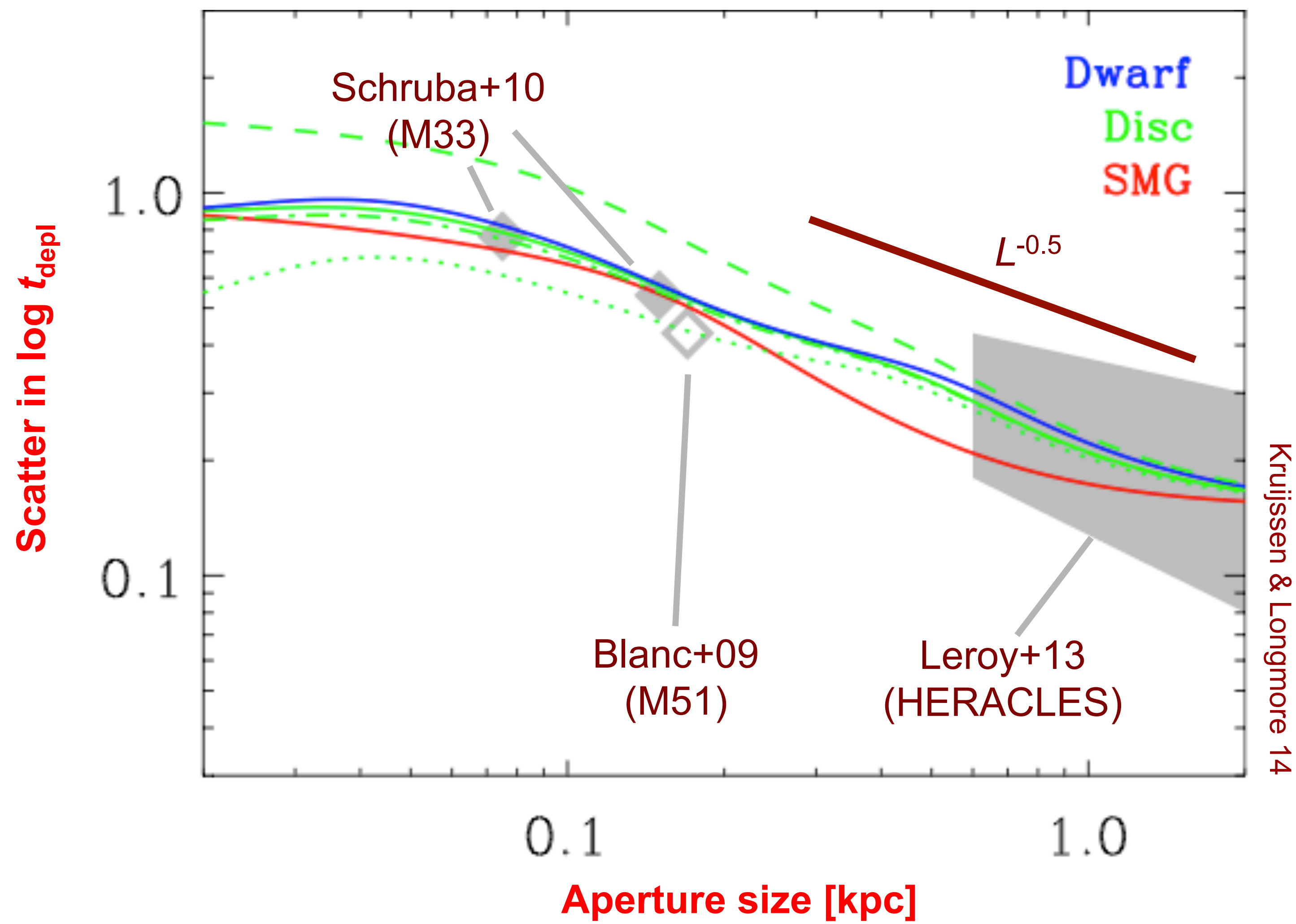
Effect when randomly placing an aperture



Scatter versus (randomly placed) aperture size



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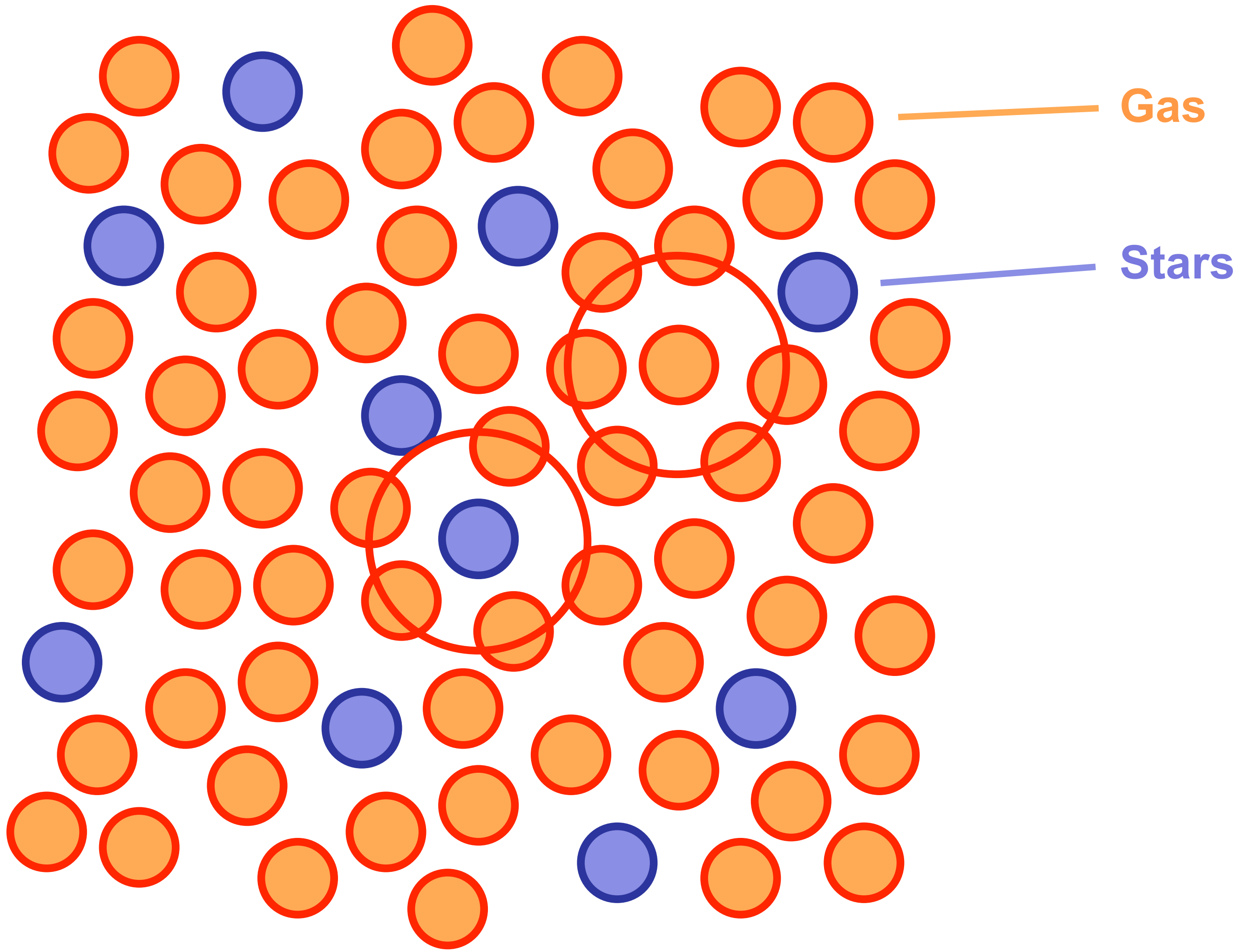
Effect when placing an aperture on peaks of gas or star formation



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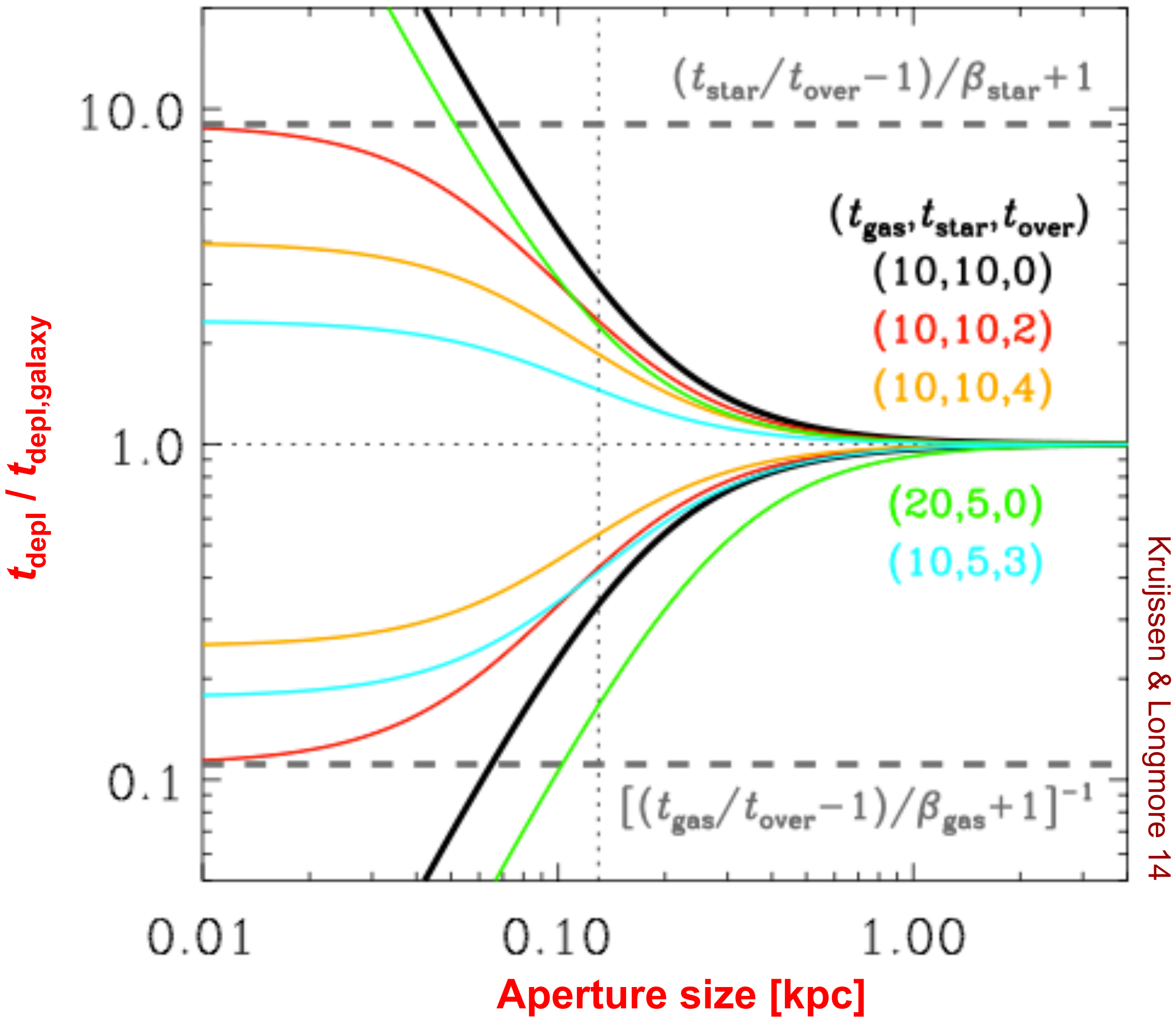
Gas depletion time bias versus (specifically placed) aperture size



Centre on:

gas

stars

An uncertainty principle for star formation

✧ Simple interpretative framework describing multi-scale SF

✧ Potentially very powerful tool to obtain:
- time-scales involved in SF process (duration, "cloud" lifetimes, etc.)
- time spent by gas at different densities (by combining different tracers)

✧ Improvements with respect to previous work:
- self-consistently accounts for statistics ➔ direct translation to time-scales
- no need to resolve individual clouds ➔ works out to $z \sim 4$

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This is what ALMA was made to do

Physics and scale dependence of galactic SF relations

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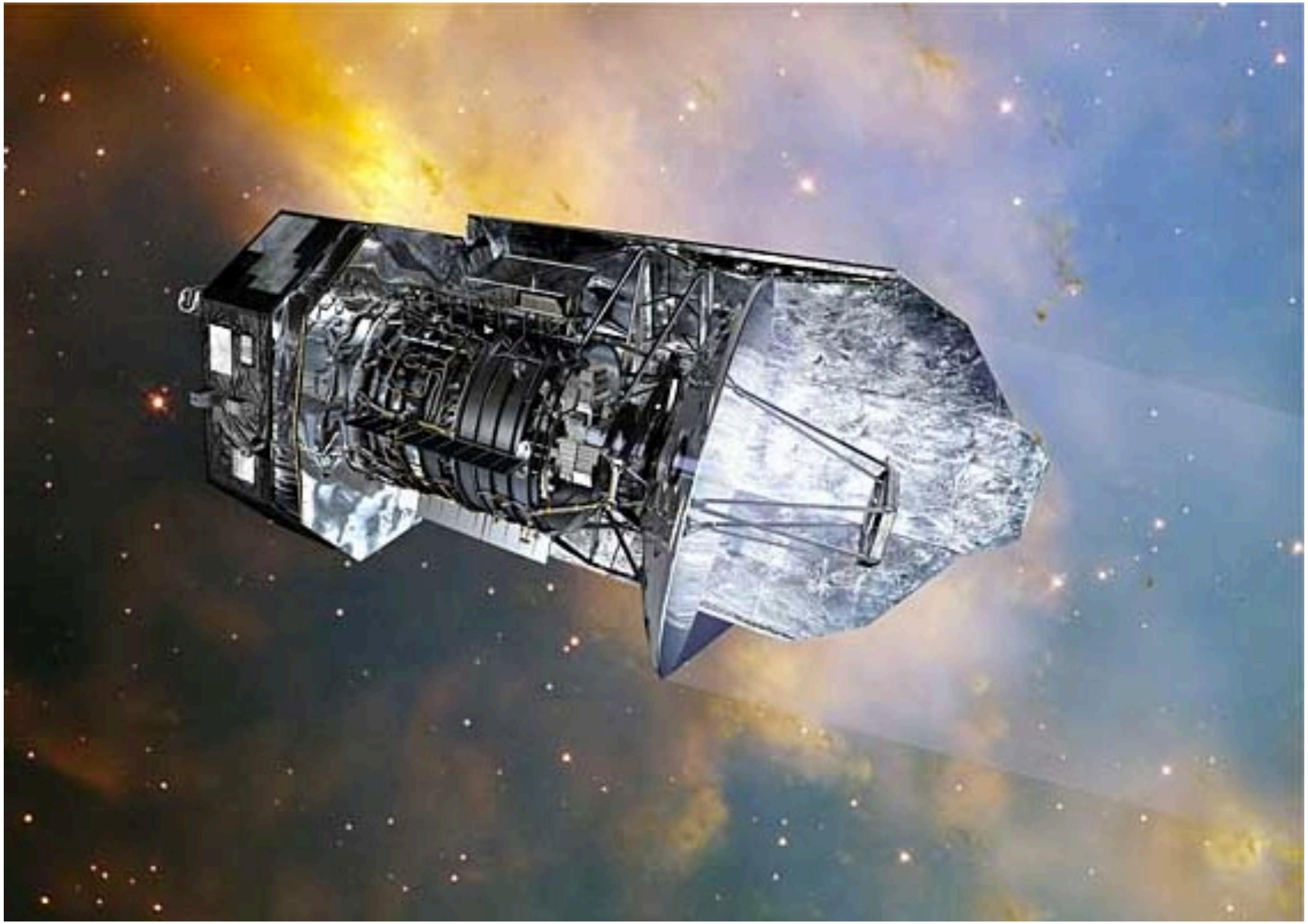
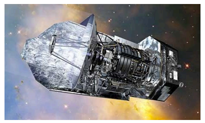



SOFIA
NASA
DLR



2. practical application

Kruijssen, Schruba & Longmore, in prep.

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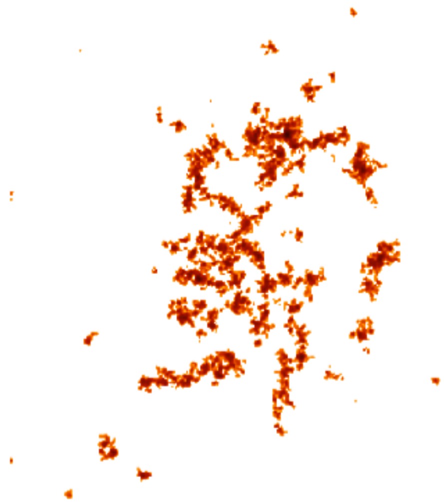
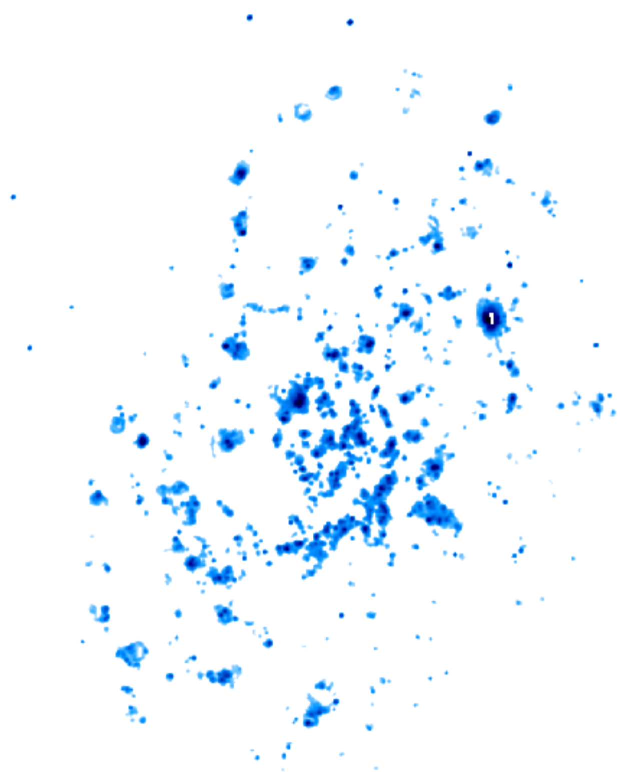
Pipeline to characterise cloud-scale physics

✧ Step 1: select tracers

CO(1-0)

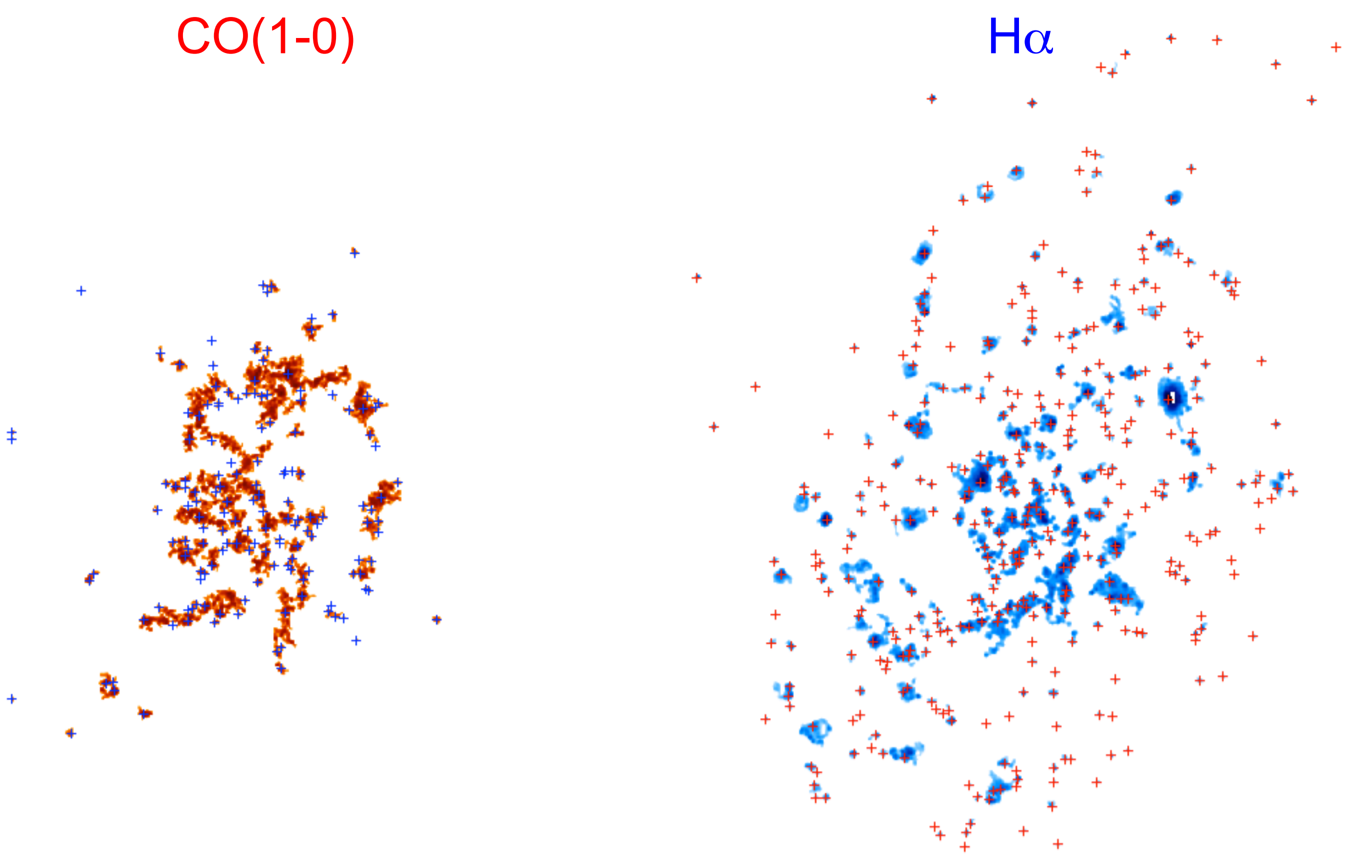


Hα → ~ 6 Myr



Pipeline to characterise cloud-scale physics

✧ Step 2: select emission peaks



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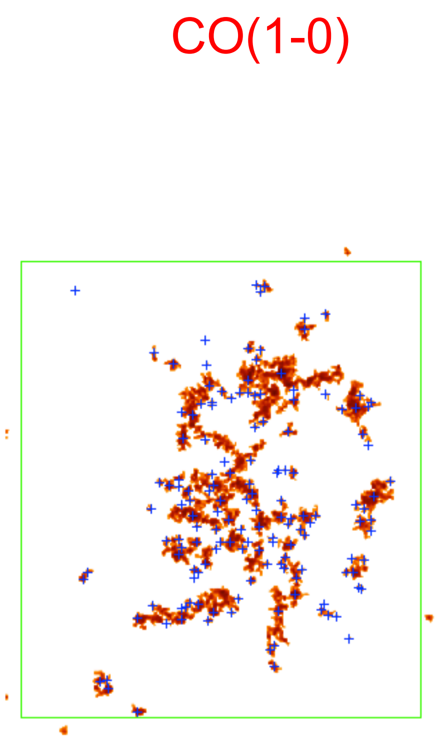
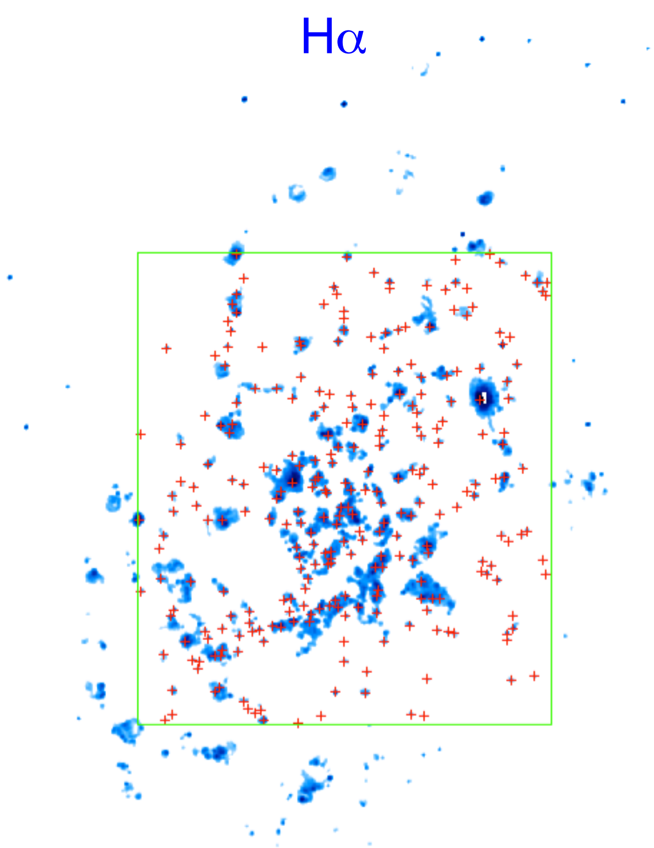
Pipeline to characterise cloud-scale physics

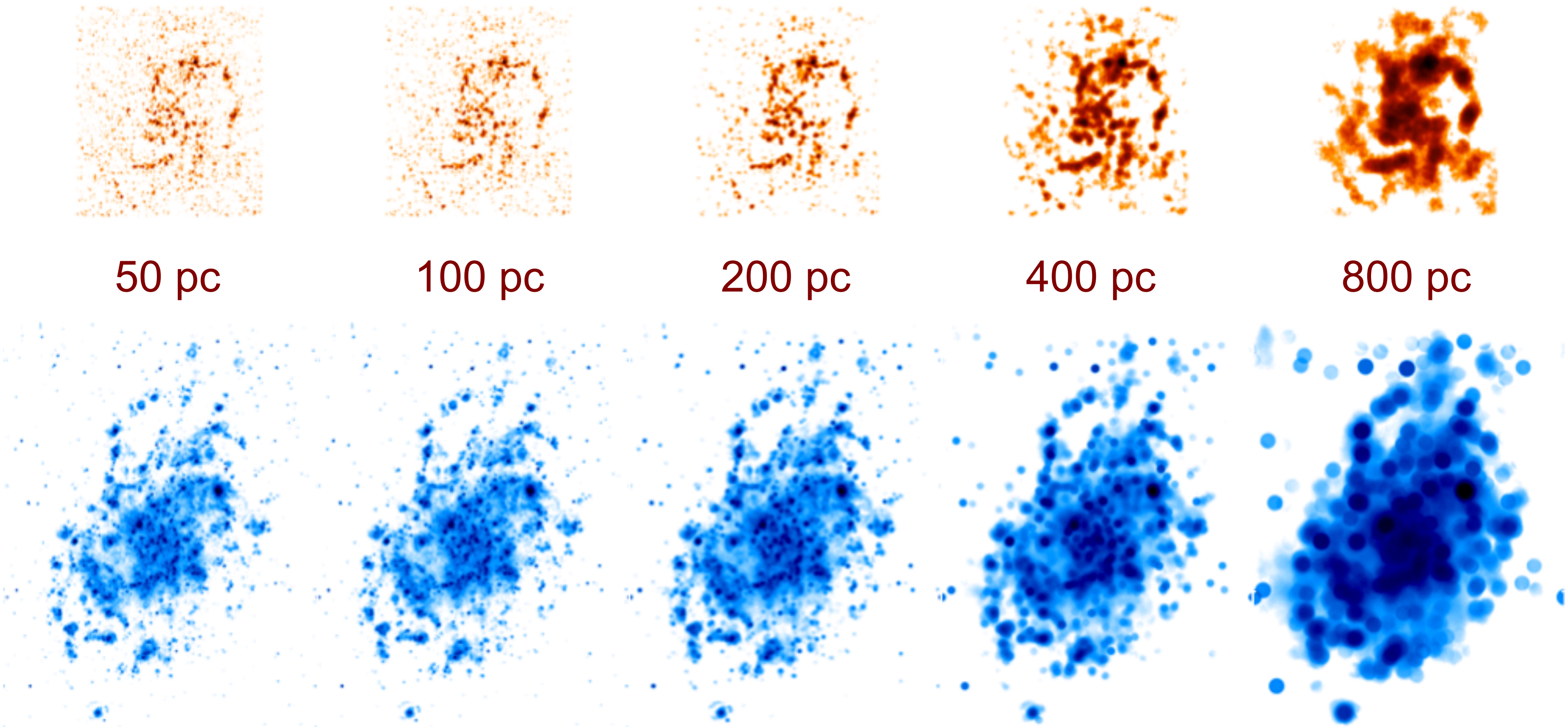
✧ Step 3: cut peak sample





Pipeline to characterise cloud-scale physics

✧ Step 4: convolve maps with top-hat kernels of varying size



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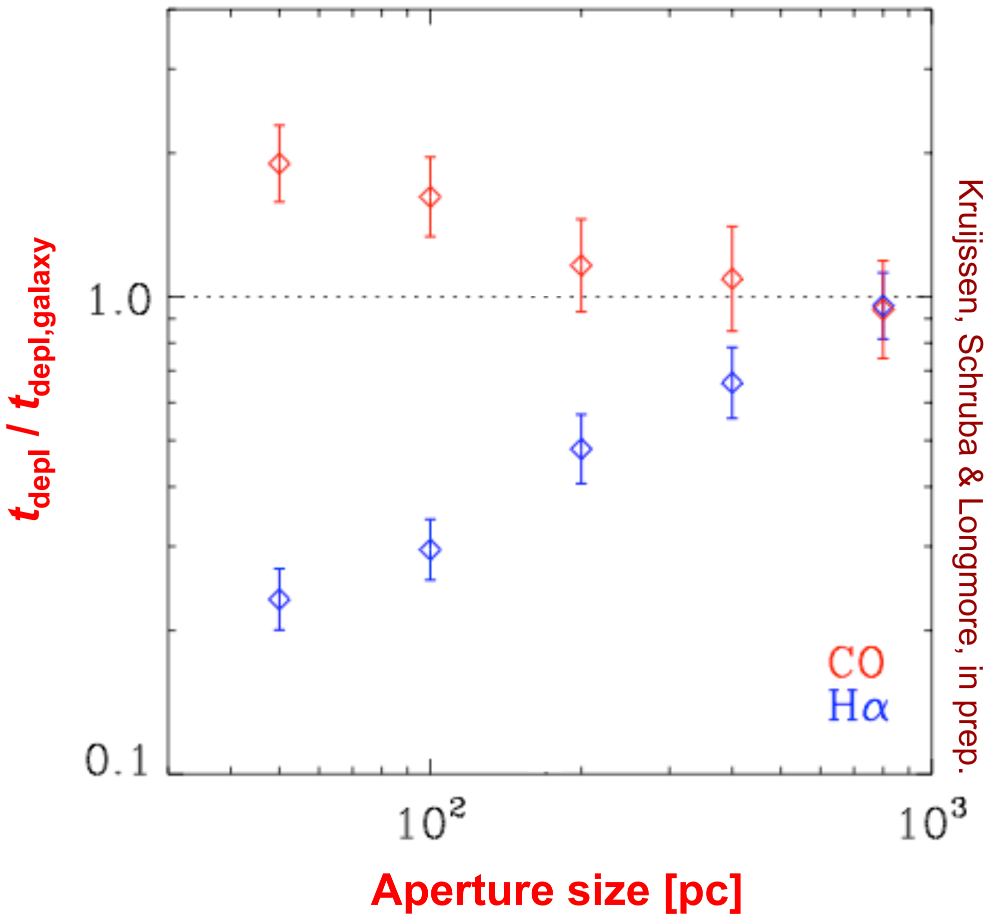
Pipeline to characterise cloud-scale physics

✧ Step 5: depletion time bias (= CO-to-Hα flux ratio w.r.t. galactic average)



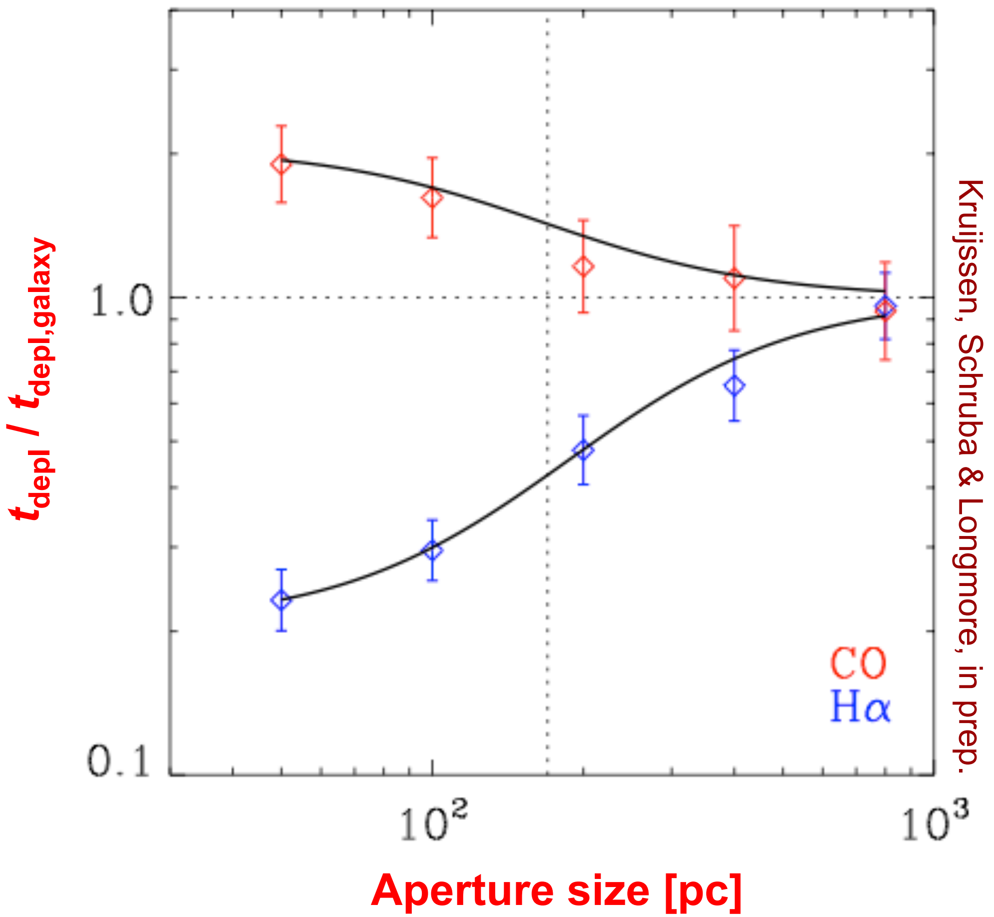
Centre on:

gas

stars

Pipeline to characterise cloud-scale physics

✧ Step 6: fit depletion time bias with KL14[++] model and obtain $t_{\rm gas}$, $t_{\rm over}$, λ, ε, $v_{\rm fb}$



Centre on:

gas

stars

3. numerical testing

Kruijssen, White, Schruba, Hu & Longmore, in prep.

How well does it work?

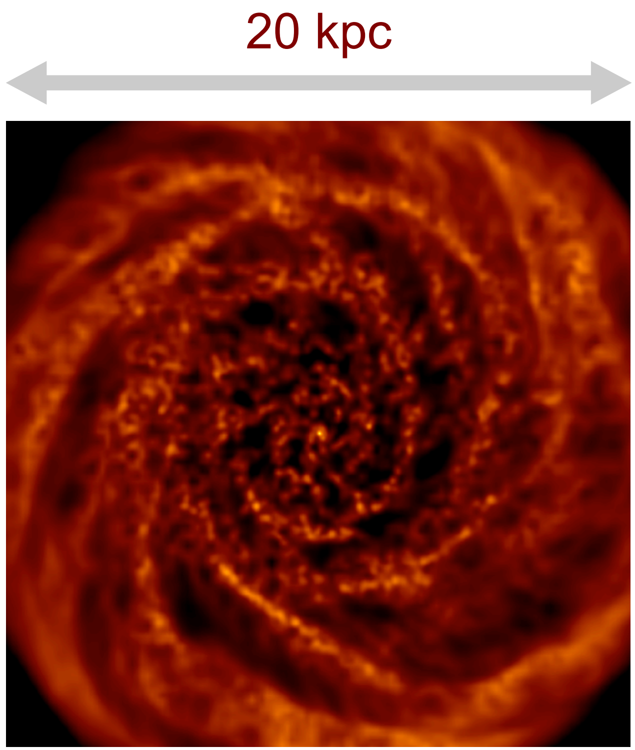
(Kruijssen, White, Schruba, Hu, Longmore)

✧ Test using numerical simulations

✧ 'New SPH' version of Gadget3 – see Chia-Yu Hu et al. (2014)
- pressure-entropy SPH
- Wendland smoothing kernel
- improved artificial viscosity
- artificial thermal energy conduction

✧ M33-like disc, resolution in clouds is < 20 pc

✧ Age-bin the stars and use maps for tests



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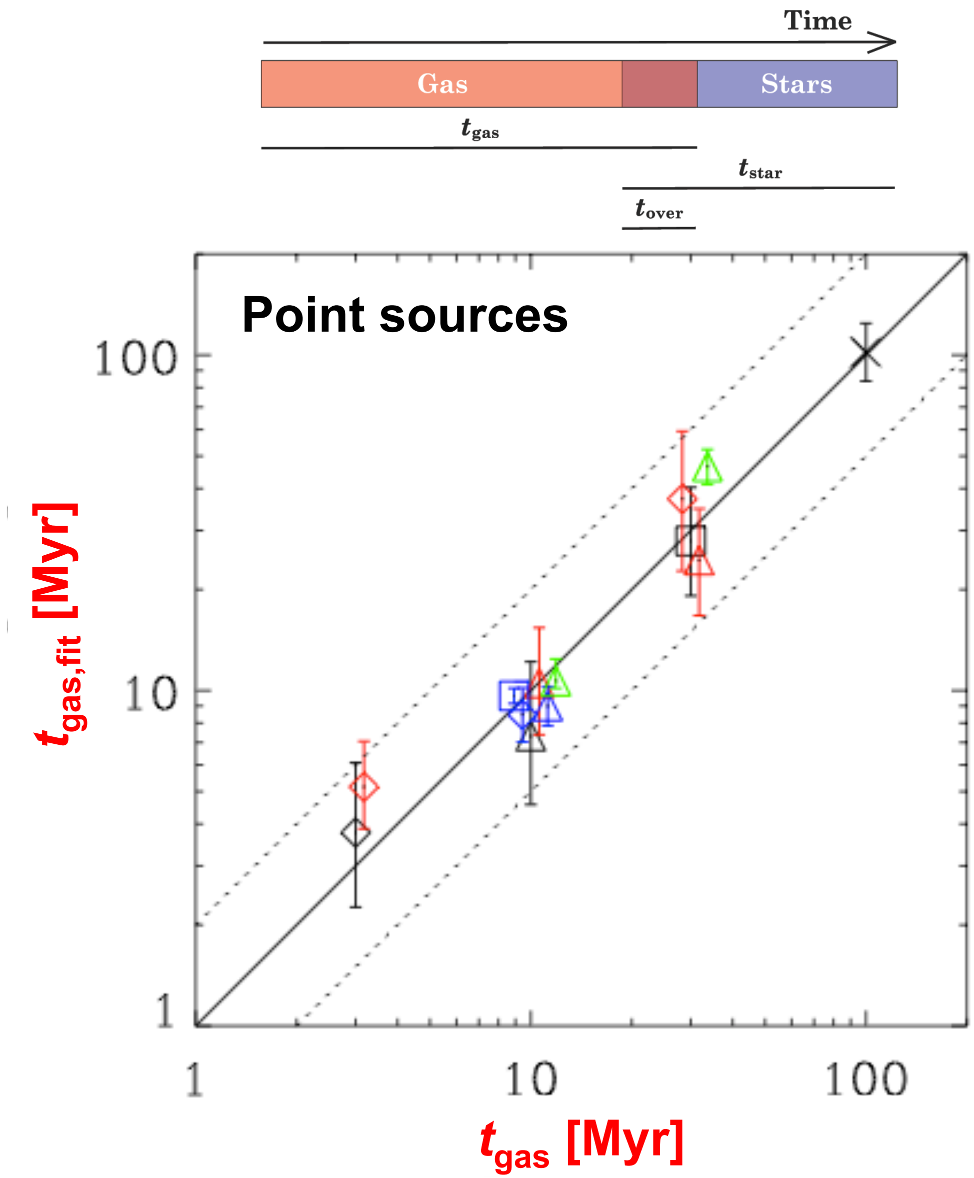
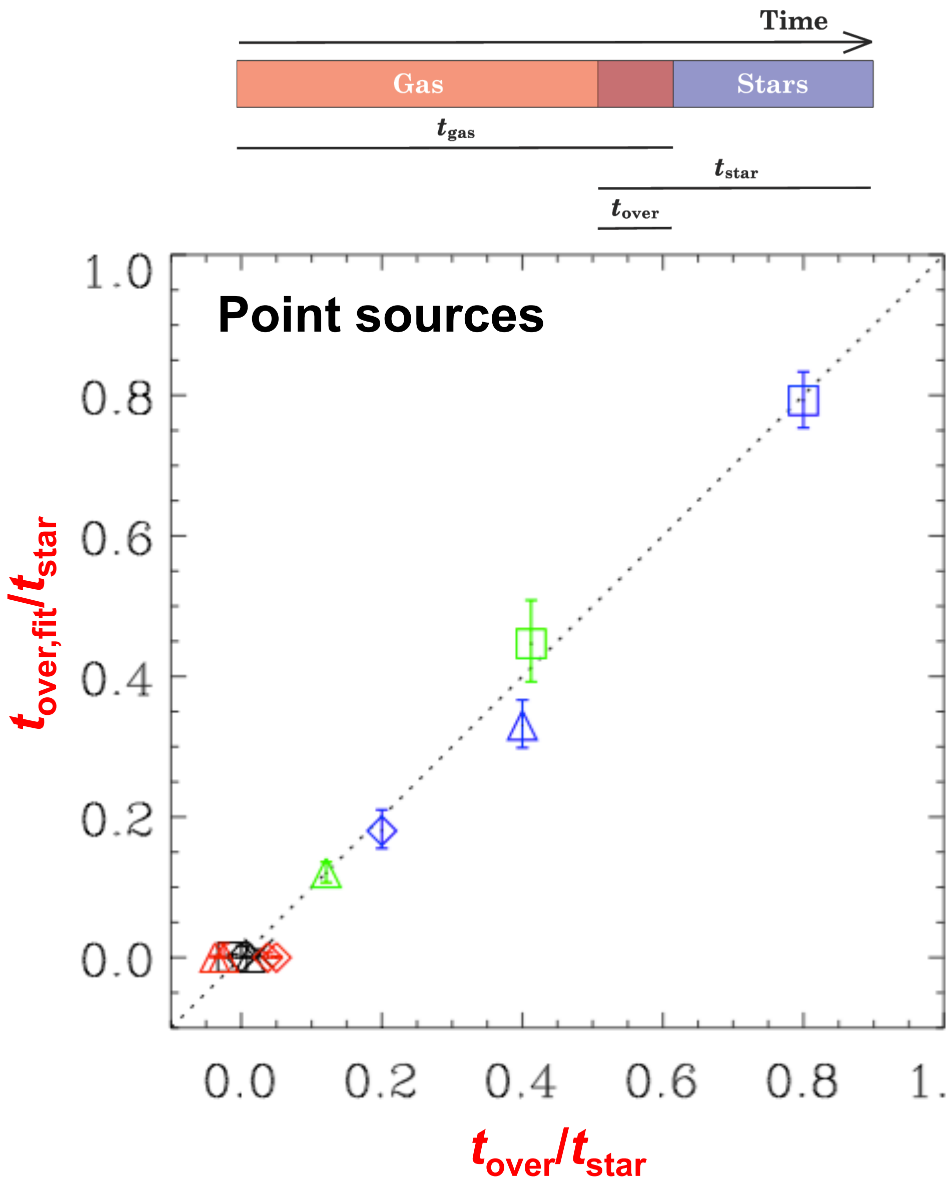
Current pipeline is accurate to within a factor of 2



Kruijssen+, in prep.

Current pipeline yields even more accurate “durations” of SF & FB



Kruijssen+, in prep.

First test passed

Numerical simulations show that the method can be used to reliably measure tracer lifetimes

4. application

Physics and scale dependence of galactic SF relations

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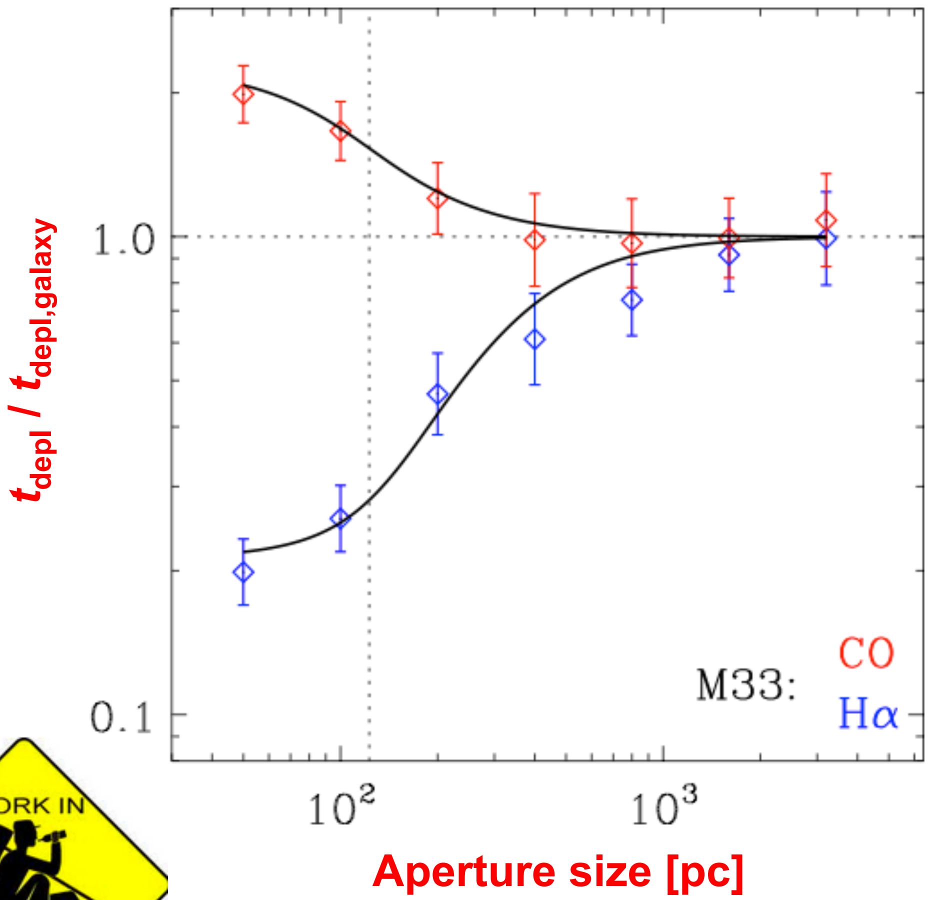
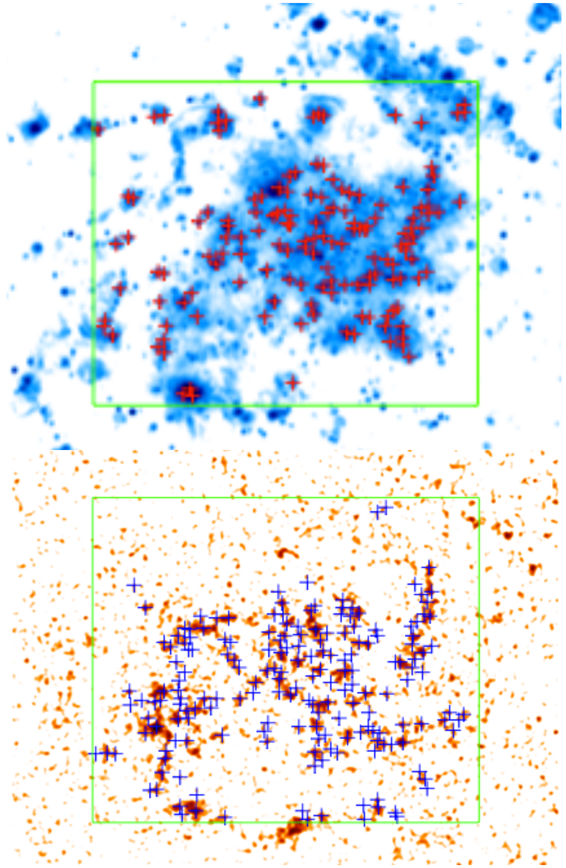
Second test: application to M33

✧ Using Hα and CO(1-0) (Rosolowsky+07)



Kruijssen, Schruba & Longmore, in prep.



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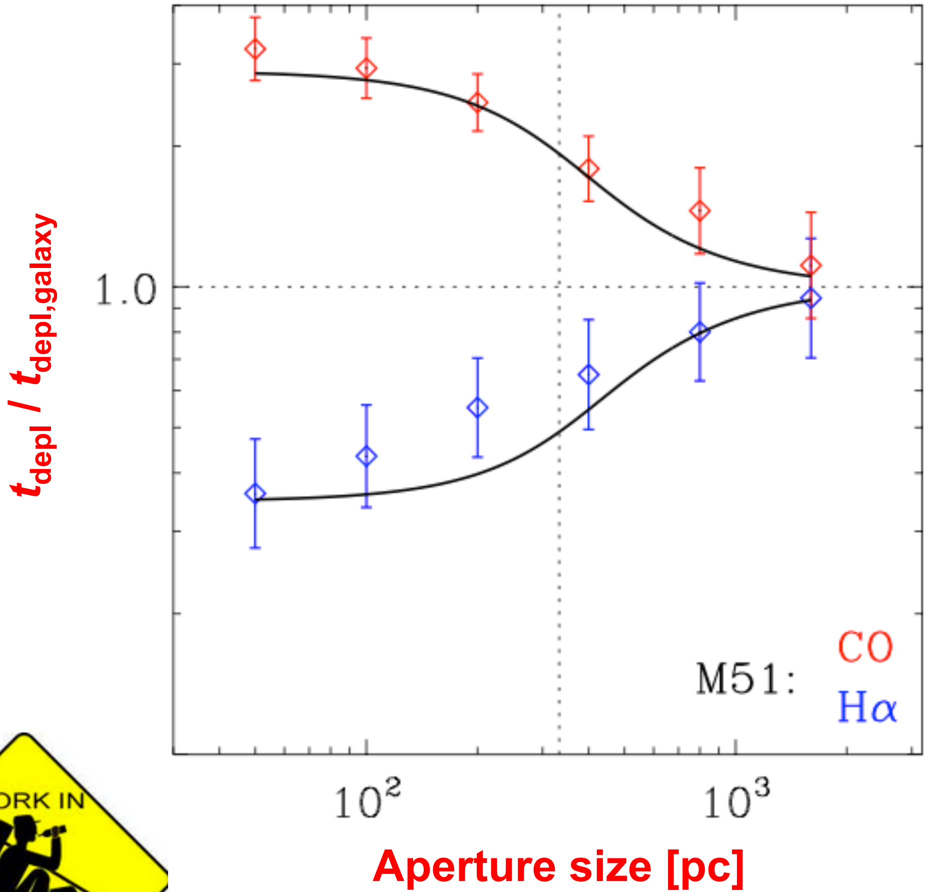
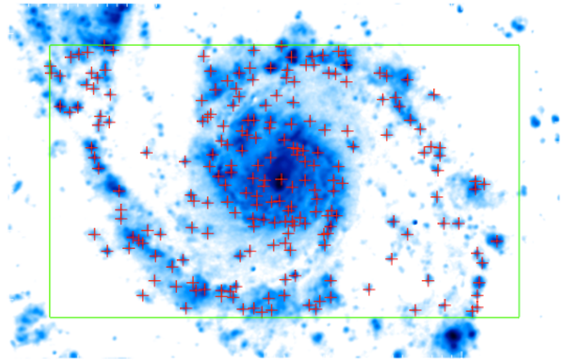
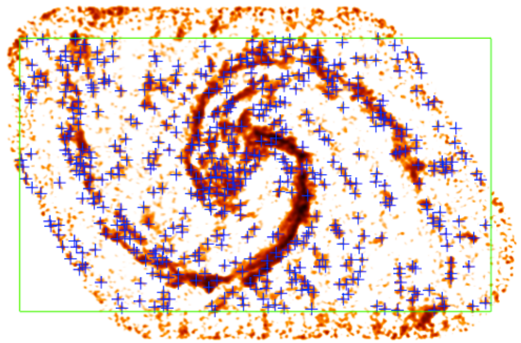
Application to the arms (!) of M51

✧ Using Hα and CO(1-0) (PAWS; Schinnerer+13)



Kruijssen, Schruba, Longmore + PAWS, in prep.





Interpretation – physics of cloud-scale star formation?

see talks by Padoan, Chabrier, Fukui, Onishi

- Tempting to draw physical conclusions
- Compare t_{gas} ~ 30 Myr to $t_{dyn,gal} = R/V$ ~ 35 Myr and $t_{dyn,GMC}$ ~ 10 Myr
  ➔ large fraction of supervirial, transient clouds, hence low $\varepsilon \sim 0.03$?
  cf. Dobbs+11
- t_{over} ~ 3 Myr suggests HII regions/winds/radiation end star formation
- λ ~ 100 – 300 pc similar to the Toomre length $\pi G\Sigma/\Omega^2$ ~ 200 pc
- Tentative interpretation – only a handful of galaxies so far

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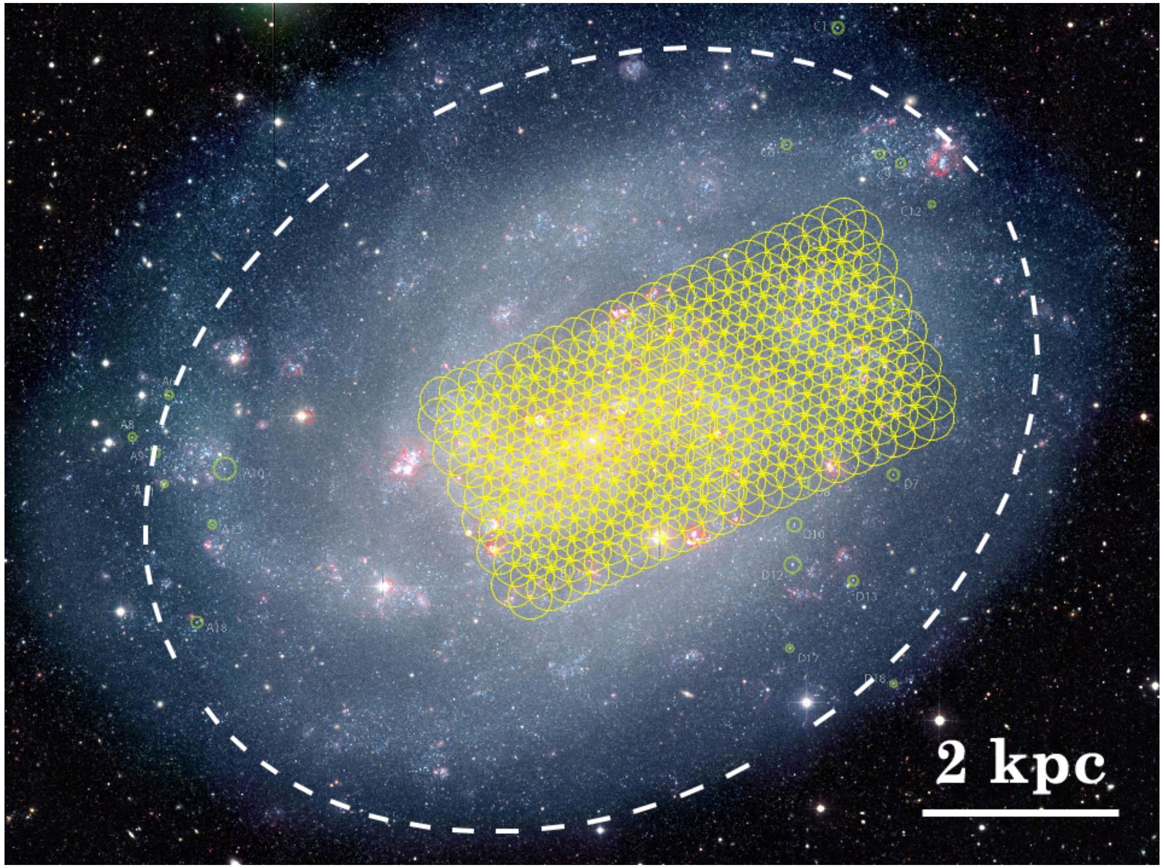
Future application at ~15 pc resolution & few $10^3\ M_\odot$ sensitivity

NGC 300: 8 + 20 hours (ext'd + compact) ALMA Cycle 2 time



(Schruba & Kruijssen + Longmore, Tacconi, van Dishoeck, Dalcanton)

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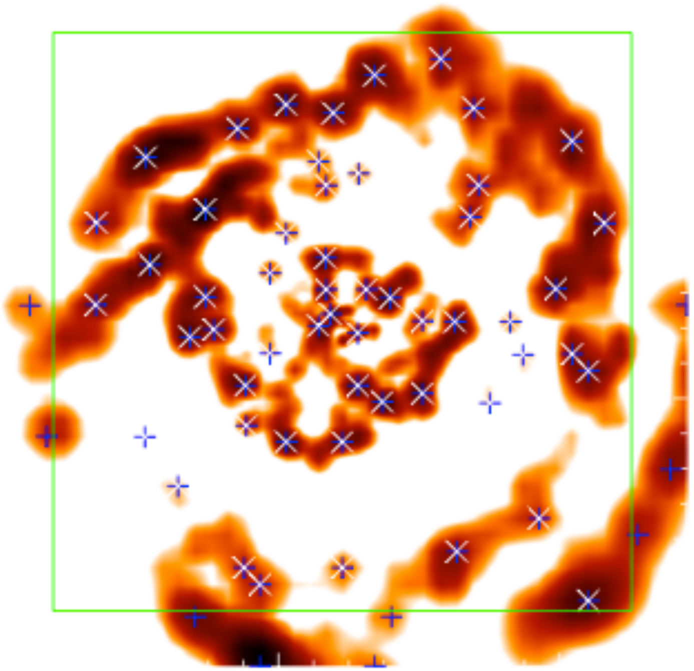
Method opens up entire observable Universe for cloud-scale SF studies

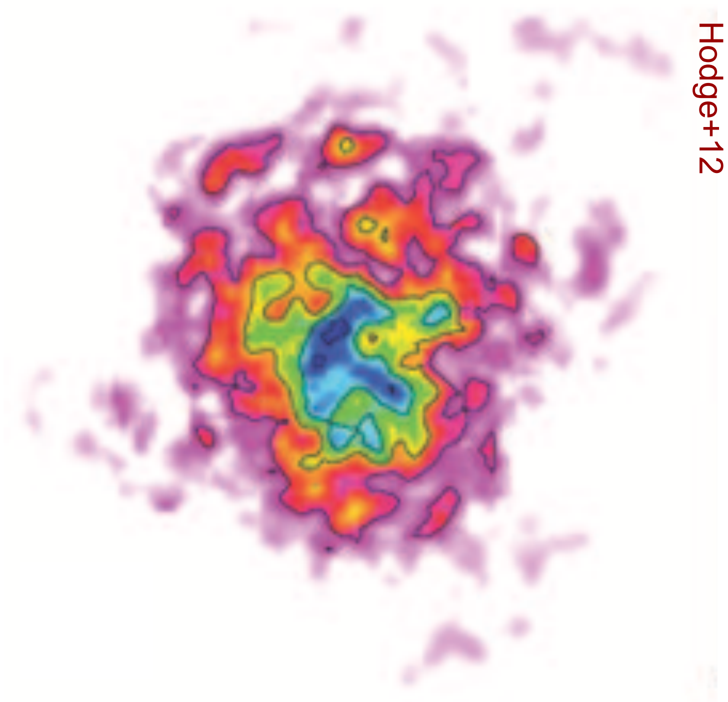
see lots of talks on Thursday and Friday



Low-resolution simulation

t_{gas} = 30 Myr

$t_{\mathrm{gas,fit}} = 32^{+27}_{-12}$ Myr



Observed sub-mm galaxy CO(2–1)

z = 4.05

Conclusions

- ✧ Simple framework explains scale dependence of galactic SF relations
- ✧ Powerful method to constrain cloud-scale SF physics out to $z \sim 4$
- ✧ Numerical simulations show measured time-scales are accurate
- ✧ "The GMC Lifetime" does not exist – it is environmentally dependent
- ✧ *Method applies to any correlation that connects subsequent phases*
- ✧ Public code available at http://www.mpa-garching.mpg.de/KL14principle