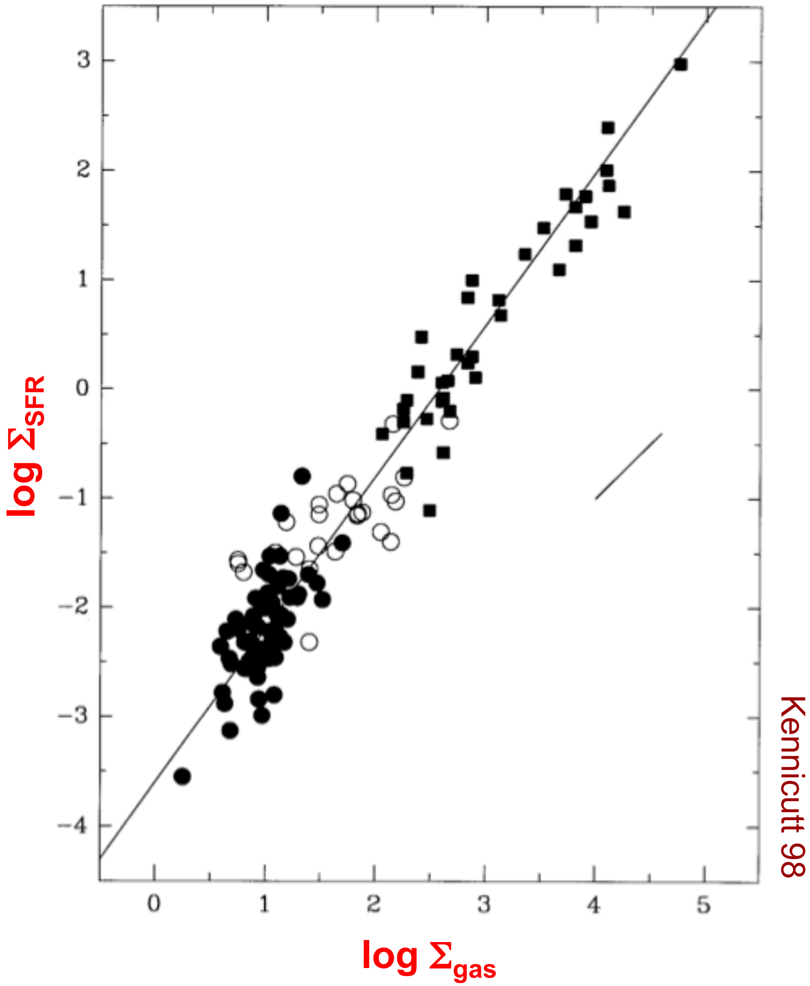
The multi-scale physics of galactic star formation and a solution for the GMC lifetime 'problem'

J. M. Diederik Kruijssen
MPA

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

How do galaxies turn their gas into stars?



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

Schmidt 59
Kennicutt 98

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

Elmegreen 97
Silk 97

Star formation occurs in localised events

NGC 300, GALEX

Decomposition of the star formation relation

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

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

Problem #1: need to resolve clouds

Problem #2: how to measure time-scales?

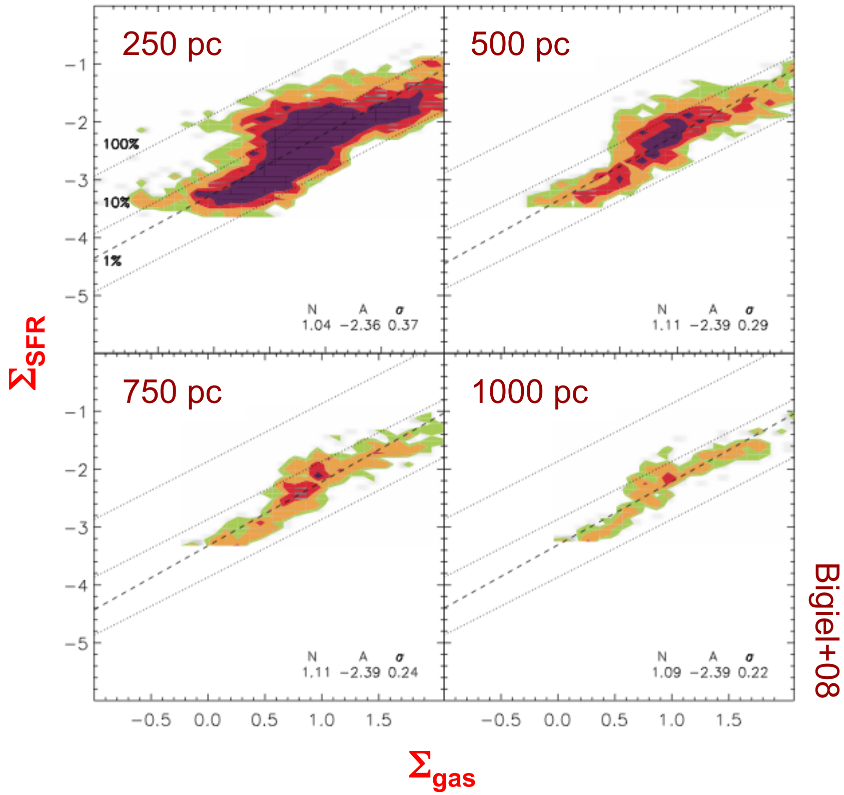
Introduction
Principle
Simulations
Observations

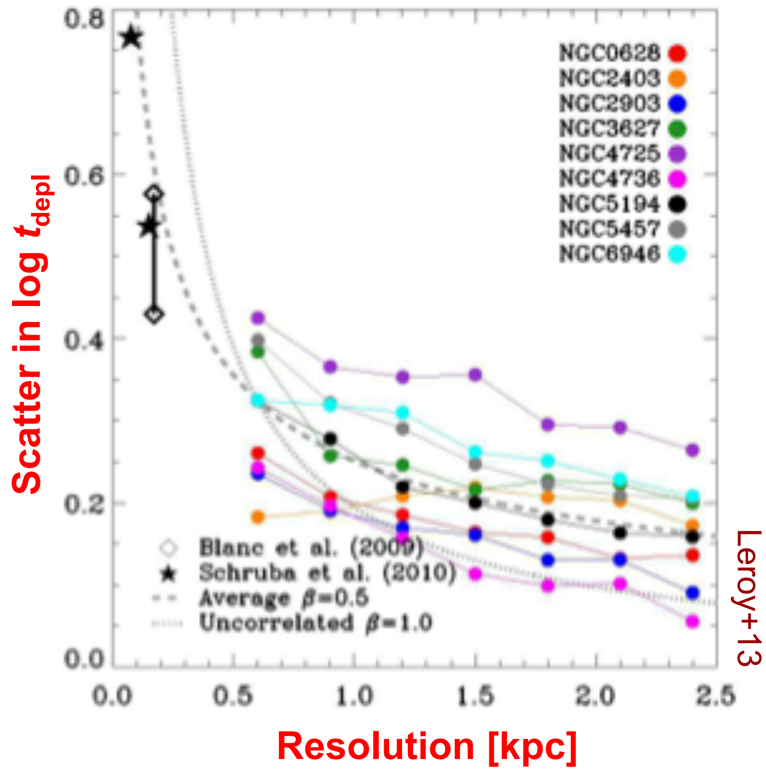
Spatially resolved star formation relations

see talk by Leroy

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

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





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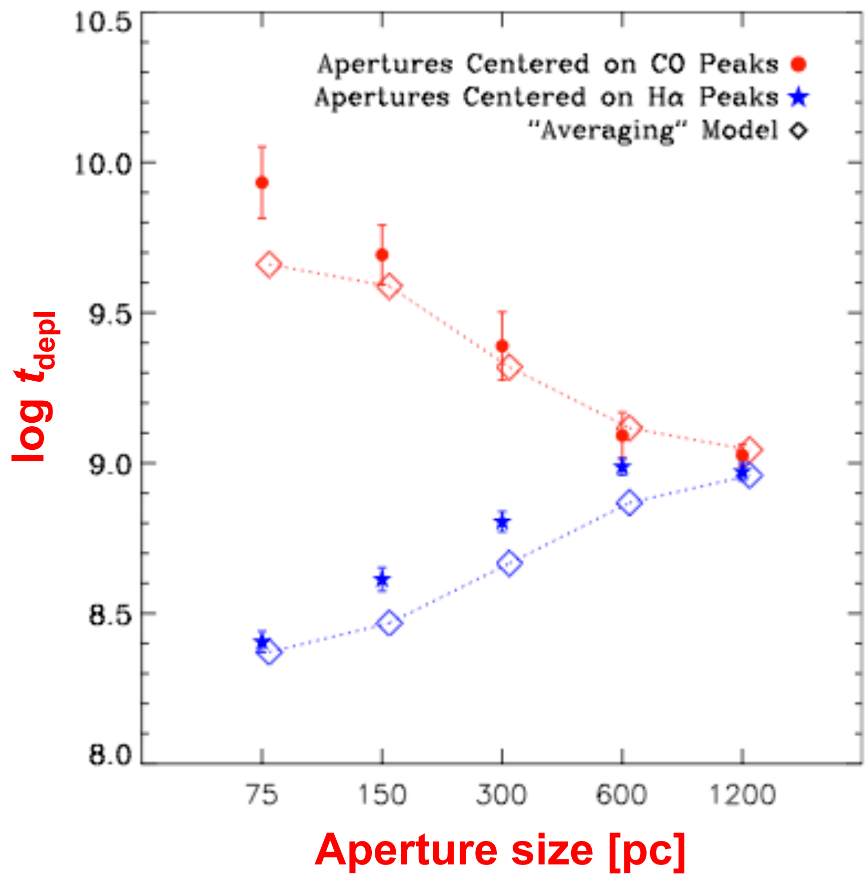
✧ …or *bias* when focussing apertures on gas or stellar peaks



Schruba+10

Centre on:

gas

stars

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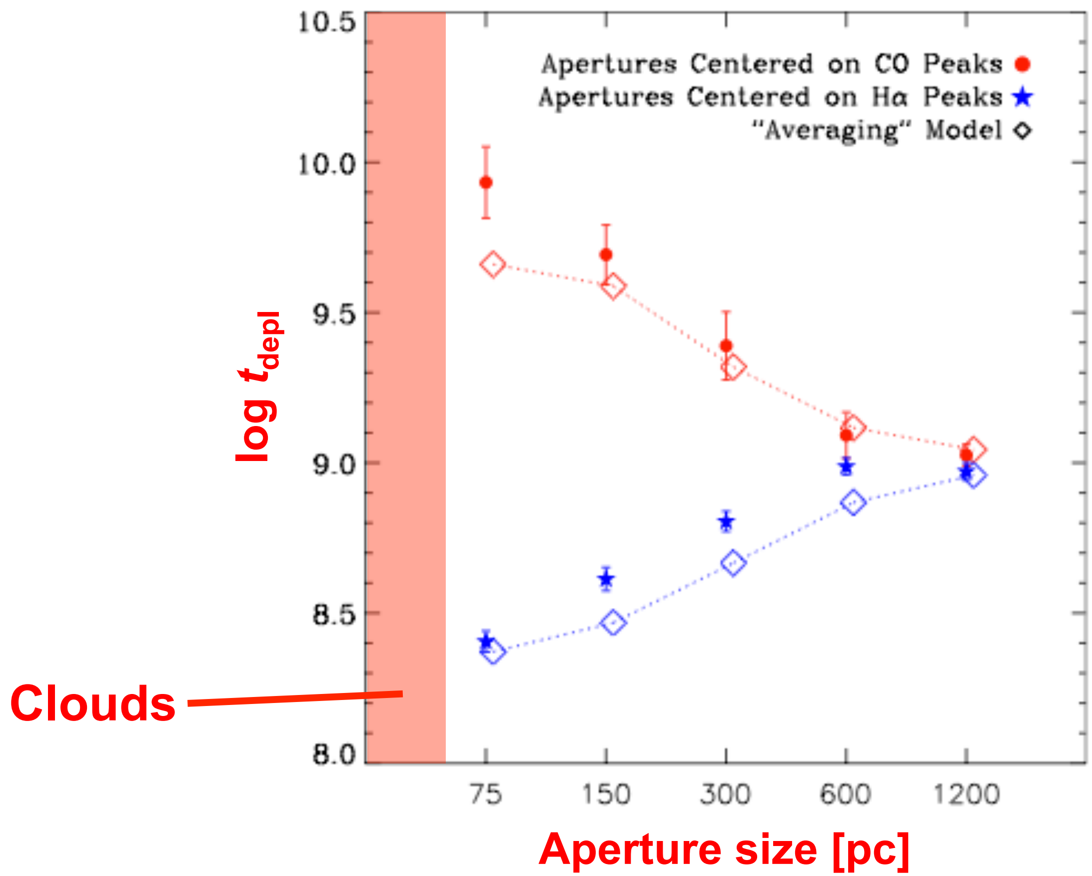

Schruba+10

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.

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

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Decomposition of the star formation relation

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

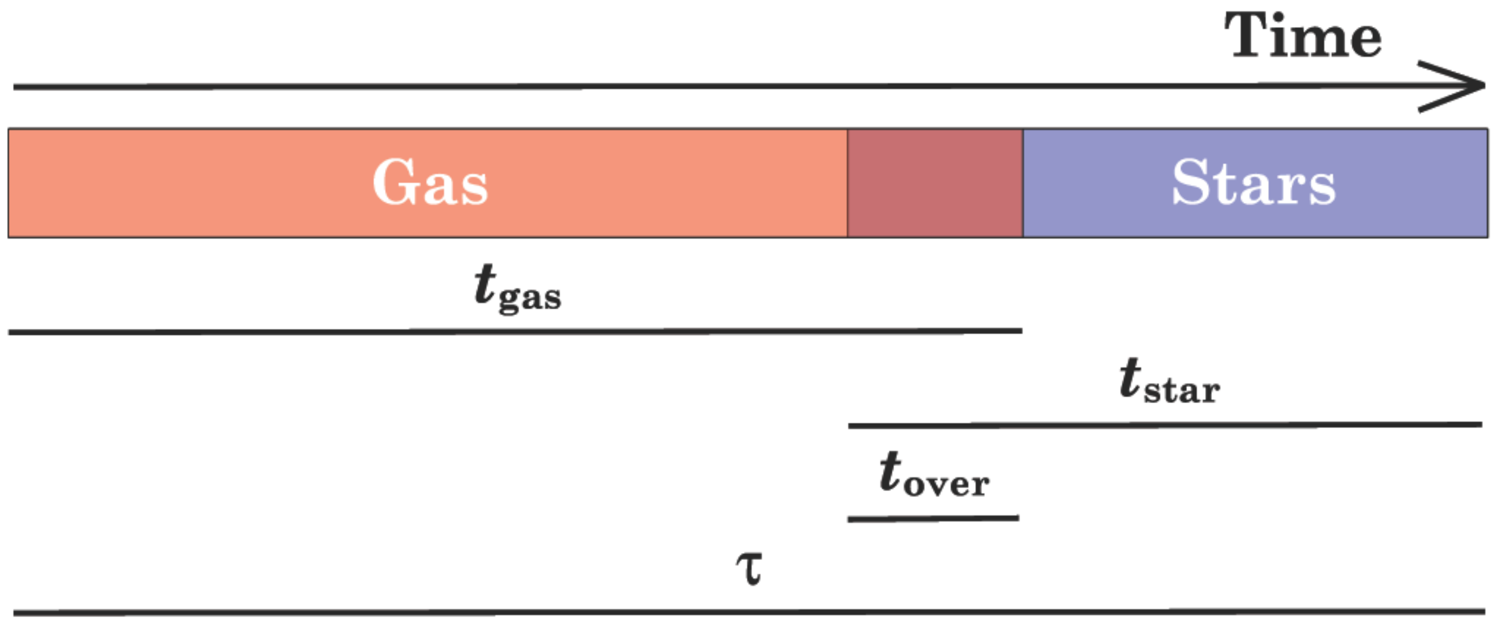
$$\mathrm{SFR} = \sum_{\mathrm{clouds}} \frac{\epsilon_{\mathrm{cloud}}}{t_{\mathrm{SF,cloud}}} M_{\mathrm{cloud}}$$

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

1. a toy model

Kruijssen & Longmore 2014, MNRAS 439, 3239

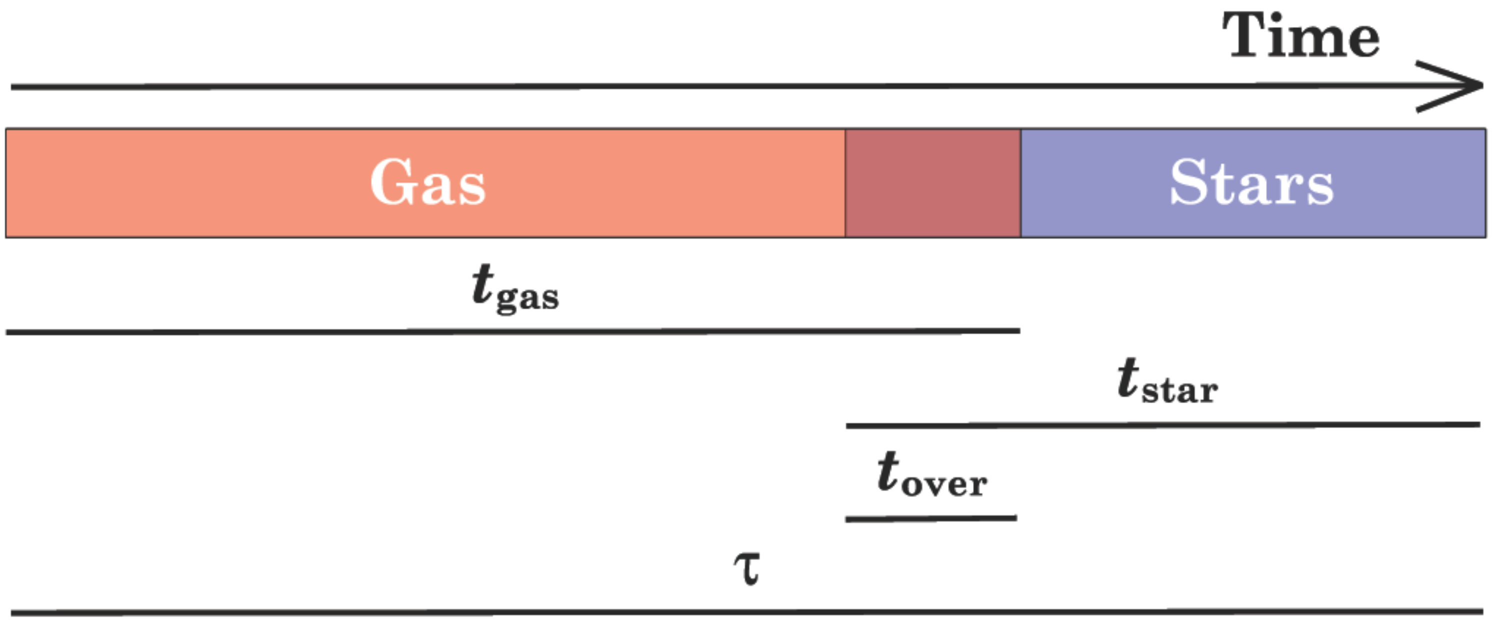
A statistical toy model (1)



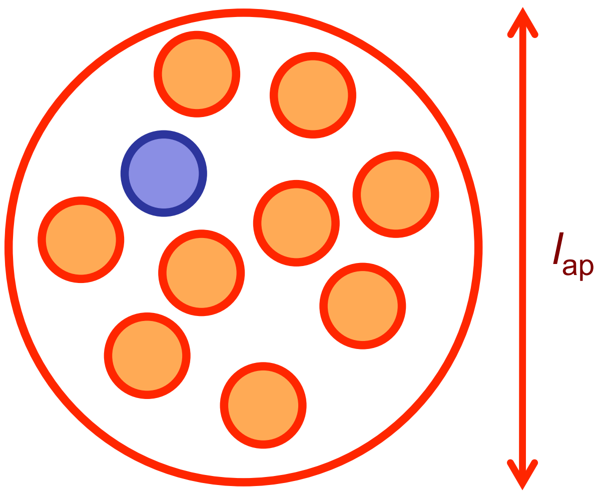
✧ Galactic SF relation results from homogeneous sampling of time sequence

✧ Time-integration of single region gives galactic SF relation

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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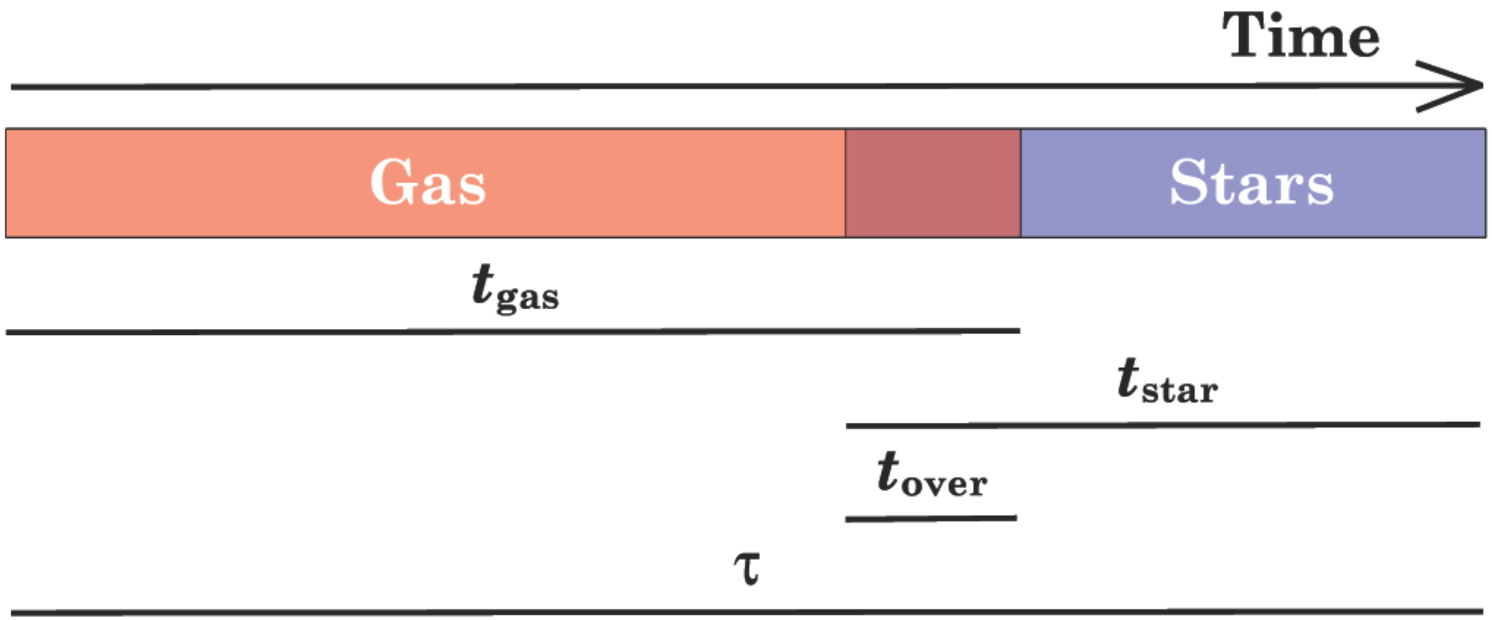

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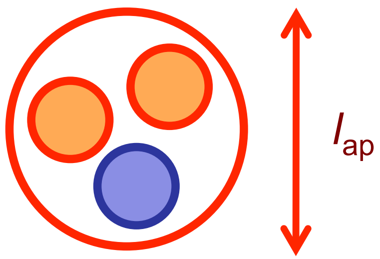


- Example for $t_{gas} = 2 \times t_{star}$

An uncertainty principle for star formation

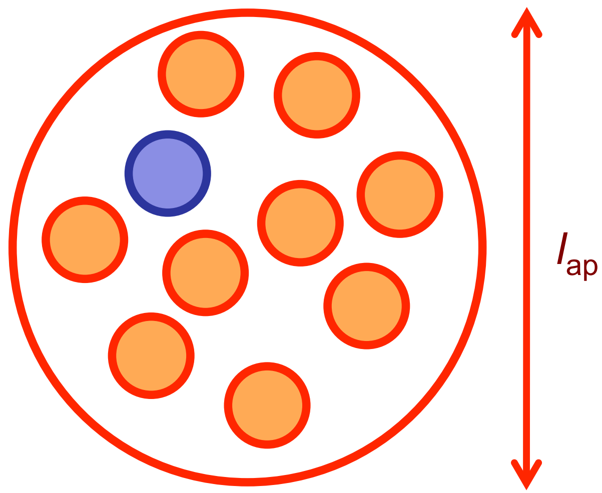
Kruijssen & Longmore 14

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

- Δx: Size-scale over which SF relation is spatially averaged
- Δt: Duration of shortest SF phase
- λ: Separation of independent regions
- τ: 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



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Kruijssen & Longmore 14

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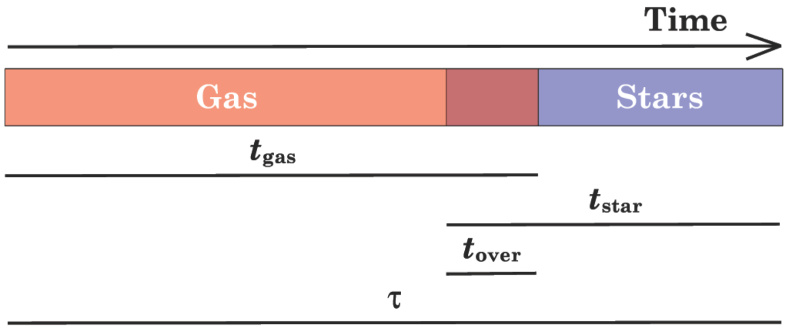
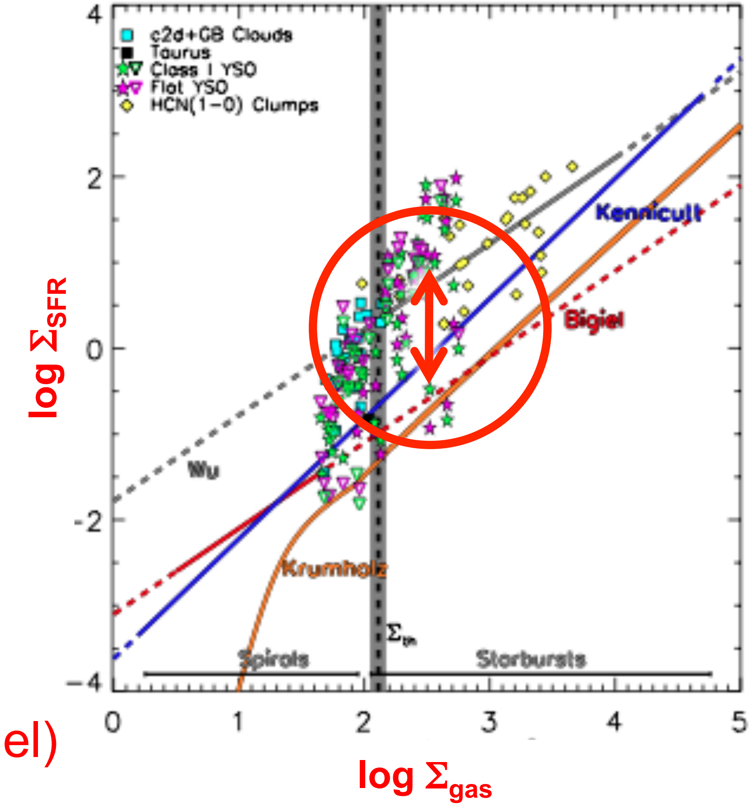


If this condition is not satisfied:

- ➔ 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 Molinari, Forbrich, Vutisalchavakul



Heiderman+10

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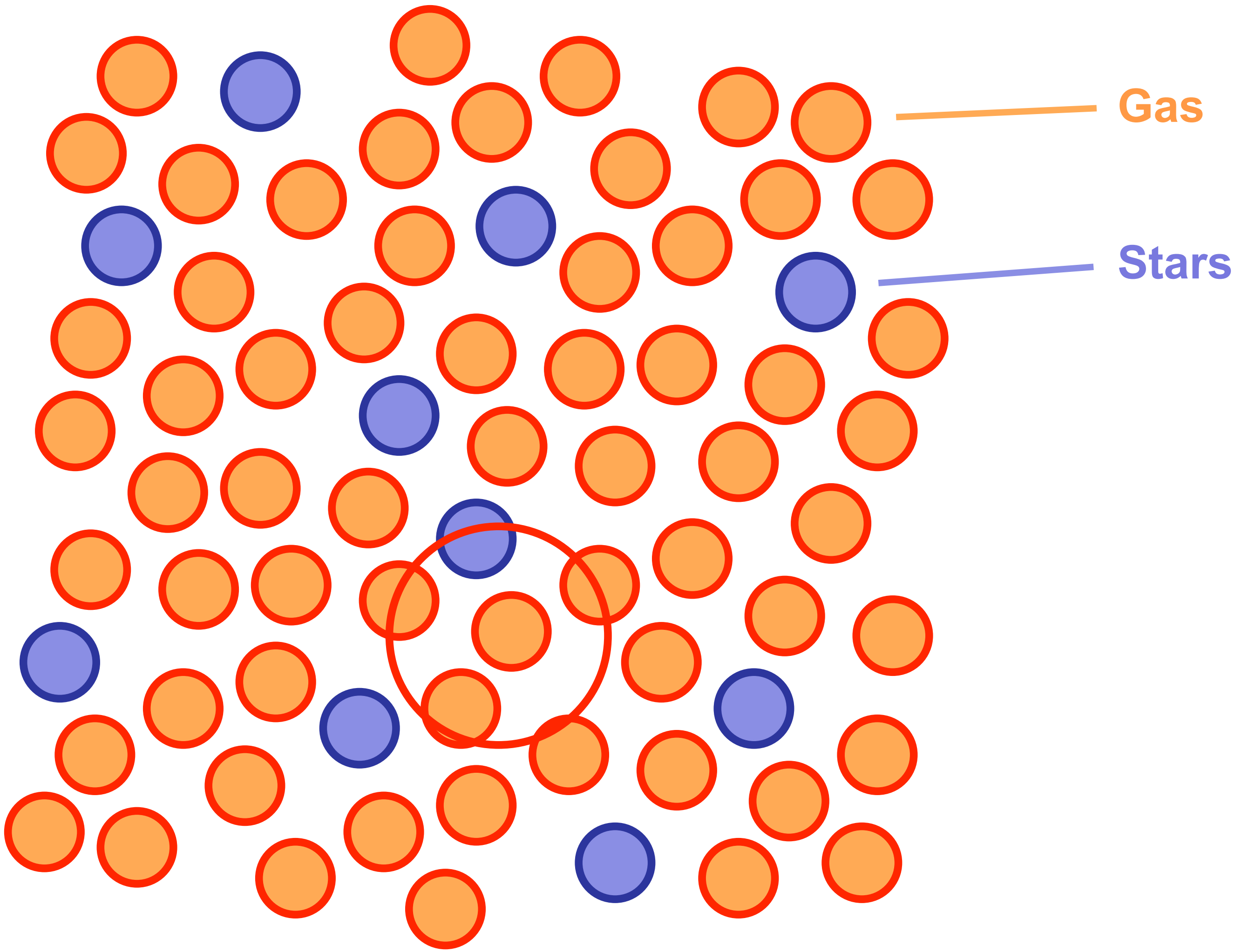
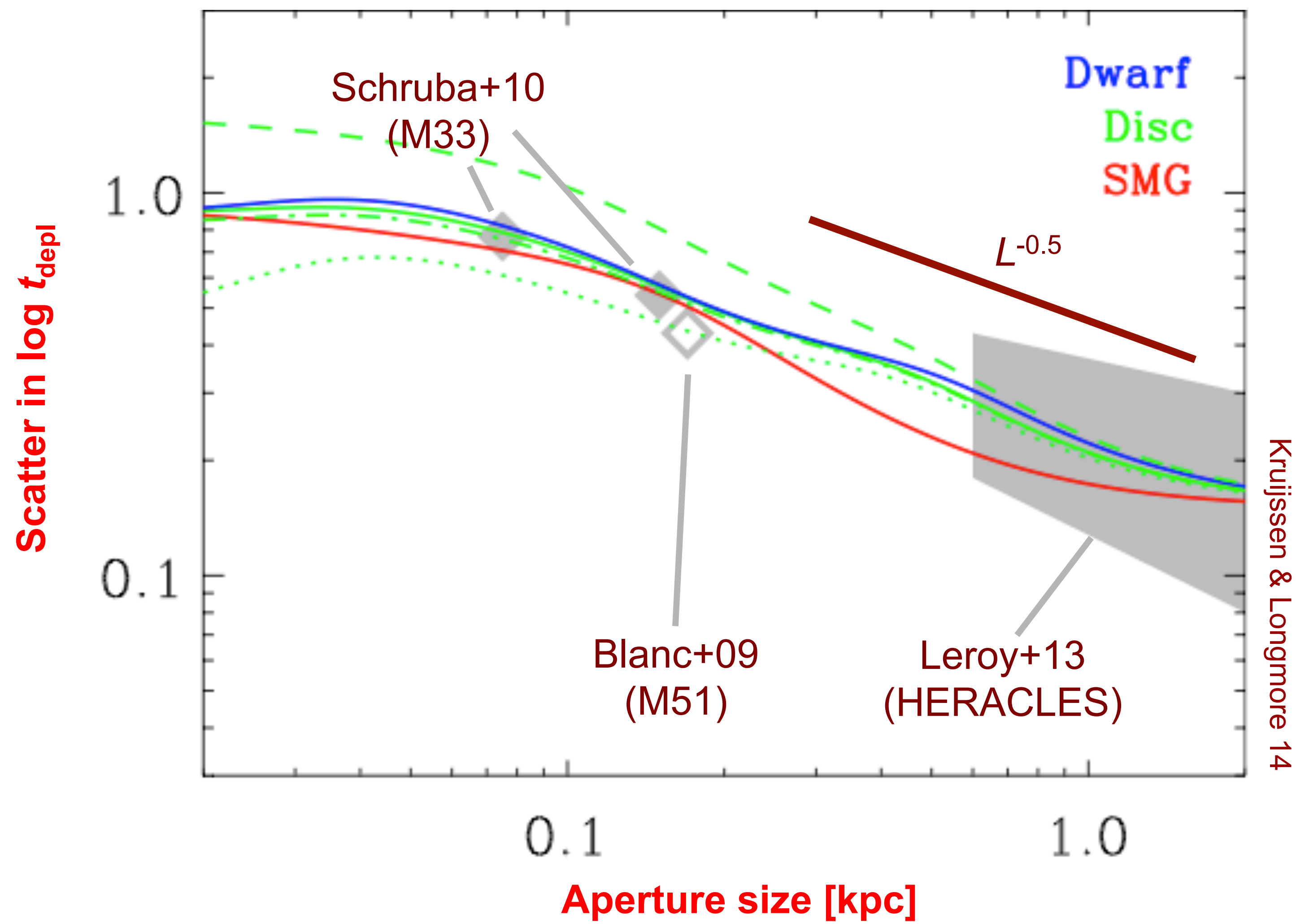
Effect when randomly placing an aperture



Scatter versus (randomly placed) aperture size



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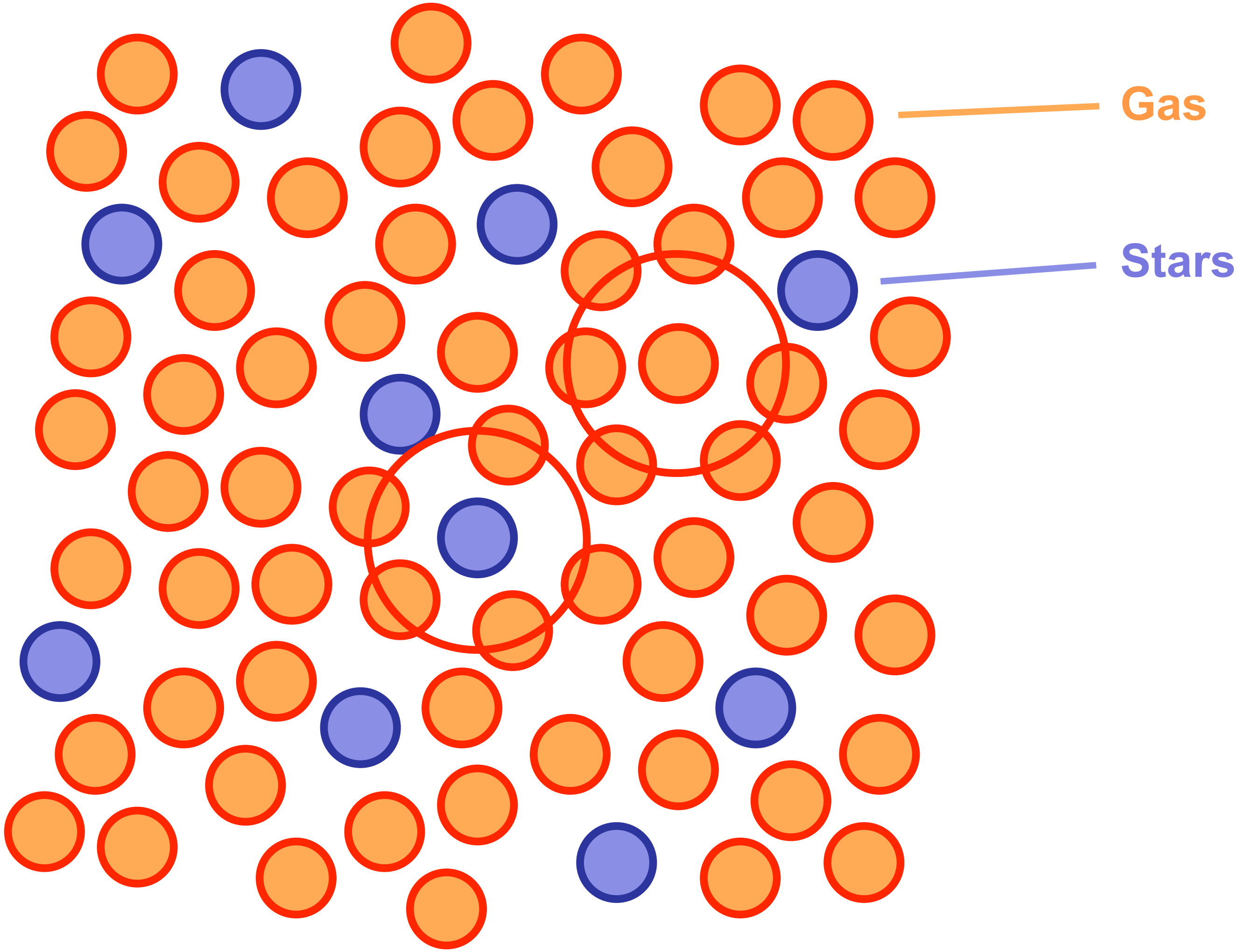
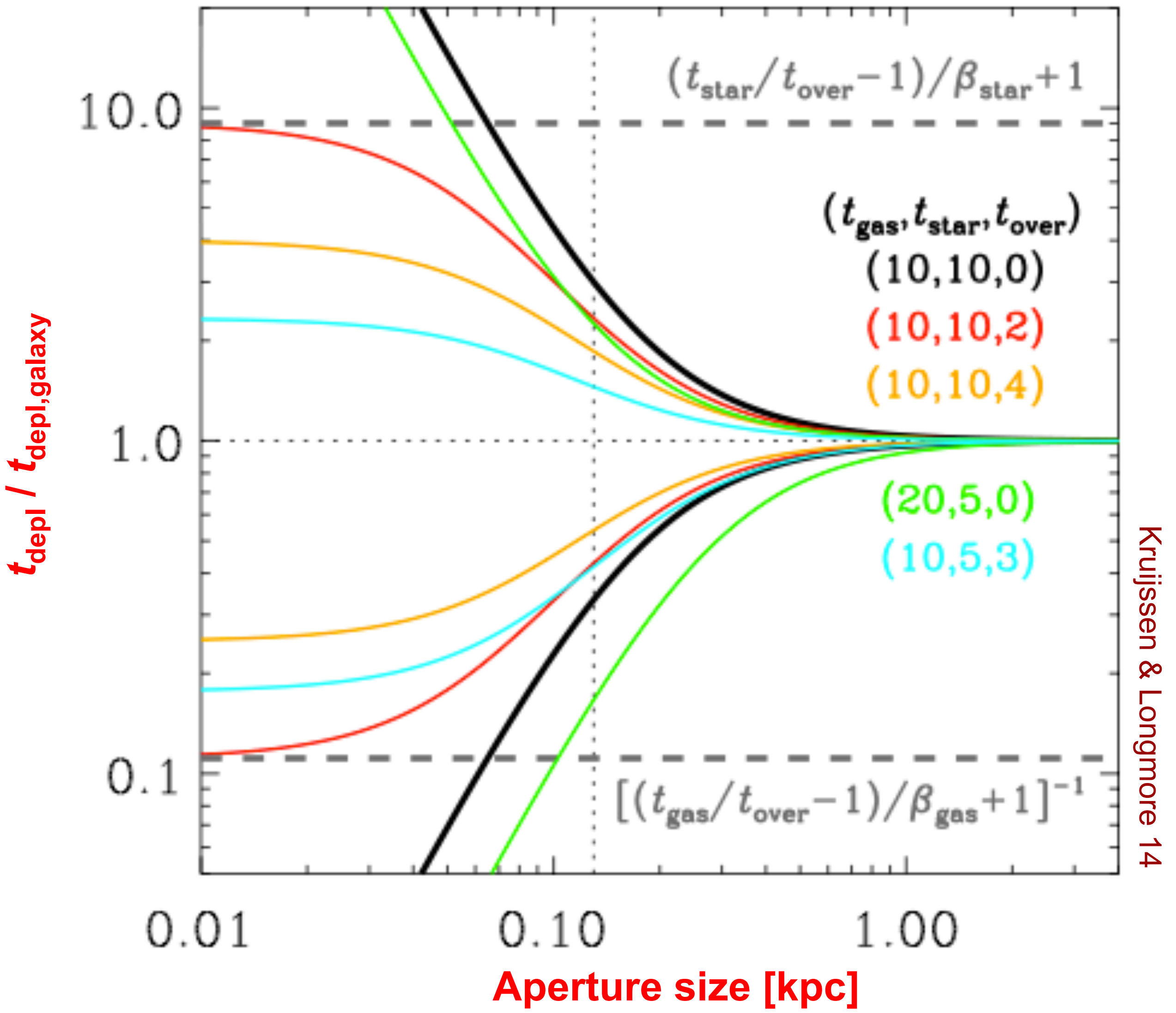
Effect when placing an aperture on peaks of gas or star formation



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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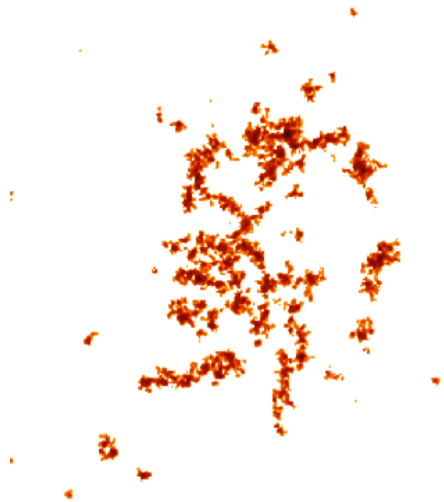
This is what ALMA was made to do

2. practical application

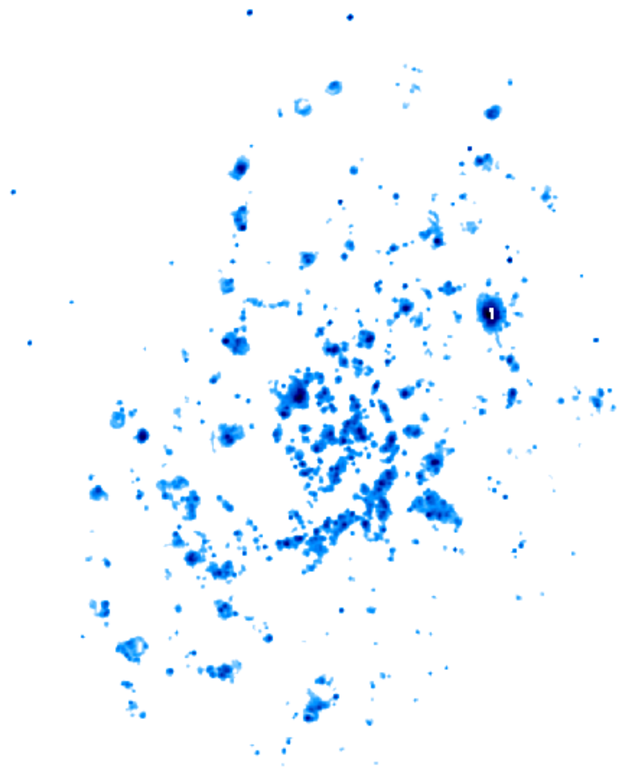
Pipeline to characterise cloud-scale physics

✧ Step 1: select tracers

CO(1-0)

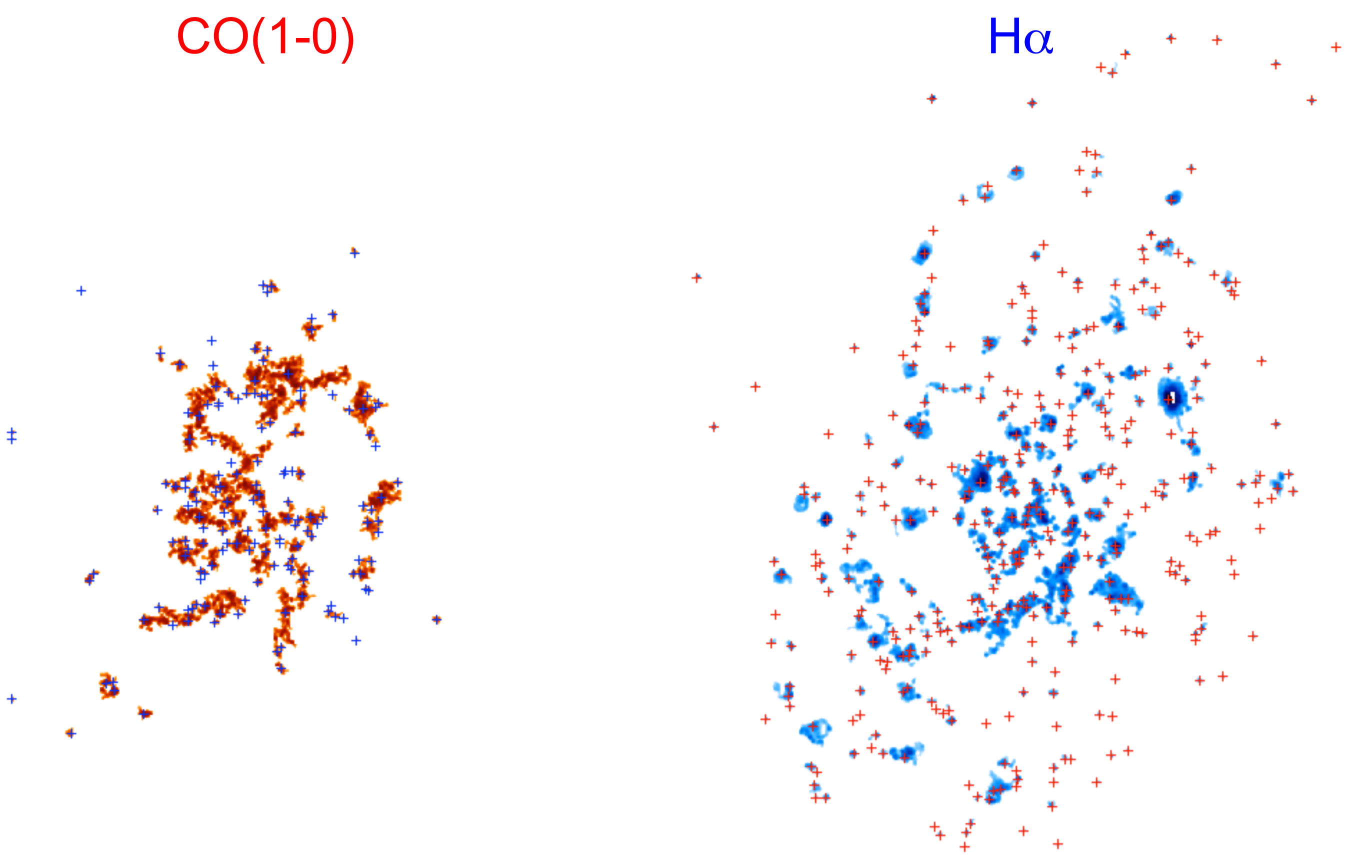


Hα → ~ 6 Myr



Pipeline to characterise cloud-scale physics

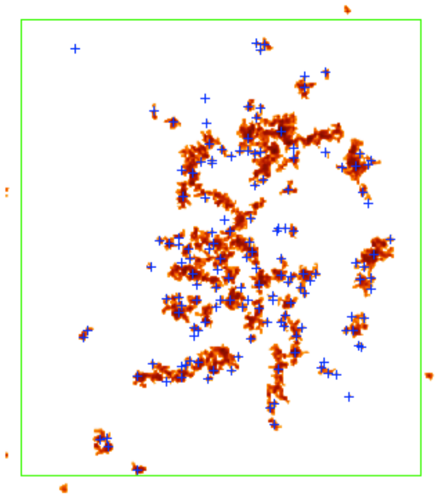
✧ Step 2: select emission peaks



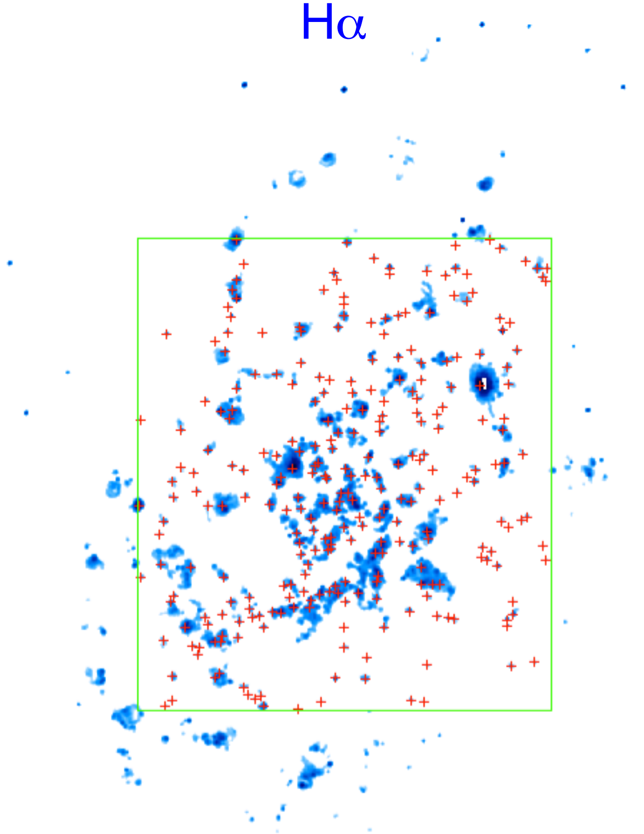
Pipeline to characterise cloud-scale physics

✧ Step 3: cut peak sample

CO(1-0)



Hα



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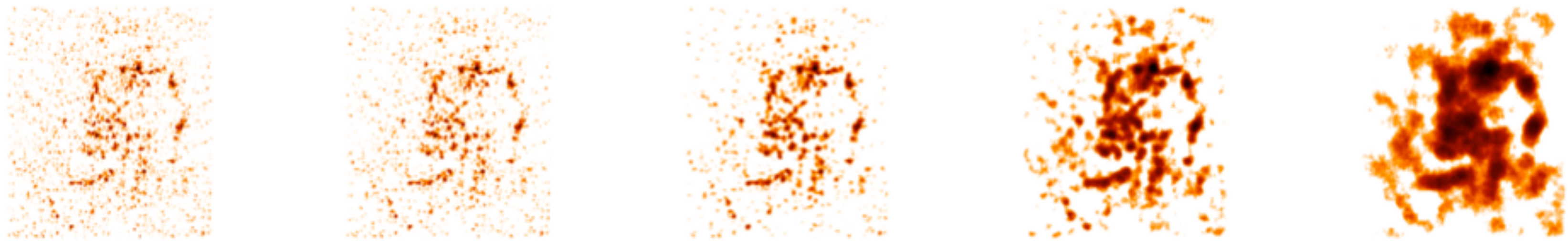
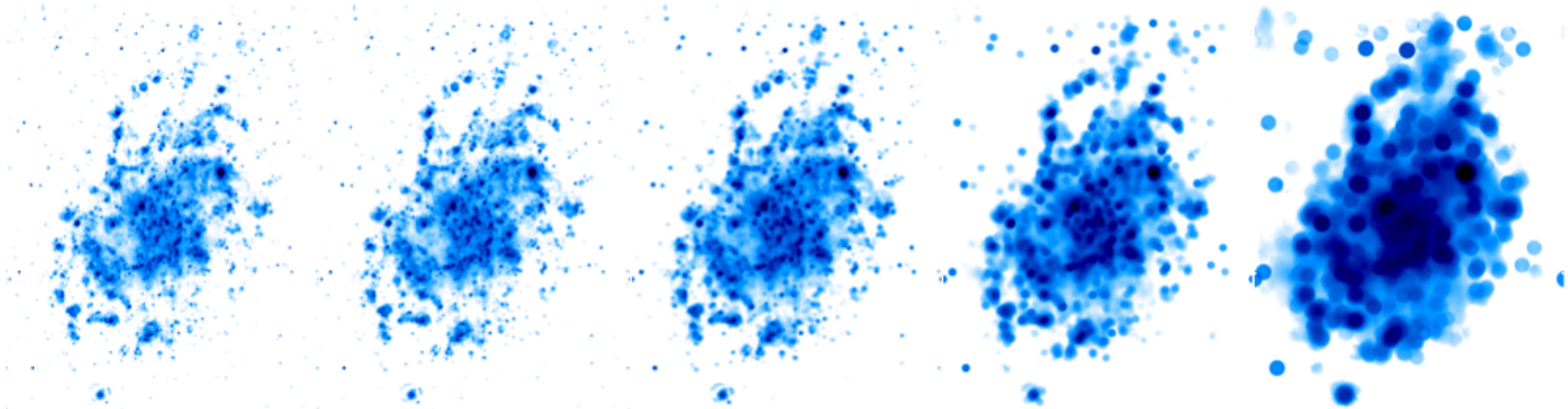
Pipeline to characterise cloud-scale physics

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



50 pc | 100 pc | 200 pc | 400 pc | 800 pc



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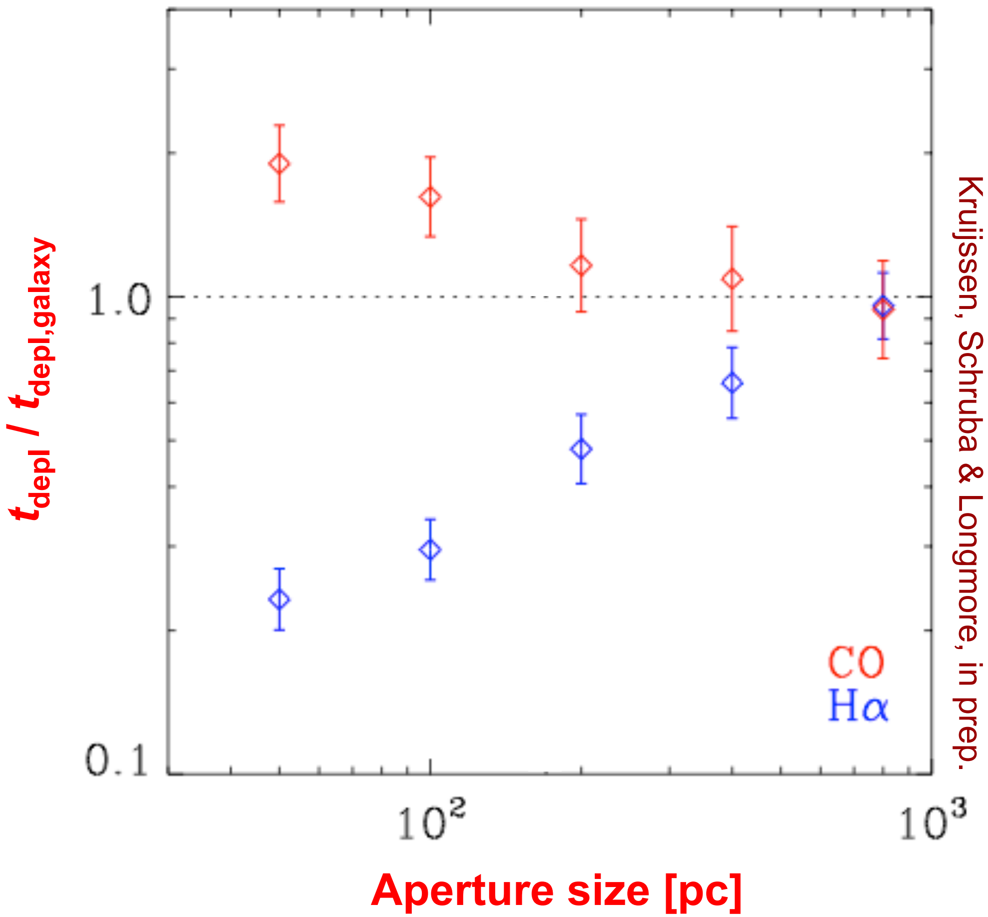
Pipeline to characterise cloud-scale physics

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



Kruijssen, Schruba & Longmore, in prep.

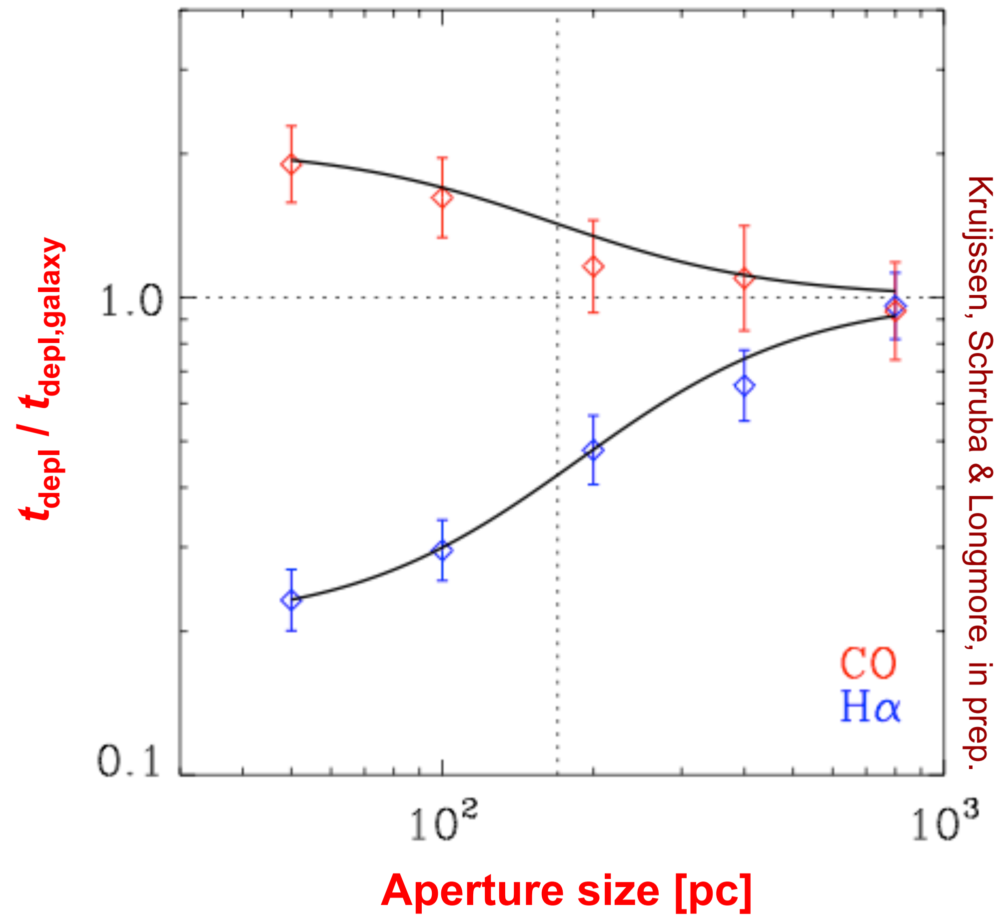
Centre on:

gas

stars

Pipeline to characterise cloud-scale physics

✧ Step 6: fit depletion time bias and obtain t_{gas}, t_{over}, λ, ε



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3. numerical testing

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How well does it work?

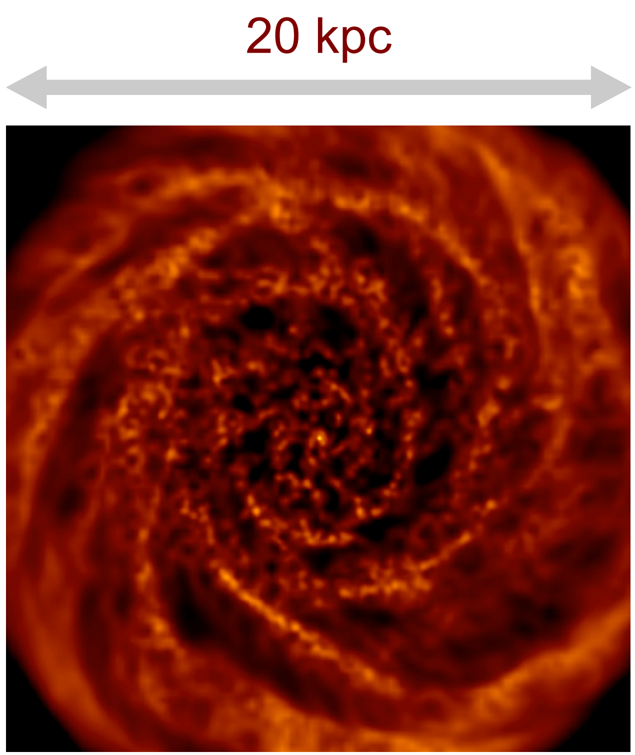
(Kruijssen, White, Schruba, Hu, Longmore)

✧ Test using numerical simulations

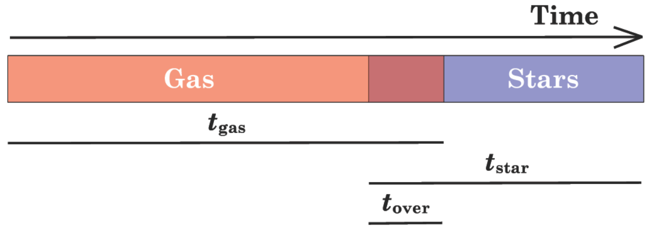
✧ 'New SPH' version of Gadget3 – see Chia-Yu Hu et al. (2014)
- pressure-entropy SPH
- Wendland smoothing kernel
- improved artificial viscosity
- artificial thermal energy conduction

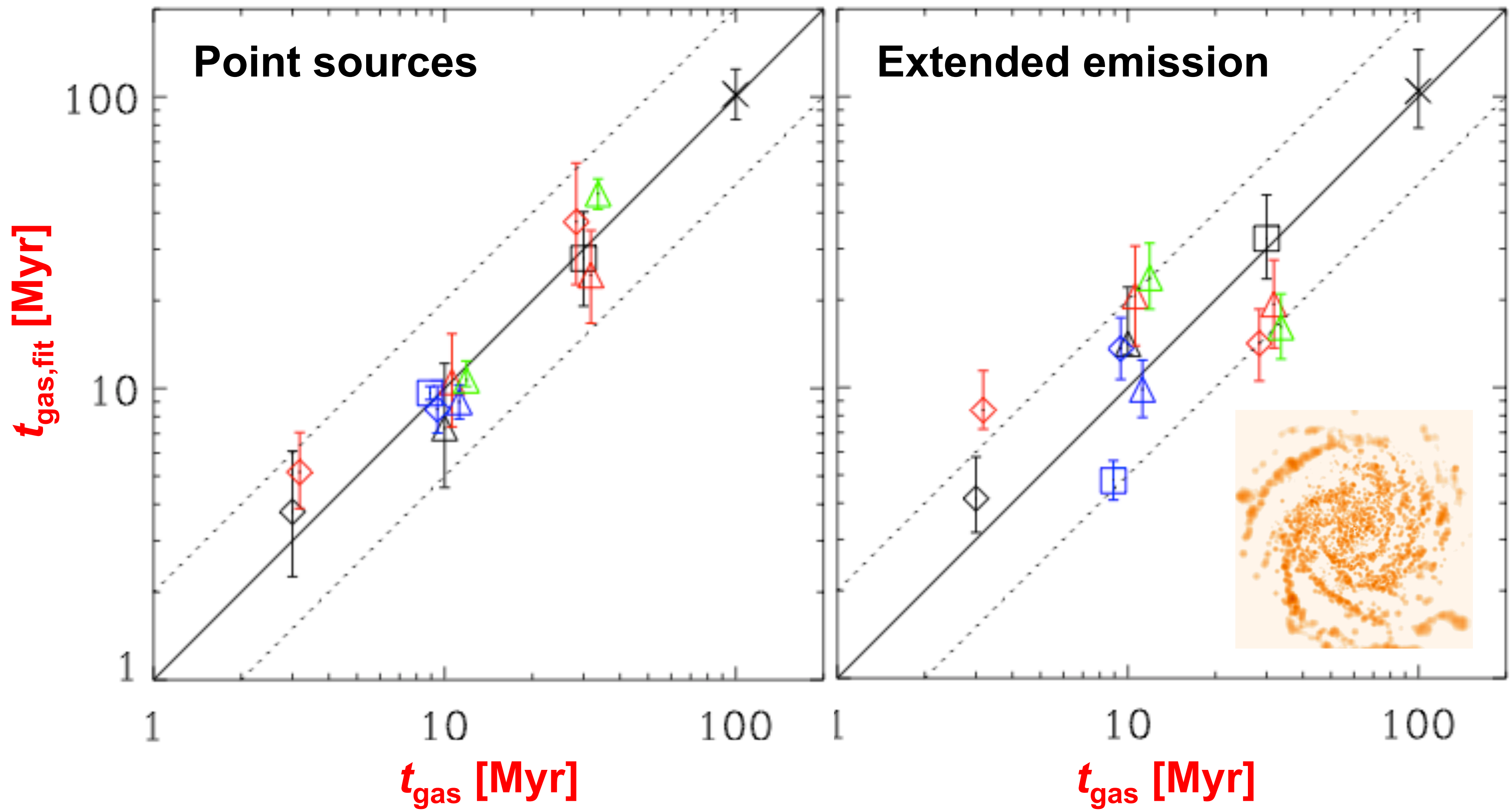
✧ M33-like disc, resolution in clouds is < 20 pc

✧ Age-bin the stars and use maps for tests



Current pipeline is accurate to within a factor of 2





Kruijssen+, in prep.

First test passed

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

4. application

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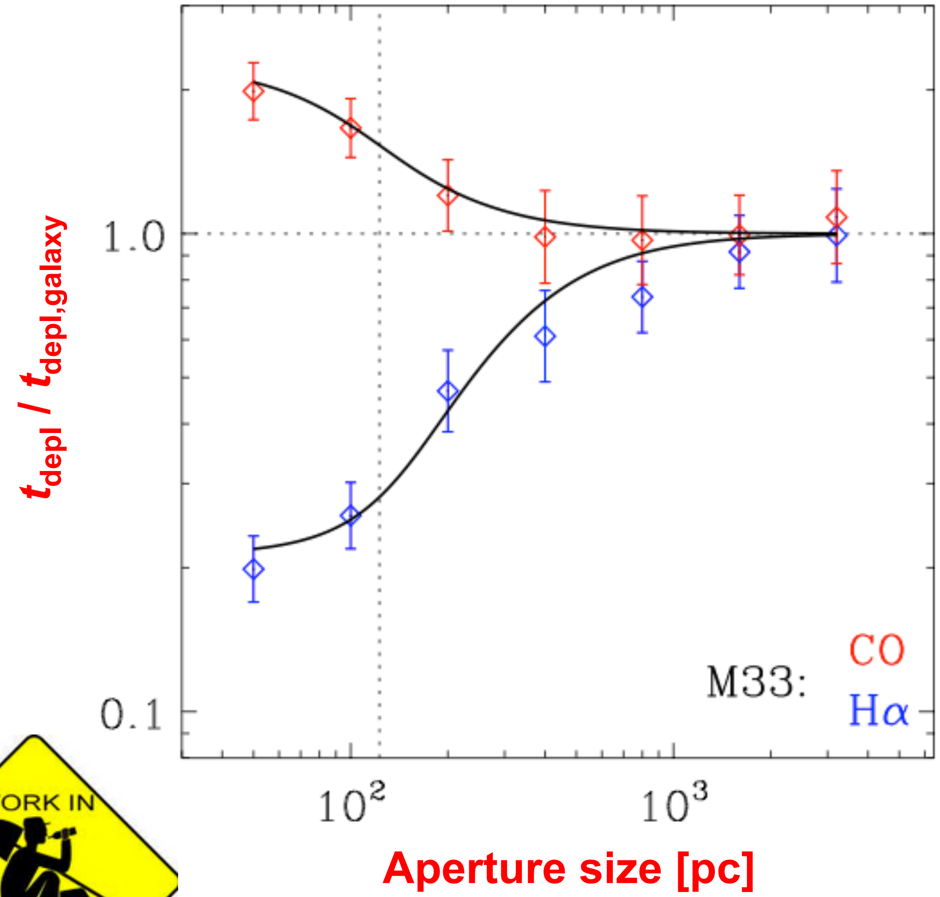
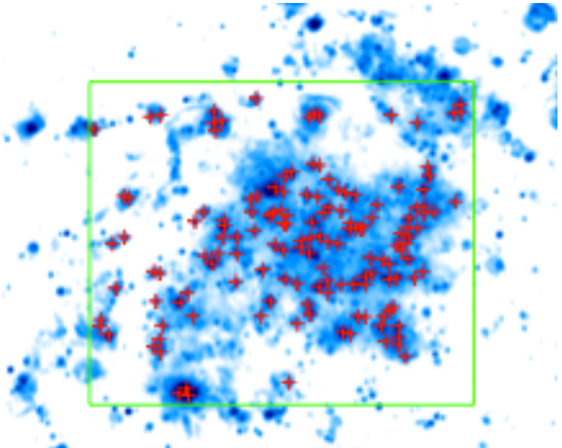
Second test: application to M33

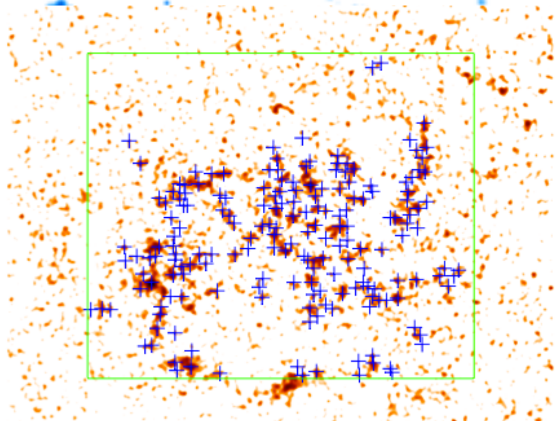
✧ Using Hα and CO(1-0) (Rosolowsky+07)

see talk by Braine



Kruijssen, Schruba & Longmore, in prep.





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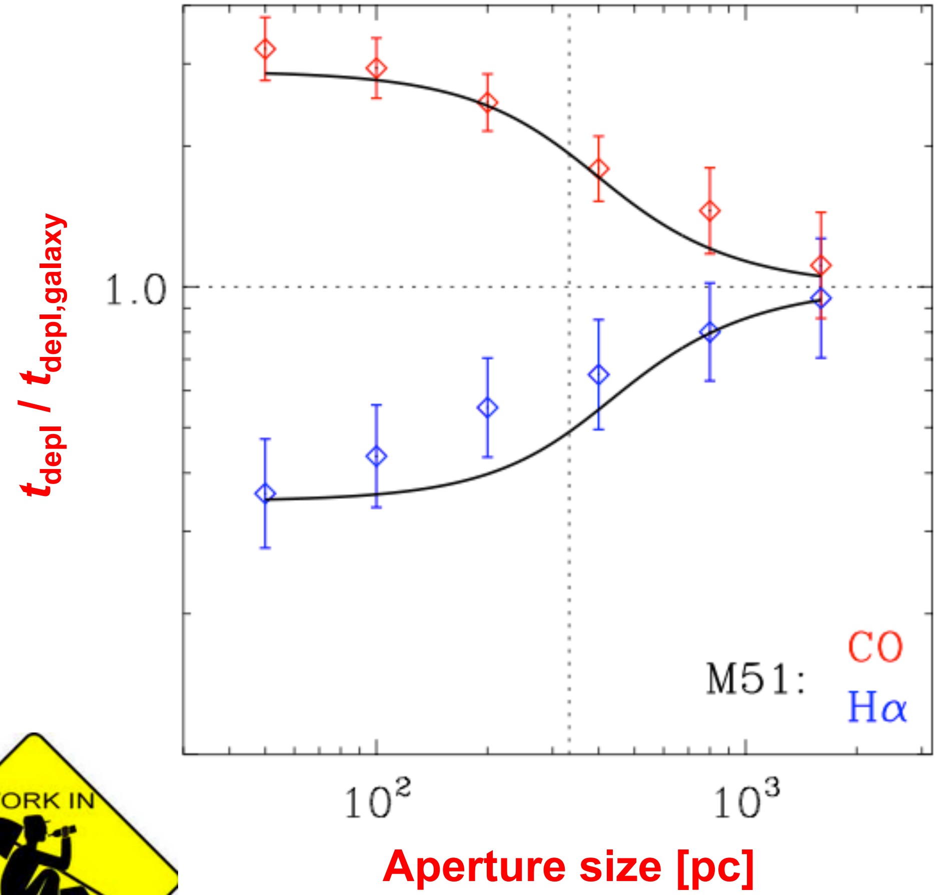
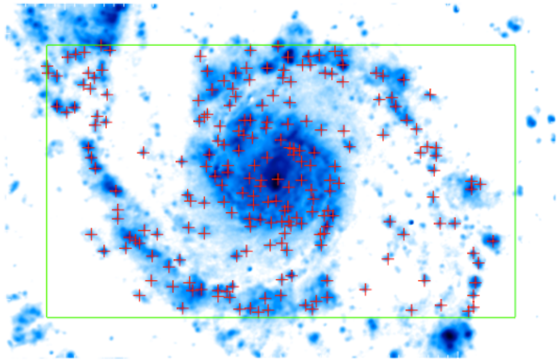
Application to M51

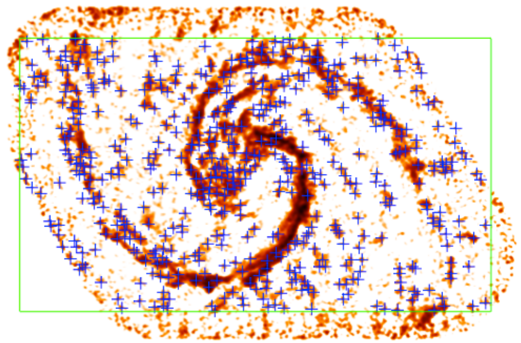
✧ Using Hα and CO(1-0) (PAWS; Schinnerer+13)

see talk by Hughes



Kruijssen, Schruba, Longmore + PAWS, in prep.





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Interpretation – physics of cloud-scale star formation?

see talks by Clark, Krumholz

✧ 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 disrupt clouds & end star formation

✧ $\lambda \sim 100 - 300$ pc similar to the Toomre length $\pi G\Sigma/\Omega^2 \sim 200$ pc

✧ Tentative interpretation – only three galaxies so far

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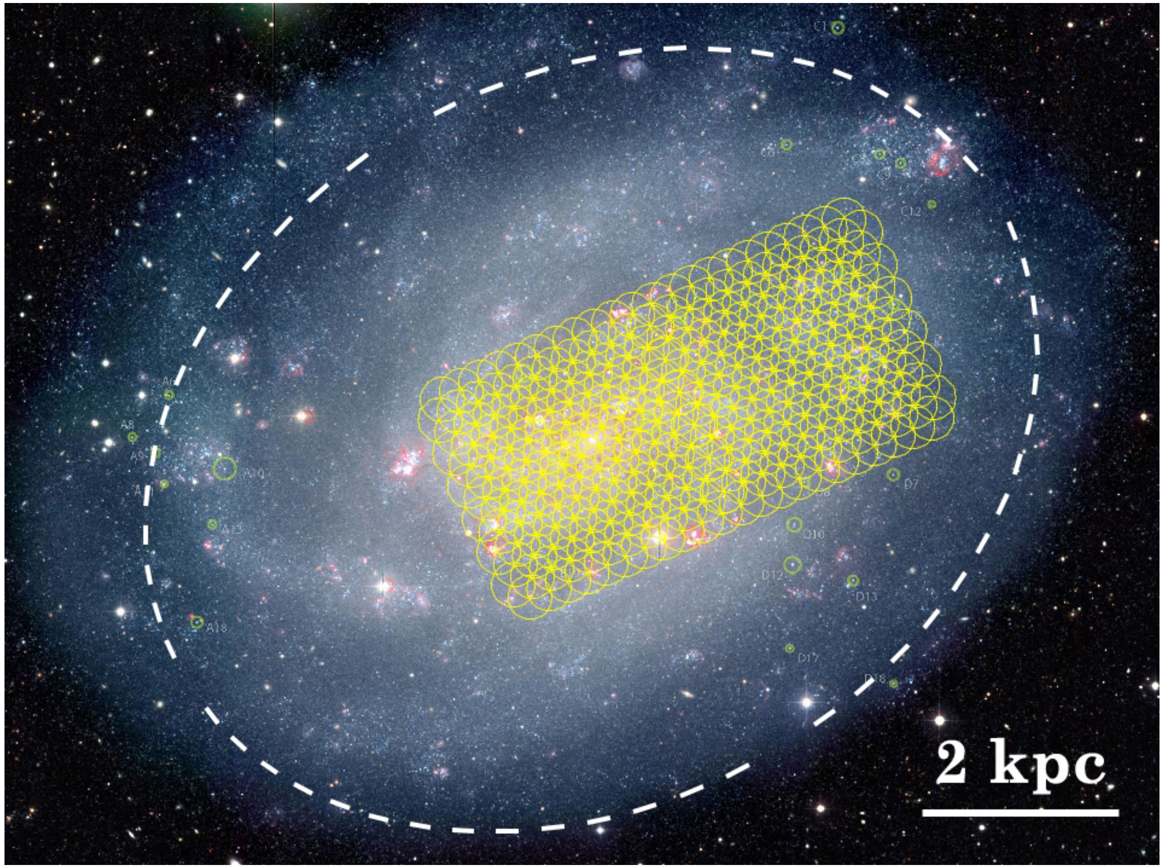
Future application at ~15 pc resolution & few 10^3 $M_\odot$ sensitivity

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



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

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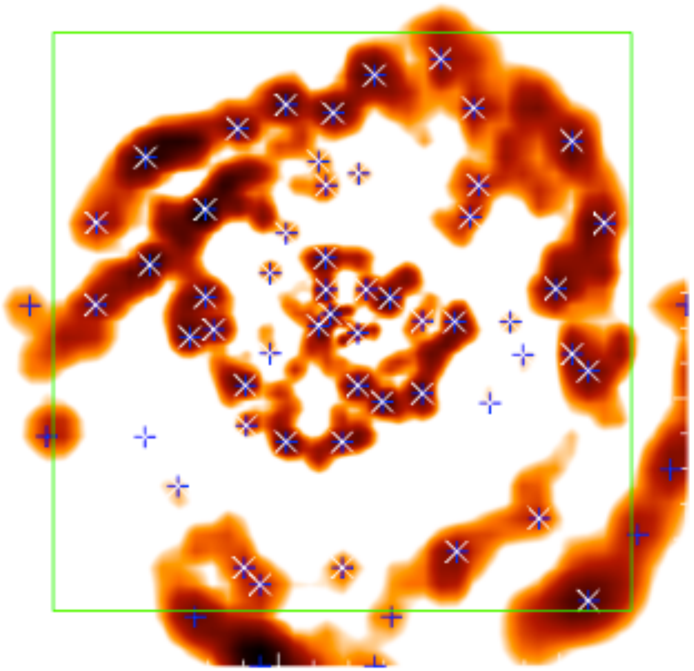
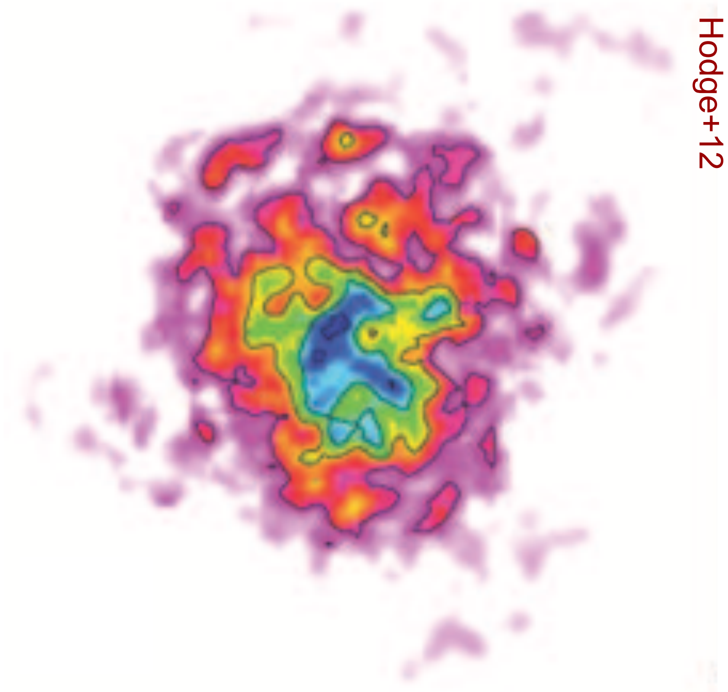
Method opens up entire observable Universe for cloud-scale SF studies



Low-resolution simulation

$t_{\rm gas}$ = 30 Myr

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



Observed sub-mm galaxy CO(2–1)

$z = 4.05$

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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