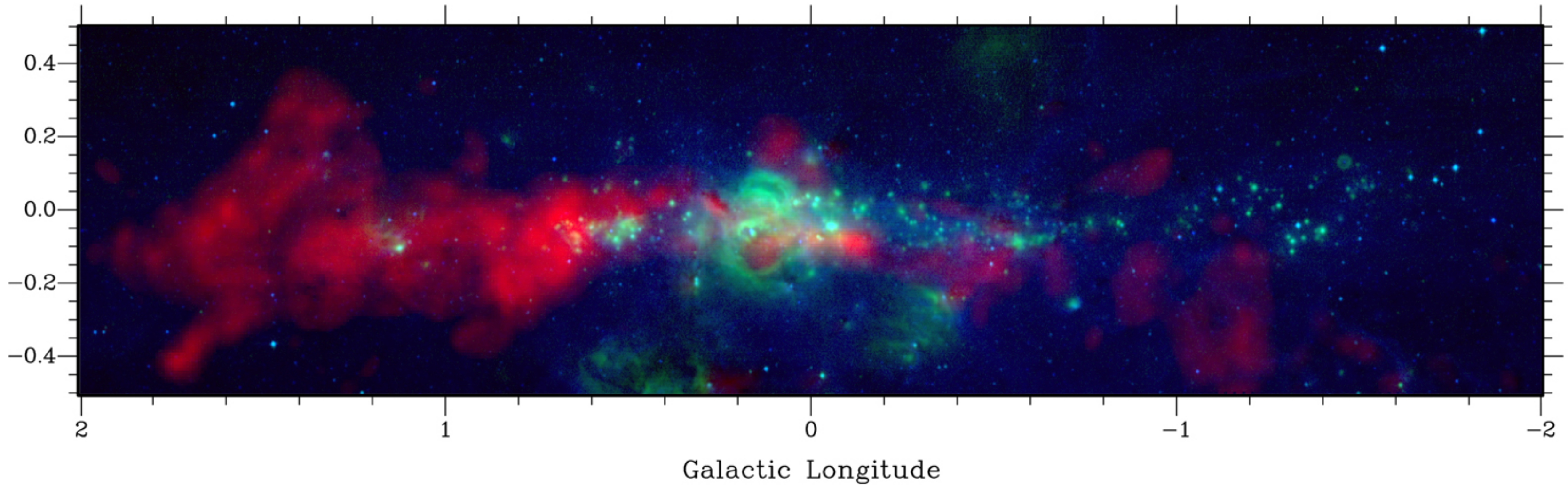
Introduction
CMZ
SF relations
Conclusions

# What controls star formation in the Central Molecular Zone?

(JMDK+13, MNRAS submitted, arXiv:1303.6286)

# Why do galactic star formation relations break down below a certain spatial scale?

(JMDK & Longmore 13, MNRAS submitted; JMDK, Schruba, Longmore, Bigiel, in prep.)




**Diederik Kruijssen**
**MPA Garching**

with Steve Longmore, Bruce Elmegreen, Norm Murray, John Bally,
Leonardo Testi, Rob Kennicutt, Andreas Schruba, Frank Bigiel

# WHAT SETS THE SFR?

JMDK+13, MNRAS submitted, arXiv:1303.6286

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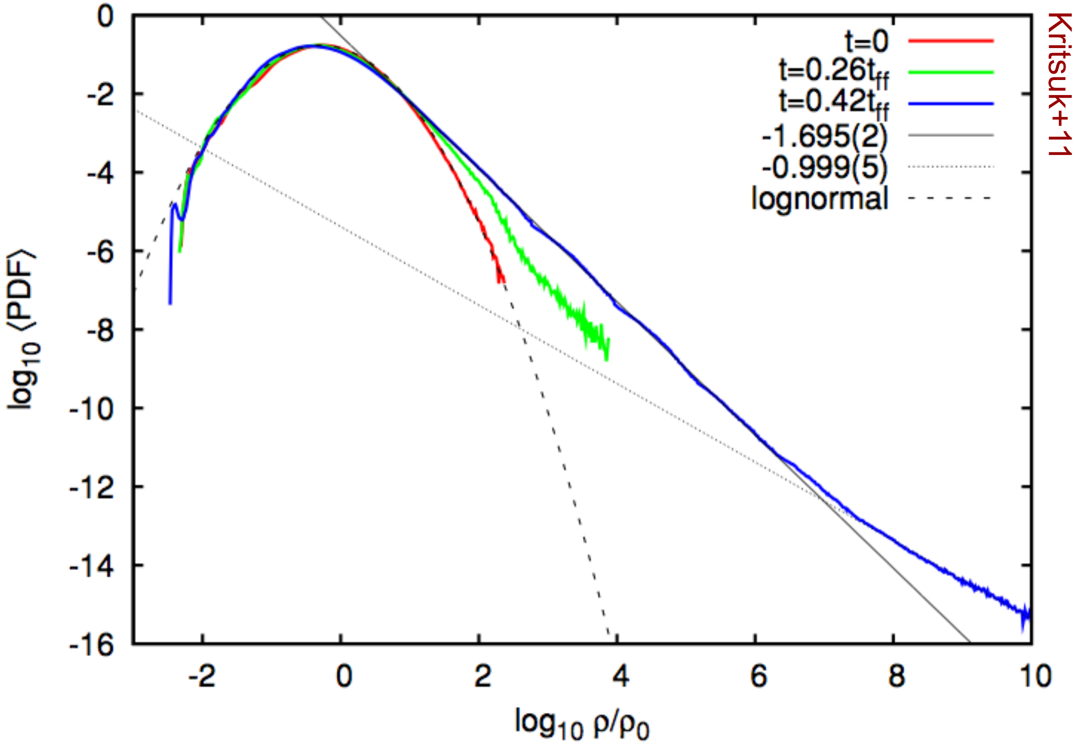
## The gas density PDF




✧ Log-normal with median and dispersion set by Mach number

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## The density threshold for SF

- Mach number in the CMZ ~ 70, mean density $n_0 \sim 2 \times 10^4$ cm$^{-3}$
- Current SFR: less than 0.5% of gas above density threshold for SF
- Required threshold density for star formation is $n > 10^7$ cm$^{-3}$
  (cf. the $n \sim 10^4$ cm$^{-3}$ that is observed by Lada+10 in the solar n'hood)

## A low SFR in the CMZ: why?

- ✧ Toomre or shear stability — Gas not self-gravitating except in 100-pc ring
- ✧ Episodic star formation — Evidence of previous star formation is seen
- ✧ Cloud disruption by tidal shocks
- ✧ Galactic tidal field
- ✧ Turbulence — Density threshold for SF increases with $M^2$. Predicts $n \sim 10^8\ \mathrm{cm}^{-3}$

Yes
Maybe/partially
No

$$x_{\rm turb} \equiv n/n_0 = A_x \alpha_{\rm vir} \mathcal{M}^2$$

Krumholz & McKee 05, Padoan & Nordlund 11

$$n_{\rm turb} \equiv x_{\rm turb} n_0 \sim 2 \times 10^8\ \mathrm{cm}^{-3}$$ **CMZ**

$$10^4\ \mathrm{cm}^{-3}$$ **Solar neighbourhood**

(cf. Lada+10 threshold of $10^4$ cm$^{-3}$)

# WHAT IS DRIVING THE TURBULENCE?

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## What is driving the turbulence?

- Turbulence dissipates on a vertical crossing time ($t_{diss}$ ~ 3 Myr)
- Classical turbulence drivers fail in the CMZ
  (magnetorotational & gravitational instabilities, outflows, ionizing radiation, SNe)
- Bar inflow not sufficiently energetic *if steady-state* ($t_{diss}$ = 10 – 20 Myr)
  Krumholz & JMDK, in prep.
- Episodic star formation: final piece of the puzzle…?

# The CMZ & spatially resolved star formation relations



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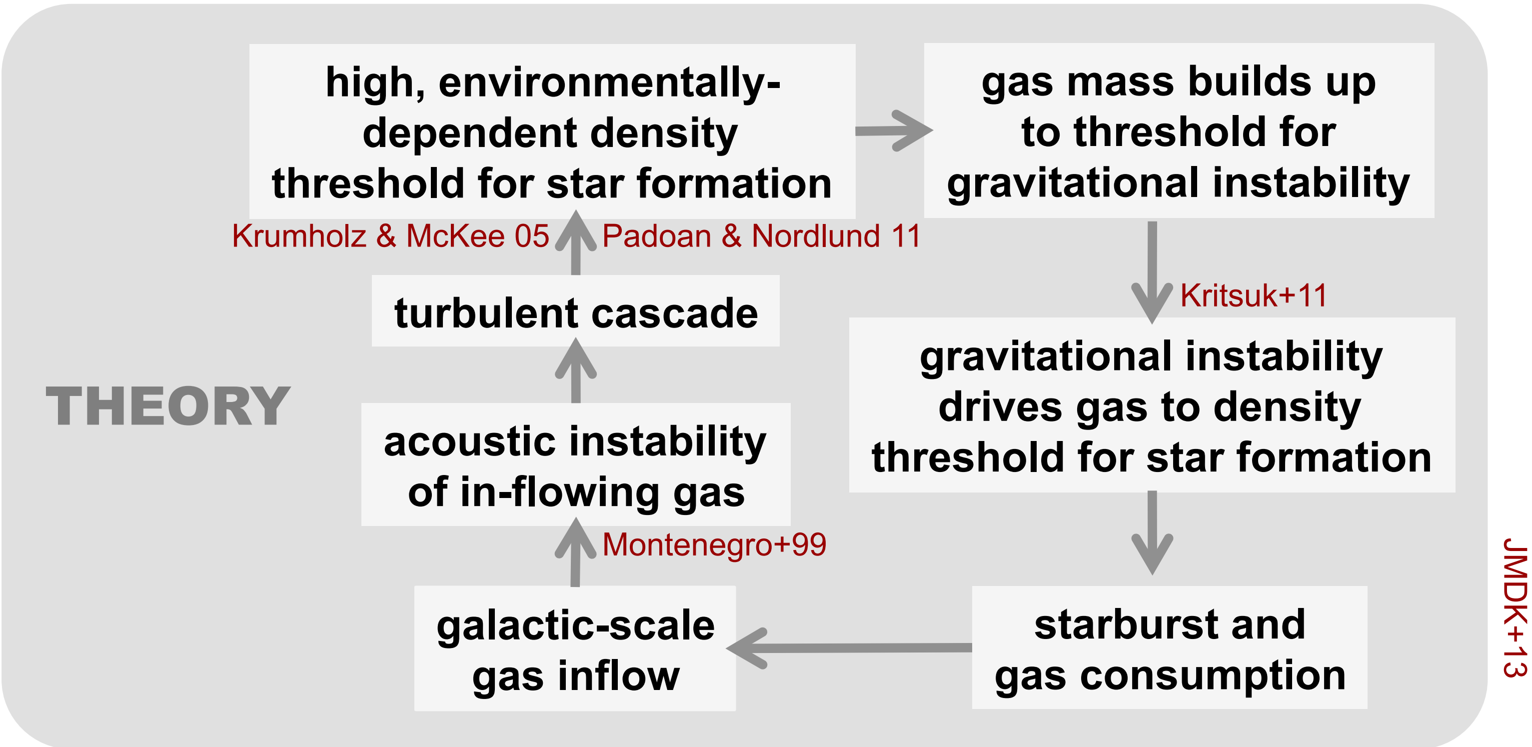
## A self-consistent cycle of star formation?

✧ Different plausible mechanisms may affect different stages of a single cycle



## Implications & speculation

✧ Scenario needs detailed observational & numerical testing

✧ Extragalactic work will provide additional constraints

✧ “Prediction”: ~1/3 of galaxy centres super-Kennicutt, ~2/3 sub-Kennicutt

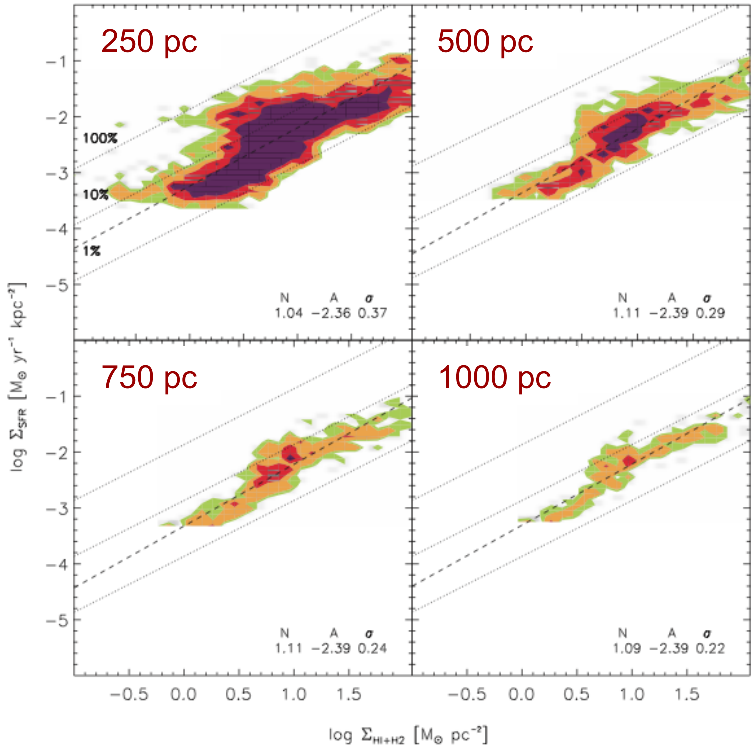
✧ Key question in galaxy formation simulations: which SF recipe?

➔ Numerical simulations with a classical Schmidt-type SF recipe cannot accurately model the gas and SF physics of the CMZ

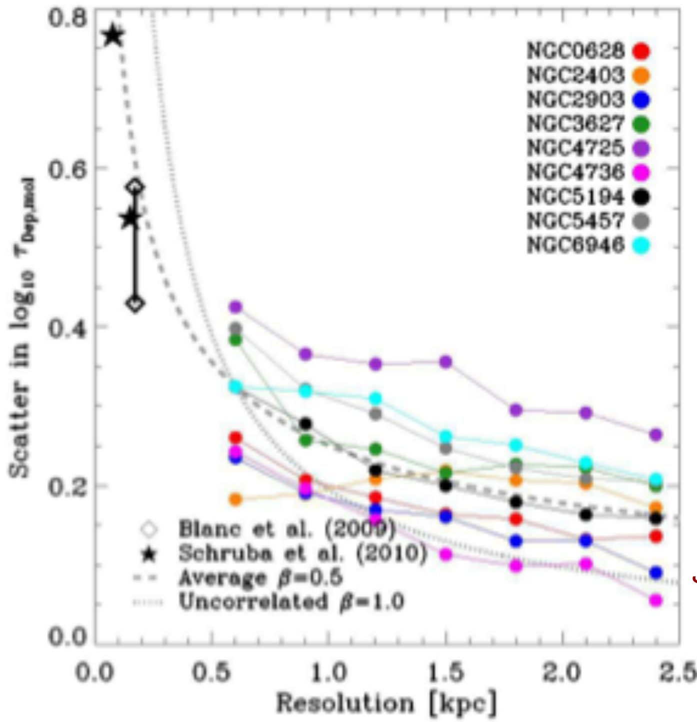
✧ Key question in SMBH growth: how to keep gas from forming stars?

# AT WHICH SCALES DO SF RELATIONS BREAK?

JMDK & Longmore 13
JMDK, Schruba, Longmore, Bigiel, in prep.




Bigiel+08




Leroy+13

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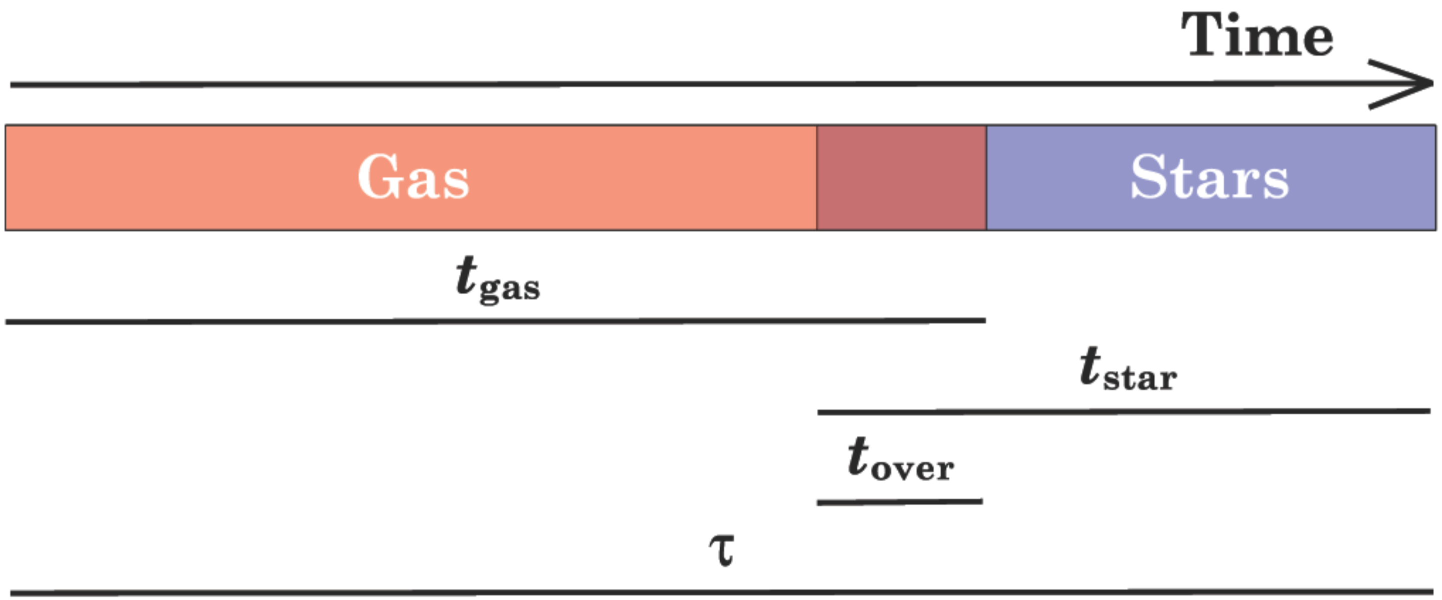
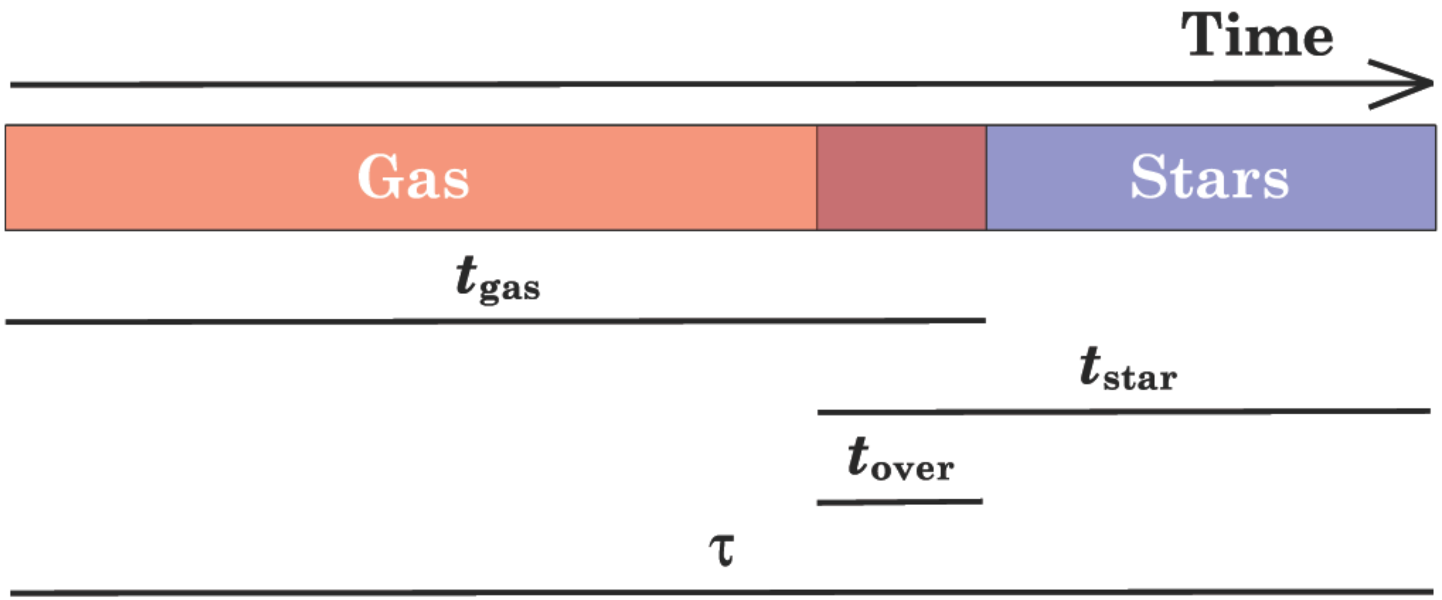
## An uncertainty principle for star formation




✧ If the physics of SF are universal:
time-integration of single region gives galactic SF relation

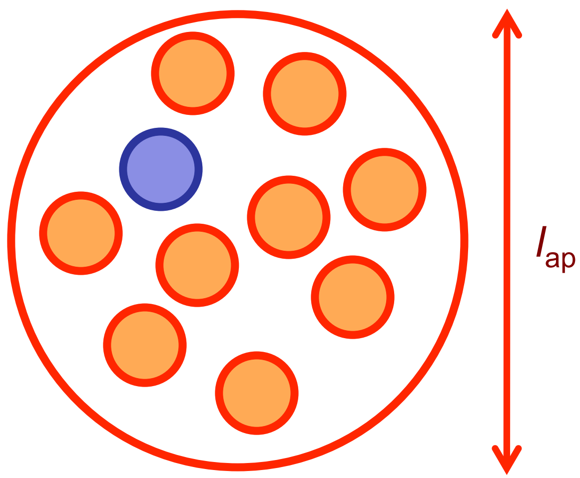
## An uncertainty principle for star formation




✧ 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 $t_{gas} = 9 \times t_{star}$



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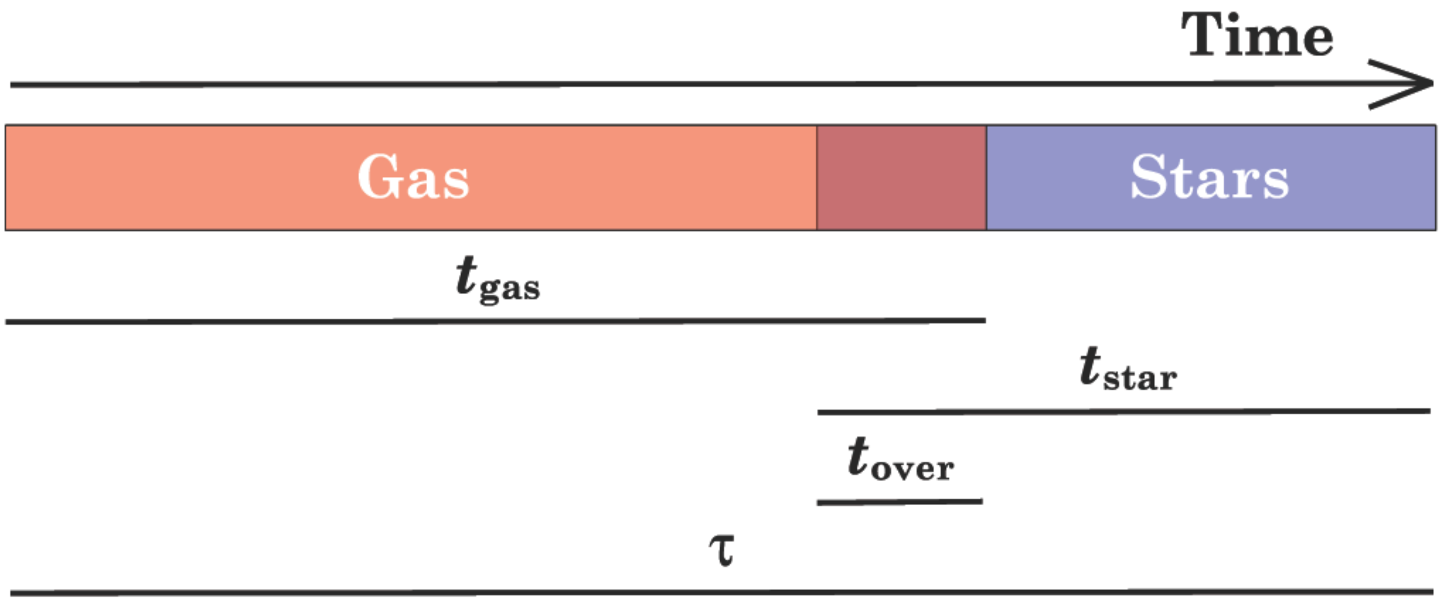
## An uncertainty principle for star formation

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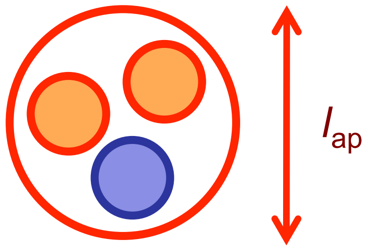


- Example for $t_{gas}$ = 2 x $t_{star}$

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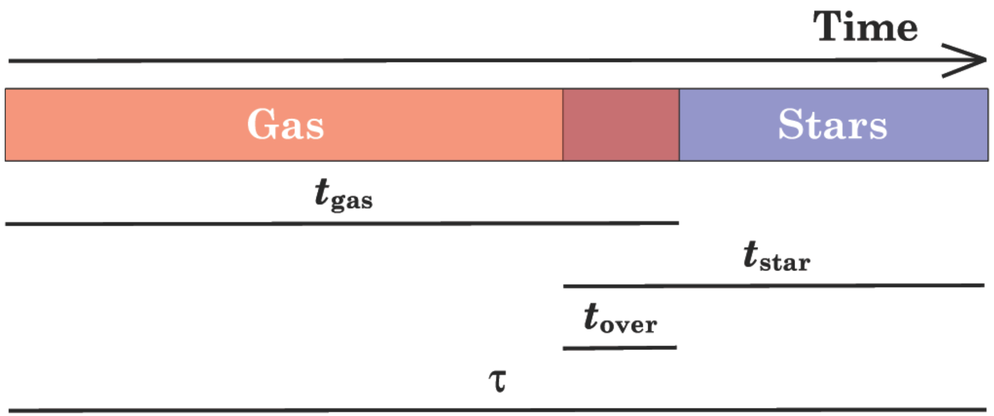
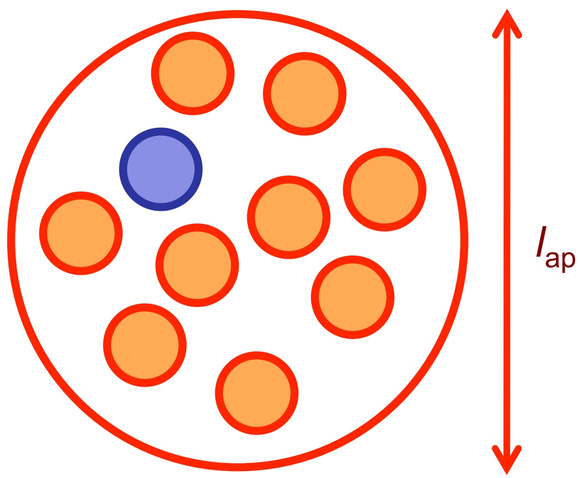
## An uncertainty principle for star formation

$$\left(\frac{\Delta x}{\lambda}\right)^2 \geqslant \frac{\tau}{\Delta t}$$

- $\Delta x$: Size-scale over which SF relation is spatially averaged
- $\lambda$: Size-scale of independent regions
- $\tau$: Total duration of the SF process
- $\Delta t$: Duration of shortest SF phase



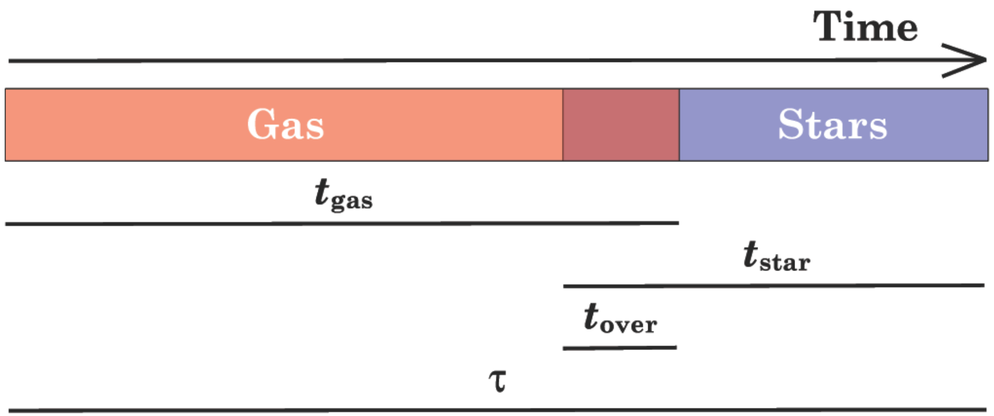



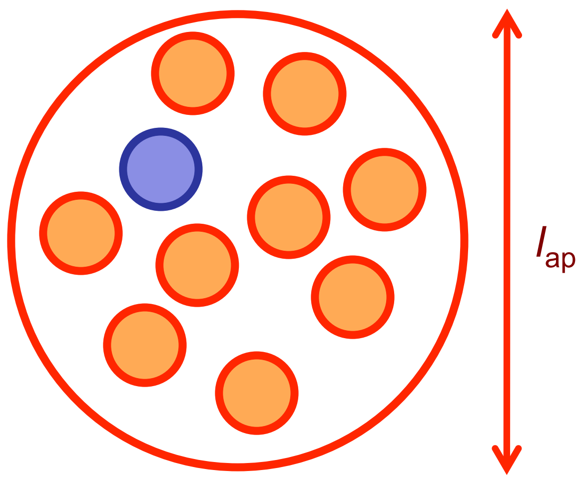
## An uncertainty principle for star formation

$$\left(\frac{\Delta x}{\lambda}\right)^2 \geqslant \frac{\tau}{\Delta t}$$

Number of independent regions *within aperture*

Number of *required* independent regions



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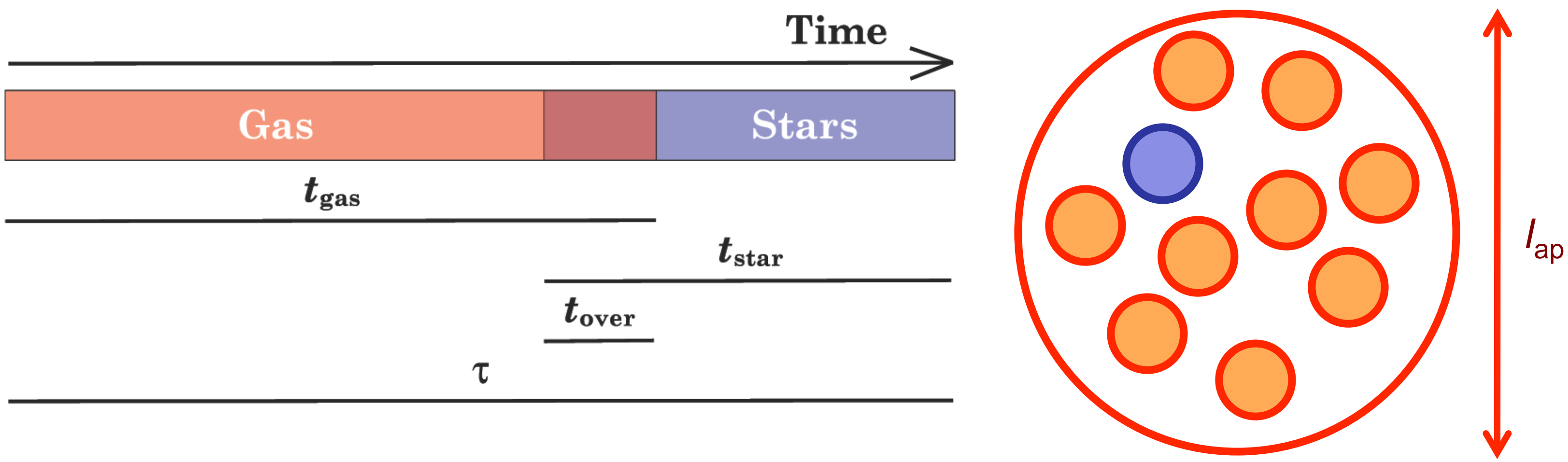
## An uncertainty principle for star formation

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



## An uncertainty principle for star formation

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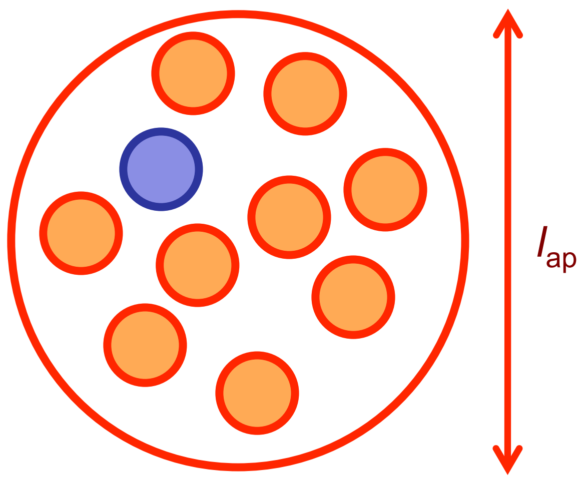
- $\Delta x$: Size-scale over which SF relation is spatially averaged
- $\Delta t$: Duration of shortest SF phase
- $\lambda$: Size-scale of independent regions
- $\tau$: Total duration of the SF process

If this condition is satisfied, the “shortest” tracer is always well-sampled within the aperture

➔ Galactic SF relation is retrieved



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## Three different minimum size-scales

$$\Delta x \geqslant \Delta x_{\rm samp} \equiv \left(\frac{\tau}{t_{\rm ph}}\right)^{1/2} \lambda$$

$$\Delta x \geqslant \Delta x_{\rm IMF} \equiv \left(\frac{4{\rm SFR}_{\rm min}}{\pi \Sigma_{\rm SFR}}\right)^{1/2}$$

$$\Delta x \geqslant \Delta x_{\rm drift} \equiv \frac{1}{2}\sigma\tau$$

$$\Delta x \geqslant \Delta x_{\rm tot} \equiv \max\{\Delta x_{\rm samp}, \Delta x_{\rm IMF}, \Delta x_{\rm drift}\}$$

## Application with a (very) simple 1D disc galaxy model

✧ Logarithmic potential ($V$ = 200 km s$^{-1}$, solid-body in central kpc)

✧ Exponential gas surface density profile with:
- $\Sigma(0)$ = 200 M$_\odot$ pc$^{-2}$
- $R_s$ = 2.5 kpc
- $\sigma$ = 10 km s$^{-1}$ (in central kpc $\sigma$ = 50 km s$^{-1}$)

✧ $\Sigma_{SFR}$ profile by assuming a large-scale Schmidt-Kennicutt relation

✧ Size-scale of independent regions is assumed to be Toomre length

✧ $t_{gas} \sim \Omega^{-1}$, $t_{star}$ = 2 Myr (H$\alpha$) and $t_{over}$ = 0 Myr

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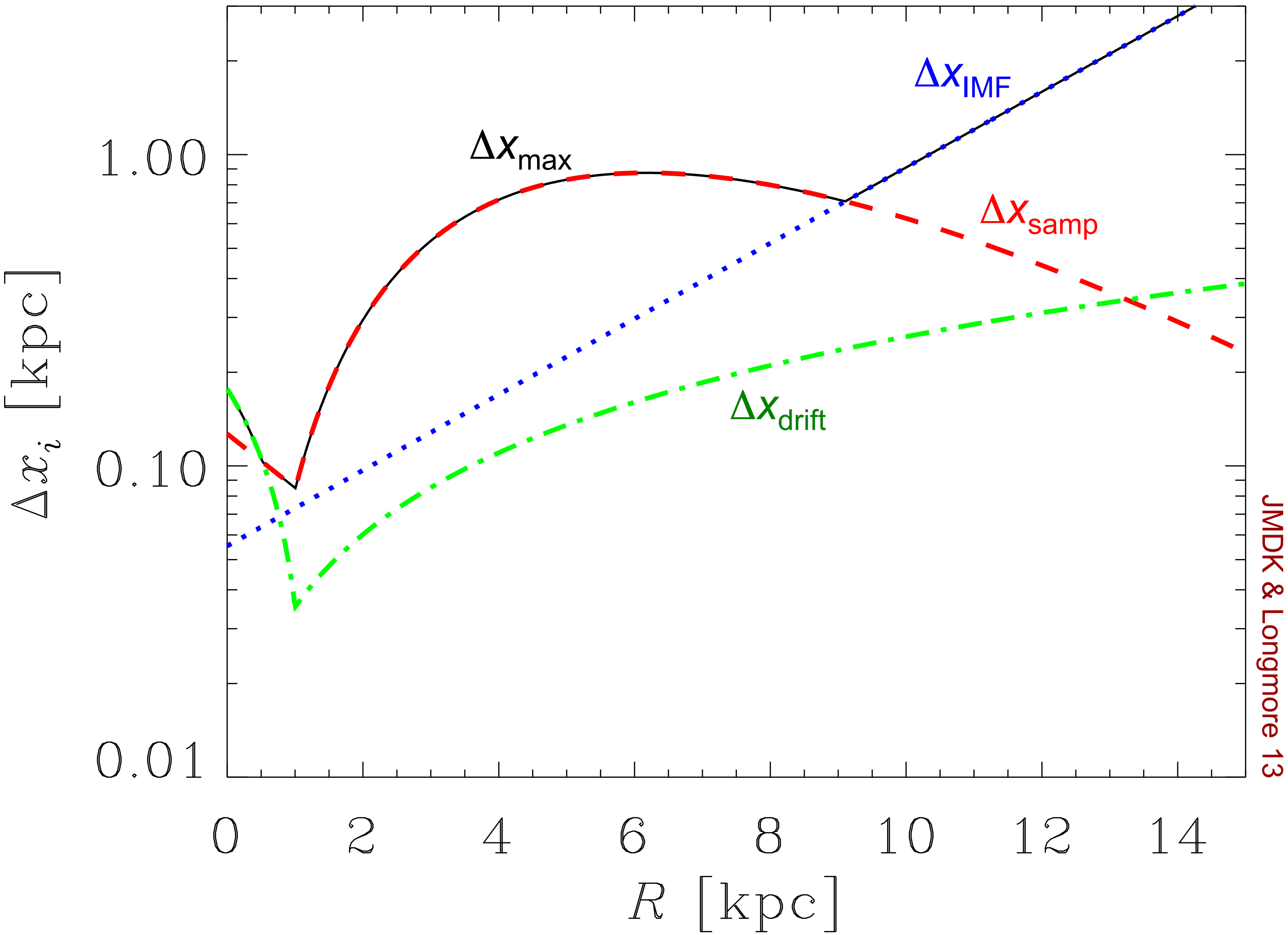
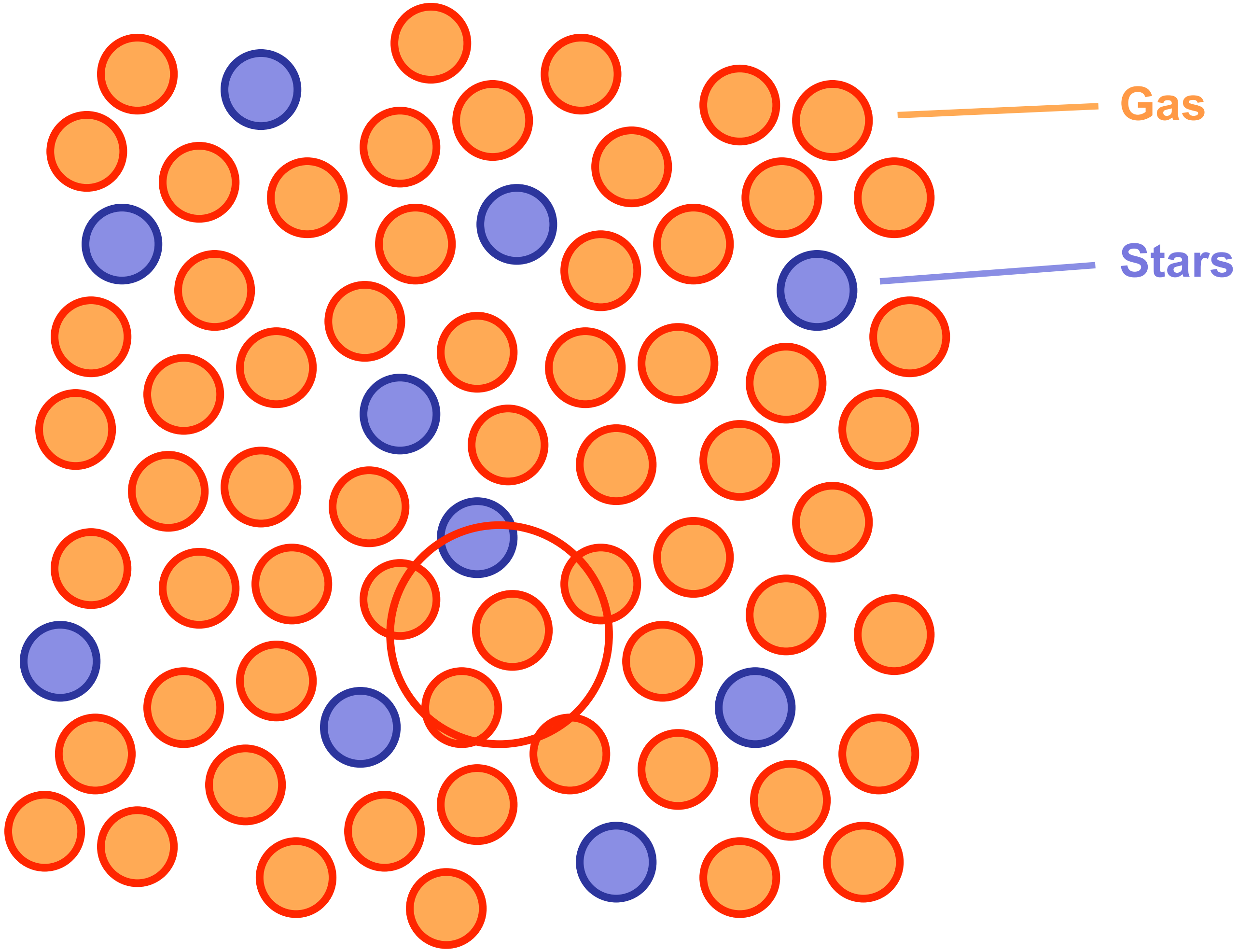
## Variation of minimum size-scale(s) with galactocentric radius

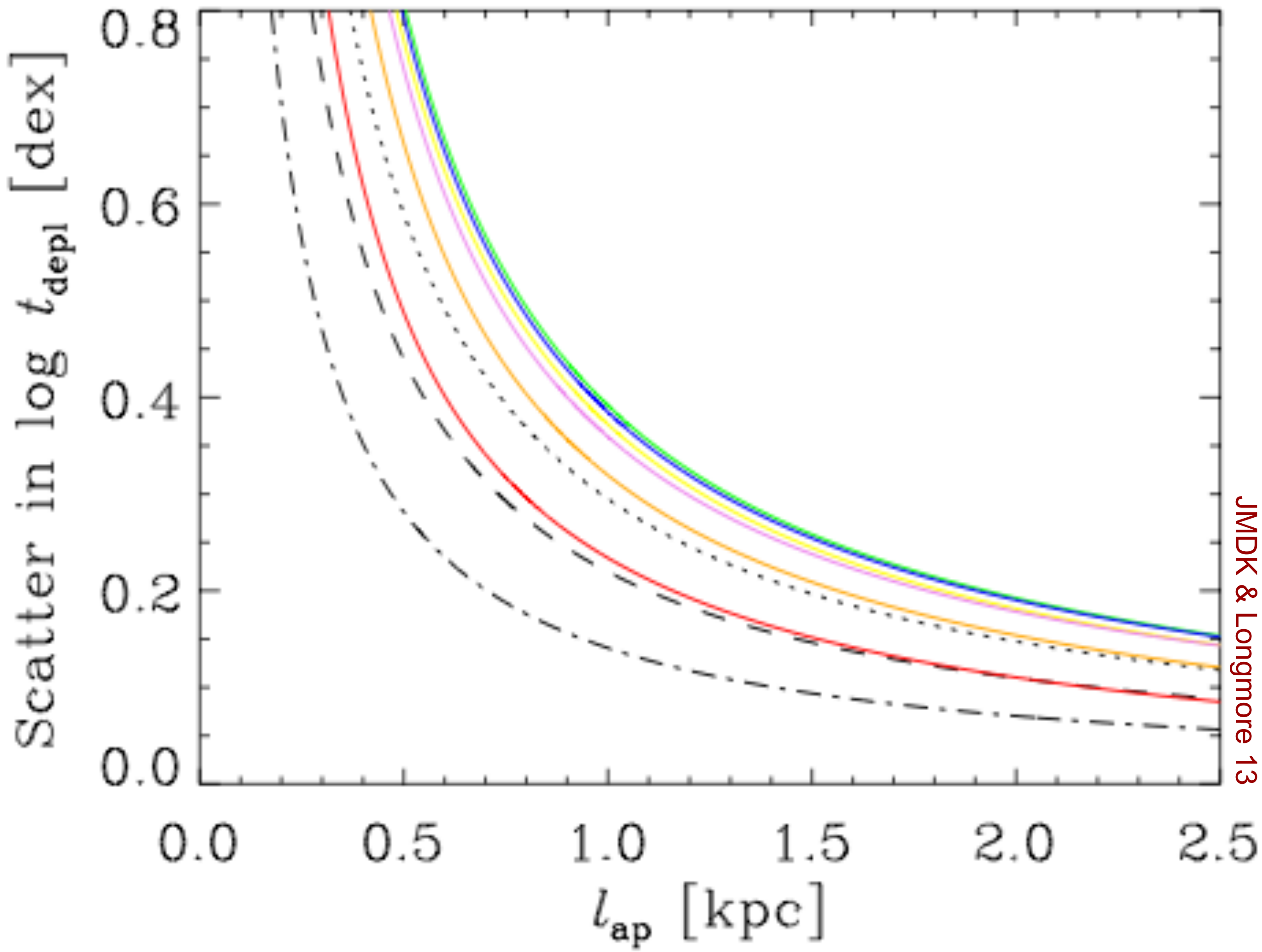


## Effect when randomly placing an aperture



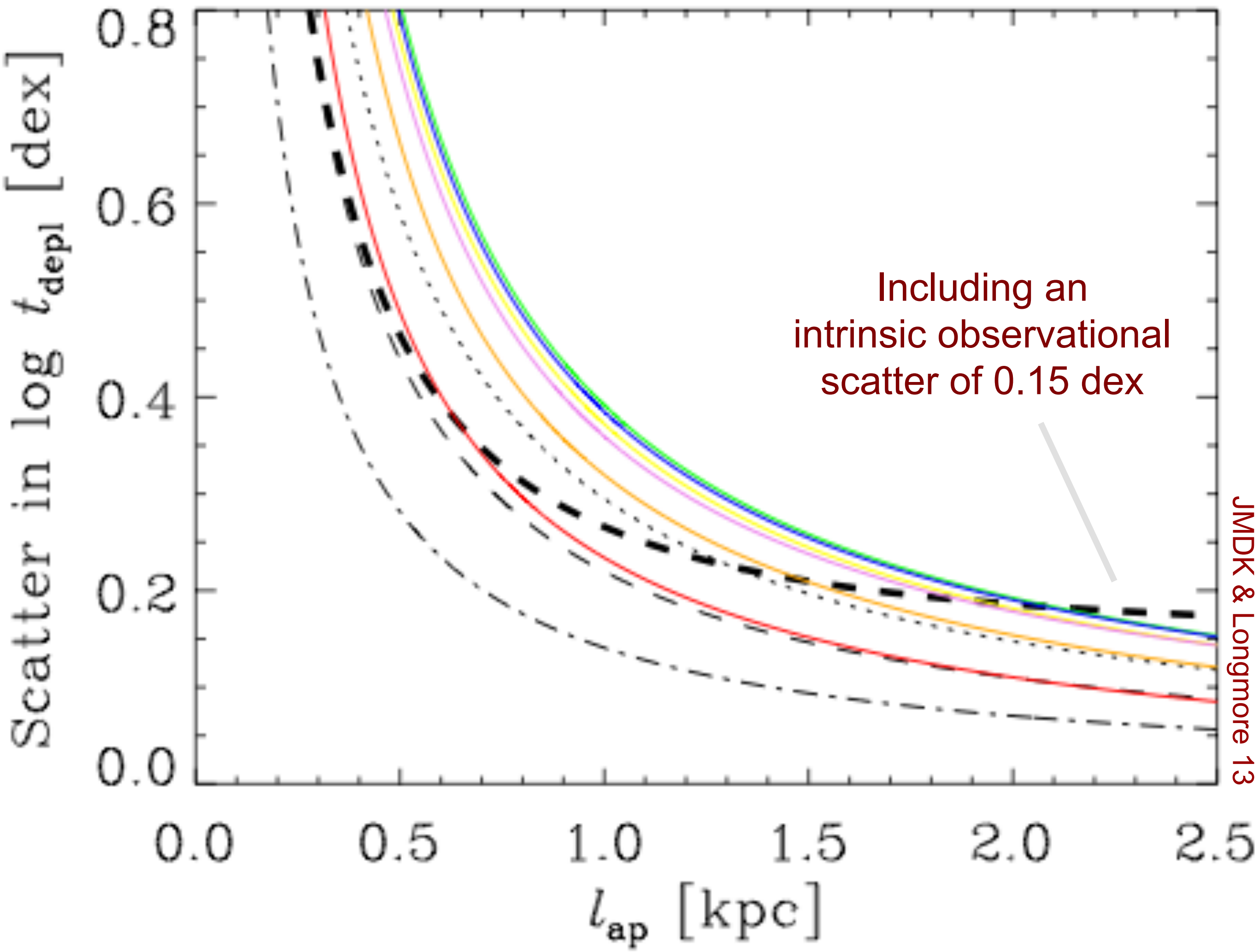
## Predicted scatter versus (randomly placed) aperture size

see e.g. Schruba's talk




JMDK & Longmore 13

## Predicted scatter versus (randomly placed) aperture size



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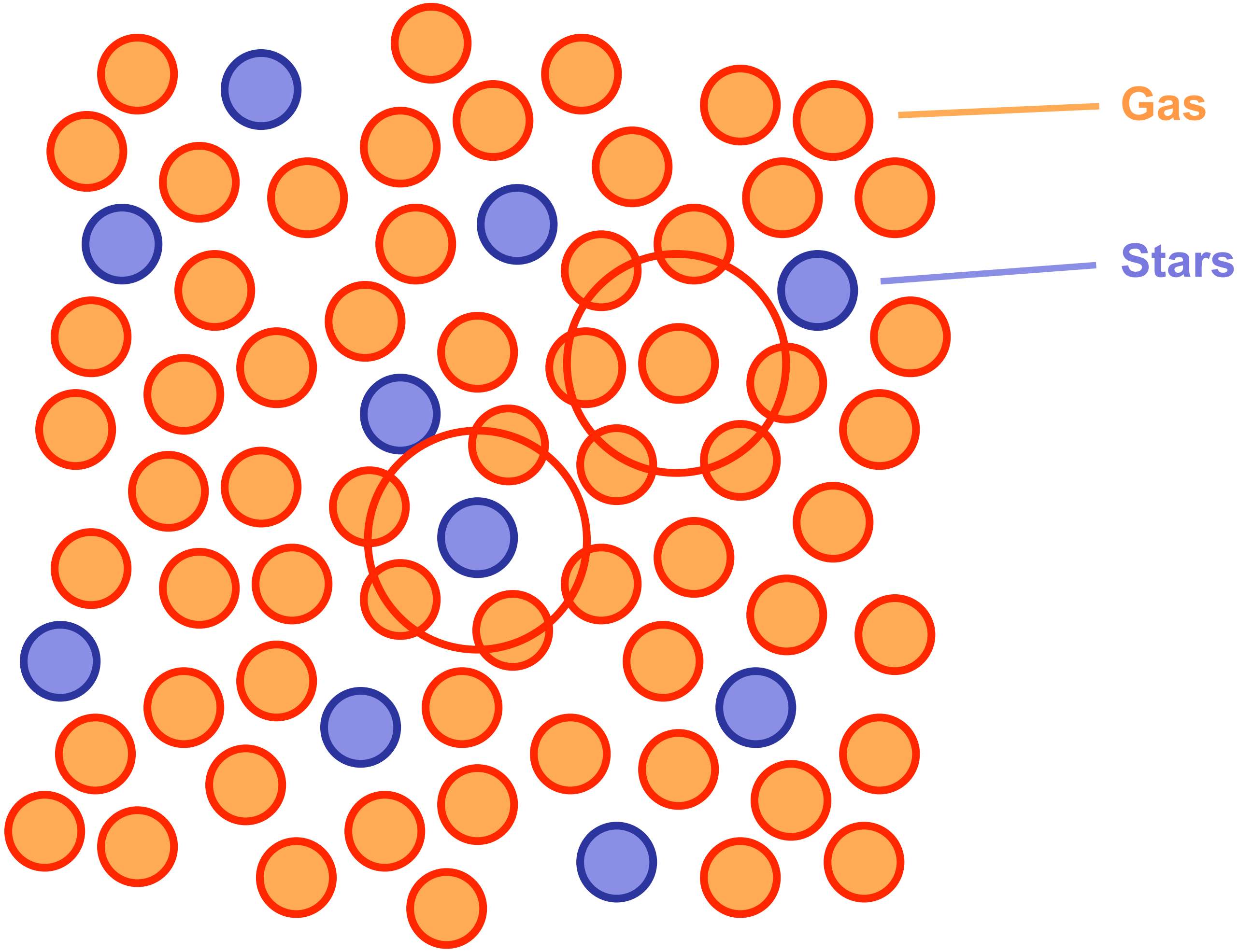
## Effect when placing an aperture on peaks of gas or star formation



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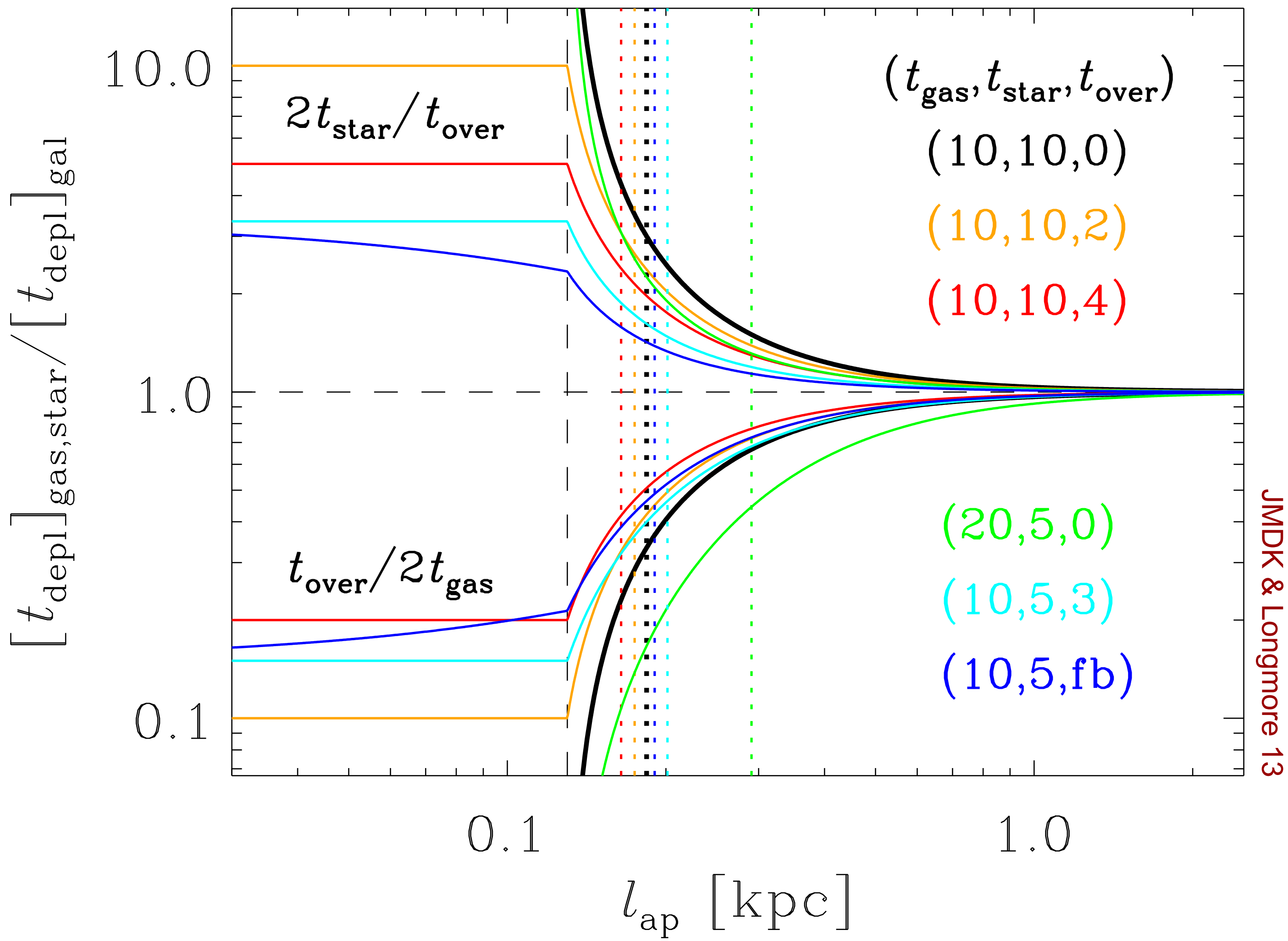
## Gas depletion time bias versus (specifically placed) aperture size

see e.g. Schruba's, Faesi's talks




Centre on:

**gas**

**stars**

## An uncertainty principle for star formation

✧ Simple interpretative framework

✧ Potentially very powerful to obtain:

- time-scales involved in SF process (duration, "cloud" lifetimes, etc.)
- time spent by gas at different densities (by combining different tracers)
- size-scales of independent regions

✧ Small-scale SF relations are *fundamentally different* to galactic SF relations

cf. Lada+10, Heiderman+10, Gutermuth+11

✧ First verification with observations underway

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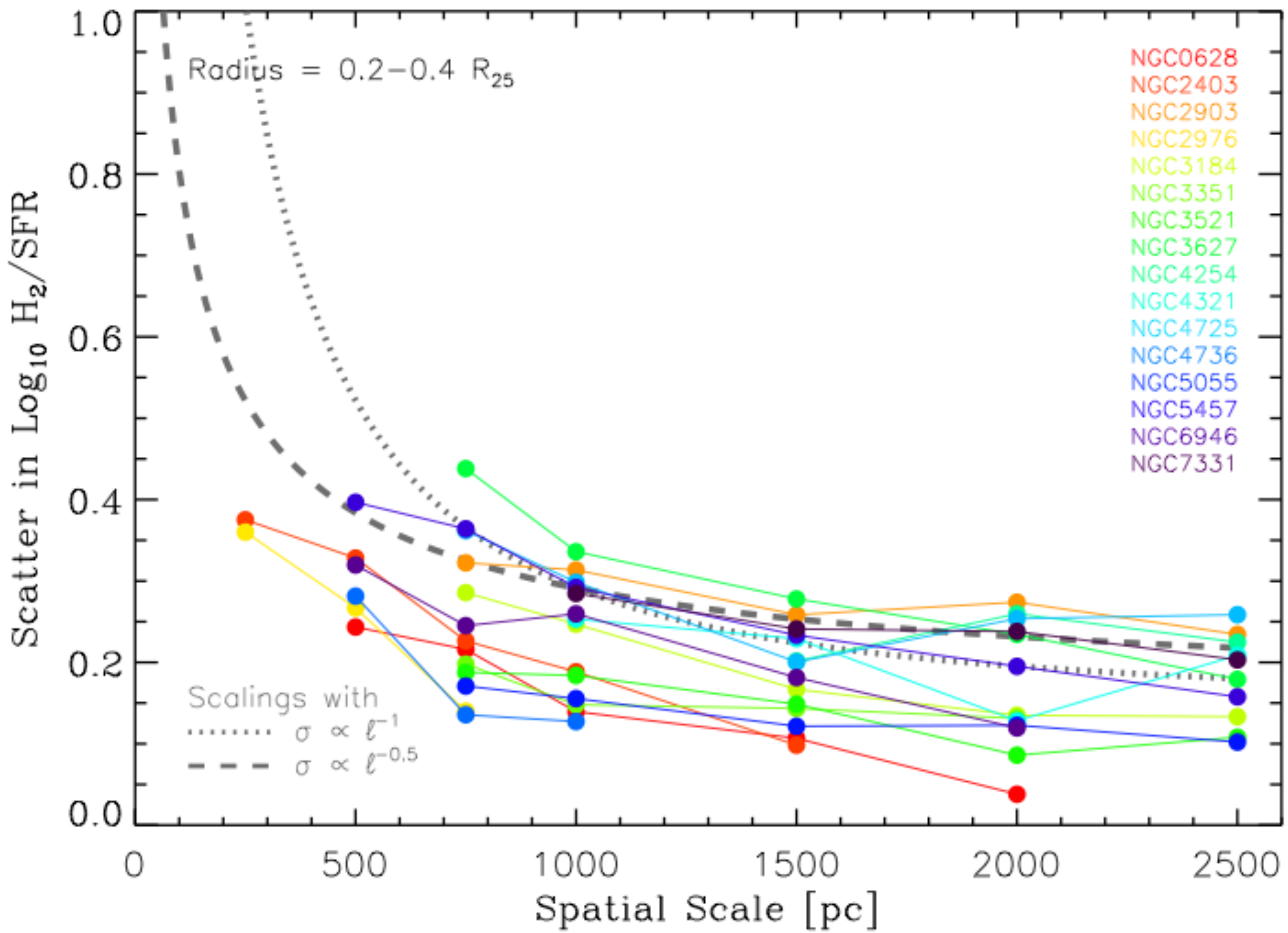
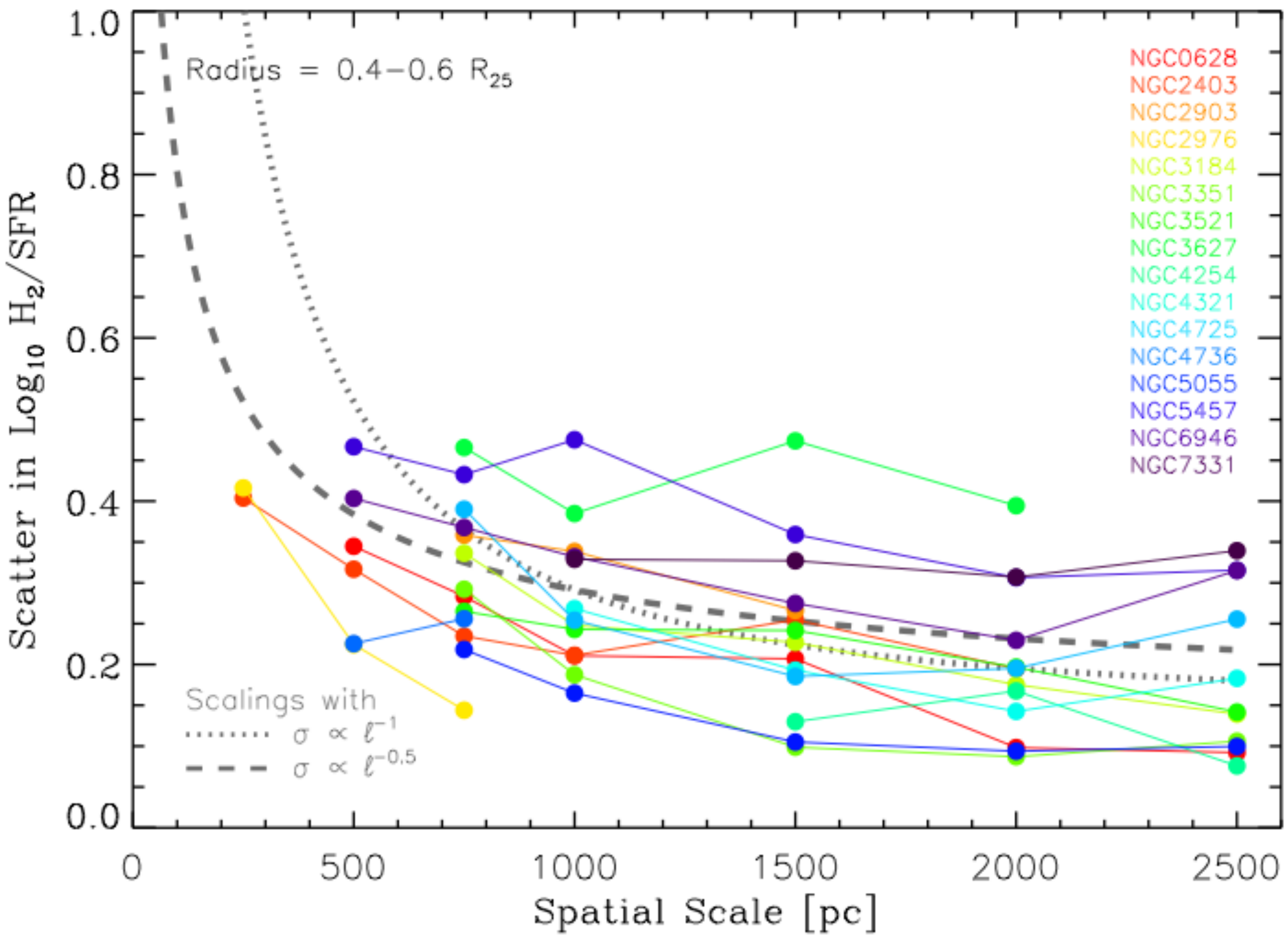
## Observed scatter versus aperture size: small galactocentric radii



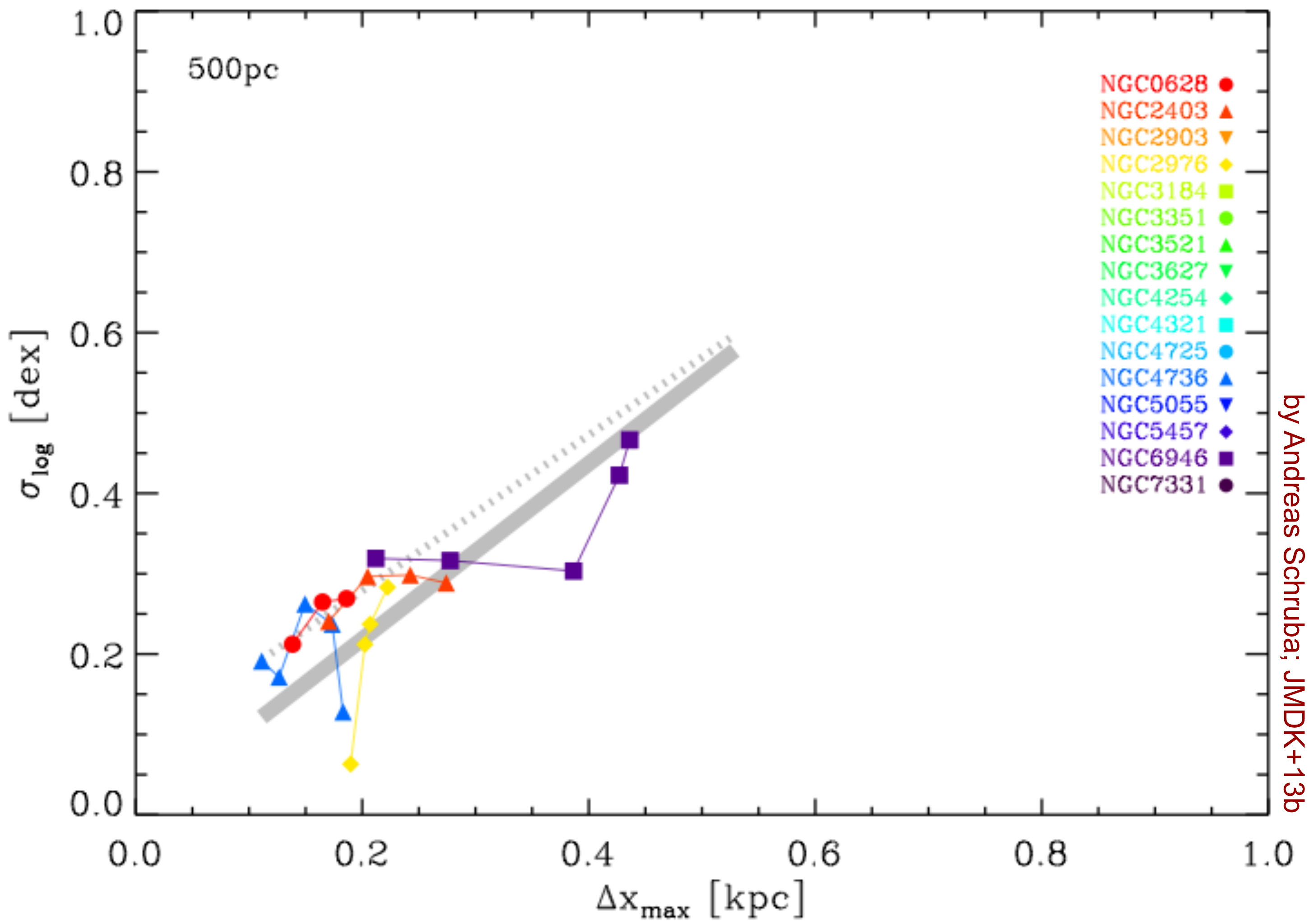

by Andreas Schruba; JMDK+13b

## Observed scatter versus aperture size: large galactocentric radii




by Andreas Schruba; JMDK+13b

## Observed scatter versus predicted minimum size-scale: small aperture




by Andreas Schruba; JMDK+13b

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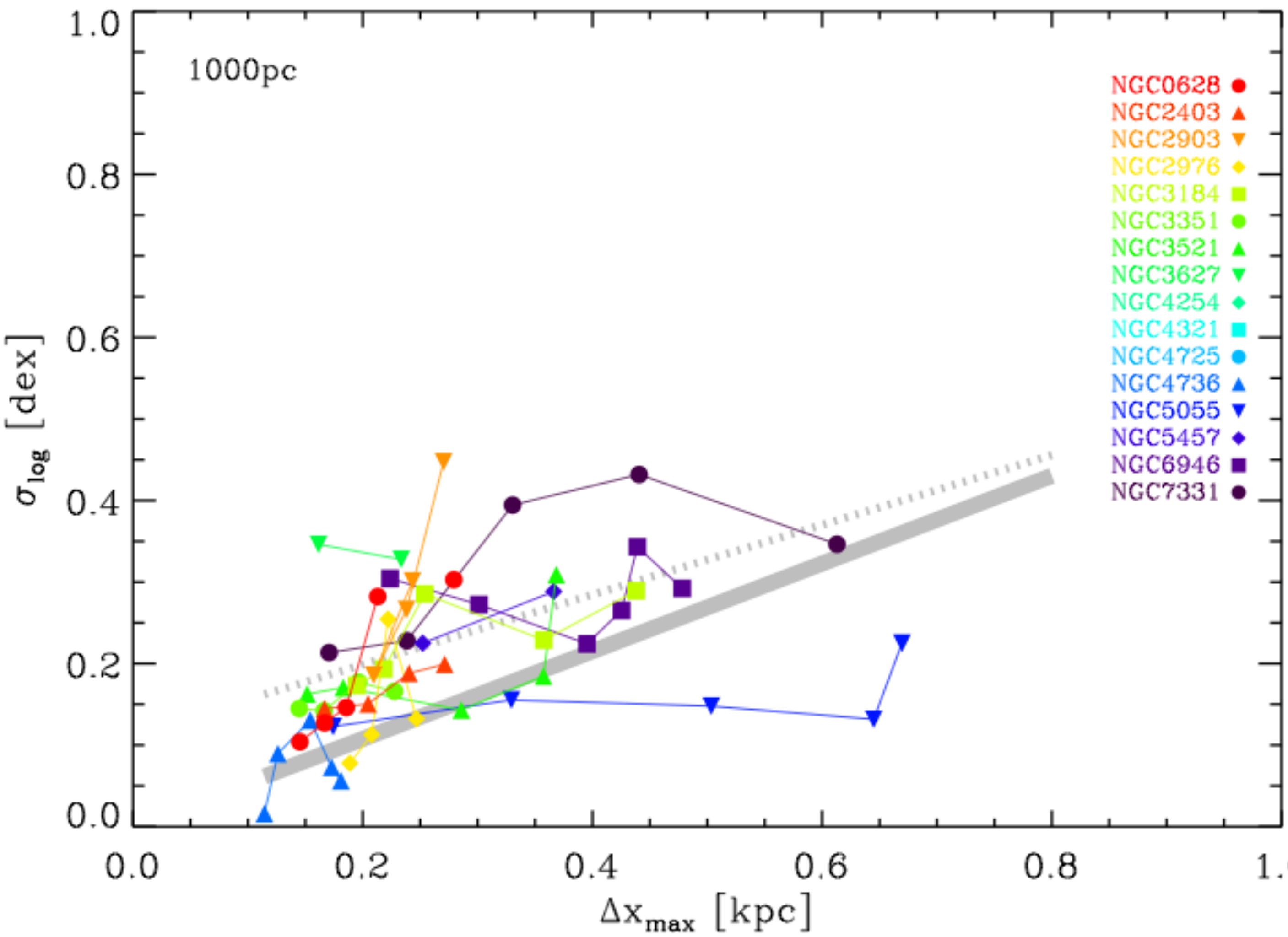
## Observed scatter versus predicted minimum size-scale: large aperture




by Andreas Schruba; JMDK+13b

## Comparison to observations

✧ First results: observations follow simple framework

➔ Future applications desirable

✧ Some confidence applying framework: CMZ has $\Delta x_{\rm tot}$ = 80 pc

➔ Discrepant SFR in the CMZ is not due to statistical effects

# The CMZ & spatially resolved star formation relations



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