4HS

THE 4MOST HEMISPHERE SURVEY

Mapping mass and motion across the southern sky

Edward (ned) Taylor entaylor@swin.edu.au

Cosmic Ecosystems in Radio and Optical, 9/12/24

Distance measures and cosmology

- I will admit that i get very confused about this, but …

  … the right thing to do is to use: $$D_L = D_c\,(1 + z_{\rm obs})$$

```
from astropy.cosmology import FlatLambdaCDM
cosmo = FlatLambdaCDM(H0=70., Om0=0.3)      # make your choice

z_cosmo = convert_helio_to_cmb_frame(z_obs) # <-- you do :(

D_CM = cosmo.comoving_distance(z_cosmo)     # okay

D_L = cosmo.luminosity_distance(z_cosmo)    # <-- no!
D_L = D_CM * (1. + z_obs)                   # <-- yes!
```

And i forgot to say the most important bit about dipoles!

- Peculiar velocities/bulk flows create a random/systematic distance error.
- The signature of a dipole is a directional boost/dampening of observed luminosities.
- This is most simply seen as a directional excess/deficit of source counts.

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As astronomers, what can we measure?

surface brightness
... and ... nope, that's it!

okay, fine, also gravitational waves.

*** a.f.o. position:**
- integrated (total?) flux
- size, shape, orientation, etc.

*** a.f.o. wavelength:**
- physical processes
- line-of-sight velocity

*** a.f.o. time:**
- variability; reverb. mapping, etc.
- microlensing!

~~measuring~~ estimating the masses of galaxies

1. mass from **luminosity**
2. mass from **dynamics**
3. mass from **gravitational lensing**
4. mass from **clustering**

~~measuring~~ estimating mass from luminosity

If you understand (ie, if you can model):

1. the emission mechanism(s), and

2. the process of radiative transfer/absorption,

then you can estimate the amount of material needed to produce the observed luminosity.

~~measuring~~ estimating HI masses from 21 cm line emission

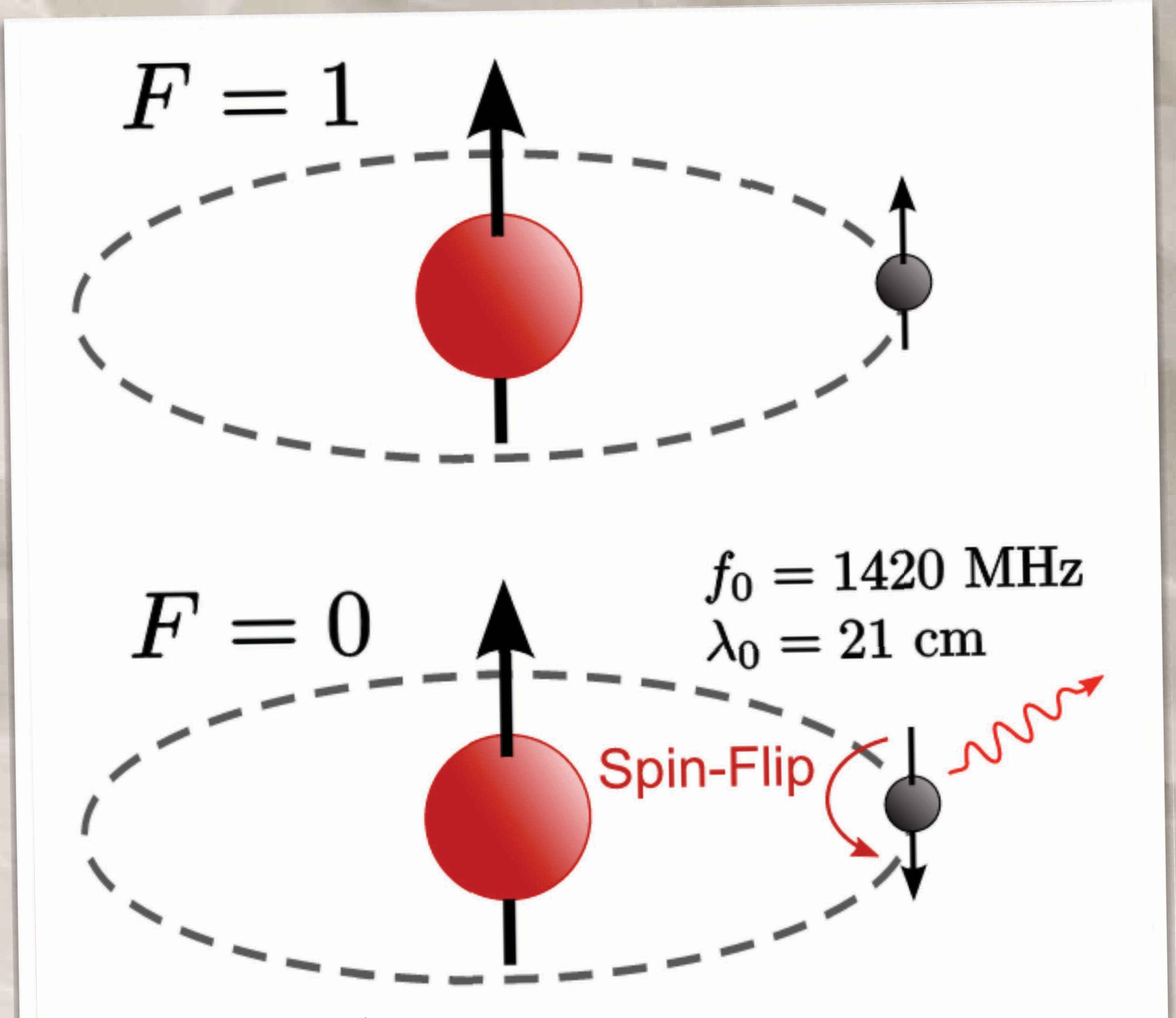


image source: wikipedia commons

hyperfine splitting
of the ground state.

collisionally excited
+ long (10^7 yr) lifetime
=> Boltzmann distrib.

cooling efficiency
=> T ~ 10^4 K.

no self-absorption;
no dust attenuation.

~~measuring~~ estimating HI masses from 21 cm line emission

observed(ish) quantities

$$\left[\frac{M_{\rm HI}}{M_\odot}\right] = 2.36 \times 10^5 \left[\frac{S_{\rm HI}}{\rm Jy}\right] \left[\frac{D}{\rm Mpc}\right]^{-2}$$

estimated property

* physics lives here *
(ie. model dependent)

~~measuring~~ estimating mass from luminosity

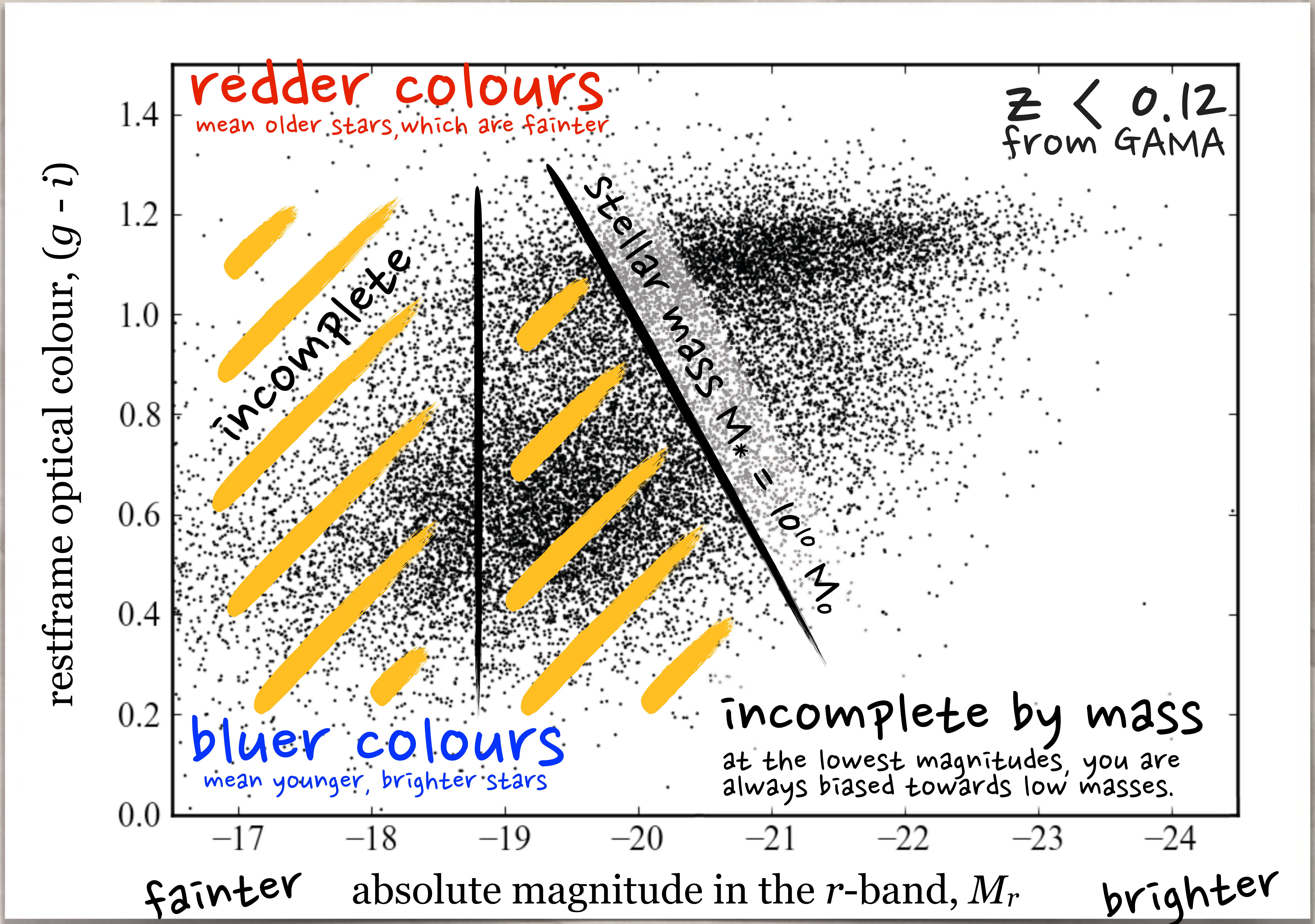
If you understand (ie, if you can model):

1. the emission/absorption mechanism(s), and
2. the process of radiative transfer,

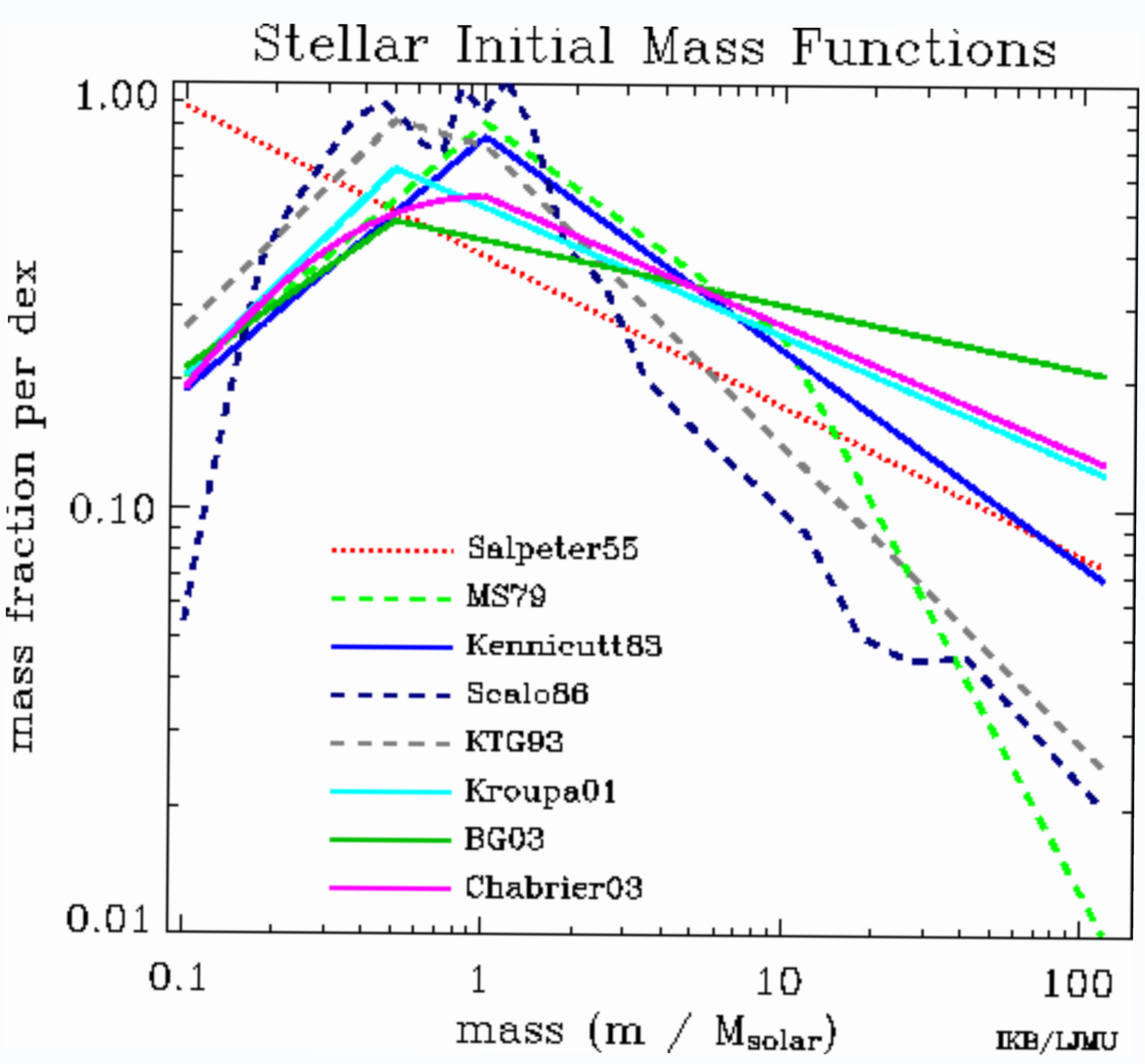
then you can estimate the amount of material needed to produce the observed luminosity.

$$M = M/L \times L$$

the colour-magnitude diagram



stars at the start



credit: Ivan Baldry

- The stellar Initial Mass Function (IMF) is the answer to the following question:

  "If I form some large number of stars, what is the mass distribution among those stars?"

SSPs: simple/single-age stellar populations

theoretical stellar evolution tracks for individual stars
(Bruzual & Charlot 2003; Maraston 2005; PEGASE):

stellar_spectrum[wl, initial_mass, age, metallicity] : $f(\lambda, M, t, Z)$

+ observational constraints on the initial mass function
(Salpeter 1955; Kroupa 2001; Chabrier 2003):

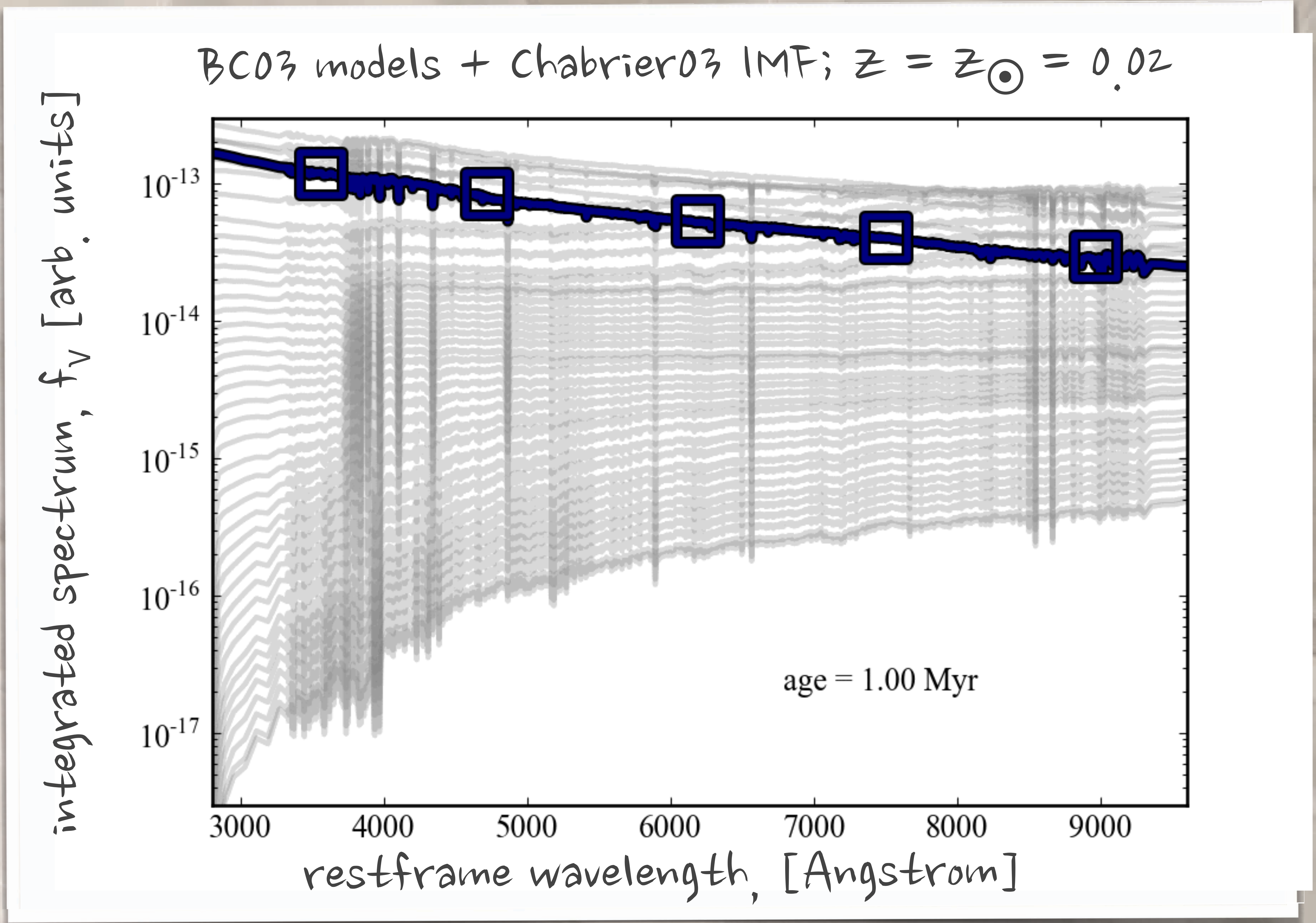
relative_number[initial_mass] : $p(M)\, dM$

= the evolving spectrum of a single-aged stellar population:

SSP_spectrum[wl, age, metallicity] :

$$f_{SSP}(\lambda, t, Z) = \int dM\, p(M)\, f(\lambda, M, t, Z)$$

SSP spectral evolution



CSPs: composite stellar populations

the evolving spectrum of a single–aged stellar population:

SSP_spectrum[wavelength, age, metallicity] :

$$f_{SSP}(\lambda, t, Z) = \int dM\, p(M)\, f(\lambda, M, t, Z)$$

+ some (for now) totally arbitrary star formation history:

SFH[cosmic_time {, metallicity?}] : $\psi_*(t, Z)\, dt$

= the evolving spectrum for a general stellar population

cSP_spectrum[wavelength, cosmic_time]

$$f_{cSP}(\lambda, t \mid \psi_*(t, Z)) = \int dt' \int dZ\, \psi_*(t'; Z) \int dM\, p(M)\, f_{star}(\lambda, M, t - t', Z)$$

recipe for a galaxy

ingredients: given (or assuming) all of the following –

Stellar spectral evolution models : $f_{star}(\lambda, M, t, Z)$

Stellar initial mass function : $p(M)\, dM$

Star formation history : $\psi_*(t'; Z)$

cSP_spectrum[wavelength, SFH, age, metal] :

$$f(\lambda, t) = \int_0^t dt' \int dZ\, \psi_*(t'; Z) \int dM\, p(M)\, f_{star}(\lambda, M, t-t', Z)$$

Dust extinction/attenuation/obscuration $E(A_V, \lambda)$

soup: the evolving spectrum for a general stellar pop'n –

model_spectrum[wavelength, age, dust, SFH, metal] :

$$f_{model}(\lambda, t, A_V \mid \psi_*(t, Z))$$

$$= 10^{-0.4\, A_V}\, E(\lambda) \int_0^t dt' \int dZ\, \psi_*(t'; Z) \int dM\, p(M)\, f_{star}(\lambda, M, t-t', Z)$$

~~measuring~~ estimating stellar masses from luminosity

The whole point of doing all this is to get:

galaxy spectra/SEDs as a function of
stellar population properties.

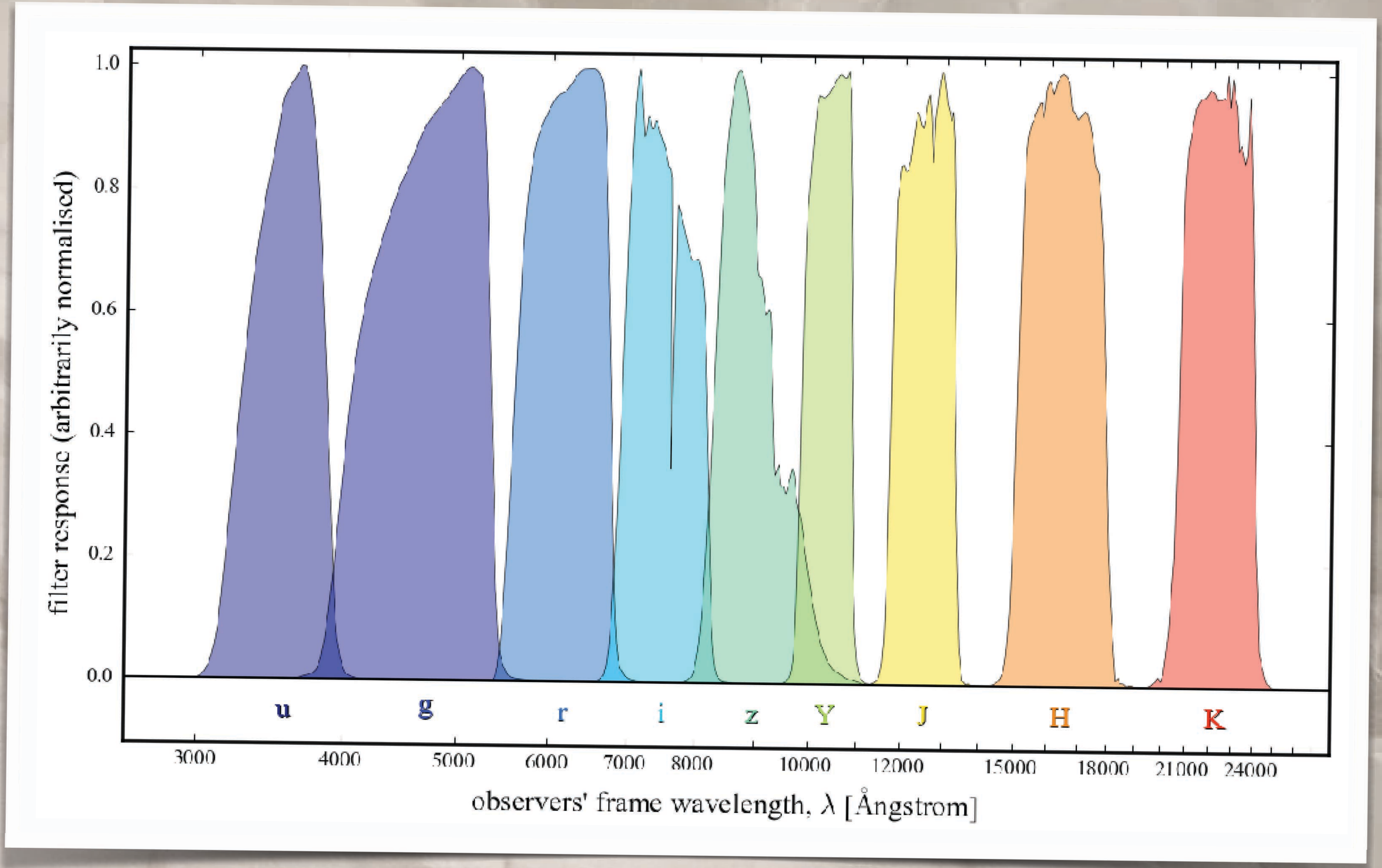
ie. $f(\lambda)$, given/assuming t_{form}, τ, A_V, Z

This gives you the tools to estimate:

stellar population properties of a galaxy,
as a function of the observed spectrum/SED.

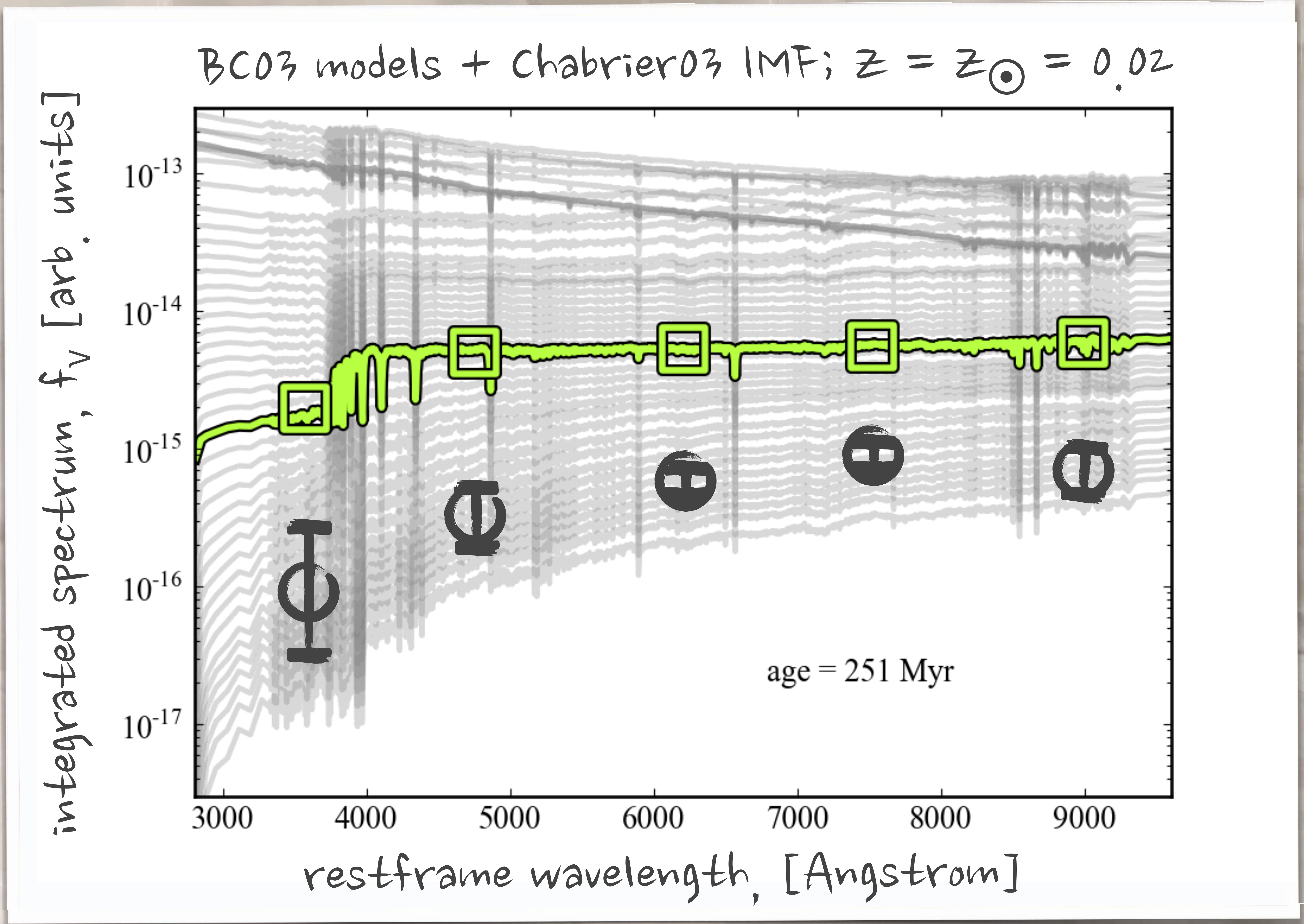
ie. t_{form}, τ, A_V, Z, M^*/L, given $f(\lambda)$

broadband photometry

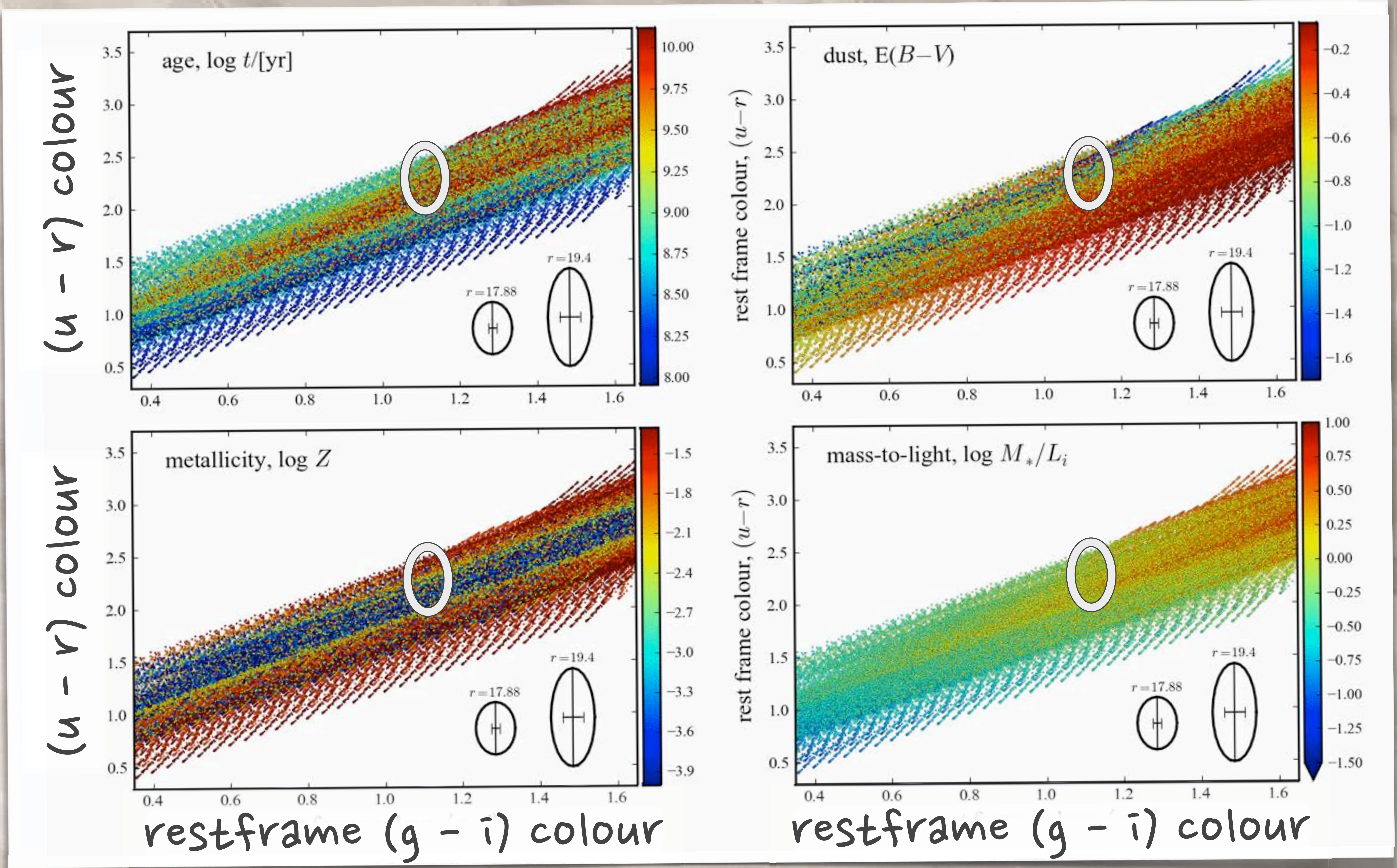


broadband_flux : $F_x \sim \int \lambda \, d\lambda \, t_x(\lambda) \, f_\lambda(t; z)$

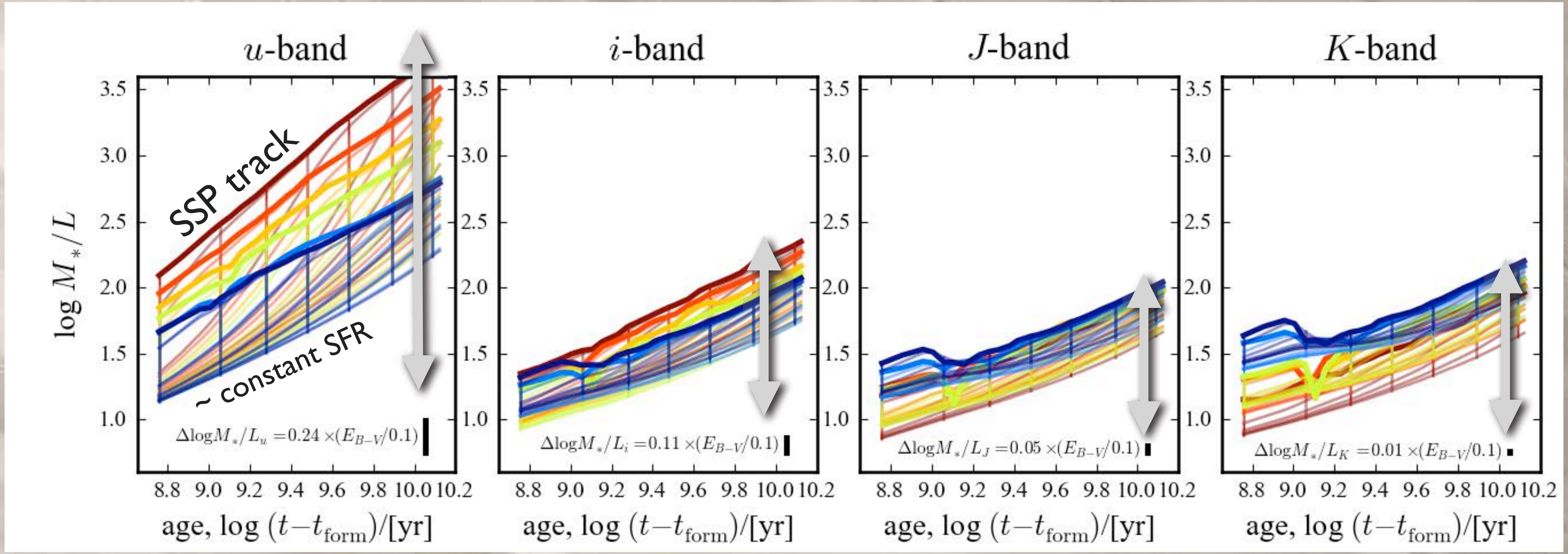
SSP spectral evolution



estimating SP properties from broadband colours



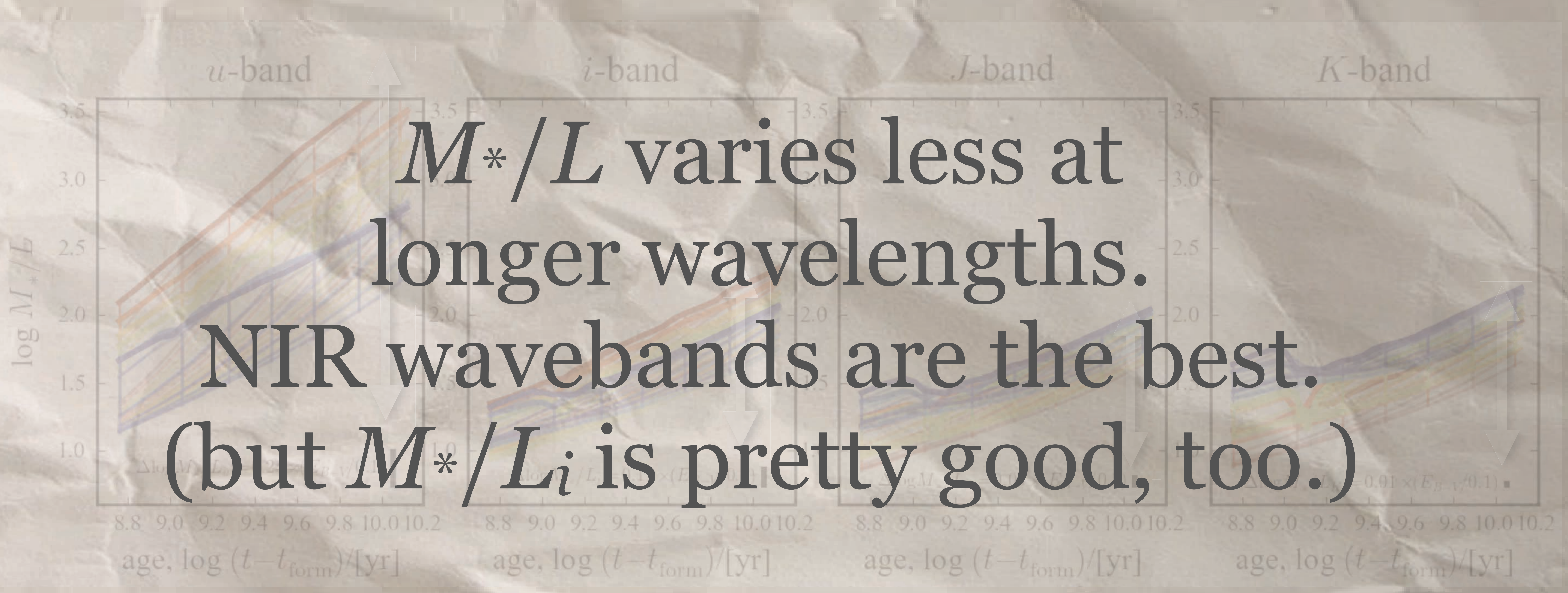
variations in M_*/L in different wavebands



implied mass accuracy:

× 22 × 5.5 × 4.0 × 4.5

variations in M_*/L in different wavebands

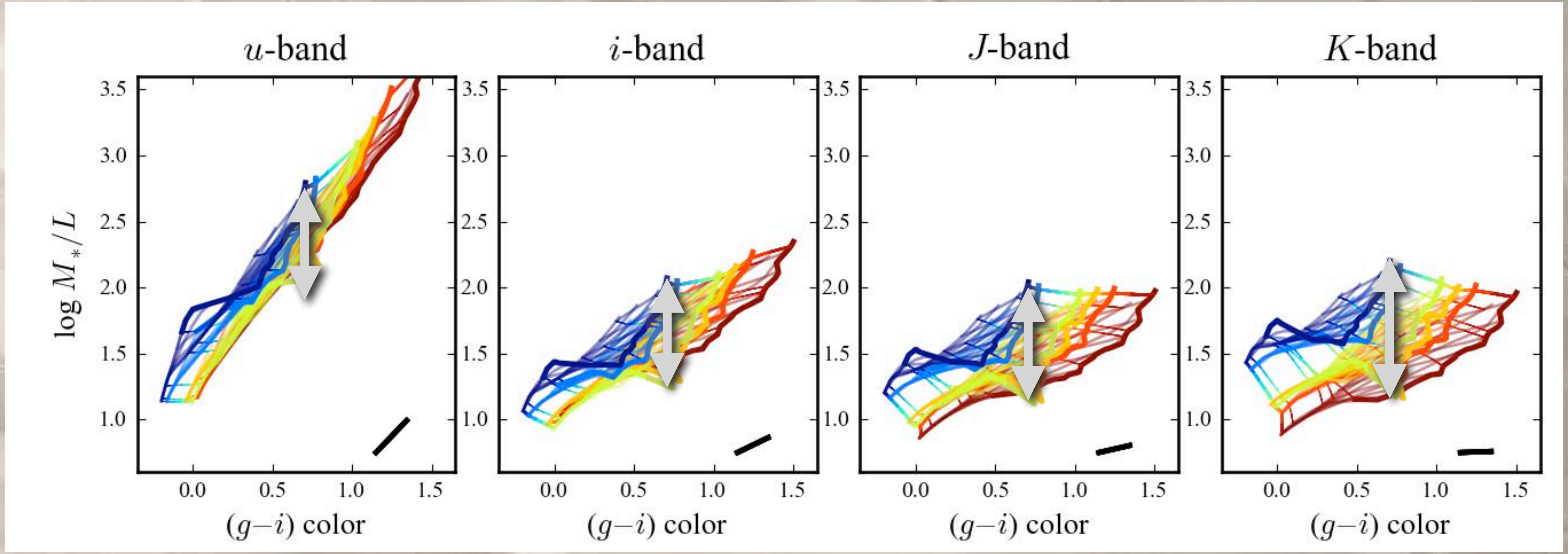


M_*/L varies less at longer wavelengths.
NIR wavebands are the best.
(but M_*/L_i is pretty good, too.)

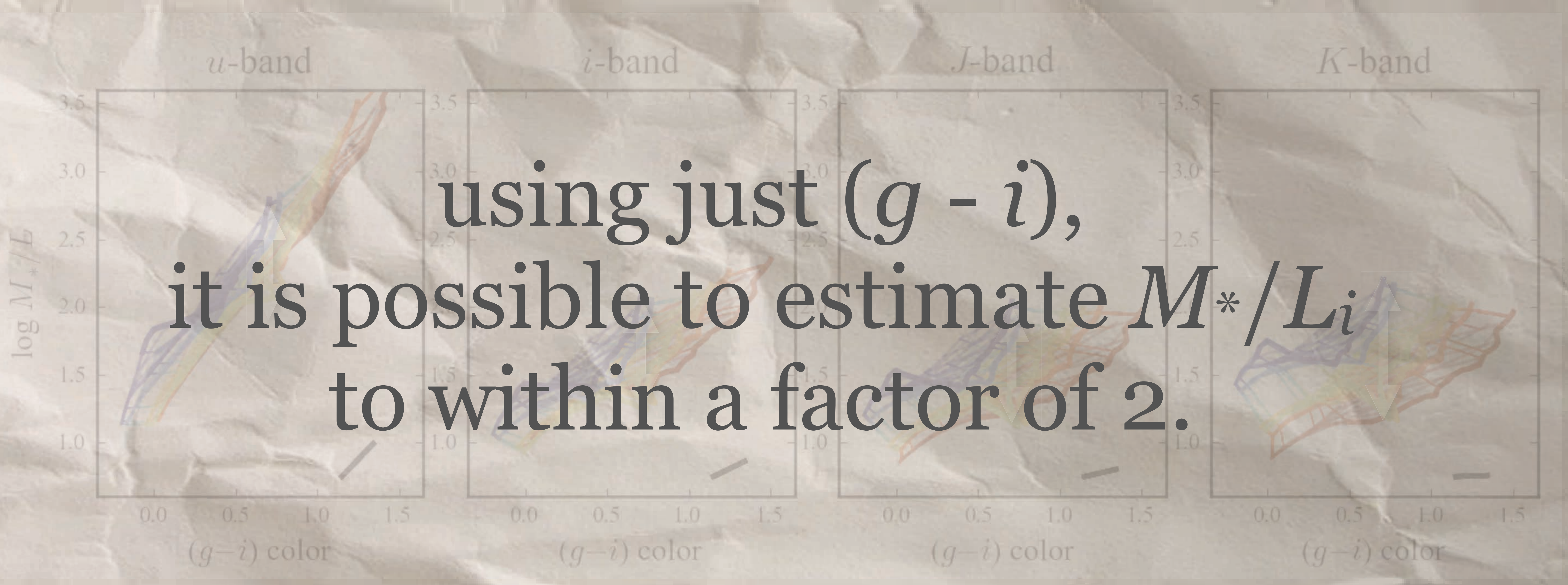
implied mass accuracy:

× 22 × 5.5 × 4.0 × 4.5

variations in M_*/L in different wavebands



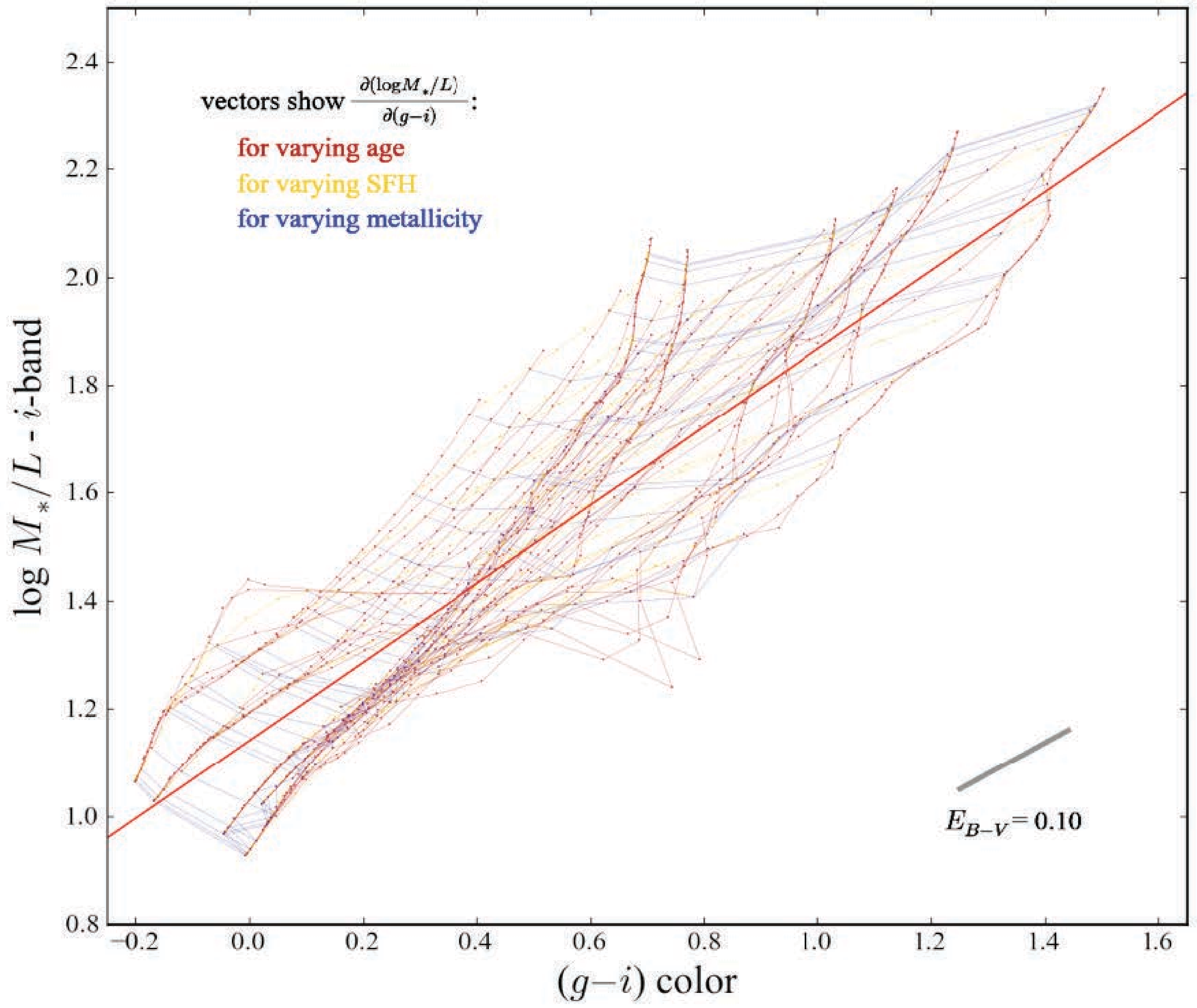
variations in M_*/L in different wavebands

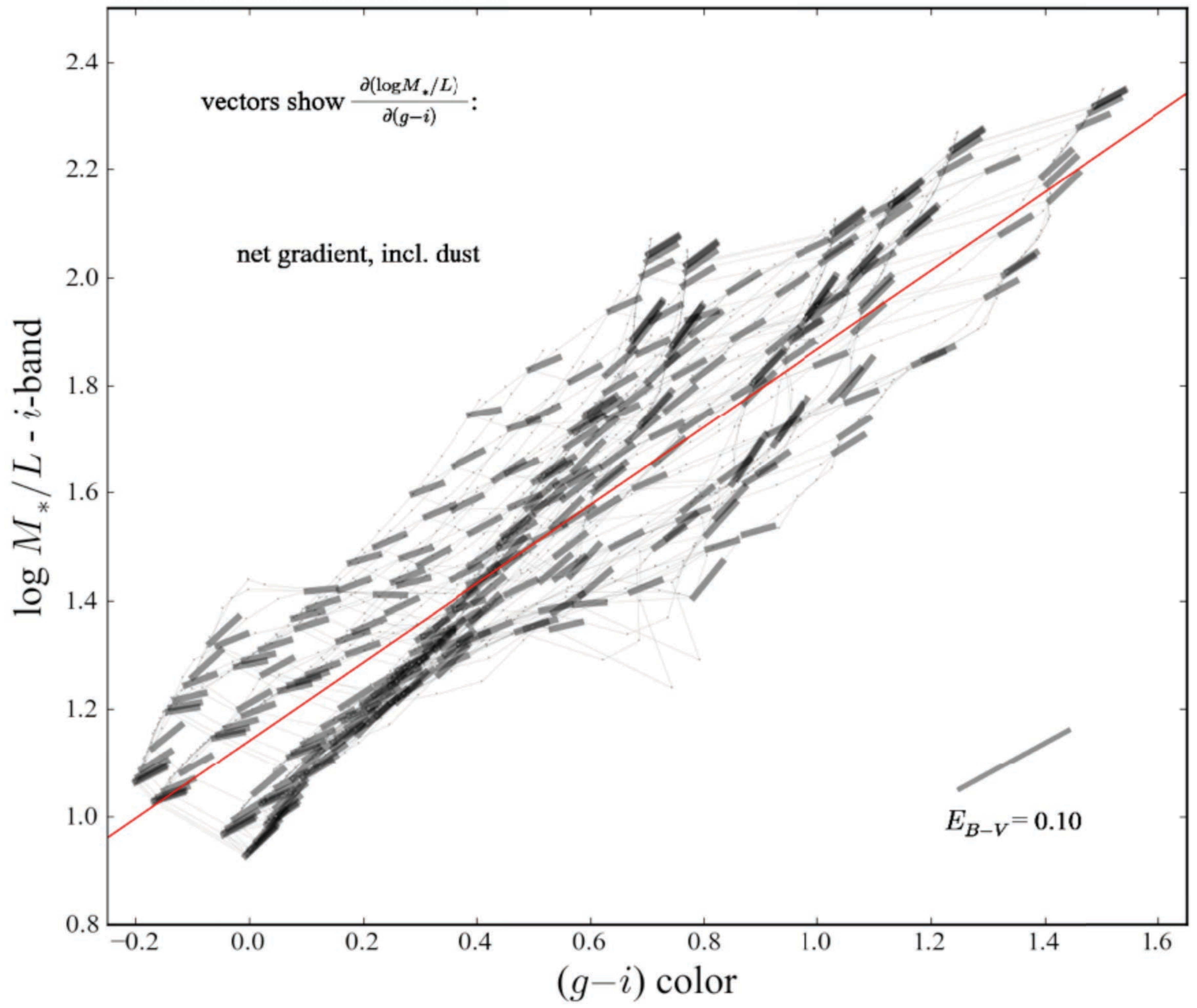


using just (g - i),
it is possible to estimate M_*/L_i
to within a factor of 2.

implied mass accuracy:

× 3 × 2 × 3 × 4

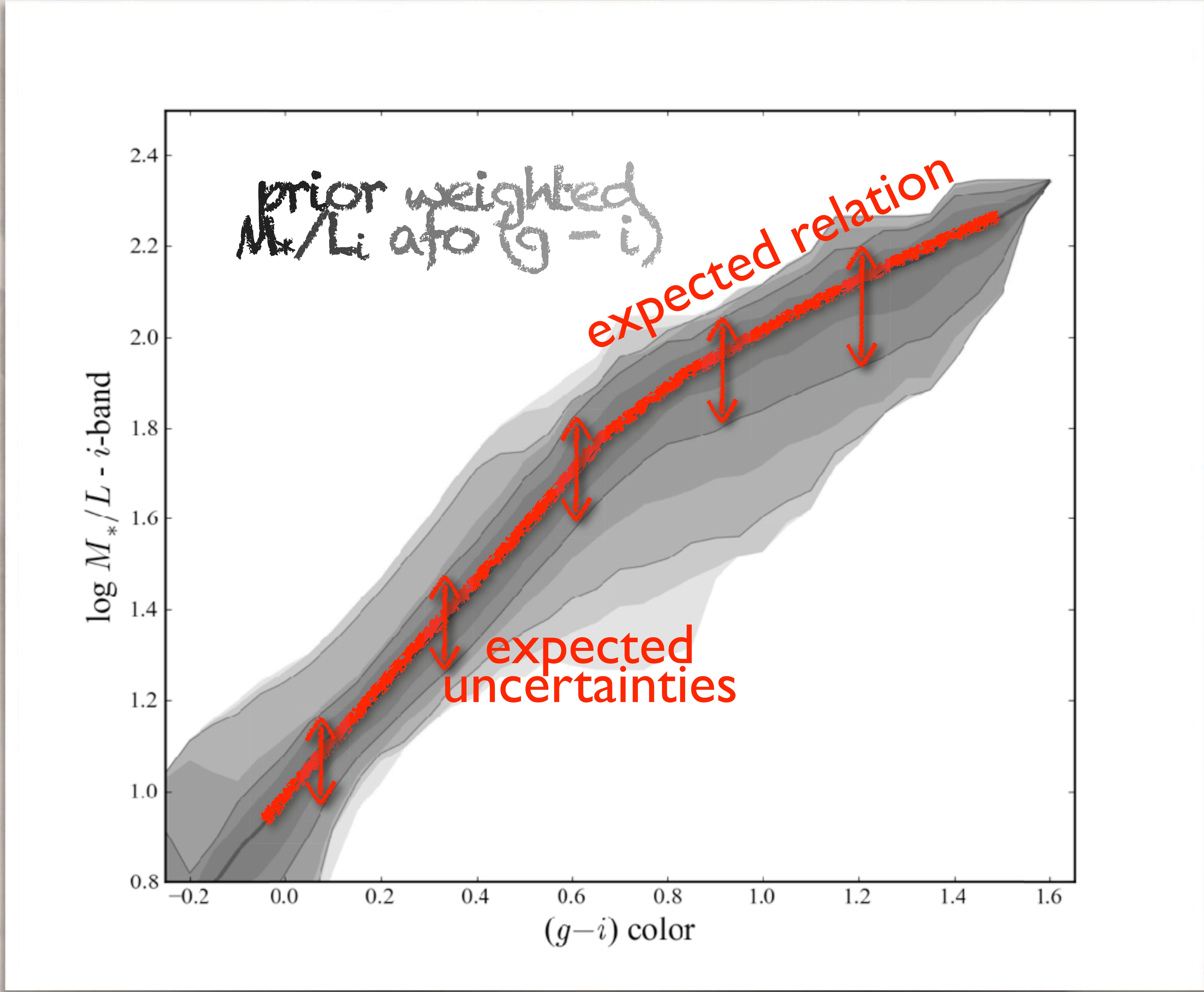

vectors show ∂(log M*/L)/∂(g−i):
for varying age
for varying SFH
for varying metallicity
E_B−V = 0.10
log M*/L - i-band
(g−i) color
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
−0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6



vectors show $\frac{\partial \langle \log M_*/L \rangle}{\partial (g-i)}$:
net gradient, incl. dust
$E_{B-V} = 0.10$
$\log M_*/L$ - i-band
$(g-i)$ color

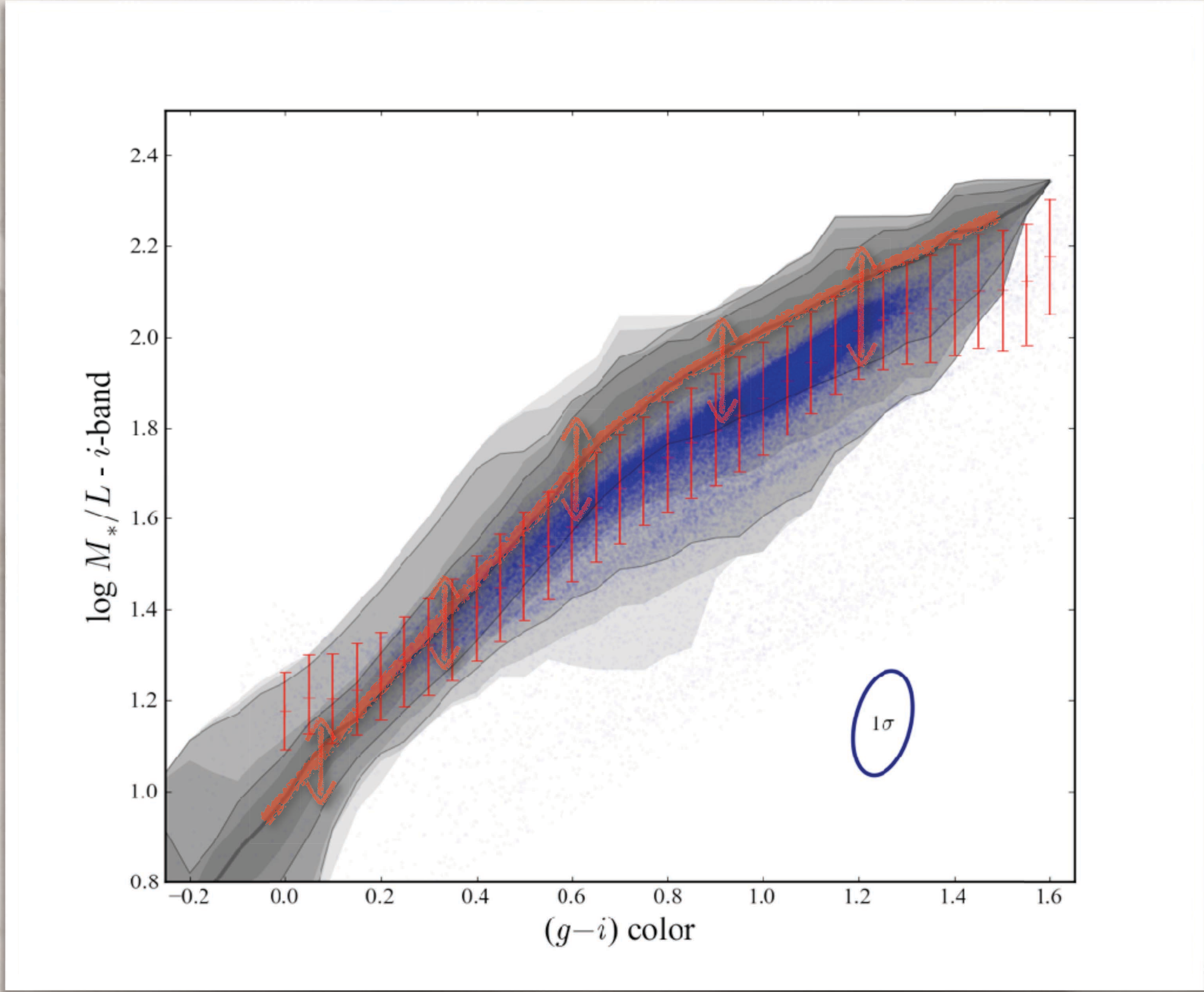
making life easier:

an empirical relation between (g - i) and M_*/L_i



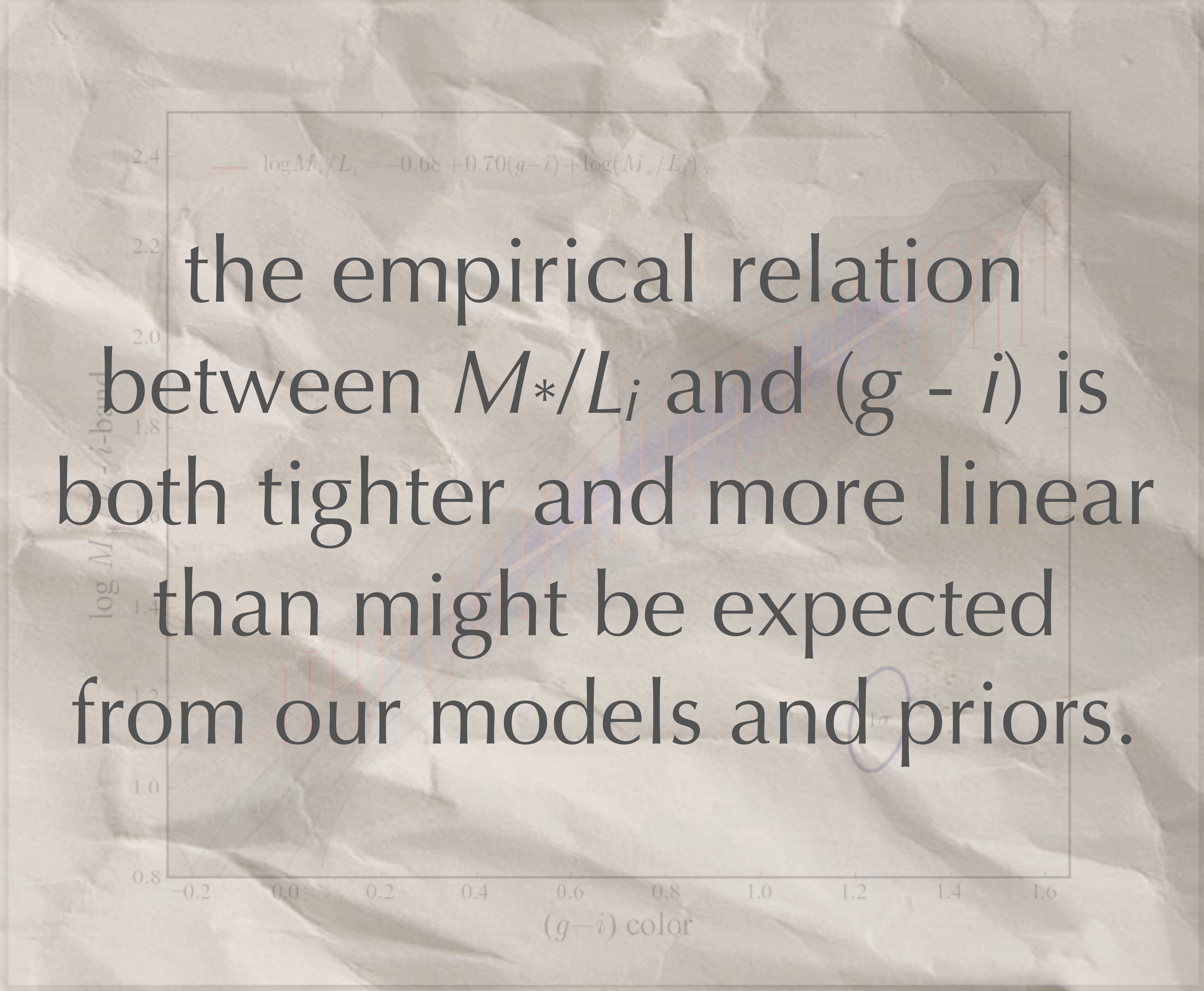
making life easier:

an empirical relation between (g - i) and M_*/L_i



making life easier:

an empirical relation between (*g* - *i*) and M_*/L_i



the empirical relation between M_*/L_i and (*g* - *i*) is both tighter and more linear than might be expected from our models and priors.

folklore: NIR data provides a better estimate of stellar mass

- M_*/L_{NIR} varies less with time
- M_*/L_{NIR} is less sensitive to the precise SFH
- L_{NIR} is substantially less affected by dust

folklore: NIR data provides a better estimate of stellar mass

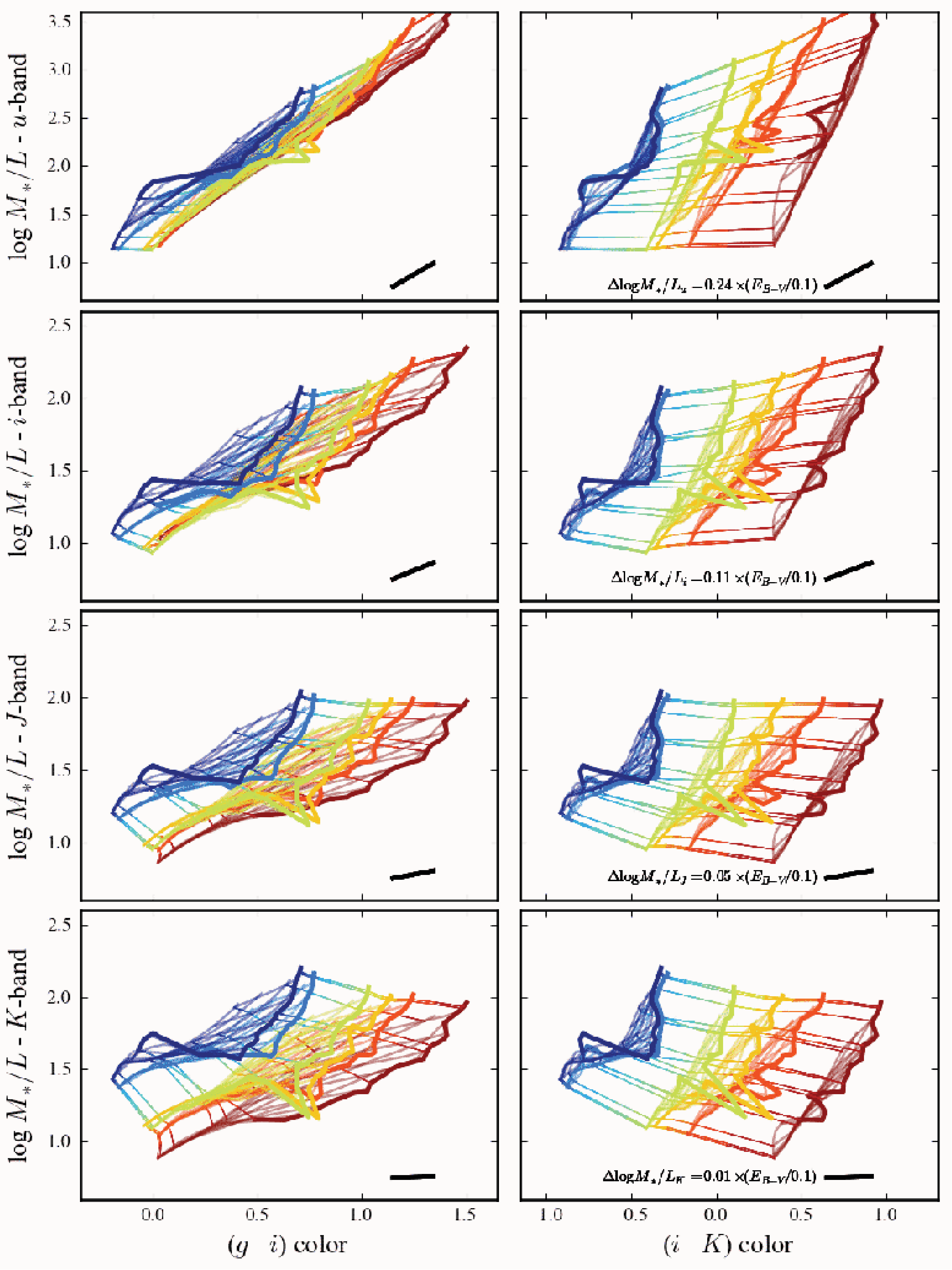
- M_*/L_{NIR} varies less with time
- M_*/L_{NIR} is less sensitive to the precise SFH
- L_{NIR} is substantially less affected by dust

NIR data breaks the
age-dust-metallicity degeneracy
and so provides a better
estimate of stellar mass

(g - i) tells you about M_*/L_i

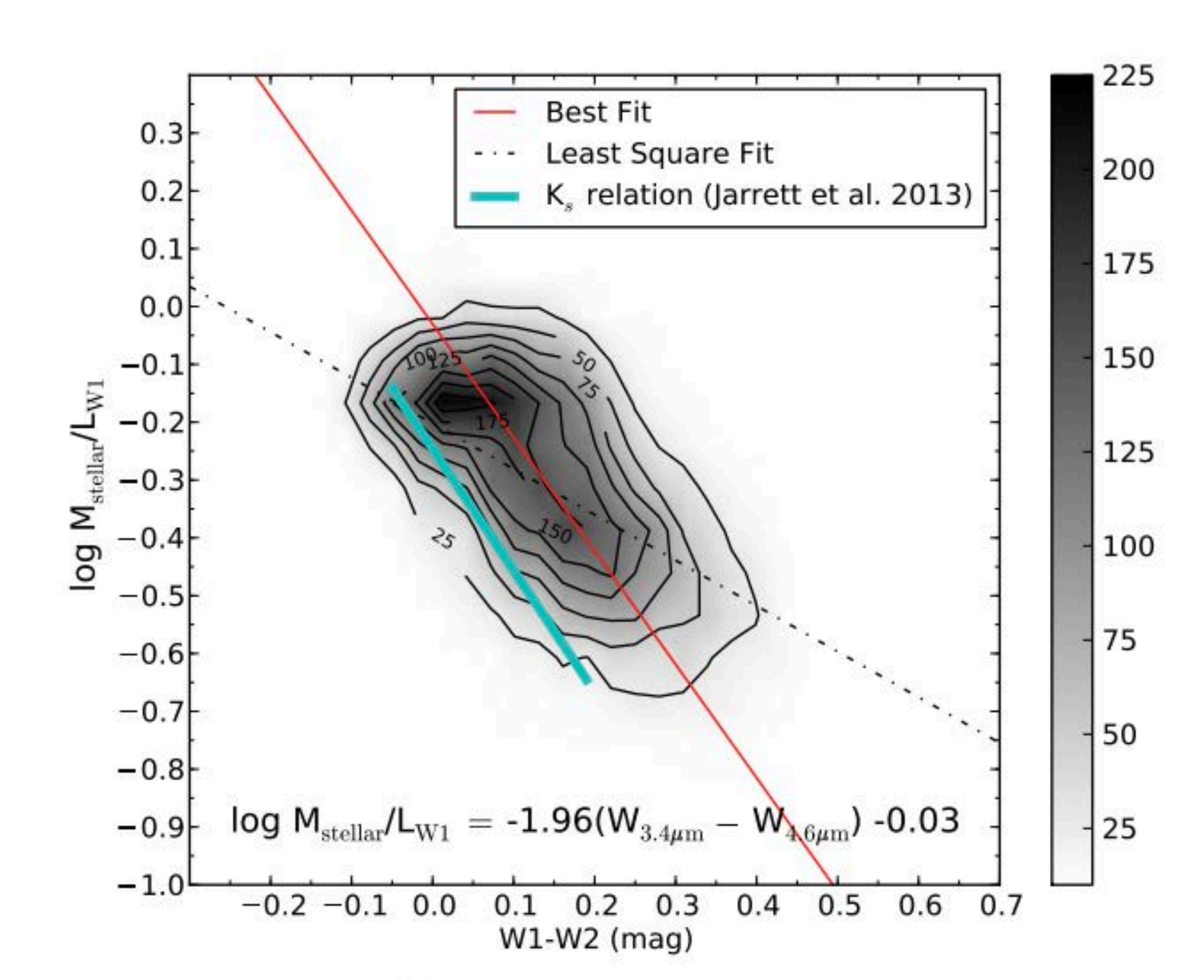
(i - K) tells you about metallicity

the NIR contains no information about M_*/L

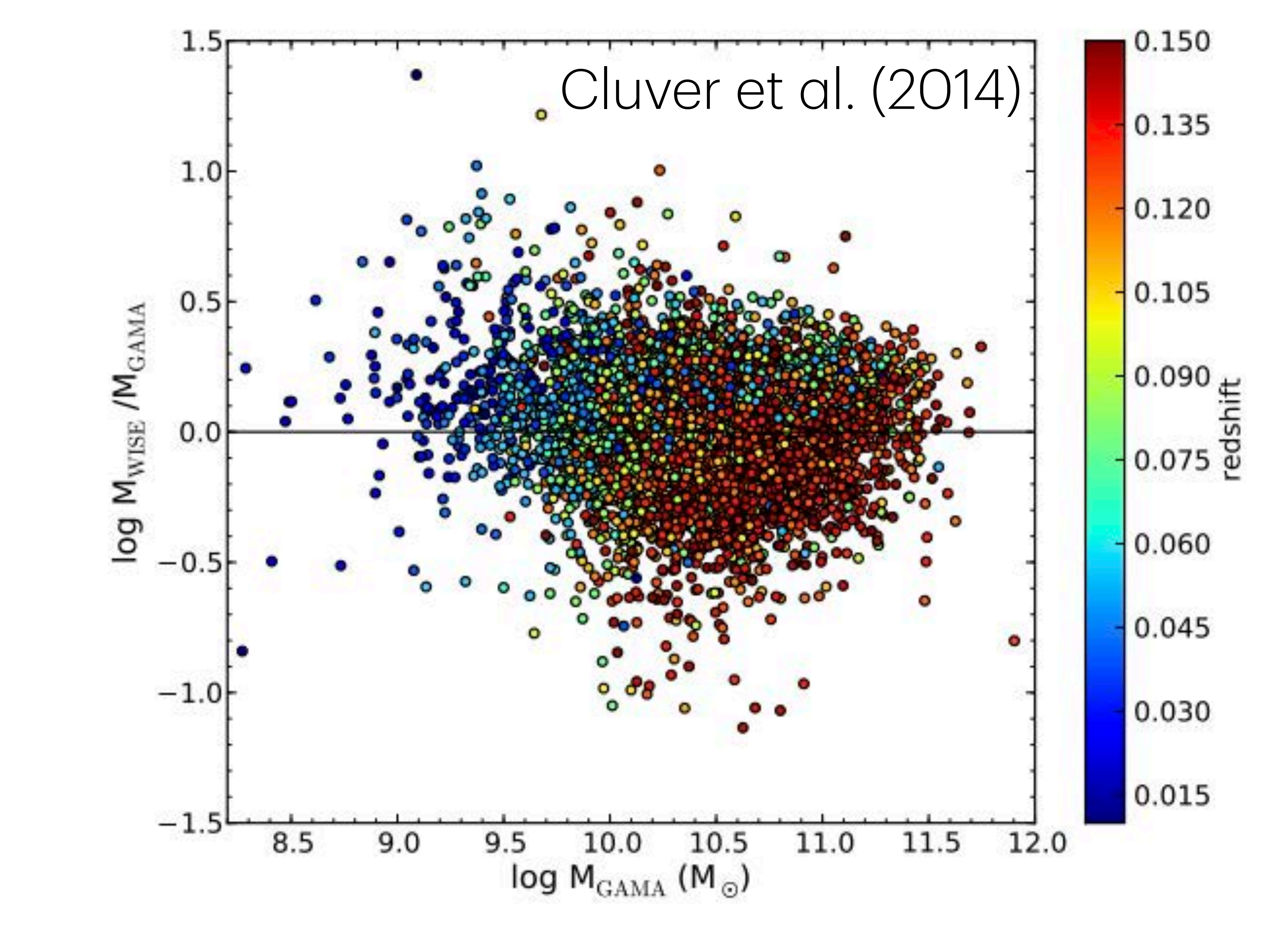


making life easier:

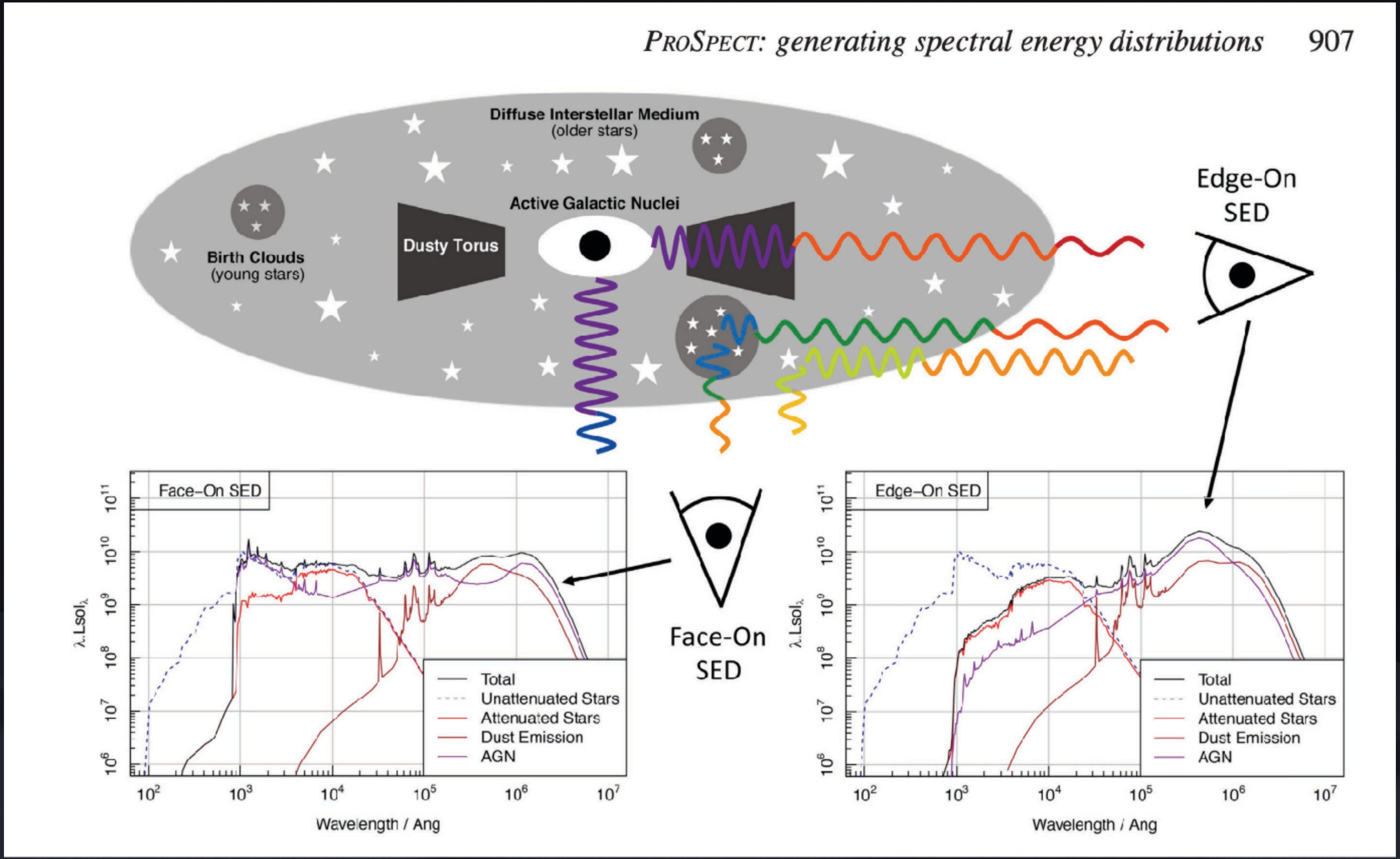
an empirical relation between infrared colours and M_*/L



(b) All Sources $z < 0.12$

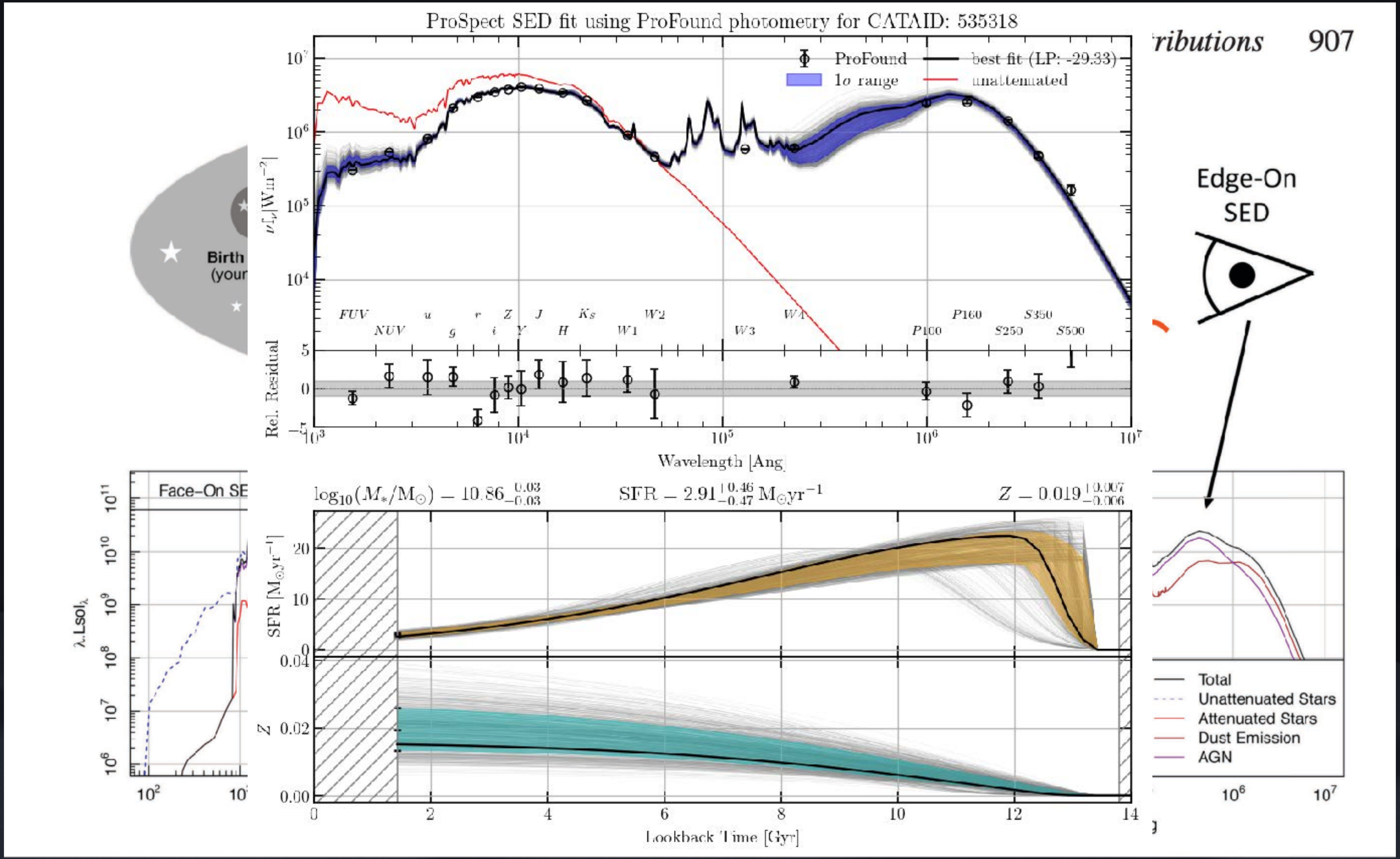


Much more sophisticated models are possible



ProSpect (Robotham+2020)

Much more sophisticated models are possible



ProSpect (Robotham+2020)

More sophisticated models are not always much better!

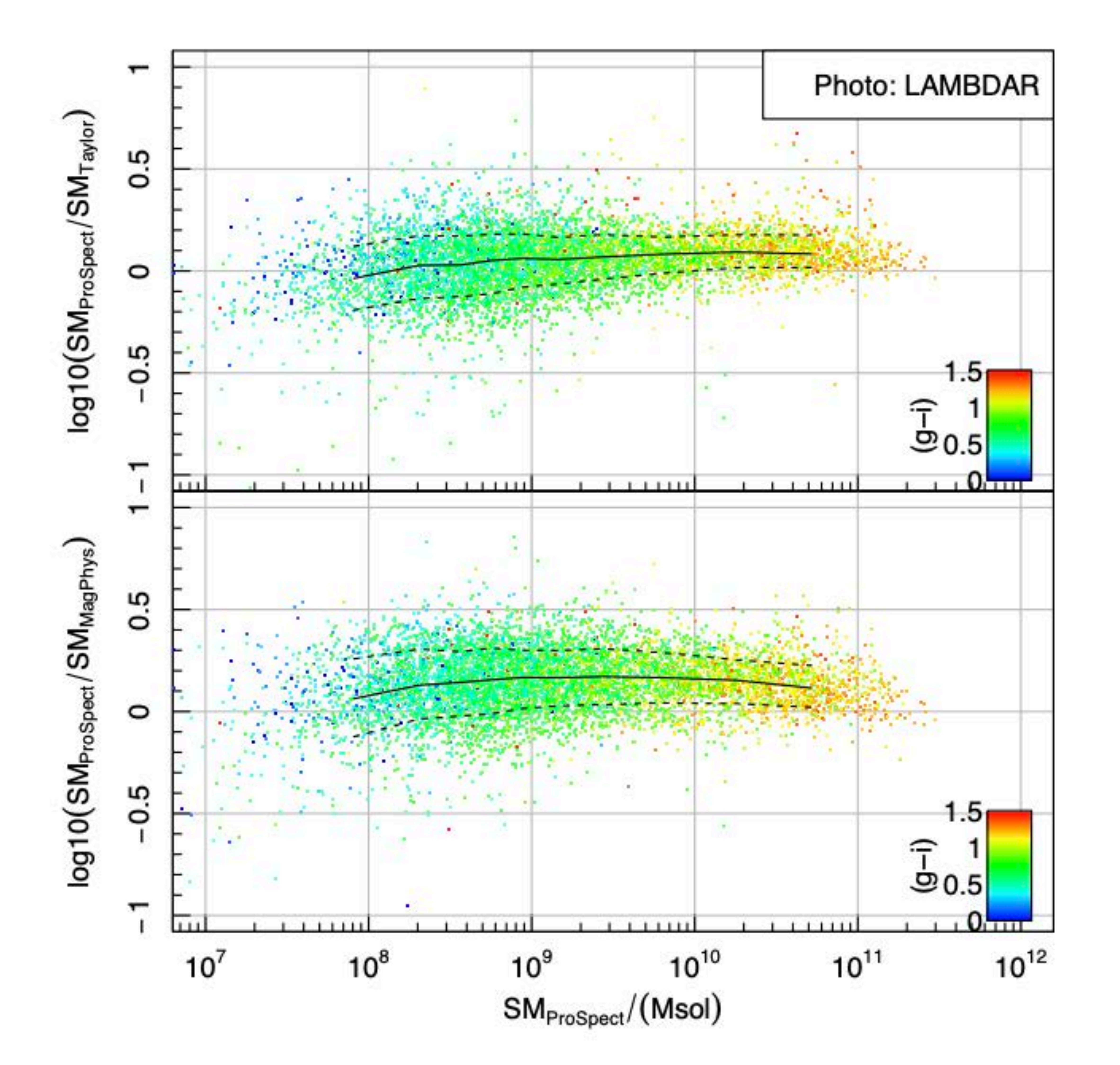


Figure 33. In this figure, we compare the impact of running different code on the same photometric data product (LAMBDAR). There are systematic differences for both comparison sets (MAGPHYS and Taylor; da Cunha et al. 2008; Taylor et al. 2011, respectively). The median offset to MAGPHYS is 0.15 dex with 0.14 dex scatter, and the median offset to Taylor is 0.06 dex with 0.13 dex scatter. This means the different codes are broadly consistent within their expected scatter, but PROSPECT returns systematically more massive galaxies when using the exact same input data. There are no strong gradients in $g - i$ colour, beyond more massive galaxies being typically redder.

ProSpect (Robotham+2020)

~~measuring~~ estimating mass from luminosity

If you understand (ie, if you can model):

1. the emission/absorption mechanism(s), and
2. the process of radiative transfer,

$$M = M/L \times L$$

then you can estimate the amount of material needed to produce the observed luminosity.

~~measuring~~ estimating mass from dynamics

If you understand (ie, if you can model)
the dynamics of the system,

then you can estimate the amount of material
needed to produce the observed velocities.

what can we measure?
long slit (2D) spectroscopy

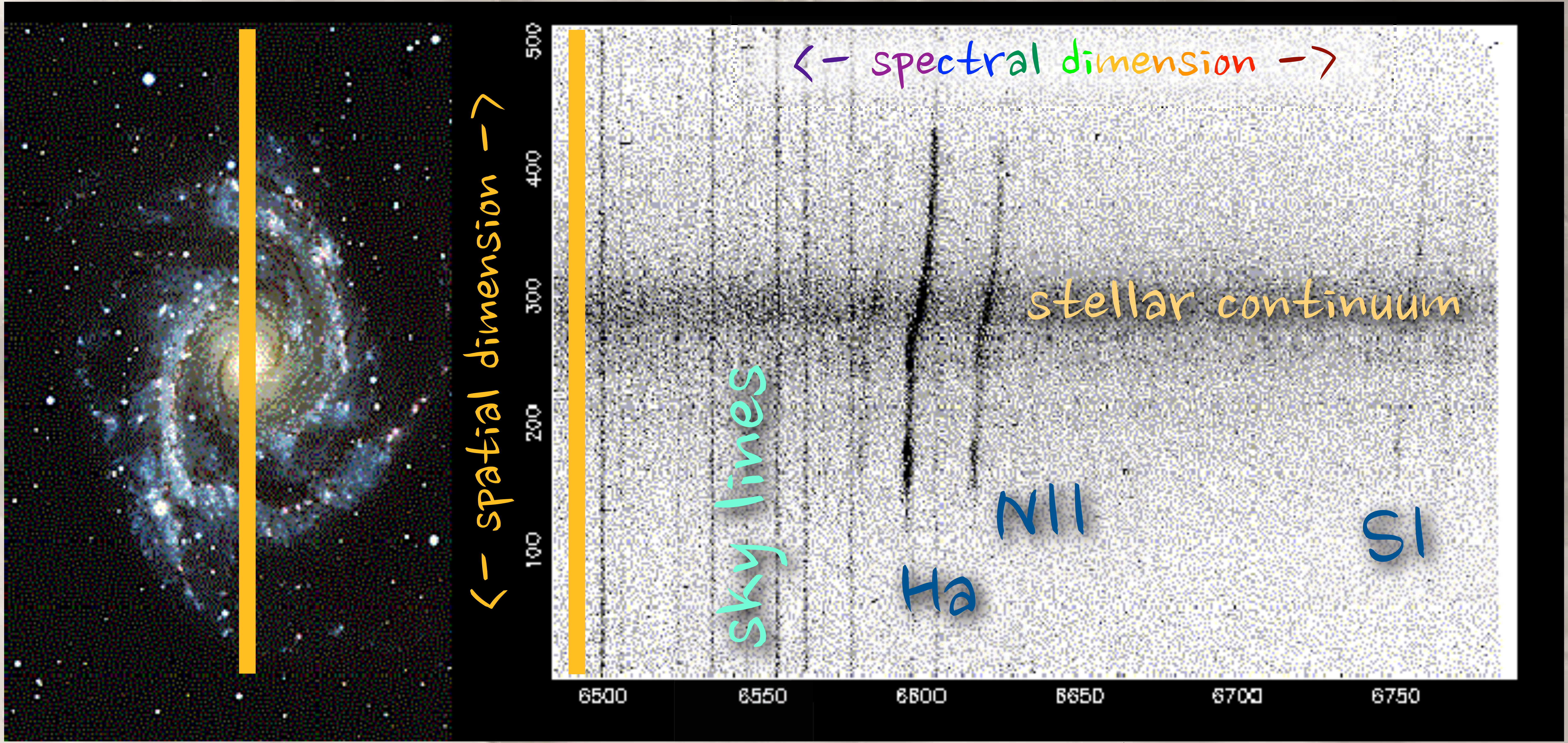
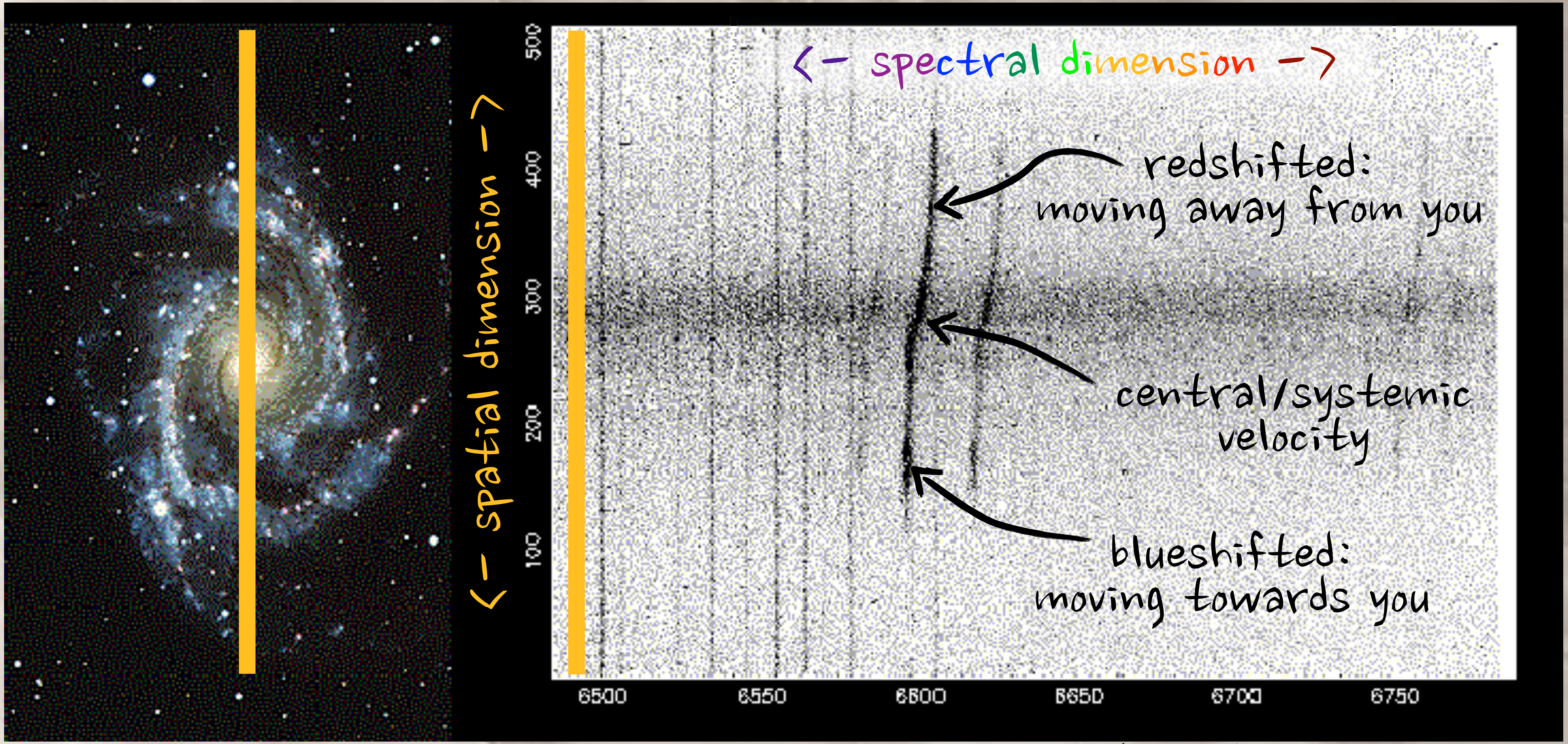


image source: Chris Mihos (burro.cwru.edu)

what can we measure?
line of sight velocities



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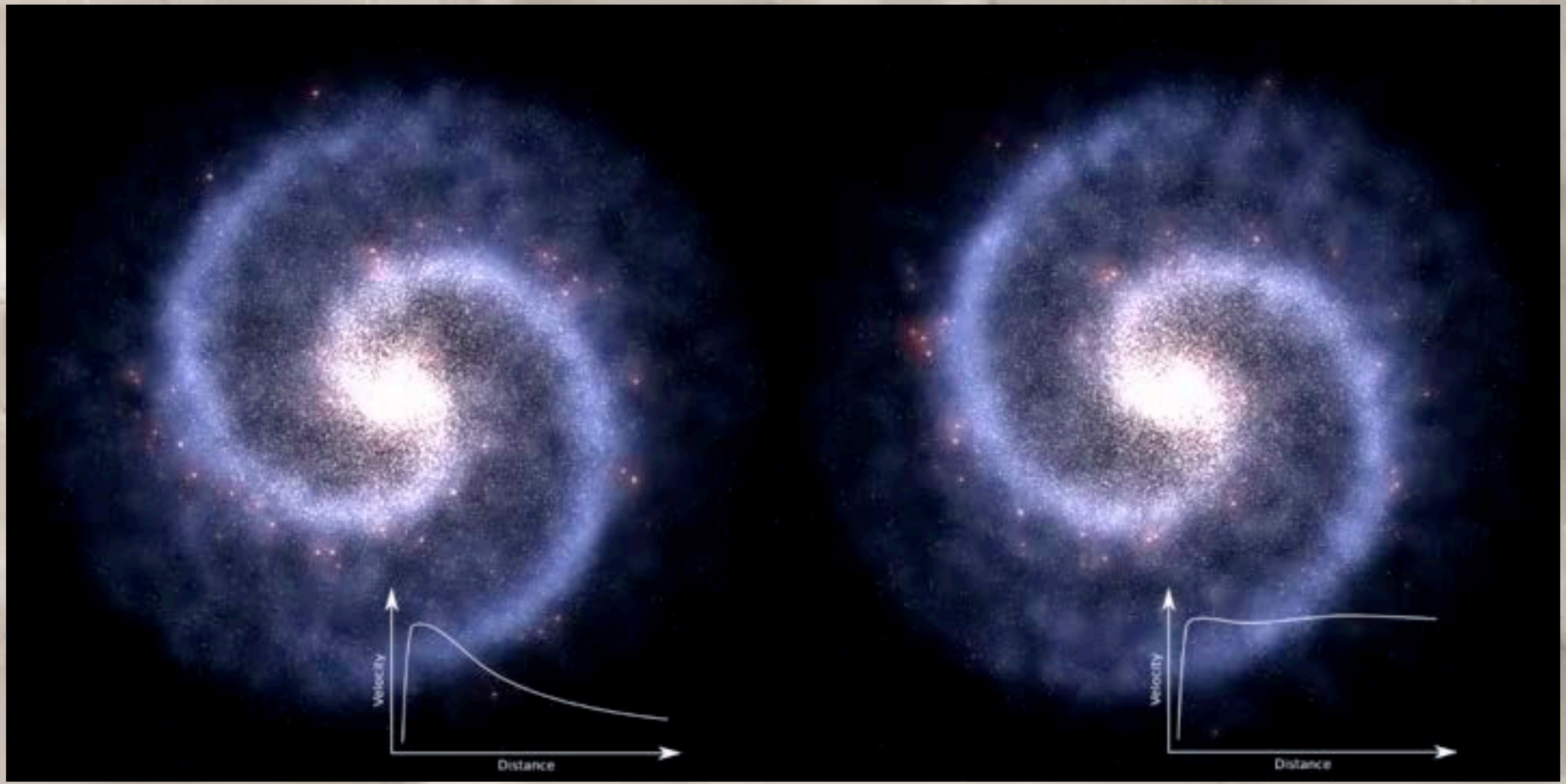
spiral galaxy rotation curves as evidence for dark matter

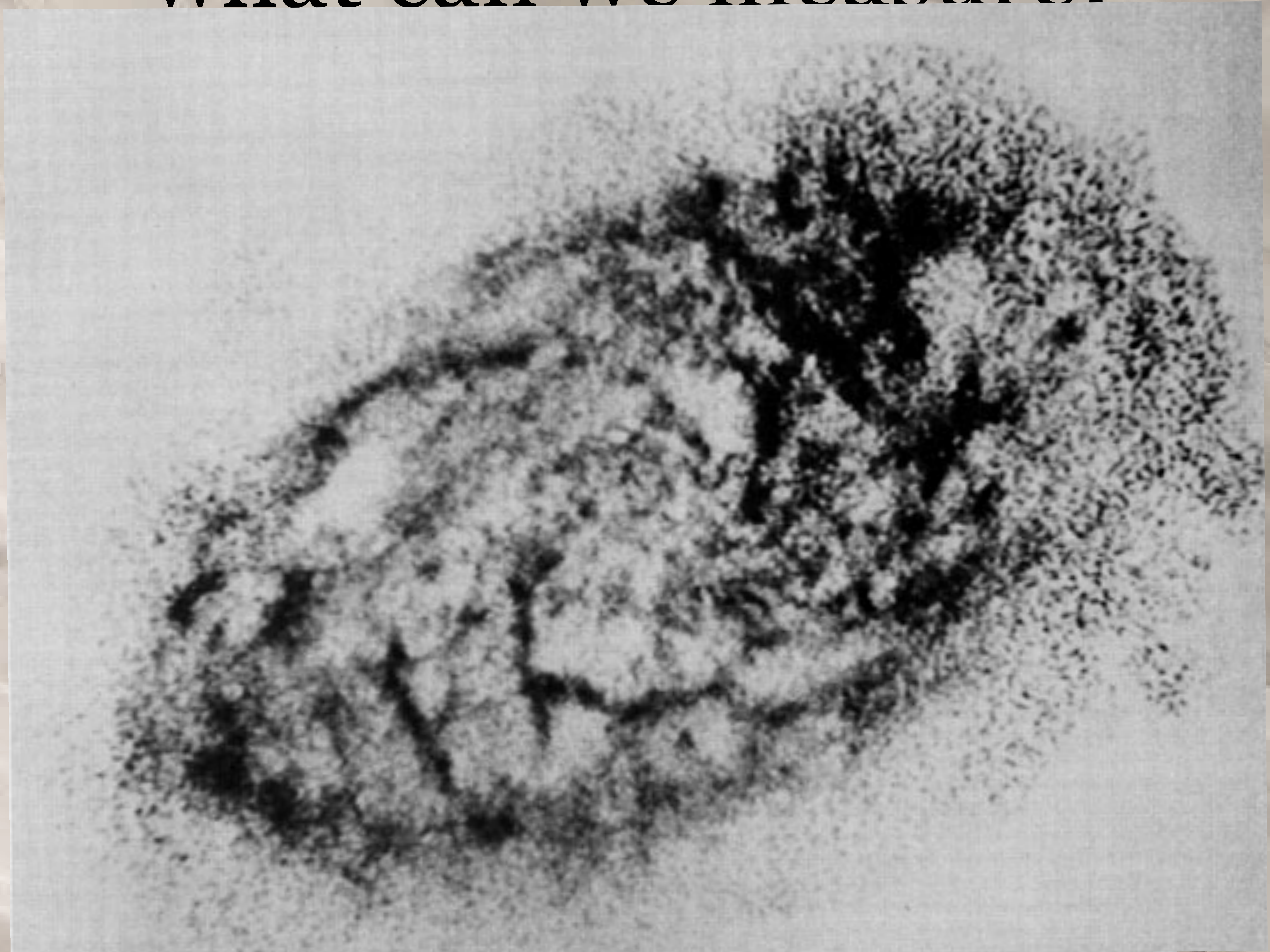


to the observer

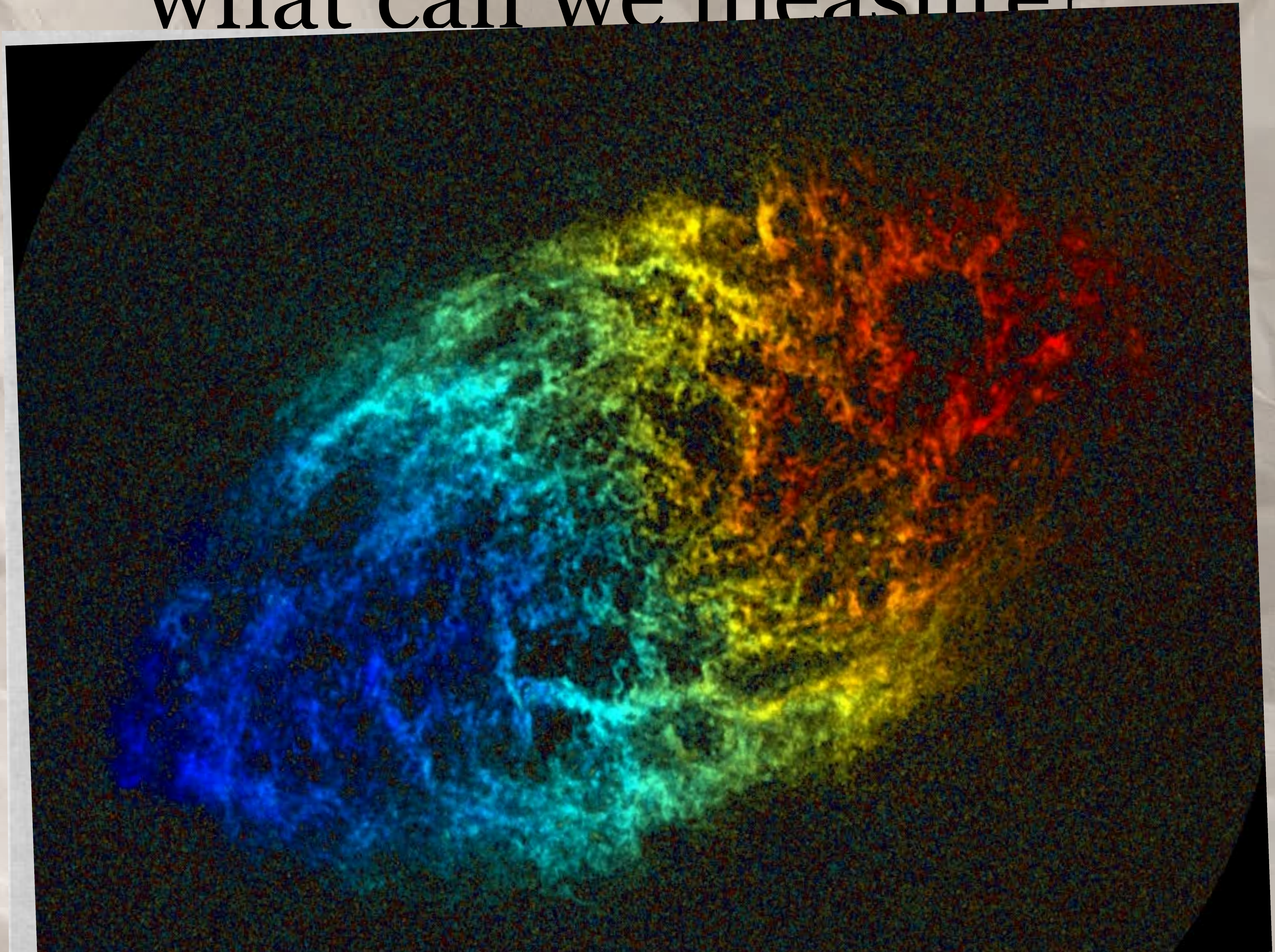
to the observer

what can we measure?
line of sight (HI) velocities

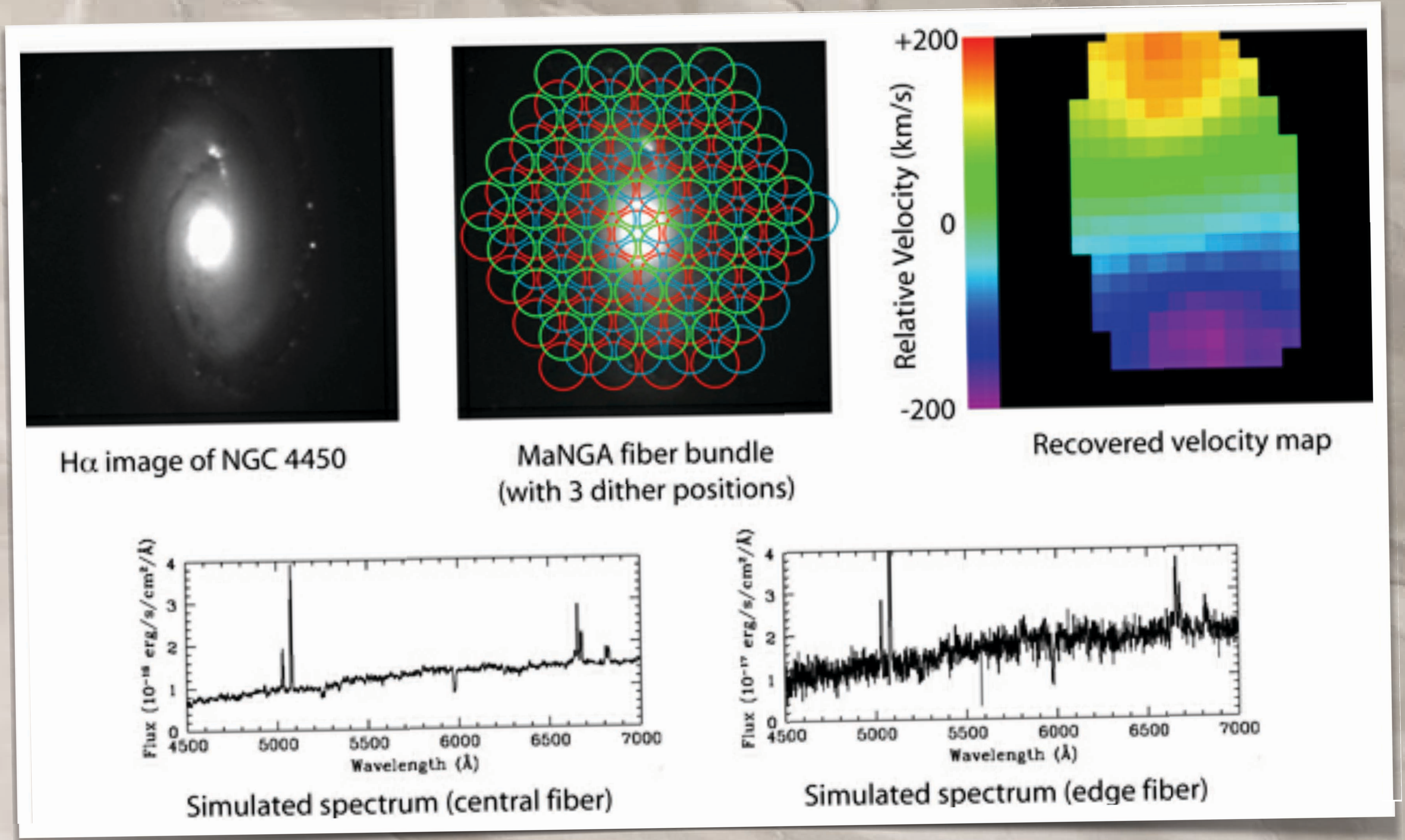
what can we measure?



what can we measure?



what can we measure?
integral field (3D) spectroscopy



Hα image of NGC 4450

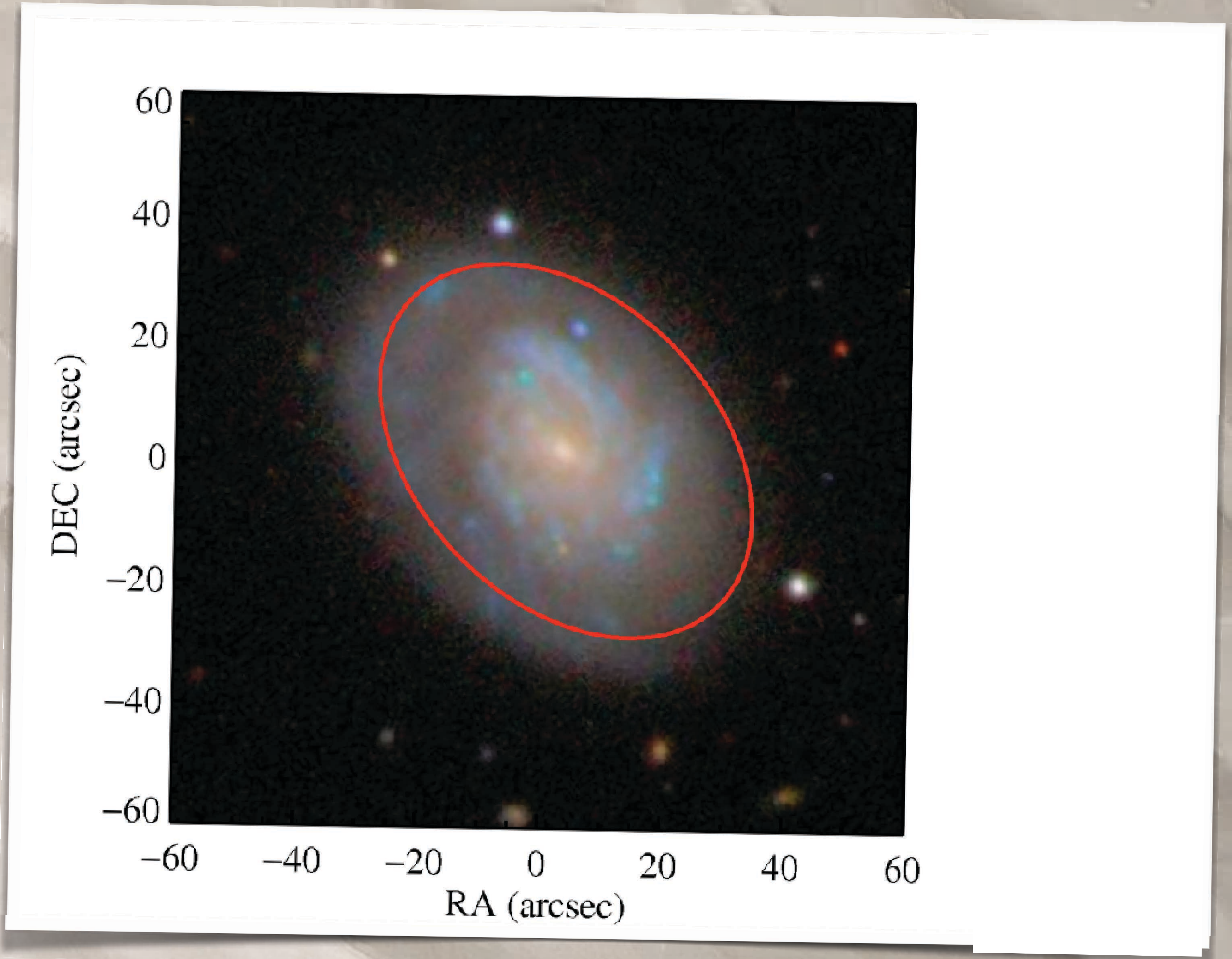
MaNGA fiber bundle (with 3 dither positions)

Recovered velocity map

Simulated spectrum (central fiber)

Simulated spectrum (edge fiber)

what can we measure?
integral field (3D) spectroscopy



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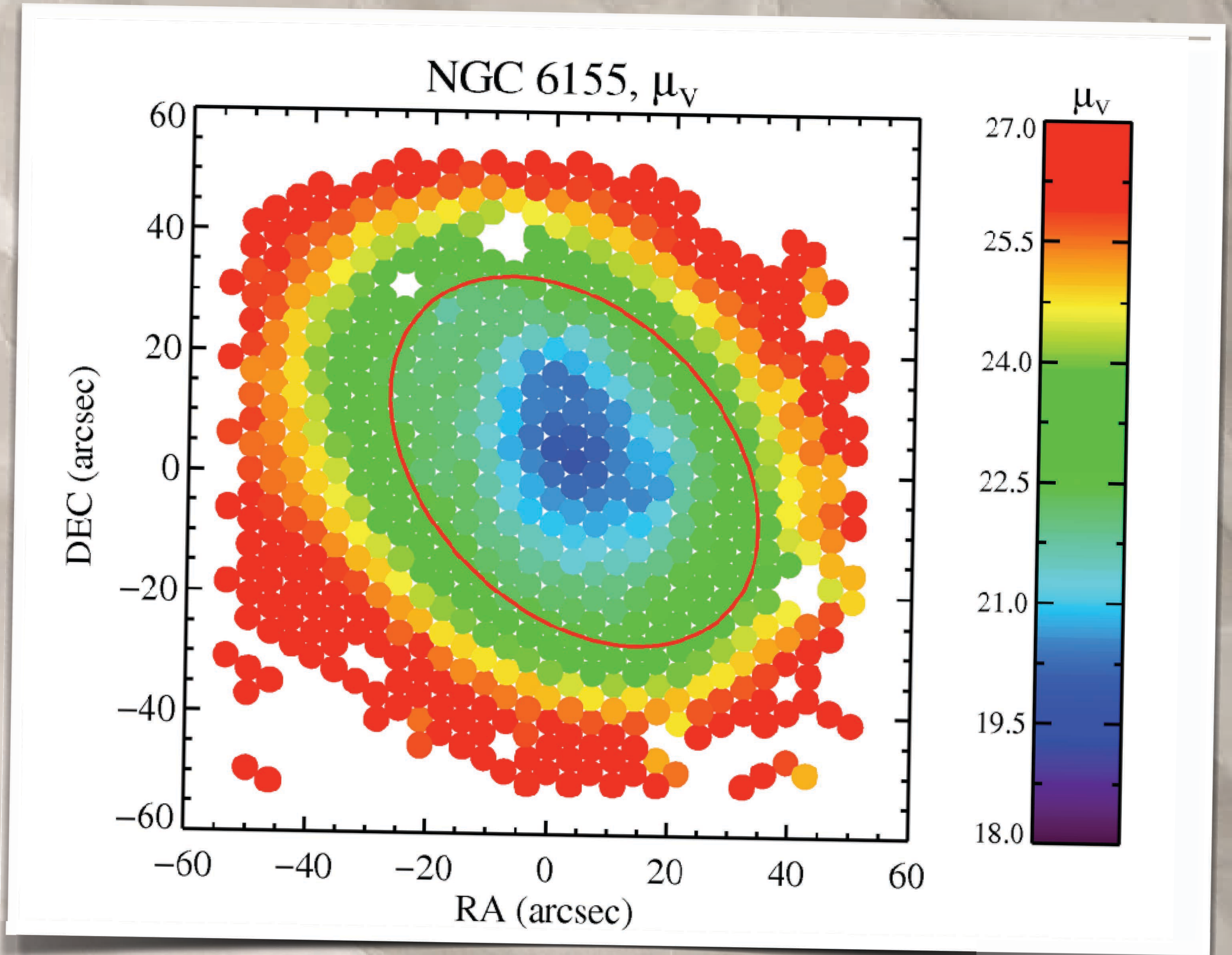
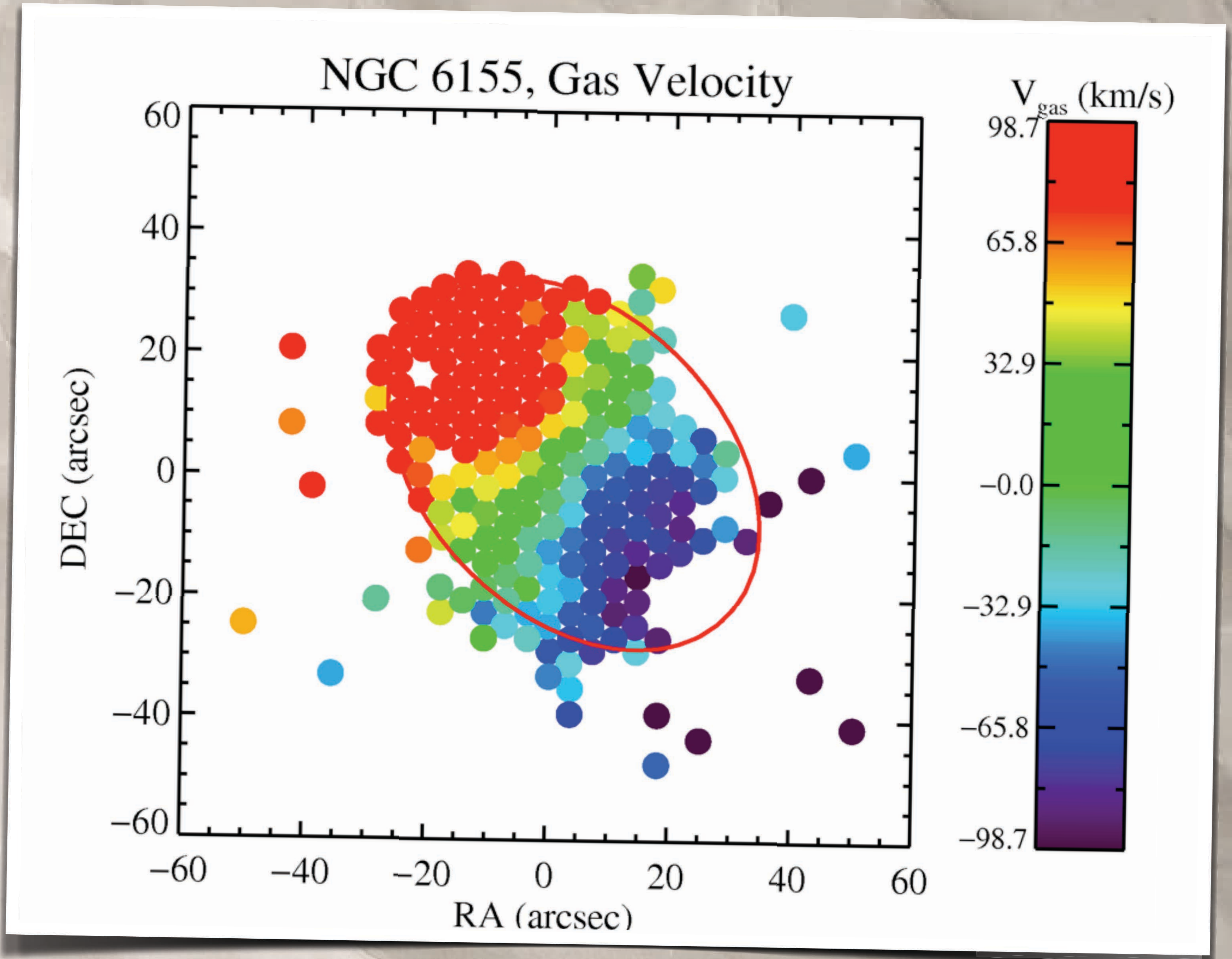
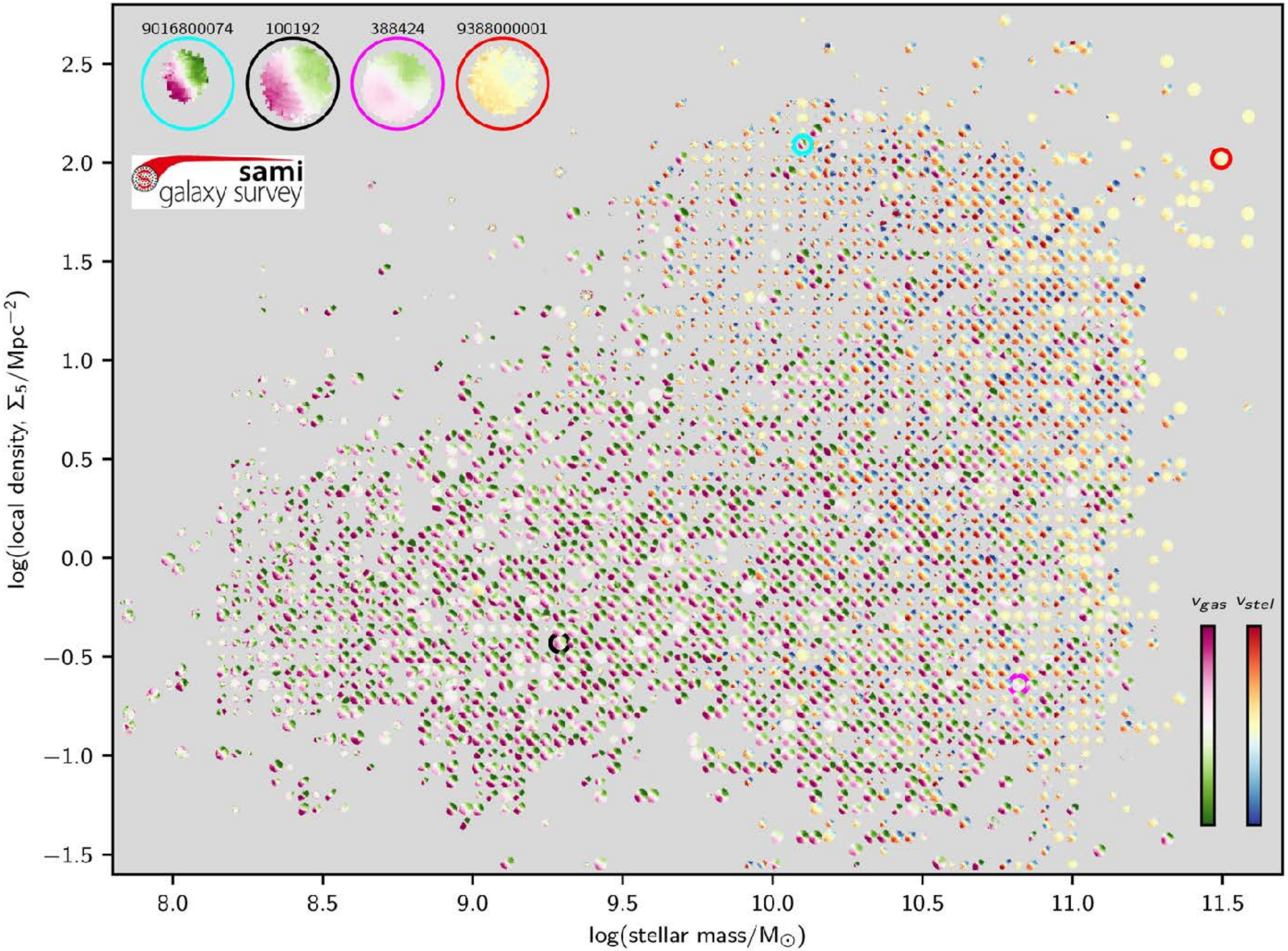
integral field (3D) spectroscopy

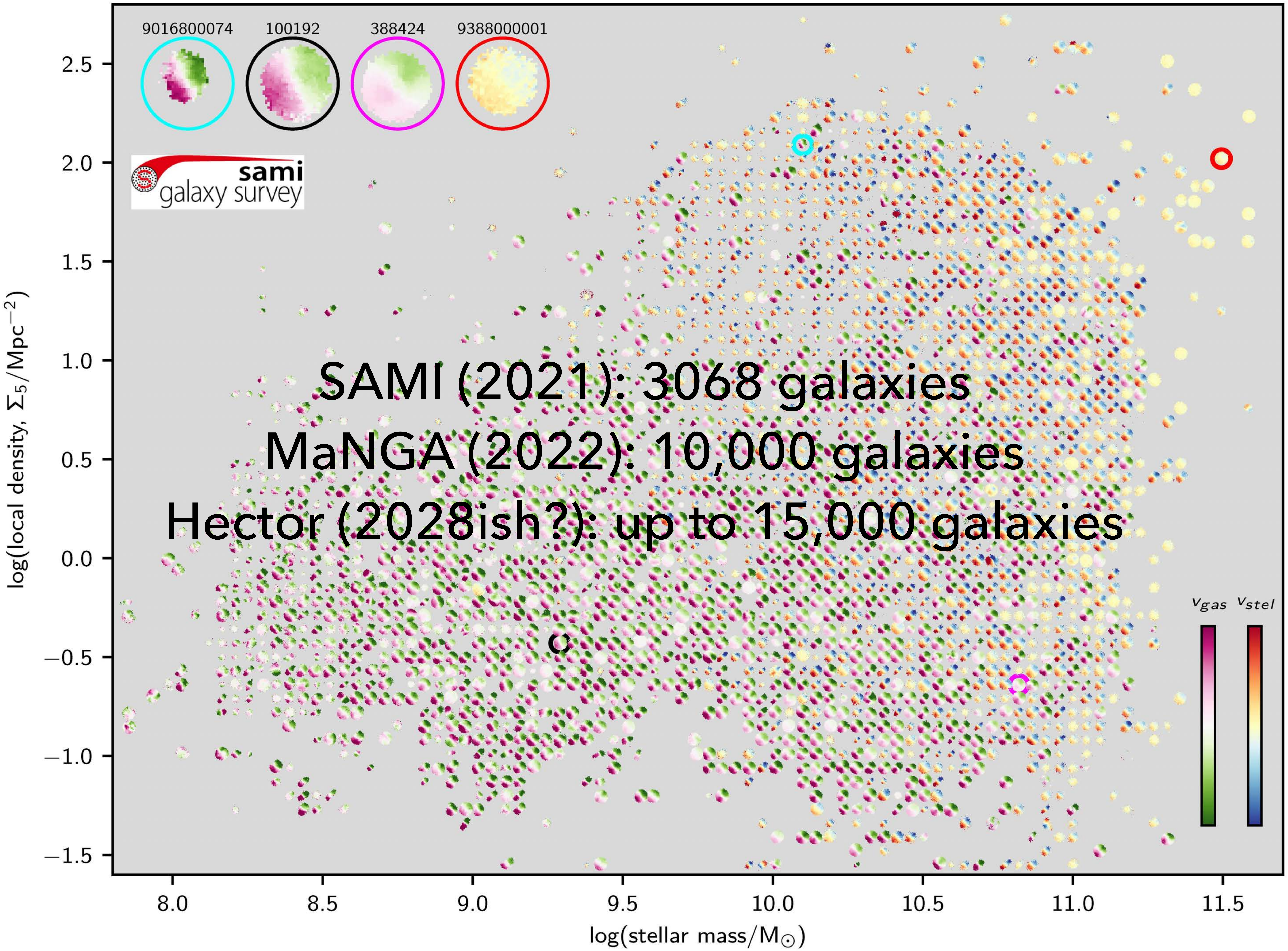


what can we measure?
integral field (3D) spectroscopy





9016800074
100192
388424
9388000001
sami
galaxy survey
log(local density, Σ5/Mpc−2)
log(stellar mass/M⊙)
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5
vgas
vstel



9016800074
100192
388424
9388000001
sami galaxy survey
SAMI (2021): 3068 galaxies
MaNGA (2022): 10,000 galaxies
Hector (2028ish?): up to 15,000 galaxies
log(local density, Σ_5/Mpc^{-2})
log(stellar mass/$M_\odot$)
v_{gas}
v_{stel}
2.5
2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
8.0
8.5
9.0
9.5
10.0
10.5
11.0
11.5

~~measuring~~ estimating mass from dynamics

If you understand (ie, if you can model)
the dynamics of a galaxy system,

then you can estimate the amount of material
needed to produce the observed velocities.

what can we measure?
flux-weighted velocity profiles

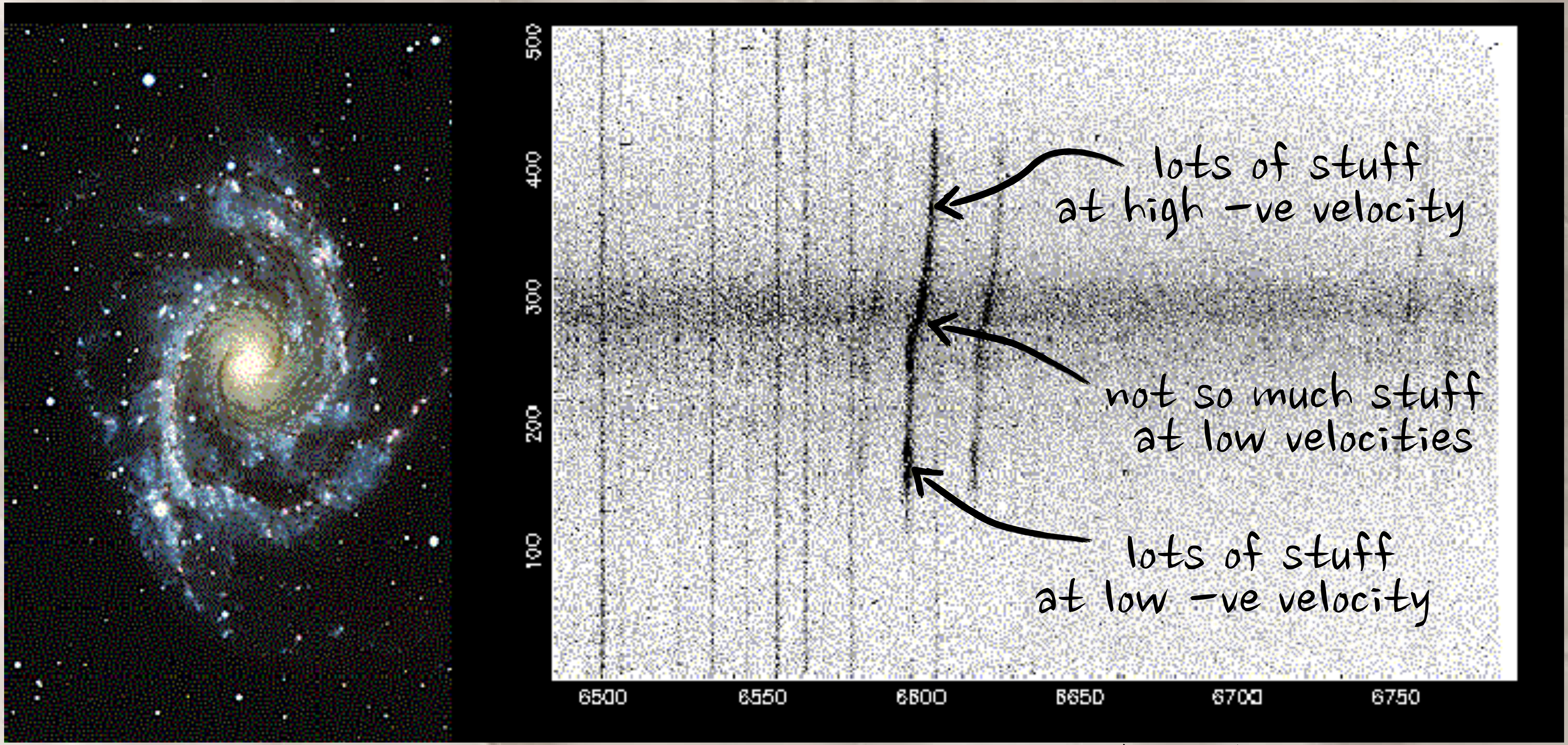
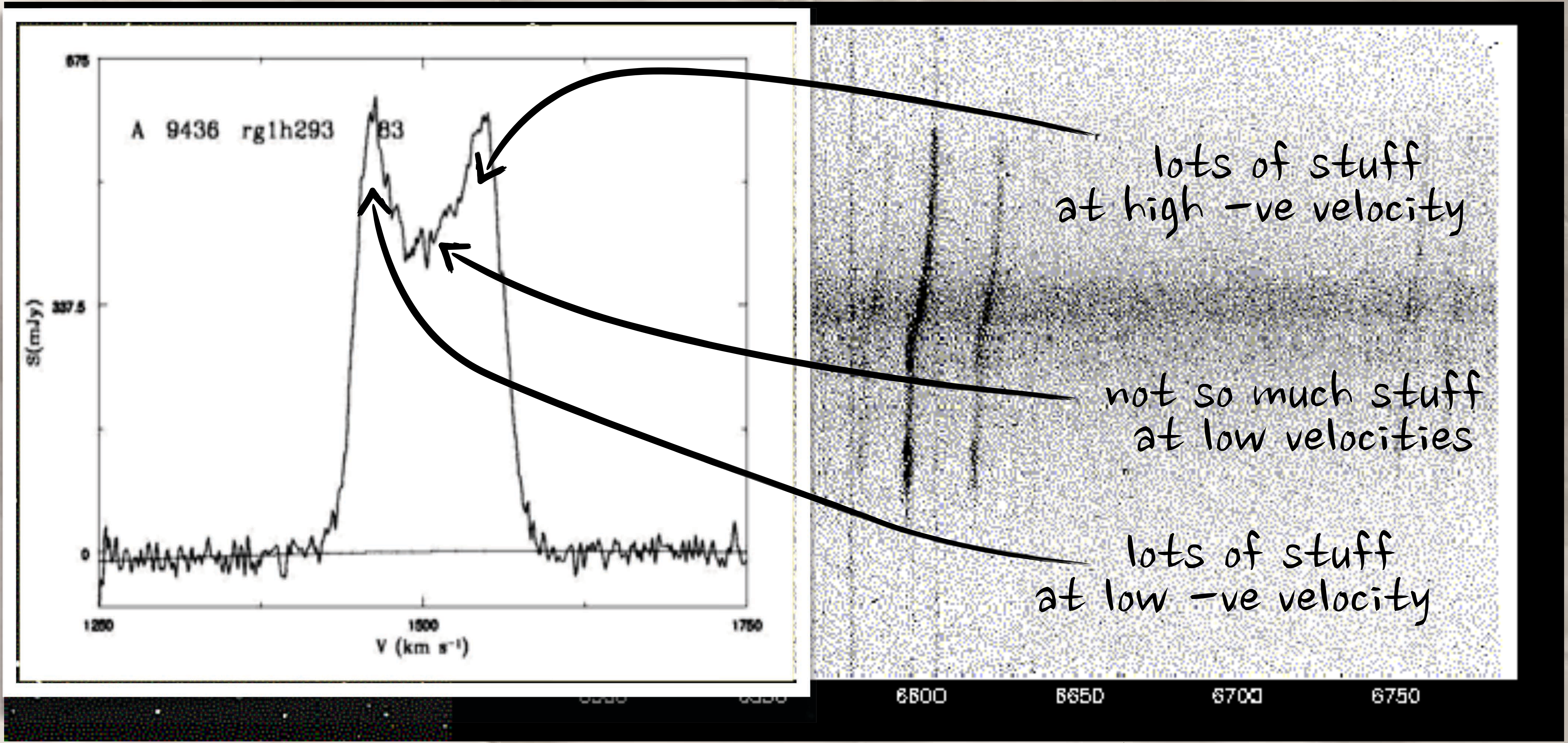


image source: Chris Mihos (burro.cwru.edu)

what can we measure?
flux-weighted velocity profiles



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what can we measure?
flux-weighted velocity profiles

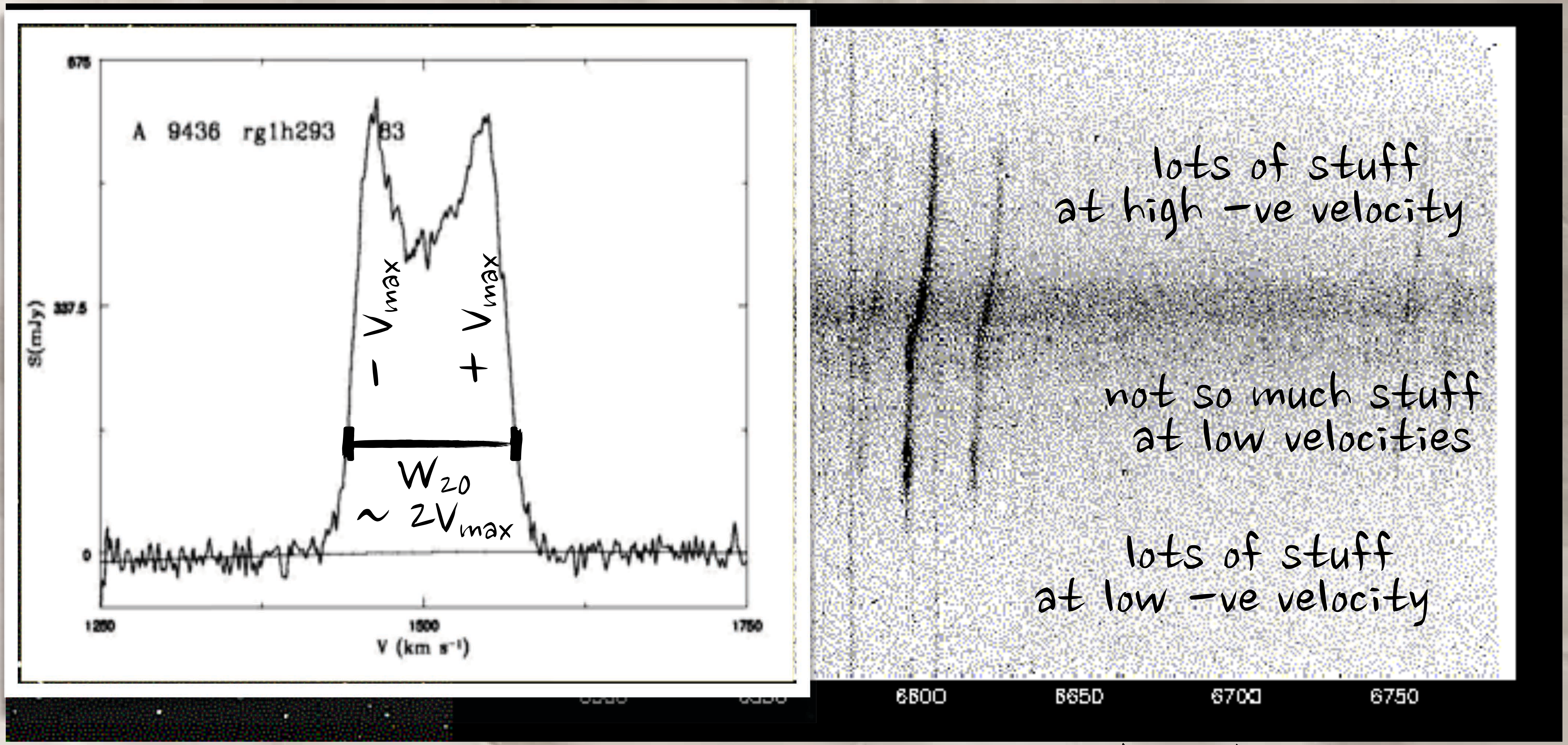
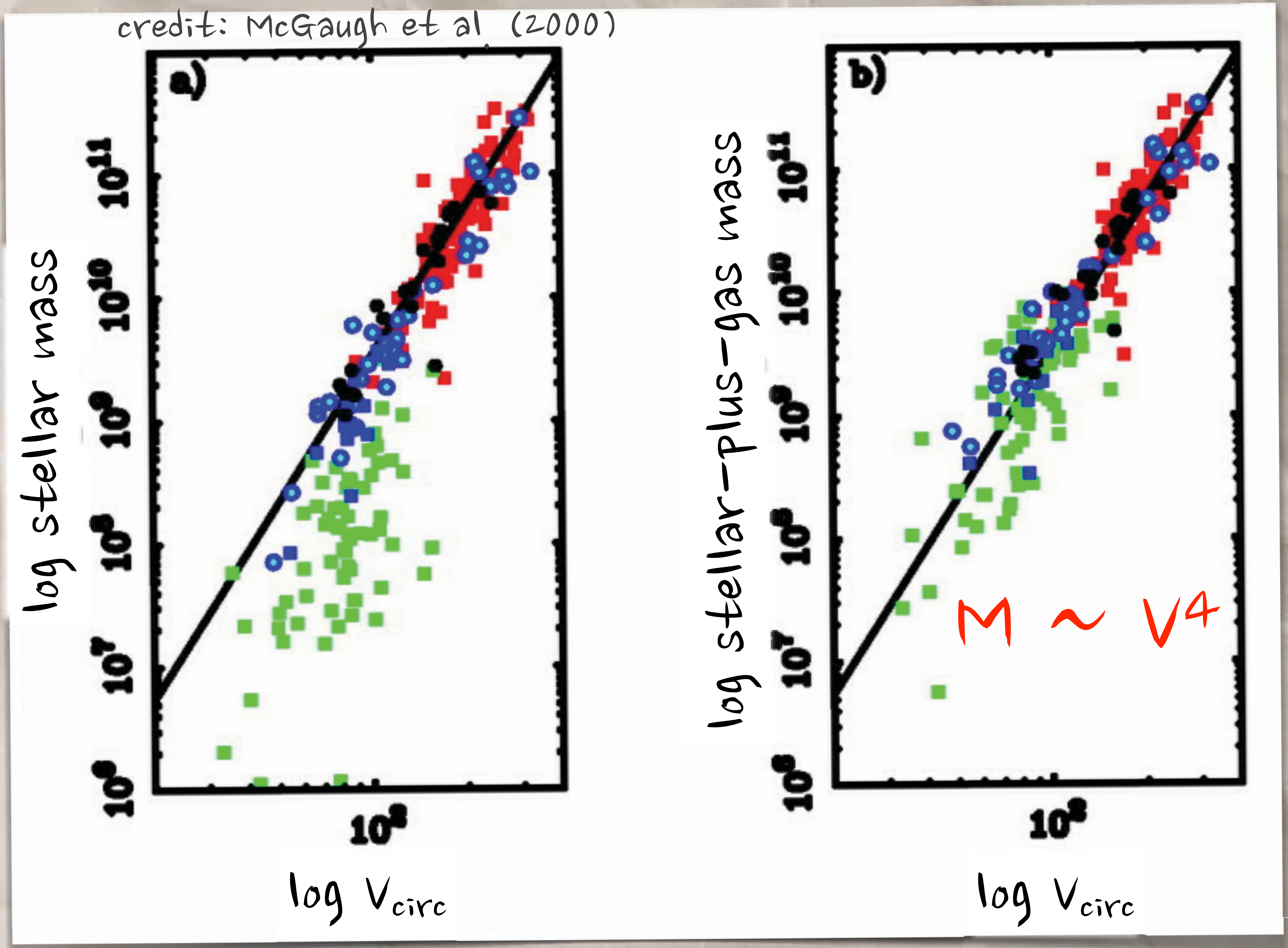
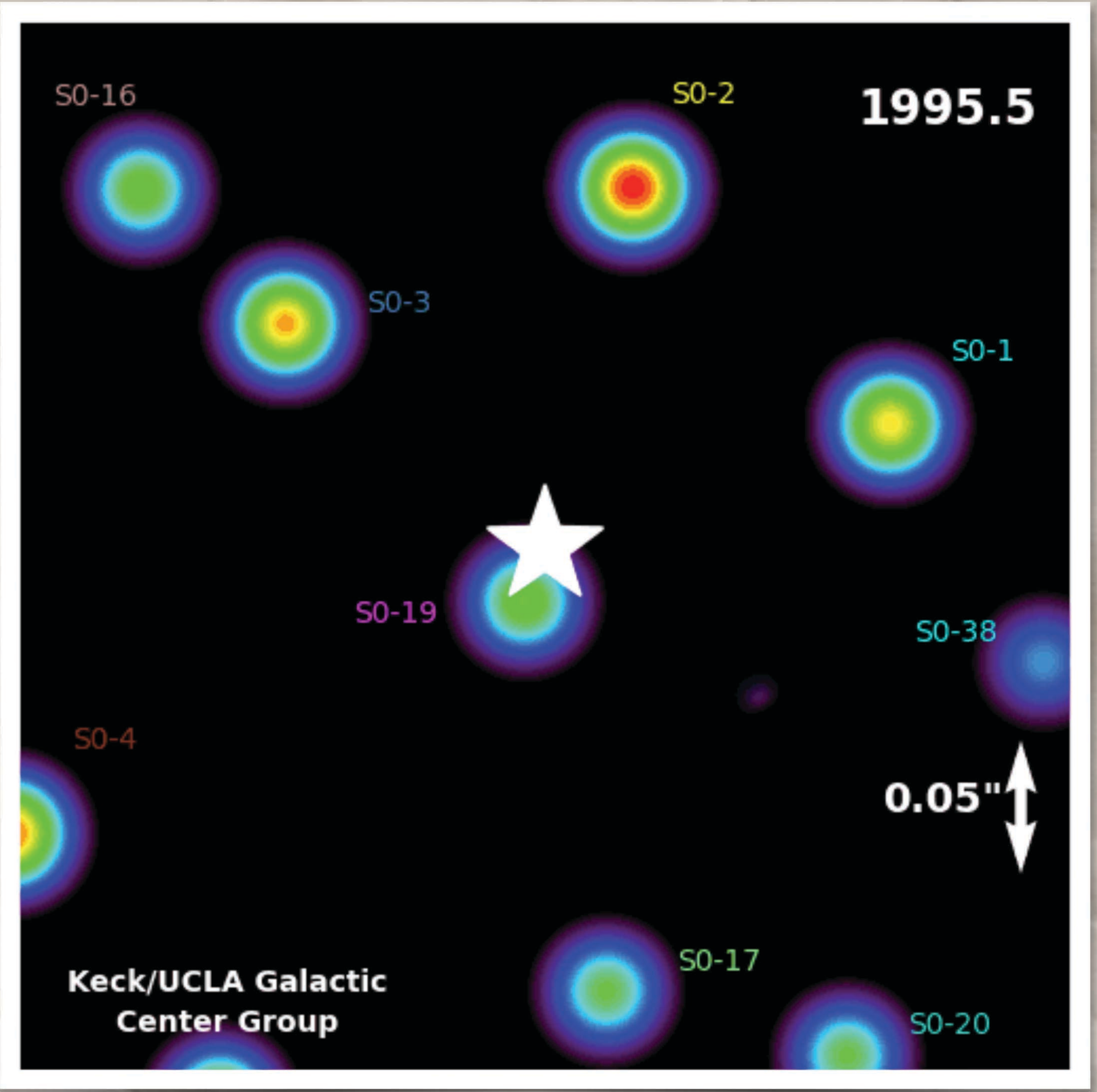


image source: Chris Mihos (burro.cwru.edu)

the (baryonic) Tully-Fisher relation



what can we measure?
los. velocity dispersion



the virial theorem

Clausius' virial: $\chi_i \equiv \vec{r}_i \cdot \vec{p}_i$

time derivative = 0 $\dot{\chi}_i = \dot{\vec{r}}_i \cdot \vec{p}_i + \vec{r}_i \cdot \dot{\vec{p}}_i = 0$

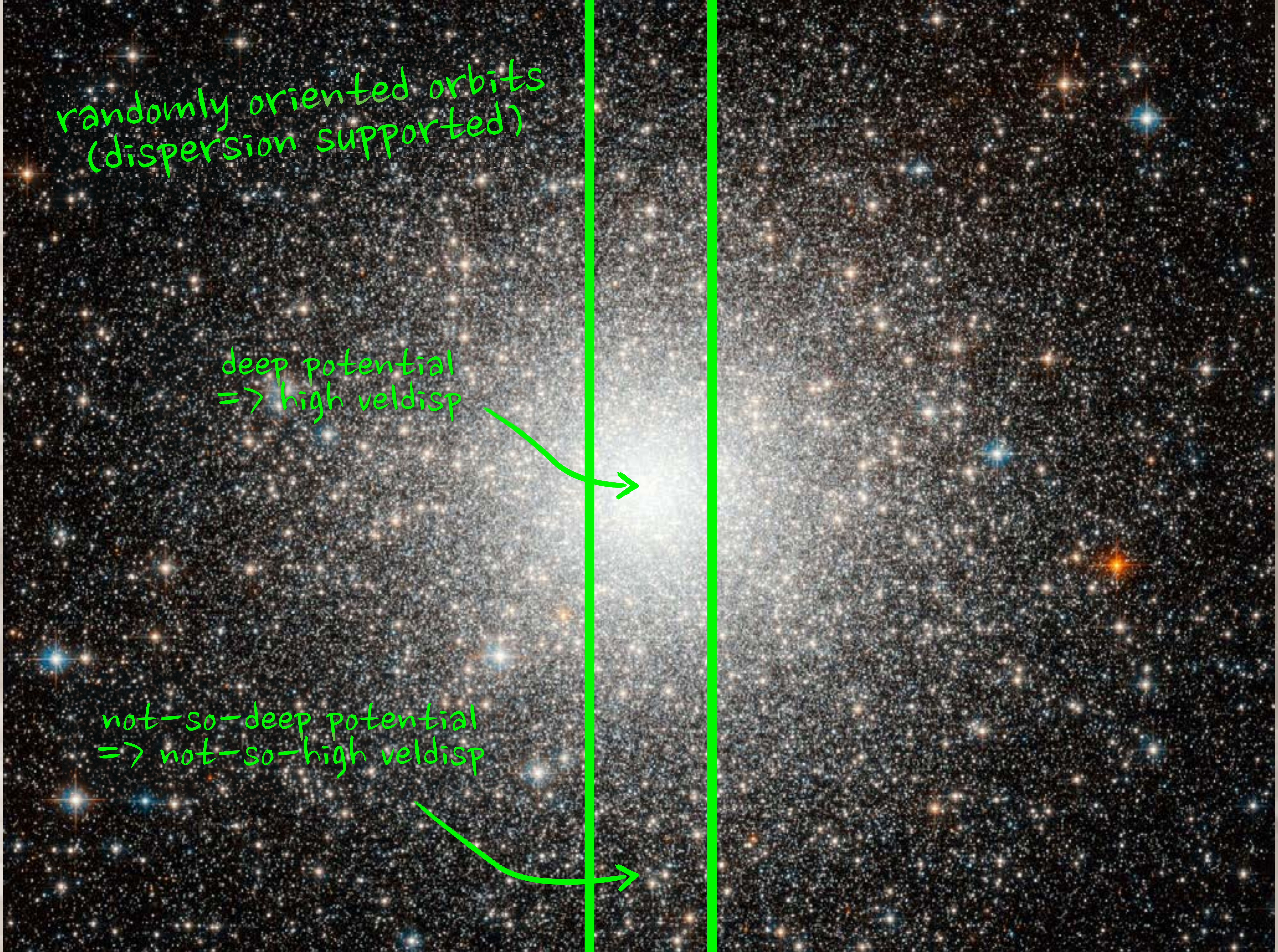
Newton:
p = m dv/dt
and dp/dt = F

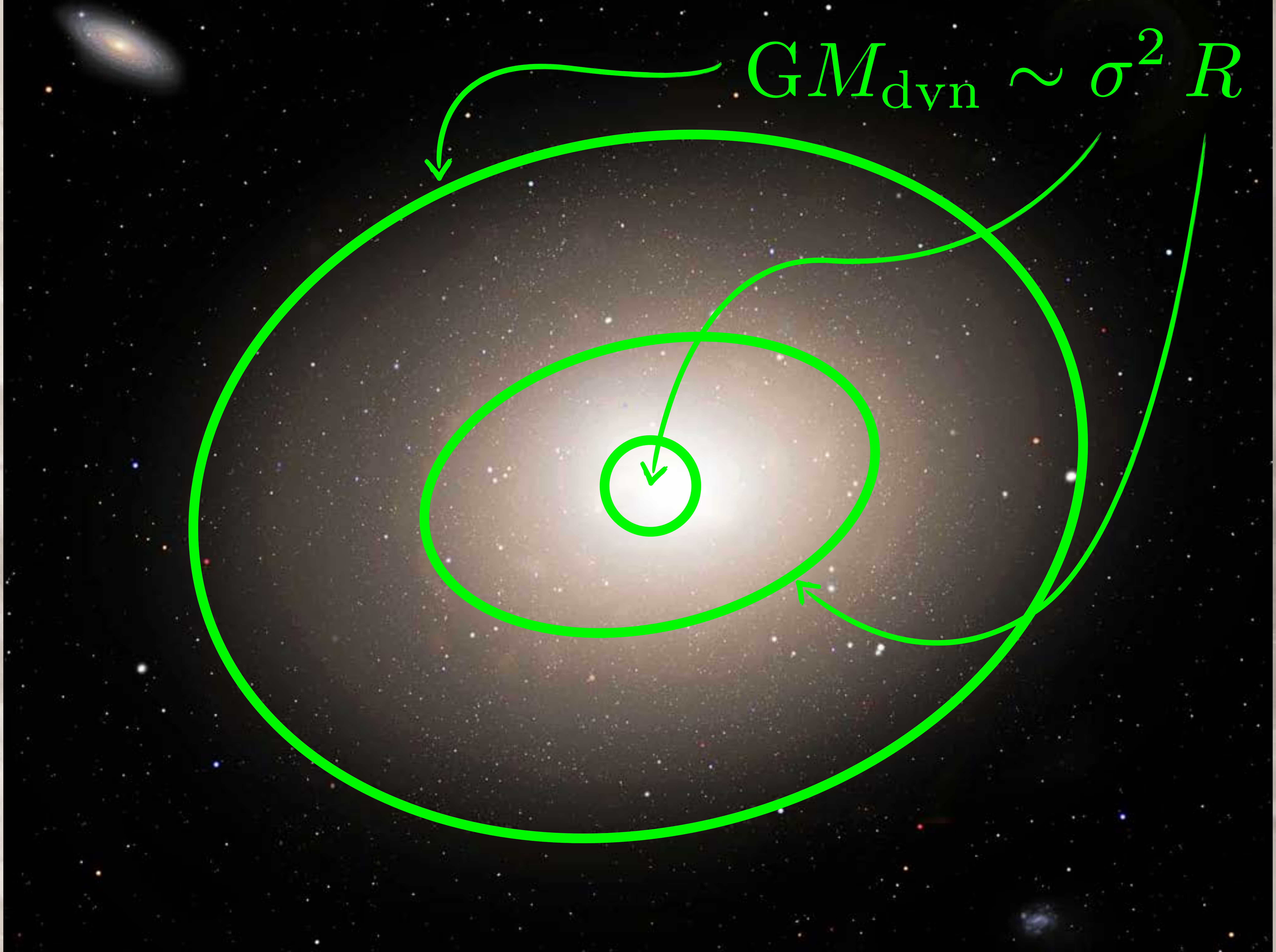
$$m_i \, \vec{v}_i \cdot \vec{v}_i + \vec{r}_i \cdot \vec{F}_i = 0$$

1. stationary system (d/dt = 0 on average)

2. radial forces (F = U / r on average)

=> Keplerian orbits


randomly oriented orbits
(dispersion supported)
deep potential
=> high veldisp
not-so-deep potential
=> not-so-high veldisp


$GM_{\rm dyn} \sim \sigma^2 R$

not the virial theorem

$$\mathrm{G}M_{\mathrm{dyn}} \sim \sigma^2\, R$$

Ciotti, Bertin & del Principe (2002; A&A 386, 149)

– simulate the dynamics of a stellar system
of known shape and size, and constant M/L.

– 'calibrate' a dynamical measure of mass.

~~measuring~~ estimating mass from dynamics

If you understand (ie, if you can model)
the dynamics of a galaxy system,

then you can estimate the amount of material
needed to produce the observed velocities.

~~measuring~~ estimating mass from dynamics

This works for :

1. planets around stars
(and satellites around planets)

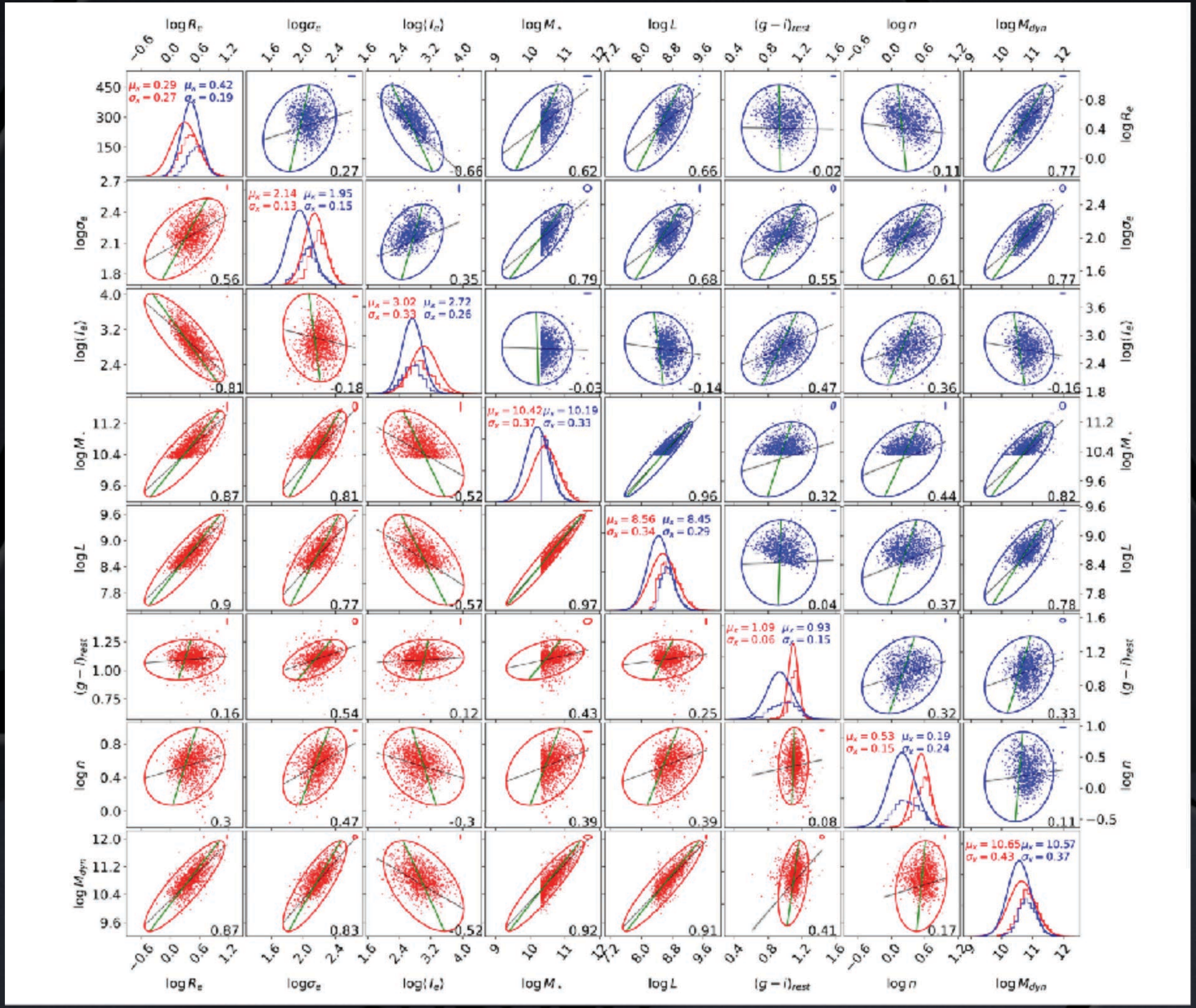
2. stars in globular clusters

3. stars (or globular clusters) in galaxies

4. galaxies in groups or clusters

The Stellar-to-Dynamical Mass Relation
B. Dogruel, ENT, et al. (2023)

- Stellar mass limited sample: log M* > 10.3 and z < 0.12.
- Carefully calibrated & validated velocity dispersions from ppxf.
- Full and proper forward modelling of 8-D galaxy parameter space.
- ***This is the only way to fully and properly isolate real correlations and/or control for confounders.***



4HS PIs: M Cluver & E N Taylor <4hs-pi@4most.eu>

The Stellar-to-Dynamical Mass Relation B. Dogruel, ENT, et al. (2023)

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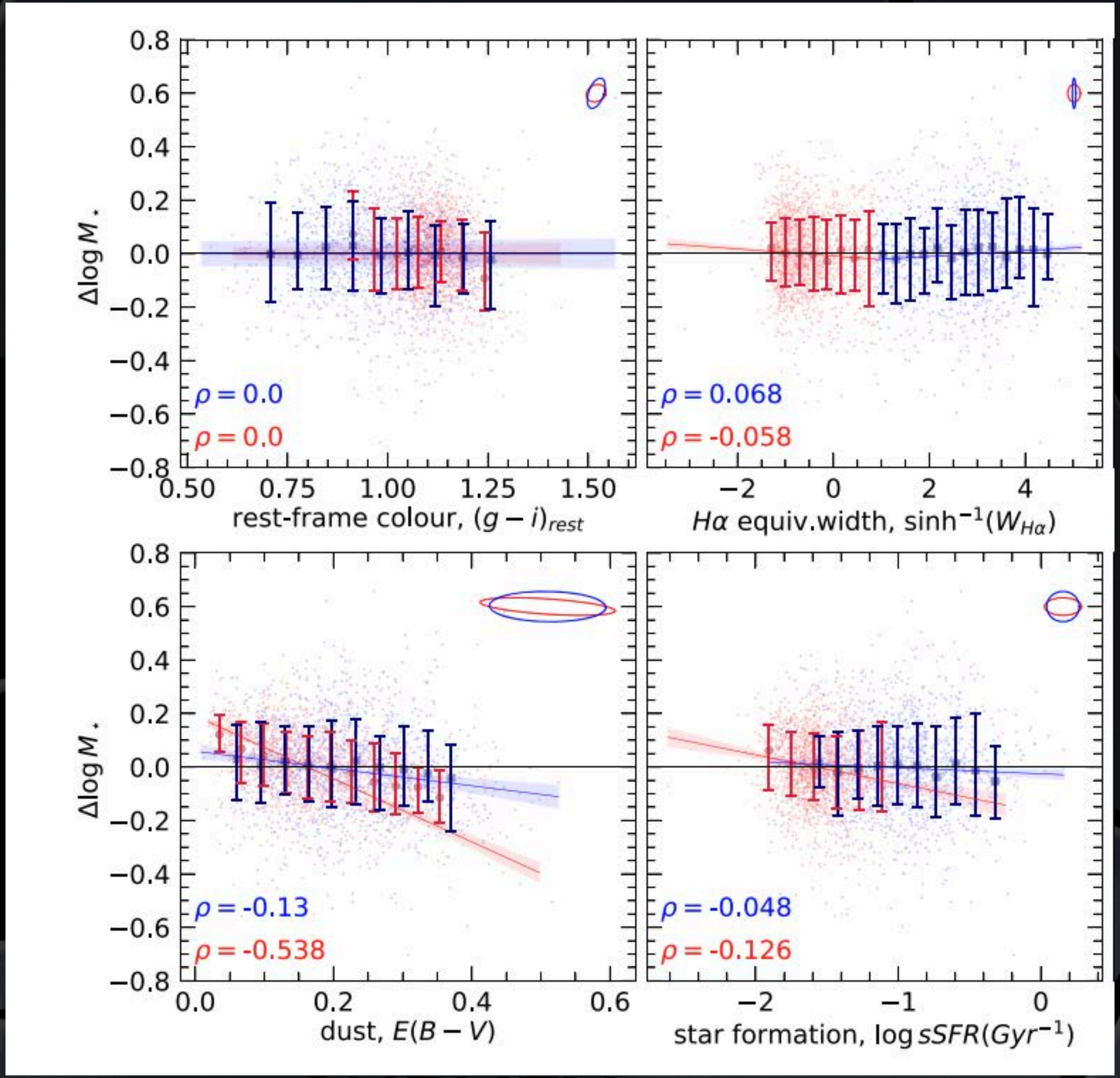
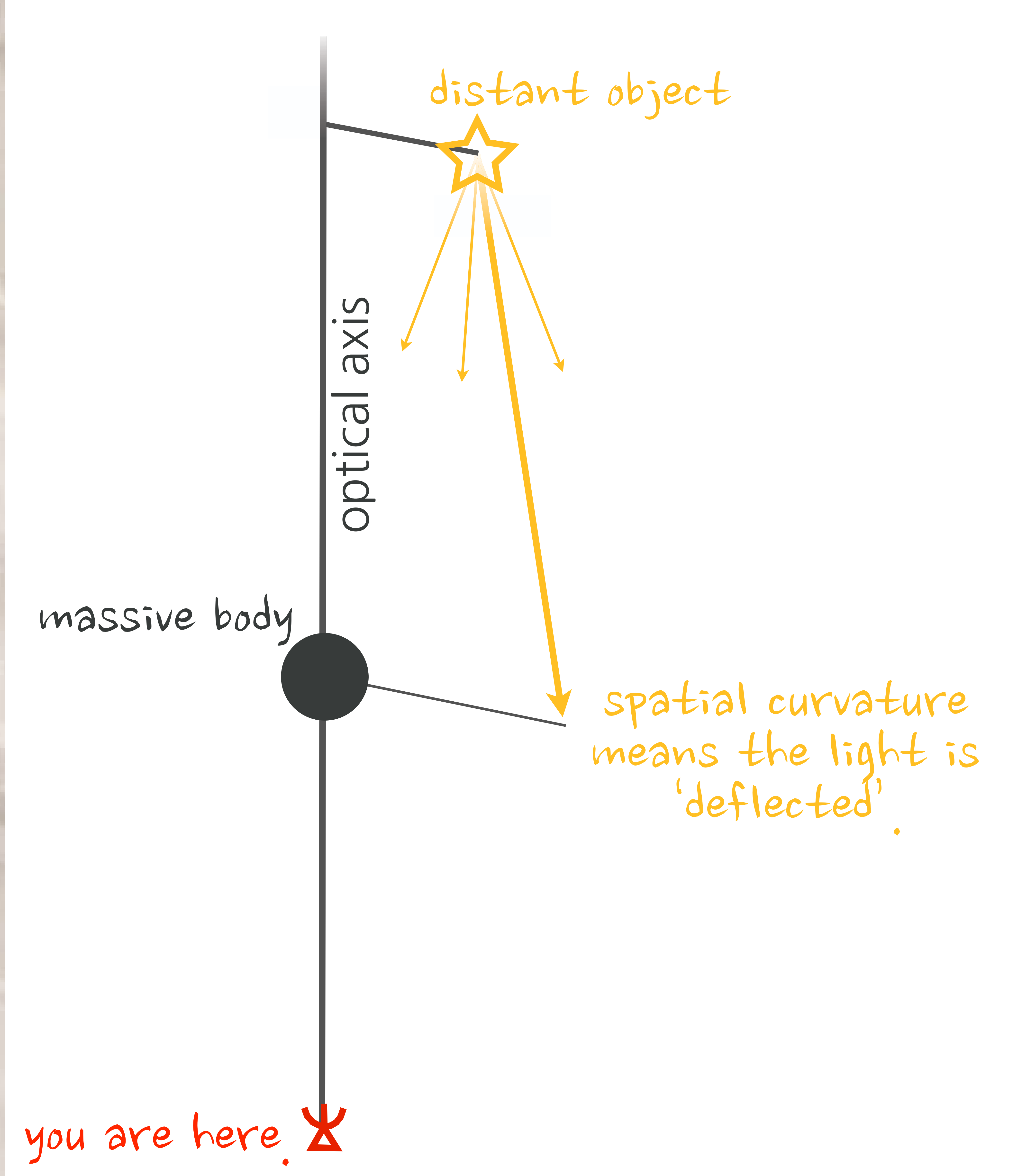
- Carefully calibrated & validated velocity dispersions from ppxf.
- Full and proper forward modelling of 8-D galaxy parameter space.
- ***This is the only way to fully and properly isolate real correlations and/or control for confounders.***
- Very close correspondance between stellar and dynamical mass estimates!

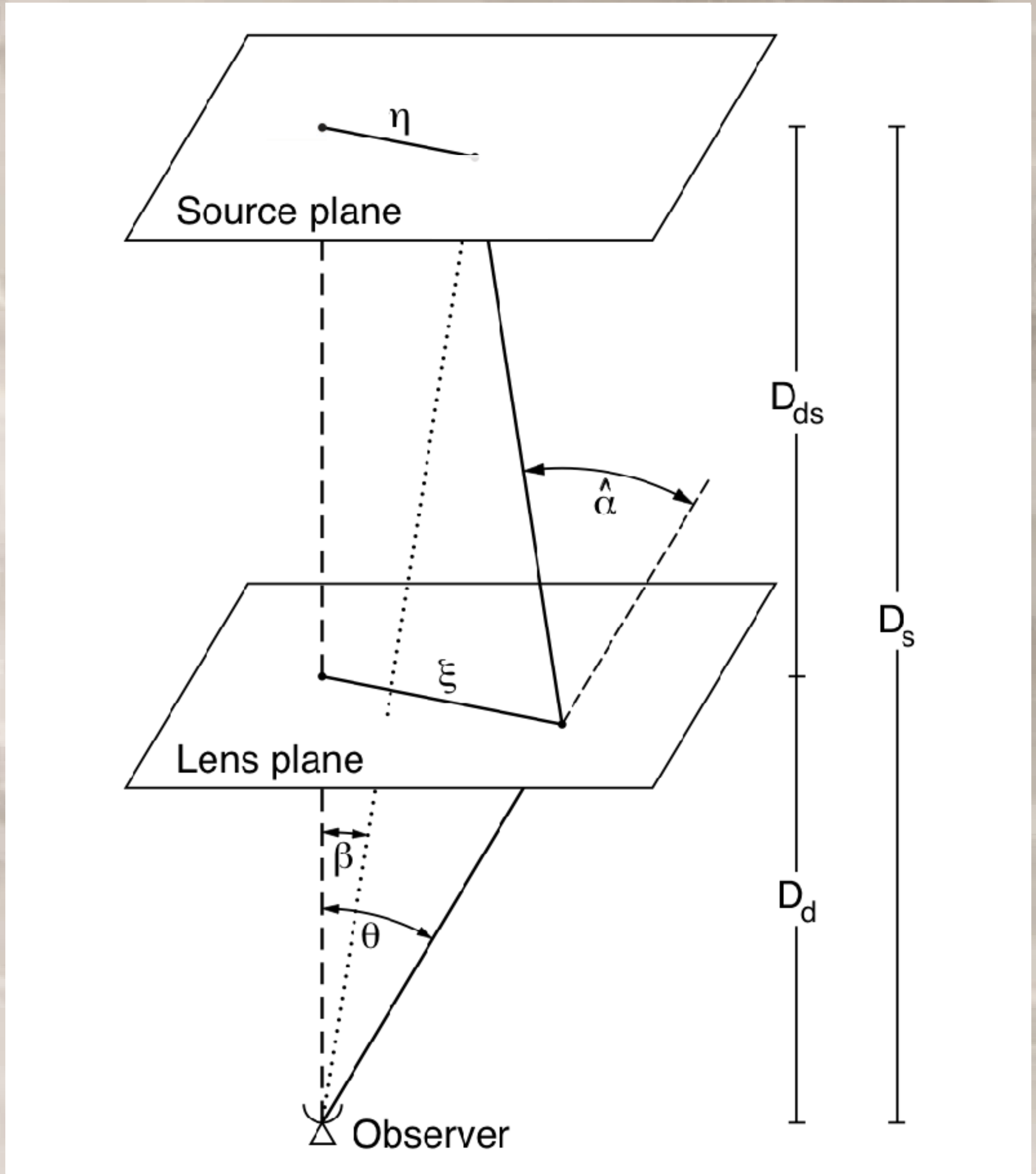


~~measuring~~ estimating the masses of galaxies

1. mass from **luminosity**
2. mass from **dynamics**
3. mass from **gravitational lensing**
4. mass from **clustering**



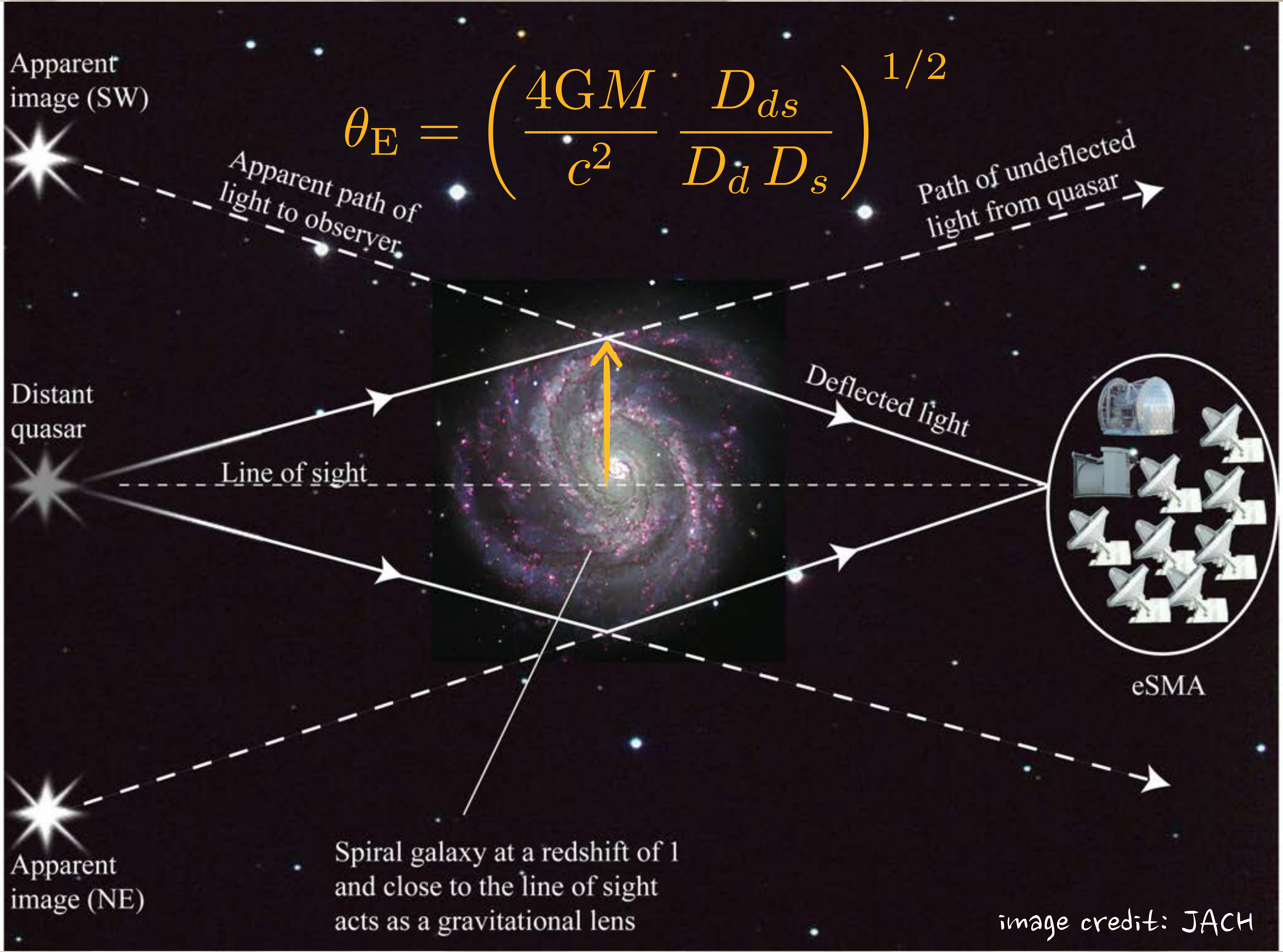
GR: Mass distorts space.



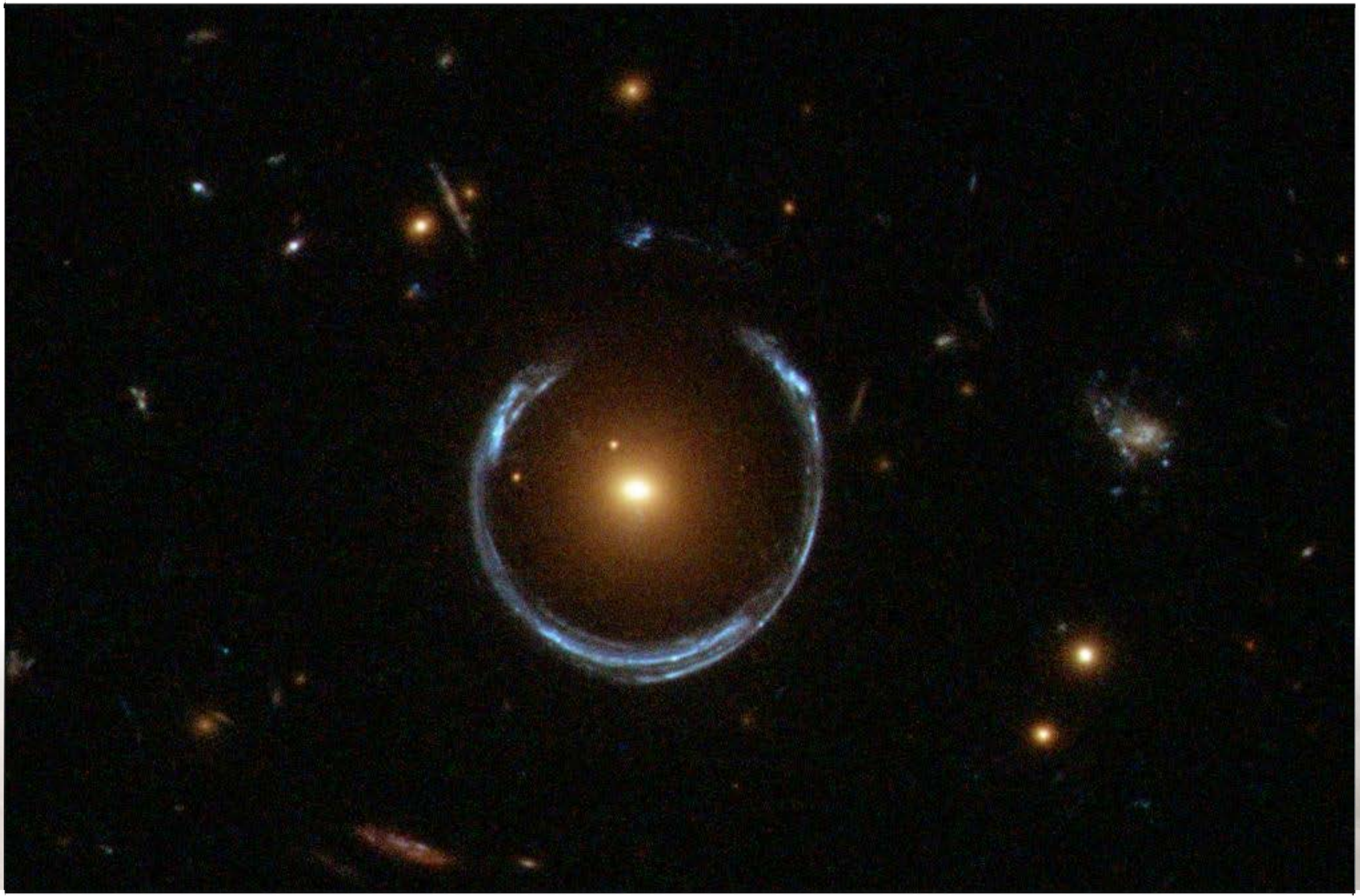
Bartelmann & Schneider (2001)

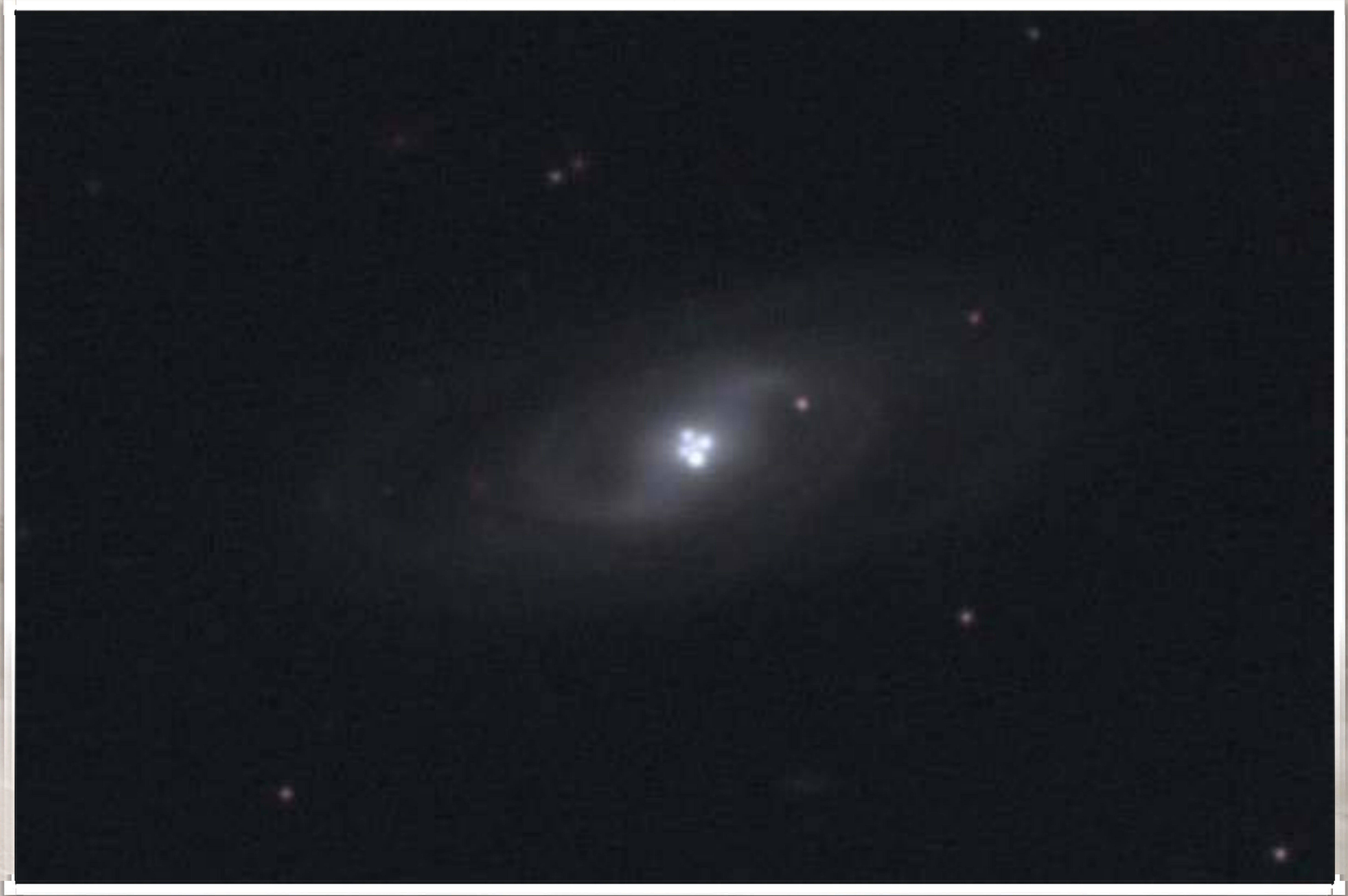
GR: Mass distorts space.

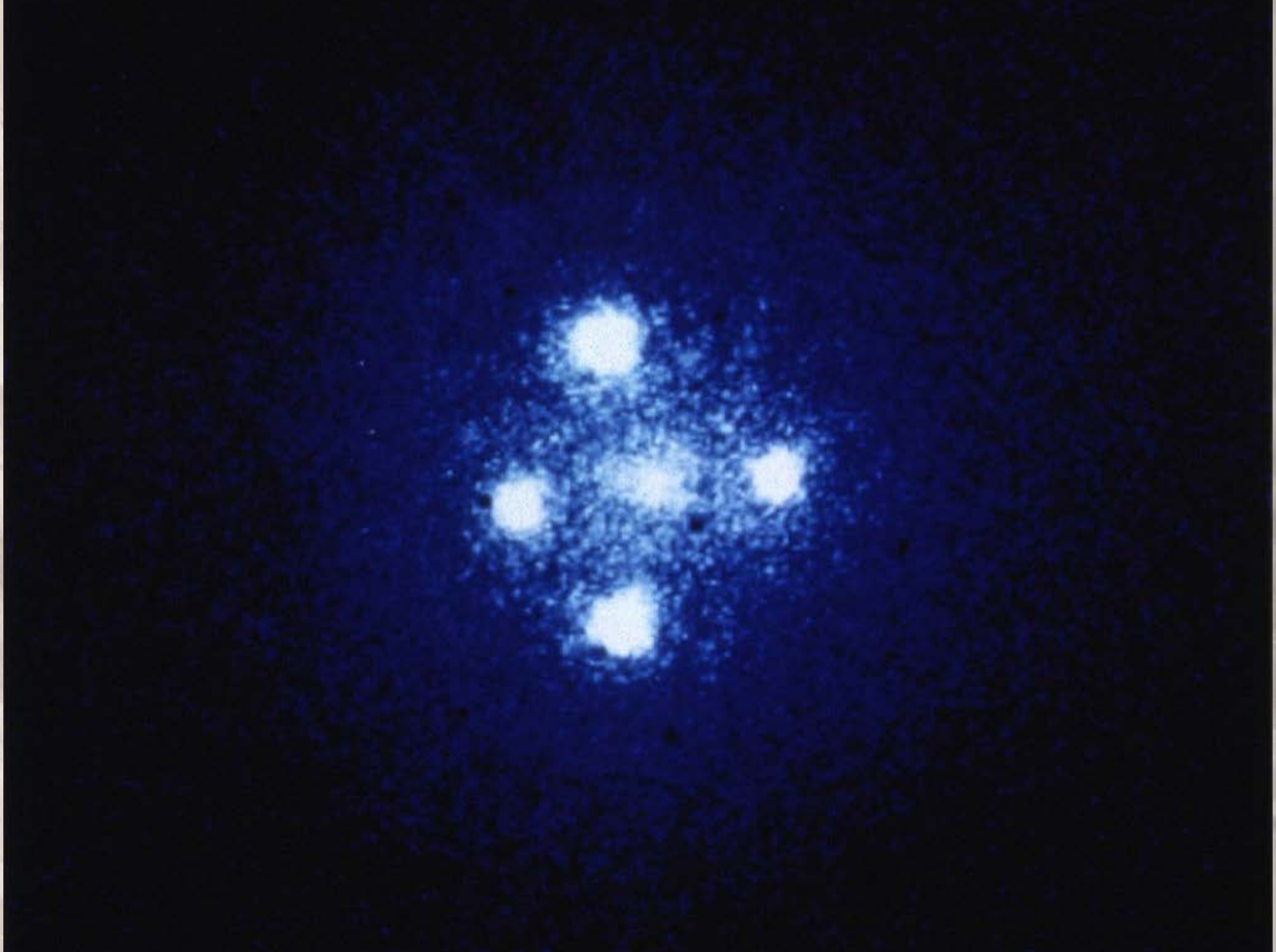
Large-scale mass concentrations act like lenses.



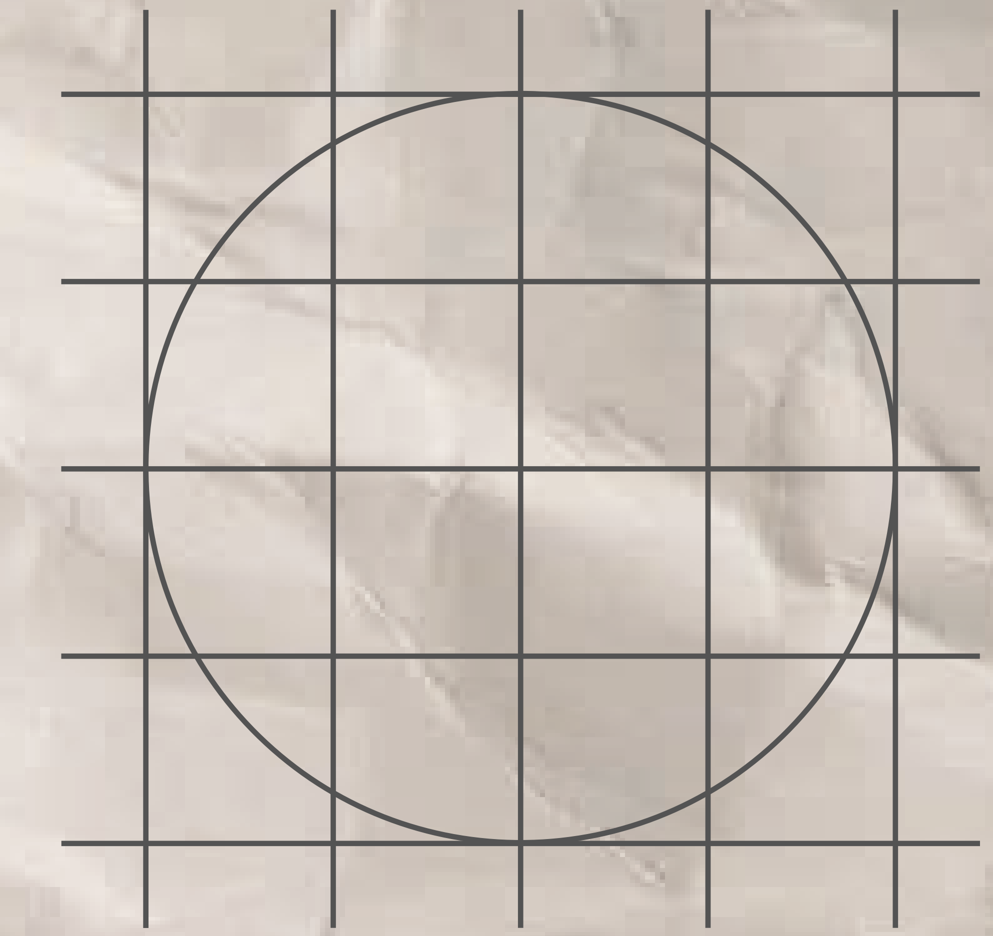
Apparent image (SW)
$$\theta_{\mathrm{E}} = \left(\frac{4GM}{c^2}\frac{D_{ds}}{D_d\,D_s}\right)^{1/2}$$
Apparent path of light to observer
Path of undeflected light from quasar
Distant quasar
Deflected light
Line of sight
eSMA
Apparent image (NE)
Spiral galaxy at a redshift of 1 and close to the line of sight acts as a gravitational lens
image credit: JACH



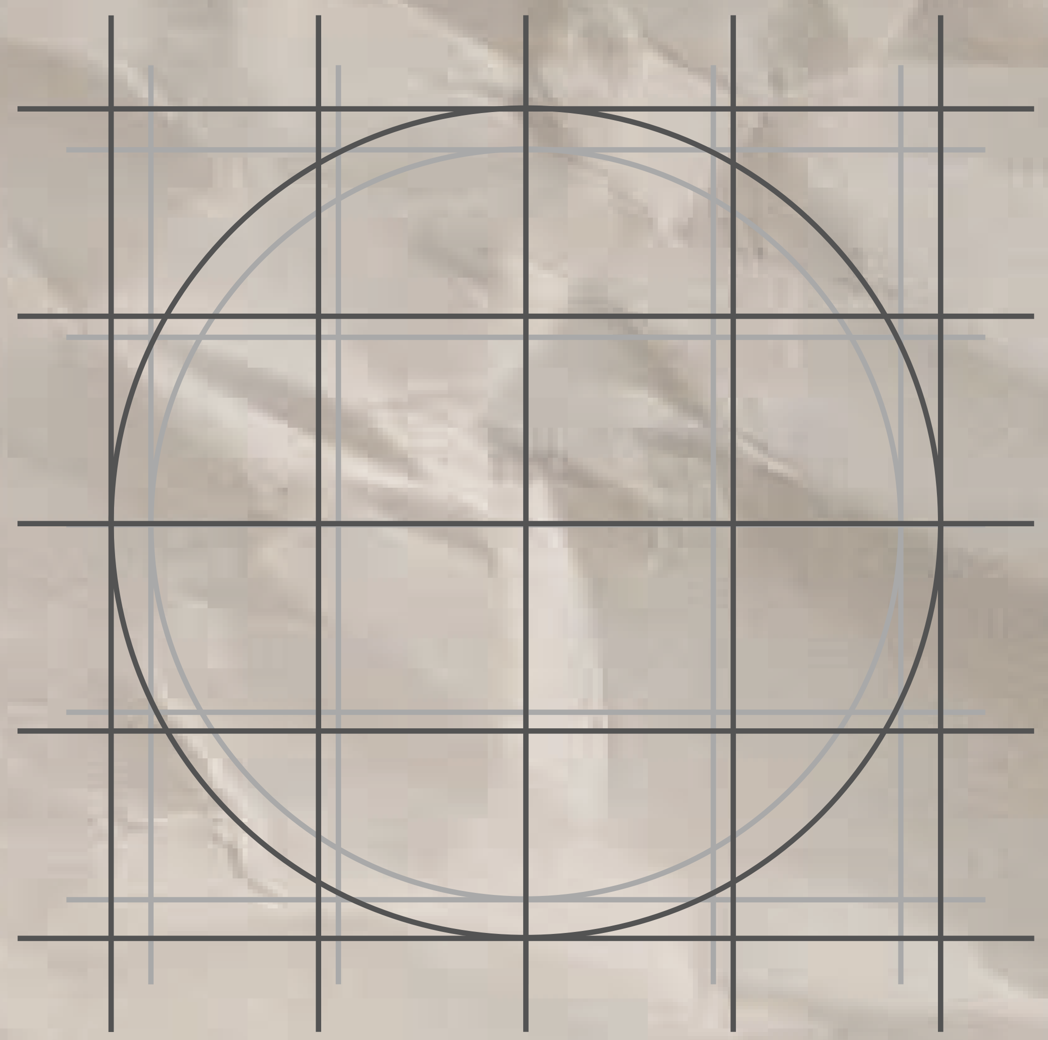




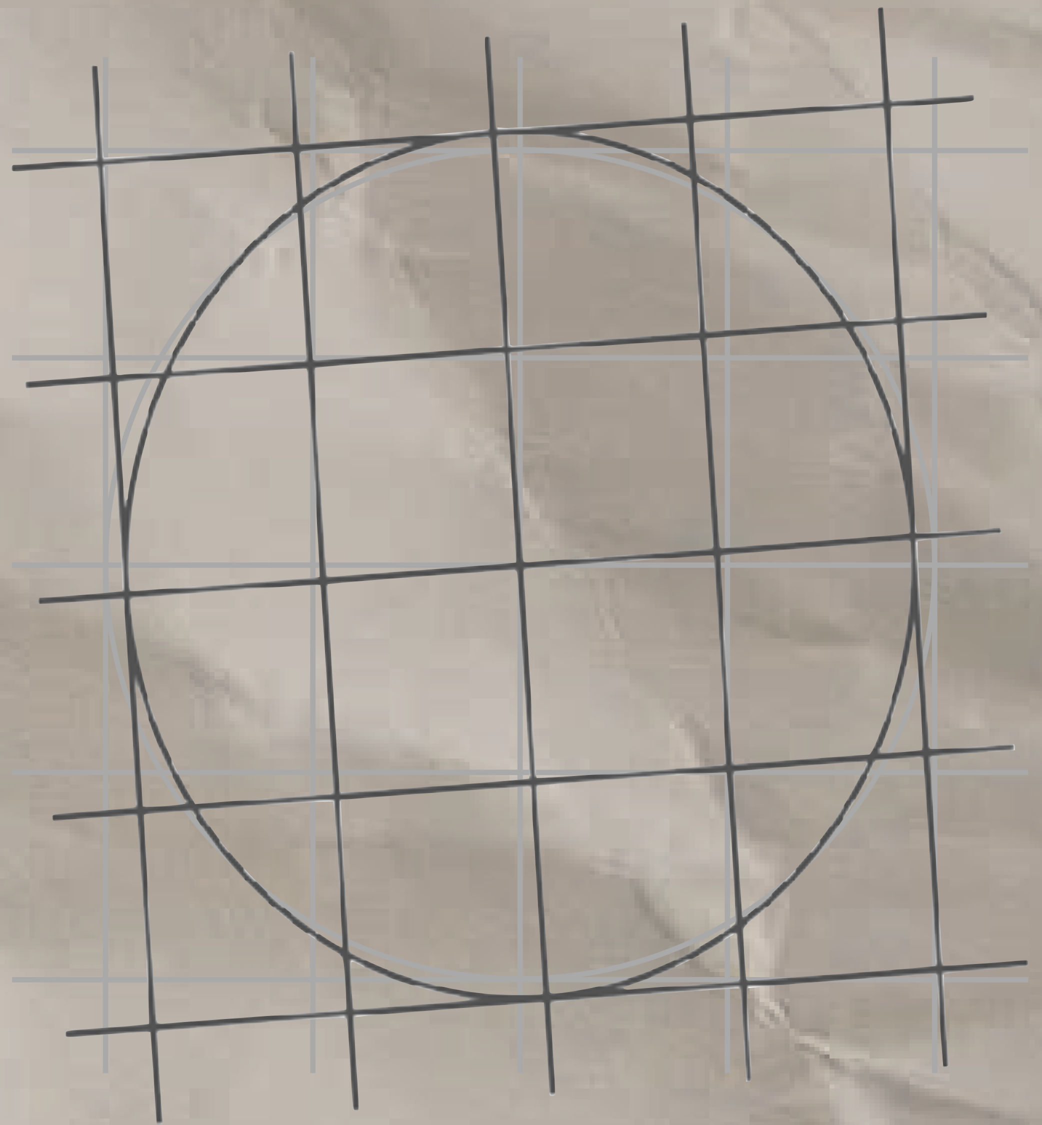
Lenses do two things: magnify and distort.



reference image

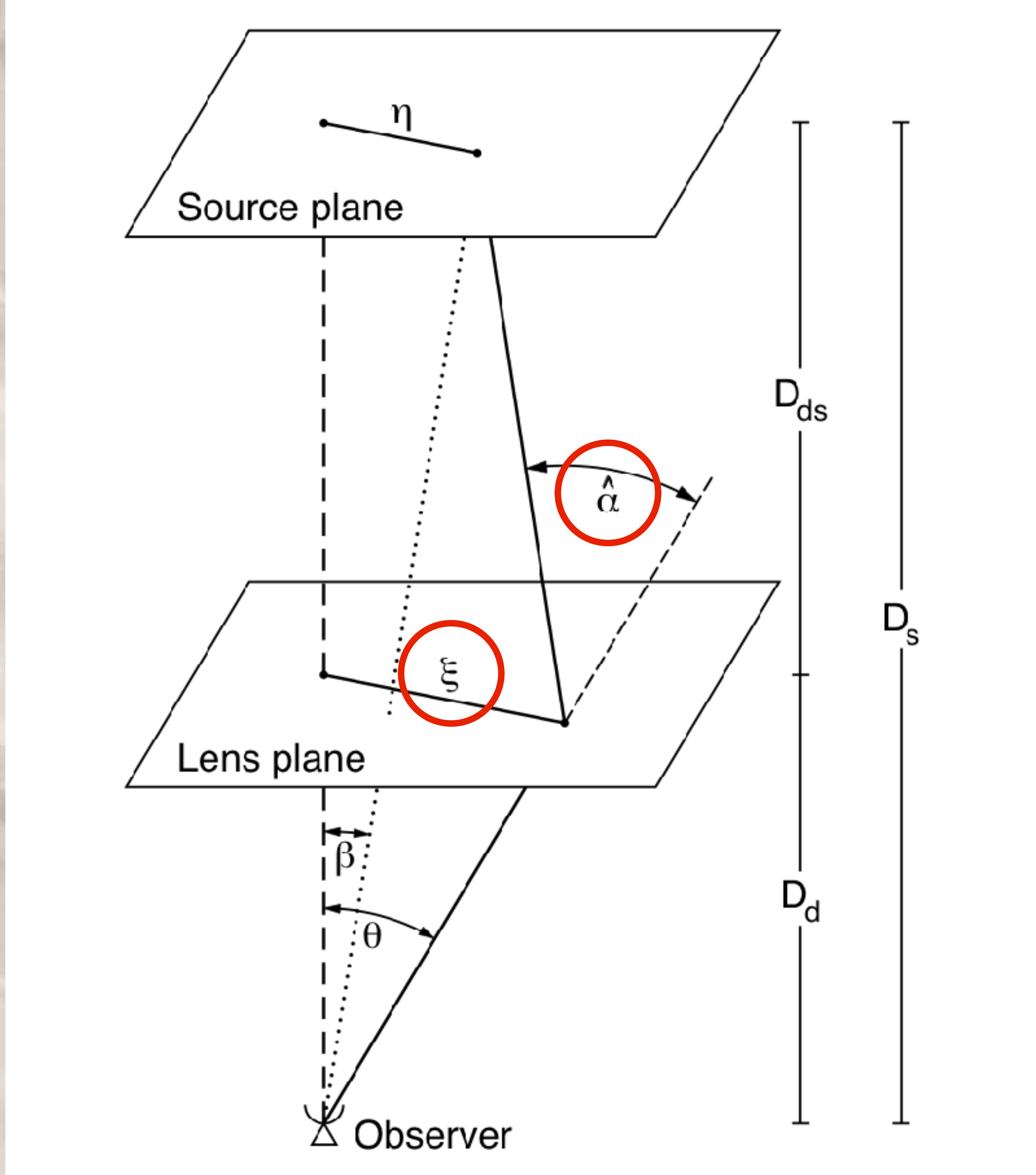


with magnification



with magnification and distortion

In optical terms, this kind of distortion is called astigmatism. In geometric terms, this kind of transformation is a shear.



Bartelmann & Schneider (2001)

$\vec{\beta}$ describes the 'true' location of the light.

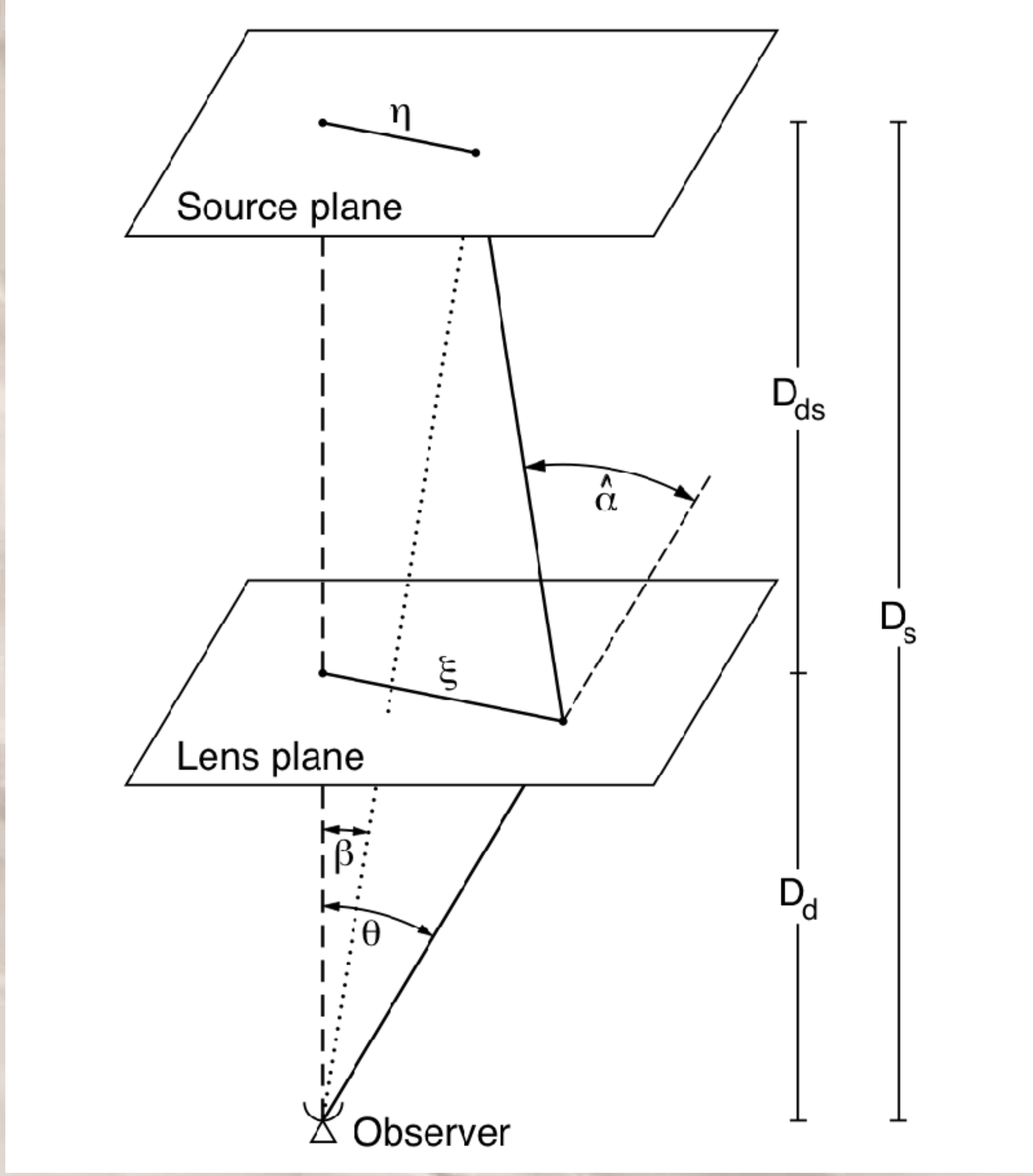
$\vec{\theta}$ describes the observed position of the light.

$\frac{\partial \vec{\beta}(\vec{\theta})}{\partial \vec{\theta}}$ describes distortion in the observed image.

$\vec{\alpha}$ describes the degree of deflection for the light.

$$\vec{\alpha}(\vec{\theta}) = \vec{\beta}(\vec{\theta}) - \vec{\theta}$$

$$\vec{\alpha} = \nabla \Phi(\vec{\xi})$$

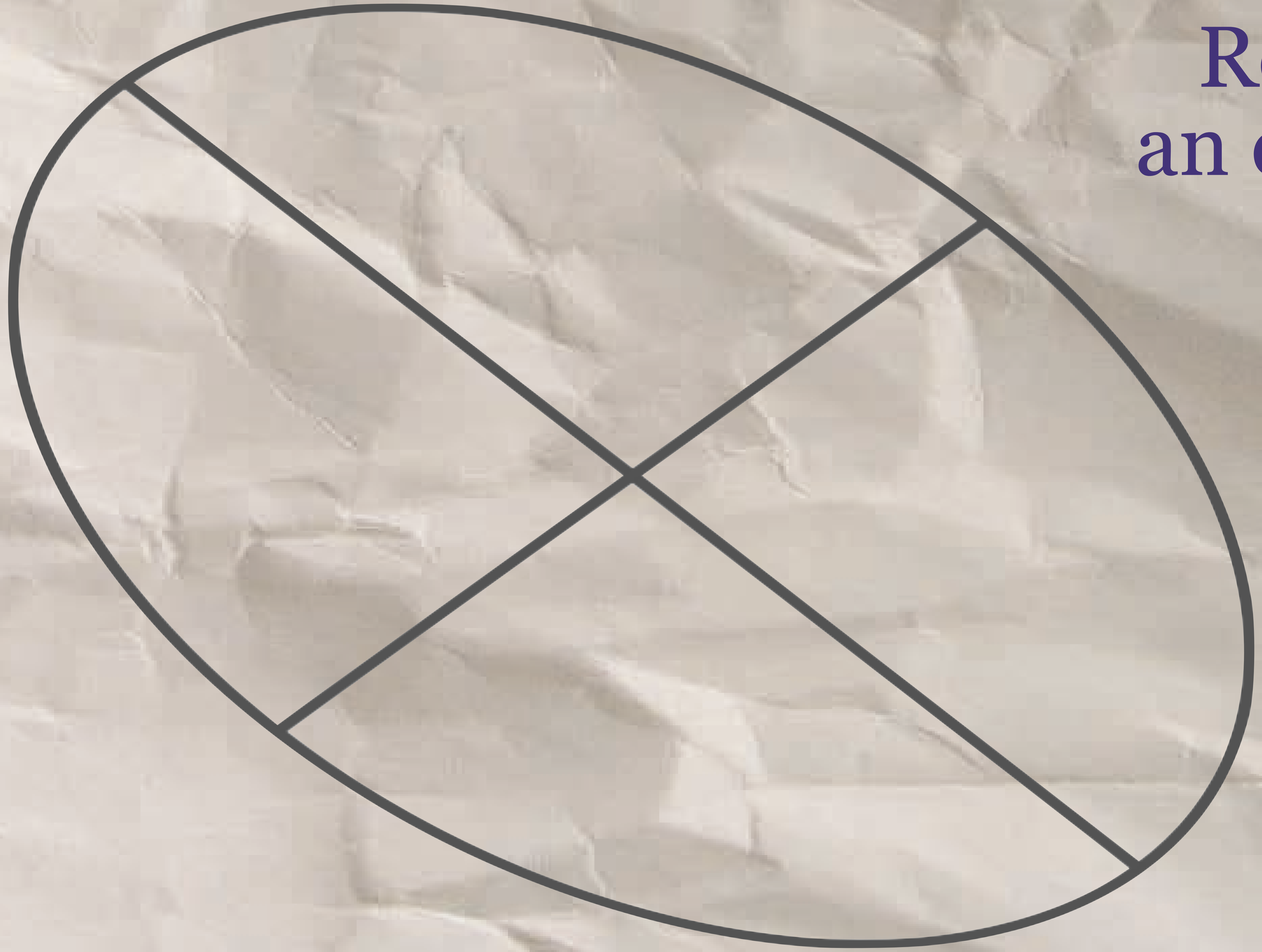


Bartelmann & Schneider (2001)

GR: Mass distorts space.

In the 'weak' regime, the degree of lensing maps directly to the gradient of the 2D projected potential across the ray bundle.

Consequences of shear



Roughly speaking,
an elliptical source is:

1. magnified
2. elongated
3. rotated
4. distorted

Weak lensing studies focus on statistical correlations in the ellipticities and orientations among many (independent) background sources.

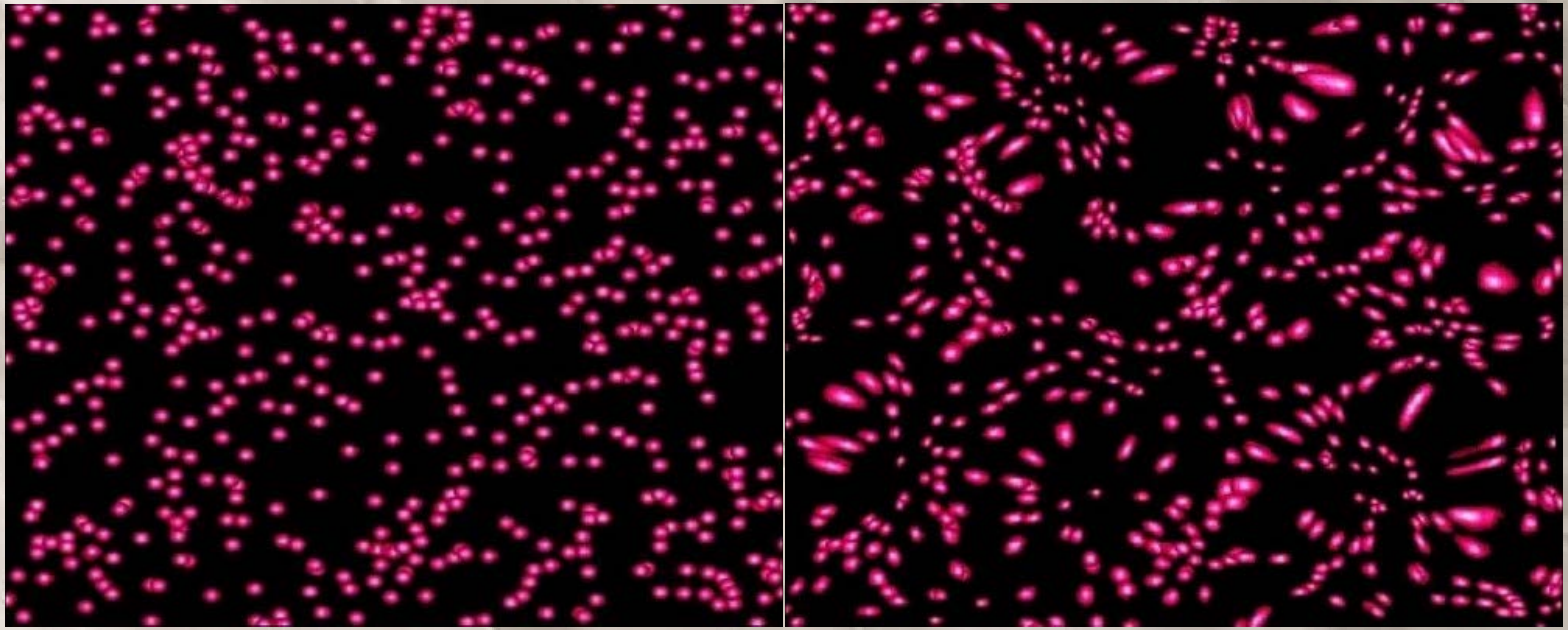


image: Smoot Lensing Group; aether.lbl.gov

Weak lensing studies focus on statistical correlations in the ellipticities and orientations among many (independent) background sources.

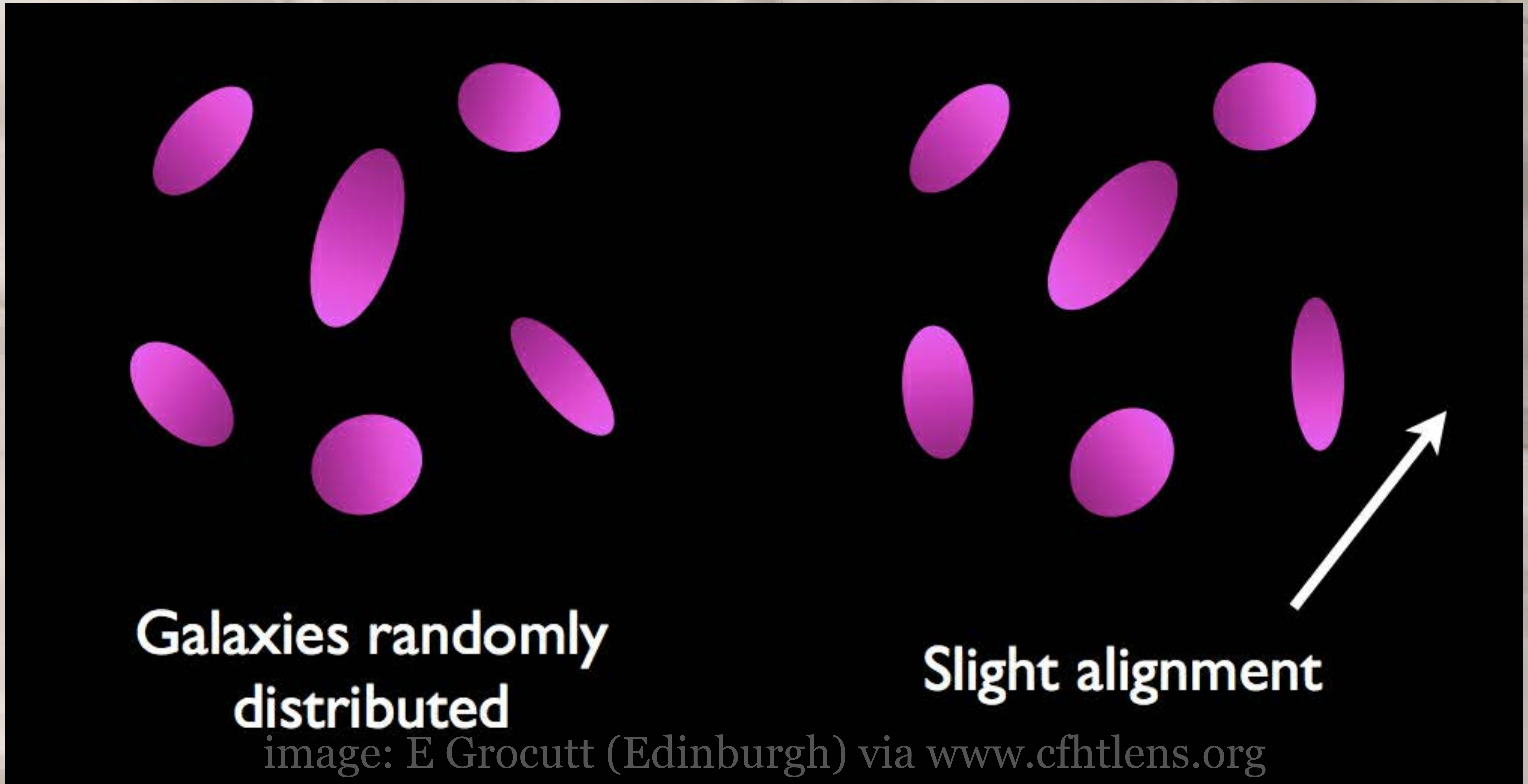
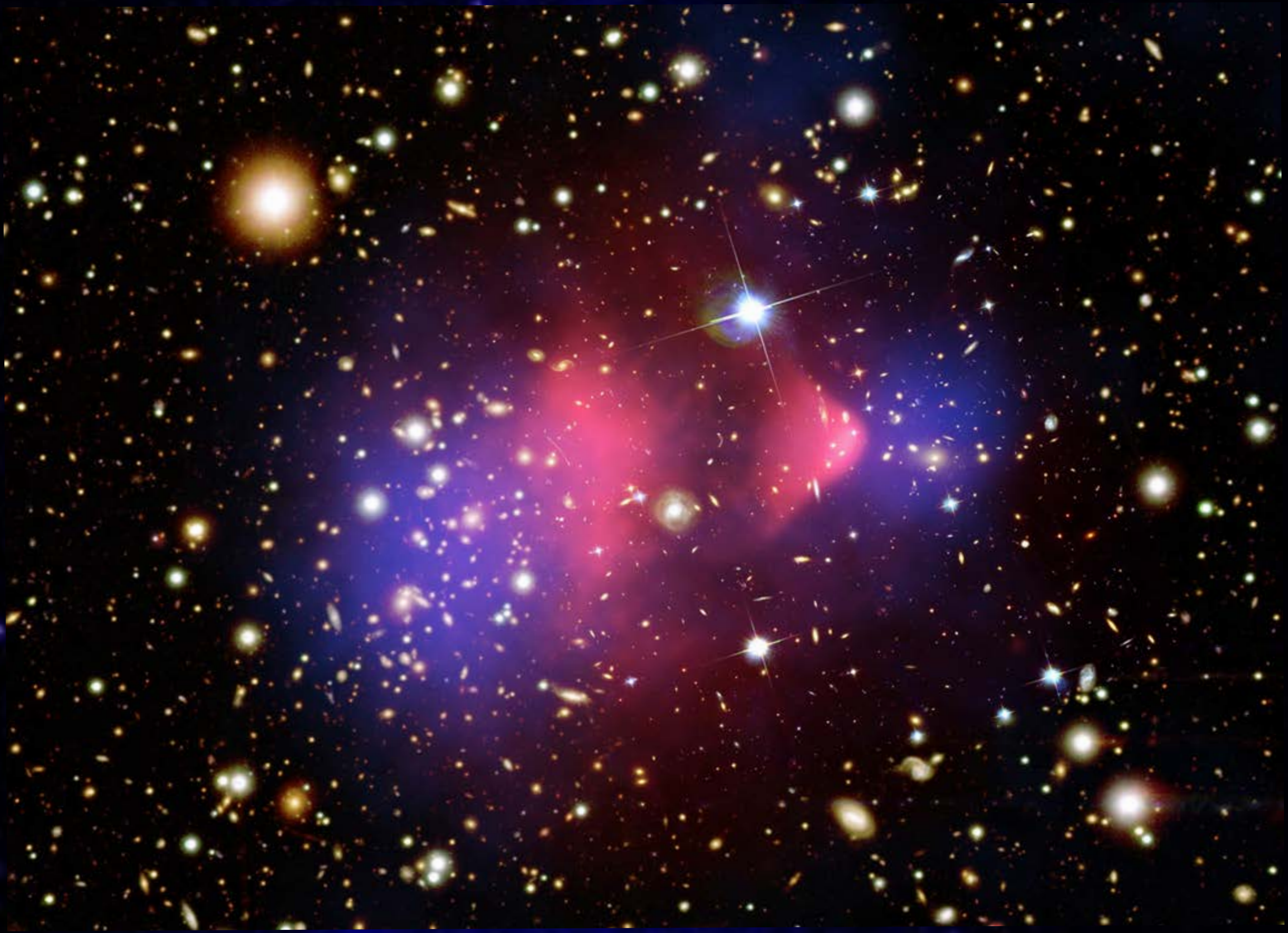


image: E Grocutt (Edinburgh) via www.cfhtlens.org



Lensing in a nutshell

degree of shear

ellipticities/alignments of background sources

redshift distribution of background sources

$$\gamma(\theta) \approx \theta_E / 2\theta$$

$$\approx \left(\frac{8\pi^2 G}{3c^2} \frac{M(R)}{R} \frac{D_{ds}(z_d, z_s)}{D_d(z_d)\, D_s(z_s)} \right)^{1/2}$$

GR physics

2D-projected gravitational potential

geometry (angular diameter distances)

aie … the rub.

– the effects of weak lensing are weak,
so shape measurements must be perfect.
(need to understand the astigmatisms of your telescope)

– there are a finite number of galaxies
in the (observable) universe
… and most of them are very faint!

– there is a fundamental limit to the
shear strength that can be measured.
individual galaxies are off limits.
(Actually, not true! But this is another story …)

e pluribus unum (stacking)

many insignificant measurements can be combined to get one significant measure of the population average.

$$\left(\frac{\langle\gamma_i\rangle}{\Delta\langle\gamma_i\rangle}\right)^2 = \sum_i \left(\frac{\gamma_i}{\Delta\gamma_i}\right)^2$$

$$\Delta\langle\gamma_i\rangle \sim \frac{\langle\Delta\gamma_i\rangle}{\sqrt{N}}$$

e pluribus unum (stacking)

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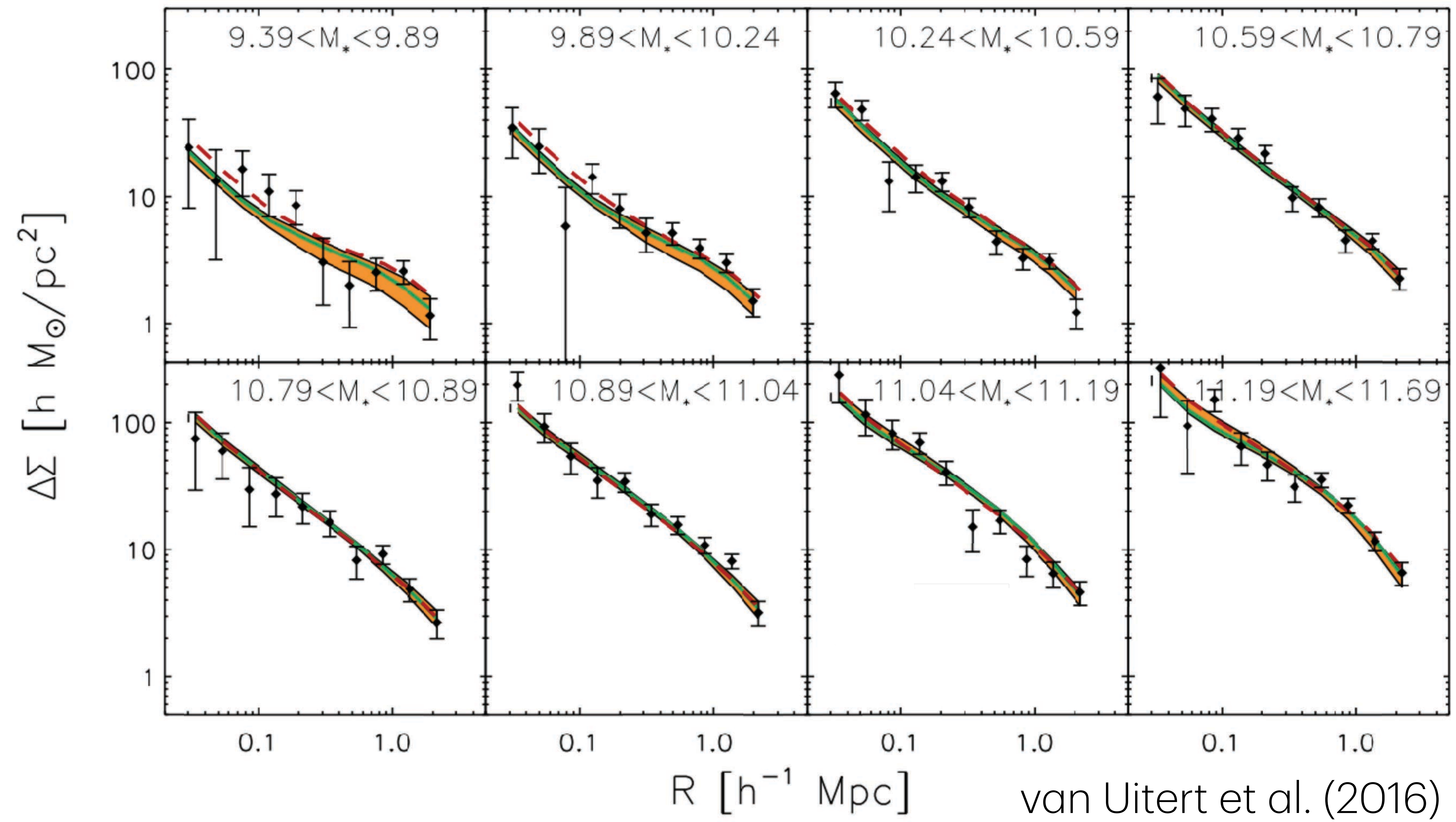

van Uitert et al. (2016)

e pluribus unum (stacking)

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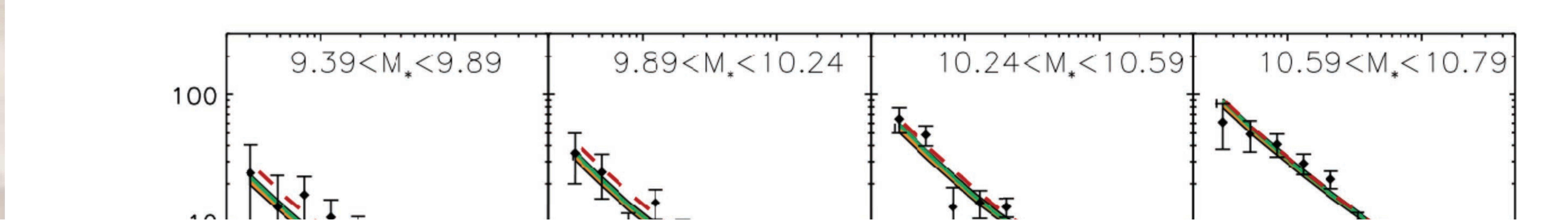

	M1 [9.39,9.89]		M2 [9.89,10.24]		M3 [10.24,10.59]		M4 [10.59,11.79]		M5 [10.79,10.89]		M6 [10.89,11.04]		M7 [11.04,11.19]		M8 [11.19,11.69]	
	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$	N_{lens}	$\langle z \rangle$
All	15819	0.17	19175	0.21	24459	0.25	11475	0.29	3976	0.31	3885	0.32	1894	0.34	1143	0.35
Cen ($N_{fof} \geqslant 5$)	15	0.08	55	0.12	185	0.16	242	0.18	185	0.19	276	0.21	241	0.23	209	0.26
Sat ($N_{fof} \geqslant 5$)	1755	0.14	2392	0.18	3002	0.22	1267	0.26	388	0.27	343	0.27	138	0.29	65	0.32

$R\ [h^{-1}\ Mpc]$

van Uitert et al. (2016)

e pluribus unum (stacking)

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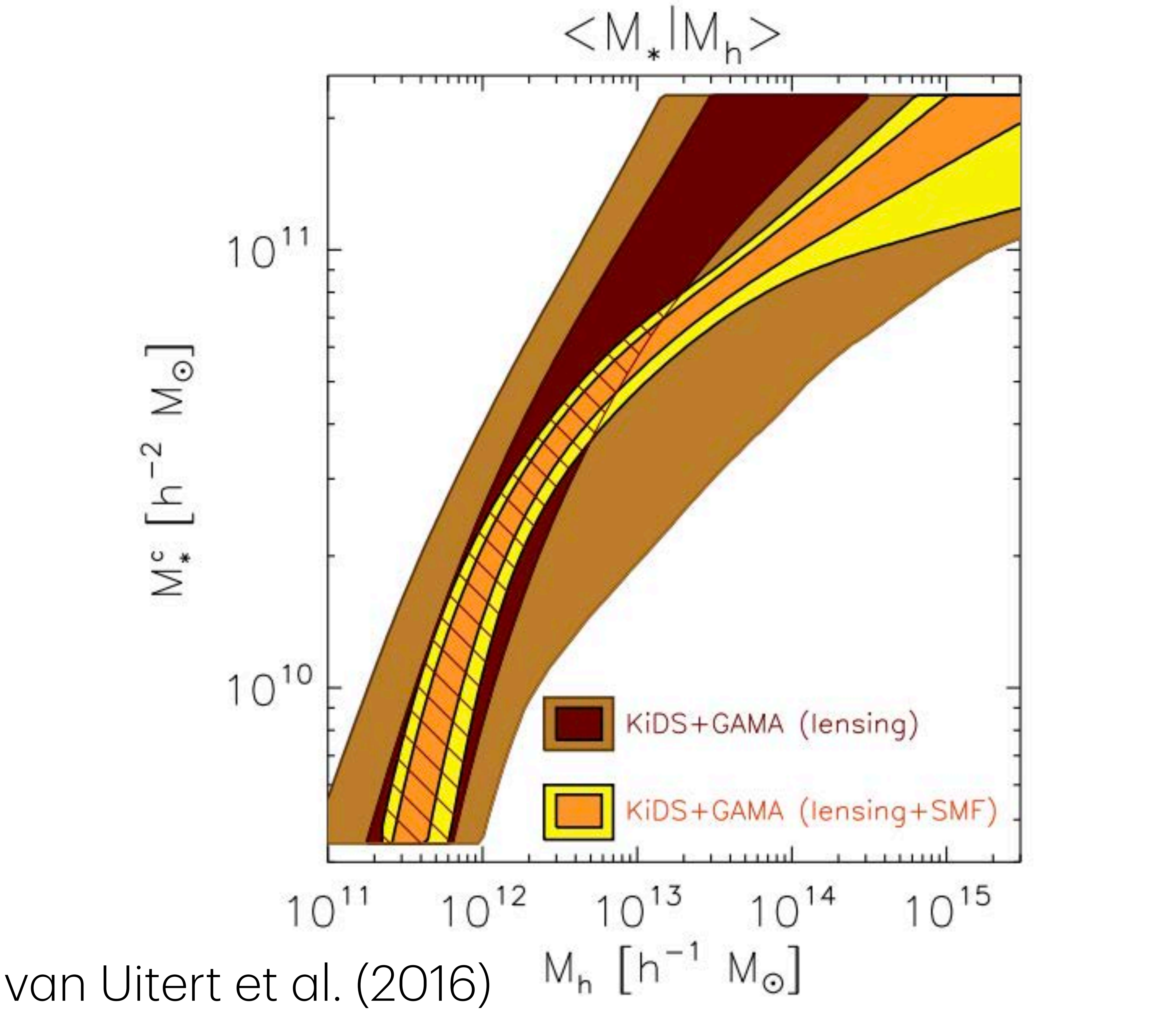
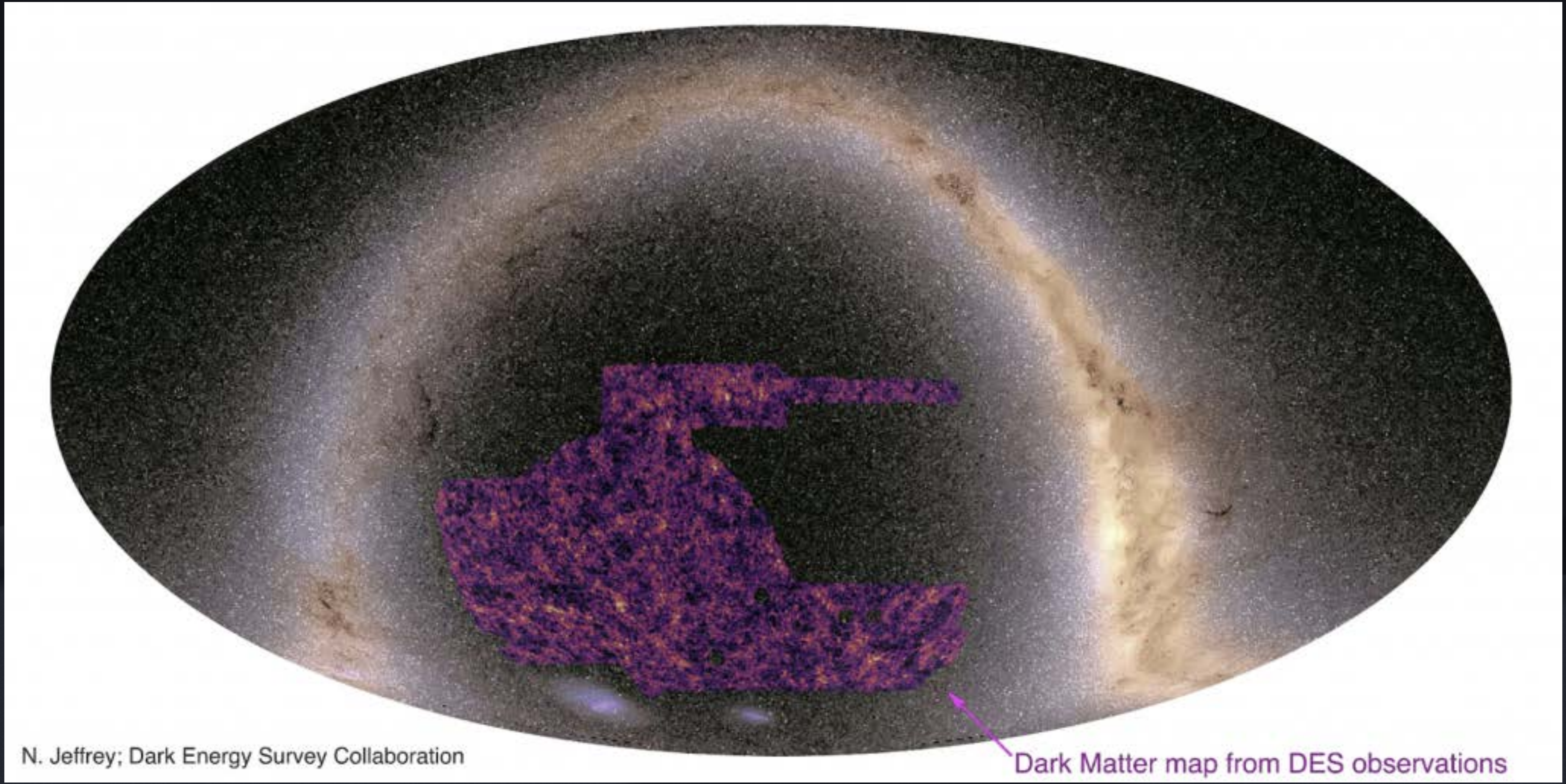
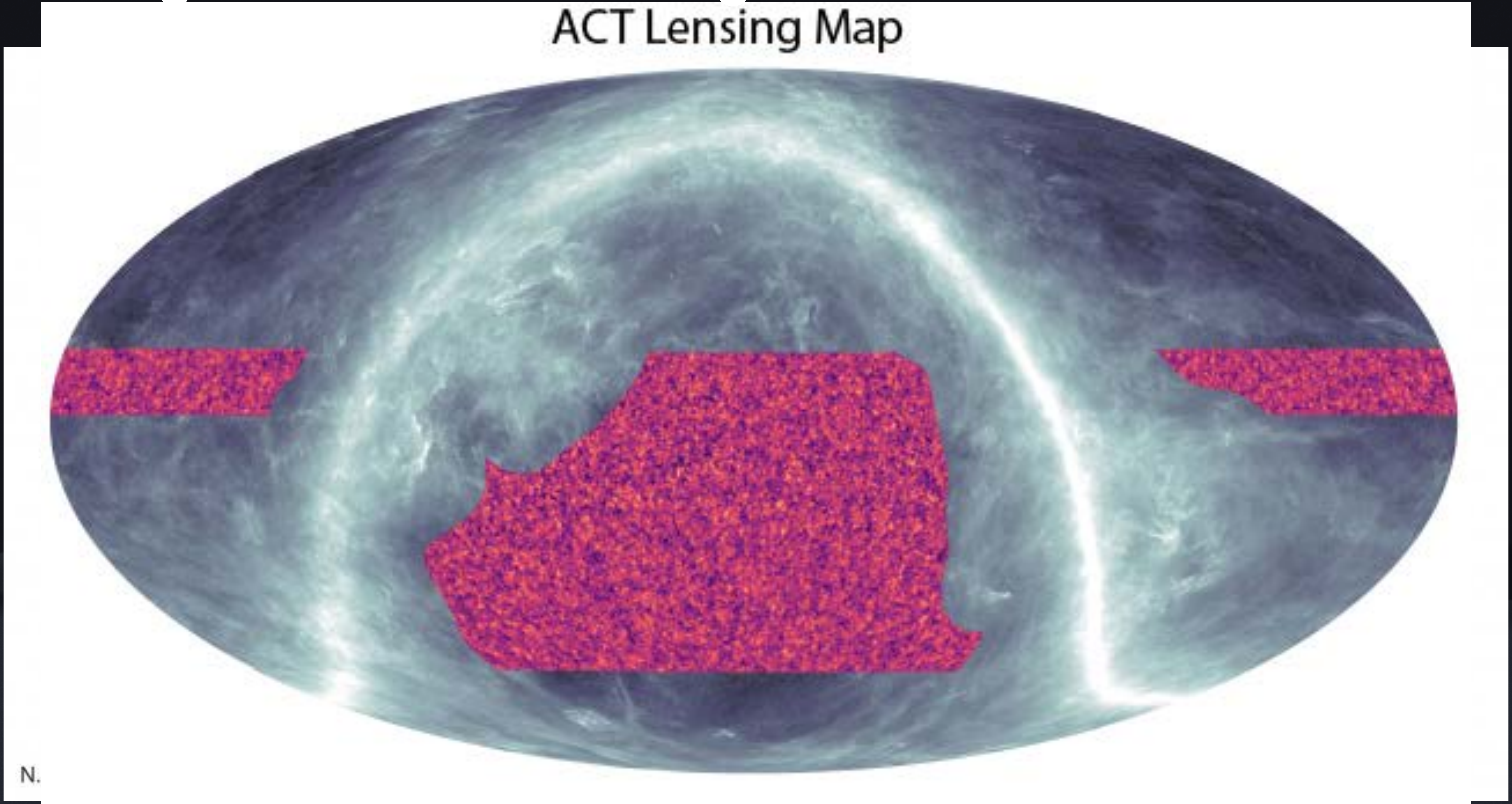


van Uitert et al. (2016)

Weak gravitational lensing: the DES dark web



Weak gravitational lensing: the ACT dark web



~~measuring~~ estimating mass from gravitational lensing

If you understand (ie, if you can model):

1. the intrinsic shape distribution, and

2. the redshift distribution

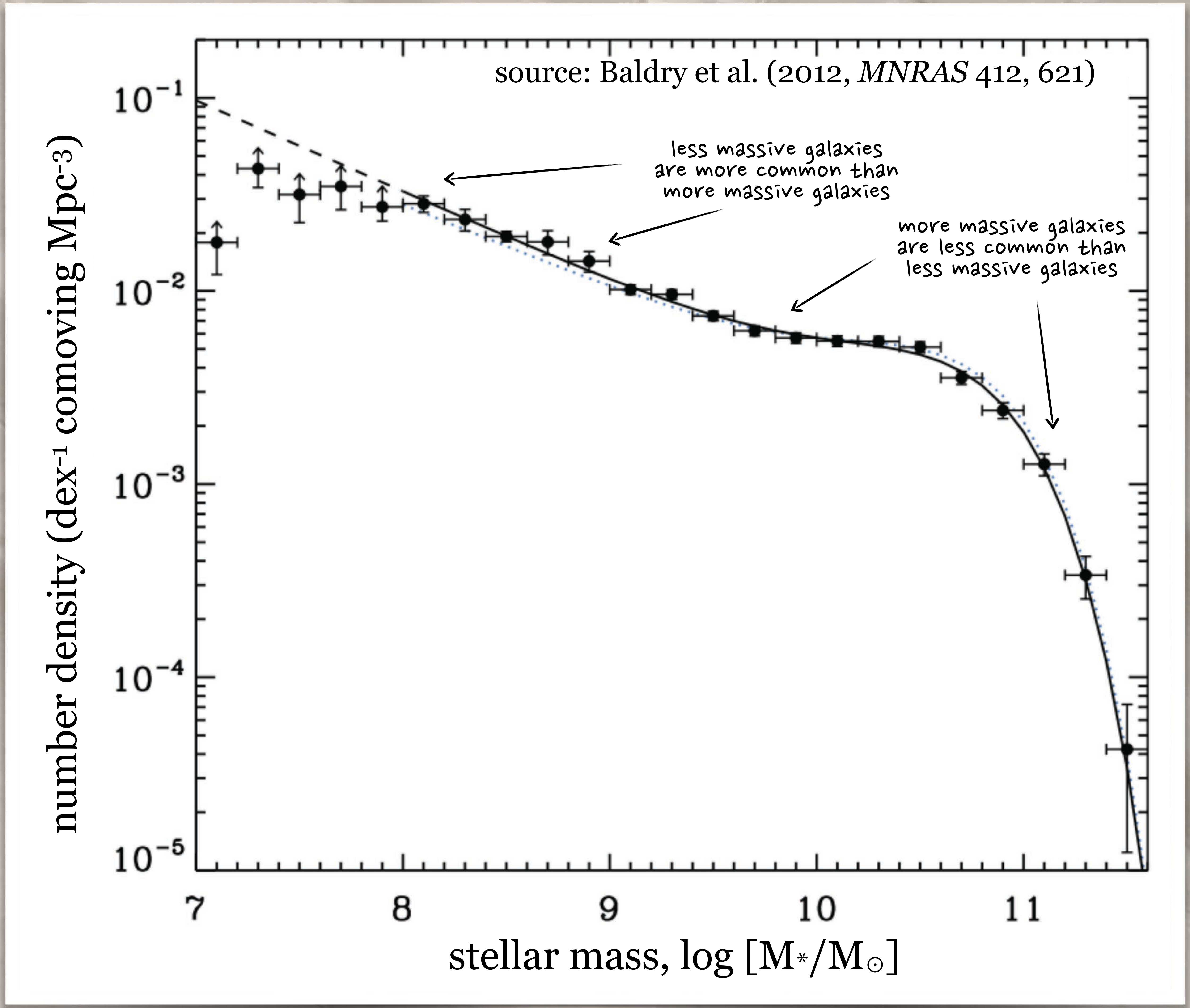
of the 'background' galaxy population,

then you can exploit the physical phenomenon of (weak) gravitational lensing to map the (2D projected) gravitational potential (thus mass) of cluster- and galaxy-scale mass concentrations.

~~measuring~~ estimating the masses of galaxies

1. mass from **luminosity**
2. mass from **dynamics**
3. mass from **gravitational lensing**
4. mass from **clustering**

finally, the mass function: How many galaxies are there?



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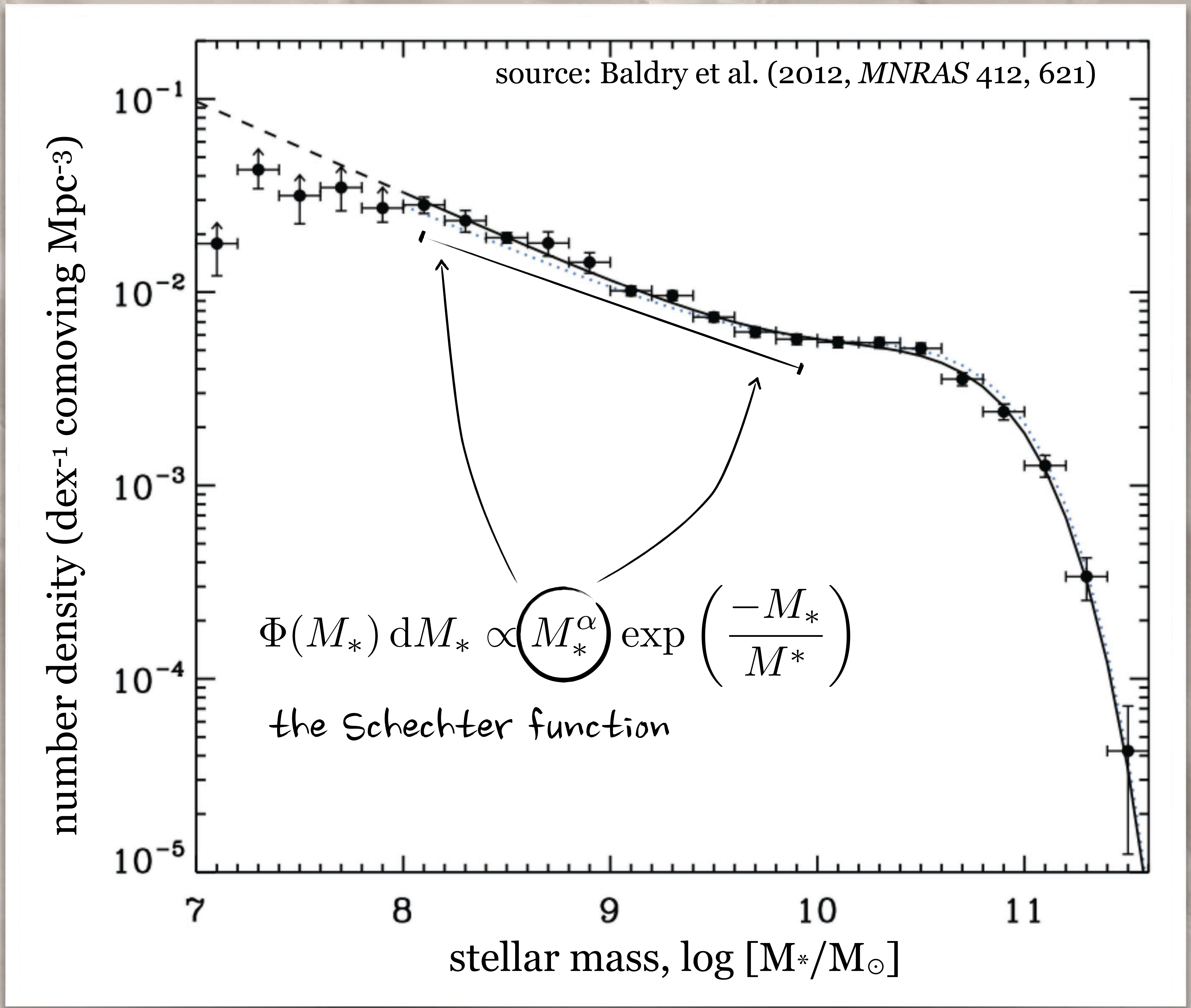

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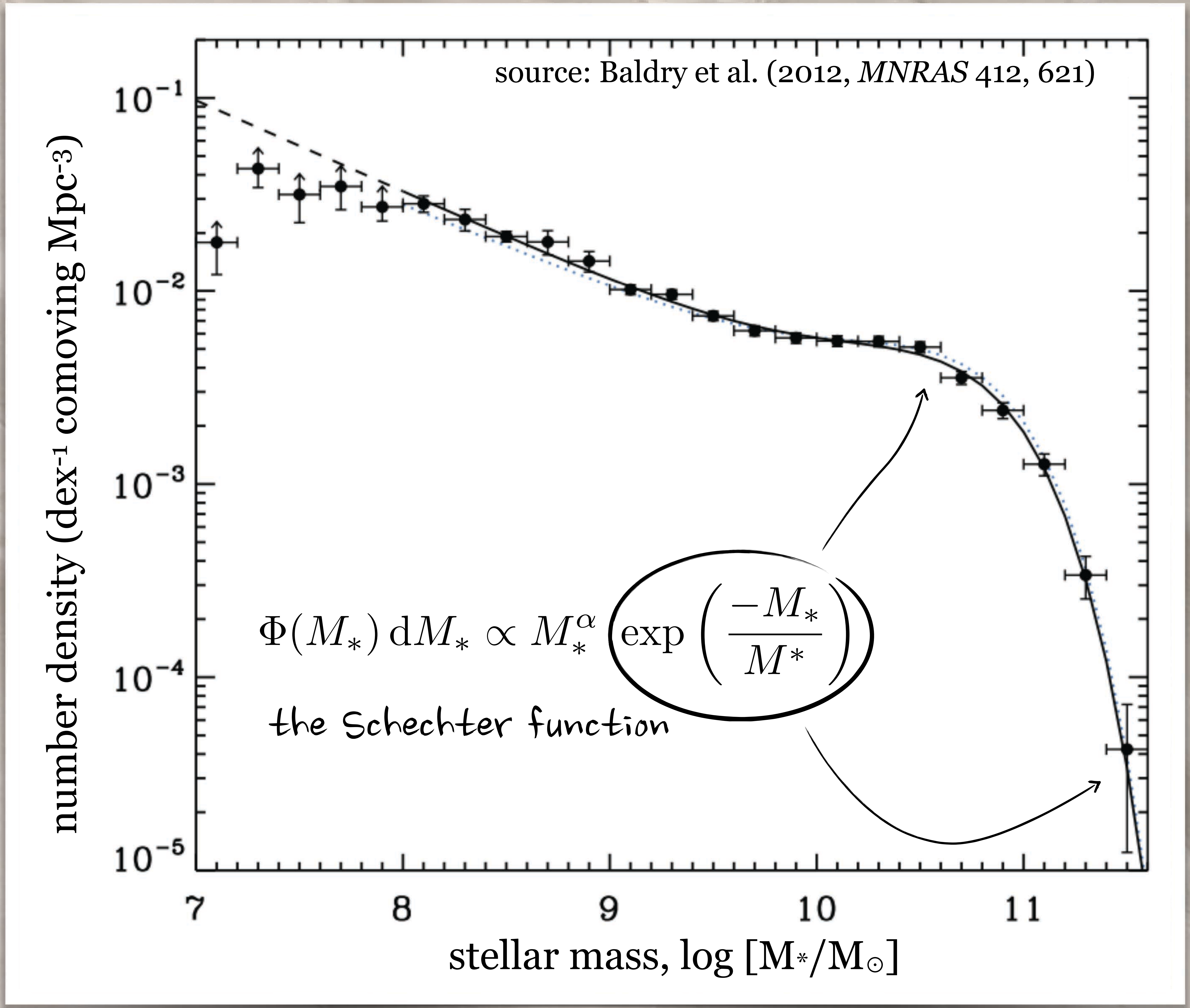
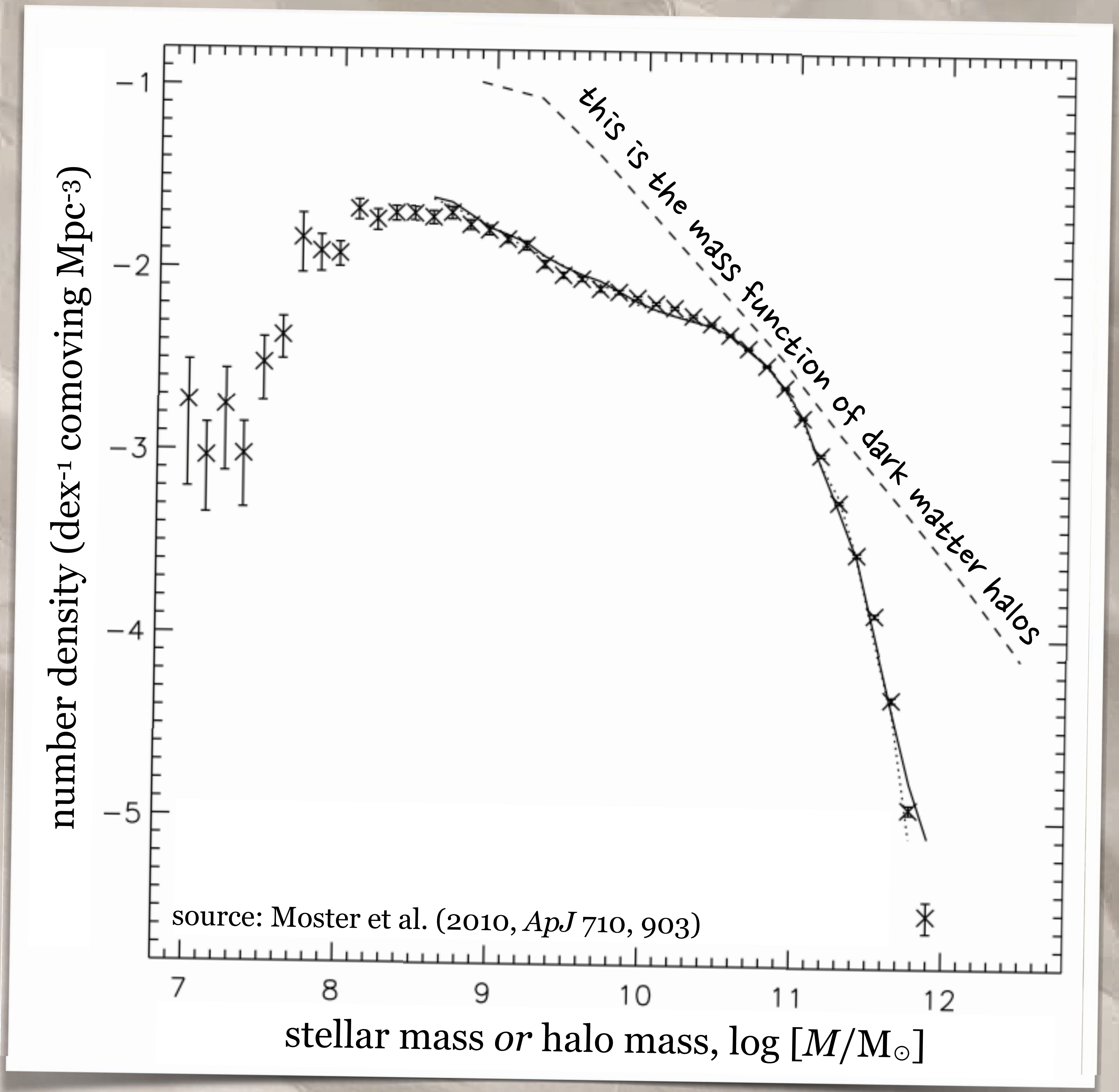
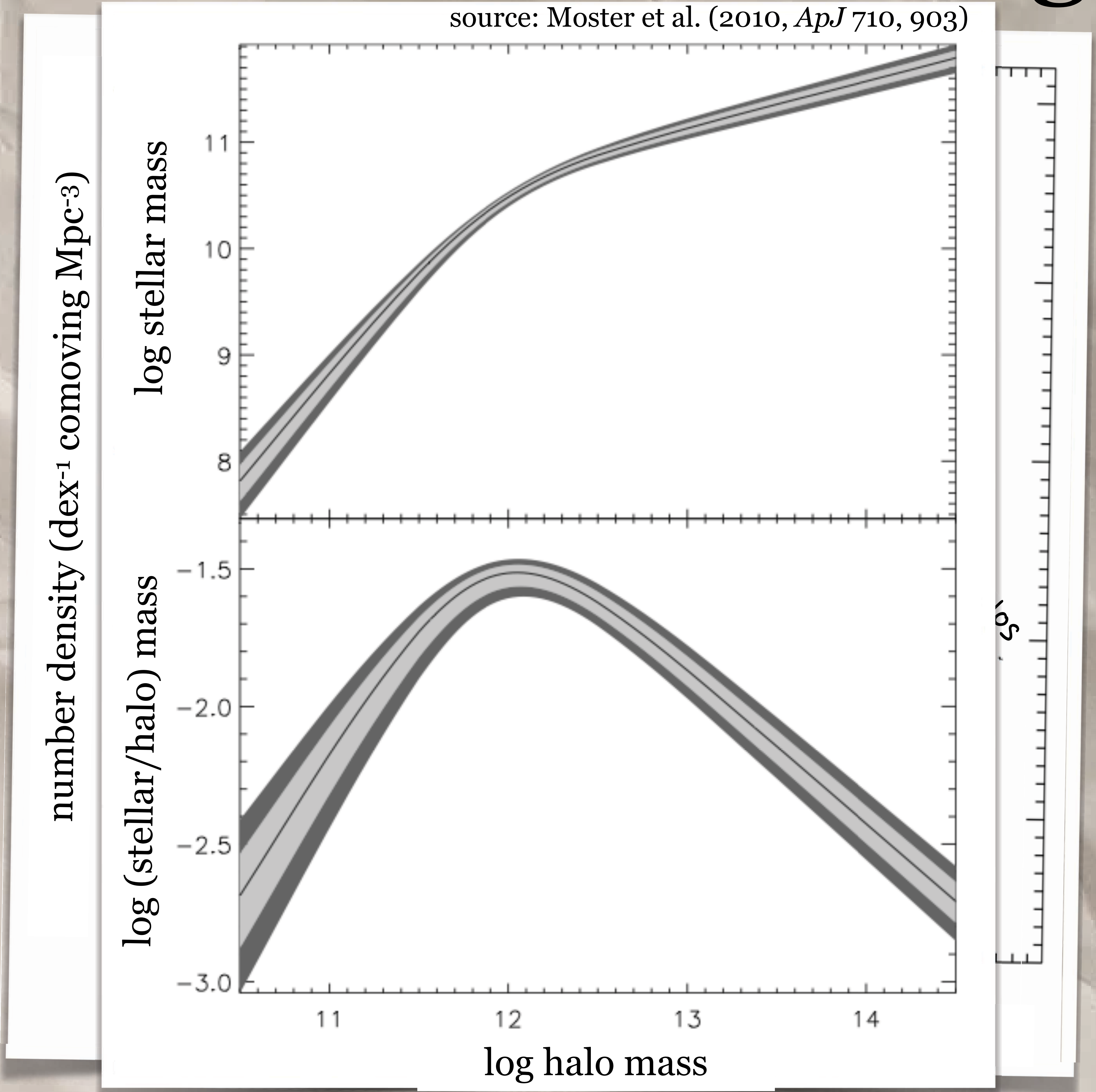


abundance matching



abundance matching

source: Moster et al. (2010, *ApJ* 710, 903)



abundance matching

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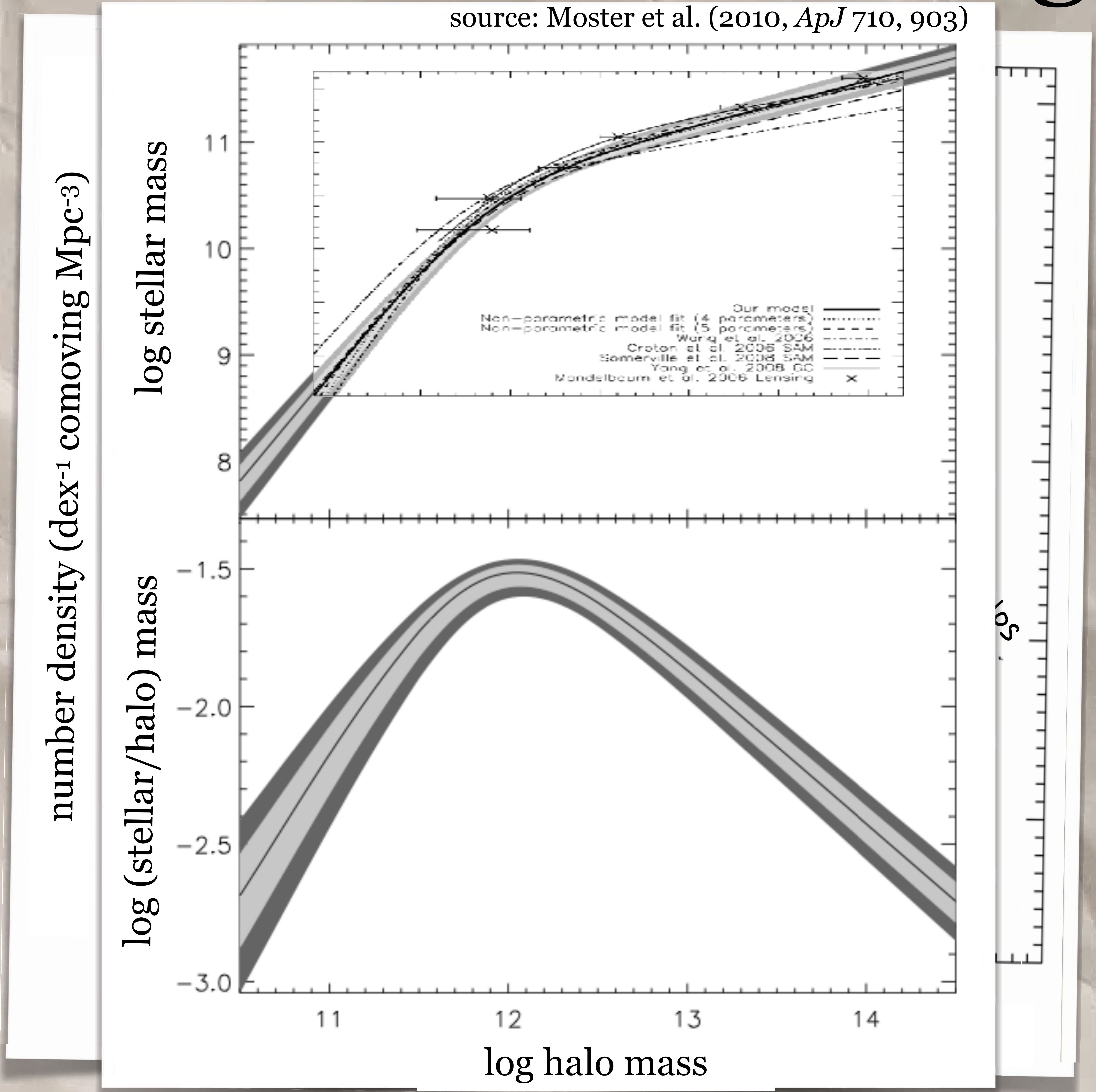
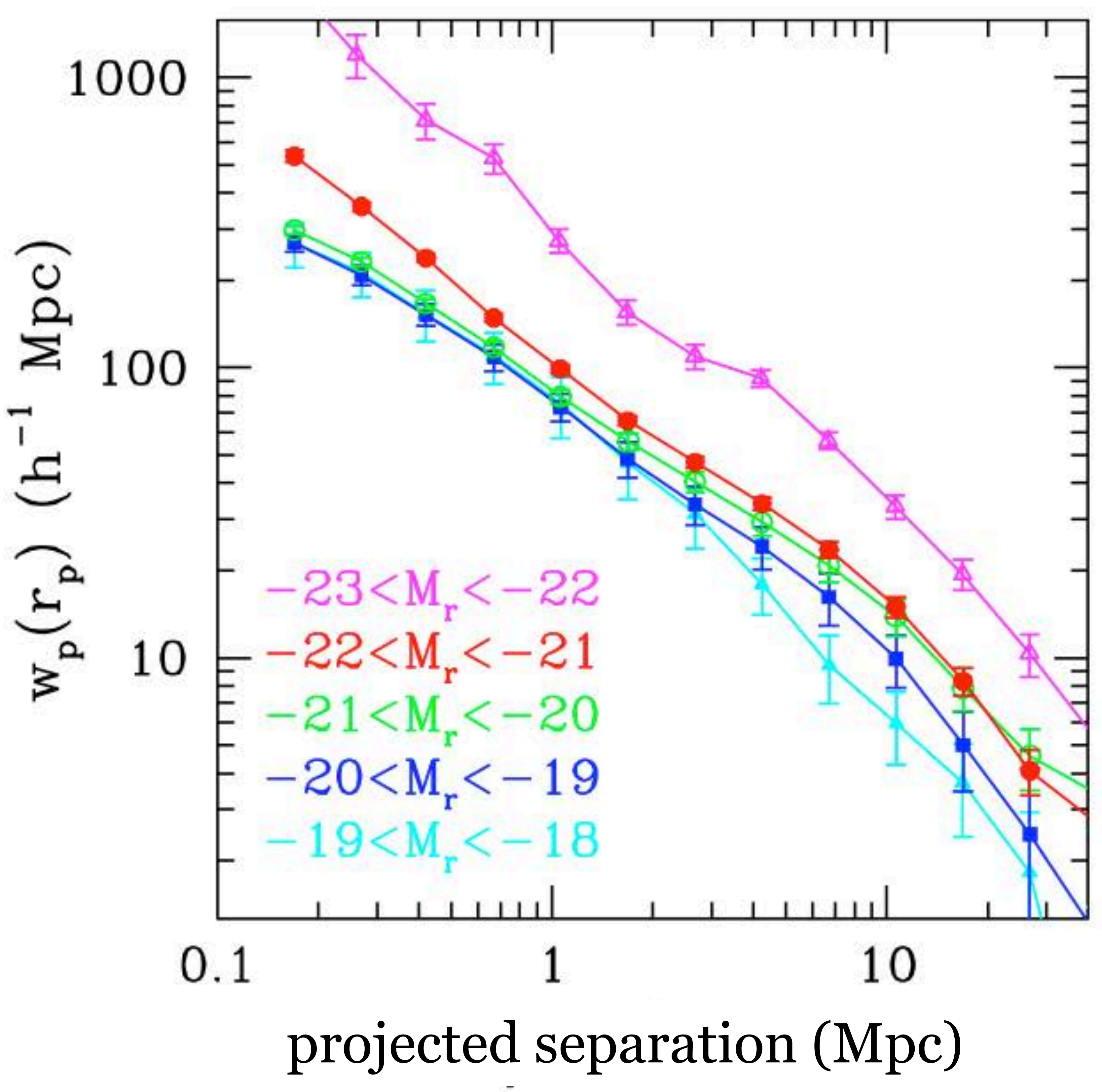
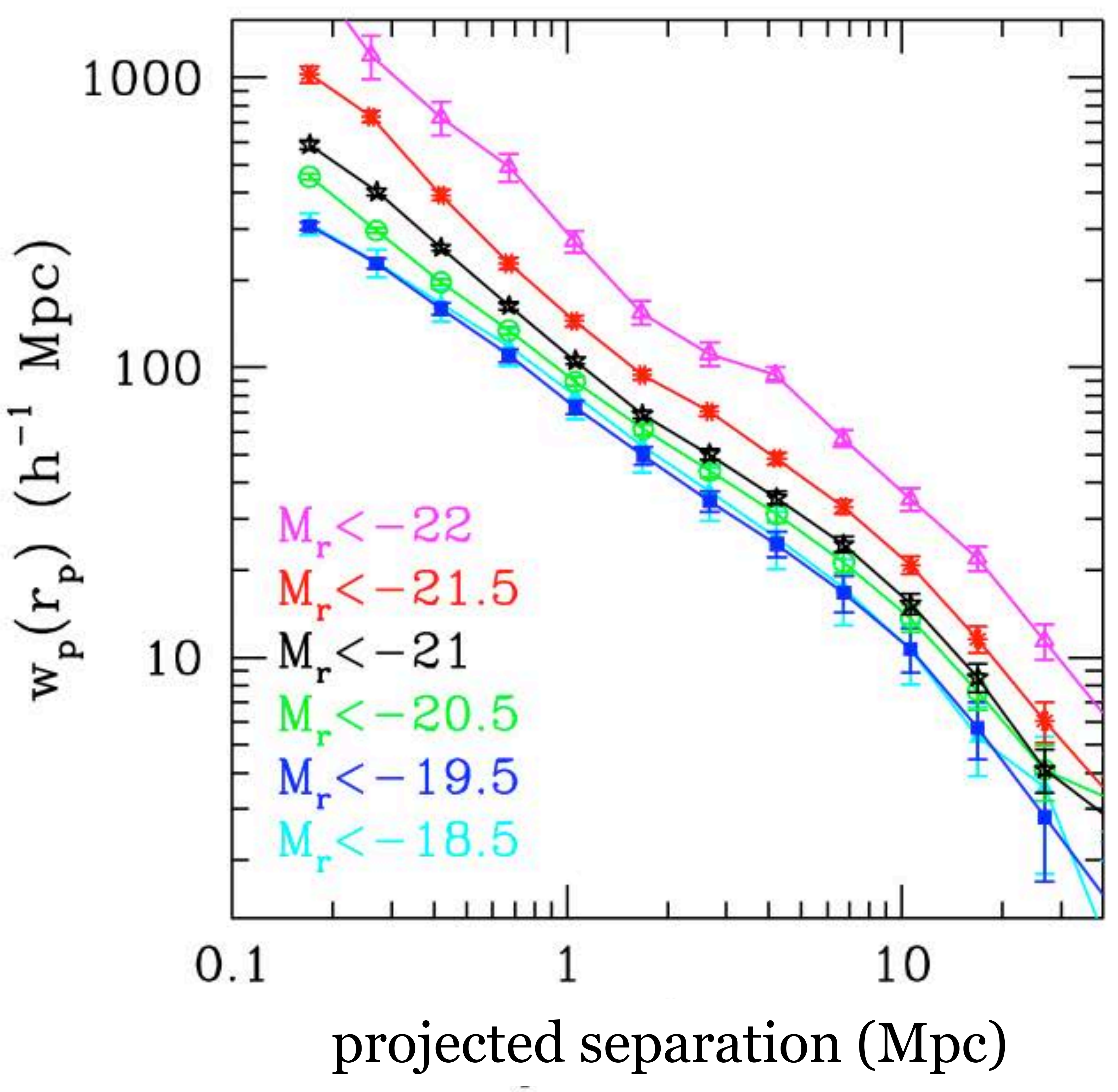


the correlation function:

source: Zehavi et al. (2012, *ApJ* 736, 59)





given that i have a galaxy at one location,
what are the odds of me finding another one
at some particular distance away?

halo occupation distribution modelling

if you know :

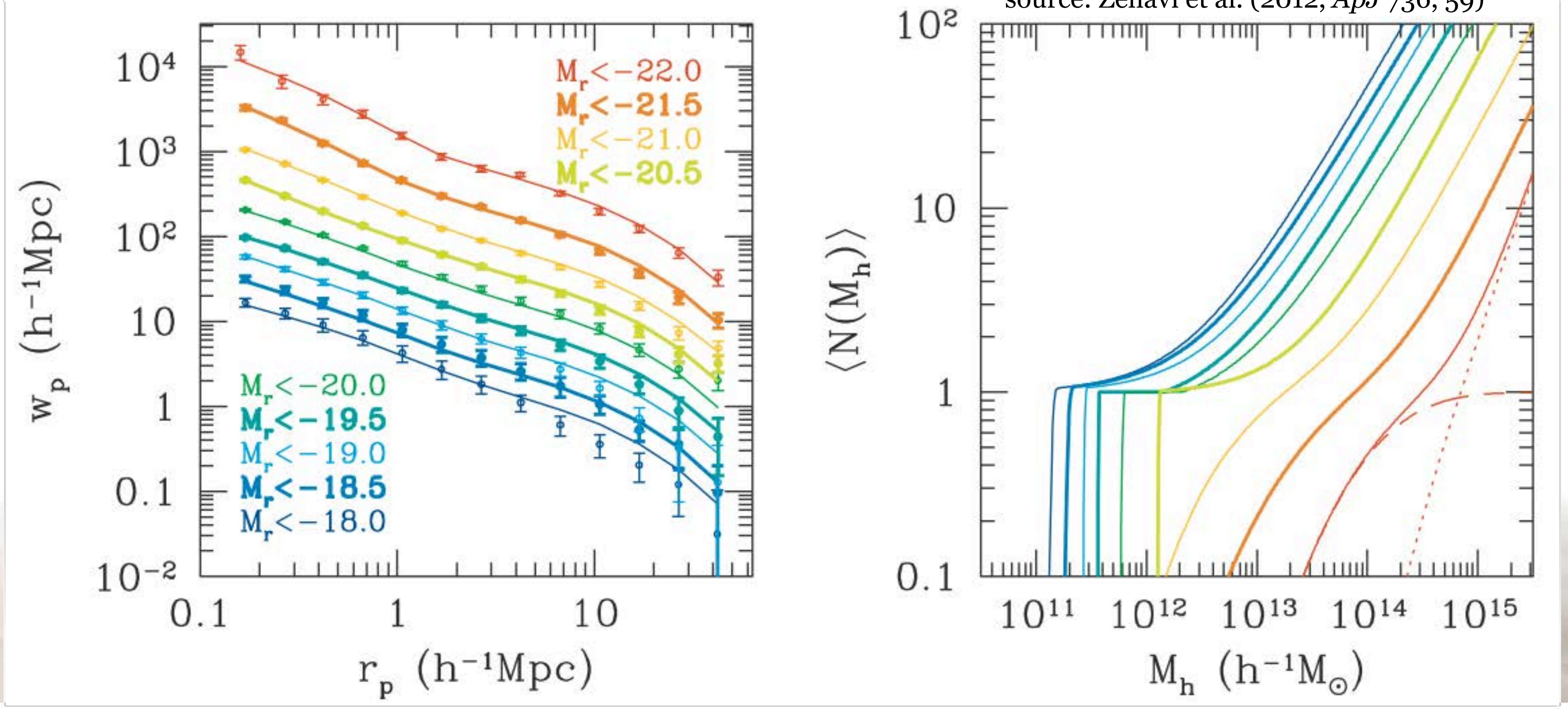
- the galaxy mass/luminosity function
- the galaxy correlation function
- the halo mass function; and
- the halo correlation function

then you can combine them all to get

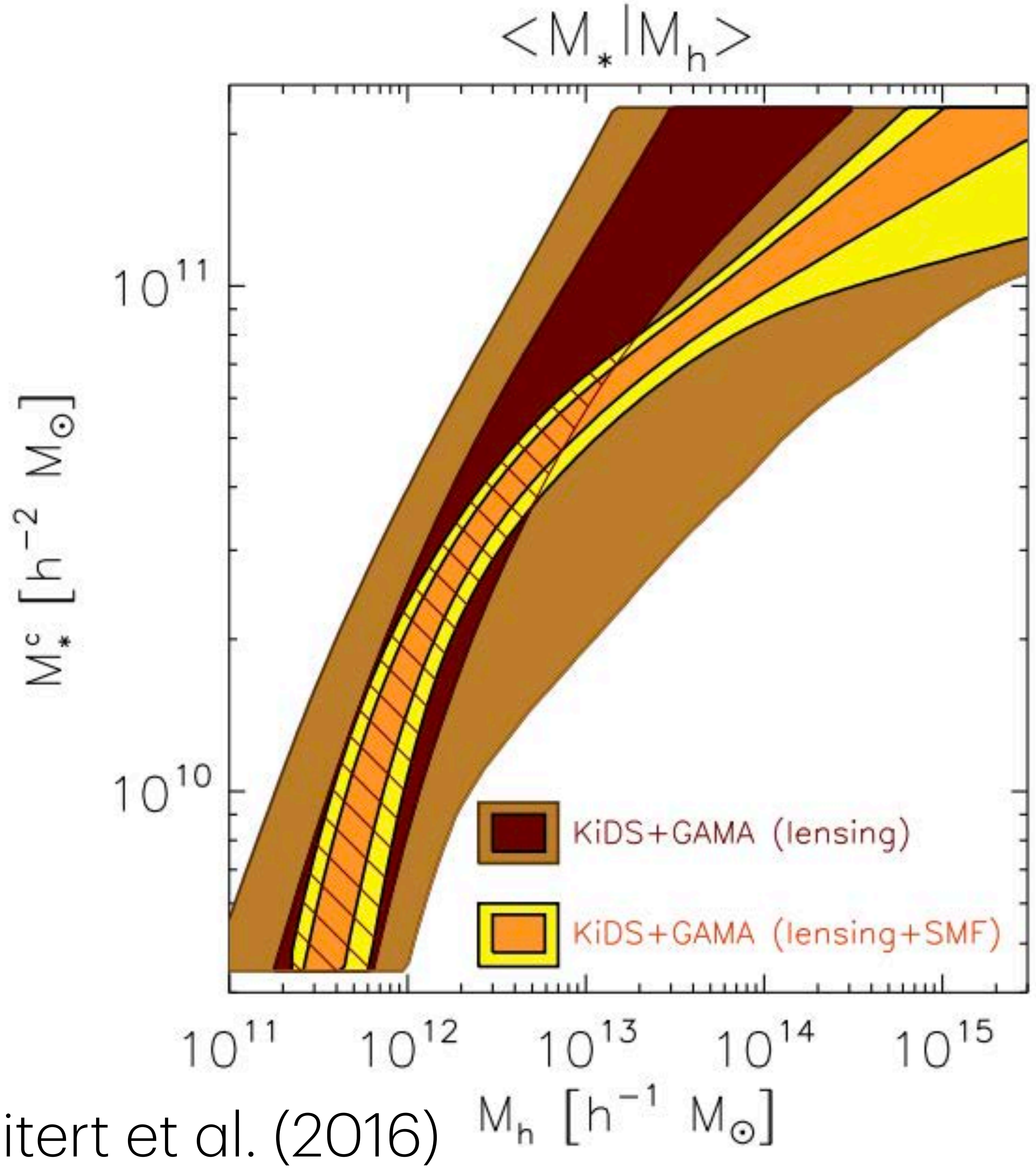
a self-consistent description which tells you
the average number of galaxies per halo,
as a function halo mass.

halo occupation distribution modelling

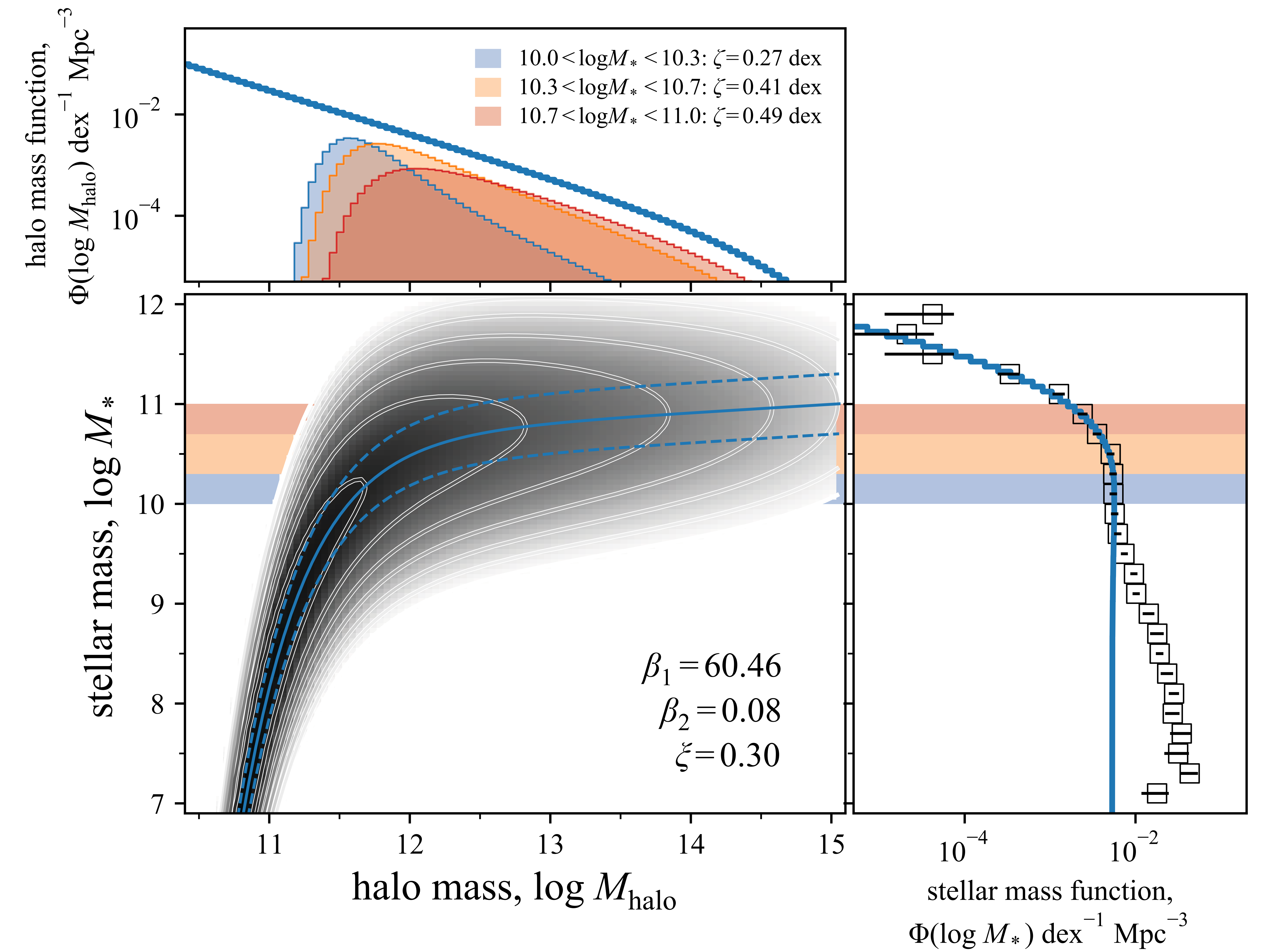
source: Zehavi et al. (2012, *ApJ* 736, 59)



a word of caution: halo modelling and weak lensing



van Uitert et al. (2016)



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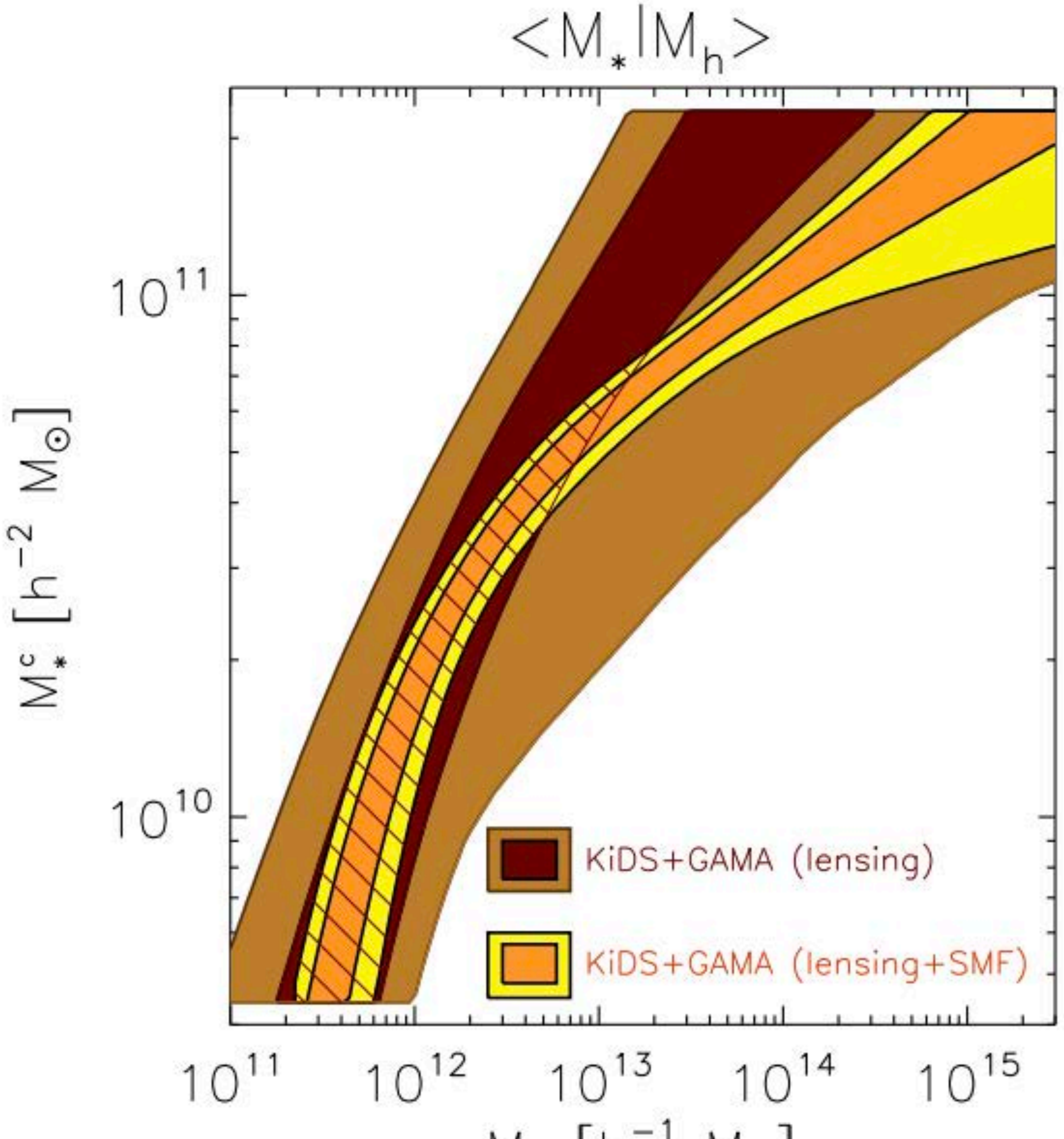
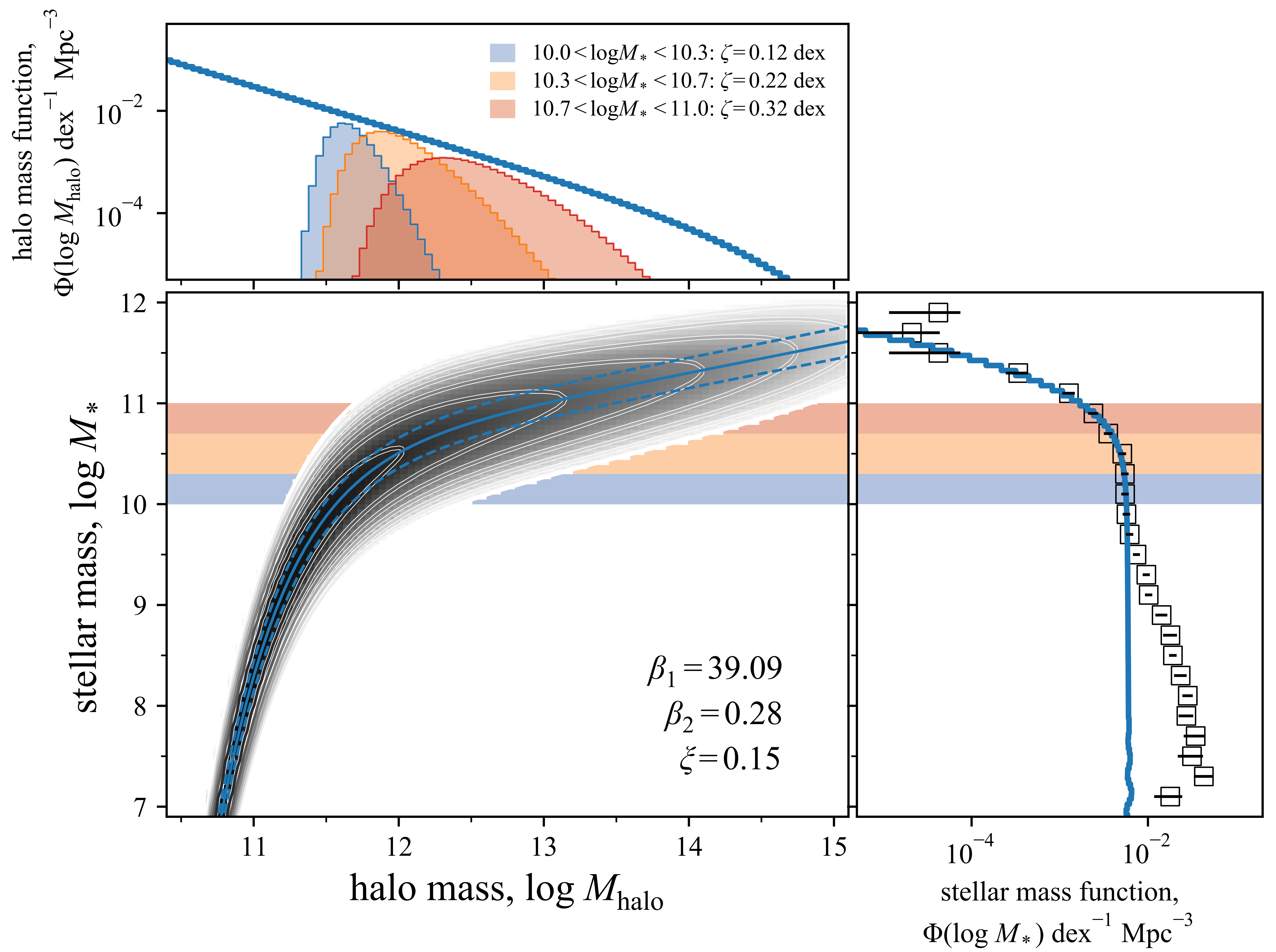
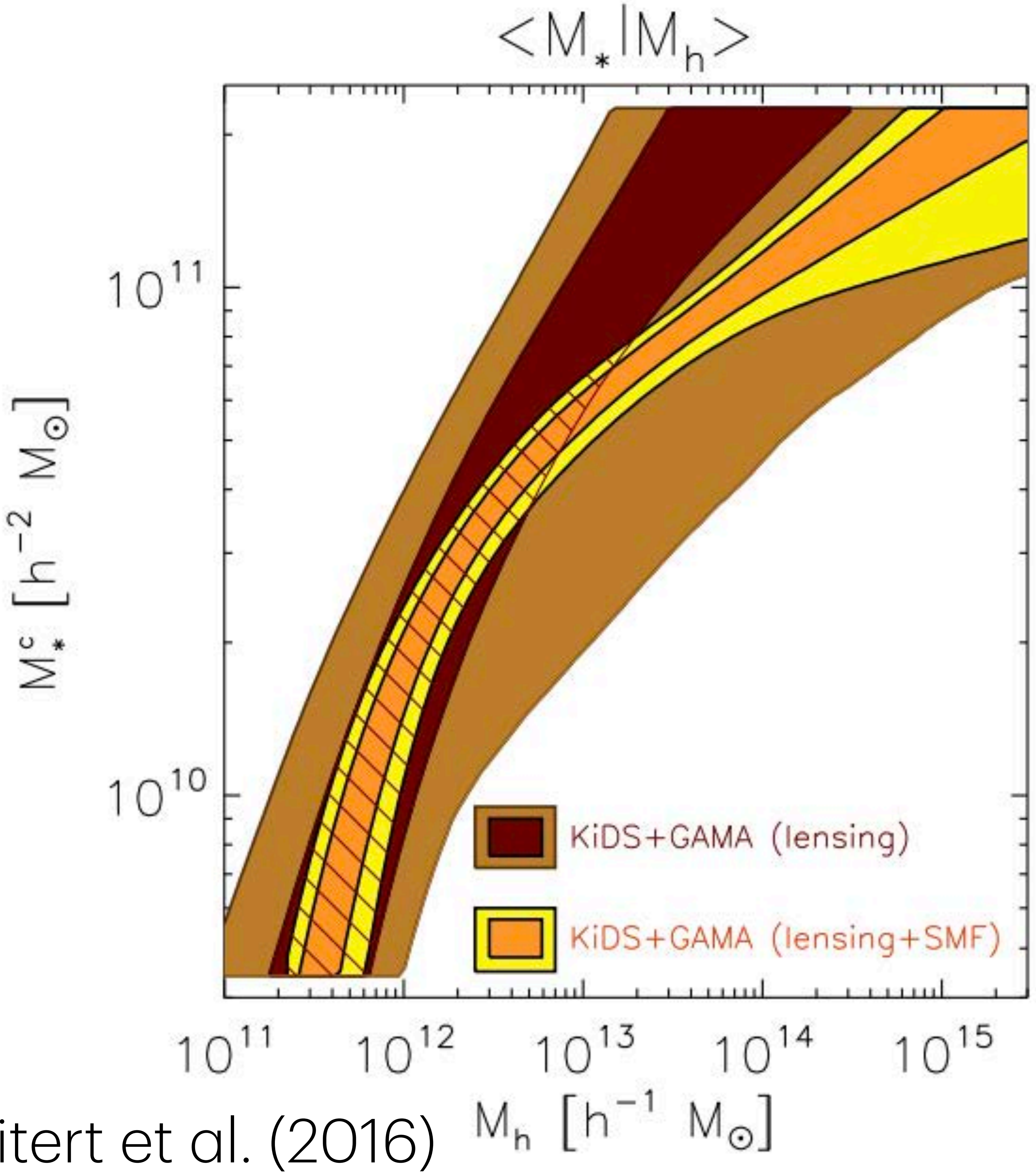


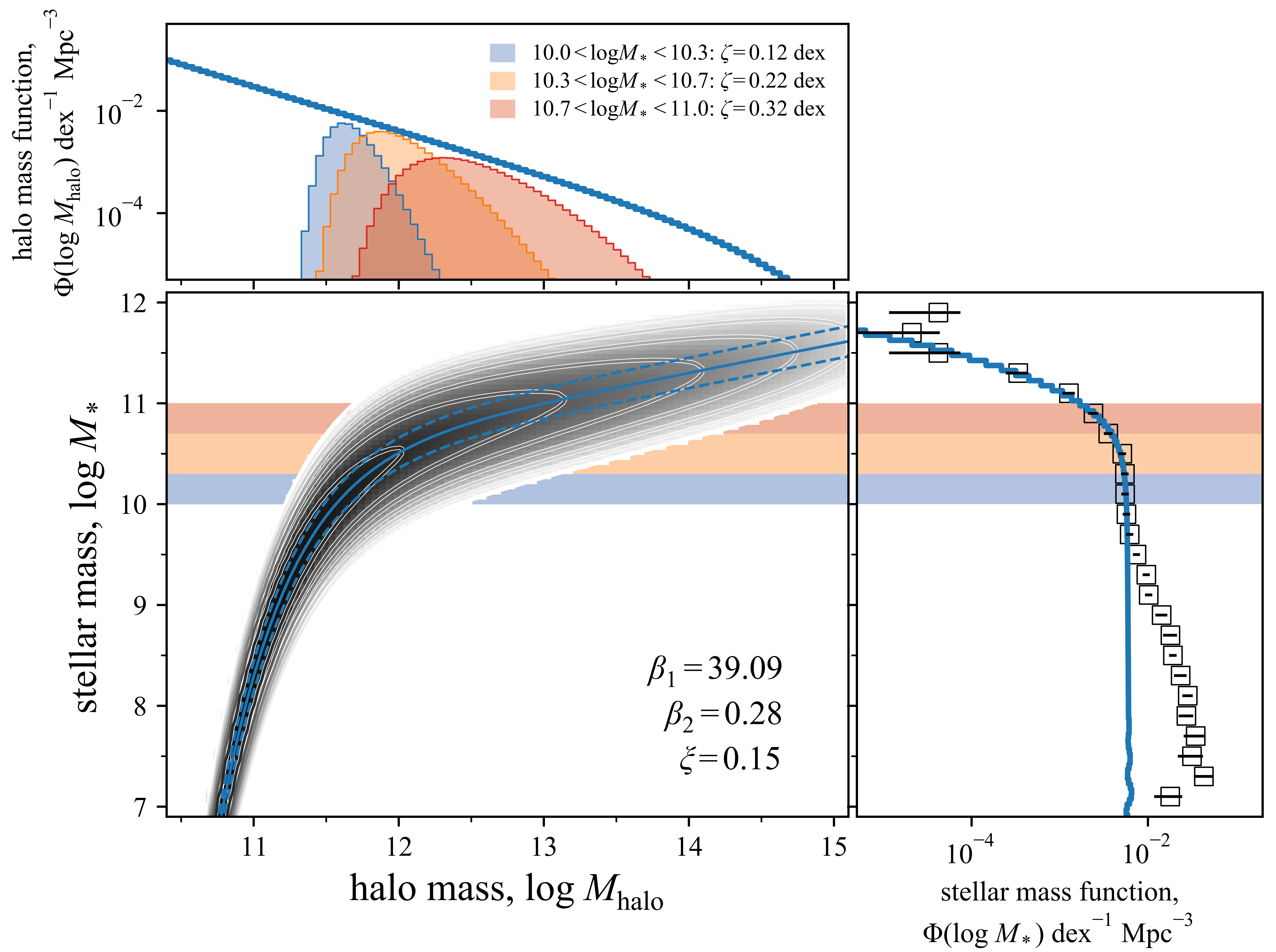
van Uitert et al. (2016)



while i'm here: what is Eddington bias?



van Uitert et al. (2016)



~~measuring~~ estimating the masses of galaxies

1. mass from **luminosity**
2. mass from **dynamics**
3. mass from **gravitational lensing**
4. mass from **clustering**

Measuring the halo mass function ~directly

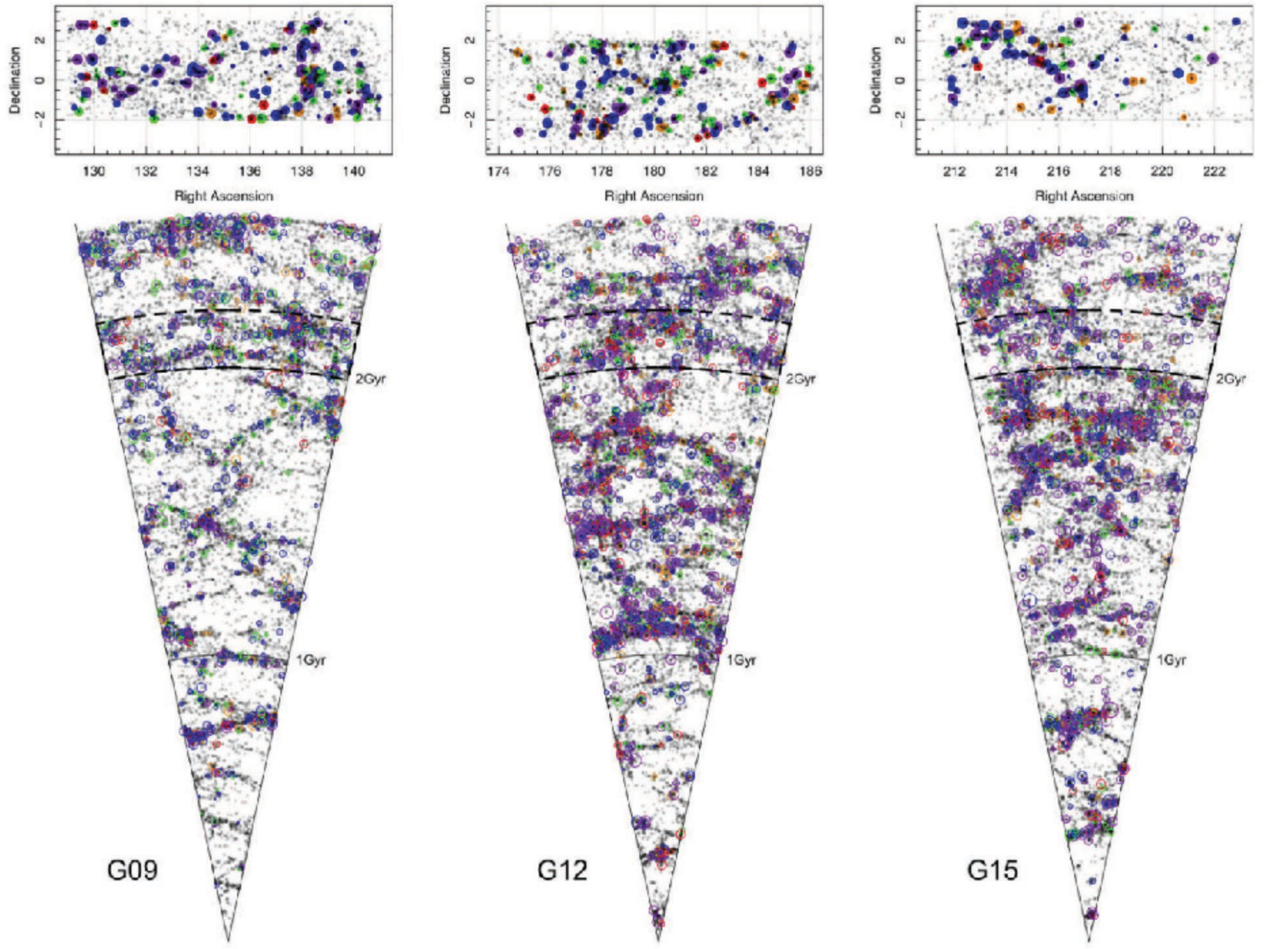


Figure 2. Each panel shows a cone plot of the GAMA group (coloured circles) and galaxy (grey dots) distributions to a maximum redshift of 0.3, indicating lookback time (lower cones), and in (upper panels) right ascension and declination for a narrow redshift slice indicated by the dashed rectangles in the lower panels. The group circles are coloured according to multiplicity, with 'blue', 'green', 'orange', 'red', and 'purple' denoting multiplicities ($N_{\rm FoF}$) of 3, 4, 5, 6, and >6, respectively. Circle sizes are scaled according to $\log_{10}(M_{\rm FoF})$.

Measuring the halo mass function ~directly

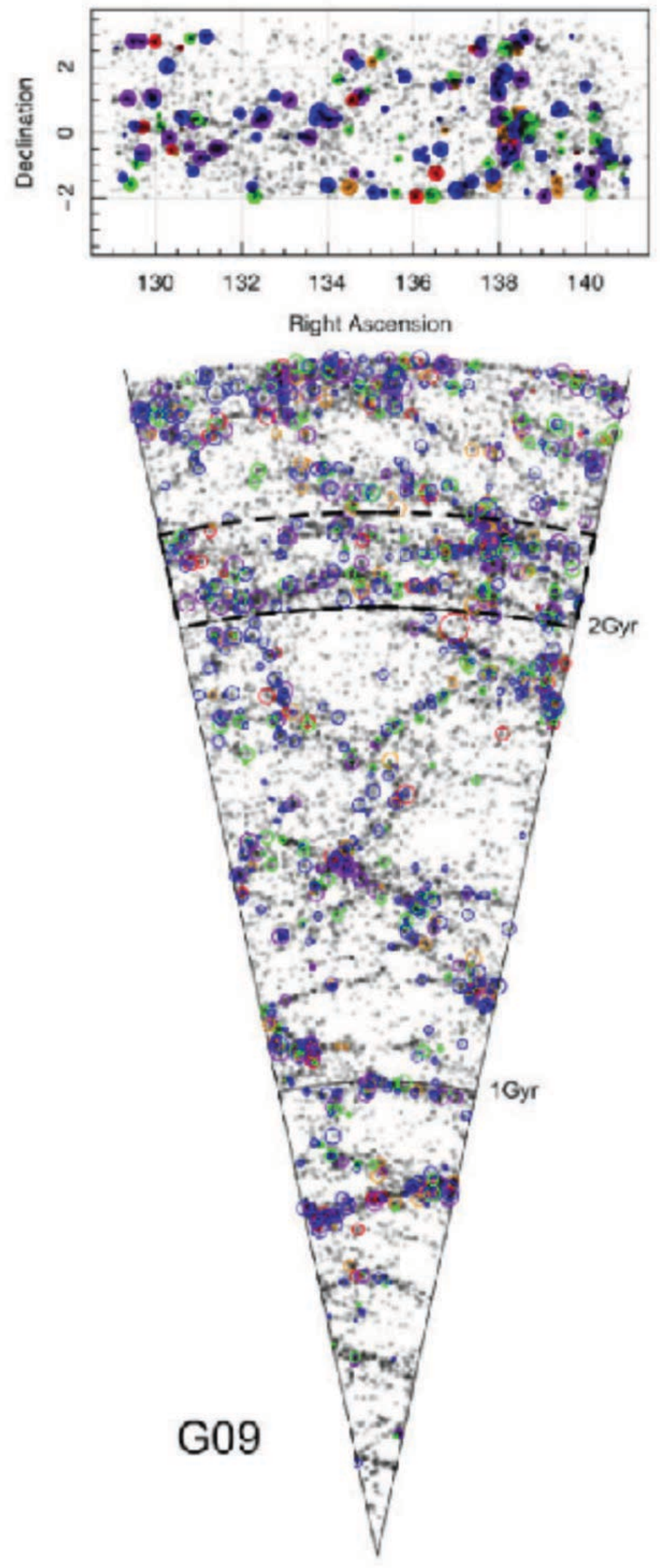


Figure 2. Each panel shows a cone plot of the GAMA lookback time (lower cones), and in (upper panels) rig panels. The group circles are coloured according to m and >6, respectively. Circle sizes are scaled according

2154 *S. P. Driver et al.*

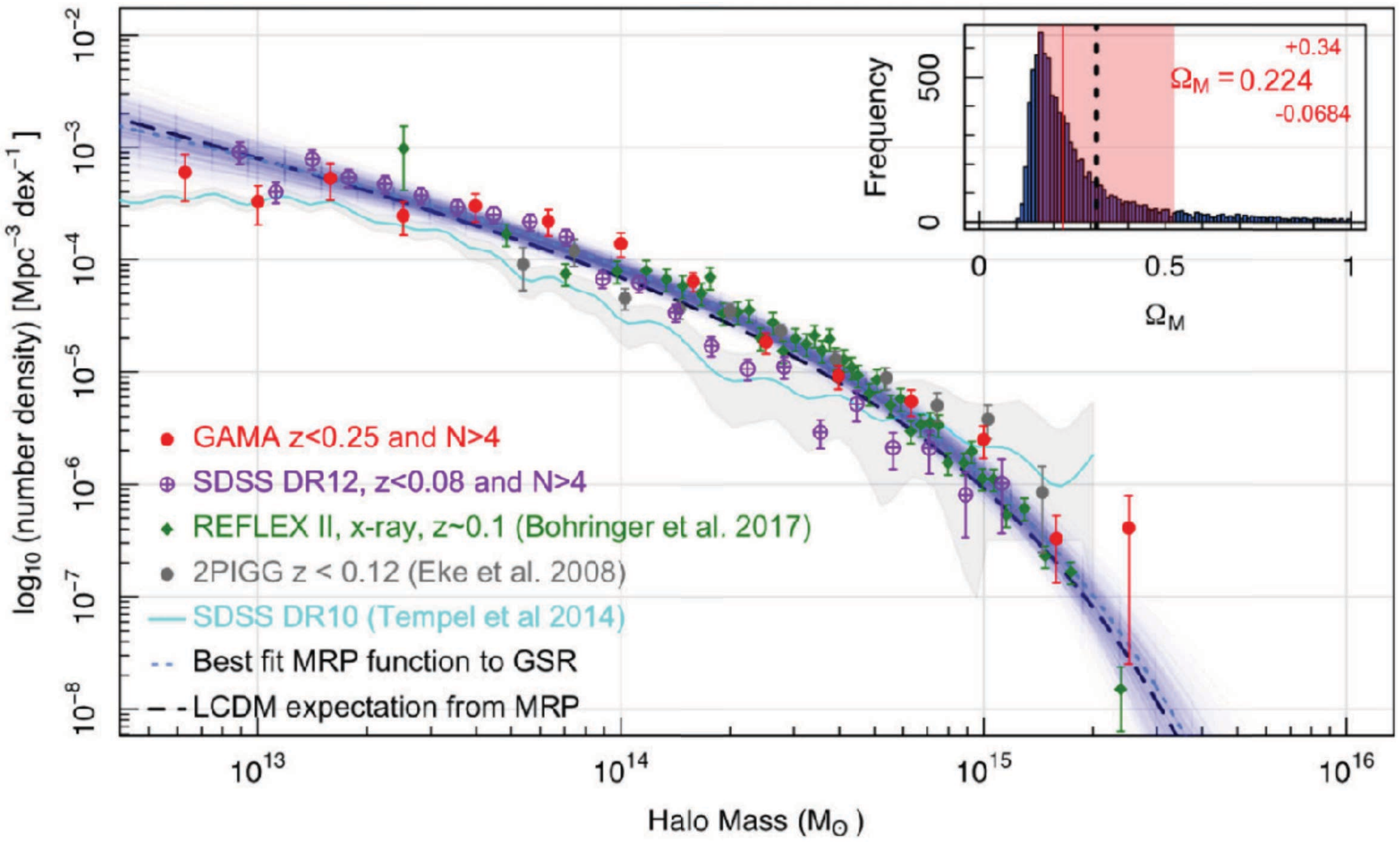


Figure 11. The combined empirical HMF data (as indicated). Shown as black and blue dashed lines are the ΛCDM prediction and the best MRP function fit to the combined GAMA, SDSS, and REFLEX II data along with the spread of MRP fits in blue that show the results from our Monte Carlo refitting. The inset panel shows the integral of the Monte Carlo MRP fits to zero mass (blue histogram) with the red band showing the 1σ error range. The vertical black dashed line shows the Planck 2018 value for Ω_M.

assumption is the mother of all modelling

know thyself (and others).

doubt others (and thyself).

play.


4HS
c. 2030
Everything, Everywhere, ~~All at Once~~