Testing gravity with low dark matter galaxies

Alpine Cosmology Workshop 2016

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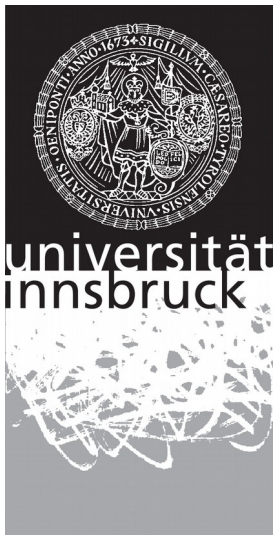
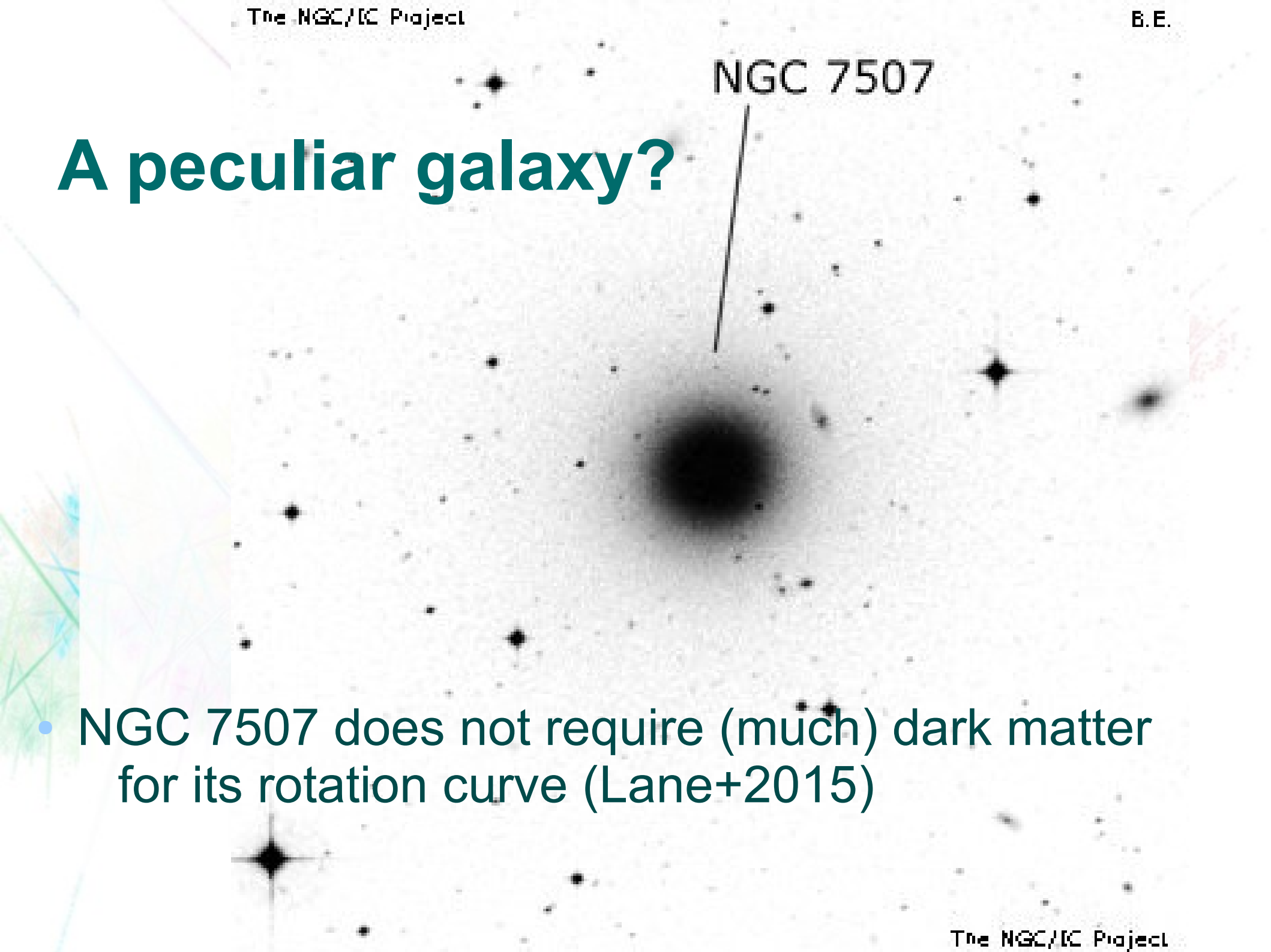




A peculiar galaxy?

- NGC 7507 does not require (much) dark matter for its rotation curve (Lane+2015)

NGC 7507

- Elliptical galaxy (E0)

- "isolated" elliptical → **field elliptical**

  in a pair with the spiral galaxy NGC 7513
  (Reduzzi&Rampazzo,1995)

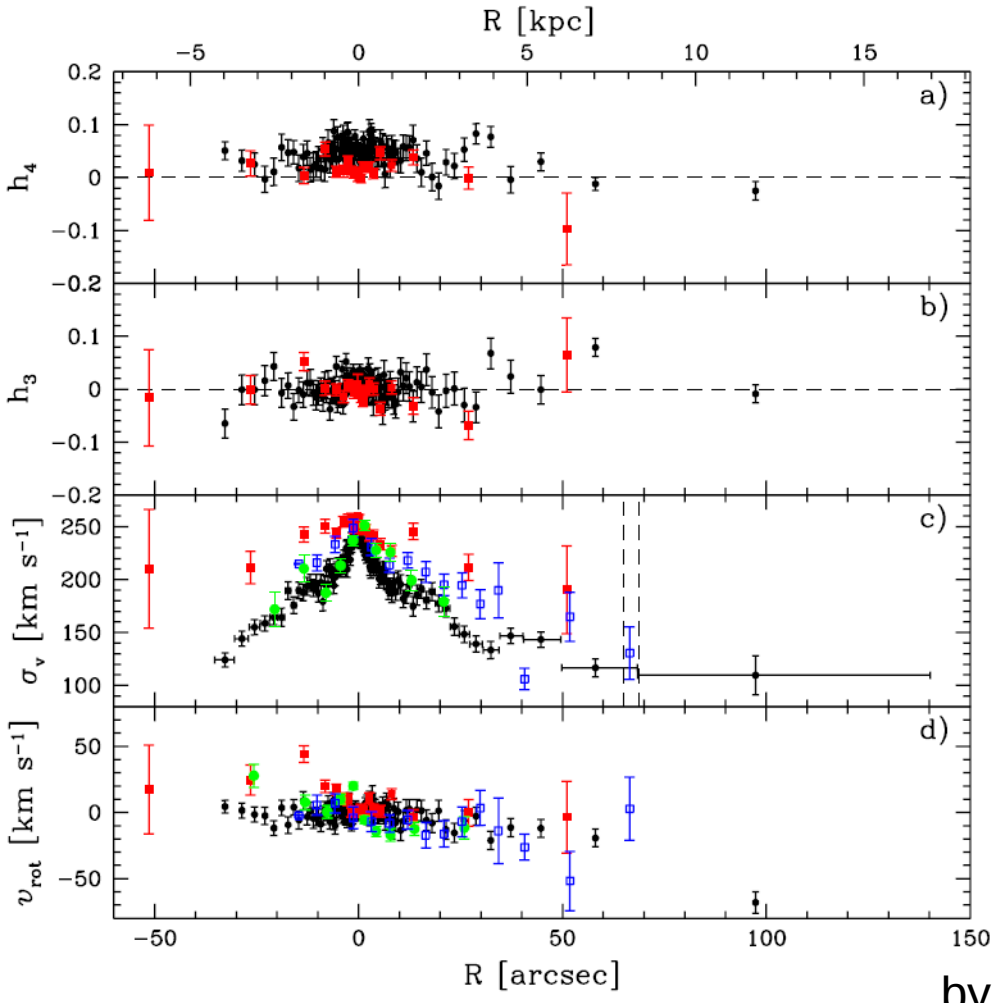
- Nearby galaxy: 23.22 ± 1.8 Mpc (Salinas+2012)

- Counter-rotating outer halo and "σ-bump"
  → **major merger remnant**

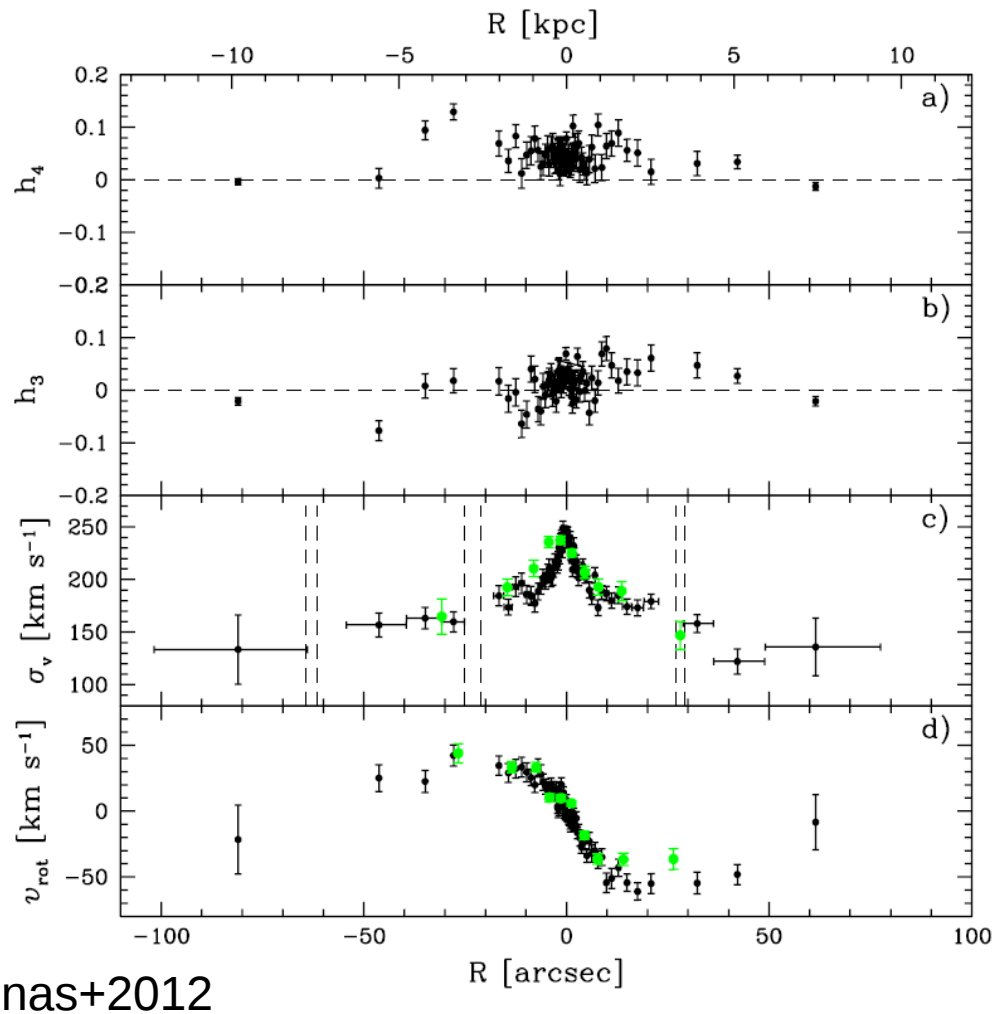
Observations of NGC 7507

- **Inner kinematics** by Salinas+ 2012 with the Gemini Multi-Object Spectrograph (GMOS)

near the major axis

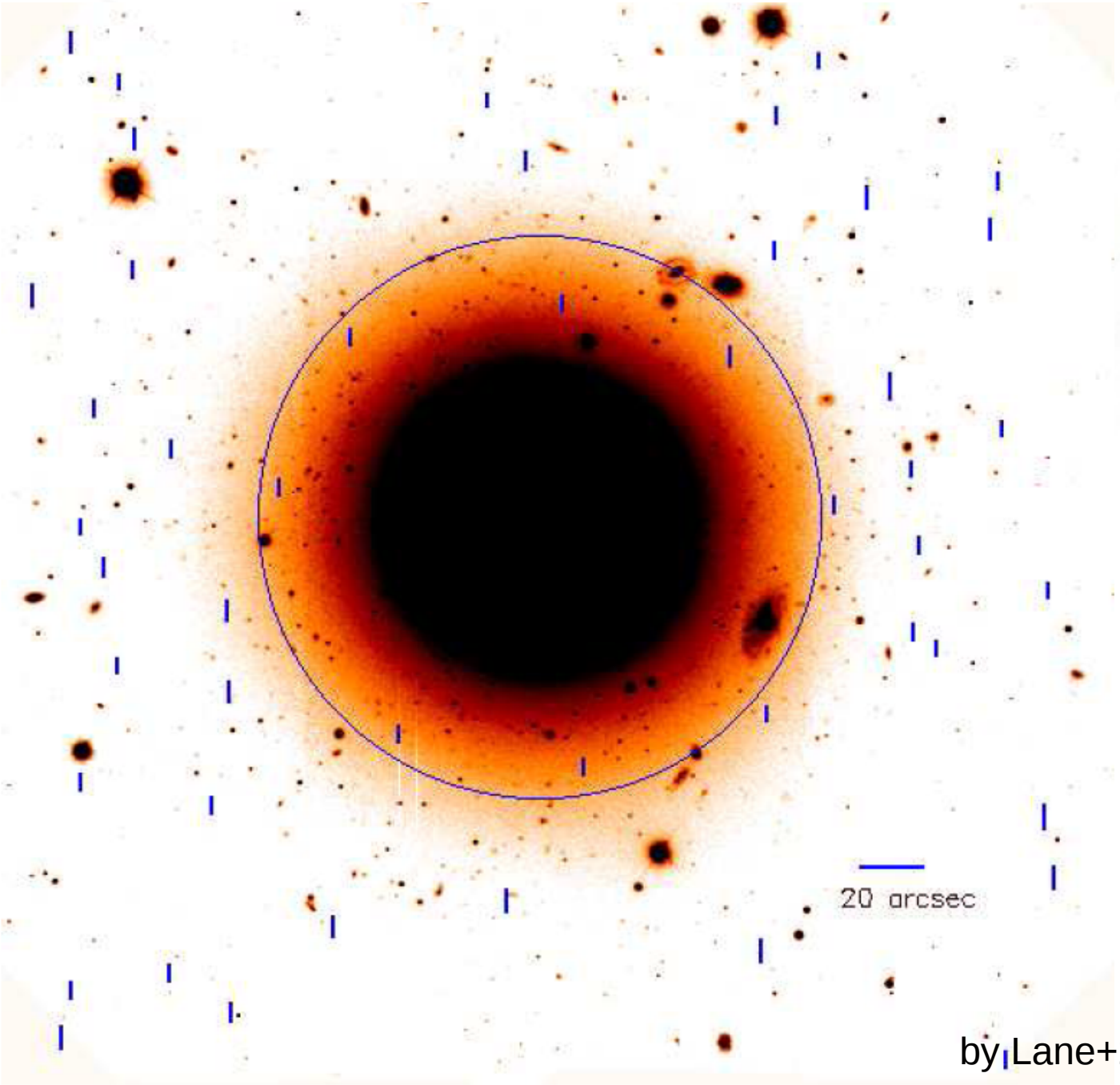


near the minor axis



by Salinas+2012

- **Outer kinematics** by Lane+2015 with GMOS using globular clusters and planetary nebulae in the halo

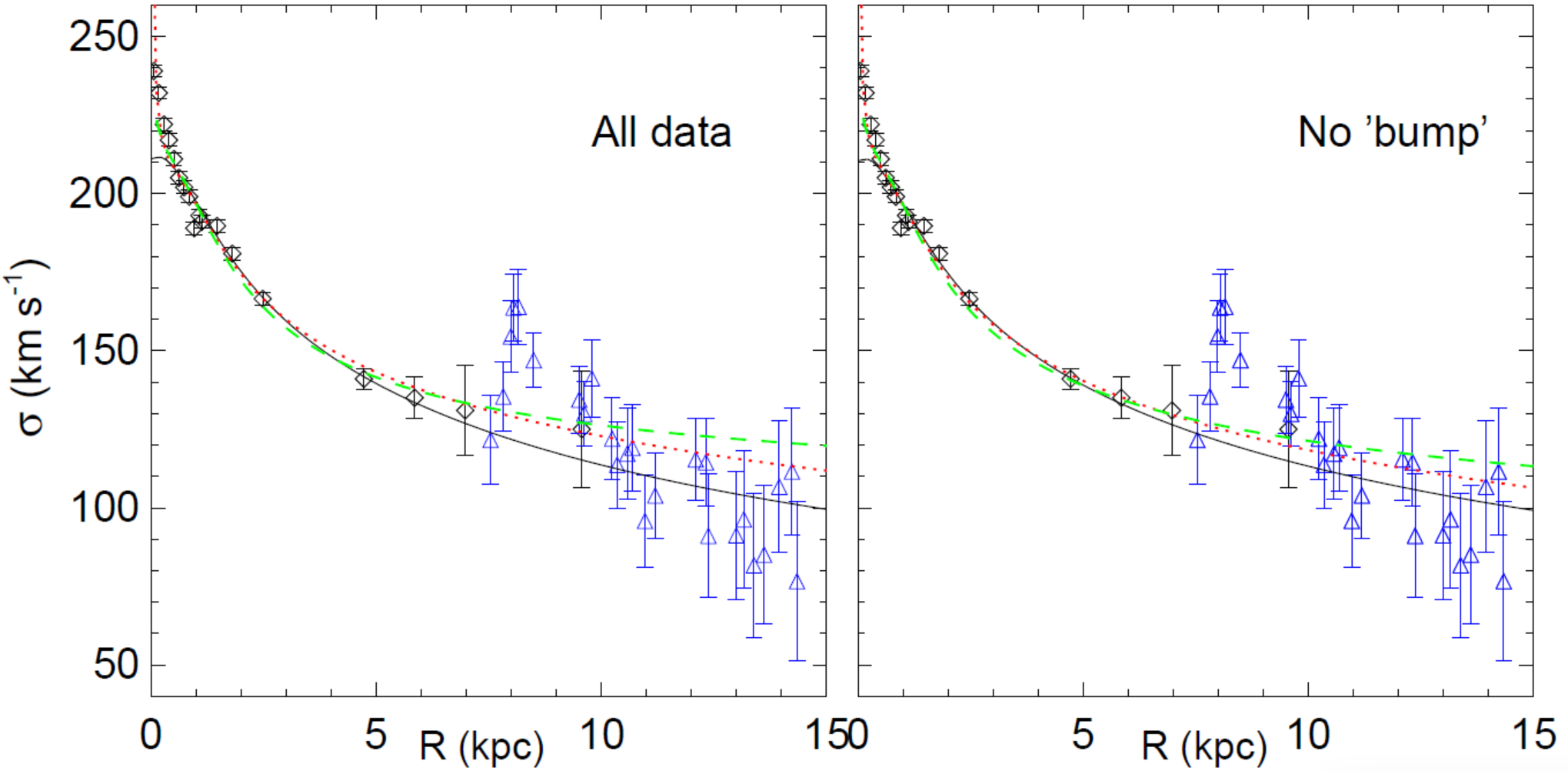


by Lane+2015

The mass of NGC 7507

- **Stellar mass: $2 \cdot 10^{11}$ $M_\odot$** (Salinas+ 2012)
- Field elliptical tend to populate less massive dark matter halos (Niemi+2010)
- Dark matter mass of **~10^{13} $M_\odot$ expected** (Lane+2015)
- Dynamical models (Mamon&Łokas,2005 and Schuberth+2010)⟶ dark matter content

Model	M_{DM} [$M_\odot$]	χ^2	M_{DM} [$M_\odot$]	χ^2
Stellar only (no DM)	0	111.4	0	65.1
β-model	$2.68 \cdot 10^{11}$	88.1	$1.52 \cdot 10^{11}$	55.5
Anisotropic (max DM)	$1.12 \cdot 10^{12}$	97.3	$6.93 \cdot 10^{11}$	67.5



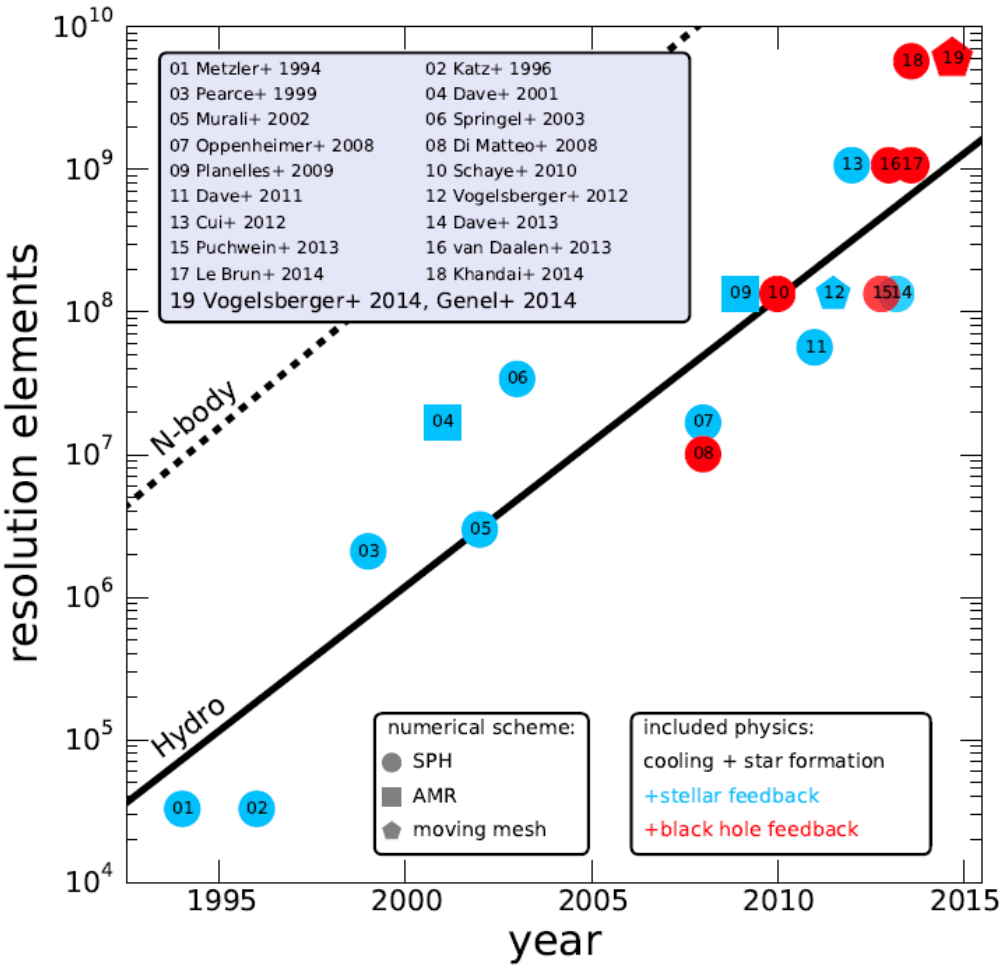
by Lane+2015

How exotic is NGC 7507?

- Is NGC 7507 truly (almost) dark matter free?
- Is it **compatible with the Λ-CDM model?**
- How **common/rare** are galaxies like **NGC 7507**?
- → comparison to **numerical simulations** that consider baryonic matter

The Illustris simulation

- Large-scale numerical simulation (Vogelsberger+2014)
- Volume: cube with **106.5 Mpc** side length
- **3 x ~6 · 10⁹**
  - DM particles
  - hydro cells
  - MC tracers

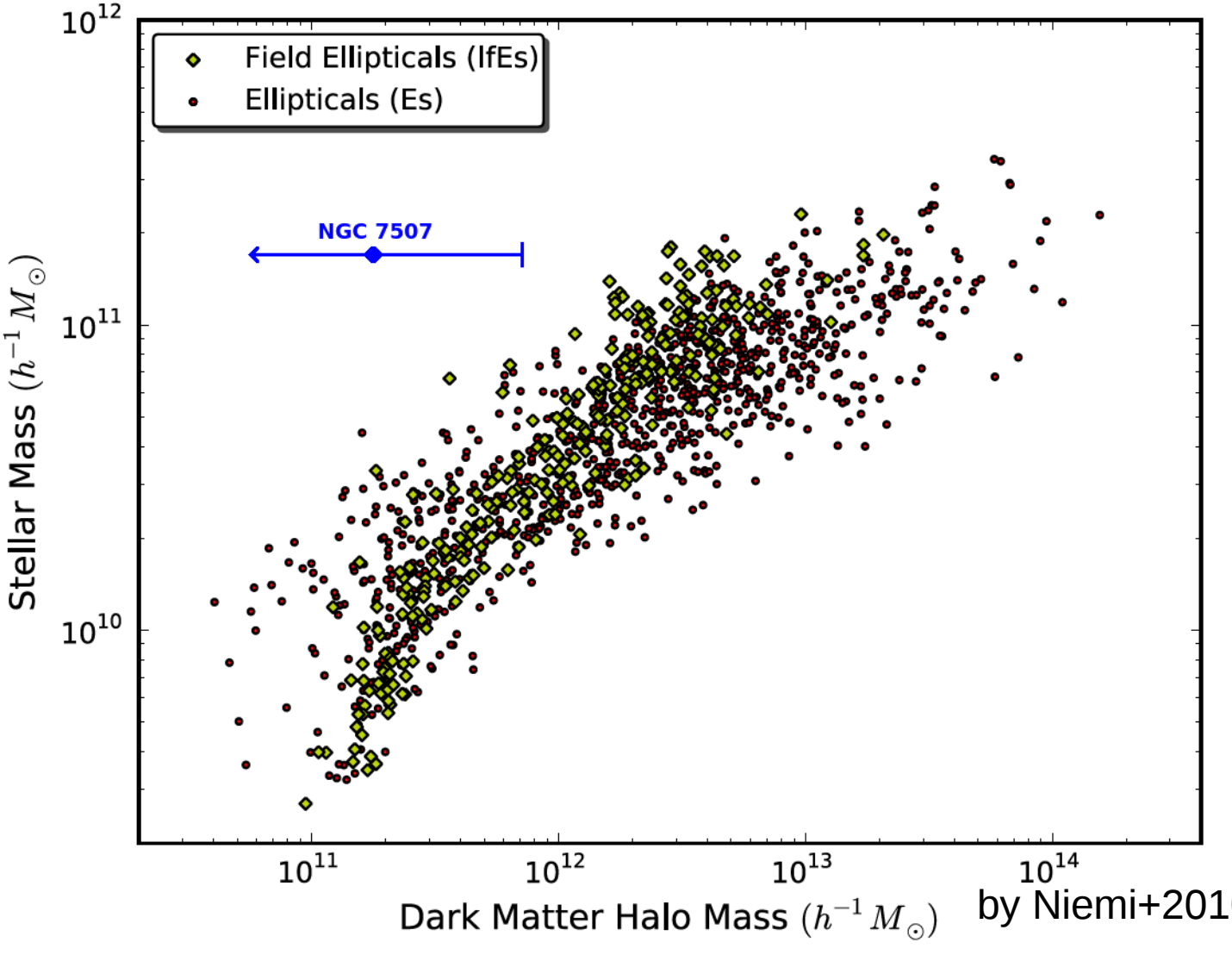


by Illustris

- Coupled dynamics of dark matter and gas: the **AREPO code**
- **Ideal hydrodynamics:** adaptive mesh
- **Gravity:**
  - Tree code (short distance)
  - Particle mesh (long distance)
- **Galaxy formation model:**
  - Gas cooling and photo-ionization
  - Star formation and ISM model
  - Stellar evolution
  - Stellar feedback
  - Black holes and SMBH feedback

The search for low dark matter galaxies

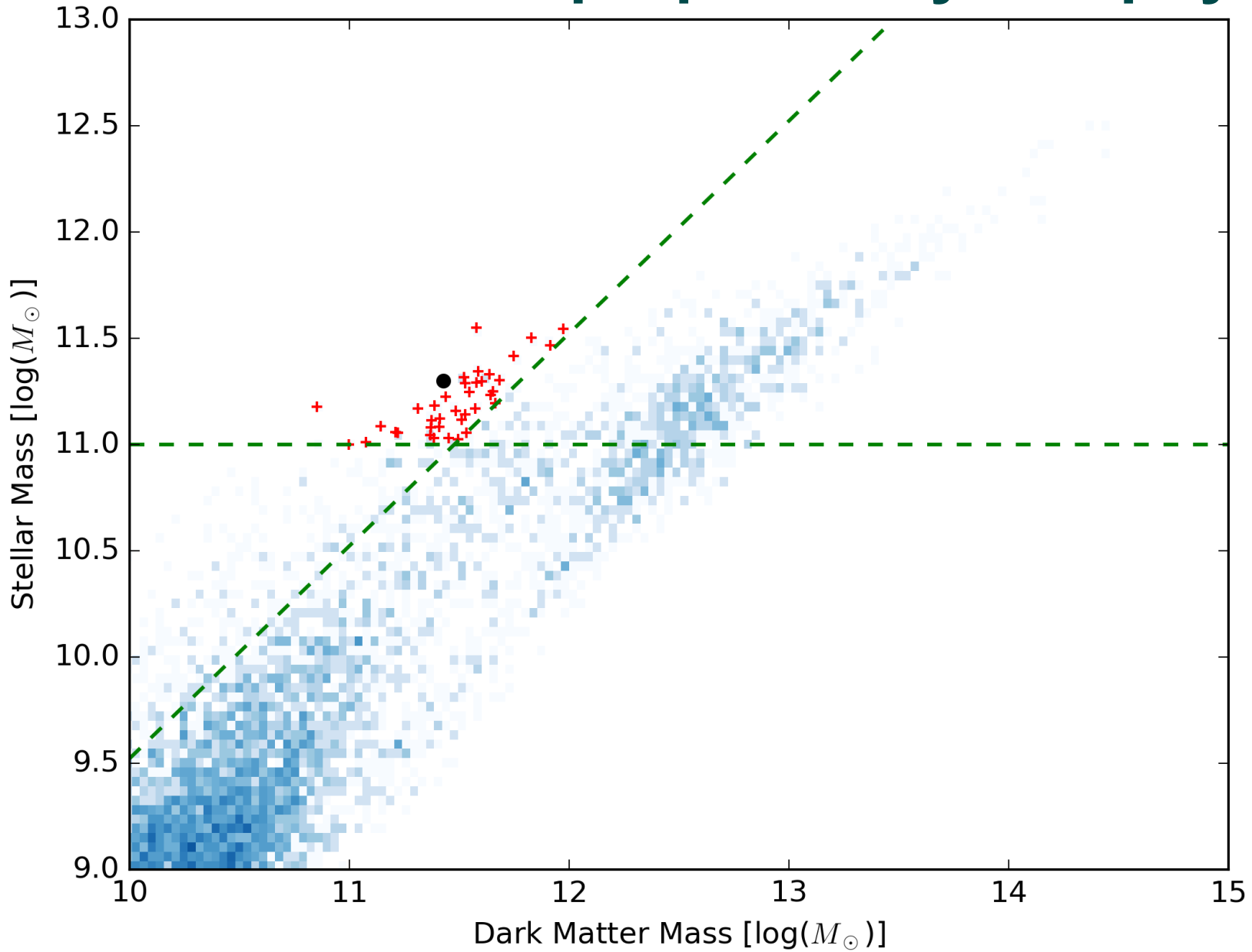
- In the Millennium simulation (Niemi+2010):



by Niemi+2010

Baryonic physics → **only semi-analytical models** in DM halos

- Illustris simulation: **“proper” baryonic physics**

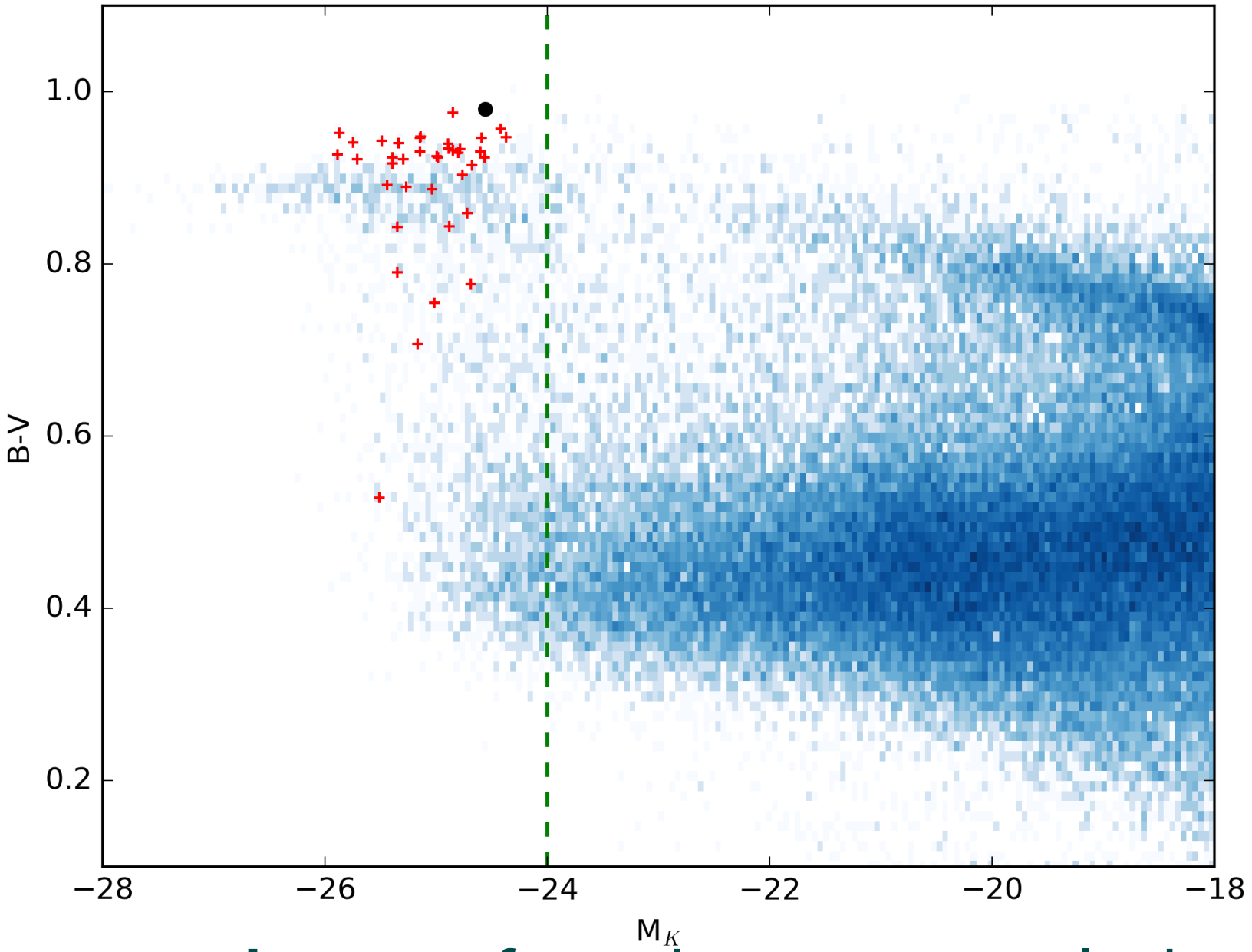


- **There are low dark matter galaxies!**

How to identify low dark matter galaxies in surveys?

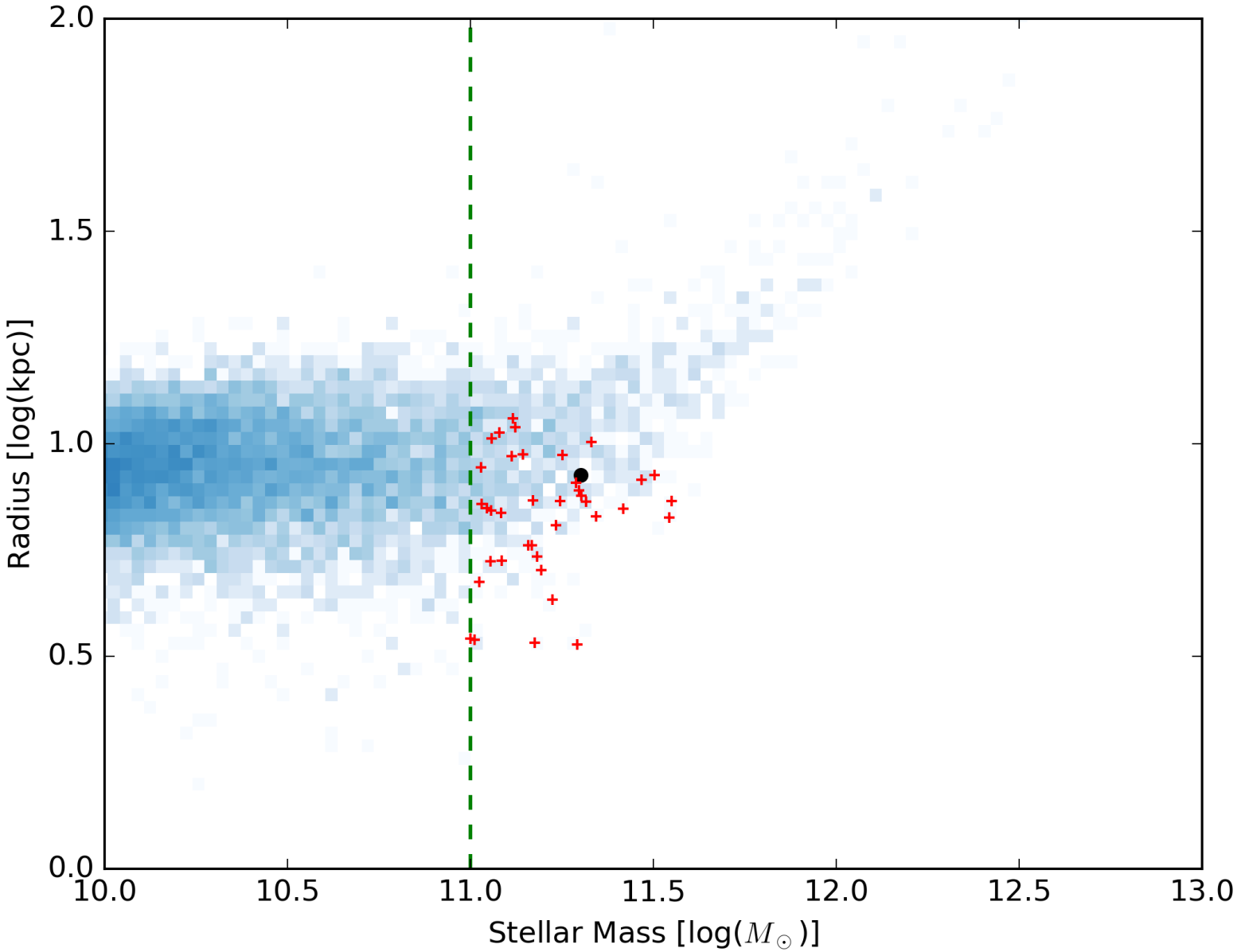
- Preliminary definition of a (big) low dark matter galaxy
  - $M_*/M_{tot}>0.25$
  - $M_*>10^{11}\ M_\odot$
- **38 galaxies** in the Illustris simulation out of 856 with stellar masses beyond $10^{11}\ M_\odot$ or 2364 brighter than -24 mag in the K band
- Use galaxies in simulated data to find **outstanding and simple** observational criteria

Colour-Magnitude Diagram



- **very red** – even for red sequence galaxies

Stellar mass-size relation



- Relatively **compact** for their stellar masses

Other potential criteria

- Kinematics: slight tendency towards **slow rotators** (typical for mergers)
- Relatively **high metallicity** (typical for ETG)
- **Low star formation rate** (typical for ETG)
- Preference for **field environment** – still uncertain

False negatives / false positives

- Combine and refine criteria
- **Mock catalogues** based on the Illustris simulation to test their efficiency
- Find the best set of criteria
  - Get as many low dark matter galaxies as possible
  - Have the lowest possible contamination of others
- Apply on **surveys** → **follow-up observations**

Testing gravity

- Baryons in **dark matter** halos

  → **stochastic process**

- **Modifying gravity**

  →one **strict law** for each specific (baryonic) matter distribution

- **Low dark matter galaxies**

  → excellent **laboratories** to **test** these theories

MOdified Gravity

- Also known as Scalar–Tensor–Vector Gravity

- Additional Lagrangians (**scalar and vector fields**) are added to the Einstein-Hilbert action

$$S = \int \left(\mathcal{L}_G + \mathcal{L}_M + \mathcal{L}_V + \mathcal{L}_S \right) d^4 x$$

- In the case of **spherical symmetry, static vacuum**:

$$F = -\frac{G_N M m_{test}}{r^2} \left(1 + \alpha - \alpha \left(1 + \mu r \right) e^{-\mu r} \right)$$

with $\alpha = \frac{G_\infty - G_N}{G_N} \frac{M}{\left(\sqrt{M} + E \right)^2}$

$$\mu = \frac{D}{\sqrt{M}}$$

- Can explain:
  - **rotation curves** (Brownstein&Moffat,2006a, Moffat&Toth,2009)
  - **cluster masses** (Brownstein&Moffat,2006b)

f(R) gravity

- Modification of Einstein Hilbert action:
  a **function f of the Ricci scalar R**

$$S = \int \frac{c^4}{16\pi G} f(R) \sqrt{-g}\, d^4 x$$

- G_{eff} is **time and scale dependent**

- **Rotation curves of galaxies** can be reproduced under the “right” approximations/assumptions (Cardone&Capozziello,2011,2013, Asgari&Saffari,2010)

MOdified Newtonian Dynamics

- Simple modification of Newtonian force (Milgrom,1983)

$$F_N = m\,\mu\left(\frac{a}{a_0}\right)a \qquad \mu = \left(1+\left(\frac{a_0}{a}\right)^2\right)^{-\frac{1}{2}}$$

- $a >> a_0$: classic Newtonian dynamics $\mu=1$
- $a << a_0$: **deep-MOND** $\mu=a/a_0$

- **Tully-Fisher relation** appears naturally

$$\frac{GMm}{r^2} = \frac{ma^2}{a_0} = \frac{m\left(\frac{v^2}{r}\right)^2}{a_0} \longrightarrow v^4 = G a_0 M$$

- Complete theory: **modified Poisson equation** (Bekenstein&Milgrom,1984)

$$\nabla \cdot \left(\mu\left(\frac{\|\nabla \Phi\|}{a_0}\right) \nabla \Phi \right) = 4\pi G \rho$$

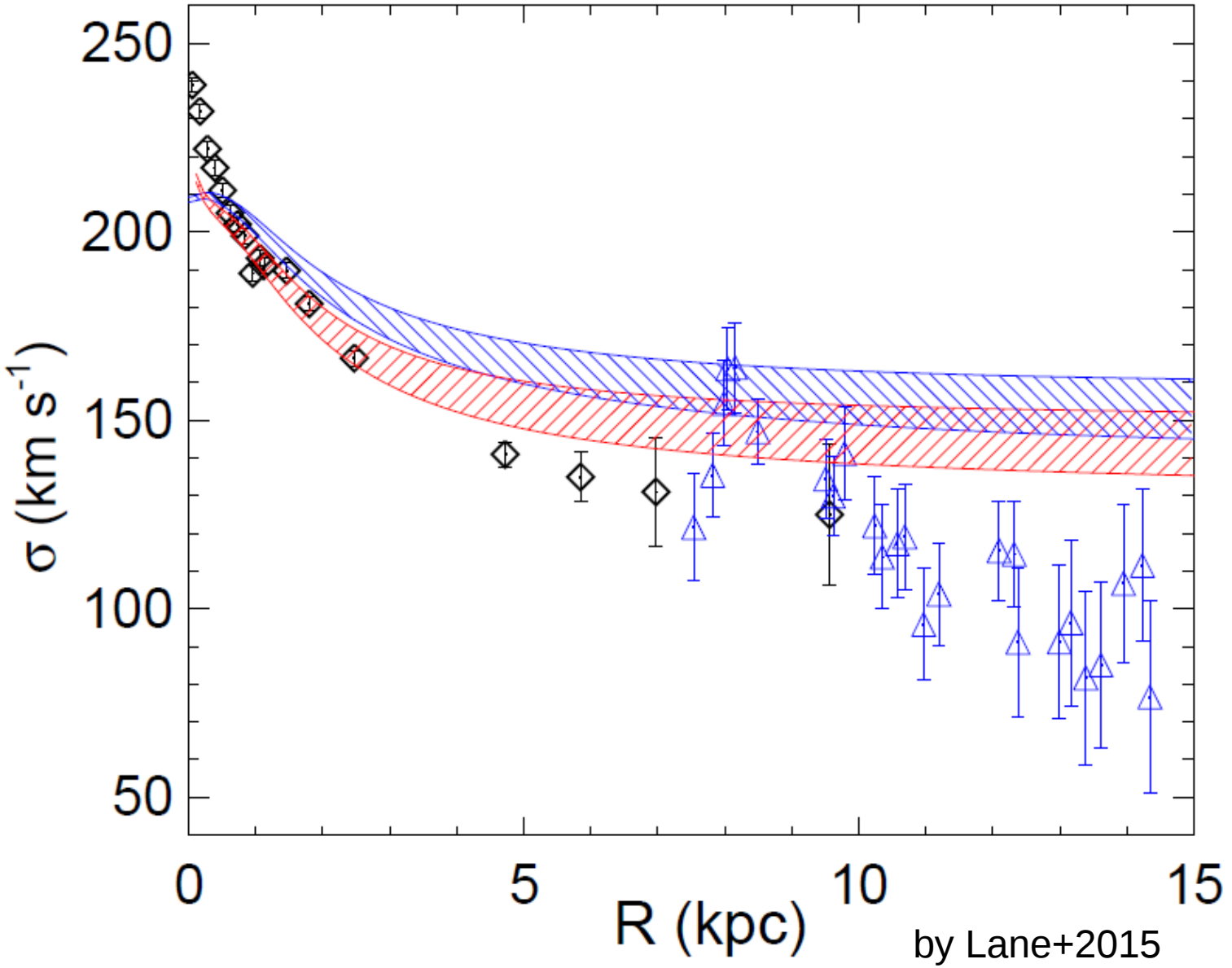
- Relativistic extension: **TeVeS** (Bekenstein:2004)

- MOND works well for **rotation curves of galaxies** (Douglas+2006, McGaugh,2011) and the **masses of tidal dwarf galaxies** (Bournaud+2007, Gentile+2007, Kroupa,2012)

- MOND has known **problems** with the **masses of galaxy clusters** (Aguirre+2001, Clowe+2006) and the **dynamics of galaxy groups** (Shi,2009, but disputed Kroupa,2014)

Results for NGC 7507

- Rotation curve **incompatible with MOND** (Lane+2014)



by Lane+2015

Summary & Conclusions

- **NGC 7507** is a nearby **field elliptical** galaxy
- Observations show that NGC 7507 has a very **low dark matter content** (Lane+2014)
- Search for galaxies similar to NGC 7507 in the **Illustris simulation**
- **38** such **galaxies** found in the simulation

- Low dark matter galaxies tend to be **red**, **compact** and (possibly) located in **field environment**

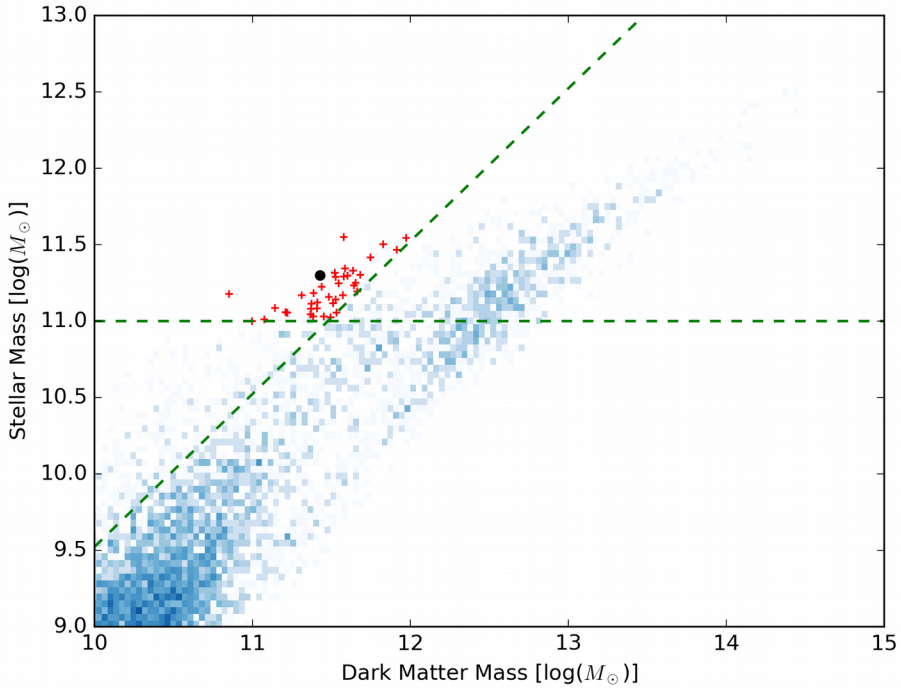
- Refine criteria to detect such galaxies in surveys

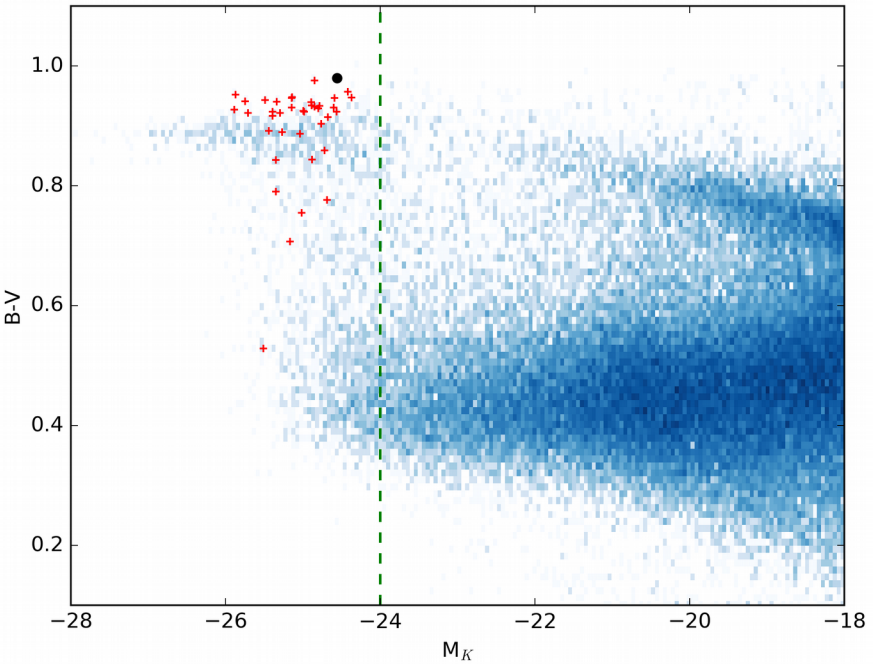
- Excellent laboratories to test the **dark matter** paradigm against **alternative theories of gravity**

- **MOND** can**not** reproduce the **rotation curve** of NGC 7507 (Lane+2014)

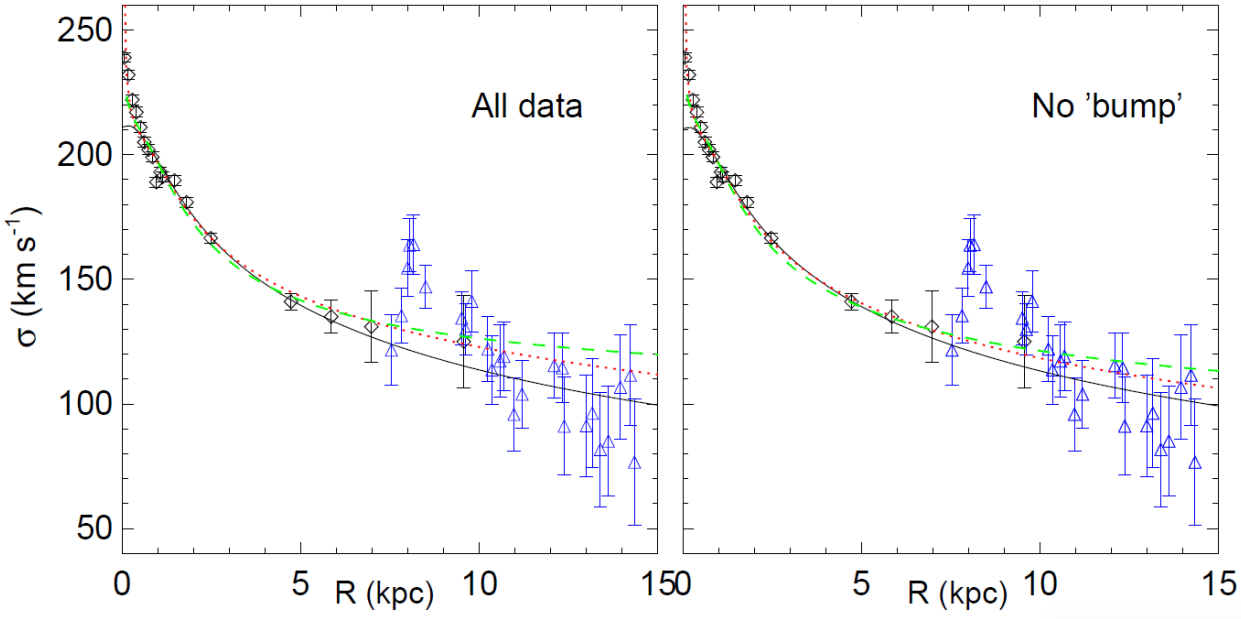
Outlook

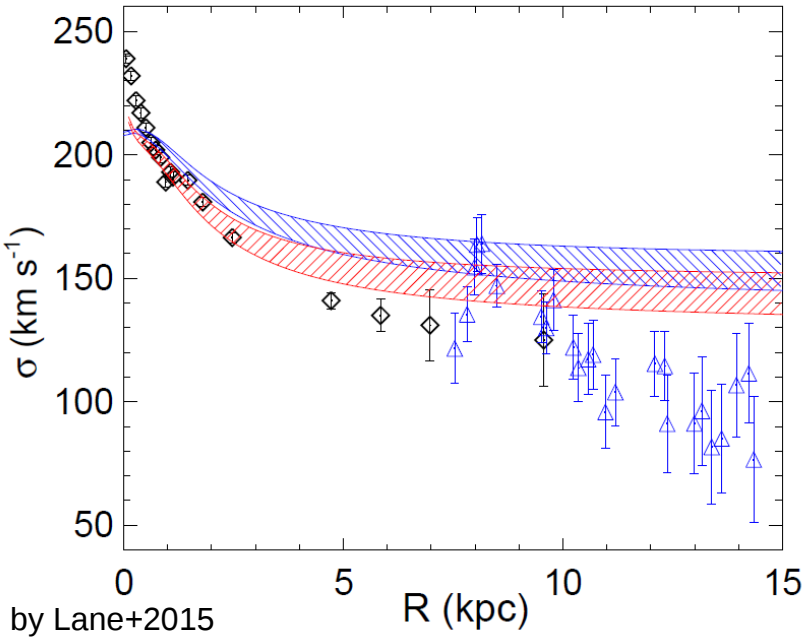
- Applying the **criteria** on various **surveys**
- List of **candidates**
- **Follow-up observations** to filter false positives
- Use dynamical models to **test** various **theories of gravity** vs. **dark matter** in these galaxies.





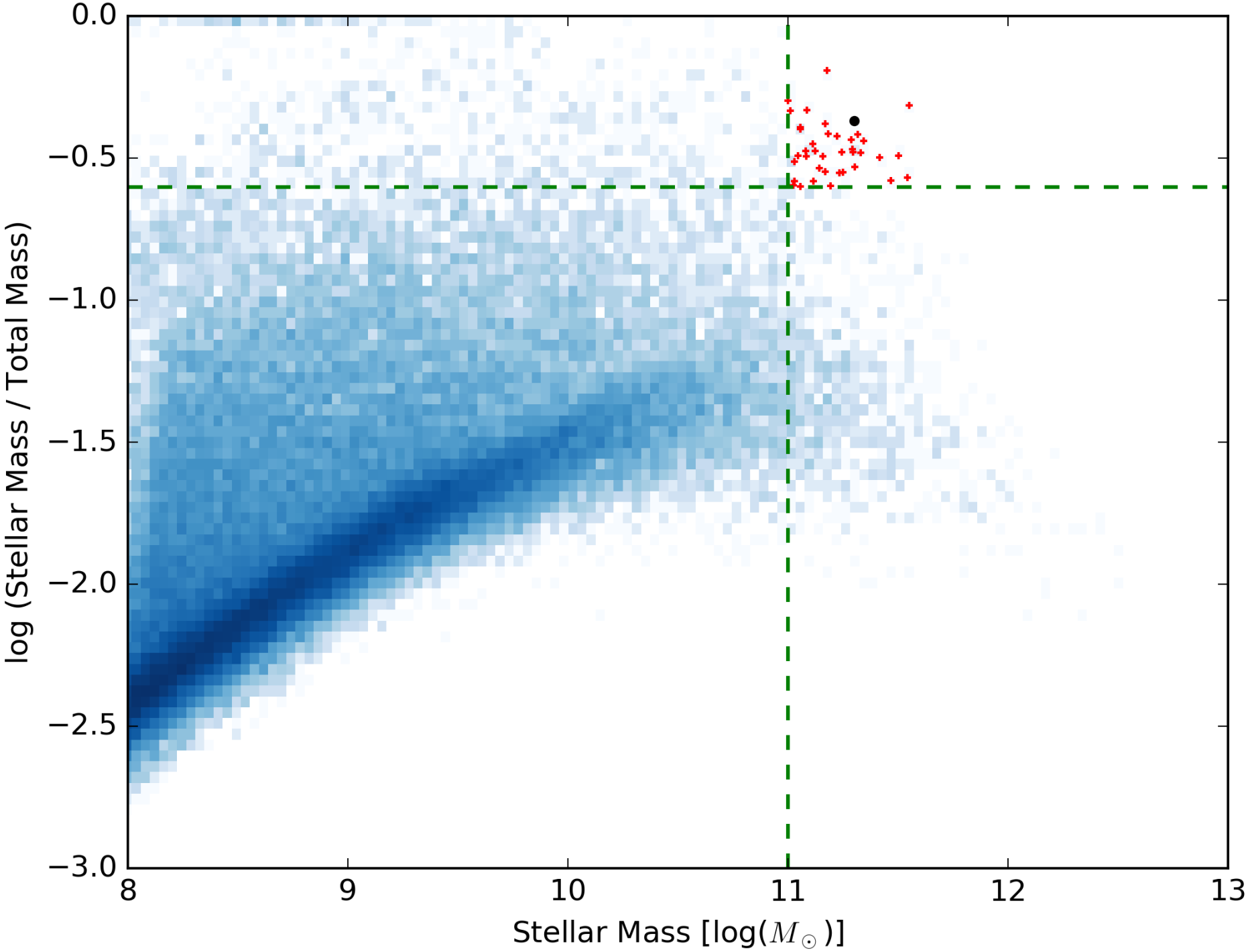
ANY QUESTIONS?



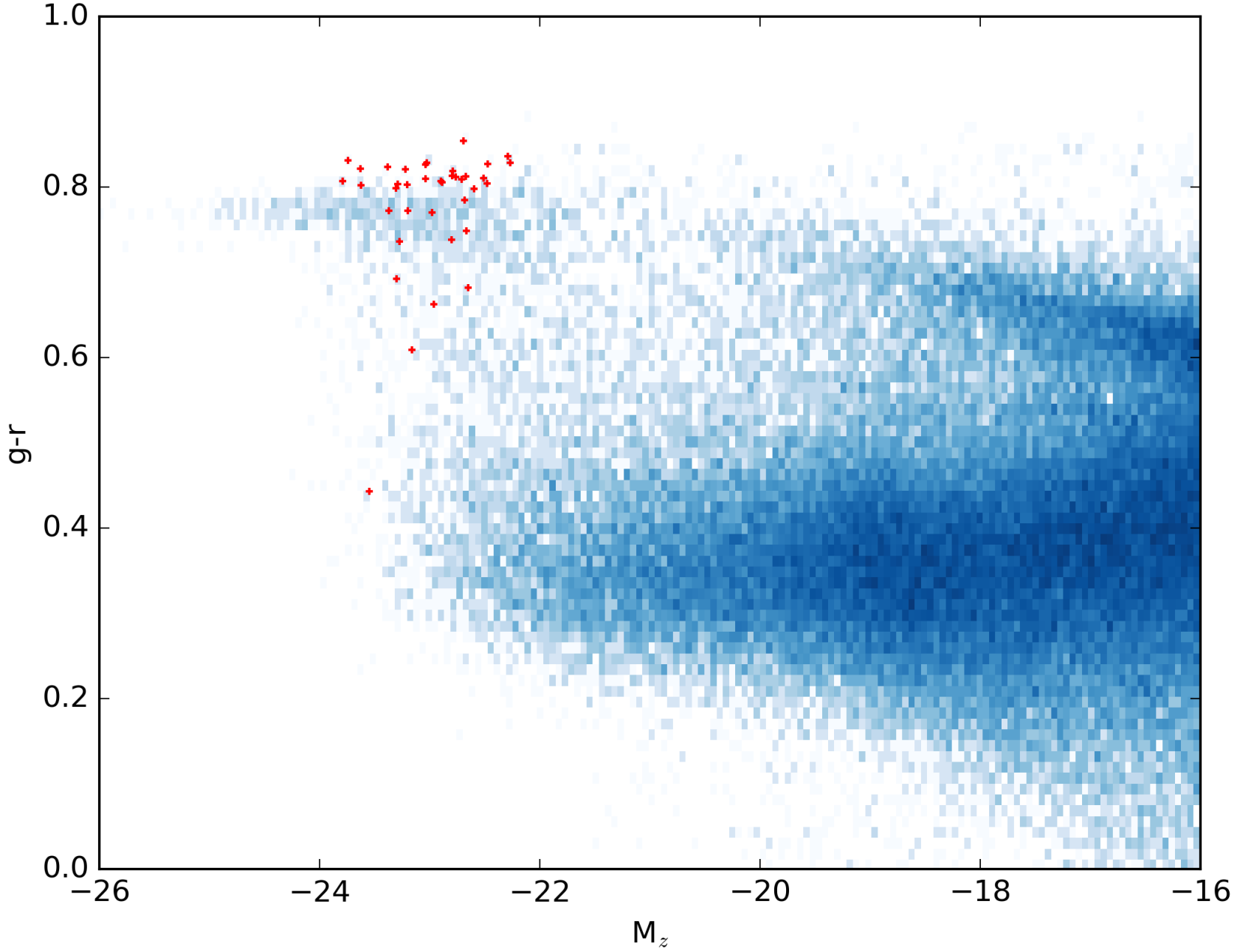


by Lane+2015

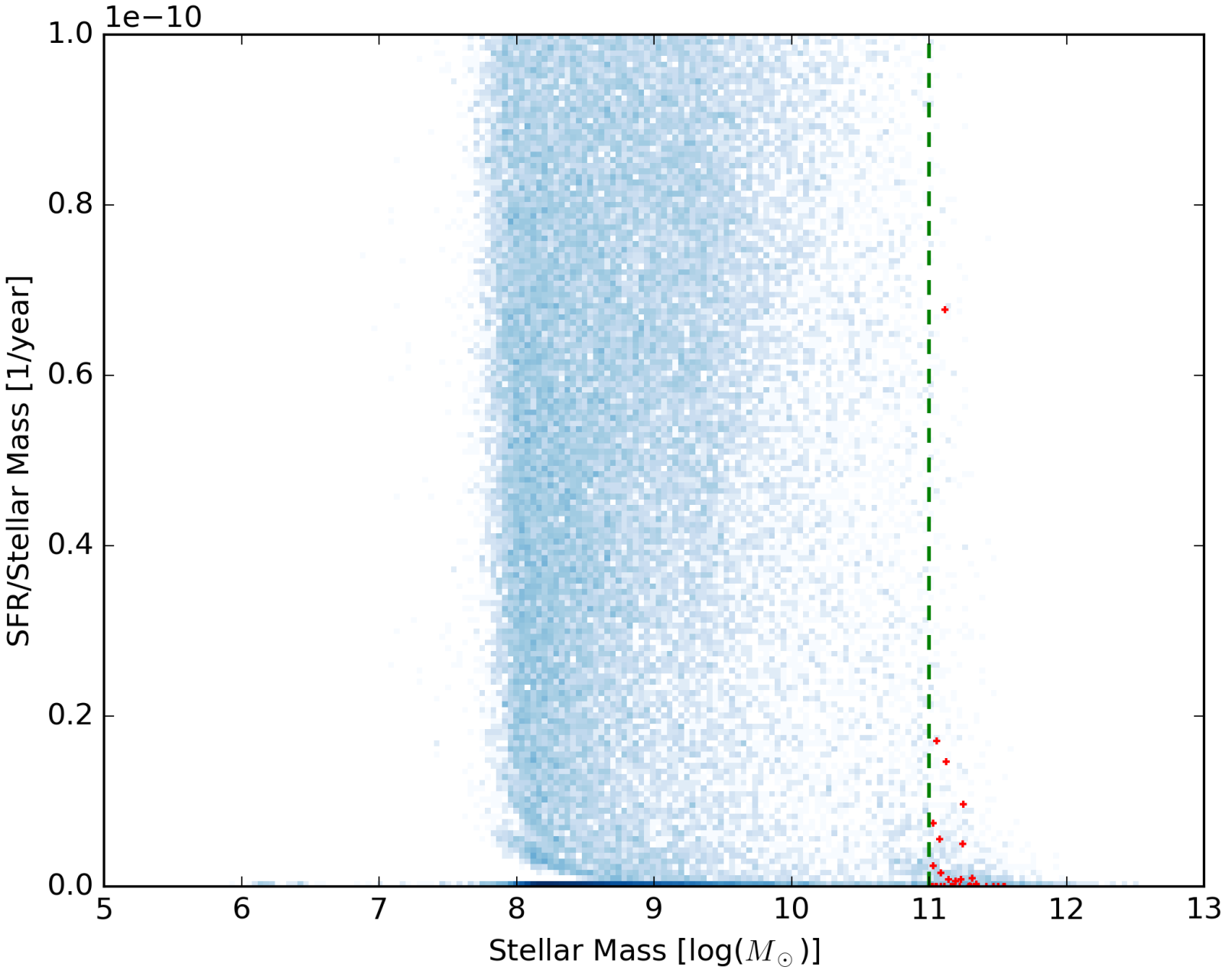
ADDITIONAL SLIDES


0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
log (Stellar Mass / Total Mass)
8
9
10
11
12
13
Stellar Mass [log($M_\odot$)]

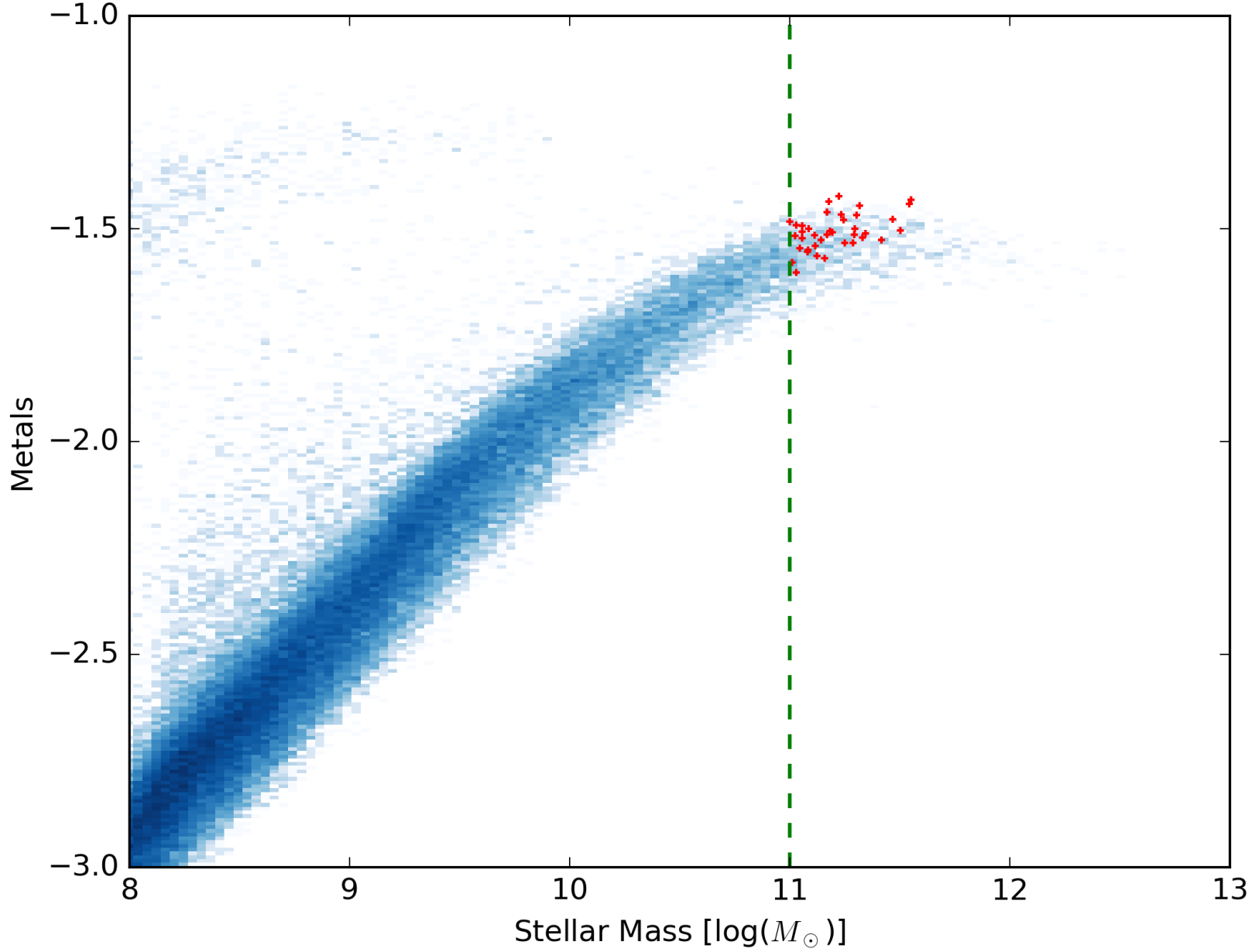
CMD SDSS

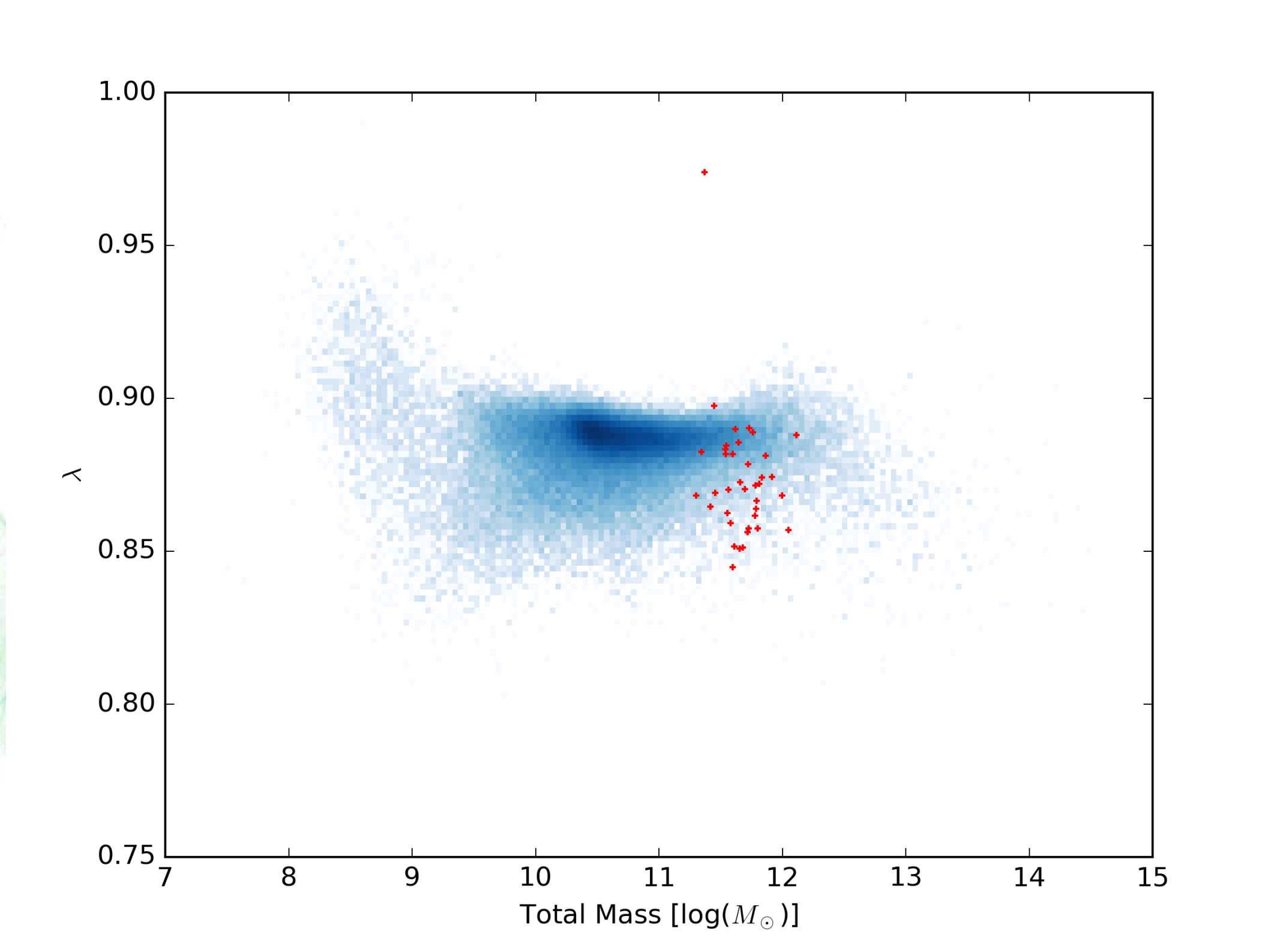


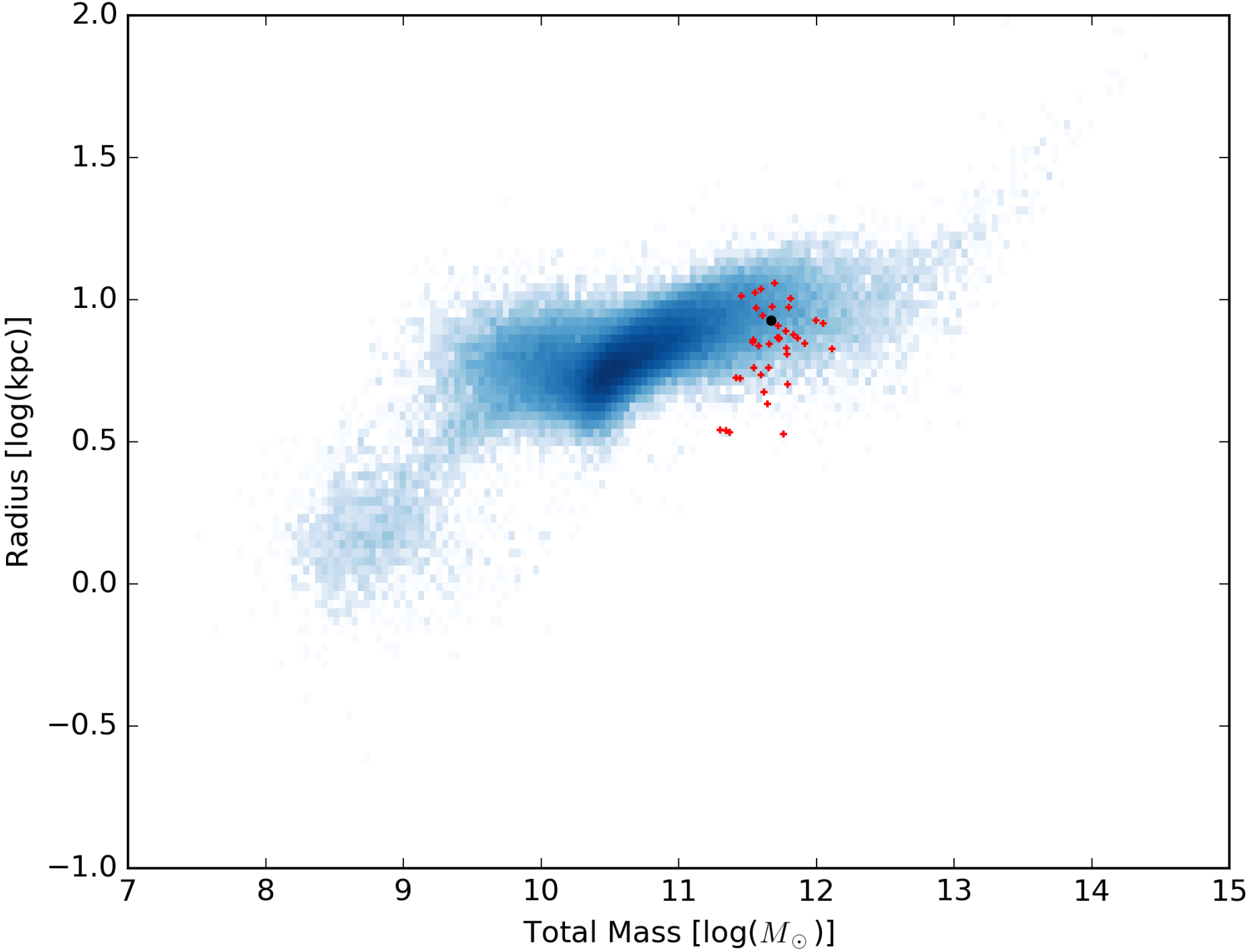
Star Formation Rate



Metallicity




1.00
0.95
0.90
0.85
0.80
0.75
λ
7
8
9
10
11
12
13
14
15
Total Mass [log($M_\odot$)]


2.0
1.5
1.0
0.5
0.0
−0.5
−1.0
Radius [log(kpc)]
7
8
9
10
11
12
13
14
15
Total Mass [log($M_\odot$)]

Merger trees according to the Millennium simulation

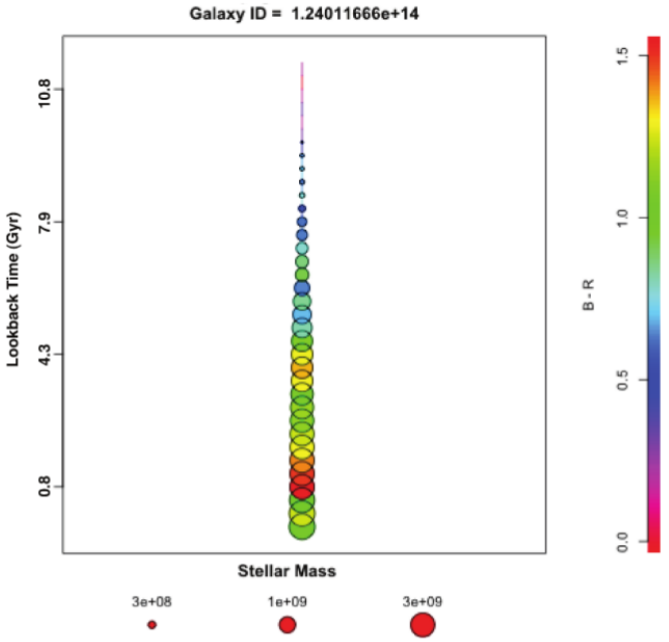


Figure 14. Example of a merger tree of an IfE galaxy that has developed alone without any significant merging events. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^8\,h^{-1}\,\mathrm{M}_\odot$ are shown.

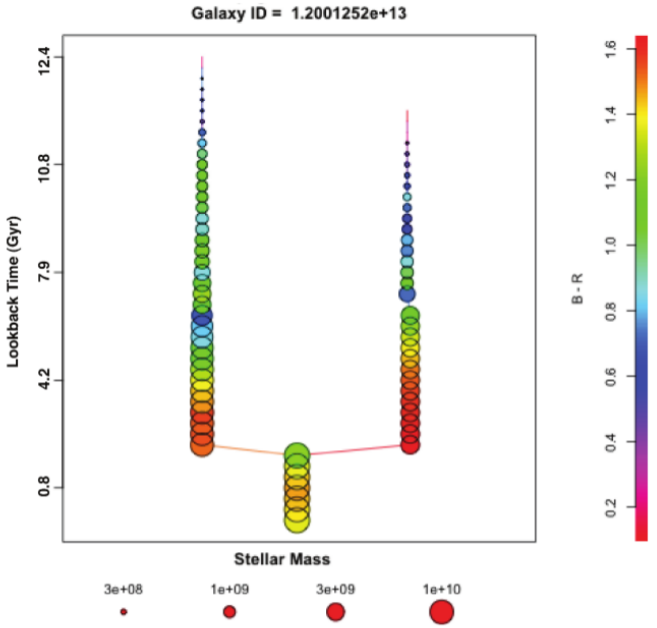


Figure 15. Example of a merger tree of an IfE galaxy that has undergone an equal-sized merger. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^8\,h^{-1}\,\mathrm{M}_\odot$ are shown.

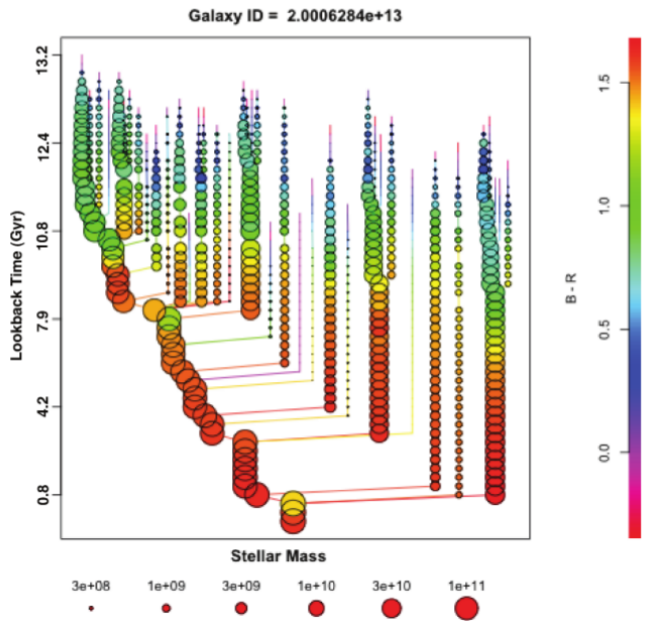
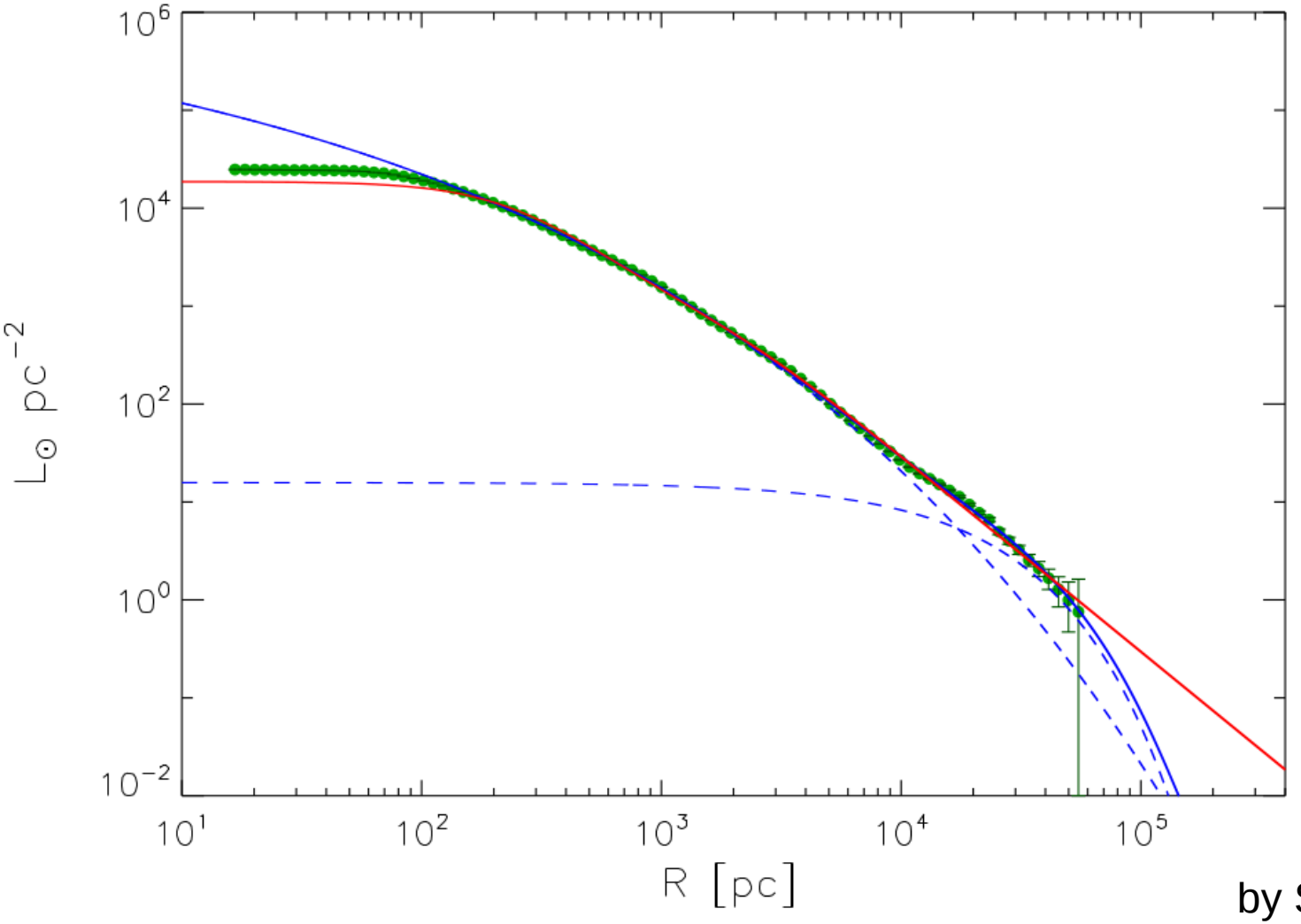


Figure 16. Example of a merger tree of an IfE galaxy that has undergone multiple merging events, but not any equal-sized ones. Symbols are colour-coded as a function of the $B - R$ colour and their area scales with the stellar mass. Only progenitors more massive than $10^8\,h^{-1}\,\mathrm{M}_\odot$ are shown.

all figures by Niemi+2010

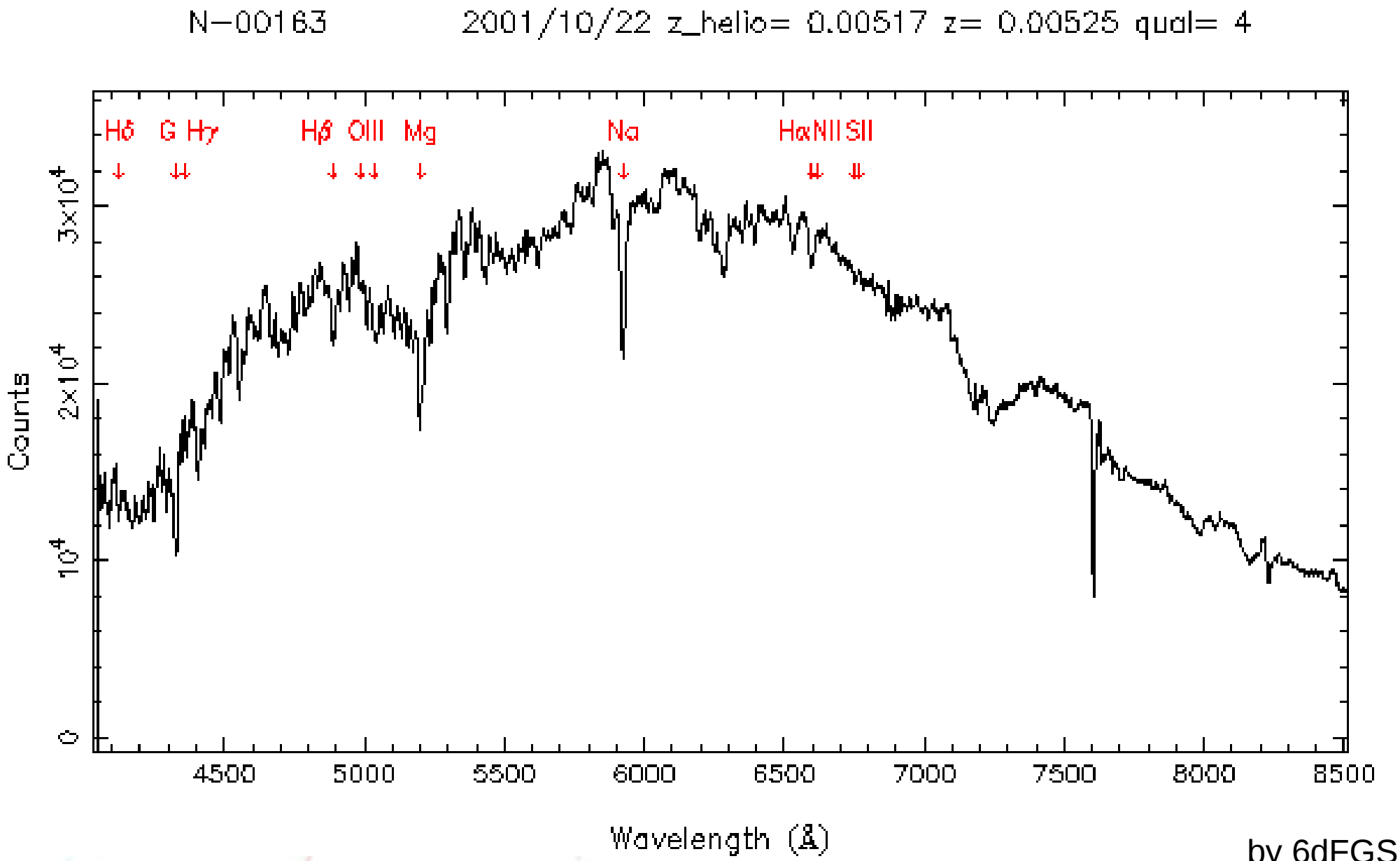
Surface brightness profile



by Salinas+2012

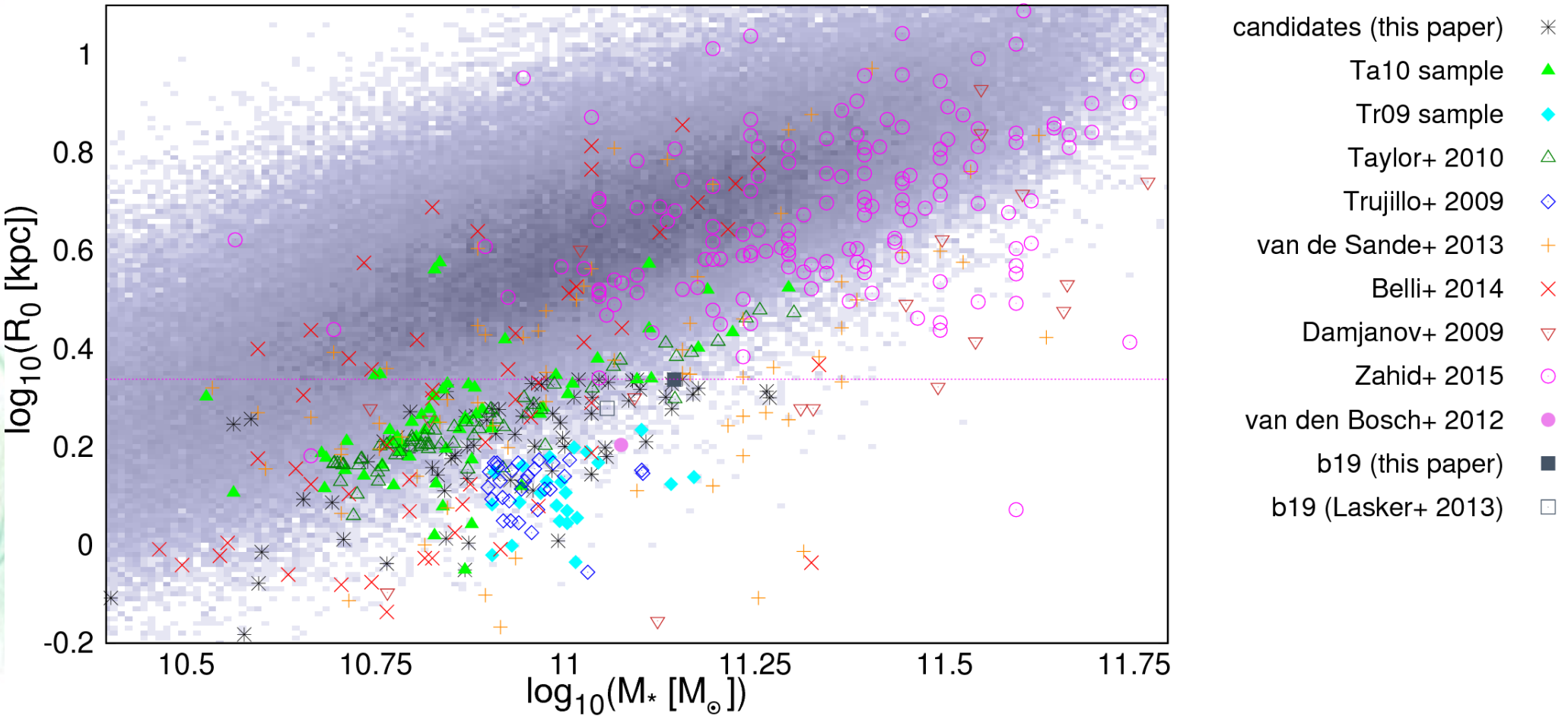
Fig. 3. Surface brightness profile of NGC 7507. The green dots indicate the R photometry in units of $L_\odot$ pc^{-2}. The dashed blue lines represent the two Sersic profiles, while the solid blue line is their sum. The red solid line represents the double β model.

Spectrum of NGC 7507



by 6dFGS

Red nugget survivors



by Saulder+2015

N/A

I have not prepared a slide for this question.