Q&A session, 10 May 2016
Dark Matter in the Milky Way
MITP, 2-13 May 2016

1. What is cosmic variance and how do you deal with it in large scale structure simulations when you interpret your results?

   Speaker: Federico Marinacci

2. How do we figure out selection functions for astronomical surveys – i.e. how do we work out what we cannot see?

   Speaker: Else Starkenburg

3. For a better determination of the Milky Way dark matter density profile, what data are the most important at every Galactocentric radius, and why?

   Speaker: Hamish Silverwood

4. What data would be ideally needed in order to better constrain the dark matter density profile in the innermost region of the Galaxy (say, inner 1–2 kpc)?

   Speakers: Miguel Pato and Fabio Iocco

5. Regarding measuring kinematics in nearby dwarfs, which upcoming instruments are most promising? What scales do we aim to reach in the next five years?

   Speaker: Kyle Oman

6. In general, when we talk about a dark matter particle, we talk about it – and simulate it – as one specific type (either cold or warm, either self-interacting or not...). How realistic is this really? What are the chances that there is a whole range of particles in the "dark sector" just like we know there is in the light sector?

   Speaker: David Cerdeño

7. How can a fully relativistic approach modify a galaxy's rotation curve?

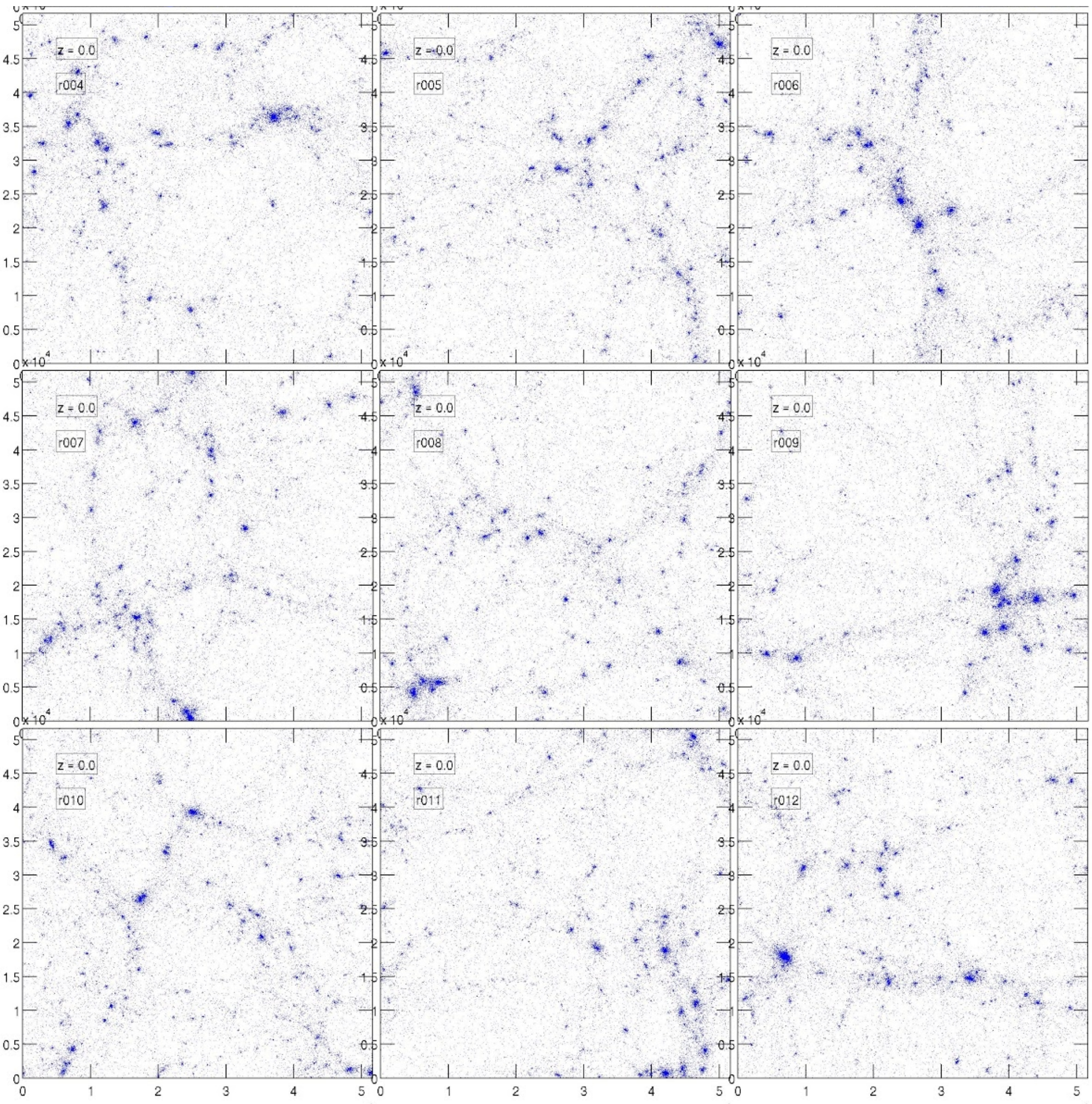
   Speakers: Francesc Ferrer and Aaron Dutton [answer shifted to journal club]

Cosmic variance

Uncertainty in the observational estimates of the volume density of extragalactic objects such as galaxies or quasars arising from the underlying large-scale density fluctuations. This is often a significant source of uncertainty, especially in deep galaxy surveys, which tend to cover relatively small areas.

(Somerville et al. 2004)

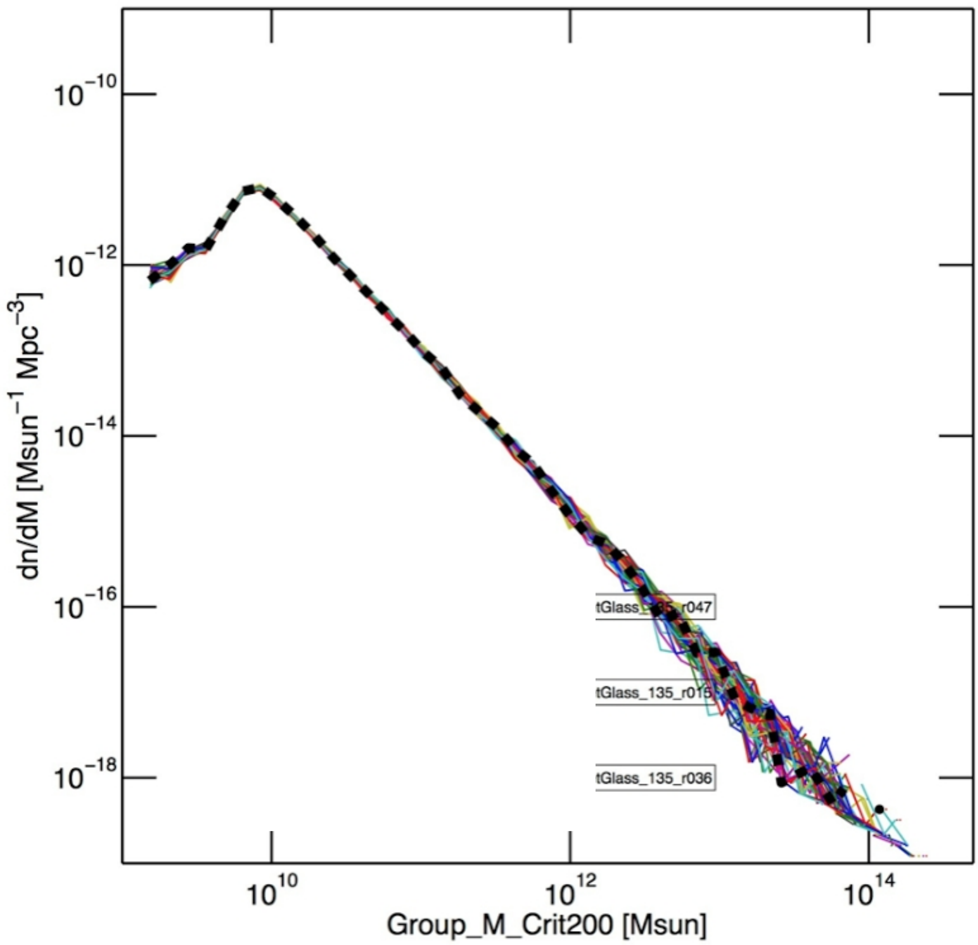
An example



Realizations of initial condition for a cosmological simulation.

L = 35 Mpc/h

An example



Halo number density (in small volumes) depends on the particular realization

More technically: cosmic variance can be neglected if the cosmological volume considered is larger that the typical clustering scales of the objects studied

Countermeasures

- Simulate a large enough volume (can be computationally expensive)

- Study statistically many realizations and take the one that most closely follows the “expected” mean trend

Else Starkenburg

Selection functions:

Photometry, most important considerations are:

- Magitude limits (be aware there is also a *bright* limit and changes from filter to filter)
- Footprint

Spectroscopy:

- Can be *very* complicated, because you have to select which targets to observe a spectrum for. In (at least some of the) current design for future large surveys this topic is taken very seriously. If we want to be able to understand the Milky Way as a galaxy using these data, we have to make sure that the selection functions are very well understood so we are aware of any biases in the data collection.

"For a better determination of the Milky Way dark matter density profile, what data are the most important at every Galactocentric radius, and why?"

How much total mass there is:

- Stellar kinematics
  3D position, 3D velocity, metallicity, age..)
- Gas kinematics
- Masers (microwave lasers)

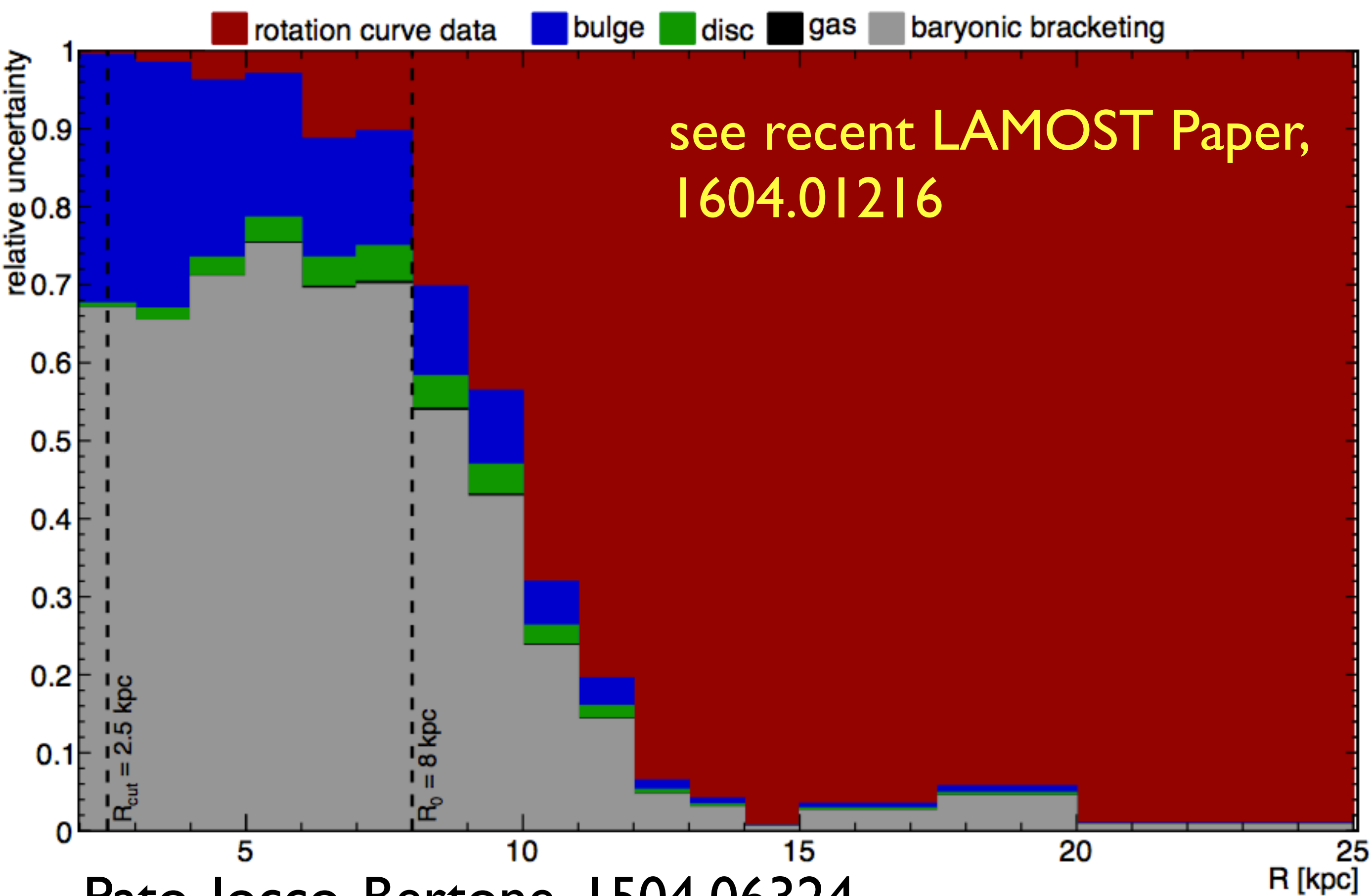
- Analyze using Rotation Curves or Vertical Motions in the disc

How much of it is Dark Matter:

- Add up all the baryon densities, subtract this from total density.
- Maybe assume something about the DM profile, measure kinematics where DM>baryons (e.g. vertical tracer velocities assuming constant DM density)

Rotation Curve Method

Relative uncertainty of each model component

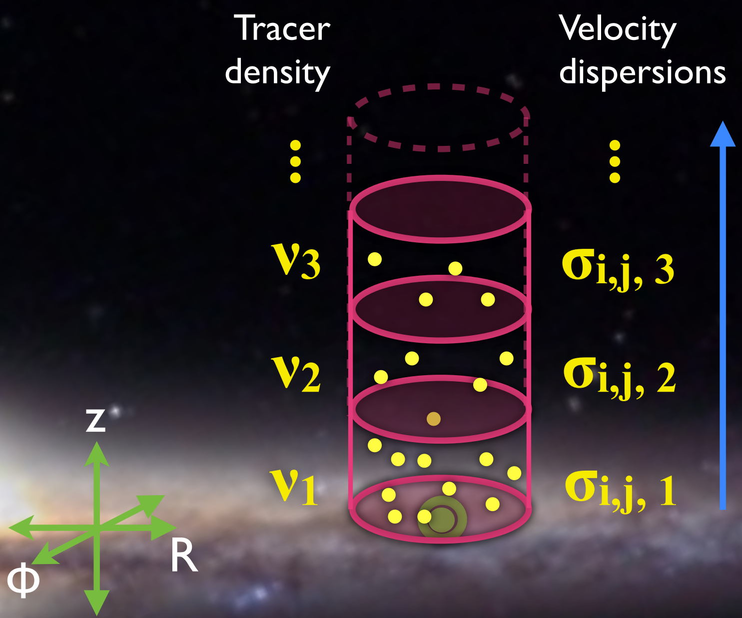


Pato, Iocco, Bertone, 1504.06324

Our Method

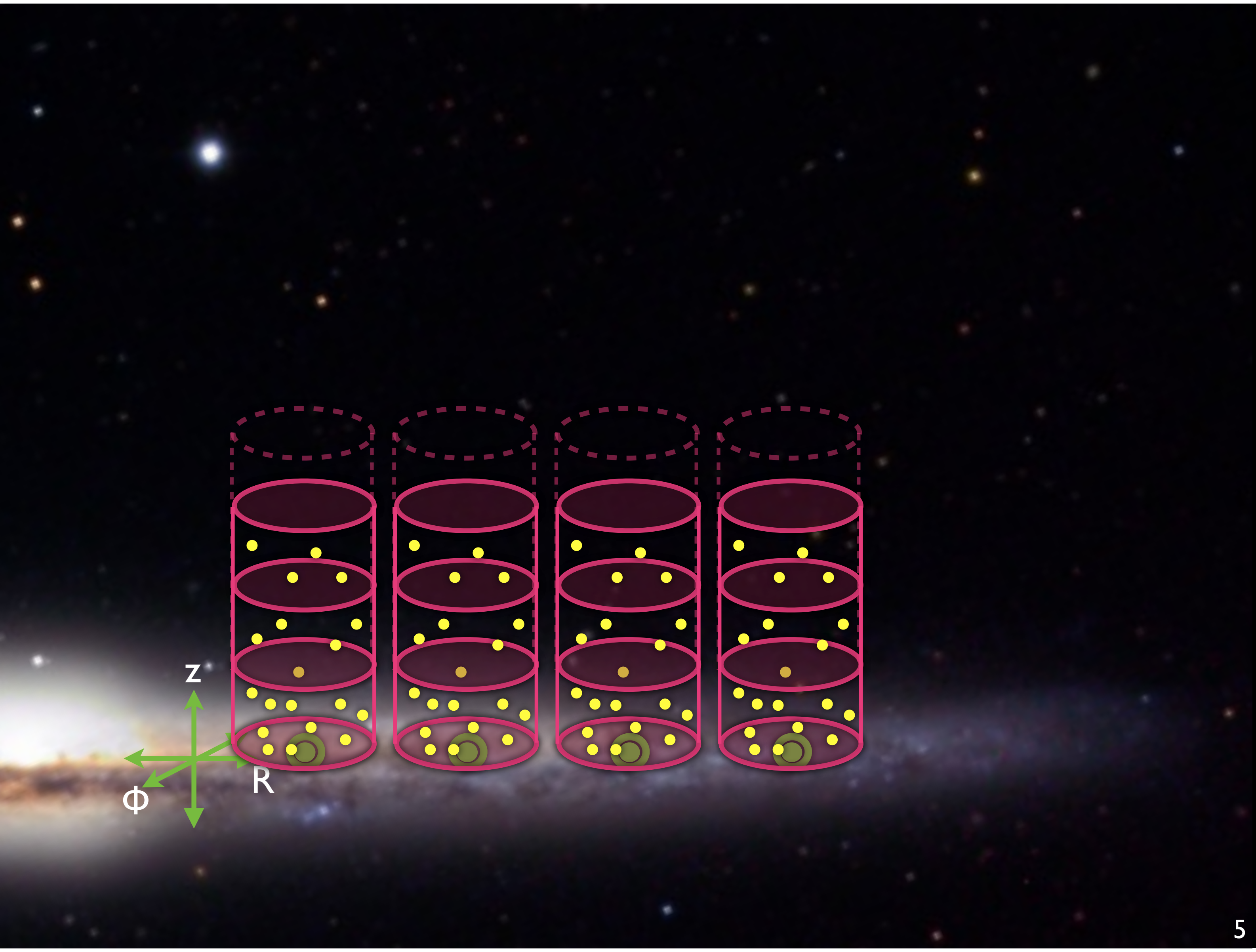
- Local measurements in z-direction and R-direction
- Data points are **positions** and **velocities** for a set of tracer stars in a cylindrical volume.
- data is binned to get **tracer density** and **velocity dispersions**

$$\sigma_{ij}^2(\mathbf{x}) = \overline{v_i v_j} - \overline{v}_i \overline{v}_j$$



Constant DM density

- Use only the z-direction Jeans equations, account for radial (& axial) data via a correction term.


z
R
Φ

Mainz Institute for Theoretical Physics

What data would be ideally suited to constrain the dark matter density profile in the innermost region of the Galaxy (say, inner 1-2 Kpc)?

Miguel Pato
Fabio Iocco

$r \simeq 0.3$ mpc - 0.03 pc
Tracers: S-stars
potential: black hole

$r \simeq 0.03$ pc - 10 pc
Tracers: O/WR stars, late-type stars, molecular gas
potential: black hole + star cluster

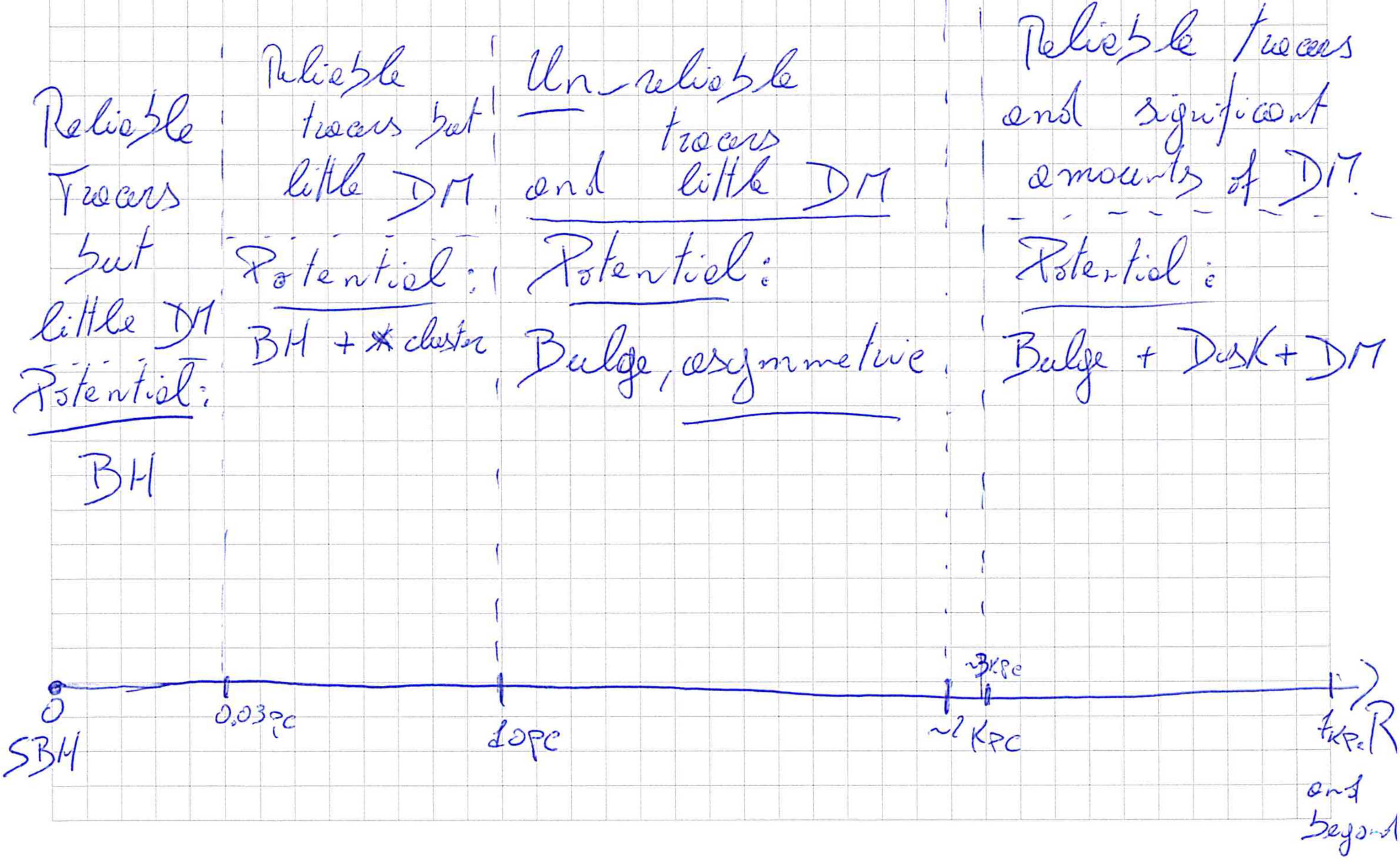
} reliable tracers but little dark matter

$r \simeq 100$ pc - 2 Kpc
Tracers: gas (but: not sure if follow gravitational potential, no circular orbits ⇒ no distance info)
stars (as far as I know, no available tracers at these radii)
future: MOONS (2019), WFIRST (2030?) } IR
Gaia (now) → no good (optical)
potential: baryons (mostly)

} unreliable or inexistent tracers and little dark matter

$r \simeq 3$-7 Kpc
Tracers: gas, stars, masers
potential: baryons + dark matter

} reliable tracers and significant dark matter



Regarding measuring kinematics in nearby dwarfs, which upcoming instruments are more promising? What scales do we aim to reach in the next 5 years?

Technical side is not so bad now, IMHO modeling has a bit of 'catching up' to do.

- Tilted ring model for gas (or other rotation) based measurements is relatively poorly understood.
- Models for dispersion based measurements are relatively simplistic, I think more can be done here, though this is in part driven by the difficulty in obtaining large numbers of stellar spectra.

Anticipated advances:

- SKA for HI. Looks like ~0.1arcsec resolution at 1.4GHz with a 1sq. deg. FOV. My radio-astronomy-fu is not strong enough to translate sensitivities into required time on source, but I imagine it is short. 1.5 dex increase in resolution points to at least 100x more accessible dwarf targets (conservative guess for keeping time on source reasonable), possibly up to $>10^4$ increase, large FOV at larger distances could allow multiple simultaneous targets (?). This all points toward the possibility of a volume-limited sample.
- IFU time is slowly getting cheaper, which is useful since optical can access multiple independent tracers simultaneously. While I don't think this is the path to larger surveys in the near future, could be a big help beating down systematics. Integrated light spectra of dispersion dominated systems is difficult but not impossible; improvement to model is necessary if we hope to get a substantial increase in dispersion dominated targets (or a lot of 30m class time I guess).
- Upcoming many-fibre spectrographs (4MOST, WEAVE, ...) will finally allow a reasonable sampling of stars in spectroscopy for nearby dSphs. This is probably the most immediate anticipated advance (or IFUs?).
- On longer (?) timescales, it is apparently plausible to get proper motion rotation measurements out to D~a few Mpc with Hubble-like equipment and a ~20 year baseline. Note that this is one place where GAIA is not the answer, HST/JWST/Similar are superior astrometry instruments at D≳100kpc. See work of Kallivayalil.

In general, when talking about a DM particle, we talk about it and simulate it as "one" specific type of DM (cold warm, self interacting...)
How realistic?
whole range of particles in the dark sector?

DM production
- WIMPs (thermal)
- eWIMPs (gravitinos or axinos) non thermal
- freeze-in
- asymmetric DM
- axions.
- neutrinos

Various mechanisms can COEXIST.

DM models
- "Rogue" DM in simplified scenarios
- Whole DM sector in complete models (SUSY?)

Atomic DM
- See e.g. Kaplan.

DARK ATOMS.