19th June 2018

GRAPPA Student Seminar

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GRAPPA

GRavitation AstroParticle Physics Amsterdam

Today's Schedule

- Presentations

- Lecture

  - "Cracks" in ΛCDM [Bradley]

  - Dark Matter-electron scattering [Bradley]

[Break]

  - Indirect searches with anti-matter [Daniele]

  - Primordial Black Holes [Daniele]

“Cracks” in ΛCDM

[arXiv:1707.04256]

Theoretical issues

- What is Dark Matter?

- What is Dark Energy (and what is it so small)?
  The “Cosmological Constant Problem”

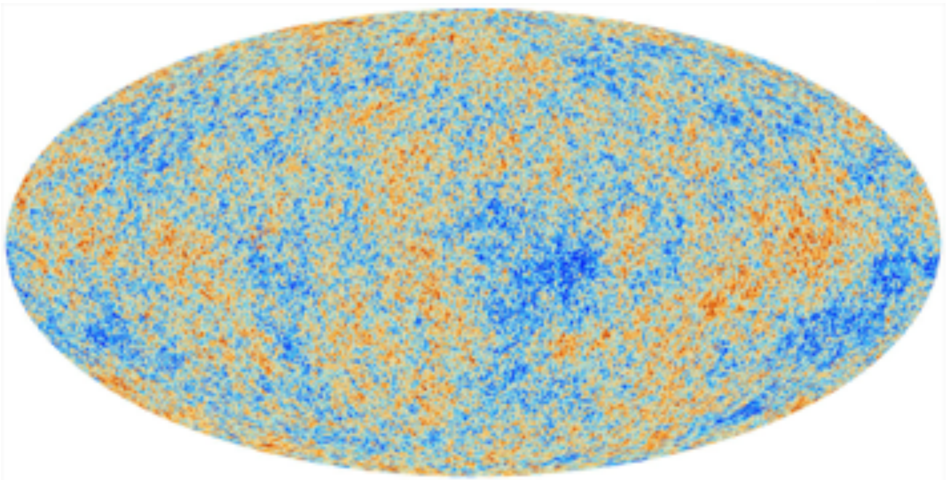
- Problems with initial conditions: Where does inflation come from? Are the inflationary initial conditions ‘special’?

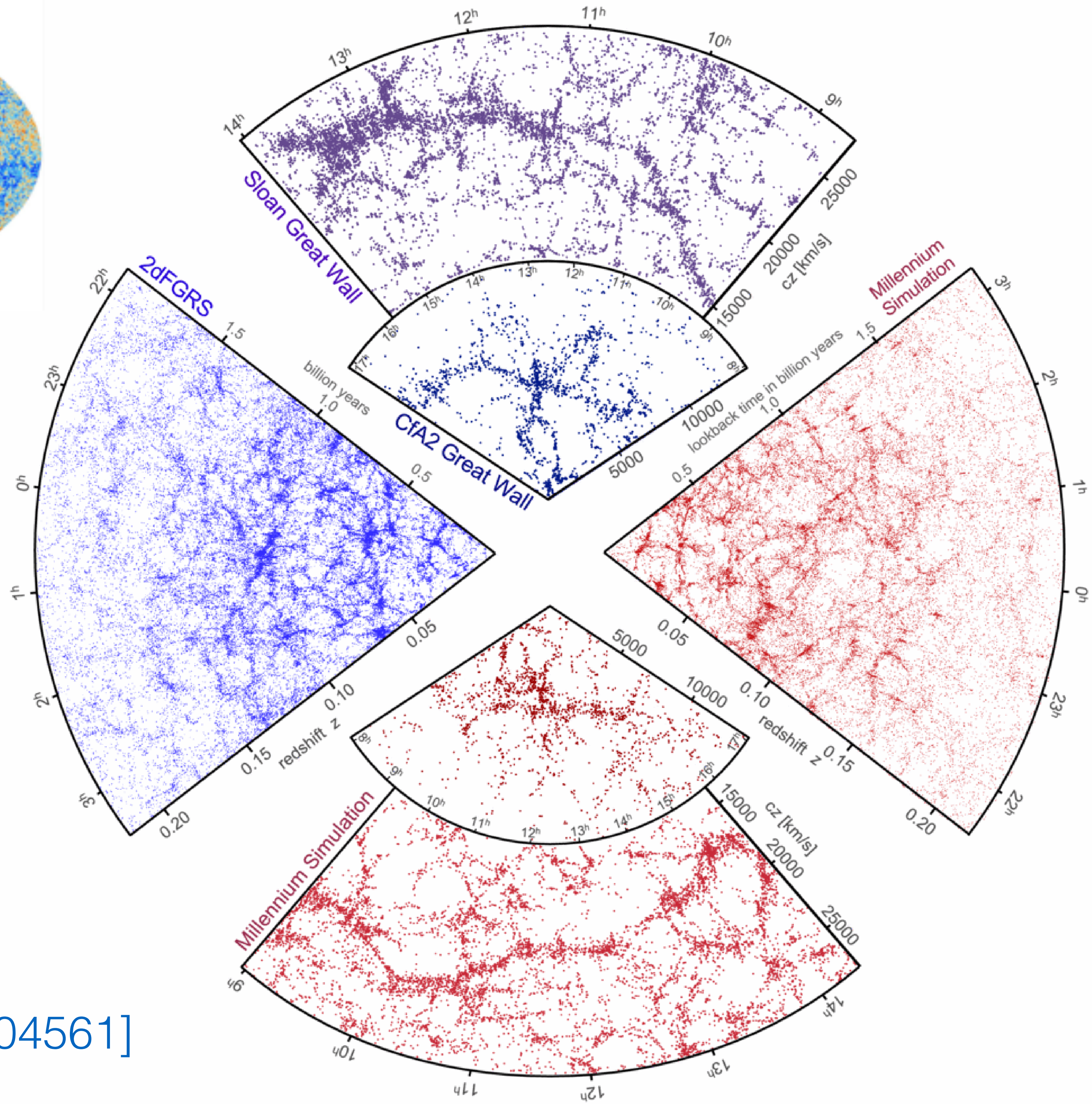
[see e.g. arXiv:1610.06192]

Observational issues

Can a ΛCDM cosmology produce a Universe which looks like ours?

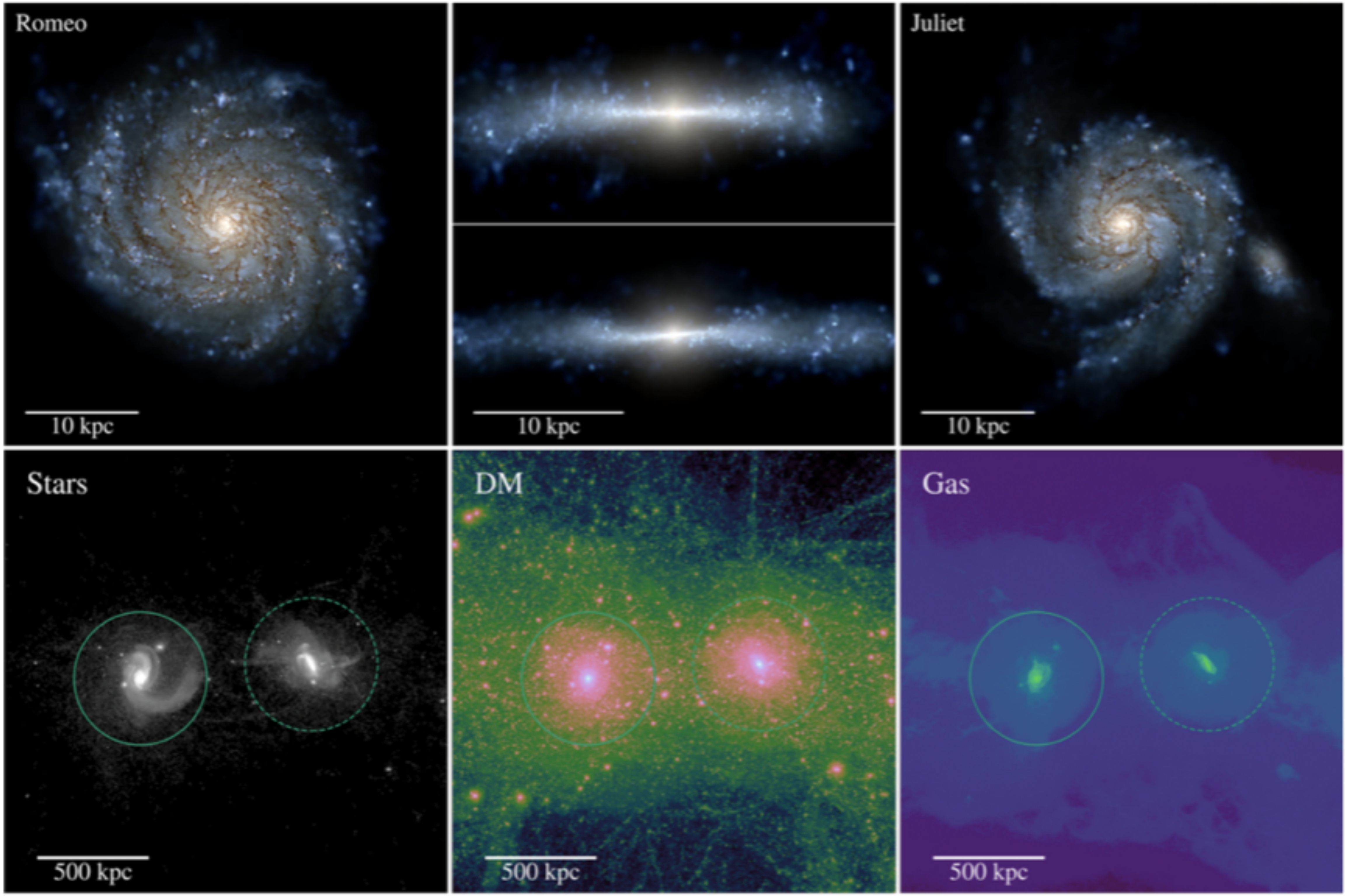
Large Scale Structure





[astro-ph/0604561]

Small Scale Structure



[FIRE simulations, arXiv:1806.04143]

“Small-Scale Crisis”

“Small-scale”: $M \approx 10^{11} M_\odot \, , R_{\rm vir} \lesssim 150 \text{ kpc}$

(i.e. Milky Way mass and below)

On these scales simulations seem to deviate from observations in a number of ways:

- Existence of Bulge-less disk galaxies
- “Missing Satellites” Problem
- “Cusp/Core” Problem
- “Too Big To Fail” Problem

[Review, e.g. arXiv:1707.04256]

“Small-Scale Crisis”

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[Review, e.g. arXiv:1707.04256]

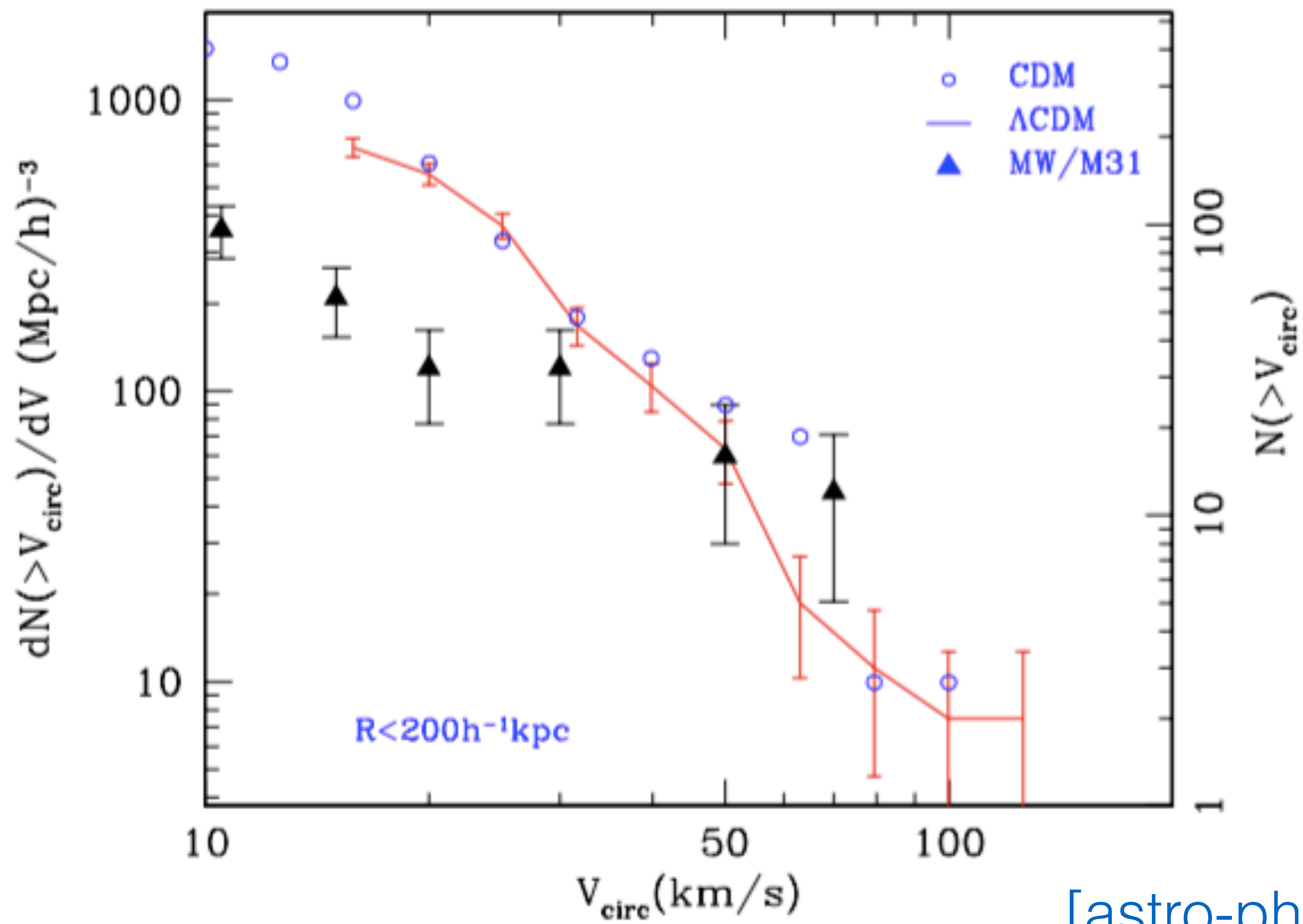
Dark Matter Only Simulations

http://www.ucolick.org/~diemand/vl/movies/vl_form_z12to0.mpg

[Via Lactea Simulation]

“Missing Satellites” Problem

Cumulative number of satellites



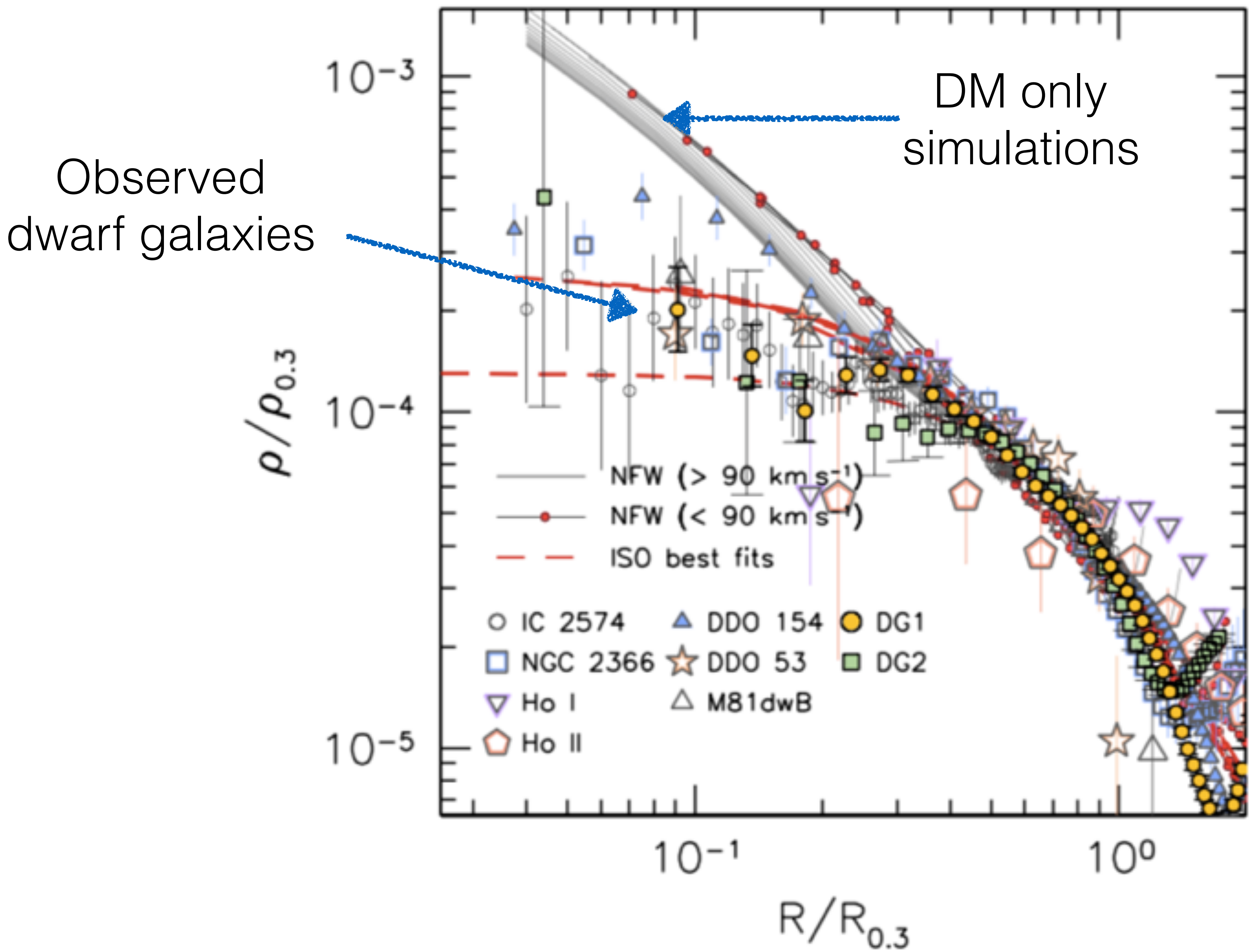
[astro-ph/9901240]

Satellite mass proxy

Expect to see O(1000) star forming satellites of the Milky Way
Observe only O(50).

[But see also, arXiv:1711.06267]

Cusp/Core Problem



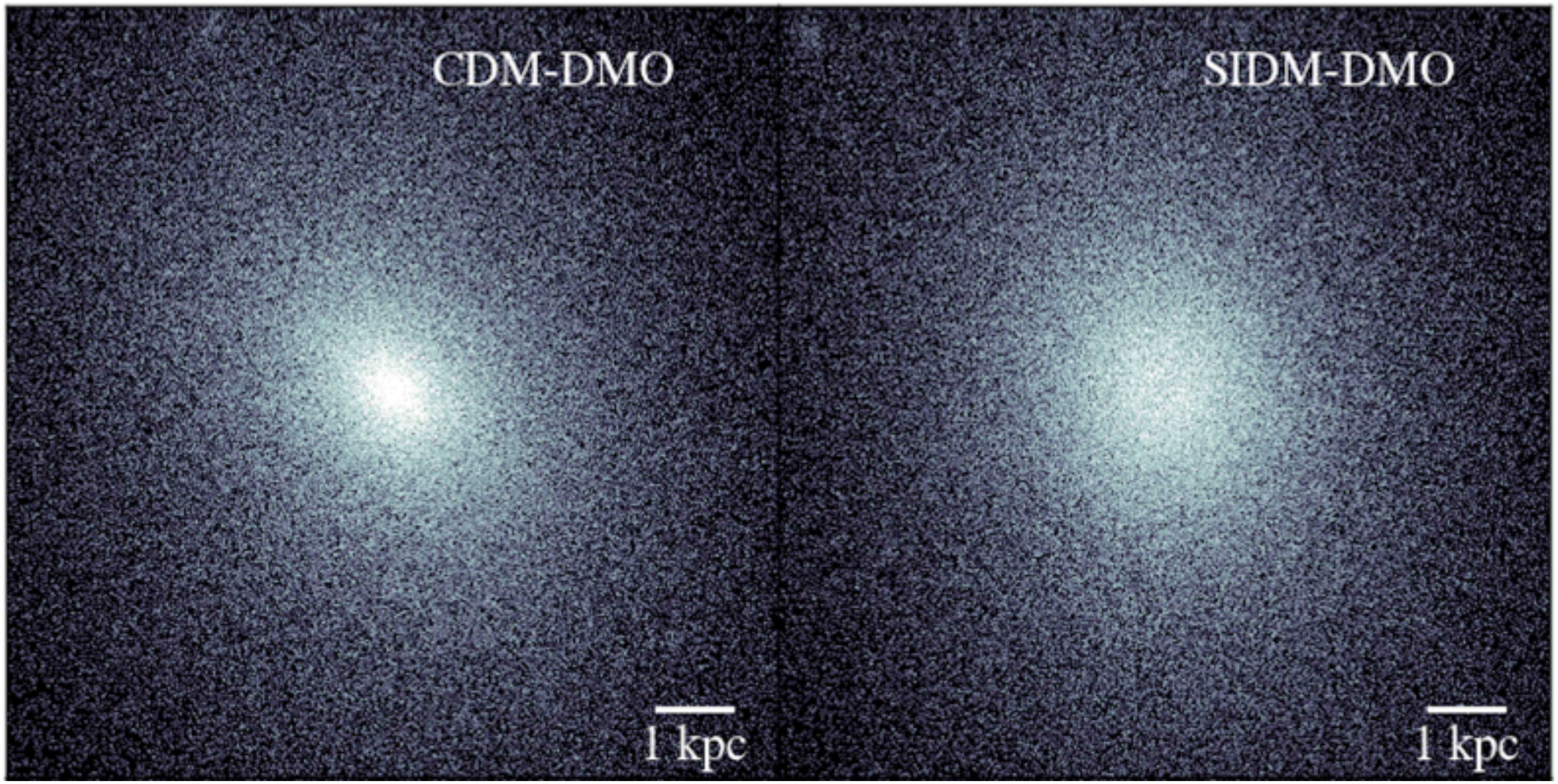
[arXiv:1011.2777]

Solutions beyond ΛCDM

Many particle physics proposals for changing the properties of DM halos on small scales and solving these “small scale crises”:

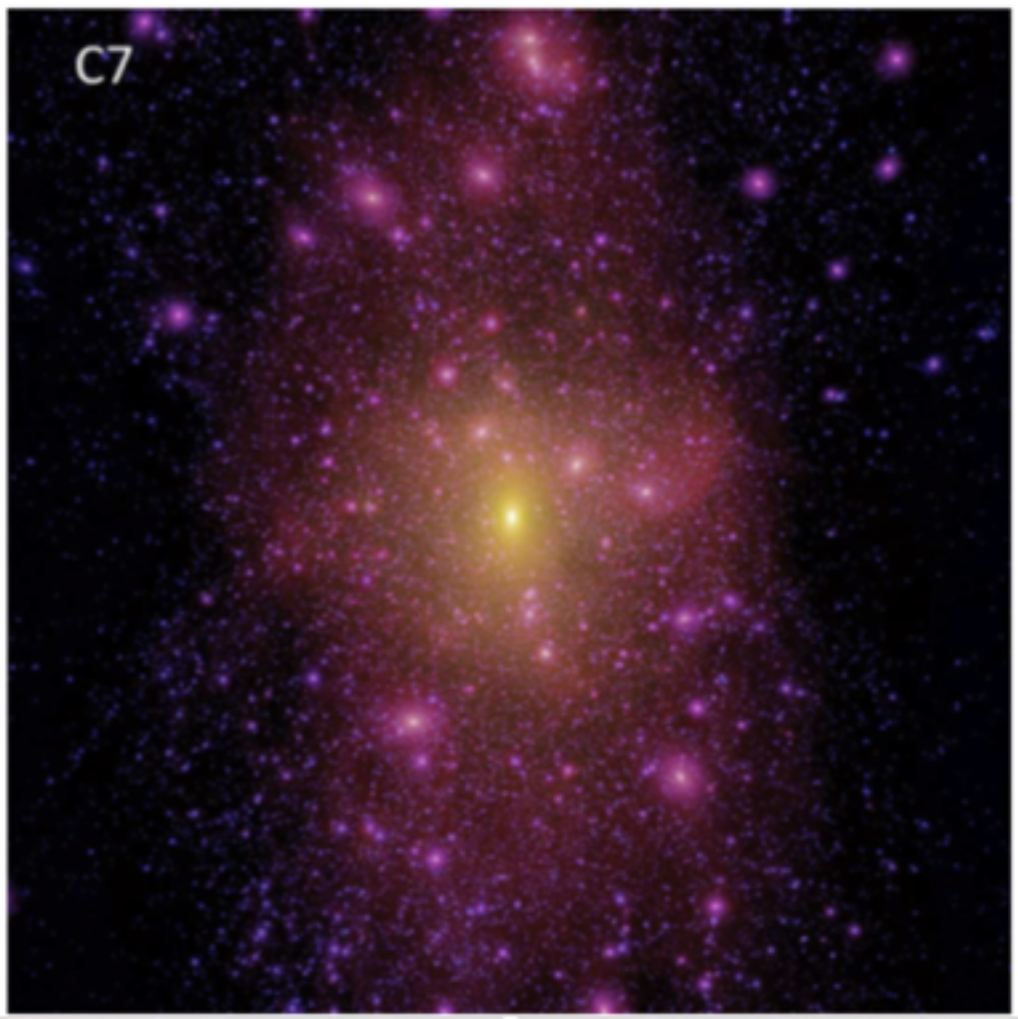
- Warm Dark Matter
- Self-interacting Dark Matter
- Ultra-light “fuzzy” Dark Matter
- and others…

Solutions beyond ΛCDM: Self-interacting DM

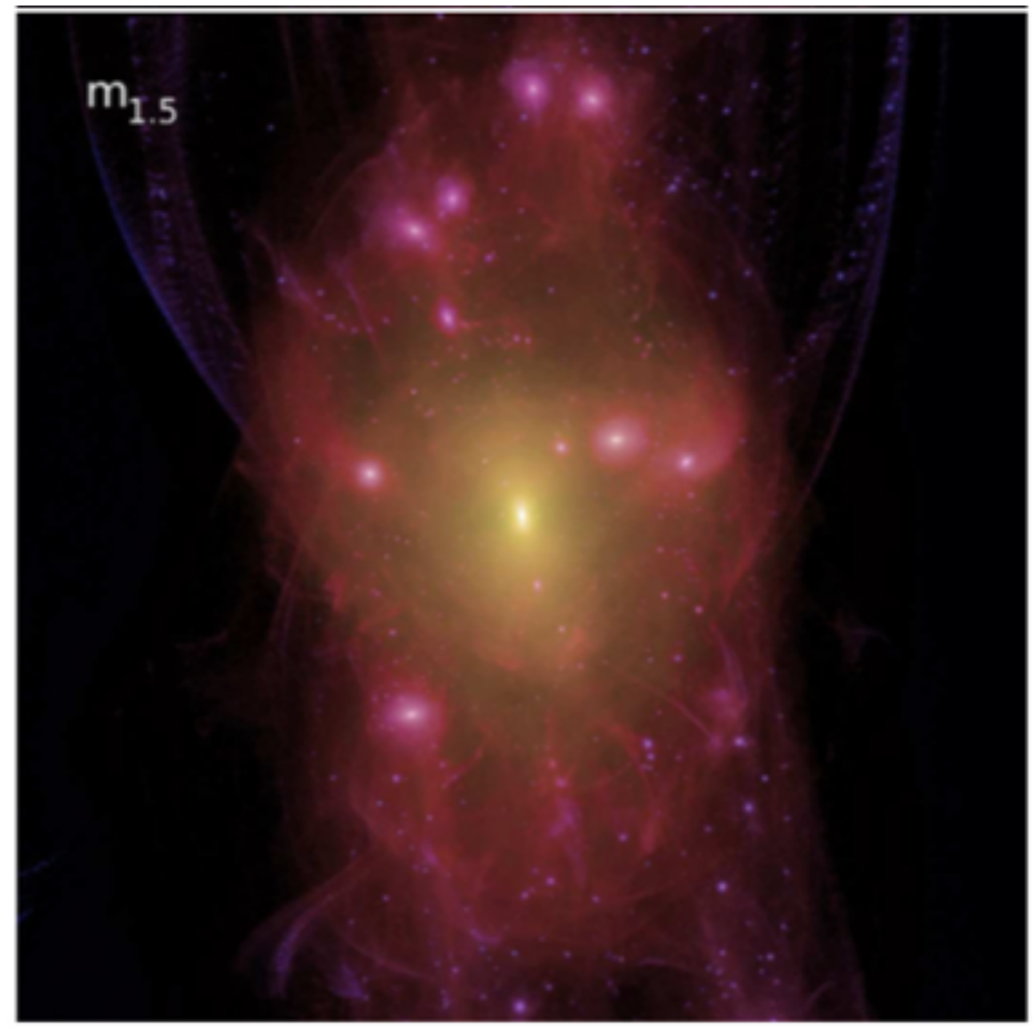


[arXiv:1208.3026, arXiv:1706.07514]

Solutions beyond ΛCDM: Warm DM



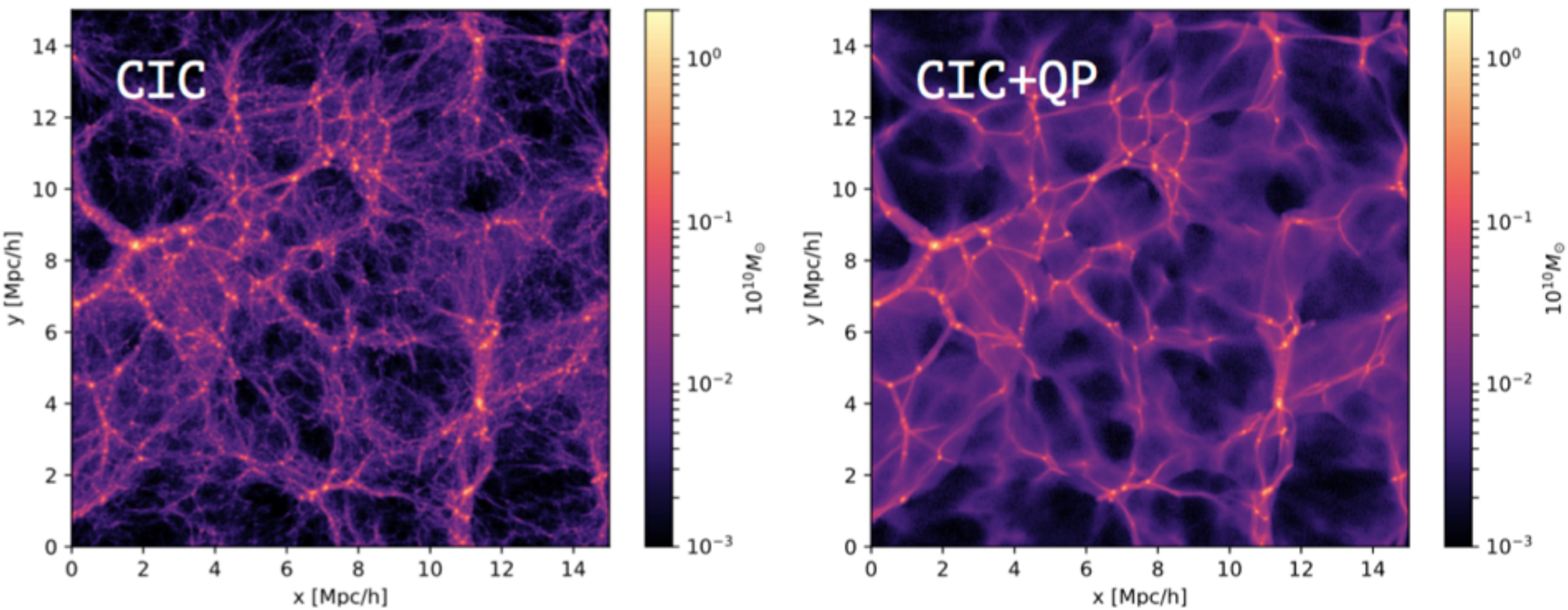
Cold Dark Matter



Warm Dark Matter

[arXiv:1308.1399]

Solutions beyond ΛCDM: Fuzzy DM



[arXiv:1801.08144]

Solutions

	Warm Dark Matter	Self-interacting Dark Matter	
Bulge-less disk galaxies			
Cusp/Core Problem		✓	
Too Big to Fail	✓	✓	
Missing Satellites	✓		

Credit: Alyson Brooks

Solutions

	Warm Dark Matter	Self-interacting Dark Matter	CDM + Baryons
Bulge-less disk galaxies			✓
Cusp/Core Problem		✓	✓
Too Big to Fail	✓	✓	✓
Missing Satellites	✓		✓

Credit: Alyson Brooks

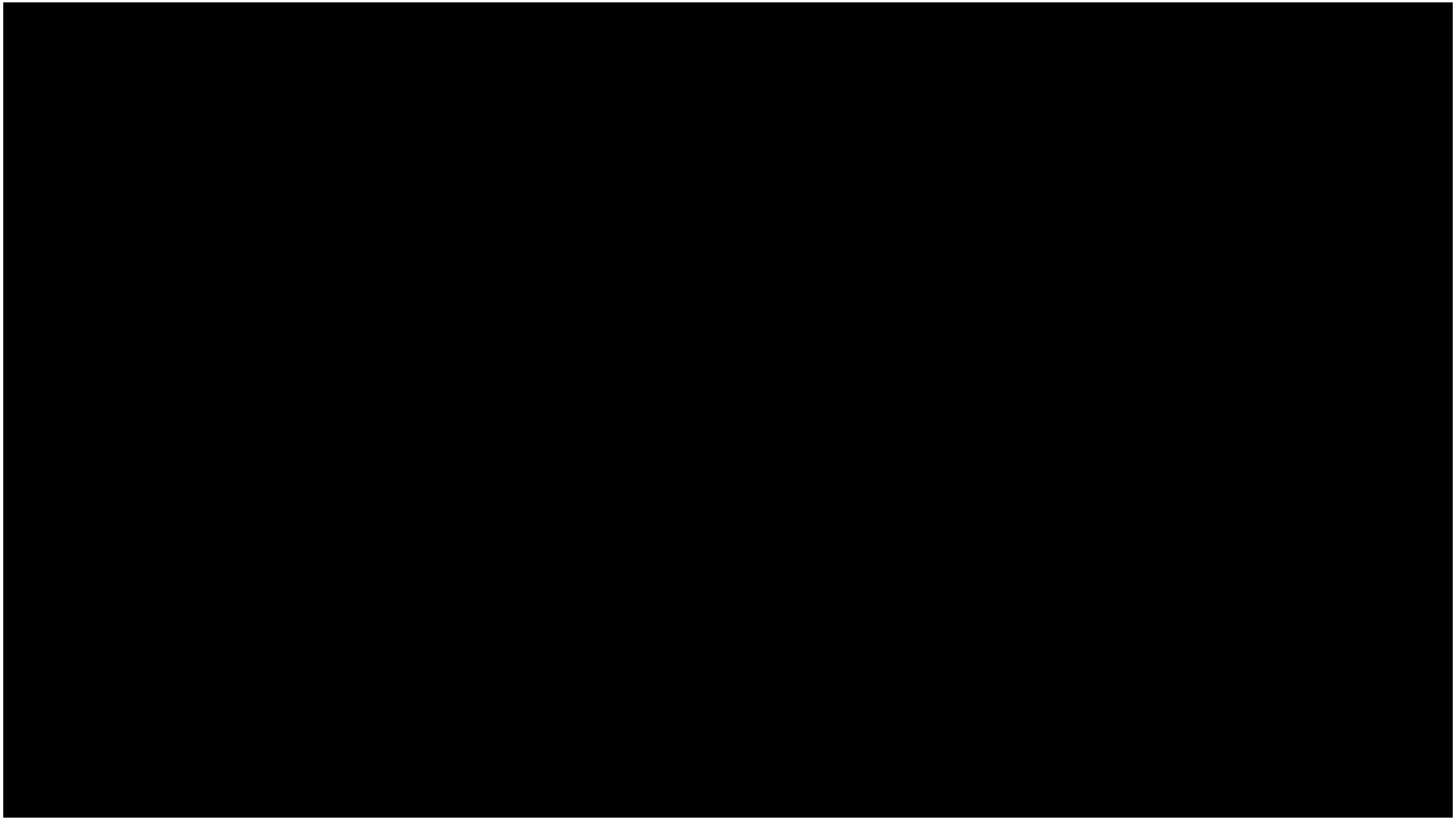
Hydrodynamical Simulations

Real galaxies contain **baryons**, in the form of gas and stars. Need to include this complicated physics, including:

- Gas cooling
- Star formation and stellar evolution
- Supermassive black hole formation and evolution
- Supernova feedback
- AGN feedback

Note that all this physics happens below the resolution of the simulations - need a prescription for adding it 'sub-grid'…

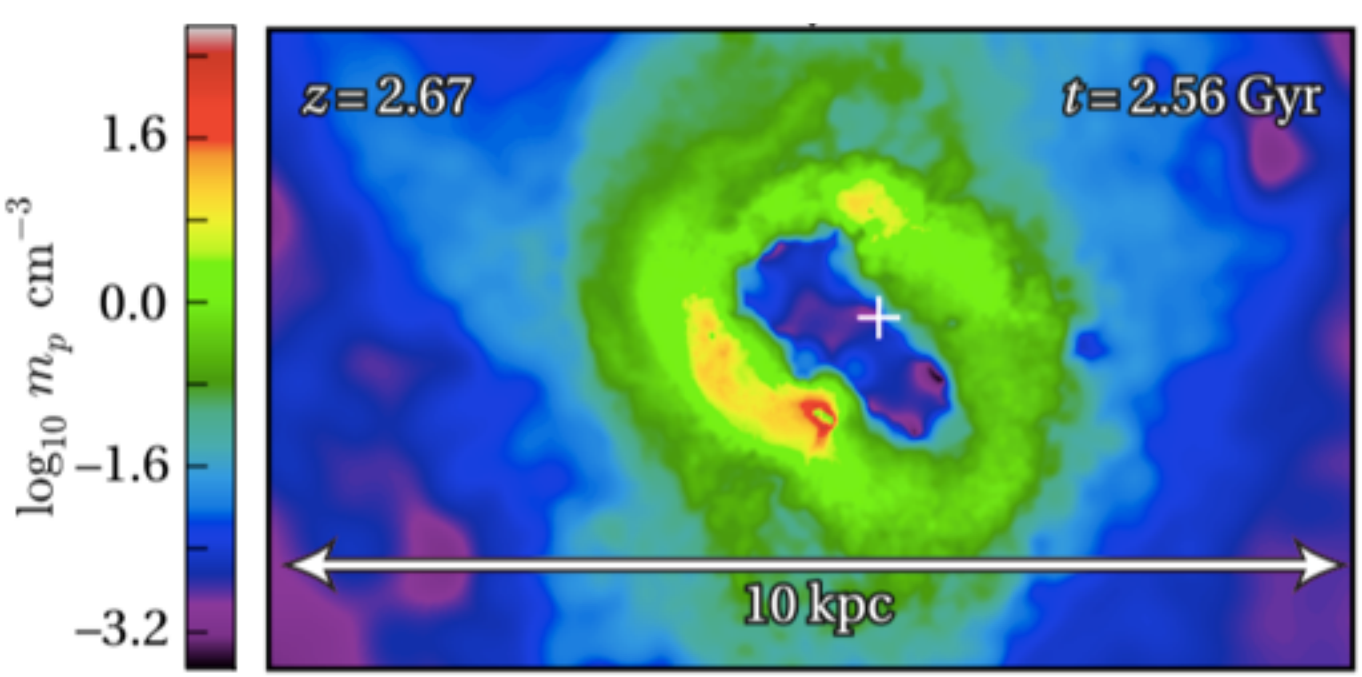
Hydrodynamical Simulations

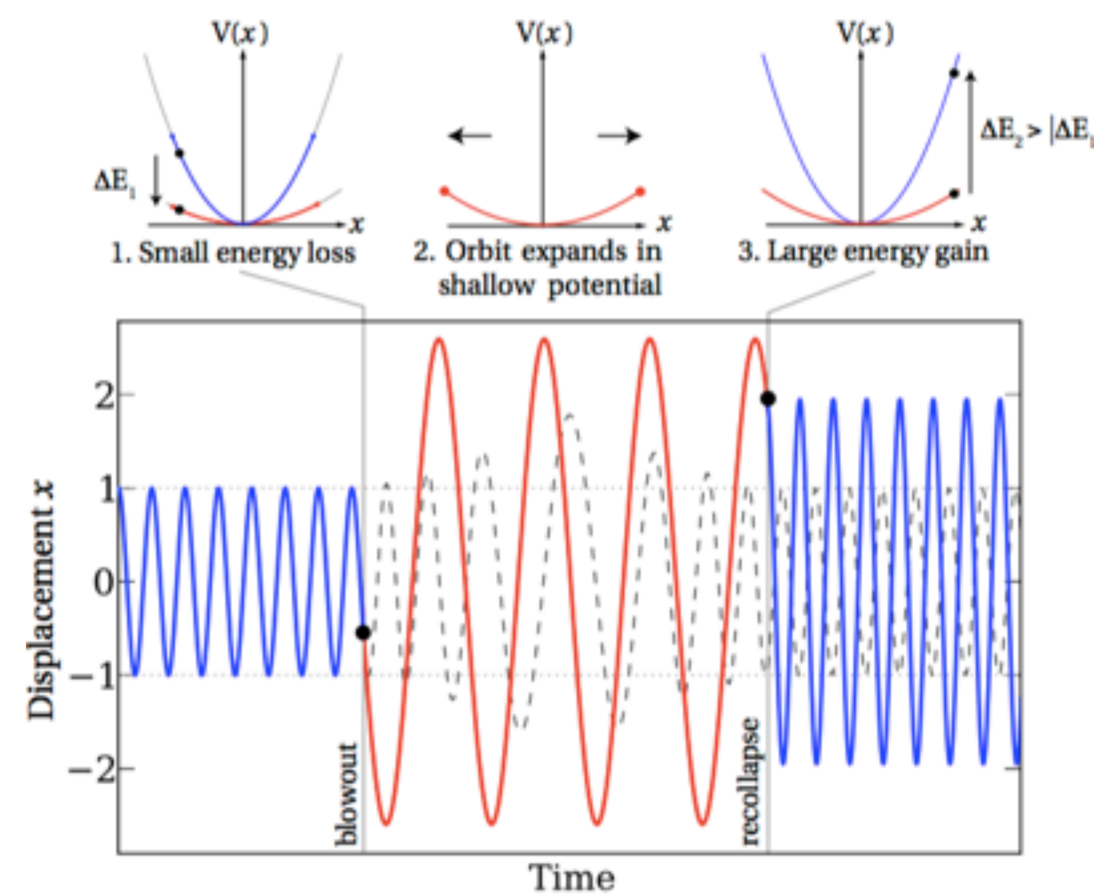


[Illustris Collaboration]

Cusp/Core problem and Feedback

Supernova feedback leads to rapidly varying gravitational potential which causes the DM orbits to widen and reduces the central density…





…and also blows out gas, reducing star formation…

[arXiv:1106.0499, arXiv:1410.3825]

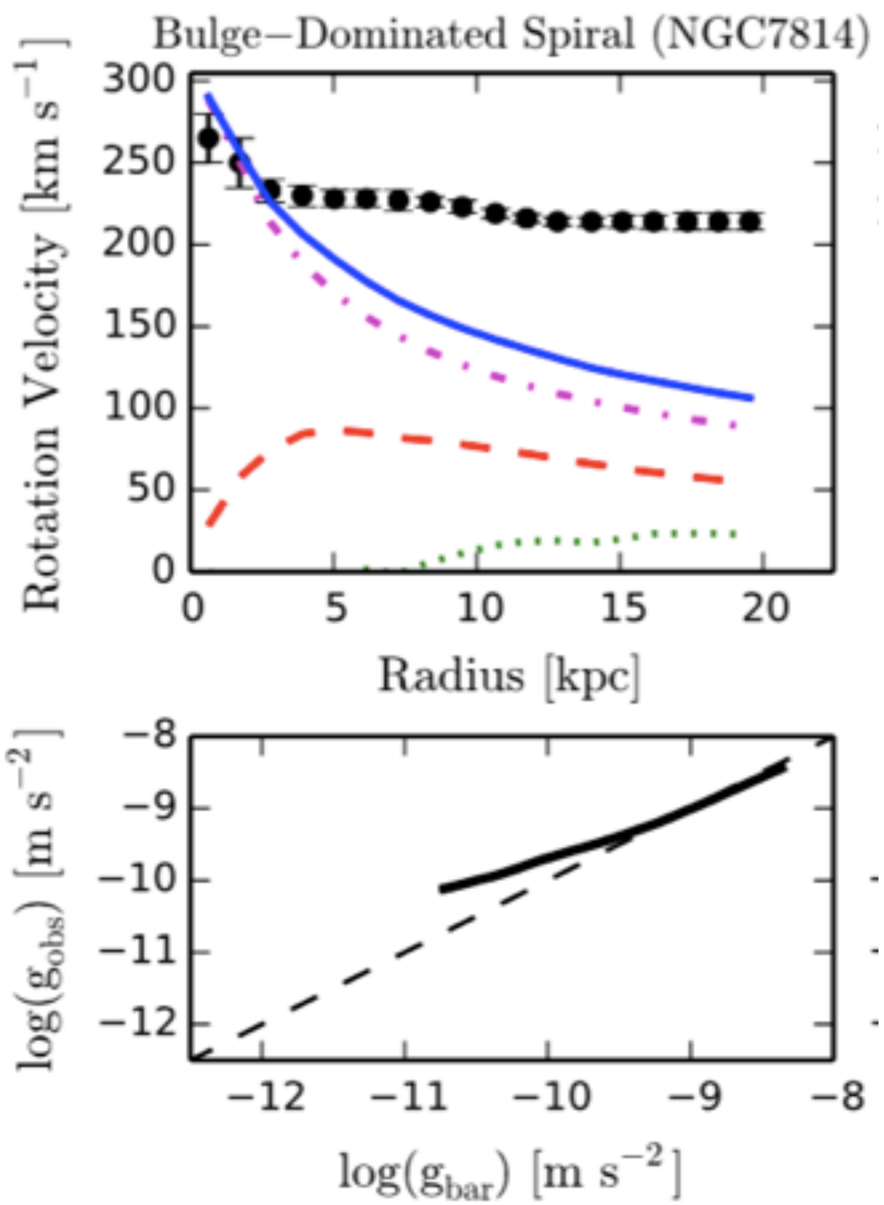
Baryons as a solution

- No matter what new properties of DM you might add, baryons *need* to be included in simulations

- Baryons can drastically change the properties of small scale DM halos and galaxies. They *could* also resolve the ‘small scale crises’ of CDM.

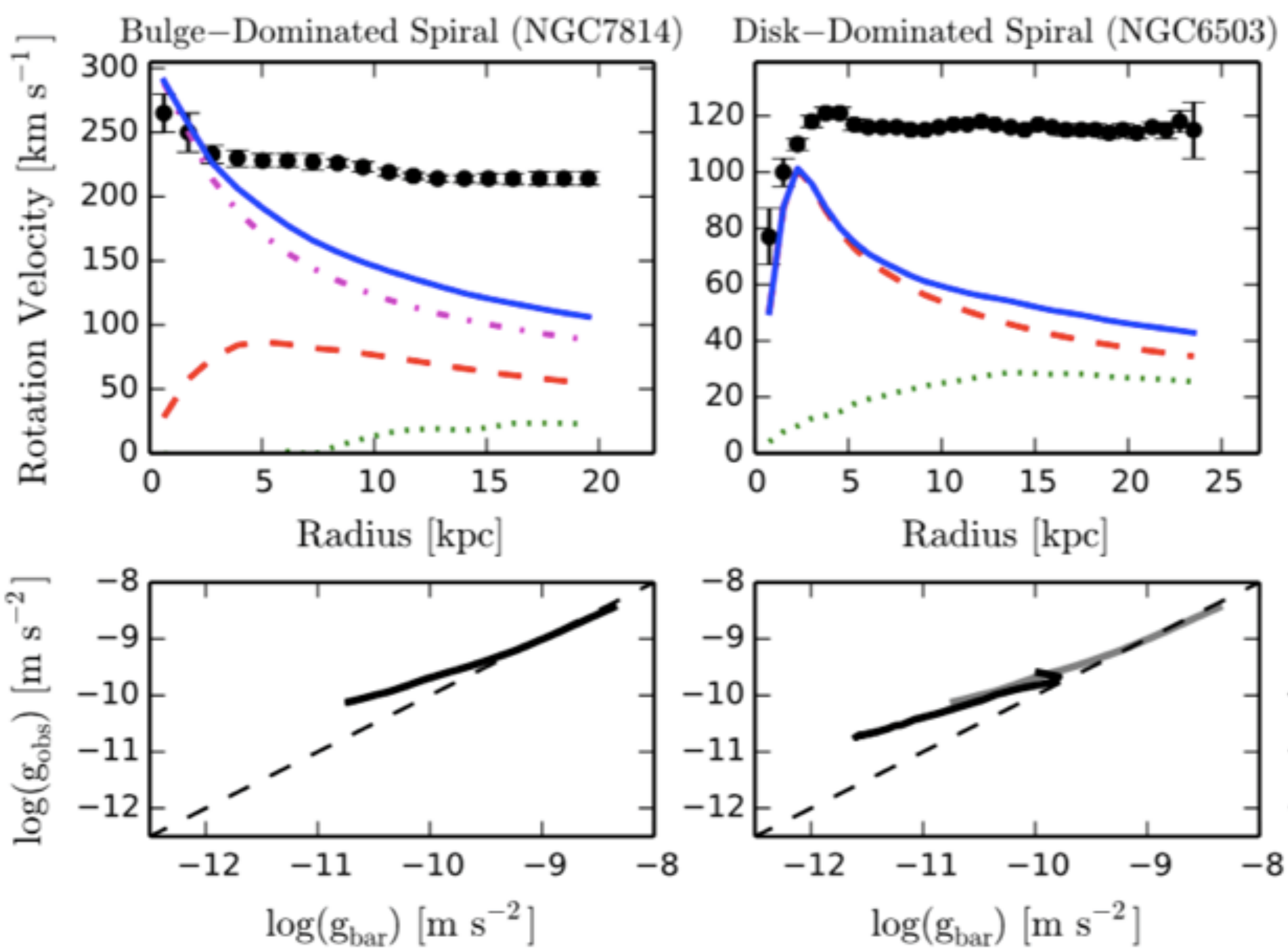
- But hydrodynamical simulations will never resolve down to the scales of single stars. They rely on “sub-grid” recipes and showing that baryons will *always* resolve small scale problems is hard.

Flat rotation Curves



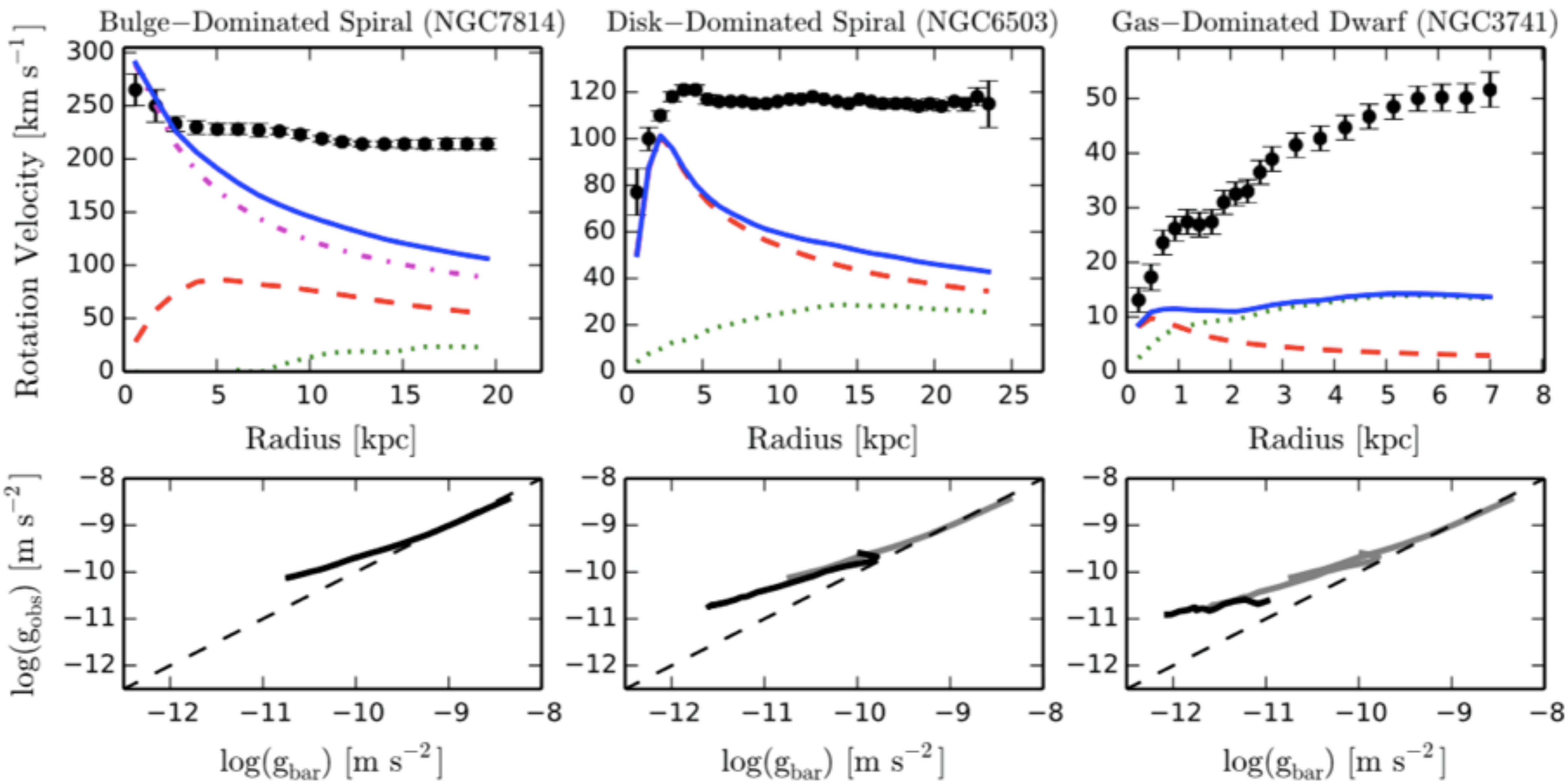
[arXiv:1609.05917]

Flat rotation Curves



[arXiv:1609.05917]

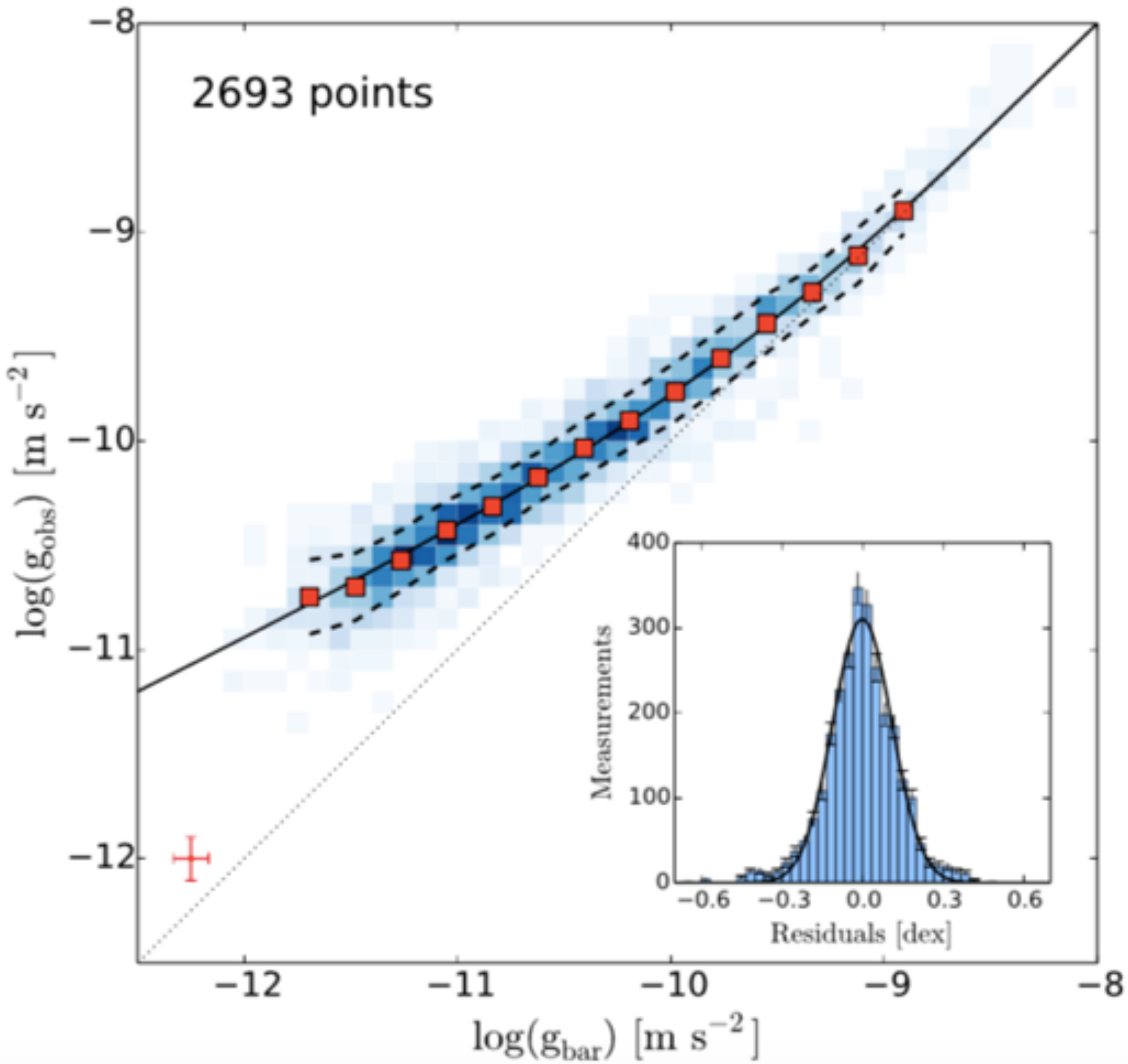
Flat rotation Curves



[arXiv:1609.05917]

Radial Acceleration Relation

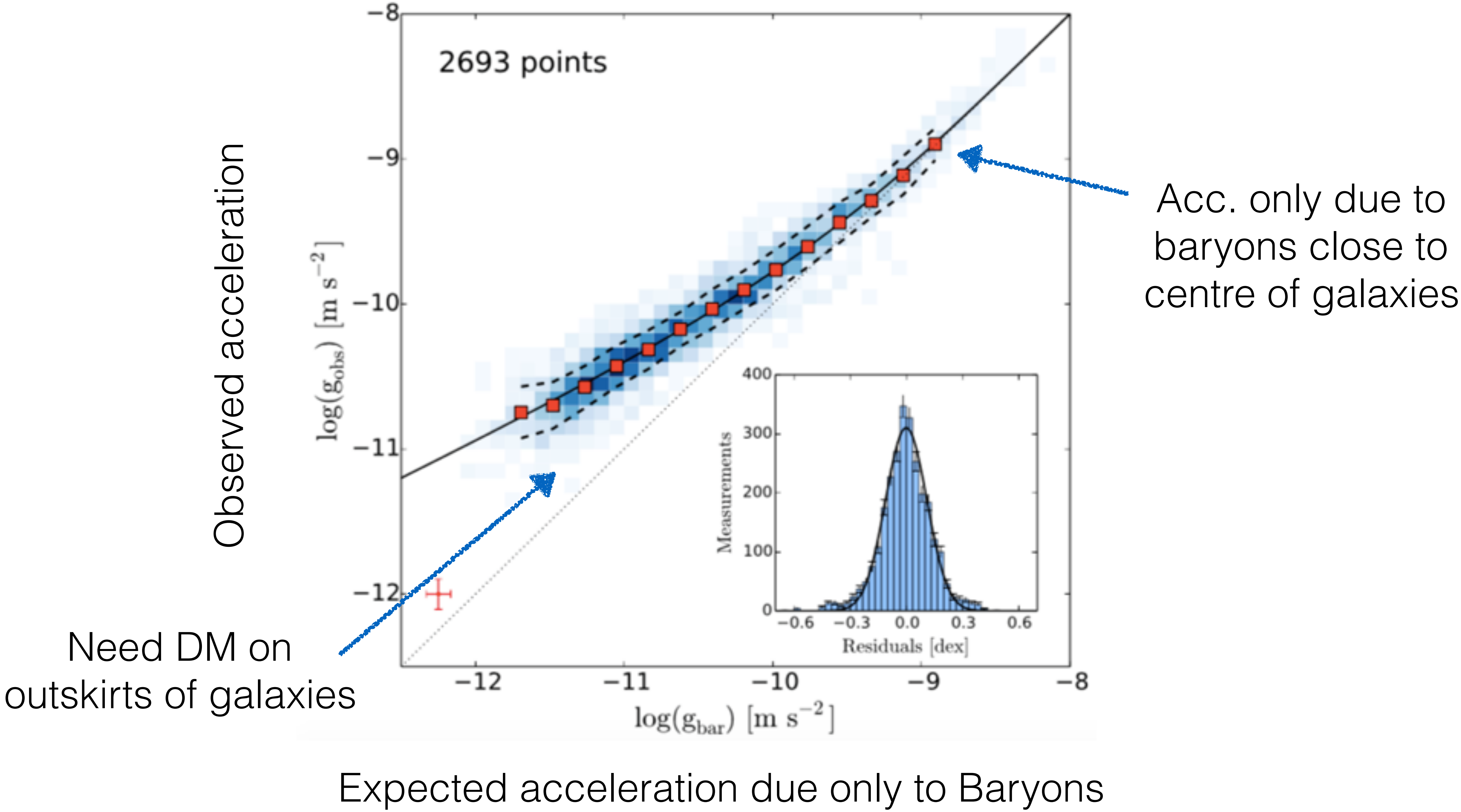
Observed acceleration



Expected acceleration due only to Baryons

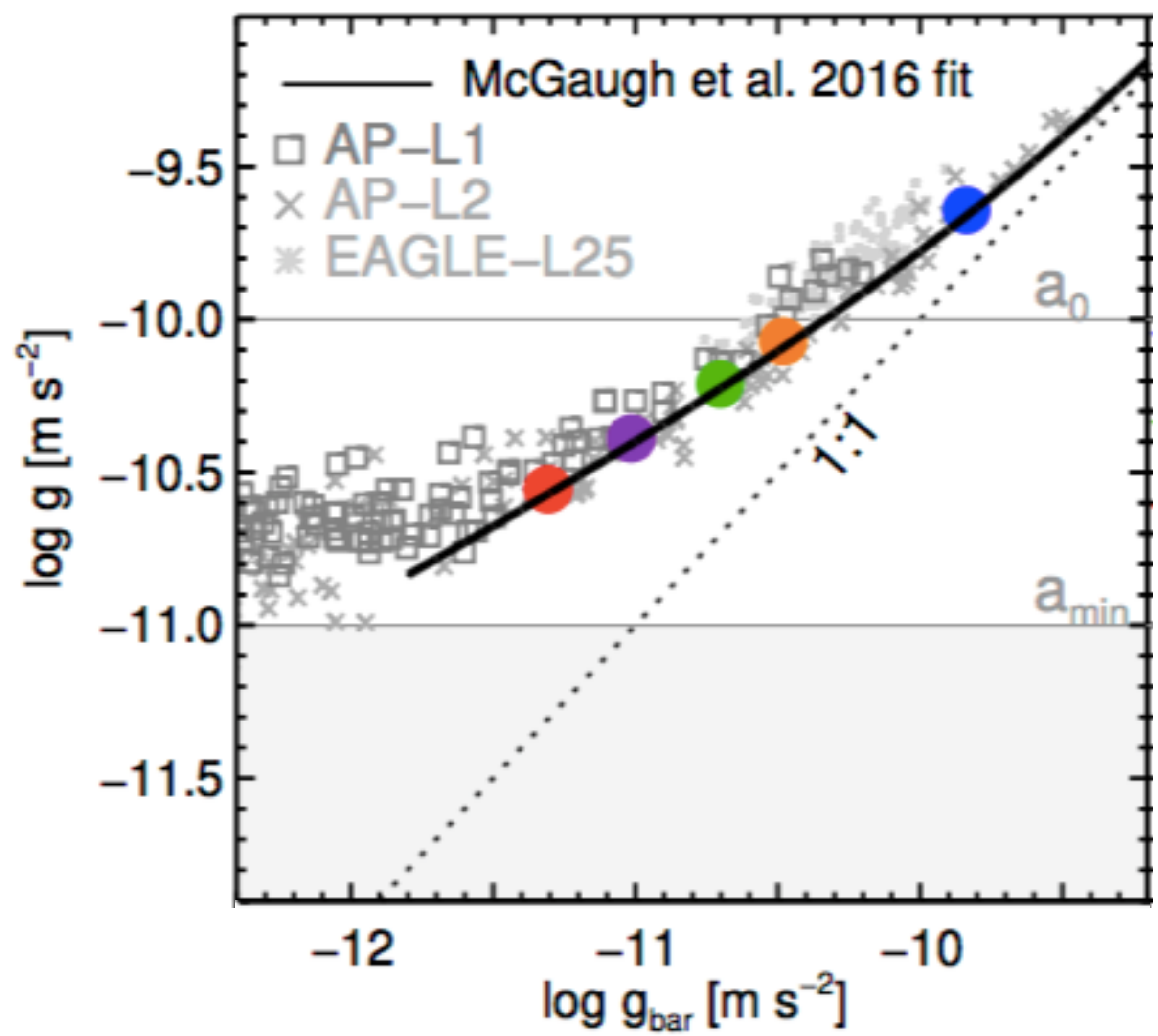
[arXiv:1609.05917]

Radial Acceleration Relation



[arXiv:1609.05917]

Radial Acceleration Relation in ΛCDM



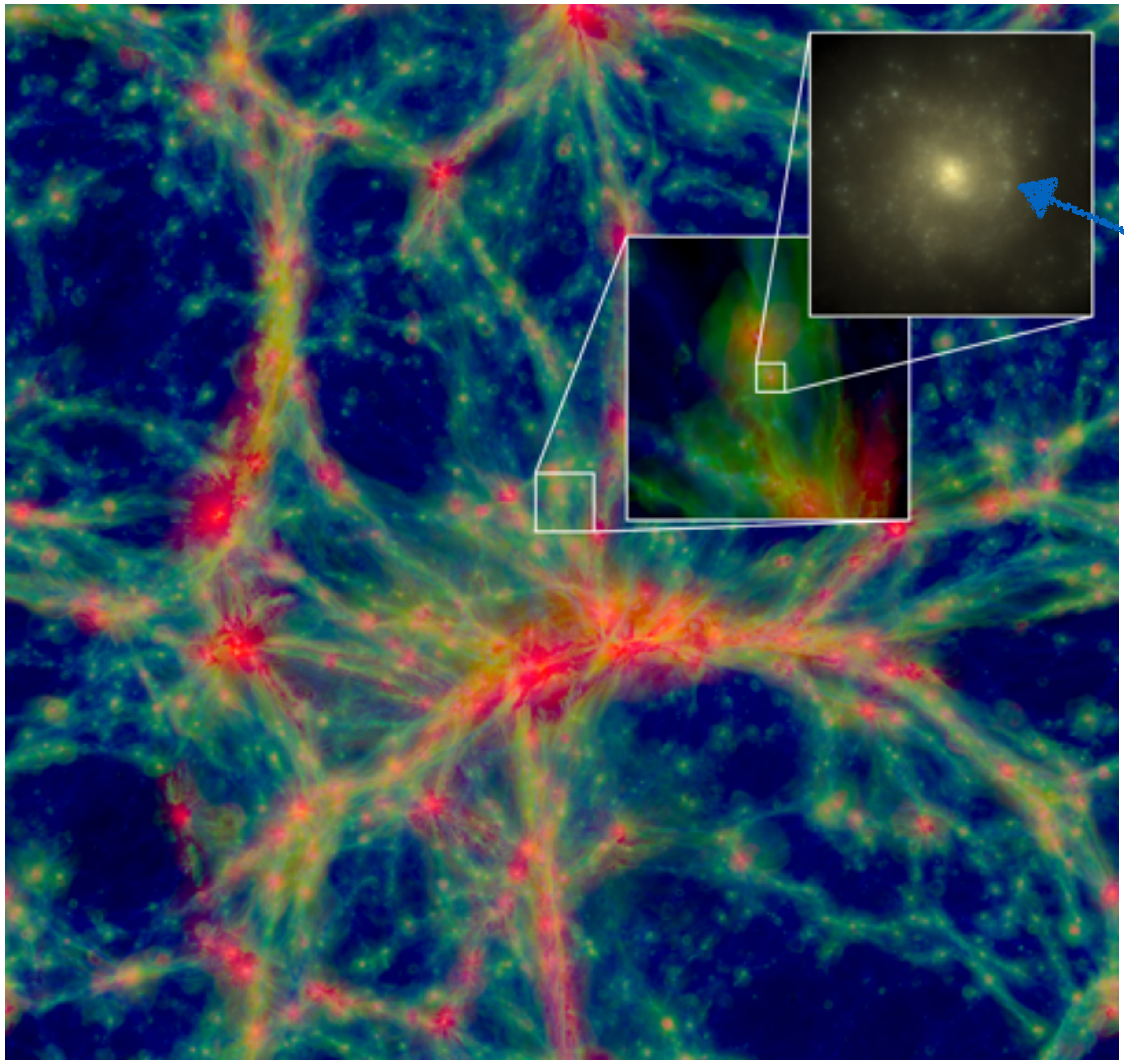
Galaxies in simulations do show such a scaling.
But the observations are consistent with zero scatter.
Do ΛCDM galaxies stick to the solid line as tightly as observed galaxies?

[arXiv:1612.06329]

Group 1: Report and Presentation

- Summarise the current “cracks” in ΛCDM on small scales
- Discuss some suggested solutions in terms of new particle physics
- Discuss how baryonic physics in hydrodynamical simulations may also provide a solution
- *If time allows:* Discuss the radial acceleration relation and whether it is a problem in ΛCDM

2 minute break…



Let's keep zooming in here

[EAGLE simulation]

Dark Matter-Electron Scattering

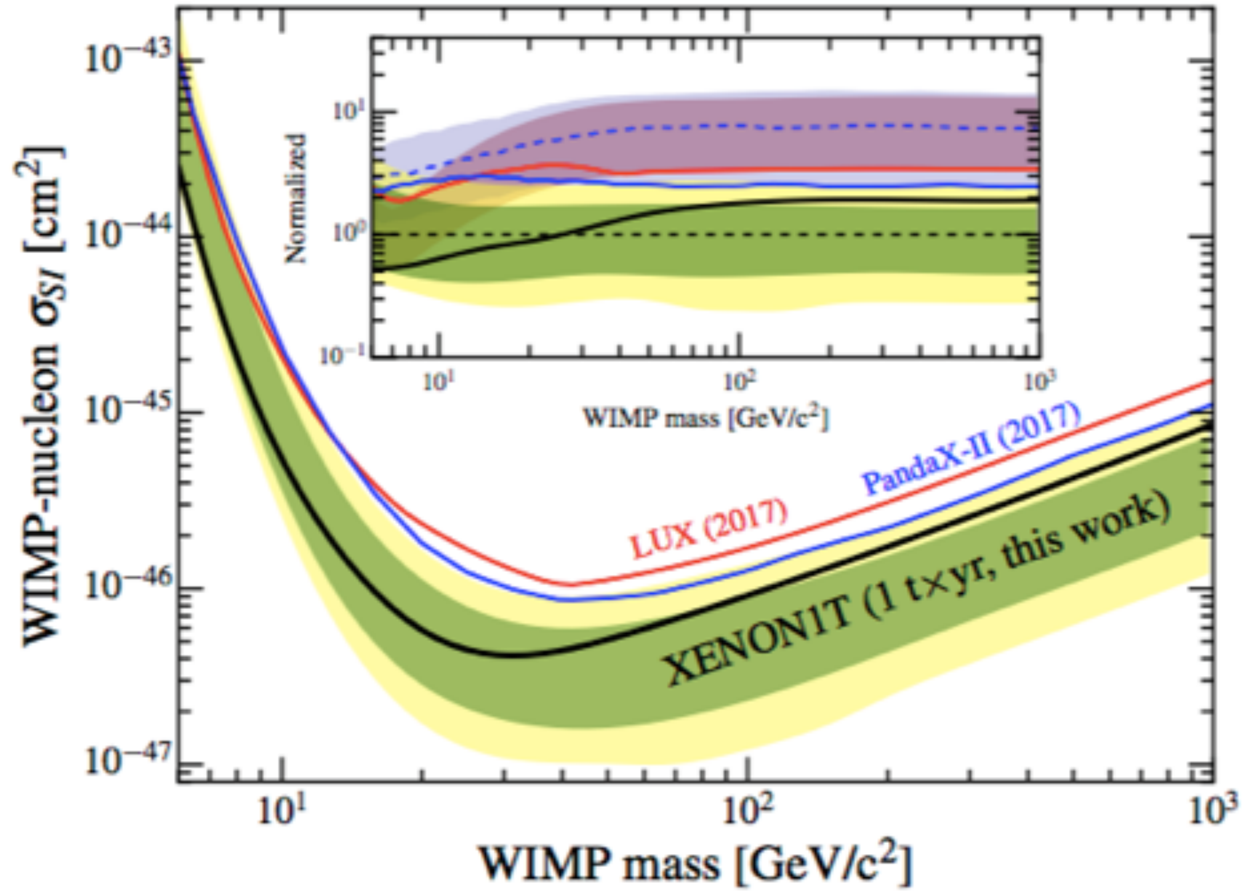
Dark Matter Direct Detection

For light DM, maximum elastic recoil energy is:

$$E_{\max} \approx 2m_\chi^2 v^2 / m_N$$

Fastest DM particles:

$$v \sim 750\,\mathrm{km/s}$$



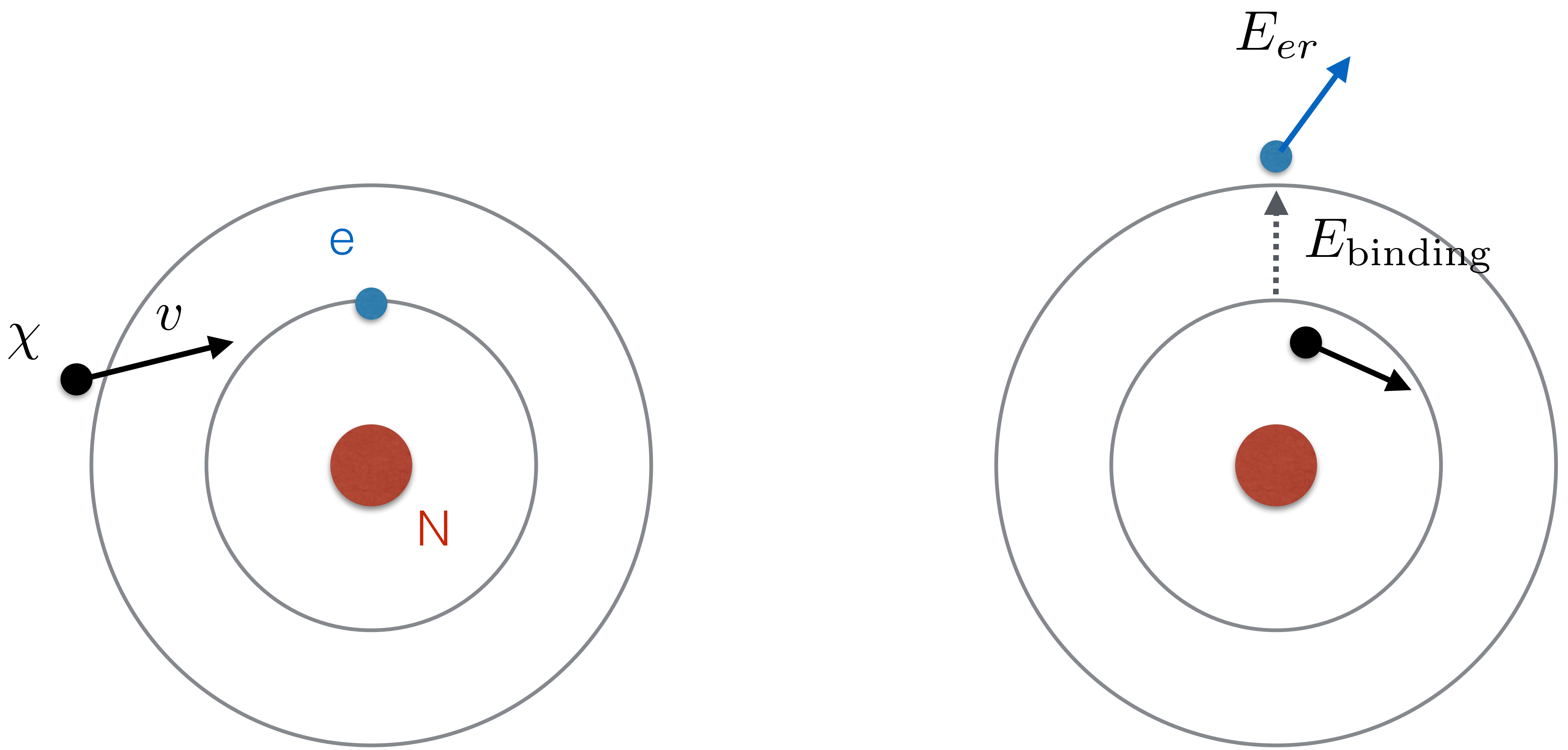
[XENON1T collaboration]

Max. recoil energy:

$$E_{\max} \approx 100\,\mathrm{eV}\left(\frac{m_\chi}{1\,\mathrm{GeV}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_N}\right)$$

Lighter nuclei can probe lighter DM, but there is a limit…

DM-electron scattering



Momentum transfer, q

Kinematics of DM-Electron scattering

If we have an *inelastic* process, then the kinematics can be quite different. Consider recoiling with an electron and unbinding it:

$$\Delta E_e = E_{\text{binding}} + E_{er}$$

$$\Delta E_{\text{DM}} = \vec{v} \cdot \vec{q} - q^2/(2m_\chi)$$

Minimum velocity required is:

$$v_{\min} = \frac{\left(|E^{nl}_{\text{binding}}| + E_{er}\right)}{q} + \frac{q}{2m_\chi}$$

For typical atomic processes,

$$q_0 \sim \alpha m_e = 3.73 \times 10^4 \, \text{eV}$$

$$E_{\text{bind}} \sim 10 \, \text{eV}$$

$$\Rightarrow v_{\min} \approx 750 \, \text{km/s} \quad \text{for} \quad m_\chi \gtrsim 20 \, \text{MeV}$$

[arXiv:1108.5383]

DM-electron scattering rate

$$\frac{dR_{ion}}{d\ln E_R} = N_T \frac{\rho_\chi}{m_\chi} \frac{d\left\langle \sigma_{ion} v \right\rangle}{d\ln E_R}$$

$$\frac{d\left\langle \sigma^i_{ion} v \right\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}} \int q dq |f^i_{ion}\left(k', q\right)|^2 |F_{\mathrm{DM}}(q)|^2 \eta\left(v_{\min}\right)$$

[arXiv:1108.5383]

DM-electron scattering rate

$$\frac{dR_{ion}}{d\ln E_R} = N_T \frac{\rho_\chi}{m_\chi} \frac{d\langle\sigma_{ion} v\rangle}{d\ln E_R}$$

Free electron scattering cross section

Dark Matter Form Factor

$$\frac{d\langle\sigma^i_{ion} v\rangle}{d\ln E_R} = \frac{\boxed{\overline{\sigma}_e}}{8\mu^2_{\chi e}} \int q\,dq \boxed{\left|f^i_{ion}(k', q)\right|^2} \boxed{\left|F_{\mathrm{DM}}(q)\right|^2} \boxed{\eta(v_{\mathrm{min}})}$$

"Atomic form factor": sum over all possible initial and final states

Integral over DM velocities

[arXiv:1108.5383]

DM-electron scattering rate

$$\frac{dR_{ion}}{d\ln E_R} = N_T \frac{\rho_\chi}{m_\chi} \frac{d\langle\sigma_{ion} v\rangle}{d\ln E_R}$$

$$\frac{d\langle\sigma^i_{ion} v\rangle}{d\ln E_R} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}} \int q dq |f^i_{ion}(k', q)|^2 |F_{\rm DM}(q)|^2 \eta(v_{\rm min})$$

Can enhance the scattering rate by:

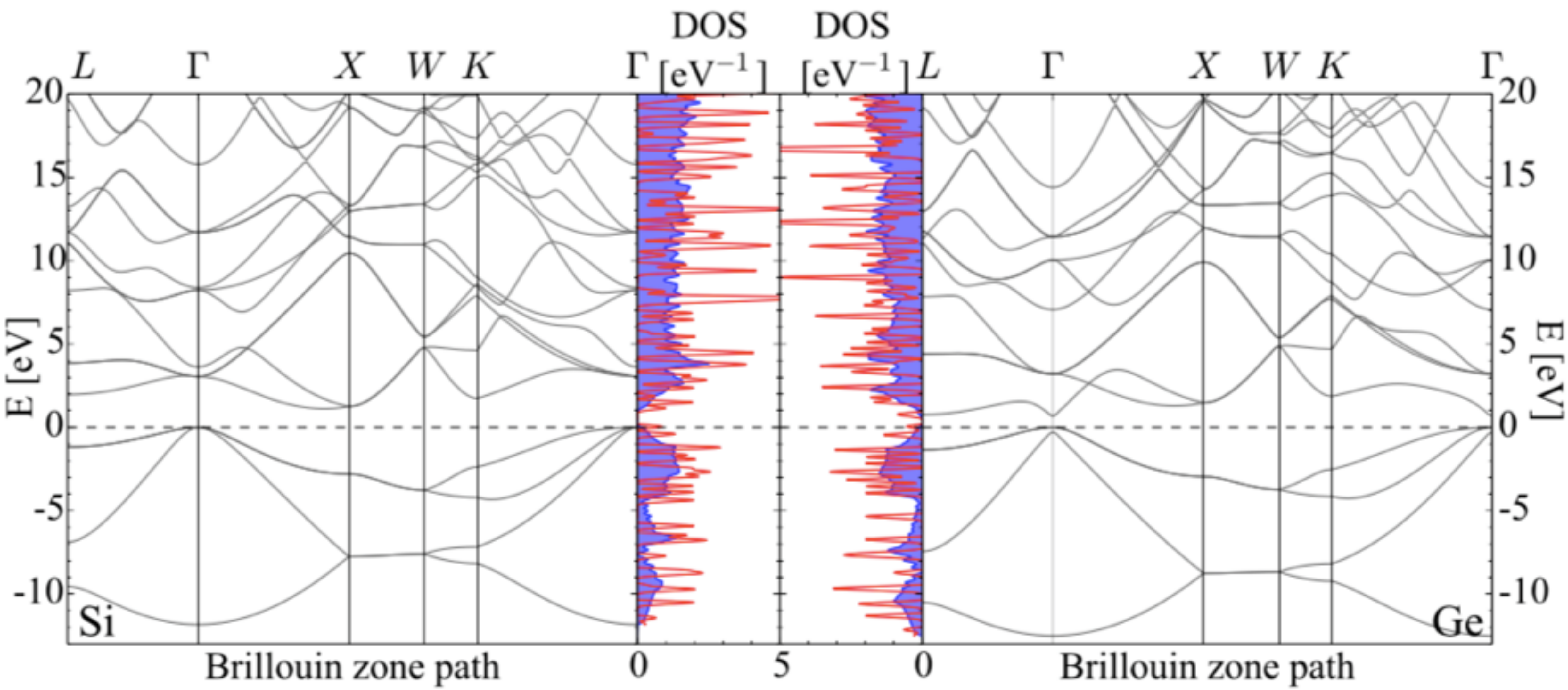
- Decreasing $v_{\rm min}$ by decreasing the binding energy
- Increasing $f_{\rm ion}$ by using large, high Z targets

[arXiv:1108.5383]

Atomic/crystal structure

Need to sum over all electron states:

$$f_{cryst}^{i+i'_j}(\mathbf{q},\mathbf{k}) = \sum_G \psi^*_{i'}(\mathbf{k}+\mathbf{G}+\mathbf{q})\psi_i(\mathbf{k}+\mathbf{G})$$



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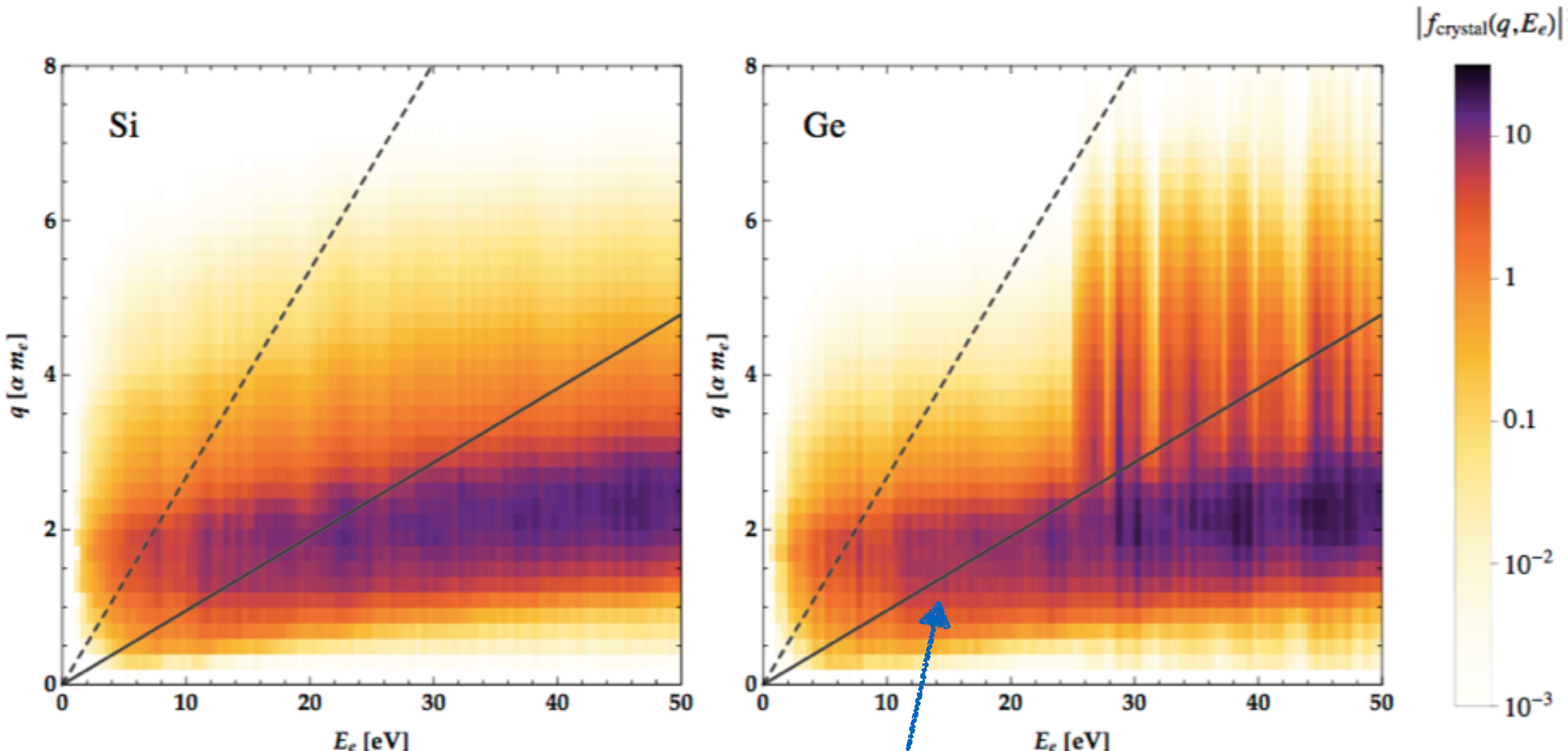
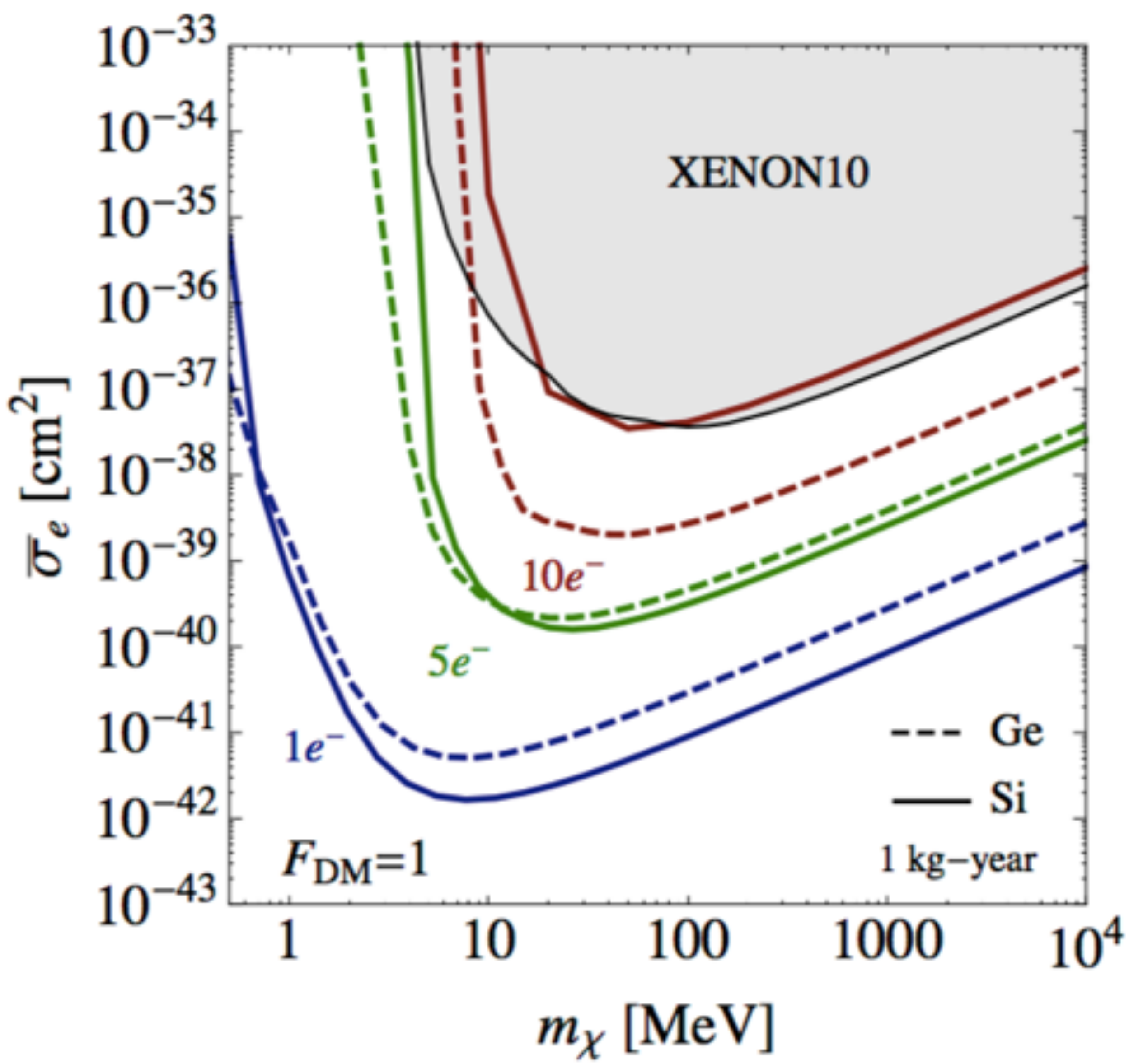


Escape speed cut off below this line

Searches with Semi-conductors

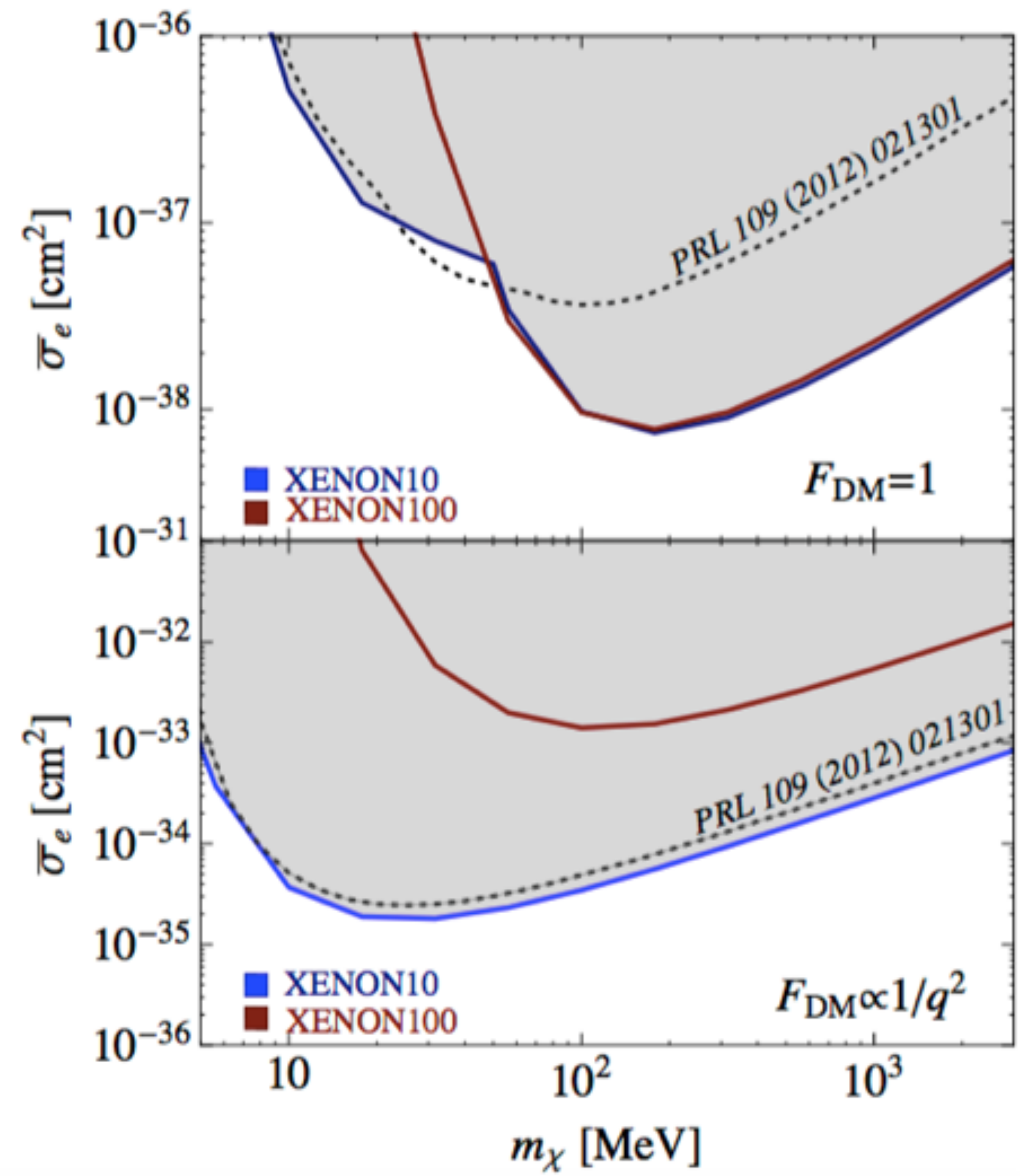
DM could excite electrons across narrow band gap in e.g. Si (1.11 eV) or Ge (0.67 eV). Produce electron-hole pairs:



[arXiv:1509.01598, arXiv:1804.00088]

Searches with Noble Liquids

Look for small numbers of ionised electrons (which appear as an ‘S2’ photoelectron signal):

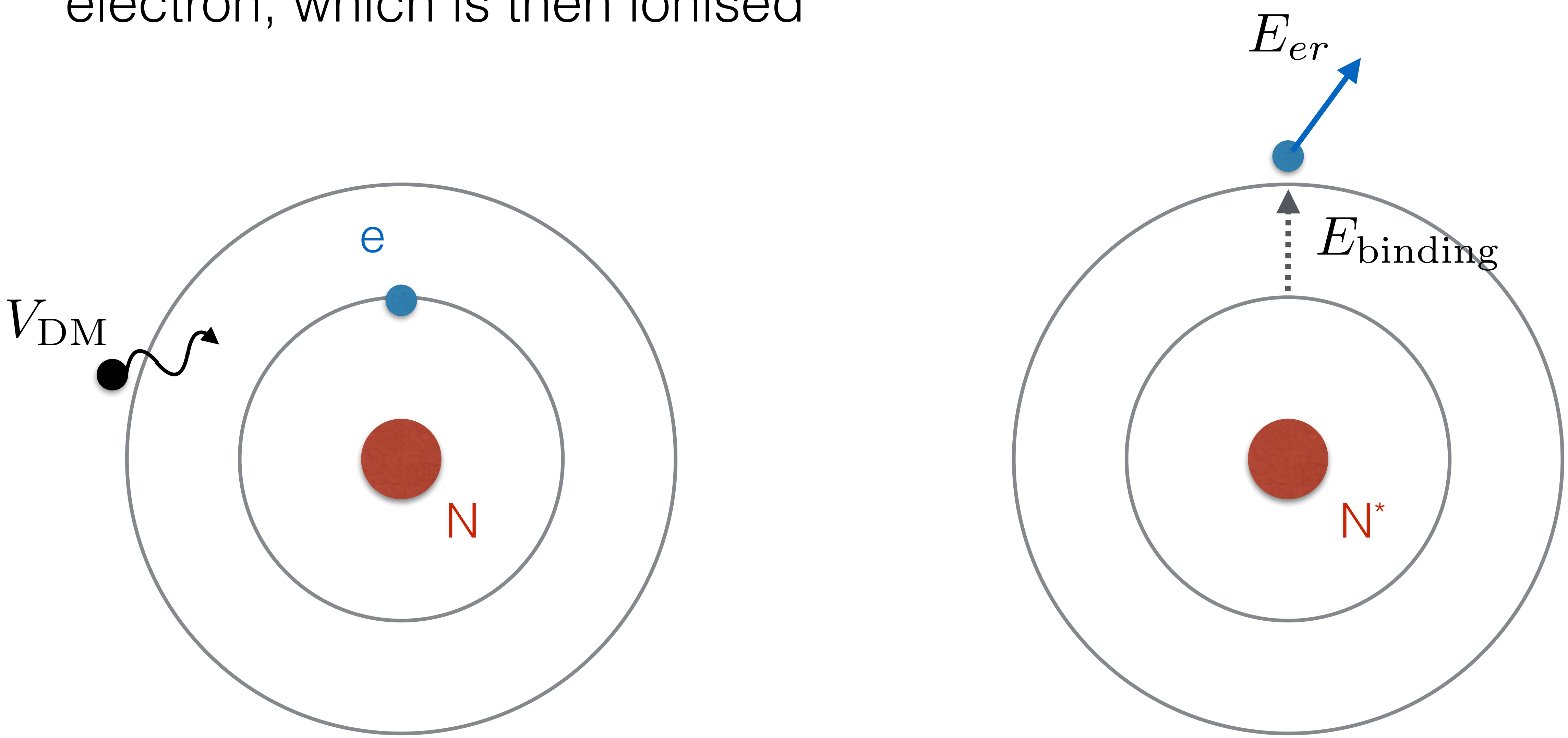


Typical binding energy >13 eV.

[arXiv:1703.00910, arXiv:1802.06998]

Dark Photon absorption

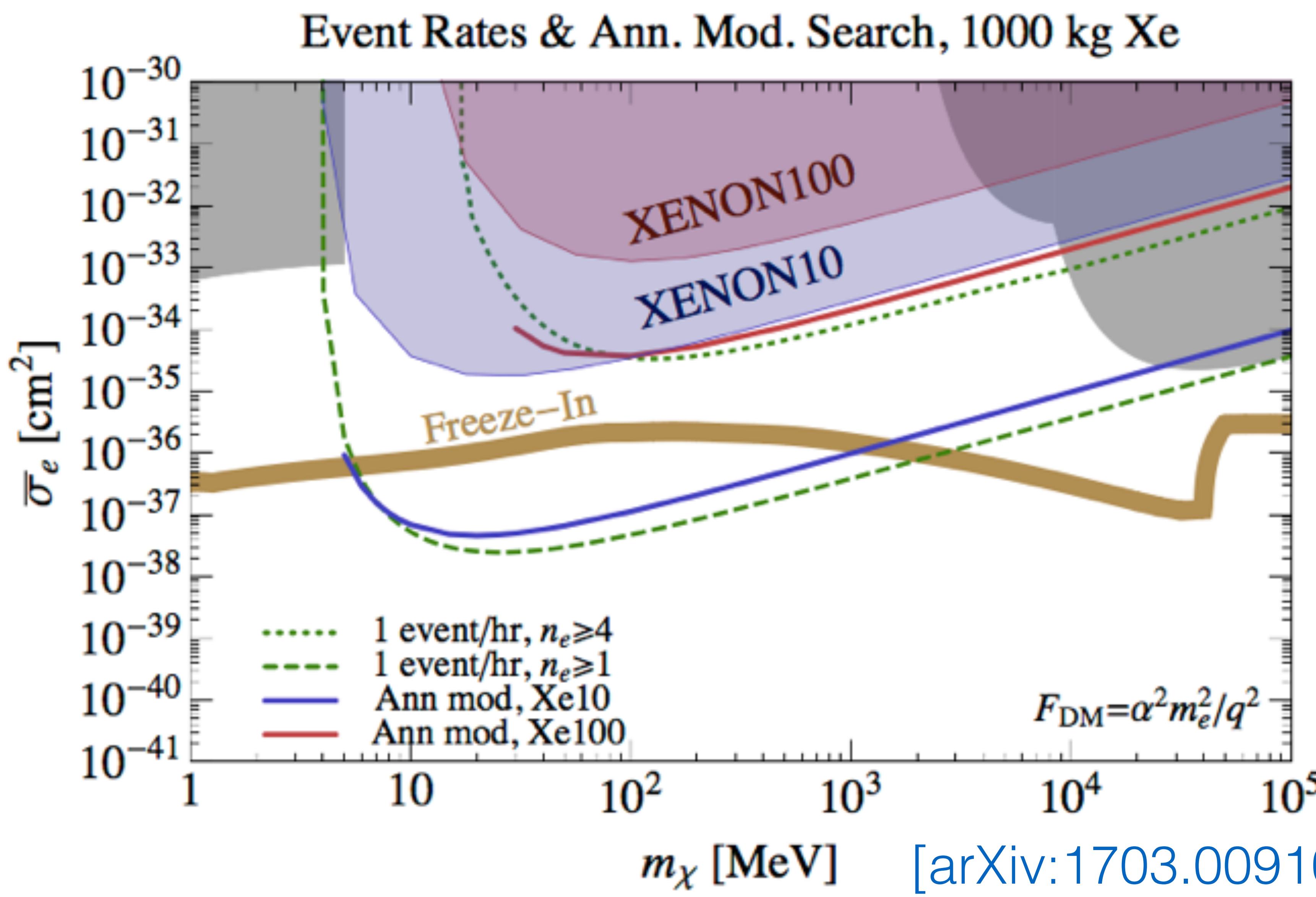
If Dark Matter is a light boson, it could be absorbed by an electron, which is then ionised



$$V_{\mathrm{DM}} + \mathrm{Xe} \to e^{-} + \mathrm{Xe}^{+}$$

[arXiv:1412.8378, arXiv:1608.02123]

Making sub-GeV Dark Matter



[arXiv:1703.00910]

Freeze-in: [arXiv:0911.1120]

Probing even lower masses

Available energy in direct searches is set by maximum kinetic energy of DM particles $E_{\mathrm{max}} \sim m_\chi v_{\mathrm{max}}^2/2$ and how efficiently it can be transferred to detector

DM-electron scattering probes down to low DM masses because the 'excitation energy' - in this case the binding energy - is small.

If we want to probe down to even lighter DM masses, we (in principle) just need to find systems with even smaller excitation energies…

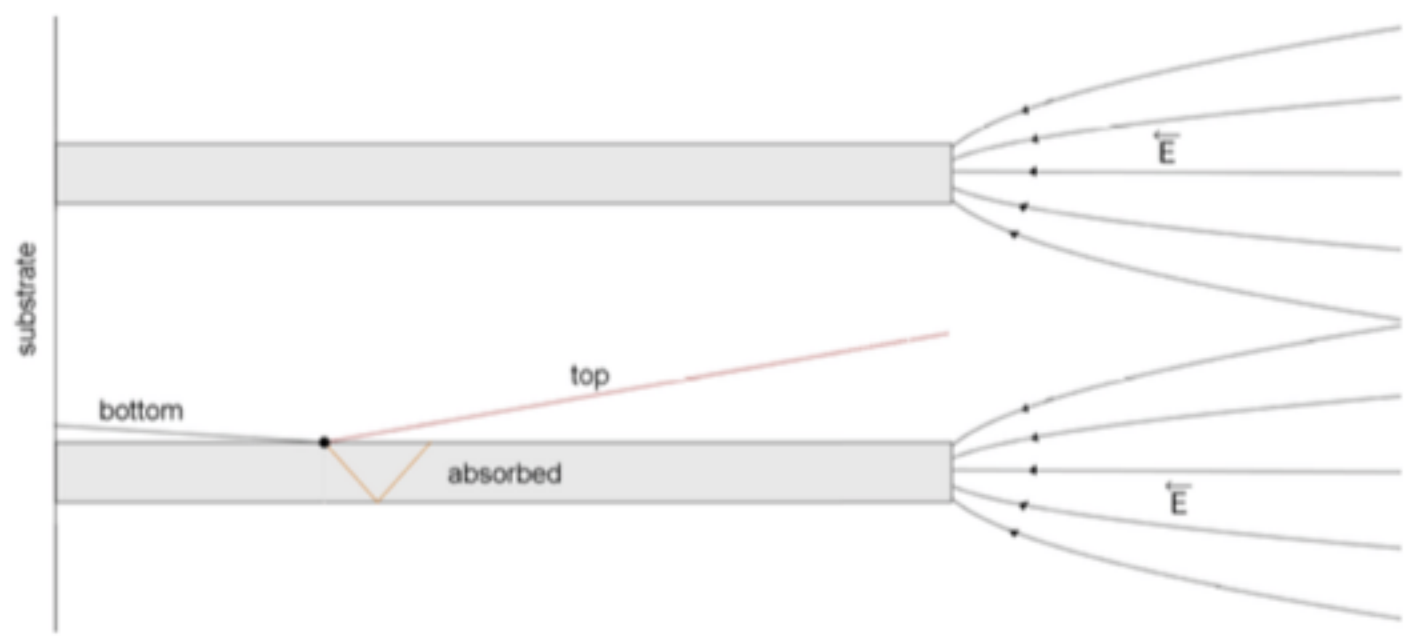
Leads to some new (sometimes strange) ideas…

New (sometimes strange) ideas I

- Electron scattering in scintillators [arXiv:1607.01009]

- Optical phonons in polar materials [arXiv:1712.06598]

- Electron scattering in carbon nanotubes [arXiv:1706.02487]



New (sometimes strange) ideas II

- Chemical bond-breaking by DM scattering

  [arXiv:1608.02940]

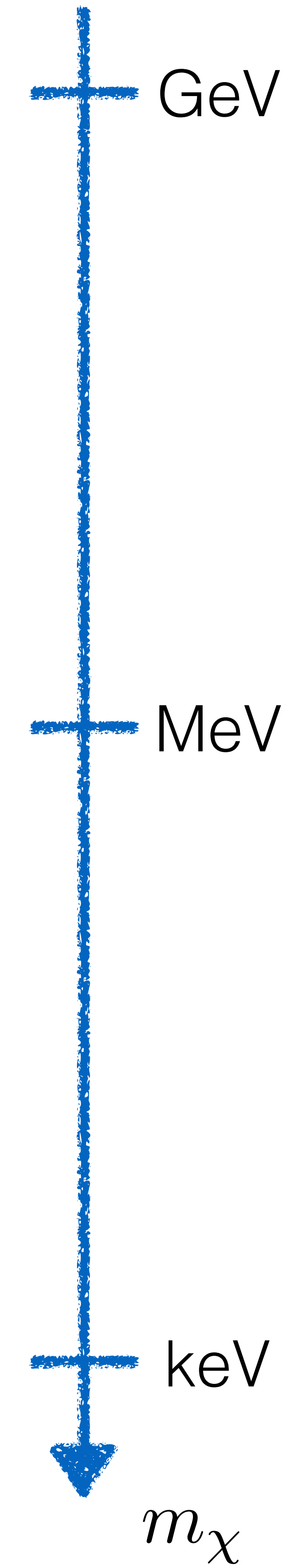
- MeV-scale direct detection in Dirac materials (the 3D analogue of graphene)

  [arXiv:1708.08929]

- Direct detection using superfluids

  [arXiv:1504.07237]

- Direct detection with superconductors (breaking cooper pairs) [arXiv:1611.06228]



Group 4: Report and Presentation

- What is the motivation behind DM-electron scattering searches?
- How can DM-electron scattering be detected?
- Summarise the current status of DM-electron scattering searches and prospects for the future
- List some of the proposals for searches probing even lower DM masses - what sort of mass ranges are they relevant for and why?