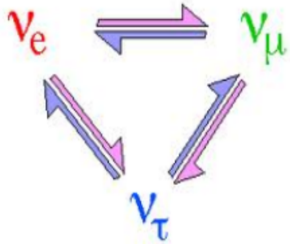


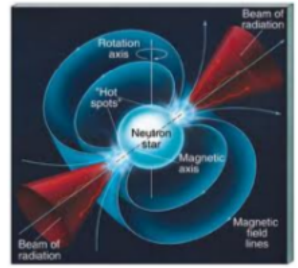

AAPCOS 2015

Direct detection of dark matter in universal bound states

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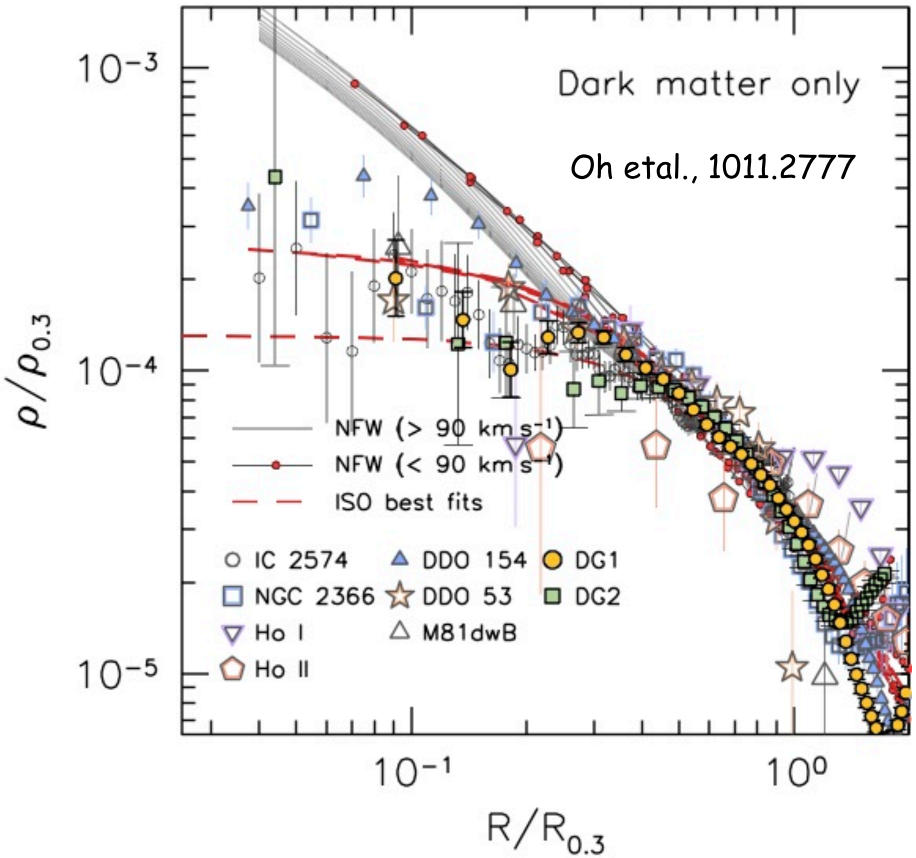
Stanford University
SLAC National Accelerator Laboratory

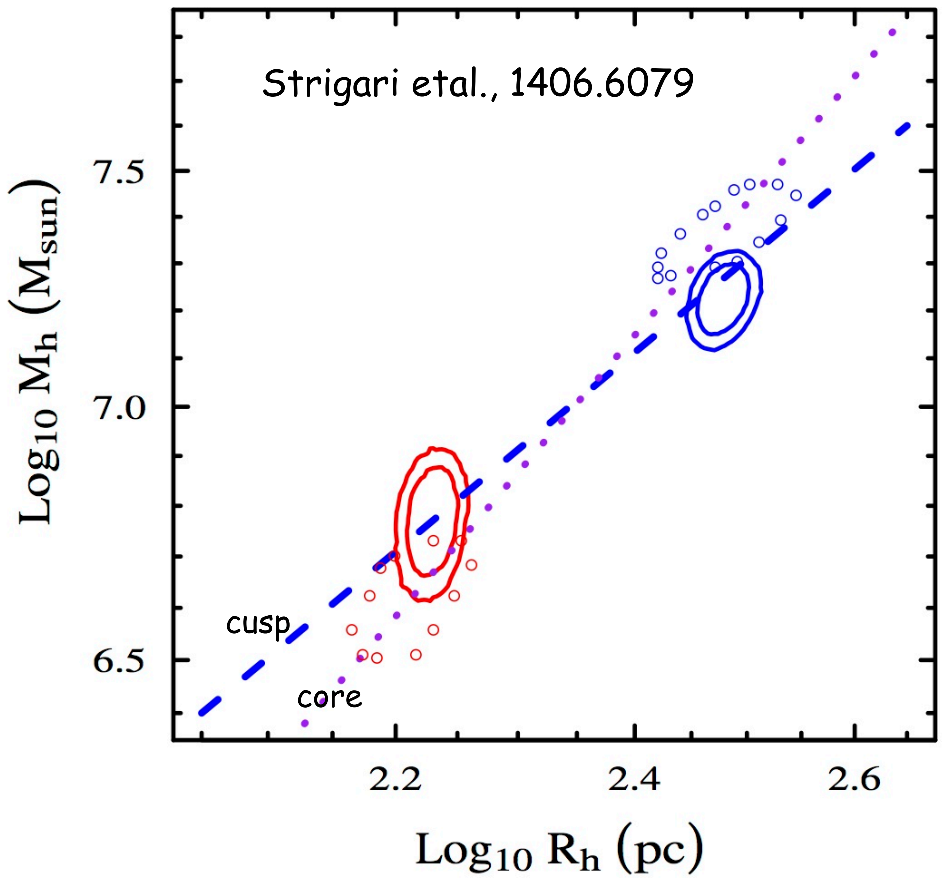
Thanks to my collaborator: E Braaten

1311.6368 PRD and 1505.02772 PRD

The small-scale crisis of ΛCDM

Core vs cusp problem

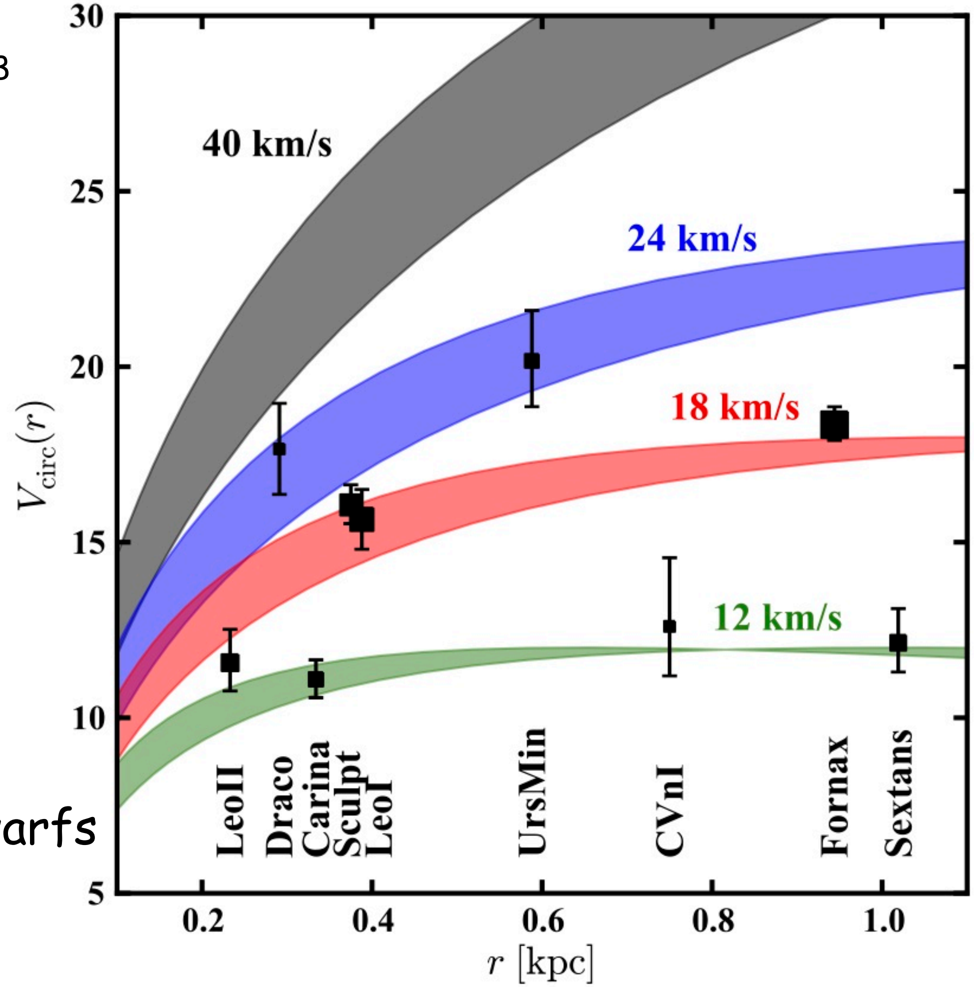




Controversy about this issue not yet settled

Too big to fail problem

Boylan-Kolchin etal., 1111.2048

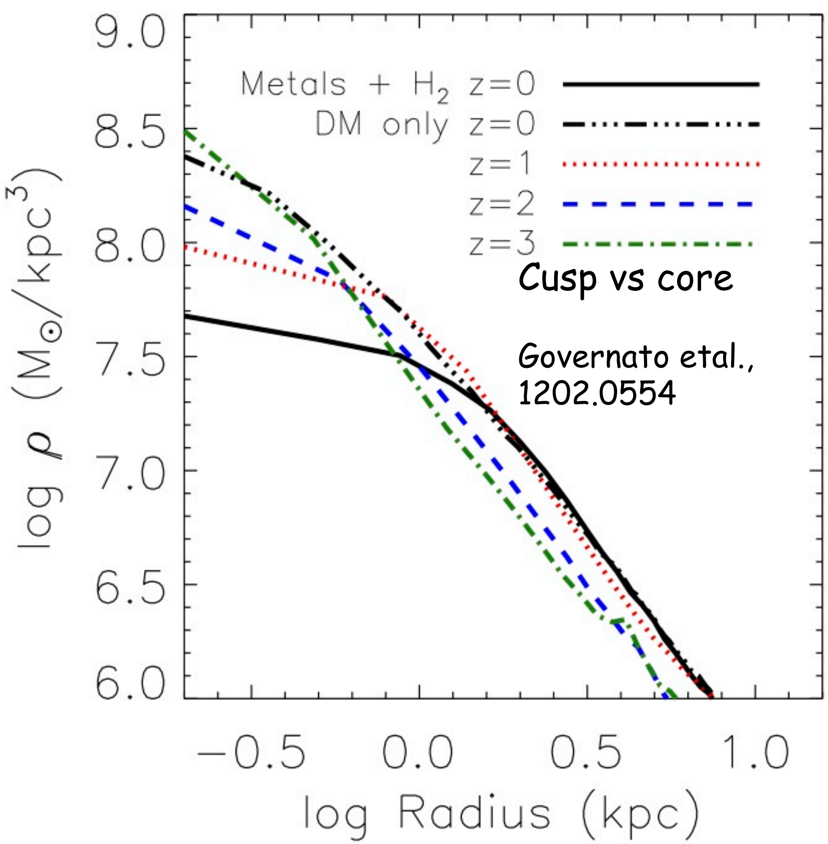


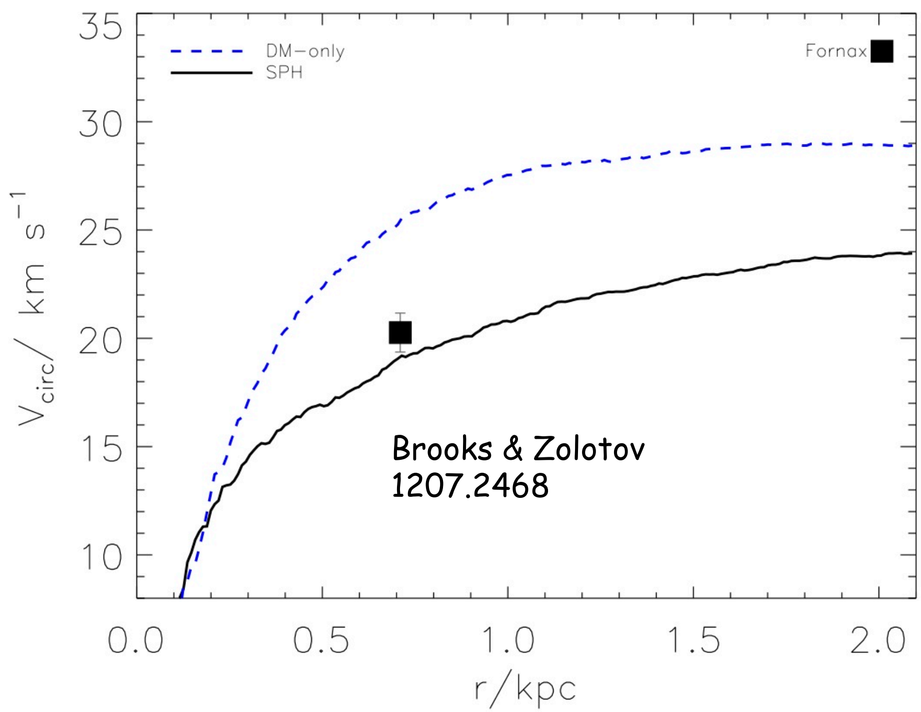
Milky Way dwarfs

The Milky Way dwarfs are not in the most massive dark matter halos --- predicted satellites are too dense

Potential solution to these problems

Baryons matter



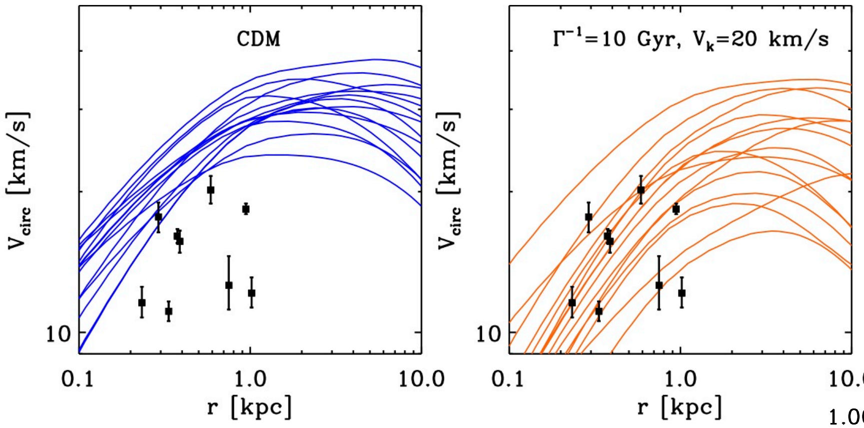


Too big to fail

Baryons have the potential to solve all these problems

Alternative dark matter models

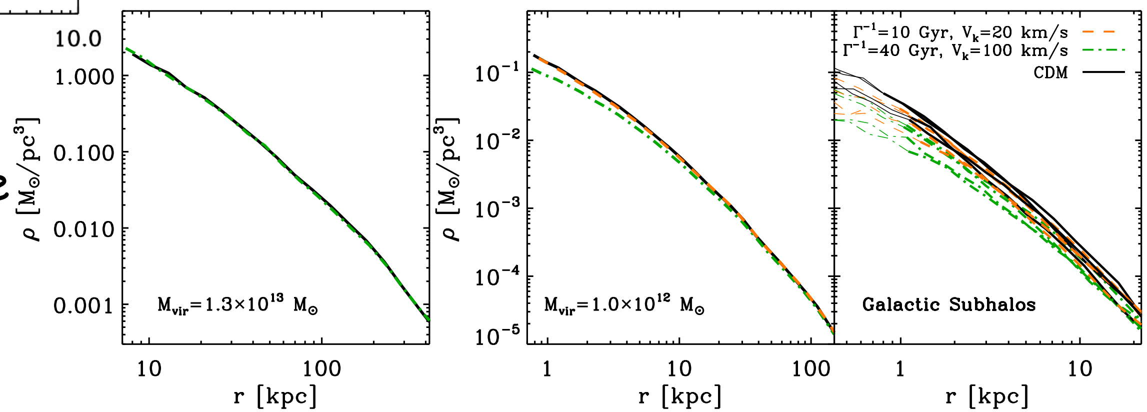
Decaying dark matter (Strigari etal., 0606281, Wang etal., 1406.0527)

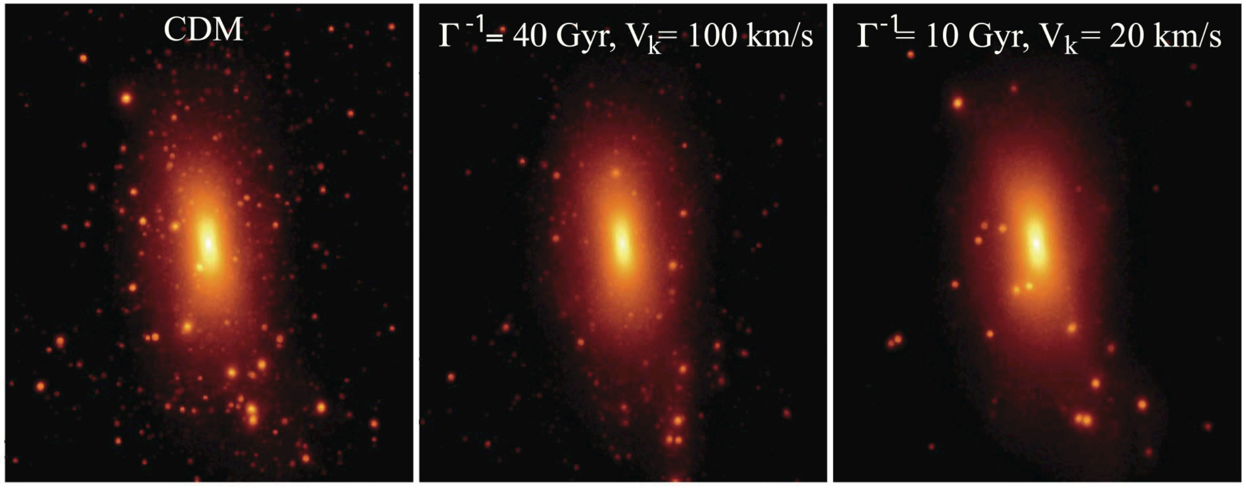


✔ Solves too big to fail

✗ Cannot solve cusp vs core

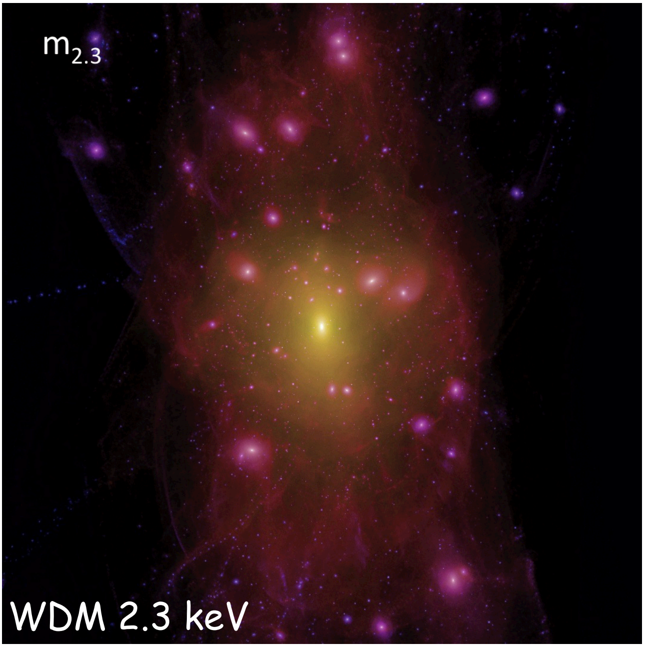
Include baryons?





✔ Lowers the number of satellites

Warm dark matter

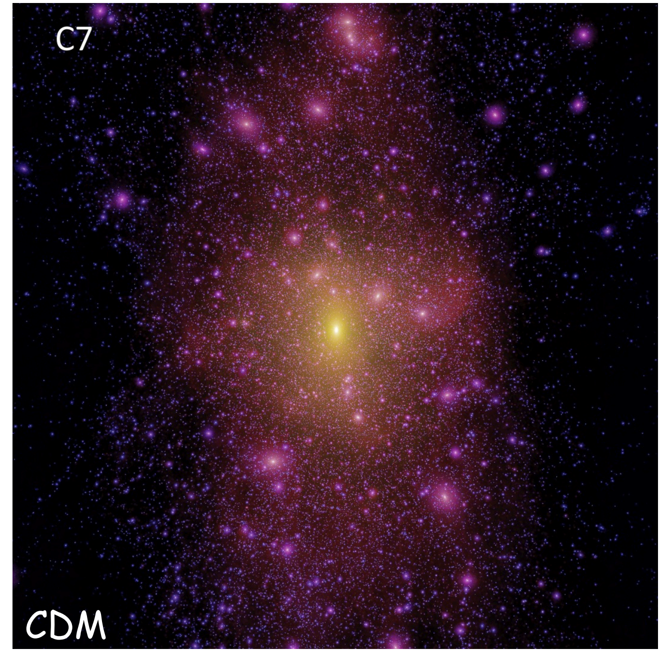


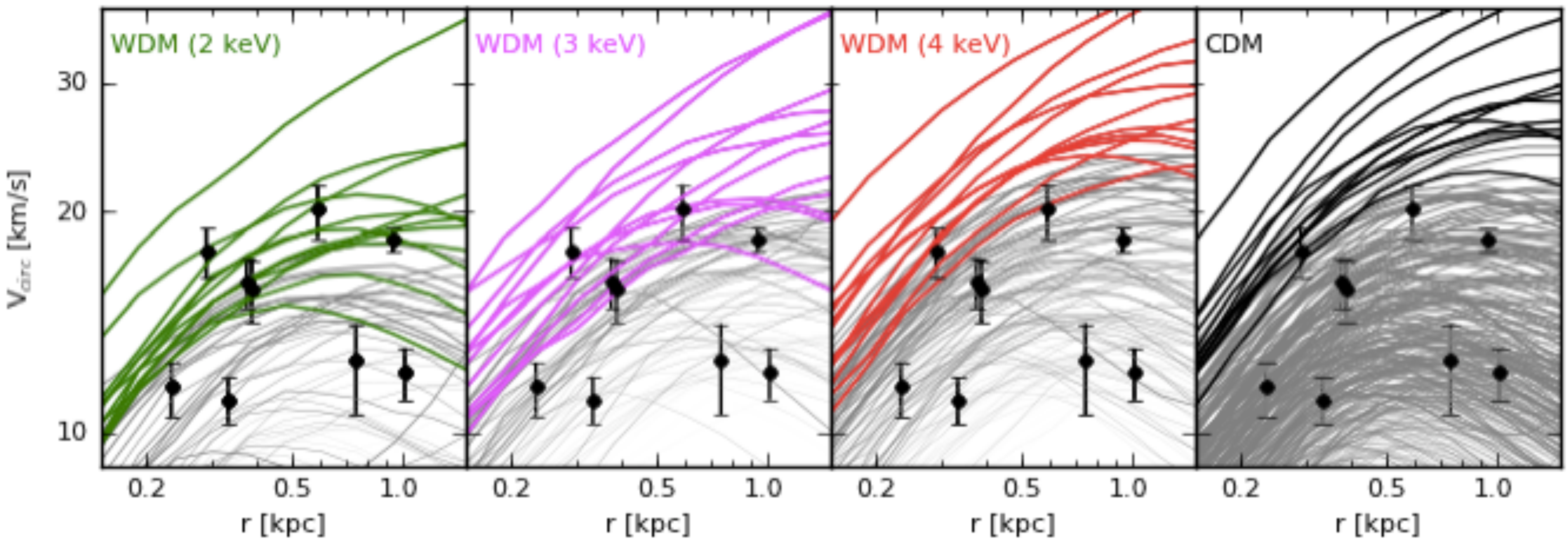
✔ Lowers the number of satellites

Lovell etal., 1308.1399
Schneider etal., 1309.5960

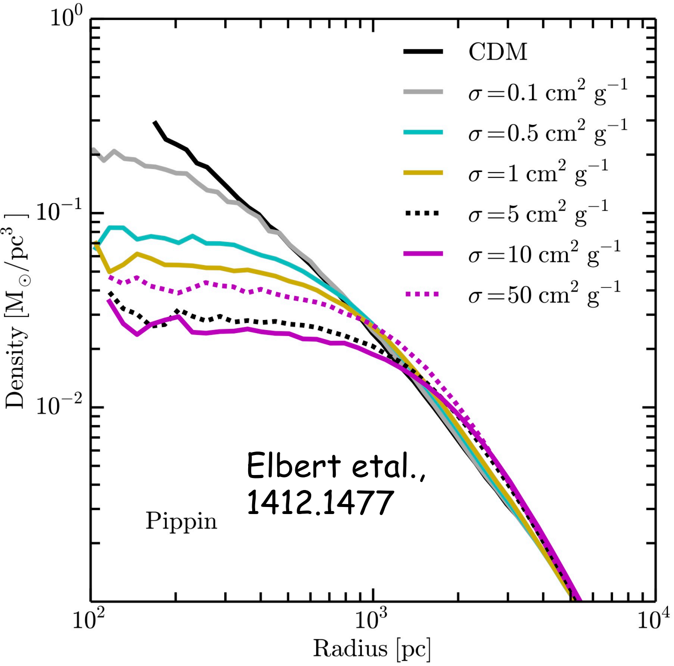
✔ Solves too big to fail
✗ Core is too small

Ruled out by Lyman-α?



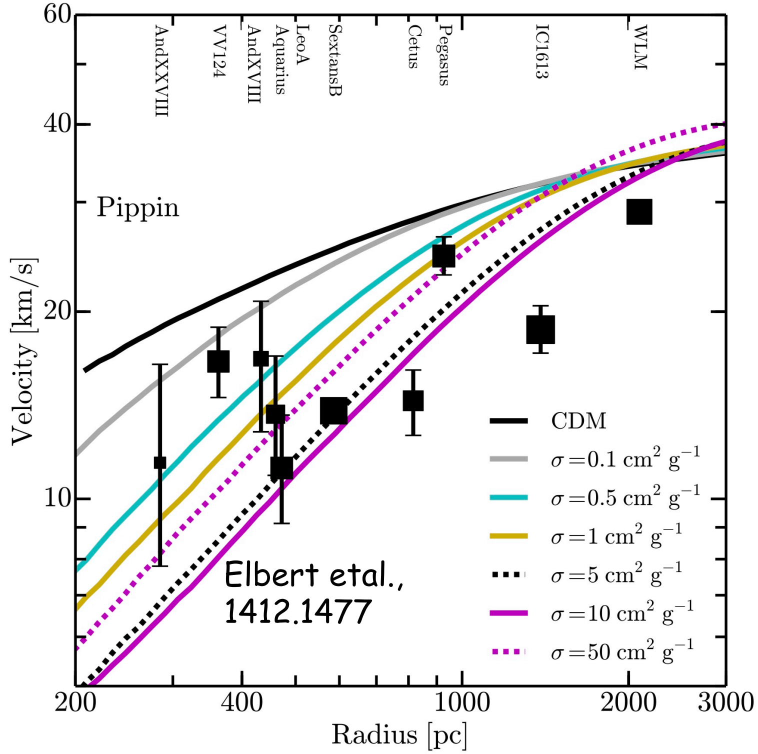


Self-interacting dark matter (SIDM) (Spergel & Steinhardt 9909386)



✔ Solves the core vs cusp problem

✔ Solves too big to fail



Are baryons important in SIDM simulations?

See: Kaplinghat etal., 1311.6524, Fry etal., 1501.00497

Self-interacting dark matter

Self-scattering cross-section

$$\Gamma = n\sigma v = \frac{\rho}{m}\sigma v$$

$$\Gamma^{-1} \sim \mathrm{Gyr} \qquad \rho = 0.4\,\mathrm{GeV\,cm^{-3}} \qquad v = 10^{-3}$$

$$\sigma/m \approx 1\,\mathrm{cm^2\,g^{-1}}$$

Nuclear physics cross-sections!

Dark matter will interact with itself during lifetime of the Galaxy

Energy exchange and heat transport

Dark matter is collisional --- scatter before reaching the center for the halo

Small scale structure problems in ΛCDM

1. Core vs cusp problem

2. "Too big to fail" problem

Baryonic solutions exist, but can dark matter solve it?

Need self-interacting cross sections at low velocities

$$\frac{\sigma_{\mathrm{el}}}{m} \approx 1\,\mathrm{cm}^2\,\mathrm{g}^{-1} \quad \text{at} \quad v \approx 10\,\mathrm{km\,s}^{-1}$$

Talk to Kamakshya P Modak for discussions about the microphysical models of SIDM
KP Modak 1509.00874

Universality

A predictive formalism to obtain "strong" interactions at non relativistic physics is to have a near threshold s-wave resonance for a pair of particles

Egs. Deuteron (bound state of proton and neutron)

X(3872) --- probably

Diatomic He^4 molecule --- binding energy of 10^{-7} eV

.....

Accidental fine-tuning of an s-wave resonance near the appropriate threshold

Numerous examples in cold atom physics

Can we use these ideas in dark matter physics?

Near threshold S-wave resonance

- Non relativistic enhancements can be explained by the presence of a near threshold S-wave resonance

- If S-wave resonance is sufficiently close to threshold, all mechanisms give same universal behavior

- Universal = independent of microphysics

Elastic cross section $\sigma_{\rm el} \sim 1/v^2$

Annihilation rate $v\sigma_{\rm ann} \sim 1/v^2$

- A single complex parameter, the S-wave scattering length, governs all the lower-energy behavior of the dark matter

S-wave scattering length = a

$$a = 1/\gamma$$

γ = inverse scattering length

Universal cross sections

Small complex inverse scattering length $|\gamma| << 1/\text{range}$

k = relative momentum

Elastic cross section

$$\sigma_{\text{el}} = \frac{8\pi}{|-ik-\gamma|^2}$$

Annihilation cross section

$$\sigma_{\text{ann}} = \frac{8\pi\,\text{Im}\,\gamma}{k|-ik-\gamma|^2}$$

These are for indistinguishable particles

Universal bound state

- If the resonance is below the threshold, it is a bound state of the two identical dark matter particles – "darkonium"

- The resonance can be thought of as a dark deuteron

- Binding energy $E_B = \frac{(\mathrm{Re}\,\gamma)^2 - (\mathrm{Im}\,\gamma)^2}{m}$

- Decay width $\Gamma_{\mathrm{darkonium}} = \frac{4(\mathrm{Re}\,\gamma)(\mathrm{Im}\,\gamma)}{m}$

- Stability of the darkonium implies $\mathrm{Im}\,\gamma \to 0$ and that also implies that $\sigma_{\mathrm{ann}} \to 0$

Dark matter in universal bound states

- If dark matter is asymmetric, the resonance is stable and can act as the dark matter candidate

- Assume that the bound state survives the cosmic evolution

- Look for the signatures of the bound state in direct detection experiment

- For elastic scattering, the bound state will leave an imprint of its structure (form factor) and it can also break up; novel signature of bound state dark matter in this context

Interplay between self-interaction cross section and binding energy

$\sigma_{\rm el}/m = 1\,{\rm cm}^2\,{\rm g}^{-1}$ at $v = 10\,{\rm km}\,s^{-1}$

implies $E_B = 0.52\,{\rm keV}$ for $m = 100\,{\rm GeV}$

and

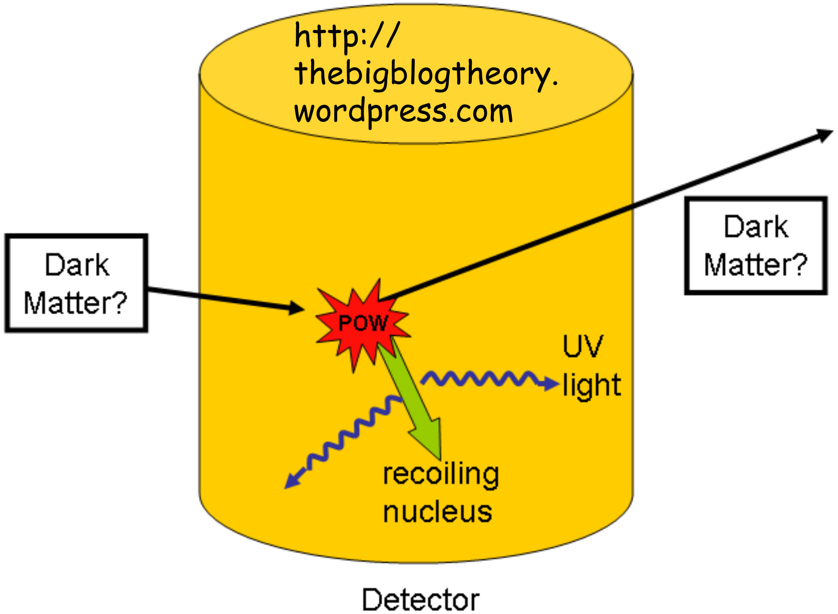
$E_B = 54\,{\rm keV}$ for $m = 10\,{\rm GeV}$

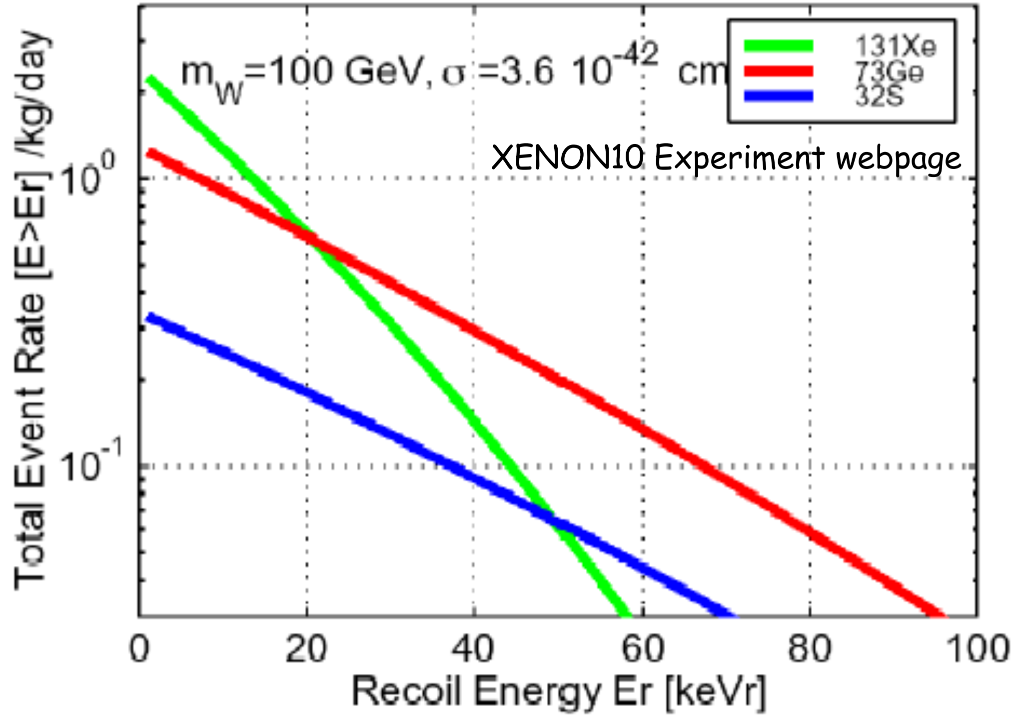
Larger the elastic cross section, smaller the binding energy

$$E_B = \frac{8\pi}{m\sigma_{\rm el}} - \frac{k^2}{m}$$

Direct detection of darkonium

Direct detection



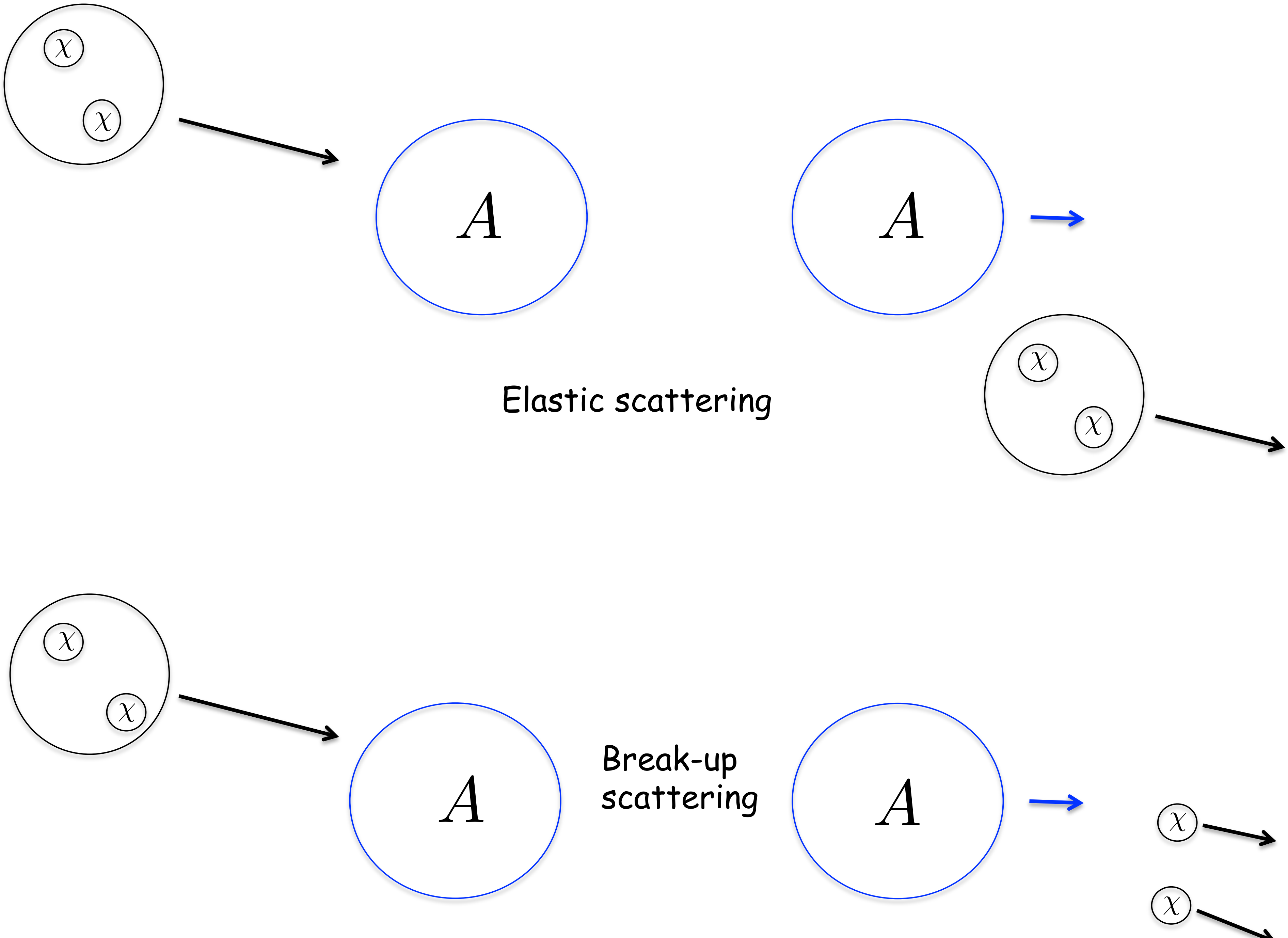


$$\mathrm{DM} + \mathrm{SM} \to \mathrm{DM} + \mathrm{SM}$$

Search for interaction of dark matter particles with Standard Model particles

Can detect the incoming direction of the dark matter particle

See talk by P Gondolo, V Zacek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Elastic scattering
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Break-up
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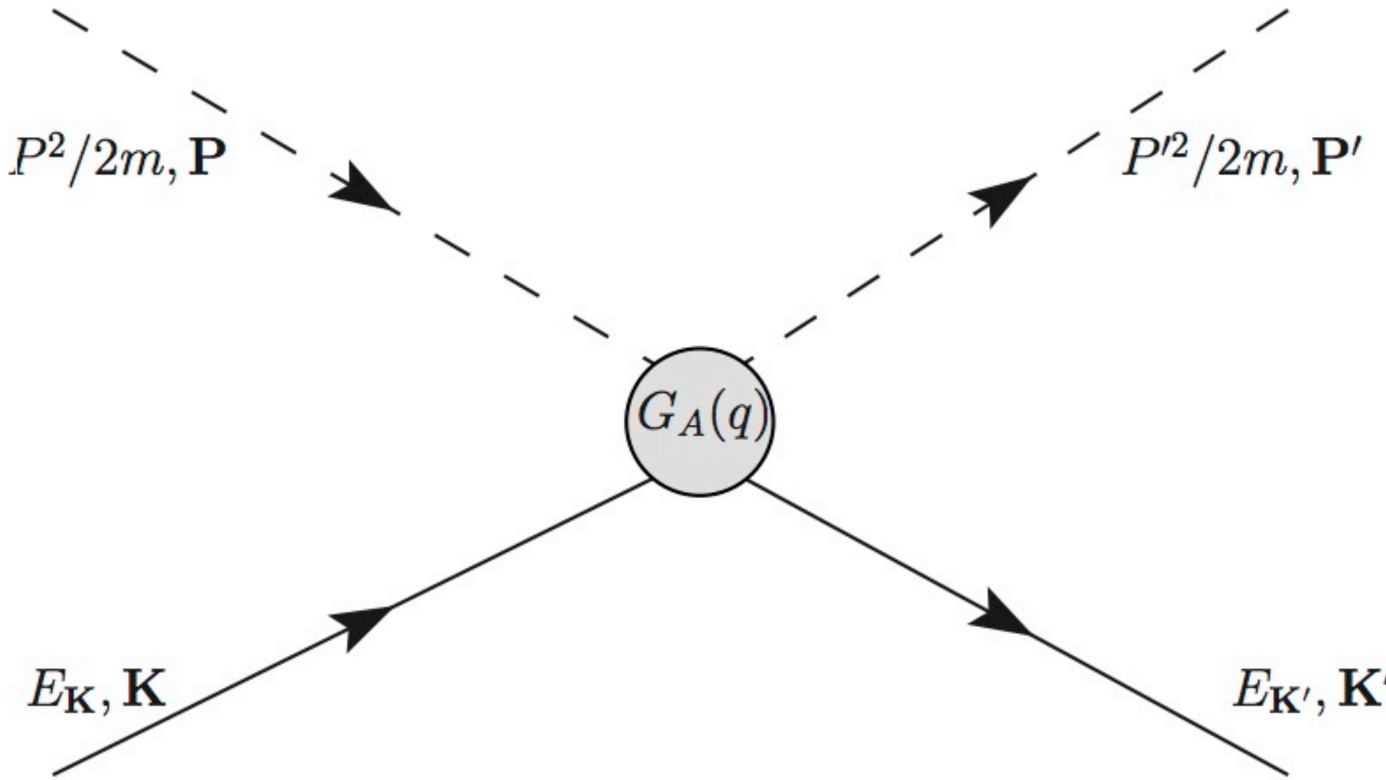
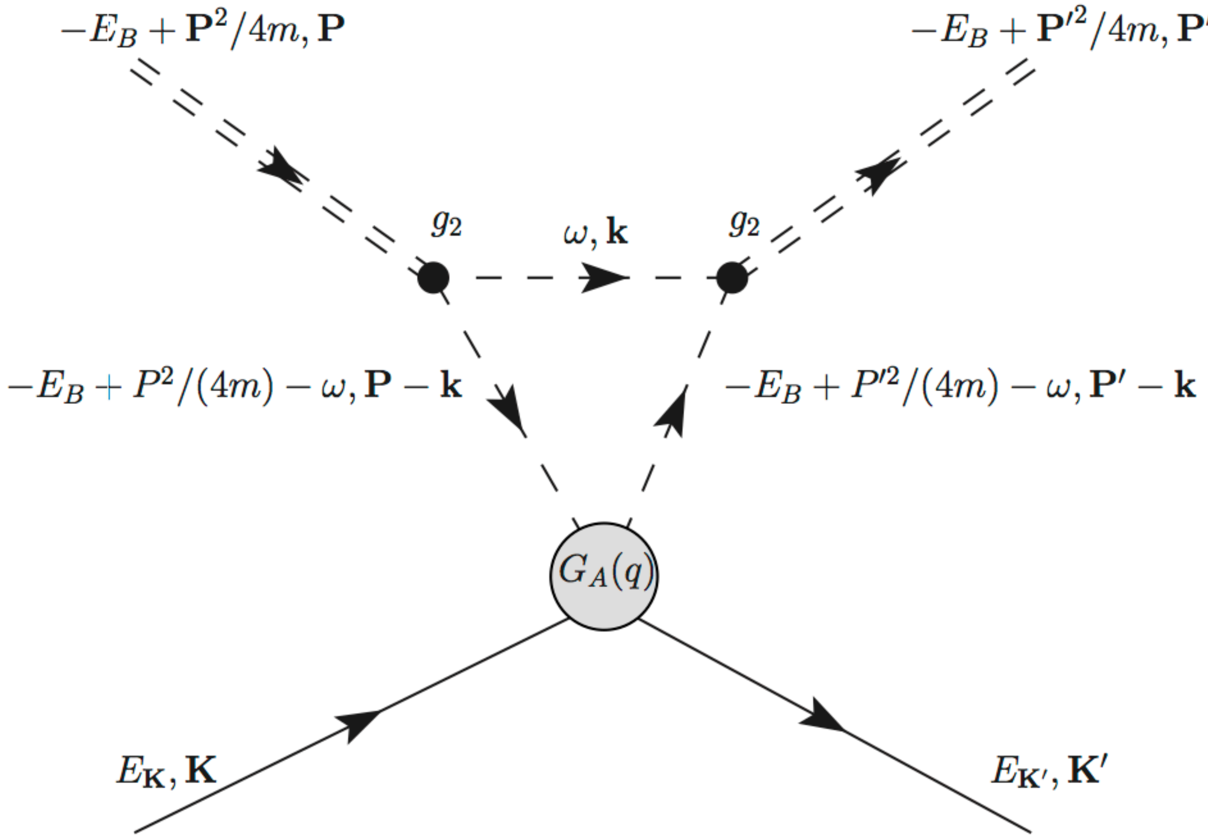
Particle scattering



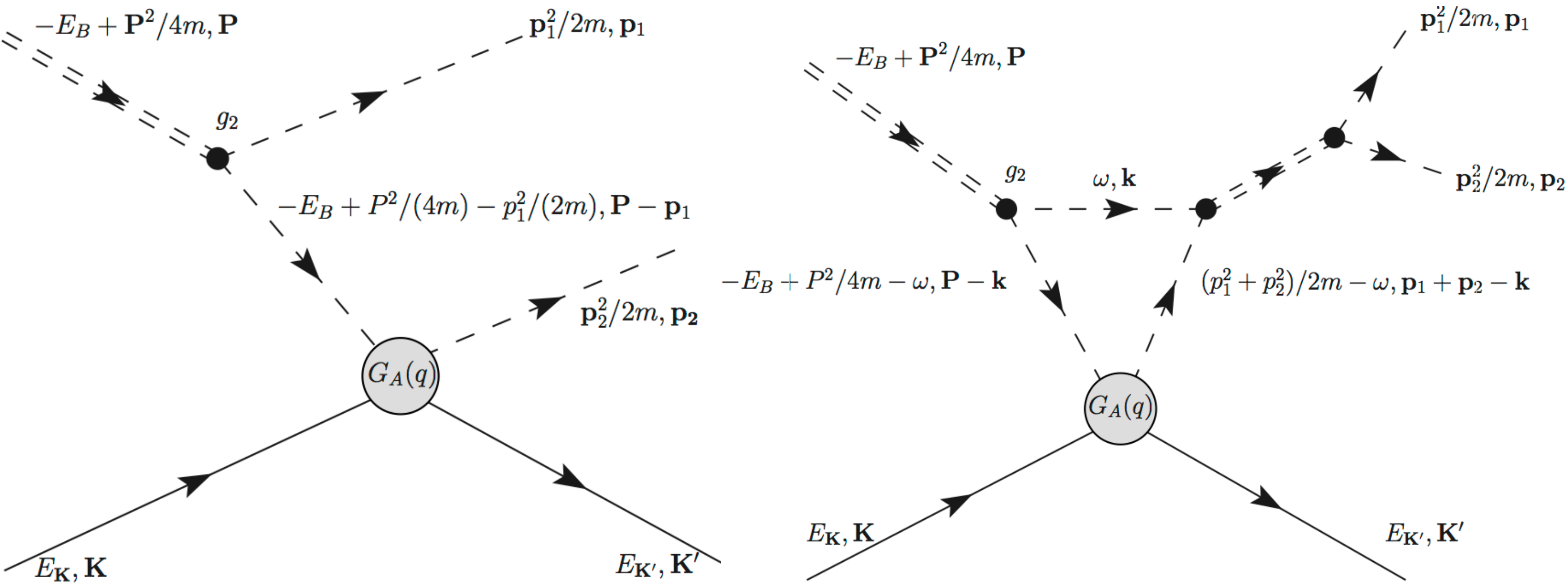
The interaction between the dark matter particle and nuclei is an arbitrary constant

Darkonium elastic scattering



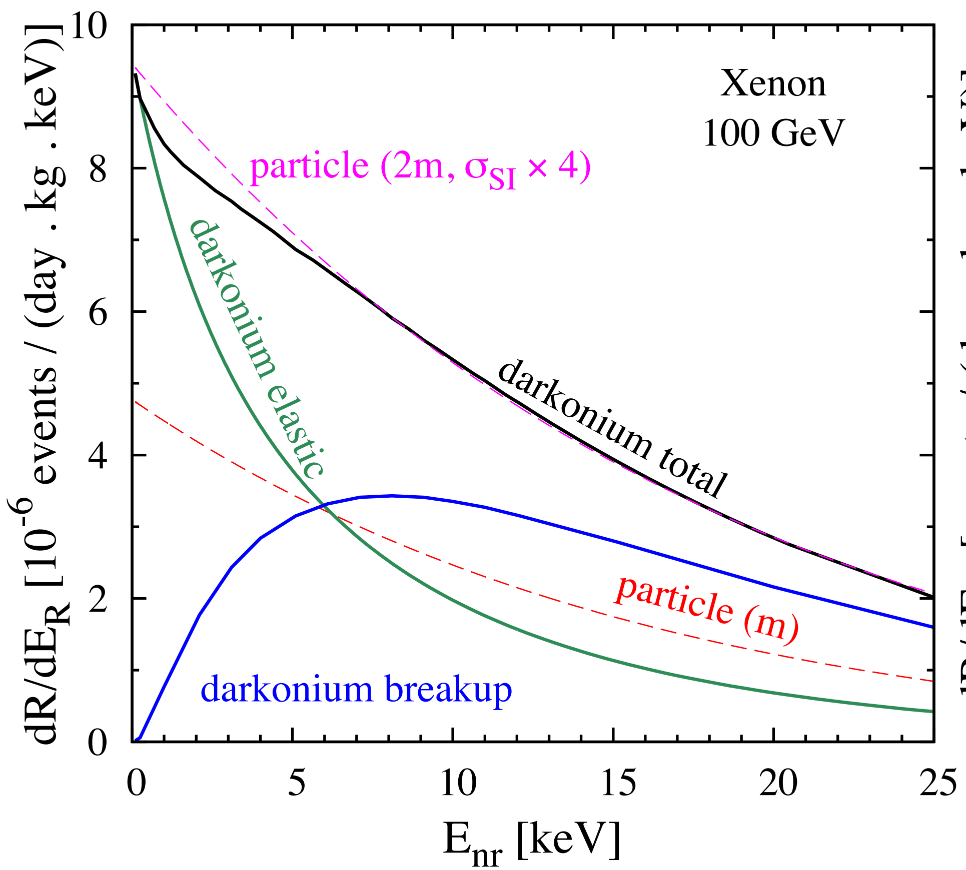
Form factor of darkonium $F(q) = \frac{4\gamma}{q} \tan^{-1} \frac{q}{4\gamma}$

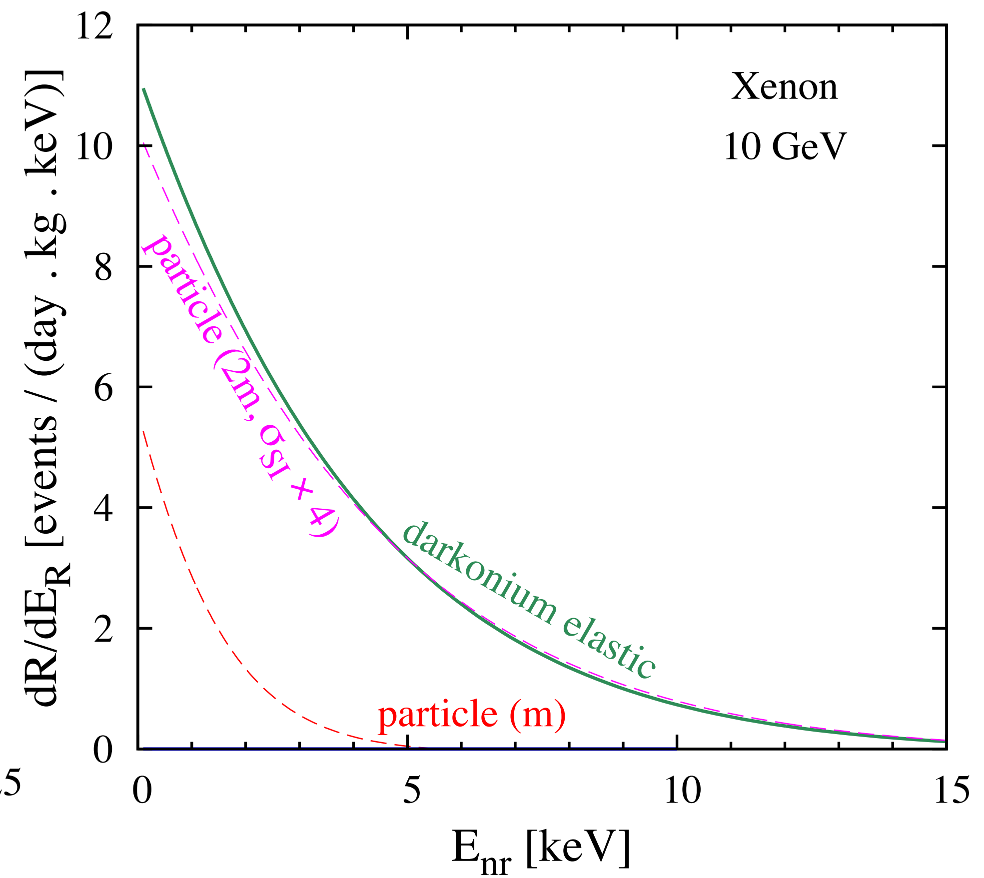
Darkonium breakup



Darkonium breakup only possible for low enough binding energy

Recoil spectrum in Xenon detectors

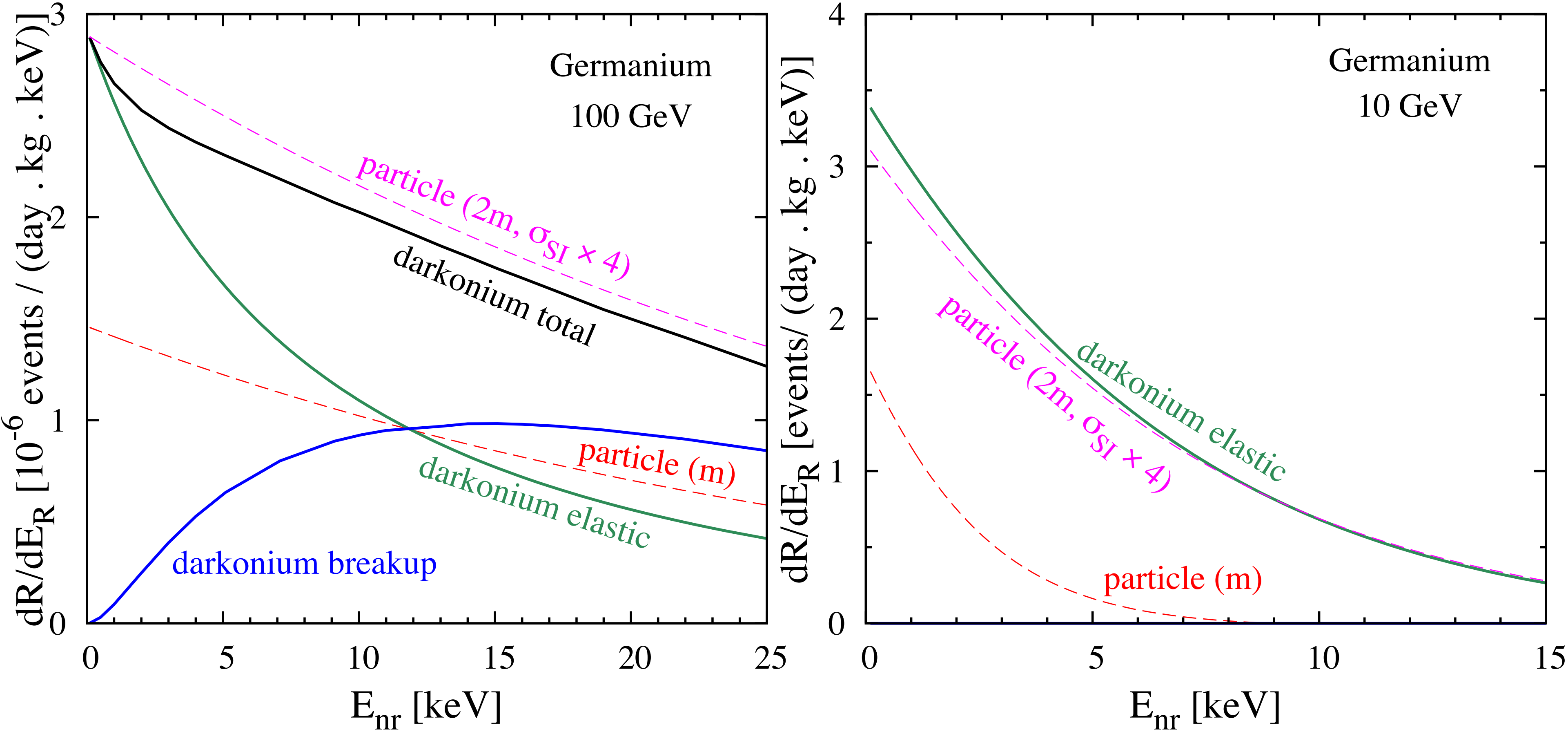




We assume spin-independent coupling between dark matter and nucleon

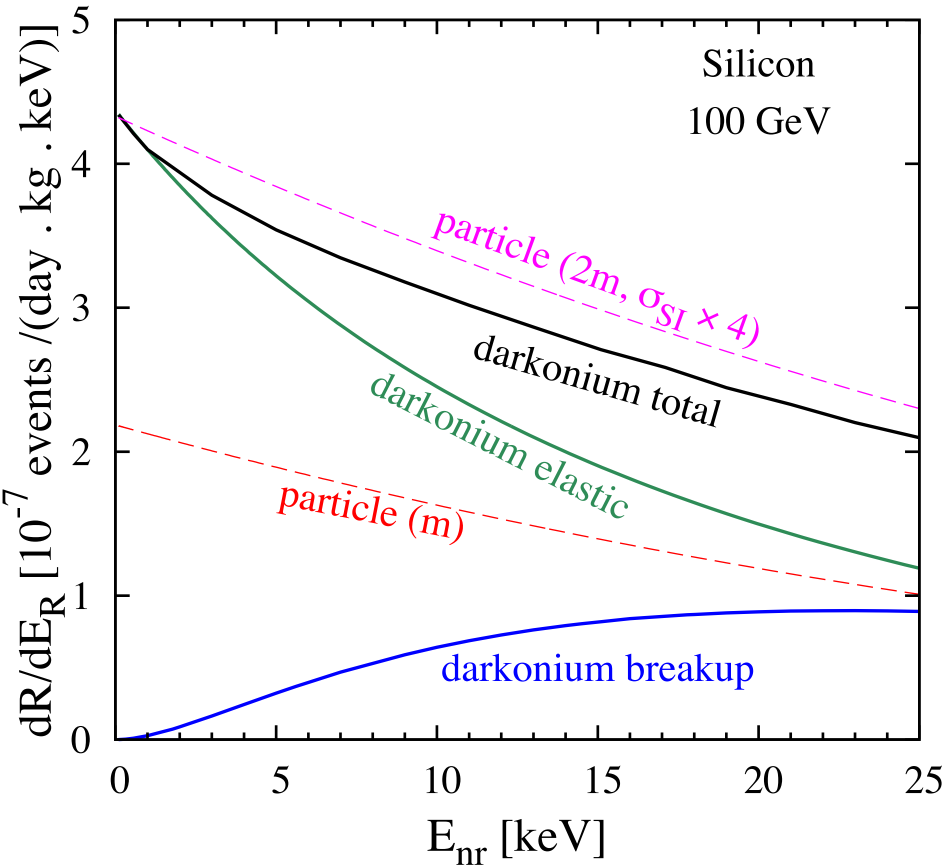
The exact value of σ_{SI} is just a normalization constant

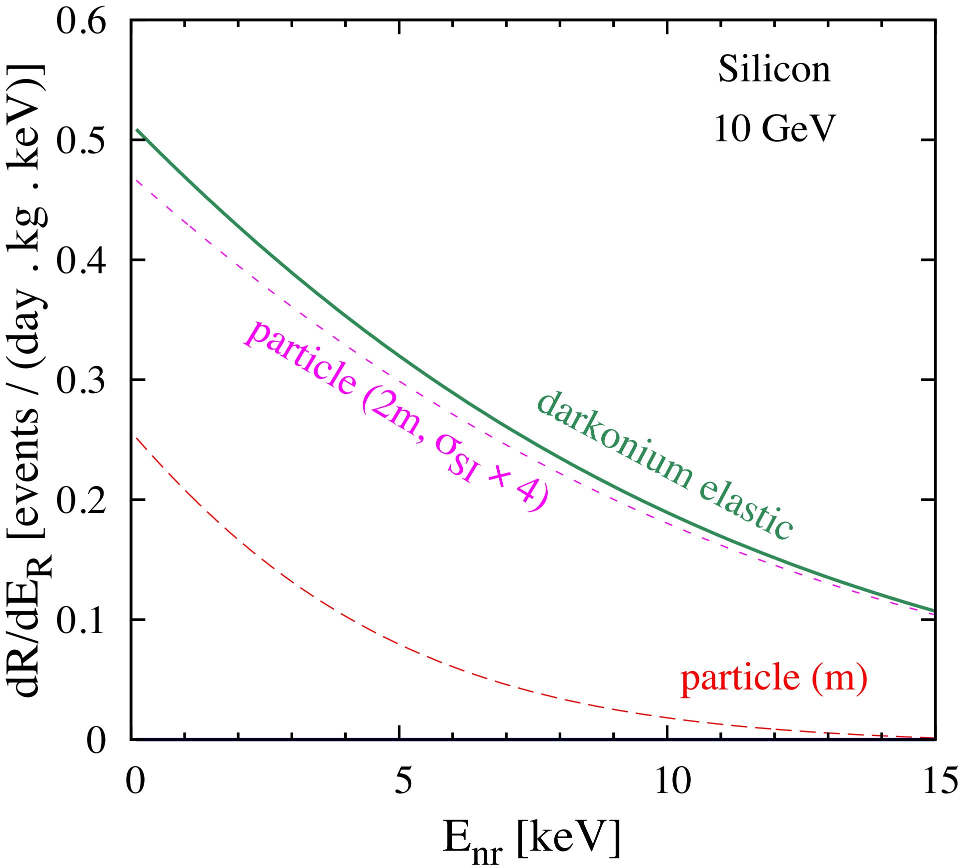
Recoil spectrum in Germanium detectors



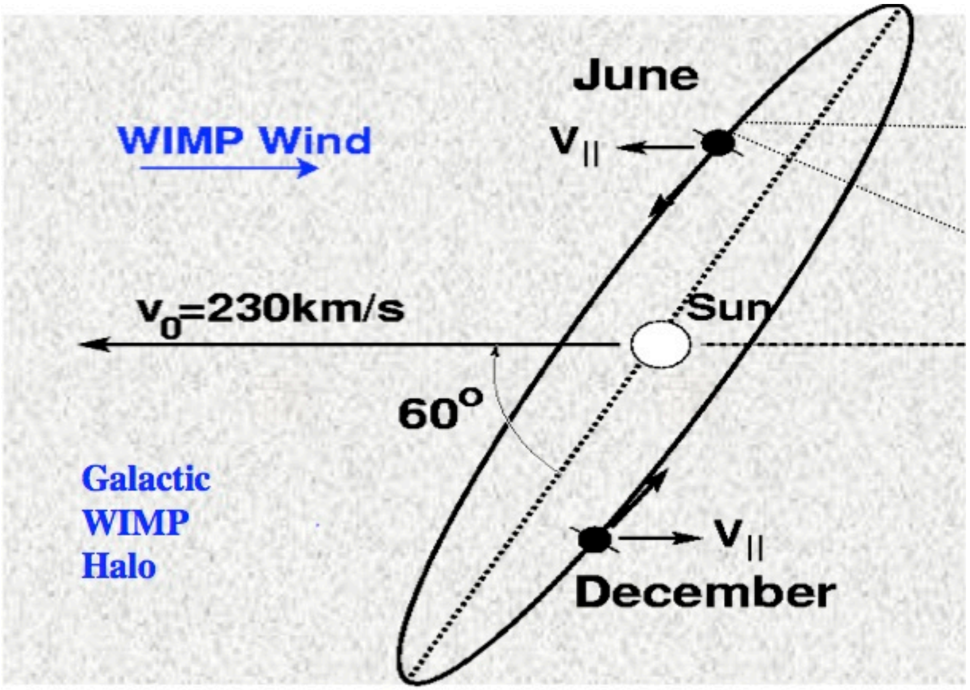
A larger value of the self-interaction cross section will produce a more dramatic signal

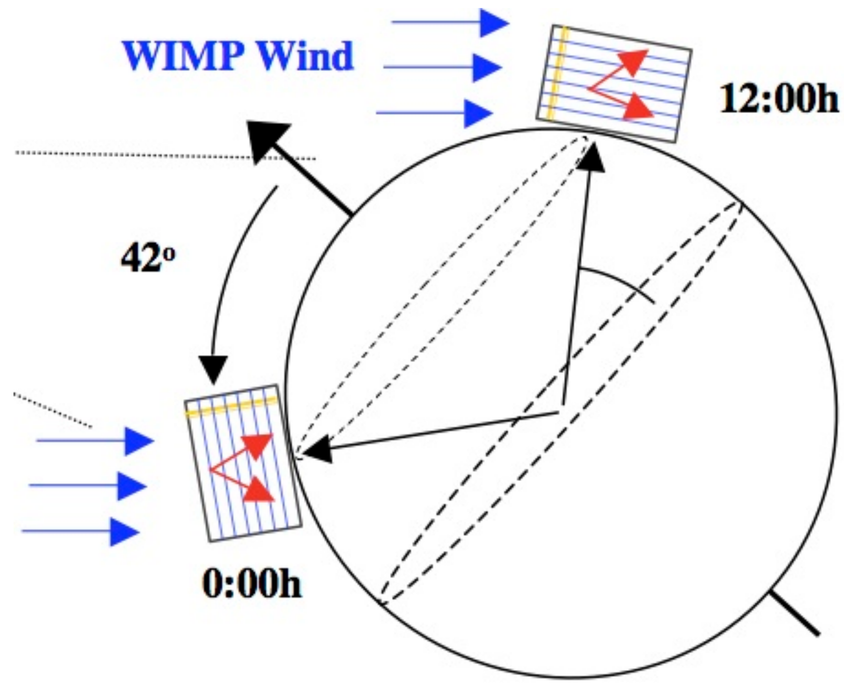
Recoil spectrum in Silicon detectors





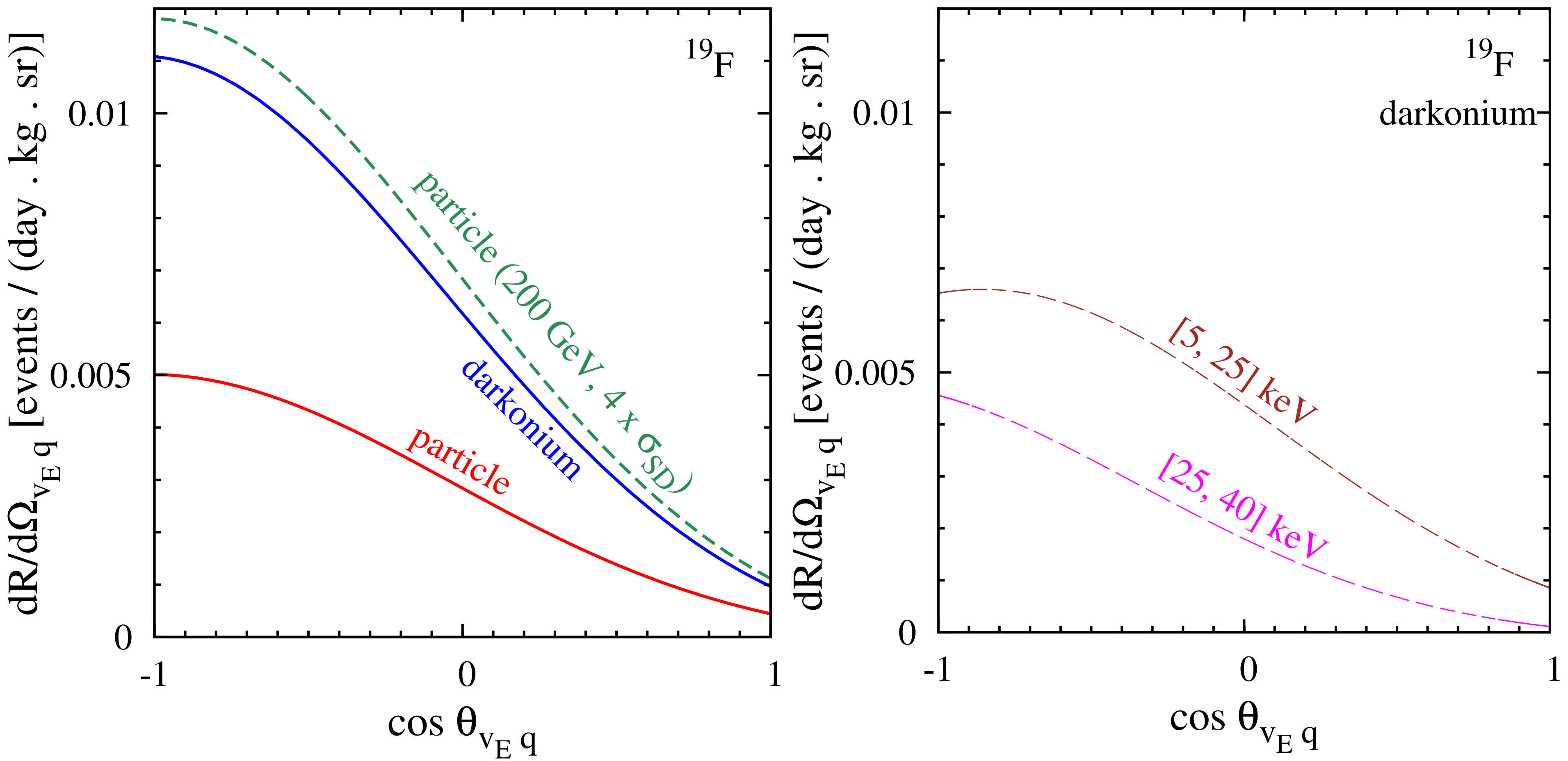
Directional detection of dark matter





From D Loomba TeVPA/ IDM 2014

Angular recoil spectrum

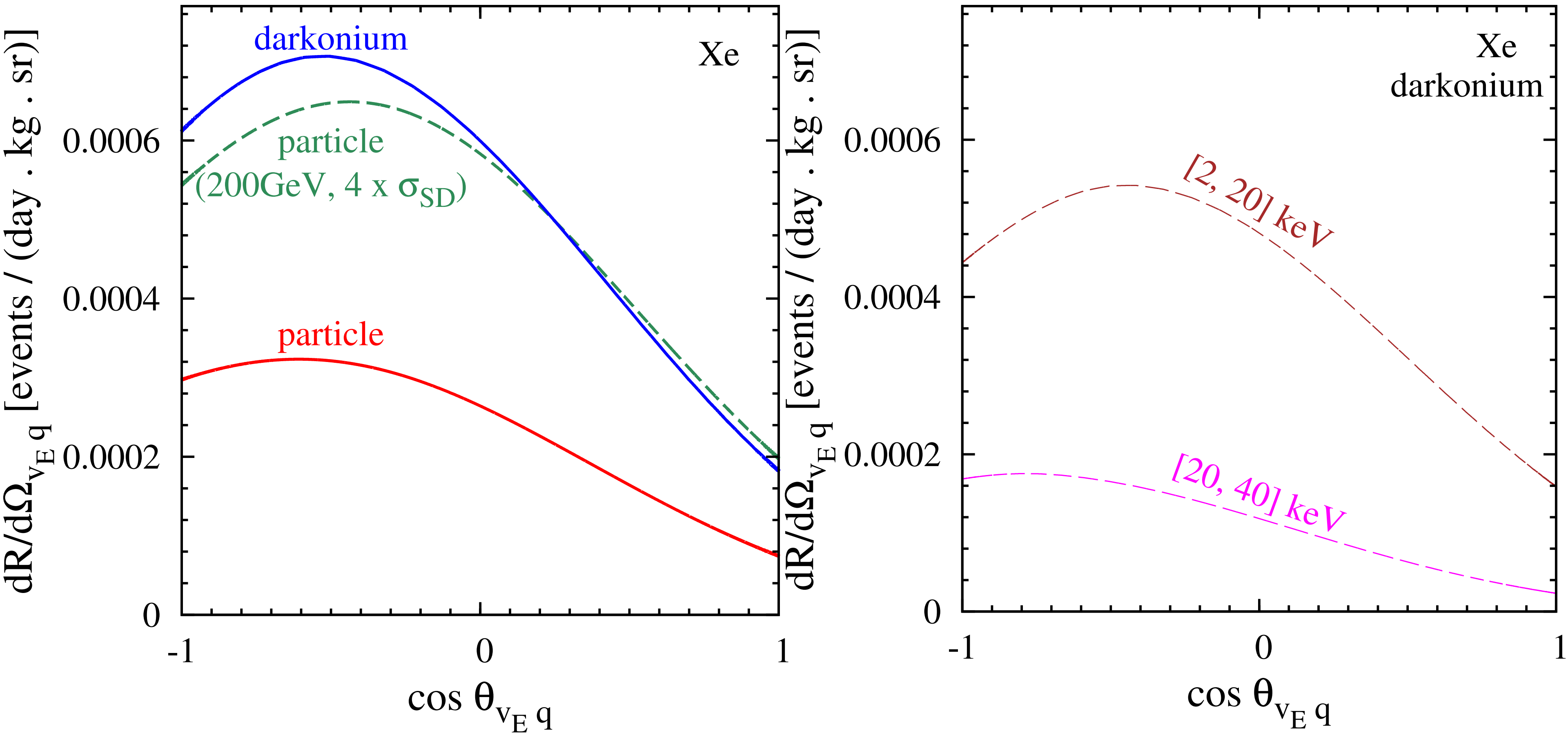


Dark matter particle mass = 100 GeV

Target = ^{19}F

Spin-dependent cross section = 10^{-39} cm^2 (arbitrary normalisation)

Angular recoil spectrum



Target Xenon nuclei

Isotopes relevant to spin-dependent interactions considered

Conclusions

- Strong self-interaction between two dark matter particles can be due to a near threshold S-wave resonance
- Universality implies that the s-wave scattering length determines all the scattering properties
- The resultant bound state of dark matter can leave novel signatures in dark matter direct detection experiments
- These signatures will give confirmation about dark matter self interactions

Some formulas

- We denote the inverse scattering length by γ

$$\sigma_{\rm el} = \frac{8\pi}{|-ik-\gamma|^2} \qquad \sigma_{\rm ann} = \frac{8\pi\,{\rm Im}\,\gamma}{k|-ik-\gamma|^2}$$

$$E_B = \frac{({\rm Re}\,\gamma)^2 - ({\rm Im}\,\gamma)^2}{m} \qquad \Gamma_{\rm darkonium} = \frac{4({\rm Re}\,\gamma)({\rm Im}\,\gamma)}{m}$$

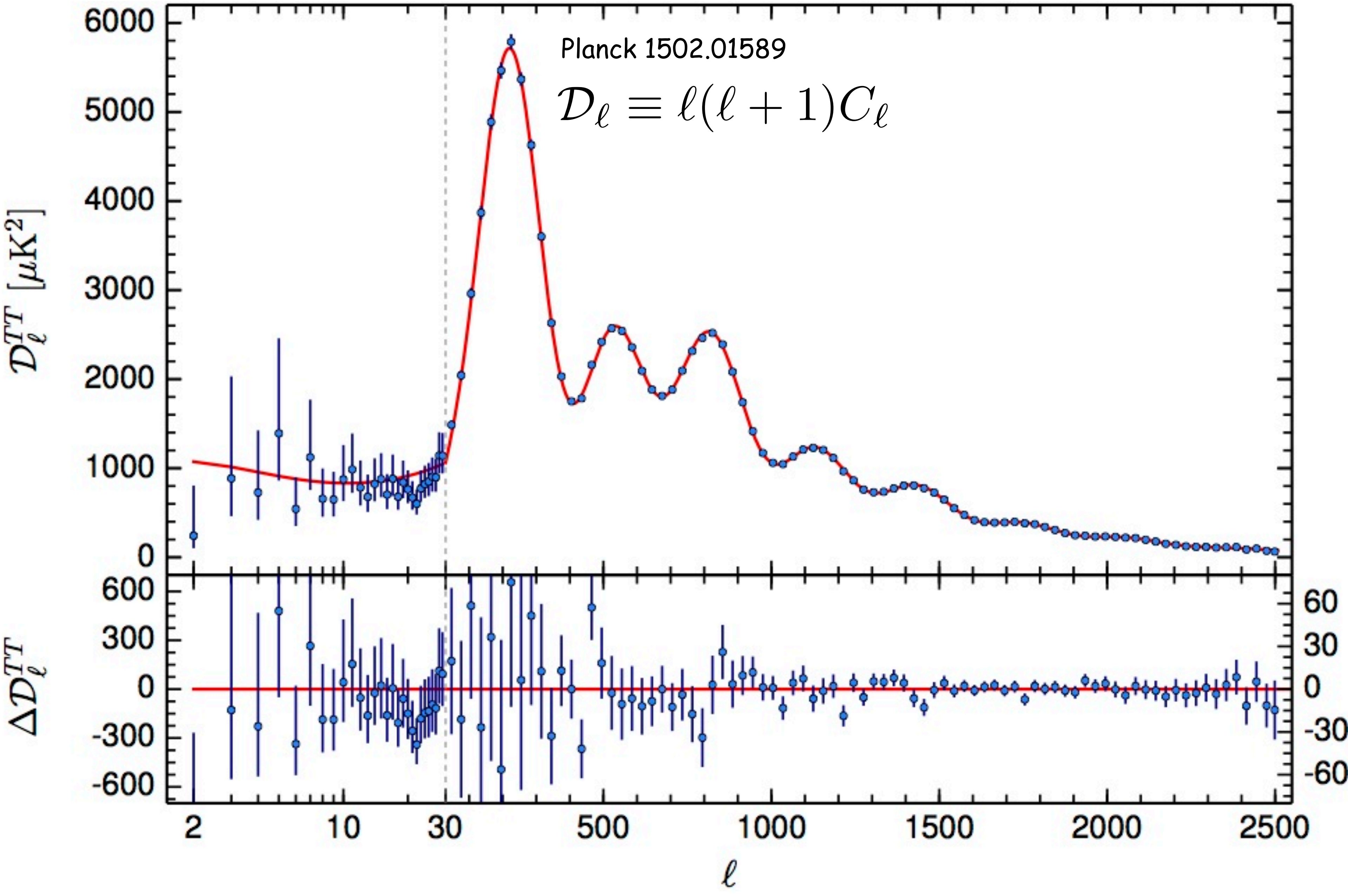
- Stability of the darkonium implies ${\rm Im}\,\gamma \to 0$ and that also implies that $\sigma_{\rm ann} \to 0$

- We calculate γ by assuming that $\sigma_{\rm el}/m = 1\,{\rm cm}^2/{\rm g}$ at v = 10 km/s

- The "small scale structure problem" are most severe at dwarf galaxies

The success of ΛCDM

Cosmic Microwave Background --- largest scales



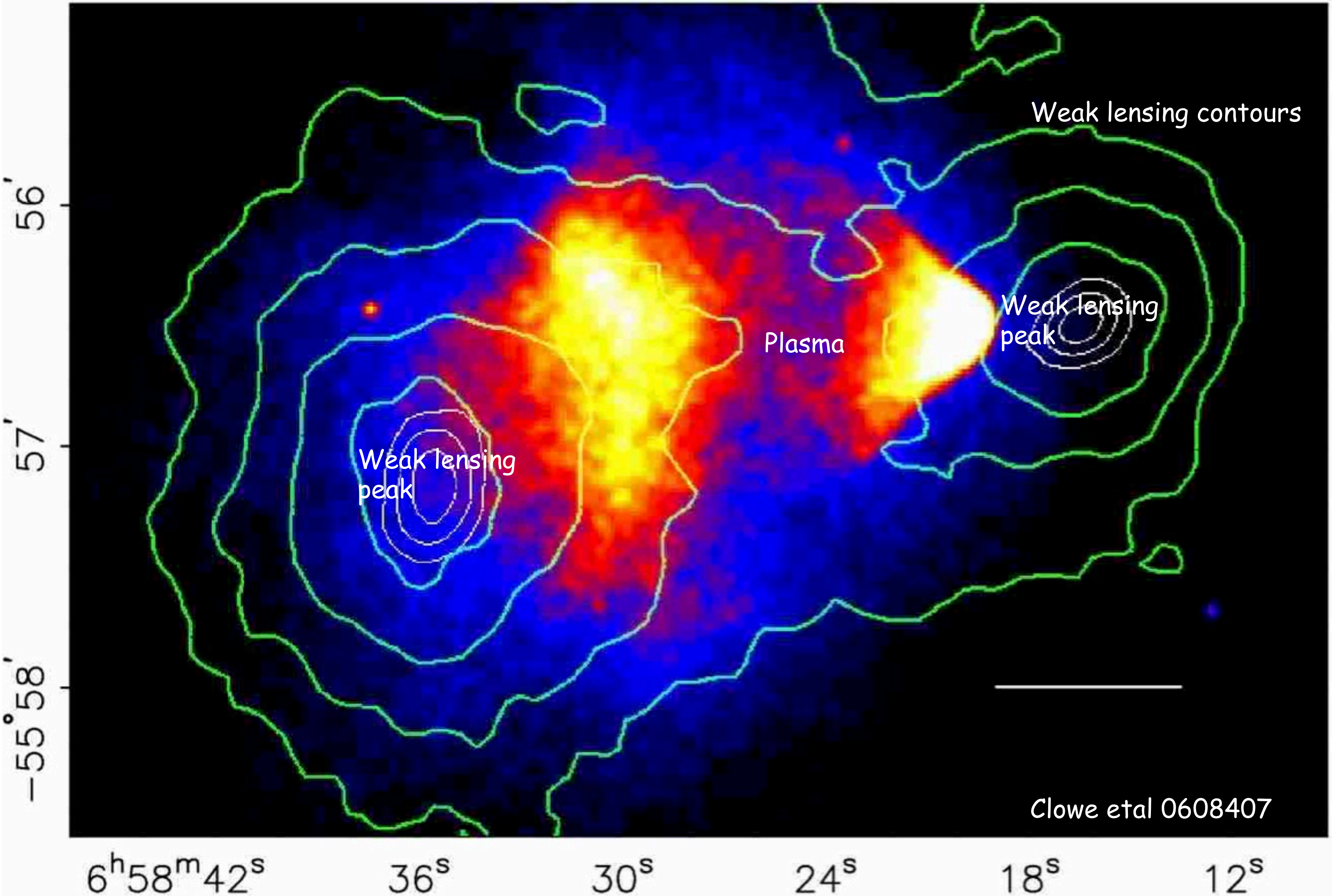
Illustris Simulation

Real observation from Hubble eXtreme Deep Field
Observations: left side

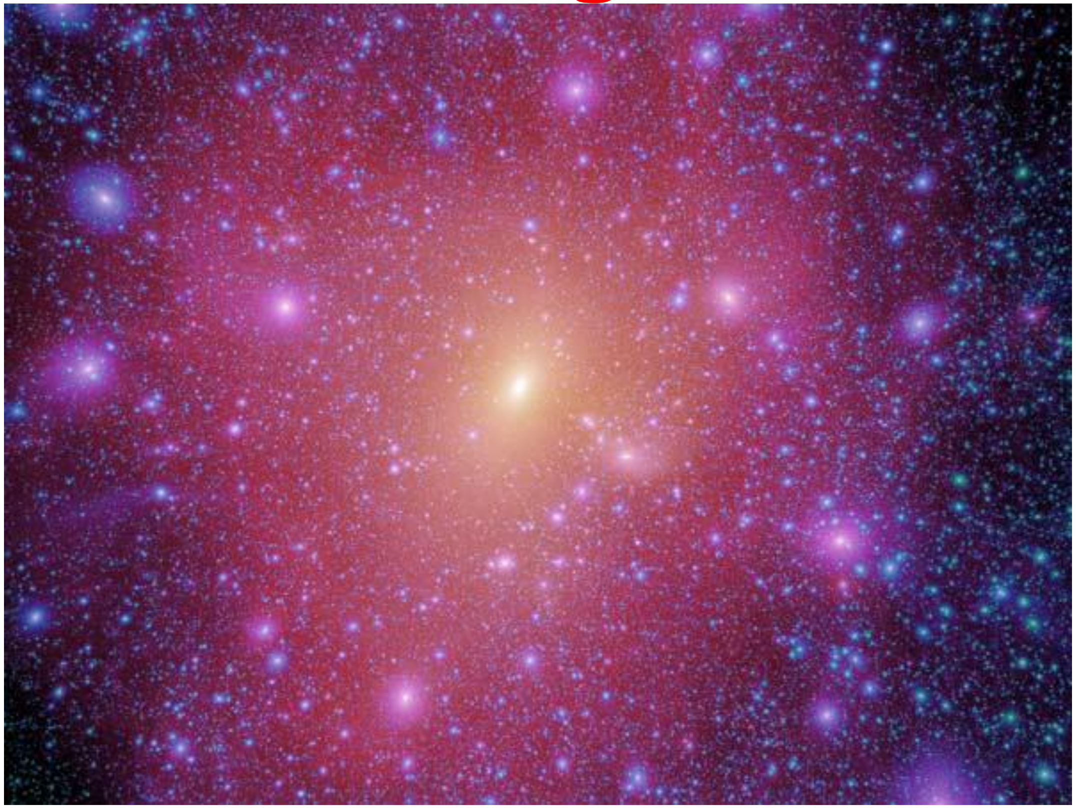
http://www.illustris-project.org/media/

Mock observation from Illustris: right side

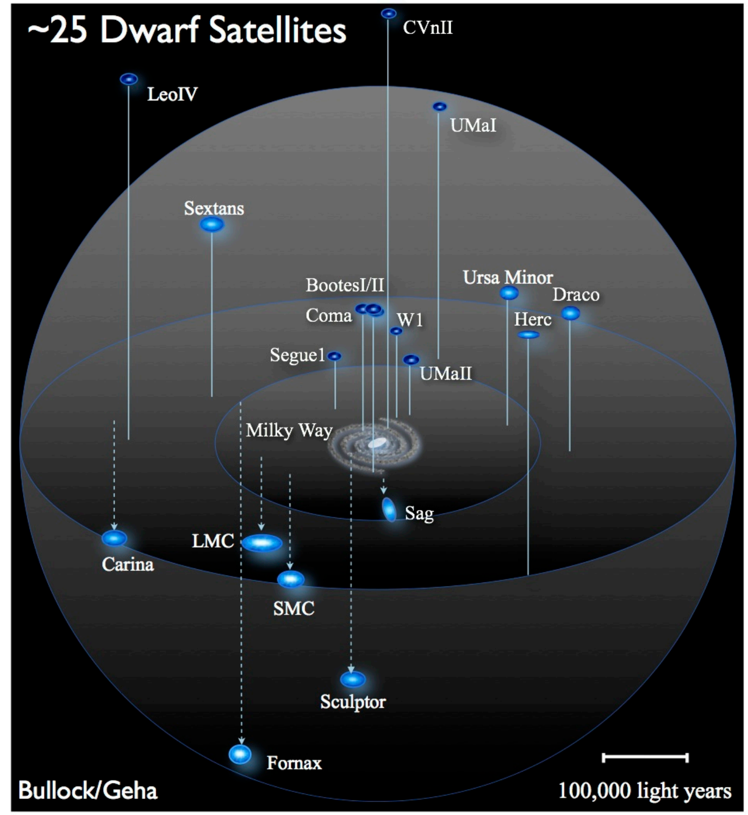
Cluster collision



Missing satellites problem



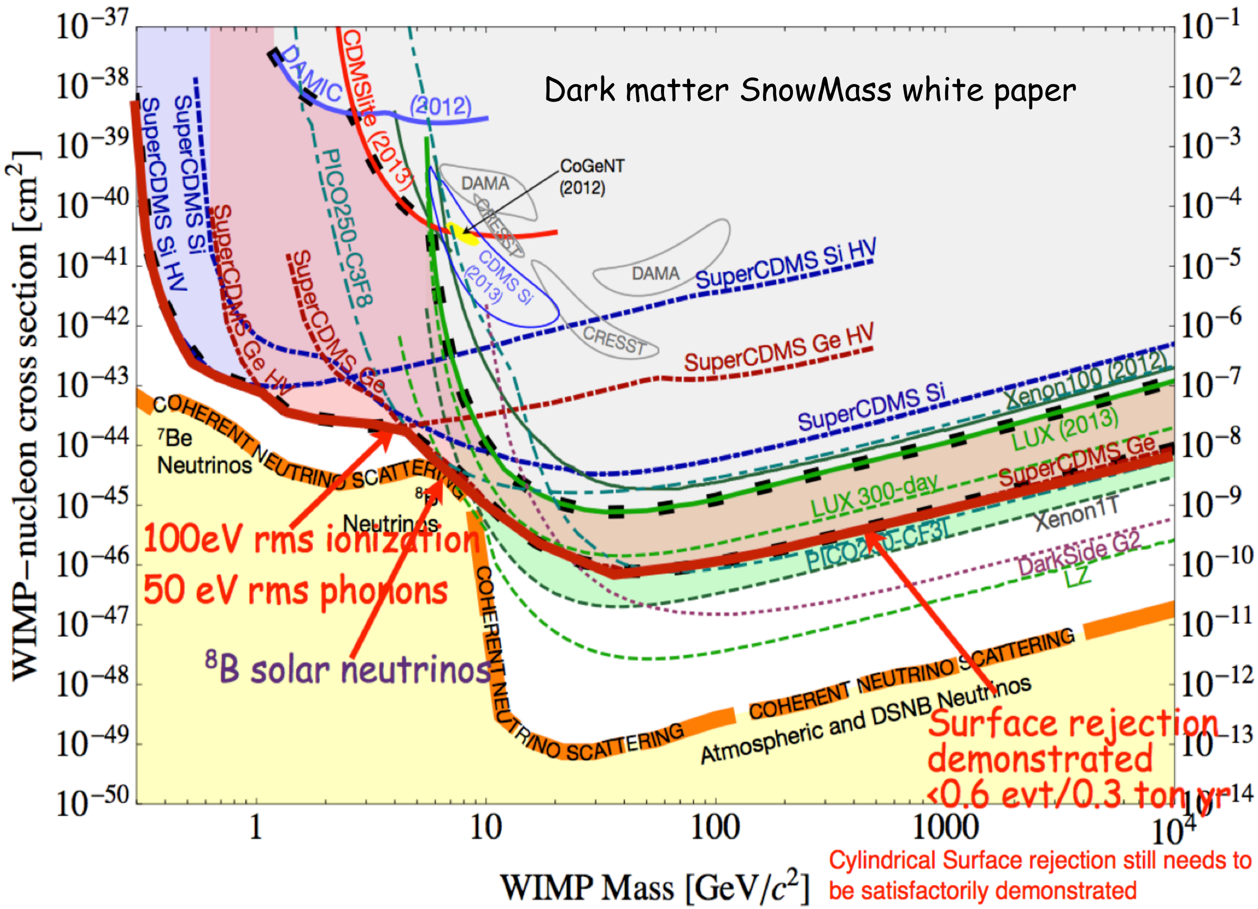
Simulation Aquarius project



Approximately an order of magnitude of "missing satellites"

Will increased sky coverage help? Yes!

Direct detection limits



Typically all "anomalies" are near the threshold of the detector

Direct probe of the local dark matter density and velocity profile

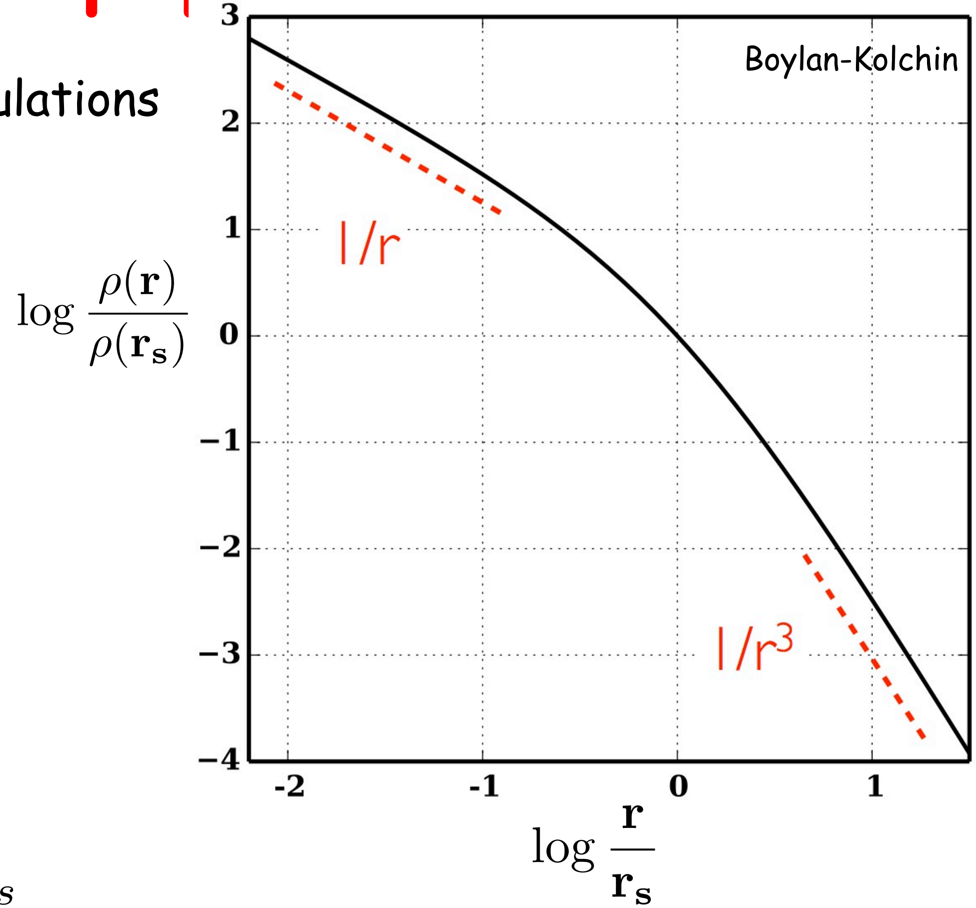
Can soon re-discover neutrinos using this technique!

No discovery yet

Core vs cusp problem

From simulations

$$\rho(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$



2 free parameters: ρ_s and r_s

Typically replaced by more meaningful parameters from simulations:

$\mathrm{M_{vir}}$ and $\mathrm{c_{vir} = r_{vir}/r_s}$