Galaxy Clusters as Laboratories for Astroparticle Physics

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in collaboration with

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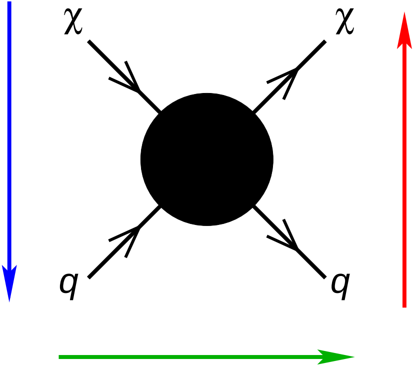
Outline

1. Dark matter searches
   - Models
   - Sources
   - Boost factors
2. DM constraints from γ rays
   - Spectra
   - Constraints
   - Conclusions
3. ΛCDM small-scale problems
   - Problems
   - Solutions
   - Our Model

Outline

Searching for dark matter (DM)

correct relic density → DM annihilation in the Early Universe



DM annihilation:
indirect detection

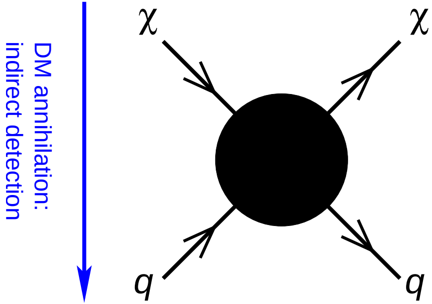
DM production:
particle colliders

DM scattering:
direct detection

(slide concept Feng)

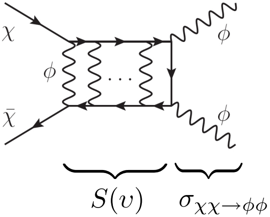
1. “Standard” supersymmetric DM

consider benchmark models of **supersymmetric DM**



2. DM with Yukawa-type interactions

- heavy DM interacts through light force carrier ϕ
- repeated exchange of ϕ → Sommerfeld effect
- multiply cross-section by enhancement factor S



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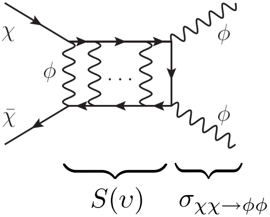
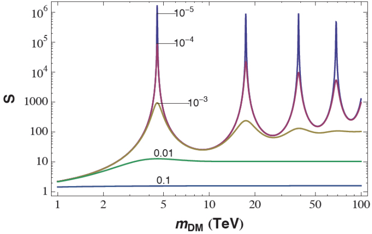
    - off resonance: $S \propto v^{-1}$
    - on resonance: $S \propto v^{-2}$





Lattanzi, Silk (2009)

2. DM with Yukawa-type interactions

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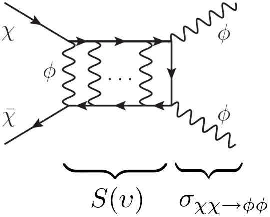
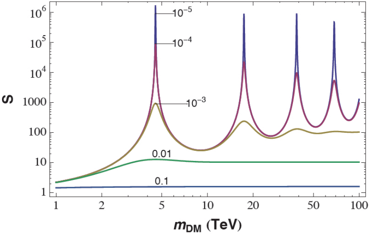
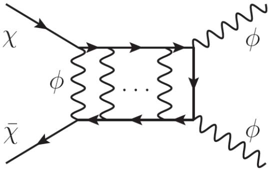
- multiply cross-section by enhancement factor S
- near bound state resonances expected:
    - off resonance: $S \propto v^{-1}$
    - on resonance: $S \propto v^{-2}$
- for $m_\phi \lesssim 100$ MeV, ϕ can only decay into leptons (e, μ) $\rightarrow$ leptophilic DM



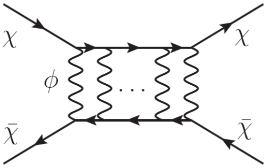


Lattanzi, Silk (2009)

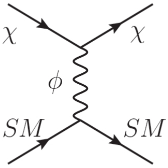
Diagrams of DM with Yukawa-type interactions



annihilation



self-scattering

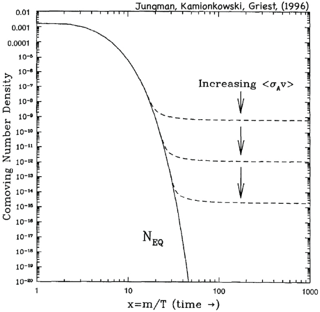


scattering

Thermal history of WIMPs

chemical decoupling:

- annihilations cease at $x = m_\chi / T \sim 25$ (rate $\propto n_\chi n_\chi$)
- “freeze out” of comoving number density
- *sets relic abundance*



Jungman, Kamionkowski, Griest, (1996)

Thermal history of WIMPs

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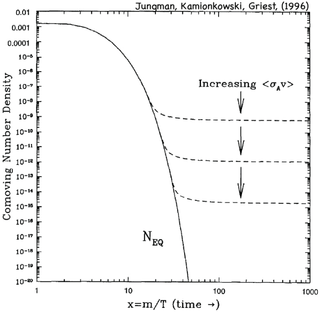
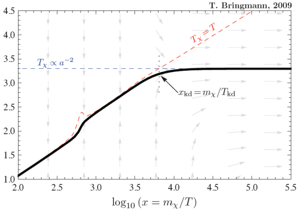
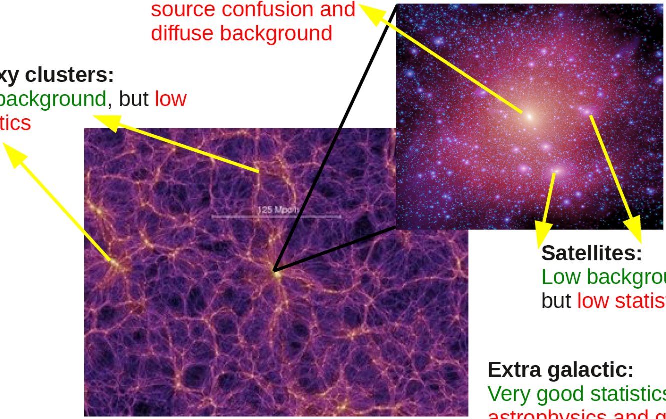
kinetic decoupling:

- scattering off standard model particles in thermal heat bath
- ceases at $x \gg 25$ (rate $\propto n_\chi n_{\mathrm{SM}}$)
- WIMPs cool down faster
- *sets cutoff mass for smallest subhalos, M_{min}*





Indirect DM searches: sources



Galactic center:
Good statistics, but
source confusion and
diffuse background

Milky Way halo:
Very good statistics,
but diffuse background

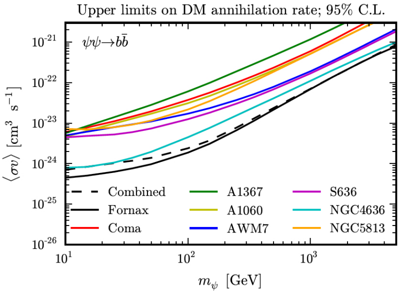
Galaxy clusters:
Low background, but low
statistics

Satellites:
Low background,
but low statistics

Extra galactic:
Very good statistics, but
astrophysics and galactic
diffuse foregrounds

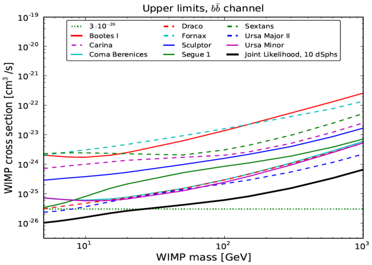
DM searches in clusters vs. dwarfs

Galaxy clusters:



Huang et al. 2011 (see also Ando & Nagai 2012)

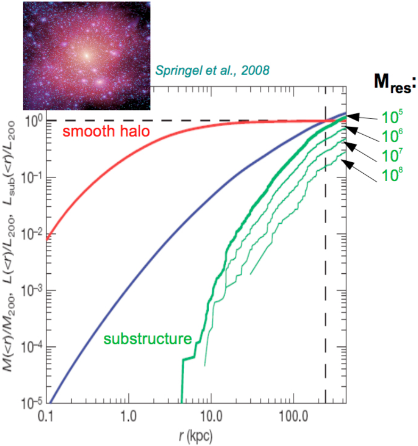
Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

- combined limits for dwarf galaxies $\sim$ 20 times more constraining
- is this really true? → consider substructure!

Enhancement from DM substructures



Springel et al., 2008

Constant offset in the luminosity from substructures between different mass resolutions in the simulation (M_{res}).

$$\text{Norm} \propto M_{res}^{-0.226}$$

Extrapolate to the minimal mass of dark matter halos (M_{min}) that can form.

The cold dark matter scenario suggests $M_{min} \sim 10^{-6}\,M_\odot$.

Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

$$L_{sub}(<r) \propto (M_{200} / M_{res})^{0.226}$$

Luminosity boosted by ~1000 in clusters

Pinzke et al. 2011, Gao et al 2011

Galaxy clusters vs. dwarf galaxies

- DM annihilation flux of smooth (unresolved) halo:

$$F \propto \int \mathrm{d}V \frac{\rho^2}{D^2} \sim f(c)\,\frac{M}{D^2}$$

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→ smooth component of best dwarf and cluster targets are equally bright!

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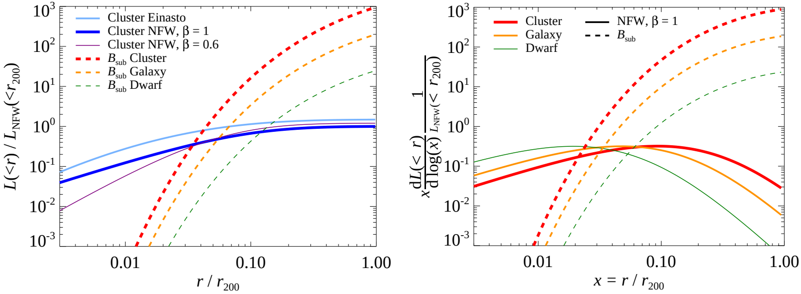
→ smooth component of best dwarf and cluster targets are equally bright!

- DM substructure is less concentrated compared to the smooth halo (dynamical friction, tidal heating and disruption): the DM luminosity is dominated by substructure at the virial radius, *if* present!
  → these regions are tidally stripped in dwarf galaxies
  → in cluster, subhalos enhance DM luminosity by up to 1000

(e.g., Pinzke, C.P., Bergström 2011; Gao et al. 2011)

Spatial DM distribution

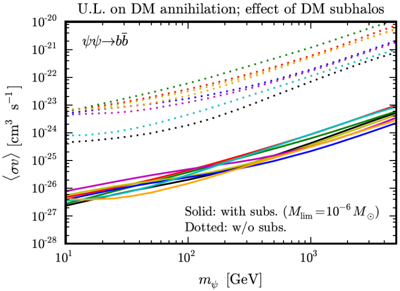


Pinzke, C.P., Bergström 2011

- form of smooth density profile only important for central region, majority of smooth flux accumulates around $r \simeq r_s/3$
- emission from substructures dominated by outer regions → spatially extended
- large boost in clusters (~ 1000); smaller boost in dwarf satellites (~ 20) → much smaller if outskirts are tidally stripped

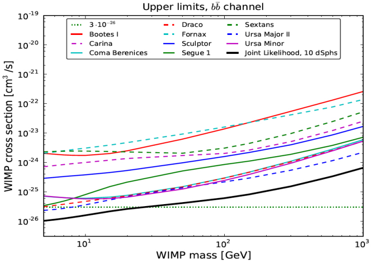
DM searches in clusters vs. dwarfs

Clusters with substructures:



Huang et al. 2011 (see also Ando & Nagai 2012)

Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

- galaxy clusters $\sim$ 10 times more constraining than dwarf satellites when accounting for substructures!

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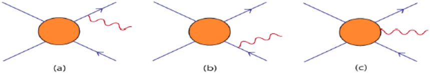
DM-induced gamma rays: *leptophilic models*

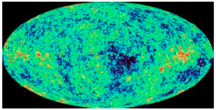
Annihilation rate in these models enhanced by **Sommerfeld effect** as well as **DM substructures**.

Gamma-ray emission components:

- Final state radiation



- IC on background radiation fields (CMB, starlight and dust)



DM-induced gamma rays: *SUSY benchmark models*

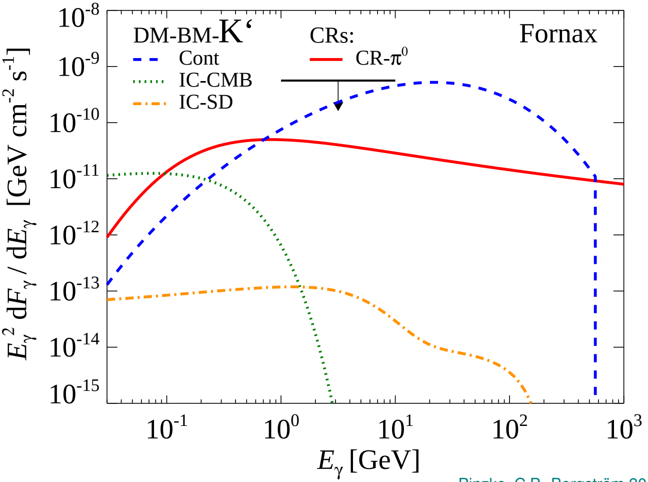
Representation of high mass (~1 TeV) DM models with high gamma-ray emission.

Luminosity **boosted by substructures** in the smooth DM halo.

Gamma-ray emission components:

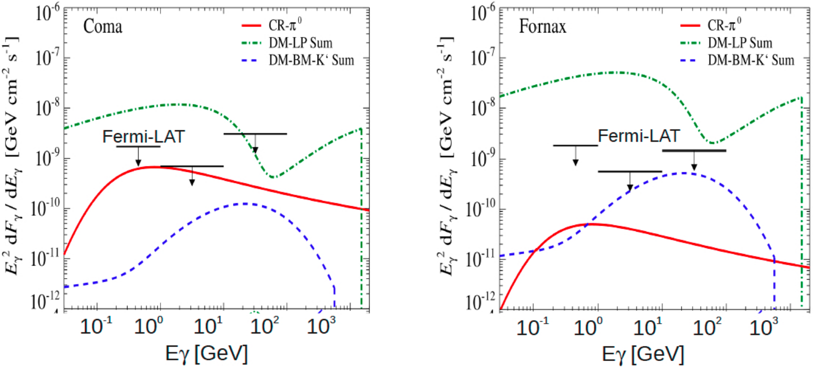
- Annihilating neutralinos emitting continuum emission
- Final state radiation
- IC on background radiation fields (CMB, starlight and dust)

Gamma-ray spectrum: benchmark DM model vs. CRs



Pinzke, C.P., Bergström 2011

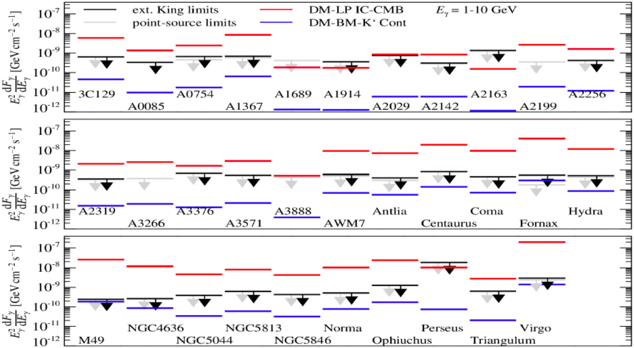
Comparing clusters and emission processes



Pinzke, C.P., Bergström 2011

- **Fornax:** comparably high DM-induced gamma-ray flux and low CR-induced emission → tight limits on DM properties
- **Coma:** CR-induced emission soon in reach for Fermi

DM flux predictions vs. observations



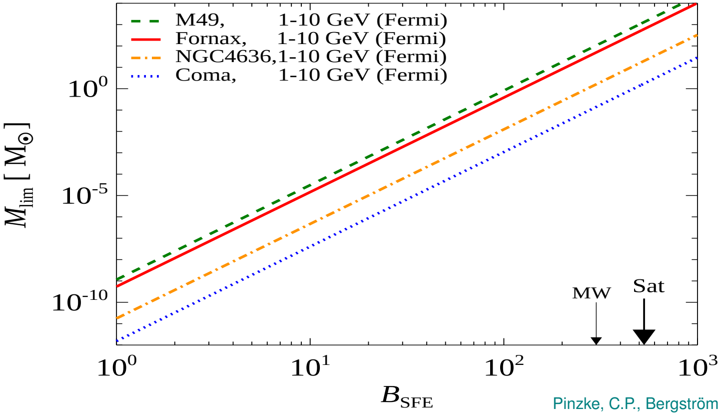
Pinzke et al. 2011

Emission from leptophilic models in most clusters detectable with Fermi-LAT after 18 months of operation.

Supersymmetric DM models will start being probed in coming years.

Brightest clusters: Fornax, Ophiuchus, M49, Centaurus (and Virgo).

Constraining boost factors *(leptophilic models)*



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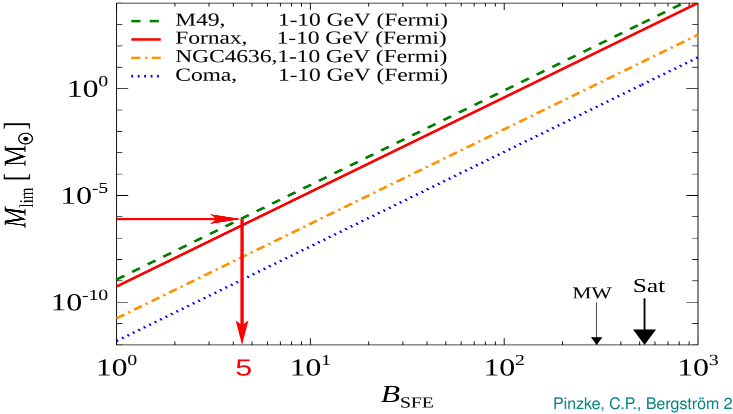
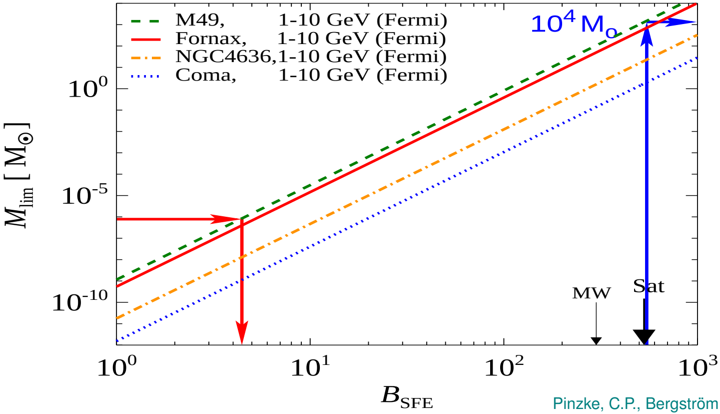


Pinzke, C.P., Bergström 2011

- Fornax and M49 constrain the saturated boost from Sommerfeld enhancement (SFE) to < 5

Constraining boost factors *(leptophilic models)*



Pinzke, C.P., Bergström 2011

- Alternatively, if SFE is realized in Nature, this would limit the substructure mass to $M_{\rm lim} > 10^4 M_\odot$ – a challenge for structure formation and most particle physics models (van den Aarssen et al. 2012)

Conclusions on dark matter searches in clusters

Galaxy clusters are competitive sources for constraining dark matter:

- cluster luminosity boosted by $\sim$ 1000 (for $M_{\text{min}} \simeq 10^{-6}\,\mathrm{M}_{\odot}$)
- flat brightness profiles and spatially extended → challenging for IACTs, better probed by Fermi-LAT

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Leptophilic DM models:

- Fermi-LAT data constrains the Sommerfeld enhancement to < 5
- if DM interpretation of lepton excess seen by PAMELA/Fermi is correct, then smallest subhalos have $M > 10^4\,\mathrm{M}_\odot$

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SUSY benchmark models:

- accounting for substructure boost allows to constrain interesting DM parameter space ($\langle\sigma v\rangle \lesssim 3\times10^{-26}\,\mathrm{cm}^3\,\mathrm{s}^{-1}$, $m_\chi \gtrsim 100$ GeV)

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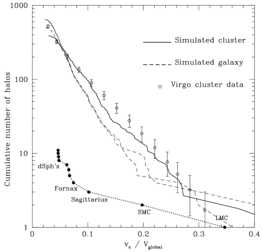
ΛCDM small-scale problems

1. Missing satellites?



Moore et al. 1999

→ many more satellites in simulations of MW-sized galaxies than observed

ΛCDM small-scale problems

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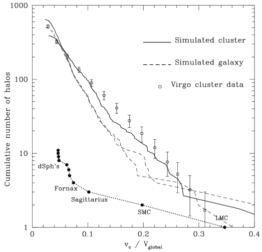

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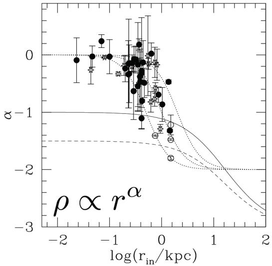

Blok et al. 2001

→ cuspy inner density profiles predicted by simulations not found in observations

ΛCDM small-scale problems

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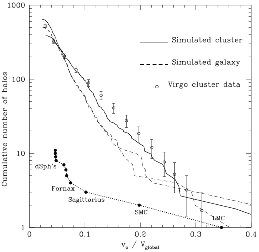

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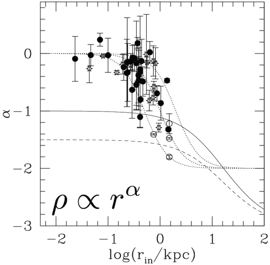

Blok et al. 2001

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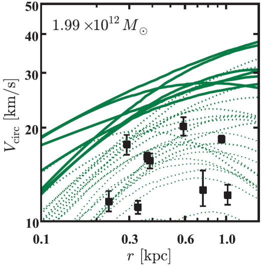
3. Too big to fail?



Boylan-Kolchin et al. 2011

→ most massive sub-halos in simulations too dense to host observed brightest dwarf satellites

Solutions?

many possibilities, no consensus reached yet:

- astrophysical solutions:
  increased gas entropy, suppress cooling efficiency, SN feedback, large velocity anisotropy, other baryonic feedback, increased stochasticity of galaxy formation, small MW mass,. . .
- dark matter solutions:
  warm DM, interacting DM, DM from late decays, large annihilation rates, condensates, . . .
- all have shortcomings and/or solve at most 2 problems at the time!

Solutions?

velocity-dependent self-interacting dark matter:

- scattering cross-section for Yukawa potential Khrapak et al. (2003)
  $\sigma_{\chi\bar{\chi}} =$ const. unnatural from particle physics viewpoint!
- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma

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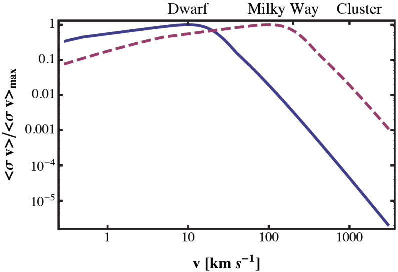
  $\sigma_{\chi\bar{\chi}} =$ const. unnatural from particle physics viewpoint!
- elastic DM self-scattering is completely analogous to screened Coulomb scattering in a plasma
- cored profiles possible without violating astrophysical constraints
  Feng et al. (2010), Loeb & Weiner (2011)
- N-body simulations: “too big to fail” problem avoided
  Vogelsberger et al. (2012)
- what about missing satellites?



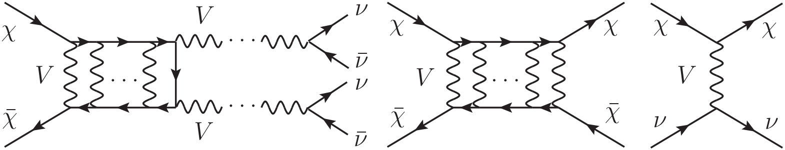
Loeb & Weiner (2011)

Our model

van den Aarssen, Bringmann, C.P. (2012)

- assume light vector mediator coupling to dark matter and neutrinos:

$$\mathcal{L}_{\rm int} \supset -g_\chi \bar{\chi} \not{V} \chi - g_\nu \bar{\nu} \not{V} \nu$$



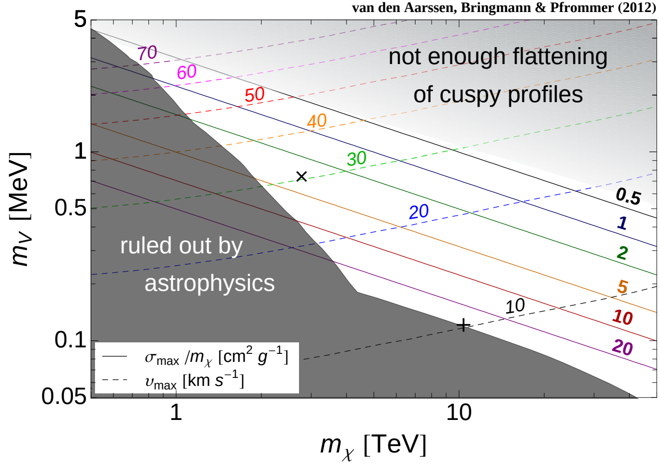
annihilation
→ relic density
→ indirect 4ν detection signal from galactic center(?)

self-scattering
→ changes inner density and velocity profiles of dwarf galaxies

scattering
→ large $M_{\rm min}$

"Cusp vs. core" and "too big to fail" problems

- demand correct relic density
  → unique relation between $(v_{\max}, \sigma_{\max})$ and (m_χ, m_V)


van den Aarssen, Bringmann & Pfrommer (2012)

DM scattering off standard model particles

- free-streaming of WIMPs after kinetic decoupling creates cutoff in power spectrum
- acoustic oscillations leads to similar cutoff
- cutoff scale is set by size of horizon at KD: late KD → high M_min
- $M_\mathrm{min} = \max(M_\mathrm{fs}, M_\mathrm{ao})$: only objects with $M \geq M_\mathrm{min}$ form

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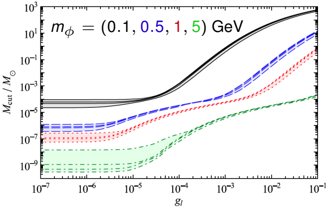
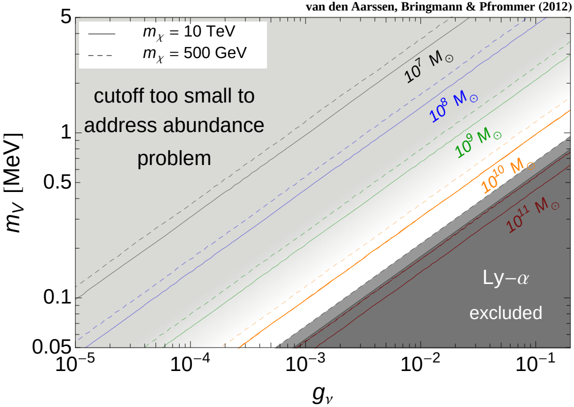
- scalar mediator:
  - scatters off ϕ, $\mu^\pm$, $e^\pm$
  - saturation at $M_{\text{min}} \sim 10^3\,\text{M}_\odot$
  - ν's negligible: $|\mathcal{M}_{\phi l\to\phi l}|^2 \propto m_l^2$
- vector mediator:
  - ν's contribute: $|\mathcal{M}_{V\nu\to V\nu}|^2 \propto E_\nu^2$
  - M_{min} increases to $\mathcal{O}(10^{11}\text{M}_\odot)$



van den Aarssen et al. (2012)

“Missing satellites” problem

- now compute M_{min} from kinetic decoupling temperature . . .



- in this simple phenomenological model, it is possible to simultaneously solve all small-scale problems of ΛCDM!

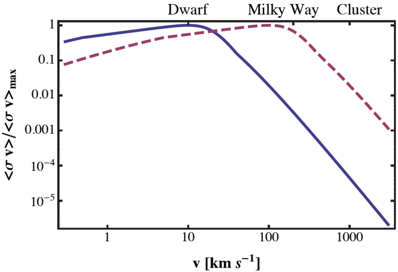
Cored central density profiles of clusters

- velocity-dependent DM self-scattering cores out central density slopes in clusters with rate

$$\Gamma \sim \frac{\rho}{m_\chi} \langle \sigma_{\chi\bar{\chi}} v \rangle \sim H$$

- ellipticals/clusters, $f_s = 10 - 100$:

$$\Gamma \sim \frac{f_s \rho}{m_\chi} \frac{\langle \sigma_{\chi\bar{\chi}} v \rangle|_{\max}}{f_s}$$

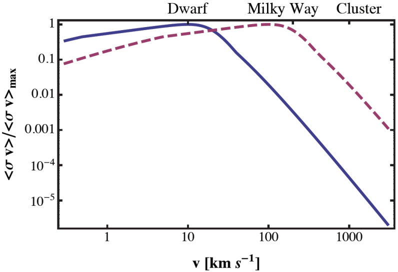


Loeb & Weiner (2011)

Cored central density profiles of clusters

- velocity-dependent DM self-scattering cores out central density slopes in clusters with rate

$$\Gamma \sim \frac{\rho}{m_\chi}\langle\sigma_{\chi\bar{\chi}}v\rangle \sim H$$



Loeb & Weiner (2011)

- ellipticals/clusters, $f_s = 10 - 100$:

$$\Gamma \sim \frac{f_s \rho}{m_\chi}\frac{\langle\sigma_{\chi\bar{\chi}}v\rangle|_{\max}}{f_s}$$

- using $\rho \sim 1/r$ for $r \ll r_s$:

$$\left.\frac{r_{\text{core}}}{r_{200}}\right|_{\text{cluster}} \sim \frac{1}{f_s}\left.\frac{r_{\text{core}}}{r_{200}}\right|_{\text{dwarf}} \sim \frac{1}{f_s 10} \quad\Rightarrow\quad r_{\text{core}}(10^{15}\mathrm{M}_\odot) \sim \mathcal{O}(1-10\,\text{kpc})$$

- need simulations to understand interplay of hierarchical evolution and determination of cluster-r_{core}: merging history → scatter

Conclusions on small-scale problems of ΛCDM

small-scale problems of ΛCDM can be solved by a DM model with:

- velocity-dependent self-interactions mediated by (sub-)MeV vector:
  → transforms cusps to cores and solves “too big to fail” problem
- much later kinetic decoupling than in standard case follows naturally for vector mediator coupling to neutrinos:
  → potentially solves “missing satellites” problem
- predicts cores in clusters on scales $\mathcal{O}(1-10\,\text{kpc})$

→ need further model building and simulations to confirm

Literature for the talk

Dark matter constraints from clusters:

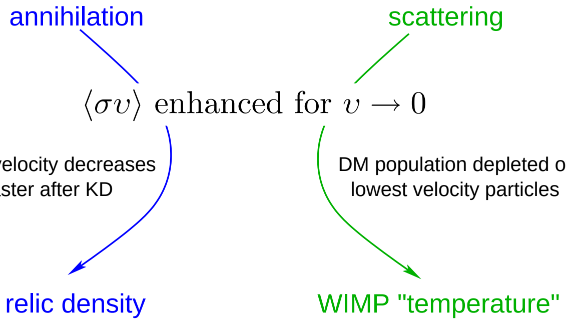
- Pinzke, Pfrommer, Bergström, *Prospects of detecting gamma-ray emission from galaxy clusters: cosmic rays and dark matter annihilations*, 2011, *Phys. Rev. D* 84, 123509.
- Pinzke, Pfrommer, Bergström, *Gamma-rays from dark matter annihilations strongly constrain the substructure in halos*, 2009, *Phys. Rev. Lett.*, 103, 181302.

Small-scale problems of ΛCDM:

- van den Aarssen, Bringmann, Pfrommer, *Dark matter with long-range interactions as a solution to all small-scale problems of ΛCDM cosmology?* 2012, *Phys. Rev. Lett.* 109, 231301.

Additional slides

Interplay between chemical and kinetic decoupling



annihilation

scattering

$$\langle \sigma v \rangle \text{ enhanced for } v \rightarrow 0$$

DM velocity decreases
faster after KD

DM population depleted of
lowest velocity particles

relic density

WIMP "temperature"

important: self−scattering ensures the
Maxwellian velocity distribution!

(use set of coupled Boltzmann equations to solve for thermal history of WIMPs)