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Thermal decoupling and small-scale structure in DM models with Yukawa-like interactions

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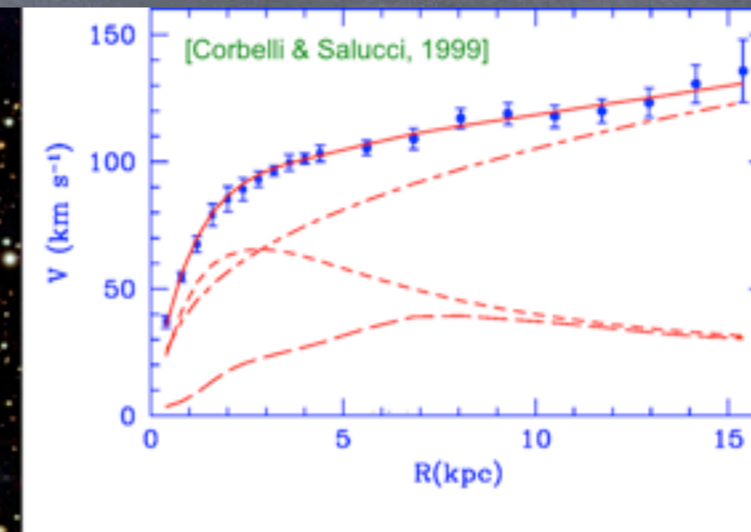
[arXiv:1202.5456 [hep-ph]]

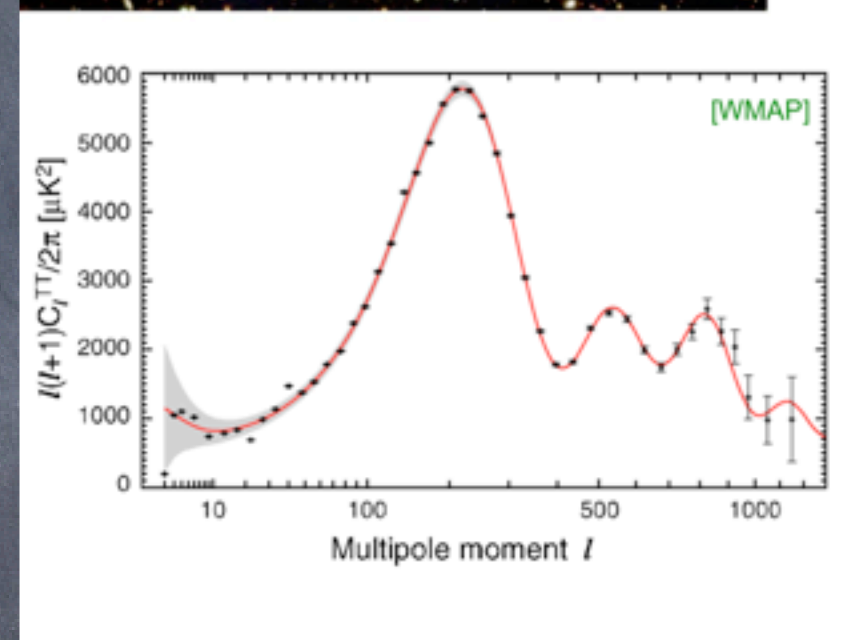
L.v.d.A., Torsten Bringmann, Christoph Pfrommer
[arXiv:1205.5809 [astro-ph.CO]]

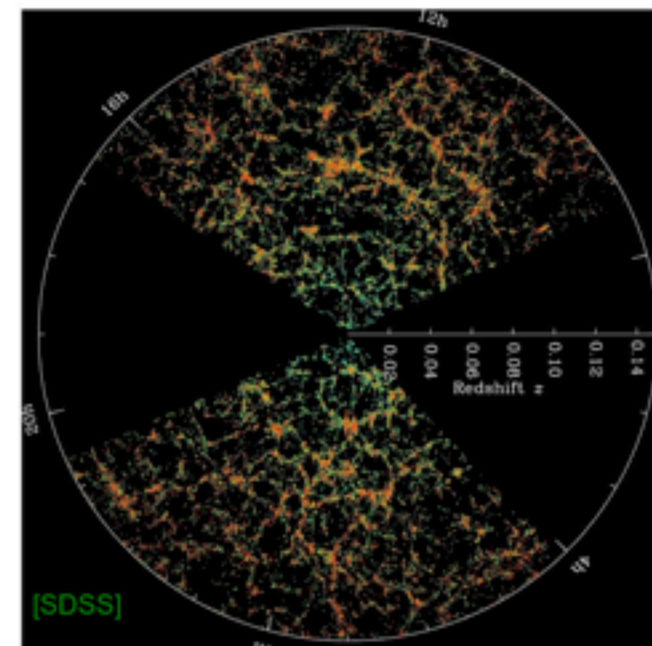
Dark Matter

What do we know?

- $\Omega_{DM} \cong 0.23$
- electically neutral
- non-baryonic
- collisionless
- Cold -> Large scale stucture







WIMPs are good candidates:

> motivation from particle physics

> right relic abundance comes out naturally (WIMP miracle)

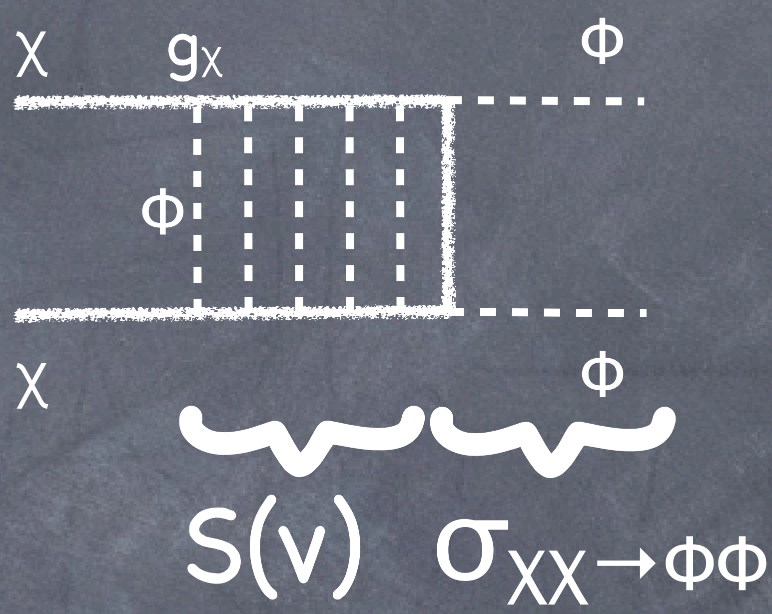
DM with Yukawa-like interactions

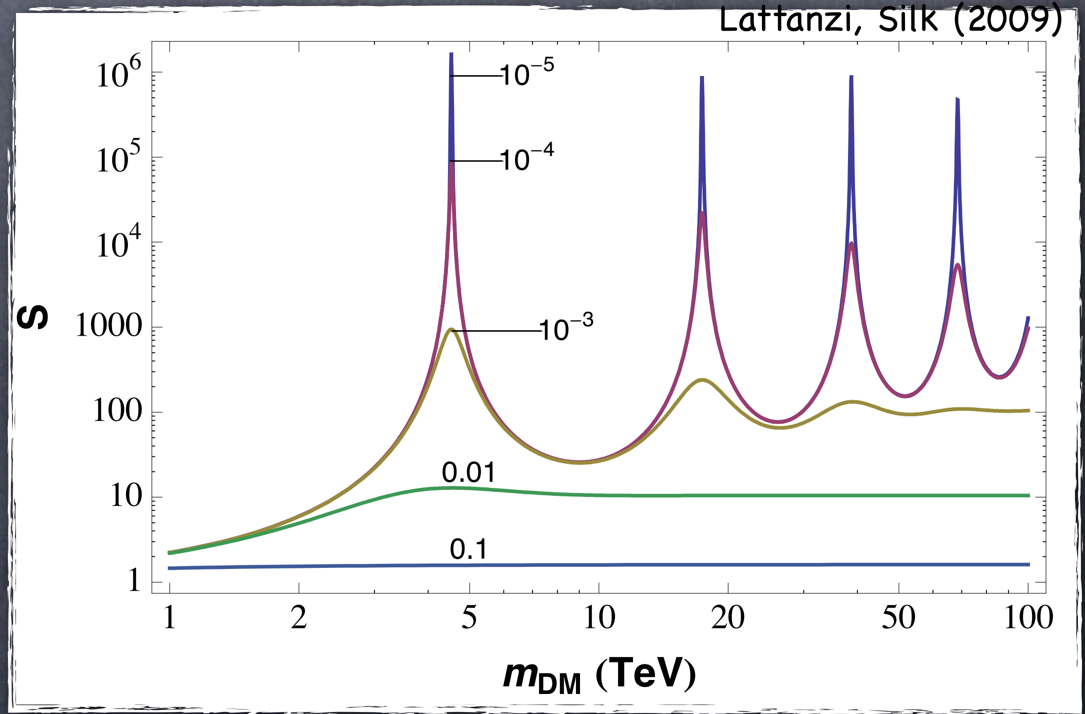
- heavy DM interacts through light force carrier Φ
- repeated exchange of Φ

  -> Sommerfeld effect
- multiply cross-section by

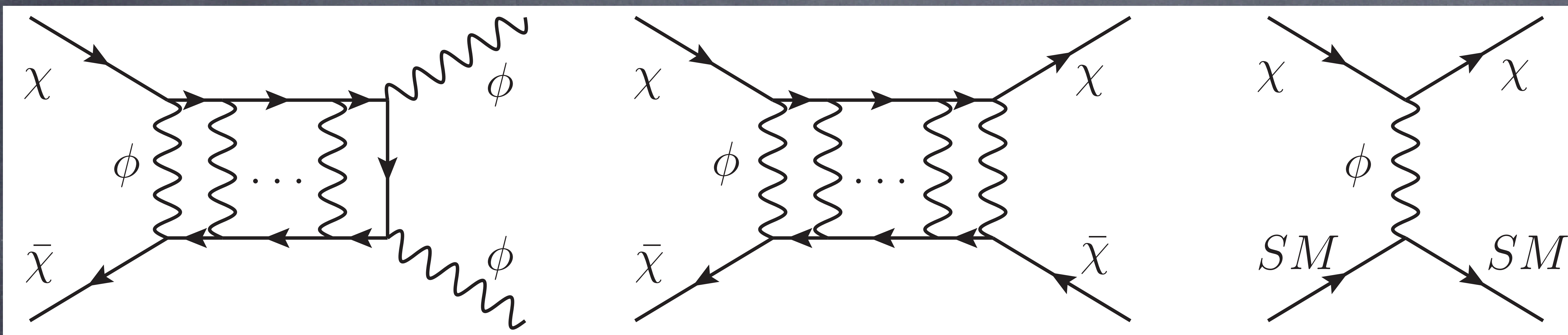
  enhancement factor S
- resonances expected

  near bound state:
  - off resonance $S \sim v^{-1}$
  - resonance $S \sim v^{-2}$





Important interactions



annihilation self-scattering scattering

First part of talk

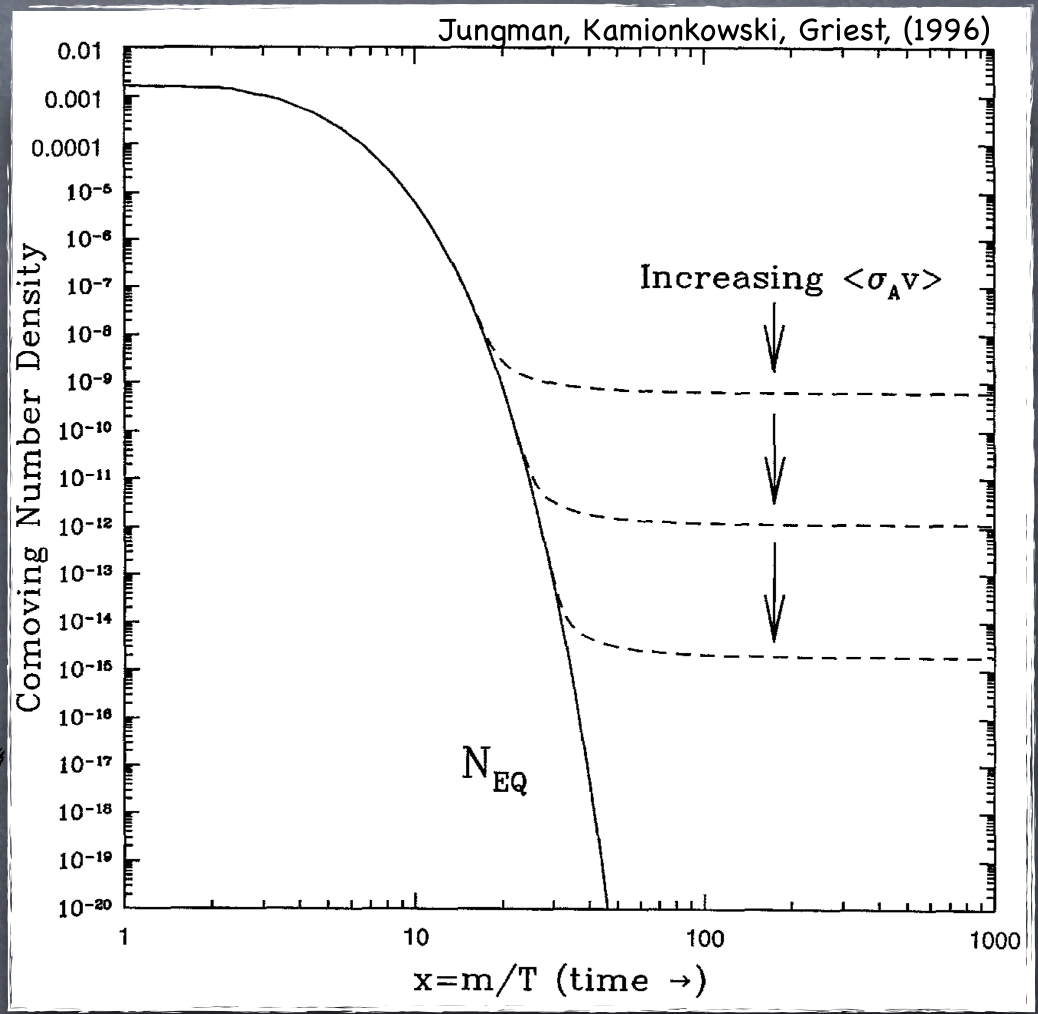
Second part of talk

Part I: Thermal history of WIMPs

Chemical decoupling

- annihilations cease at x~25 (rate $\propto n_\chi n_\chi$)
- number density "freezes out"
- sets relic abundance

$$Y = \frac{n_\chi}{s}$$

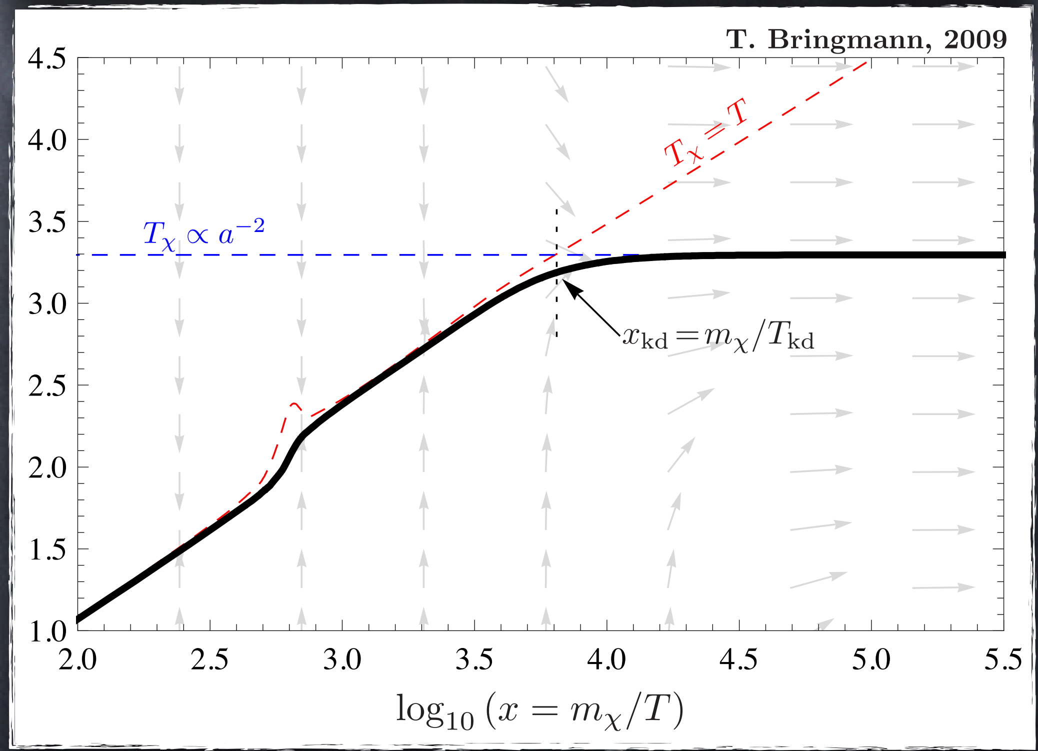


Kinetic decoupling

- scattering off heat bath particles

  ceases at x≫25 (rate $\propto n_\chi n_{SM}$)
- WIMPs cool down faster
- sets cutoff mass for smallest subhalos

$$y = \frac{m_\chi T_\chi}{s^{2/3}}$$



Interplay between chemical and kinetic decoupling

annihilation

scattering

$\langle\sigma v\rangle$ enhanced for $v \to 0$

DM velocity decreases faster after KD

DM population depleted of lowest velocity particles

relic density

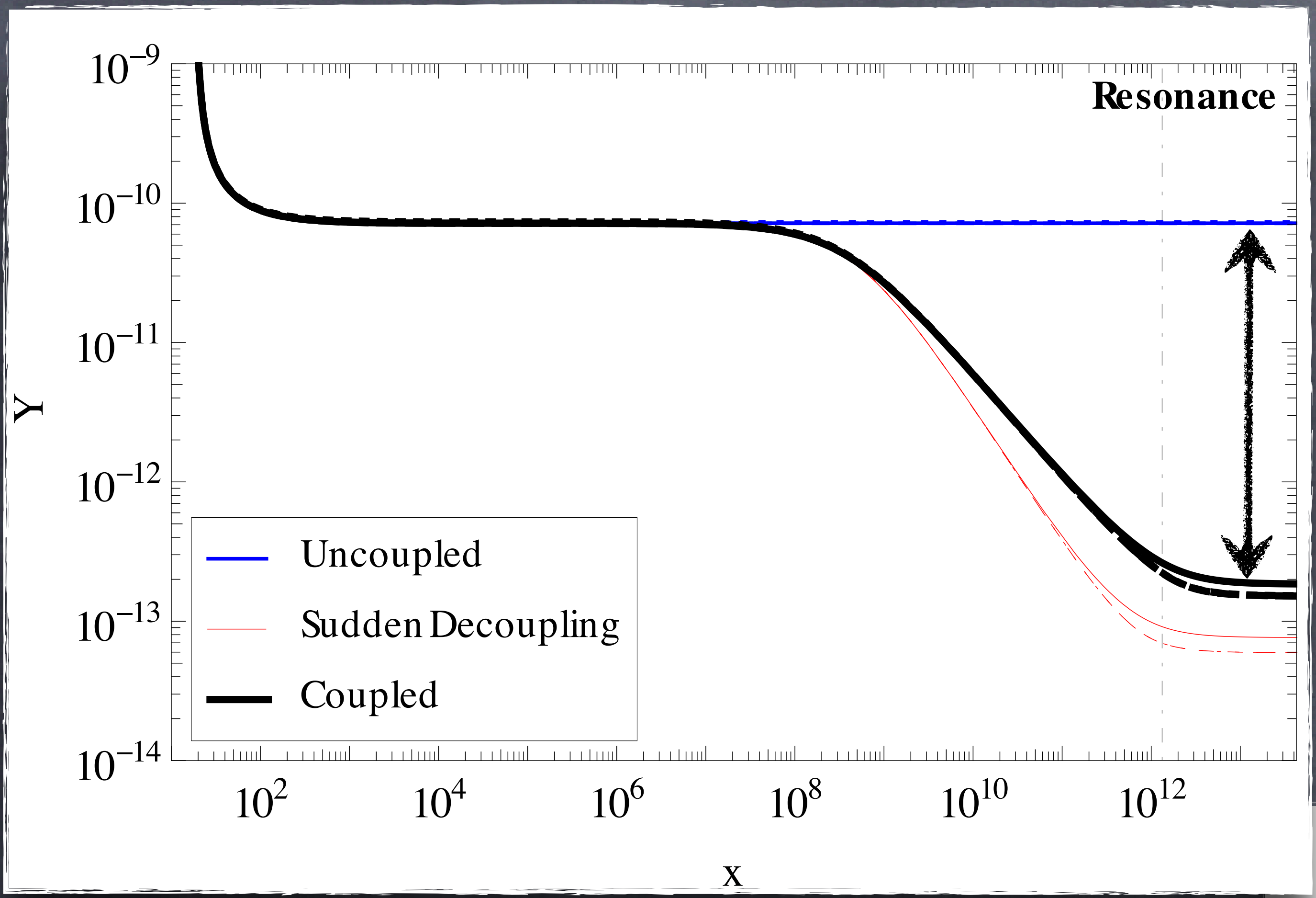
WIMP "temperature"

consistent description: set of coupled Boltzmann eq's

$$\frac{Y'}{Y} = -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx} sY \left.\langle\sigma v_{\rm rel}\rangle\right|_{x=m_\chi^2/(s^{2/3}y)} \qquad \frac{y'}{y} = -\frac{1-\frac{x}{3}\frac{g'_{*S}}{g_{*S}}}{Hx}\left[2m_\chi c(T)\left(1-\frac{y_{\rm eq}}{y}\right) - sY\Big(\langle\sigma v_{\rm rel}\rangle - \langle\sigma v_{\rm rel}\rangle_2\Big)_{x=m_\chi^2/(s^{2/3}y)}\right]$$

[arXiv:1202.5456 [hep-ph]]

New era of annihilations



here model: scalar mediator on resonance

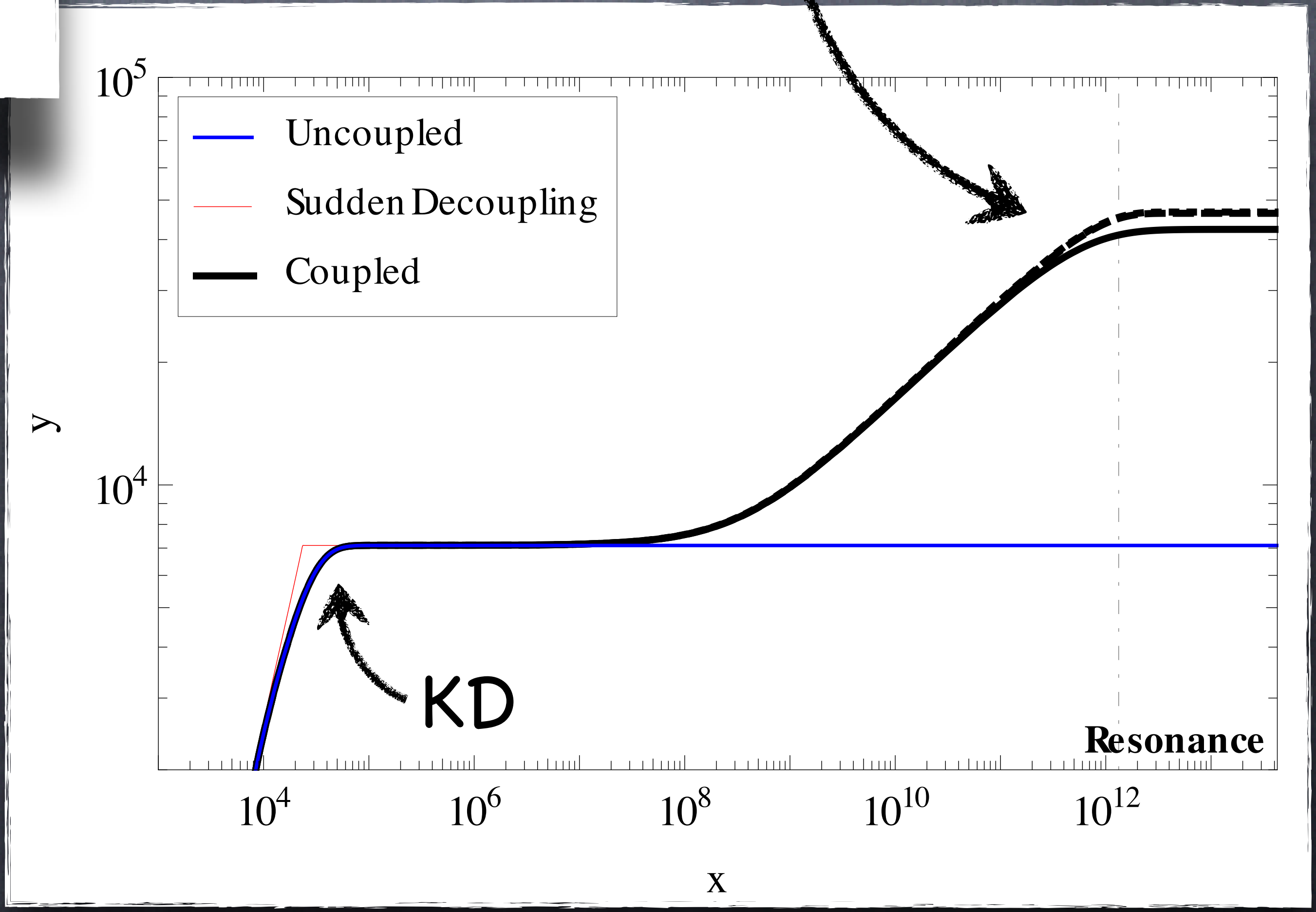
O(400)!

WIMPs finally decouple -> M_{cut}

Important:

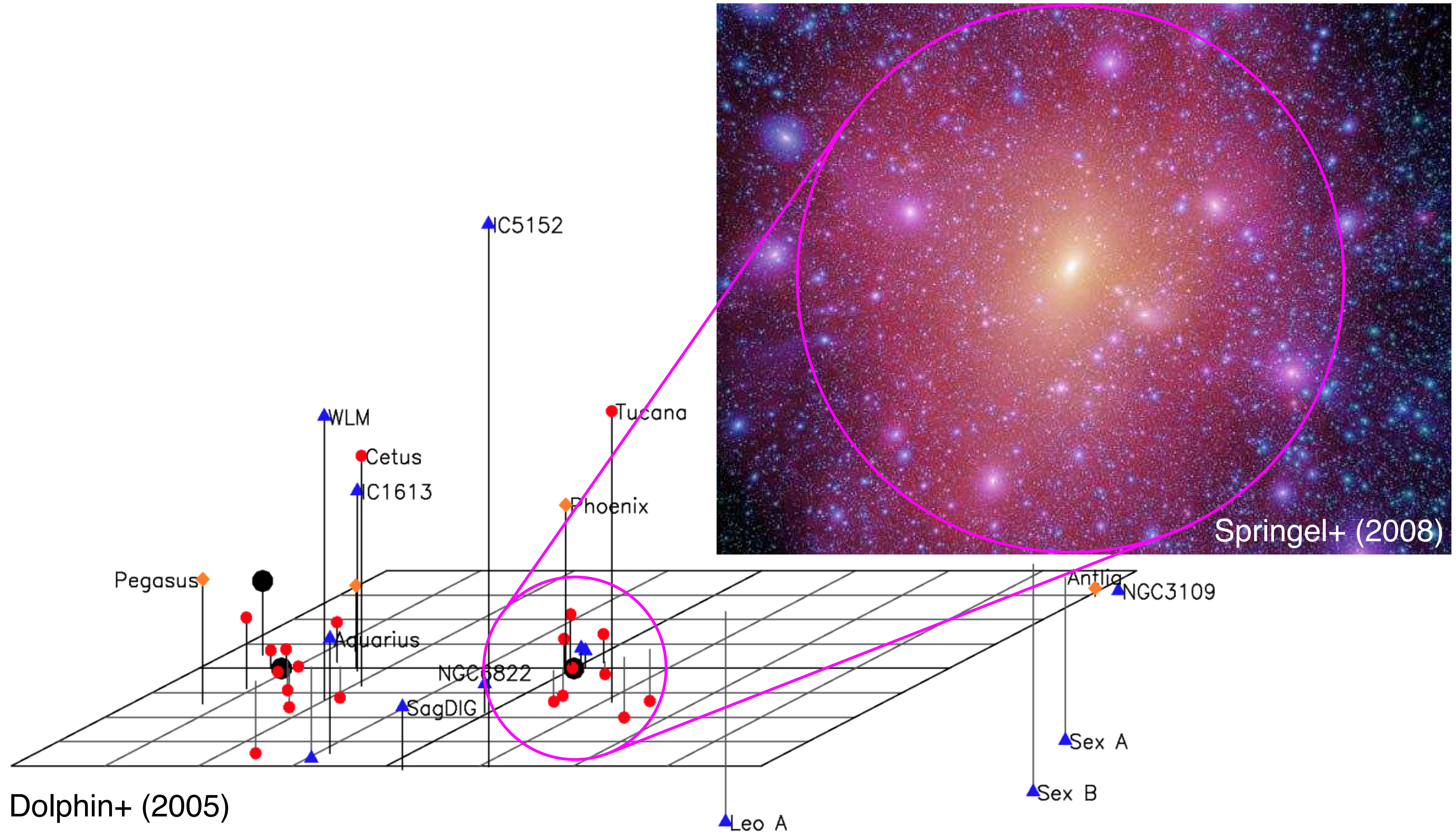
self-scattering ensures Maxwellian velocity distribution

need to check separately for every model!



Part II: Small-scale problems of ΛCDM Cosmology

"Missing satellite" problem in the Milky Way

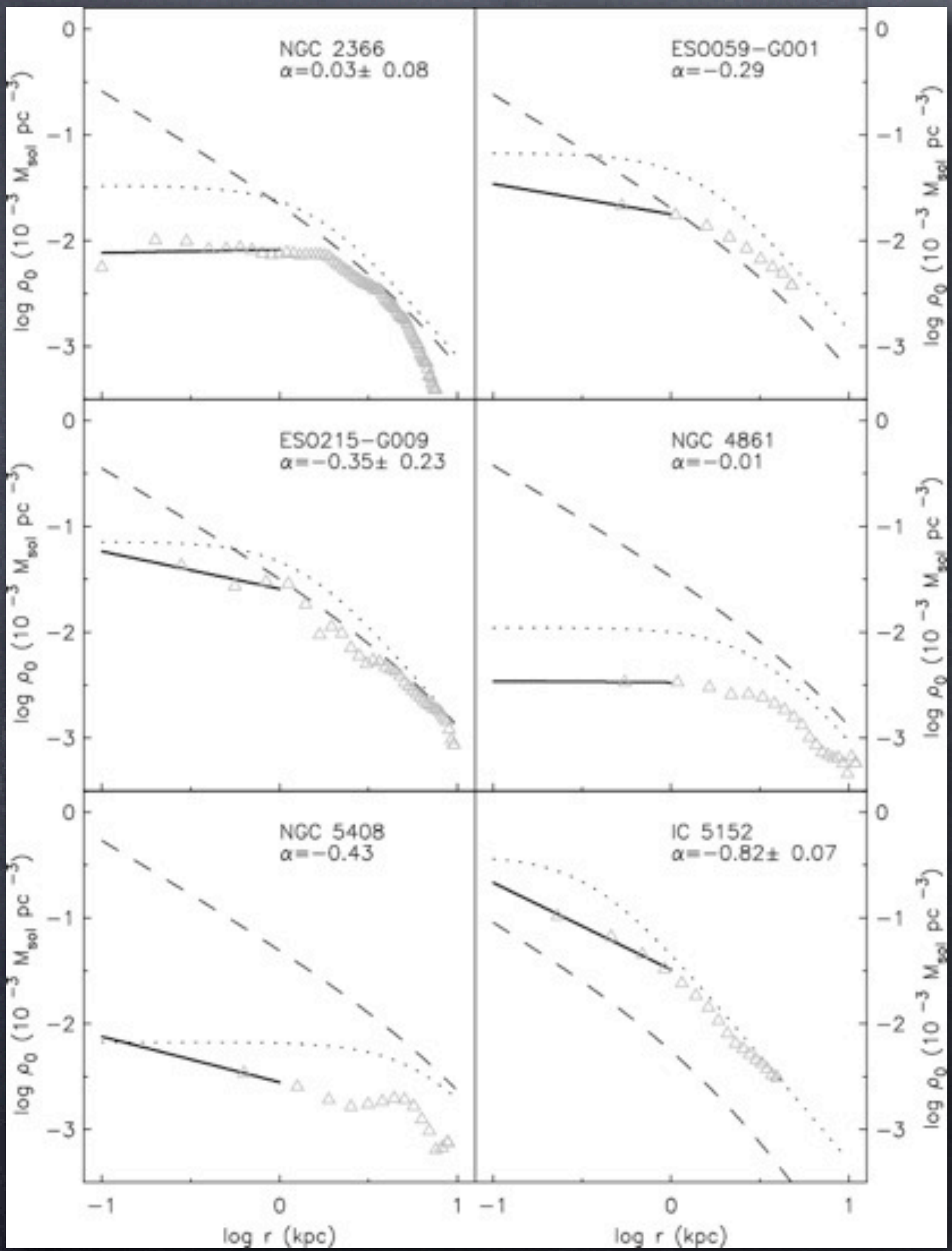


Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!

slide reproduced with permission from Christoph Pfrommer

The cusp vs. core problem

J. van Eymeren, C. Trachternach, B. S. Koribalski, R.-J. Dettmar (2009)



observations of dwarf galaxies show core-like inner structure whereas a cusp is predicted from simulations

"The density profiles of all sample galaxies derived from the observed rotation curves (open grey triangles). Their inner slopes are measured by applying a least square fit to all data points within the innermost kpc (bold black lines). The fitted values of and the uncertainties are placed into the upper right corner of each panel. Note that the rotation curves of ESO 059-G001, NGC 4861, and NGC 5408 only contain two points in the inner 1 kpc. Therefore, no uncertainties can be given. The long-dashed and dotted lines show the NFW and the ISO profiles, respectively, using the parameters of the minimum-disc case."

The "Too big to fail"-problem

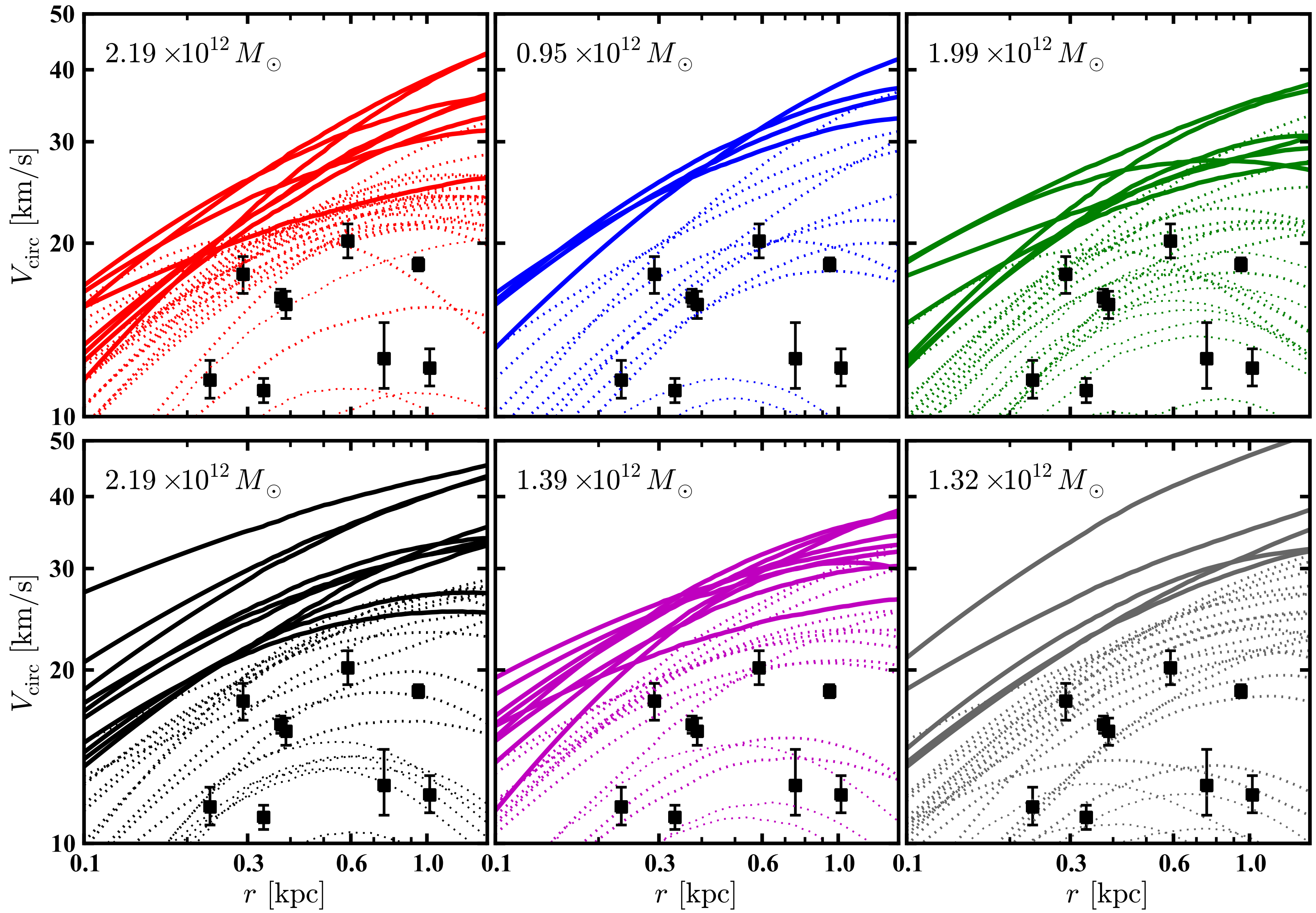


Figure 3. Rotation curves for all subhalos with $V_{infall} > 30\,km\,s^{-1}$ and $V_{max} > 10\,km\,s^{-1}$, after excluding Magellanic Cloud analogs, in each of the six Aquarius simulations (top row, from left to right: A, B, C; bottom row: D, E, F). Subhalos that are at least $2\,\sigma$ denser than every bright MW dwarf spheroidal are plotted with solid curves, while the remaining subhalos are plotted as dotted curves. Data points with errors show measured V_{circ} values for the bright MW dSphs. Not only does each halo have several subhalos that are too dense to host any of the dSphs, each halo also has several massive subhalos (nominally capable of forming stars) with V_{circ} comparable to the MW dSphs that have no bright counterpart in the MW. In total, between 7 and 22 of these massive subhalos are unaccounted for in each halo.

most massive subhalos in simulations of MW sized halos are too dense to host observed brightest satellites!

Small-scale problems of ΛCDM Cosmology

- **missing satellites:** simulations predict many more subhalos than number of galaxy satellites inferred from observed galaxy luminosities and HI mass functions

  proposed solutions: increase gas entropy before collapse, suppress cooling efficiency, photo-evaporation, supernovae feedback, WDM...

- **Cusp/Core:** observed cores of dSph and LSB galaxies in tension with cuspy internal density structure obtained by simulations.

  proposed solutions: large velocity anisotropy, baryonic feedback, IDM, vdSIDM...

- **"too big to fail":** most massive subhalos in simulations of MW sized halos too dense to host observed brightest satellites.

  proposed solutions: increased stochasticity of galaxy formation, low MW mass, (WDM), vdSIDM...

Most solutions have shortcomings or only solve 1 or 2 problems at the same time

Self-scattering in structure formation

velocity dependent Self-Interacting DM is promising:

[Loeb, Weiner (2011)], [Vogelsberger, Zavala, Loeb (2012)]

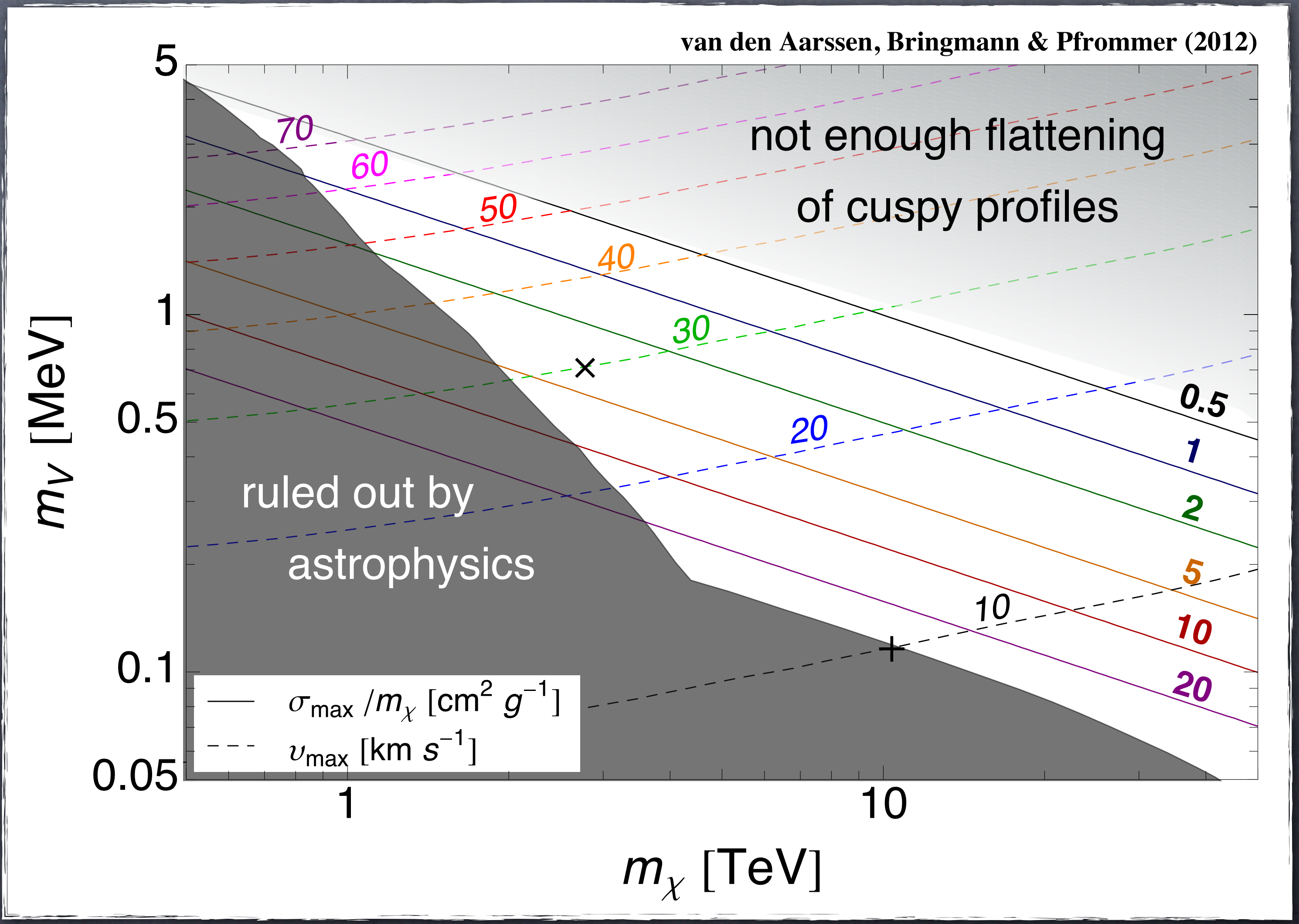
- avoids astrophysical constraints (unlike SIDM)
- produces cored subhalos without affecting inner density profiles on larger scales
- most massive subhalos are less dense and consistent with observations

2 benchmark models (σ_{max}, v_{max}) solve:

✓ cusp/core
✓ "too big to fail"

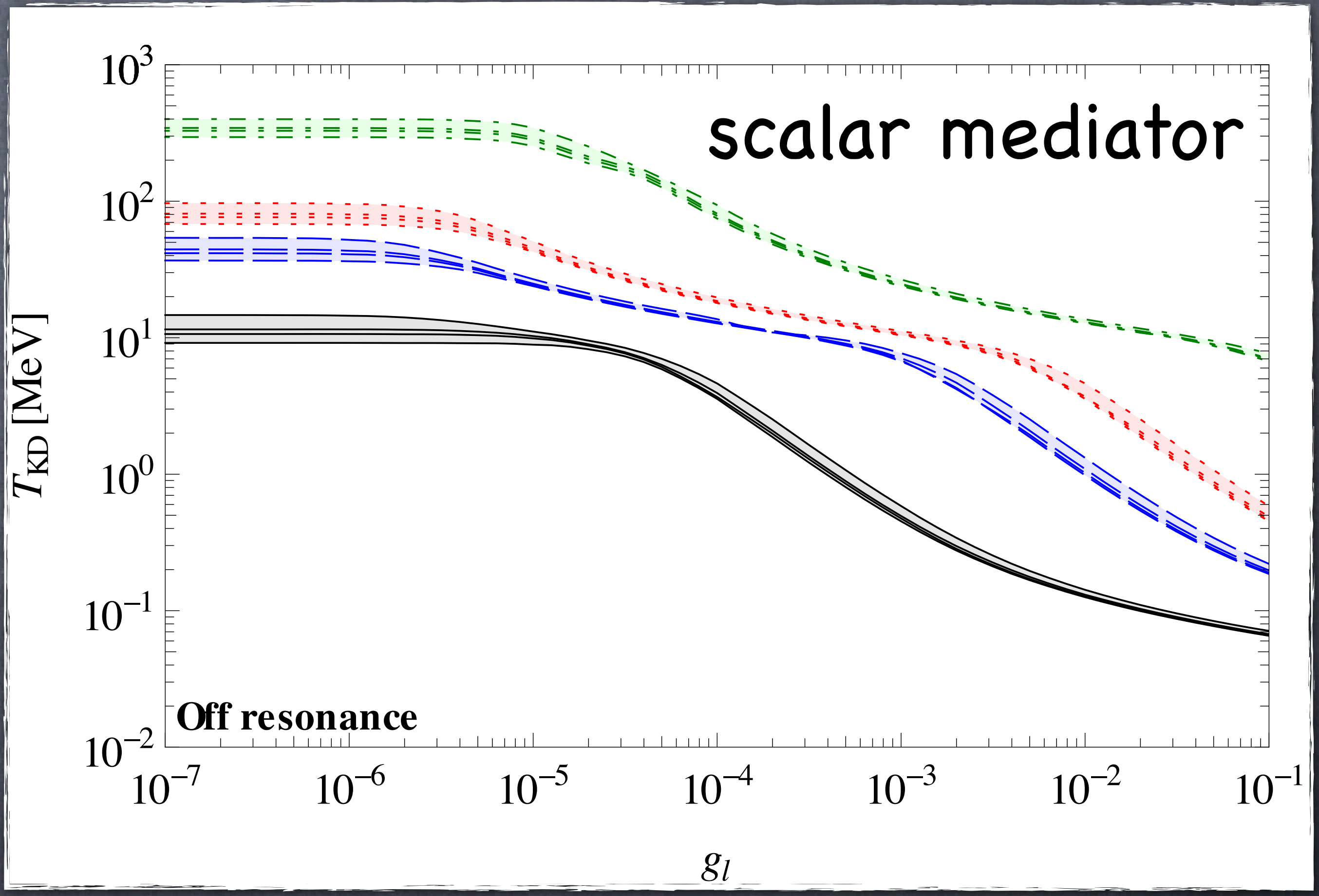
translated to (m_χ, $m_{A'}$), where V is a vector mediator

need m_χ > 600 GeV
$m_{A'}$ = O((sub) MeV)



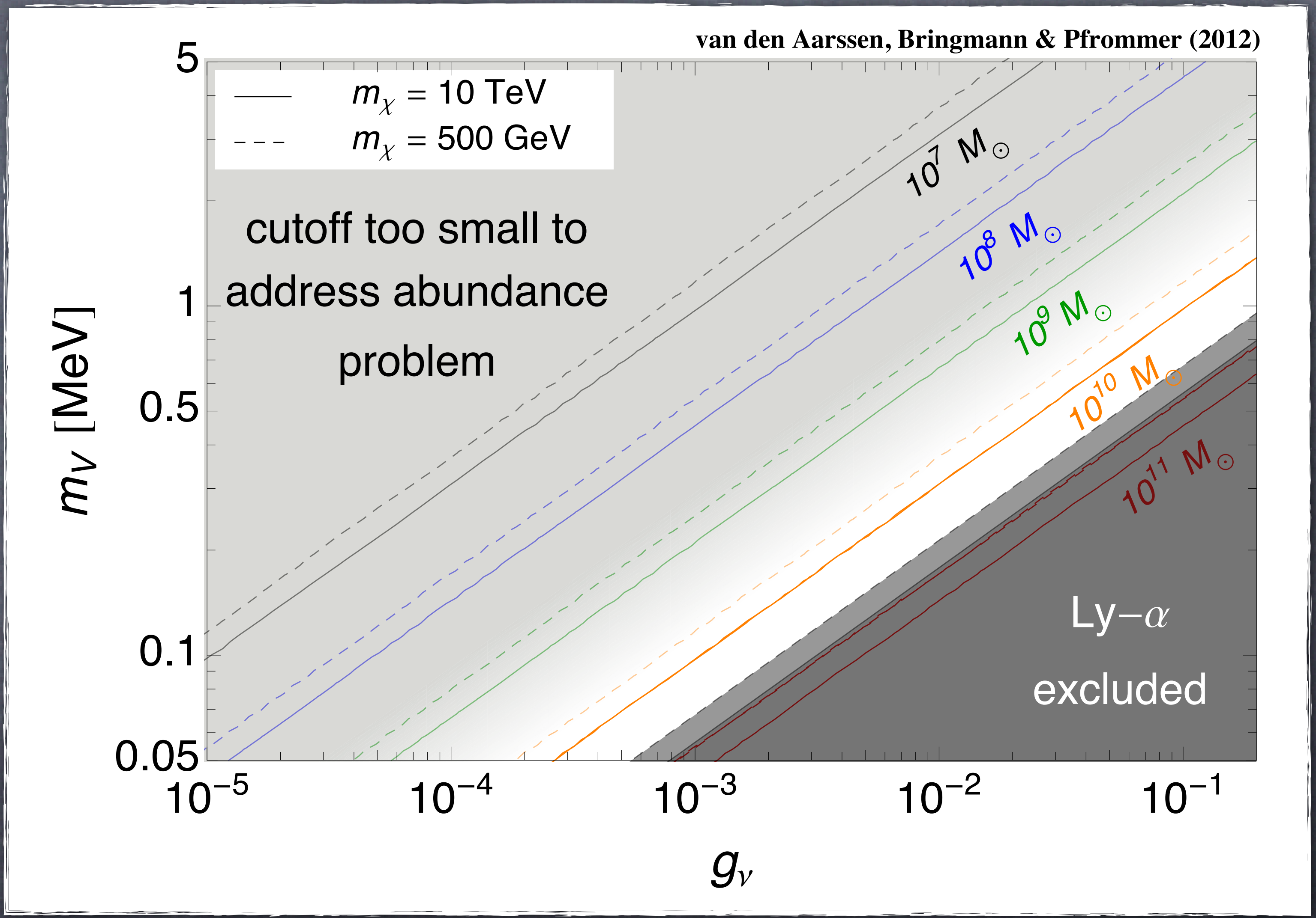
DM scattering off other particles

- freestreaming of WIMPs after kinetic decoupling creates cutoff in powerspectrum
- acoustic oscillations leads to similar cutoff
- cutoff scale is set by size of horizon at KD: late KD -> high M_{cut}
- $M_{cut} = Max(M_{fs}, M_{ao})$: only objects with $M \geqq M_{cut}$ form
- scattering for
  - scalar mediator
    - scatters off Φ, $\mu^{\pm}$ and $e^{\pm}$
    - Saturation of $T_{KD} \sim 0{,}1$ MeV
    - ν's negligible: $|M_{\Phi\nu \to \Phi\nu}|^2 \propto m_\nu^2$
  - vector mediator:
    - ν's contribute: $|M_{V\nu \to V\nu}|^2 \propto E_\nu^2$
    - T_{KD} can decrease to O(keV)!



Missing satellites and the cutoff mass

- DM with vector mediator scattering off neutrino's: very late decoupling -> high M_{cut}
- Lyman-α bounds: $M_{cut} < 5.1 \times 10^{10} M_{\odot}$ ($m_{wdm} > 1$ keV)
- M_{cut} that can solve missing satellite problem inferred from N-body simulations with WDM



✓ possibly solves also missing satellites problem!

[arXiv:1205.5809 [astro-ph.CO]]

More simulations and model building needed to confirm.

Conclusions

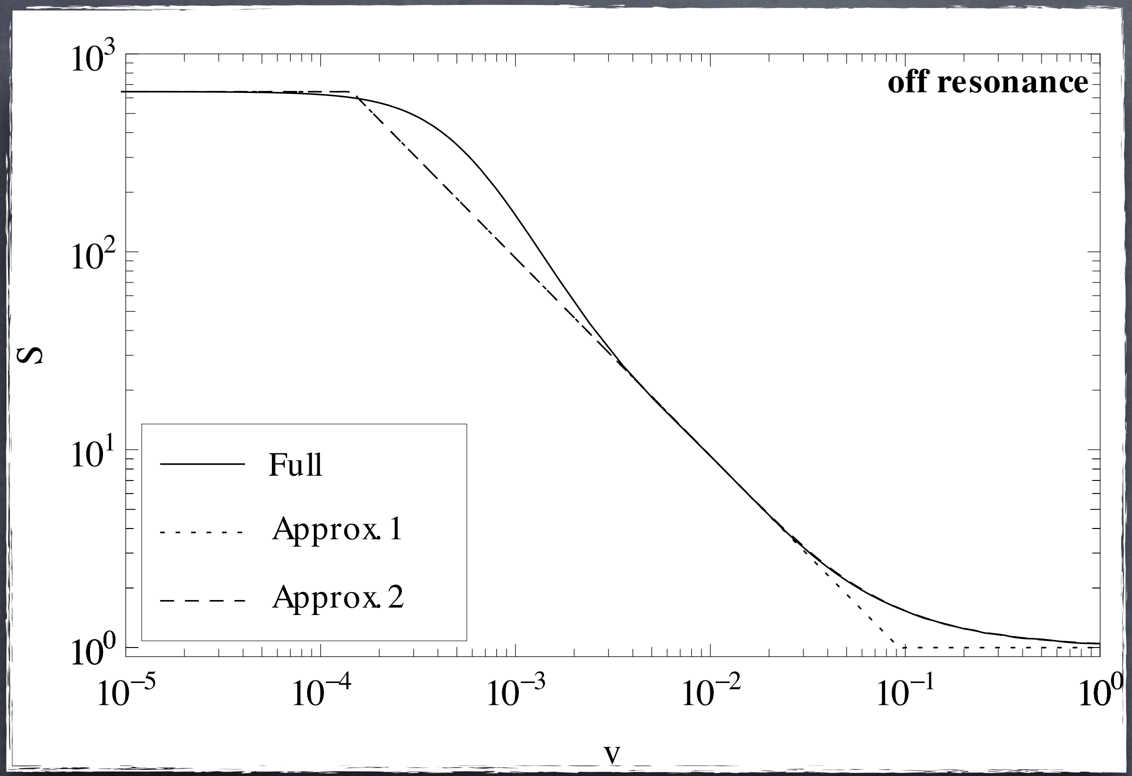
- First consistent framework to describe interplay between chemical and kinetic decoupling
  - possibility of new era of annihilations
- Small-scale problems of ΛCDM Cosmology can be solved by a DM model with:
  - velocity-dependent self-interactions mediated by (sub)MeV vector mediator
  - much later kinetic decoupling than in standard case follows naturally for vector mediator coupling to neutrinos

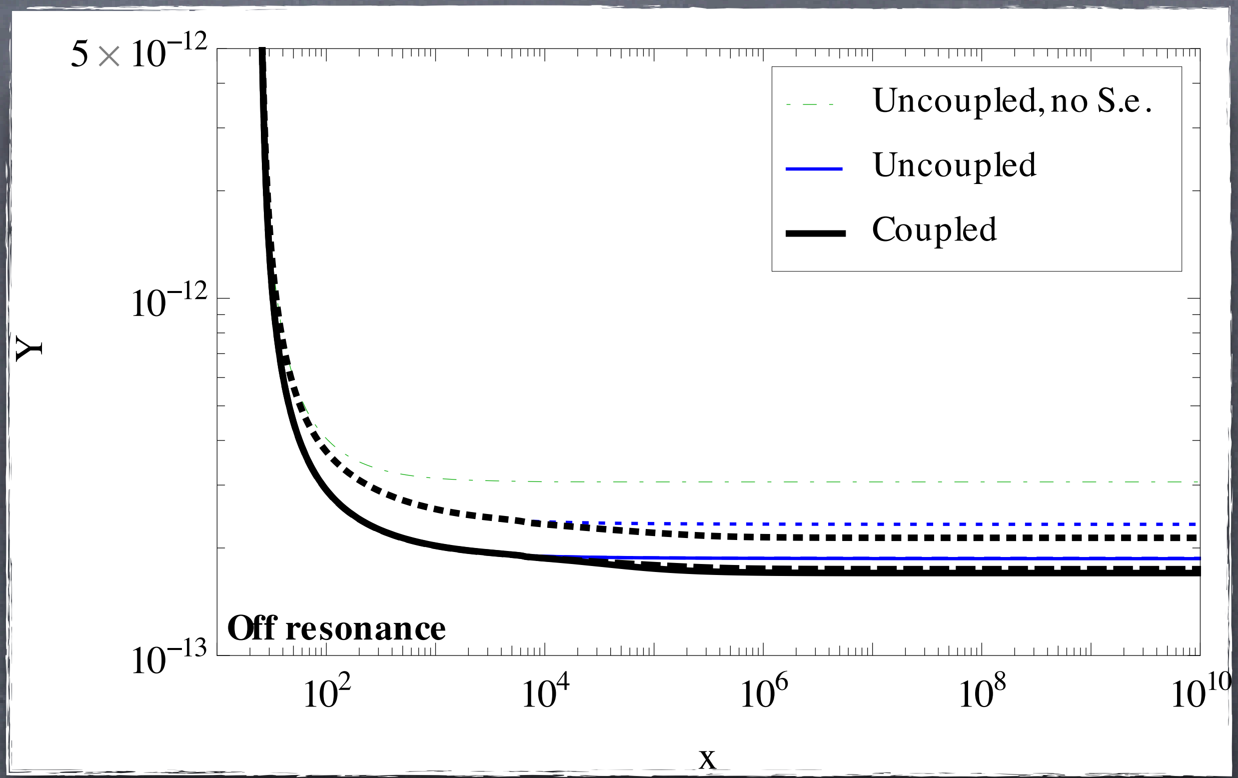
Need further model building and simulations to confirm.

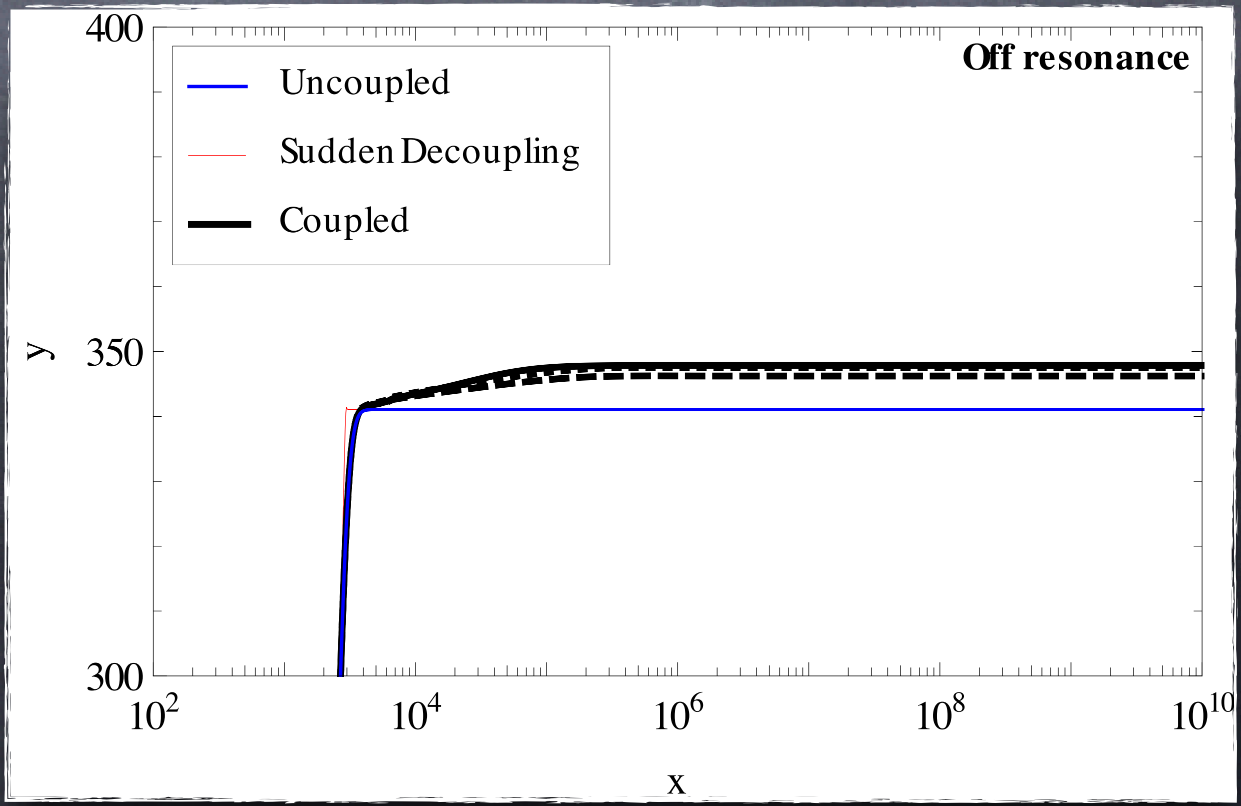
Thank you for your attention!

Backup Slides

off resonance: S~1/v



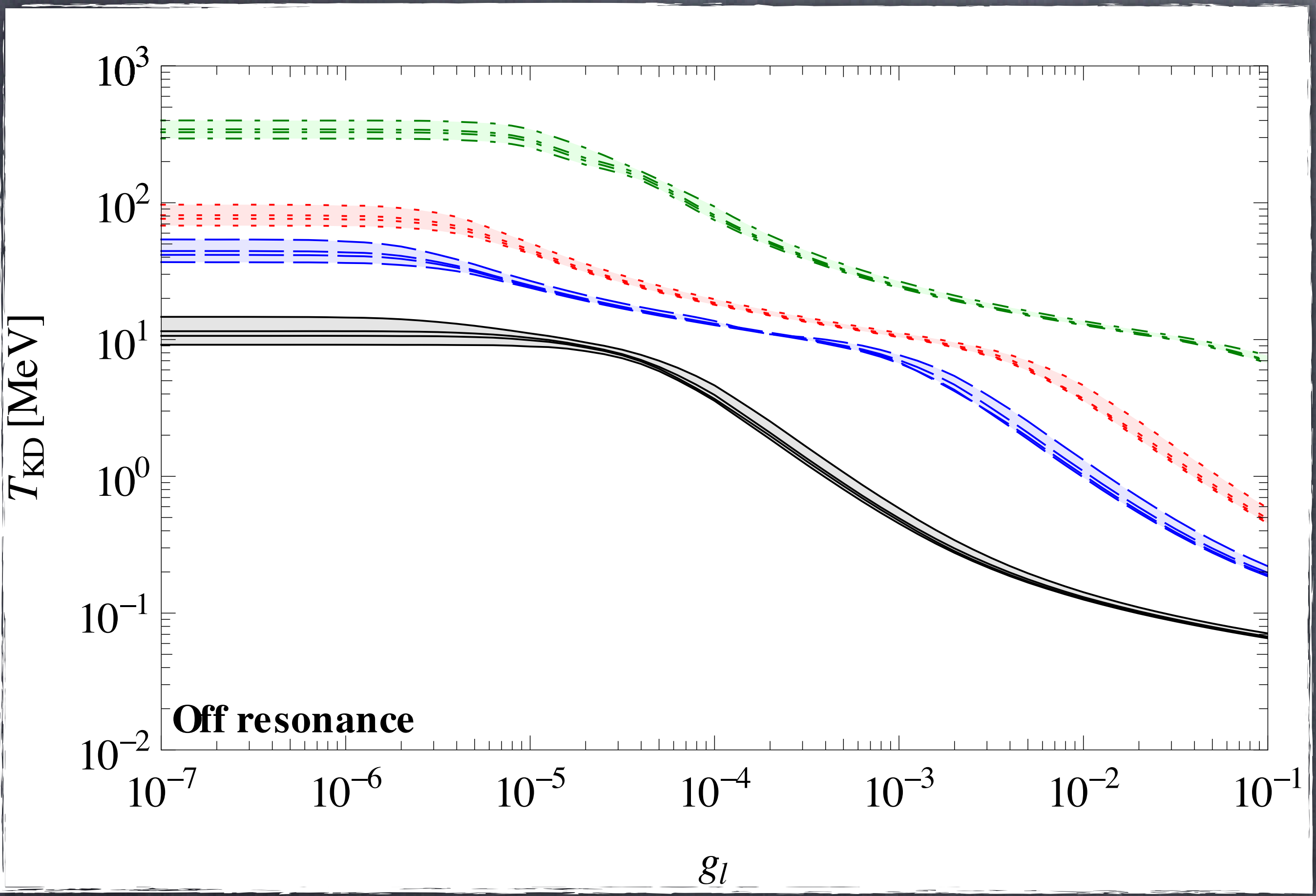


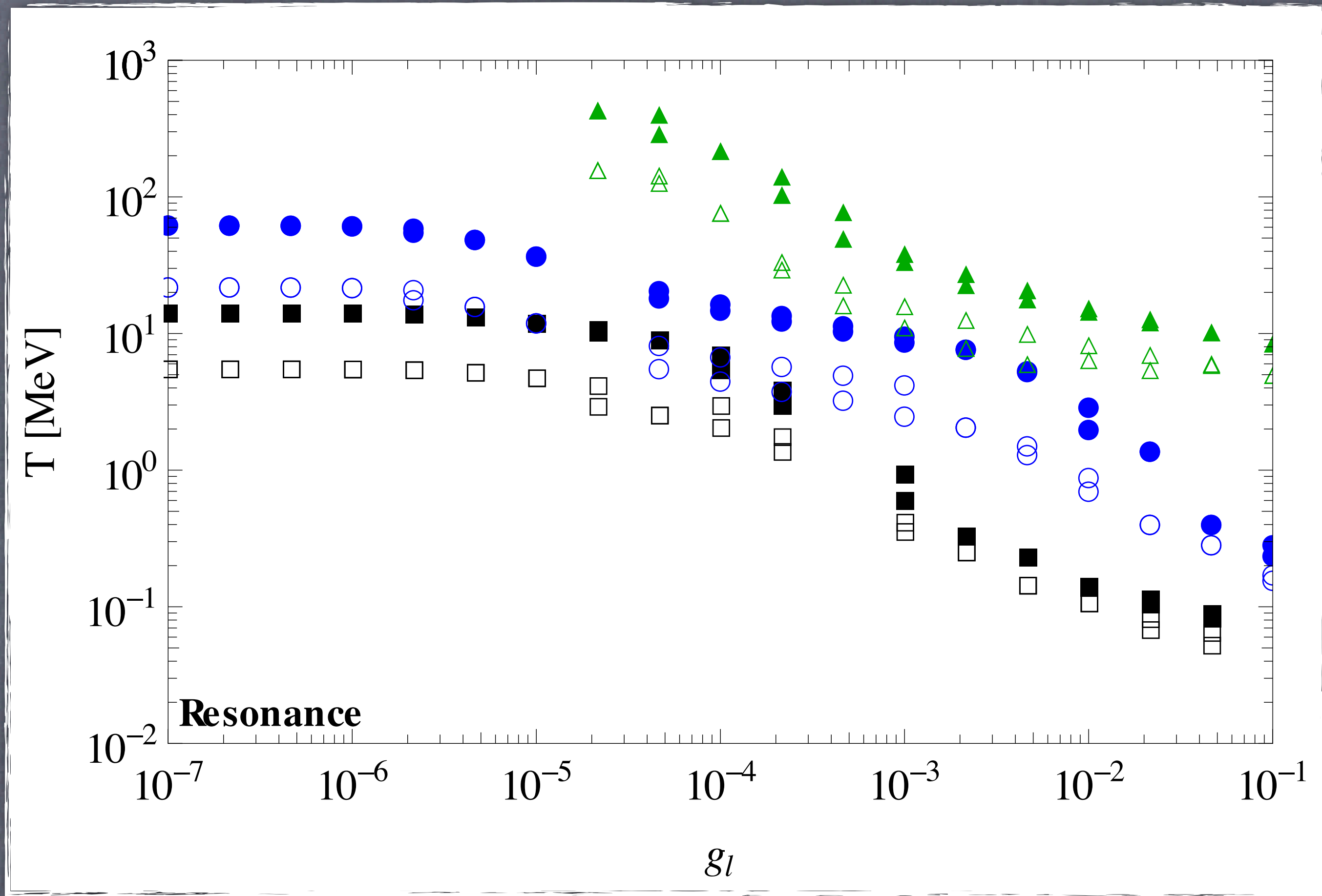


Kinetic decoupling temperature

off resonance

resonance





bottom to top:

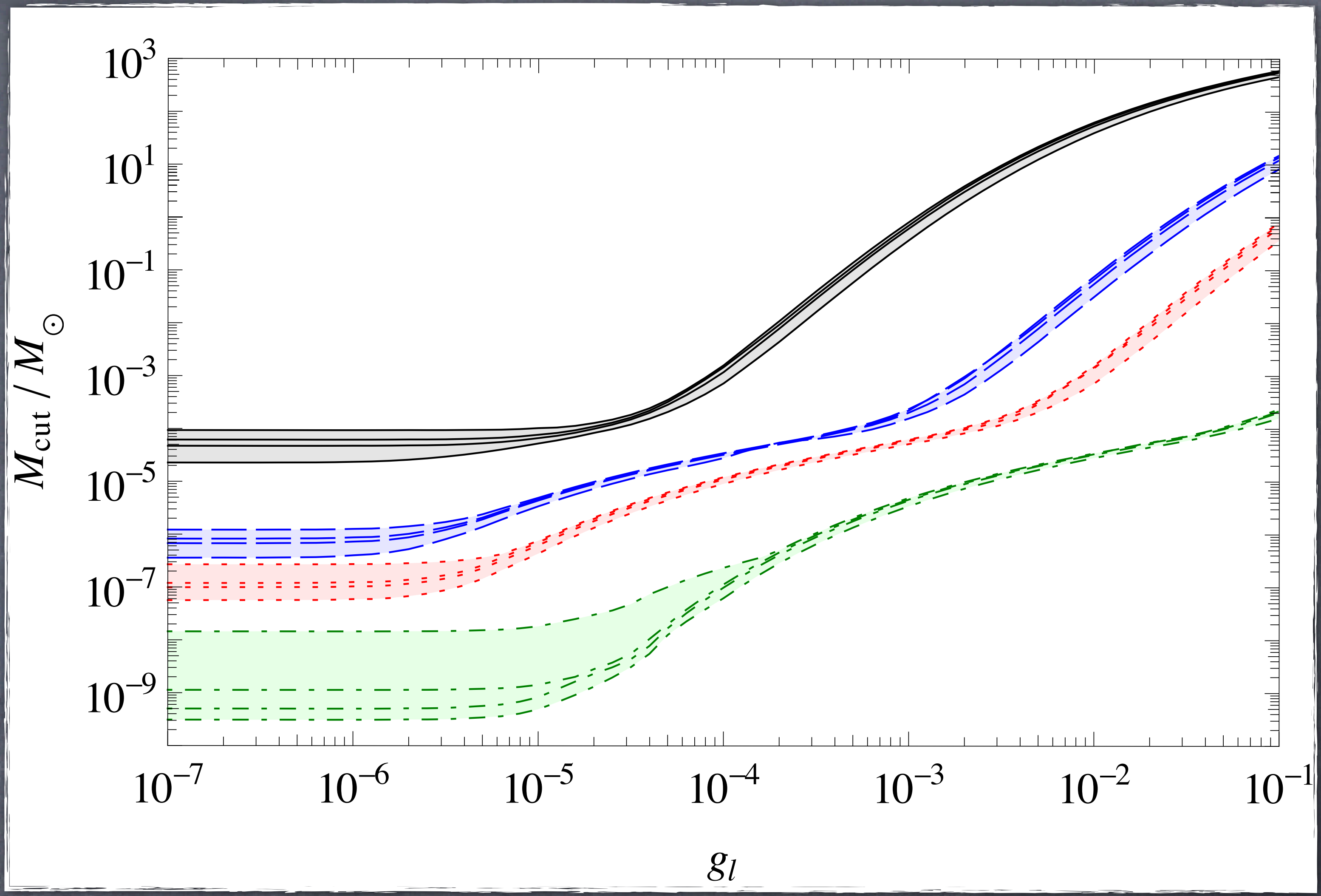
m_χ = 100 GeV
500 GeV
1 TeV
5 TeV

m_Φ = 100 MeV
500 MeV
1 GeV
5 GeV

Smallest DM protohalos

m_ϕ = 100 MeV
500 MeV
1 GeV
5 GeV

top to bottom:
m_χ = 100 GeV
500 GeV
1 TeV
5 TeV



off resonance: $M_{cut}/M_\odot \sim 3 \times 10^{-10} - 600$

resonance: $M_{cut}/M_\odot \sim 7 \times 10^{-9} - 1100$

The smallest protohaloes

Free streaming of WIMPs after kinetic decoupling

- washes out density fluctuations on small scales (like baryonic oscillations)
- translates to mass-scale $M_{\rm cut}$ of smallest gravitationally bound objects
- depends strongly on particle physics $\Rightarrow$ not necessarily $M_{\rm cut} \sim 10^{-6} M_\odot$!