**Discoveries and Open Puzzles in Particle Physics and Gravitation**

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# Variants of self-interacting dark matter

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*(HEPHY, Vienna)*

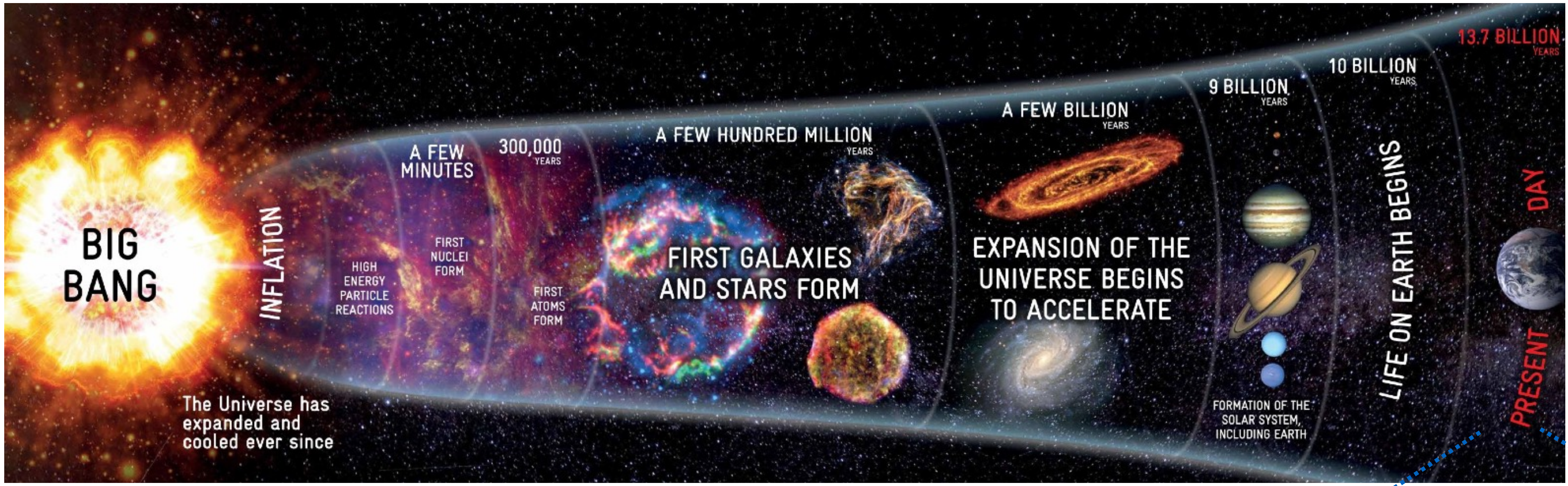
In collaboration with Camilo Garcia-Cely, Hitoshi Murayama

—1803.09762(JCAP), 1810.04709(PRL)

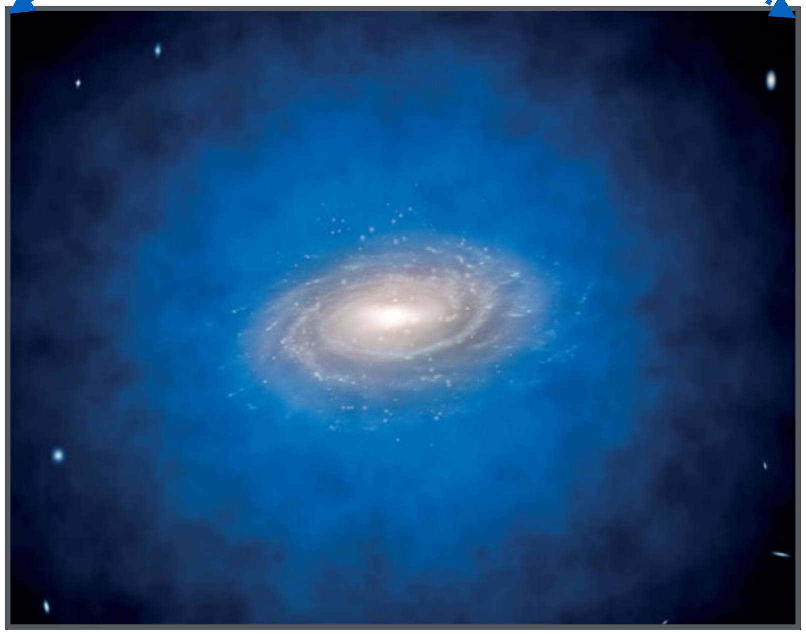
ÖAW ÖSTERREICHISCHE AKADEMIE DER WISSENSCHAFTEN

HEPHY Institut für Hochenergiephysik

# **Standard Cosmology** is well established.



*kpc - Mpc*

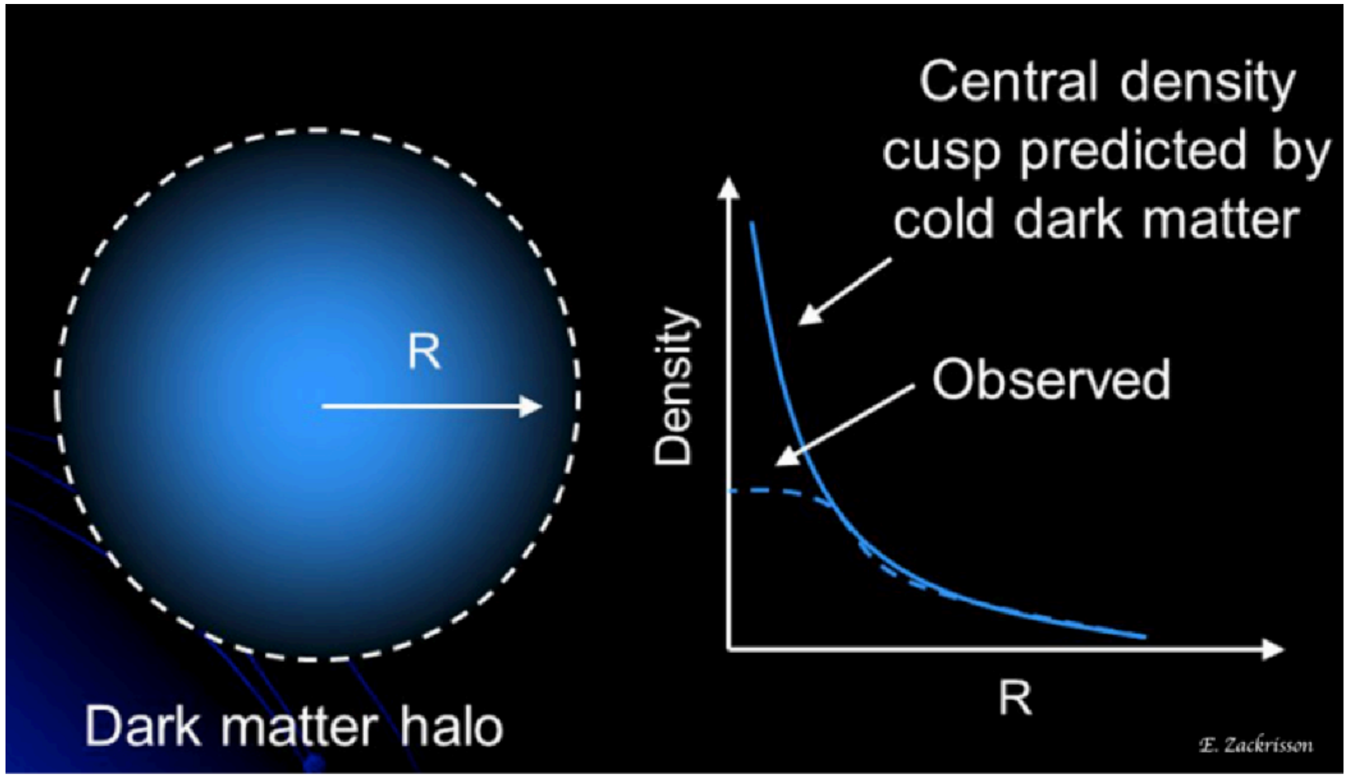


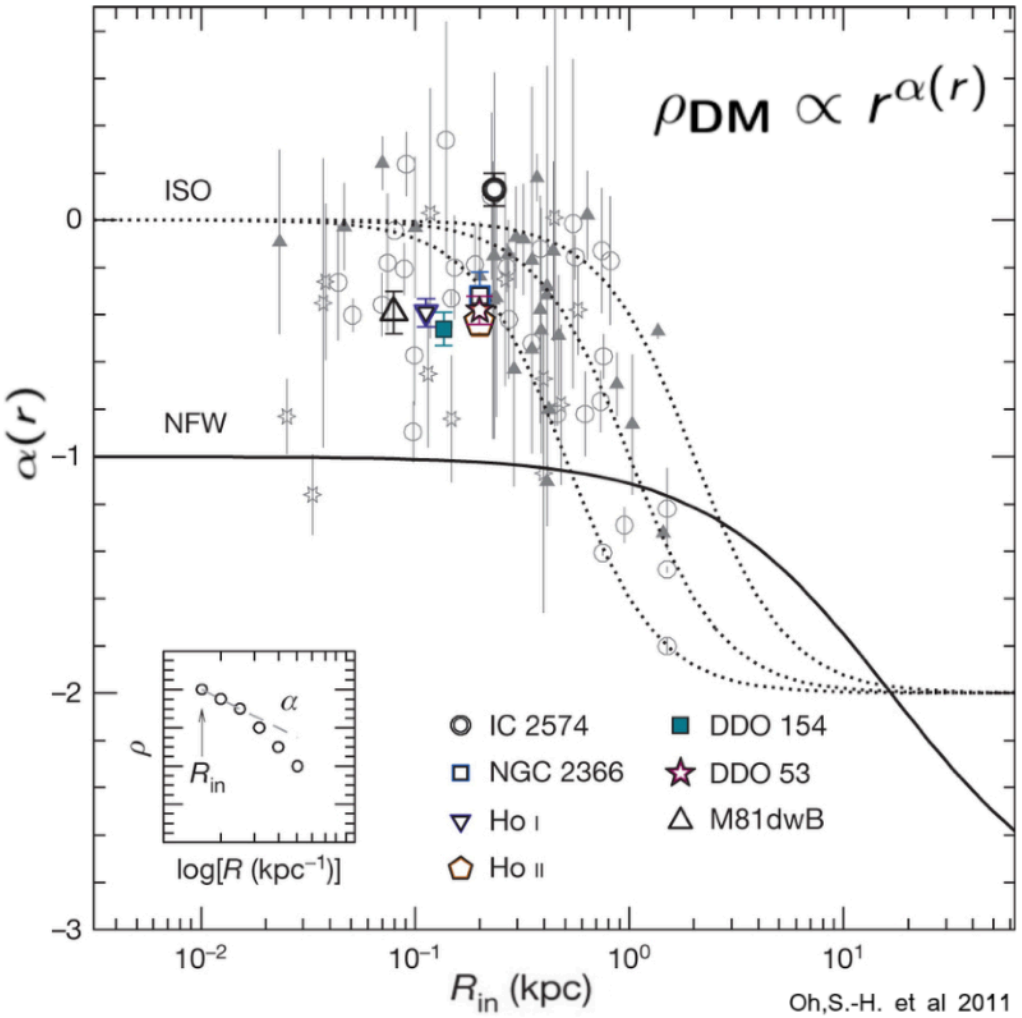
Yet, there are still astrophysical **puzzles** at scales below cluster sizes. One of them is:

**Mass deficit** in small dark matter halos.

# Dark matter (satellite) halo **mass deficit?**

1. **Dark matter cores** of kpc size are preferred by observed circular velocities in dwarf/low-surface-brightness (LSB) galaxies, while simulations suggest cusps [Moore 1994; Burkert 1995, …].





Oh,S.-H. et al 2011

# Dark matter (satellite) halo mass deficit?

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**(core/cusp problem)**

2. **Non-observation of very massive satellite halos** predicted by simulations in our Milky Way [M.Boylan-Kolchin et al. 2011, 2012] and others [Ferrero et al. 2011].

**(too-big-to-fail problem)**

3. Given the long lifetime of dwarfs, some globular/star clusters are expected to be destroyed, or sink to the center **if their host halos are cuspy** [J. Binney & S.Tremaine 2008, F. Contenta et al. 2017, P. Boldrini et al. 2018, …].

**(GC timing problem)**

# A simple picture

# **More heat/entropy** needed in halo centre (if confirmed)

Heat needed to make a kpc dark core: $10^{53} - 10^{55}$ erg

- Baryonic effects? heated by supernova / in-falling clumps.

  Each supernova deposits $\sim 10^{51}$ erg in interstellar medium *[e.g. Madau, Shen, Governato 2014, …]*

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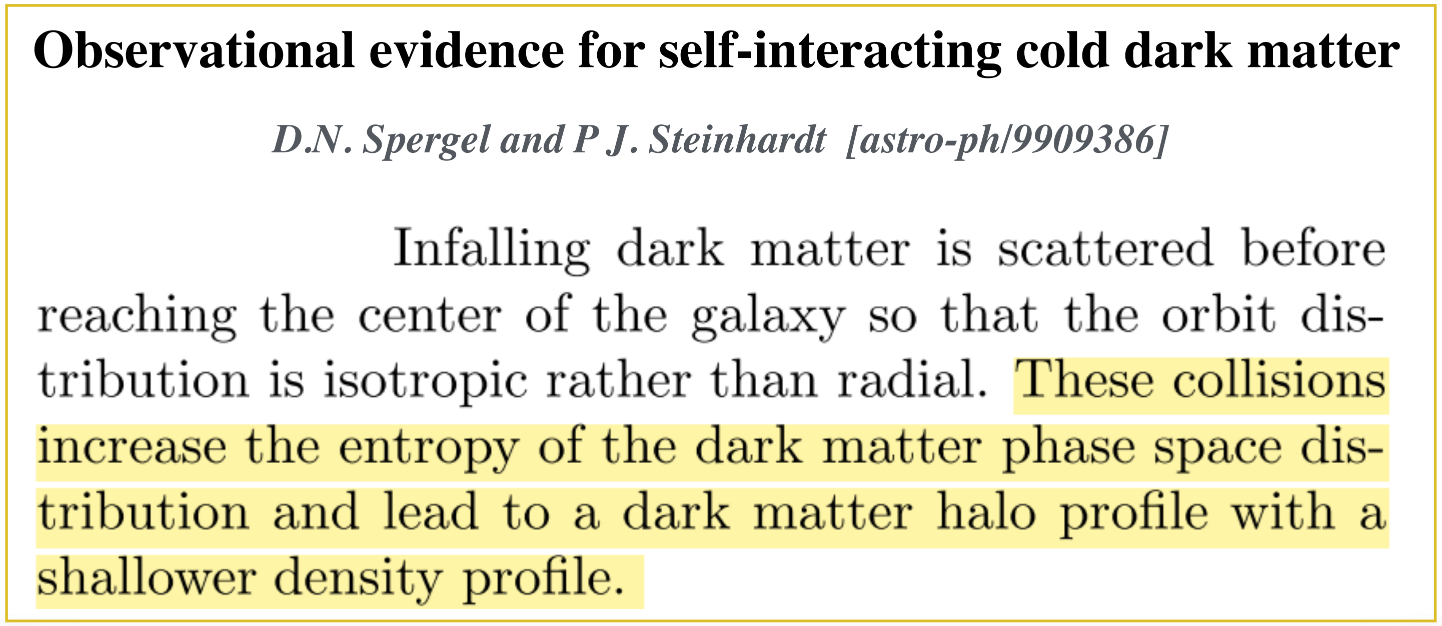
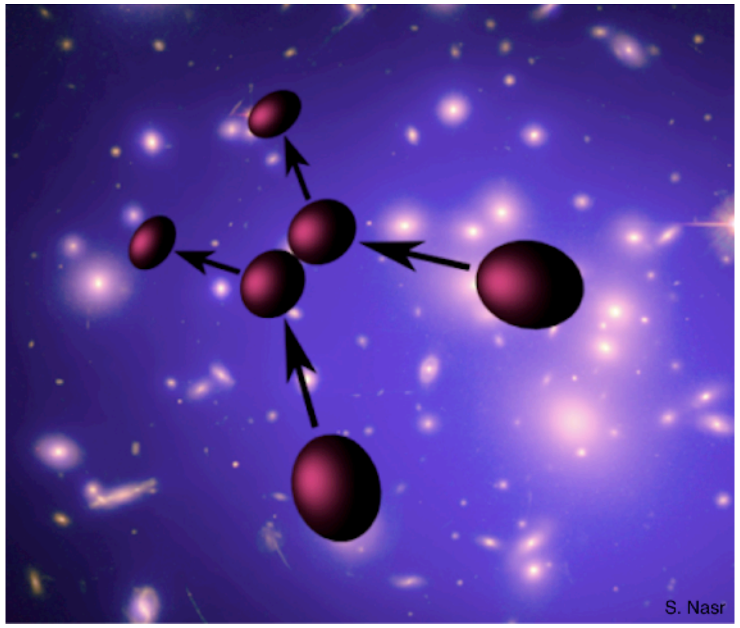
- Self-interacting dark matter? (also decaying / fuzzy dark matter, ….)



**Observational evidence for self-interacting cold dark matter**

*D.N. Spergel and P J. Steinhardt [astro-ph/9909386]*

Infalling dark matter is scattered before reaching the center of the galaxy so that the orbit distribution is isotropic rather than radial. These collisions increase the entropy of the dark matter phase space distribution and lead to a dark matter halo profile with a shallower density profile.



O(1) scattering per (central) particle → $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim 0.5 - 10 {\rm cm}^2/{\rm g}$

# A more complicated picture

# Self-interacting dark matter (SIDM)?

- Stronger self-scattering **needed** for (dwarf-sized) halos

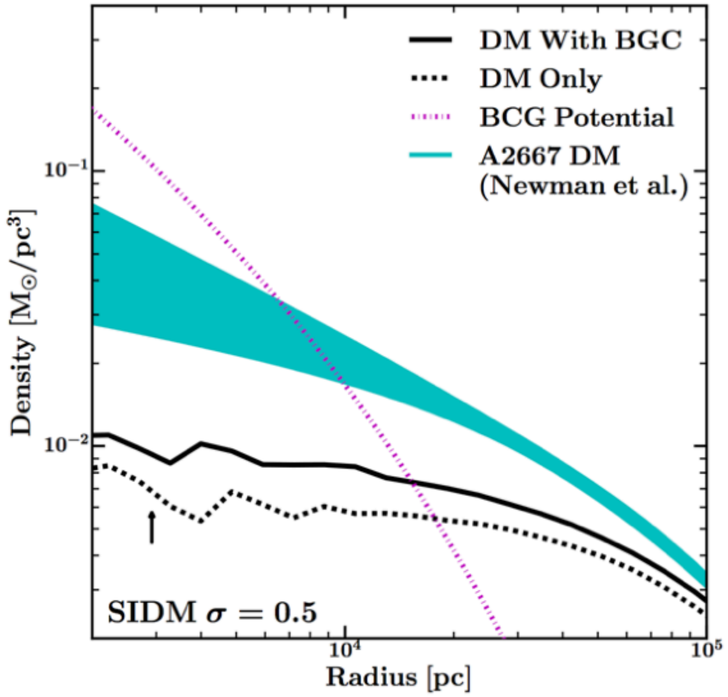
[O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

😄 $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \sim 0.5 - 10 {\rm cm}^2/{\rm g}$ at dwarf scales of DM velocity ~ 10 km/s

- Weaker self-scattering **favored** by cluster merging/halo profiles etc.

[O. D. Elbert et al. 2016, K. Bondarenko 2016,….]

😭 $\frac{\sigma_{\rm SI}}{m_{\rm DM}} \leq 0.2 - 1 {\rm cm}^2/{\rm g}$ at cluster scales of DM velocity ~ 1000km/s



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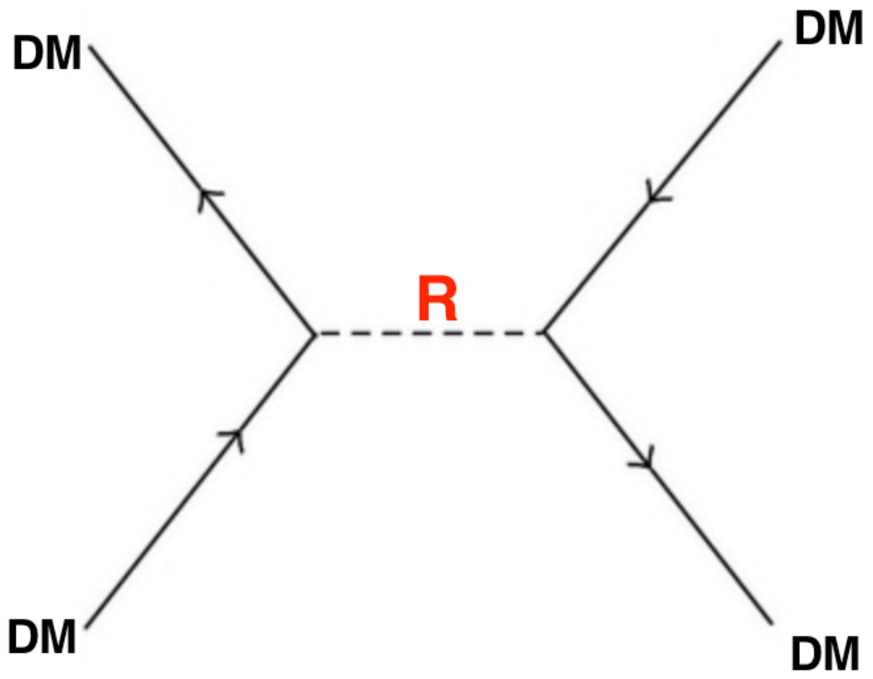
↓

**A velocity-dependence in DM self-scattering?**

Popular choice: a light mediator [Spergel&Steinhardt 1999, N. Arkani-Hamed, et al. 2018, J. Feng et al 2009, …]

# 1. SIDM via a resonance

[XC, C. Garcia-Cely, H. Murayama, 1810.04709]



$$\text{If } v_R^2 \equiv \frac{m_R - 2m_{\rm DM}}{m_{\rm DM}} \ll 1$$

An enhancement
&
**a velocity-dependence**

$$\sigma \; = \; \sigma_0 + \frac{4\pi\, S}{m E(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}$$

t/u - channel

$$E(v) = \frac{1}{2}\frac{m}{2}v^2 \qquad \text{and} \qquad S = \frac{2J_R + 1}{(2J_{\rm DM} + 1)^2}$$

$$\Gamma(v) = m_R \gamma v^{2L+1}$$

L — partial wave

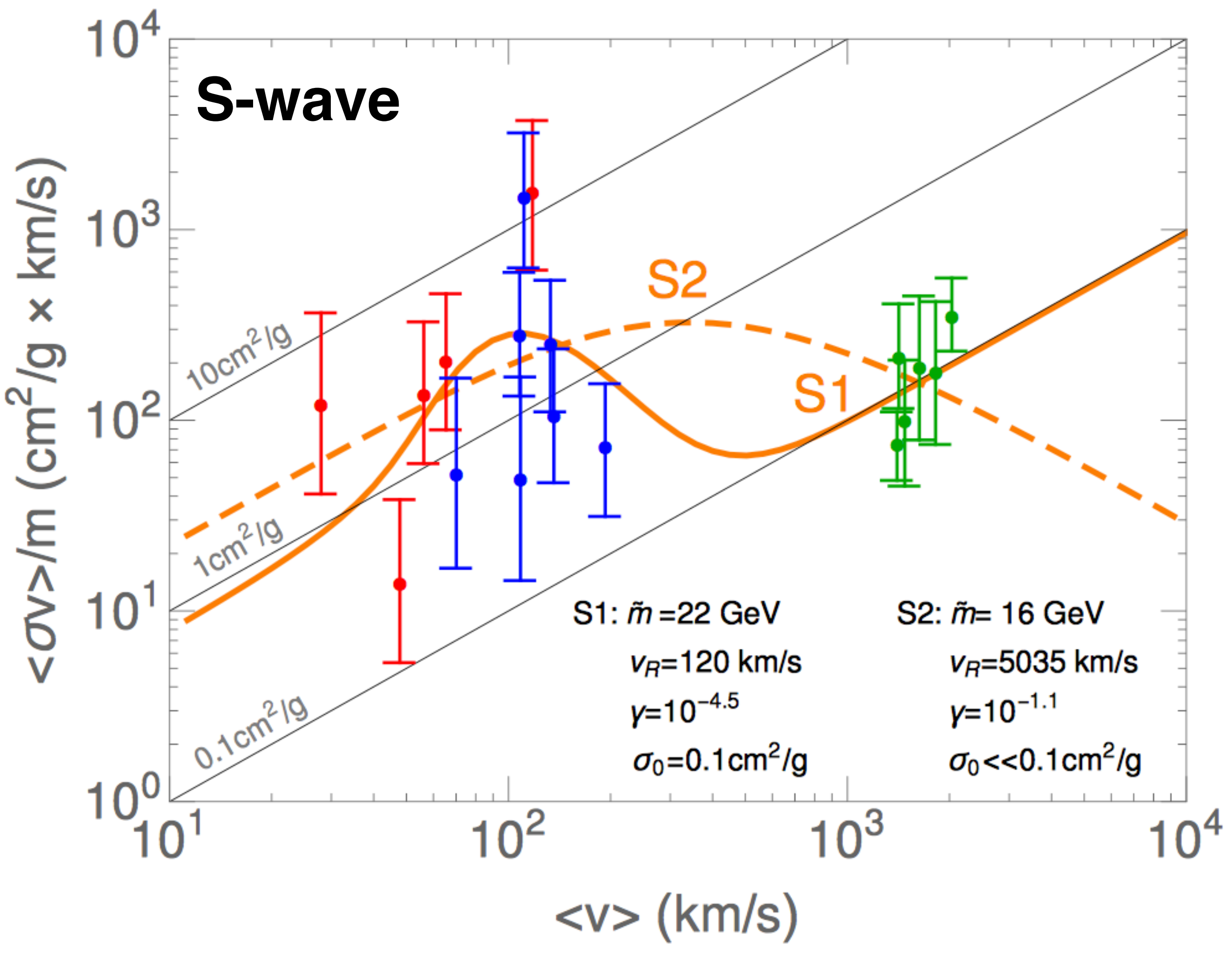
$\gamma$ — couplings

$v_R$ — **near resonance**

# 1. SIDM via a resonance [XC, C. Garcia-Cely, H. Murayama, 1810.04709]

$$\sigma = \sigma_0 + \frac{4\pi\, S}{mE(v)} \cdot \frac{\Gamma(v)^2/4}{(E(v) - E(v_R))^2 + \Gamma(v)^2/4}$$

Integrate the scattering cross section over the DM velocity Gaussian distribution:



Data points from [M. Kaplinghat, S. Tulin, and H.-B. Yu 1508.03339]

**Fine-Tuning?**

- S1: narrow-width:

$$1/10^6$$

- S2: broad-width:

$$1/10^2$$

# 2. DM self-heating mechanism

[XC, C. Garcia-Cely 1803.09762]

Semi-annihilation $\mathrm{DM} + \mathrm{DM} \to \mathrm{DM} + \phi_{\mathrm{light}}$

kinetic energy gain: $\delta E$~ DM mass

**A fraction of its kinetic energy,** $\xi \cdot \delta E$, per process is absorbed by the halo via self-scattering

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

Such semi-annihilation increases **the halo entropy** with a rate

$$ds \equiv \frac{dU}{T} \simeq \frac{\xi}{v_{\mathrm{DM}}^2} \times \underline{(n_{\mathrm{DM}}^2 \sigma_{\mathrm{semi}} v)}$$

$T \simeq m_{\mathrm{DM}} v_{\mathrm{DM}}^2$

$\sim 10^{-6}$ annihilation per particle

(enhanced) velocity-dependence $\sim 10^6$

# 2. DM self-heating mechanism [XC, C. Garcia-Cely 1803.09762]

The halo is modelled numerically as a spherical **gravo-thermal fluid with some simplifications** [following K.-J. Ahn & P. R. Shapiro, 2005]

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = -\frac{\rho^2}{m}\langle \sigma v_{\rm semi} \rangle \,,$$

(density)

$$\rho \left( \frac{\partial \mathbf{V}}{\partial t} + (\nabla \mathbf{V} \cdot \nabla)\mathbf{V} \right) = -\rho \nabla \Phi - \nabla p \,,$$

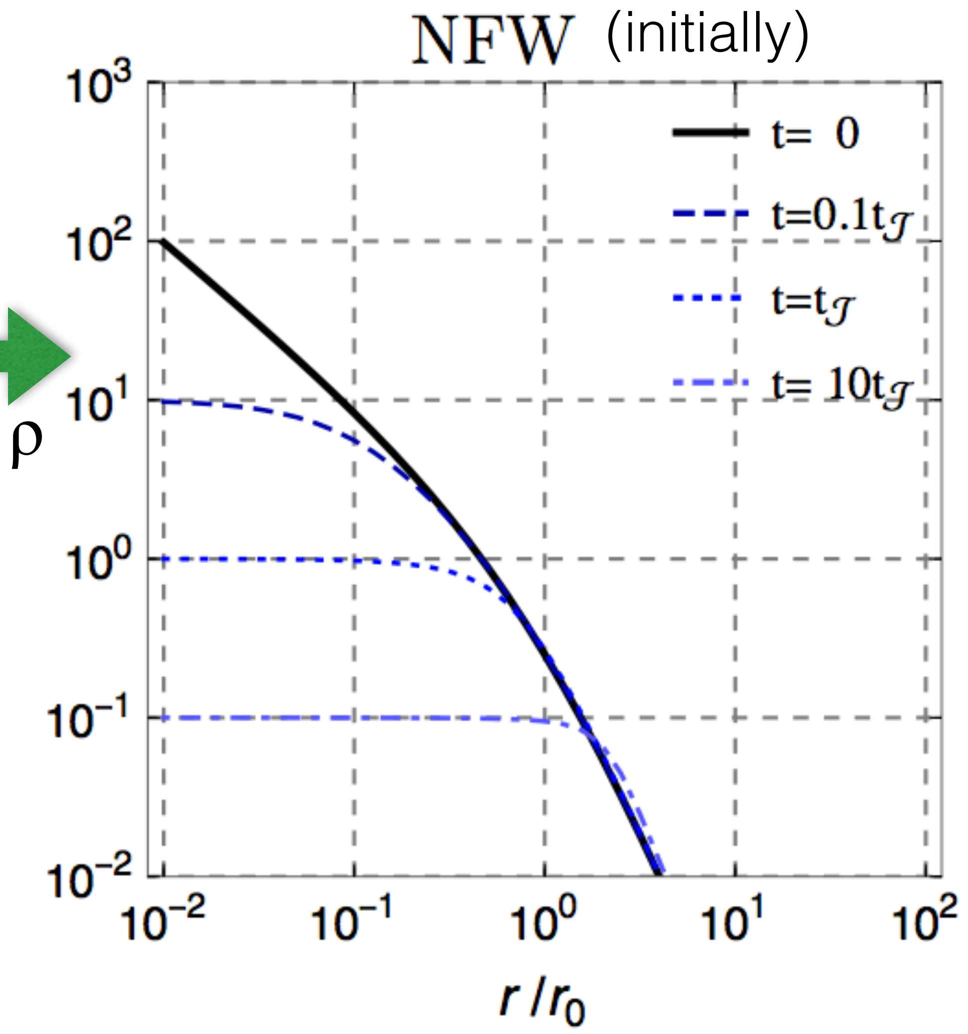
(pressure)

$$\nabla^2 \Phi = 4\pi G \rho \,,$$

(gravity)

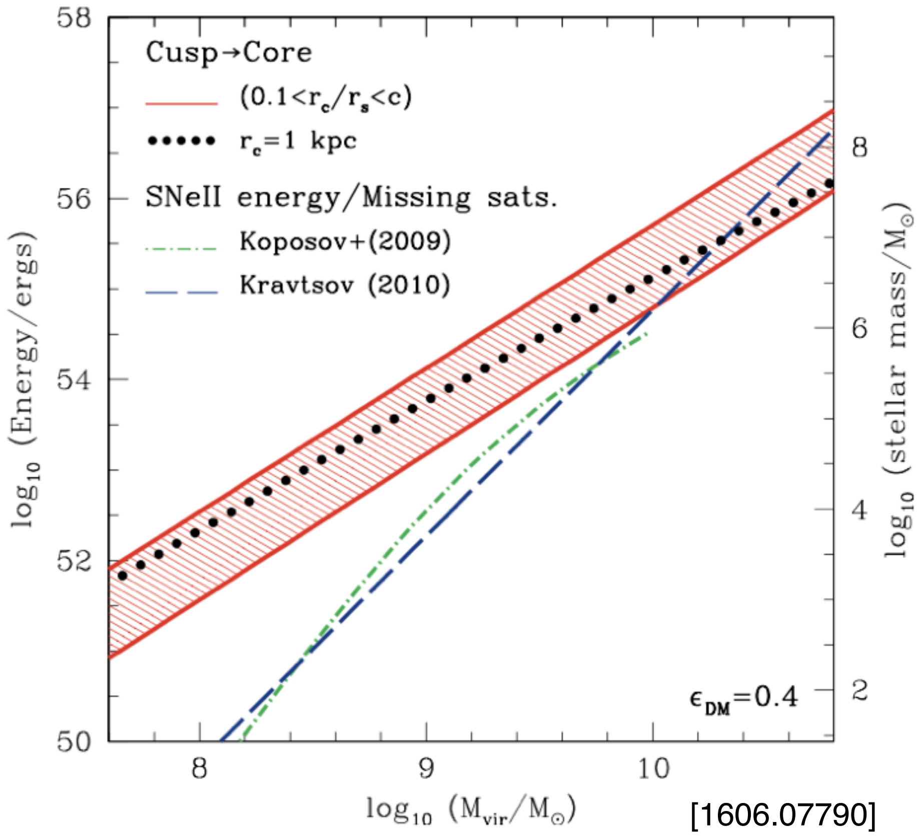
$$T \left( \frac{\partial s}{\partial t} + \mathbf{V} \cdot \nabla s \right) = \frac{\delta q}{\delta t}\bigg|_{\rm absorption} = T\, \frac{\rho\, \mathcal{J}}{m_{\rm DM}^2} \langle \sigma v_{\rm semi} \rangle$$

(entropy)



# A complicated picture for astrophysics too:

- Baryonic effects?
  - **Enough energy?** Need enough and energetic **star formation** (i.e. higher star formation threshold) [A. Pontzen et al. 2012, Garrison-Kimmel, et al. 2013, Maxwell, Wadsley&Couchman 2015, …]



[1606.07790]

- Systematic uncertainties?
  - **HI gas and star motions** may not be faithful tracer of gravity [Schneider et a. 2016, Read et al. 2016, A. M. Brooks et al. 2017, R. Verbeke et al. 2017, J. C. B. Pineda et al 2017….],
- DM-baryon conspiracy?
  - **Diversity in density profiles** *vs.* **Universal scaling laws** (Tully-Fisher, surface density, …). Can self-interacting DM **regularize** baryonic feedbacks?

# Conclusions

# Conclusions

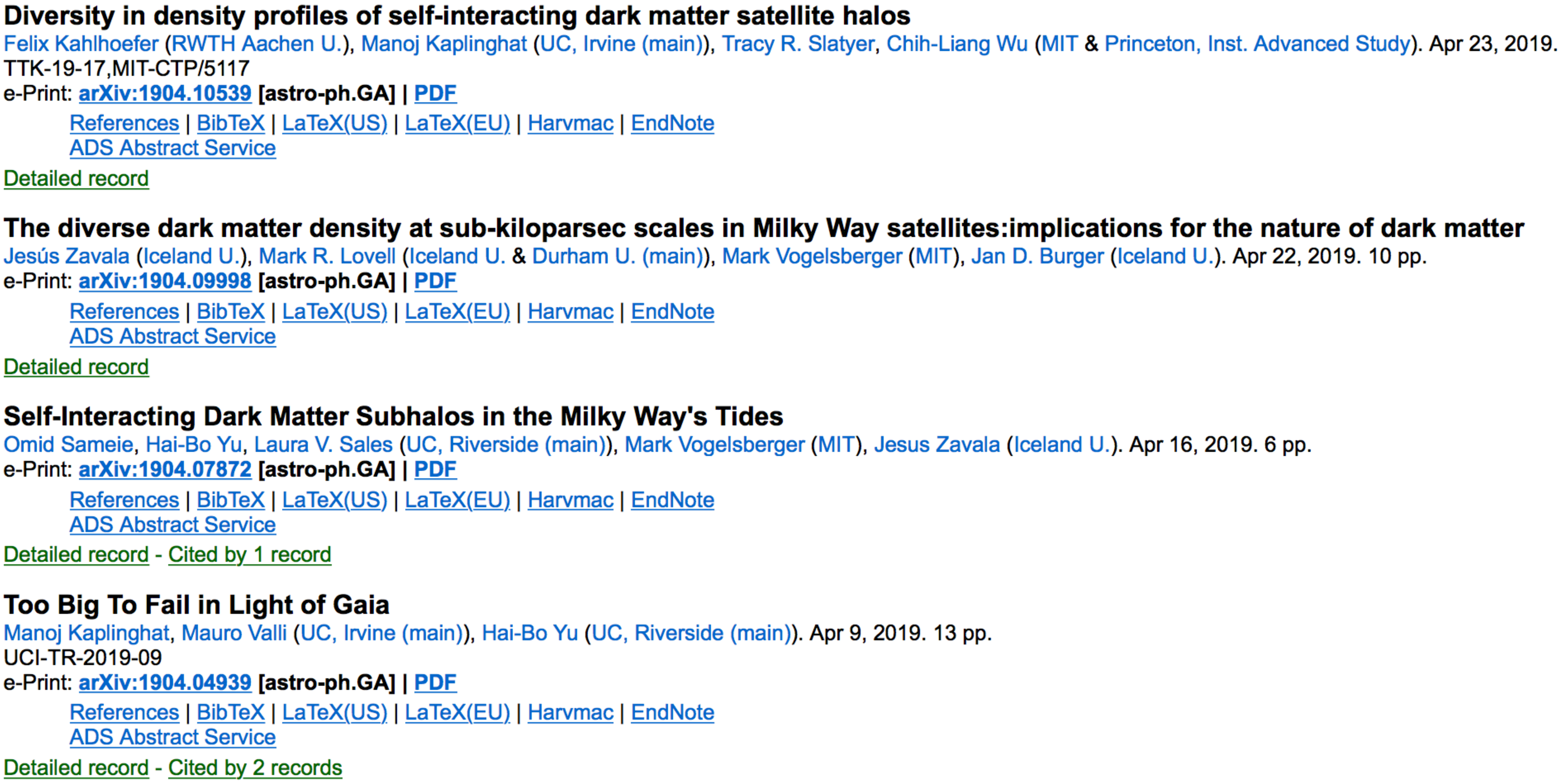
- **Apparent halo mass deficit may be hint of non-conventional DM;**

- **Self-interacting dark matter** do address such mass deficit.
    - Velocity-dependence seems necessary;
    - Various models (light mediator, resonant, self-heating, form factor,…).

- **Better simulations and measurements are required** (to understand baryon effects, halo evolution, sub-halos with little stars, velocity anisotropies, …).

Thanks!

# Most recently on tidal stripping & SIDM



**Diversity in density profiles of self-interacting dark matter satellite halos**
Felix Kahlhoefer (RWTH Aachen U.), Manoj Kaplinghat (UC, Irvine (main)), Tracy R. Slatyer, Chih-Liang Wu (MIT & Princeton, Inst. Advanced Study). Apr 23, 2019.
TTK-19-17,MIT-CTP/5117
e-Print: **arXiv:1904.10539** **[astro-ph.GA]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

**The diverse dark matter density at sub-kiloparsec scales in Milky Way satellites:implications for the nature of dark matter**
Jesús Zavala (Iceland U.), Mark R. Lovell (Iceland U. & Durham U. (main)), Mark Vogelsberger (MIT), Jan D. Burger (Iceland U.). Apr 22, 2019. 10 pp.
e-Print: **arXiv:1904.09998** **[astro-ph.GA]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record

**Self-Interacting Dark Matter Subhalos in the Milky Way's Tides**
Omid Sameie, Hai-Bo Yu, Laura V. Sales (UC, Riverside (main)), Mark Vogelsberger (MIT), Jesus Zavala (Iceland U.). Apr 16, 2019. 6 pp.
e-Print: **arXiv:1904.07872** **[astro-ph.GA]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 1 record

**Too Big To Fail in Light of Gaia**
Manoj Kaplinghat, Mauro Valli (UC, Irvine (main)), Hai-Bo Yu (UC, Riverside (main)). Apr 9, 2019. 13 pp.
UCI-TR-2019-09
e-Print: **arXiv:1904.04939** **[astro-ph.GA]** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service
Detailed record - Cited by 2 records

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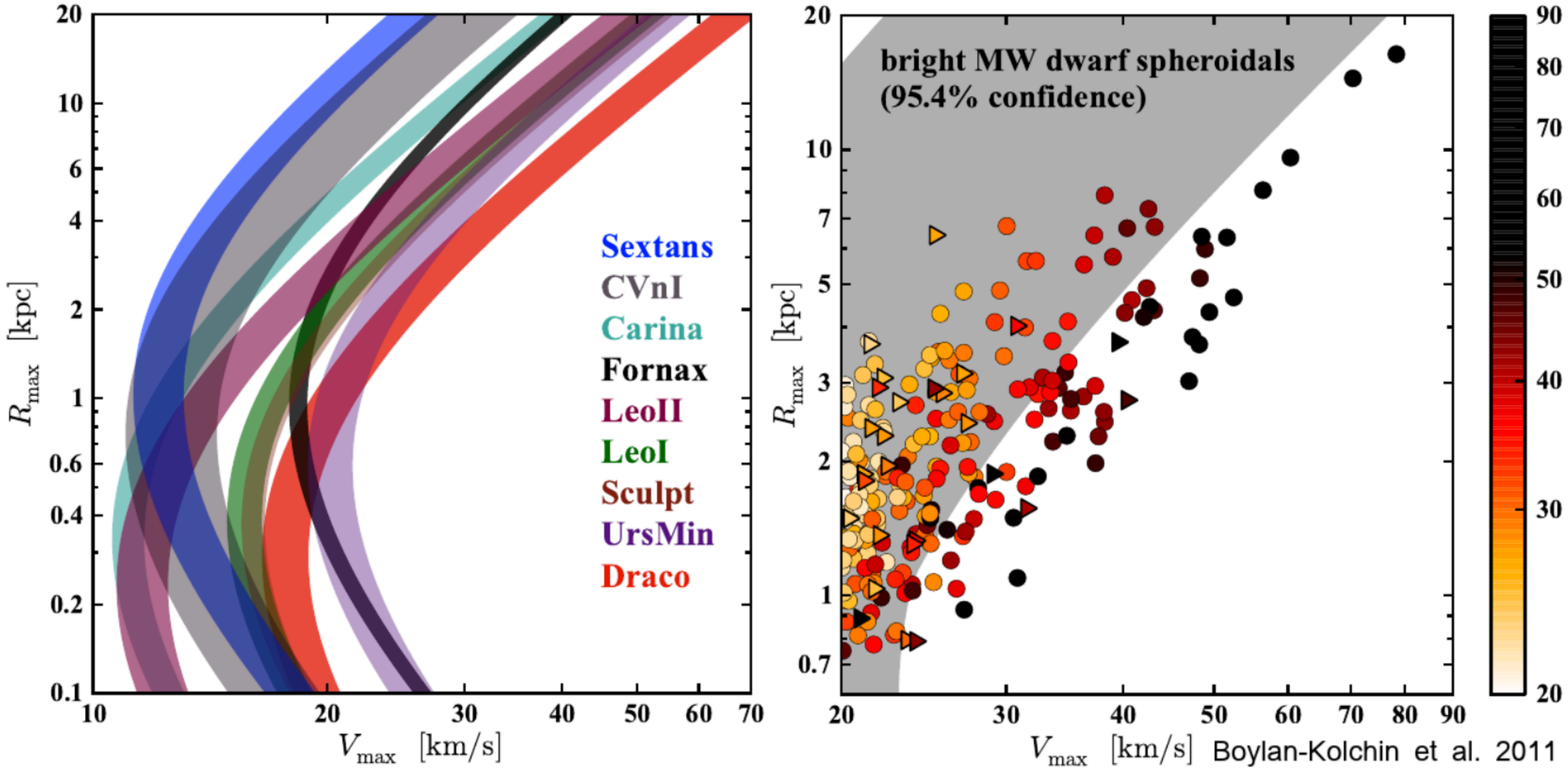

Boylan-Kolchin et al. 2011

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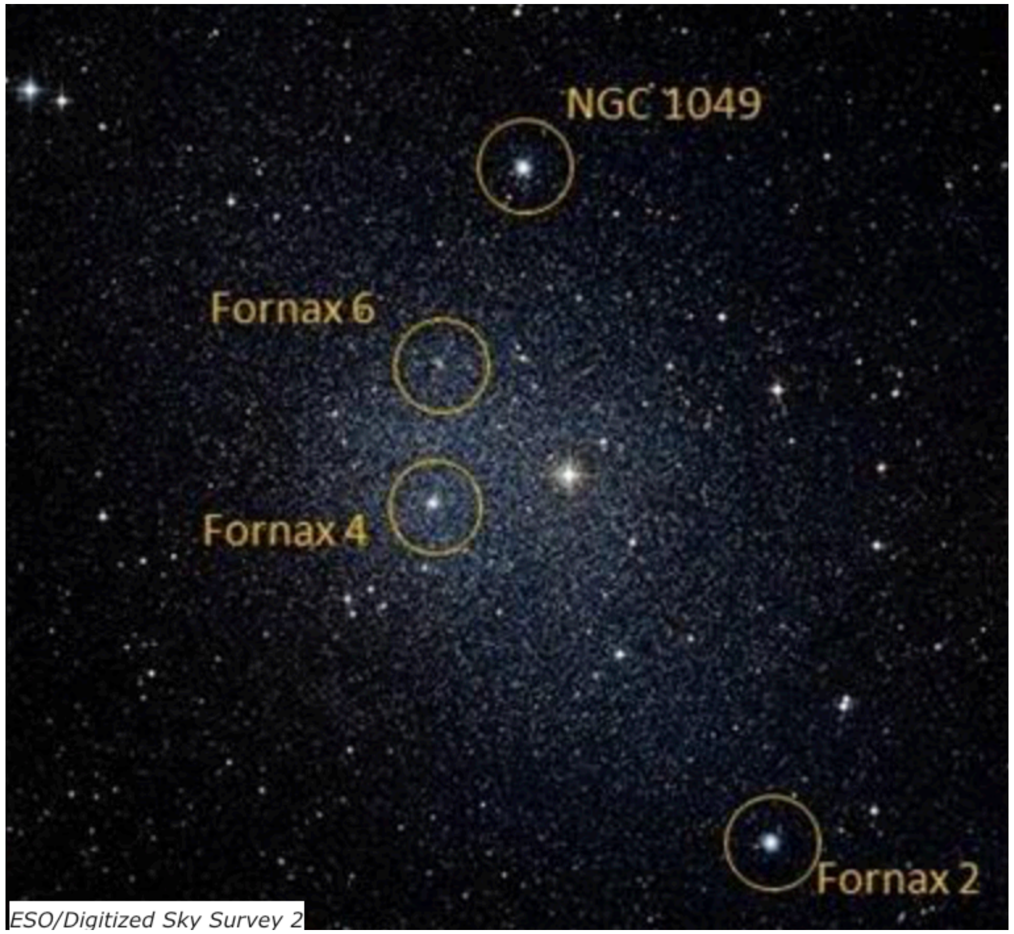
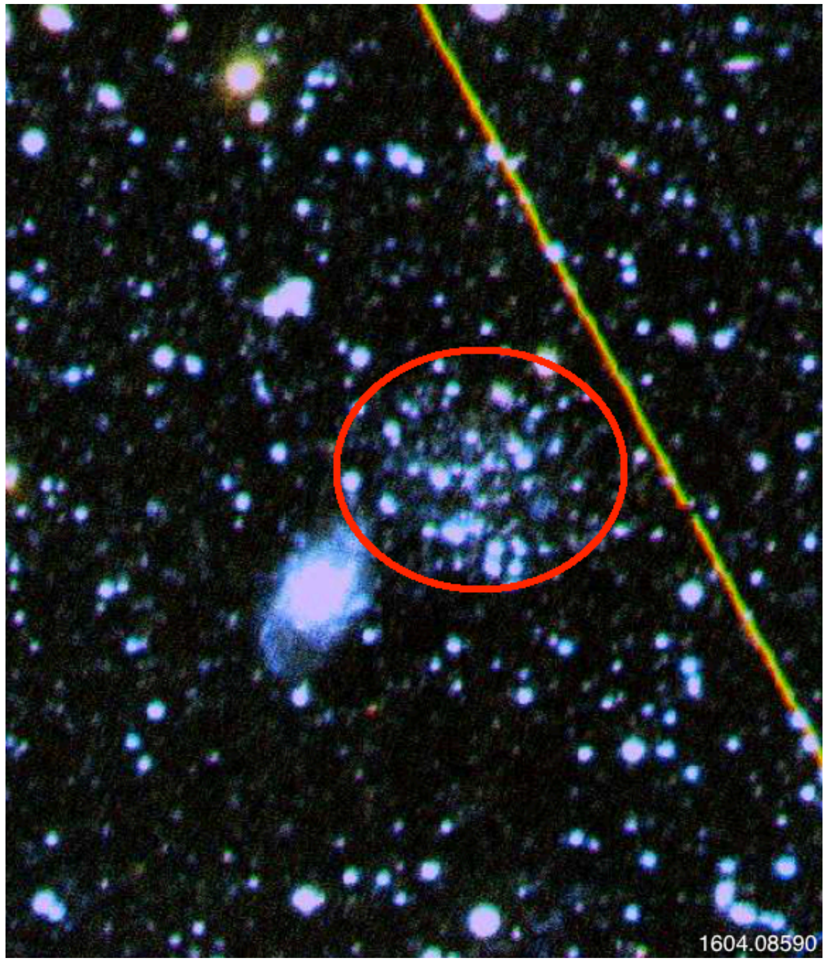


ESO/Digitized Sky Survey 2

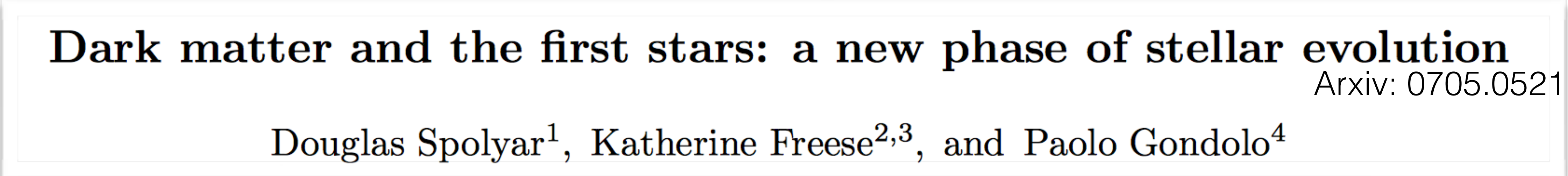
Fornax


1604.08590

Eridanus II

# Examples of DM annihilation heating up baryons

**A few previous studies for baryonic astrophysics:**



## Dark matter and the first stars: a new phase of stellar evolution

Arxiv: 0705.0521

Douglas Spolyar[1], Katherine Freese[2,3], and Paolo Gondolo[4]

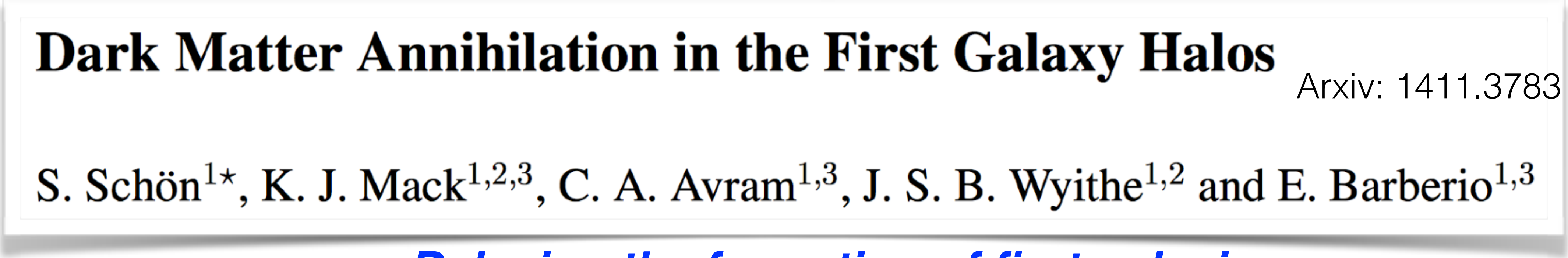
***Giant stars that are powered by DM annihilation…***

## The impact of dark matter decays and annihilations on the formation of the first structures

Arxiv: astro-ph/0606483

E. Ripamonti[1], M. Mapelli[2], A. Ferrara[2]

***Evacuating gas and increasing the gas temperature…***



## Dark Matter Annihilation in the First Galaxy Halos

Arxiv: 1411.3783

S. Schön[1⋆], K. J. Mack[1,2,3], C. A. Avram[1,3], J. S. B. Wyithe[1,2] and E. Barberio[1,3]

***Delaying the formation of first galaxies…***