Summary talk for SIDM

Céline Boehm

IPPP, Durham

LAPTH, Annecy

Copenhagen, August 2017

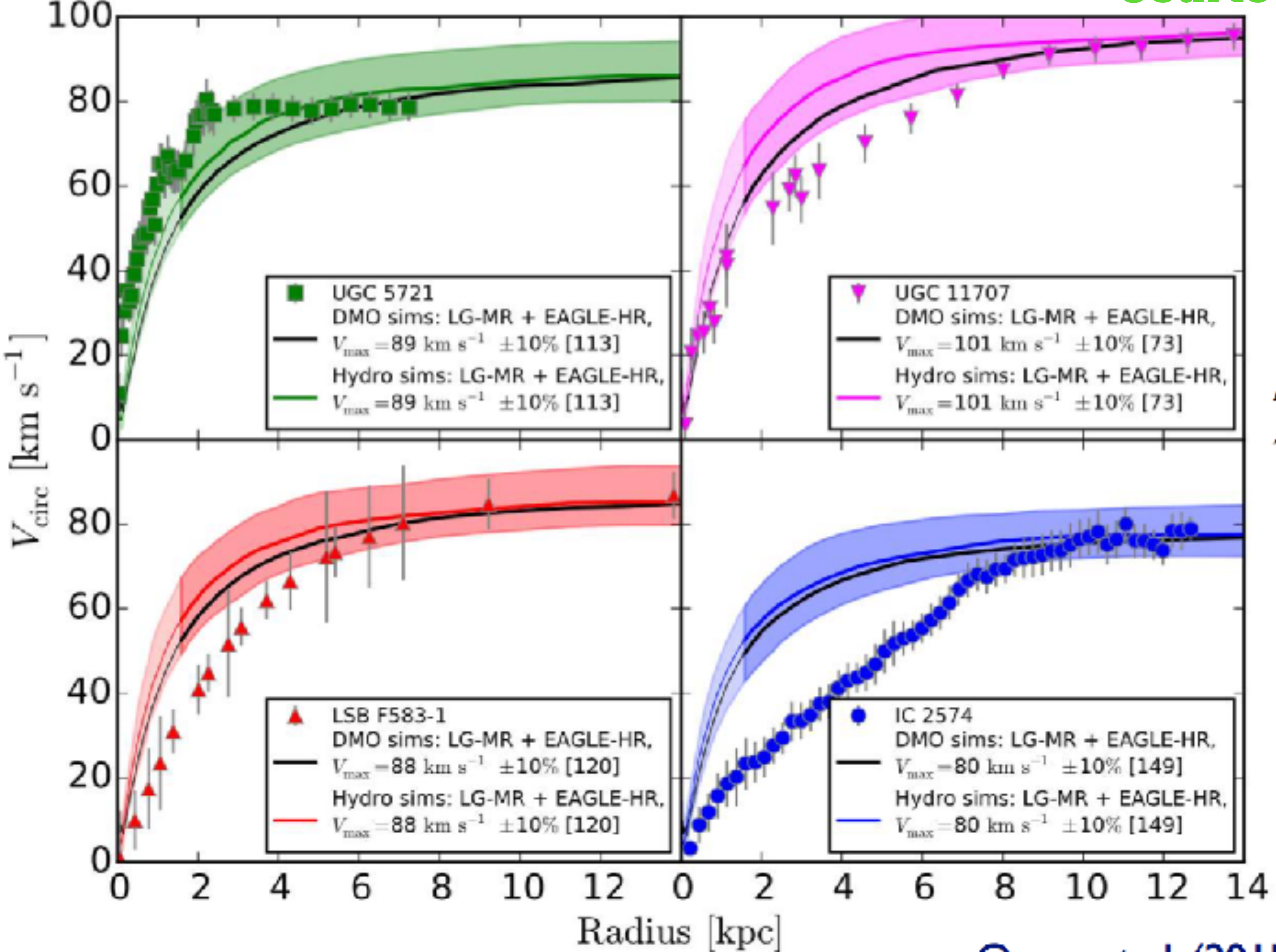
courtesy Andrew Pontzen

Some challenges to ΛCDM

1. Anomalies in the cosmic microwave background
2. The under-abundance of dwarf galaxies (aka “missing satellites”)
3. The unexpected dark matter distribution around dwarf galaxies (aka “cusp/core”)
4. The low masses of dwarf galaxies (aka “too big to fail”)
5. Unexpected alignments in the distribution of dwarf galaxies
6. The existence of a common acceleration scale

The Diversity Problem

Courtesy Hai-Bo Yu



All galaxies have the same Vmax!

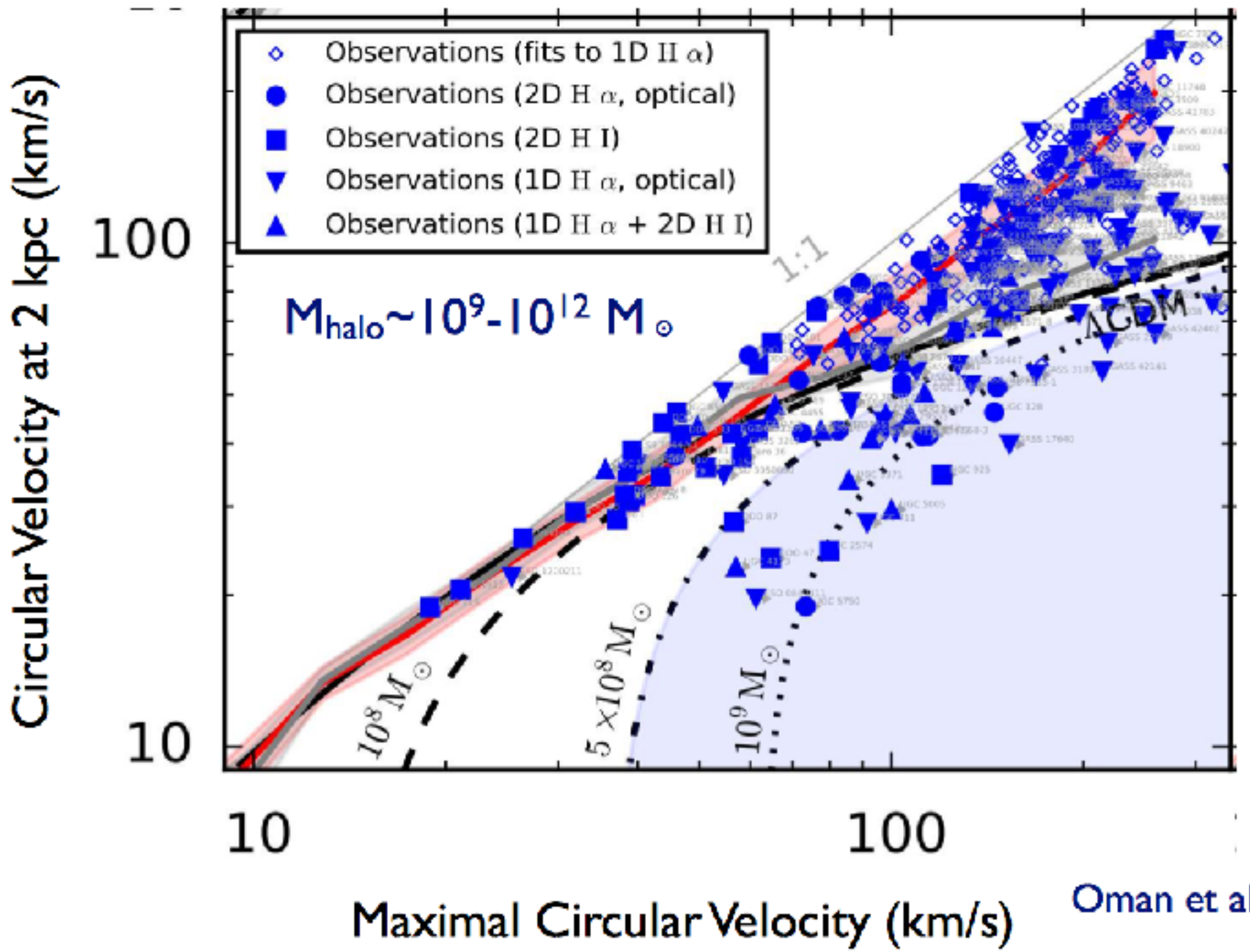
Oman et al. (2015)

Colored bands: hydrodynamic simulations of ΛCDM

See also Kuzio de Naray, Martinez, Bullock, Kaplinghat (2009)

Courtesy Hai-Bo Yu

A Big Challenge for ΛCDM



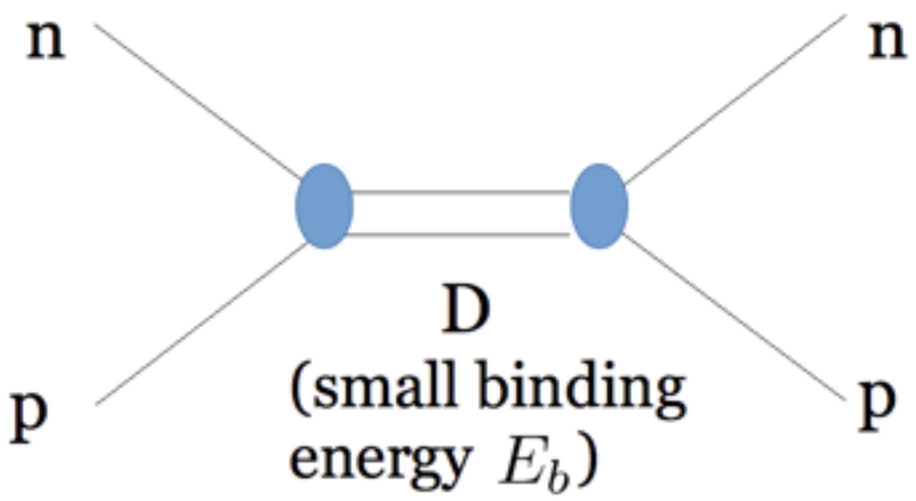
Oman et al. (2015)

V_{circ}(2kpc) has a factor of 3-4 scatter for fixed V_{max}

What about ~ baryonic DM?

cross section needs to be ~ 0.1-10 cm^2/g

Courtesy Bryan Zaldivar



- large (~20b) xsection due to large scattering length

$$\lim_{k \to 0} \sigma = 4\pi a^2$$

- a diverges for $E_b \to 0$ bound state

DM not a baryon because

* charged
* signatures of interactions in P(k)

The Silk damping

letters to nature

Nature **215**, 1155 - 1156 (09 September 1967); doi:10.1038/2151155a0

Fluctuations in the Primordial Fireball

JOSEPH SILK

Harvard College Observatory, Cambridge, Massachusetts.

ONE of the overwhelming difficulties of realistic cosmological models is the inadequacy of Einstein's gravitational theory to explain the process of galaxy formation[1–6]. A means of evading this problem has been to postulate an initial spectrum of primordial fluctuations[7]. The interpretation of the recently discovered 3° K microwave background as being of cosmological origin[8,9] implies that fluctuations may not condense out of the expanding universe until an epoch when matter and radiation have decoupled[4], at a temperature T_D of the order of 4,000° K. The question may then be posed: would fluctuations in the primordial fireball survive to an epoch when galaxy formation is possible ?

References

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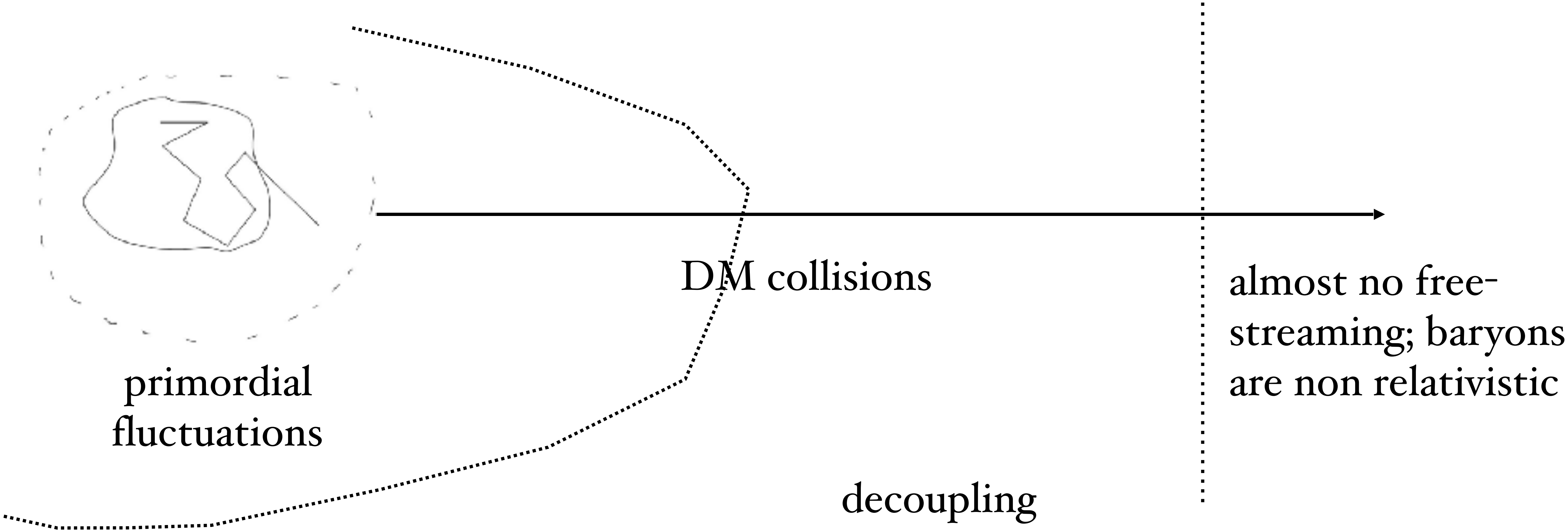
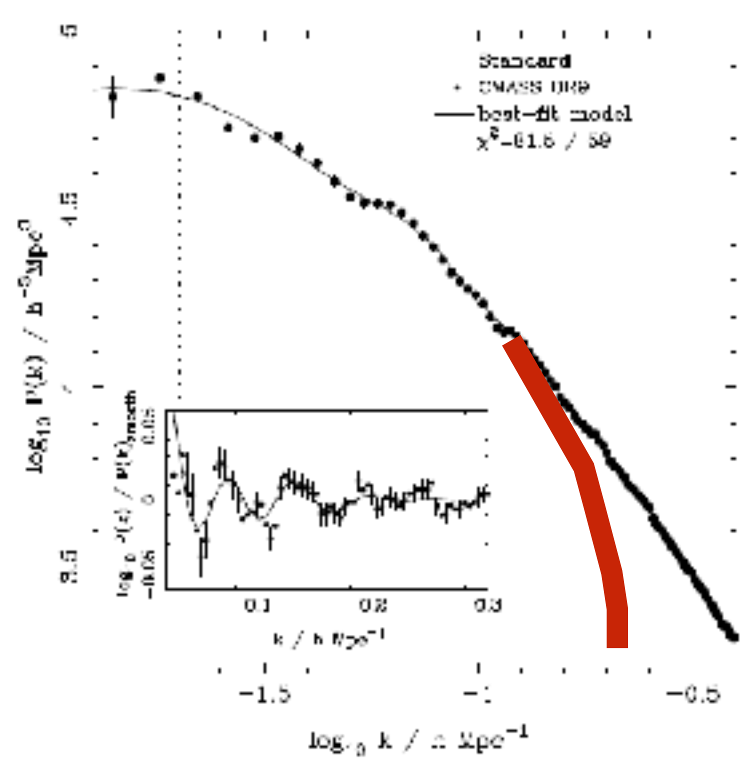
The damping mechanisms in the case of baryons

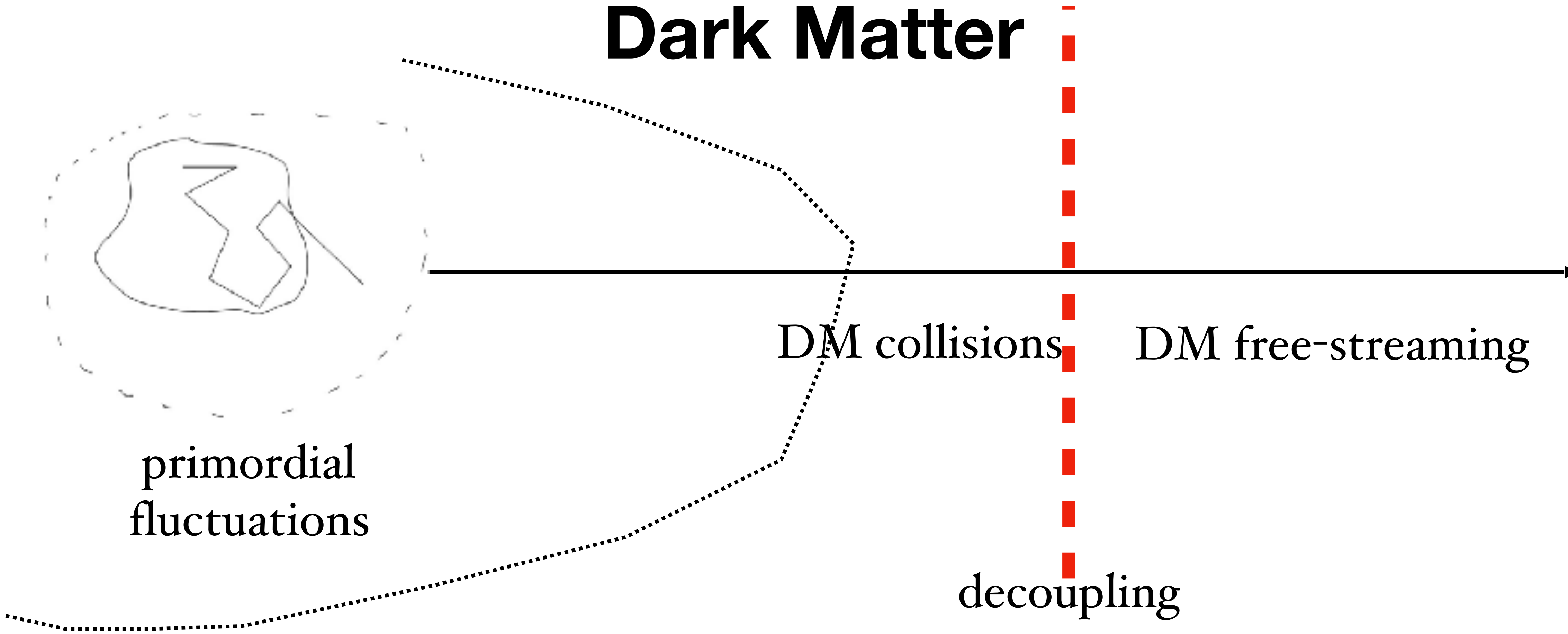


Fluctuations first erased by collisional damping



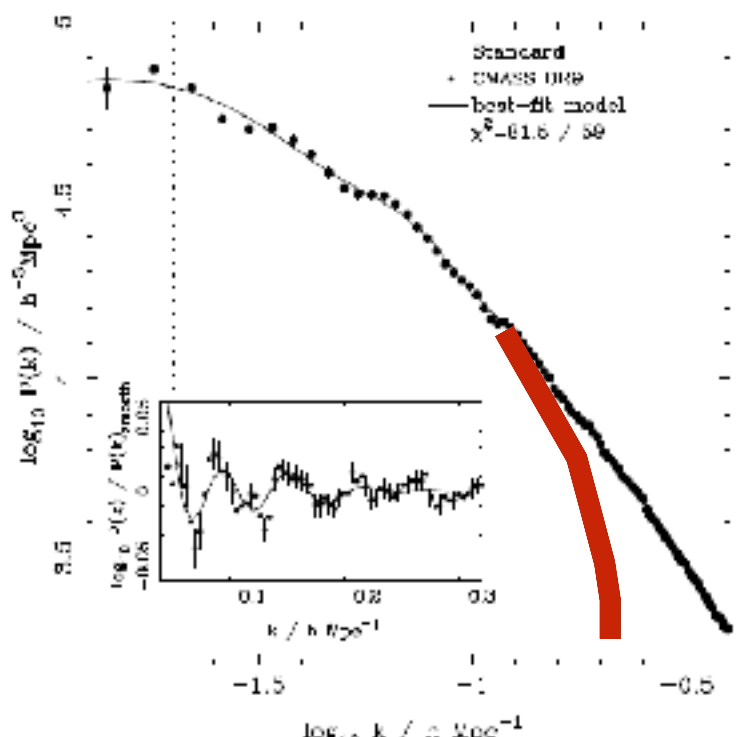
cut-off is at too high scale and it is more or less the end of the story but the beginning for DM

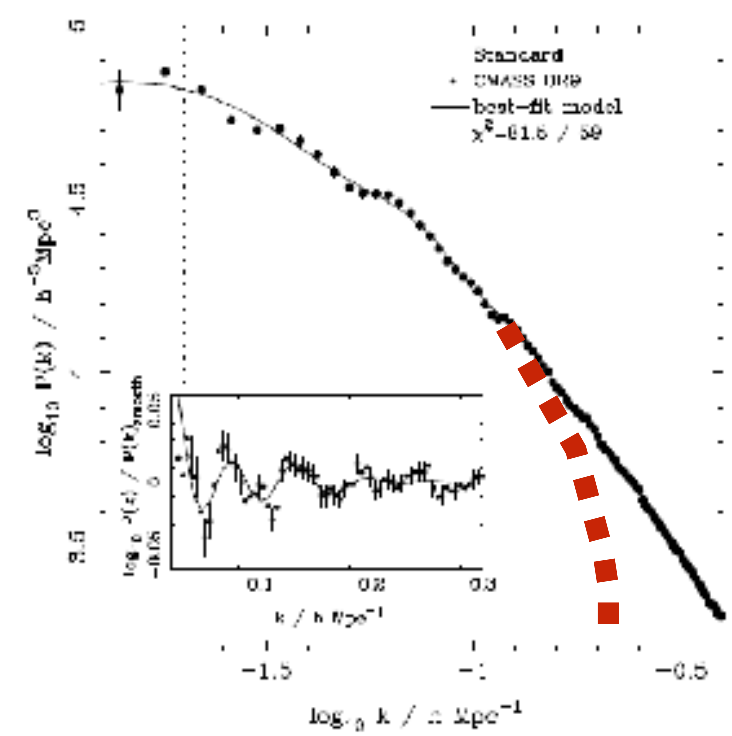
The different damping mechanisms in the case of Dark Matter



Fluctuations first erased by collisional damping

then free-streaming





Let us start with the free-streaming as it is the most well-known effect

Free-streaming when DM has (even small) collisions

(**astro-ph/0012504**, **astro-ph/0410591**)

depends on mass

$$l_{\rm fs} = \int_{t_{\rm dec}}^{t_0} \frac{v(t)}{a(t)}\, dt$$

depends on interactions

depends on the history of the Universe

Very different expressions

$$\int_{t_{dec}}^{t_{nr}} \frac{c}{a(t)} dt + \int_{t_{nr}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} < \mathrm{t_{nr}}$$

$$\int_{t_{dec}}^{t_0} \frac{v(t)}{a(t)} dt \quad \text{if} \quad \mathrm{t_{dec}} > \mathrm{t_{nr}}$$

Free-streaming

(astro-ph/0012504, astro-ph/0410591)

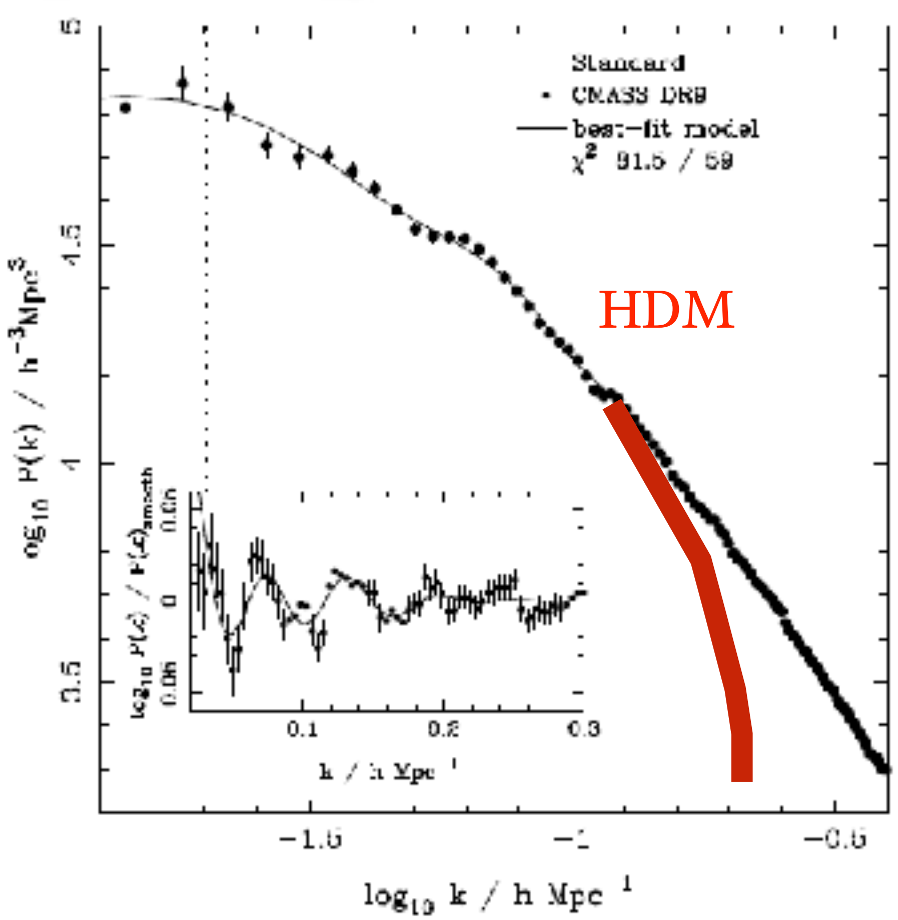
$$l_{\rm fs} = \int_{t_{\rm dec}}^{t_0} \frac{v(t)}{a(t)}\, dt$$

No interaction, tdec = "0"time; $\int_{t_{\rm dec}\to 0}^{t_{nr}} dt\ldots + \int_{t_{\rm nr}}^{t_0} dt\ldots$

Region I

$$l_{\rm struct} \sim 100 \text{ kpc} \left(\frac{\rm m_{DM}}{\rm keV}\right)^{-4/3}$$

(Bode and Ostriker)



$$T(k) = \left[1 + (\alpha k)^{2\mu}\right]^{-5/\mu}$$

$$\alpha = 0.048 \left[\frac{m_{\rm DM}}{\rm keV}\right]^{-1.15} \left[\frac{\Omega_{\rm DM}}{0.4}\right]^{0.15} \left[\frac{h}{0.65}\right]^{1.3} \frac{\rm Mpc}{h}$$

can apply the same for SUSY (Hoffman)

Generalising the free-streaming

Free-streaming for generalised DM models

(astro-ph/0012504, astro-ph/0410591)

3 parameters $\Gamma,\ m_{DM},\ t_{eq}$

- Γ → $t_{\rm dec(DM)} = 1/\Gamma_{\rm dec}$
- m_{DM} → $t_{\rm NR}$
- t_{eq} → equality matter-radiation → $t_{\rm eq}$

3 characteristic times/scale-factors ====>> 6 DM configurations

sterile neutrino →	Region I	$a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$	
	Region II	$a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$	← WIMPs-like
self-interactions →	Region III	$a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$	
neutrinos →	Region IV	$a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$	
	Region V	$a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$	
	Region VI	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$	

DM physics without having a DM model

(astro-ph/0012504, astro-ph/0410591)

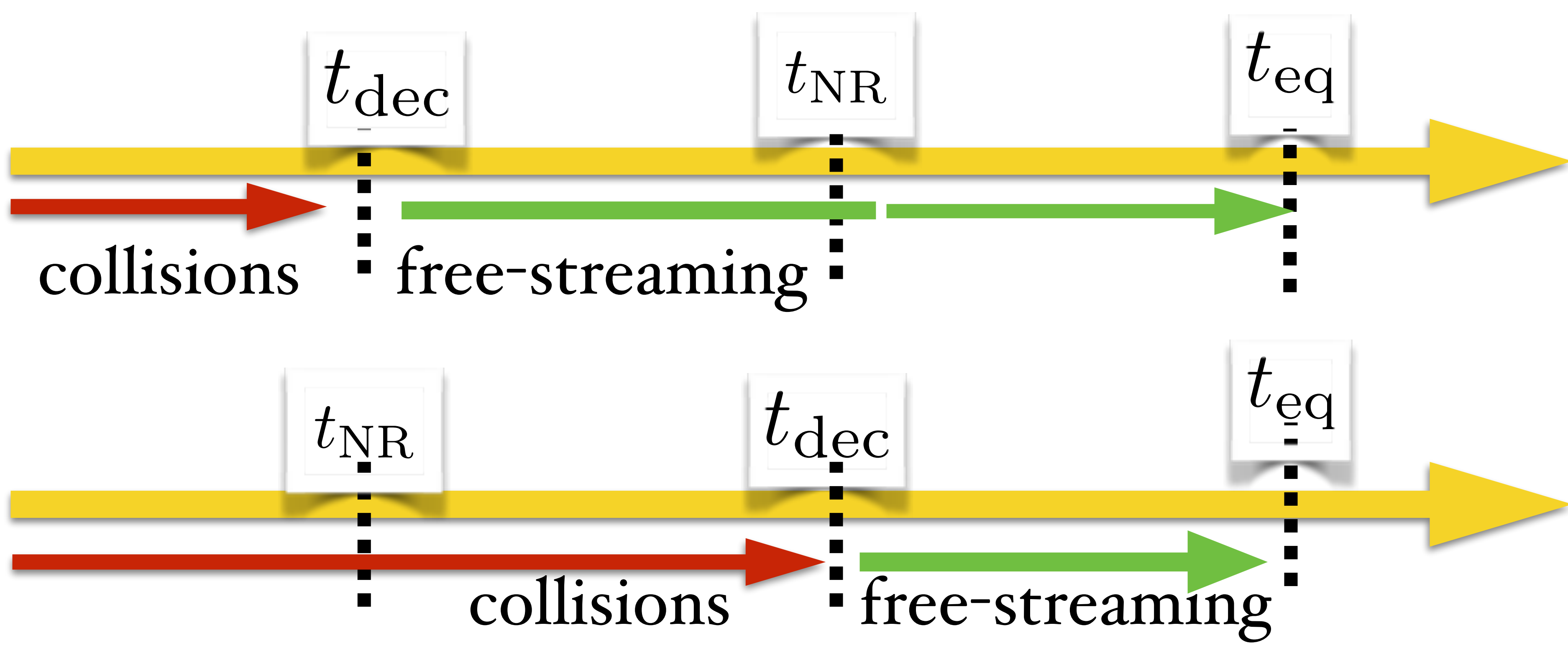
Region I	$a_{dec(dm)} < a_{nr} < a_{eq(\gamma+\nu)}$
Region II	$a_{nr} < a_{dec(dm)} < a_{eq(\gamma+\nu)}$
Region III	$a_{nr} < a_{eq(\gamma+\nu)} < a_{dec(dm)}$
Region IV	$a_{dec(dm)} < a_{eq(\gamma+\nu)} < a_{nr}$
Region V	$a_{eq(\gamma+\nu)} < a_{dec(dm)} < a_{nr}$
Region VI	$a_{eq(\gamma+\nu)} < a_{nr} < a_{dec(dm)}$

sterile neutrino

WIMPs-like

self-interactions

neutrinos



Classification

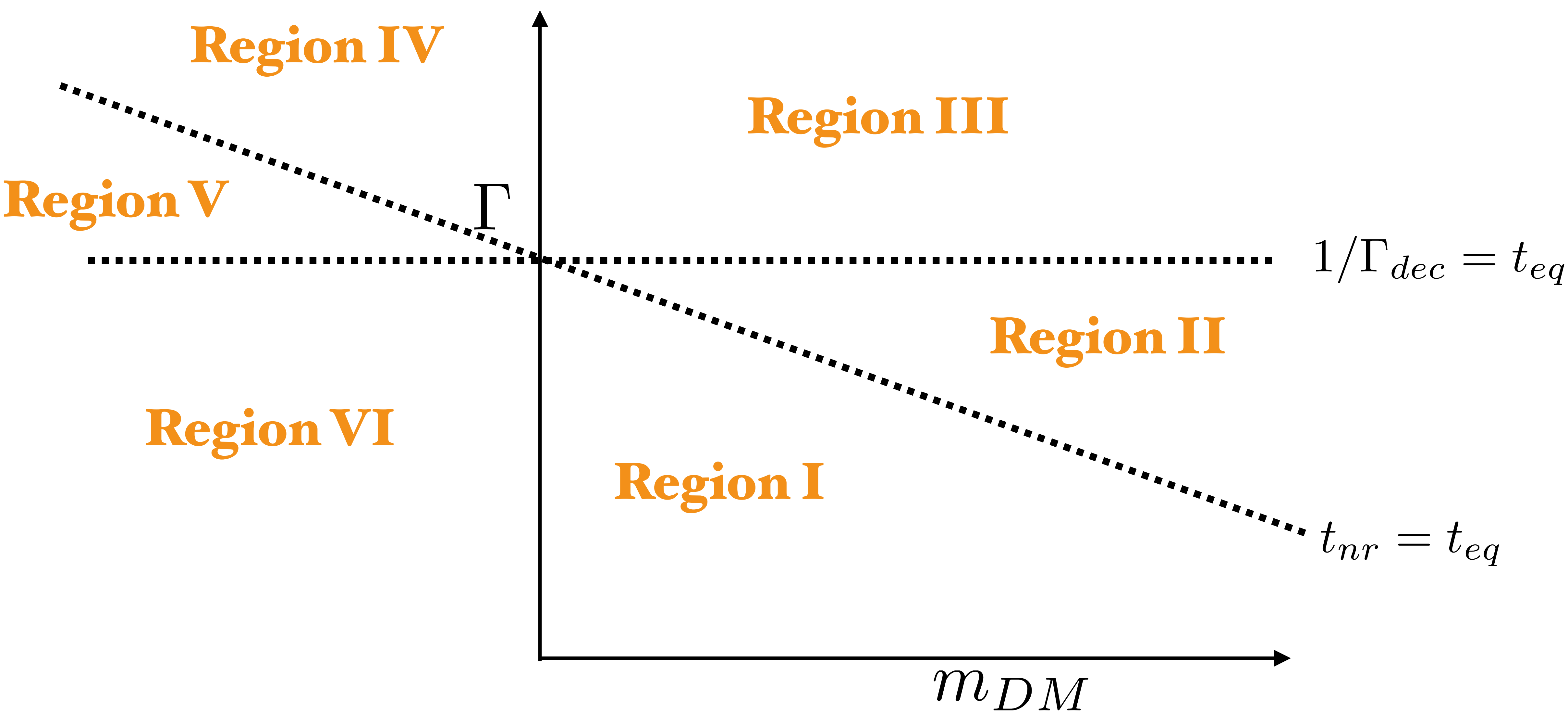
(astro-ph/0012504, astro-ph/0410591)

$\Gamma, \ m_{DM}, \ t_{eq}$

$t_{\mathrm{dec(DM)}} = 1/\Gamma_{\mathrm{dec}}$

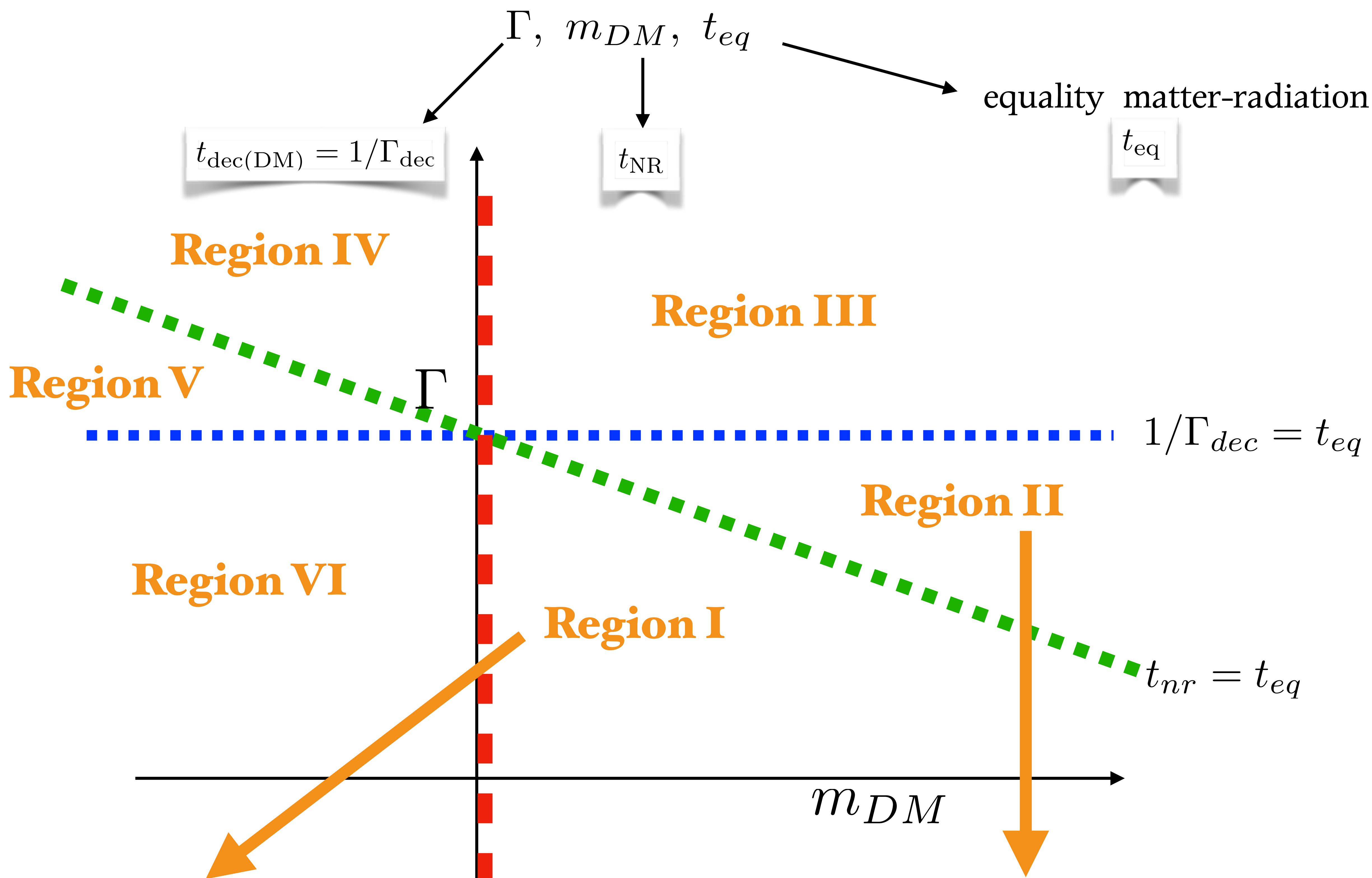
t_{NR}

equality matter-radiation t_{eq}



Classification

(astro-ph/0012504, astro-ph/0410591)

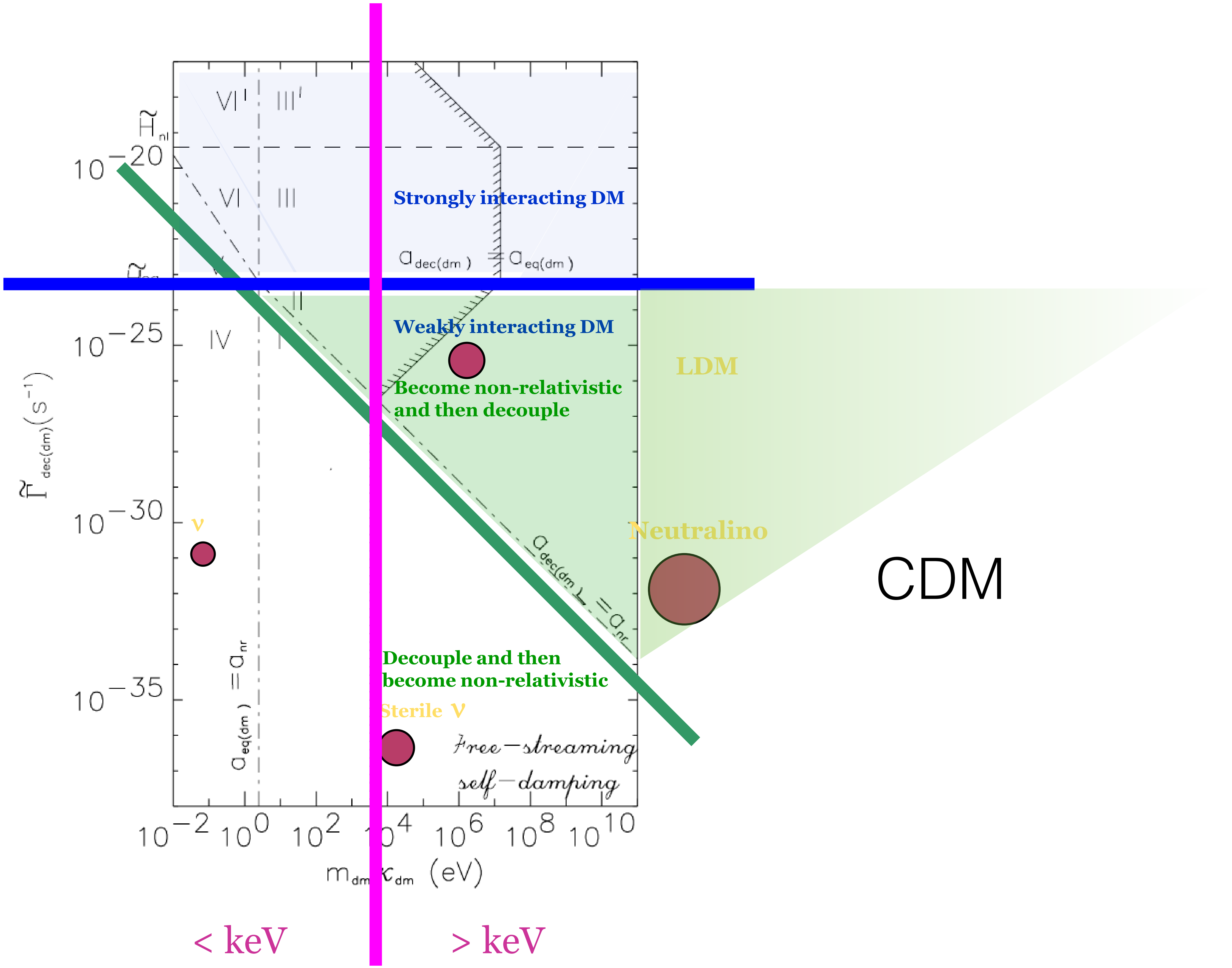


$$\int_{t_{dec}}^{t_{nr}} \frac{c}{a(t)}dt + \int_{t_{nr}}^{t_0} \frac{v(t)}{a(t)}dt \quad \text{if} \quad \mathrm{t_{dec} < t_{nr}}$$

$$\int_{t_{dec}}^{t_0} \frac{v(t)}{a(t)}dt \quad \text{if} \quad \mathrm{t_{dec} > t_{nr}}$$

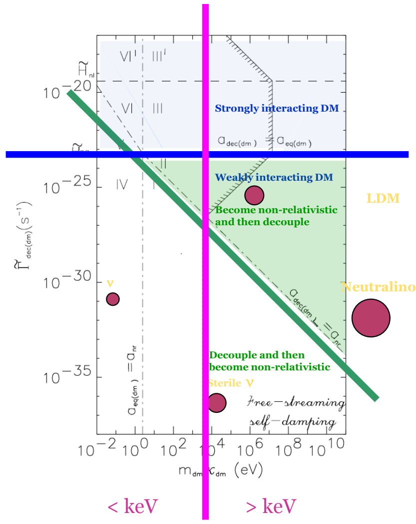
Classification

(astro-ph/0012504, astro-ph/0410591)

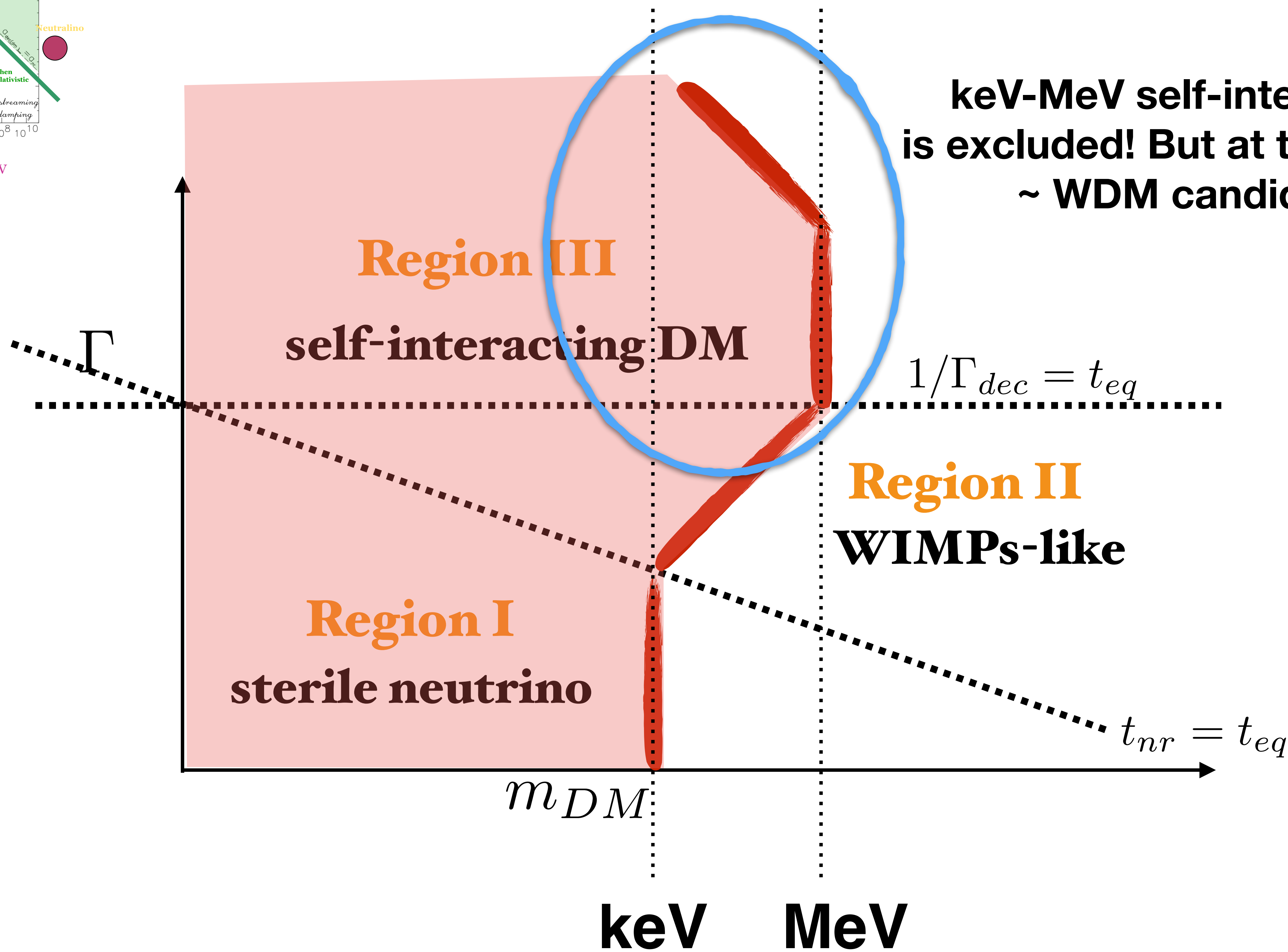


Free-streaming when DM has (even small) collisions

(astro-ph/0012504, astro-ph/0410591)



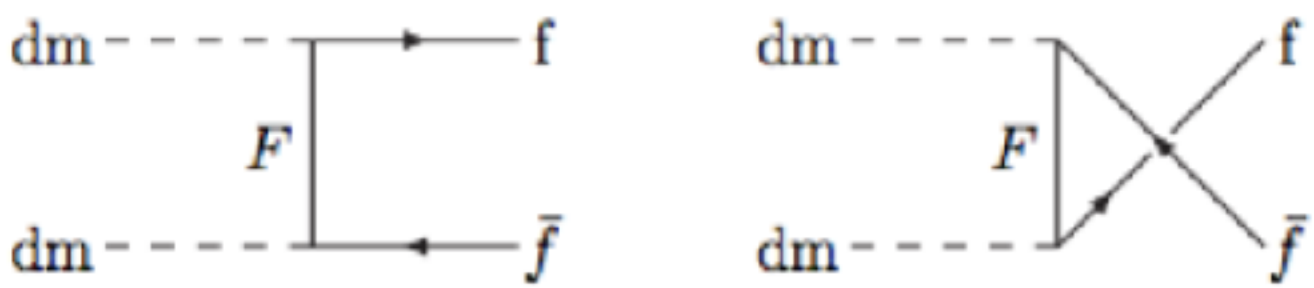
keV-MeV self-interacting is excluded! But at the border ~ WDM candidate



Can we have light Interacting DM?

OLD VERSION

How do you explain the relic abundance?

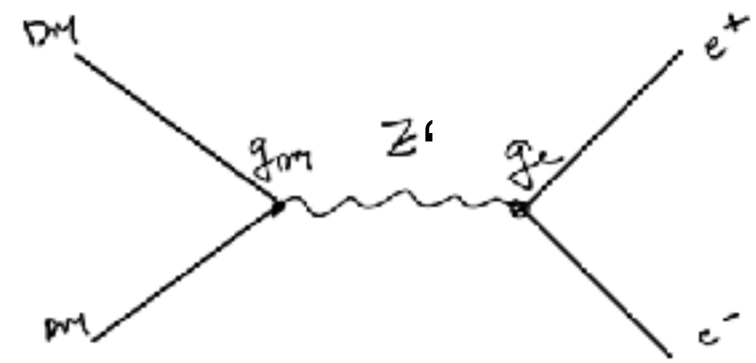


$$\sigma v \propto \frac{1}{m_F^4} \left(\left(C_l^2 + C_r^2 \right) \; m_f + 2 C_l \; C_r \; m_F \right)^2$$

$$\sigma v \propto \frac{1}{m_F^2}$$

mirror fermions

light DM is ok

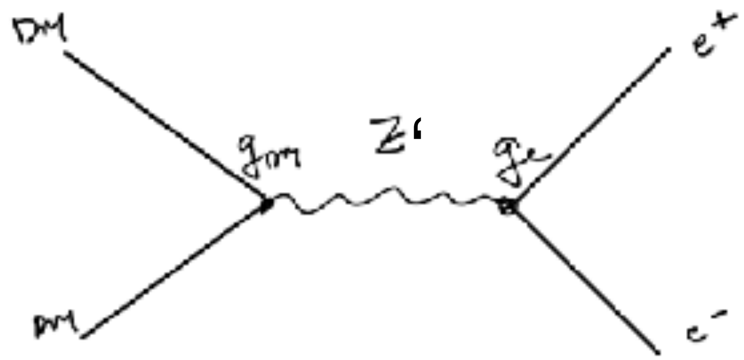


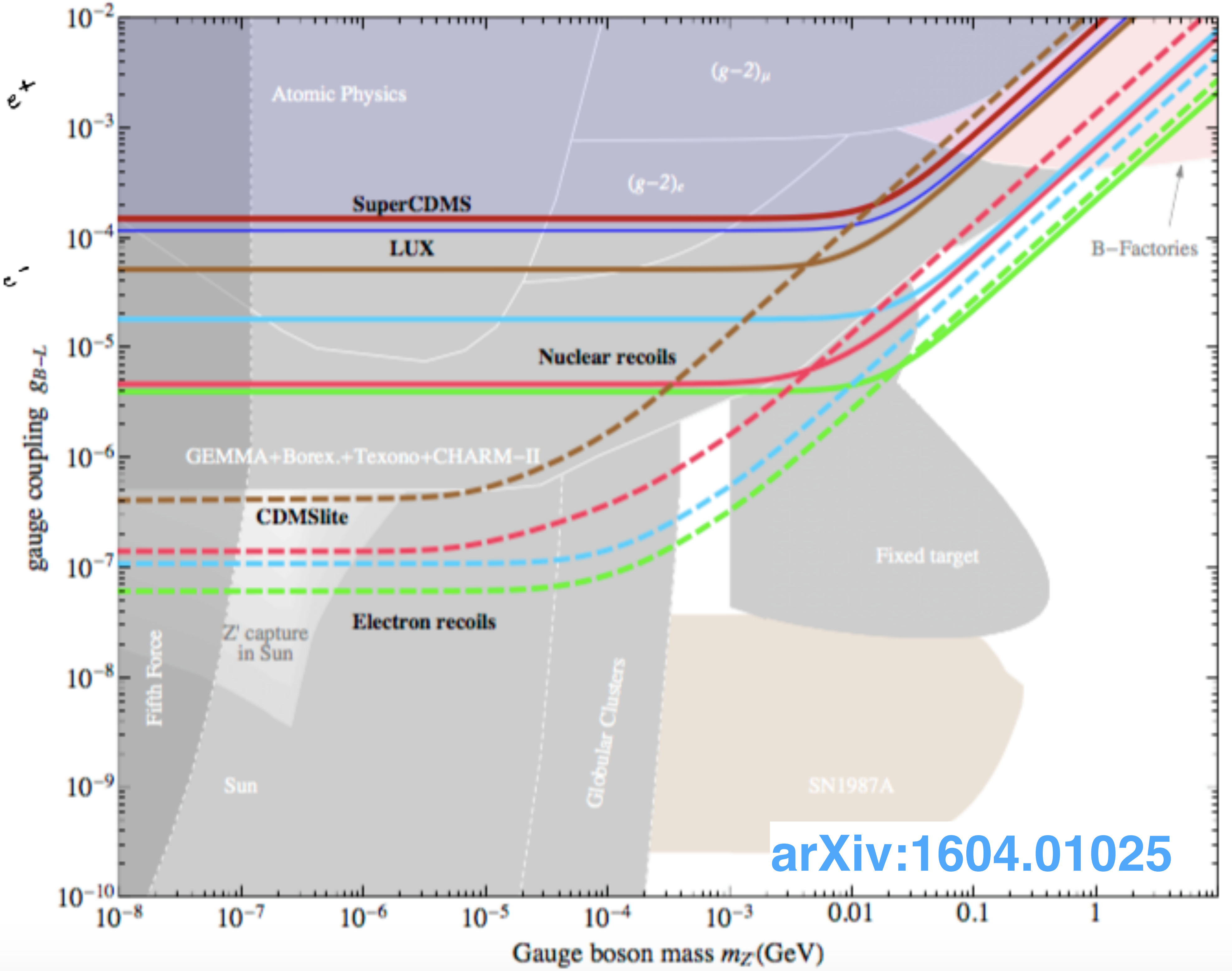
$$\sigma v \propto v^2 \; \frac{m_{\rm DM}^2}{m_{Z'}^4} \; g_{\rm DM}^2 \, g_e^2$$

$$m_{\rm DM} \simeq m_{Z'}$$

dark photons/dark Z'

light DM is ok if light mediator

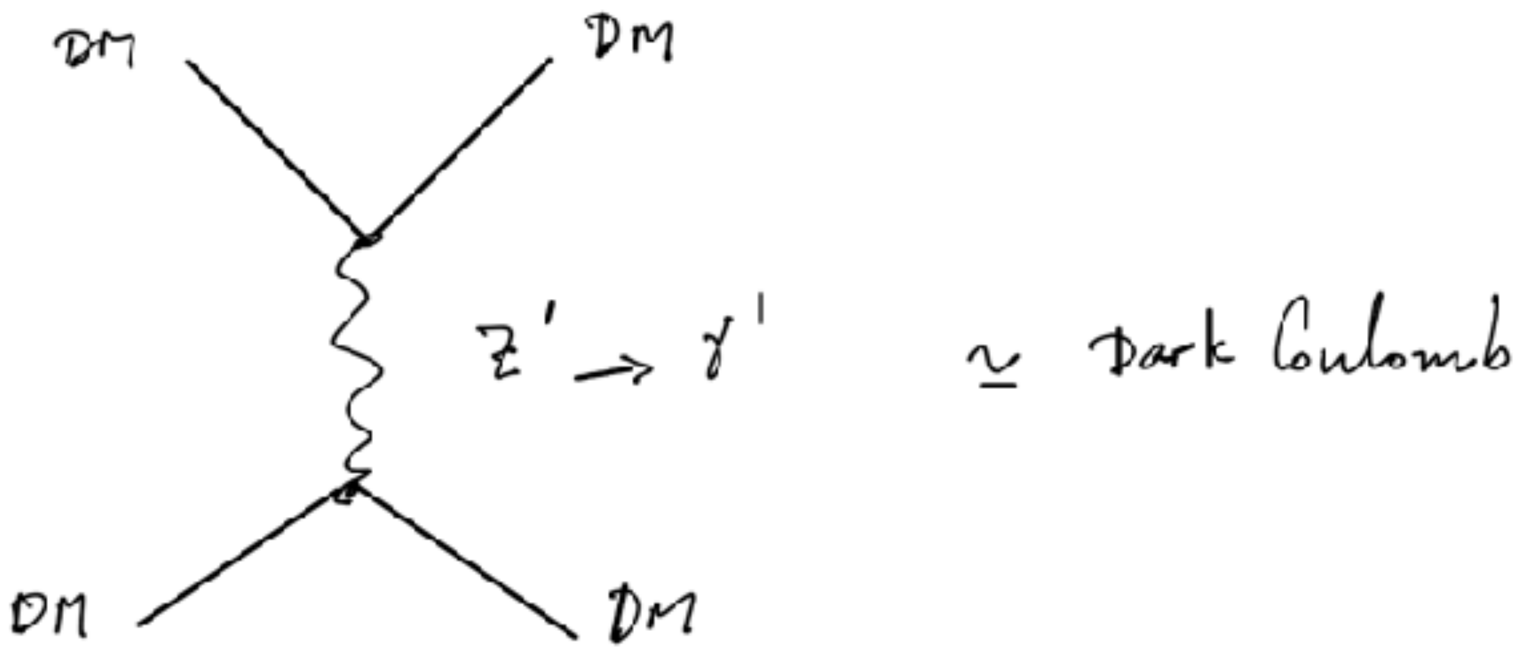




Neutrino experiments (CHARM II) also provide strong constraints!
And do expect even better limits now with the coherent interactions

Light thermal DM is hard to achieve given current constraints

but both the Z' and light DM had a life on their own



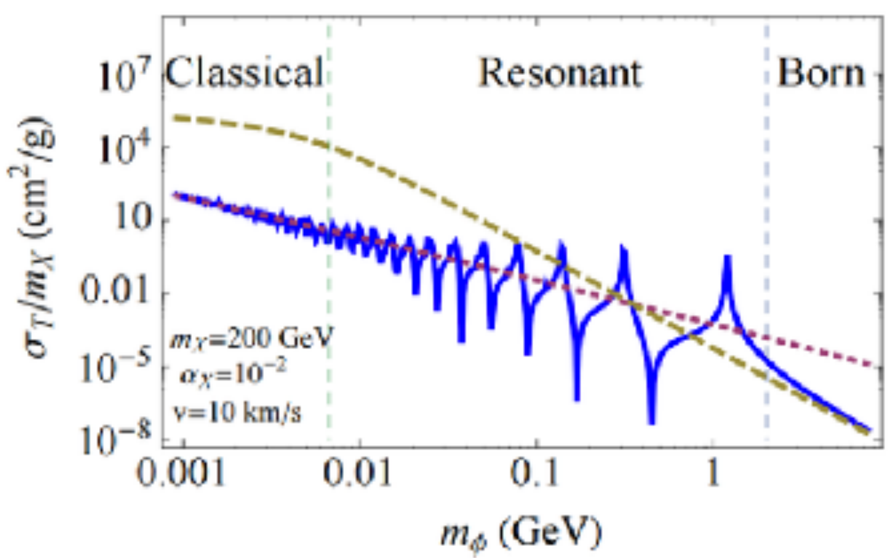
Coulomb interactions have a huge cross section
so there is room for small couplings

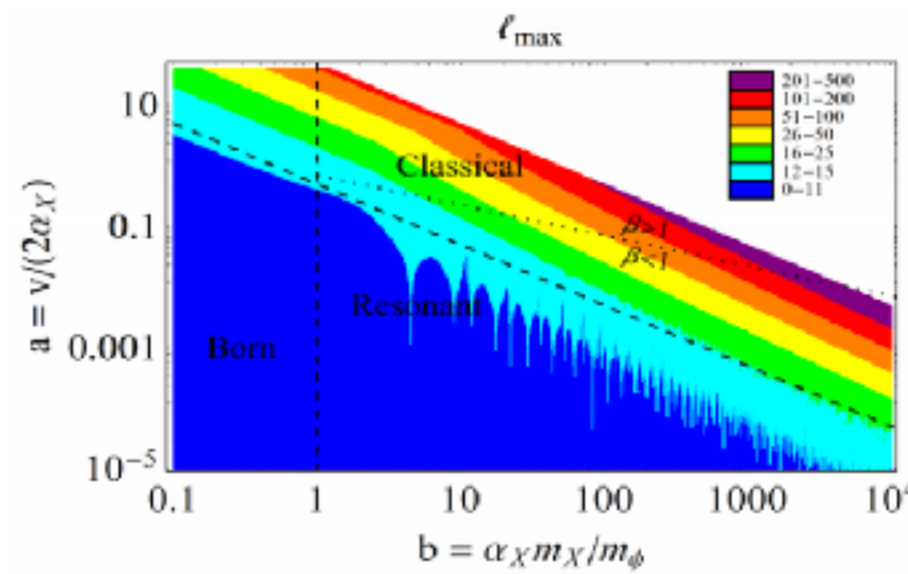
Going long-range interactions

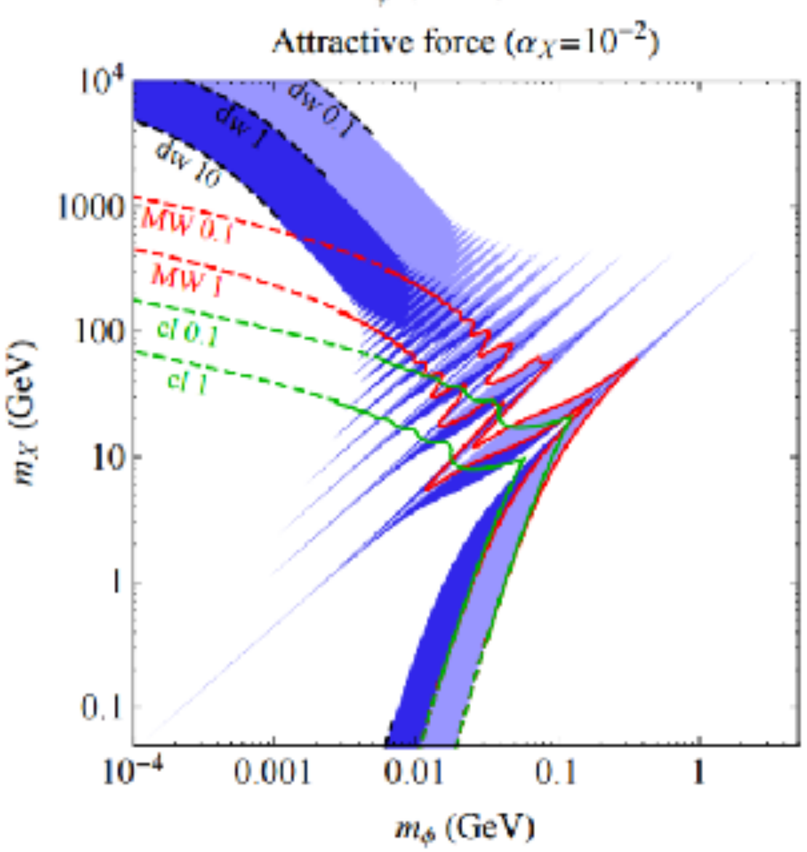
Courtesy Bryan Zaldivar

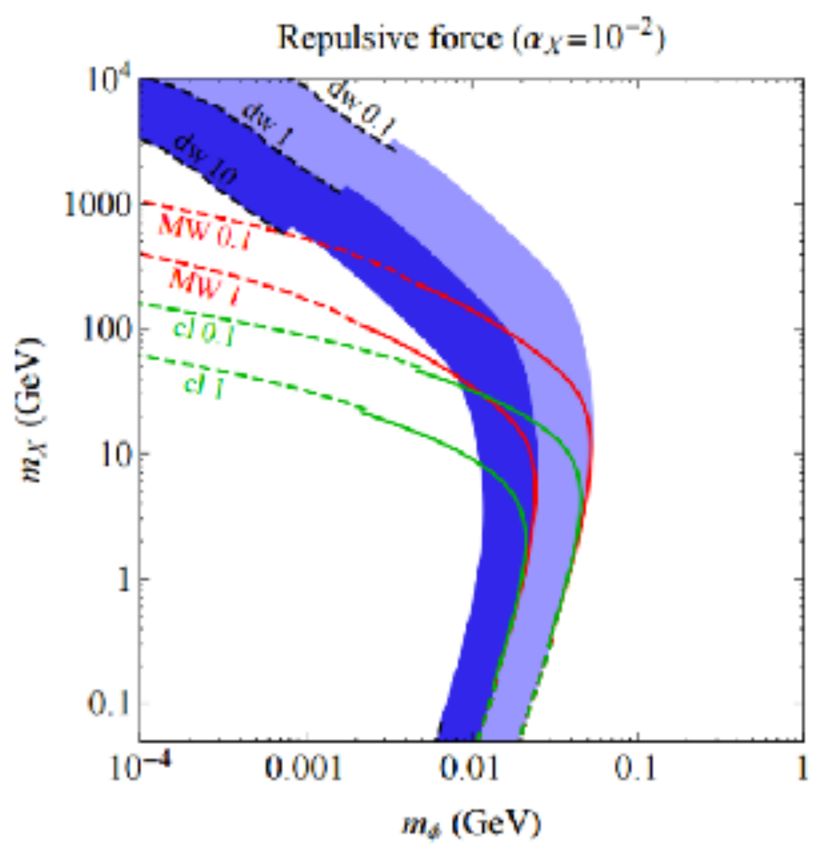
[Tulin, Yu & Zurek, 1302.3898]

Yukawa model



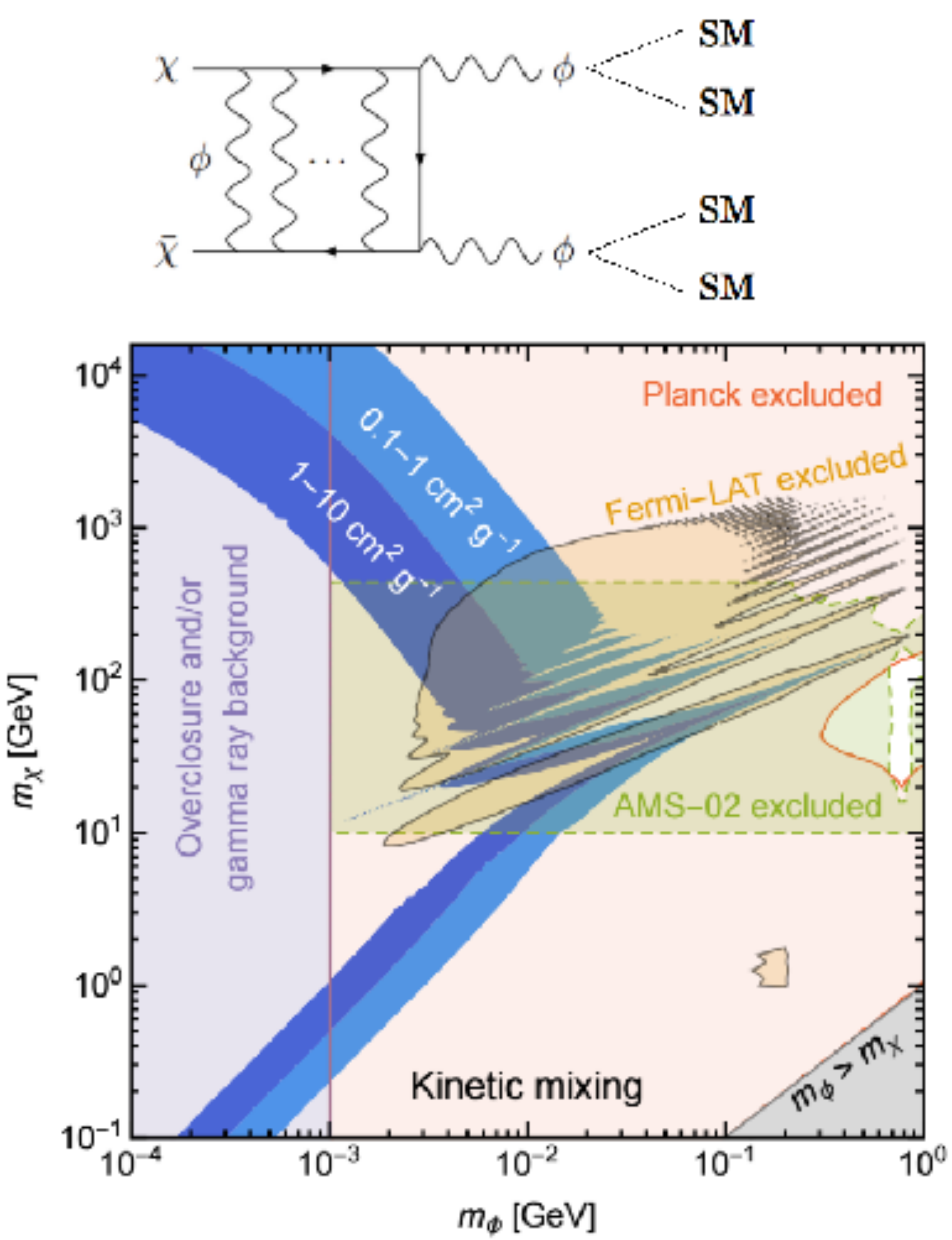






But beware of signatures ...

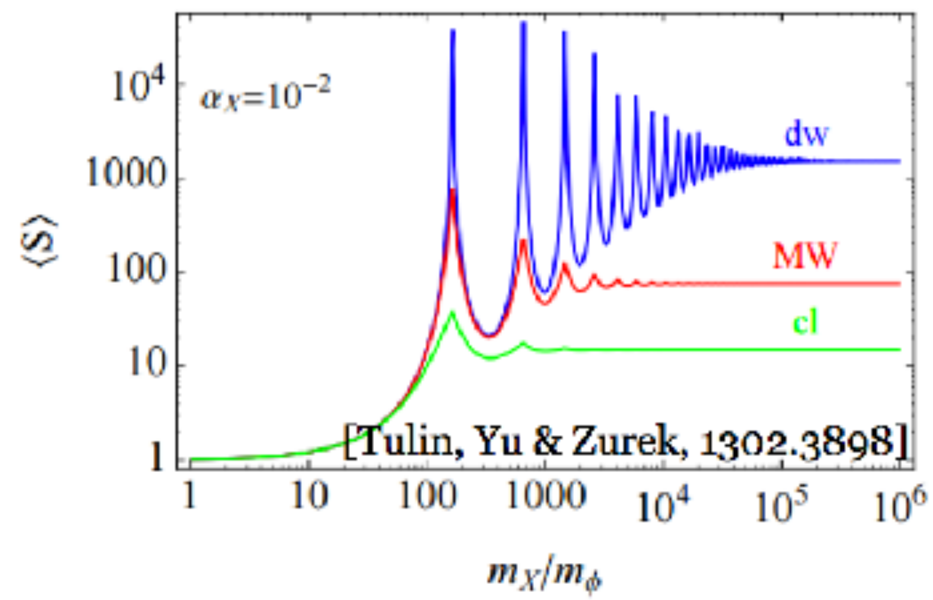
Courtesy Bryan Zaldivar



[Bringmann, Kahlhoefer, Schmidt-Hoberg & Walia, 1612.00845]

Sommerfeld enhancement:

$$\sigma v_{\rm rel} = (\sigma v_{\rm rel})_{\rm pert} \times S(v_{\rm rel})$$



Assumptions:

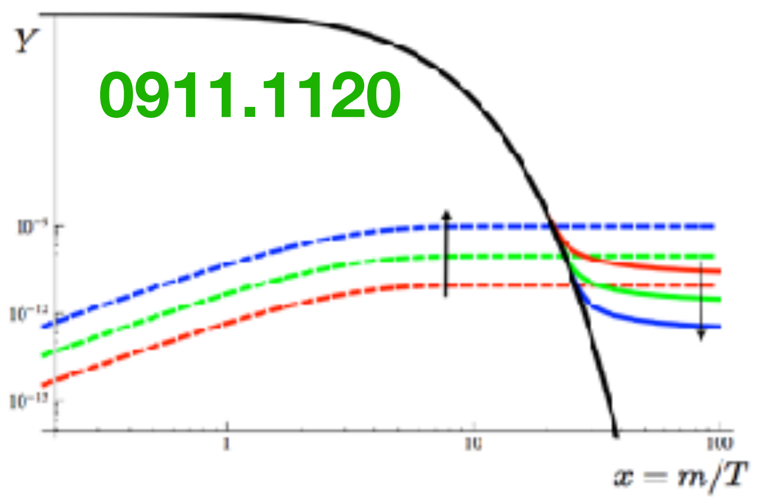
1) s-wave DM annihilation

2) kinetic-mixing w/ photons

3) dark sector thermalised with SM at some point before freeze-out

Can we have light SELF & STRONGLY Interacting DM?

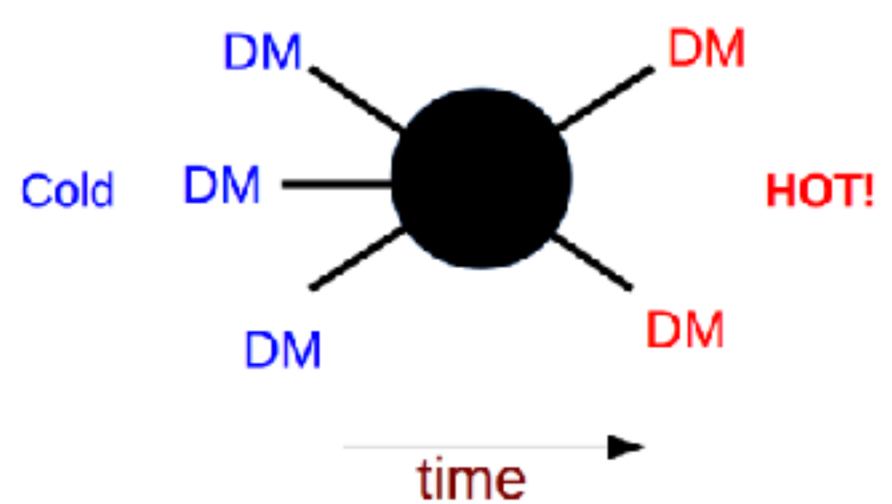
New ways to explain the relic abundance



Freeze-in mechanism but there are more...

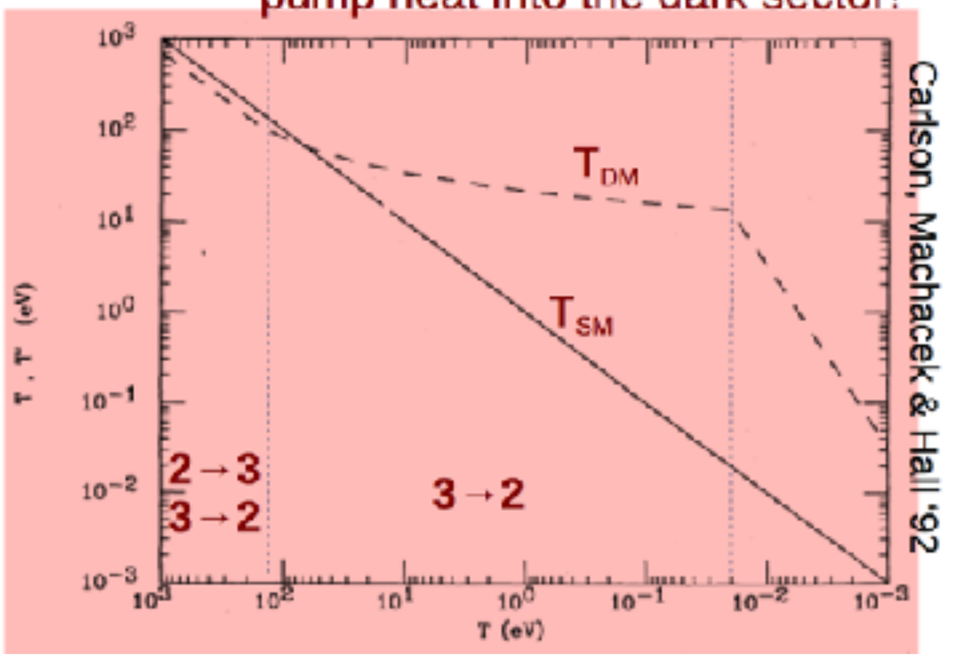
Including 3 ->2 processes

$$\frac{dn}{dt} + 3\,H\,n = -\langle\sigma v^2\rangle_{3\to2}\;(n^3 - n^2\,n_{\rm eq})$$



Nicolás BERNAL - UAN

Caveat: 3 → 2 annihilations
pump heat into the dark sector!

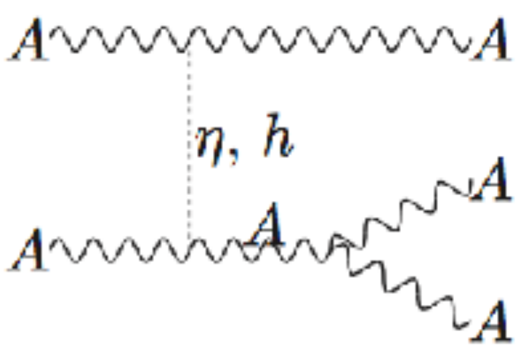


Canibal DM revived by Hochberg, Kuflik, Volansky & Wacker '14

SELF & STRONGLY Interacting DM & relic abundance

Courtesy Camilo Garcia Cely

Local $SU(2)_X$	$\rightarrow$	Global $SO(3)$
Gauge Fields A'_μ	$\rightarrow$	Massive Fields A_μ
Doublet ϕ	$\rightarrow$	Higgs-like η

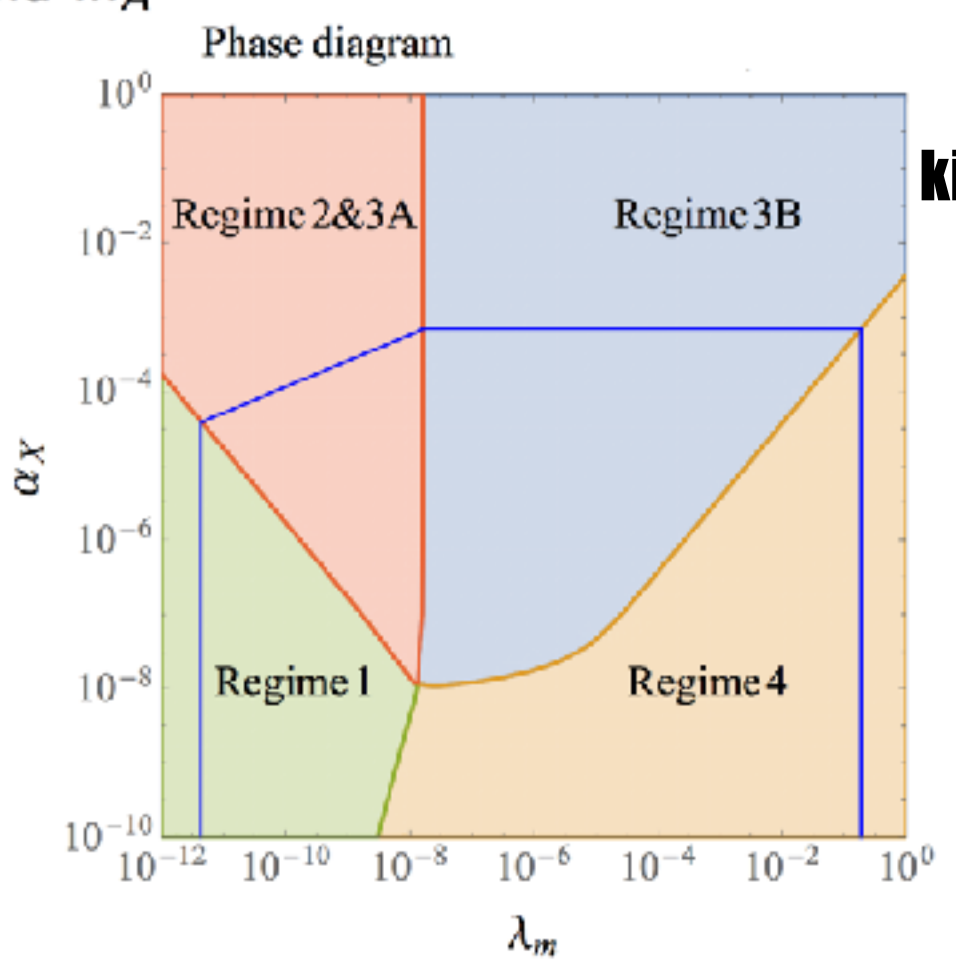


Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)

For fixed m_η and m_A

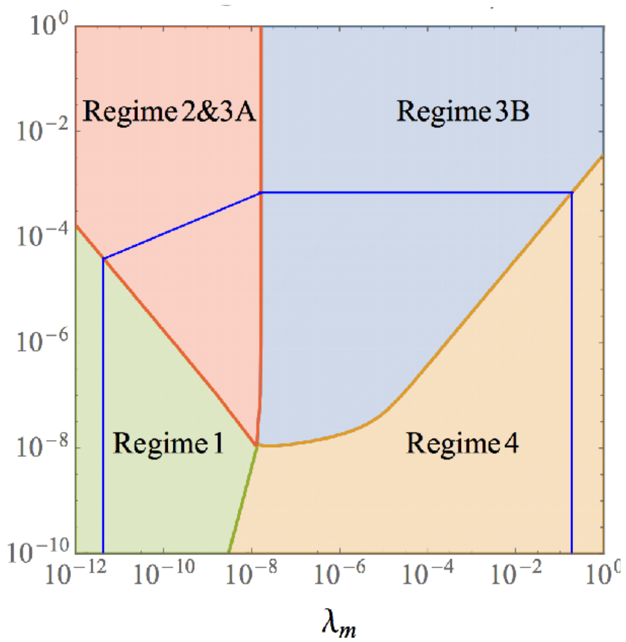
SIMPs not in kinetic equilibrium

SIMPs in kinetic equilibrium



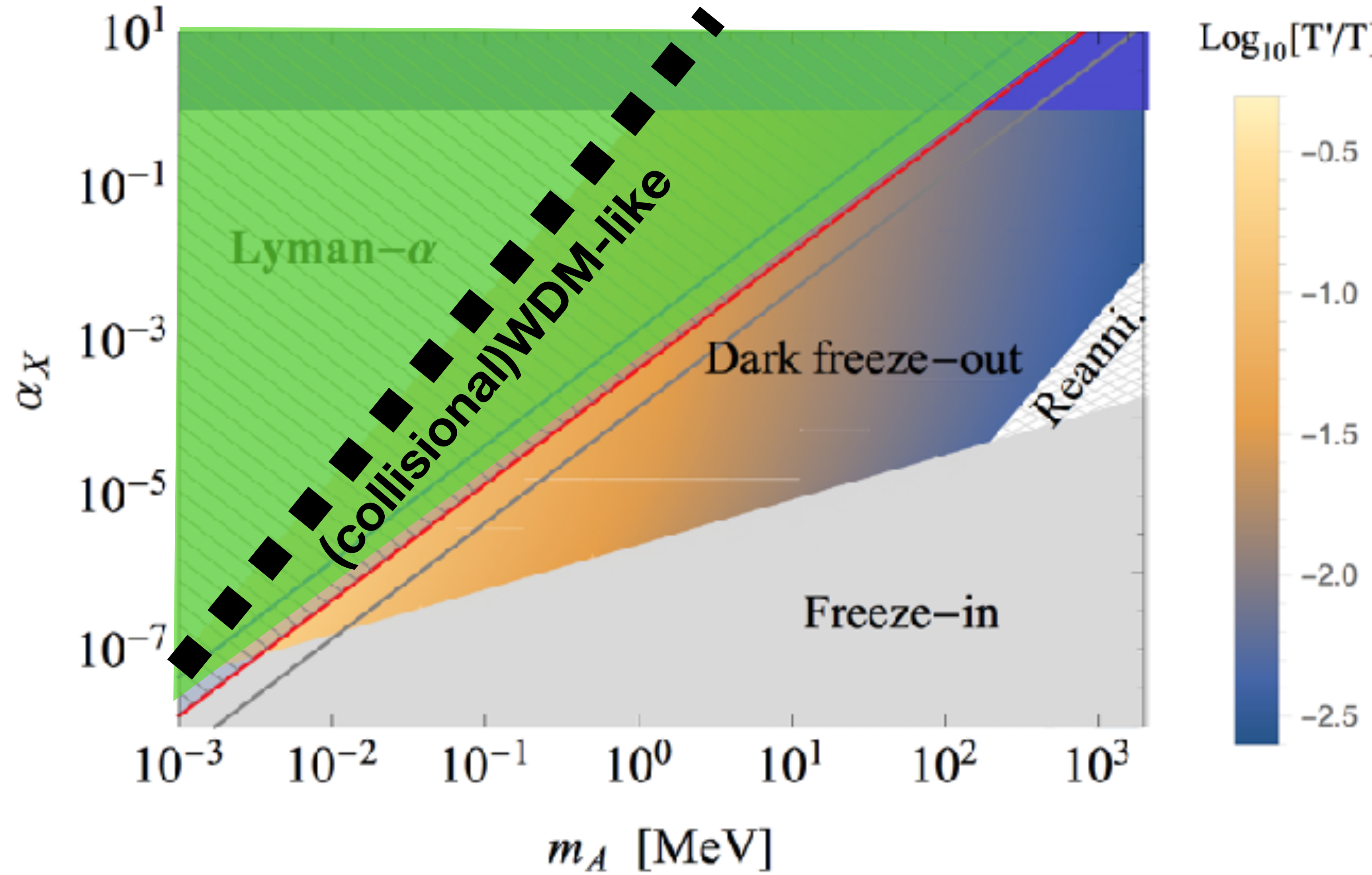
Freeze-in

Bryan's favourite



Regime 3A

Bernal, Chu, GGC, Hambye, Zaldivar (JCAP 2016)



excluded by cluster observations

Figure: Parameter space for self-Interactions

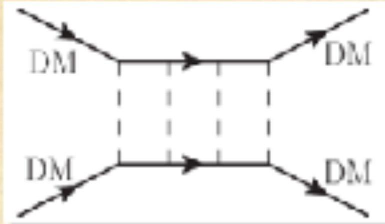
3->2 is quite constrained!

Can we have light SELF & STRONGLY Interacting DM?

DM self-interactions via a scalar mediator

or pseudo scalar mediator

(Maria's favourite?)



$$\longrightarrow V(r) \propto \frac{e^{-m_\phi r}}{r}$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{PP} = |f(\theta) \pm f(\pi - \theta)|^2$$

$$\left(\frac{d\sigma}{d\Omega}\right)^{PA} = |f(\theta)|^2$$

$$\sigma_{\tilde{T}}^{PP,PA} \equiv \int d\Omega \,(1 - |\cos\theta|) \left(\frac{d\sigma}{d\Omega}\right)^{PP,PA}$$

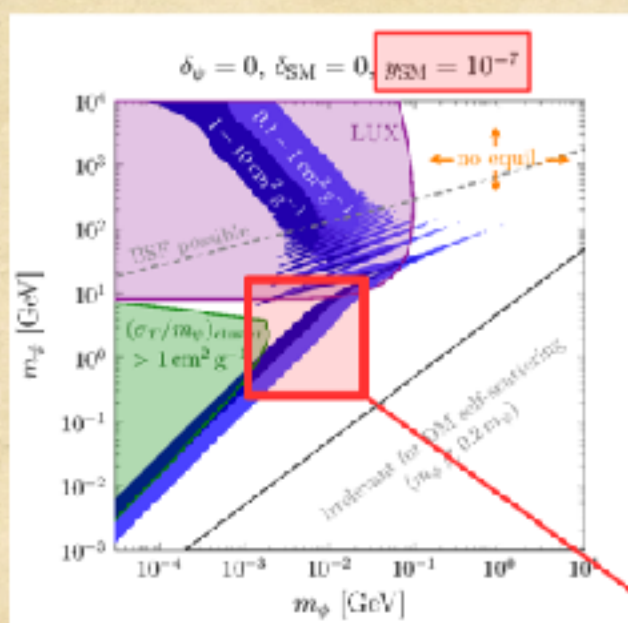
$$\sigma_{\tilde{T}} = \frac{1}{2}\left(\sigma_{\tilde{T}}^{PP} + \sigma_{\tilde{T}}^{PA}\right)$$

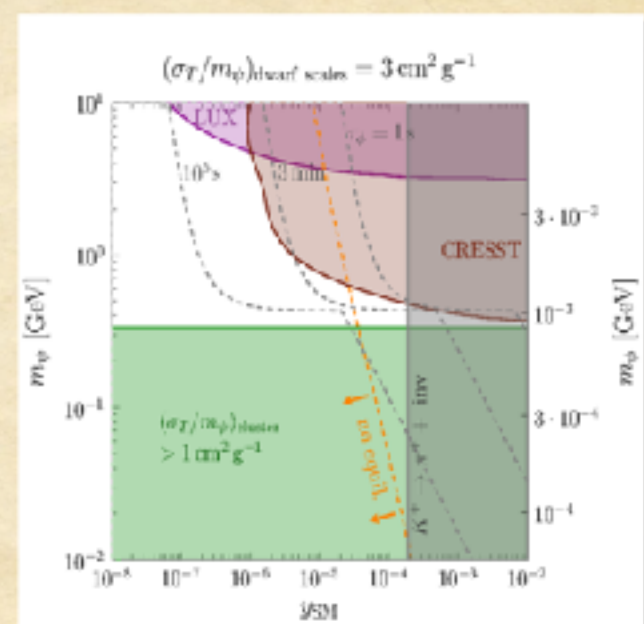
► automatically leads to the desired velocity-dependence of $\sigma_{\tilde{T}}$!

Courtesy Sebastian Wild

Direct Detection if interactions with SM

Status of SIDM via a light mediator





What to do with this model?

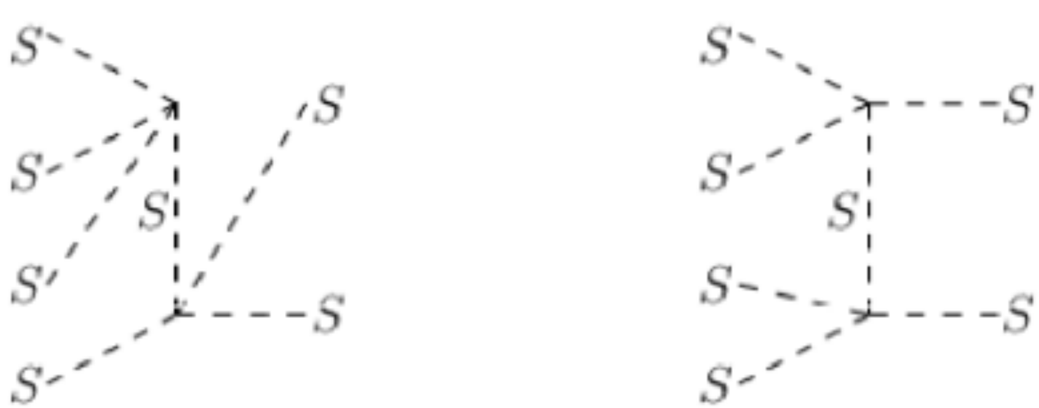
(1) Potentially remaining parameter space: $m_{DM} \sim$ GeV , $m_\phi \sim 1 - 10$ MeV

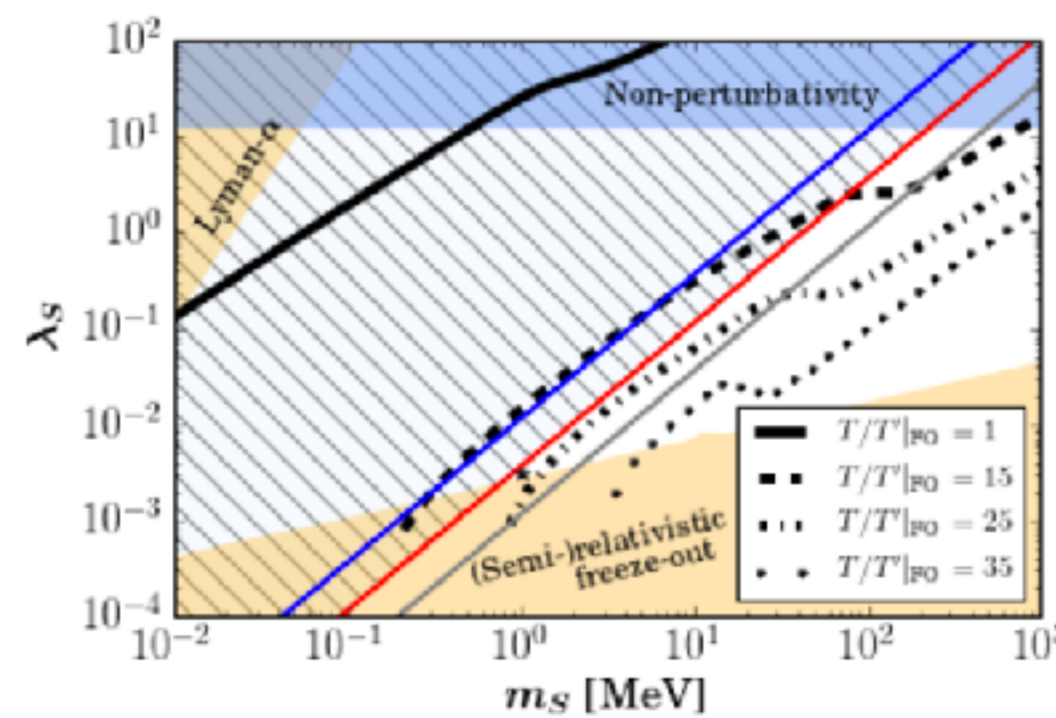
→ what can we learn from **future direct detection experiments?**

Singlet Scalar DM
4 → 2 annihilations

Courtesy Nicolas Bernal

$$\frac{dn}{dt} + 3\,H\,n = -\langle \sigma v^3 \rangle_{4\to 2}\,\left(n^4 - n^2\,n_{\rm eq}^2\right)$$

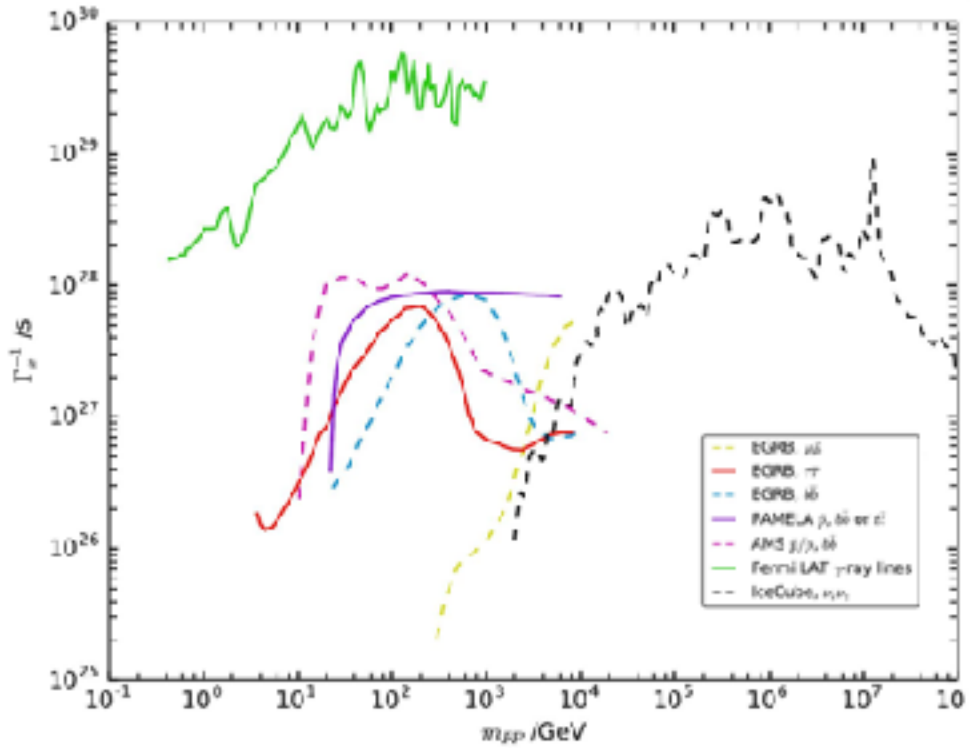




- Self-interacting DM with no light mediators → SIMP DM
- Z_2 SIMP DM generated via 4 → 2 annihilations
- DM: MeV ballpark, ‘large’ self-interactions & 'small' portal with the SM
- Difference of temperatures *dynamically* produced via freeze-in!
- Self-interactions: small velocity dependence

$T_{SM} = T_{DM}$
&
$T_{SM} \neq T_{DM}$ @ DM freeze-out

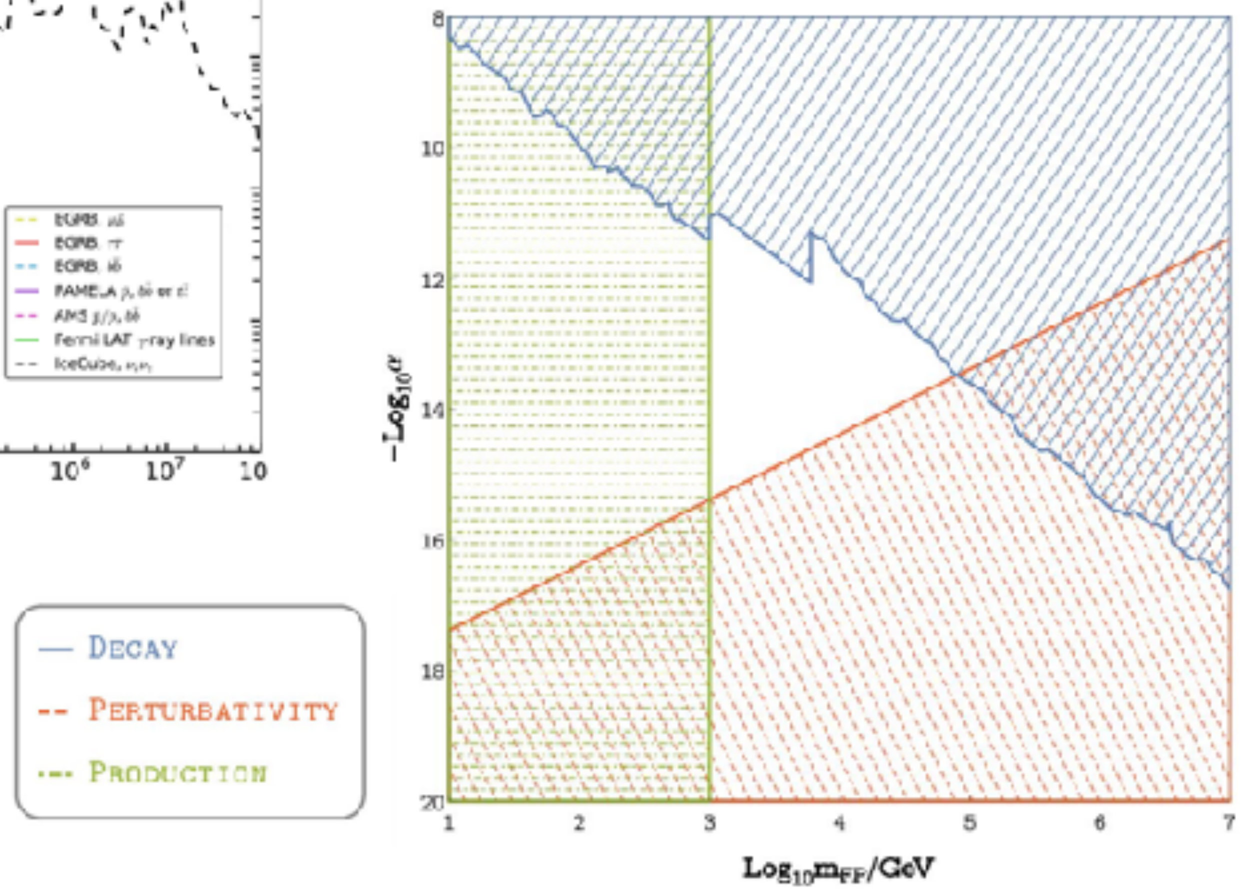
Heavy spin-2 DM



$$\Gamma(\delta M \to \mathrm{SMSM}) \sim \frac{\alpha^2 m_{FP}^3}{m_{Pl}^2}$$

Babichev, Marzola, Raidal, Schmidt-May
Urban, Veermäe, Von Strauss (PRD 2016, JCAP 2016)

Production via Freeze-in



Courtesy Camilo Garcia Cely

small couplings give GR & SIDM

subGeV SIDM candidate

$$g_{\mu\nu} = \bar{g}_{\mu\nu} + \frac{\delta G_{\mu\nu}}{m_{Pl}} + \mathcal{O}(\alpha^1), \quad f_{\mu\nu} = \bar{g}_{\mu\nu} + \frac{1}{\alpha}\frac{\delta M_{\mu\nu}}{m_{Pl}} + \mathcal{O}(\alpha^1)$$

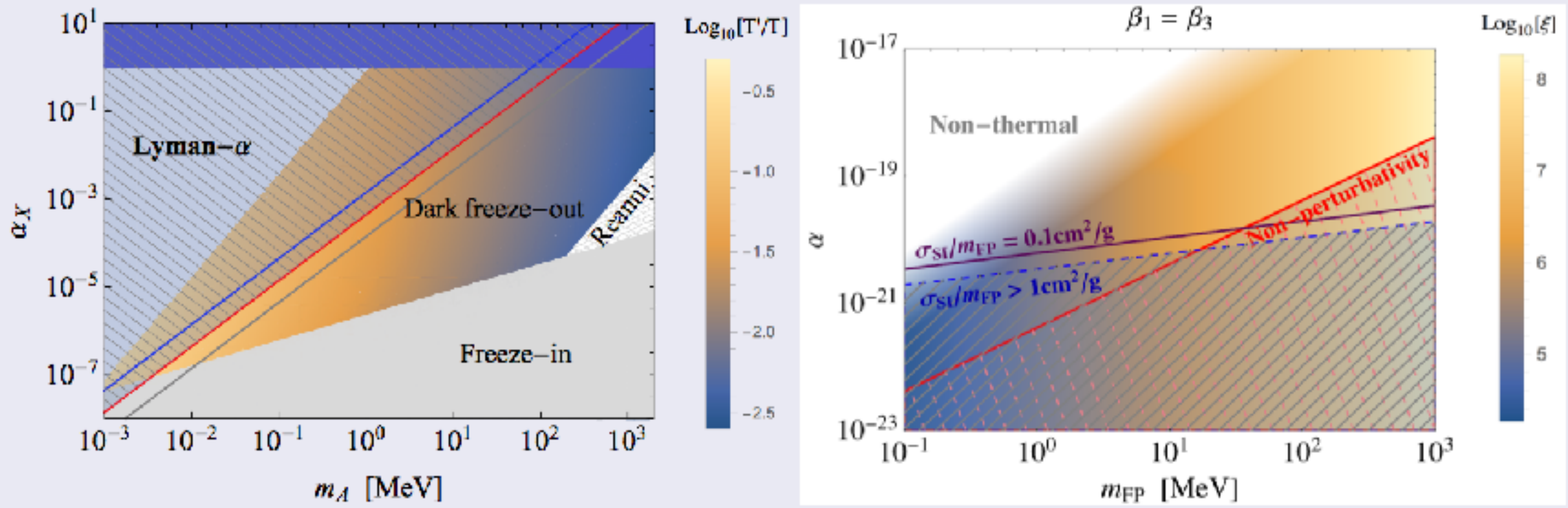
Loosely speaking, the self-interactions of δM are the same as those of δG but enhanced by powers of $1/\alpha$.

Camilo must be having some fun…

Figure: Bimetric theories naturally give rise to self-interacting spin-2 DM

Conclusions

- In bimetric theories, requiring negligible interactions between the second metric and ordinary particles naturally leads to spin-2 SIDM capable of addressing the small-scale problems.
- SIDM without light mediators can be produced via 3-to-2 annihilations. The corresponding increase of temperature is not problematic if the two sectors have a large temperature ratio before freeze-out.



Courtesy Camilo Garcia Cely

What kind of cross section?

Velocity dependence

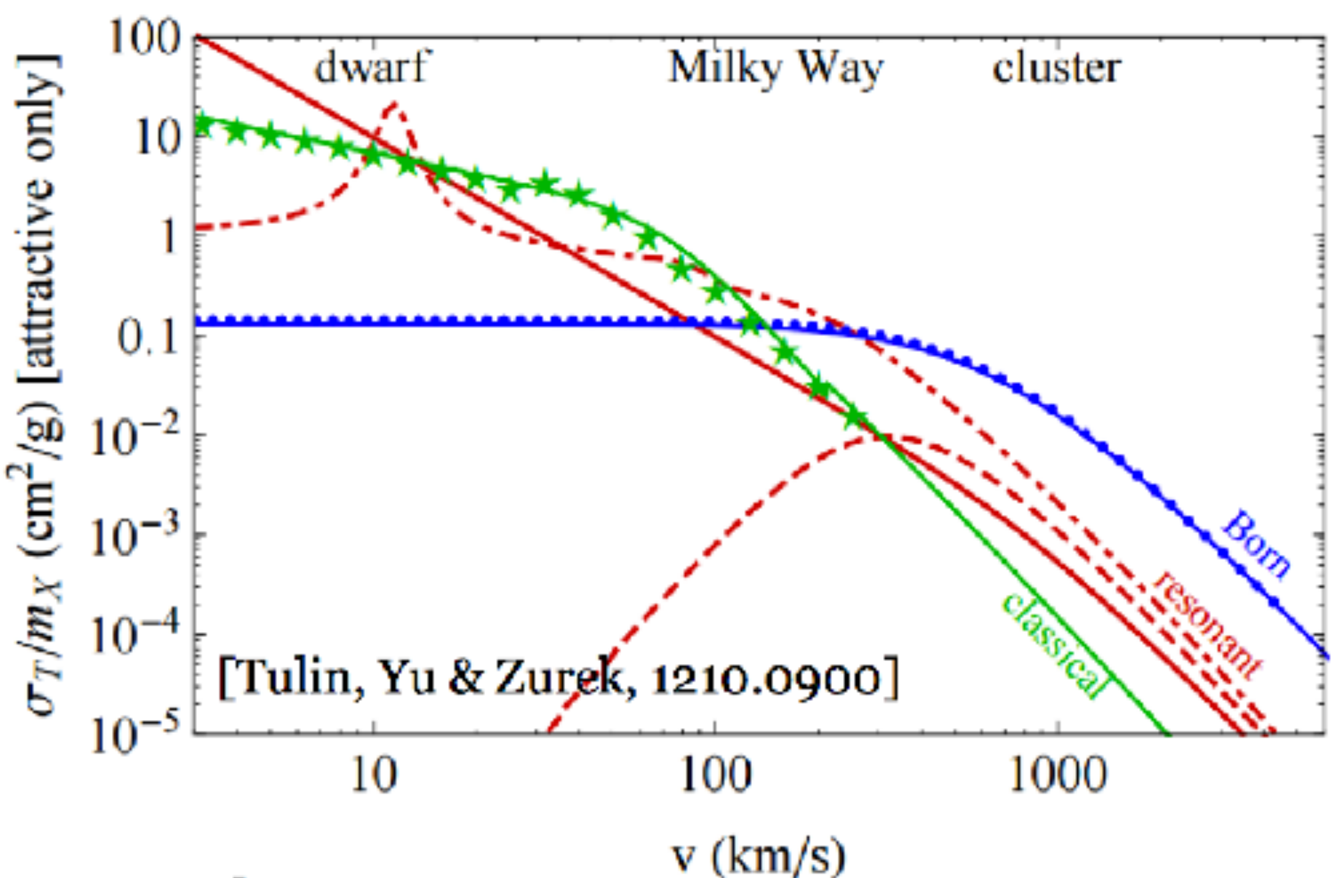
Courtesy Bryan Zaldivar

$$\mathcal{L} \supset g' \bar{\chi} \gamma^\mu \chi A'_\mu$$

- standard Yuwaka potential

$$V = \pm \frac{\alpha'}{r} e^{-m_{A'} r}$$

- other potentials are easily possible



[Bellazzini, Cliche & Tanedo, 1307.1129]

$$V = \frac{1}{4\pi r}\left[g_1 + g_2(\mathbf{s_1}\cdot\mathbf{s_2}) + \frac{g_3}{\Lambda^2 r^2}(3\mathbf{s_1}\cdot\hat{r}\;\mathbf{s_2}\cdot\hat{r} - \mathbf{s_1}\cdot\mathbf{s_2}) + \frac{g_{7,8}}{\Lambda r}(\mathbf{s_1}\pm\mathbf{s_2})(\hat{r}\times\mathbf{v})\right)$$

Interaction	g_1	g_2	g_3	g_7	g_8
$\bar{\chi}\chi\varphi$	✓	X	X	✓	X
$\bar{\chi}\gamma^5\chi\varphi$	X	X	✓	X	X
$i\bar{\chi}\gamma^\mu\gamma^5\chi\partial_\mu\varphi$	X	X	✓	X	X
$\bar{\chi}\gamma^\mu\chi A_\mu$	✓	X	X	✓	X
$i\bar{\chi}\gamma^5\gamma^\mu\chi A_\mu$	X	X	✓	X	X
$i\bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu}$	X	X	✓	X	X

What kind of cross section?

Courtesy Mauro Valli

M.V. & H.B.Yu (in prep.)

MW dSph	$\langle\sigma v\rangle$ [cm^3 g^{-1} s^{-1}]	$\langle v\rangle$ [km s^{-1}]	σ/m [cm^2 g^{-1}]
Ursa Minor	$1.2^{+2.2}_{-0.7}\times 10^2$	52^{+11}_{-7}	$2.9^{+2.7}_{-1.8}$
Sculptor	$0.53^{+0.22}_{-0.22}\times 10^2$	$39.5^{+3.0}_{-3.5}$	$1.23^{+0.62}_{-0.37}$
Draco	$0.65^{+0.54}_{-0.28}\times 10^2$	$45.7^{+3.7}_{-5.5}$	$1.60^{+0.93}_{-0.64}$
Sextans	$0.6^{+4.0}_{-0.3}\times 10^2$	51^{+16}_{-7}	$0.3^{+8.1}_{-0.2}$
Carina	$1.3^{+1.2}_{-0.6}\times 10^2$	$46.9^{+5.6}_{-4.8}$	$2.7^{+2.3}_{-1.1}$
Fornax	$0.28^{+0.16}_{-0.09}\times 10^2$	$30.9^{+2.5}_{-1.3}$	$0.93^{+0.66}_{-0.38}$
Leo II	$2.1^{+2.0}_{-1.3}\times 10^2$	53^{+13}_{-3}	$3.7^{+2.9}_{-1.7}$
Leo I	$1.04^{+0.76}_{-0.43}\times 10^2$	$45.7^{+3.4}_{-4.6}$	$2.4^{+1.5}_{-0.9}$

$$1\,\mathrm{cm^2 g^{-1}} \lesssim \sigma/m \lesssim 3\,\mathrm{cm^2 g^{-1}}$$
$$30\,\mathrm{km\,s^{-1}} \lesssim \langle v\rangle \lesssim 70\,\mathrm{km\,s^{-1}}$$

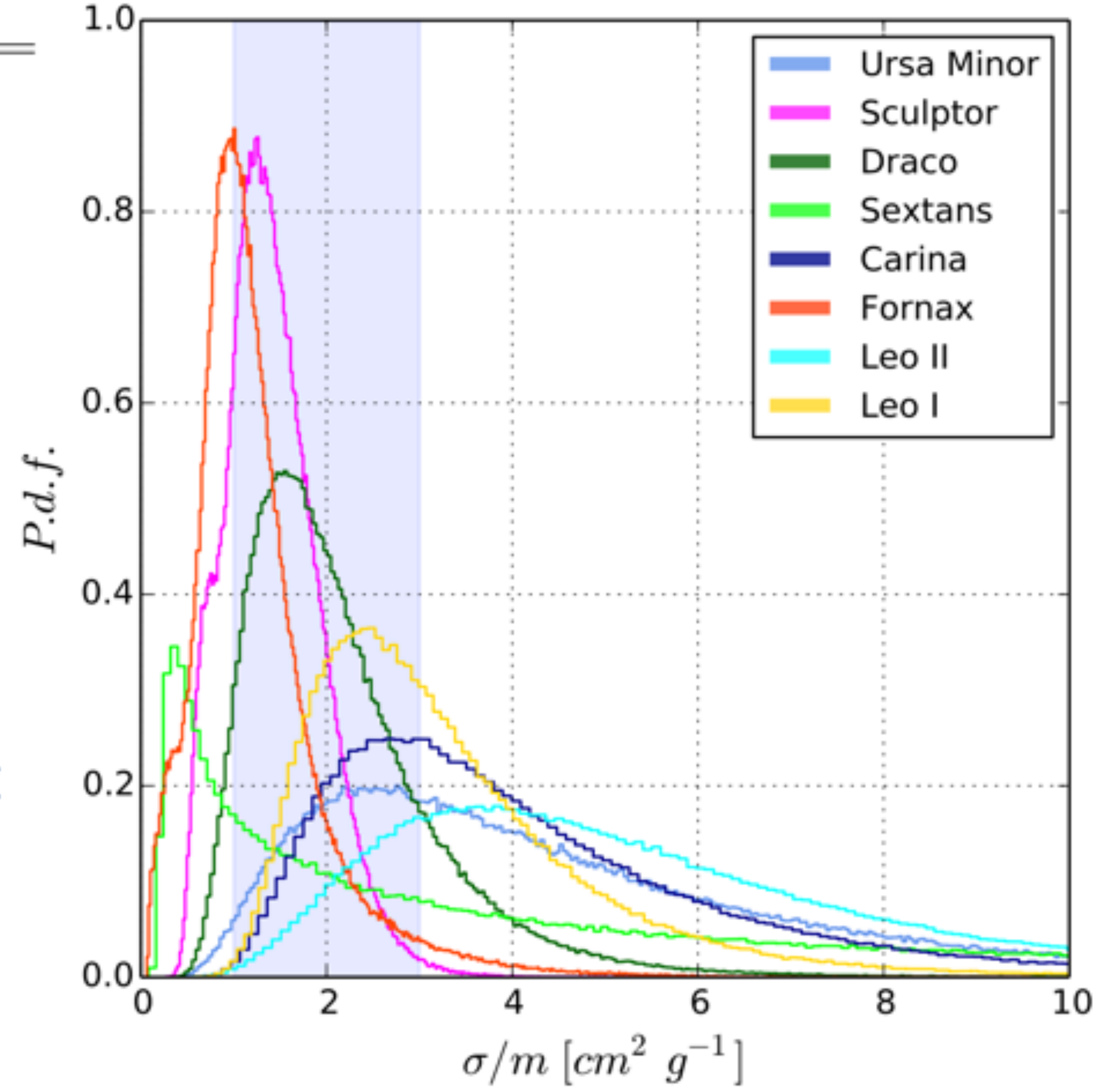
Our study on SIDM halo in MW dSphs shows:

I) X-sec range in agreement with current indications from N-body simulations.
Zavala, J. et al. '13, Elbert, O. et al. '15

II) Same SIDM ballpark to address "Core VS Cusp" in other kpc-sized systems.
Kaplinghat, M. et al. '16, Kamada, A. et al. '17

III) Some tension left btw goodness of the fit of kinematic data & outer match to CDM.

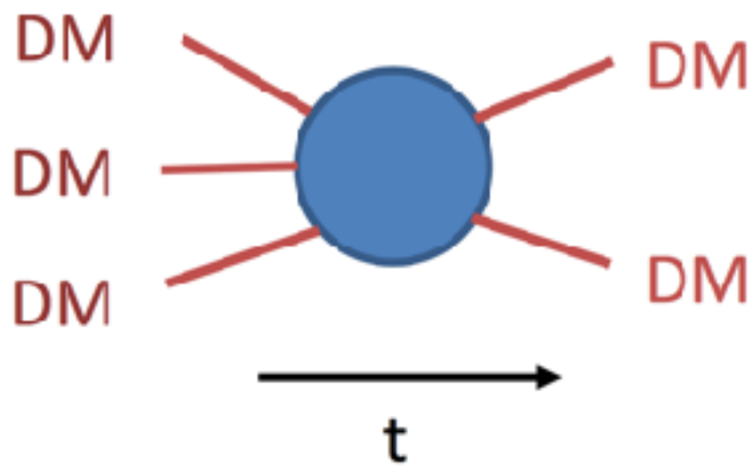
—> SIDM ameliorates TBTF problem!
Vogelsberger, M. et al. '16 (ETHOS)



What kind of cross section?

Courtesy Mauro Valli

Strongly Interacting Massive Particles



PRL 113 (2014) 171301, Hochberg,Y. et al.
PRL 115 (2015) 021301, Hochberg,Y. et al.

@ strong coupling, strong scale emerges:

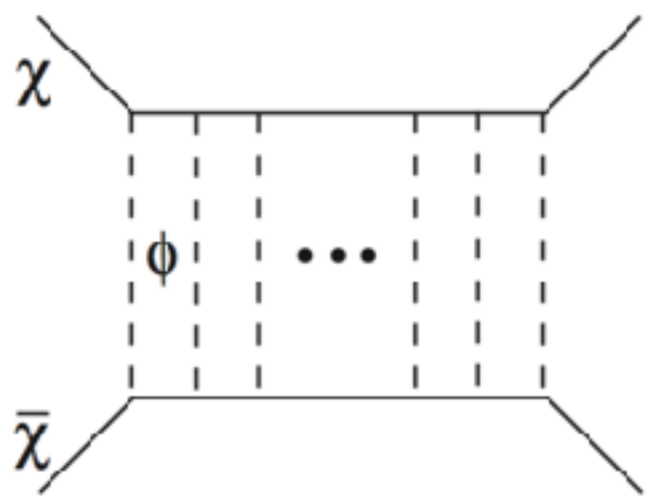
$$m_{DM} \sim \alpha_{eff} (T_{eq}^2 M_{Pl})^{1/3}$$

"Simple" realizations involve non-Abelian dark sector with QCD-like chiral symmetry breaking

Dominant 3, 4 —> 2 annihilations, dark sector cannot be completely secluded from SM

ApJ 398 (1992) 43 , E.D. Carlson, M. E. Machacek & L.J.Hall

Self-Interactions with Light Mediators



PRD 81 (2010) 083522 , M.R.Buckley & P.J.Fox
PRL 106 (2011) 171303 , A.Loeb & N.Weiner
PRL 110 (2013) 111301 , S.Tulin, K.Zurek & H.B.Yu

In the perturbative regime, large self-scattering point to MeV mediators for weak-scale DM:

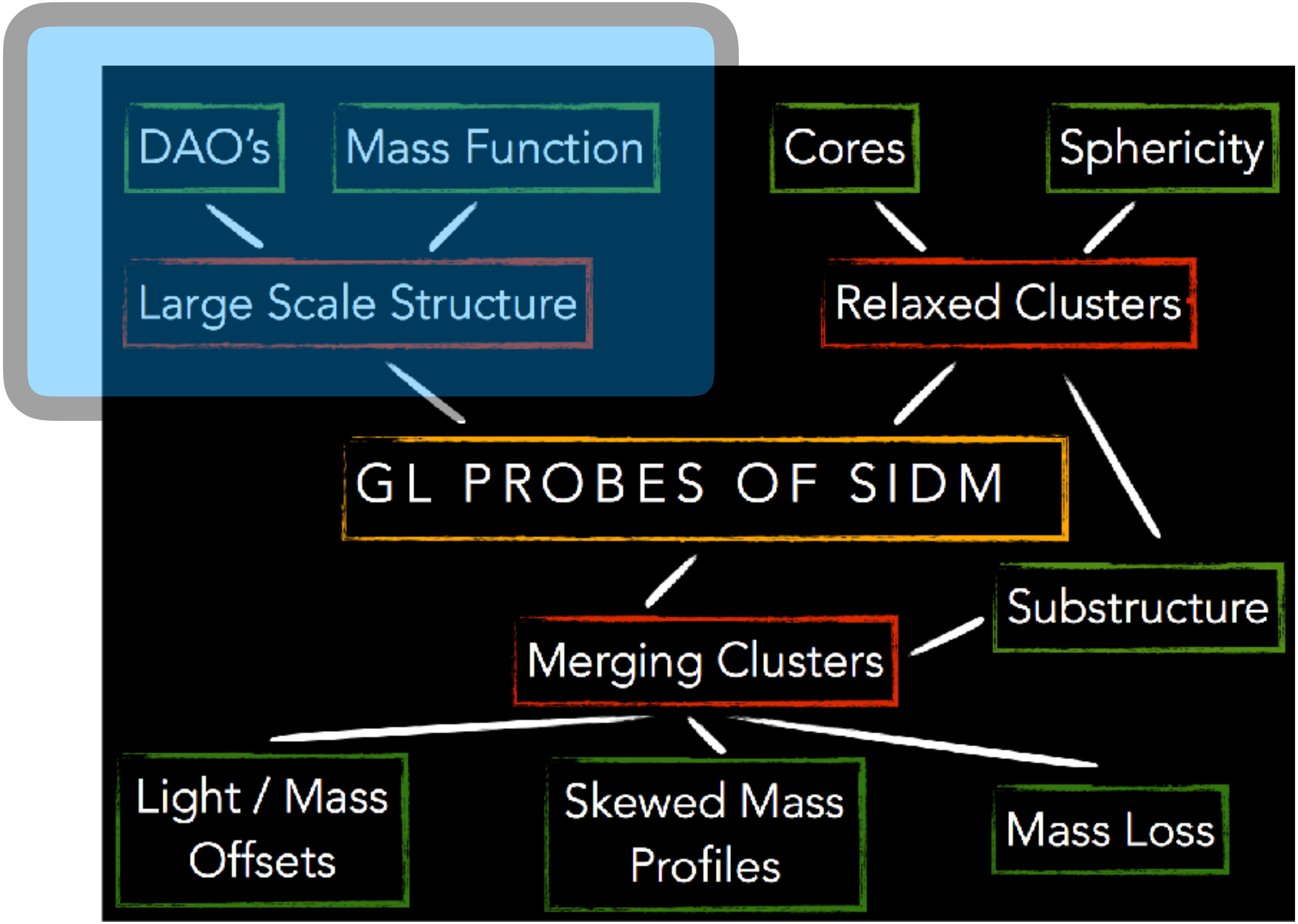
$$g^4 \frac{m_\chi^2}{m_\phi^4} \sim 10^{14} \frac{\alpha_{EW}^2}{m_\chi^2} \Rightarrow \frac{m_\phi}{m_\chi} \sim \left(\frac{g}{0.1}\right)^4 10^{-4}$$

E.g.: $U(1)_D$ coupled to SM through $U(1)_Y$ small mixing

PRD 89 (2014) 035009 , M.Kaplinghat et al.
PRL 118 (2017) 141802 , T.Bringmann et al.
arXiv:1707.02149 , F.Kahlhoefer et al.

LIGHT MEDIATOR MODELS ALLOW FOR DM V-DEPENDENT SELF-SCATTERING X-SEC!

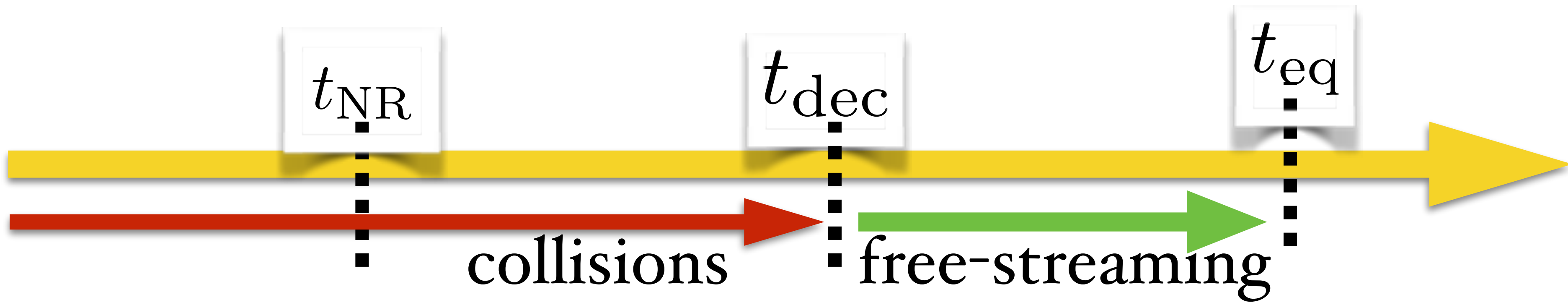
Probing SIDM
with cosmology

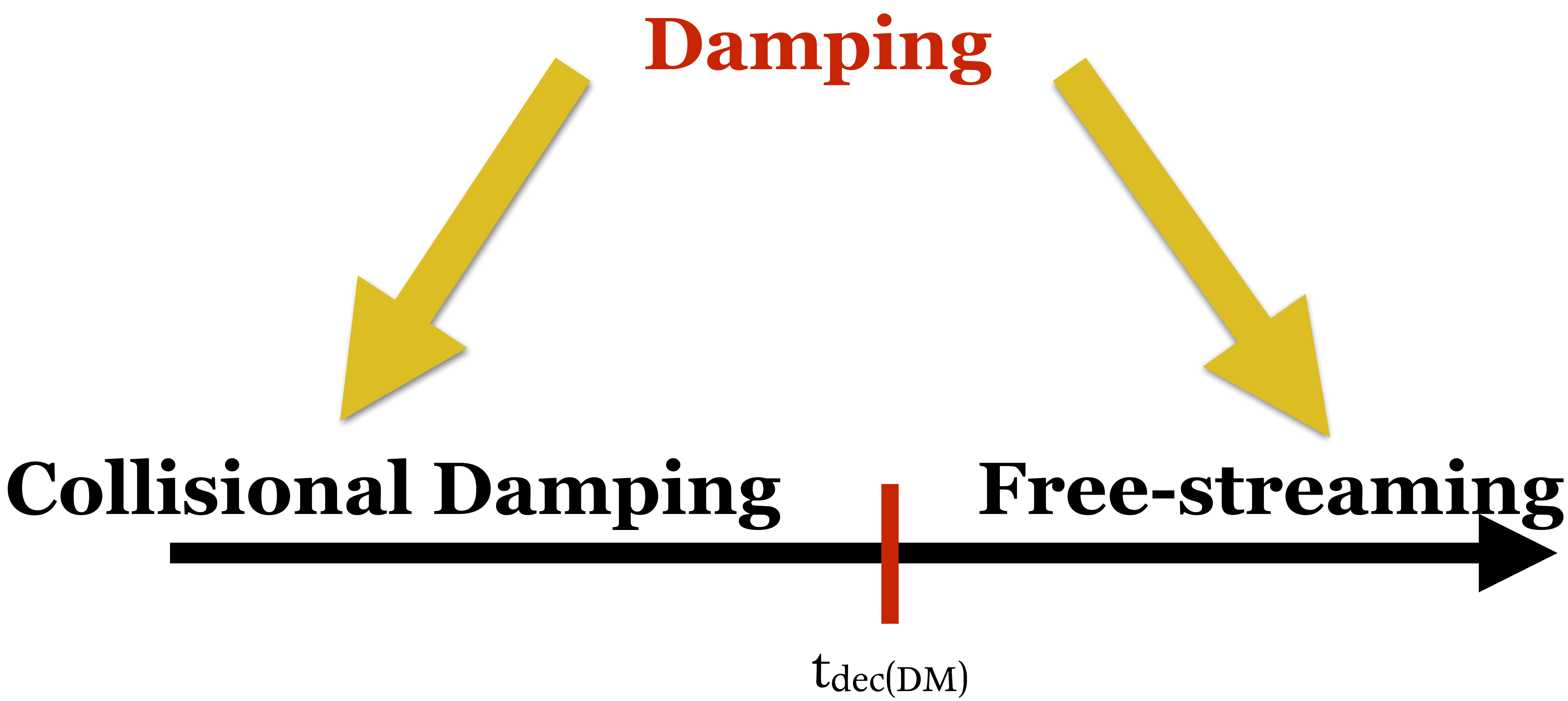


Courtesy David Harvey

But (strongly) self-interacting DM has interactions

(astro-ph/0012504, astro-ph/0410591)





$$l_{id}^2 \sim \frac{2\ \pi^2}{3} \int_0^{t_{dec(dm-i)}} \frac{\rho_i\ v_i^2}{\rho_t\ a^2\ \Gamma_i} dt$$

$$l_{fs} = \int_{t_{dec}}^{t_0} \frac{v}{a(t)} \times dt$$

Collisional damping for self-interacting DM

$$l_{id}^2 \sim \frac{2\ \pi^2}{3} \int_0^{t_{\mathrm{dec(dm-i)}}} \frac{\rho_{\mathrm{i}}\ v_i^2}{\rho_t\ a^2\ \Gamma_{\mathrm{i}}} dt$$

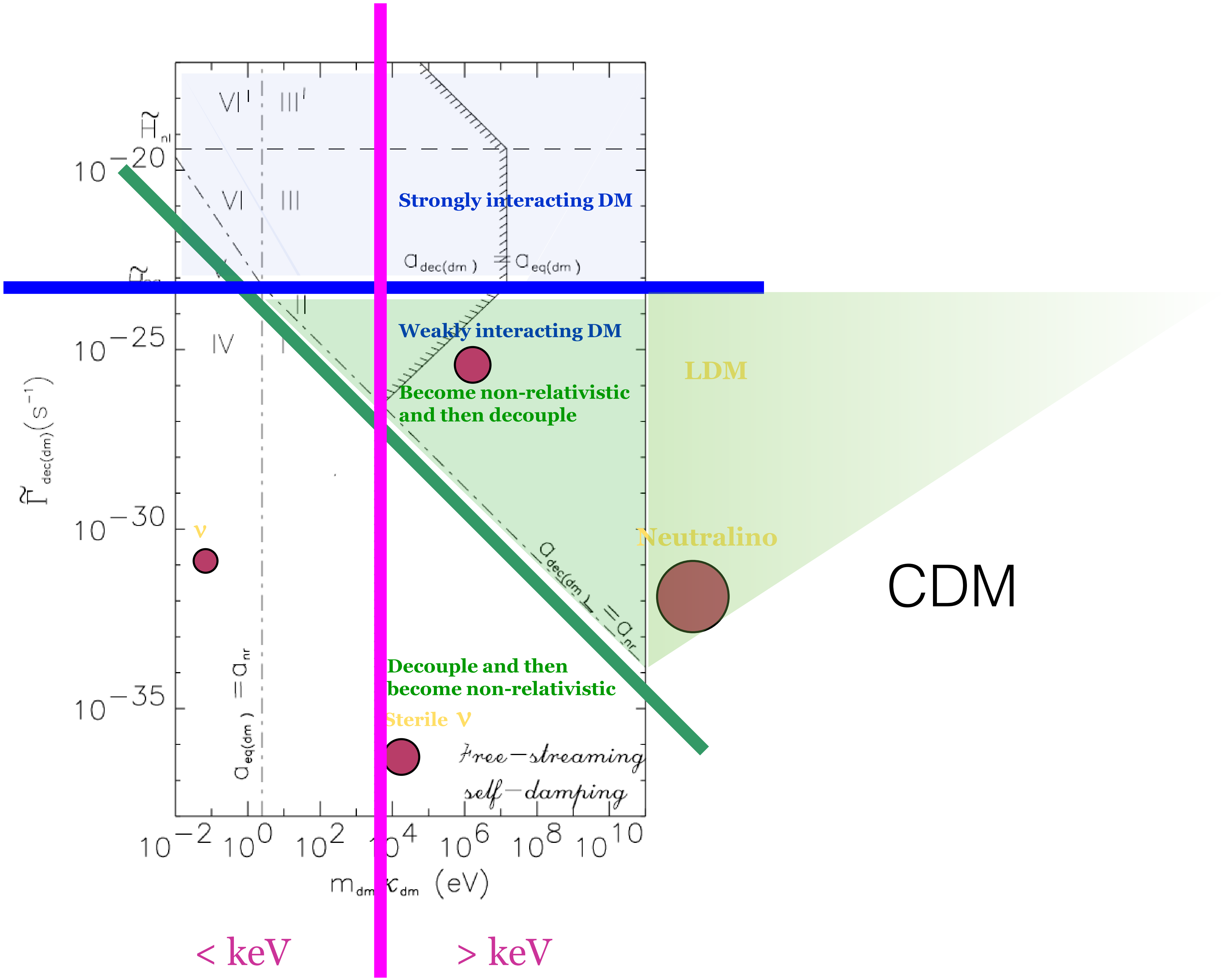
$$l_{fs} = \int_{t_{dec}}^{t_0} \frac{v}{a(t)} \times dt$$

$$l_{sd}^2 \sim \frac{2\pi^2}{3} \frac{\rho_{dm} v_{dm}^2 t}{\rho a^2 \Gamma_{dm}} (1 + \Theta_{dm}) |_{dec(dm)}$$

$$l_{sd} \sim \pi r_{dm} \left(\frac{H}{\Gamma_{dm}} \right)^{\frac{1}{2}} \frac{v_{dm} t}{a} |_{dec(dm)}$$

Classification

(astro-ph/0012504, astro-ph/0410591)



The physics of DM interactions on primordial fluctuations

astro-ph/0112522

last until DM stop interacting

efficient if the DM is coupled to a relativistic species

$$l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2\, t}{\rho\, a^2 \Gamma_i}\,(1+\Theta_i)\,\frac{dt}{t}$$

efficient if DM is coupled to a species that is also interacting with other fluids

without DM interactions

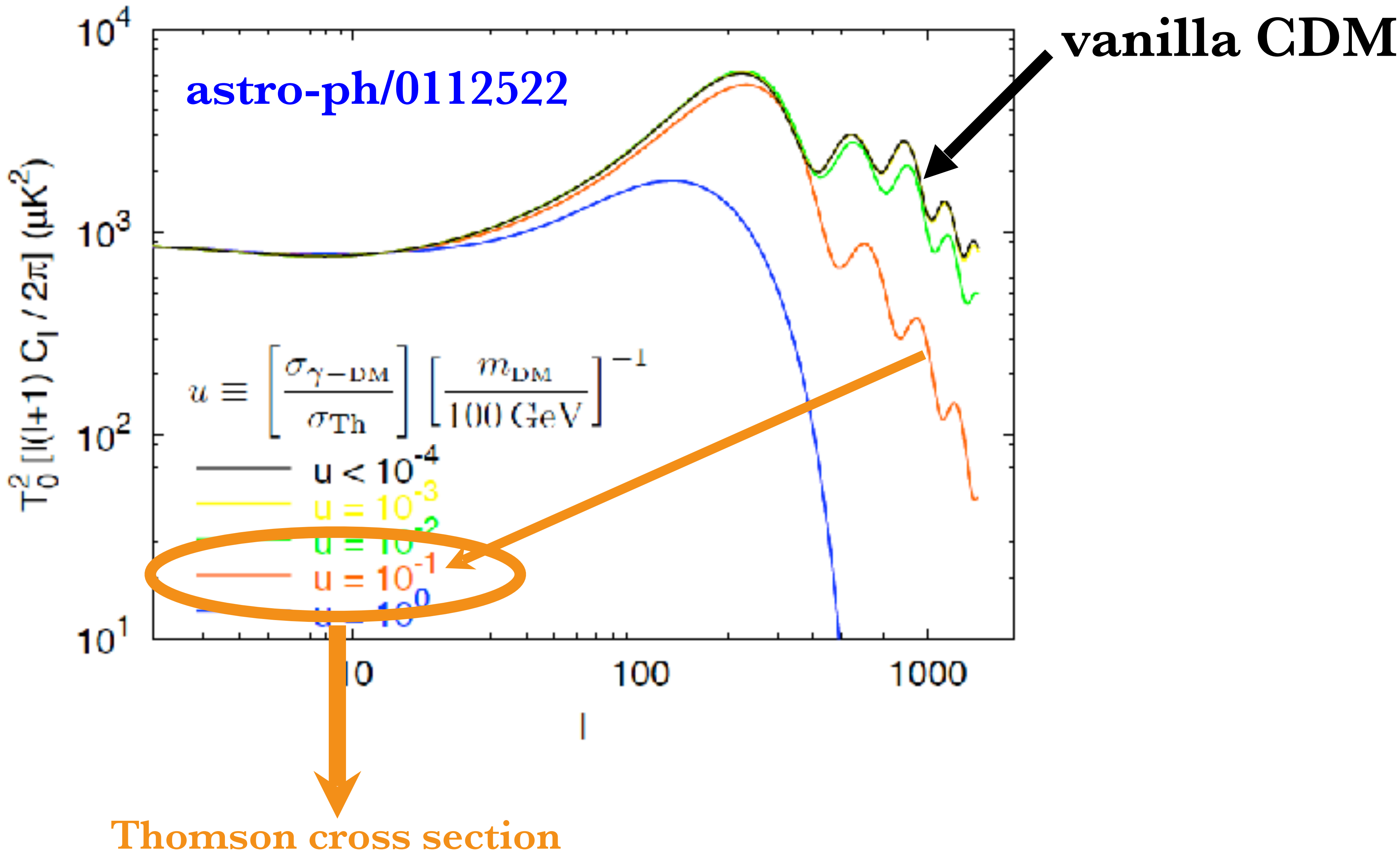
$$\begin{aligned}
\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)\\
\dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot\kappa(\theta_\gamma - \theta_b)\ ,\\
\dot\theta_{DM} &= k^2\psi - \mathcal{H}\theta_{DM}\ ,
\end{aligned}$$

with DM interactions

$$\begin{aligned}
\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma)\\
\dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right)\\
&\quad -\dot\kappa(\theta_\gamma - \theta_b) - \dot\mu(\theta_\gamma - \theta_{DM})\ ,\\
\dot\theta_{DM} &= k^2\psi - \mathcal{H}\theta_{DM} - S^{-1}\dot\mu(\theta_{DM} - \theta_\gamma)\ .
\end{aligned}$$

DM-photon interactions

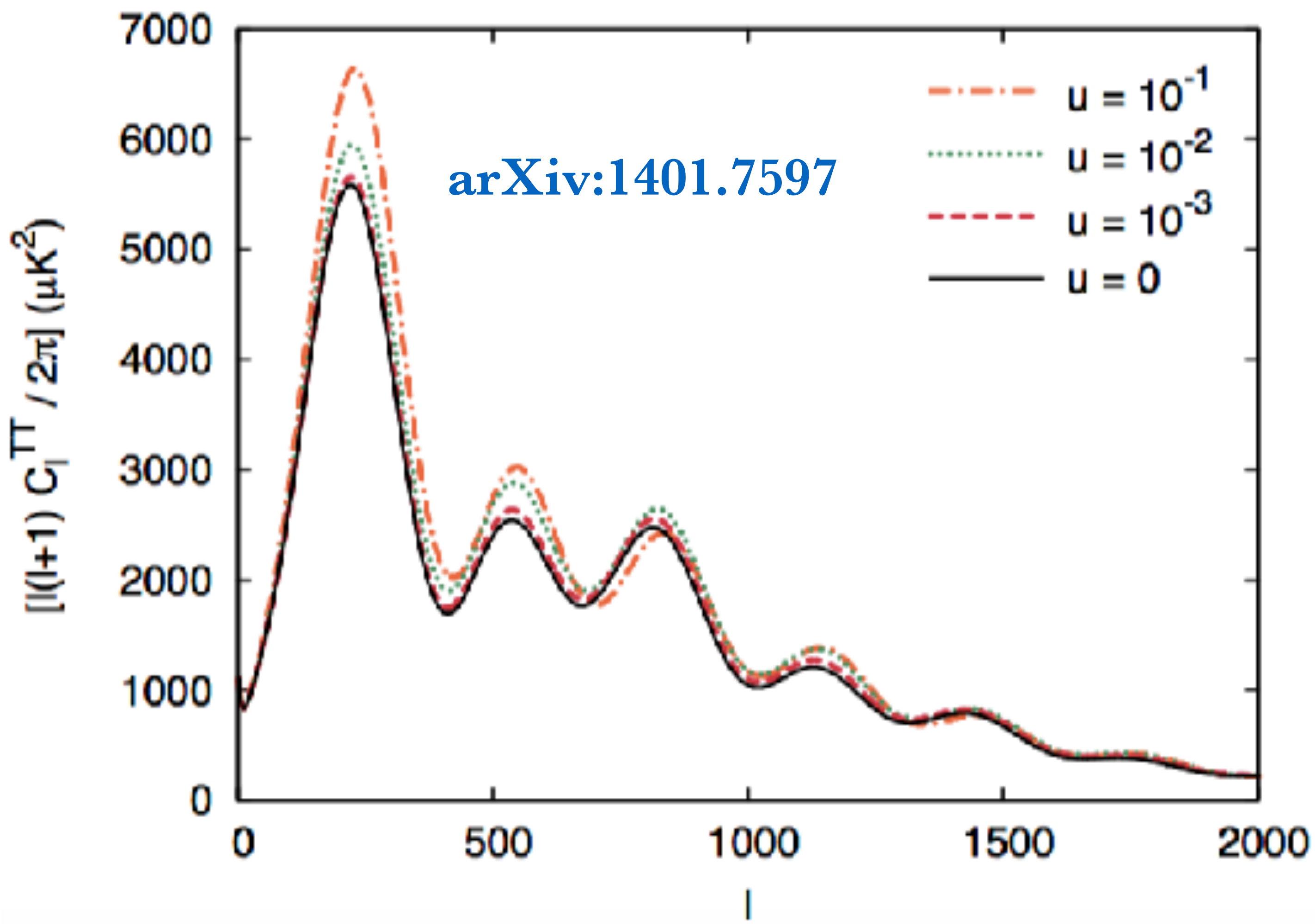
u = ratio of cross section to the DM mass (1 parameter!)



dark matter cannot be a baryon…but CMB does not prevent a coupling to photons

DM-neutrino interactions

astro-ph/0606190, arXiv:0911.4411,arXiv:astro-ph/0406355, arXiv:1310.2376, arXiv:astro-ph/0202496 [astro-ph], arXiv:1311.2937 [astro-ph.CO], arXiv:1207.3124 [astro-ph.CO], arXiv:1209.5752 [astro-ph.CO], arXiv:1212.6007



$$\sigma_{\rm DM-\nu} \lesssim 3\ 10^{-28}\ \left(\frac{m_{\rm DM}}{\rm GeV}\right)\ {\rm cm}^2$$

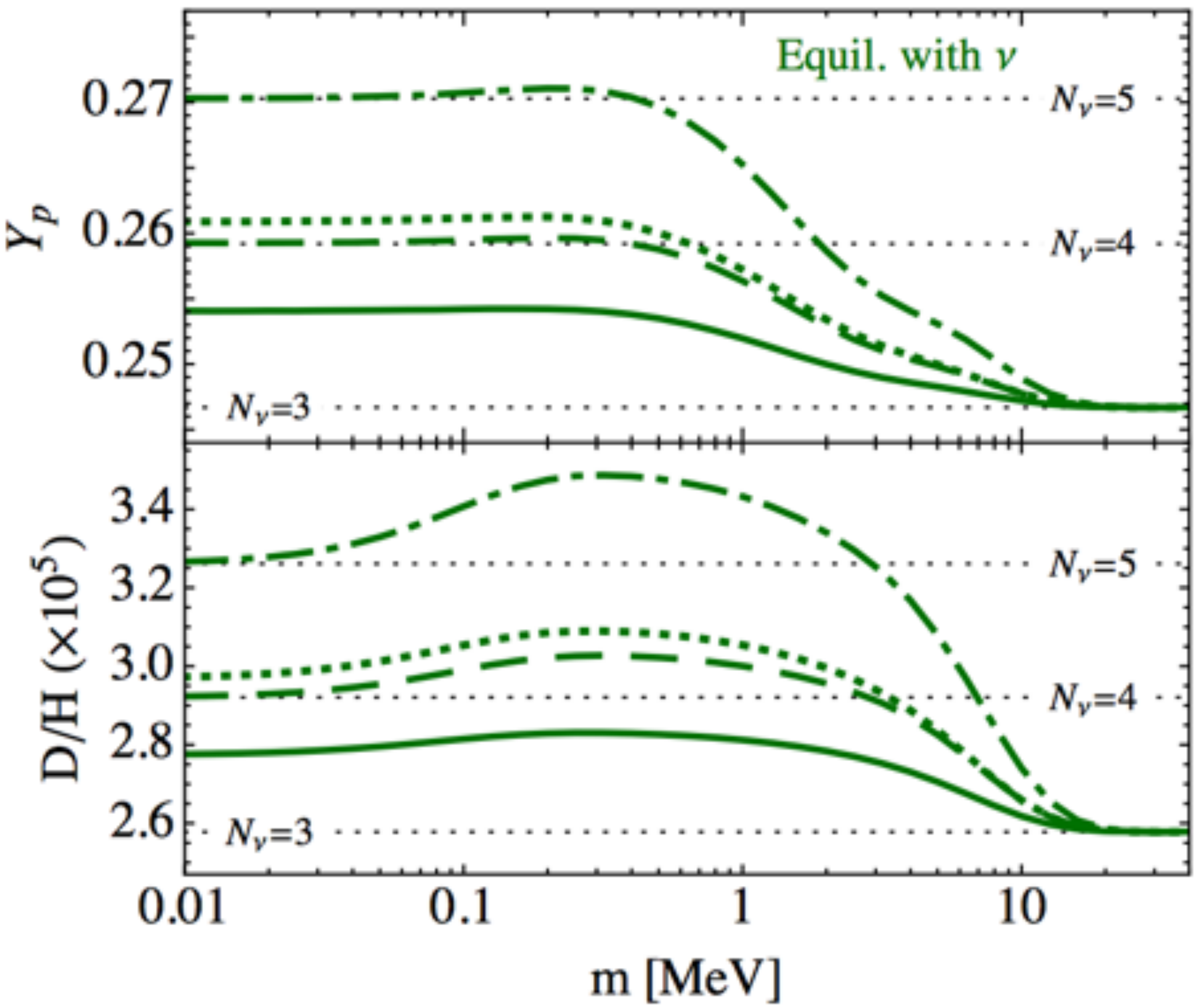
Only primordial interactions but if SIDM then primordial+late-time effects

arXiv:1205.5809

Modified CMB = modified Neff

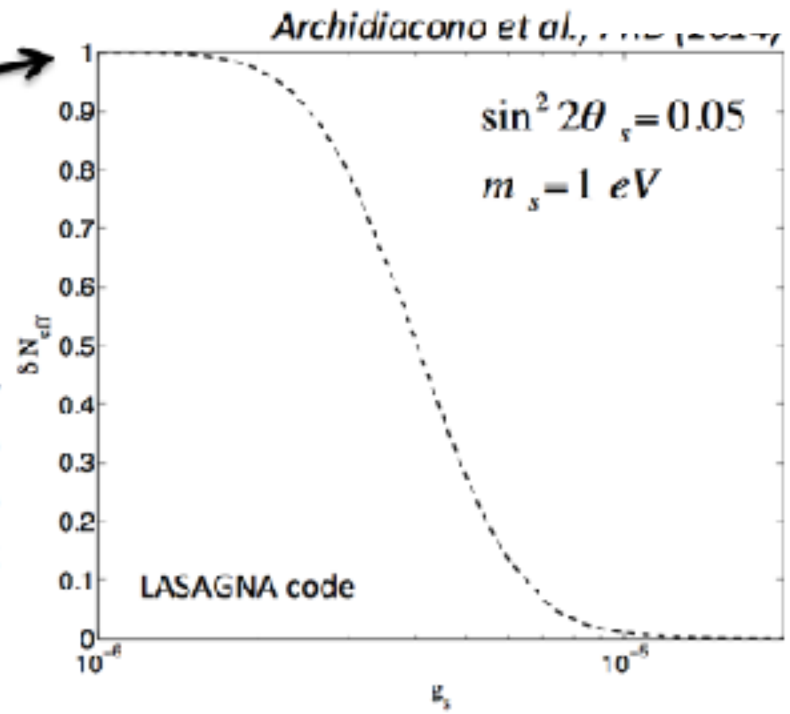
arXiv:1303.6270

arXiv:1207.0497



N_{eff} at BBN

BBN bounds:
$\Delta N_{eff} \leq 1$ (95% c.l.)



When sterile neutrinos are produced, they will create non-thermal distortions in the sterile neutrino distribution, and the sterile neutrino spectrum end up being somewhat non-thermal.

The transition between full thermalization and no thermalization occurs for coupling $10^{-6} < g_s < 10^{-5}$

Courtesy Maria Archidiacono

The physics of DM interactions on primordial fluctuations

astro-ph/0112522

last until DM stop interacting

efficient if the DM is coupled to a relativistic species

$$l_{id}^2 = \frac{2\pi^2}{3}\int_0^{t_{dec(dm-i)}} \frac{\rho_i v_i^2 t}{\rho a^2 \Gamma_i}(1+\Theta_i)\,\frac{dt}{t}$$

efficient if DM is coupled to a species that is also interacting with other fluids

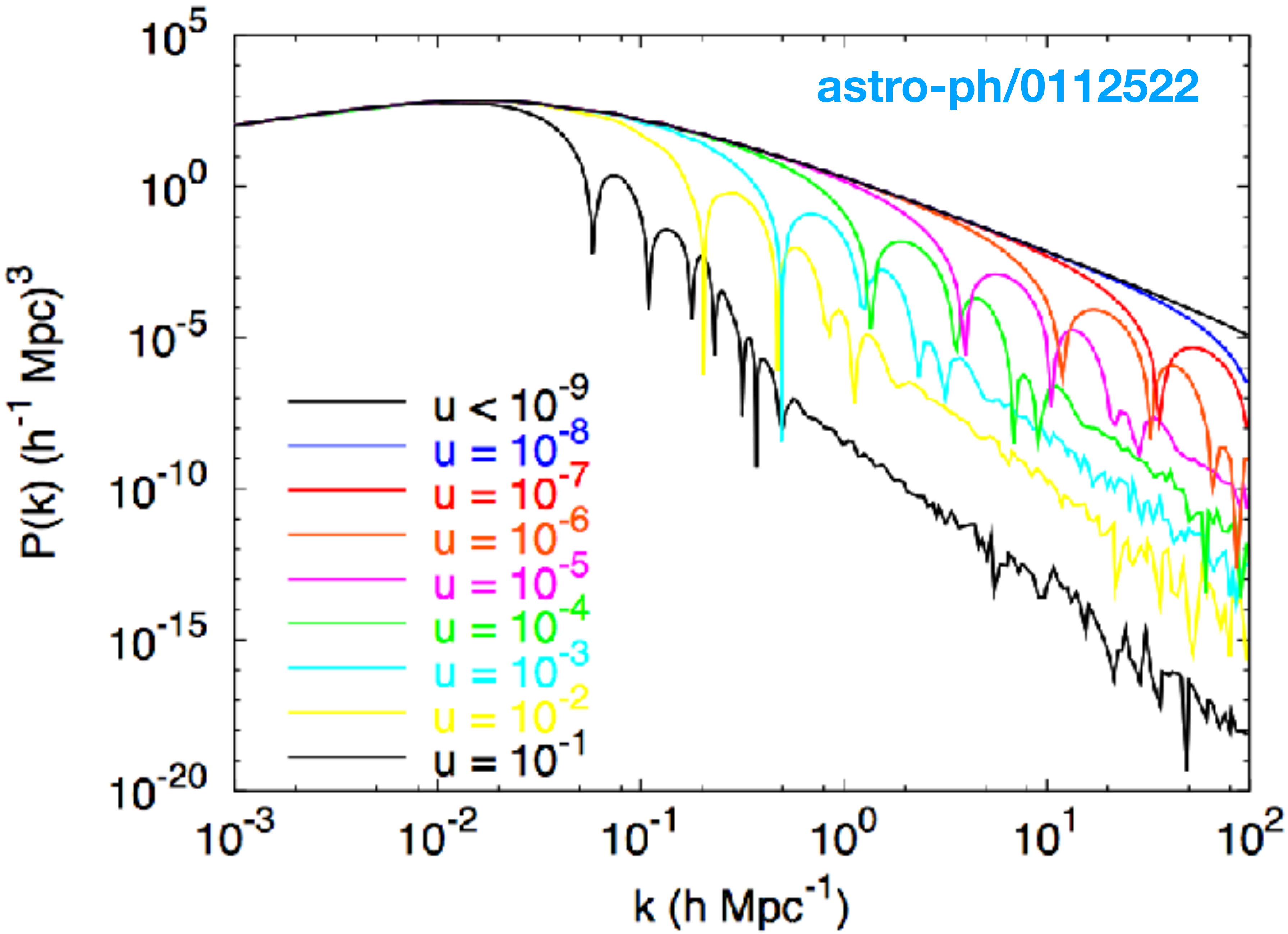
without DM interactions

$$\begin{aligned}
\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma) \\
\dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \dot\kappa(\theta_\gamma - \theta_b)\ , \\
\dot\theta_{DM} &= k^2\psi - \mathcal{H}\theta_{DM}\ ,
\end{aligned}$$

with DM interactions

$$\begin{aligned}
\dot\theta_b &= k^2\psi - \mathcal{H}\theta_b + c_s^2 k^2 \delta_b - R^{-1}\dot\kappa(\theta_b - \theta_\gamma) \\
\dot\theta_\gamma &= k^2\psi + k^2\left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) \\
&\quad - \dot\kappa(\theta_\gamma - \theta_b) - \dot\mu(\theta_\gamma - \theta_{DM})\ , \\
\dot\theta_{DM} &= k^2\psi - \mathcal{H}\theta_{DM} - S^{-1}\dot\mu(\theta_{DM} - \theta_\gamma)\ .
\end{aligned}$$

The physics of DM interactions on primordial fluctuations



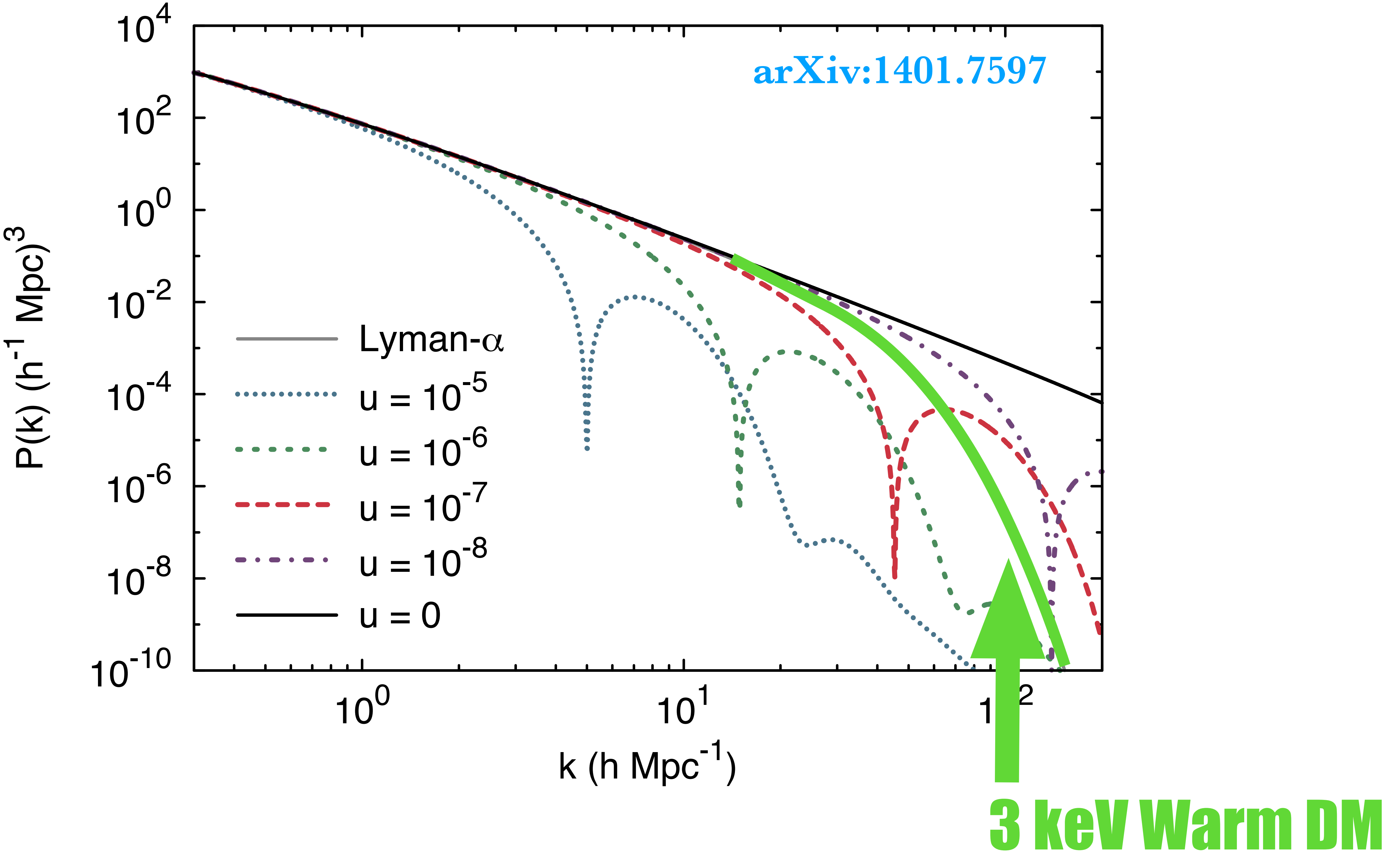
$$T_{\rm WDM} = [1 + (\alpha k)^{2\nu}]^{-5/\nu}, \qquad \alpha = 0.073\,{\rm Mpc}\,\left(u/10^{-6}\right)^{0.48}$$

astro-ph/0112522 (Steen Hansen)

P(k) for Dark Matter-neutrino interactions

Interacting DM can behave as Warm DM

astro-ph/0112522



Courtesy Maria Archidiacono

Kinetic decoupling: bounds from Ly-α

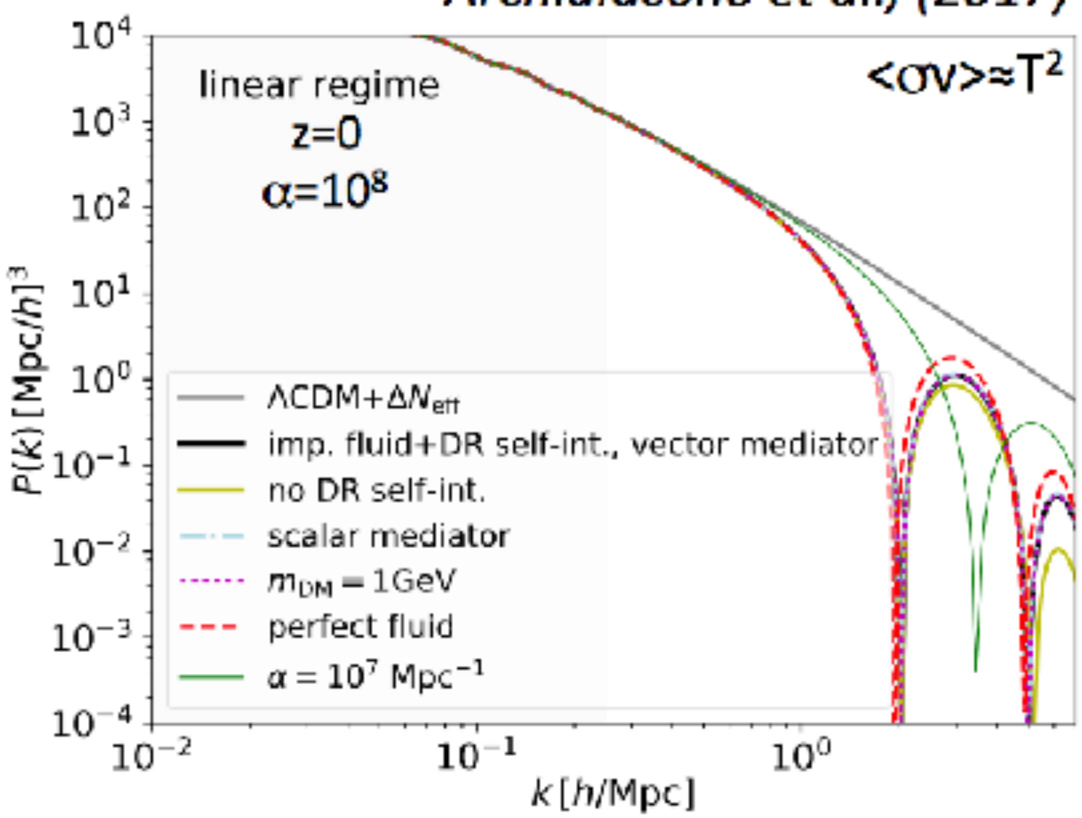
Talk by T. Binder

$$\Gamma_{DM} = H \rightarrow T_{kd}(m_\chi, m_\phi, g_\chi, g_\nu, \xi)$$

The mass of the smallest proto-halos corresponds to the mass enclosed in the Hubble horizon at the time of kinetic decoupling.

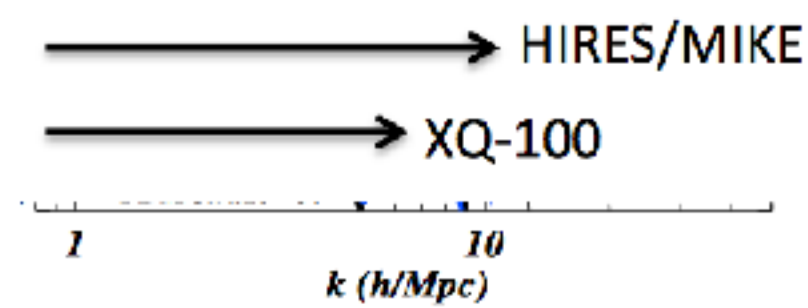
$$M_{cut} = \frac{4\pi}{3}\rho_m\left(\frac{1}{H}\right)^3 \approx 2\times10^8\left(\frac{keV}{T_{kd}}\right)^3 M_{Sun}$$

Archidiacono et al., (2017)



$$M(k) \approx 10^{12}\left(\frac{Mpc^{-1}}{k}\right)^3 M_{Sun}$$

- Non-linear regime
- Ly-α *Irsic et al., (2017)*



DM-Dark radiation interactions

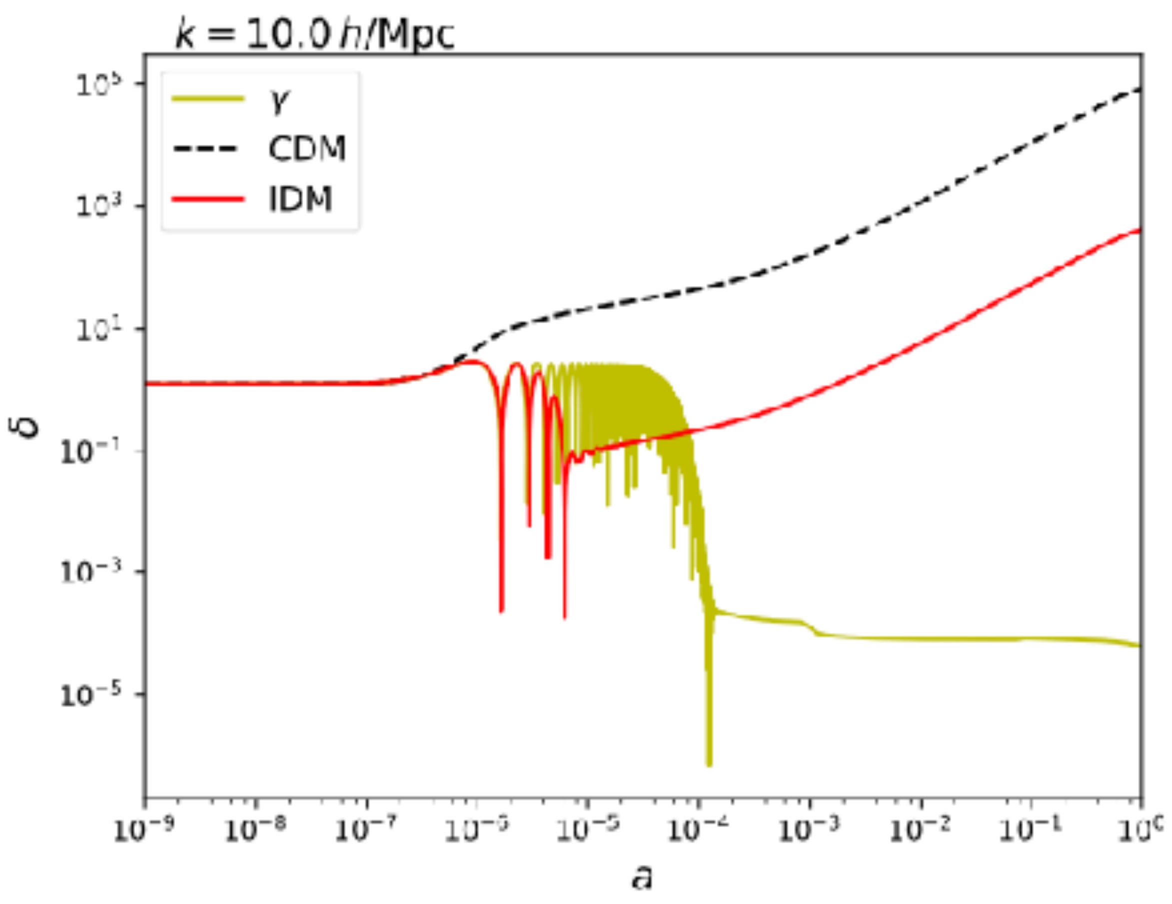
DM-Dark radiation interactions

Courtesy Maria Archidiacono

impact on CMB

The clustering of cold dark matter before baryon drag is described by the Meszaros equation: $\ddot{\delta}_c^{slow} + \frac{\dot{a}}{a}\dot{\delta}_c^{slow} = 4\pi G a^2 \rho_c \delta_c^{slow}$ CDM is self-gravitating

For photons: $(1+R)\ddot{\delta}_\gamma^{fast} + \frac{\dot{a}}{a}\dot{\delta}_\gamma^{fast} + \frac{1}{3}k^2 R \delta_\gamma^{fast} = 0$ ➔ CMB primary anisotropies



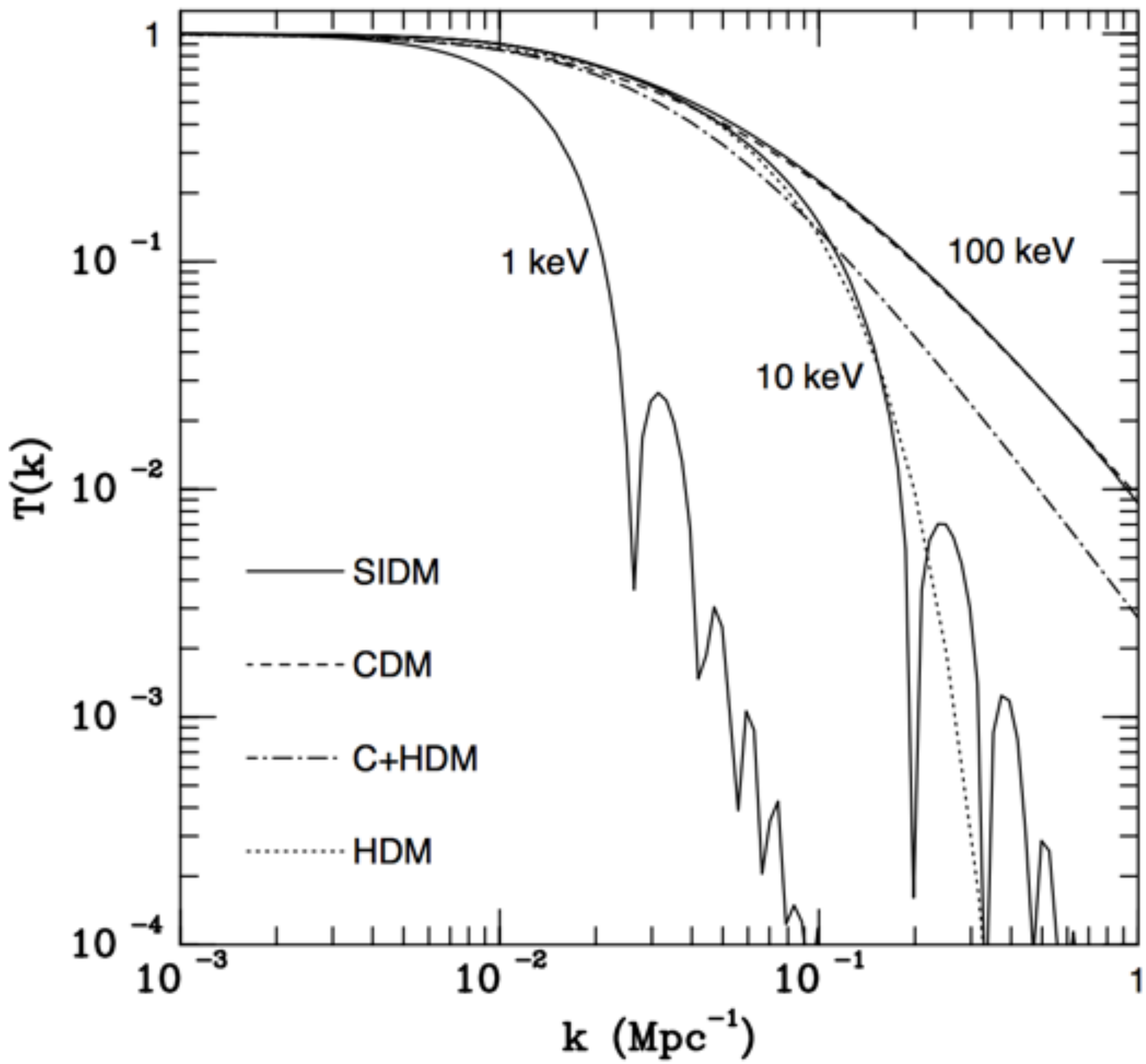
$$\dot{\delta}_{DM} + \theta_{DM} - 3\dot{\phi} = 0$$

$$\dot{\theta}_{DM} - k^2 c_D^2 \delta_{DM} + H\theta_{DM} - k^2\psi = 0$$

DM self-interactions

Self-interacting DM interactions

astro-ph/9502087 **(66 citations...)** versus the 1000s by Spergel&Steinhardt



Self-interacting dark matter **(135 citations...)**

Eric D. Carlson (Harvard U.) , Marie E. Machacek (Northeastern U.) , Lawrence J. Hall (UC, Berkeley & LBL, Berkeley)

Mar 1992 - 31 pages

Astrophys.J. 398 (1992) 43-52

DM self-collisions in N-body simulations (probabilistic approach)

The coarse-grained distribution is given by a discrete representation of N particles:

$$\hat{f}(\mathbf{x},\mathbf{v},t) = \sum_i (M_i/m) W(|\mathbf{x}-\mathbf{x}_i|; h_i)\,\delta^3(\mathbf{v}-\mathbf{v}_i)$$

Algorithm: Gravity + Probabilistic method for elastic scattering

Consider a neighbourhood around each particle:

in pairs:

$$P_{ij} = \frac{m_i}{m_\chi} W(r_{ij}, h_i)\,\sigma_T(v_{ij})\,v_{ij}\,\Delta t_i$$

total for a particle:

$$P_i = \sum_j P_{ij}/2$$

discrete version of the collisional operator

A collision happens if: $x \leqslant P_i$, where x is a random number between 0 and 1

sort neighbours by distance and pick the one with: $x \leqslant \sum_i^l P_{ij}$

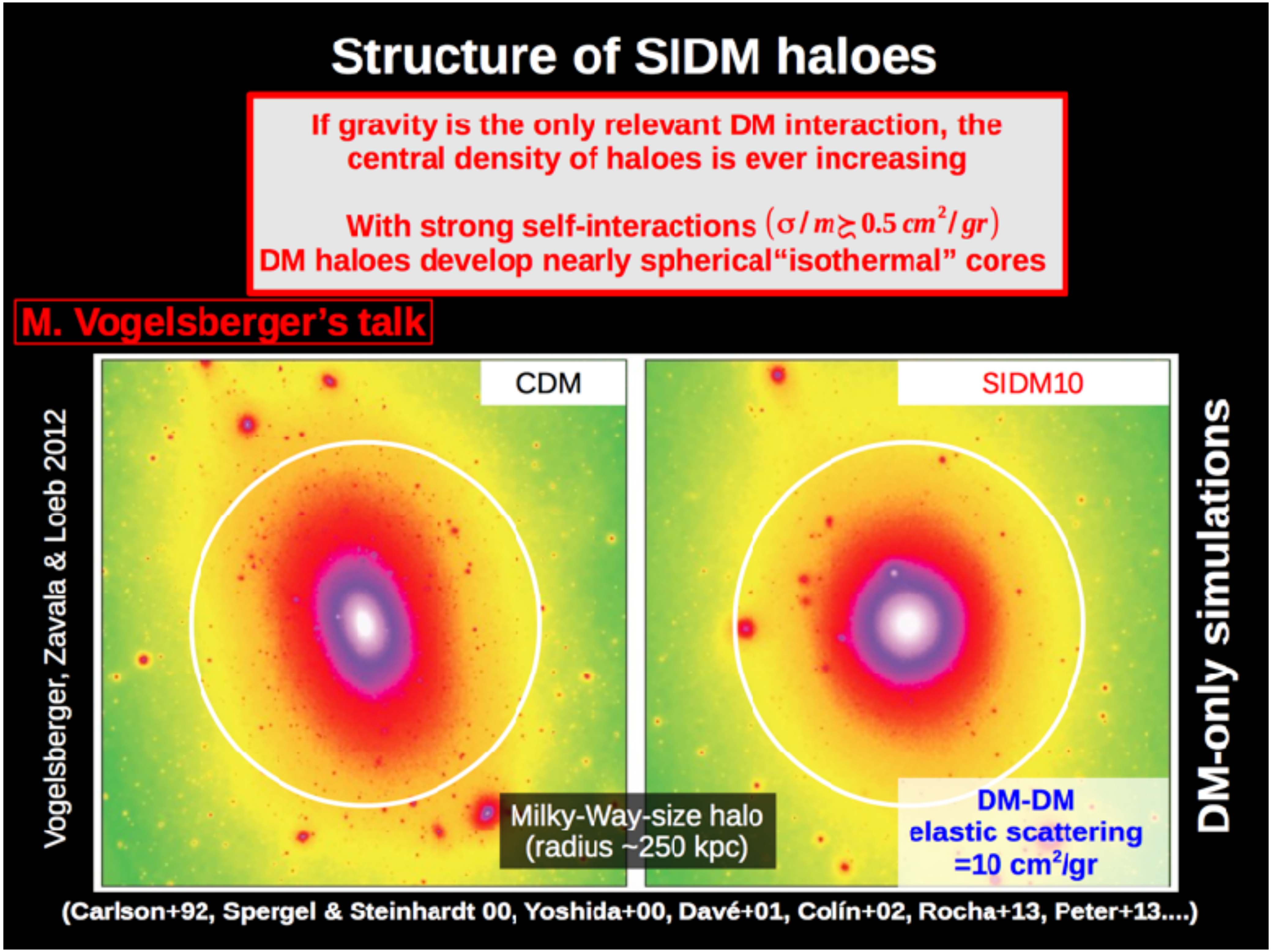
Isotropic Elastic collision:

$$\vec{v}_i = \vec{v}_{cm} + (\vec{v}_{ij}/2)\,\hat{e}$$
$$\vec{v}_j = \vec{v}_{cm} - (\vec{v}_{ij}/2)\,\hat{e}$$

randomly scattered

Kochanek & White 2000, Yoshida+2000,...Vogelsberger, Zavala, Loeb 2012, Rocha+2013

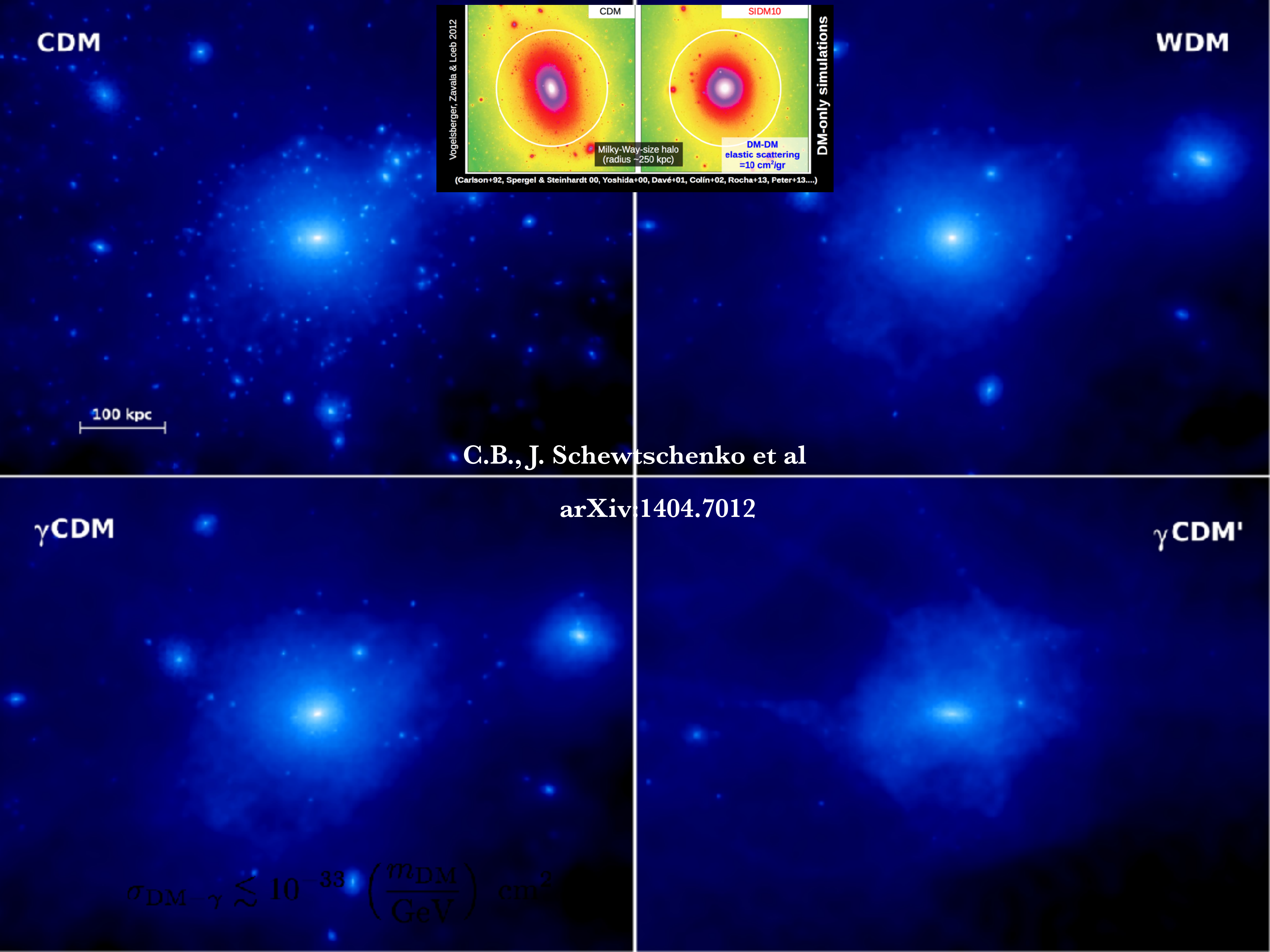
Courtesy Jesus Zavala



Francis-Yan Cyr-Racine

ALMA might not distinguish SIDM from SCDM

SIDM substructure lensing signature is not Gaussian


CDM
WDM
γCDM
γCDM'
100 kpc
CDM
SIDM10
Vogelsberger, Zavala & Loeb 2012
DM-only simulations
Milky-Way-size halo
(radius ~250 kpc)
DM-DM
elastic scattering
$=10\ cm^2/gr$
(Carlson+92, Spergel & Steinhardt 00, Yoshida+00, Davé+01, Colín+02, Rocha+13, Peter+13....)
C.B., J. Schewtschenko et al
arXiv:1404.7012
$\sigma_{\rm DM-\gamma} \lesssim 10^{-33} \left(\frac{m_{\rm DM}}{\rm GeV}\right)\ {\rm cm}^2$

Quick understanding

$$l_{id}^2 \sim \frac{2\ \pi^2}{3} \int_0^{t_{\mathrm{dec(dm-i)}}} \frac{\rho_{\mathrm{i}}\ v_i^2}{\rho_t\ a^2\ \Gamma_{\mathrm{i}}} dt$$

DM self-interactions

$$l_{sd}^2 \sim \frac{2\pi^2}{3} \frac{\rho_{dm} v_{dm}^2 t}{\not{\rho} a^2 \Gamma_{dm}} (1 + \Theta_{dm}) \left.\right|_{dec(dm)}$$

DM interactions with radiation

$$l_{id}^2 \sim \frac{2\pi^2}{3} \frac{\rho_i v_i^2 t}{\not{\rho} a^2 \Gamma_i} (1 + \Theta_i) \left.\right|_{dec(dm-i)}$$

v_i is higher, rho_i is higher

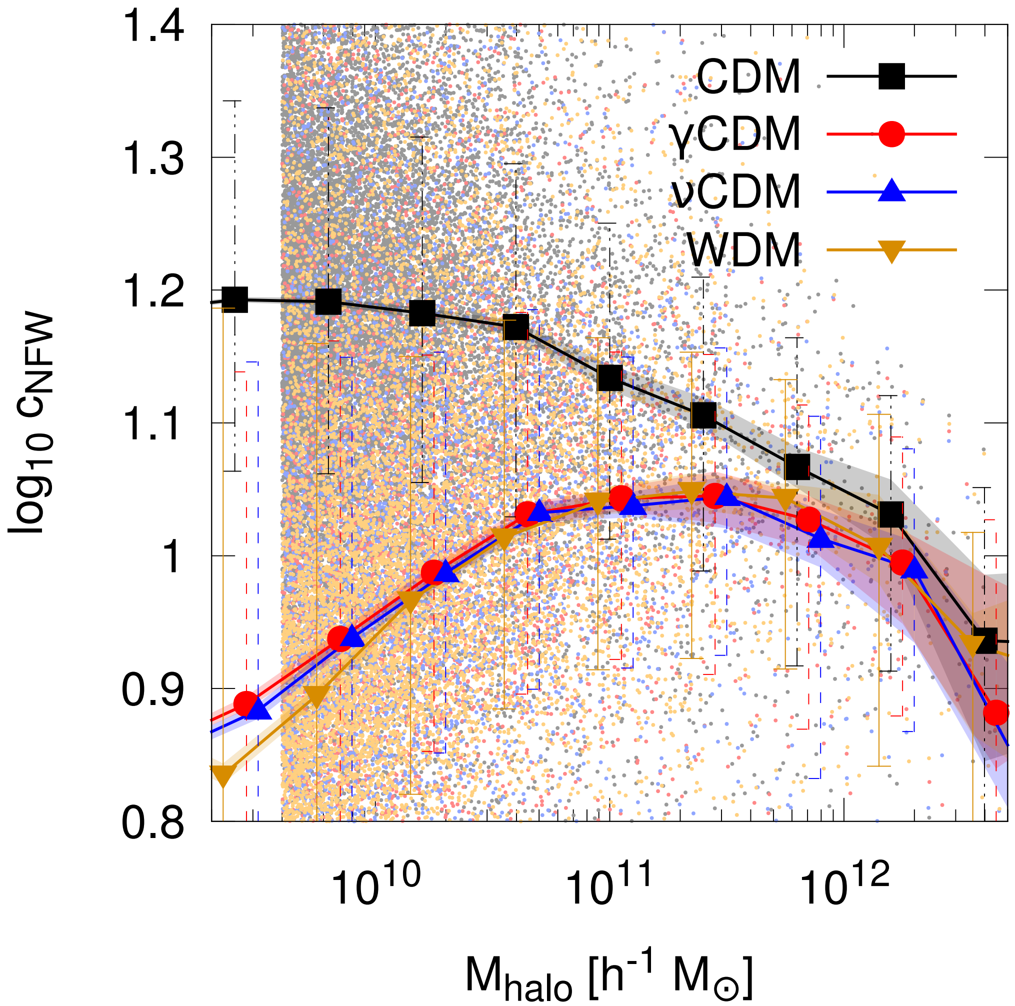
“induced damping” stronger …
as a result smaller cross section
makes the same effect as SIDM

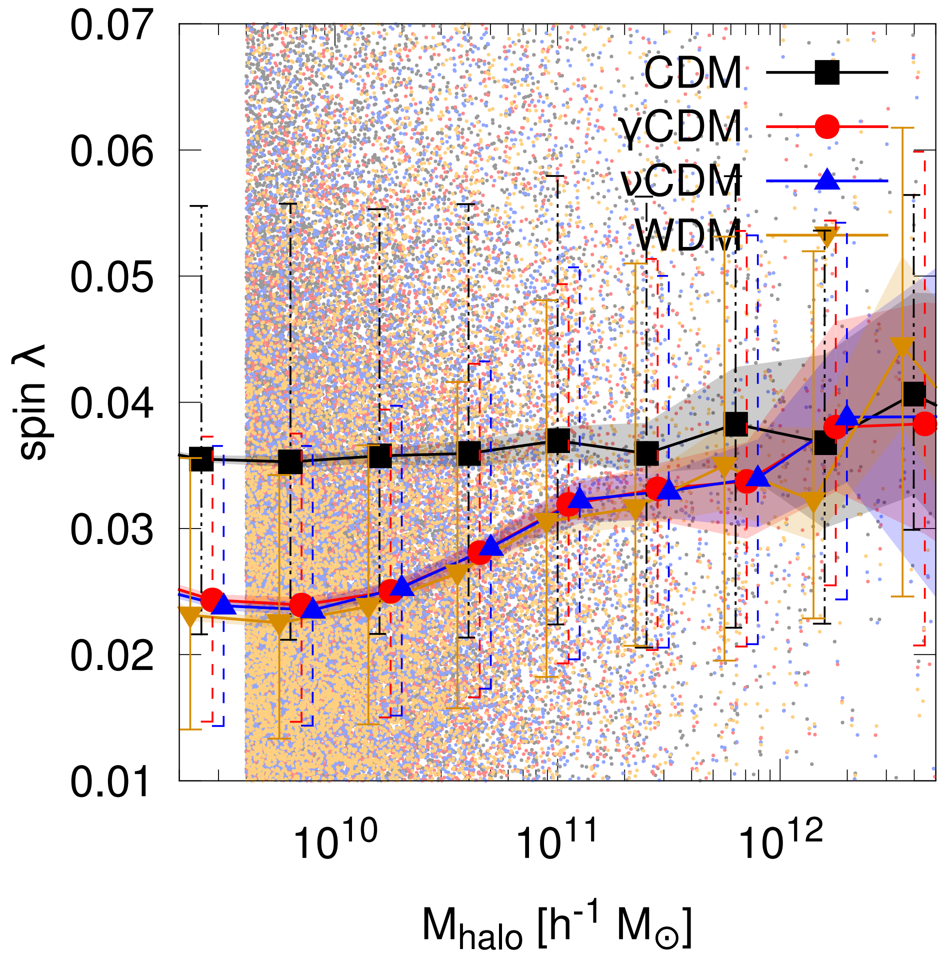
BUT SIDM has both a primordial and late-time effect!

(which others don’t have…perhaps)

Differences with CDM

http://arxiv.org/pdf/1412.4905.pdf





Differerent from CDM but quite similar to WDM

Courtesy Maria Archidiacono

	Missing satellites	Cusp vs. core	Too big to fail
Baryons	✓	✓	✓
SIDM	✗	✓	✓
SIDM + DR	✓	✓	✓
WDM	✓	✗	✓
DDM	✓	✗	✓
LFDM	✓	✗	✓
BSI	✓	✓	✗

Broken-Scale-Invariance inflationary model

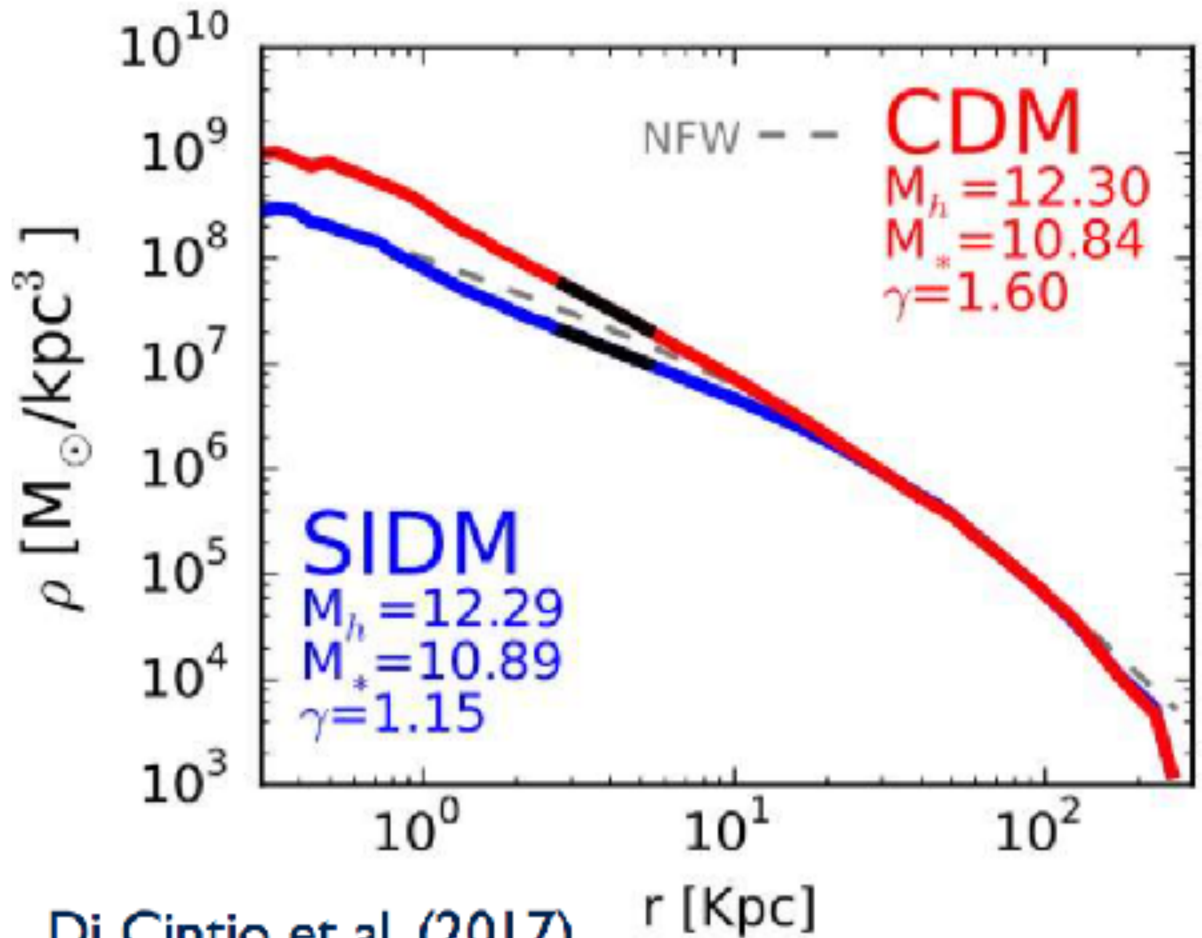
The model predicts an excess of power wrt to ΛCDM before the cutoff; thus it is highly constrained by Ly-α.

Kamionkowski et al., PRL (2000)

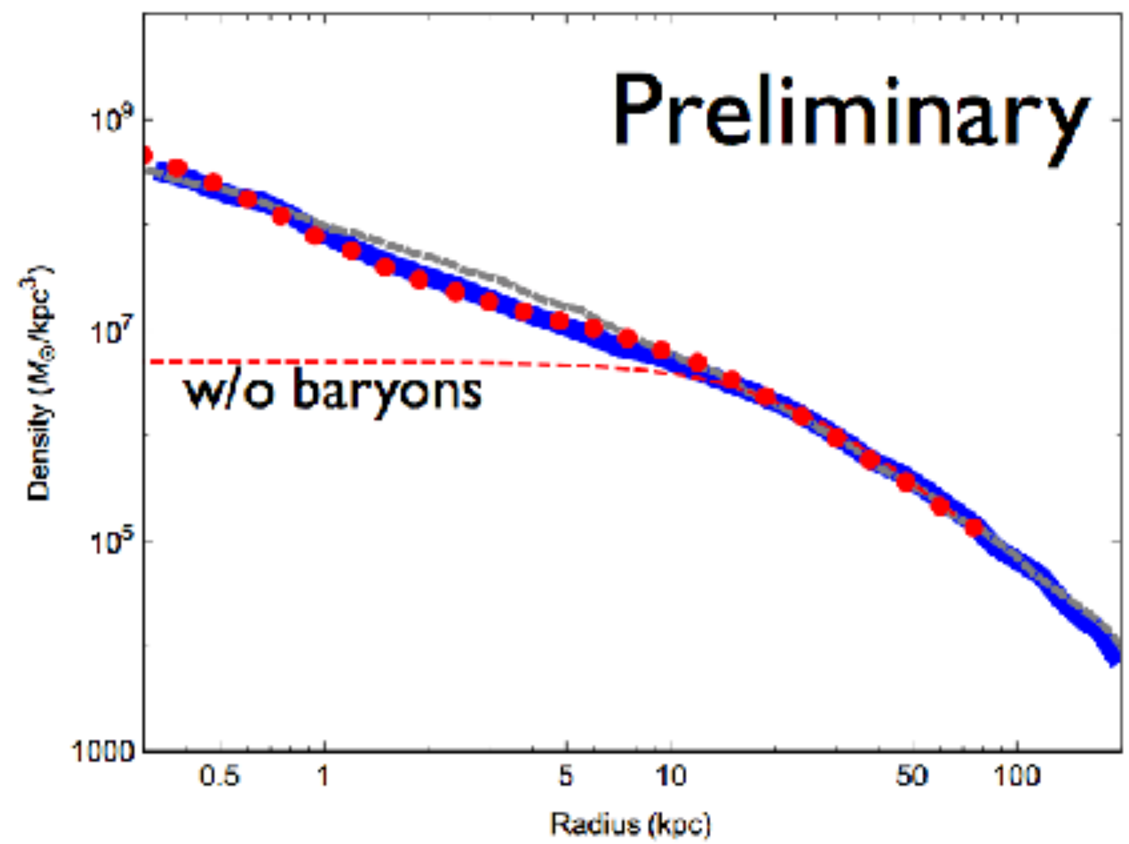
A few important points

Courtesy Hai-Bo Yu

SIDM with Strong Feedback



Di Cintio et al. (2017)



$$! _x \sim e^{-! _{tot}/! ^2_{v0}}$$

red dots: thermal distribution w/ baryons

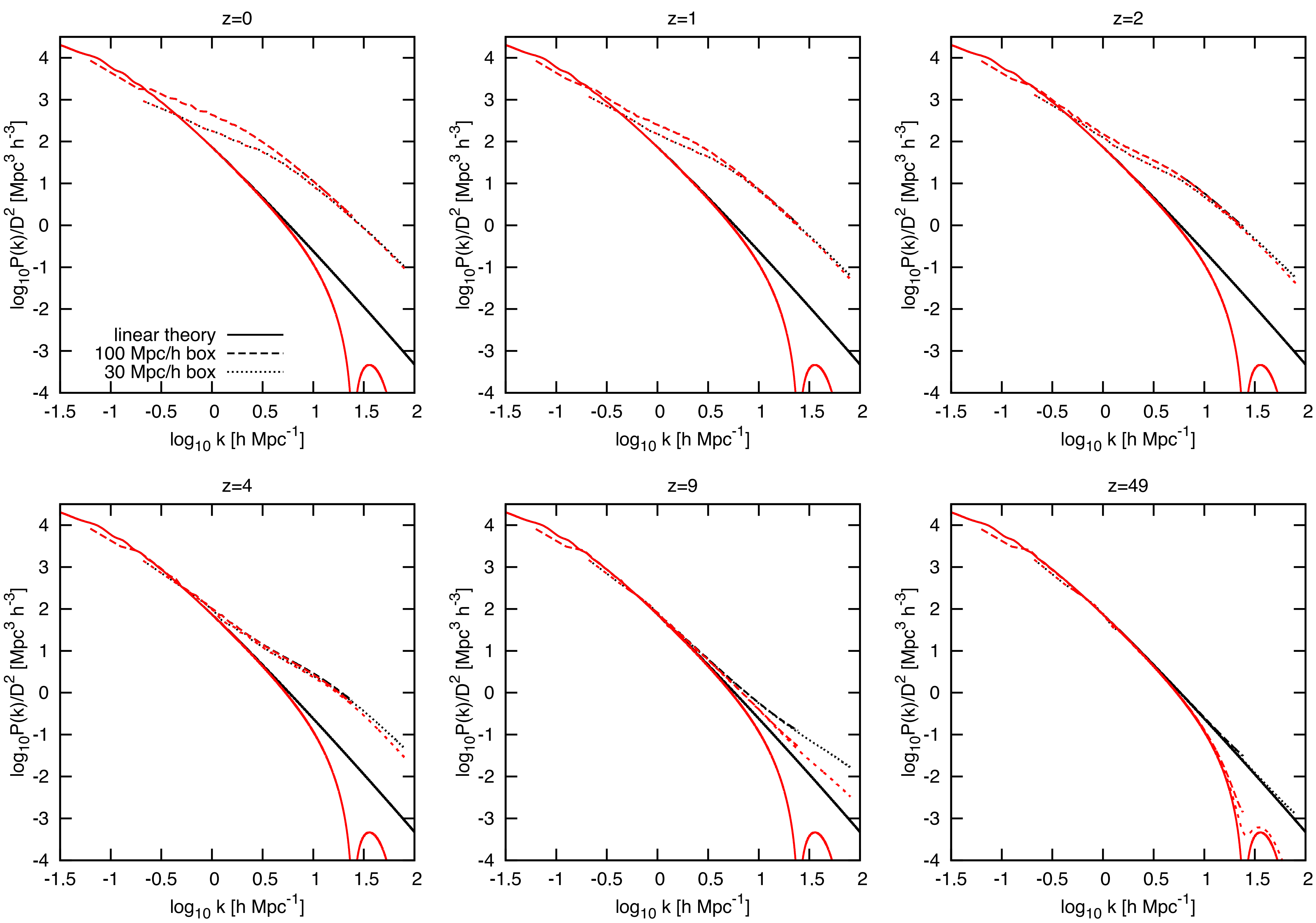
- The SIDM distribution is sensitive to the baryon distribution

Mass function

the signatures at high redshift

astro-ph/0309652

Courtesy J.A. Schewtschenko



Courtesy Laura Lopez-Honorez

WDM imprint on Reionization

similar to [Sitwell'14, Bose'16] and for different approach [Yue'12,Barkana'01, Somerville'03,Yoshida'03, Schultz'14, Dayal '14+, Rudakovskyi'16]

- Ionization level at $z \sim z_{reio}$:

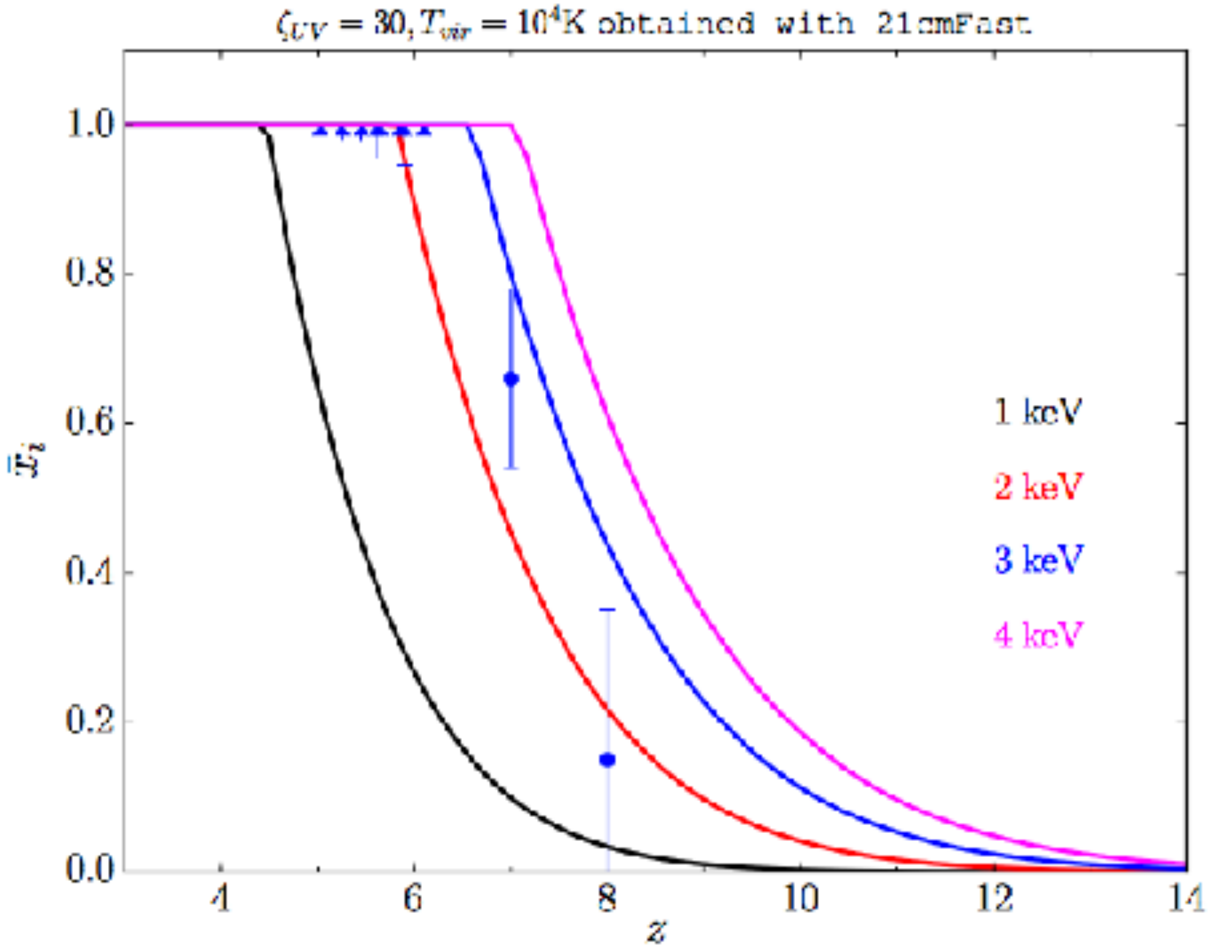
$$\bar{x}_i \approx \zeta_{UV} f_{\rm coll} \text{ with } f_{\rm coll} = f_{\rm coll}(> M_{\rm vir}^{\rm min}) = \int_{M_{\rm vir}^{\rm min}} \frac{M}{\rho_{m,0}} \frac{dn}{dM}\, dM \,.$$

- Optical depth to reionization:

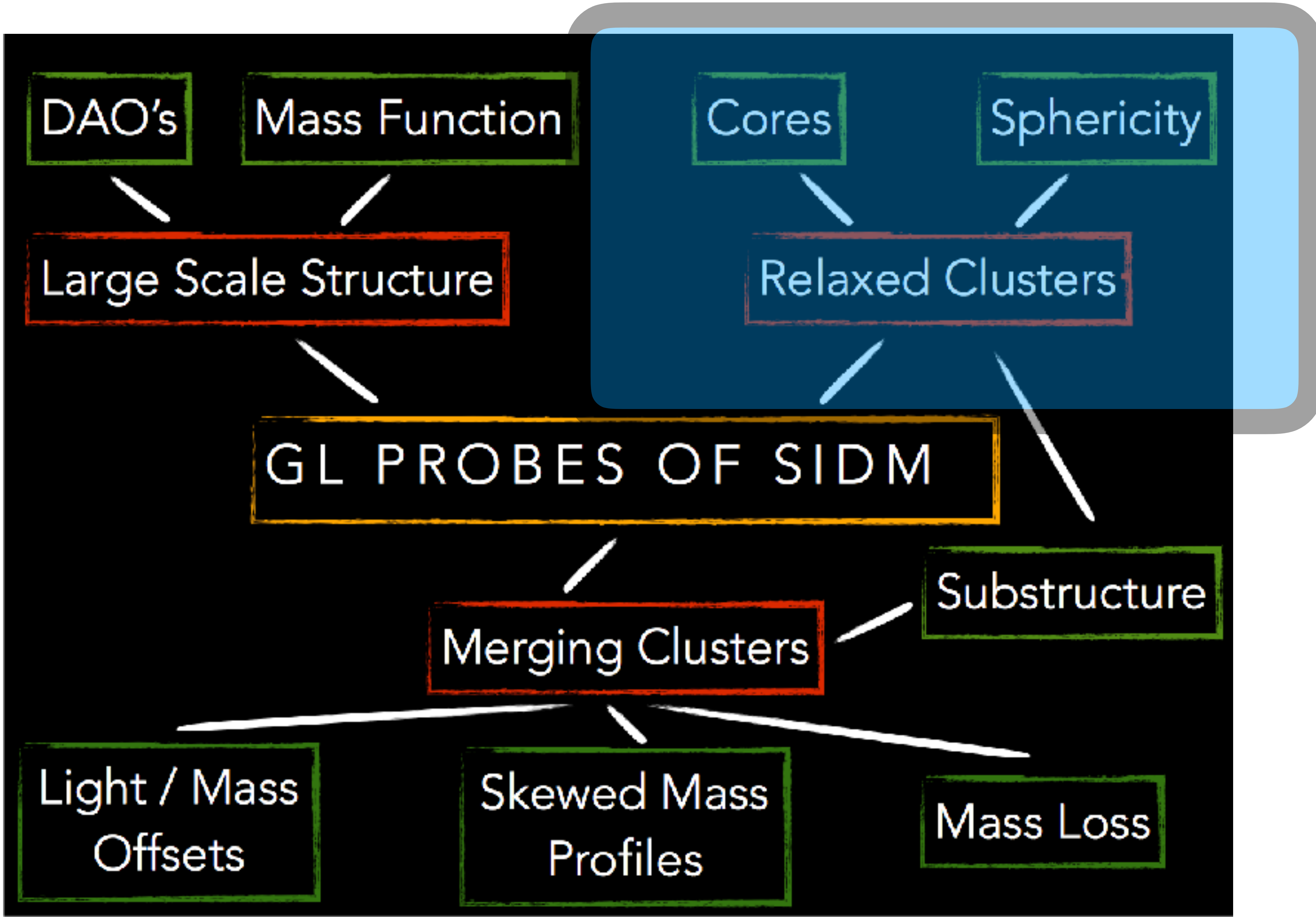
$$\tau = \sigma_T \int \bar{x}_i\, n_b\, dl \text{ and Planck: } \tau = 0.055 \pm 0.009 \text{ [Aghanim'16]}$$

Within our framework:

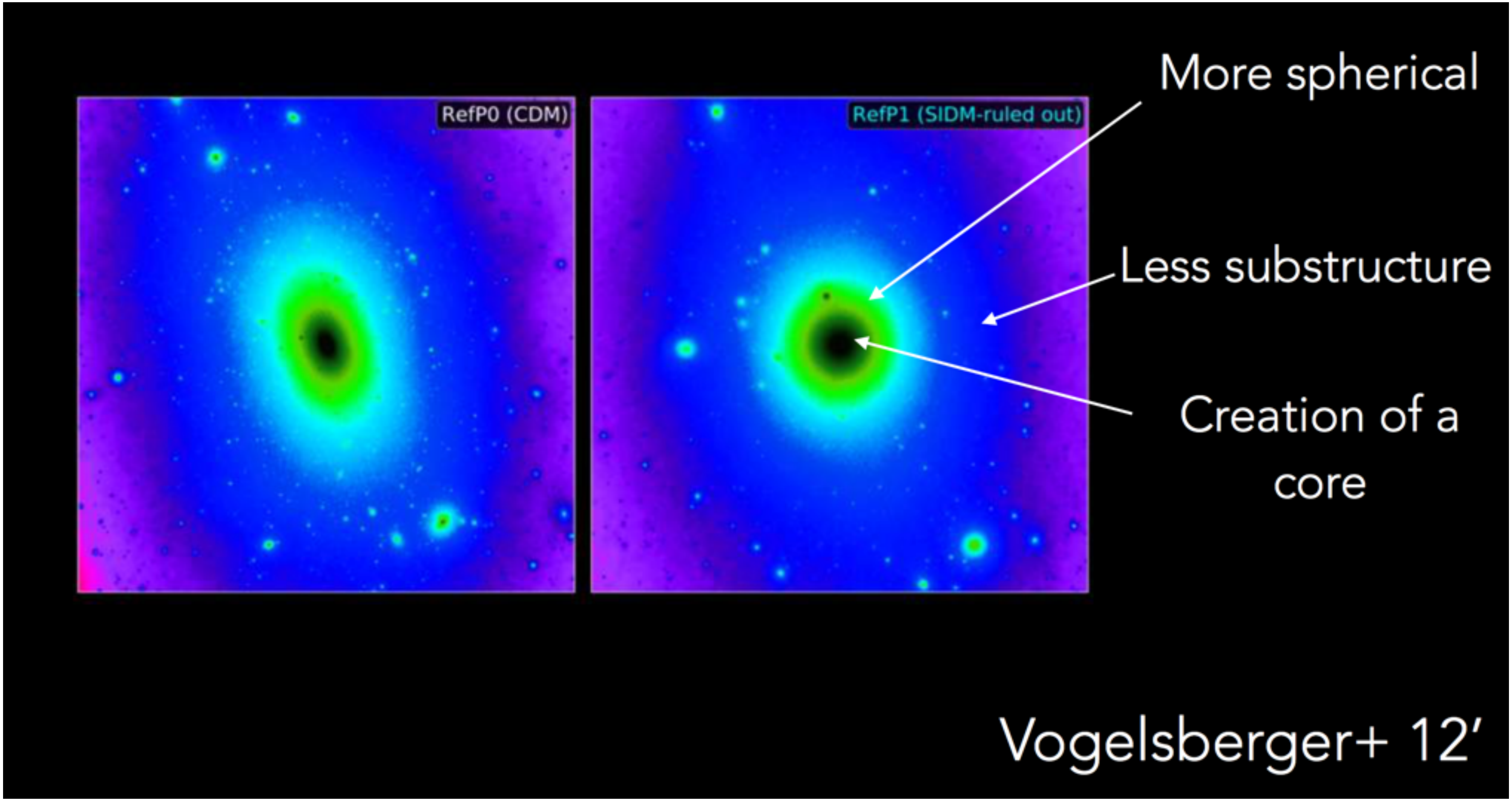
low m_X suppress structure formation at small scales
$\rightsquigarrow$ reduces $\bar{x}_i$
$\rightsquigarrow$ WDM can delay reionization



Probing SIDM with cosmology



Courtesy David Harvey



Courtesy David Harvey

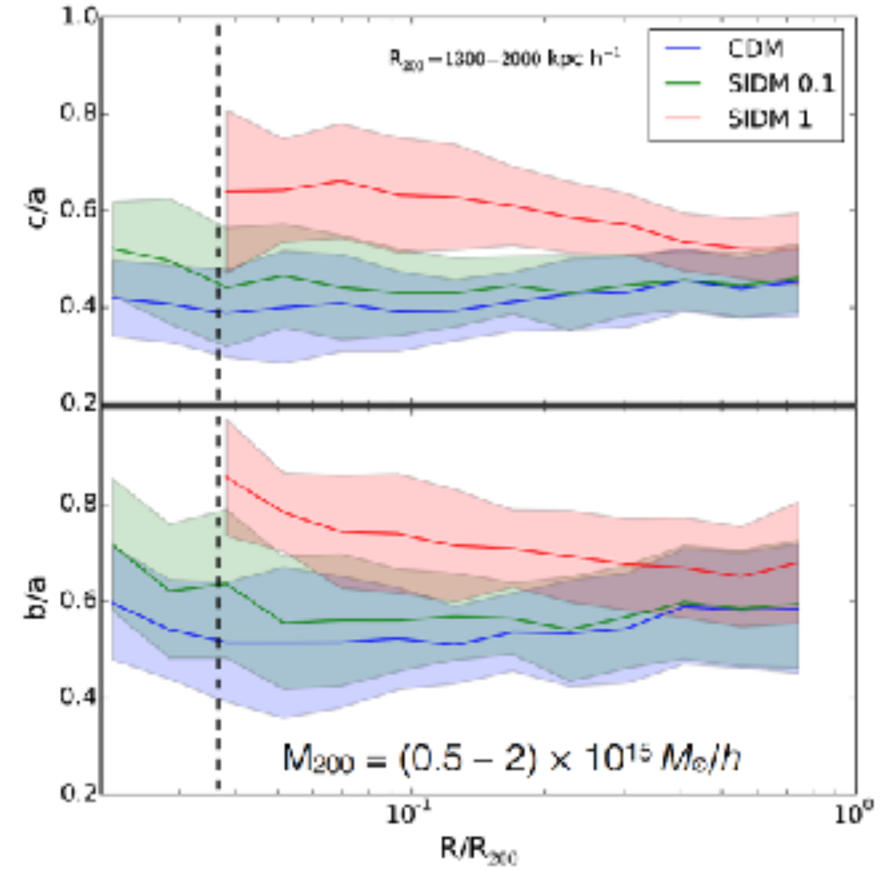
Courtesy Thejs Brinckmann

Three-pronged attack

- Halo shapes
- Density profiles
- Velocity anisotropy profiles

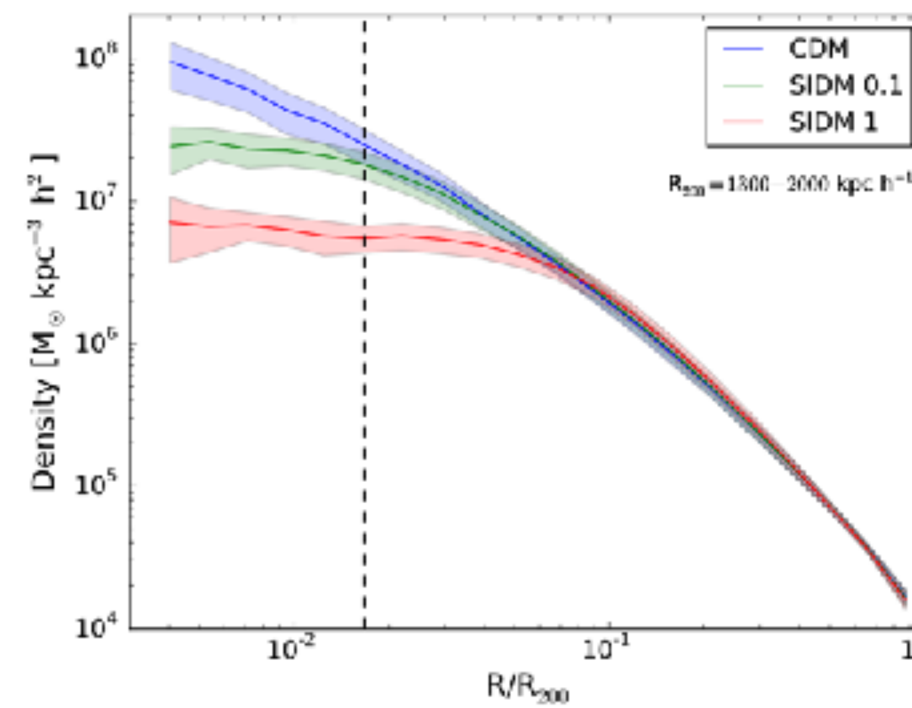
"High mass" cluster-sized haloes

- **SIDM0.1**: Hard target to reach
- **SIDM1**: Clear difference at all radii to 0.3 R_{200} ~ 450 kpc/h!
- Promising, data is available (X-ray, gravitational lensing)
- Challenge: projection effects
- Constraints: work in progress

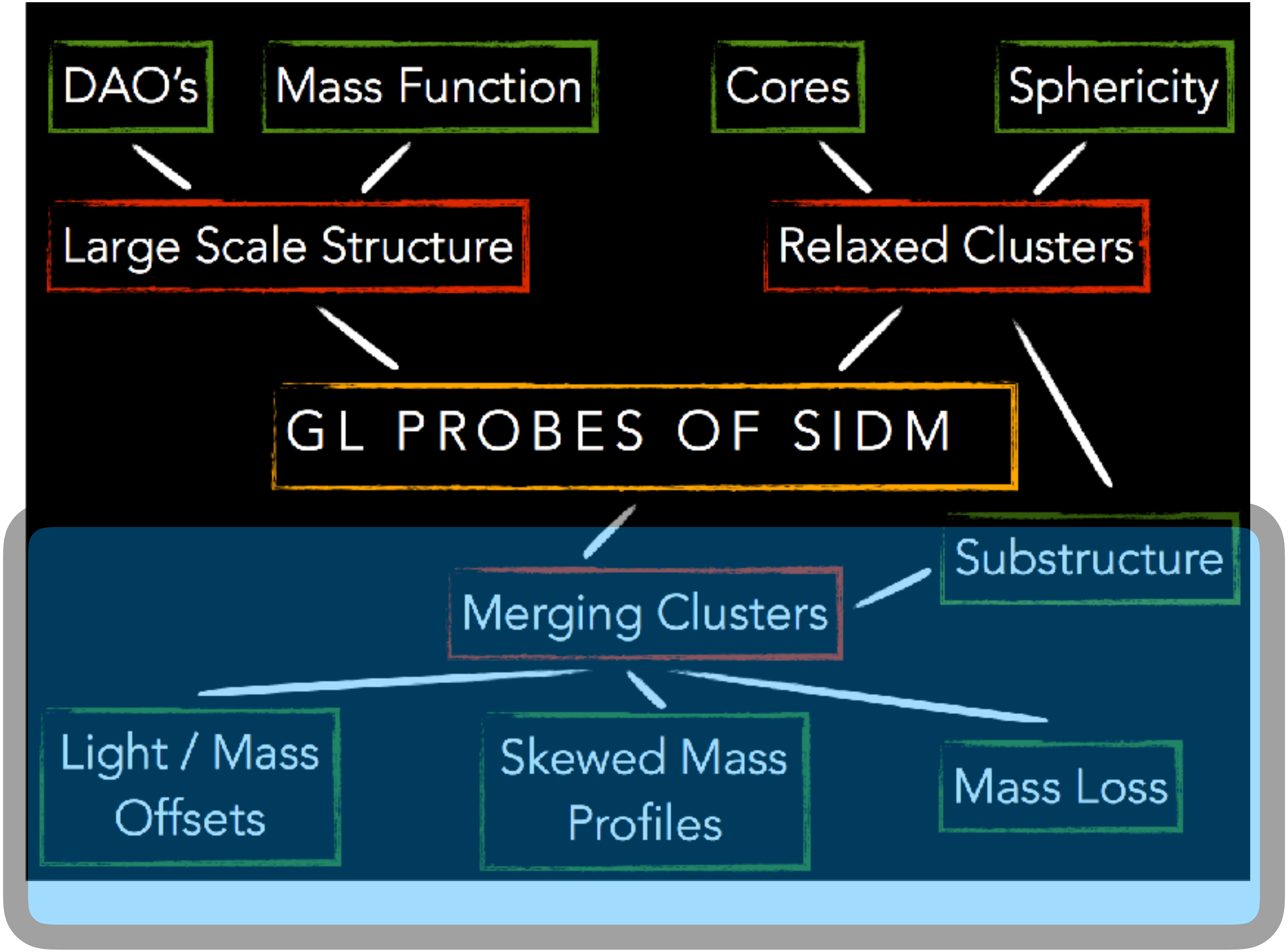


SIDM creates cored profiles
(e.g. Rocha et al. 1208.3025)

- **SIDM0.1** at resolution level
- **SIDM1** difference up to 0.04 R_{200} ~ 60 kpc/h
- Baryons are important here!
- We need ~ 0.05 – 0.1 R_{200}



velocity dispersion can constrain SIDM1 (work in progress)



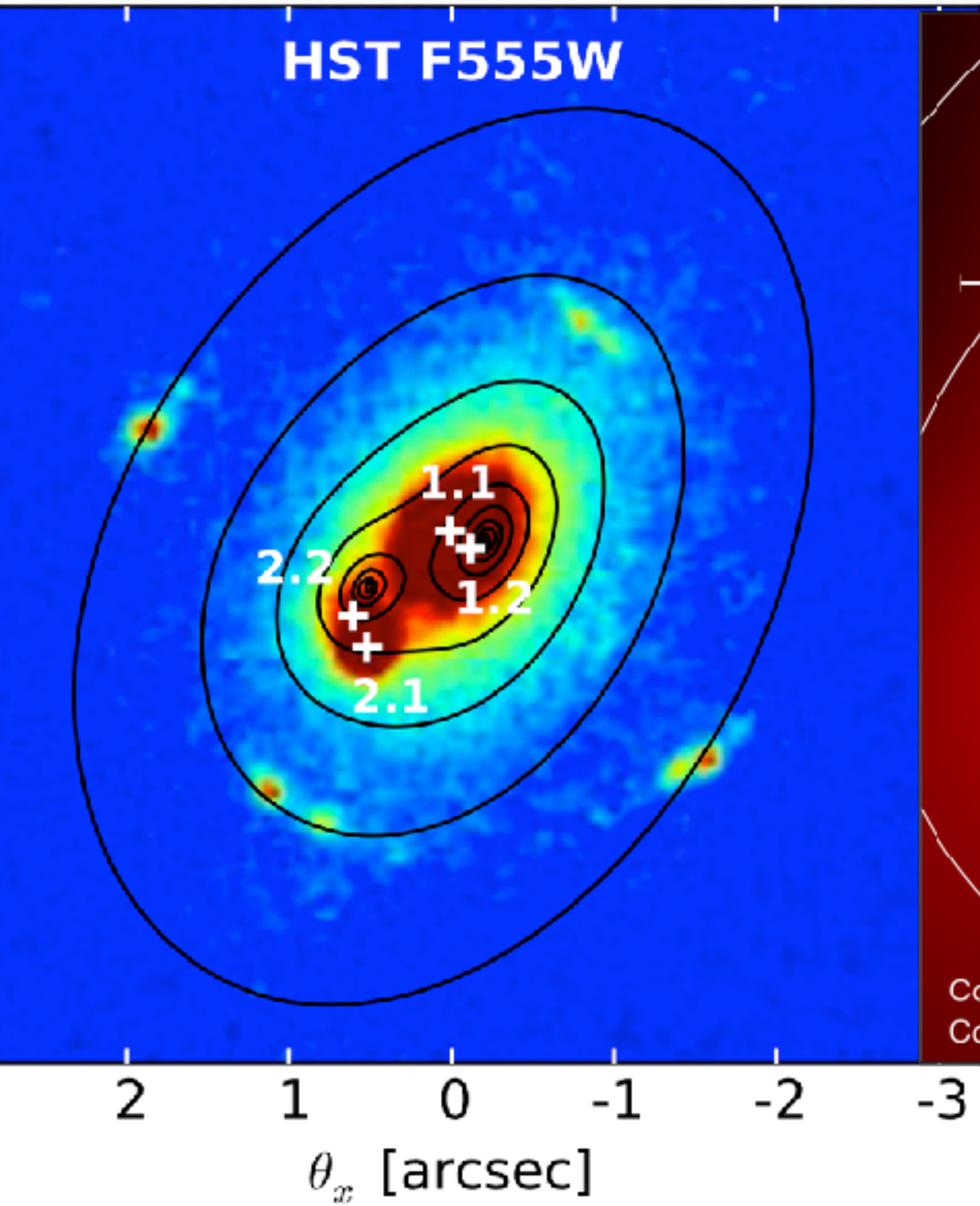
Courtesy David Harvey

Offsets in individual galaxies

Courtesy Richard Massey

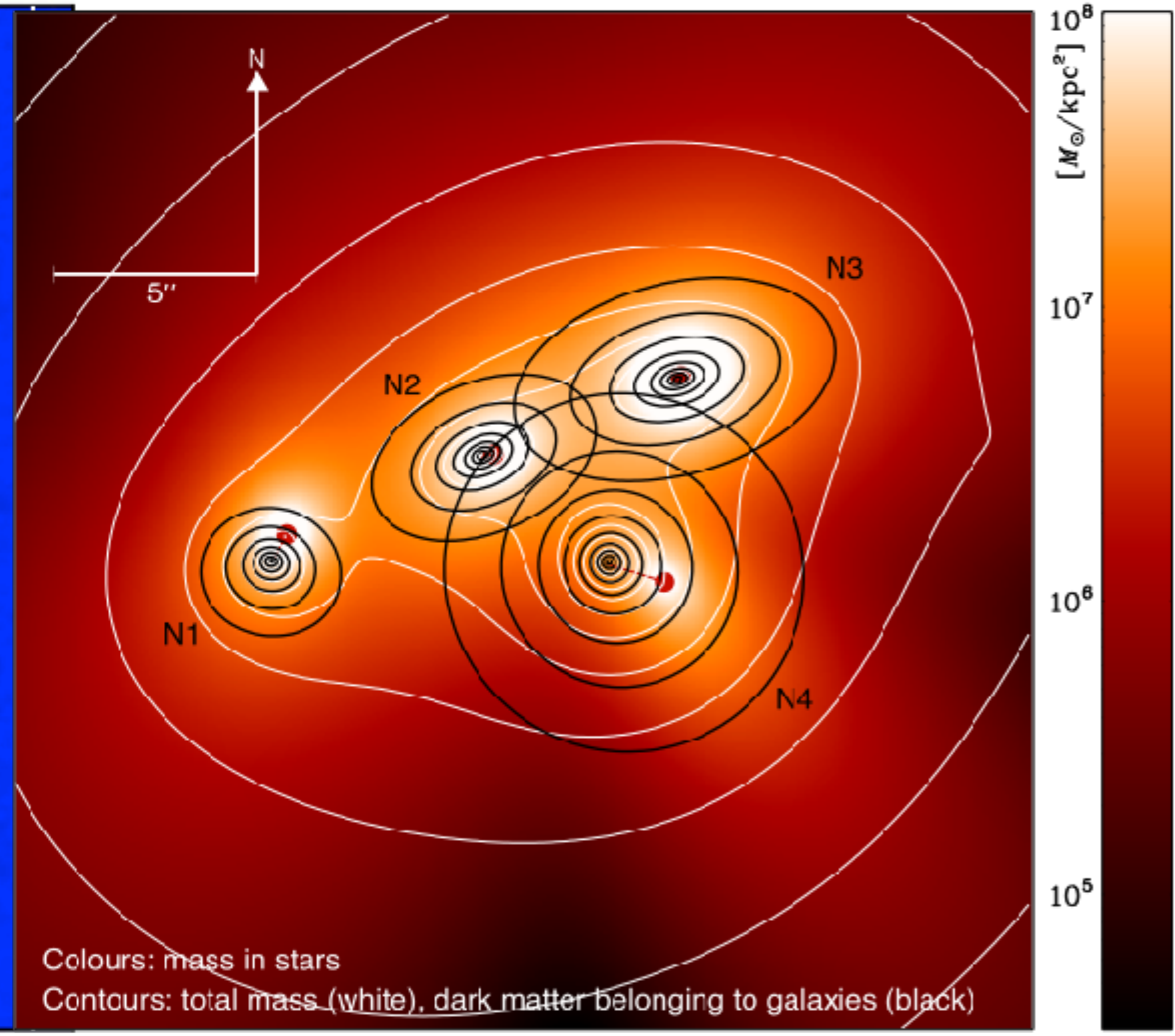
SDSS J1011+0143

Shu et al. (2016), ApJ 820, 43



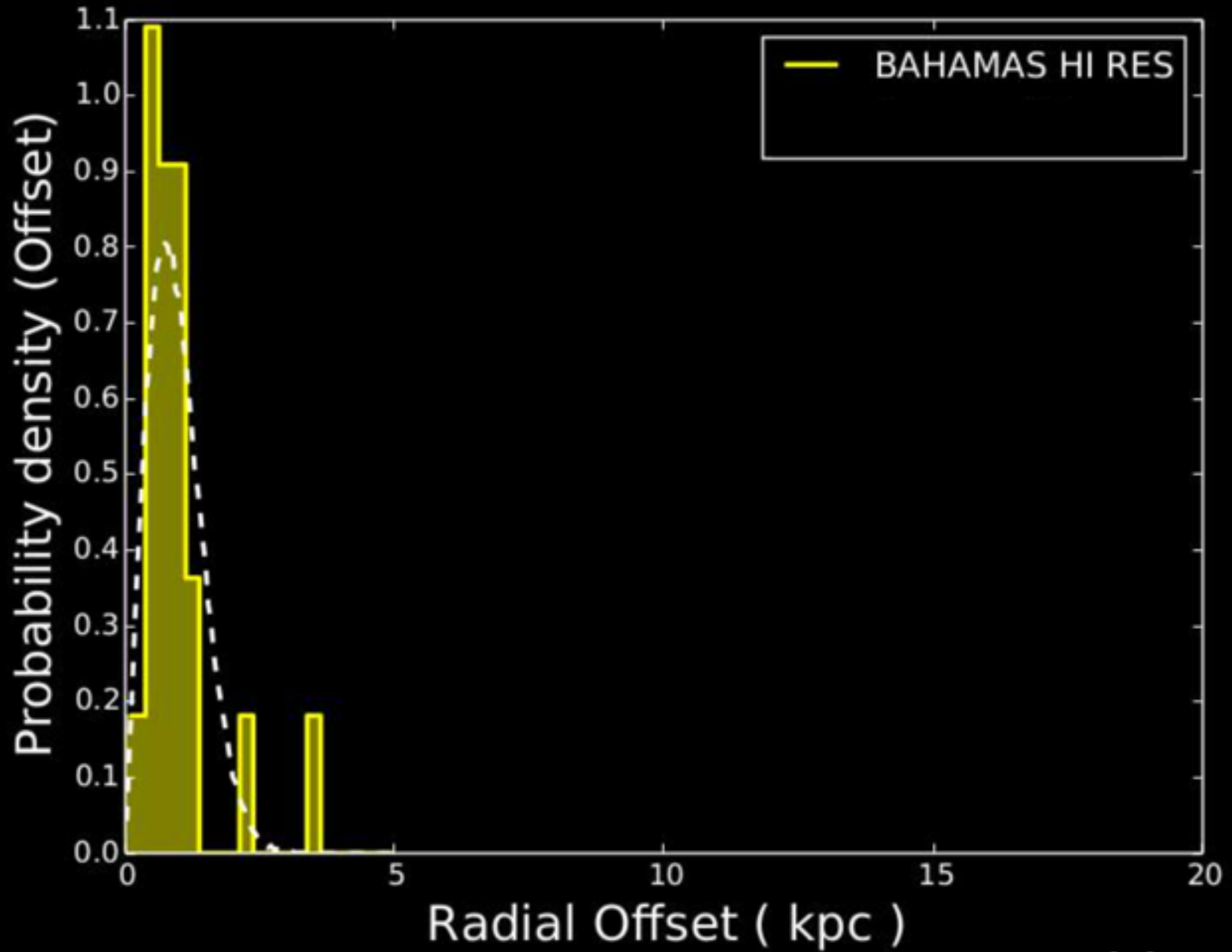
Abell 3827

Williams & Saha (2011), MNRAS 415, 0448
Massey et al. (2015), MNRAS 449, 3393
Taylor et al. (2017), MNRAS 468, 5004



Courtesy David Harvey

NO WOBBLING OBSERVED IN STANDARD MODEL DARK MATTER



Harvey+ 2017b

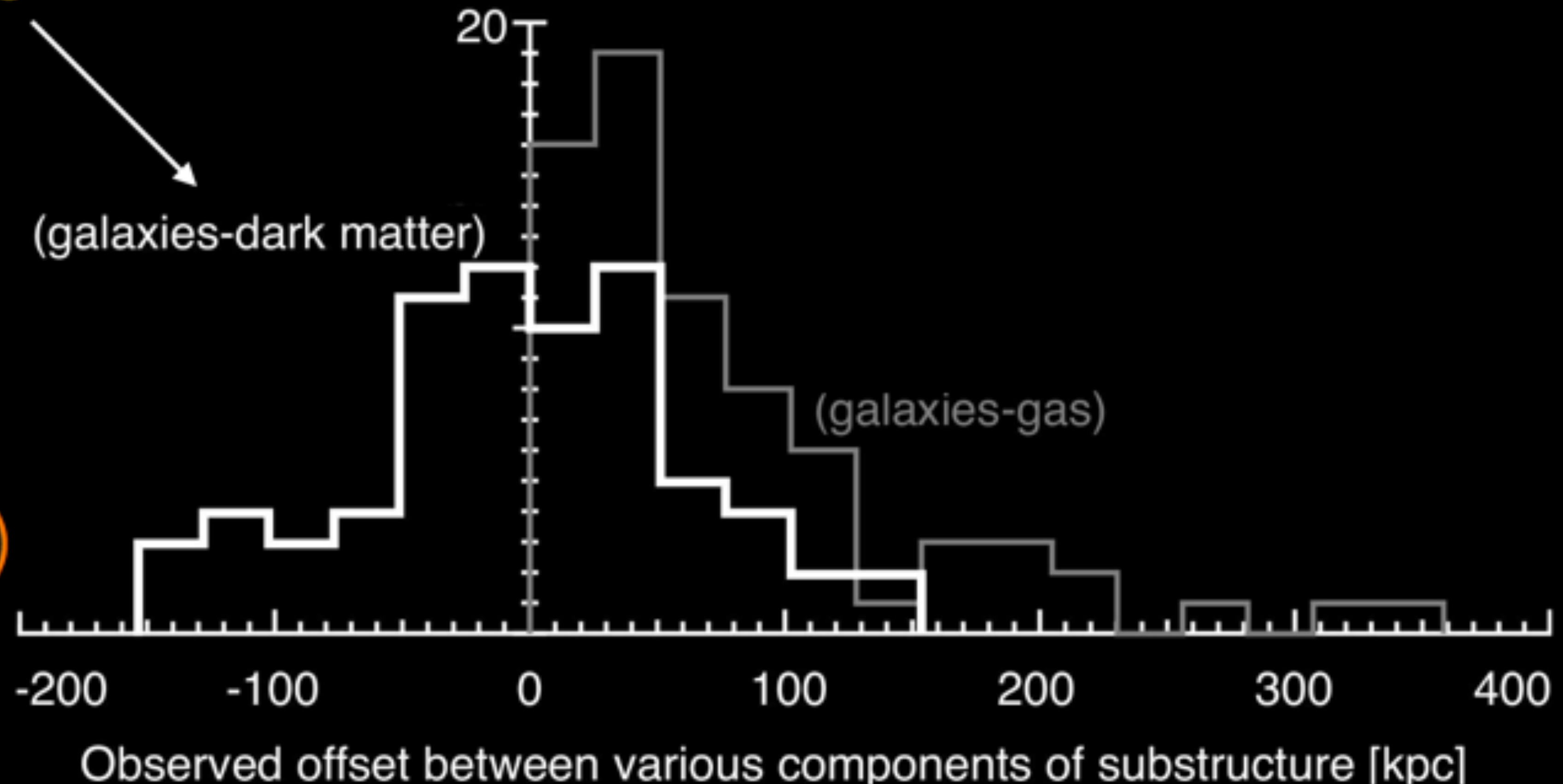
Courtesy David Harvey

DARK MATTER — GALAXY OFFSETS FROM 72 MERGING SYSTEMS

$5.8 \pm 8.2 \mathrm{kpc}$

$25 \pm 29 \mathrm{kpc}$

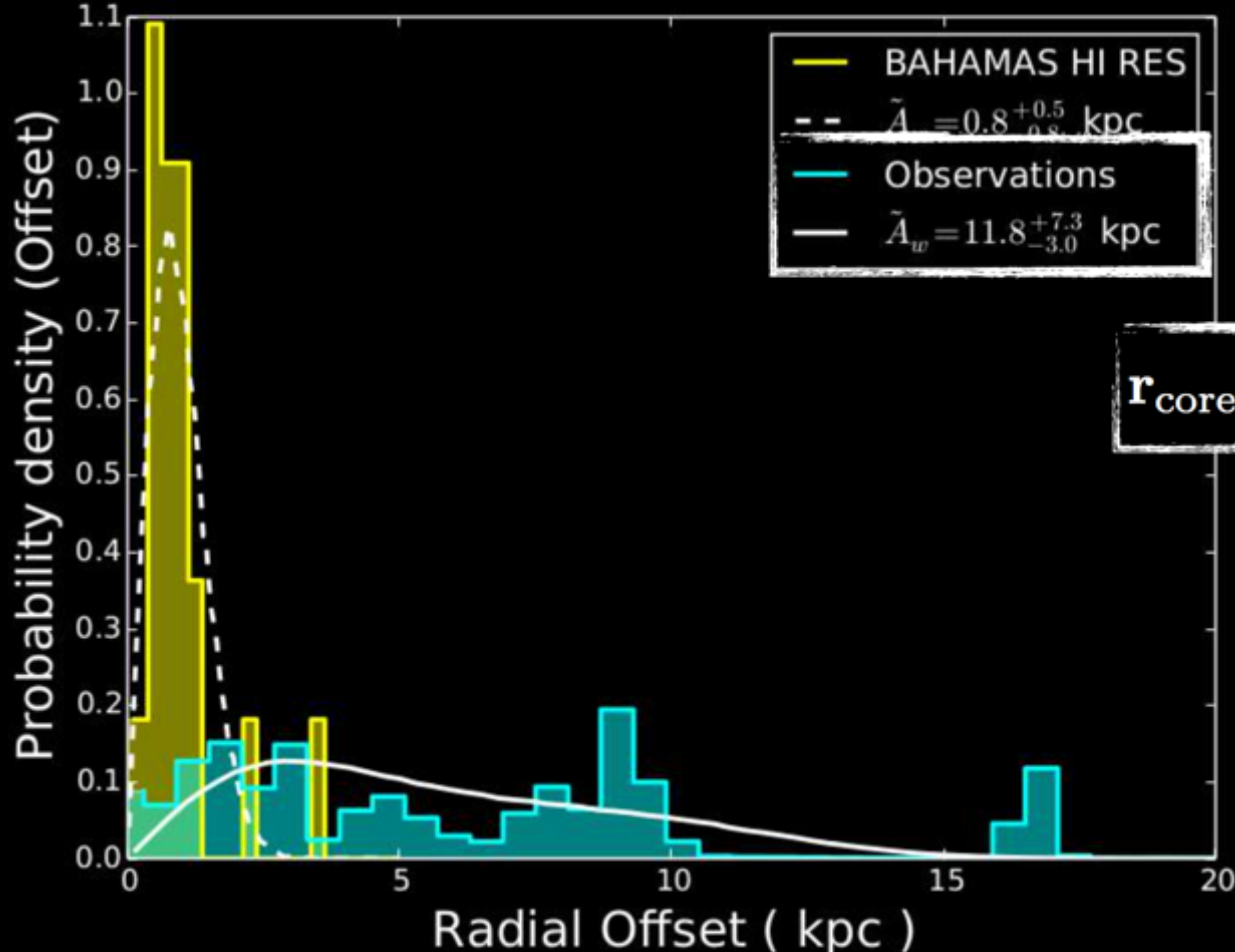
(Bullet Cluster)



Harvey+ 2015

Courtesy David Harvey

OBSERVATIONS FAVOUR NON-ZERO WOBBLE AT 3-SIGMA SIGNIFICANCE



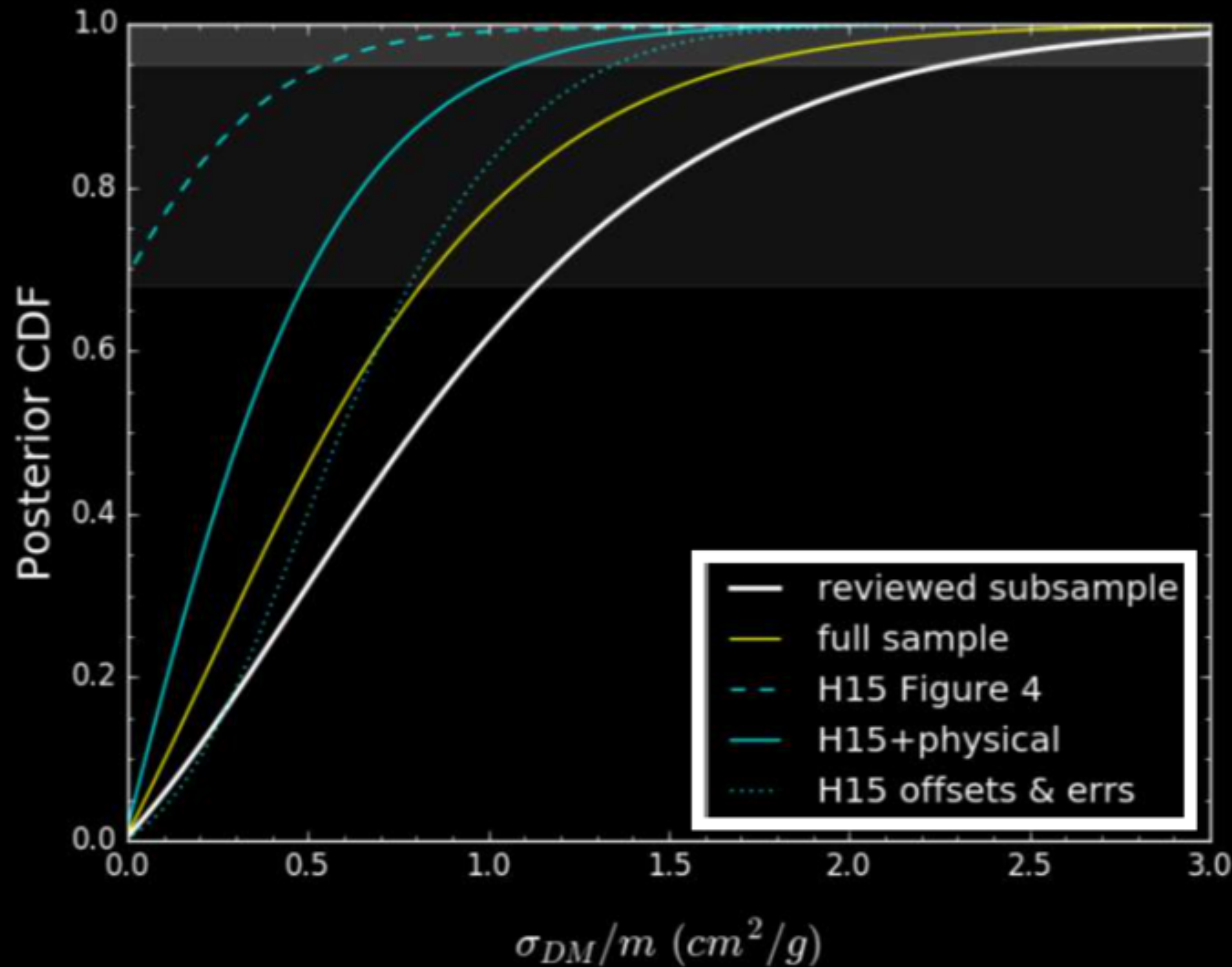
$$\mathbf{r_{core} = 13.8 \pm 1.4}\text{kpc}$$

Harvey+ 2017b

bimodality: new constraints 0.47cm^2/g

Courtesy David Harvey

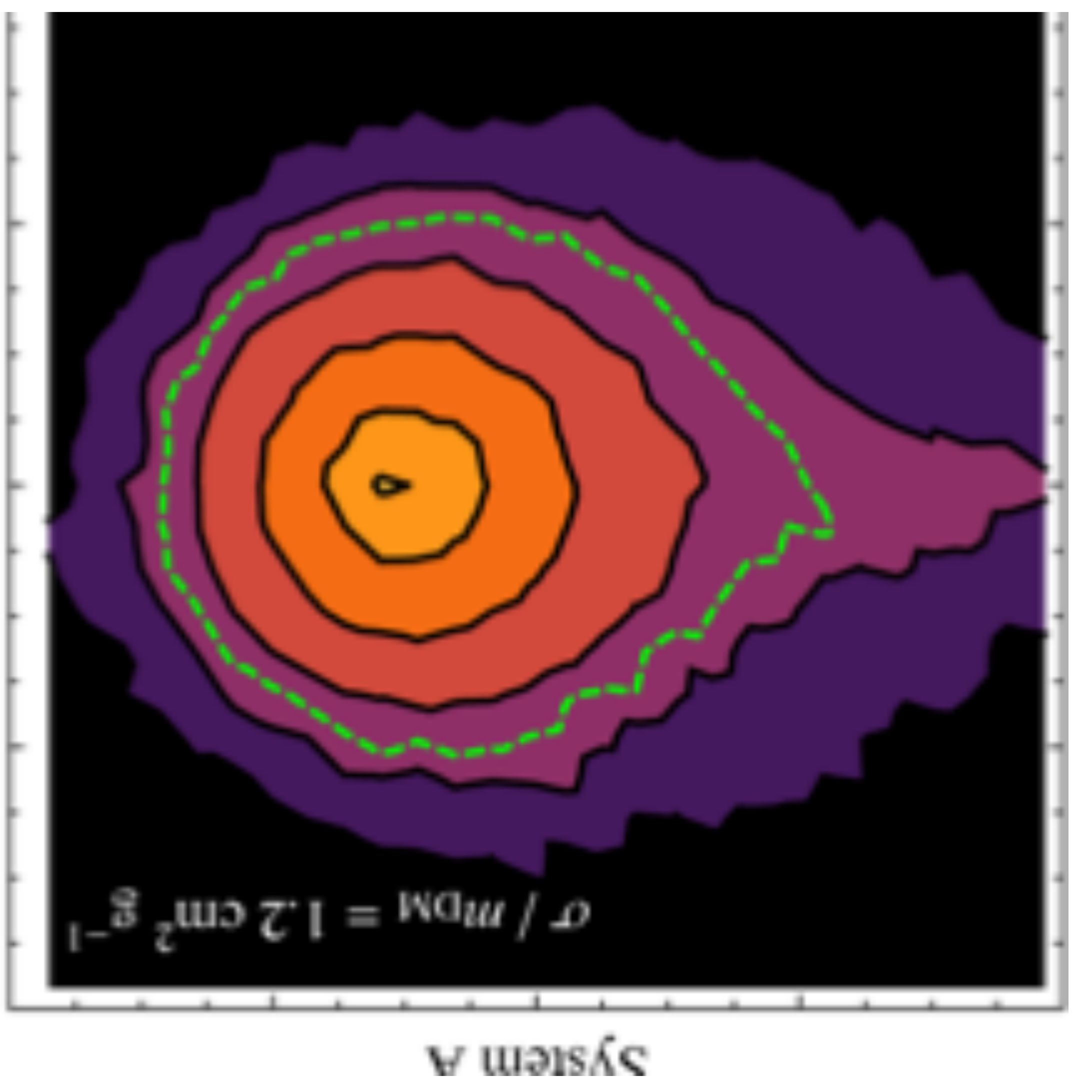
SYSTEMATICS IN MEASURING AND INTERPRETING OFFSETS



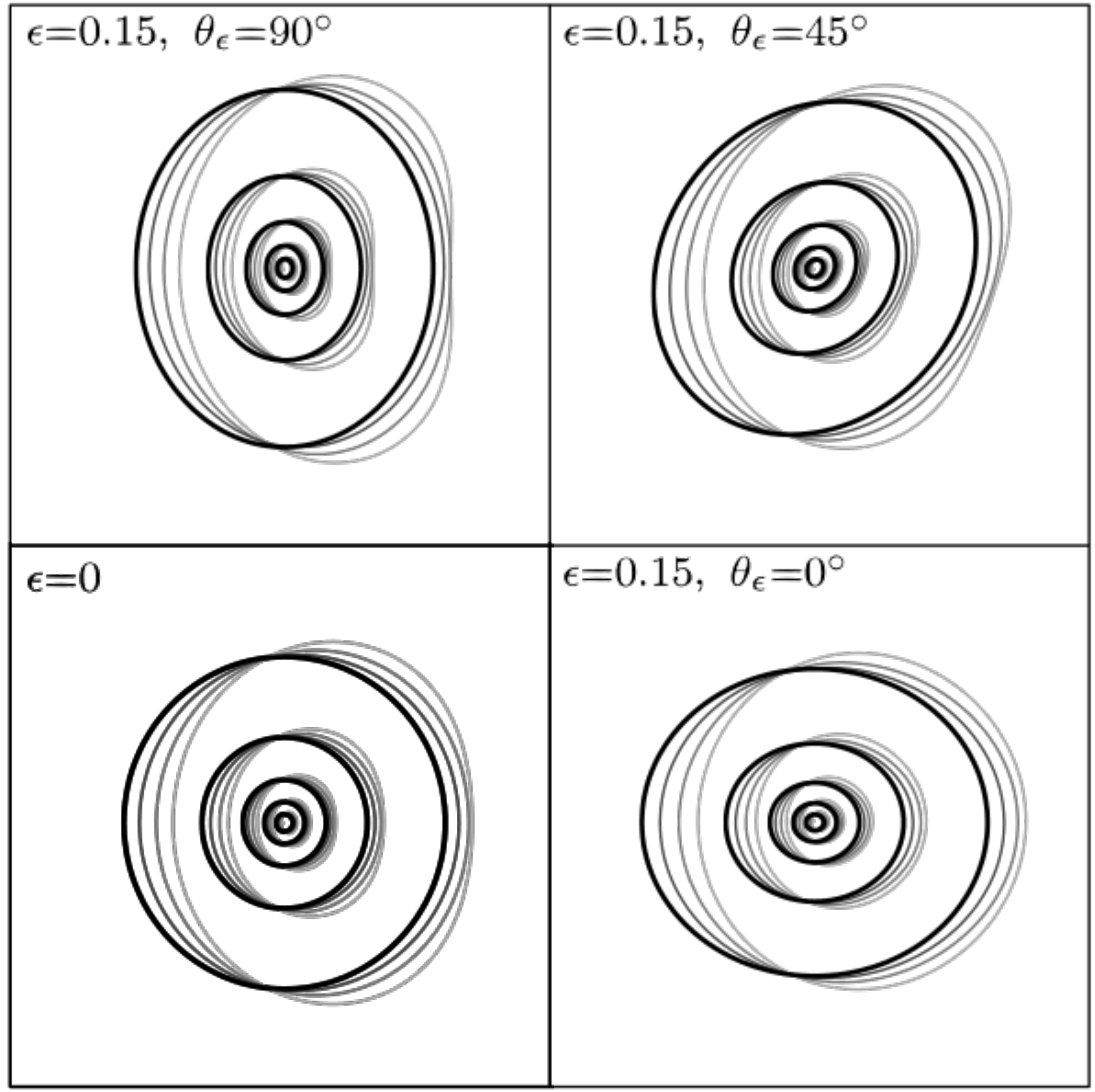
Wittman+ 2017

New ways to parameterise skewness

Courtesy Richard Massey

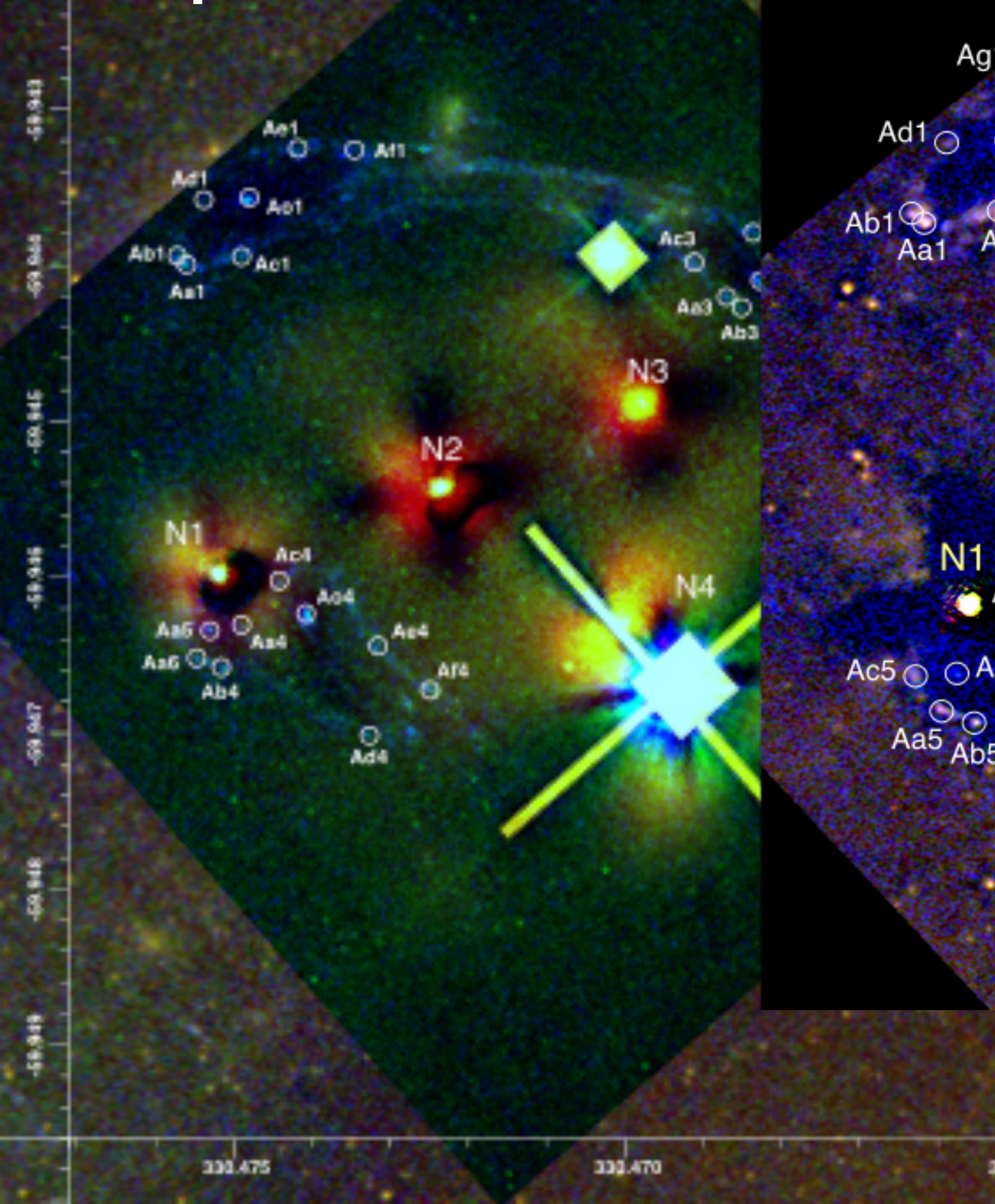


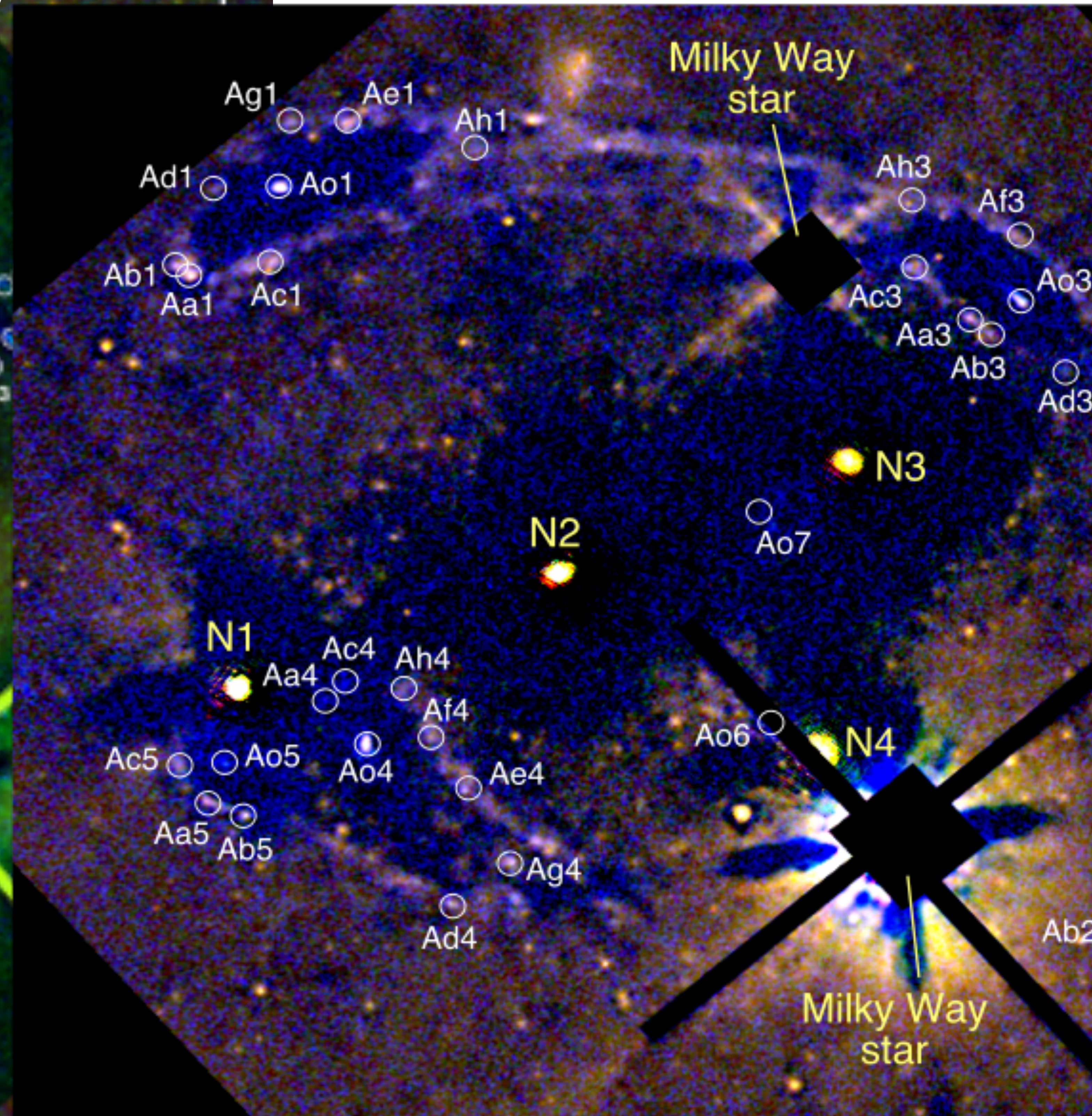
Kahlhoefer et al. (2014), MNRAS 437, 2865



Taylor et al. (2017), MNRAS 468, 5004

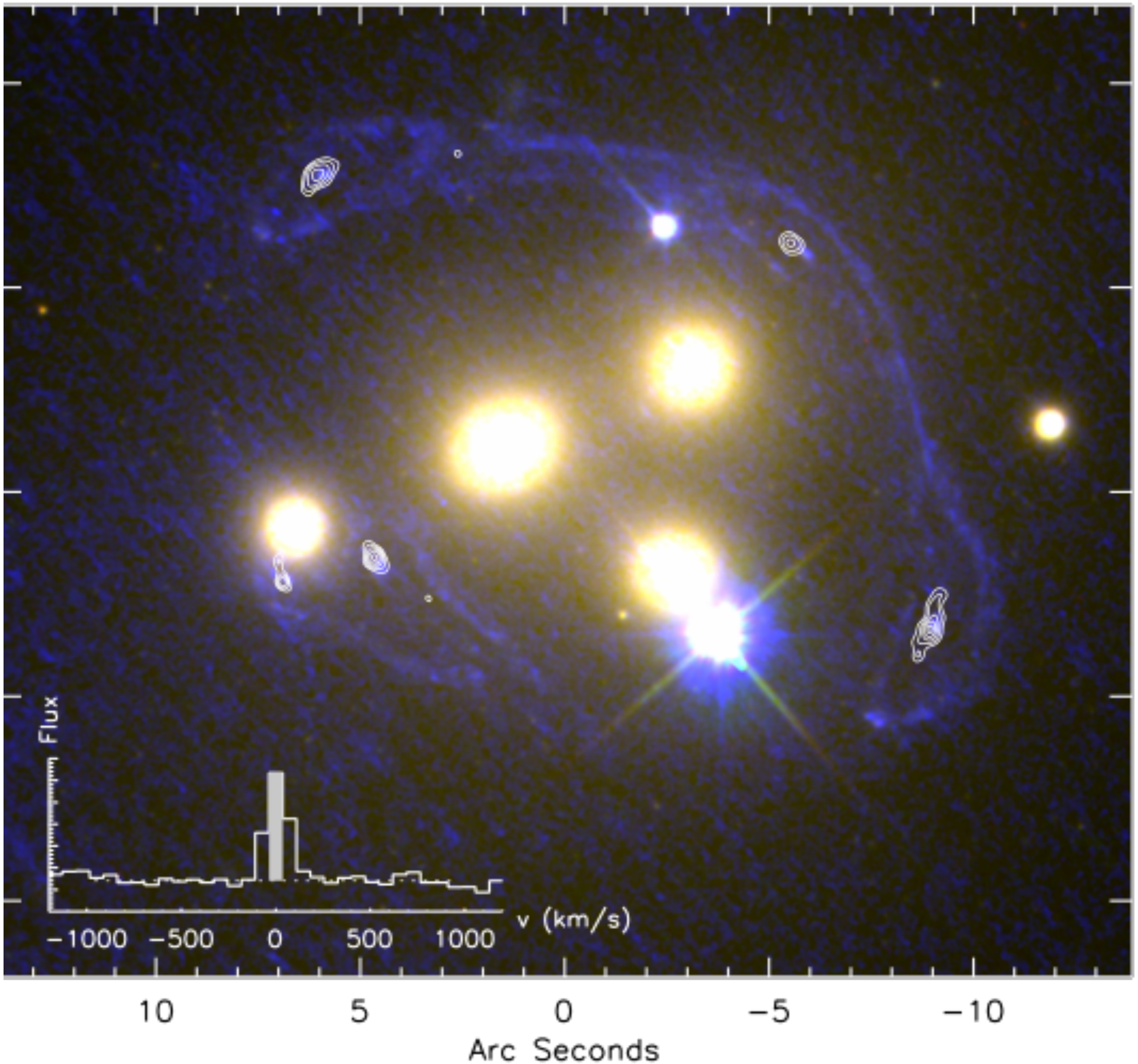
Update in 2017





Courtesy Richard Massey

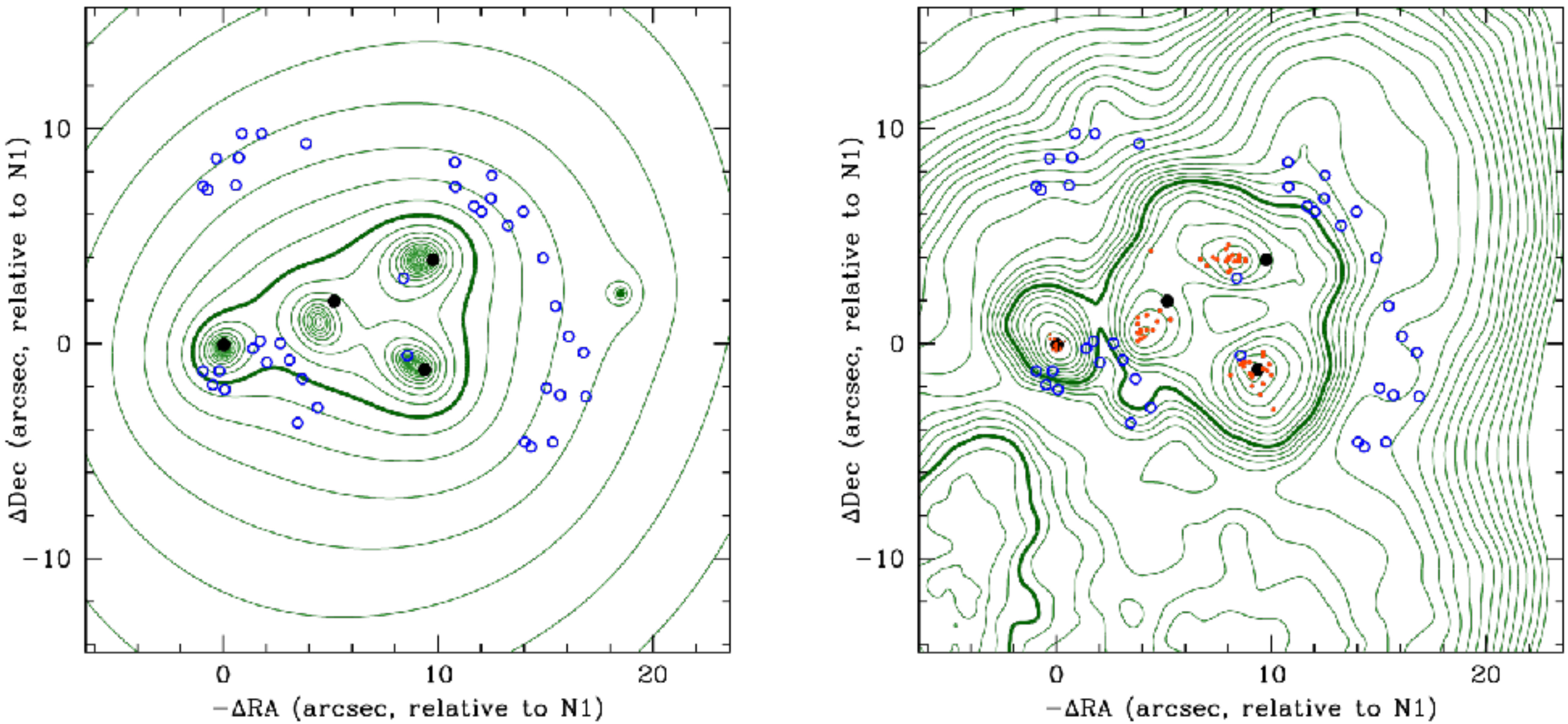
ALMA mm integral field spectroscopy (contours; background image HST)



Courtesy Richard Massey

A3827 mass distribution – 2017

Courtesy Richard Massey



No offset!!!

Offsets/wobbles in massive galaxies of Hubble Frontier Field clusters

Courtesy Liliya Williams

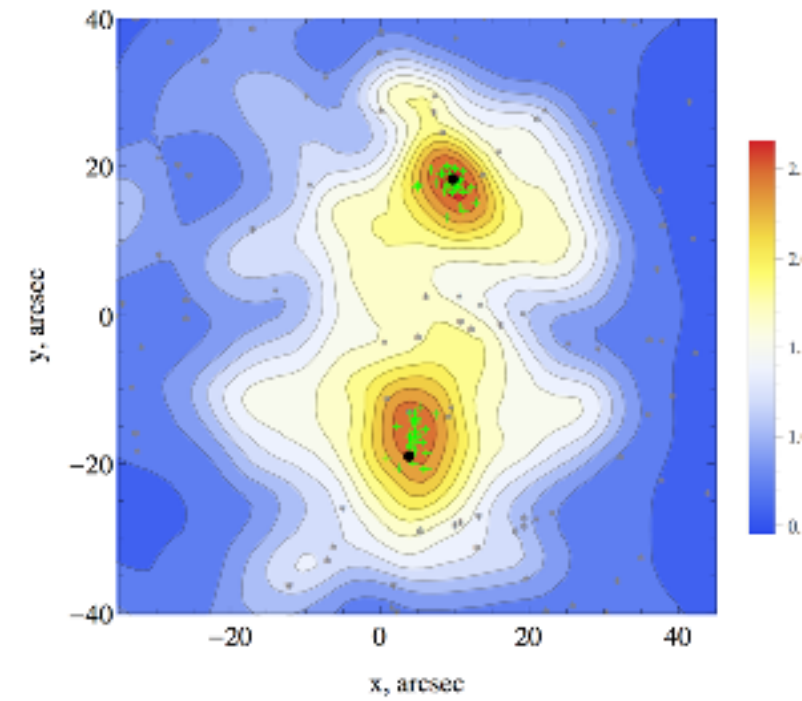
We measure mass-light offsets between central galaxies in clusters and the nearest mass peak, ~0-15 kpc, and estimate statistical significance

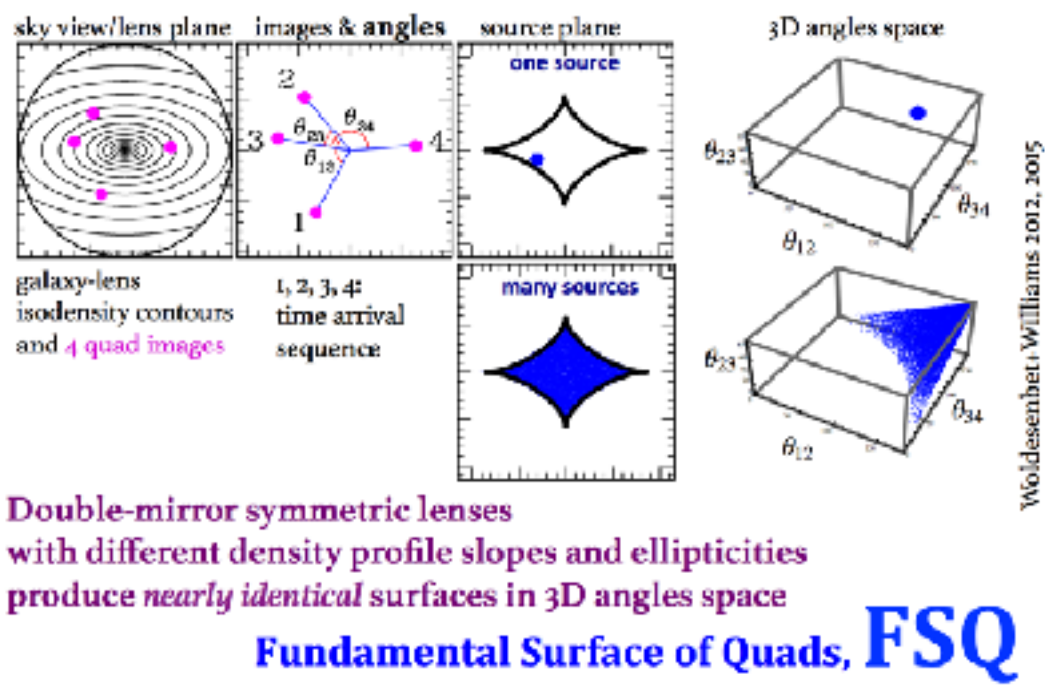
Mass-light offsets could be due to ***SIDM*** or purely ***Newtonian gravity***

Simulations give no offset for many of the clusters

None of the 5 galaxy-mass offsets is larger than ~15 kpc.

Abell370

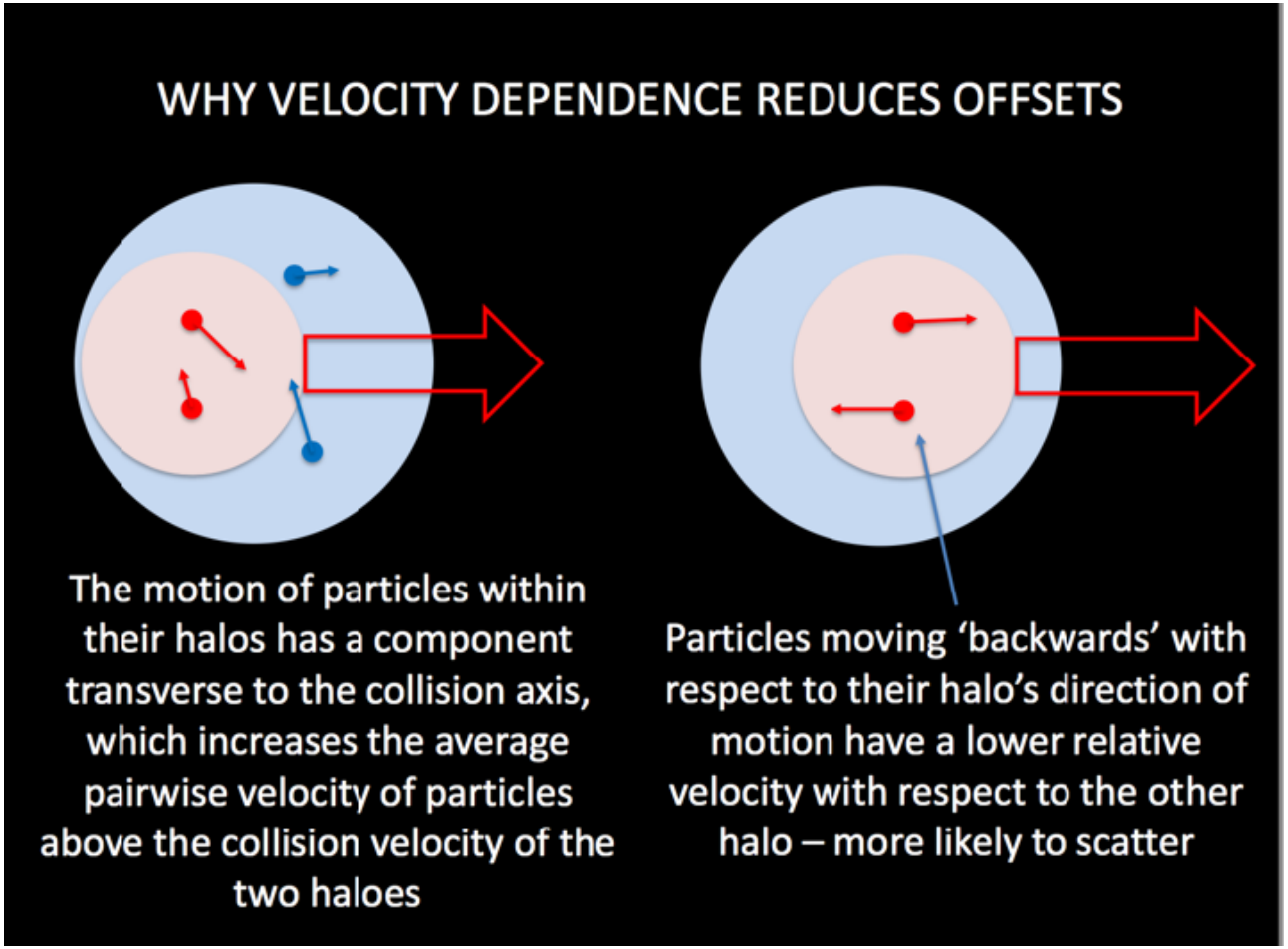




allow model free conclusions

Offseting the centers of the stellar and dark matter distribution by <1kpc can reproduce observations.

Courtesy Andrew Robertson



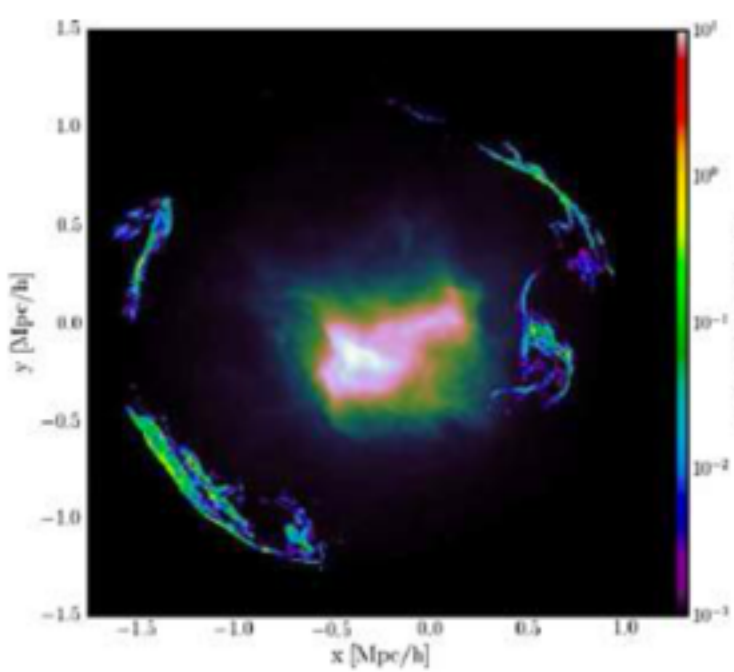
- Constraints on SIDM cross-sections from offsets in merging clusters may be over-stated
- For the simplest well-motivated velocity-dependent SIDM, expect only small offsets in merging galaxy clusters

Toward Better Merger Modeling

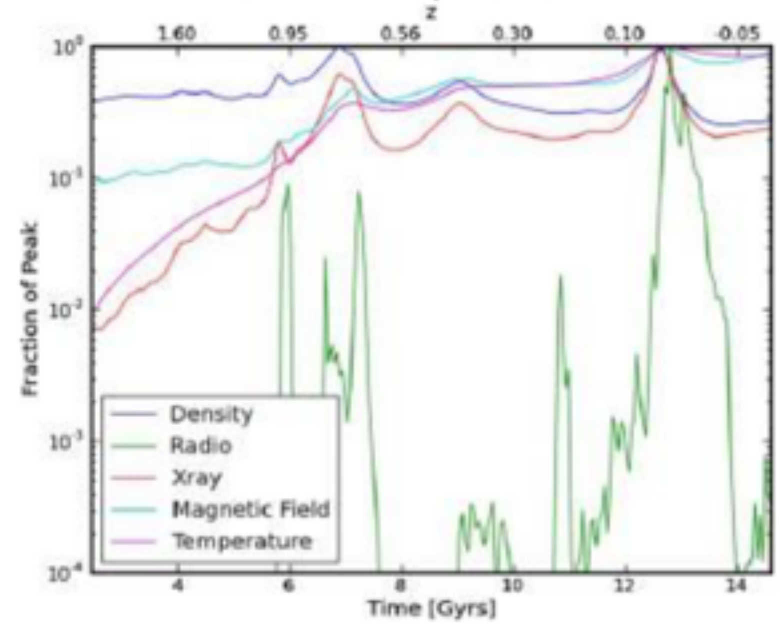
Courtesy David Wittman

merger phase matters: components change relative position over time

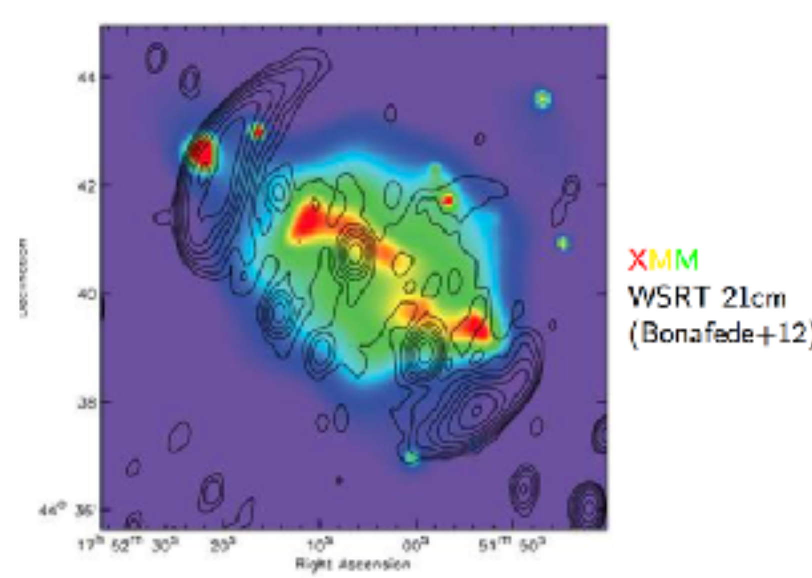
Radio selection gives more clusters



Skillman+2013



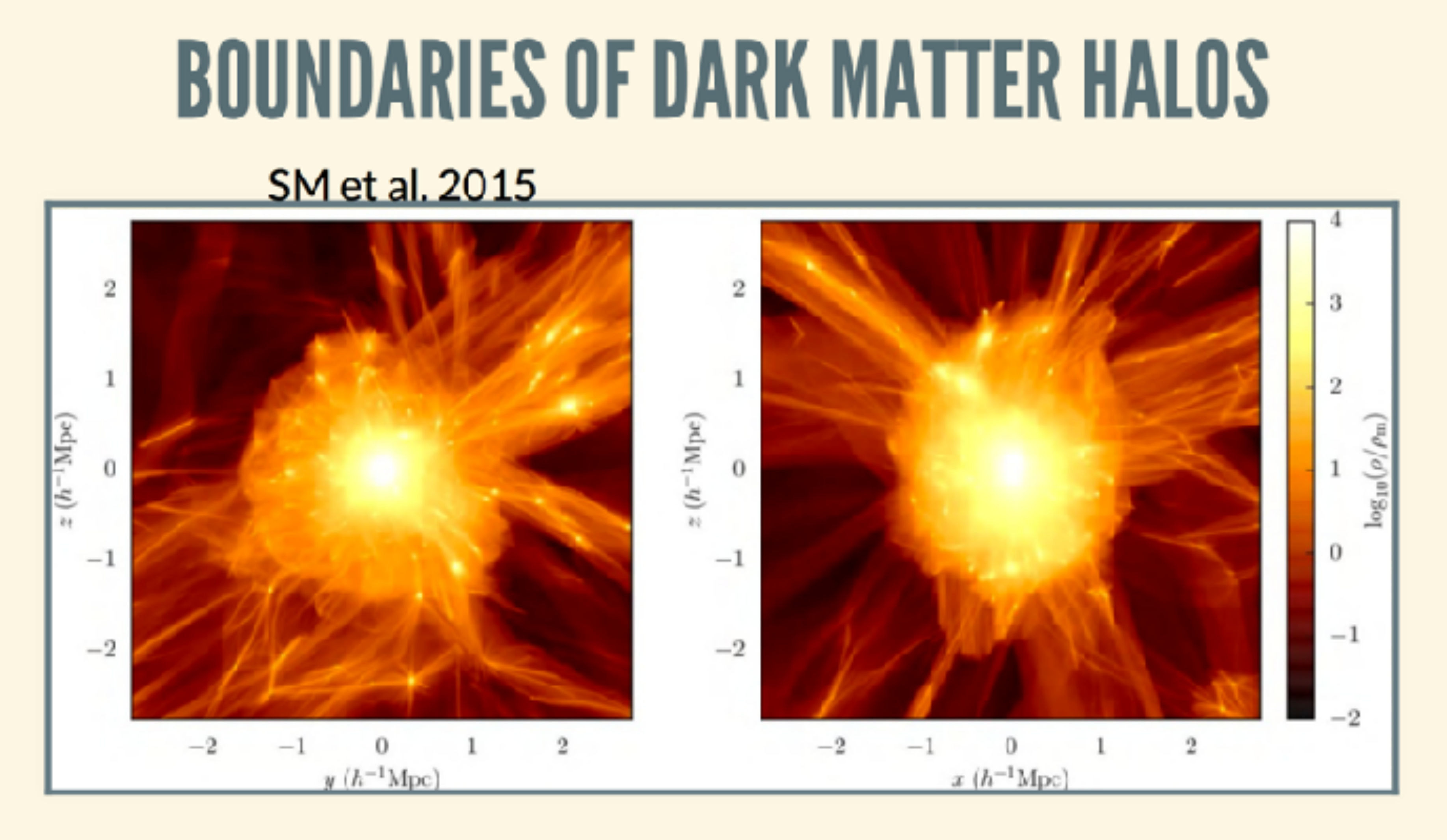
MACS J1752+4440: Two Bullets That Missed?



We can get big offset with cdm (can't tell by more than 95%)

Ng+, 1703.00010

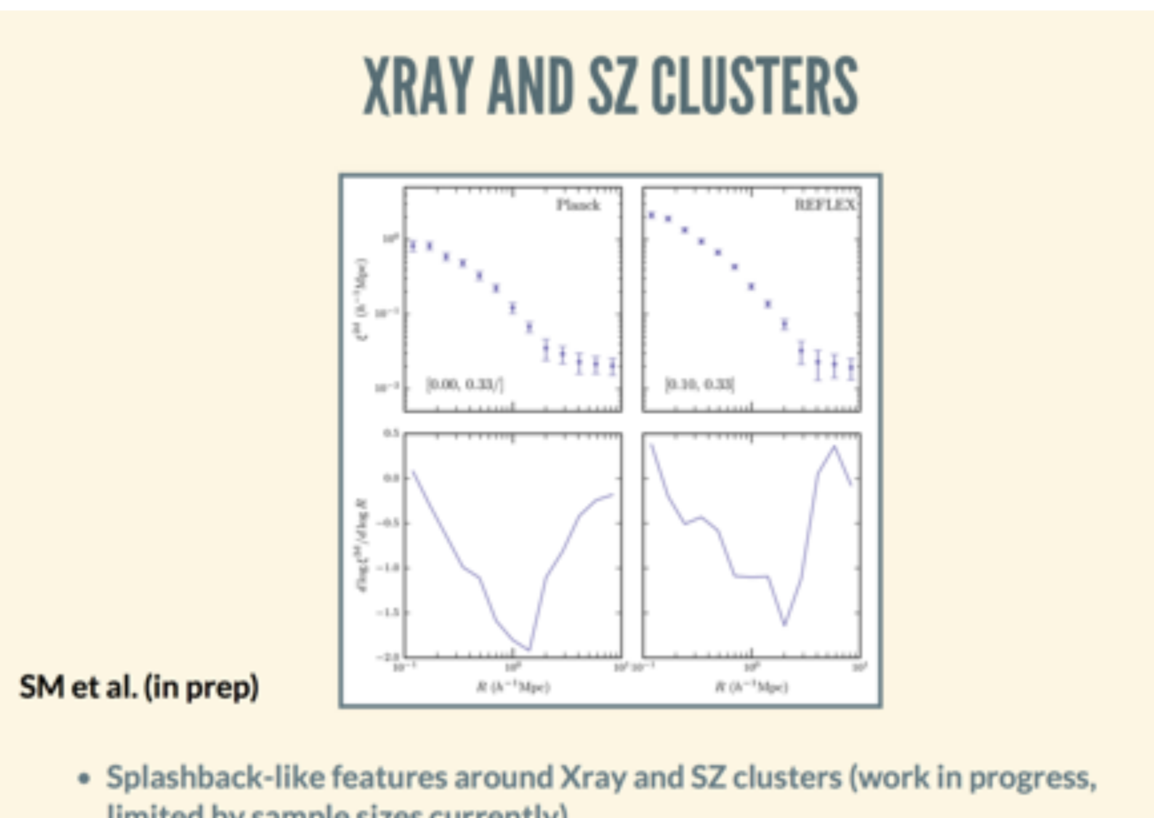
in line with the other conclusions??



Courtesy Surhud More

Edge of MW could touch Andromeda.

How do you define the edge of the halo?



last caustic — physical boundary for the DM;

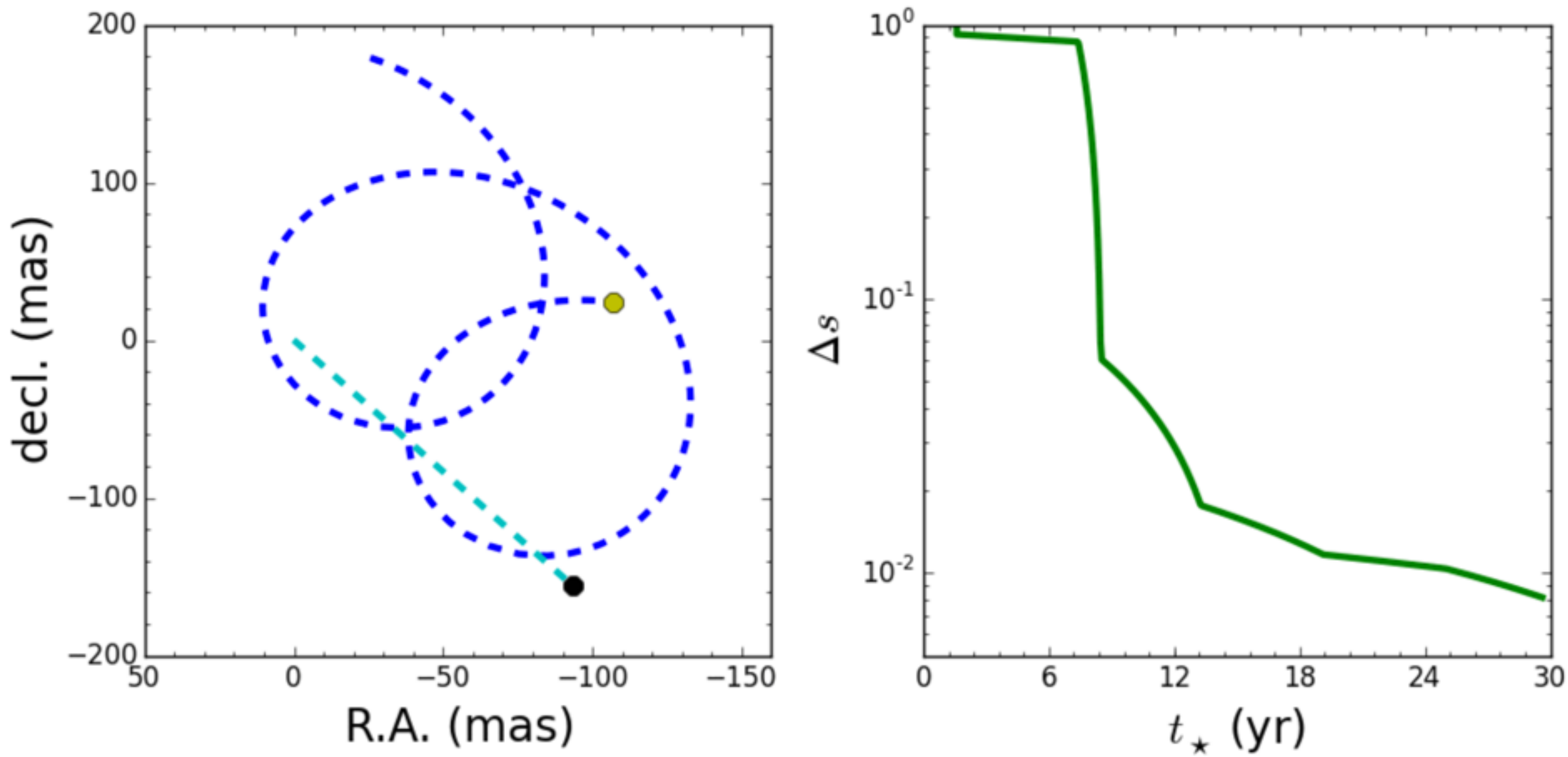
profile falls at a location that is 20% smaller than expected

SIDM then dissipative force can reduce the splash radius but ?

New signatures

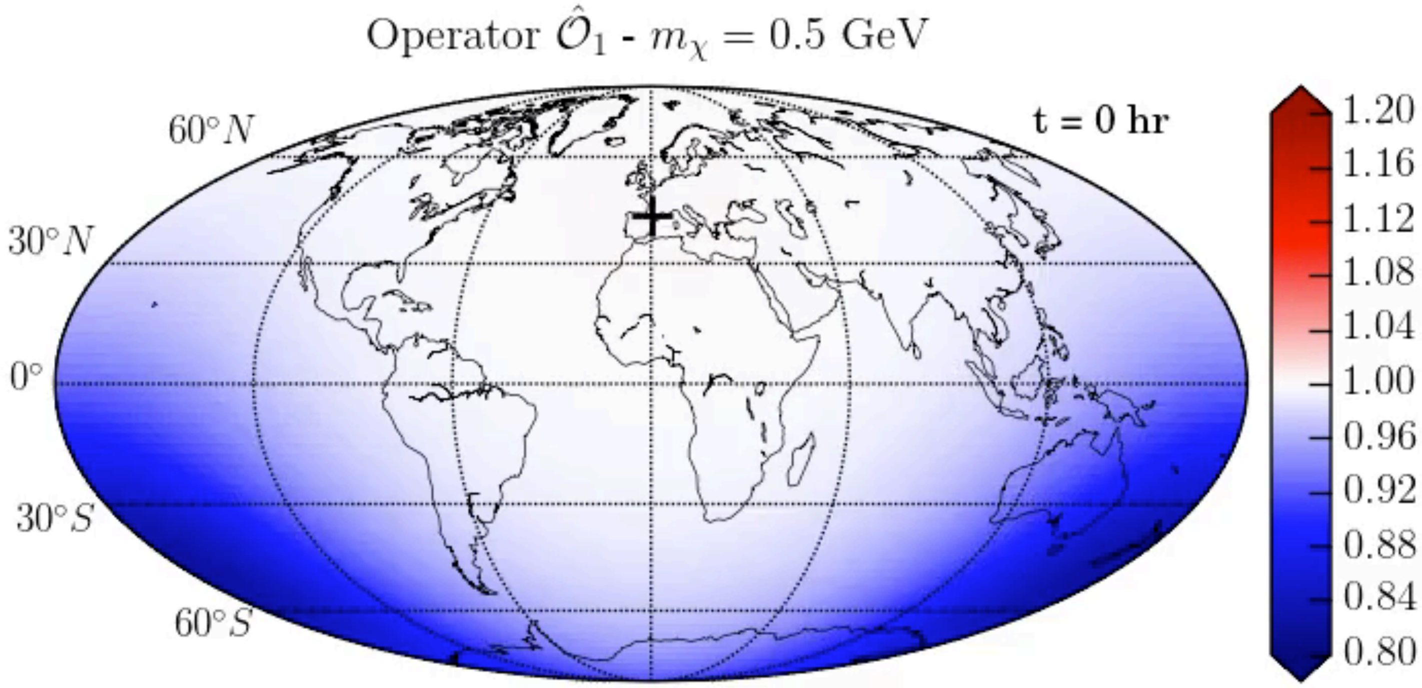
Courtesy Prasenjit Saha

Black-hole Spin Constraint



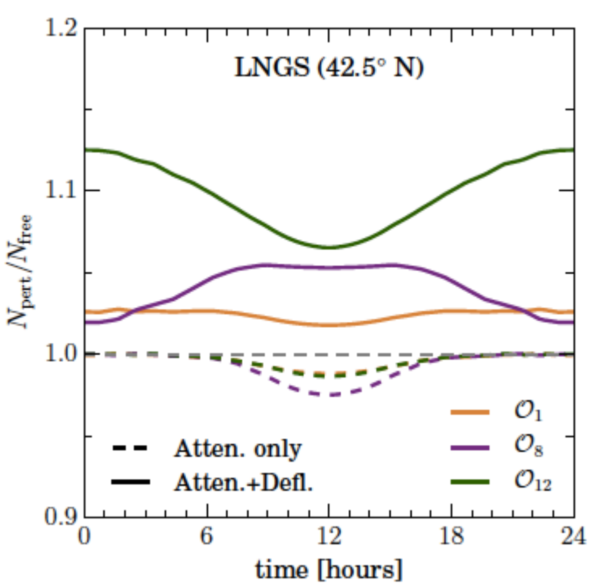
Courtesy Chris Kouvaris

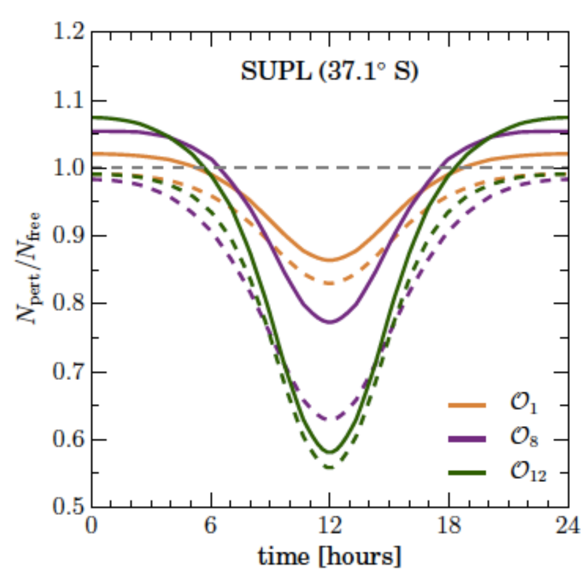
The Shadow of the Earth



Relative rate enhancement due to Earth-scattering *(attenuation only)*

(Kavanagh, CK, Catena '17)



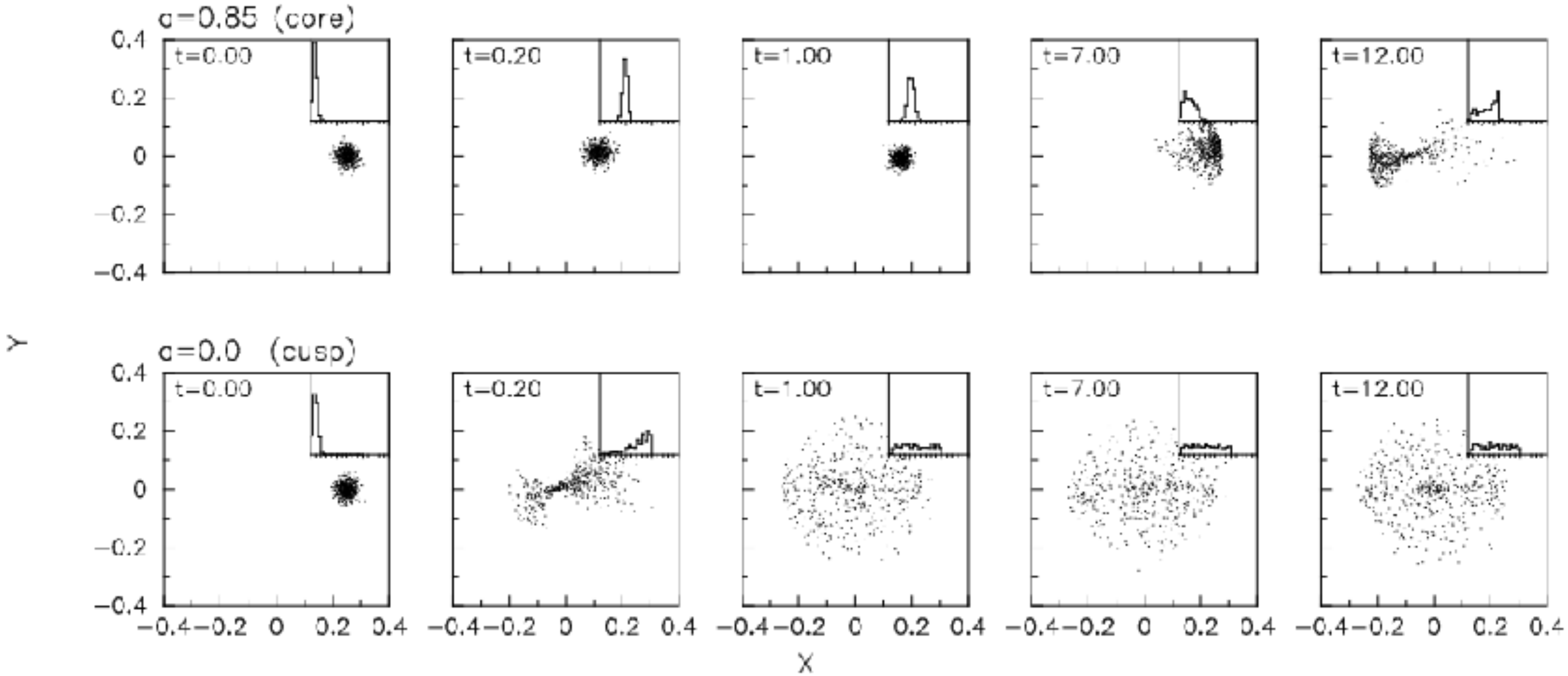


Possible signature in annual and diurnal modulation

Sabre (Australia) in a good place

Globular clusters in dSphs

GCs need **cored** DM distribution to survive inside a dSph:

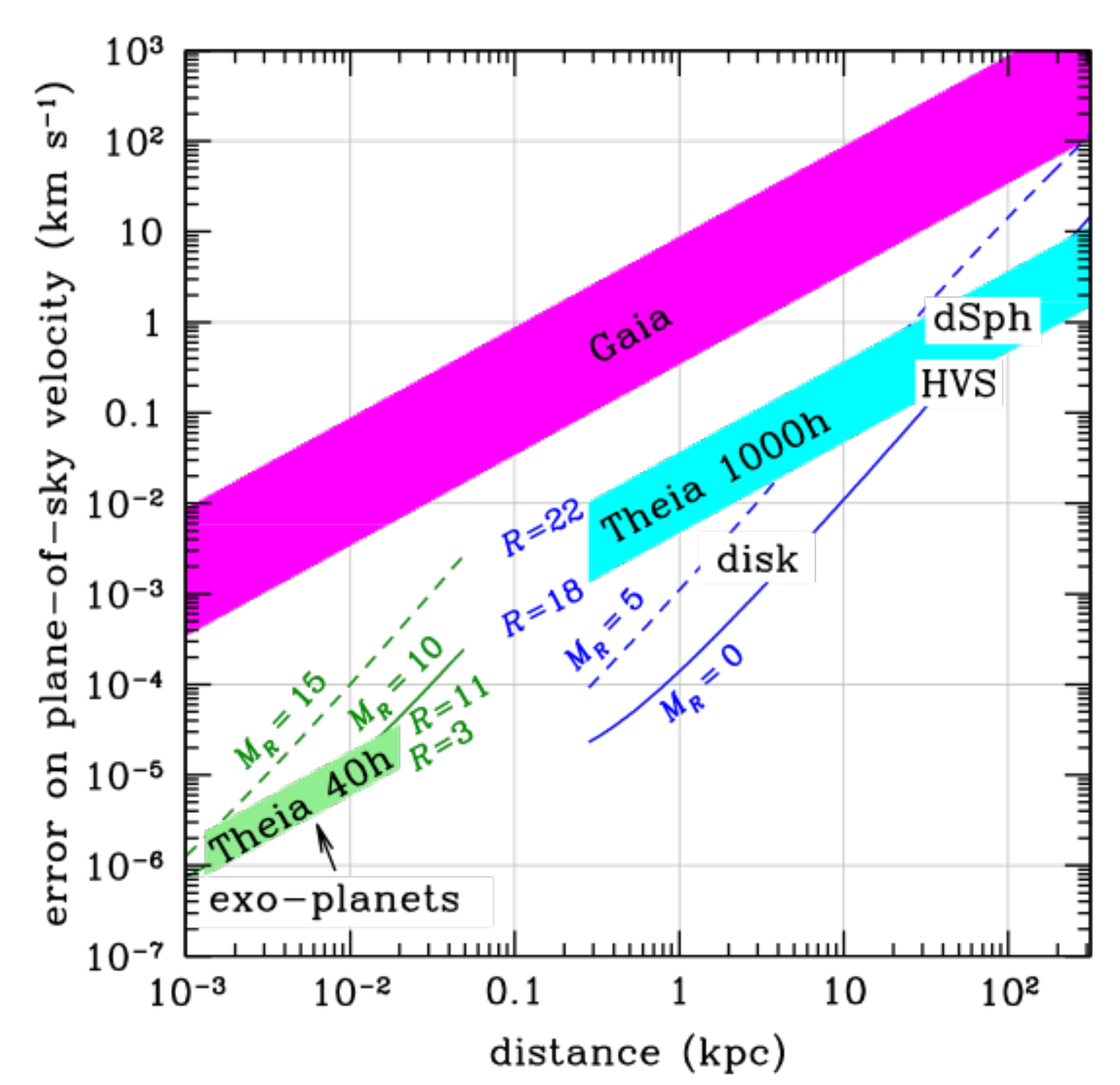


Kleyna et al., ApJ 2003 (Ursa Minor)

See also Goerdt et al., MNRAS 2006 (Fornax), Contenta et al., 2017 (Eri II), Amorisco, ApJ 2017 (Eri II & And XXV).

THEIA

Microarcsecond Astrometric Observatory



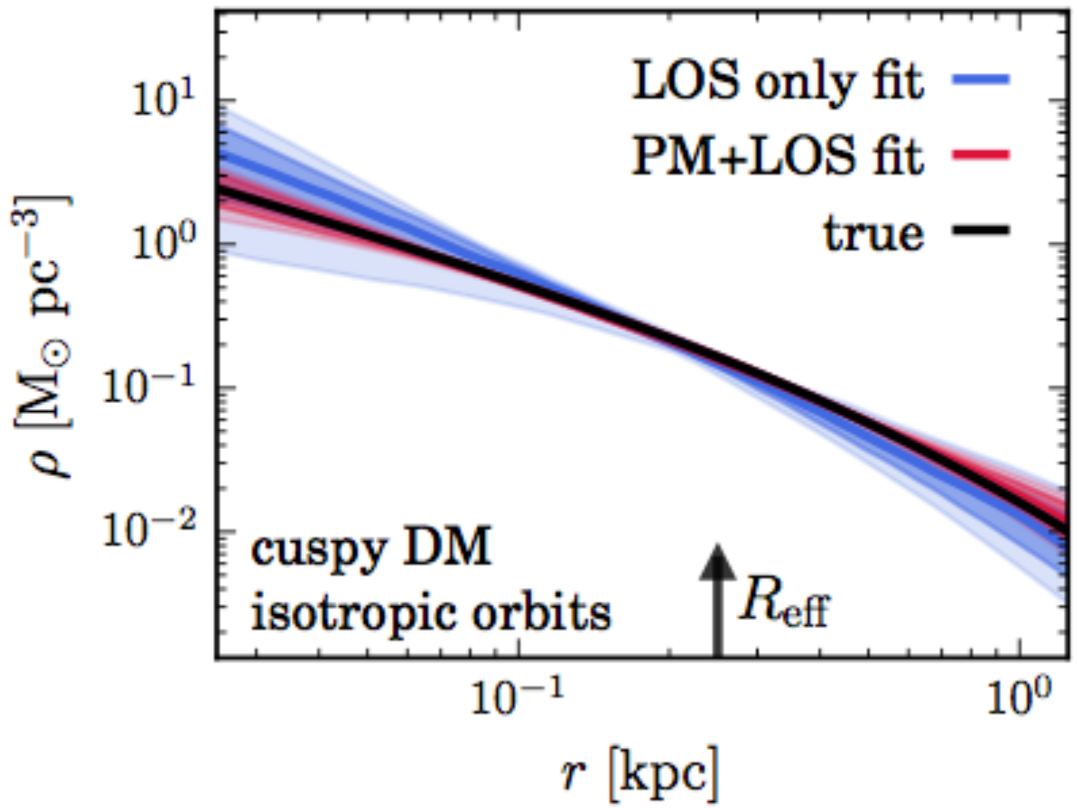
Dmytro made a point about proper motions

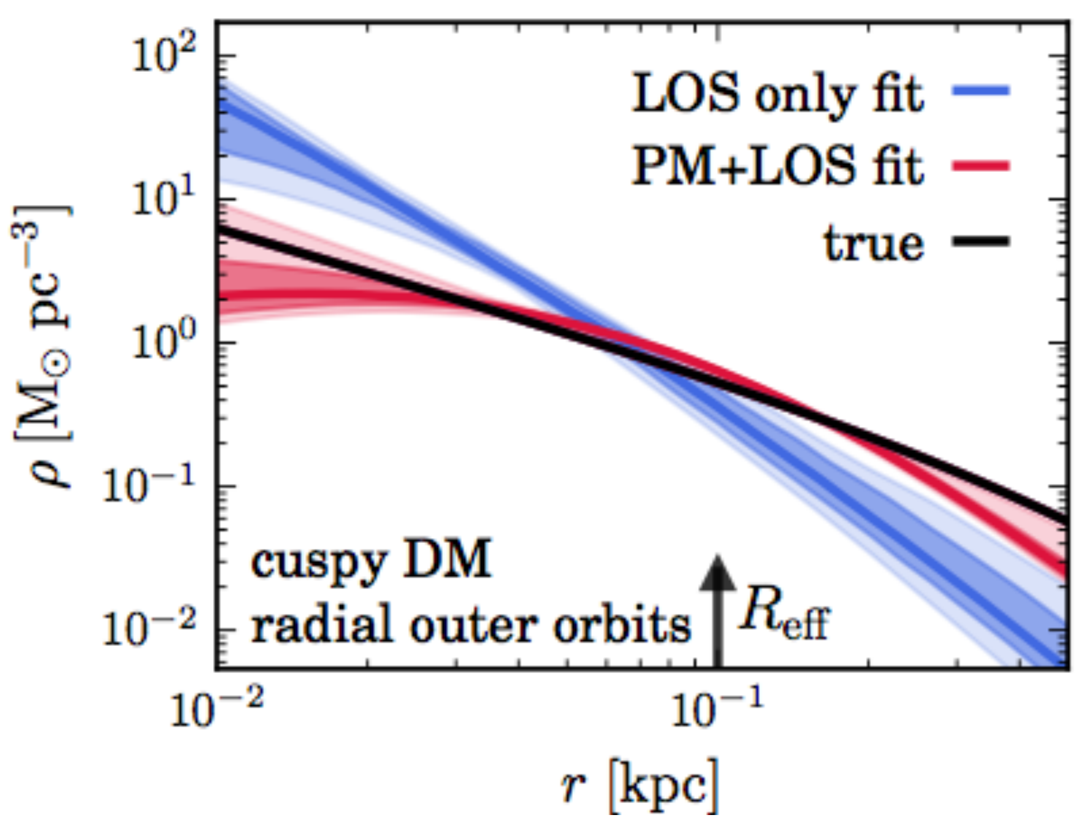
it is good...

THEIA

Microarcsecond Astrometric Observatory

Dark Matter in dSphs





CDM halos can be heated by bursty star formation inside the stellar half light radius $R_{1/2}$, if star formation proceeds for long enough.

Some **dSphs like Fornax** have formed stars for almost a Hubble time and so **should have large central dark matter cores,** while others, like **Draco and Ursa Major2 should retain their steep central dark matter cusp**.

But it depends on the DM nature.

We can tell how DM is distributed and discriminate between cusp/core distributions

Theia can probe self-interactions

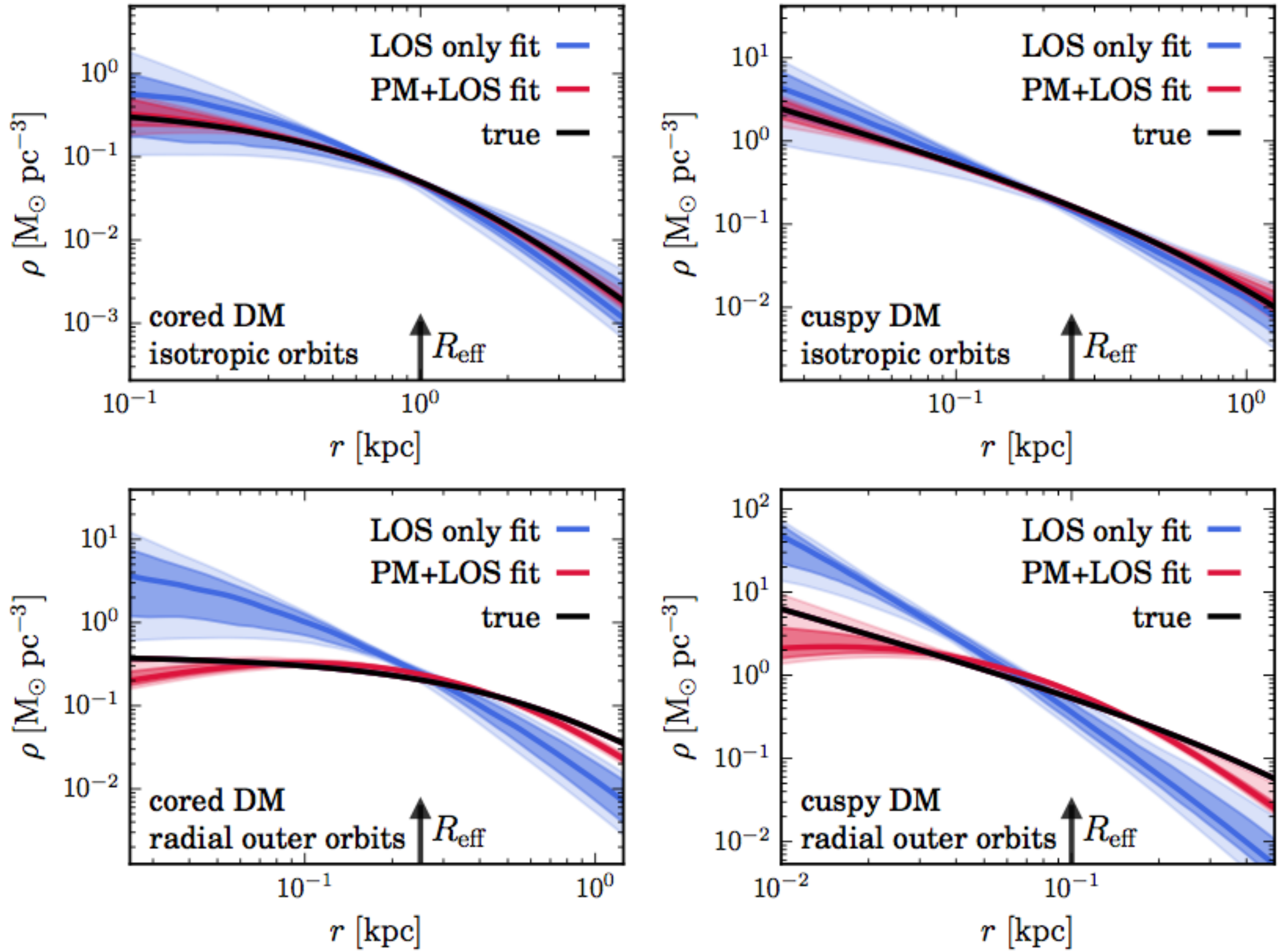


Fig. 2.2: Reconstruction of the DM halo profile of the Draco dSph without (*blue*) and with (*red*) proper motions using the mass-orbit modeling algorithm of Watkins et al. (2013). Four mocks of Draco were used, with cored (*left*) and cuspy (*right*) DM halos, and with isotropic velocities everywhere (*top*) or only in the inner regions with increasingly radial motions in the outer regions (*bottom*). The effective (half-projected light) radii of each mock is shown with the *arrows*. The stellar proper motions in the mocks were given errors, function of apparent magnitude, as expected with 1000 hours of observations spread over 4 years. Only with proper motions can the DM density profile be accurately reconstructed, properly recovering its cuspy or cored nature.

Conclusion

"Long lived" SIDM 1992...

Model building

N-body simulations

Observations

END