Complementary constraints on SIDM

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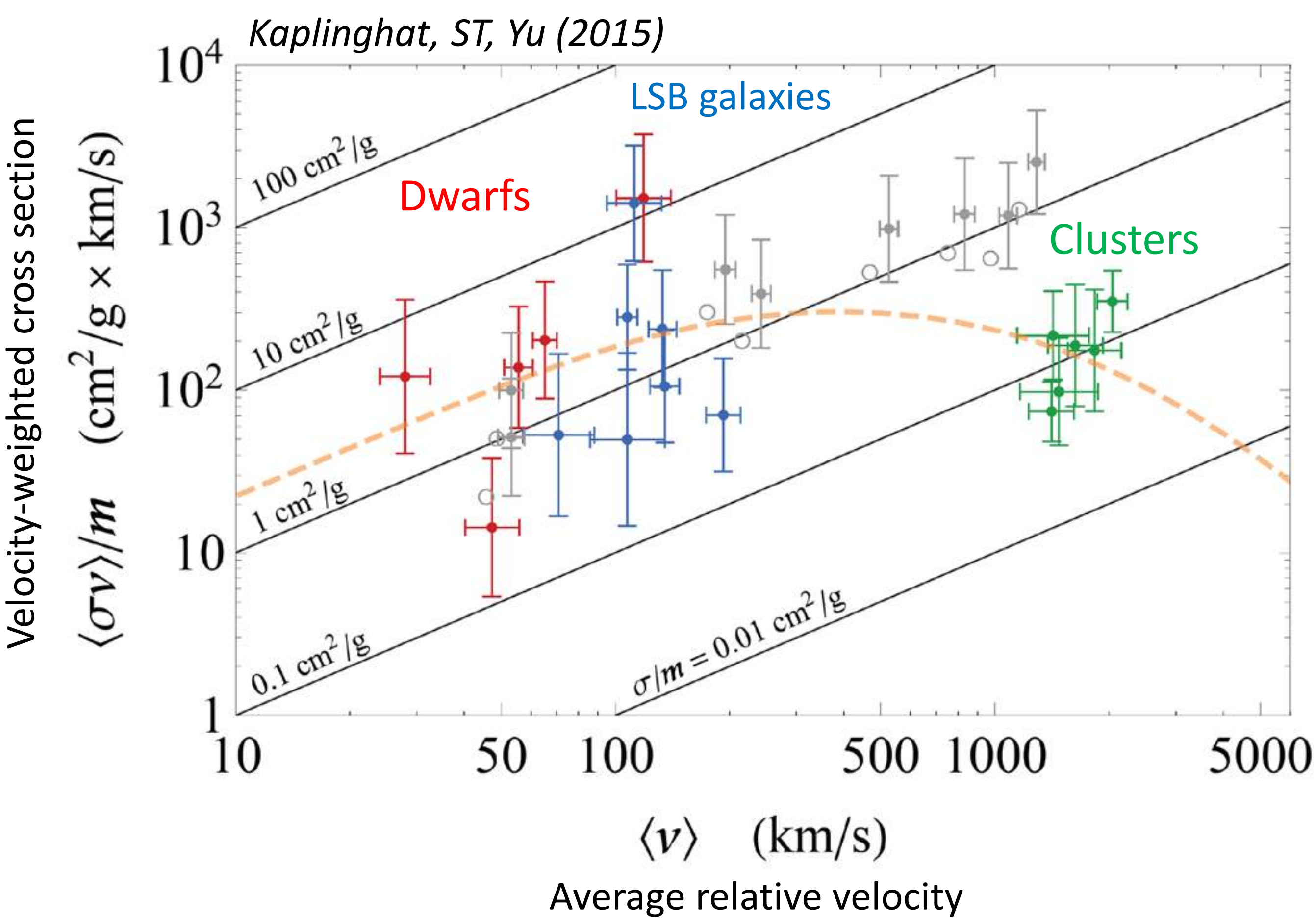
Velocity-dependent self-interactions

Dark matter self-scattering rate: $R_{\mathrm{scat}} = \sigma v_{\mathrm{rel}} \rho_{\mathrm{dm}} / m$



Simulation data at 1 cm^2/g (to verify model and get systematics)

17 MeV dark U(1) gauge boson

Galaxies:
$\sigma/m \sim$ 1–few cm^2/g

Clusters:
$\sigma/m \sim 0.1$ cm^2/g

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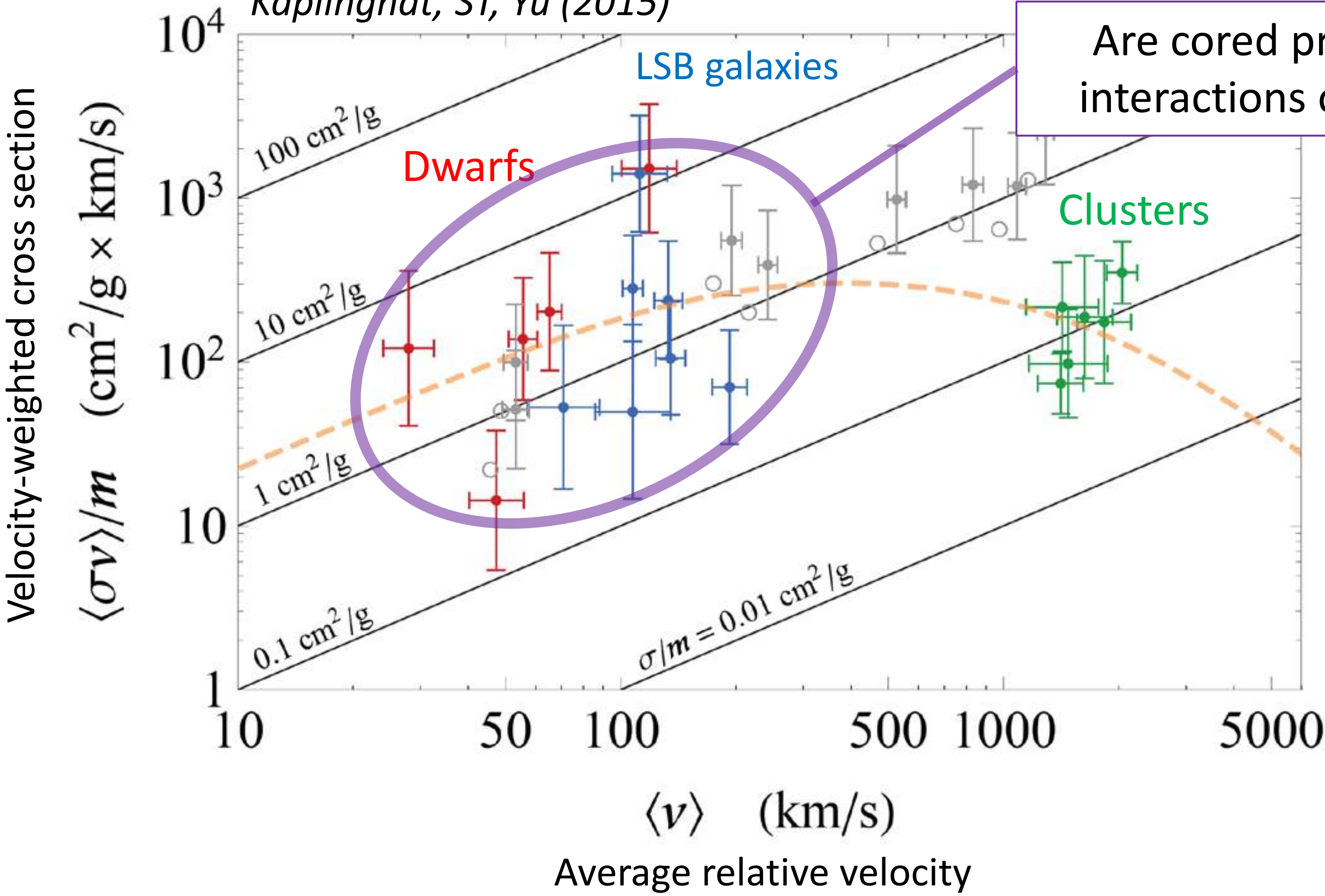
Kaplinghat, ST, Yu (2015)



Are cored profiles caused by self-interactions or baryonic feedback?

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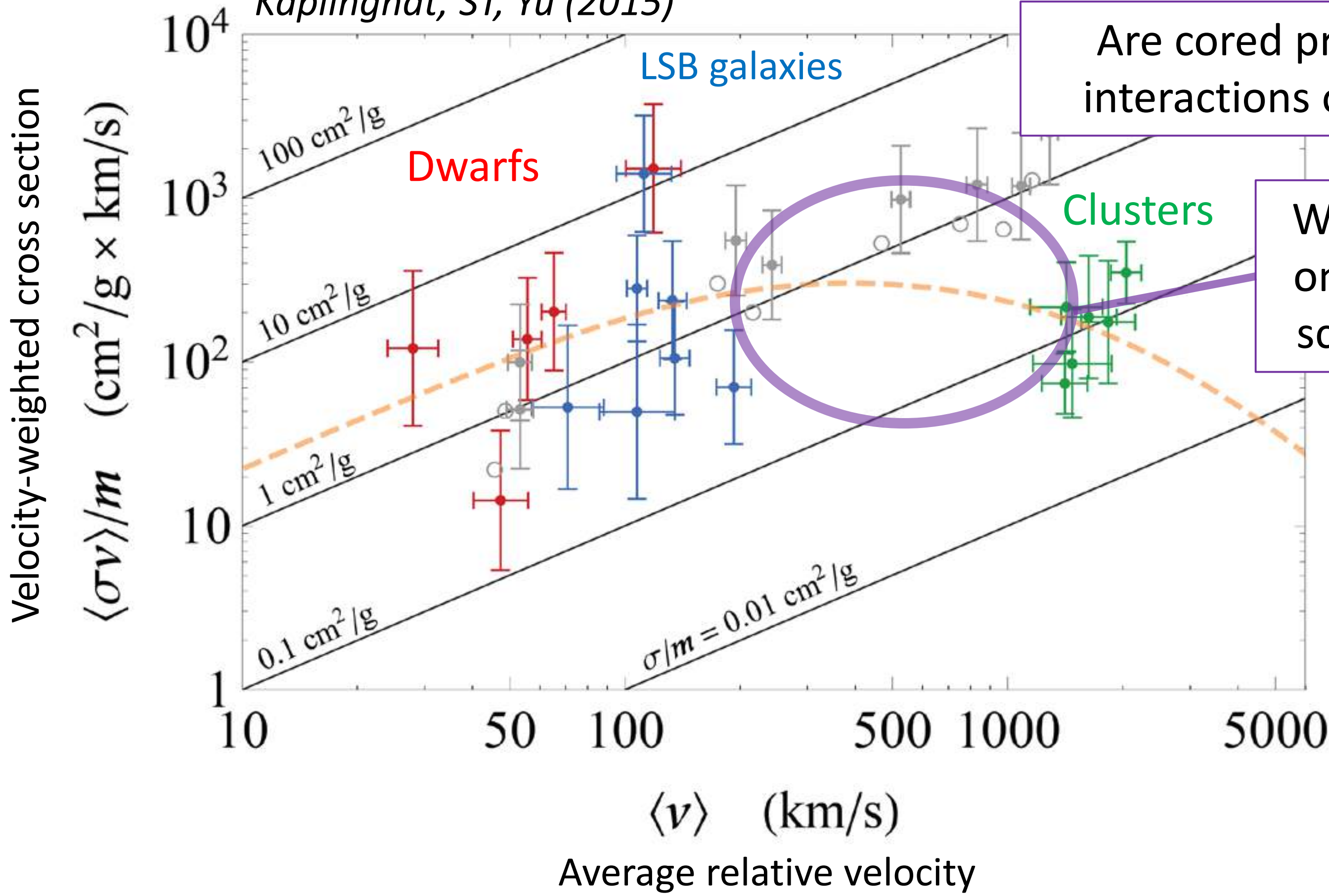

Are cored profiles caused by self-interactions or baryonic feedback?

What are the constraints on SIDM at intermediate scales (10^{13}—10^{14} M_{sol})?

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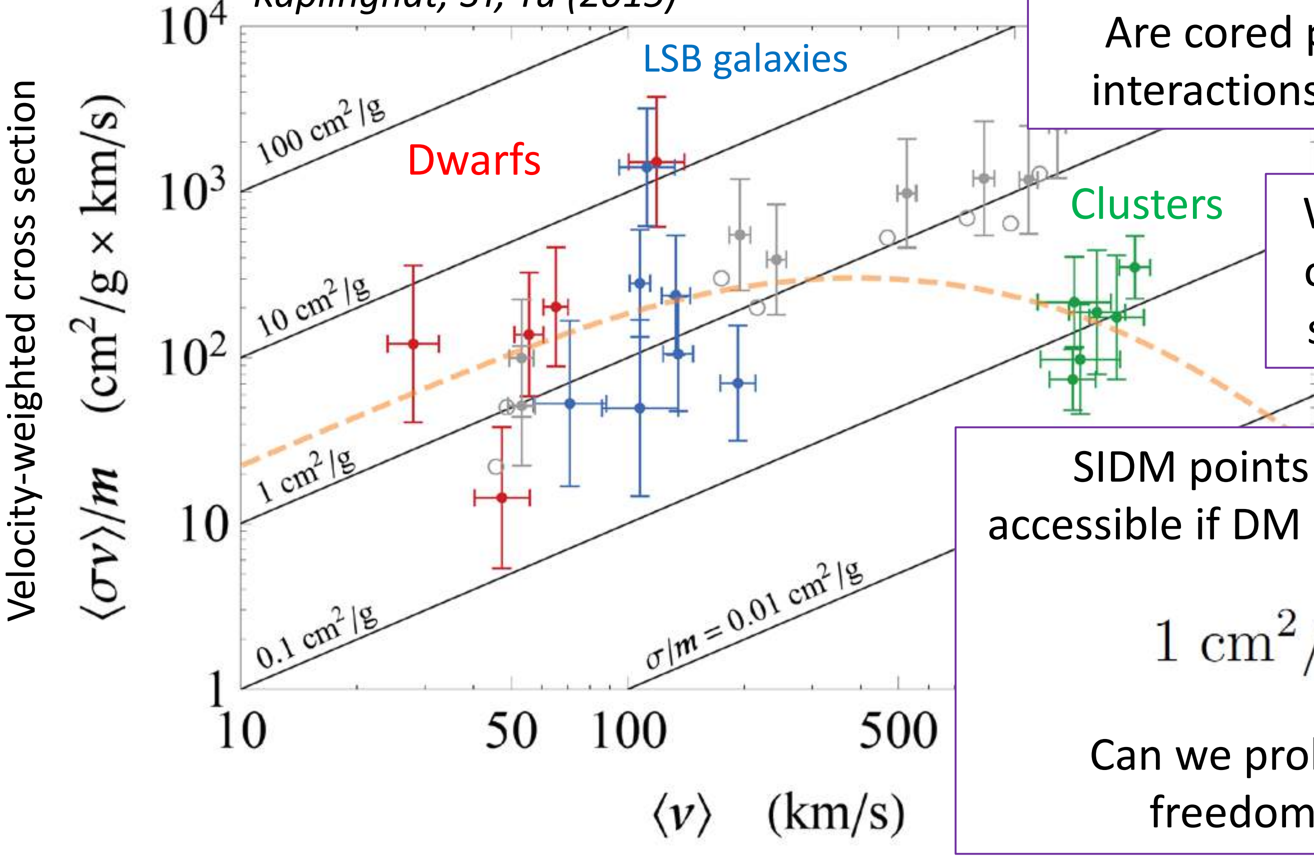

Average relative velocity

Are cored profiles caused by self-interactions or baryonic feedback?

What are the constraints on SIDM at intermediate scales (10^{13}—10^{14} M_{sol})?

SIDM points to new energy scale accessible if DM coupled to visible sector.

$$1\ \mathrm{cm}^2/\mathrm{g} \approx \left(\frac{1}{60\ \mathrm{MeV}} \right)^3$$

Can we probe SIDM degrees of freedom in laboratories?

Testing bursty feedback

Pressing question: Are all small scale issues solved by feedback?

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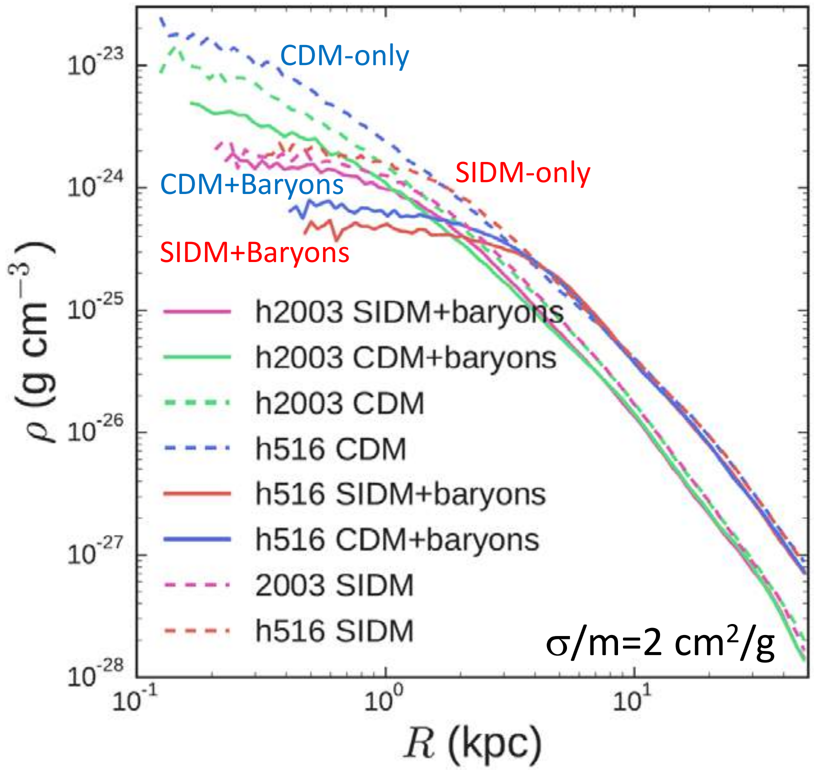
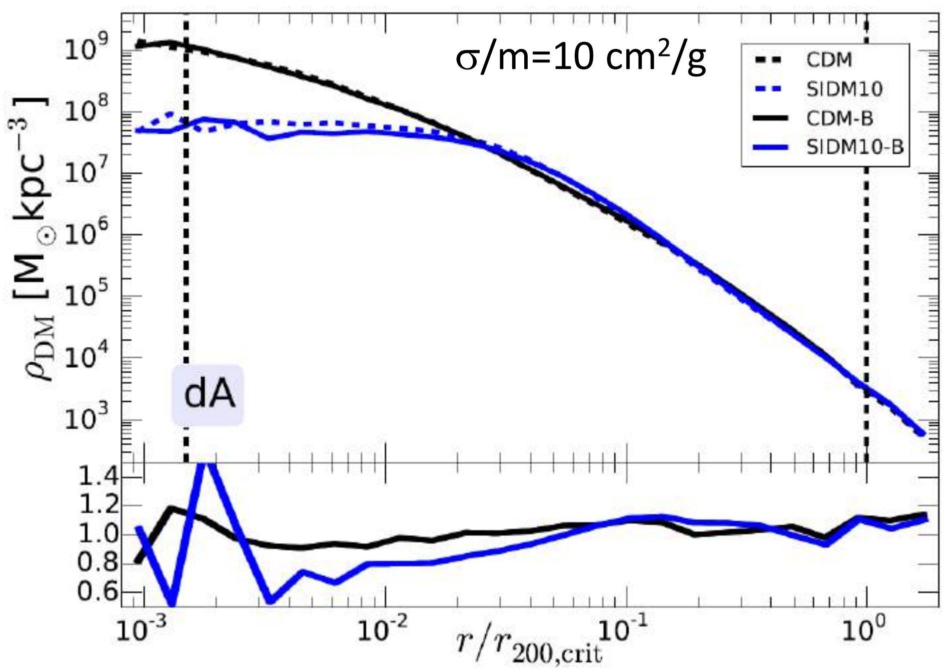
N-body simulations with SIDM + baryons

Bastidas Fry, Pontzen et al. (2015)



Bursty star formation
(High density threshold for star formation)

Vogelsberger, Zavala et al. (2014)



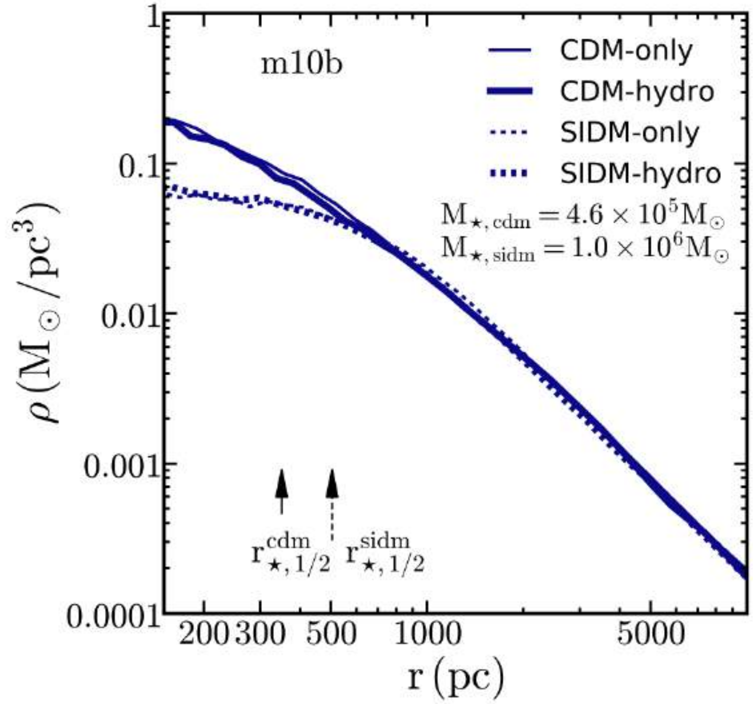
Smooth star formation
(Low density threshold)

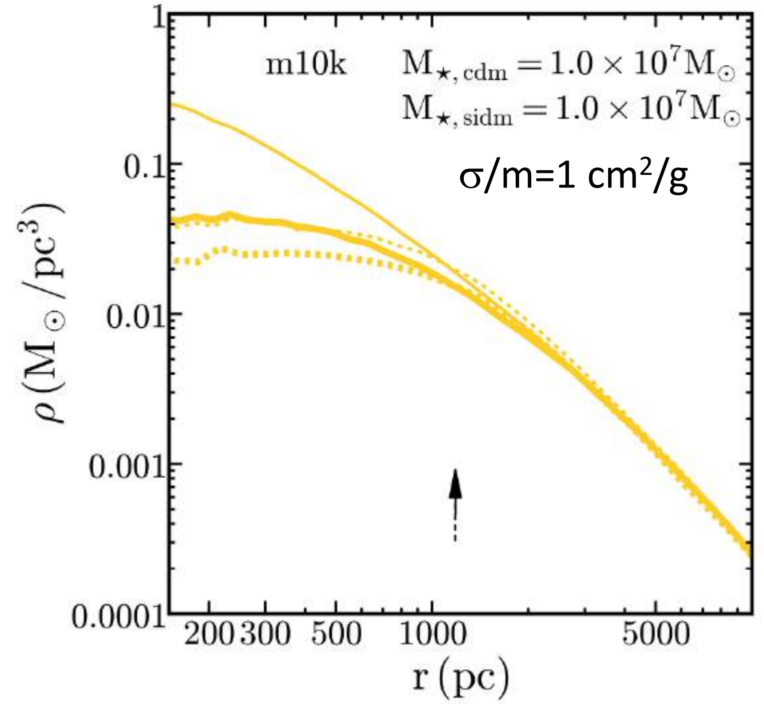
Testing bursty feedback

Pressing question: Are all small scale issues solved by feedback?

N-body simulations with SIDM + baryons

FIRE simulations: bursty star formation *Robles et al (2017)*





Resolving timescales

Presence of cored profiles: integrates over 10 Gyr of galaxy formation

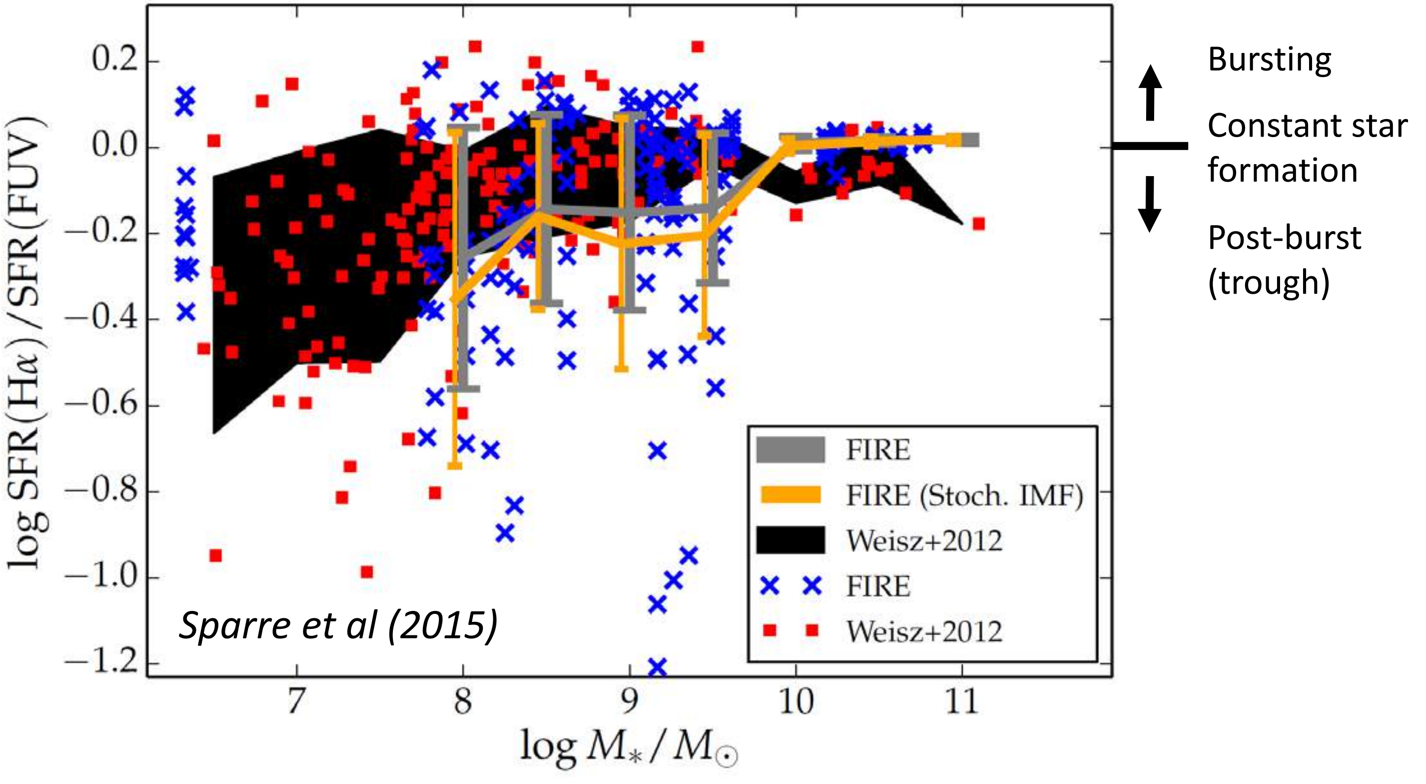
- Nonadiabatic processes acting over $\sim$ 10 Myr (feedback)?
- Adiabatic process over $\sim$ 10 Gyr (SIDM)?

Resolving timescales

Line ratios as tracer of bursty star formation

Hα = traces star formation rate over past 10 Myr

Far-UV = traces star formation rate over past 200 Myr



Resolving timescales

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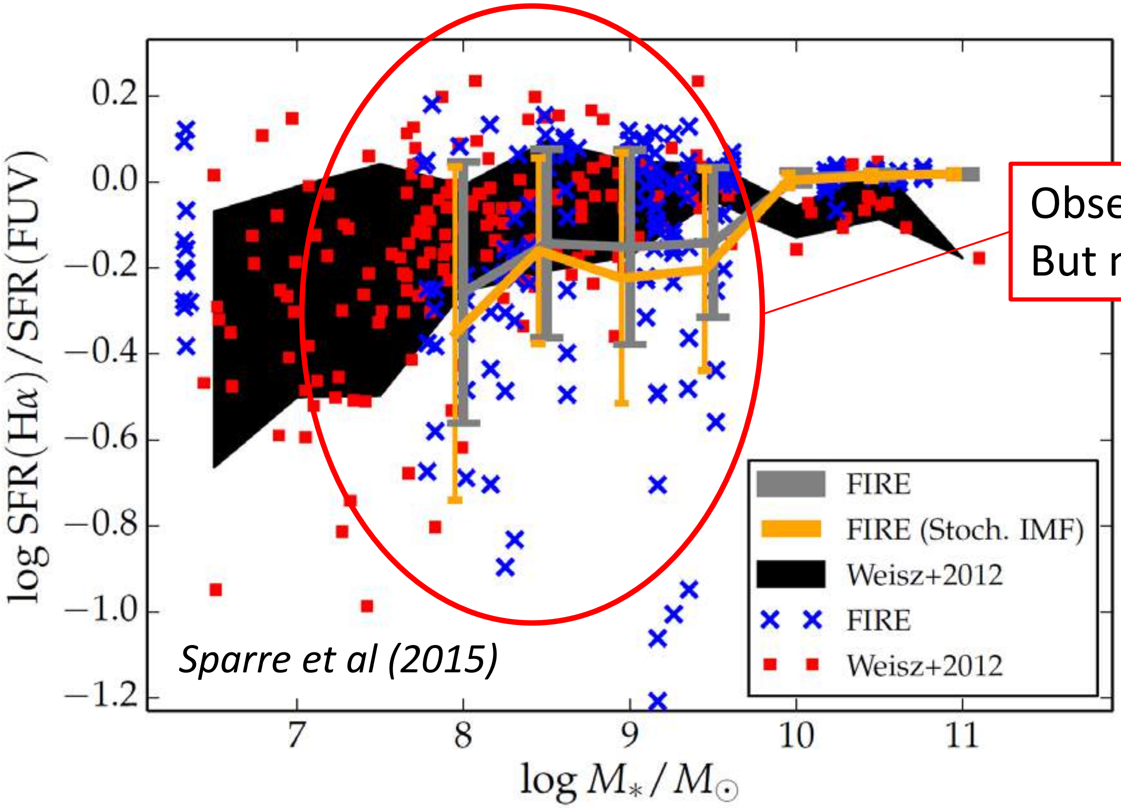


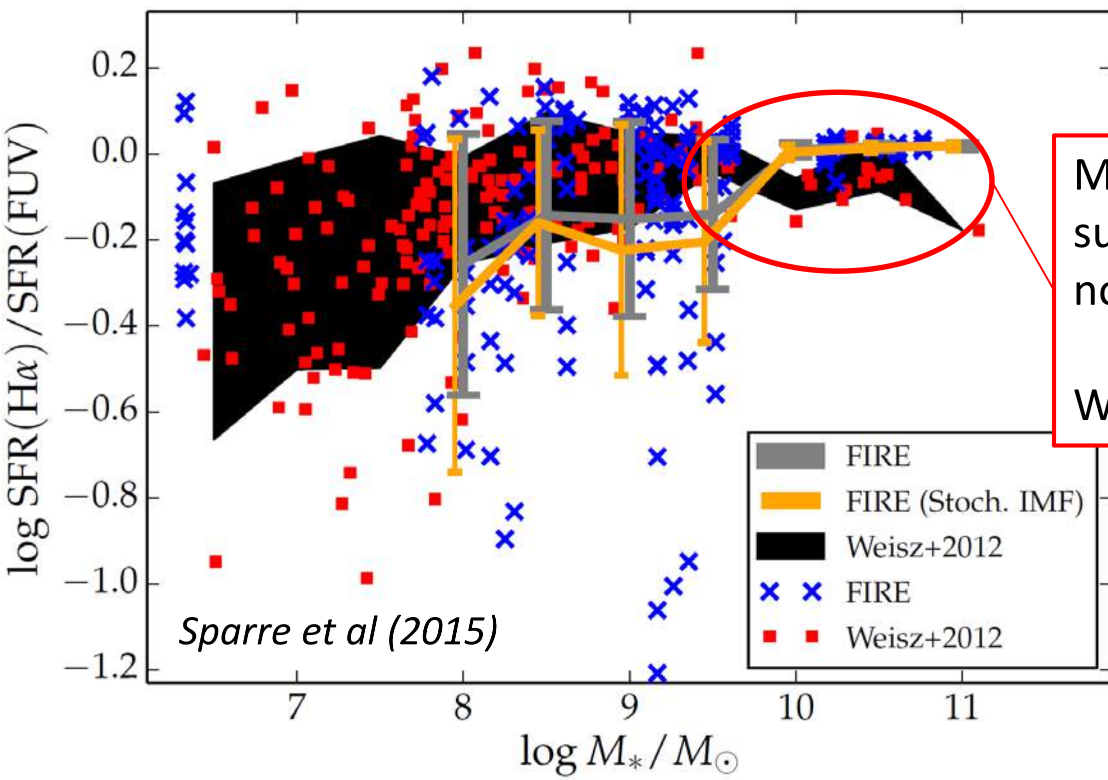
Observed nearby dwarfs are bursty
But more scatter in FIRE galaxies

Resolving timescales

Line ratios as tracer of bursty star formation

$H\alpha$ = traces star formation rate over past 10 Myr (bursts)

Far-UV = traces star formation rate over past 200 Myr



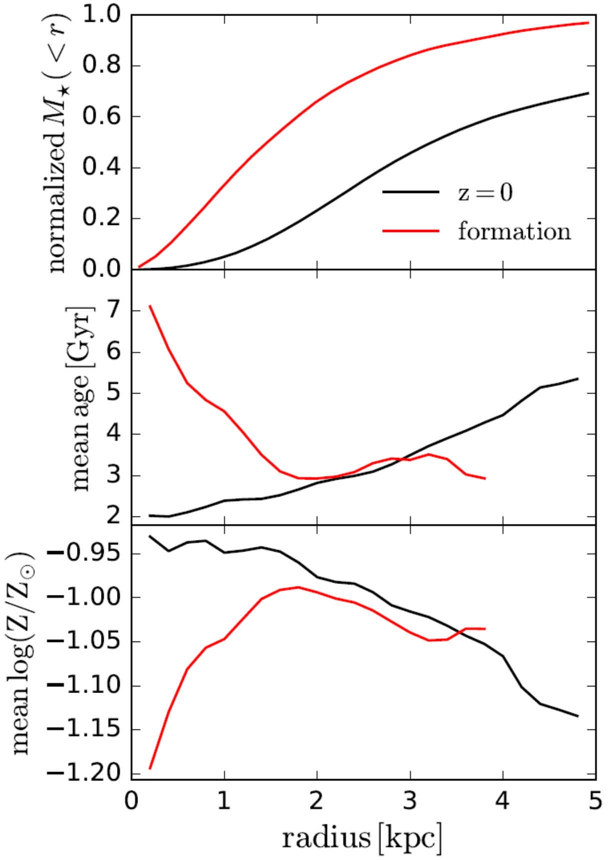
More massive galaxies (e.g. low surface brightness galaxies) are not bursty at z=0

Were they bursty in the past?

Resolving timescales

Star formation history can be imprinted on the radial distribution of stellar populations in nearby galaxies (galactic archeology)

El-Badry et al (2016)



Older metal-poor stars form earliest in the center. Bursty feedback causes them to migrate radially outward (along with DM).

Younger metal-rich stars form later throughout the galaxy, but have less time to migrate.

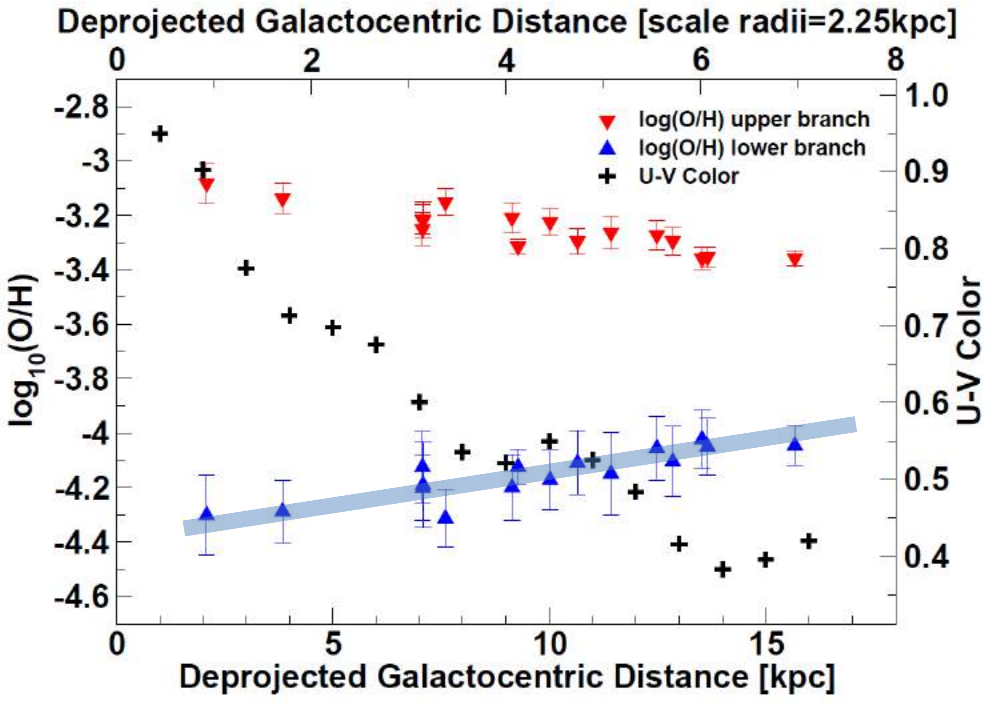
Feedback can **reverse** the age and metallicity gradients in galaxies.

How does this compare to stellar populations in SIDM halos?

Resolving timescales

Star formation history can be imprinted on the radial distribution of stellar populations in nearby galaxies (galactic archeology)

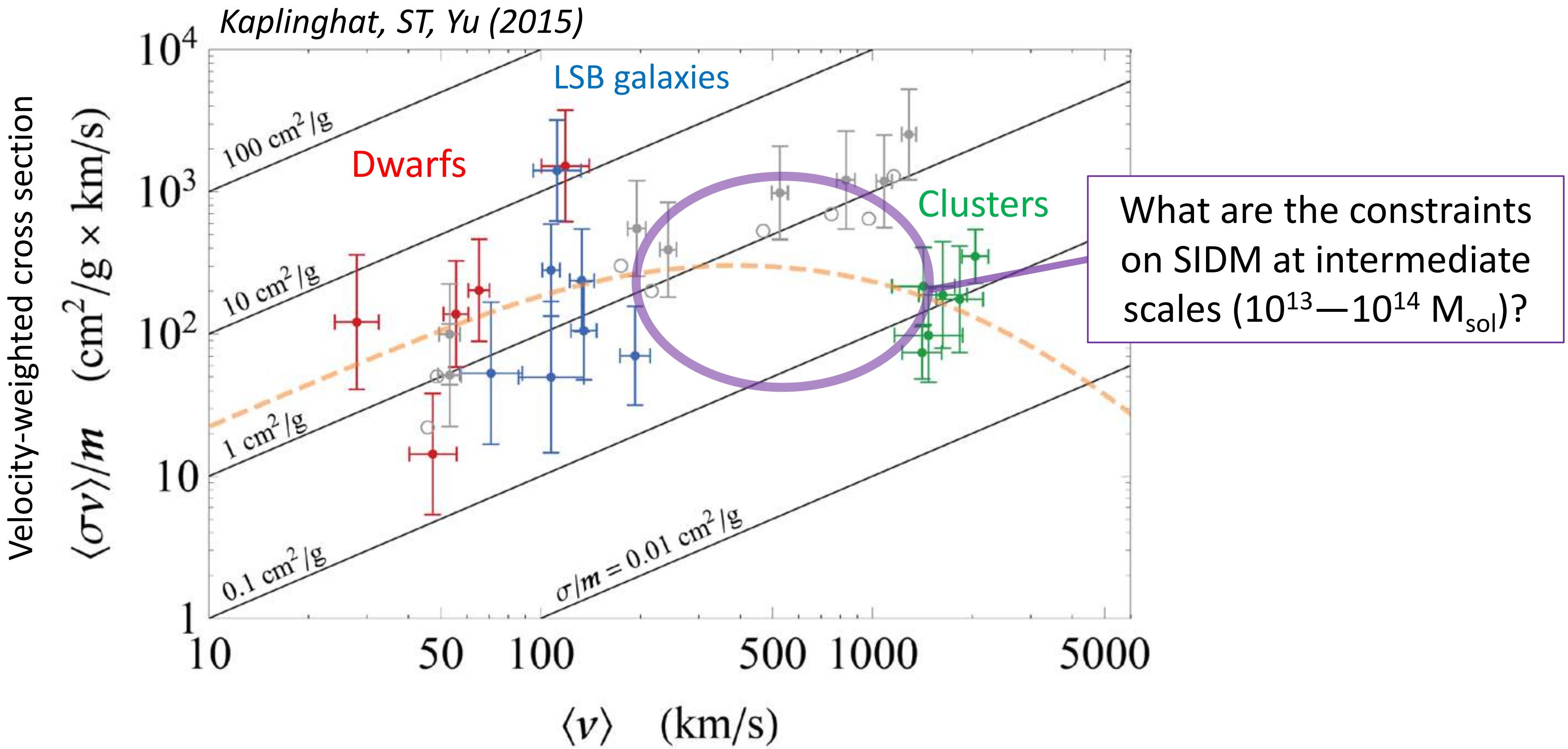
MUltiwavelength observations of the Structure, Chemistry, and Evolution of LSB galaxies (MUSCEL)
Young, Kuzio de Naray, Wang (2015)



Metallicity gradient for LSB UGC 628

Suggests older stars formed earlier in the center, younger stars formed later in the outskirts, with little radial migration.

SIDM at intermediate scales



Prediction from simple SIDM model: Cross section falls with velocity in this regime.
Can this be tested?

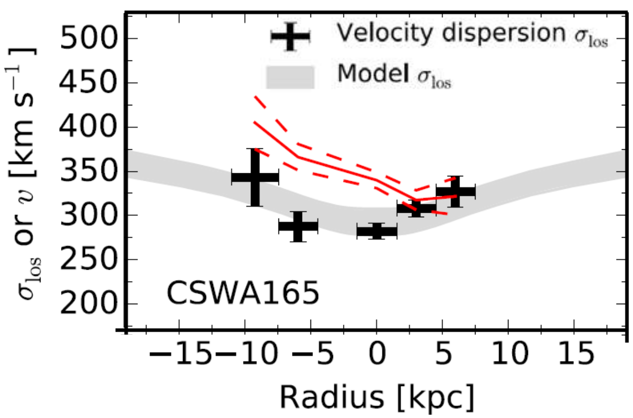
SIDM at intermediate scales

Mass profile fits of 10 group-scale halos (~10^{14} M_{sol}) with central elliptical galaxies (BGGs)

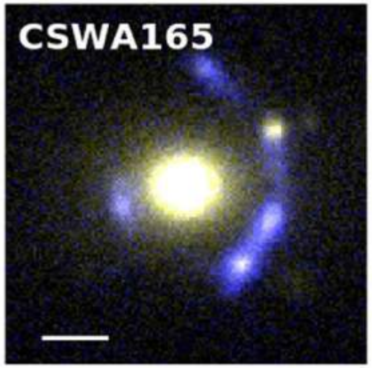
Newman, Ellis, Treu (2015)

Data include:

Stellar kinematics in BGG

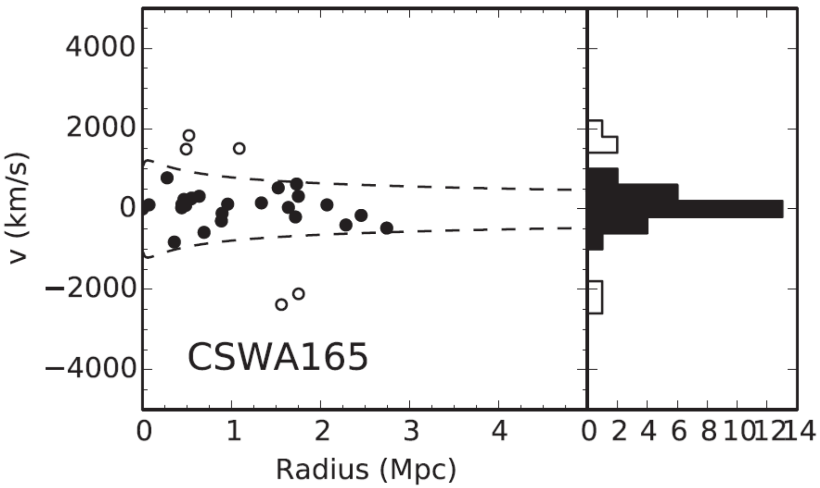


Strong lensing



CASSOWARY survey of lensing systems in SDSS

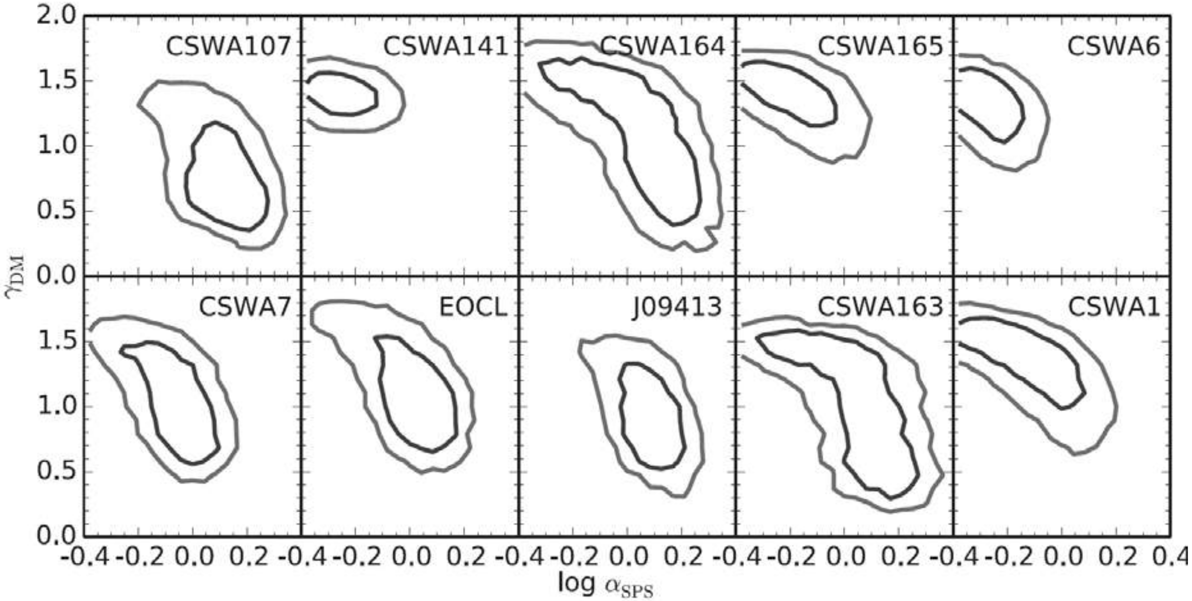
Kinematics of member galaxies



σ (km s^{-1})	$\log M_{200}/M_{\odot}$
362 ± 52	13.78 ± 0.21

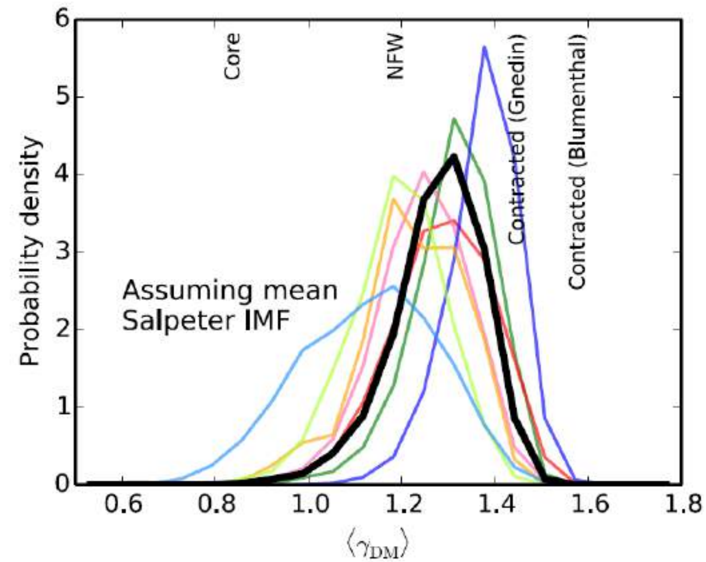
DM profiles in group-scale halos

Average inner DM slope within inner ~30 kpc ($\gamma_{DM} \sim 1$ for NFW)



Mass-to-light ratio relative to stellar model $\alpha_{\rm SPS} = \Upsilon_V / \Upsilon_V^{\rm SPS}$

Joint inner DM slope for $\alpha_{SPS} = 1$



Newman, Ellis, Treu (2015)

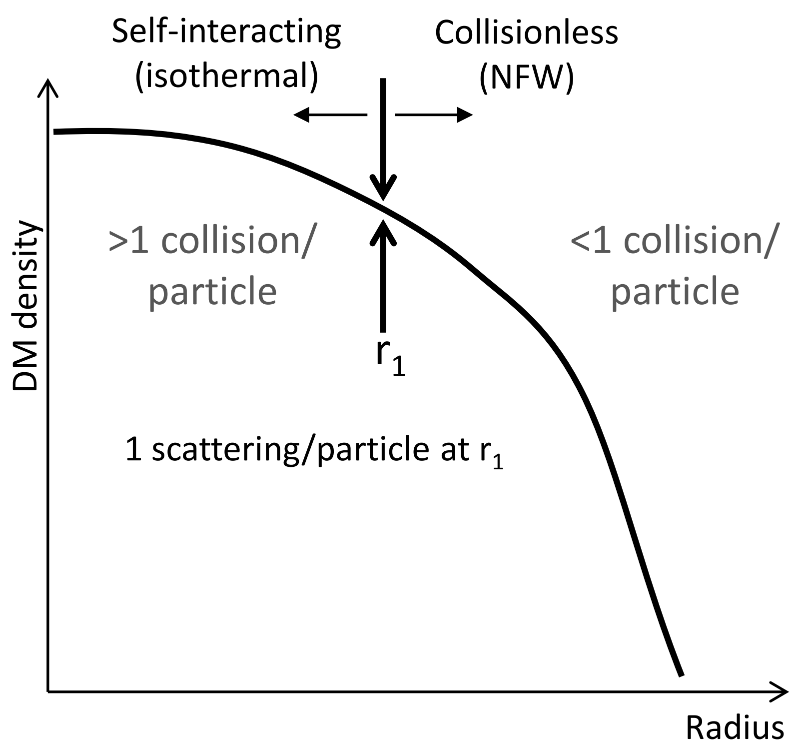
Halos are more consistent with NFW profiles than cores

What is the implication for self-interactions?

Jeans method for SIDM halo profiles

Rocha et al (2012); Kaplinghat et al (2013); Kaplinghat, ST, Yu (2015)

Observation-driven approach for deriving density profiles without N-body simulations



Match profiles at r_1:

$$\rho_{\rm dm}(r) = \begin{cases} \rho_{\rm iso}(r)\,, & r < r_1 \\ \rho_{\rm NFW}(r)\,, & r > r_1 \end{cases}$$

Solve rate equation
to get cross section:

$$\text{rate} \times \text{time} \approx \frac{\langle \sigma v \rangle}{m} \rho(r_1)\, t_{\rm age} \approx 1$$

$$\frac{\langle \sigma v_{\rm rel} \rangle}{m} = \frac{1}{\rho_{\rm dm}(r_1) t_{\rm age}}$$

Constraints on SIDM cross section

Sophia Nasr, Laura Sagunski, ST (in progress)

Scan over halo parameters M_{200}, c, Υ_*, r_1 fitting to data (MCMC).

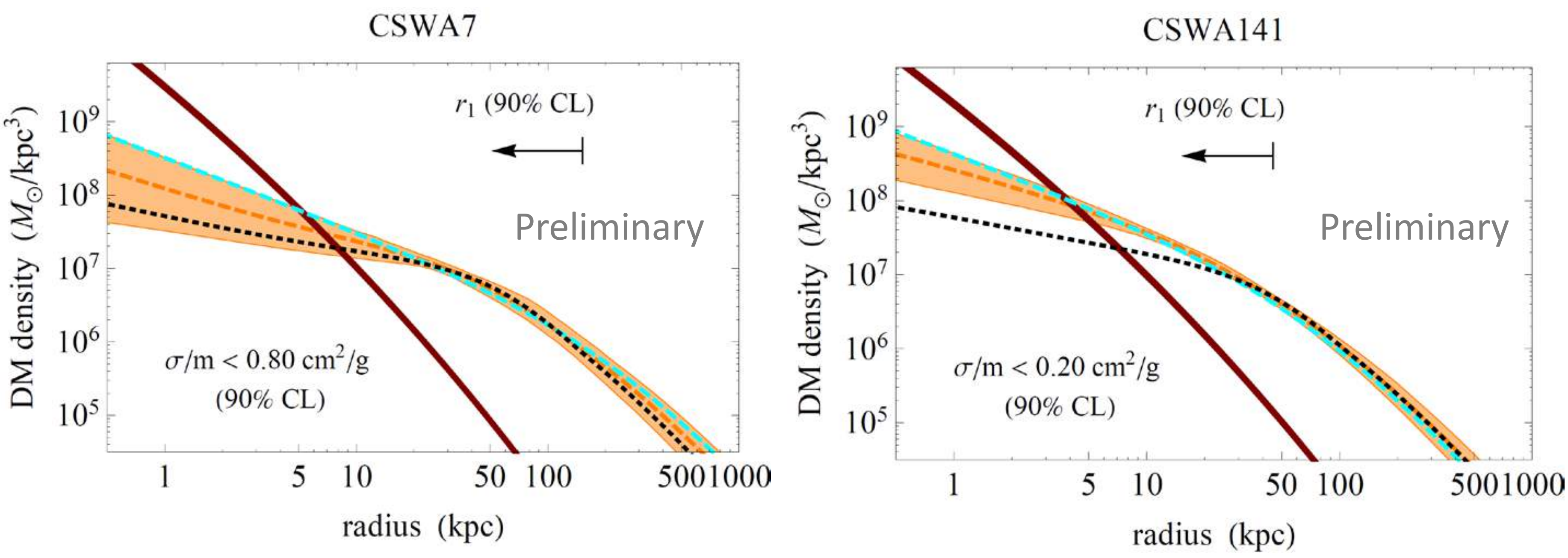
Impose priors (perhaps overly-restrictive):

(M_{200}, c) satisfy mass-concentration relation within scatter

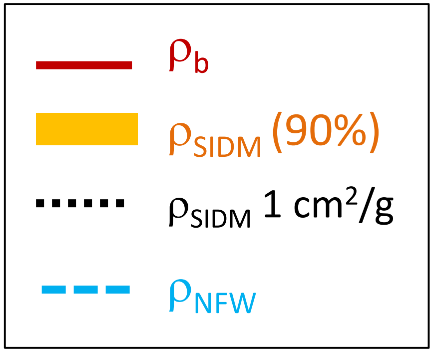
Assume Υ_* fixed assuming common IMF for all systems within 0.1 dex

Constraints on SIDM cross section

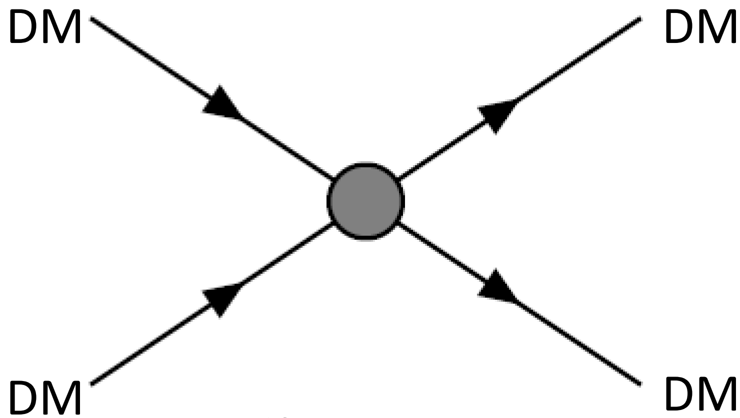
Sophia Nasr, Laura Sagunski, ST (in progress)



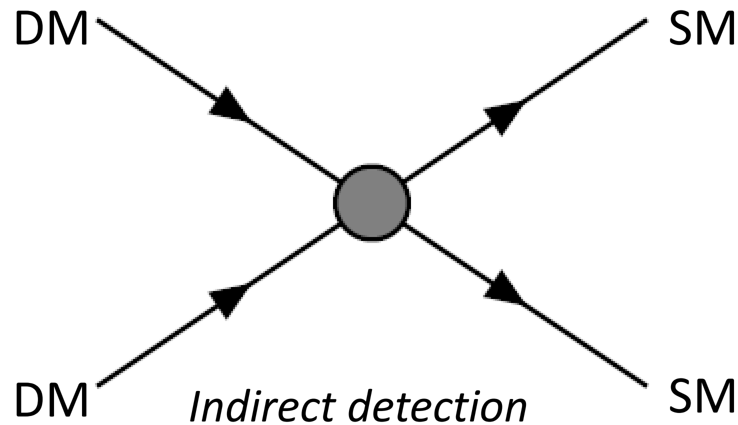
No conclusions yet, but in principle important constraints at v ~ 1000 km/s



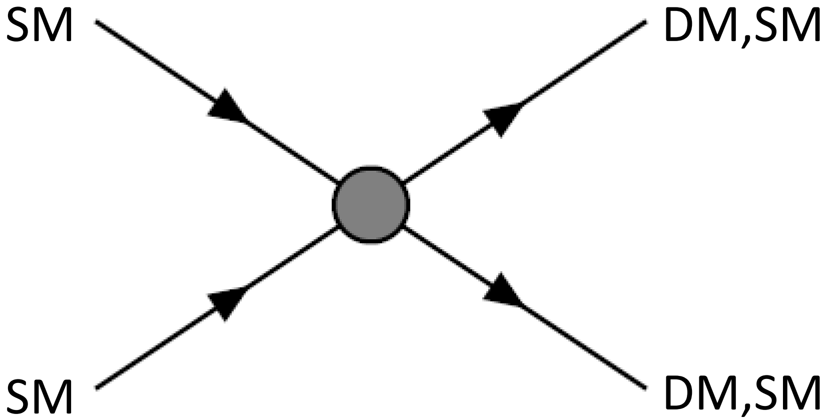
Complementary probes of SIDM



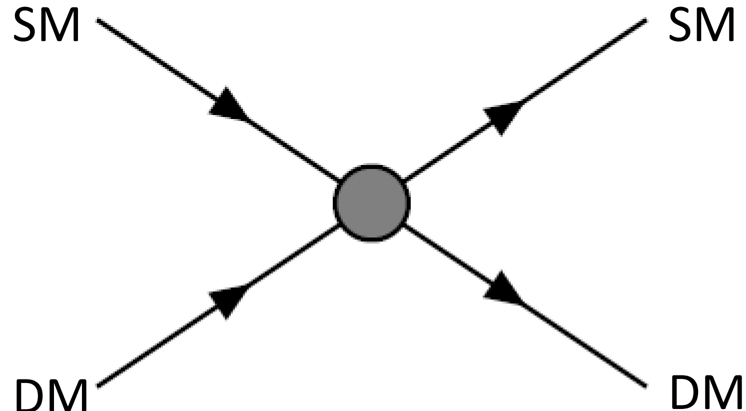
Self-interactions



Indirect detection



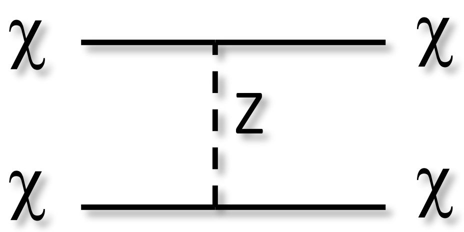
Colliders (e.g. missing energy or new resonances)



Direct detection

Particle physics of self-interactions

WIMPs have self-interactions (weak interaction)



self-interaction

χ = dark matter (e.g. SUSY particle)

Z boson = mediator particle

Cross section:

$$\sigma \sim \frac{g^4 m_\chi^2}{m_Z^4} \sim 10^{-36}\ \mathrm{cm}^2$$

Mass:

$$m_\chi \sim m_Z \sim 100\ \mathrm{GeV}$$

WIMP self-interaction cross section is way too small

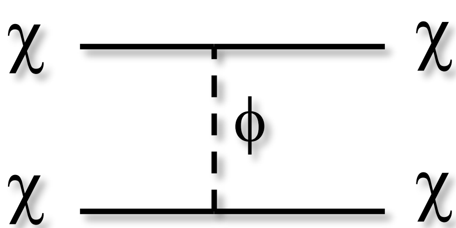
$$\sigma / m_\chi \sim 10^{-14}\ \mathrm{cm}^2/\mathrm{g}$$

Particle physics of self-interactions

Large cross section required $\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g}$

MSIDM (Minimal SIDM) model: DM + light mediator ϕ

Feng, Kaplinghat, Yu (2009); Buckley & Fox (2009); Loeb & Weiner (2011); ST, Yu, Zurek (2012+13)



self-interaction

Cross section: $\sigma \sim \dfrac{g^4 m_\chi^2}{m_\phi^4}$

Mediator mass below than weak scale

$$m_\phi \sim 1 - 100\ \mathrm{MeV}$$

Velocity-dependence controlled by mediator mass m_ϕ

Hard-sphere scattering
Constant cross section

$$m_\phi \gg m_\chi v_{\mathrm{rel}}$$

Rutherford-like scattering
Cross section falls with $1/v_{\mathrm{rel}}^4$

$$m_\phi \ll m_\chi v_{\mathrm{rel}}$$

What type of models are viable?

How are they testable **beyond** the usual SIDM observables?

- Light mediator models
- Strongly-interacting DM
  - QCD-like theories
  - Dark hadrons or dark nuclei
- Massless mediator models
  - Dark atoms
  - DM with dark radiation

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Must be largely decoupled from visible sector to avoid too-large N_{eff}

Cosmological probes
See talk by Cyr-Racine

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Compelling possibilities for SIDM to interact with visible sector

Canonical WIMP searches (focus of this talk)

Or may be decoupled
Cosmological probes

Must be largely decoupled from visible sector to avoid too-large N_{eff}

Cosmological probes
See talk by Cyr-Racine

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May be coupled to visible sector (not as compelling)
Canonical WIMP searches

Or may be decoupled
Cosmological probes

Strongly-interacting dark matter

Dark sector has non-abelian gauge symmetry

Dark matter is composite made of dark quarks

Lightest baryon B_{dark} is stable DM due to accidental symmetry (like proton)

May be dark baryon asymmetry ($\Omega_b \sim 0.2\ \Omega_{DM}$)

What is the DM baryon B_{dark}?

Many unknowns:

- Gauge group: SU(N), SO(N), Sp(N), …
- Number of colors N_c
- Number of flavors N_F
- Representations of dark quarks
- Masses of dark quarks

  Chiral or heavy flavor limit?
- Confinement scale Λ_{DM}
- Couplings to SM (assume small)

What guidance do we have?

- Stability
  DM baryons are stable
  Dark glueballs can also be cosmologically long-lived
- Minimality
- Relic density
  Assume 2→2 annihilation $m_{B_{\rm dark}} \lesssim 100\ {\rm TeV}$
- Astrophysical small scale structure (SIDM)

Self-interactions for composite DM

Low-energy cross section $\sigma = 4\pi a^2$

a = scattering length

m = DM mass

$$\sigma/m \sim 3\ \mathrm{cm}^2/\mathrm{g} \times \left(\frac{\Lambda_{\mathrm{DM}}}{m}\right)\left(\frac{\Lambda_{\mathrm{DM}}}{a^{-1}}\right)^2\left(\frac{100\ \mathrm{MeV}}{\Lambda_{\mathrm{DM}}}\right)^3$$

If dimensionful parameters set by confinement scale i.e. $m, a^{-1} \sim \Lambda_{\mathrm{DM}}$, then $\Lambda_{\mathrm{DM}} \approx \mathcal{O}(0.2 - 0.6) \times \Lambda_{\mathrm{QCD}}$ gives right σ/m on dwarf scales

Self-interactions for composite DM

Require velocity-dependent cross section

Naïve condition:

Scattering cross section transitions to being velocity dependent when $m v_{\mathrm{rel}} \gtrsim a^{-1}$

Since v << 1 (DM non-relativistic), require $ma \gg 1$

More specifically: Want σ/m to transition at v/c ~ 10^{-3}.
Expect ma ~ 10^3 may provide good fit to galaxies and clusters.

Self-interactions for composite DM

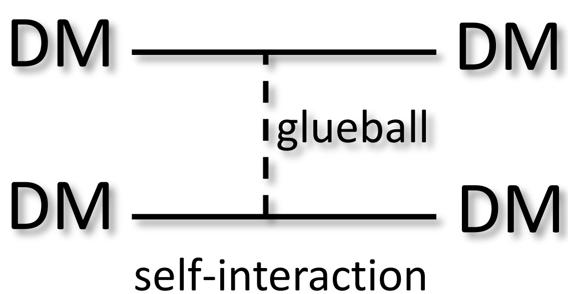
Either m or a (or both) must be much larger than naïve scaling with Λ_{DM}.

- Large mass due to heavy constituents (m >> Λ_{DM}):

Heavy flavor dark quarks

Example: SU(N) + heavy adjoint fermion (gluino) *Boddy et al. (2014)*

DM = glueballino (one heavy gluino + gluons)



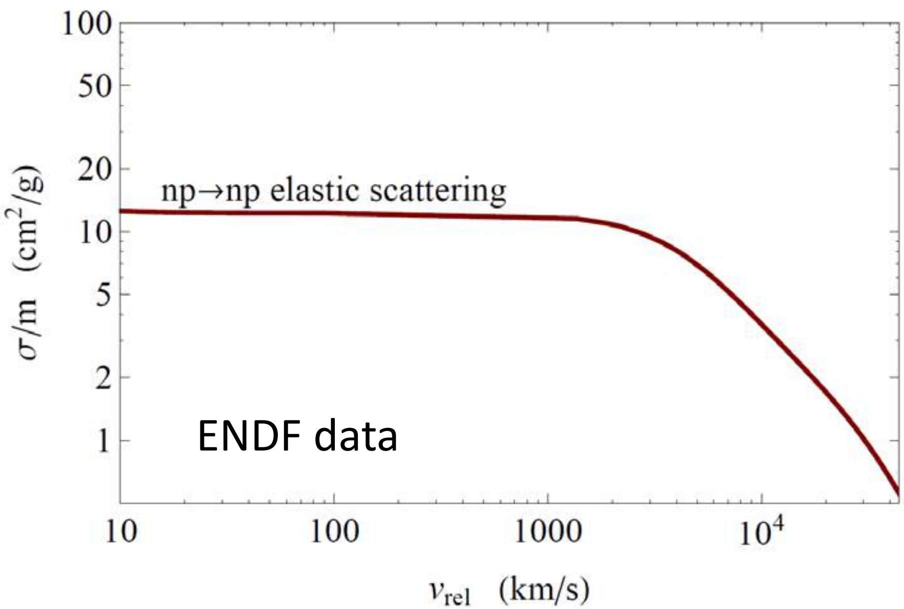
$m_{gluino} \sim 1$ TeV
$m_{glueball} \sim \Lambda_{DM} \sim 10$ MeV

Self-interactions for composite DM

- Large scattering length ($a \gg \Lambda_{DM}^{-1}$):

Example: nucleon-like DM *Cline et al. (2013)*

Elastic n-p scattering is enhanced due to weakly-bound deuteron $a^{-1} \approx 15 \text{ MeV} \ll \Lambda_{\text{QCD}}$



Note:
Fall off at v~c/(ma)~5000 km/s
Clusters require 0.1 at 1500 km/s

E.g. make $m_{DM} \sim 10m_p$ with fixed scattering length *a*

If self-interactions solve astrophysical small scale structure anomalies…

Preferred cross sections

$$\sigma/m \approx \begin{cases} 2\ \mathrm{cm}^2/\mathrm{g} & v \sim 50\ \mathrm{km/s}\ \text{(dwarf galaxies)} \\ 0.1\ \mathrm{cm}^2/\mathrm{g} & v \sim 1500\ \mathrm{km/s}\ \text{(clusters)} \end{cases}$$

Large cross section requires $\Lambda_{\mathrm{DM}} < 100$ MeV

Velocity dependence:

- Heavy flavors
- Large scattering length

A minimal theory of DM baryons

Anthony Francis, R. Jamie Hudspith, Randy Lewis, ST (work in progress)

Dark QCD-like theory with N_c=2 & N_F = 1
Fundamental fermion that is SM singlet

$$\mathscr{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{Q}(i\gamma^\mu D_\mu - m)Q$$

Q = dark quark
F = dark gluon field strength

Possible coupling to visible sector via higher dimensional operators

What are the lightest states?

Normal QCD (N_c=3):

Accidental $U(1)_B$ baryon number symmetry

Quarks have B = 1/3, antiquarks have B = -1/3

Dark QCD: weird feature of N_c=2

Fundamental representation of SU(2) is pseudoreal

Put quarks and antiquarks in unified multiplet

Accidental $SU(2)_B$ symmetry: *baryon number becomes isospin*

$$\begin{pmatrix} Q \\ \bar{Q} \end{pmatrix}$$

Baryons are isospin multiplets

Lightest baryon is spin-1 (vector) iso-triplet

$$\begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix} = \begin{pmatrix} QQ \\ \frac{1}{\sqrt{2}}(Q\bar{Q} - \bar{Q}Q) \\ \bar{Q}\bar{Q} \end{pmatrix}$$

What are the lightest states?

Normal QCD (N_f=3):

8 pseudo-Goldstone bosons + massive η' from broken $U(1)_A$

Dark QCD (N_f=1):

Zero pseudo-Goldstone bosons. Massive η' from broken $U(1)_A$

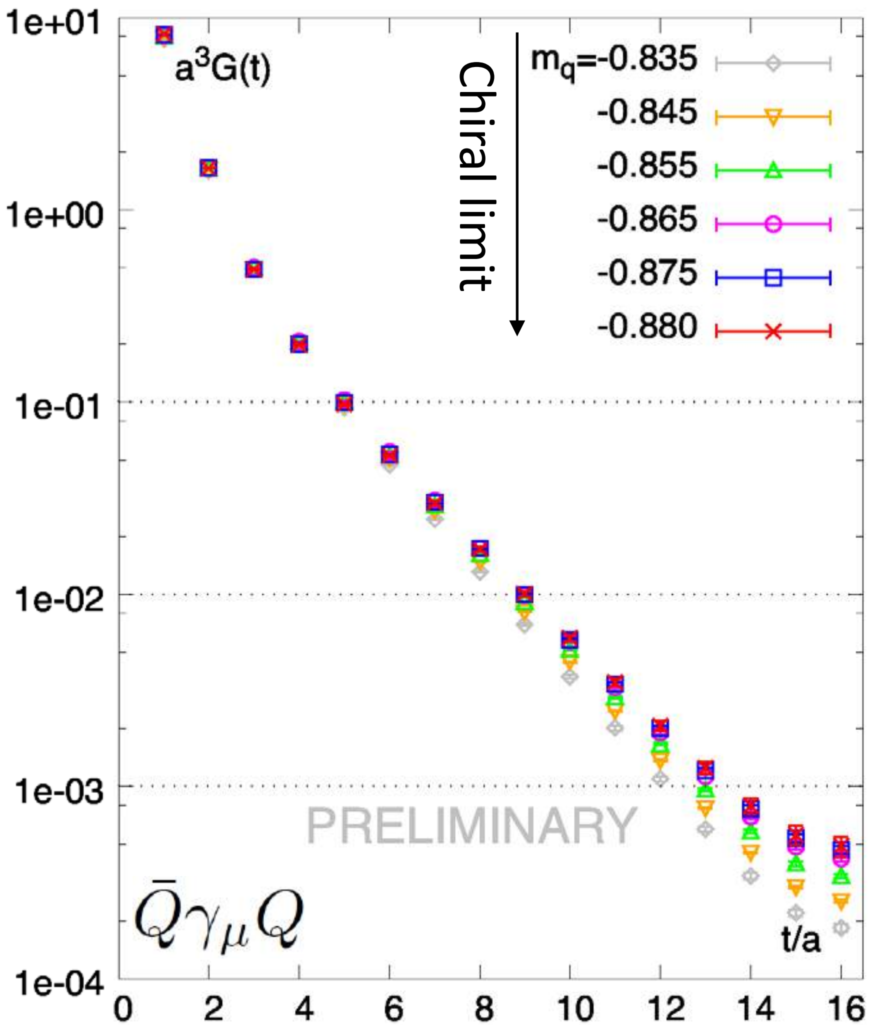
Lightest dark states: $\rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^- \end{pmatrix}$ η'

vector pseudoscalar

Which state is lighter? Normal QCD: $m_\rho < m_{\eta'}$

Dark QCD: DM annihilation $\rho\rho \rightarrow \eta'\eta'$ for $m_\rho > m_{\eta'}$

Dark matter on the lattice



Correlator:

Sum over propagators with same quantum numbers as source

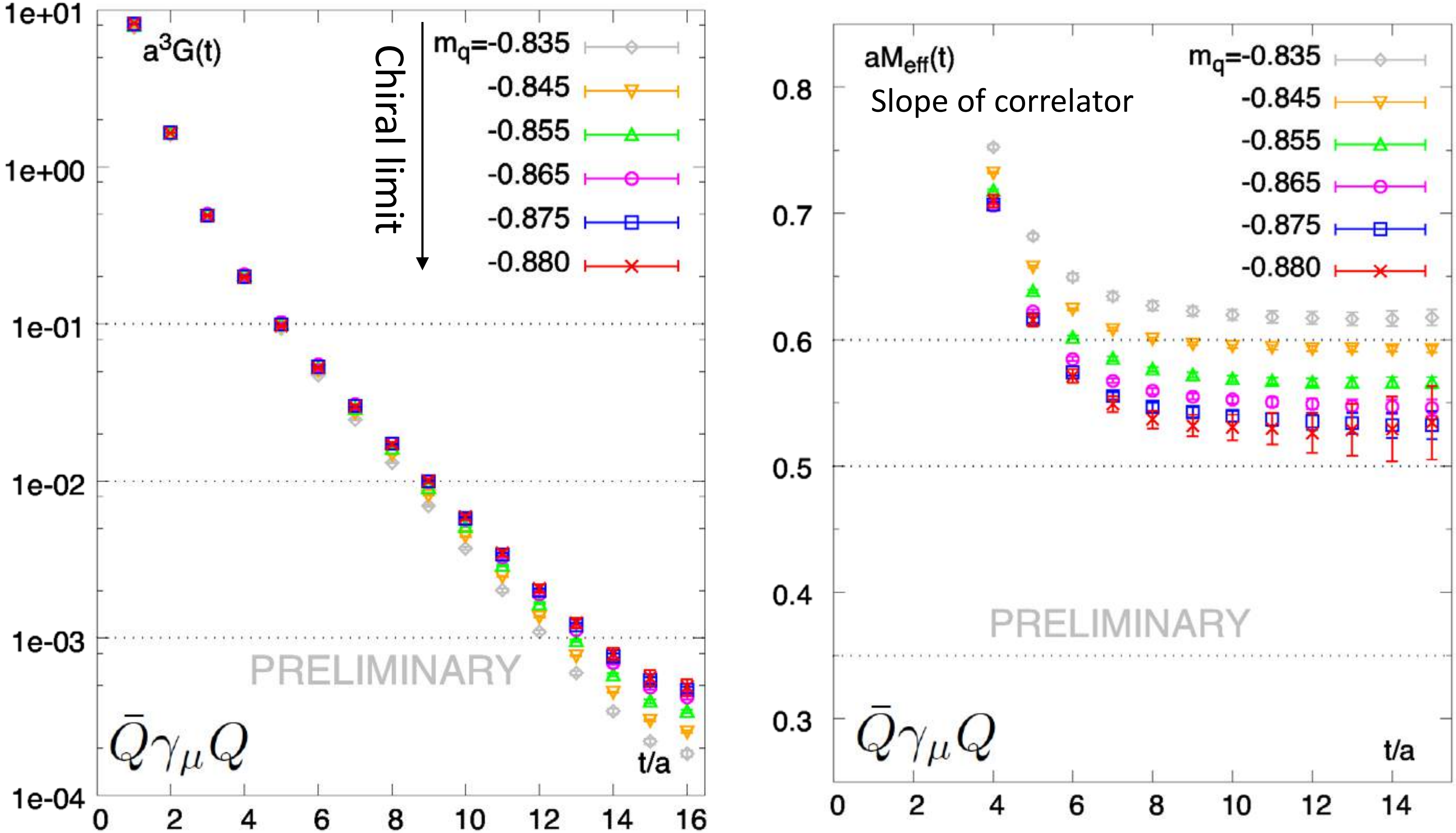
$$G(t) \sim \sum_{\text{states}\, i} e^{-m_i t} \to e^{-m_\rho t}$$

Lowest lying state decays slowest (imaginary time)

Log slope at large time gives mass

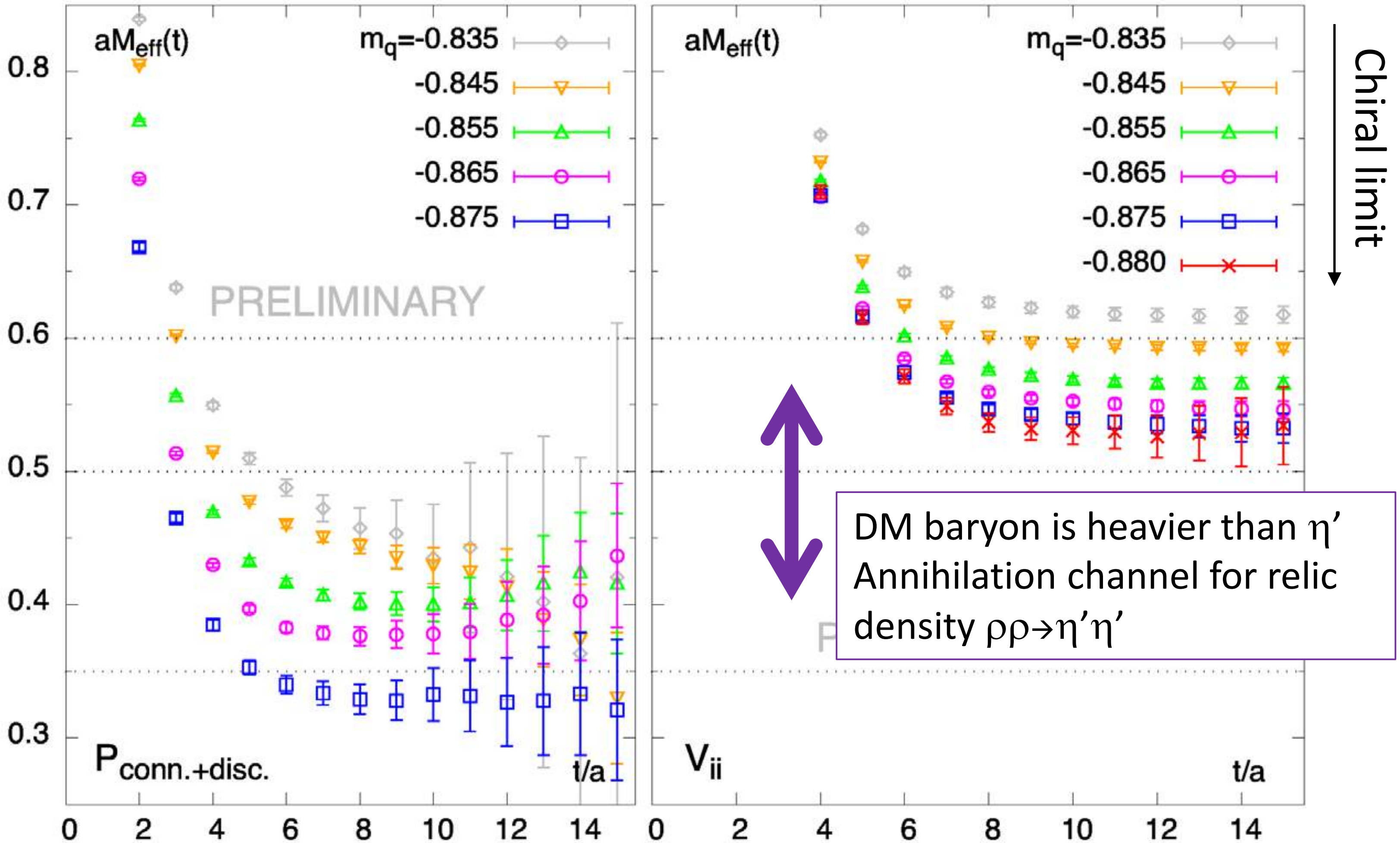
Anthony Francis, R. Jamie Hudspith, Randy Lewis, ST (work in progress)

Dark matter on the lattice



Anthony Francis, R. Jamie Hudspith, Randy Lewis, ST (work in progress)

Pseudoscalar η’ mass   Vector ρ mass (DM)



DM baryon is heavier than η’
Annihilation channel for relic density ρρ→η’η’

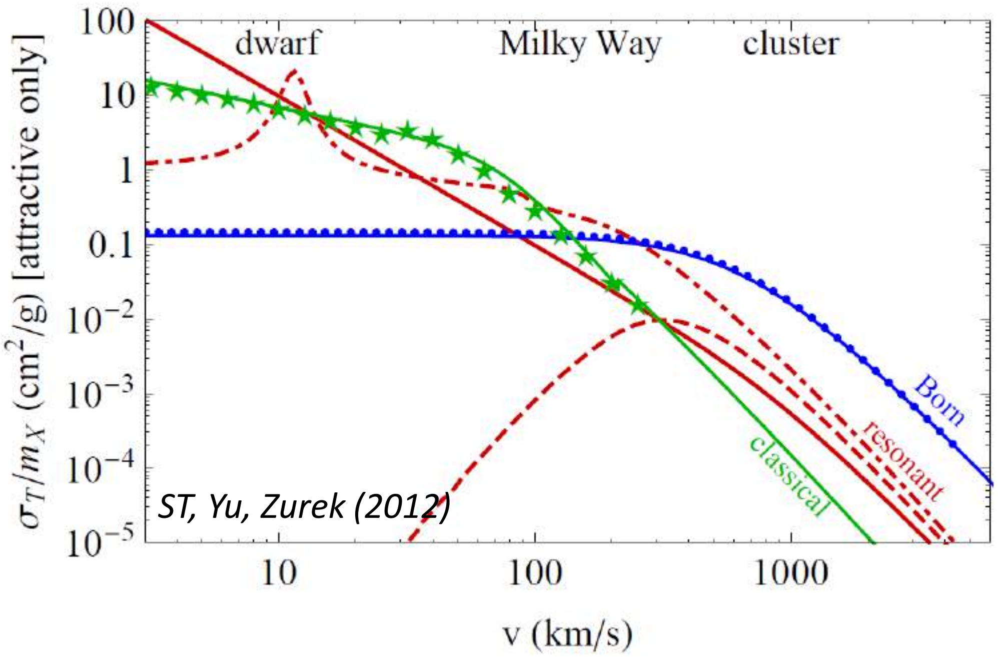
Anthony Francis, R. Jamie Hudspith, Randy Lewis, ST (work in progress)

Light mediator models

- Weakly-coupled theories
- MSIDM

$$\mathcal{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{(vector mediator)} \\ g_\chi \bar{\chi}\chi\phi & \text{(scalar mediator)} \end{cases}$$

Three parameters:
masses m_χ m_ϕ
dark fine structure constant $\alpha_\chi \equiv g_\chi^2/4\pi$



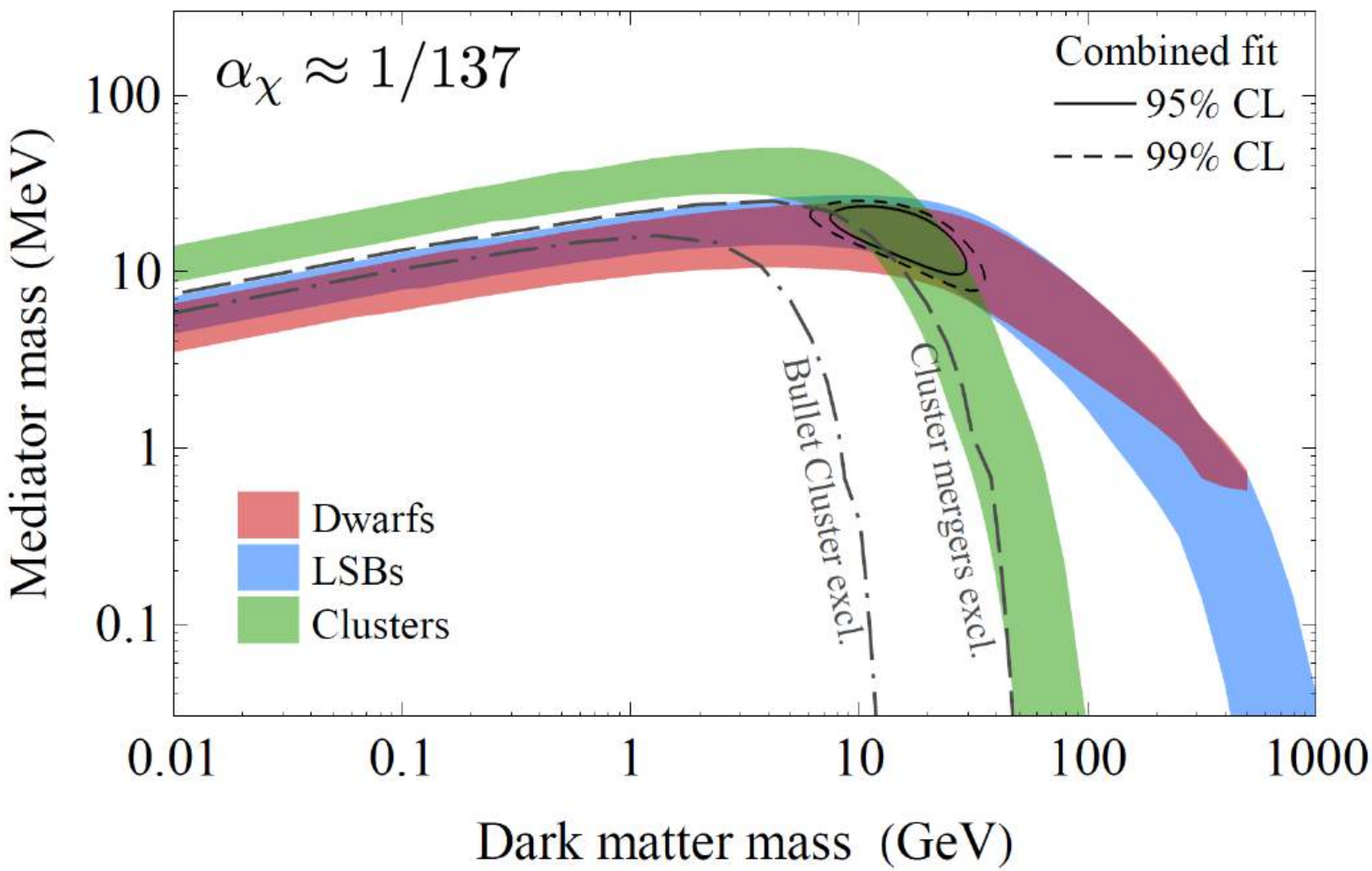
Transfer cross section for different parameter values

Wide range of velocity dependence, but typically suppressed at high velocity

Light mediator models

Fit parameters from velocity dependence <σ(v)v>/m for galaxies and clusters *for a given model*

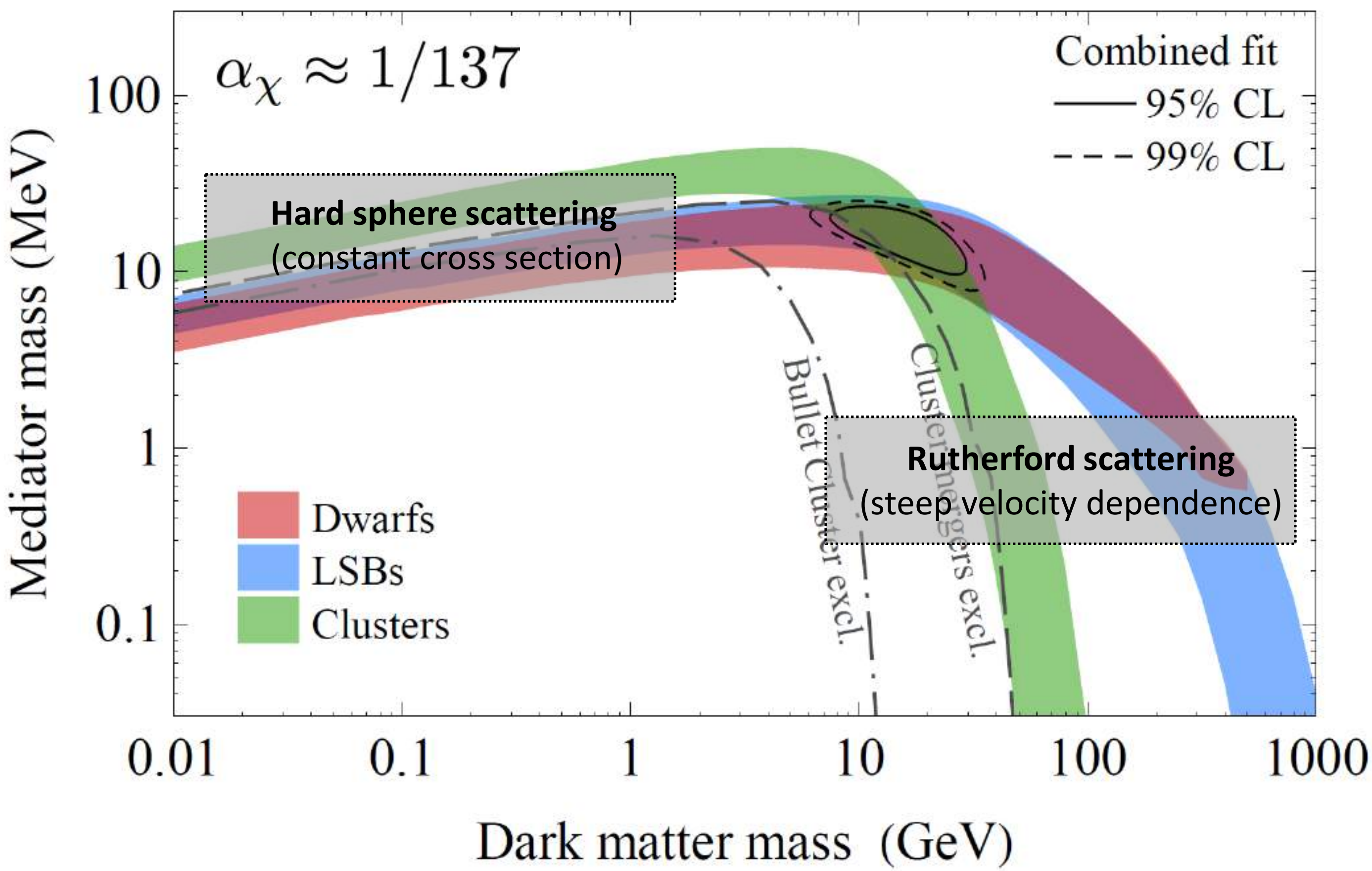
Kaplinghat, ST, Yu (2015)



Light mediator models

Fit parameters from velocity dependence <σ(v)v>/m for galaxies and clusters *for a given model*

Kaplinghat, ST, Yu (2015)



Portals for light mediators

Mediator may couple to visible sector (SM particles)

Both vector and scalar ϕ may couple via renormalizable interactions. Why not?

Vector mediator case

$$\mathcal{L}_{\text{mixing}} = \frac{\varepsilon_\gamma}{2}\,\phi_{\mu\nu}F^{\mu\nu}$$

Mixing with photon

Scalar mediator case

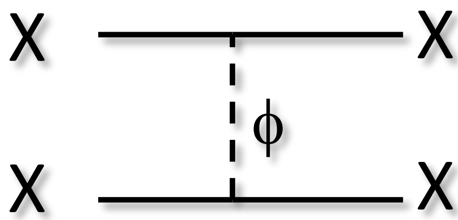
$$V(H,\phi) \supset (a\phi + b\phi^2)|H|^2$$

Mixing with Higgs boson

Cosmological useful

Thermal bath of mediators ϕ can dominate over SIDM component
Coupling allows mediator decay $\phi \rightarrow e^+e^-$ to deplete this density

Self-interacting dark matter paradigm

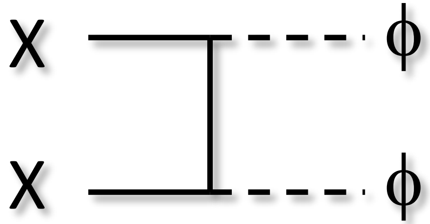


Self-interactions

DM particle X + mediator particle ϕ

$\phi \xrightarrow{\text{Decay}} \text{SM}$

(Deplete ϕ density)

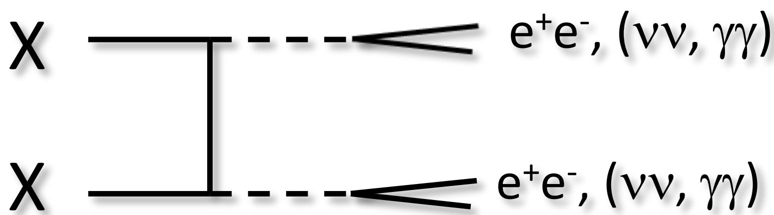


Annihilation

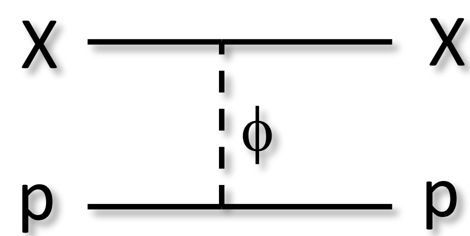
Set relic density
via freeze-out

$\text{SM} \rightarrow \phi \rightarrow \text{SM}$

Dark photon searches



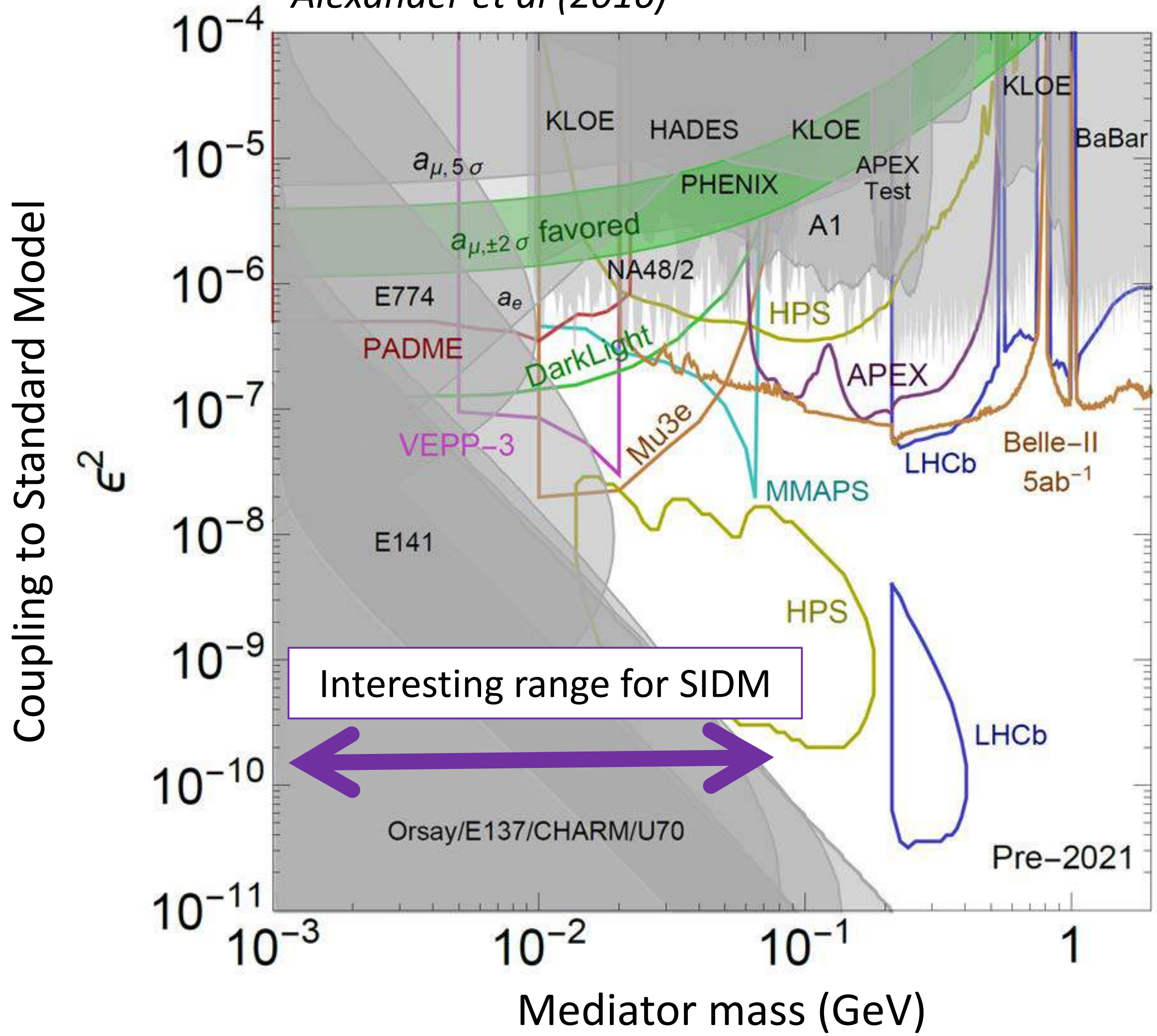
Indirect detection



Direct detection
Capture in sun/earth

Dark photon searches

Alexander et al (2016)



Directly produce light mediator ϕ through its coupling to SM particles

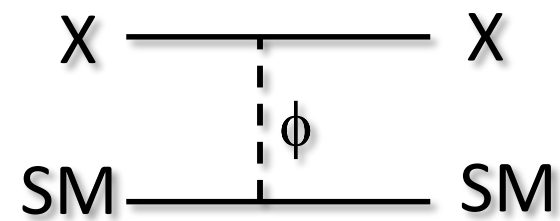
e.g., e^- beam fixed target experiments

$e^- p \rightarrow e^- p \phi (\rightarrow e^+ e^-)$

Direct detection

Strongest sensitivity to SIDM coupling with Standard Model particles

Kaplinghat, Tulin, Yu (2013); Del Nobile et al (2015)



Vector mediator case with kinetic mixing

Spin-independent proton-DM cross section (momentum transfer $q^2 = 0$)

$$\sigma_{Xp}^{\mathrm{SI}} \approx 1.5 \times 10^{-24}\ \mathrm{cm}^2 \times \varepsilon_\gamma^2 \times \left(\frac{\alpha_X}{10^{-2}}\right)\left(\frac{m_\phi}{30\ \mathrm{MeV}}\right)^{-4}$$

Present limits: for SIDM above few GeV

Coupling to SM must be very tiny (below $\sim 10^{-10}$)

Likely SIDM and Standard Model *not* in thermal contact in early Universe (during DM freeze-out)

No hope of directly producing mediators in the laboratory

Direct detection

Unique feature of SIDM vs WIMPs:
Momentum-dependent scattering

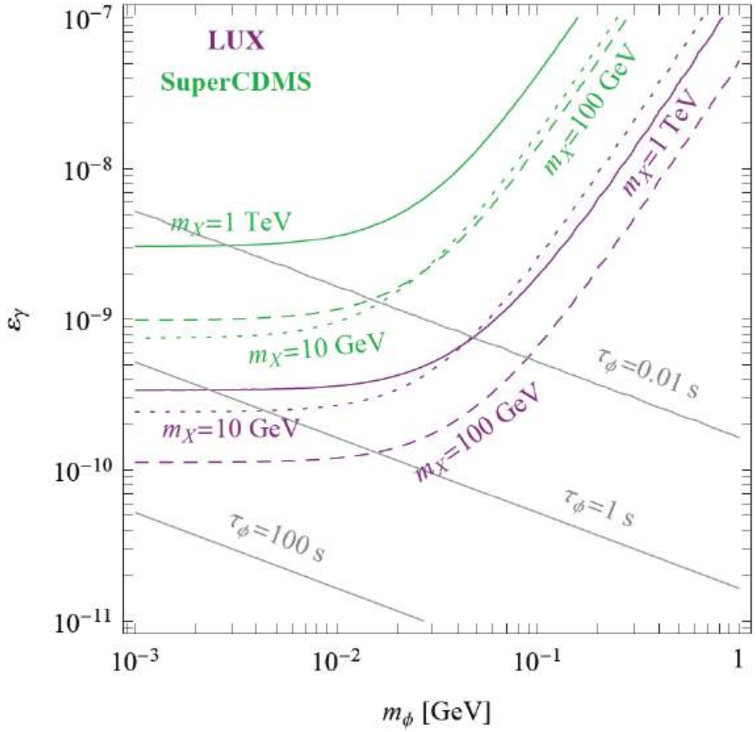
Mediator mass m_ϕ can be comparable to momentum transfer q

$$\begin{pmatrix}\text{Scattering}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{Scattering}\\ \text{rate at } q^2=0\end{pmatrix} \times \frac{m_\phi^4}{(m_\phi^2+q^2)^2}$$

Typical momentum transfer for Xenon/Germanium

m_X (GeV)	m_ϕ (MeV)	q_{Xe} (MeV)	q_{Ge} (MeV)
1000	3	127	74
100	15	62	46
10	20	10	10
5	20	5	5

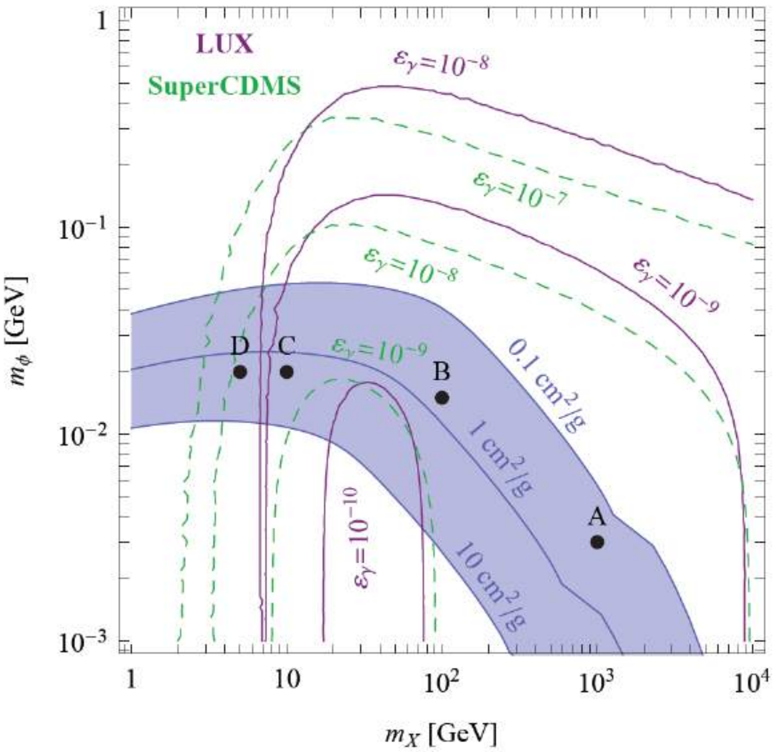
Del Nobile, Kaplinghat, Yu (2015)



Small improvements in sensitivity can explore large parameter regions for SIDM

Direct detection limits on SIDM

Del Nobile et al (2015)



SIDM above few GeV must couple *very* weakly to the SM

Blue band shows σ/m on dwarf scales preferred by rotation curves and too-big-to-fail

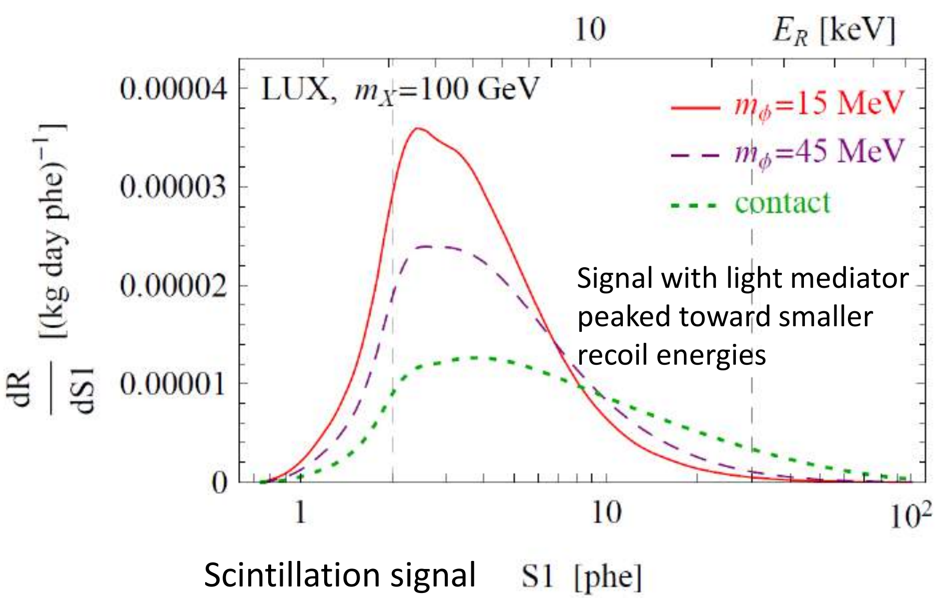
Note: Full LUX exposure is greater by factor ~3 (Comparable to Xenon1T)

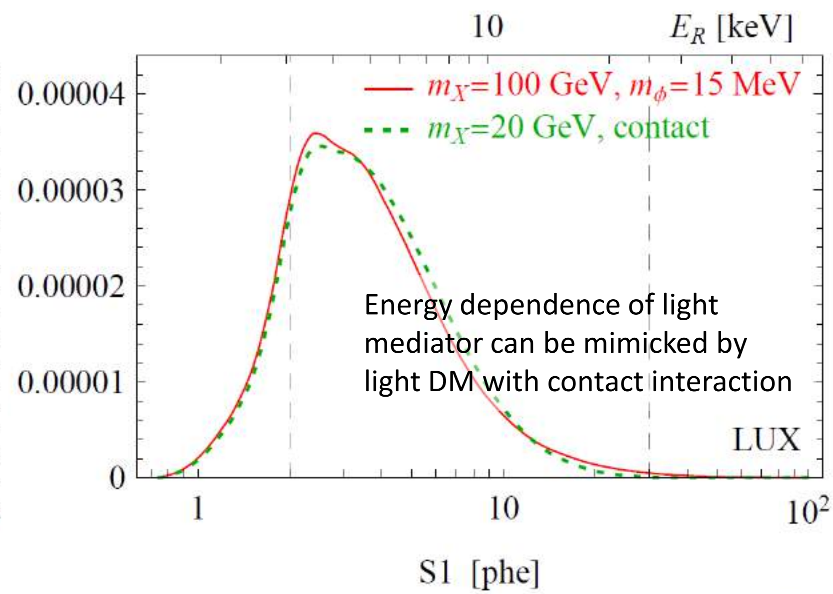
Lower threshold detectors (SuperCDMS) have greater sensitivity to lighter SIDM mass

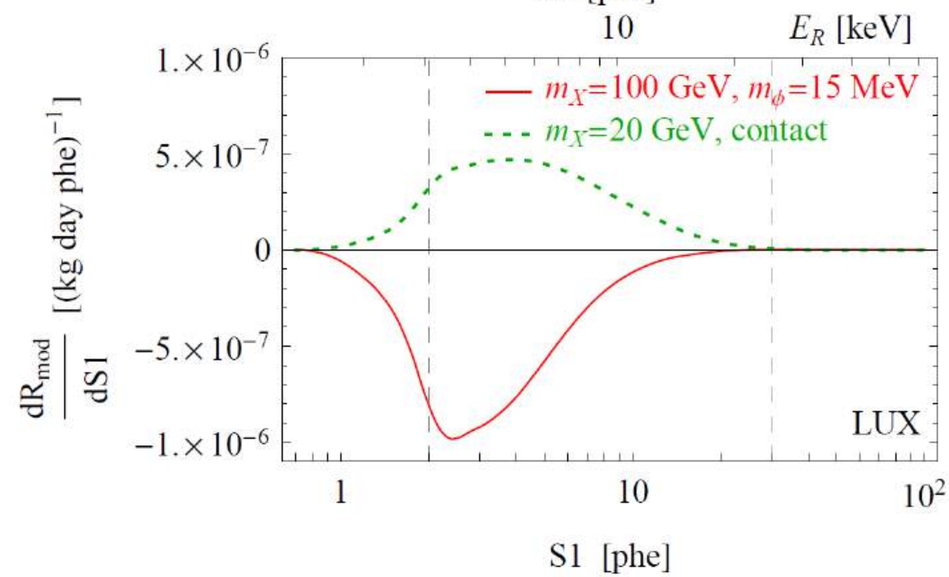
Kahlhoefer, Kulkarni, Wild (2017)

See talk by Wild

Distinguishing SIDM from WIMPs





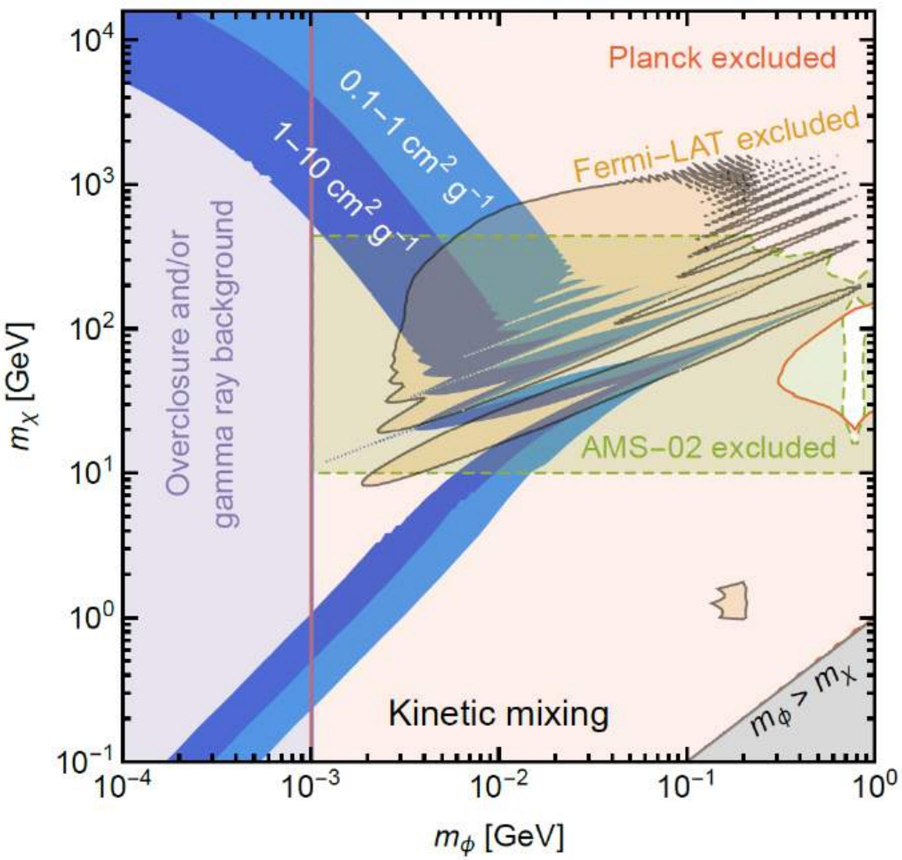


Combination of total rate + annual modulation can distinguish SIDM from WIMPs

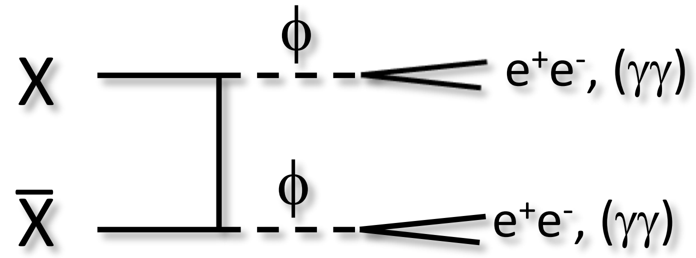
Del Nobile et al (2015)

Indirect detection constraints

Bringmann, Kahlhoefer, Schmidt-Hoberg, Walia (2016); also Cirelli et al. (2016)



Visible annihilation signals from SIDM are strongly constrained by CMB



Annihilation for high mass SIDM is boosted by large Sommerfeld factor

Caveats: Asymmetric dark matter, scalar mediator, dark sector decoupled (and cooler) during freeze-out

See talk by Wild

Conclusions

Dark Matter Self-interactions and Small Scale Structure

Sean Tulin[1,*] and Hai-Bo Yu[2,†]

Invited review Physics Reports (arXiv:1705.02358)

Contents

χ_{SIDM}

$I(J^{PC}) = ?(?^{??})$

Mass unknown

Positive observations	σ/m	v_{rel}	Observation	Refs.
Cores in spiral galaxies (dwarf/LSB galaxies)	$\gtrsim 1\ \mathrm{cm^2/g}$	$30 - 200\ \mathrm{km/s}$	Rotation curves	[77, 93]
Too-big-to-fail problem				
Milky Way	$\gtrsim 0.6\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[87]
Local Group	$\gtrsim 0.5\ \mathrm{cm^2/g}$	$50\ \mathrm{km/s}$	Stellar dispersion	[88]
Cores in clusters	$\sim 0.1\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	Stellar dispersion, lensing	[93, 103]
*** *Abell 3827 subhalo merger*	$\sim 1.5\ \mathrm{cm^2/g}$	$1500\ \mathrm{km/s}$	DM-galaxy offset	[104]
Abell 520 cluster merger	$\sim 1\ \mathrm{cm^2/g}$	$2000 - 3000\ \mathrm{km/s}$	DM-galaxy offset	[105, 106, 107]
Constraints				
Halo shapes/ellipticity	$\lesssim 1\ \mathrm{cm^2/g}$	$1300\ \mathrm{km/s}$	Cluster lensing surveys	[86]
Substructure mergers	$\lesssim 2\ \mathrm{cm^2/g}$	$\sim 500 - 4000\ \mathrm{km/s}$	DM-galaxy offset	[92, 108]
Merging clusters	$\lesssim$ few $\mathrm{cm^2/g}$	$2000 - 4000\ \mathrm{km/s}$	Post-merger halo survival (Scattering depth $\tau < 1$)	Table II
Bullet Cluster	$\lesssim 0.7\ \mathrm{cm^2/g}$	$4000\ \mathrm{km/s}$	Mass-to-light ratio	[81]

*** We do not use the following data for averages, fits, limits, etc.