Beyond Collisionless DM

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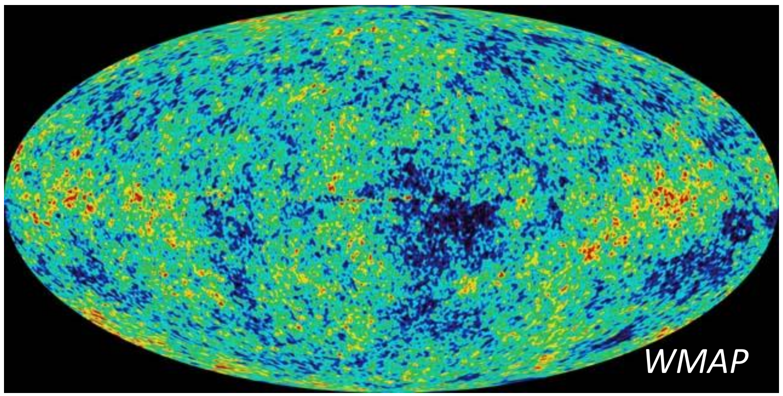
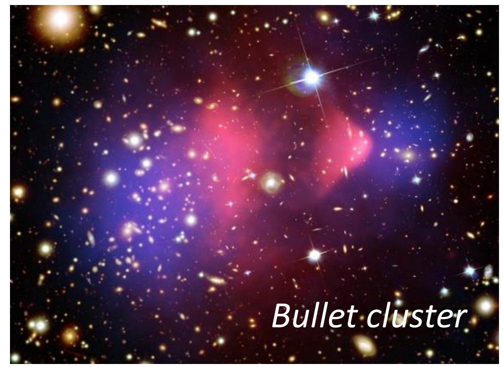
Cold collisionless dark matter paradigm

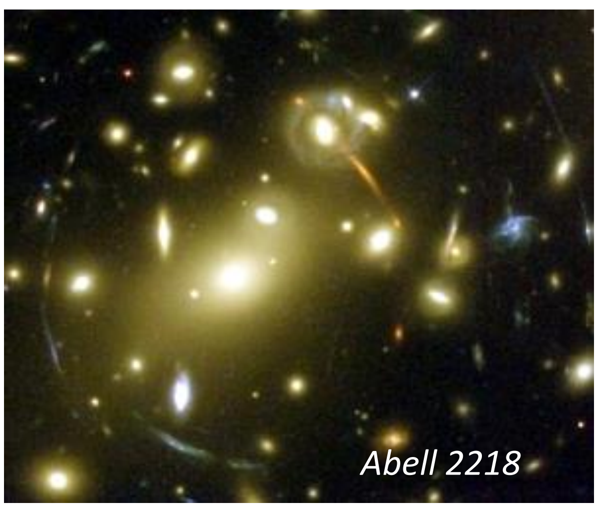
Dark matter (DM) is about 22% of the Universe

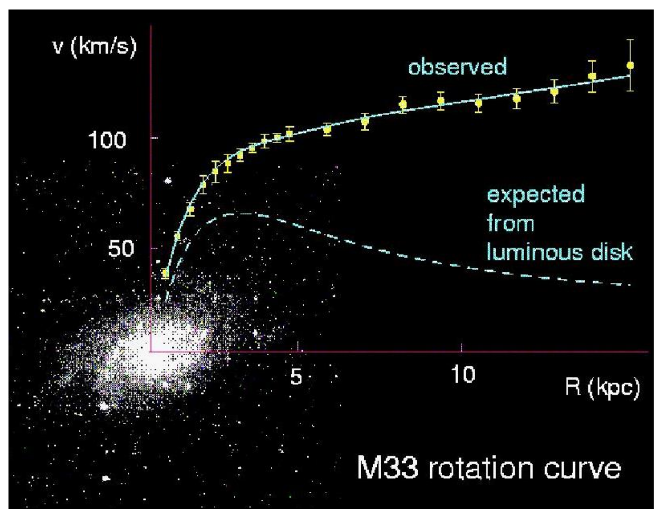




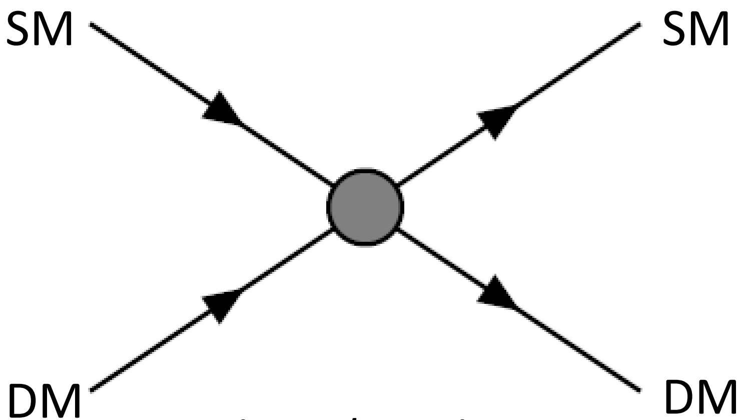
Cold collisionless dark matter (CDM) provides a good description of the structure of matter in the Universe

To date, evidence for DM from gravity only

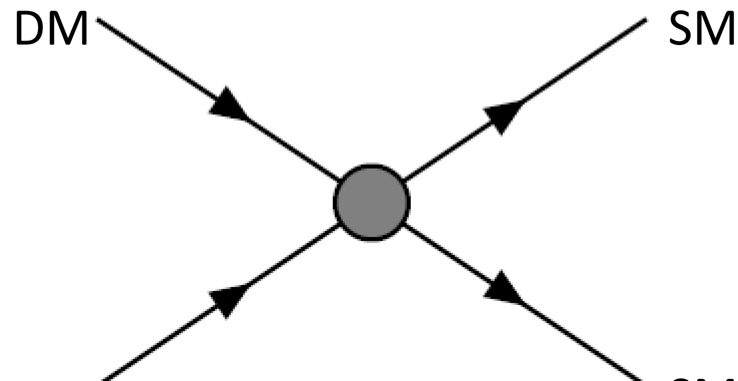




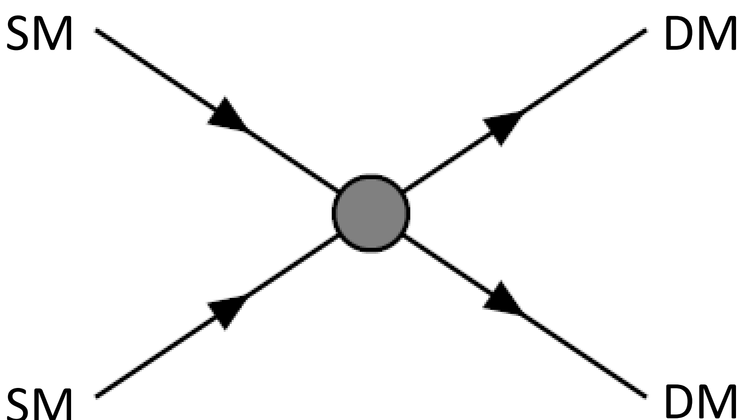
Exploring the dark sector



Direct detection



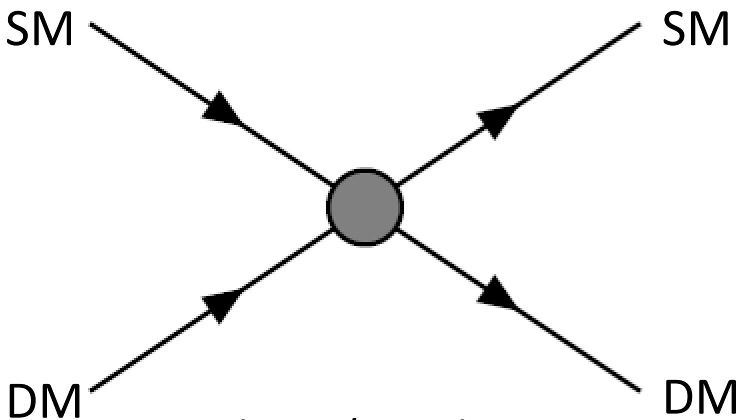
Indirect detection



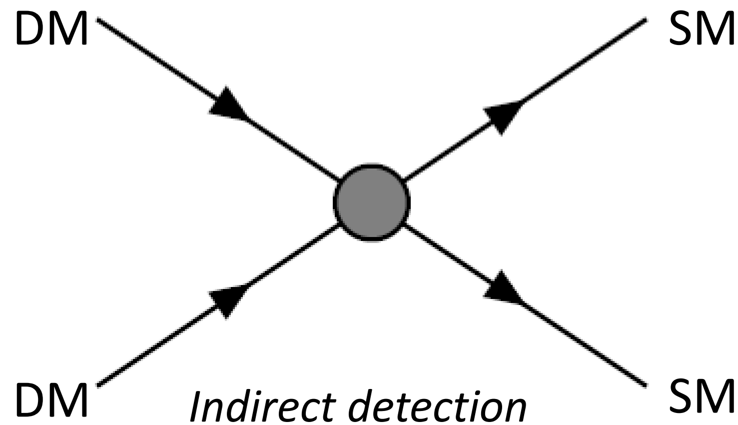
Colliders

Can we learn about the dark sector if DM has highly suppressed couplings to SM?

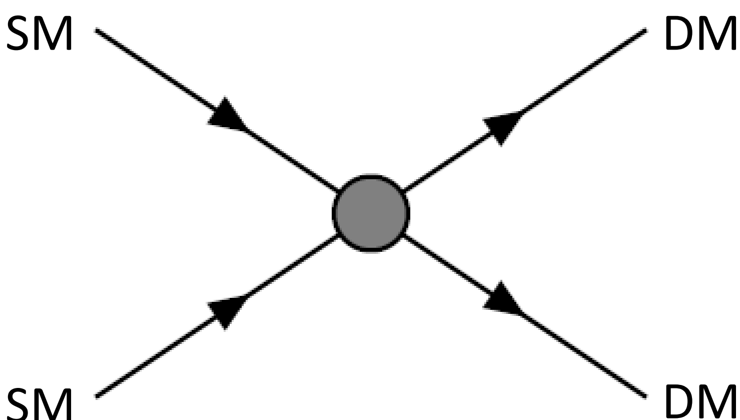
Exploring the dark sector



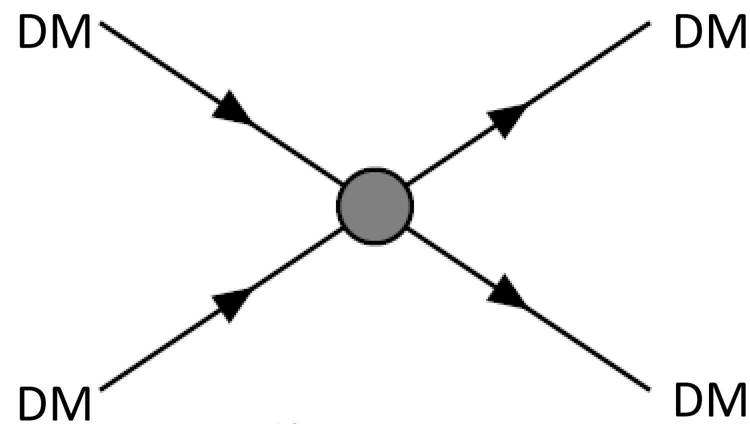
Direct detection



Indirect detection



Colliders



Self-interactions

Outline

- Cold collisionless DM paradigm in trouble (??)
  - Discrepancy between N-body simulations and astrophysical observations on smallest scales
  - Dwarf galaxies: laboratories for studying DM

- DM may have self-interactions
  - Particle physics implications of self-interacting DM

CDM in trouble

1. Core-vs-cusp problem *Moore (1994), Flores & Primack (1994)*
   – Central densities of dwarf halos exhibit cores

     DM density: $\rho \sim r^{\alpha}$ $\alpha \sim -1$ (cusp, NFW) or $\alpha \sim 0$ (core)
2. Too-big-to-fail problem *Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)*
   – Simulations predict O(10) massive MW satellites more massive than observed MW dSphs
3. Missing satellite problem *Klypin et al (1999), Moore et al (1999)*
   – Fewer small MW dSphs than predicted by simulation
   – Small enough to fail

1. Core-vs-cusp problem

Small galaxies seem to have cores (wherever we look)

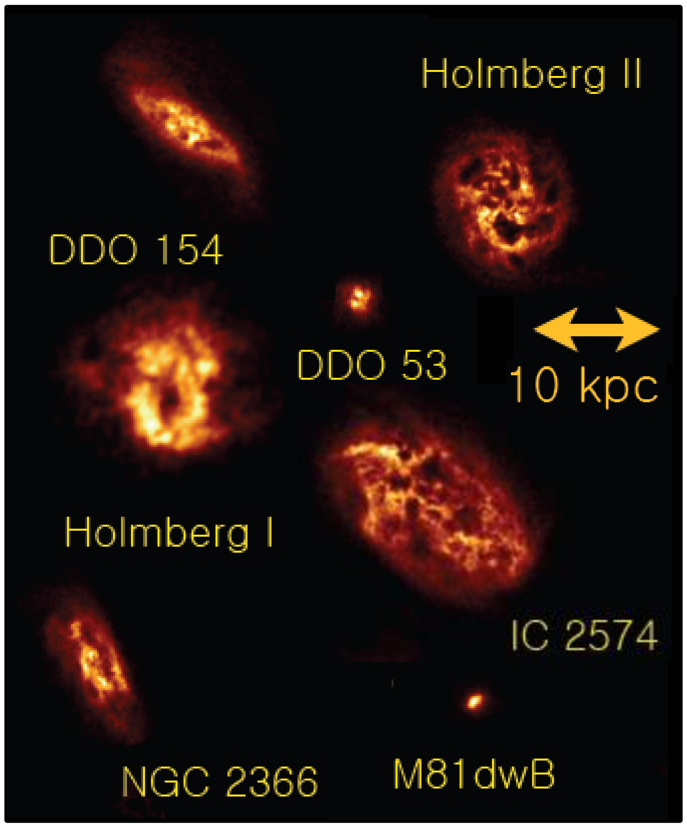
1. Dwarf galaxies outside the galaxy

2. Milky Way dwarf spheroidals

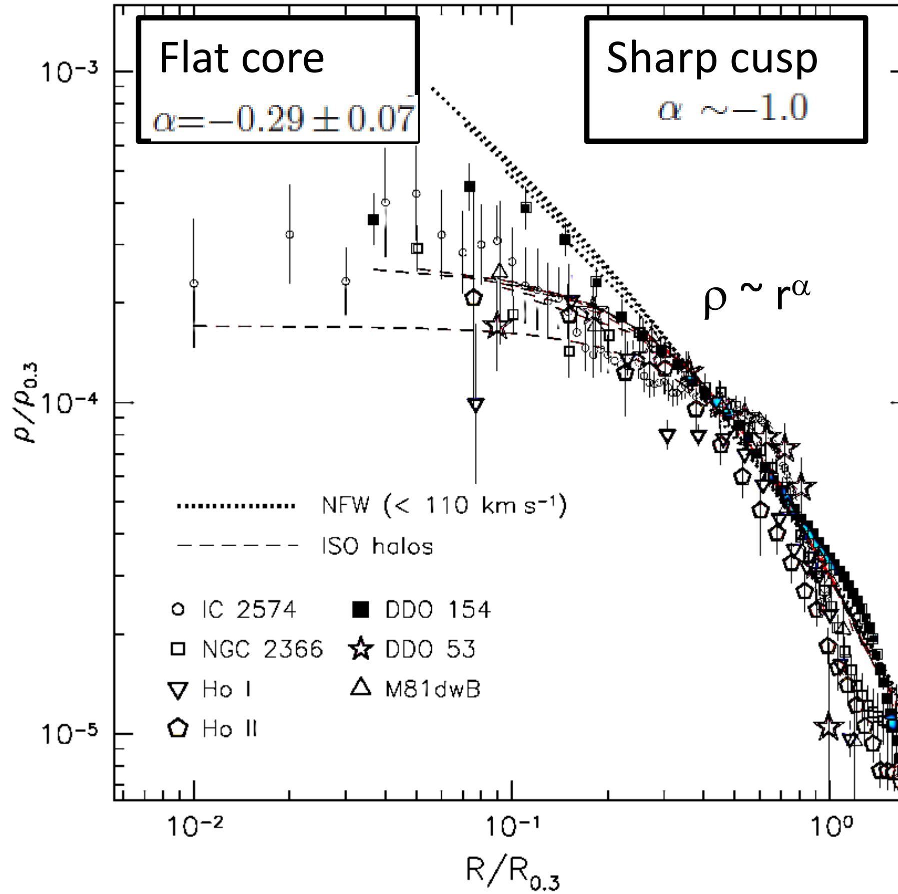
3. Low surface brightness galaxies

1. Cores in dwarfs outside MW halo

Moore (1994), Flores & Primack (1994), ...

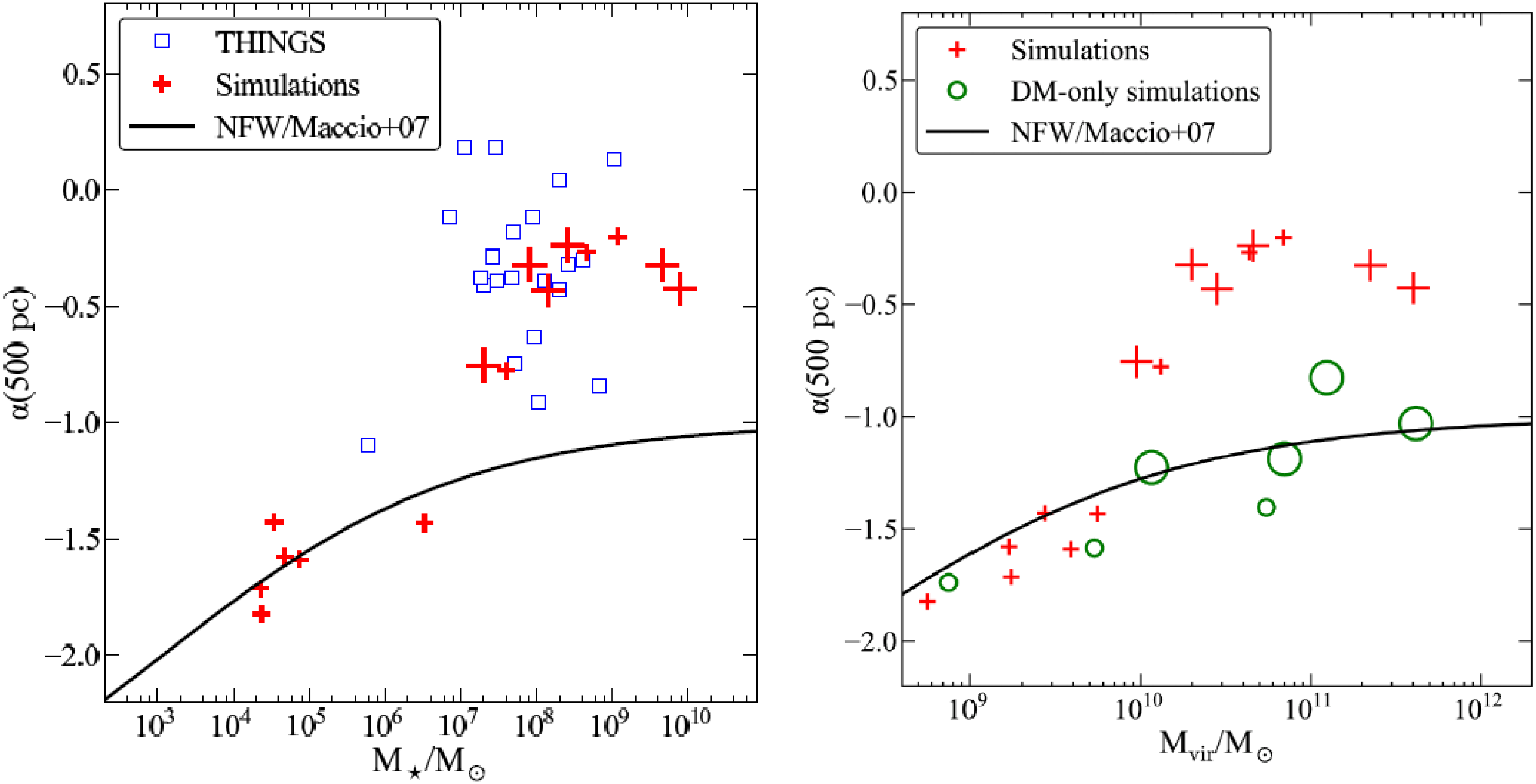


THINGS (dwarf galaxy survey) - Oh et al. (2011)



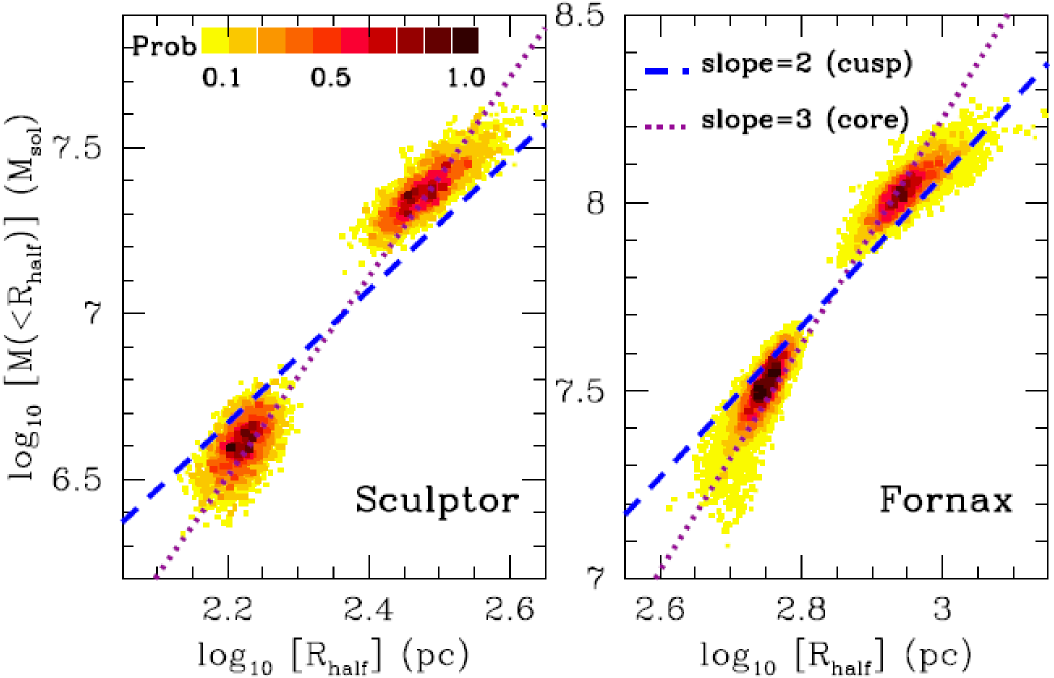
1. Cores in dwarfs outside MW halo

Governato et al. (2012)



Supernova feedback can generate cores?

1. Cores in MW dwarf spheroidals



Stellar subpopulations (metal-rich & metal-poor) as “test masses” in gravitational potential

Walker & Penarrubia (2011)

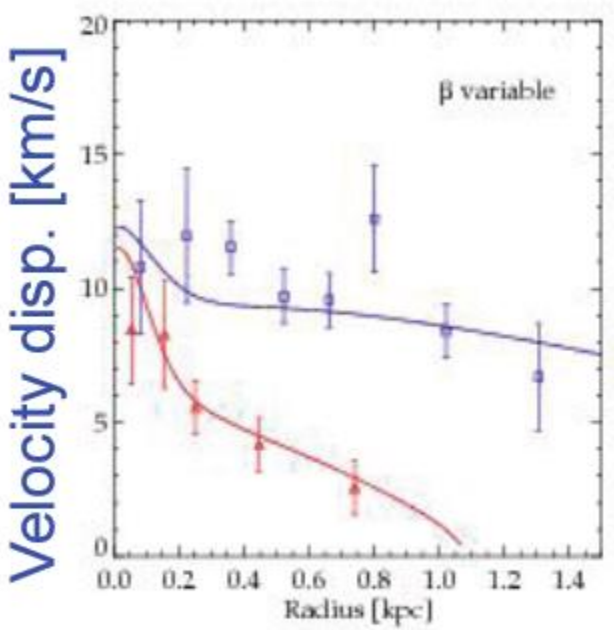
Enclosed mass $M(<r) = \int d^3r\ \rho$

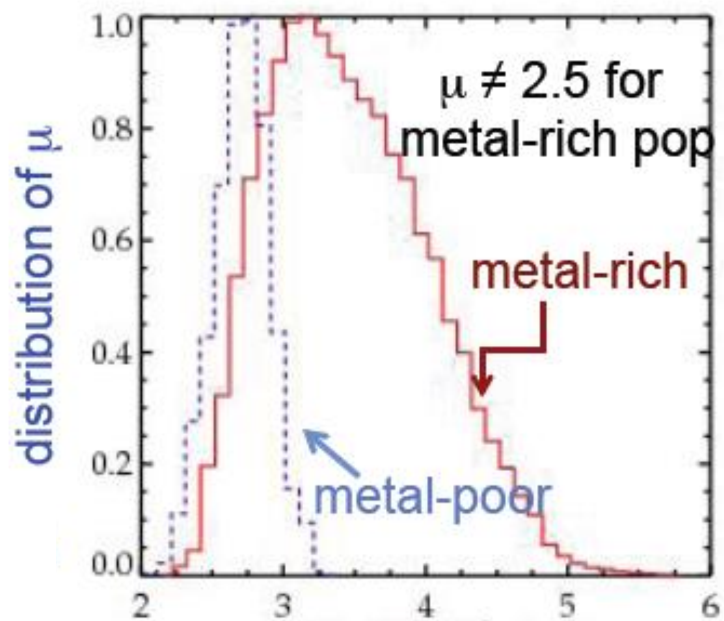
Estimate enclosed mass from line-of-sight dispersion: $M(r_{½}) = \mu\ r_{½} <\sigma_{los}^2>/G \quad \mu=2.5$

Probably not enough supernova feedback *(Garrison-Kimmel et al 2013)*
Maybe environmental effect via interaction with MW disk *(Zolotov et al 2012)*

1. Cores in MW dwarf spheroidals

MW dSphs can be consistent with NFW profiles due to uncertainty in μ





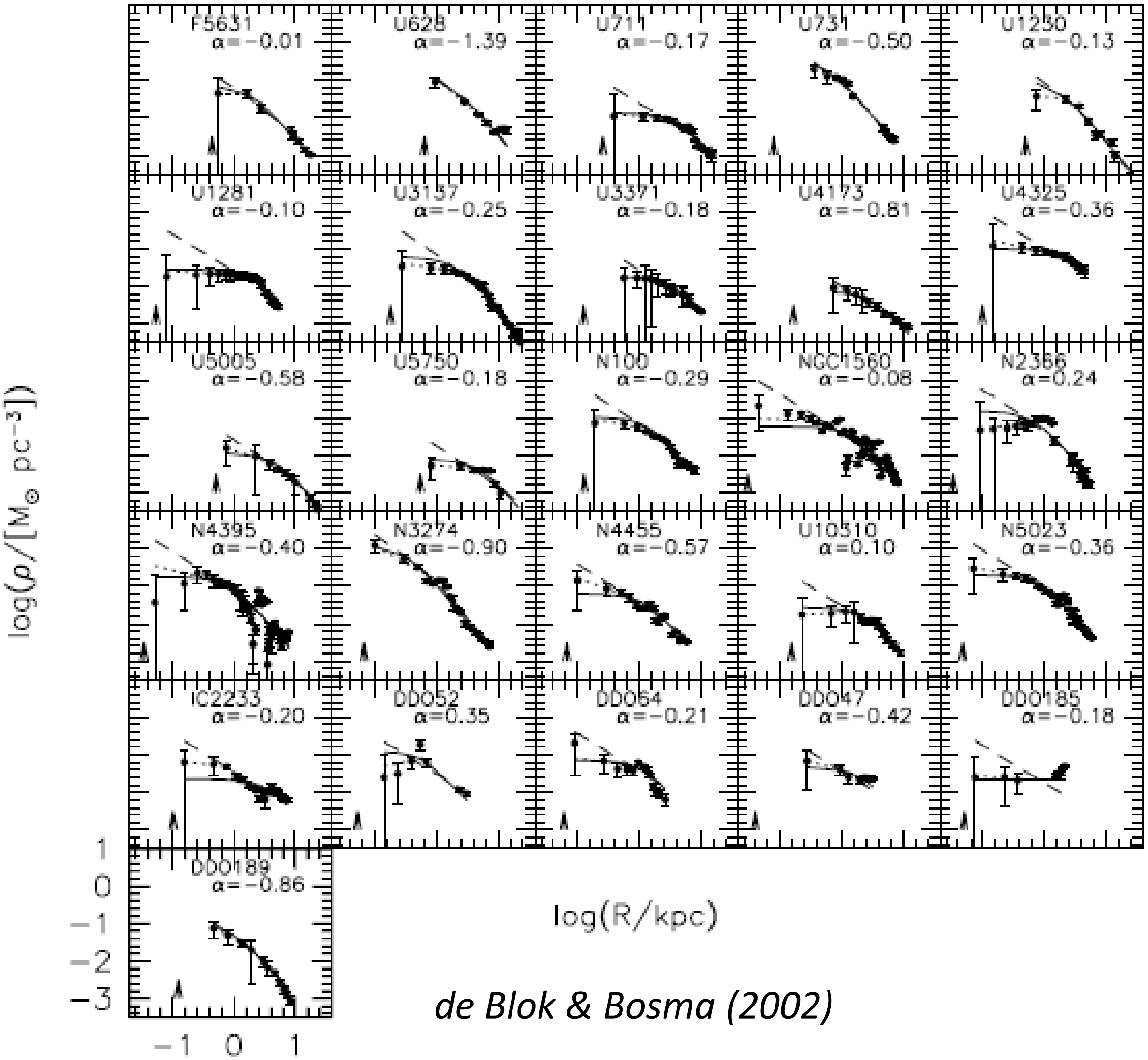
Frenk, Strigari, White (2013?) [C. Frenk's Aspen talk]

BUT cores in MW dSphs favored from longevity of ~10 Gyr old globular clusters

Cusps lead to inspiral of GCs on ~ few Gyr timescale by dynamical friction, cores do not

Sanchez-Salcedo et al (2006), Goerdt et al (2006)

1. Cores in LSBs



de Blok & Bosma (2002)

Cores in low surface brightness galaxies (LSBs)

Metal-poor galaxies with limited star formation history (more pristine)

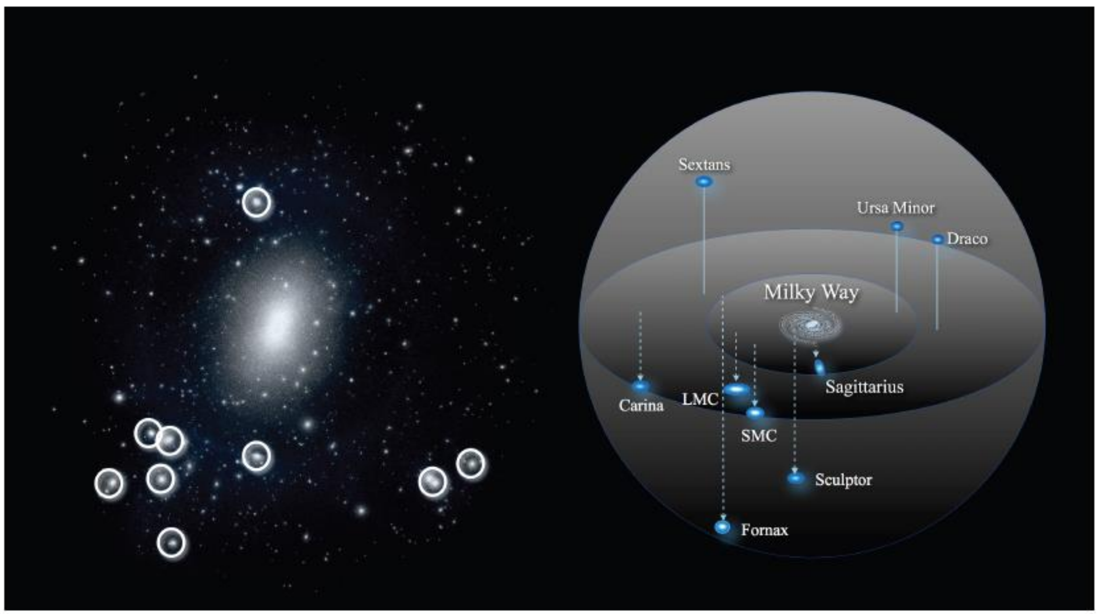
Not enough baryonic feedback to affect DM cusps

Kuzio de Naray & Spekkens (2011)

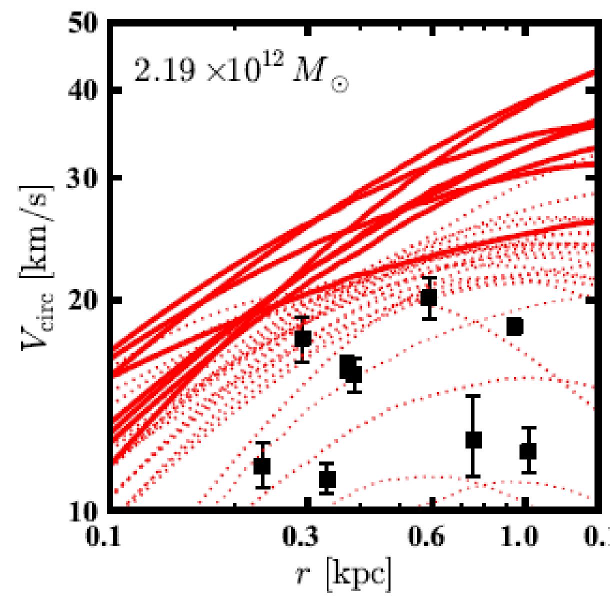
2. Too-big-to-fail problem

Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)

MW galaxy should have O(10) satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals



From Weinberg, Bullock, Governato, Kuzio de Naray, Peter (2013)



2. Too-big-to-fail problem

Boylan-Kolchin, Bullock, Kaplinghat (2011 + 2012)

MW galaxy should have O(10) satellite galaxies which are more massive than the most massive (classical) dwarf spheroidals

- Variation in number of satellites (~10% "tuning")

  Purcell & Zentner (2012)

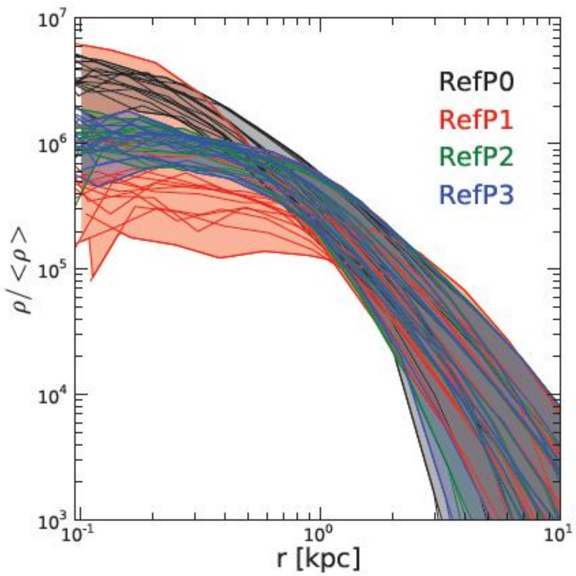
- Uncertainty in MW halo mass

Self-interactions

- Self-interactions can solve small scale structure problems

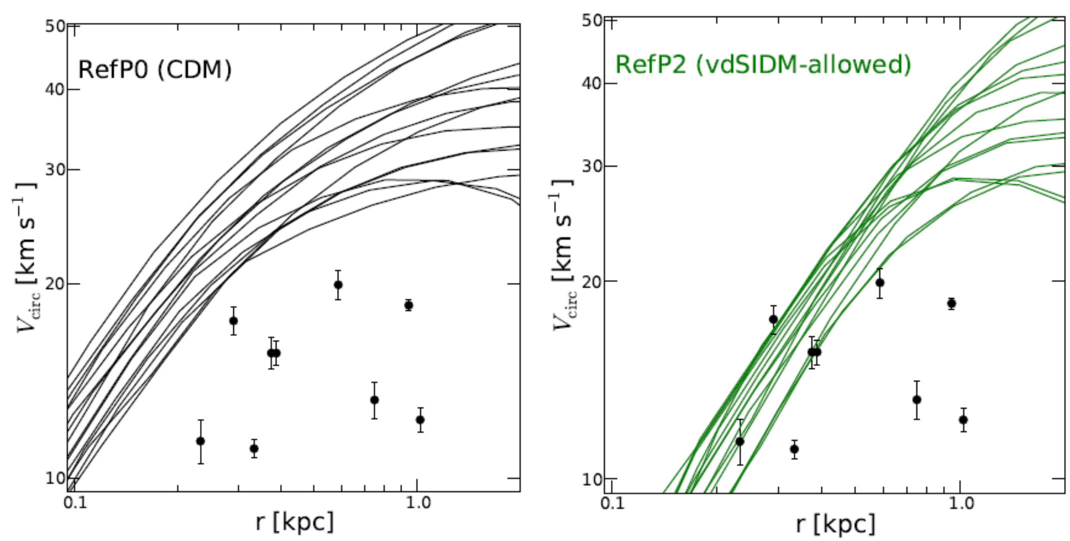
Vogelsberger, Zavala, Loeb (2012); see also Rocha et al, Peter et al (2012)

Core vs cusp problem



Black = CDM
Red/green/blue = SIDM

Too big to fail problem



DM self-scattering moves predicted circular velocities into (closer) alignment with MW dSph

Self-interacting dark matter

- What does this tell us about the underlying particle physics theory of the dark sector?

Self-interacting dark matter

- What does this tell us about the underlying particle physics theory of the dark sector?
- History of particle physics models for SIDM
  1. σ=const *Spergel & Steinhardt (2000), Dave et al (2000)*
  2. $\sigma \sim 1/v$ *Yoshida et al (2000)*
  3. $\sigma \sim 1/v^4$ (massless mediator) *Ackerman et al (2008)*
  4. Yukawa potential (finite mass mediator)

     Buckley & Fox (2009), Feng, Kaplinghat, Yu (2009), Loeb & Weiner (2010), ST, Yu, Zurek (2012 + 2013)
  5. Dark atoms *Cyr-Racine et al (2013), Fan et al (2013)*

Improved N-body simulations

Vogelsberger, Zavala, Loeb (2012); Rocha et al, Peter et al (2012)

- Constraints from larger scales weaker than previously thought

    Miralda-Escude bound (grav. lensing by elliptical cluster)

    $\sigma/m < 0.02\ \mathrm{cm}^2/\mathrm{g}$

    Peter et al. (2012): bound overestimated by 10^2 (!)

- Constant cross section $\sigma/m \sim 0.5 - 1\ \mathrm{cm}^2/\mathrm{g}$ is OK with all constraints

Five particle physics lessons for SIDM

Five particle physics lessons for SIDM

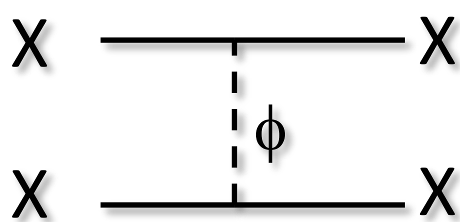
1. Large self-interaction cross section required

Figure-of-merit: $\sigma/m_\chi \sim 1\ \mathrm{cm}^2/\mathrm{g} \approx 2\ \mathrm{barns/GeV}$

– Typical WIMP: $\sigma \sim 1$ pb, $m_\chi \sim 100$ GeV

$$\sigma/m_\chi \sim 10^{-14}\ \mathrm{barns/GeV}$$

– New mediator ϕ much lighter than weak scale



self-interaction

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

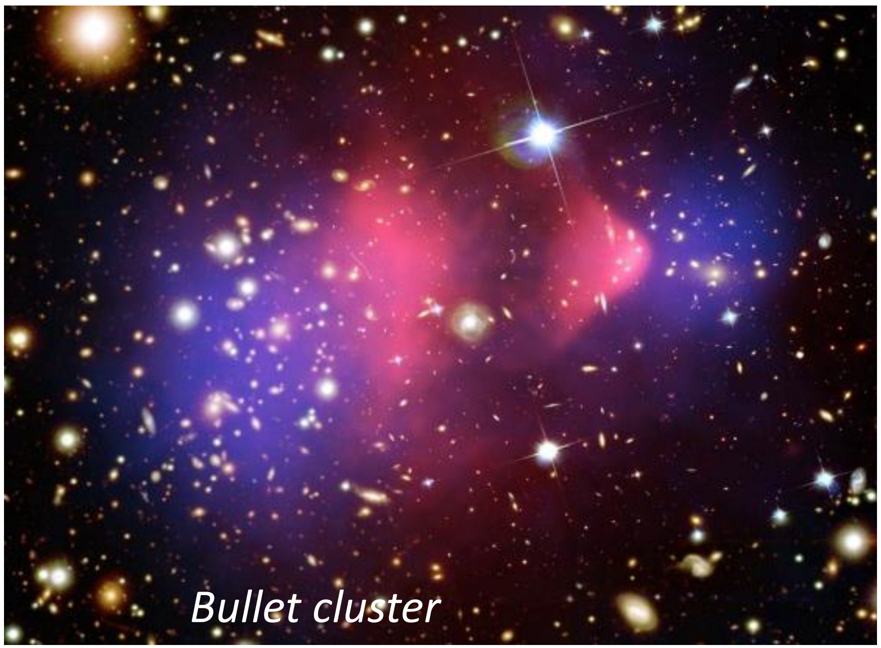
Five particle physics lessons for SIDM

2. Light mediator implies velocity-dependent self-interaction cross section

σ/m_X enhanced at low velocity, suppressed at high velocity (like Rutherford scattering)

Five particle physics lessons for SIDM

3. Different size DM halos have different velocities



Randall et al. (2007)

Buote et al. (2002); Feng et al. (2010)

DM appears collisionless on larger scales

Five particle physics lessons for SIDM

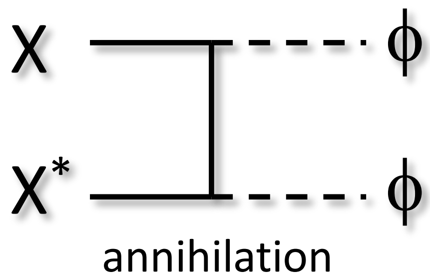
3. Different size DM halos have different velocities

Dwarfs	$v \sim 30$ km/s	SIDM
LSBs	$v \sim 100$ km/s	SIDM
MW-sized halos	$v \sim 200$ km/s	Collisionless DM
Clusters	$v \sim 1000$ km/s	Collisionless DM

Natural for self-interactions to manifest in smaller halos

Five particle physics lessons for SIDM

4. Annihilation channel for the DM relic density

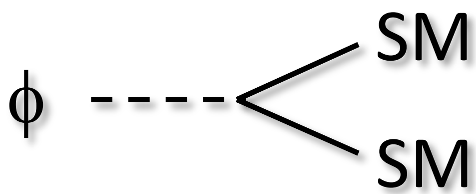


– Preserves WIMP miracle

$$\Omega_{\rm dm} \sim 0.2 \times \left(\frac{6 \times 10^{-26}\ {\rm cm}^3/{\rm s}}{\langle \sigma v \rangle_{\rm ann}} \right) \sim 0.2 \times \left(\frac{\alpha_X}{10^{-2}} \right)^{-2} \times \begin{cases} (m_X/300\ {\rm GeV})^2 & \text{vector} \\ (m_X/100\ {\rm GeV})^2 & \text{scalar} \end{cases}$$

Five particle physics lessons for SIDM

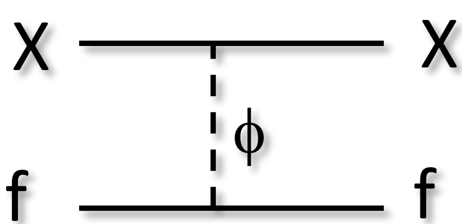
5. Mediator particles should decay before BBN



decay

Minimal setup with no new particles:
ϕ decays to SM fermions before BBN

– Upper bound on ϕ lifetime implies lower bound on direct detection cross section



Direct detection

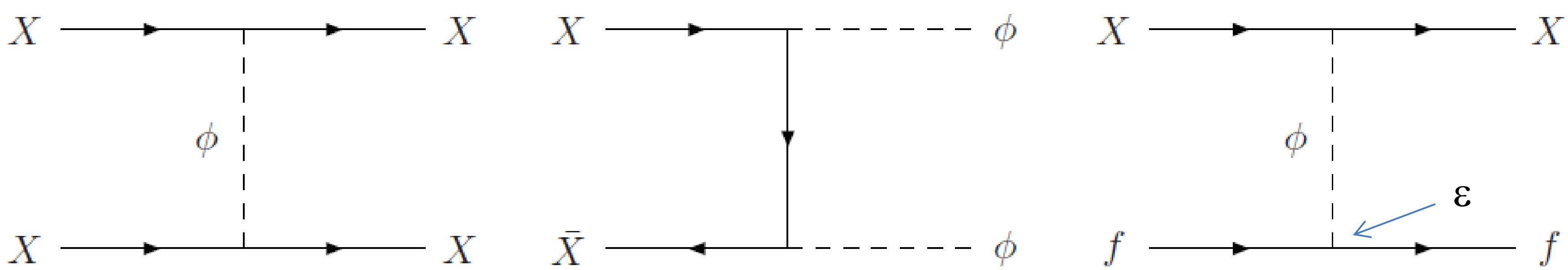
Direct detection constraints rule out large parameter region for SIDM

Simplified models for SIDM

- DM particle X + light mediator ϕ

$$\mathscr{L}_{\rm int} = \begin{cases} g_\chi \bar{\chi}\gamma^\mu \chi \phi_\mu & \text{vector mediator} \\ g_\chi \bar{\chi}\chi\phi & \text{scalar mediator} \end{cases} \qquad \alpha_X = g_X^2/(4\pi)$$

See also Bellazzini, Cliche, Tanedo (2013)



DM self-interactions | DM annihilation | Direct detection

Three portals to the dark sector

1. Vector mediator (ϕ mixes with Z or γ)
   - Kinetic mixing with photon

$$\mathscr{L}_{\rm mix} = -\frac{\varepsilon_\gamma}{2}\,\phi_{\mu\nu}F^{\mu\nu}$$

Holdom (1984); Pospelov et al (2007); Arkani-Hamed et al (2009); Lin et al (2011) …

   - Z mass mixing (ε_Z is Z-ϕ mixing angle):

$$\mathscr{L}_{\rm mix} = \varepsilon_Z m_Z^2\,\phi_\mu Z^\mu$$

Babu et al (1997); Davoudiasl et al (2012) …

2. Scalar mediator
   - Higgs mixing (ε_h is h-ϕ mixing angle)

$$\mathscr{L}_{\rm mix} = -\varepsilon_h m_h^2\,\phi h$$

Patt & Wilczek (2006), …

(Assume $\varepsilon \ll 1$, $m_\phi \sim 1 - 100$ MeV $\ll m_Z$)

Three portals to the dark sector

- Limits from BBN (want lifetime < second)
  - Kinetic mixing

$$\tau_\phi \approx 3 \text{ seconds} \times \left(\frac{\varepsilon_\gamma}{10^{-10}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

$$\text{BR}(\phi \to e^+e^-) \approx 1$$

  - Z mixing

$$\tau_\phi \approx 1 \text{ second} \times \left(\frac{\varepsilon_Z}{10^{-10}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

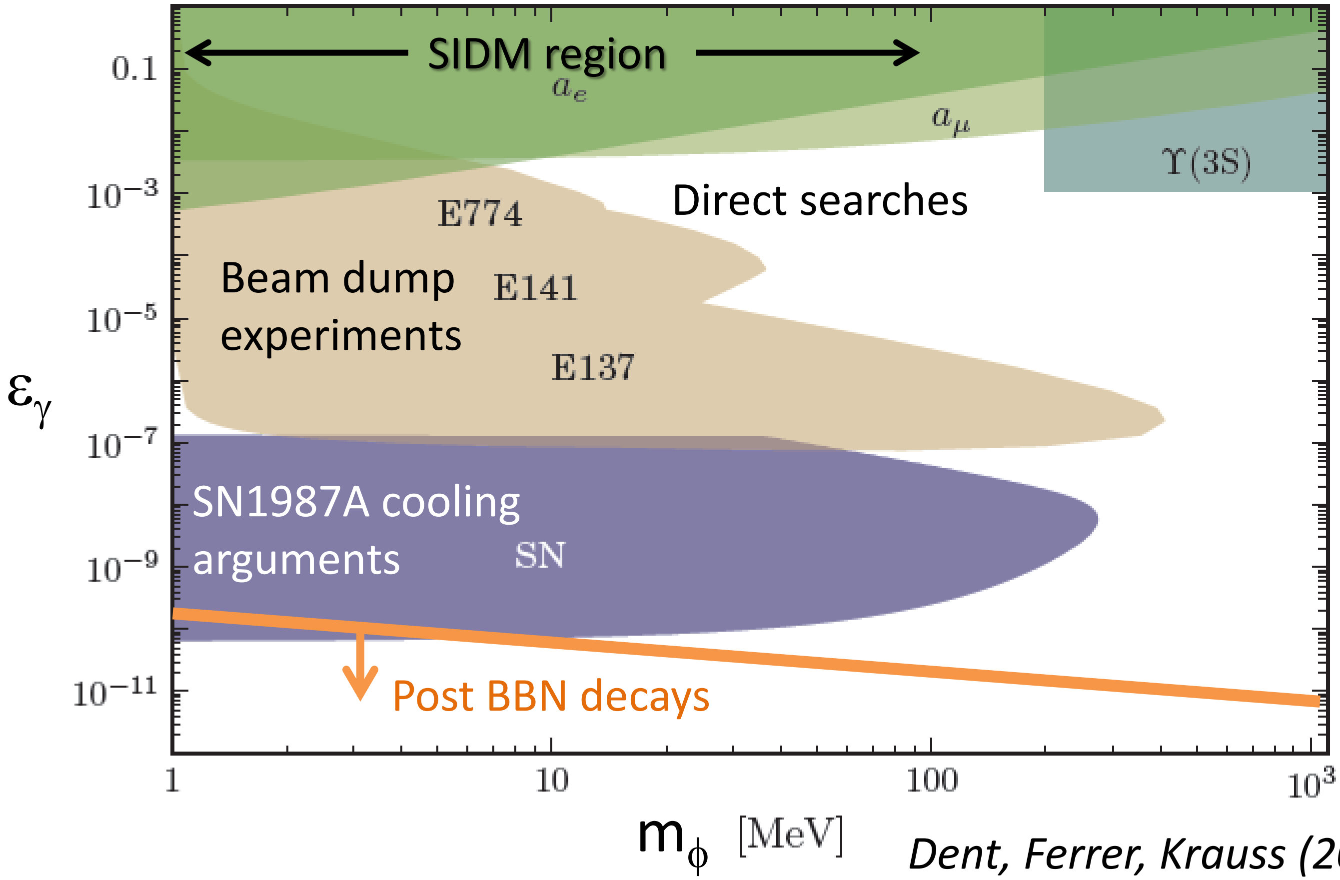
$$\text{BR}(\phi \to \nu\bar{\nu}) \approx 6/7 \text{ and } \text{BR}(\phi \to e^+e^-) \approx 1/7$$

  - Higgs mixing

$$\tau_\phi \approx 4 \text{ seconds} \times \left(\frac{\varepsilon_h}{10^{-5}}\right)^{-2} \left(\frac{m_\phi}{10 \text{ MeV}}\right)^{-1}$$

$$\text{BR}(\phi \to e^+e^-) \approx 1$$

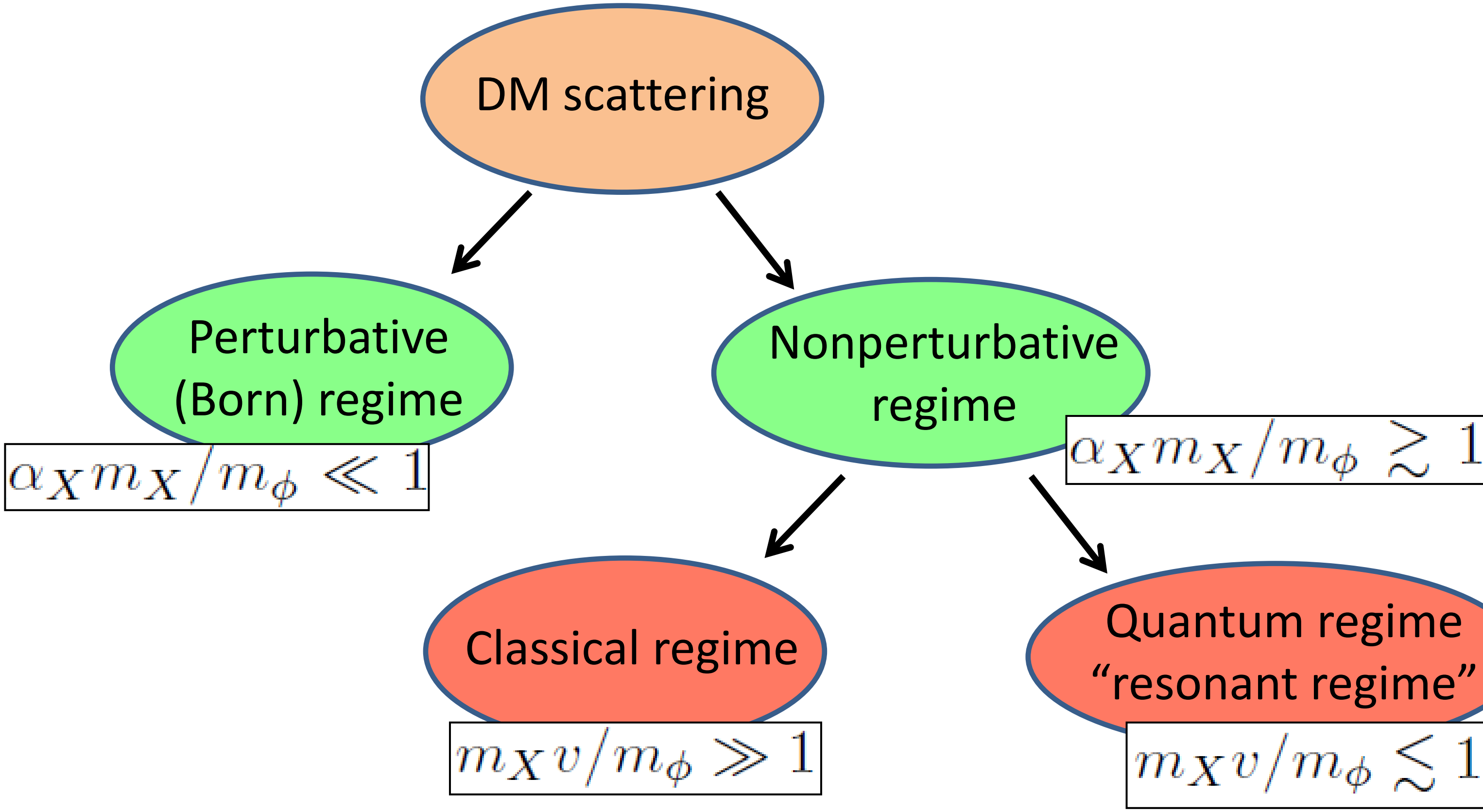
Constraints on kinetic mixing



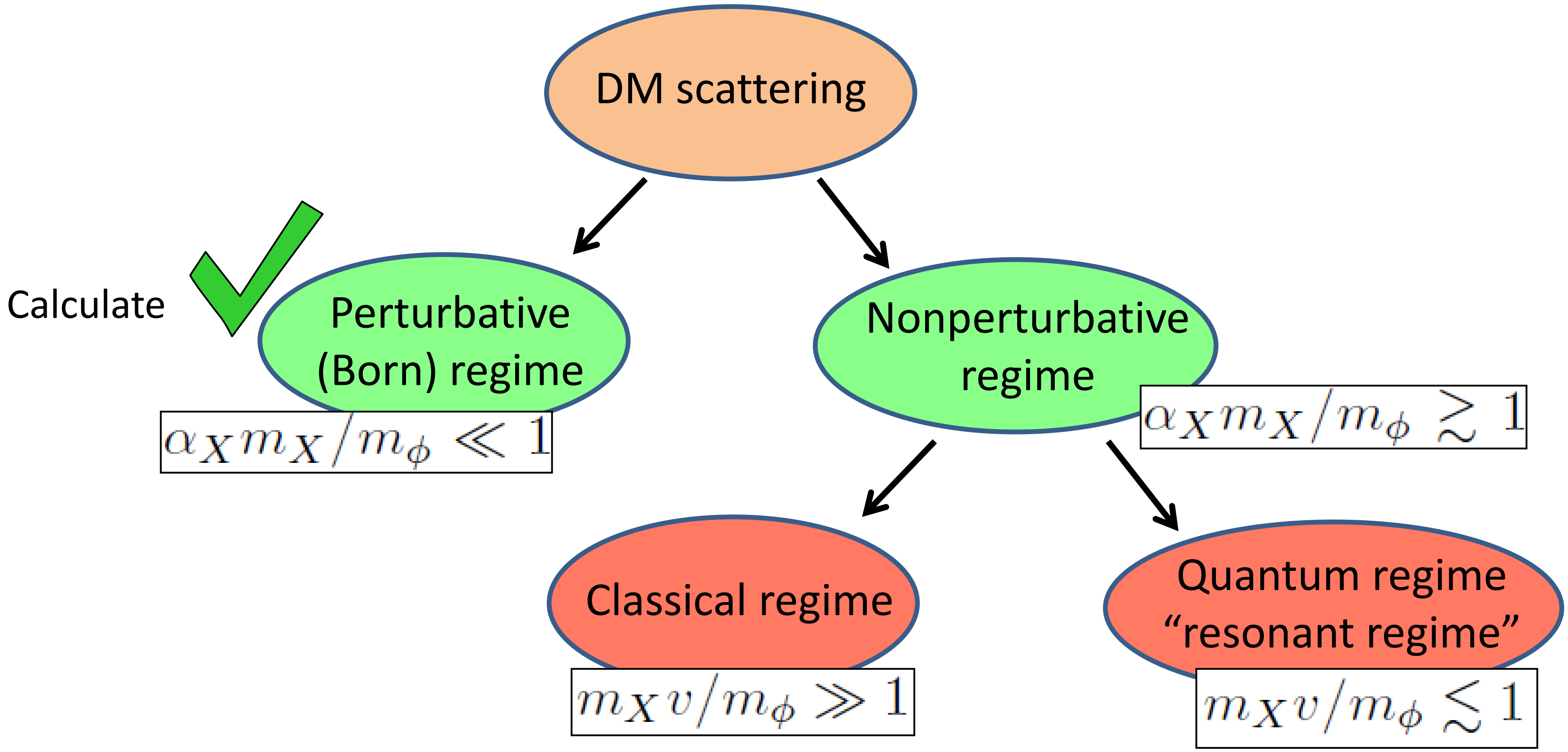
Dent, Ferrer, Krauss (2012)

Kinetic mixing case very constrained for SIDM: $\varepsilon_\gamma \sim 10^{-10}$ (!)

DM self-interaction cross section



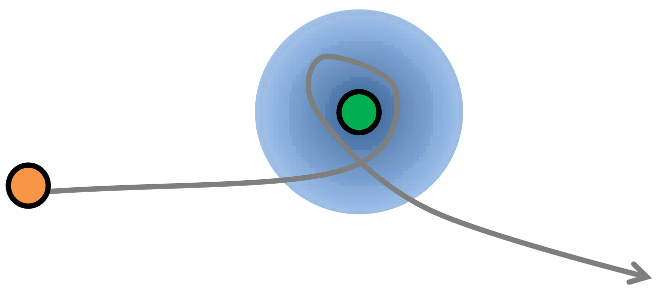
DM self-interaction cross section



Classical self-scattering

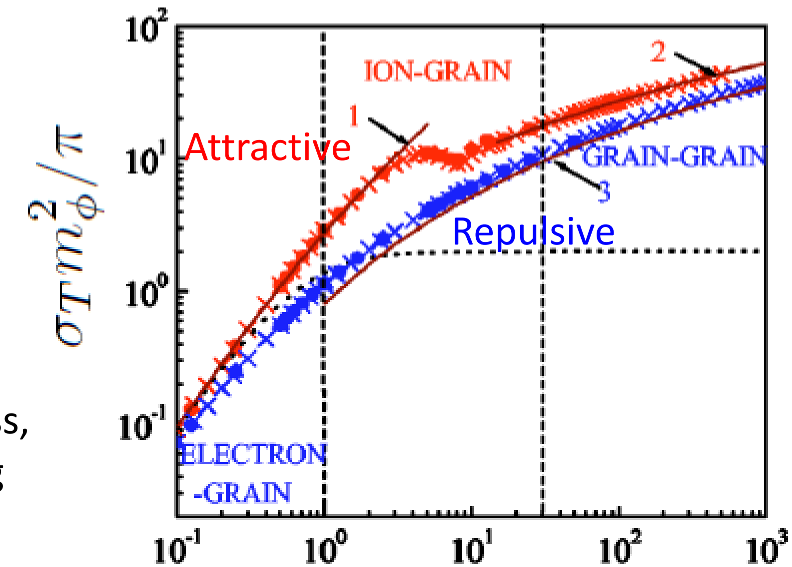
- Classical approximation for σ_T from plasma physics

Classical scattering in potential



$$V(r) = \mp \frac{\alpha_X}{r} e^{-m_\phi r}$$

m_ϕ = Debye mass,
α = EM coupling

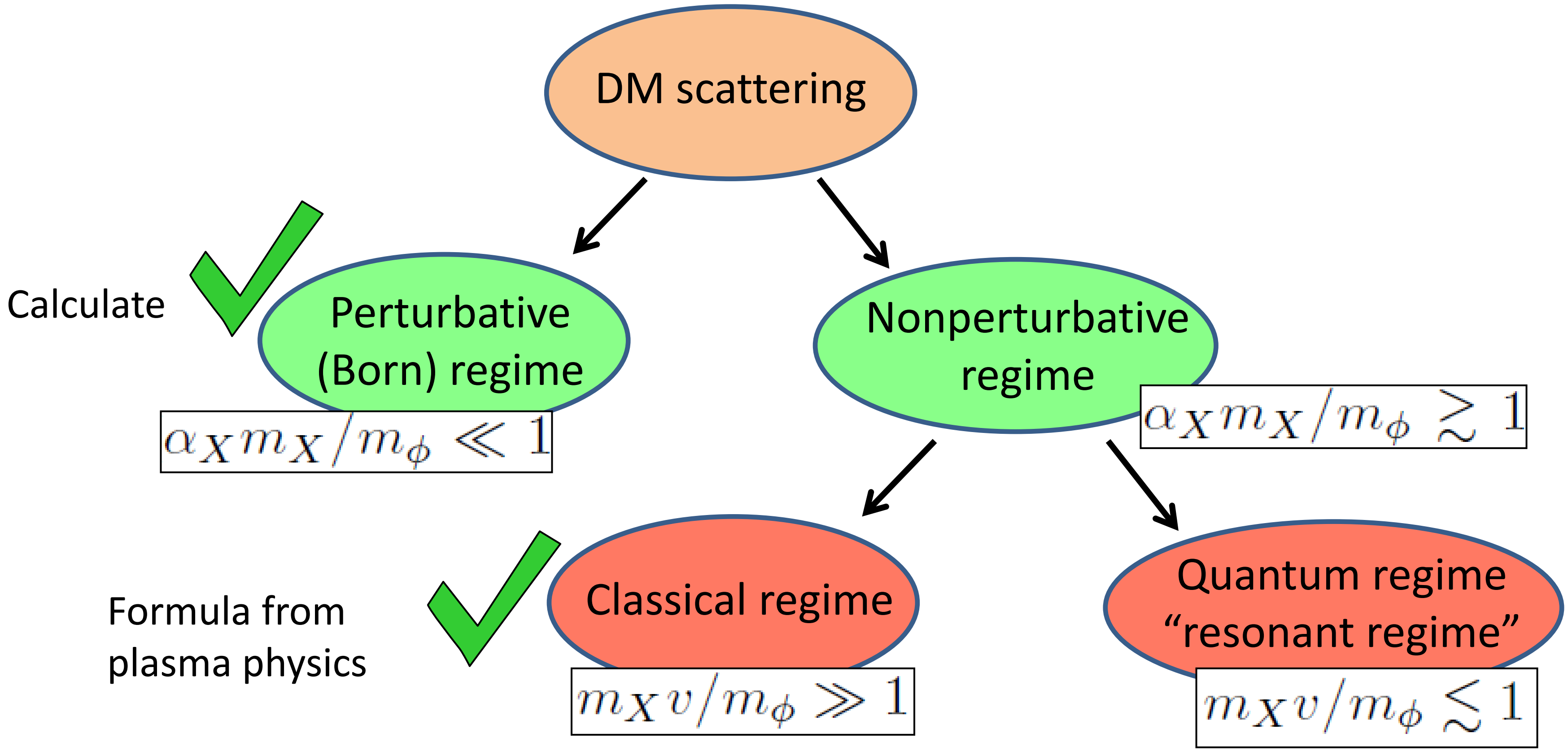


$$\beta \equiv 2\alpha_X m_\phi/(m_X v^2)$$

$$\sigma_T^{\rm clas} \approx \begin{cases} \frac{4\pi}{m_\phi^2}\beta^2 \ln\left(1+\beta^{-1}\right) & \beta \lesssim 10^{-1} \\ \frac{8\pi}{m_\phi^2}\beta^2/\left(1+1.5\beta^{1.65}\right) & 10^{-1} \lesssim \beta \lesssim 10^3 \\ \frac{\pi}{m_\phi^2}\left(\ln\beta + 1 - \frac{1}{2}\ln^{-1}\beta\right)^2 & \beta \gtrsim 10^3 \end{cases}$$

Khrapak et al (2004)

DM self-interaction cross section

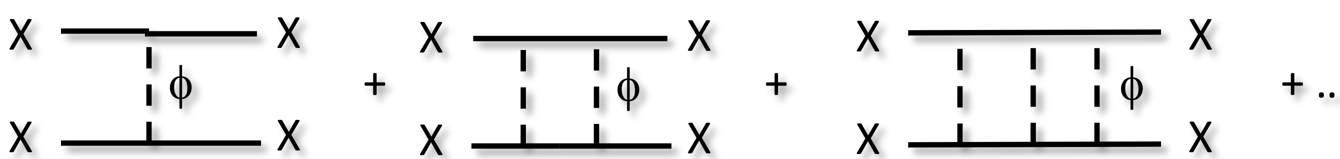


DM self-interaction cross section

- Nonperturbative calculation

  Buckley & Fox (2009),
  ST, H.-B. Yu, K. Zurek (2012 + 2013)

  – Similar to Sommerfeld enhancement for annihilation



  – Equivalent to solving the Schrodinger equation
    - Yukawa potential $V(r) = \pm \frac{\alpha_X}{r} e^{-m_\phi r}$
    - Compute phase shifts $\frac{d\sigma}{d\Omega} = \frac{1}{k^2} \left| \sum_{\ell=0}^{\infty} (2\ell + 1) e^{i\delta_\ell} P_\ell(\cos\theta) \sin\delta_\ell \right|^2$
    - Transfer cross section $\sigma_T \equiv \int d\Omega \, (1 - \cos\theta) \, d\sigma / d\Omega$

Comparison to previous work

M. Buckley & P. Fox (2009)

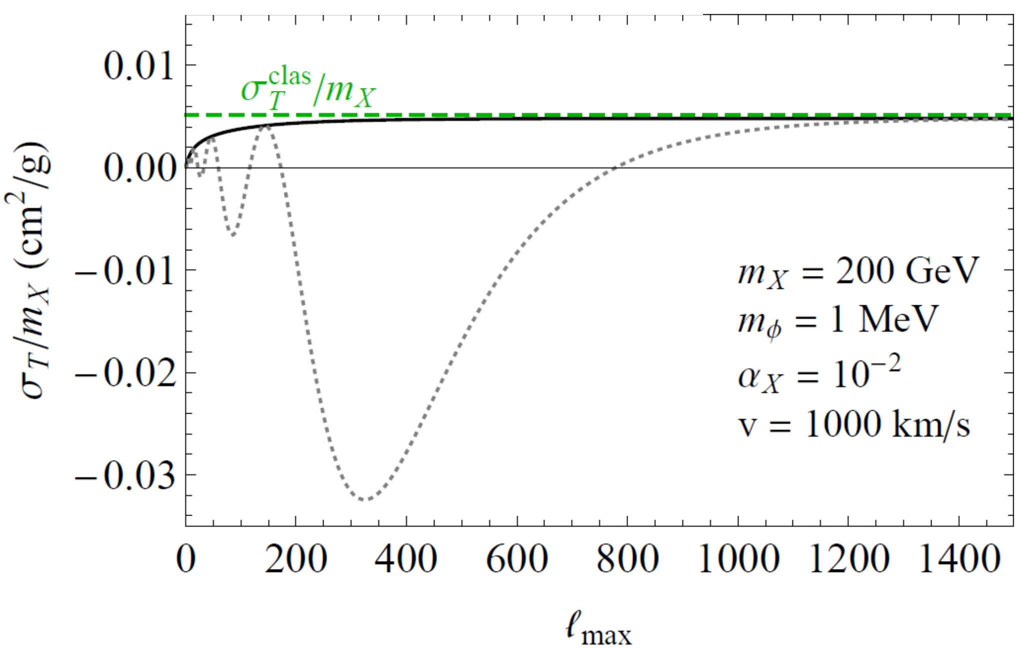
1. More efficient method for matching onto asymptotic solution of Bessel functions, not sines (B&F had $\ell_{max} = 5$)
2. More efficient formula for summing partial waves

Buckley & Fox 2009

$$\sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty \to \ell_{max}} \left[(2\ell+1)\sin^2\delta_\ell - 2(\ell+1)\sin\delta_\ell \sin\delta_{\ell+1}\cos(\delta_{\ell+1}-\delta_\ell) \right]$$

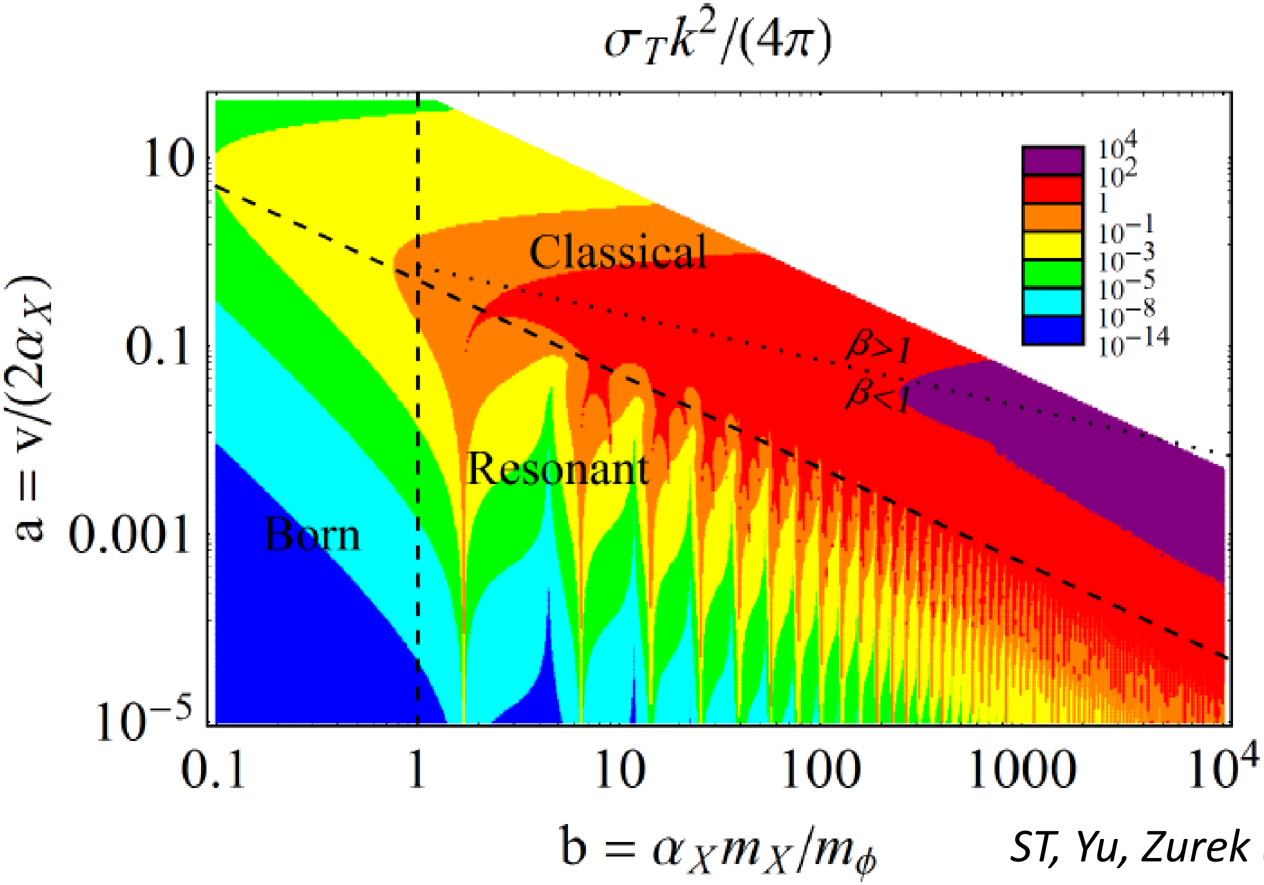
$$\sigma_T = \frac{4\pi}{k^2} \sum_{\ell=0}^{\infty \to \ell_{max}} (\ell+1)\sin^2(\delta_{\ell+1}-\delta_\ell)$$

ST, H.-B. Yu, K. Zurek (2013)



Parameter scan over SIDM

- Scan over SIDM parameters

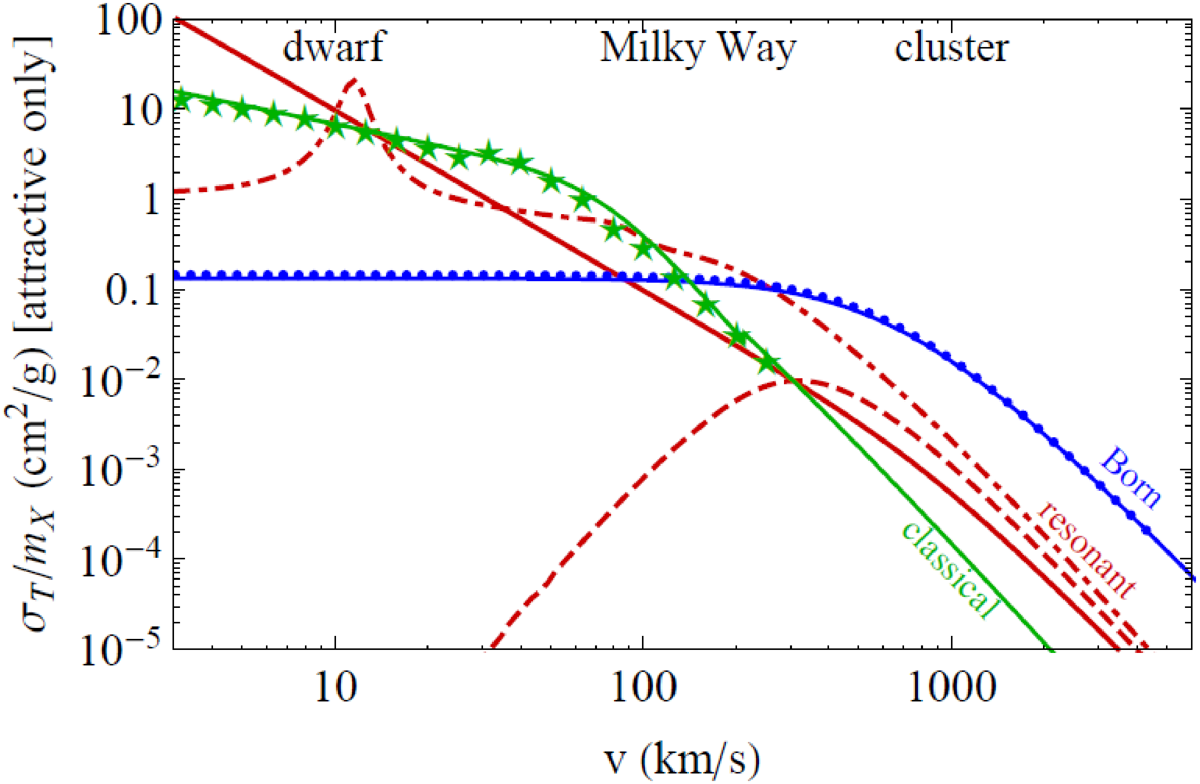


ST, Yu, Zurek (2012-2013)

What we learned from computing the self-interacting cross section

ST, Yu, Zurek (2012-2013)

1. Wide range of behavior



Proved the classical formula is valid!

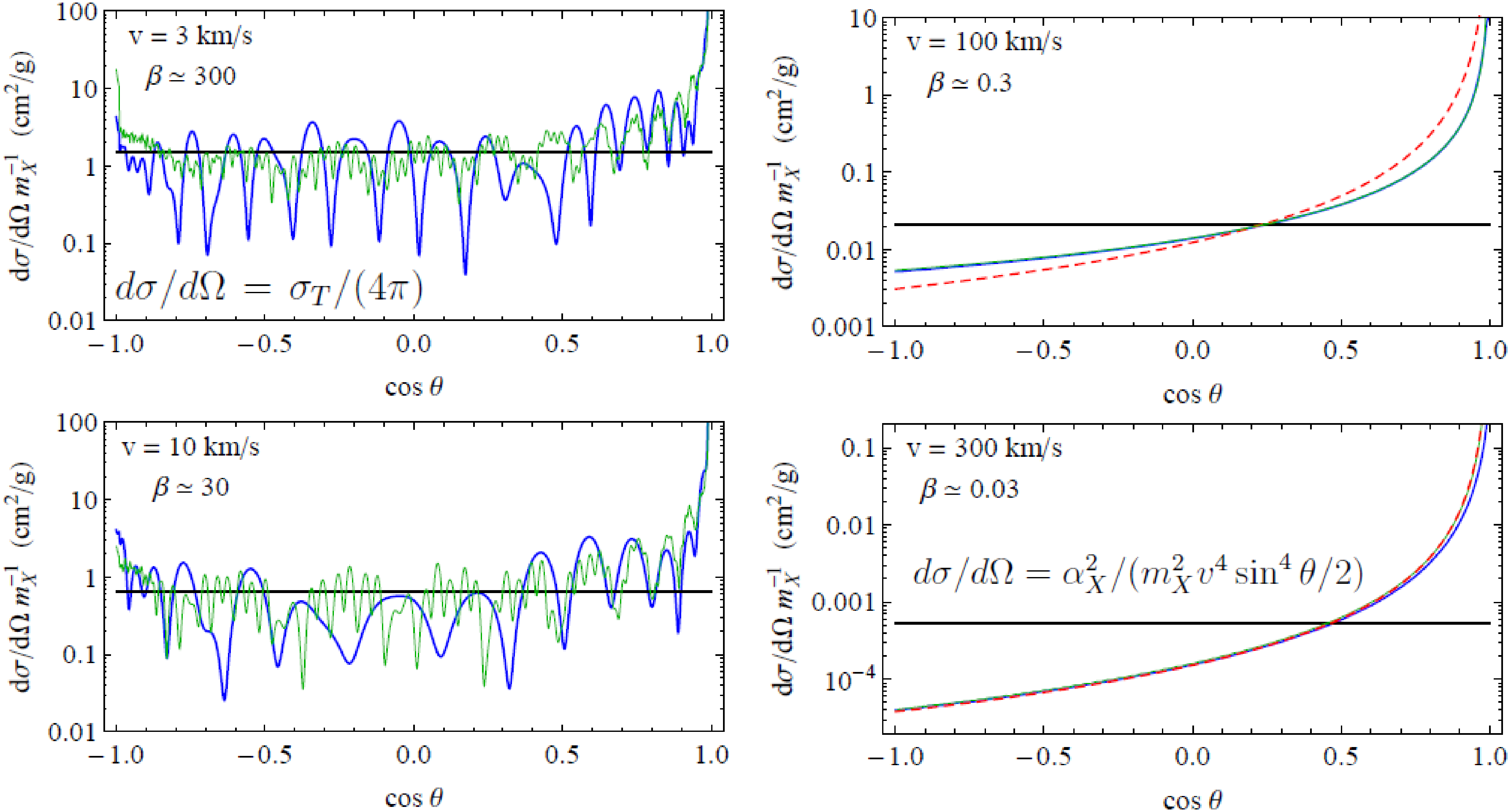
2. Angular dependence

- N-body simulations require probability to scatter with given angle θ

Need $d\sigma/d\Omega$, not just σ_T!

- N-body simulations assume isotropic scattering because angular dependence is unknown
  - Most relevant for simulations in classical regime by Vogelsberger et al, Zavala et al (2012)

2. Angular dependence



Isotropic at low velocity

Rutherford at high velocity

3. Resonant regime analytically

- New result for s-wave scattering
  - Approximation: Use Hulthen potential as proxy for Yukawa potential

$$V(r) = \pm \frac{\alpha_X \delta \, e^{-\delta r}}{1 - e^{-\delta r}} \qquad \delta \approx 1.6 m_\phi$$

  - Analytically solvable $\qquad \sigma_T^{\text{Hulthén}} = \frac{16\pi}{m_X^2 v^2} \sin^2 \delta_0$

$$\delta_0 = \arg\left(\frac{i\,\Gamma\left(\frac{i m_X v}{\kappa m_\phi}\right)}{\Gamma(\lambda_+)\Gamma(\lambda_-)} \right), \quad \lambda_\pm \equiv \begin{cases} 1 + \frac{i m_X v}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} - \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{attractive} \\ 1 + \frac{i m_X v}{2\kappa m_\phi} \pm i\sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} + \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{repulsive} \end{cases}$$

3. Resonant scattering analytically

Approximation for s-wave only scattering
Replace Yukawa → Hulthen potential

$$V(r) = \pm \frac{\alpha_X \delta \, e^{-\delta r}}{1 - e^{-\delta r}} \qquad \delta \approx 1.6 m_\phi$$

Compute s-wave phase shift analytically:

$$\delta_0 = \arg\left(\frac{i\,\Gamma\left(\frac{i m_X v}{\kappa m_\phi}\right)}{\Gamma(\lambda_+)\Gamma(\lambda_-)}\right), \quad \lambda_\pm \equiv \begin{cases} 1 + \frac{i m_X v}{2\kappa m_\phi} \pm \sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} - \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{attractive} \\ 1 + \frac{i m_X v}{2\kappa m_\phi} \pm i\sqrt{\frac{\alpha_X m_X}{\kappa m_\phi} + \frac{m_X^2 v^2}{4\kappa^2 m_\phi^2}} & \text{repulsive} \end{cases}$$

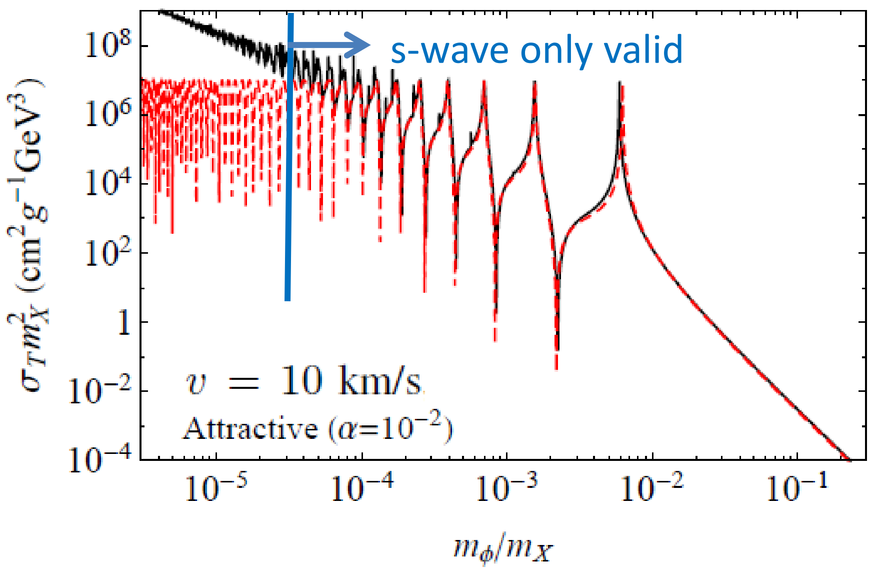
Quantum mechanical resonances = poles in Γ-function

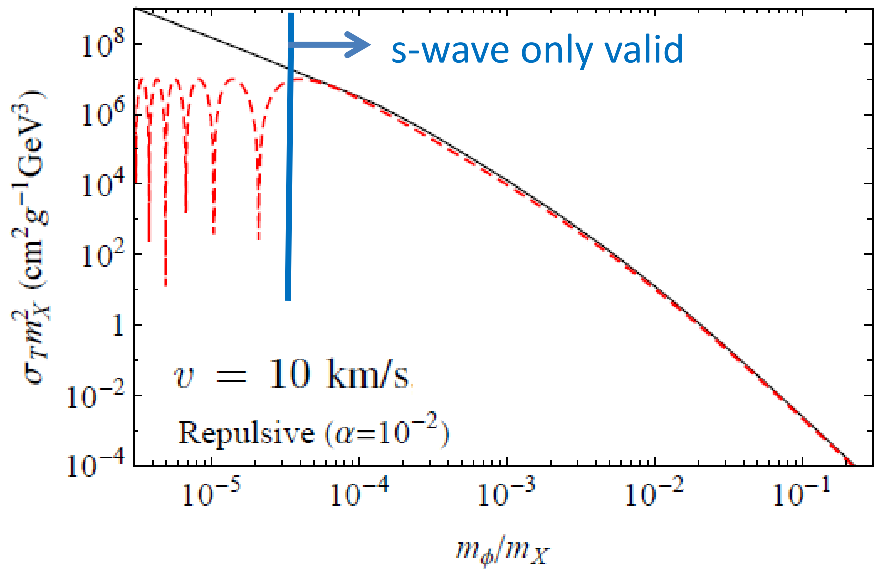
3. Resonant scattering analytically

Approximation for s-wave only scattering

Replace Yukawa → Hulthen potential

$$V(r) = \pm \frac{\alpha_X \delta\, e^{-\delta r}}{1 - e^{-\delta r}} \qquad \delta \approx 1.6 m_\phi$$

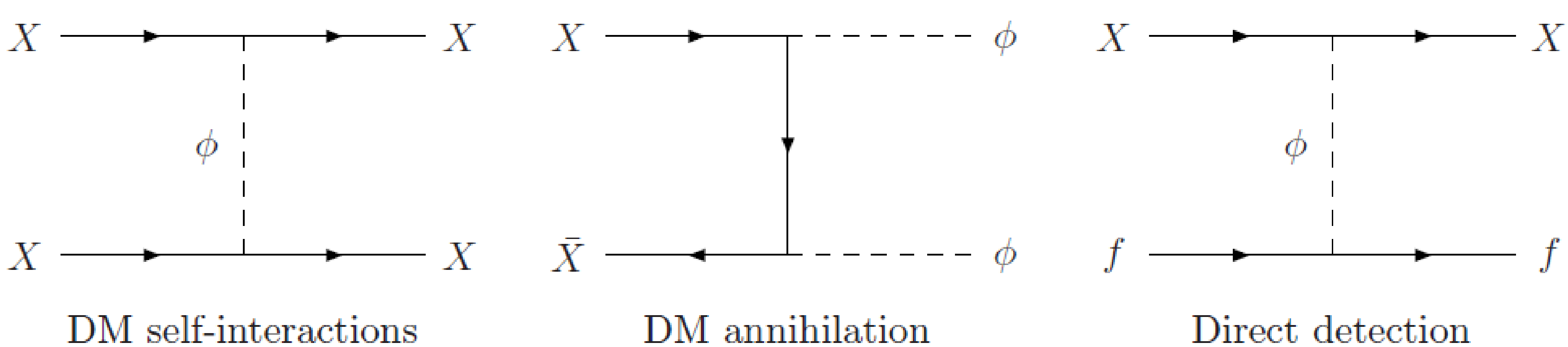




Red = analytic, black = numerical

Consistent picture of SIDM

- Self-interactions
- Relic density (& indirect detection)
- Direct detection



Direct detection rate

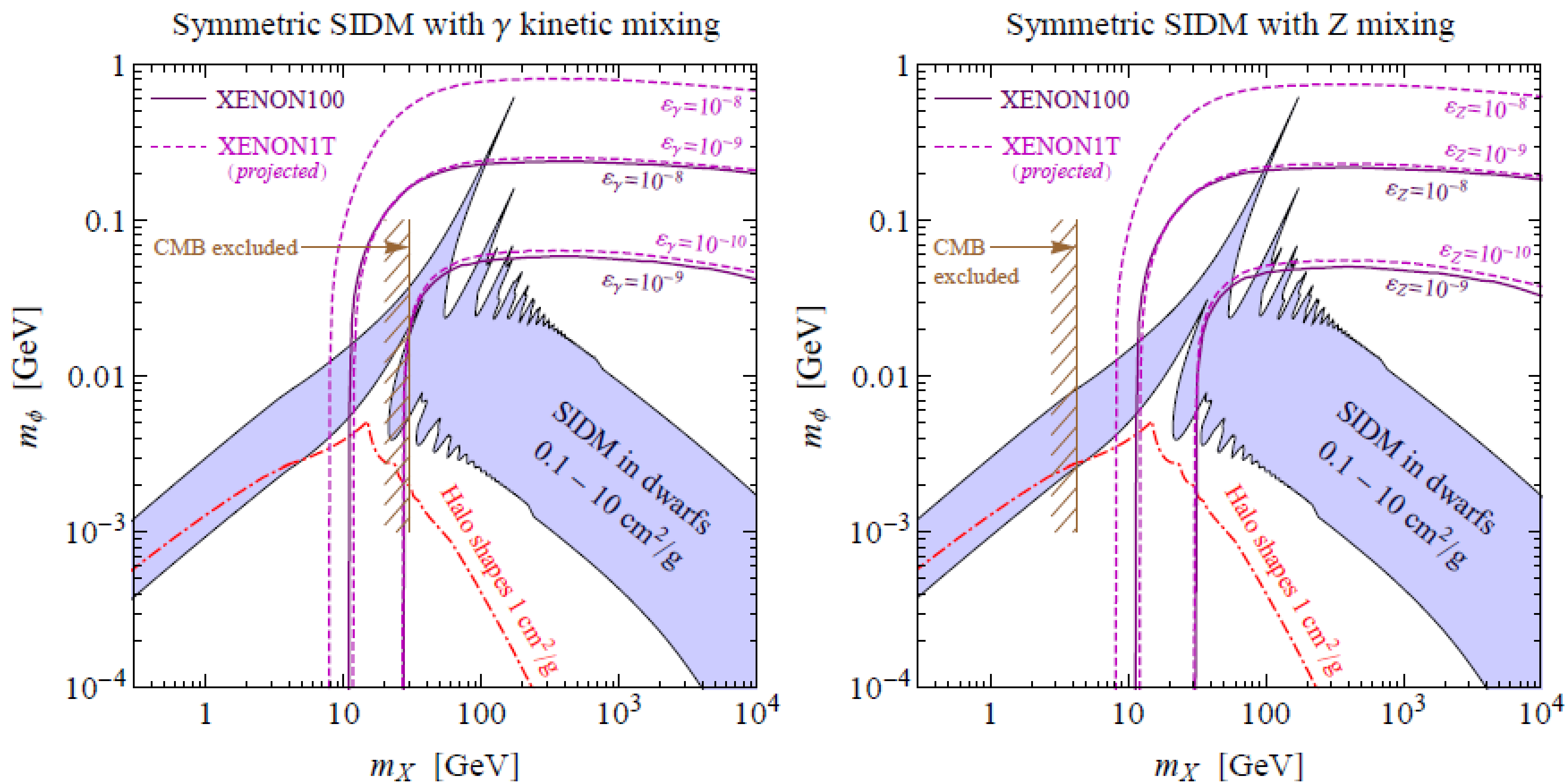
Direct detection has dependence on momentum transfer (not a contact interaction)

$$\frac{dR}{dE_R} = \frac{\rho_{\rm DM}}{m_X}\int_{v_{\rm min}} d^3v\, v\, f(\vec{v})\, \frac{d\sigma^{\rm SI}_{XN}(v,E_R)}{dE_R}$$
$$= \frac{\rho_{\rm DM}}{m_X}\int_{v_{\rm min}} d^3v\, v\, f(\vec{v})\, \left(\frac{d\sigma^{\rm SI}_{XN}(v,E_R)}{dE_R}\right)_{q^2=0} \times \frac{m_\phi^4}{(m_\phi^2+q^2)^2}$$

Momentum transfer $q = \sqrt{2m_N E_R} \sim$ 50 MeV $\sim m_\phi$

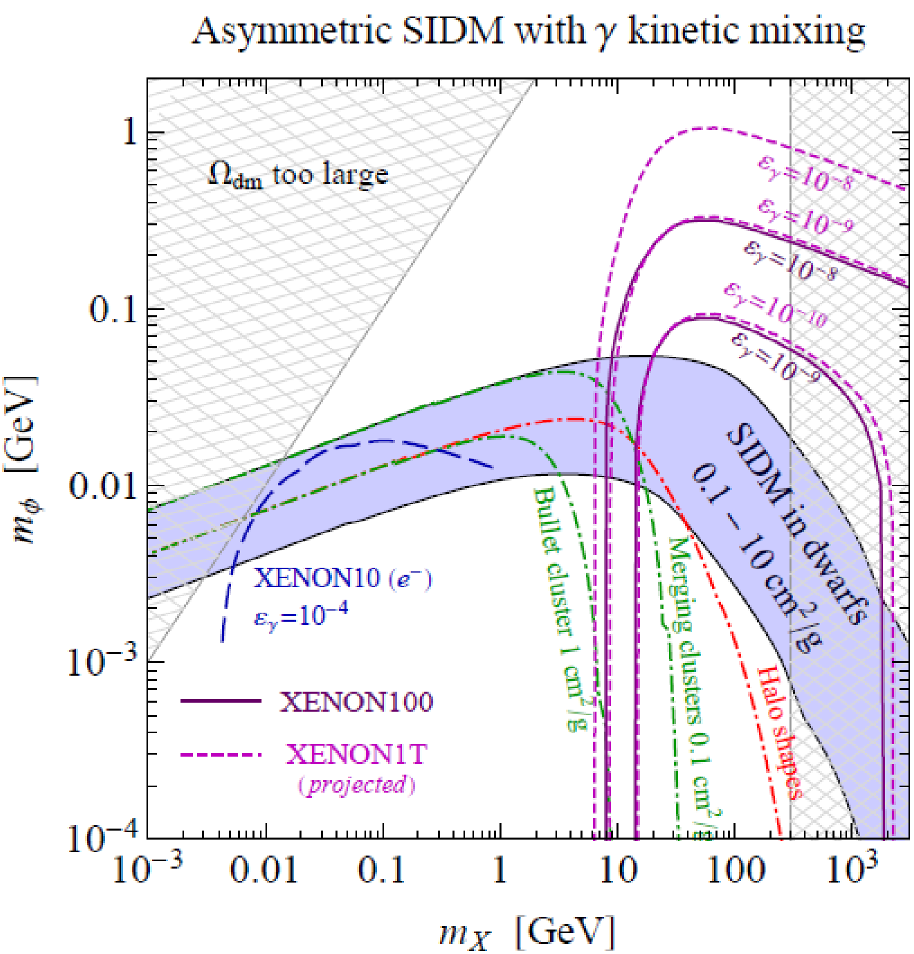
- Low energy threshold and lighter nuclei better for SIDM
- Heuristic approach: take fixed q and rescale direct detection sensitivity by this form factor

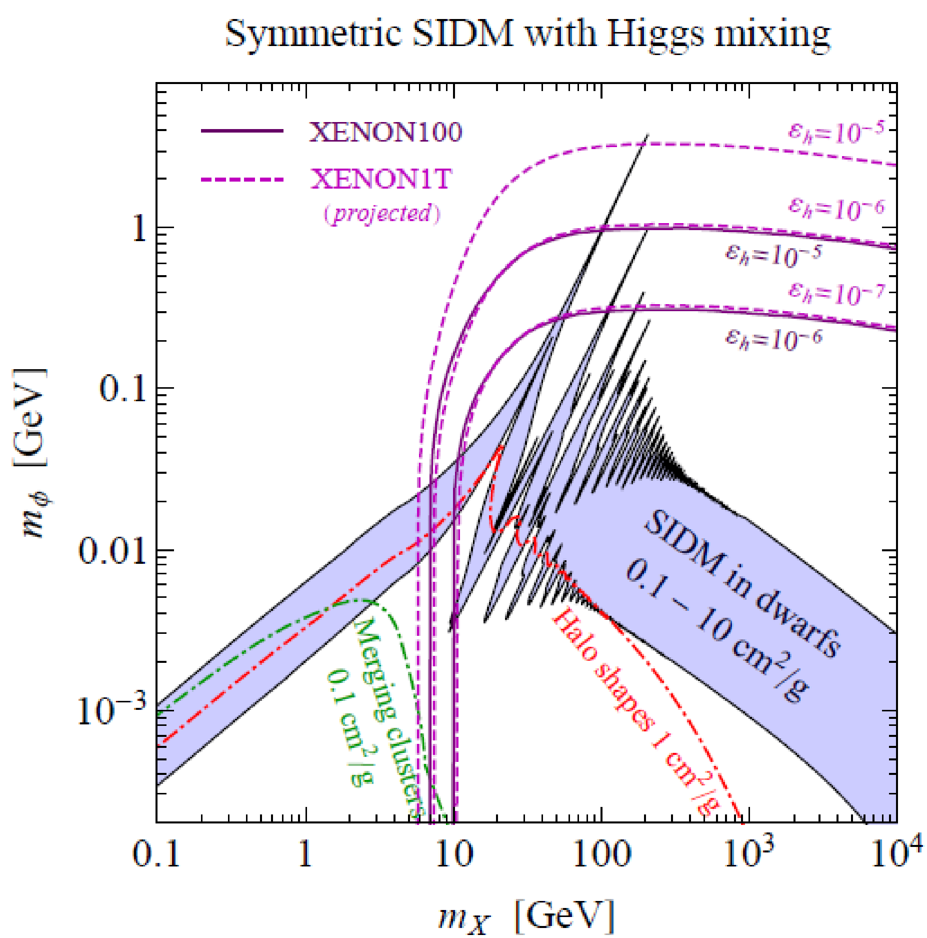
Symmetric SIDM with vector mediator



Kaplinghat, ST, Yu (2013)

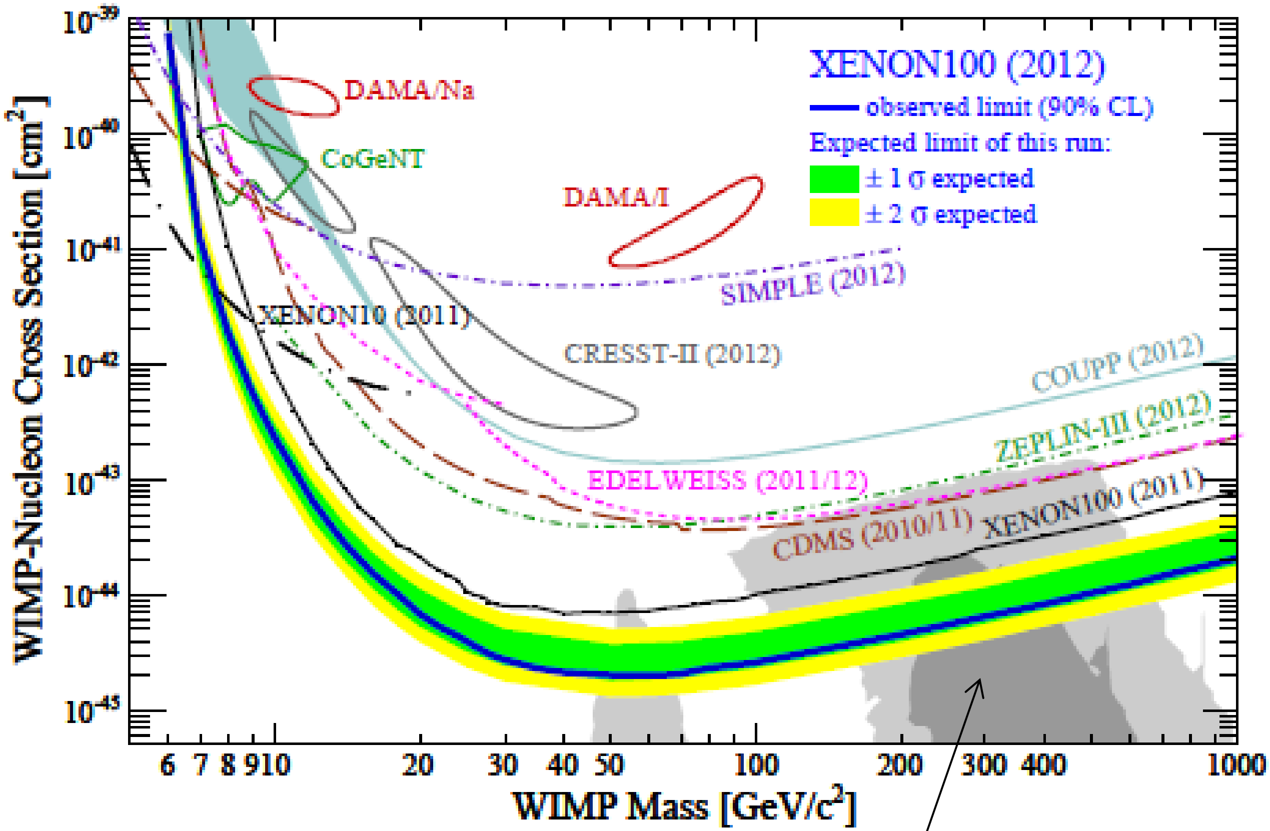
Asymmetric SIDM or scalar mediator





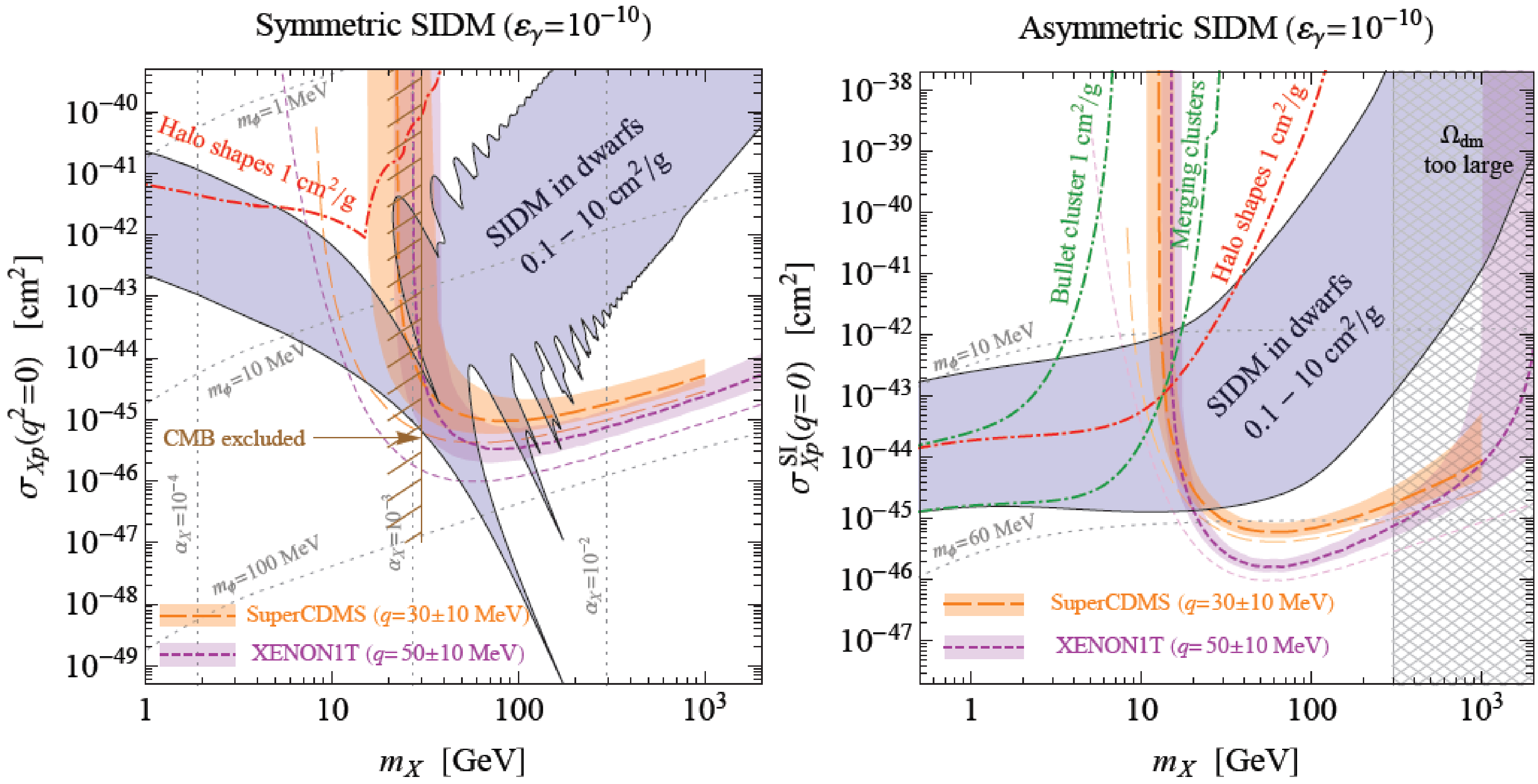
Kaplinghat, ST, Yu (2013)

Direct detection



Benchmarks from SUSY
Why should SUSY get all the attention?

SIDM benchmarks for direct detection



Kaplinghat, ST, Yu (2013)

Conclusions (part 1)

- Simplified model: DM χ + mediator ϕ
- Anomalies on dwarf scales: $m_\phi \sim 1 - 100$ MeV
- Although SIDM may be decoupled from direct detection, expect DM-SM coupling at some level
- Light mediator means direct detection sensitive to **very** small DM-SM couplings

Conclusions (part 2)

- Current direct detection not sensitive down to BBN limit ($\phi \rightarrow$ SM ~ 1 second)
- Ton-scale experiments will explore ~entire range above ~20 GeV

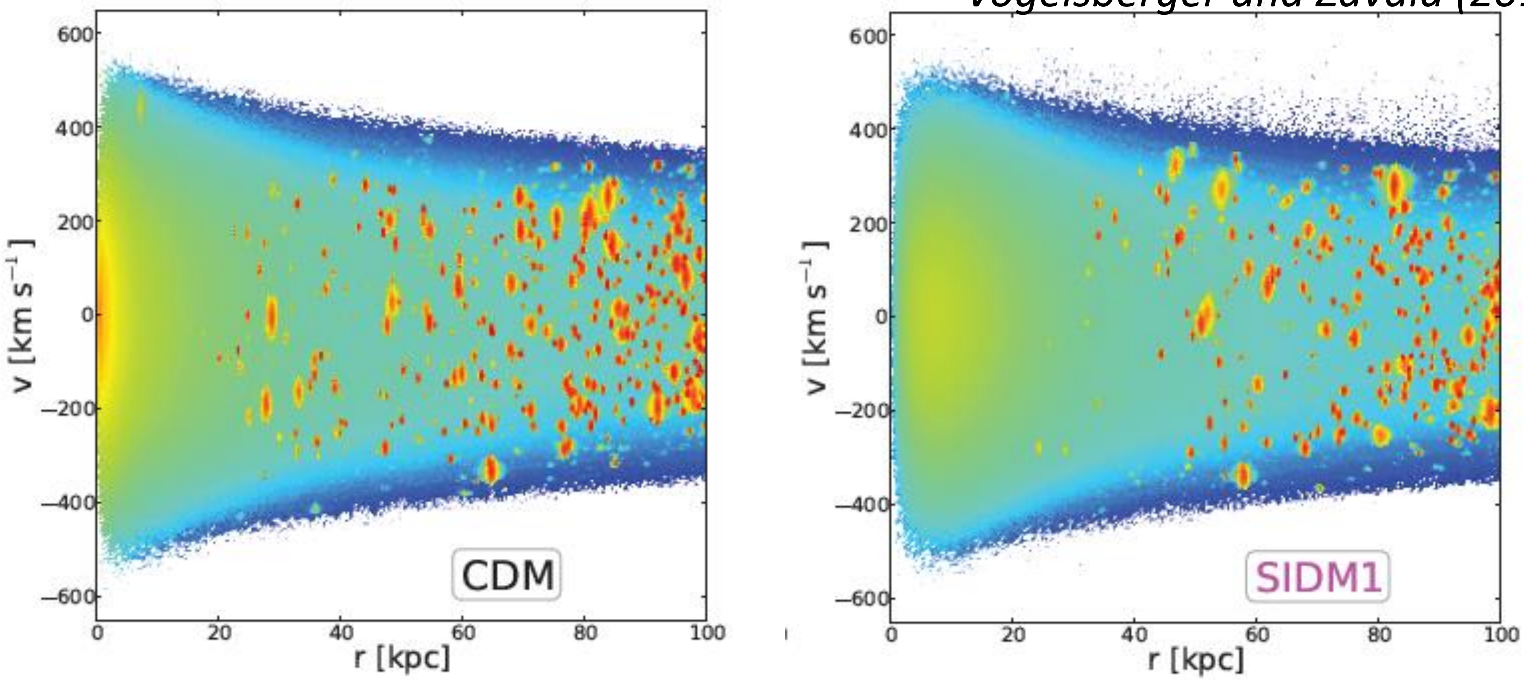
- Direct detection complementary to astrophysics
  - Constraints on large scales (e.g. Bullet Cluster) constrain SIDM at low DM mass (constant σ)
  - Direct detection constrain SIDM at WIMP-scale masses (corresponding to v-dependent σ)

Backup

SIDM and direct detection

Self-interactions change phase space distribution of DM halo

Vogelsberger and Zavala (2012)



O(10%) effect on DM recoil rate in direct detection experiments
Also effect annnual modulation amplitude and phase