Atomic Dark Matter

Keith Rehermann

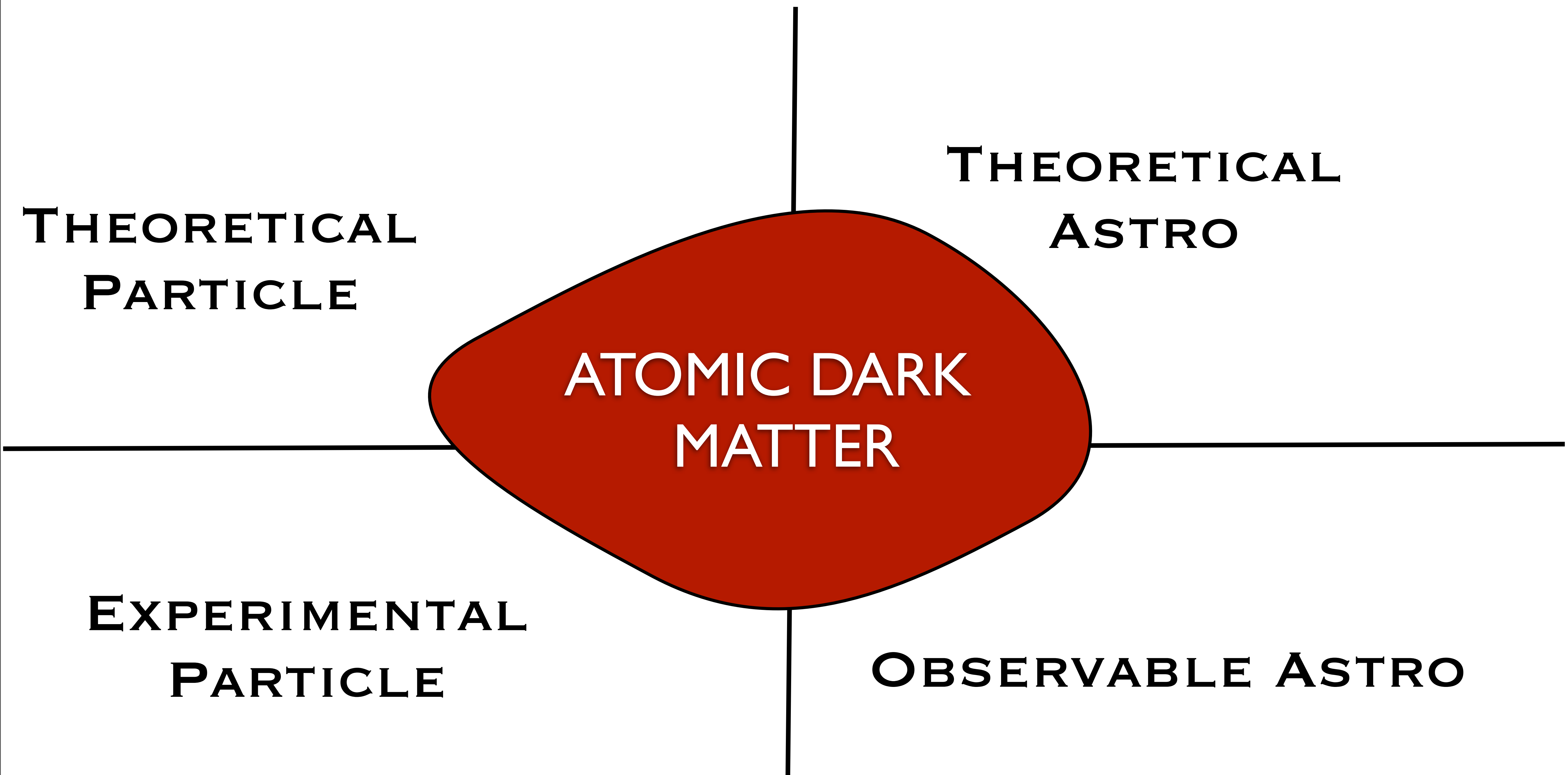
W/ DE Kaplan, C Wells, & G Krnjaic

Atomic Dark Matter

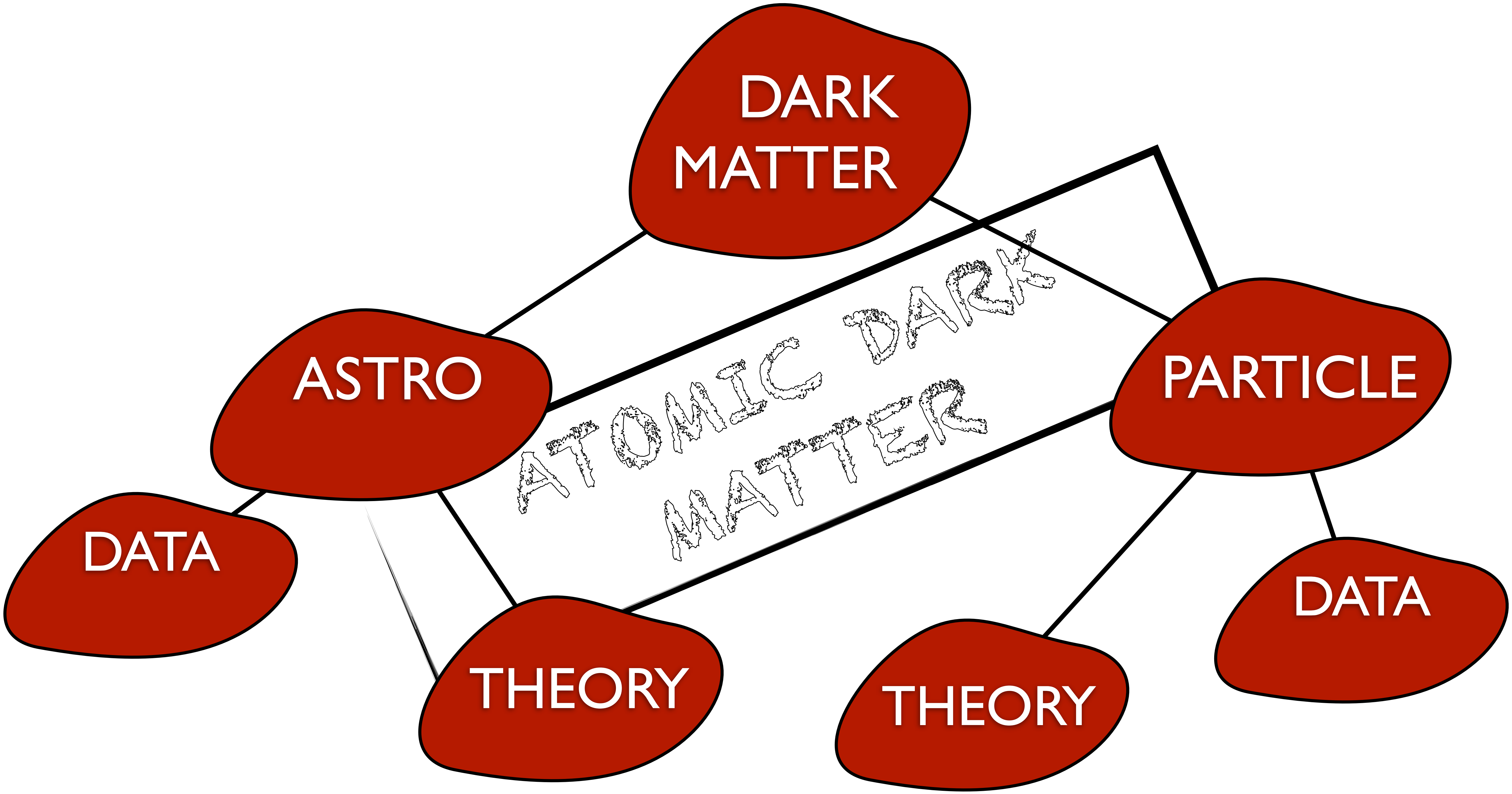
Keith Rehermann

W/ DE Kaplan, C Wells, & G Krnjaic

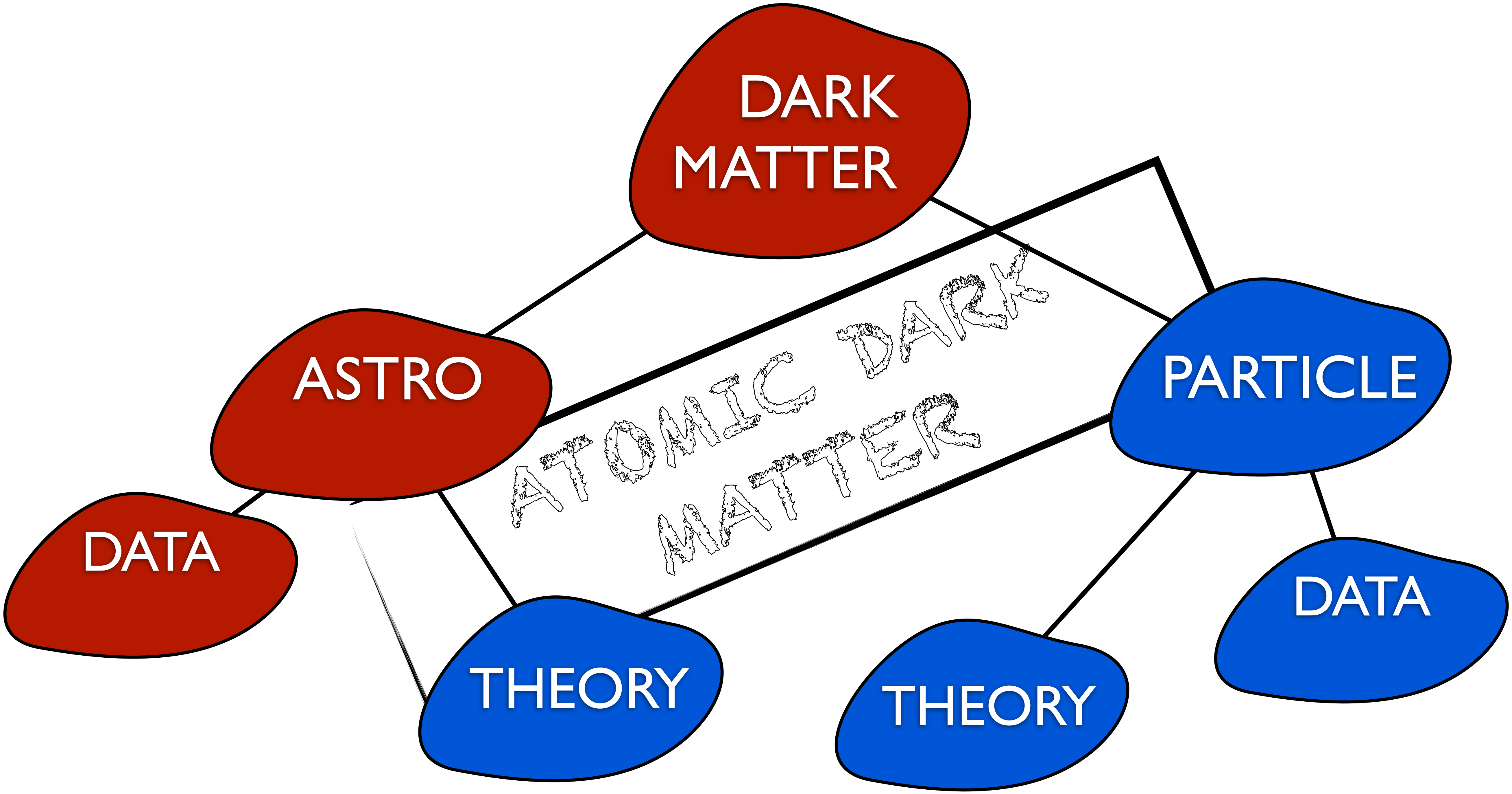
THEME: AtDM Implies Interesting Physics on Many Scales



This Diagram Will Guide Talk

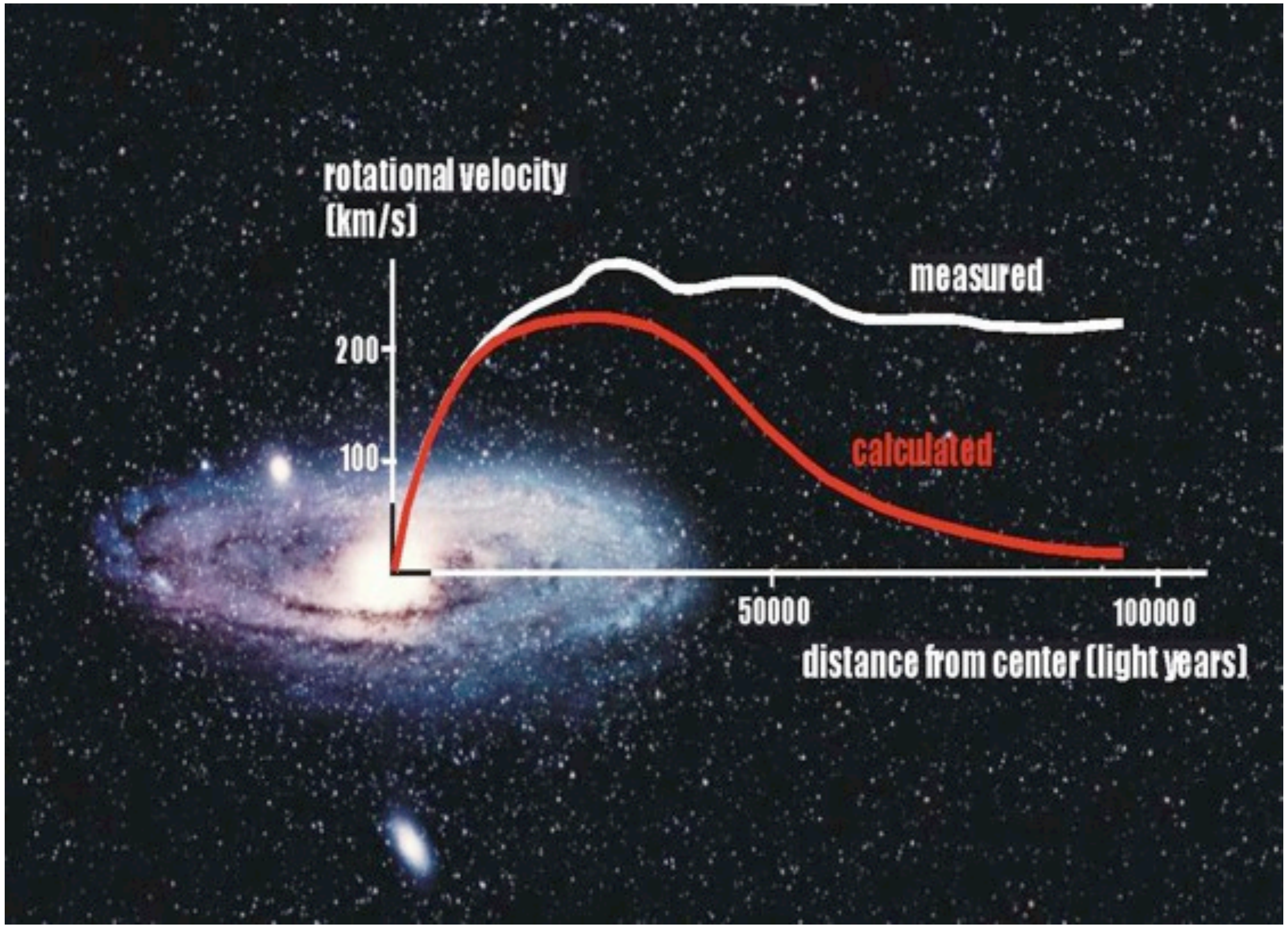


Let's Talk About Well Known Data



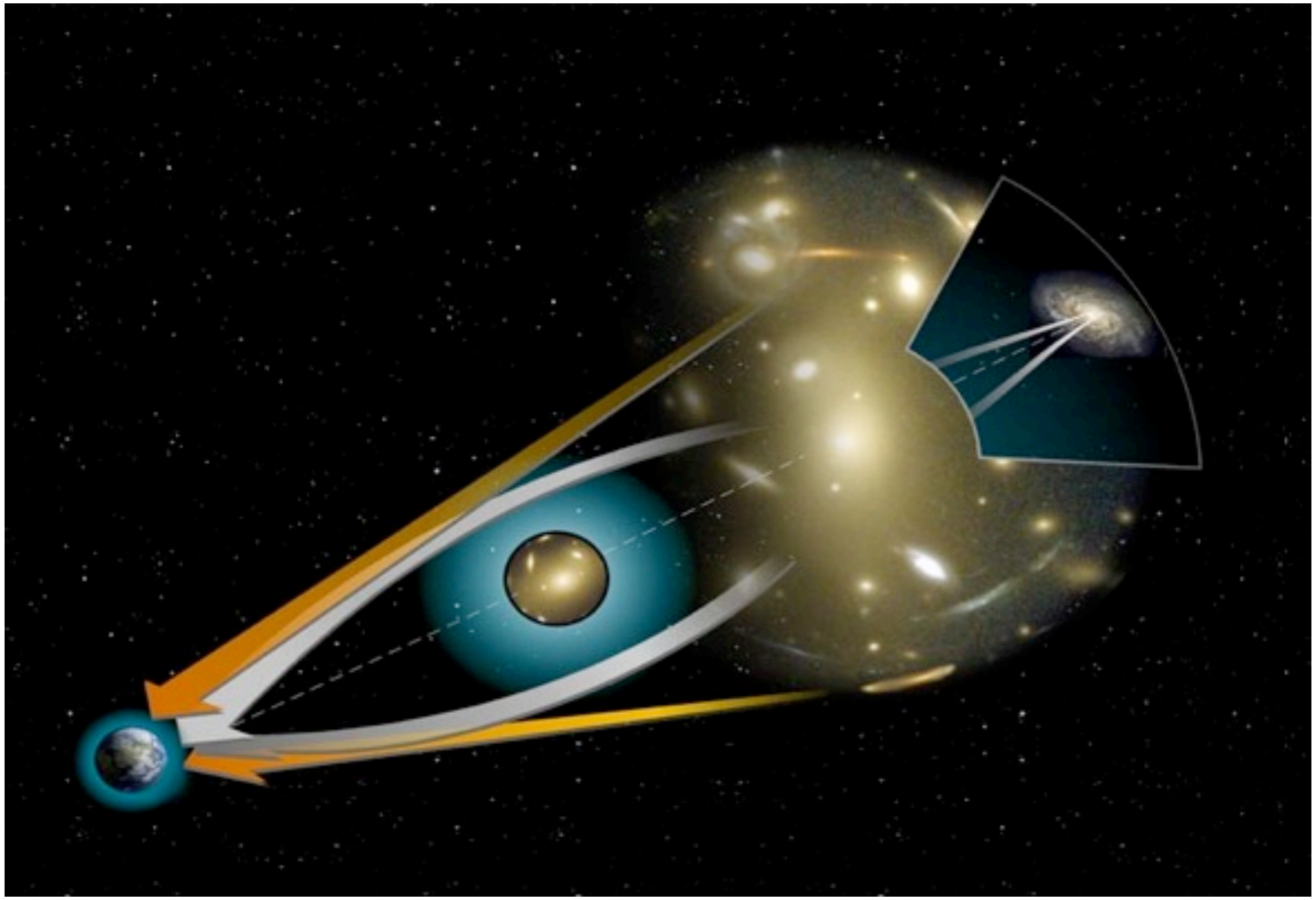
Galactic Rotation Curves Suggest Missing Mass Density

- Rotational Velocity Curves Suggest a Dark Matter Halo in which the Luminous Matter in embedded



Gravitational Lensing Observations Suggest Miss Mass Density

- Light From Distance Sources is Deflected too much given Mass Estimates From Luminous Density

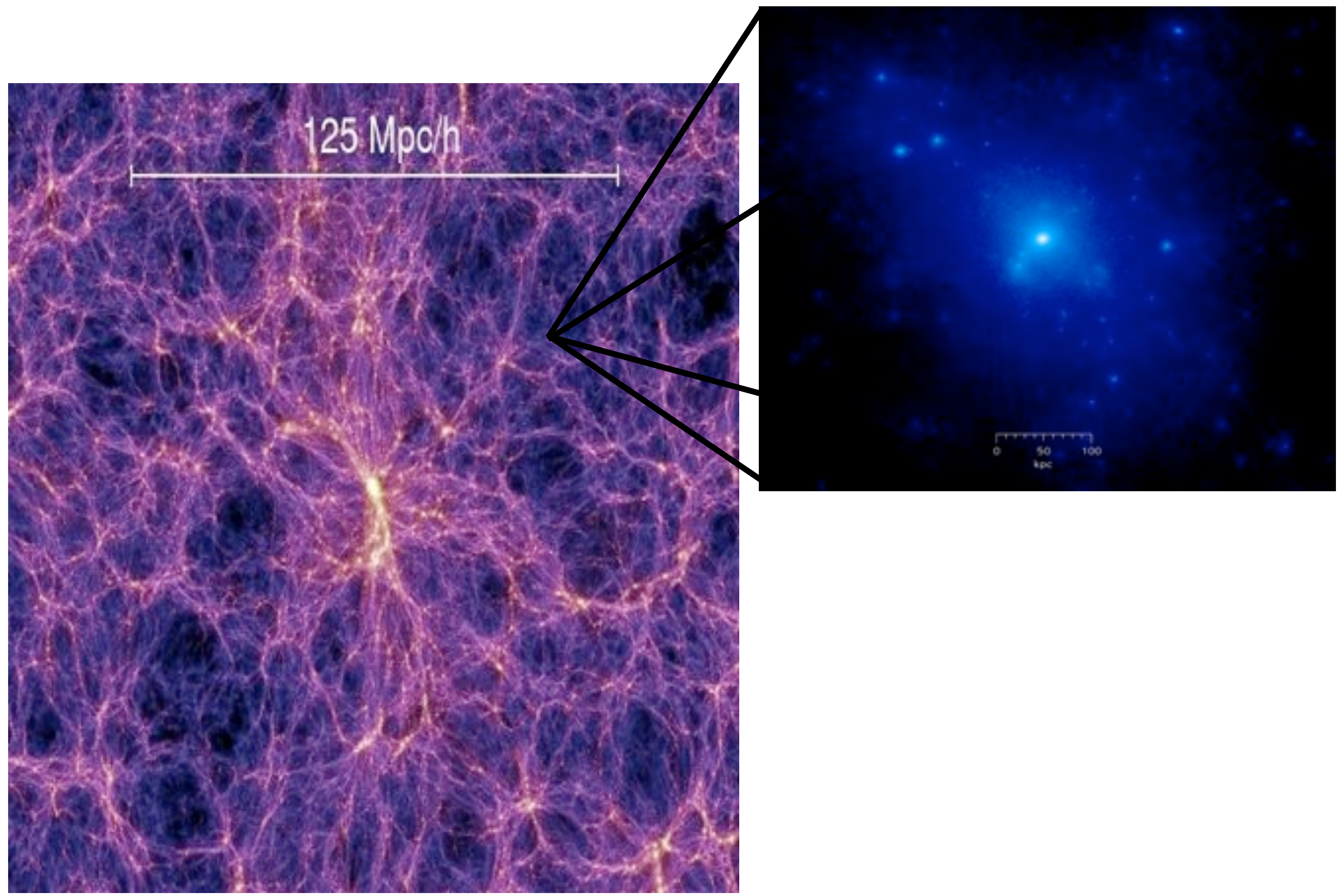


Bullet Cluster: Luminous and Non-Luminous Matter Have Different Interactions

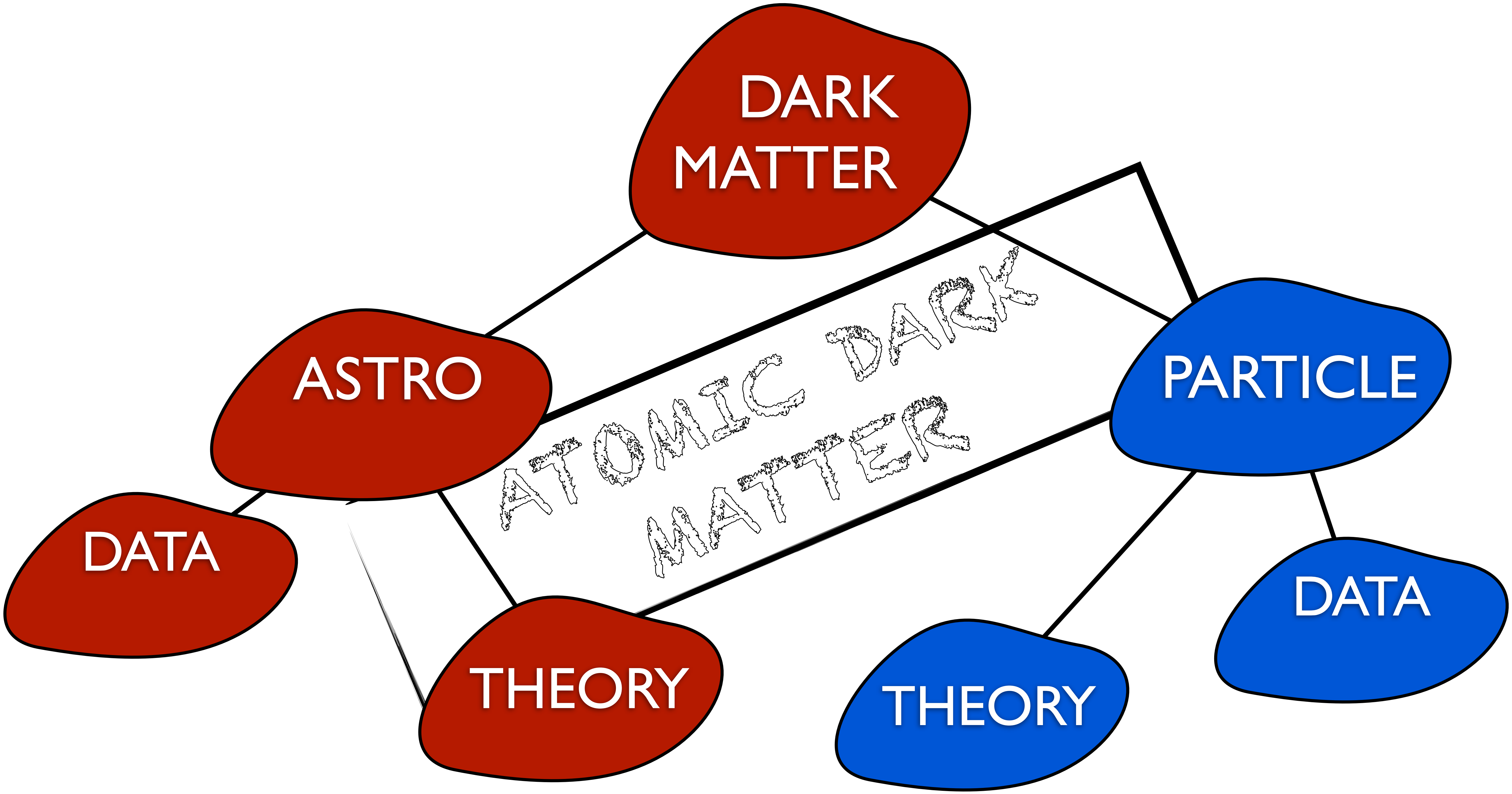
- UV Imaging and Gravitational Lensing Show Mis-Match between Mass Centers and Luminous Material in Cluster-Cluster Collision

Clustering Observations Suggest Extra Source of Gravitational Potential

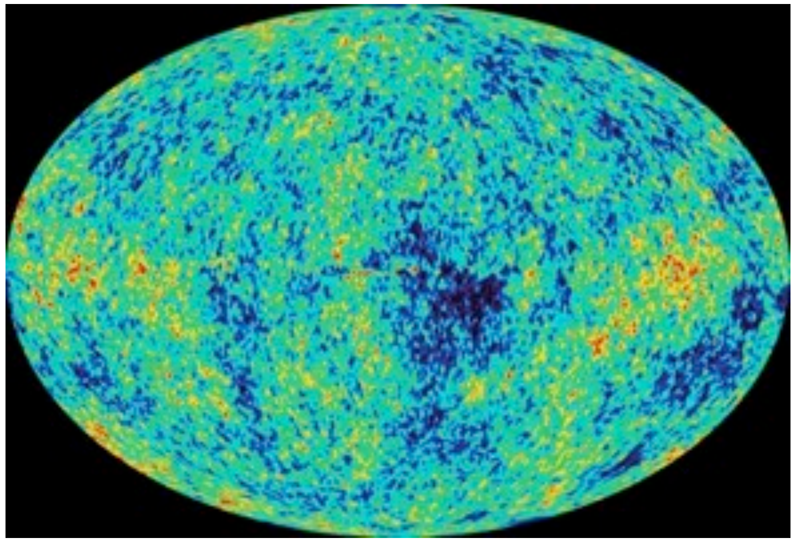
- Structure on scales from Galaxies to Cluster of Galaxies Suggest Are not well described by SM physics



Sprinkle In Some Theory

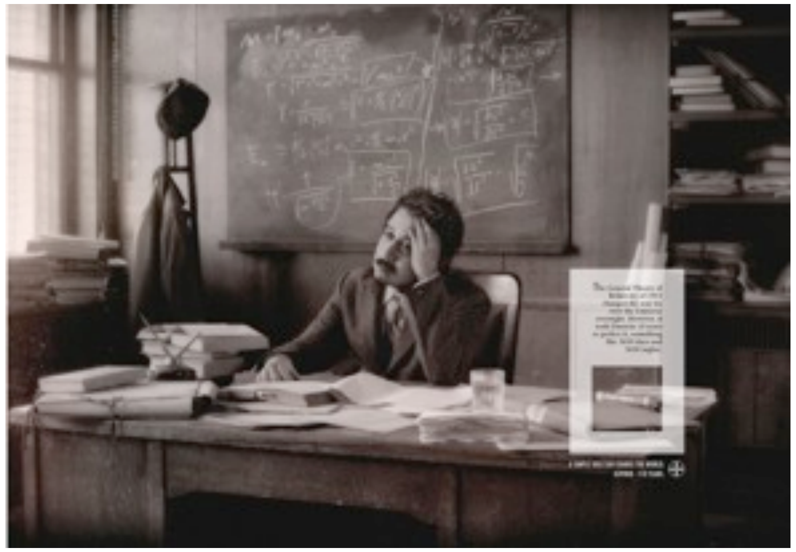


CMB & SN Ia Data Measure Energy Density Fractions

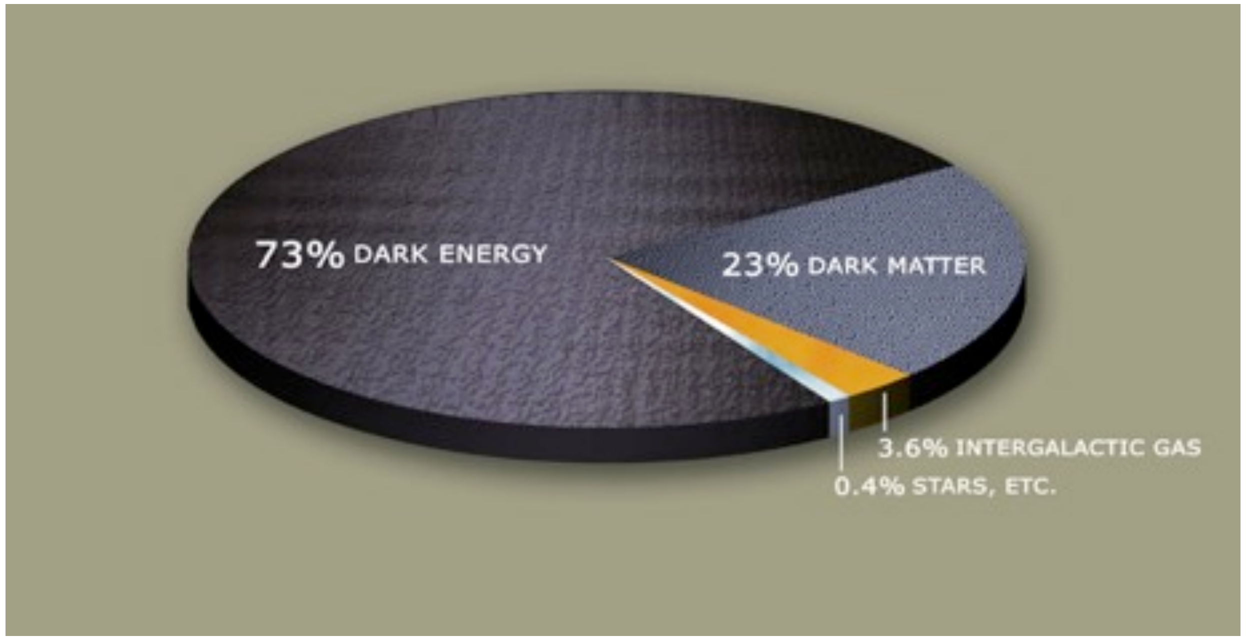


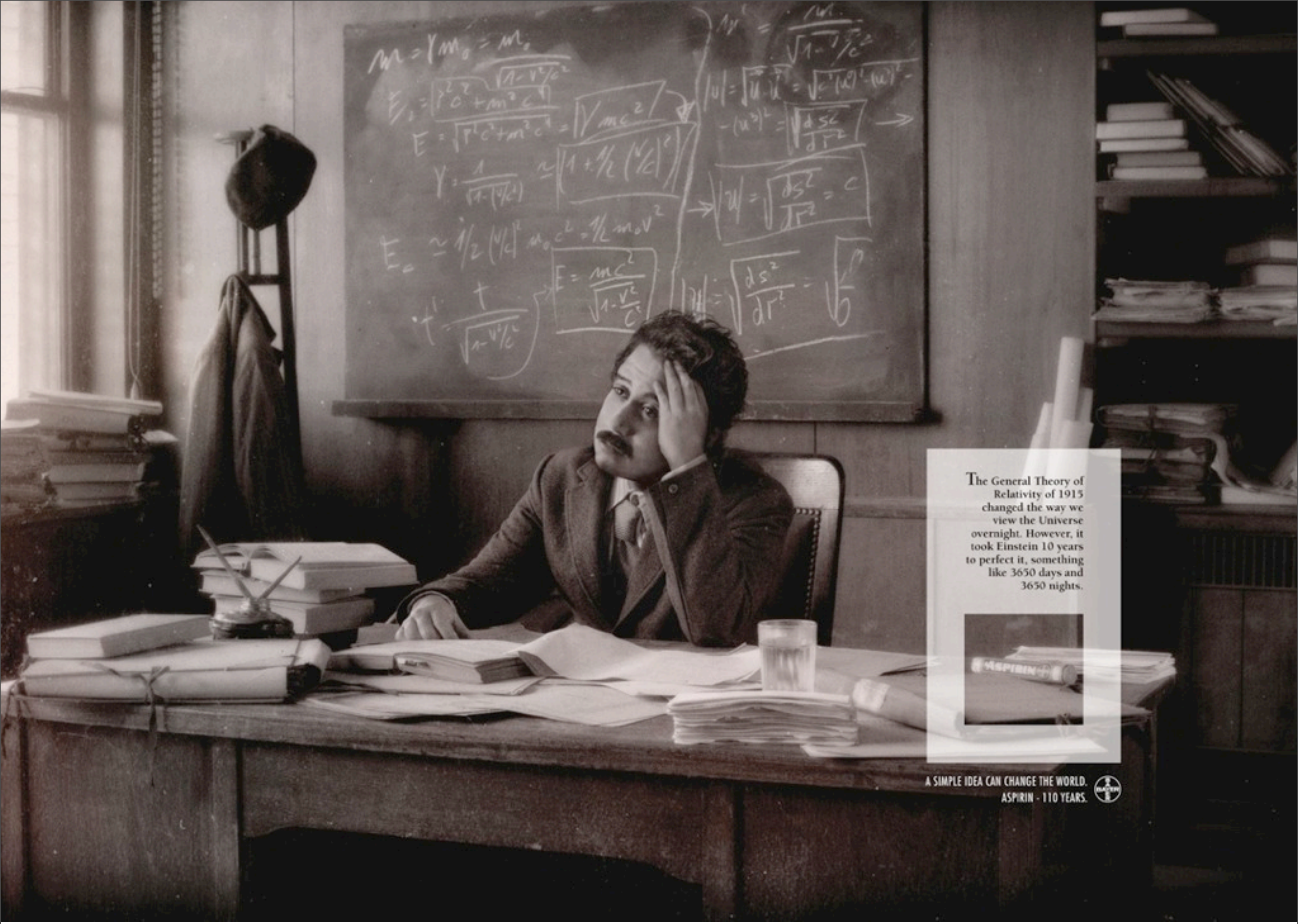
+

+

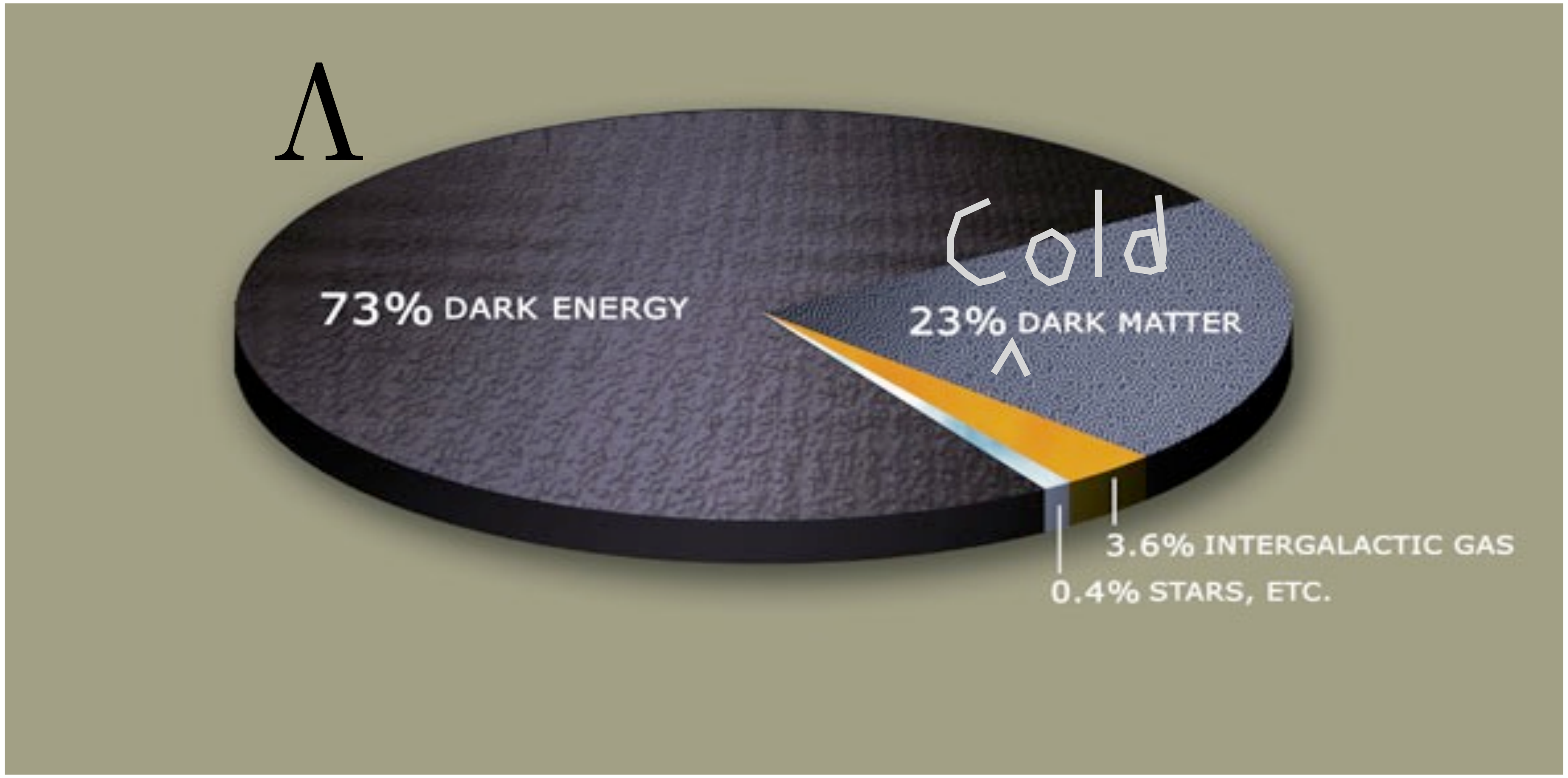


$\Longrightarrow$

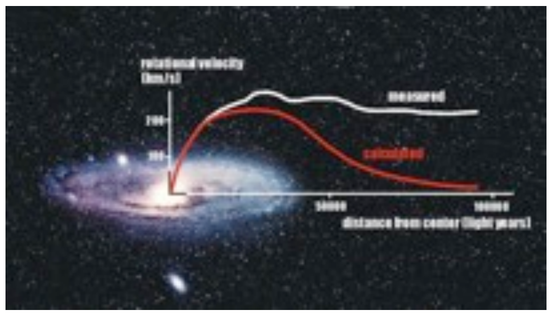



The General Theory of Relativity of 1915 changed the way we view the Universe overnight. However, it took Einstein 10 years to perfect it, something like 3650 days and 3650 nights.
ASPIRIN
A SIMPLE IDEA CAN CHANGE THE WORLD.
ASPIRIN - 110 YEARS.

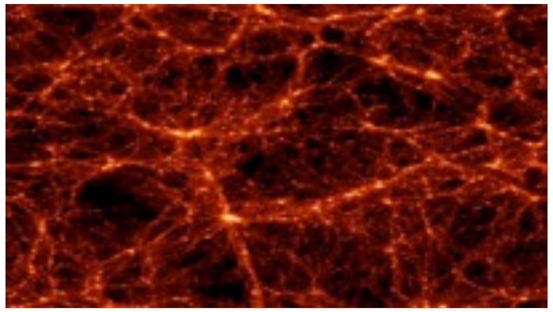
Standard Model of Cosmology is ΛCDM



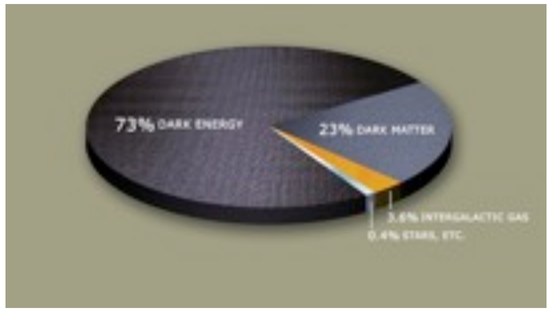
Data Constrain Particle Physics



$\longrightarrow$ *DM Electrically Neutral*

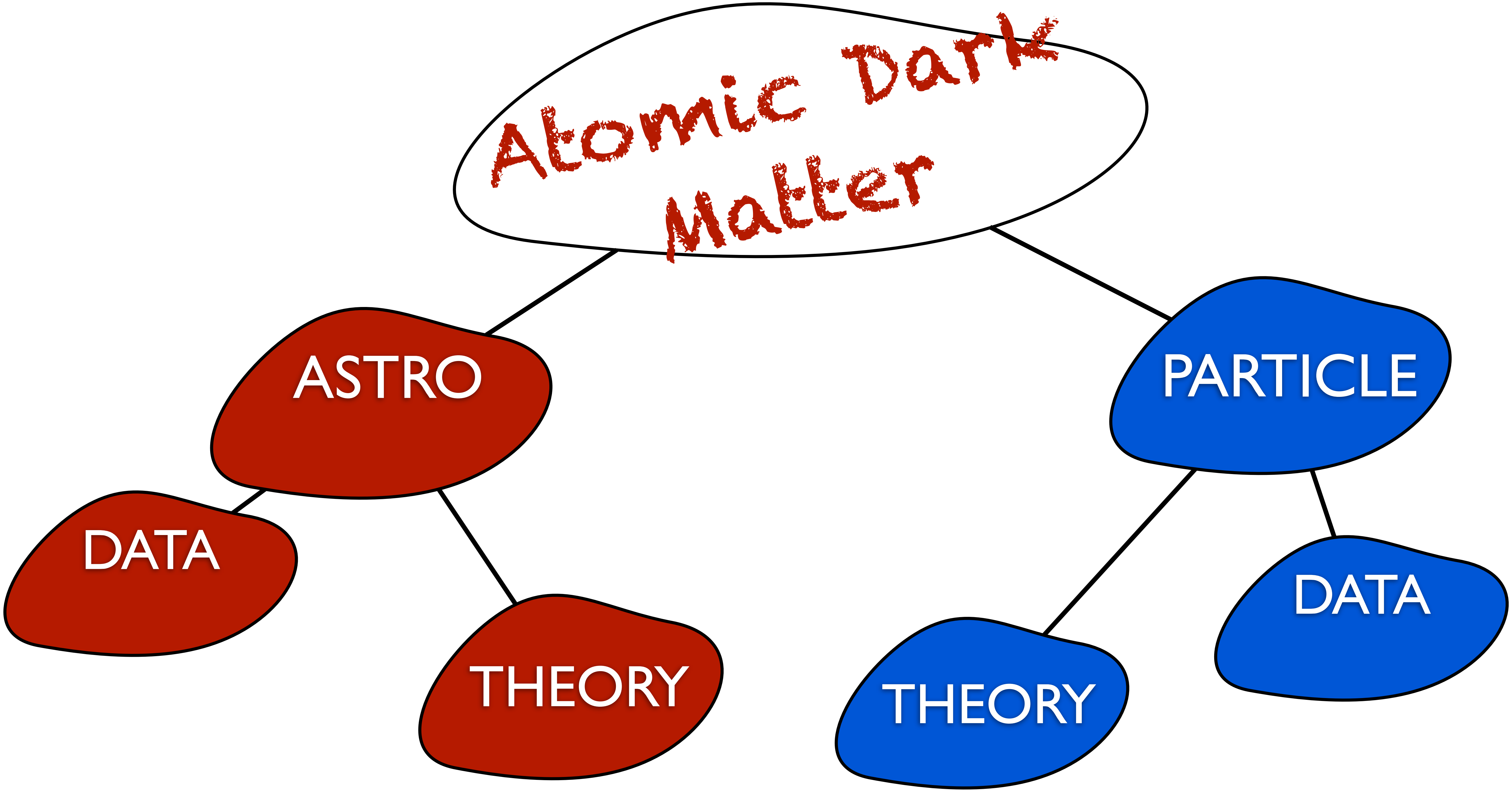


$\longrightarrow$ *Small Self-Interaction Cross Section*



$\longrightarrow < \sigma v >_{\rm ann} \approx 10^{-26}{\rm cm}^2$ *-OR- Non-Thermal*

Astrophysics of Atomic Dark Matter



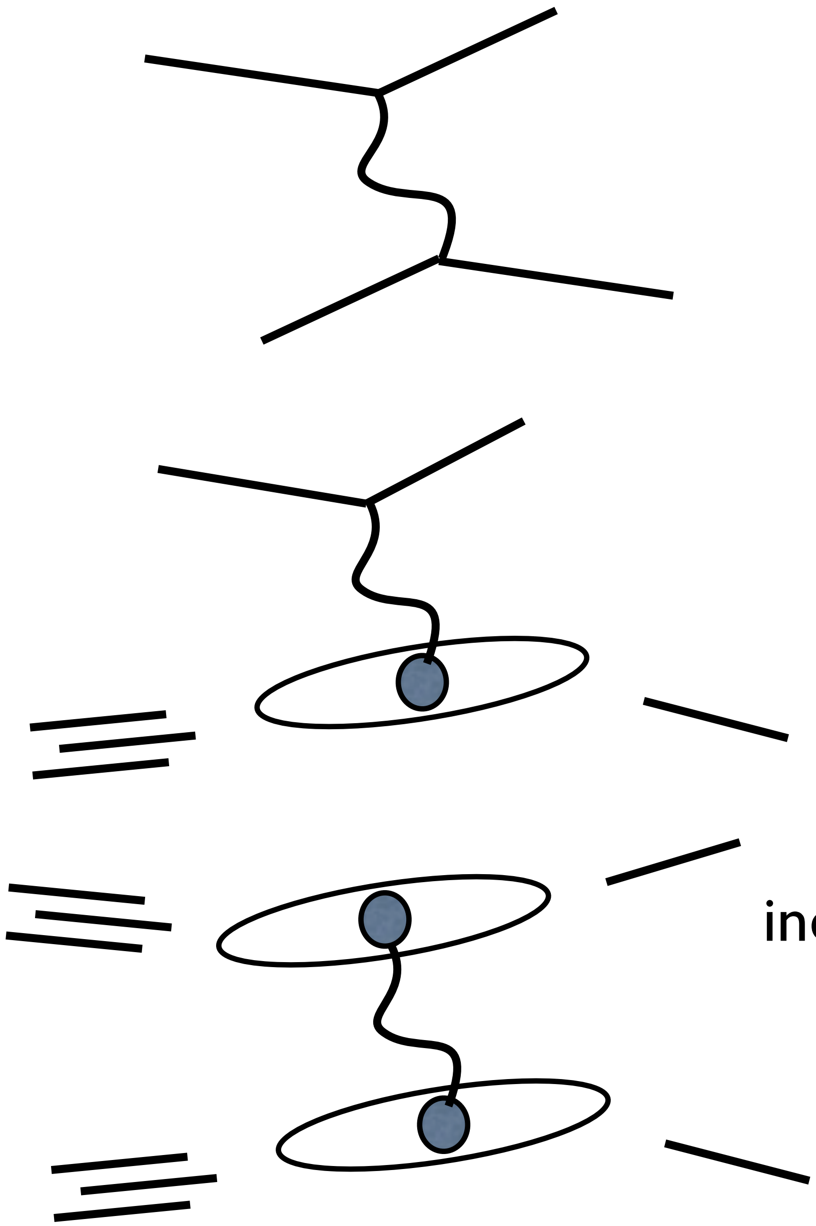
Atomic Dark Matter is Simple

$$\mathcal{L}_{dark} = \overline{\Psi}_{\mathbf{p}}(\not{D} + m_{\mathbf{p}})\Psi_{\mathbf{p}} + \overline{\Psi}_{\mathbf{e}}(\not{D} + m_{\mathbf{e}})\Psi_{\mathbf{e}}$$

$$\not{D} = i\not{\partial} + gQ\not{A} \qquad Q_{\Psi_{\mathbf{p}},\Psi_{\mathbf{e}}} = +1, -1$$

- For now asymmetry is assumed

Can Atomic Dark Matter Be “Cold”?



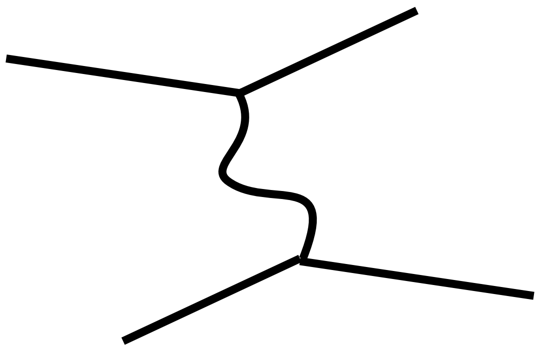
charge-charge →

charge-induced dipole →

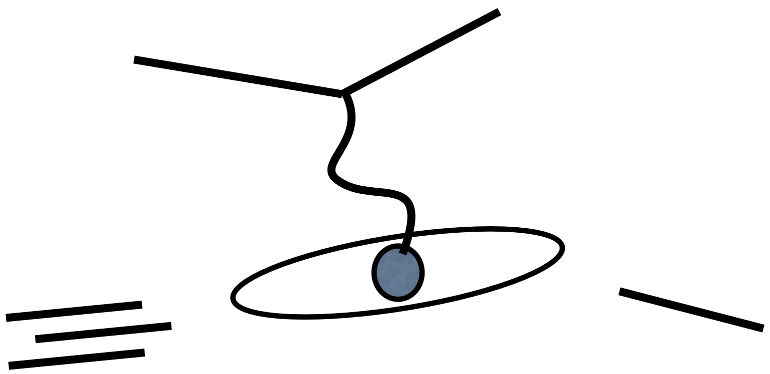
induced dipole-induced dipole →

V(r)	$\frac{d\sigma}{d\Omega}$
~ 1/r	$\frac{1}{E_{cm}^2 \sin^4 \theta/2}$
~ C/r^4	$(\kappa\, a_0)^2$
~ A/r^6	$(\kappa'\, a_0)^2$

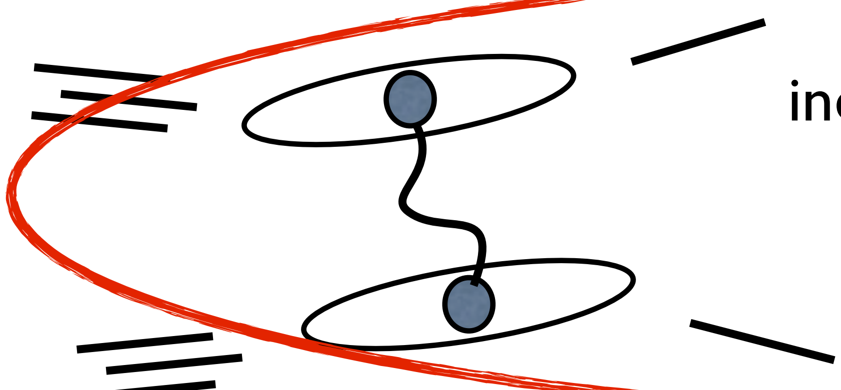
Can Atomic Dark Matter Be "Cold"?



charge-charge →



charge-induced dipole →



induced dipole-induced dipole →

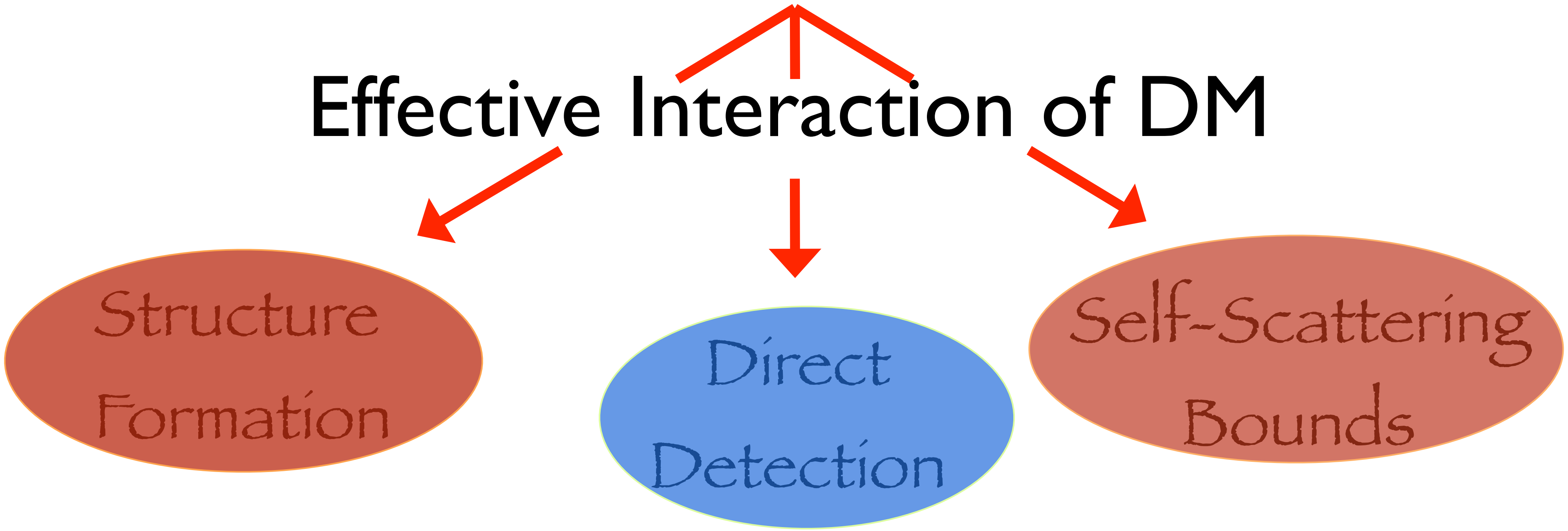
V(r)	$\frac{d\sigma}{d\Omega}$
- 1/r	$\frac{1}{E_{cm}^2 \sin^4 \theta/2}$
- C/r^4	$(\kappa\, a_0)^2$
- A/r^6	$(\kappa'\, a_0)^2$

$$\frac{d\sigma}{d\Omega} \to \text{cnst : reminiscent of s} - \text{wave scattering}$$

Residual Ionization is Key to Cosmological Dynamics

$$X_{\mathrm{e}} \equiv \frac{n_{\mathrm{e}}}{n_{\mathrm{e}} + n_{\mathrm{H}}}$$

Peebles ApJ 153, p.1



“Re”combination is Analogous to SM

Peebles ApJ 153, p.1
Dodelson ‘03
Spitzer ‘78
Ma & Bertschinger
astro-ph/9506072

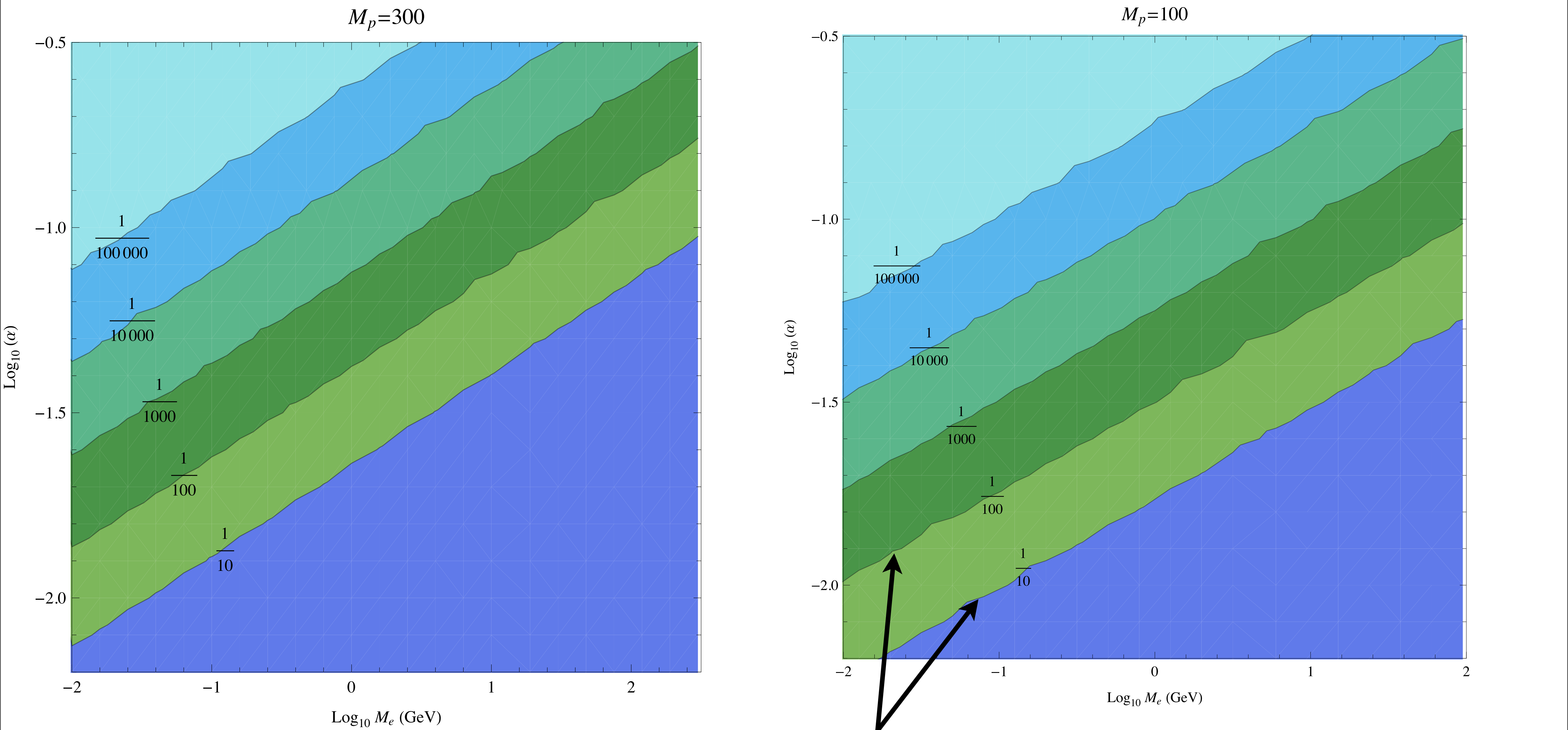
$$\mathbf{e} + \mathbf{p} \leftrightarrow \mathbf{H} + \gamma$$

Recombination governed by Boltzmann

$$\frac{dX_{\mathbf{e}}}{dx} = C\frac{1}{Hx}\left[(1 - X_{\mathbf{e}})\beta - X_{\mathbf{e}}^2 n_{DM}\langle\sigma v\rangle\right]$$

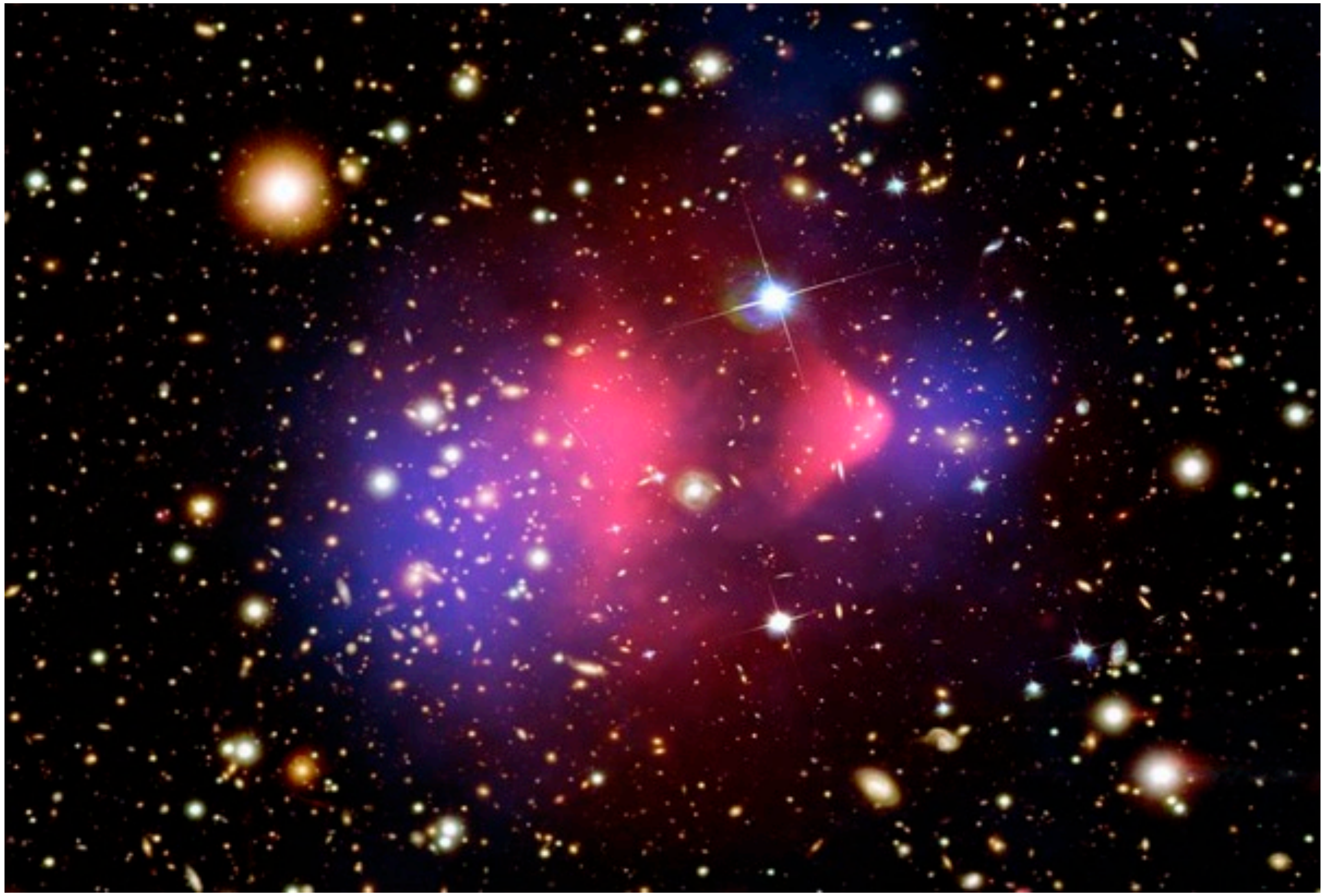
Atomic disintegration   Atom production

Efficient Atom Production

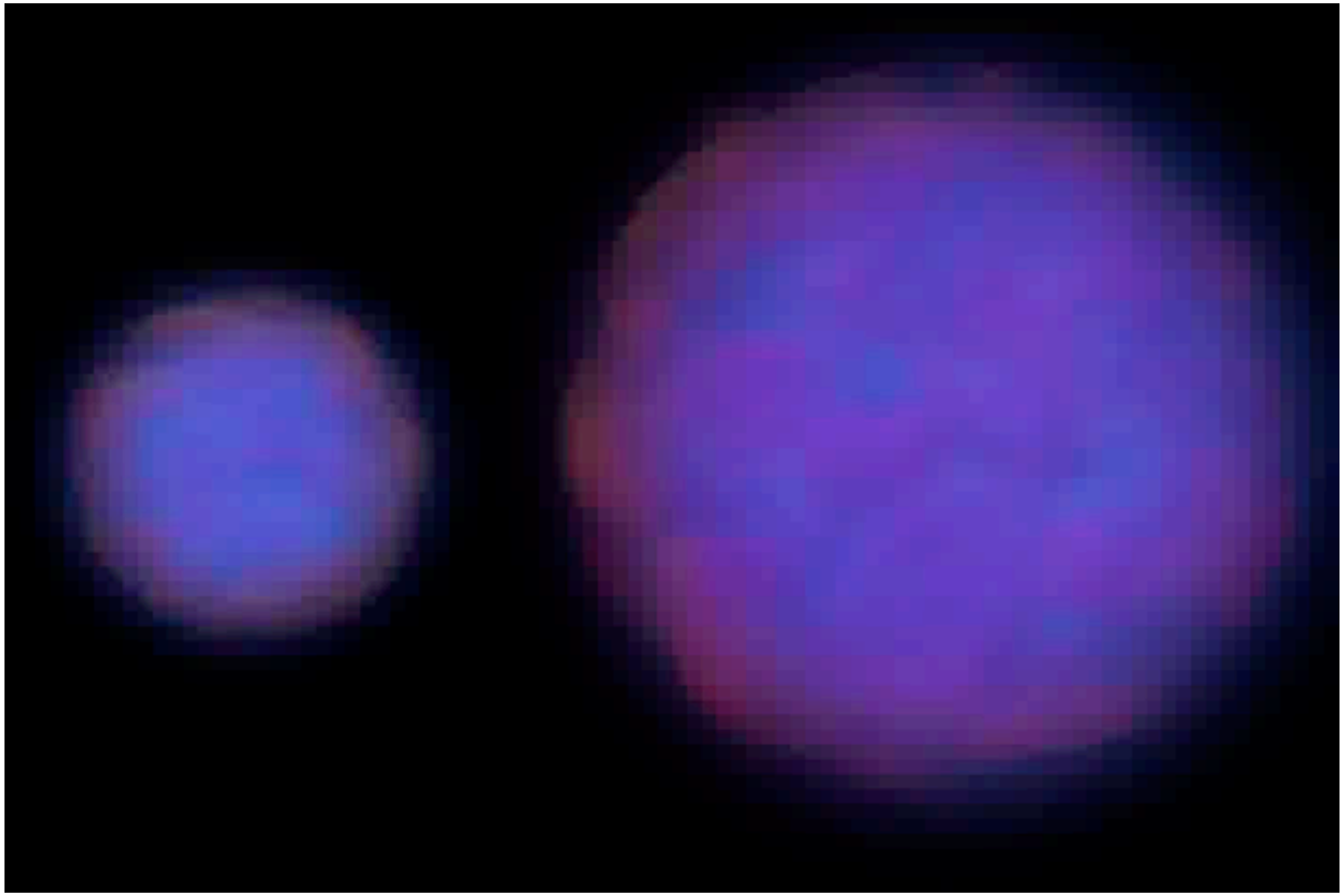


Lines of constant Xe

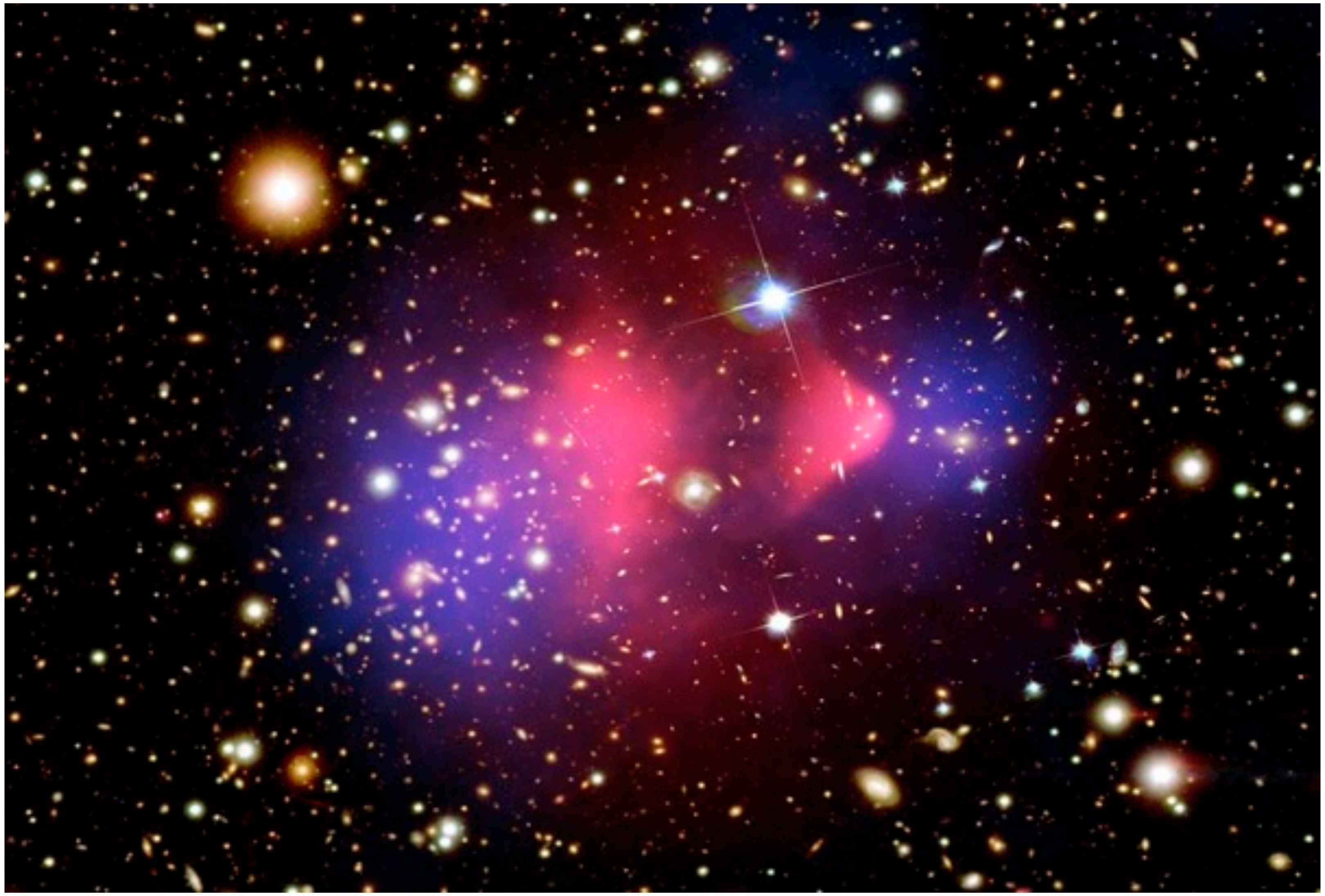
Bullet Cluster Constrains Xe and Bohr Radius



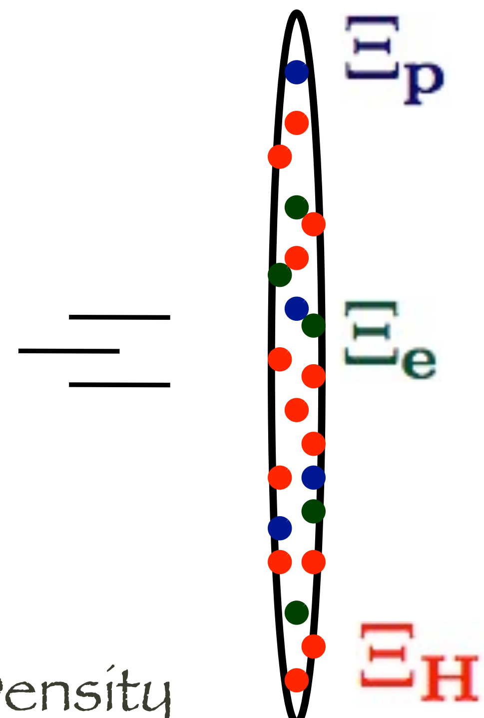
Bullet Cluster Constrains Xe and Bohr Radius



Bullet Cluster Constrains Xe and Bohr Radius

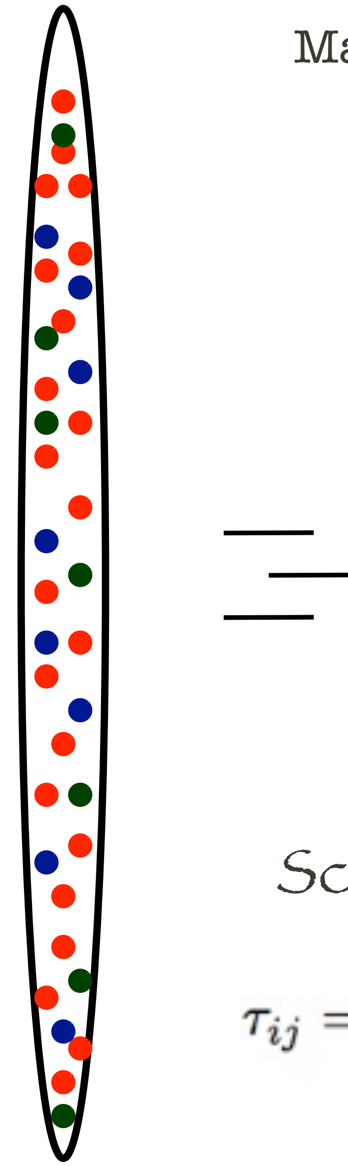


Cartoon of Bullet Cluster



Surface Density

$$\Xi_s \equiv \int_0^R \rho(z)\, dz$$

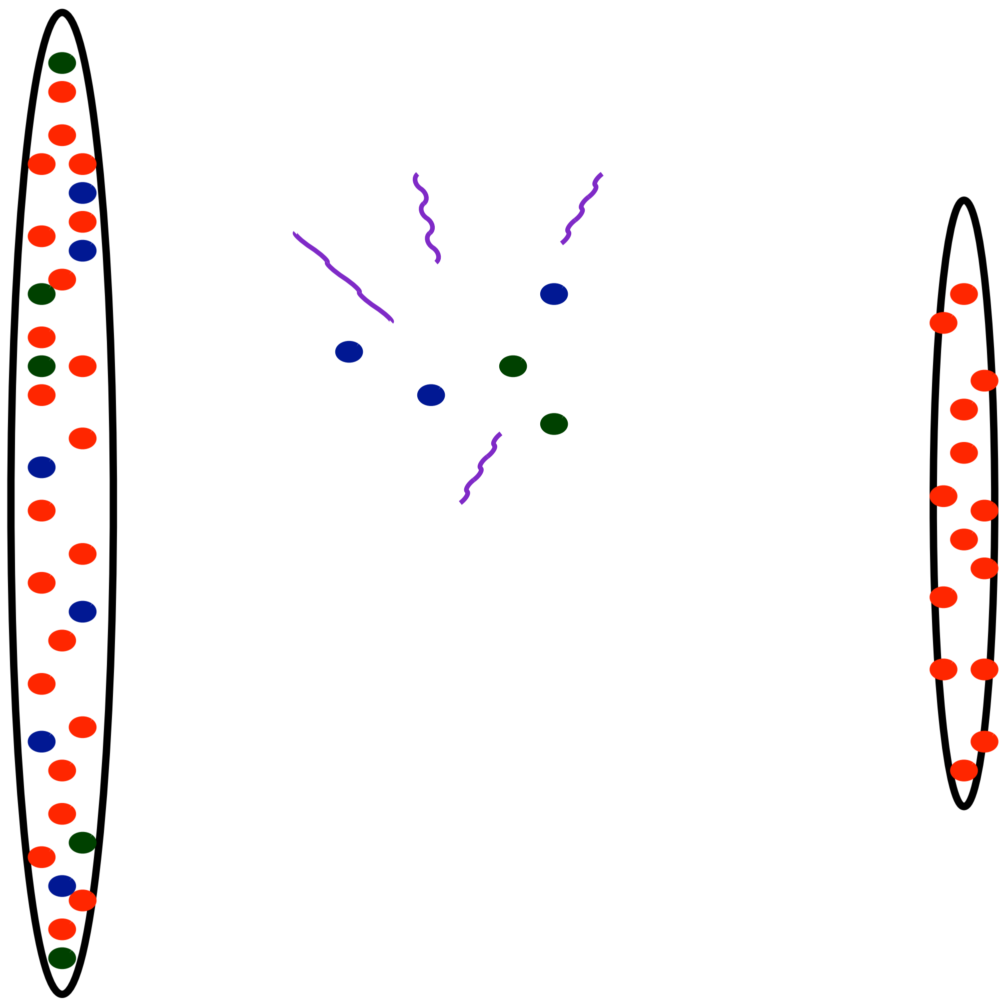


Markevitch et al
astro-ph/0309303

Scattering Depth

$$\tau_{ij} = \Xi_T \frac{f_i}{\sum_k f_k m_k} \sigma_{ij} f_j$$

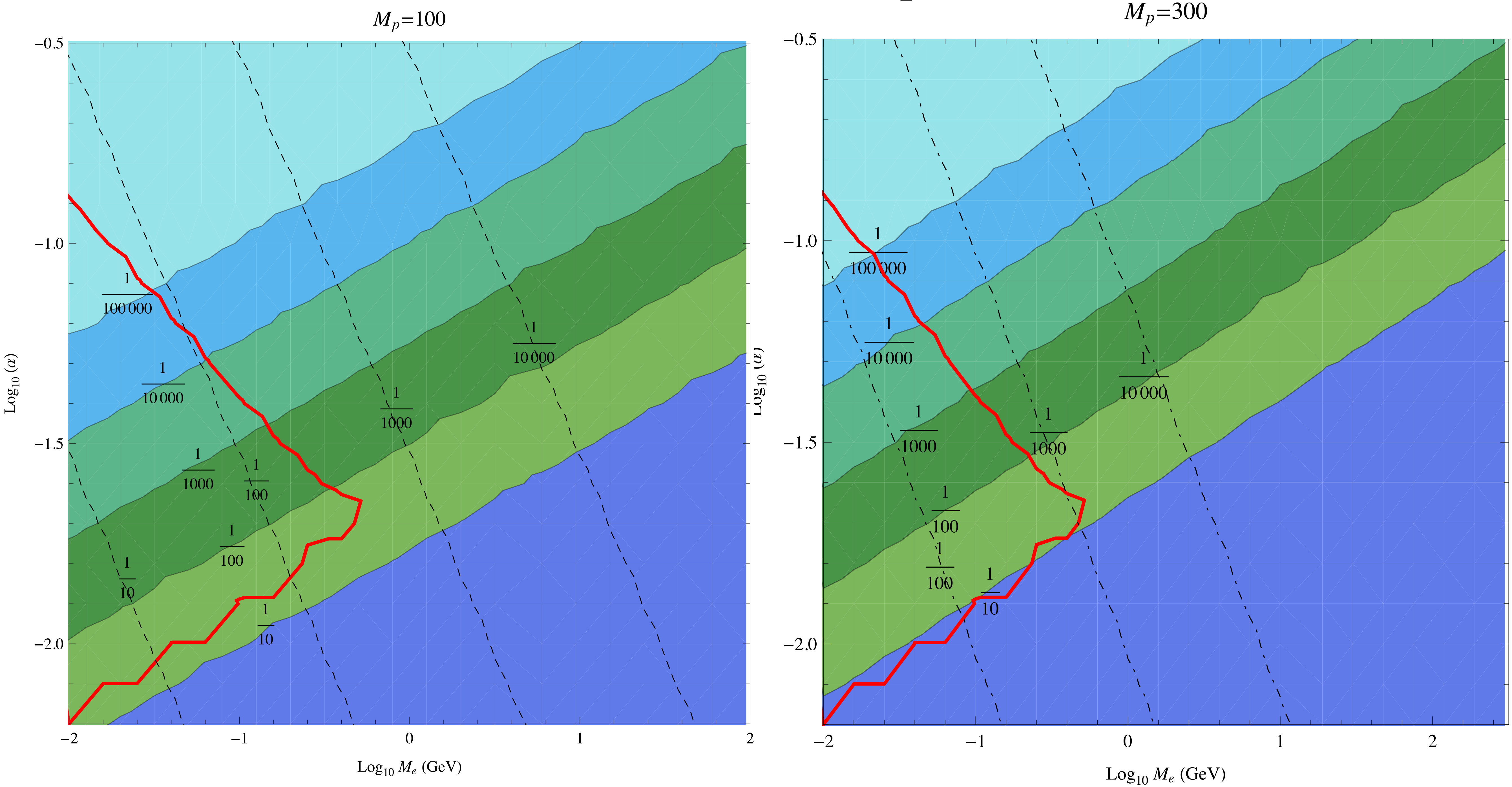
Cartoon



Markevitch et al
astro-ph/0309303

- Observations Imply ~ 30% of Original Mass is Scattered out of Bullet Cluster
- Assume All Ions are Scattered out of BC
- Constrains Scattering Depth, and thus the cross section and fractional composition of the Cluster
- $$\left(\frac{0.1}{\alpha_D}\right)^2 \left(\frac{1\,\mathrm{GeV}}{\mu_{\mathrm{H}}}\right)^2 \left(\frac{100\,\mathrm{GeV}}{m_{\mathrm{H}}}\right) \lesssim (20-200)\,\frac{0.2 - X_{\mathrm{e}}}{1 - X_{\mathrm{e}}^2}$$

Allowed Space

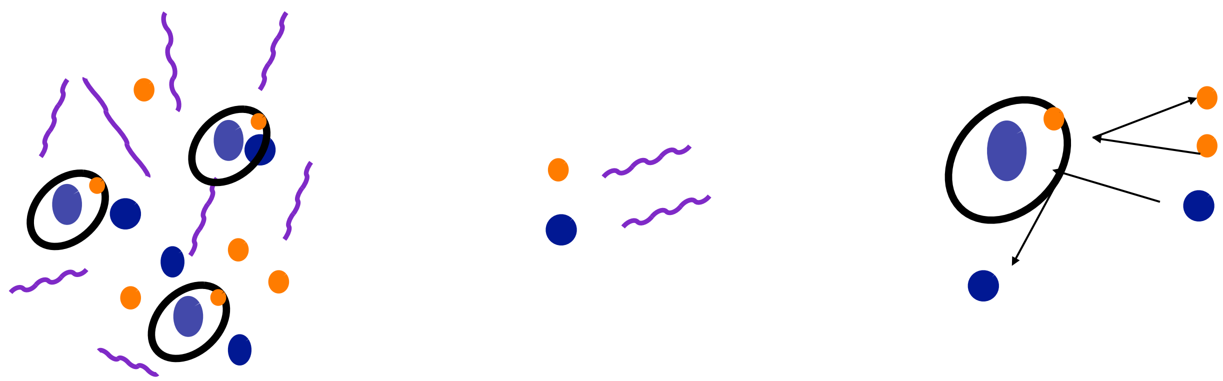


BC constraint ‐‐‐‐‐‐‐‐‐ $\frac{\sigma}{M_p + M_e}$ (cm^2/g)

Non-Standard CDM & Observable Properties

Decoupling when photons stop transferring energy to atoms

$$\Gamma(T_{dec}) = H(T_{dec})$$



$$\gamma + e,p \rightarrow \gamma + e,p \quad \& \quad e,p + H \rightarrow e,p + H$$

$$T_{dec,\,(\mathbf{p},\mathbf{e})\mathrm{H}} \simeq 0.1 \left(\frac{1}{X_{\mathbf{e}}}\right)^{2/3} \alpha_D^{4/3} \left(\frac{m_{(\mathbf{e},\mathbf{p})}}{1\,\mathrm{GeV}}\right)^{4/3} \left(\frac{m_{(\mathbf{p},\mathbf{e})}}{1\,\mathrm{GeV}}\right) \mathrm{keV}$$

$$M^{\rm strc} > \frac{4\pi}{3}\left(\frac{\pi}{k_{\rm damped}}\right)^3 \Omega_{DM}\rho_{crit}$$

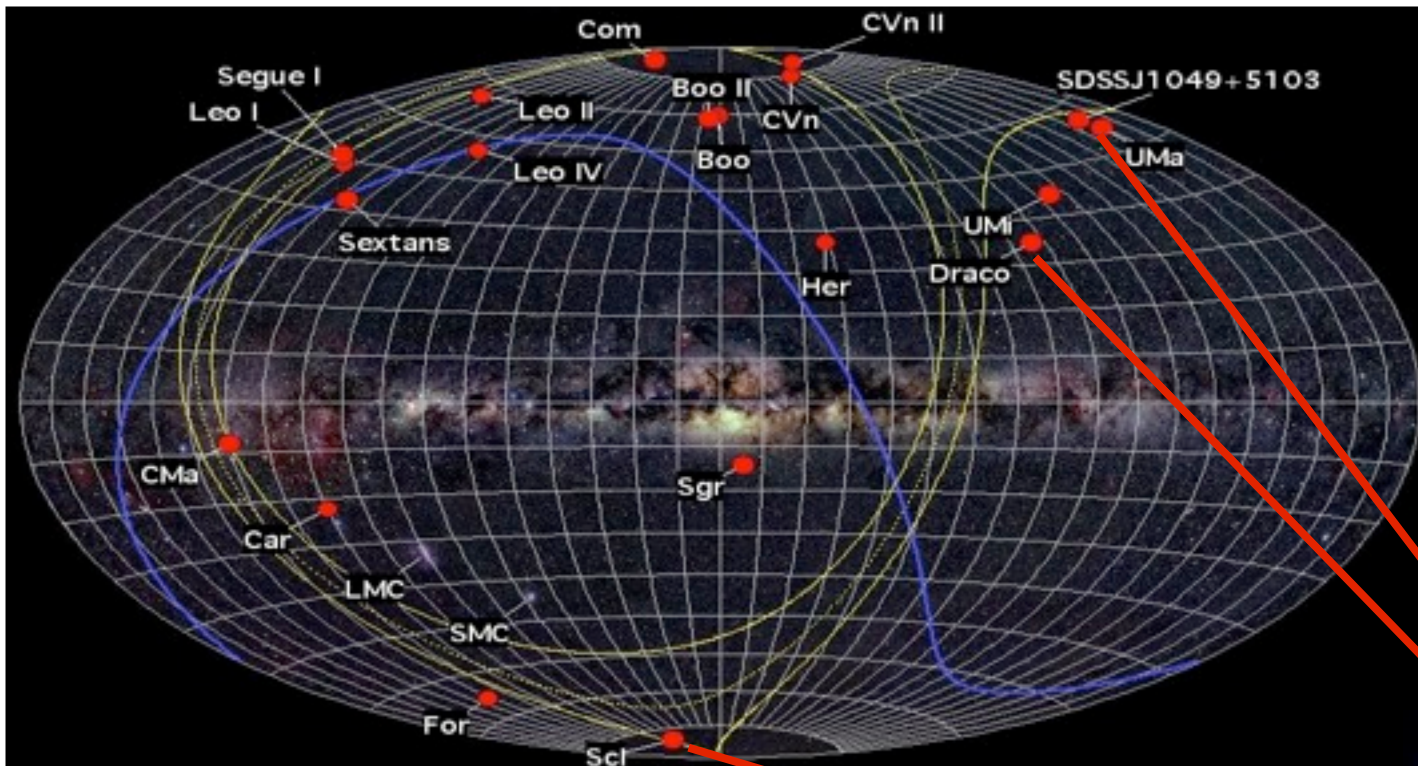
$$M^{\rm strc}_{\rm ADM} > 10^5 \left(\frac{T}{10\ \mathrm{keV}}\right)^{-3} M_\odot$$

$$M^{\rm strc}_{\rm CDM} > 10^{-4} \left(\frac{T}{10\ \mathrm{MeV}}\right)^{-3} M_\odot$$

Atomic DM can suppress power on small scales

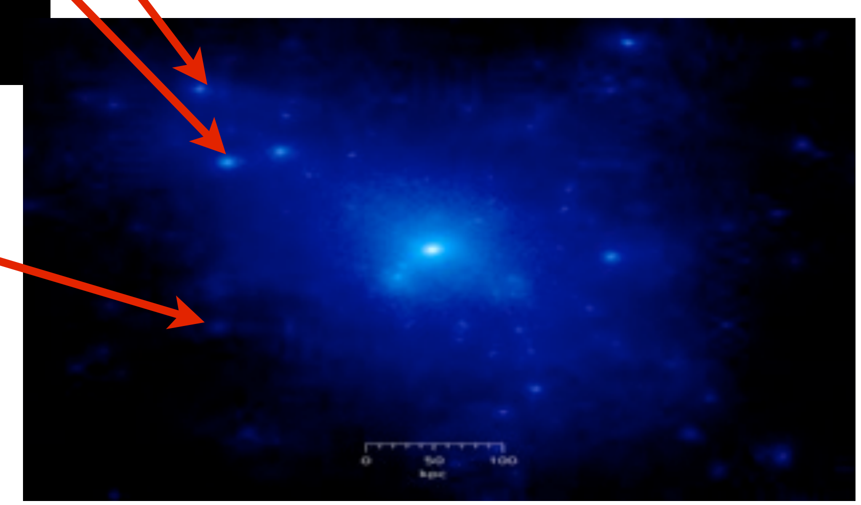
Loeb& Zaldarriaga astro-ph/0504112
Green et al. astro-ph/0309621

Decoupling Dynamics May Have Implications for 'Missing Satellites'



SMS Collaboration '08

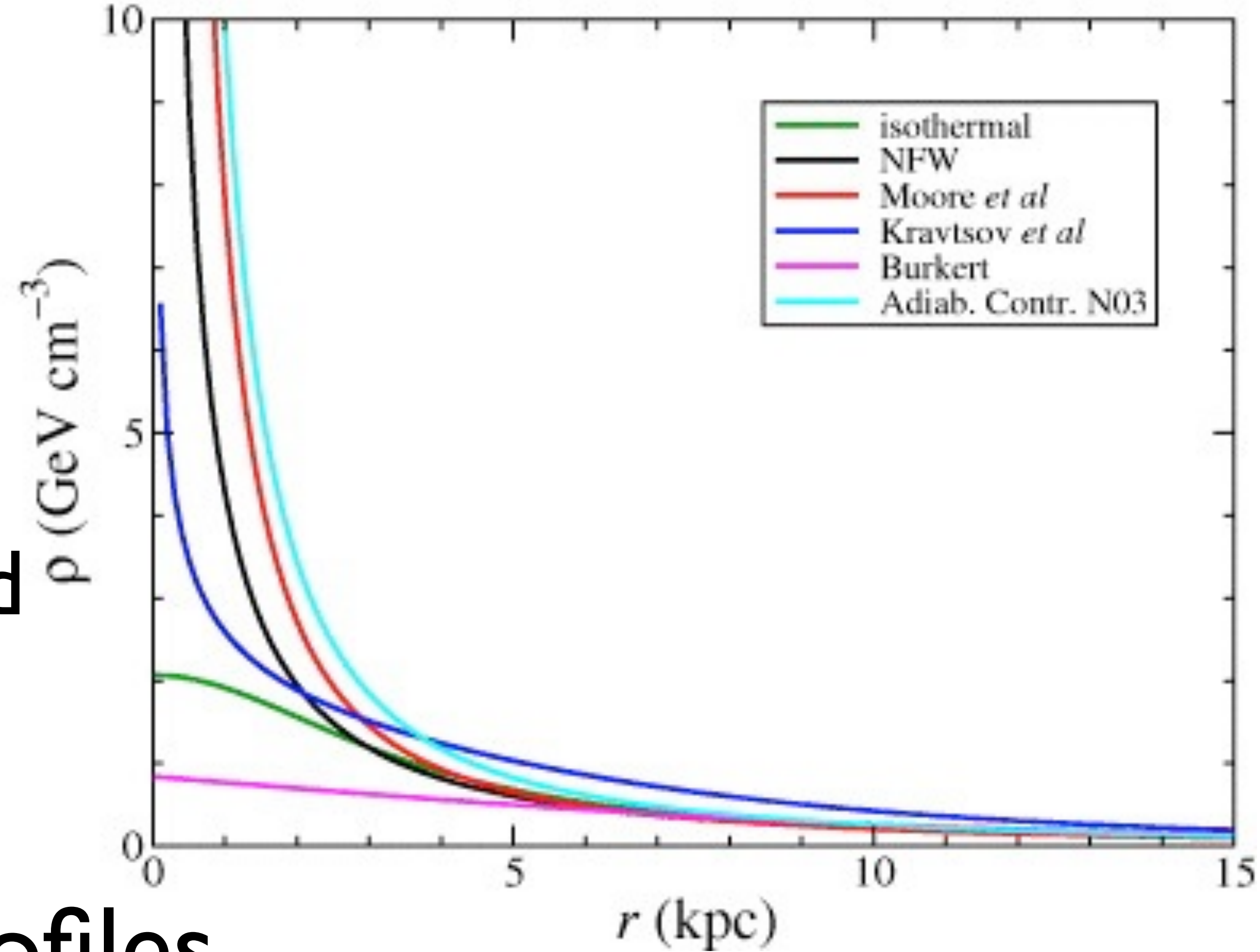
Cembranos et al hep-ph/0507150
Simon & Geha arXiv:0706.0516



About an order of magnitude too few satellites

A Word Concerning Halos

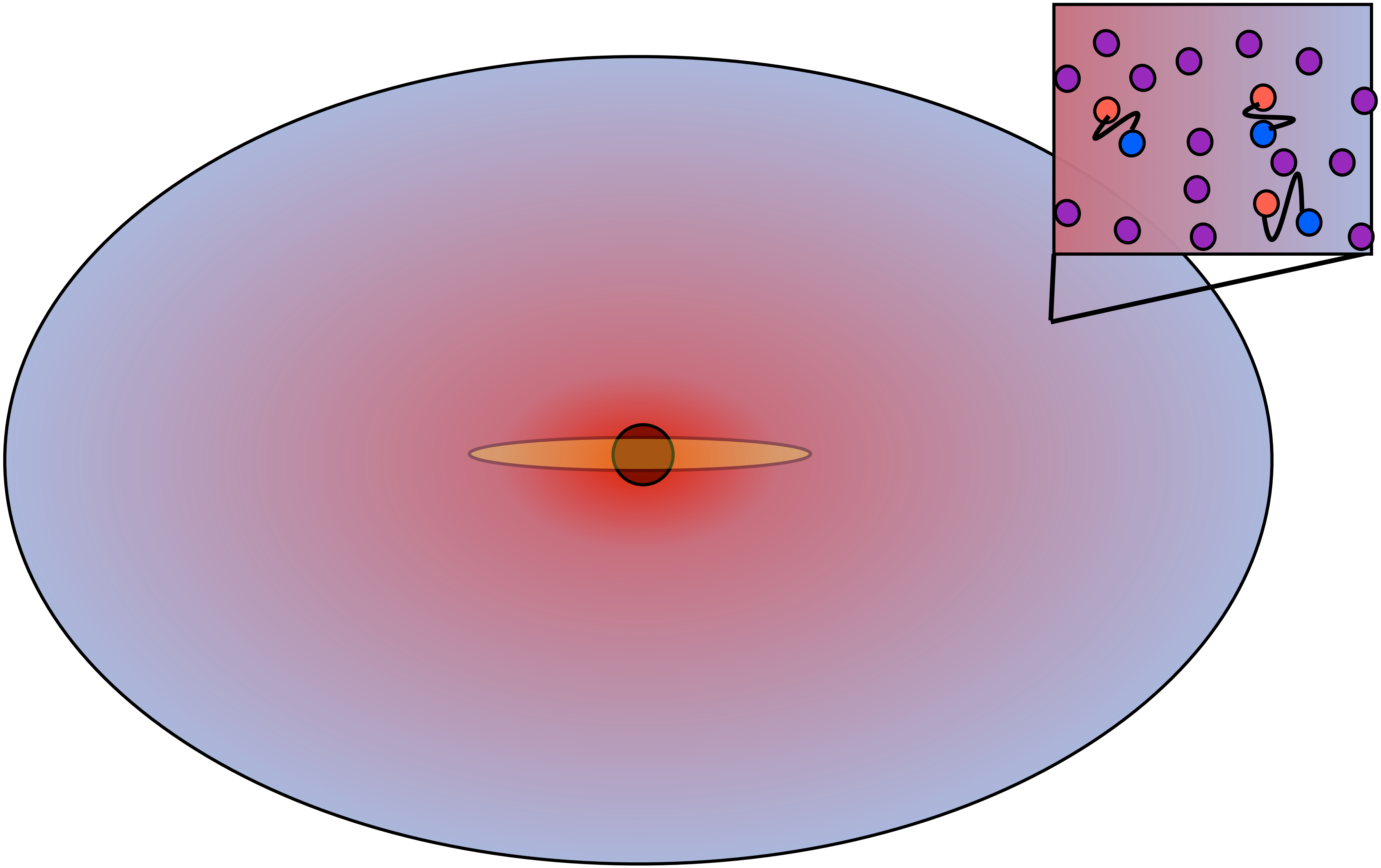
- Different Interaction Potentials for Atoms and Ions Can Effect the Radial Profiles
- Implications for Direct and Indirect Detection



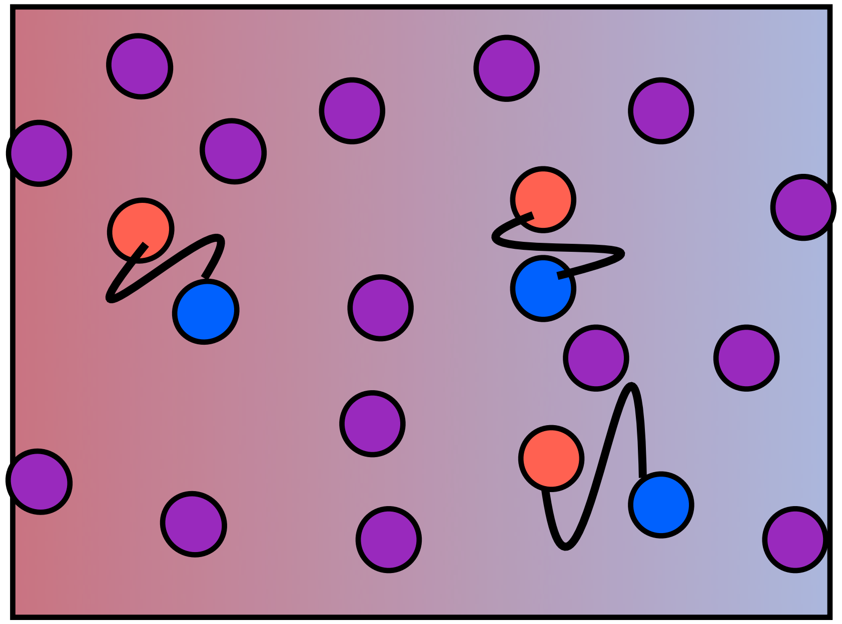
Non-Interacting Profiles

Interacting Profiles

Galactic Cartoon



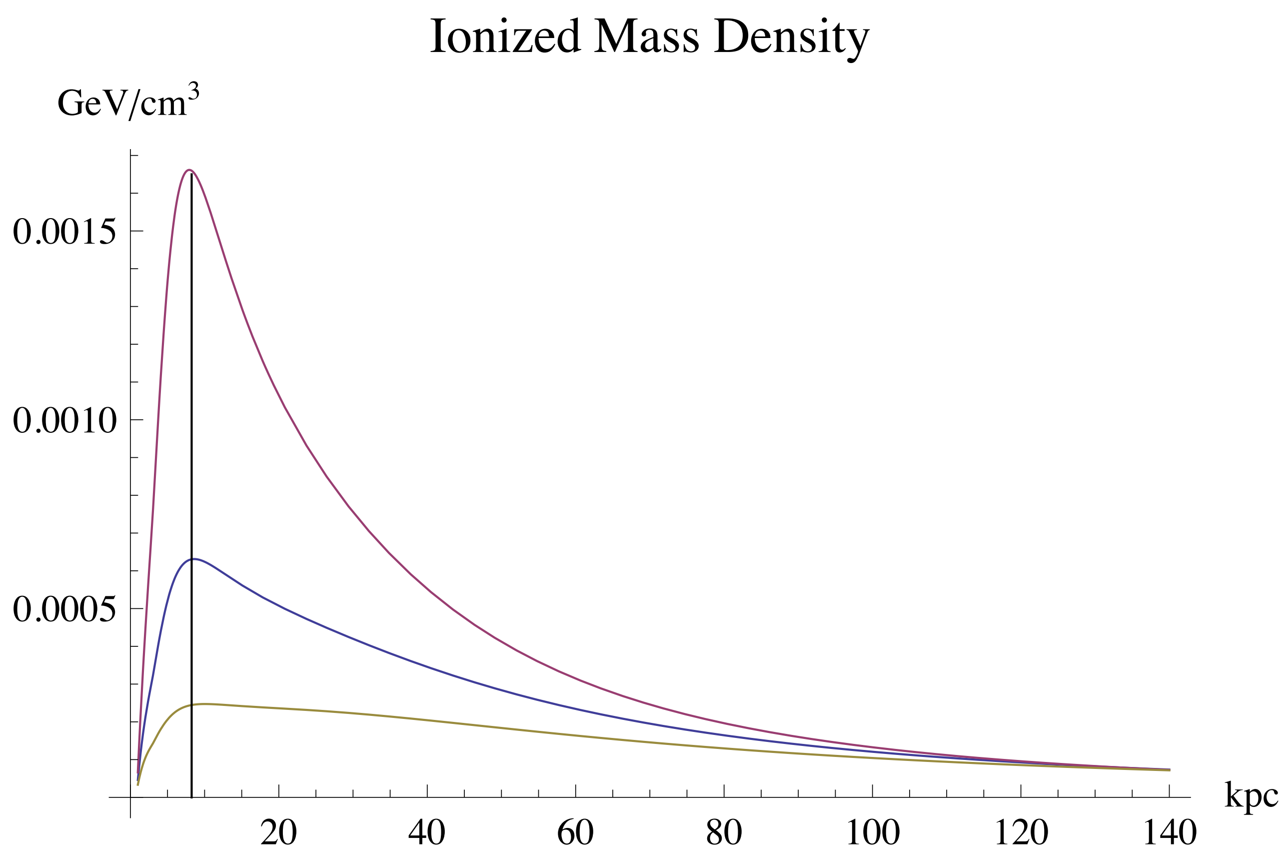
Density Distributions

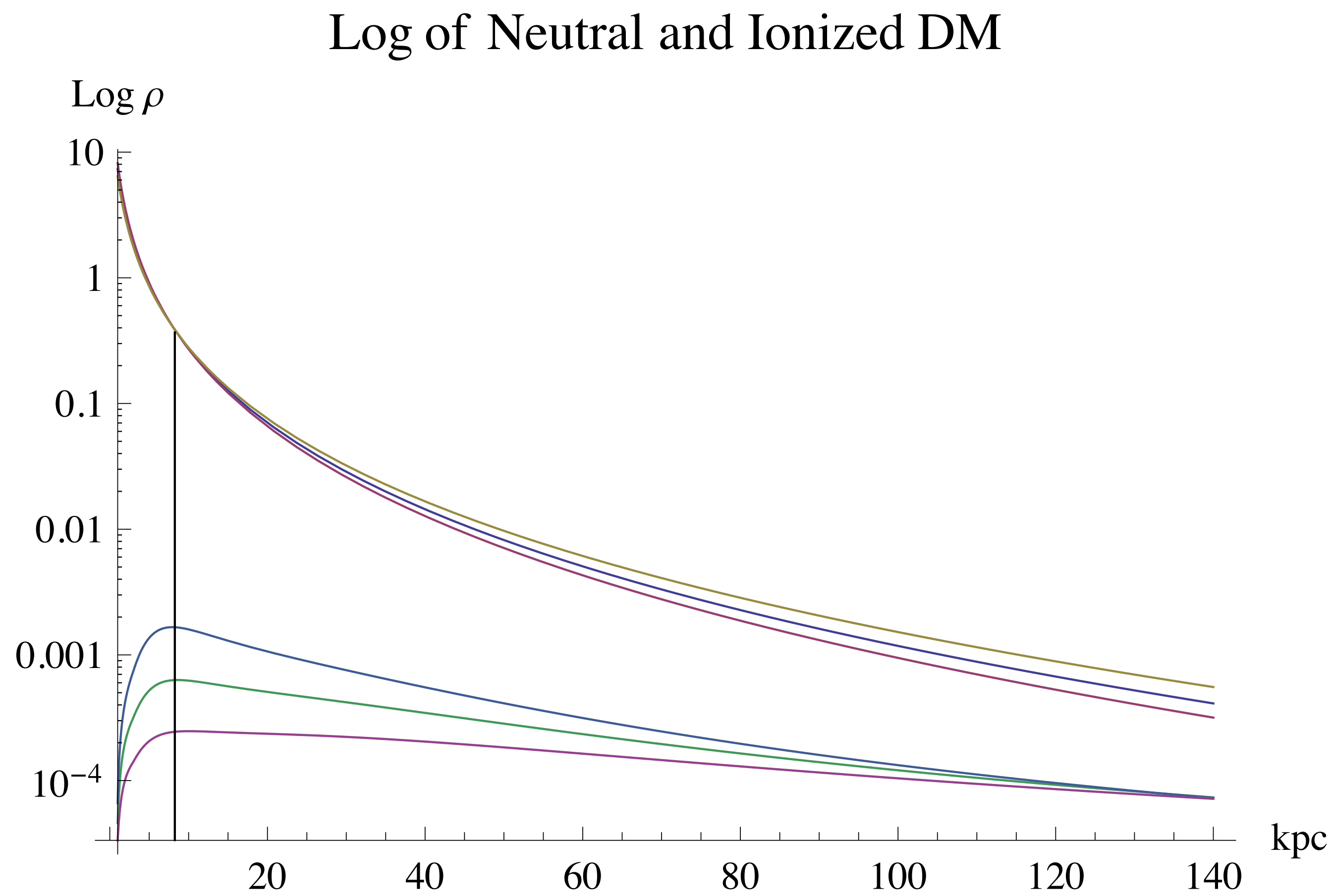


- Atoms Behave like CDM - NFW Profile
- BUT Ion Scattering Maintains Kinetic Equilibrium
- Ion Phase Space Distribution Governed by Boltzmann Stats - Isothermal Profile

$$\begin{aligned} n_\pm(r) &\sim N(X_e)\int v^2 dv f_\pm(v,r) \\ &\rightarrow N(X_e)\int v^2 dv e^{-(KE(v)-PE(r)/T} \\ &= C(X_e)\, e^{-\frac{U(r)}{T}} \end{aligned}$$

Local Ion Density is Suppressed





$$X_e(r_\odot) \sim 10^{-2} X_e^{\text{global}} \quad (X_e^{\text{global}} \lesssim 0.1)$$

$$n_\pm(r) \sim C(X_e) e^{-\frac{U(r)}{T}}$$

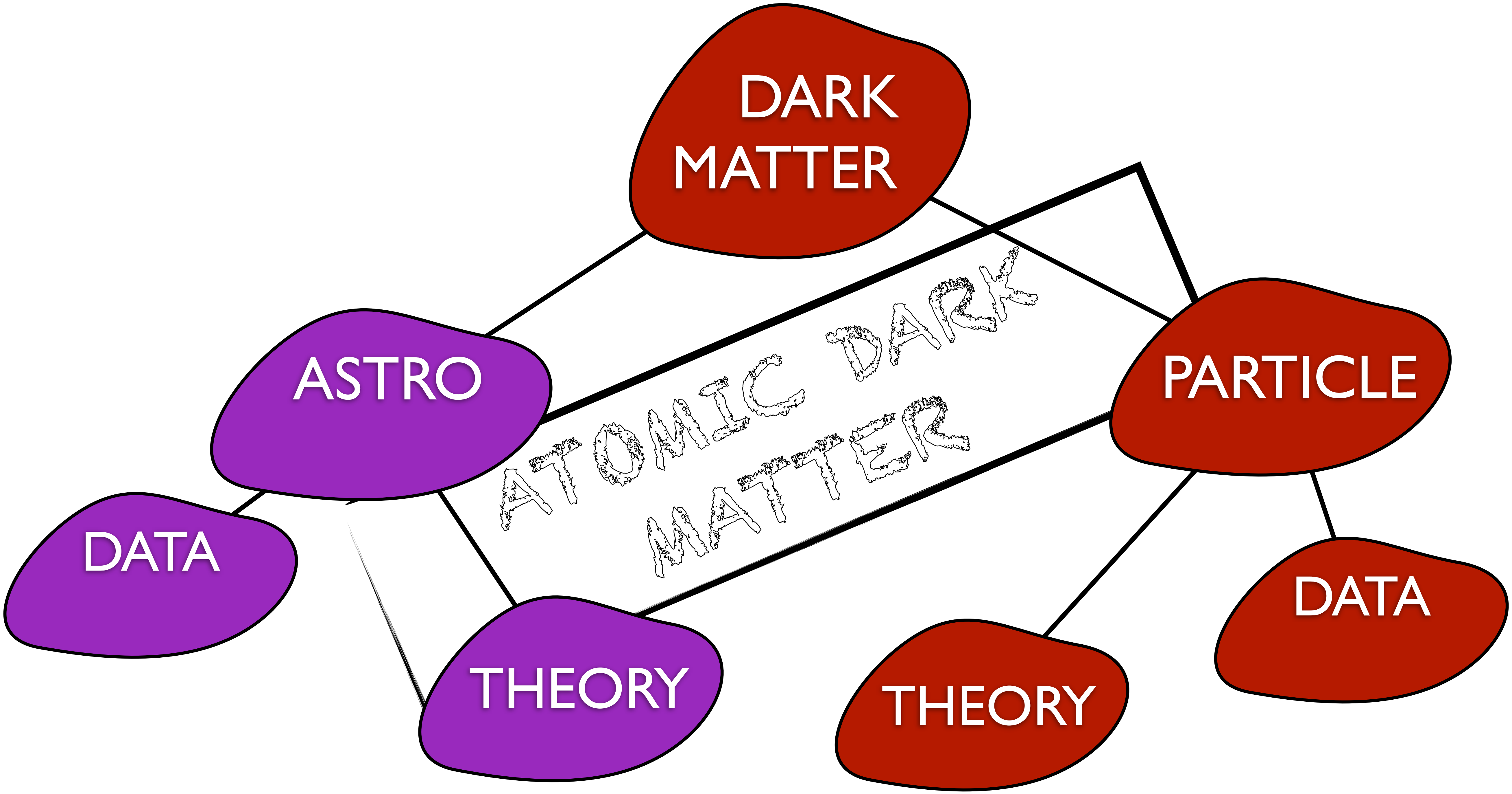
Independent of Xe

Catena & Ullio Milky Way Model 0907.0018

Atomic Dark Matter Astro Summary

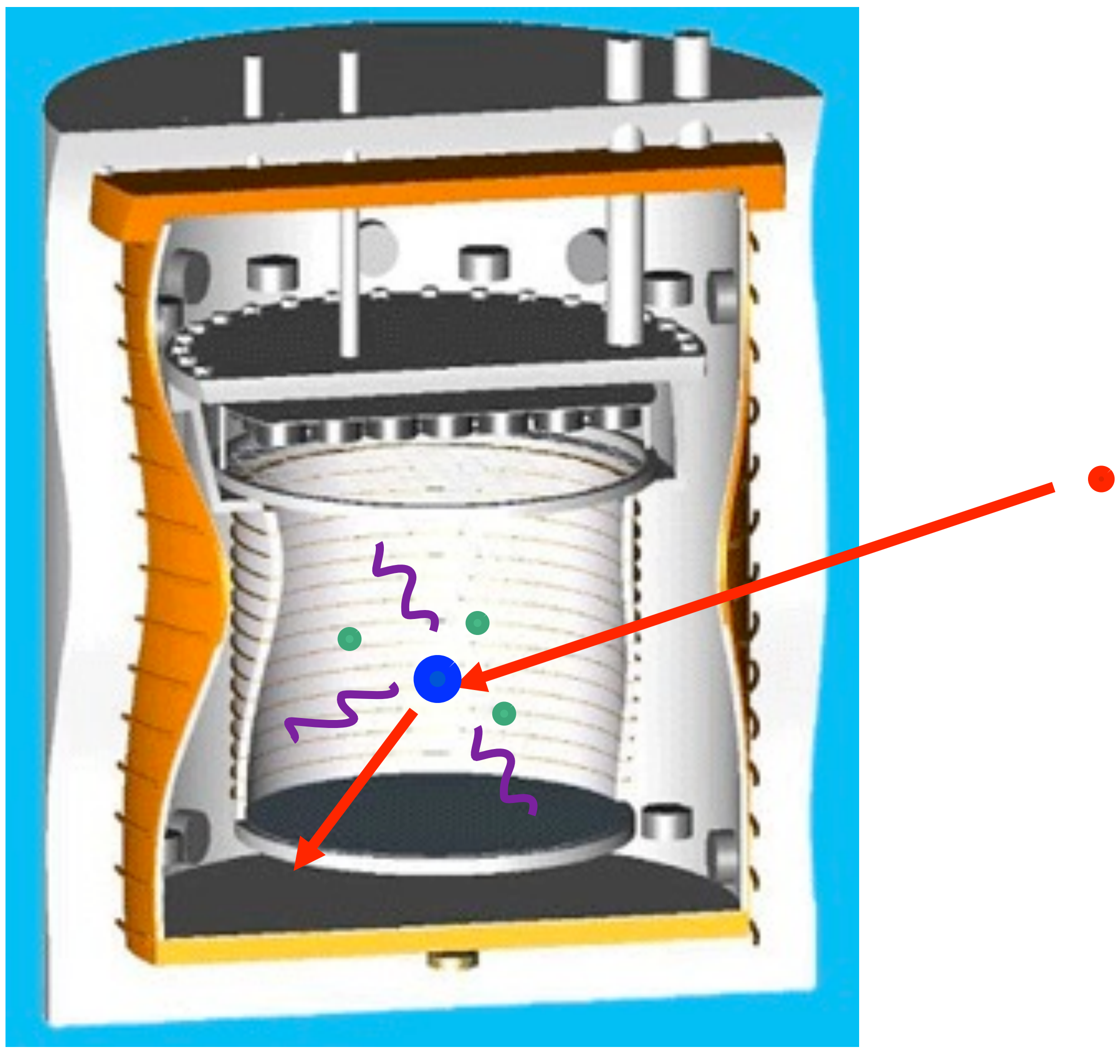
- Atomic Dark Matter has very different microscopic properties than typical CDM
  - Significant Parameter Space Consistent with Observations
  - May have Interesting Implications for Small Scale Structure
    - Late decoupling > Missing Satellites?
    - Multicomponent (Atoms and Ions) halo, likely with very different radial profiles
  - Explicit example that DM can have dynamics far more complicated than standard CDM

Now Review Standard WIMP Phenomenology



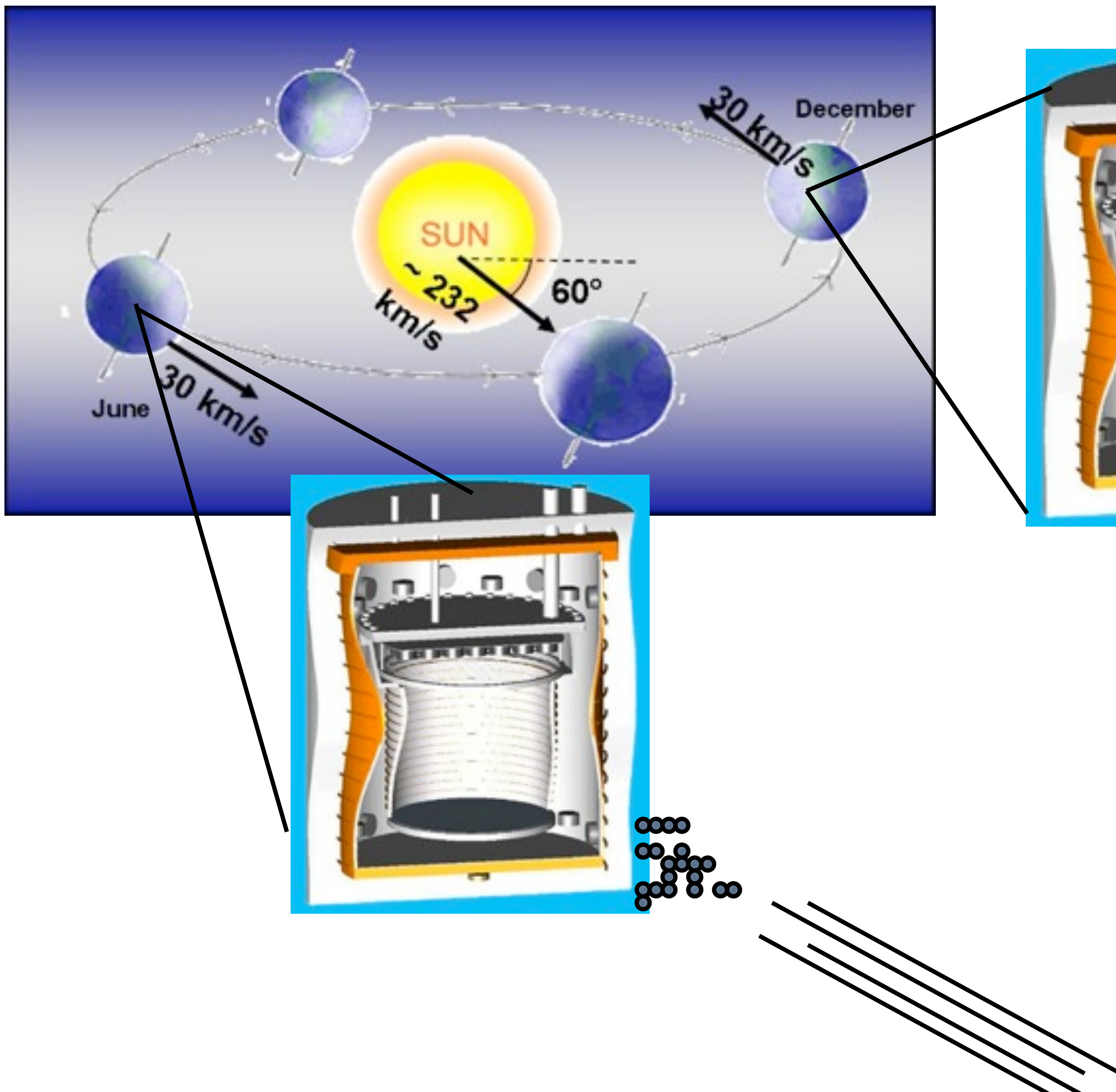
Direct Detection

Direct Detection



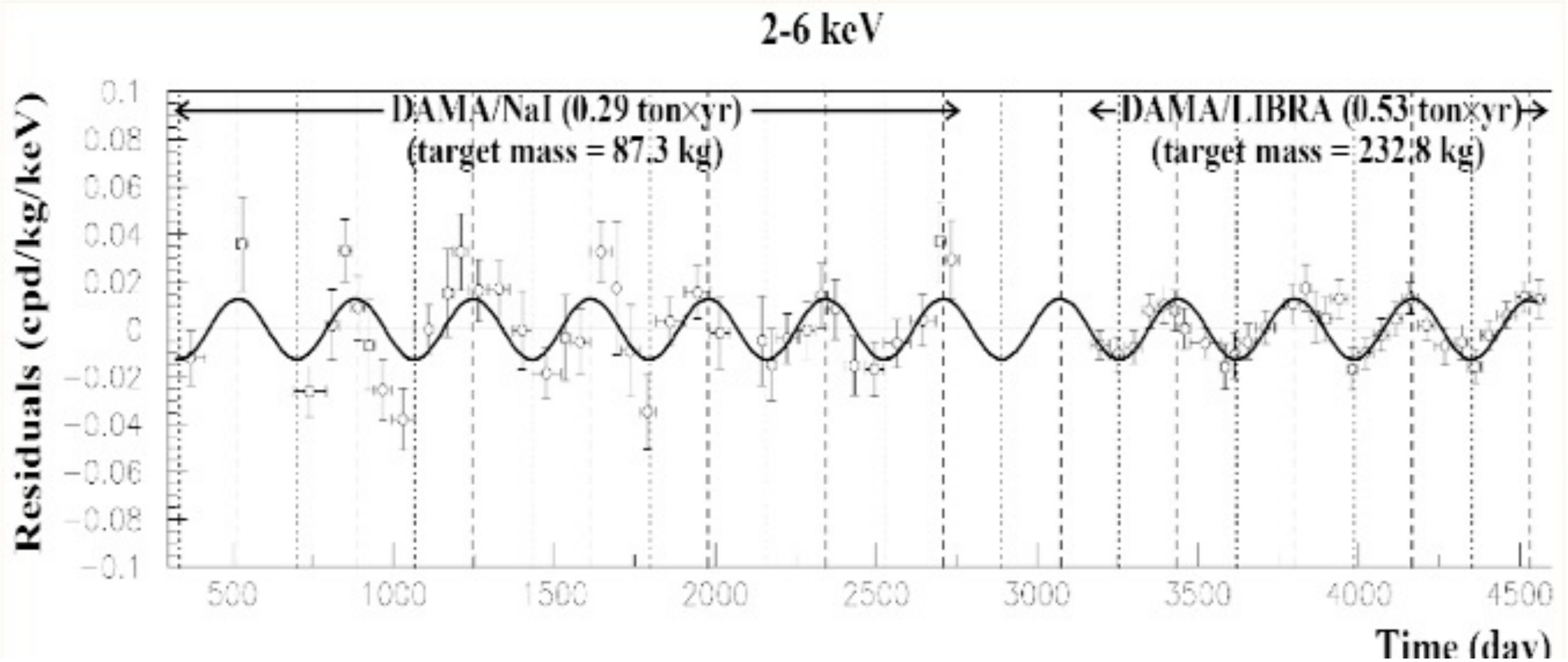
- DM Scatters off Nucleus, Depositing Electronic and Vibrational Energy

Expect Time Dependent Scattering



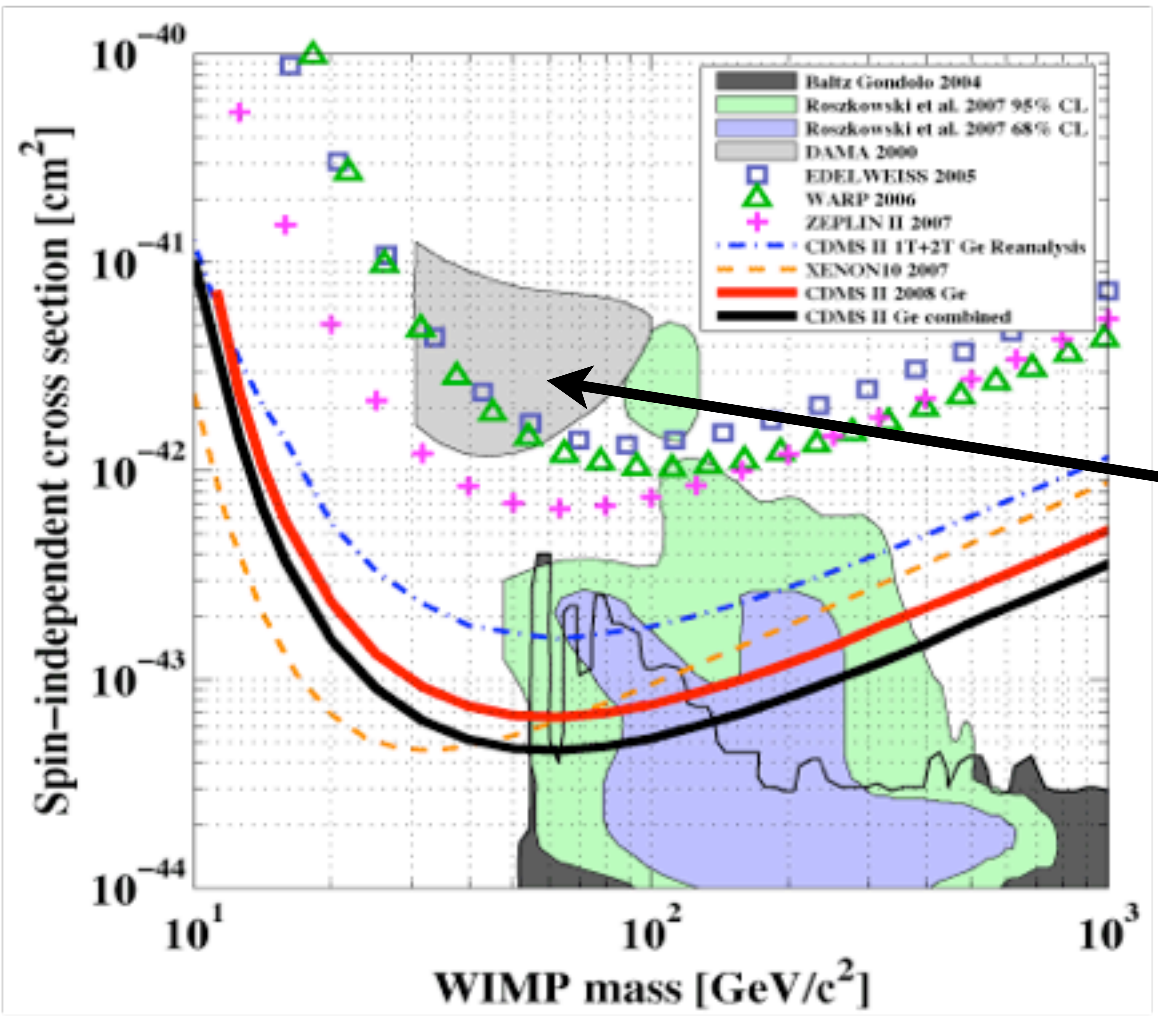
- Mean velocity of DM wrt Earth varies sinusoidally throughout the year
- Mean Lab Frame Energy oscillates as Earth orbits

DAMA Sees The Predicted Time Variation



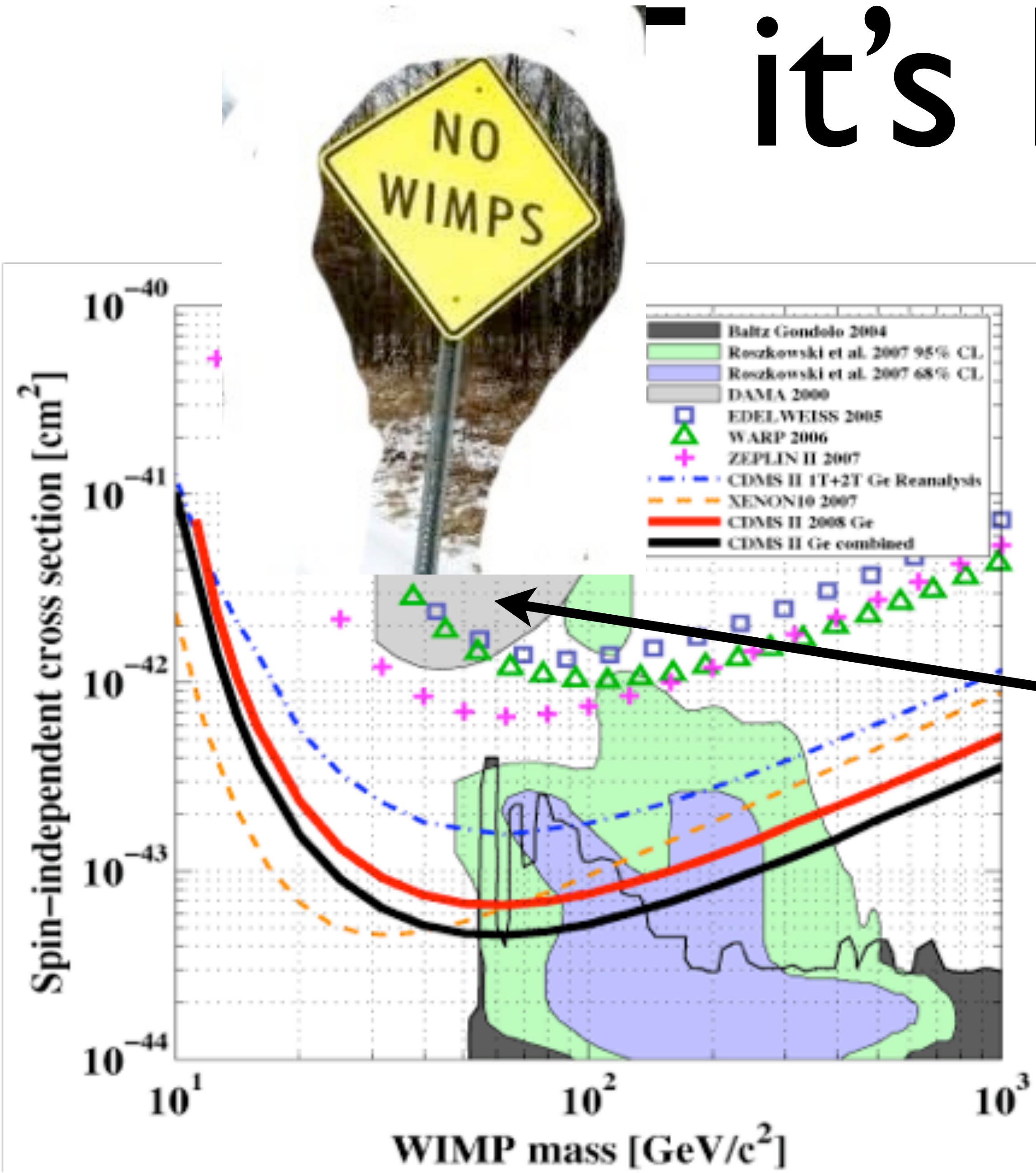
- Counts per Day per Kilogram per keV
- Exactly in phase with Earth's orbit

BUT it's Not a WIMP



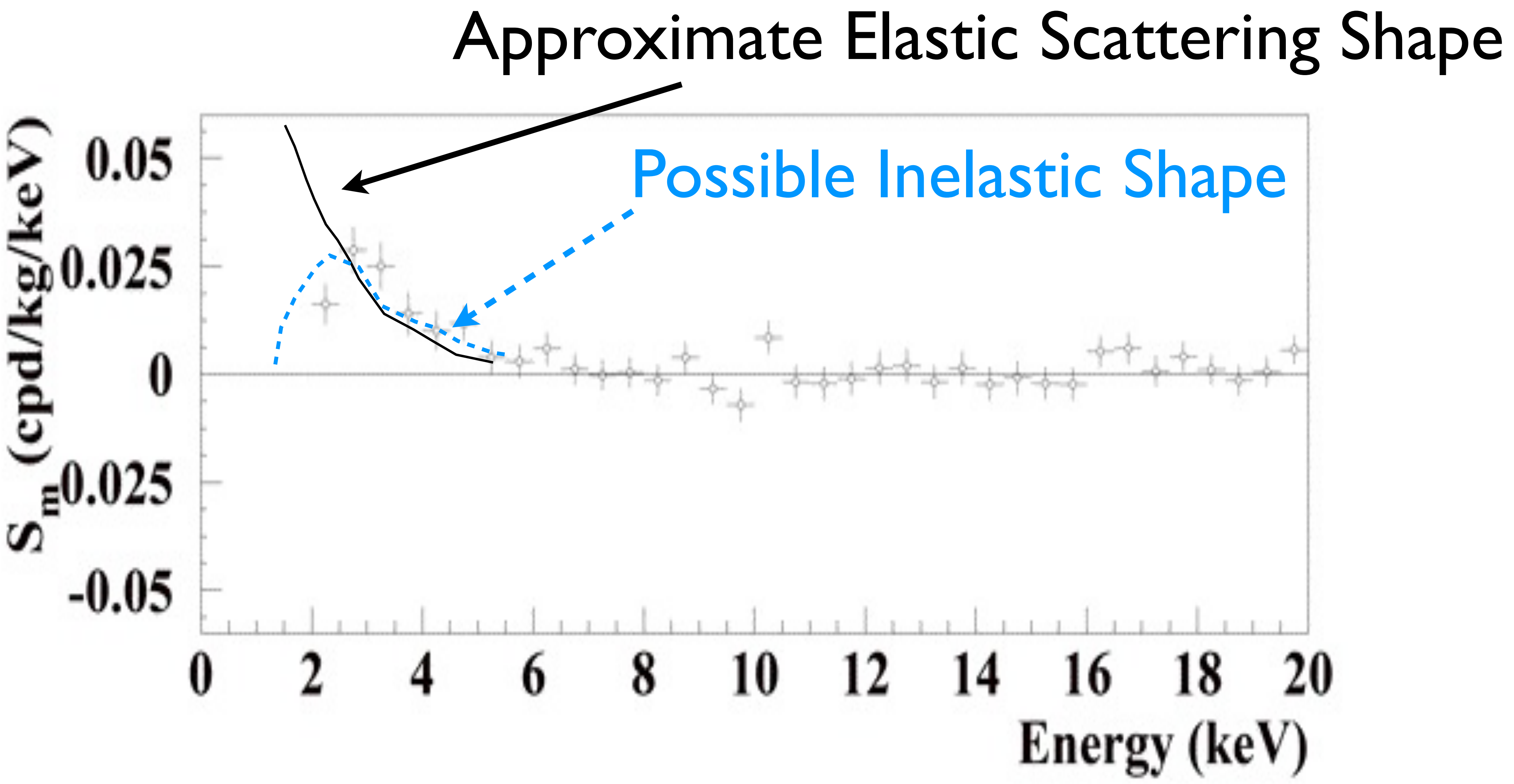
- Best fit WIMP is Ruled out by 2-3 orders of magnitude

it’s Not a WIMP

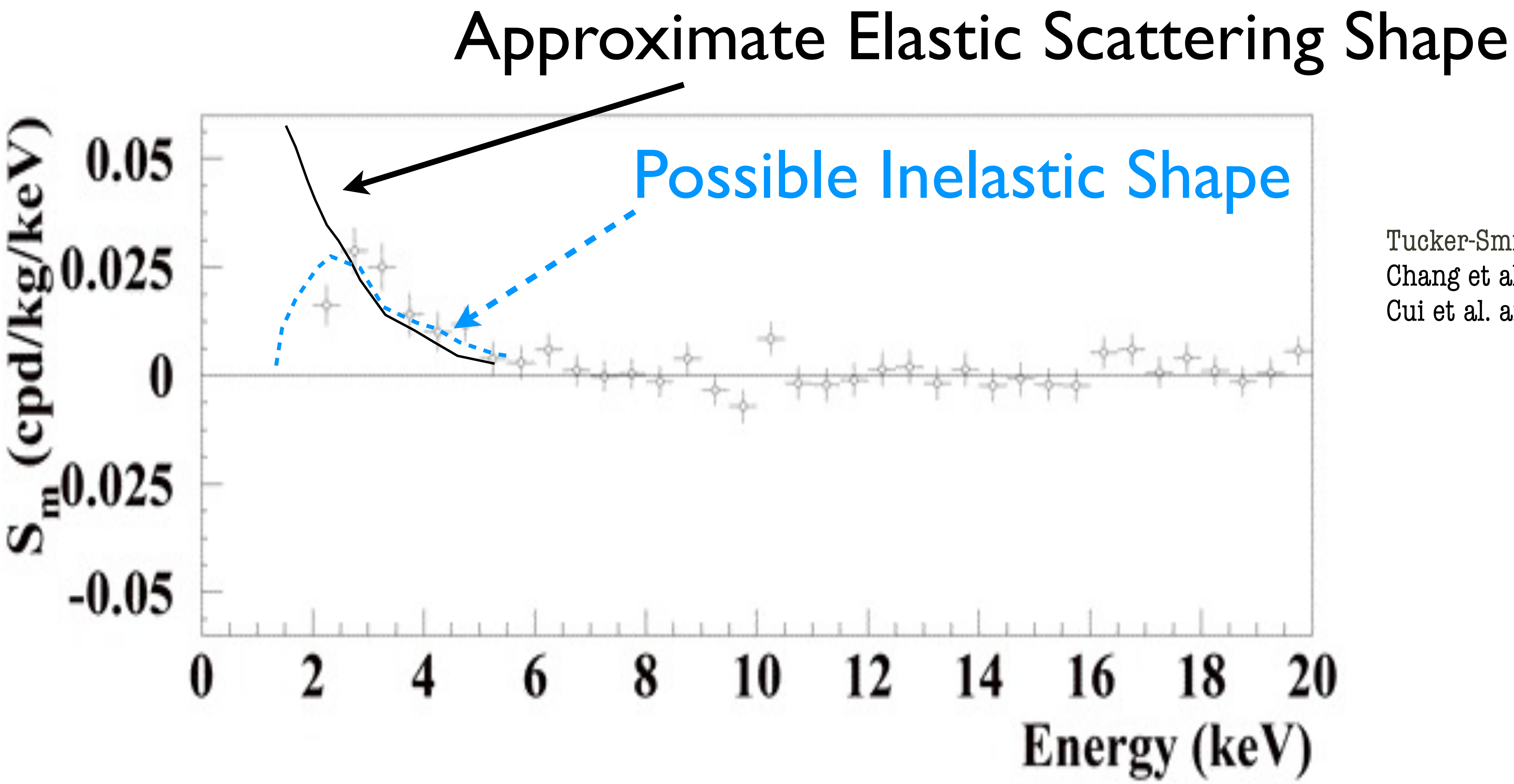


- Best fit WIMP is Ruled out by 2-3 orders of magnitude

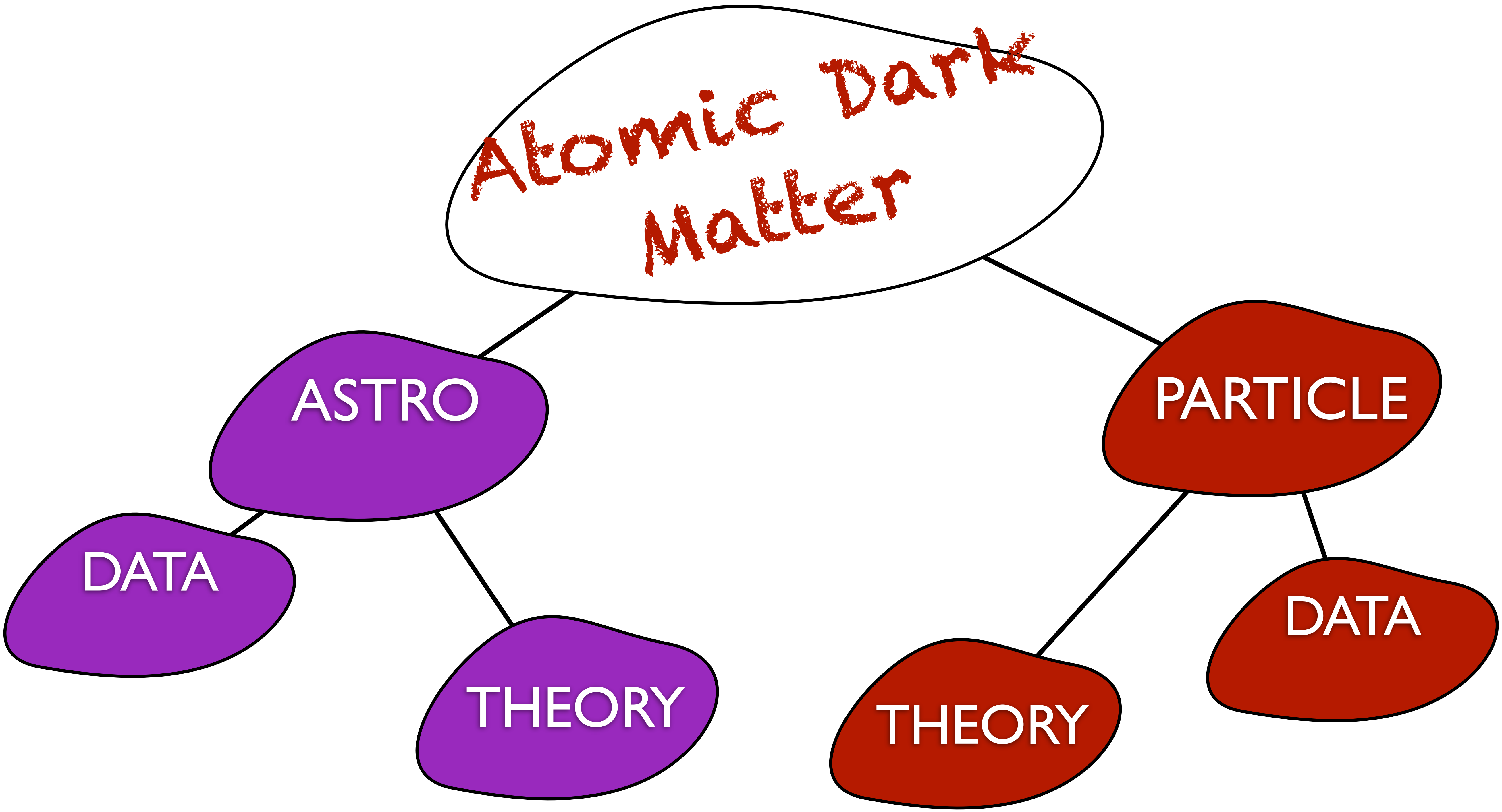
DAMA Spectrum Inconsistent with Elastic scattering



DAMA Spectrum Inconsistent with Elastic scattering



Tucker-Smith & Weiner: hep-ph/0101138
Chang et al. arxiv:0807.2250
Cui et al. arxiv:0901.0557

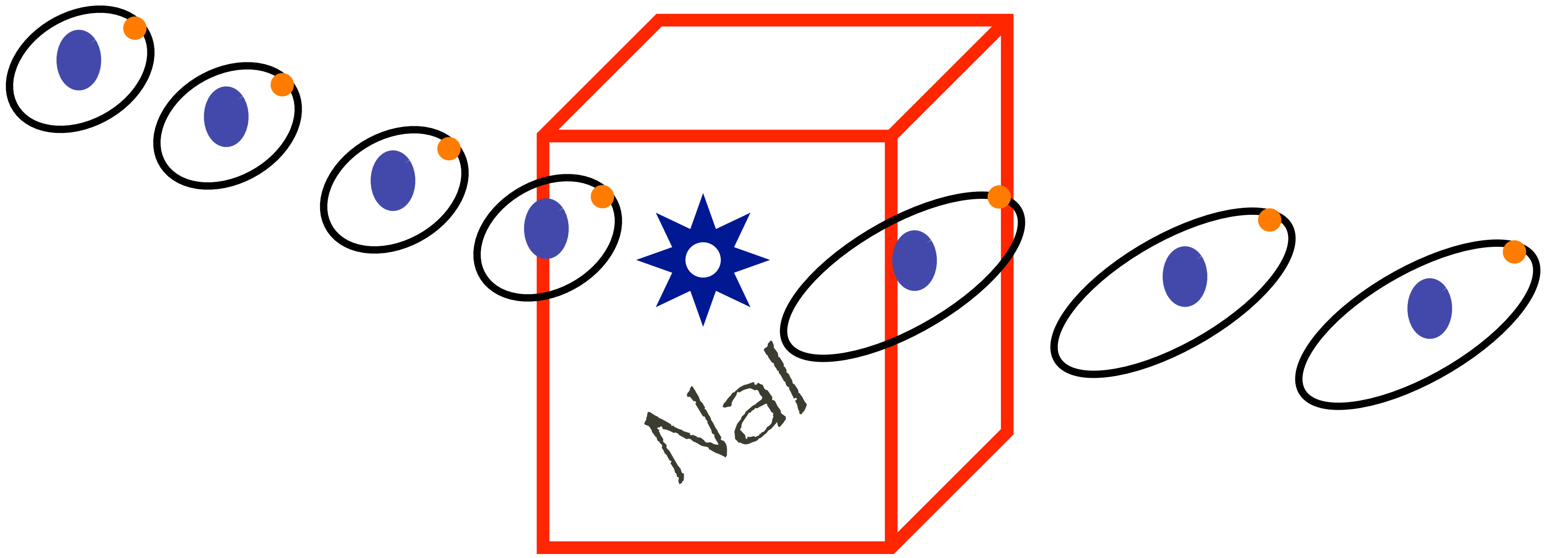

Atomic Dark Matter
ASTRO
PARTICLE
DATA
THEORY
THEORY
DATA

Atoms Have Many Energy States - Could Transitions Explain DAMA?

- Requires State Change
- Corresponding Velocity Threshold for Reaction

$$v_t = \sqrt{(2\delta)/\mu_N}$$

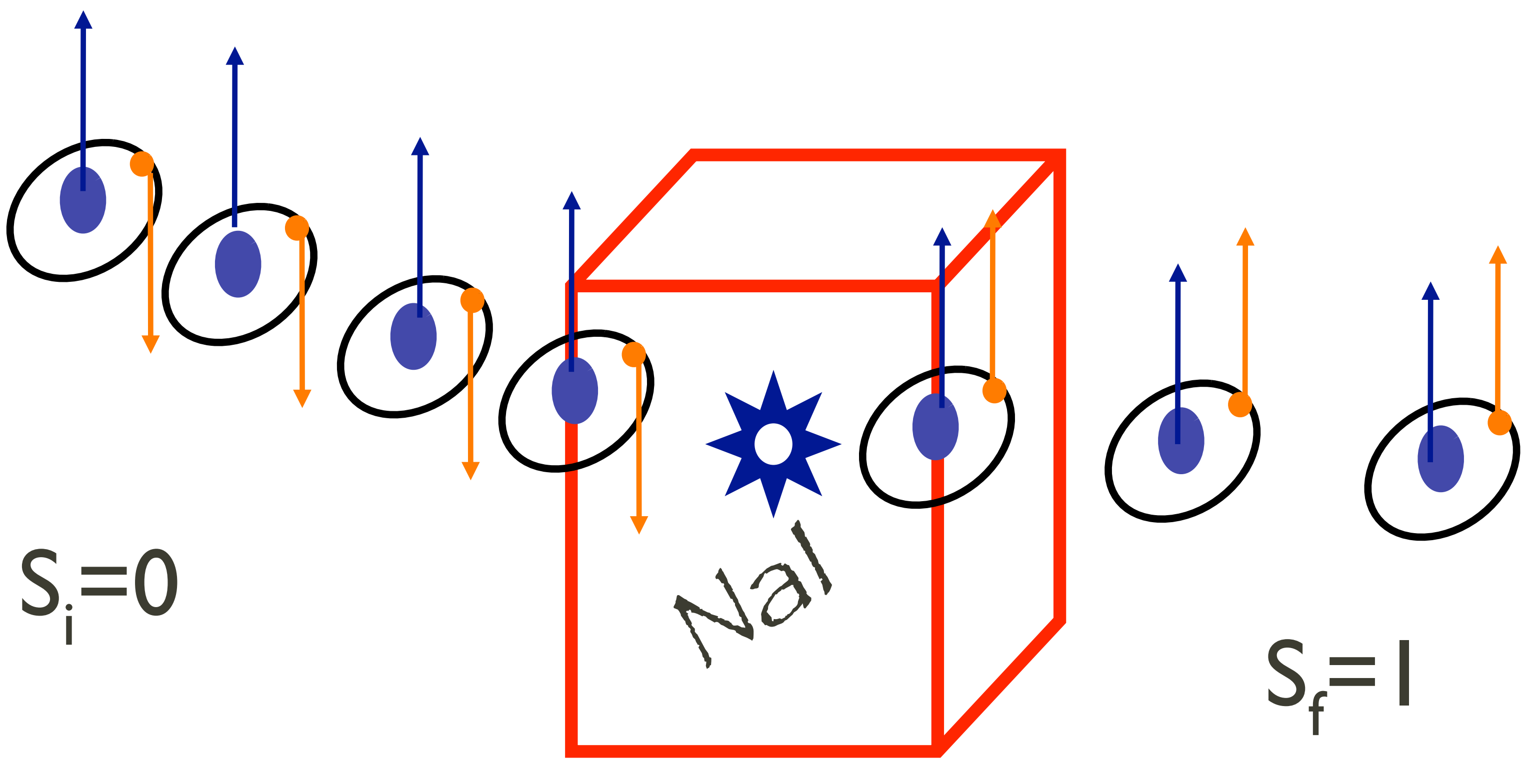
- Threshold depends on Target Mass (through reduced Mass)



Scattering excites Atom

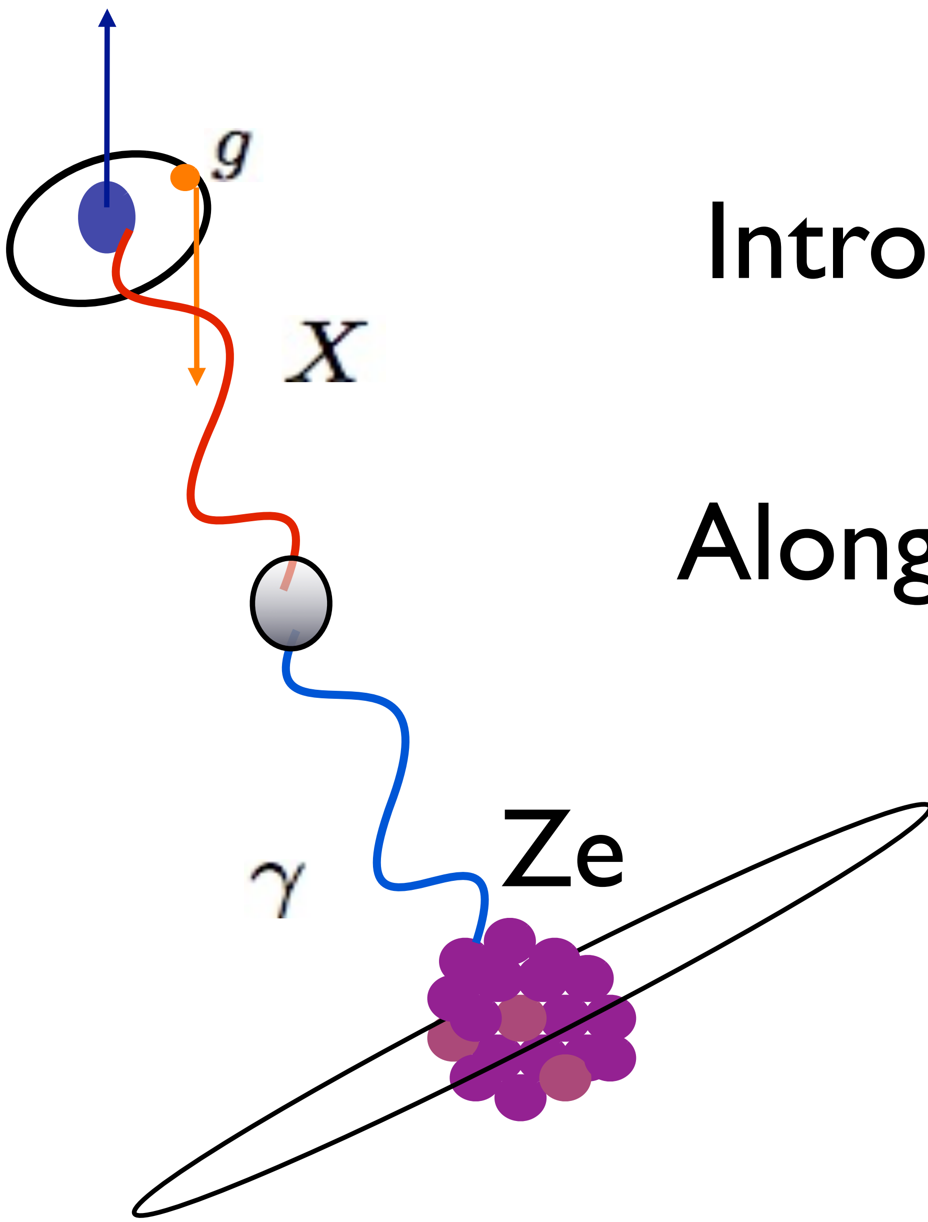
Coupling Dark Atoms to SM

Want DM to Flip Spin When Interacting with SM



$$\delta E = E_{hf} = \frac{2}{3} g_{\mathbf{e}} g_{\mathbf{p}} \alpha_D^4 \mu_H \frac{m_{\mathbf{e}}}{m_{\mathbf{p}}}$$

Introducing a DM-spin Dependent Force

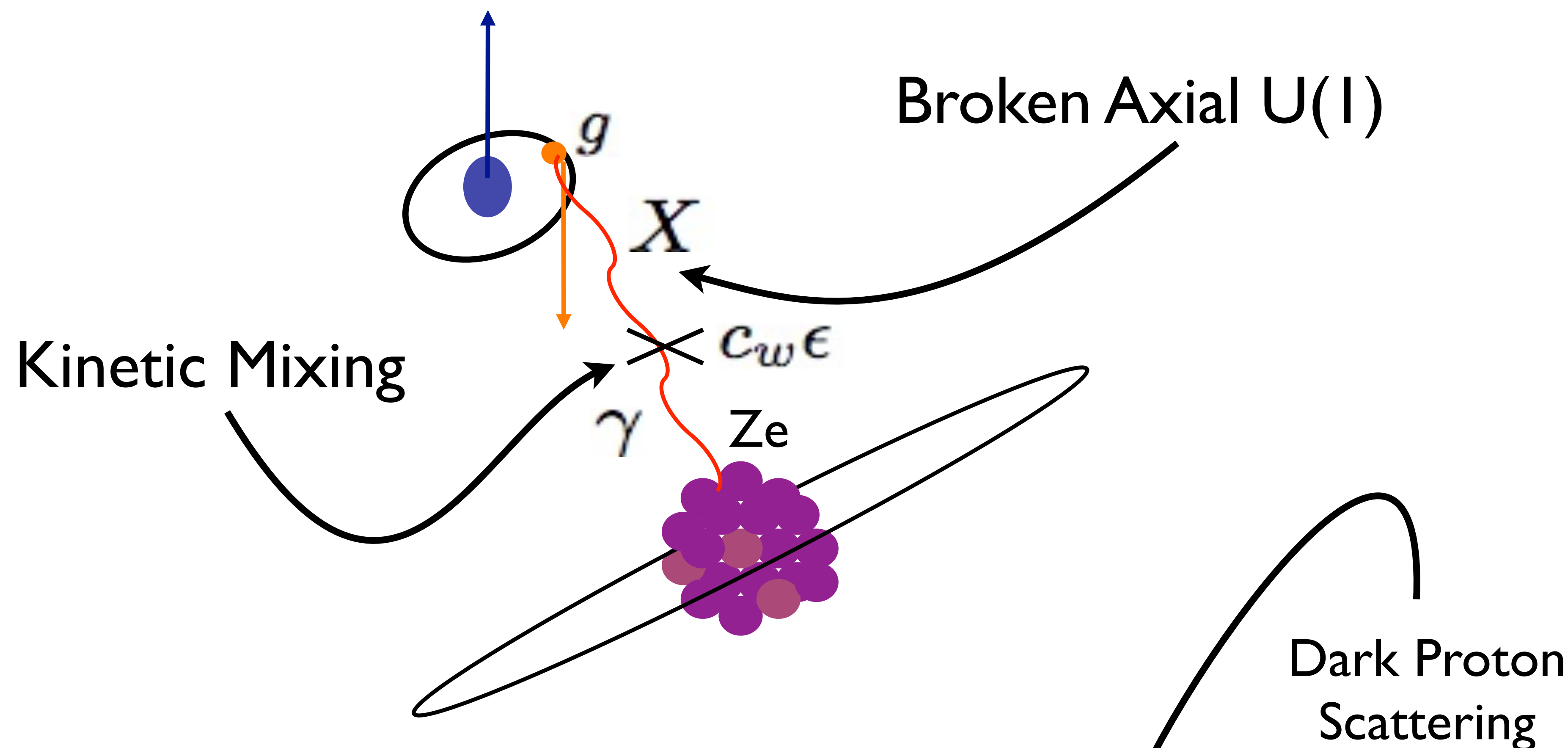


Introduce New Axial GB

$M_A \sim 1 - 10\ \mathrm{MeV}$

Along with Kinetic Mixing

DM-SM Interaction Cartoon



$$|\mathcal{M}|^2 \sim \left(\frac{g_5 e\epsilon c_w}{\vec{q}^2 + M_X^2}\right)^2 \left|C(\vec{S}_e \cdot \vec{p}_i, m_i)F_{el}(\vec{q}^2, M_H) + D(\vec{S}_p \cdot \vec{p}_i, m_i)\right|^2 |F_n|^2$$

Dark Electron Scattering

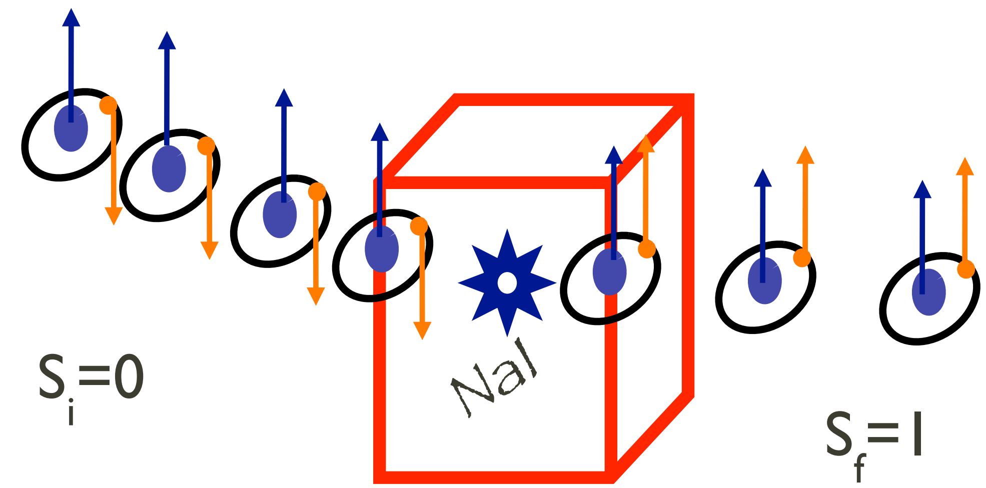
Coupling Dark Atoms to SM

Want DM to Flip Spin When Interacting with SM

$$
\begin{aligned}
\mathcal{L} &= \mathcal{L}_{SM} + \mathcal{L}_{DM} + \mathcal{L}_{Dark\,Gauge} \\
\mathcal{L}_{DM} &= \overline{\Psi}_{\mathbf{p}}(i\not\partial - g_5\gamma_5 \not X + g\not A + m_{\mathbf{p}})\Psi_{\mathbf{p}} + \\
&\quad \overline{\Psi}_{\mathbf{e}}(i\not\partial + g_5\gamma_5 \not X - g\not A + m_{\mathbf{e}})\Psi_{\mathbf{e}} - \frac{\epsilon\, s_w}{m_Z^2} J_{Z\,\mu} J_D^\mu
\end{aligned}
$$

$$
\begin{aligned}
\mathcal{L}_{Dark\,Gauge} &= -\frac{1}{4}A_{\mu\nu}^2 - \frac{1}{4}X_{\mu\nu}^2 - \\
&\quad \left(\epsilon\, c_w J^\mu_{EM} + \epsilon\, s_w \left(\frac{M_X}{m_Z}\right)^2 J_Z^\mu\right) X_\mu + \frac{M_X^2}{2} X^2
\end{aligned}
$$

$$J_D^\mu = -g_5\,\overline{\Psi}_{\mathbf{p}}\gamma^\mu\gamma_5\Psi_{\mathbf{p}} + g_5\,\overline{\Psi}_{\mathbf{e}}\gamma^\mu\gamma_5\Psi_{\mathbf{e}}$$



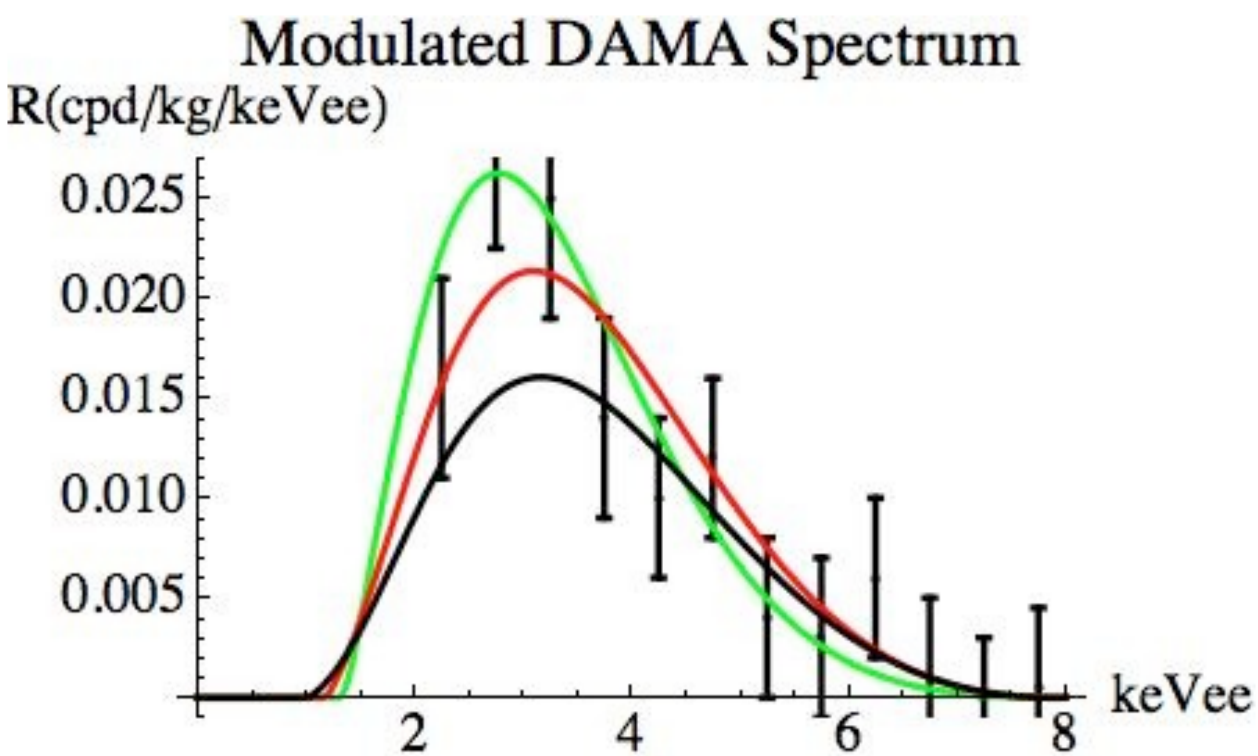
$$\delta E = E_{hf} = \frac{2}{3} g_{\mathbf{e}} g_{\mathbf{p}} \alpha_D^4 \mu_H \frac{m_{\mathbf{e}}}{m_{\mathbf{p}}}$$

Axial Vector Coupling Reduces To Spin-Spin Coupling in NR limit

Kinetic Mixing Between Broken Axial U(1) and U(1)Y lead to Scattering Between SM and DM

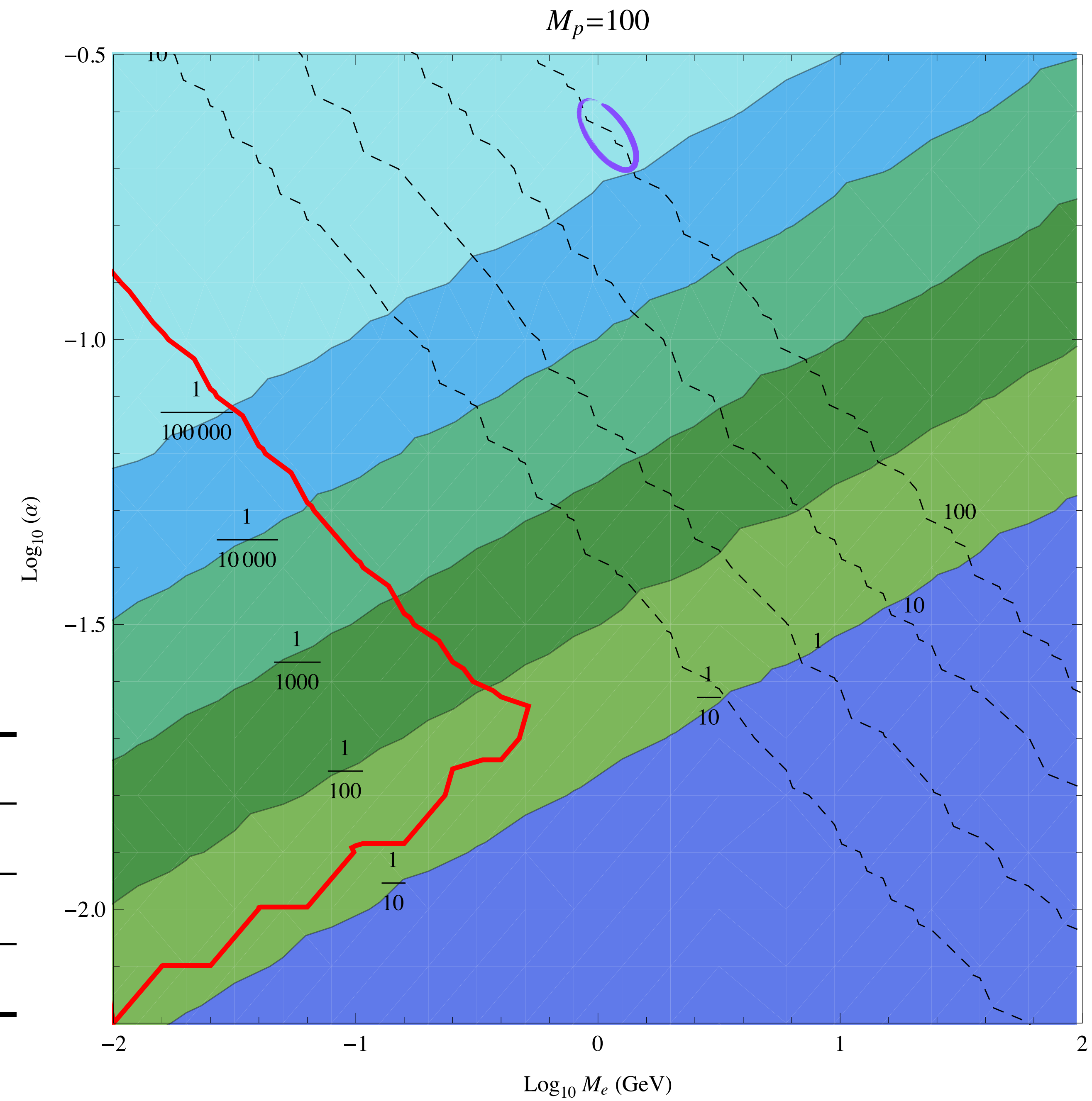
Wacker et al arXiv:0901.0557
Holdom '86

ADM Can Fit DAMA



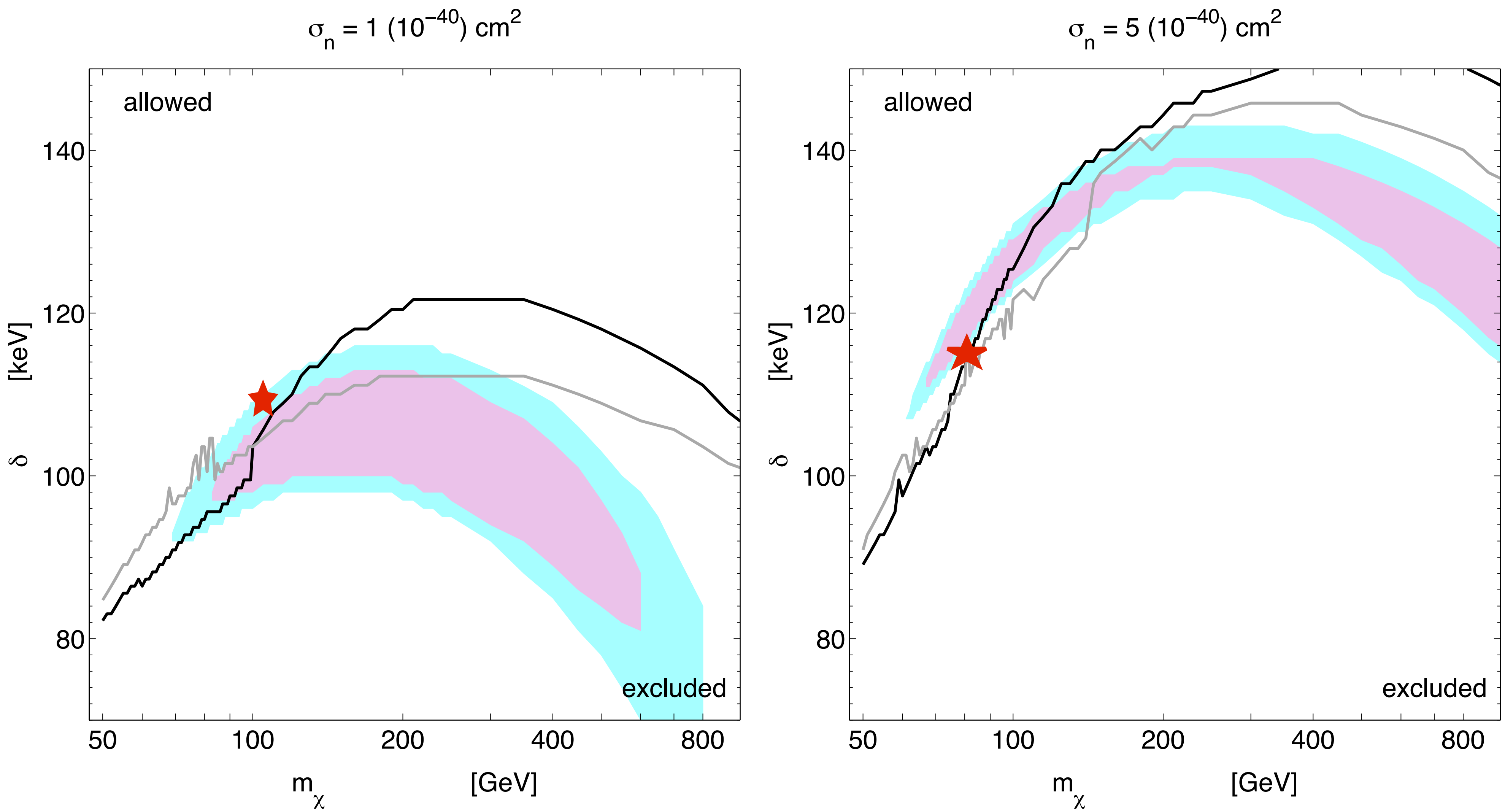
	Green	Red	Black
m_p (GeV)	70	100	200
m_e (GeV)	1.7	1.7	2.1
f_{eff} (GeV)	67	92	103

$$f_{eff}^4 = \frac{M_X^4}{2 g_5 \epsilon c_w}$$



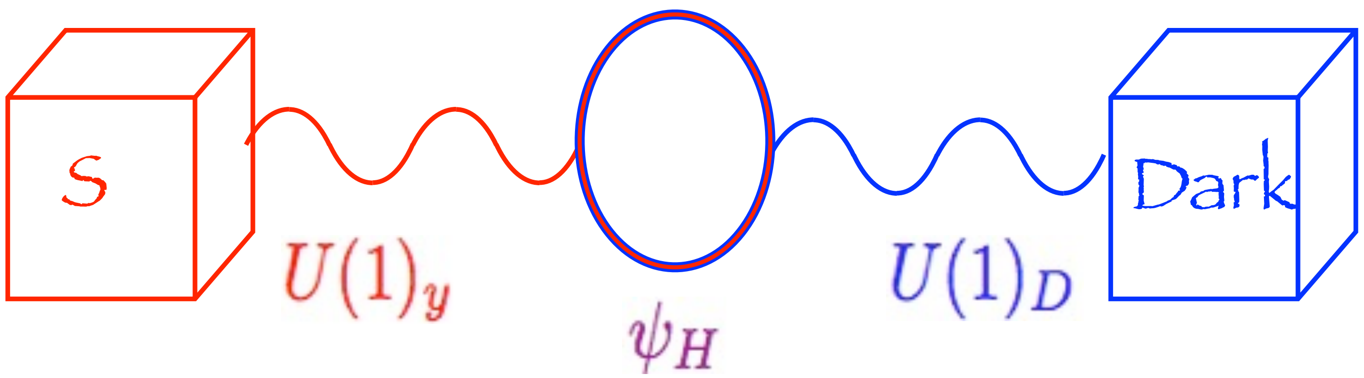
X_e <<1 => Very Small Ion Scattering Dir. Det. Rate

Bounds From Other DD Observations



XENON10 911.4438

Kinetic Mixing and Allowed Parameter Space

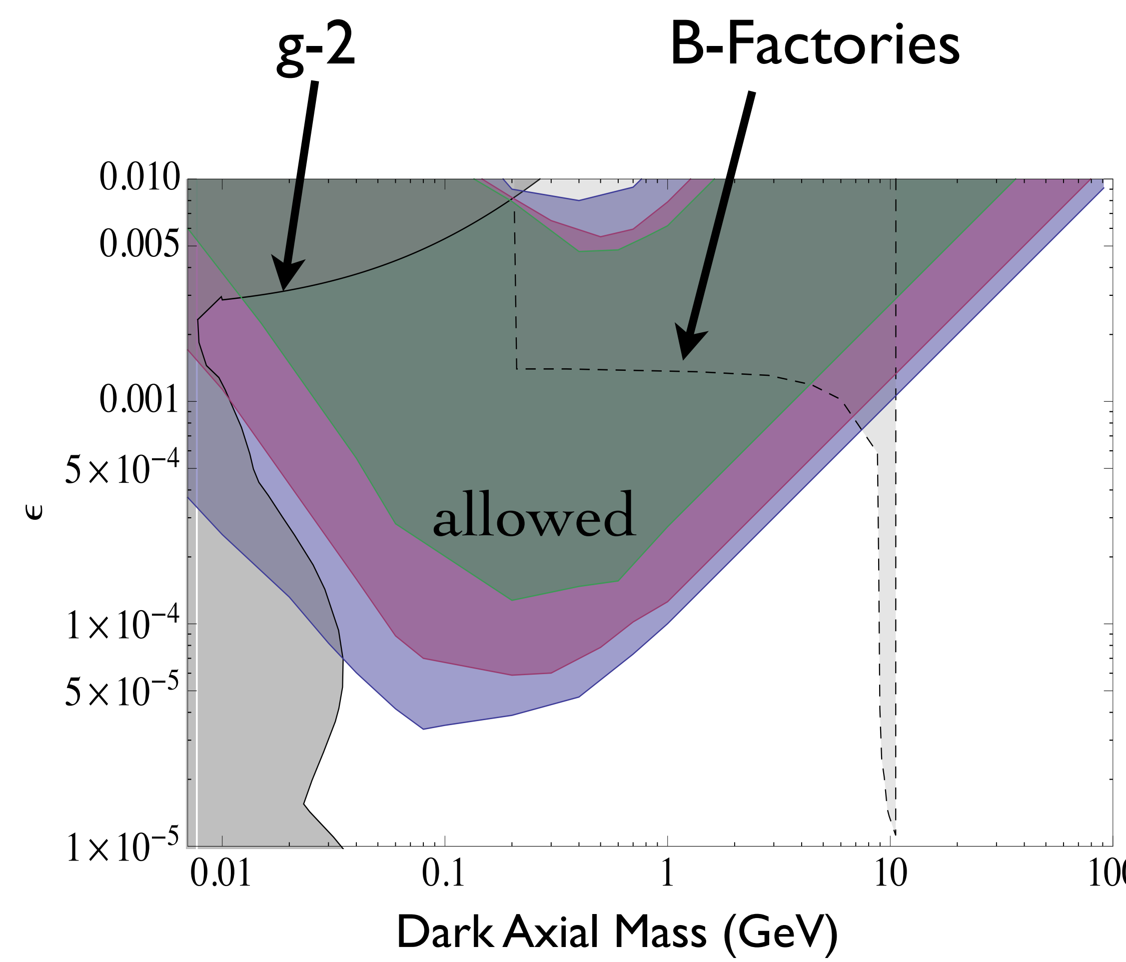


Integrate out ψ_H $\Longrightarrow$ $\mathcal{L} \ni \epsilon F_{\mu\nu,y} F_D^{\mu\nu}$

Redefine $A_\mu \rightarrow A_\mu - \epsilon A_\mu$

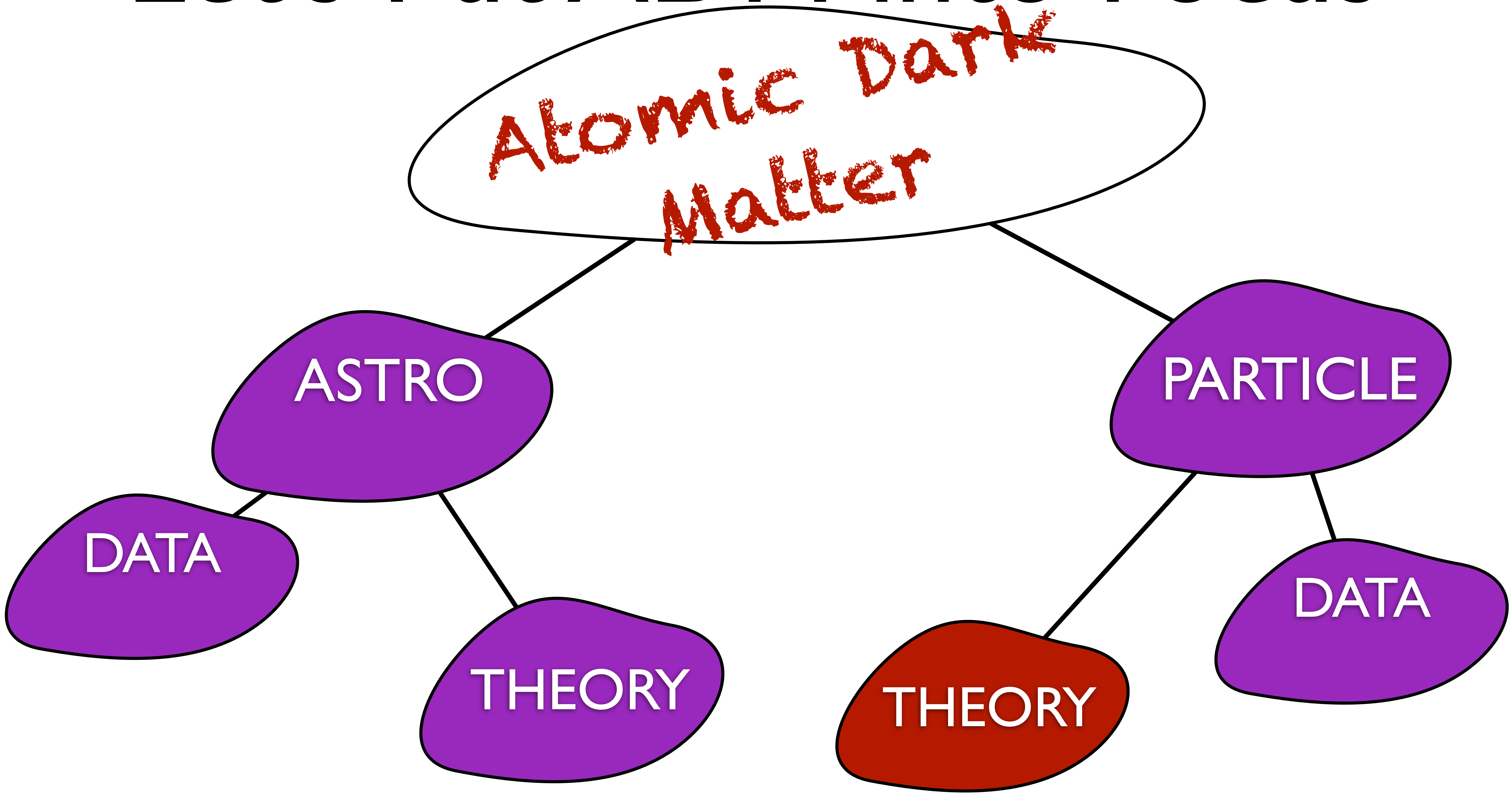
Induce coupling of SM current to A_μ

$$\mathcal{L}_{mix} = -\epsilon J_\mu^{SM} A_\mu$$



$\epsilon < (10^{-2} - 10^{-3})$ Ok for Interesting DAMA Region

Let’s Put ADM into Focus



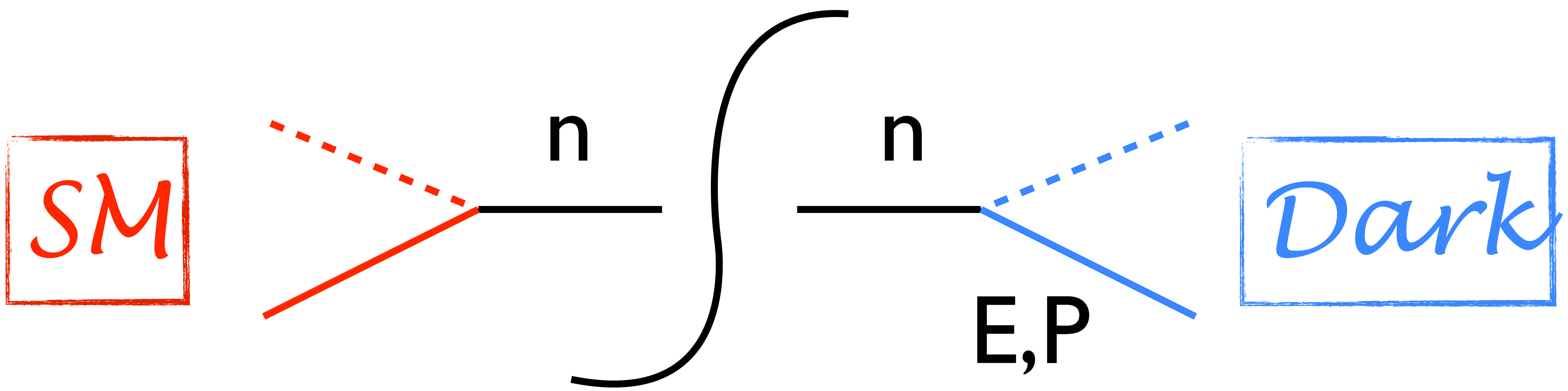
A More Complete

- Embed $U(1)_D$ to $SU(2)_D$ to avoid Landau pole below Mpl
- Introduce Higgsing Field $\mathcal{X}$
- Introduce Scalars to generate Asymmetry

	$SU(2)_D$	$U(1)_A$	$\mathcal{Z}_2$
$\mathbf{E}$	$\overline{\square}$	-1	-1
$\mathbf{E}^c$	$\square$	-2	-1
$\varphi_{\mathbf{e}}$	$\square$	1	-1
$\mathbf{P}$	$\square$	1	1
$\mathbf{P}^c$	$\overline{\square}$	2	1
$\varphi_{\mathbf{p}}$	$\overline{\square}$	-1	1
$\mathcal{X}$	Adj	3	1

Generating the Asymmetry

$$\mathcal{L} \supset -\frac{1}{2} M_n^i n_i^2 + y^{ij} n_i \ell_j h + \lambda^i_{\mathbf{e}} n_i E \varphi_{\mathbf{e}} + \lambda^i_{\mathbf{p}} n_i P \varphi_{\mathbf{p}} + y_e \mathcal{X} E E^c + y_p \mathcal{X}^\dagger P P^c + \mathrm{h.c.}$$

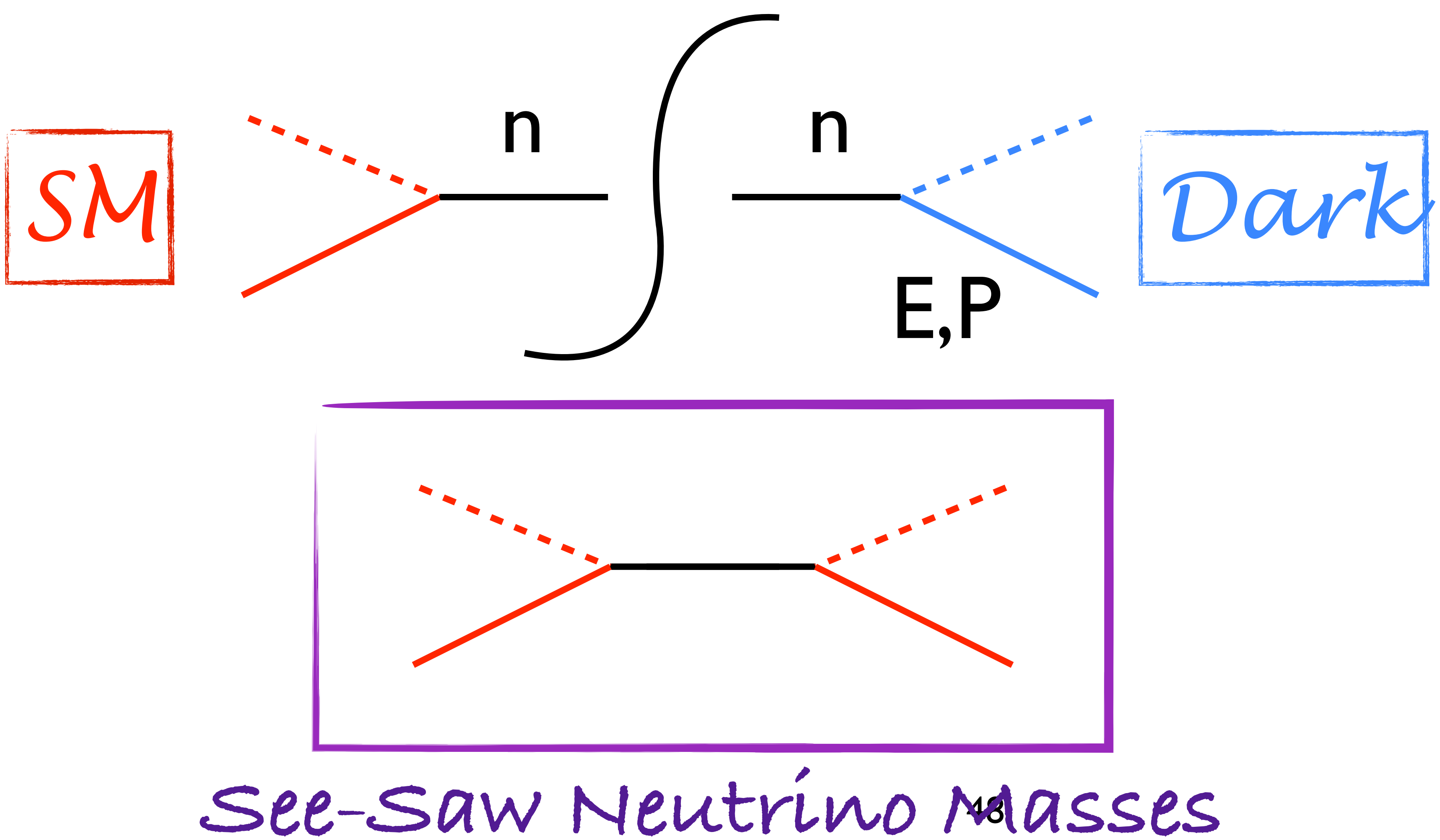


	$SU(2)_D$	$U(1)_A$	$\mathcal{Z}_2$
$\mathbf{E}$	$\overline{\Box}$	-1	-1
$\mathbf{E}^c$	$\Box$	-2	-1
$\varphi_{\mathbf{e}}$	$\Box$	1	-1
$\mathbf{P}$	$\Box$	1	1
$\mathbf{P}^c$	$\overline{\Box}$	2	1
$\varphi_{\mathbf{p}}$	$\overline{\Box}$	-1	1
$\mathcal{X}$	Adj	3	1

Falkowski et al 1101.4936
Luty PRD '91

Generating the Asymmetry

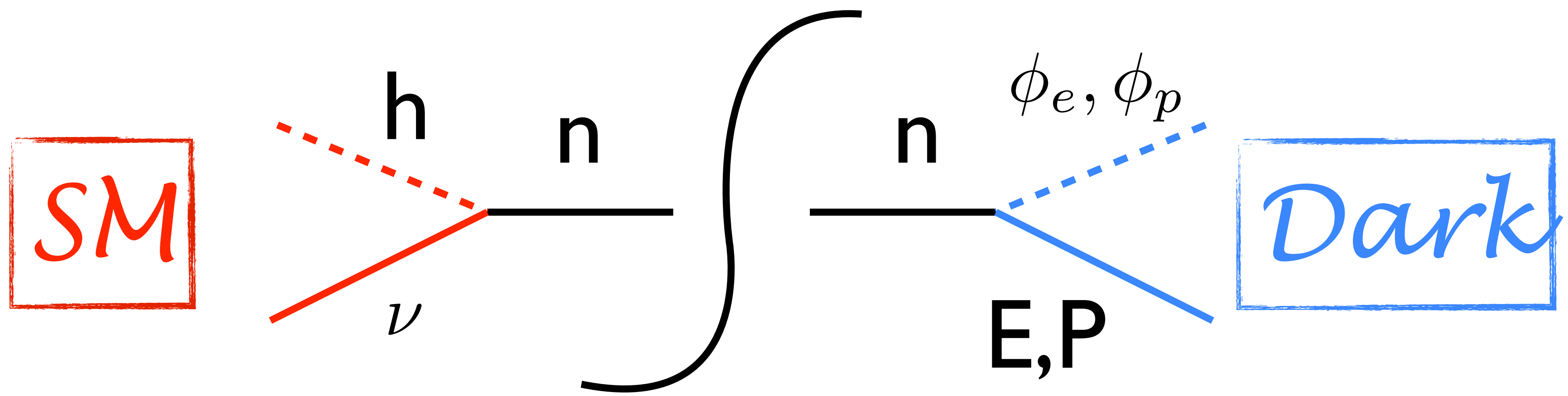
$$\mathcal{L} \supset -\frac{1}{2} M_n^i n_i^2 + y^{ij} n_i \ell_j h + \lambda_{\mathbf{e}}^i n_i E \varphi_{\mathbf{e}} + \lambda_{\mathbf{p}}^i n_i P \varphi_{\mathbf{p}} + y_e \mathcal{X} E E^c + y_p \mathcal{X}^\dagger P P^c + \text{h.c.}$$

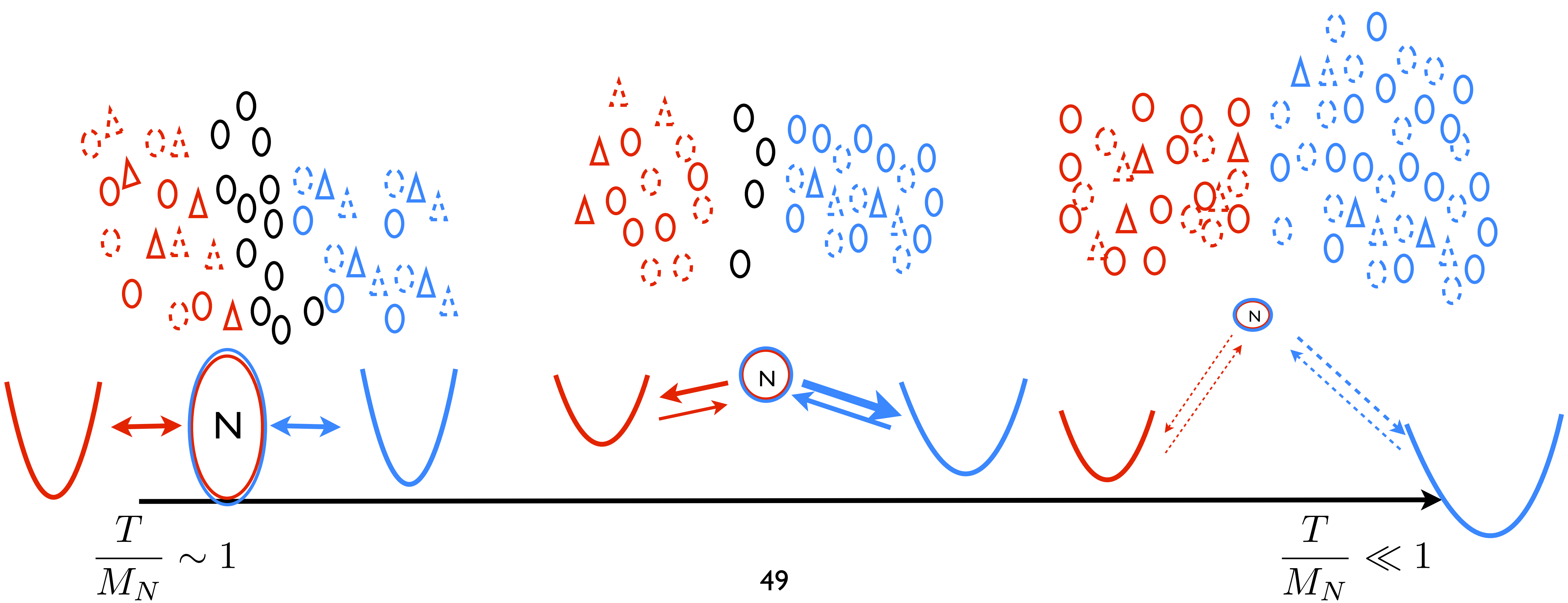


	$SU(2)_D$	$U(1)_A$	$\mathcal{Z}_2$
$\mathbf{E}$	$\overline{\square}$	-1	-1
$\mathbf{E}^c$	$\square$	-2	-1
$\varphi_{\mathbf{e}}$	$\square$	1	-1
$\mathbf{P}$	$\square$	1	1
$\mathbf{P}^c$	$\overline{\square}$	2	1
$\varphi_{\mathbf{p}}$	$\overline{\square}$	-1	1
$\mathcal{X}$	Adj	3	1

Falkowski et al 1101.4936
Luty PRD '91

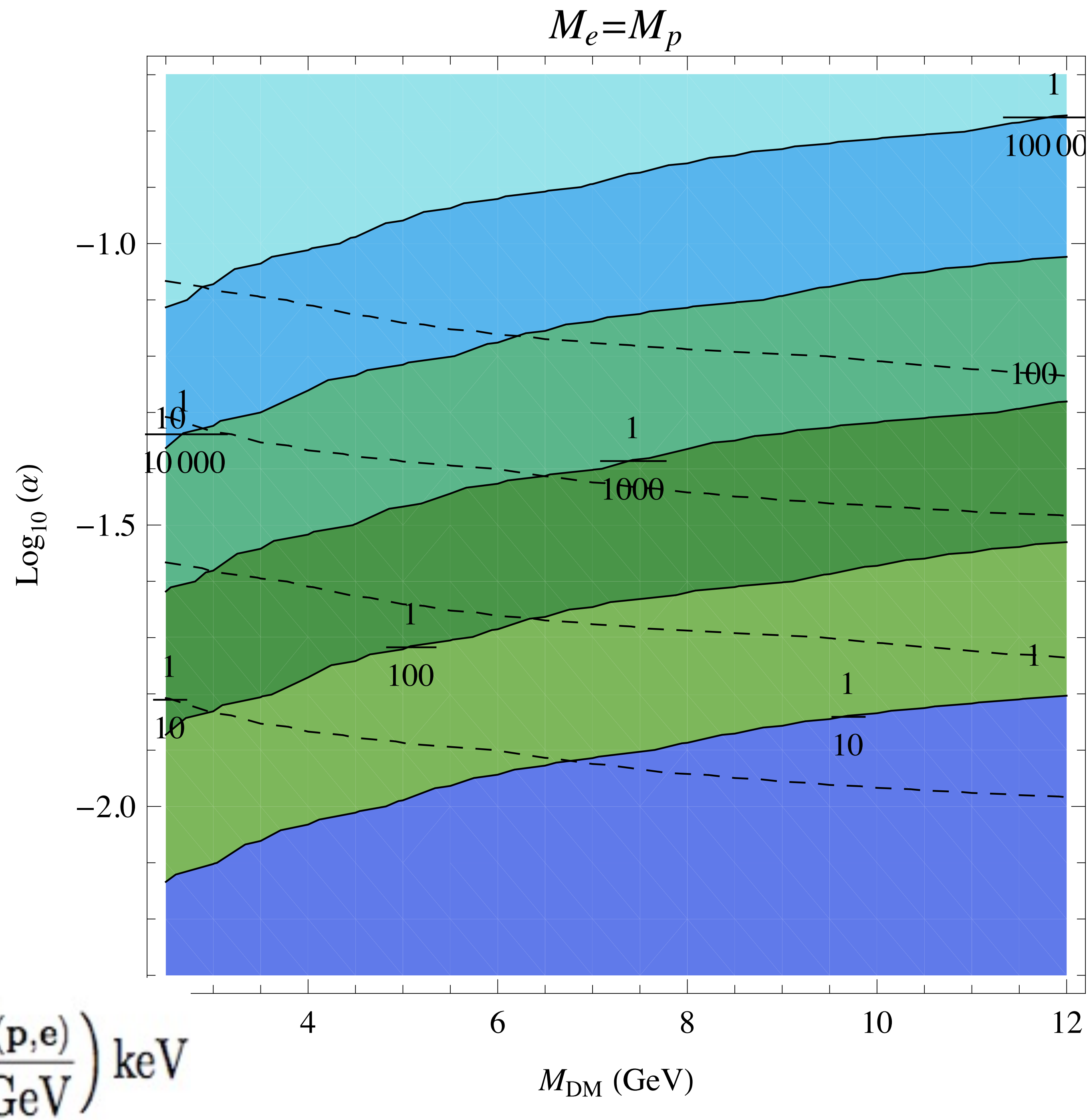
See-Saw Leptogensis





Light Dark Atoms?

- Asym Mechanism Naturally gives M_{DM}~ 10 GeV
- Parameter Space available for L~ 10 GeV Dark Atoms
- Exploring connection with DAMA and CoGENT
- Region will potentially interesting Structure formation



$$T_{dec,\,(\mathbf{p},\mathbf{e})\mathrm{H}} \simeq 0.1 \left(\frac{1}{X_{\mathbf{e}}}\right)^{2/3} \alpha_D^{4/3} \left(\frac{m_{(\mathbf{e},\mathbf{p})}}{1\,\mathrm{GeV}}\right)^{4/3} \left(\frac{m_{(\mathbf{p},\mathbf{e})}}{1\,\mathrm{GeV}}\right) \mathrm{keV}$$

ADM Conclusions

ASTRO

- ADM is Cosmologically Viable
- Interesting and Varying Dynamics, Largely Governed by Xe
- May Have Observable Consequences on Galactic and Sub-Galactic Scales
- Explicit Example of Allowed Variability in "CDM"

PARTICLE

- Can be "Modular" relative to Astro Considerations
- Explicit Example Offers Possible Explanation of DAMA Data
- Possible Multi-Channel Signal, Ion-SM and Atom-SM Scattering, Depending on Xe