Title: Old Physics, New Tricks, and the Theory of Atomic Dark Matter

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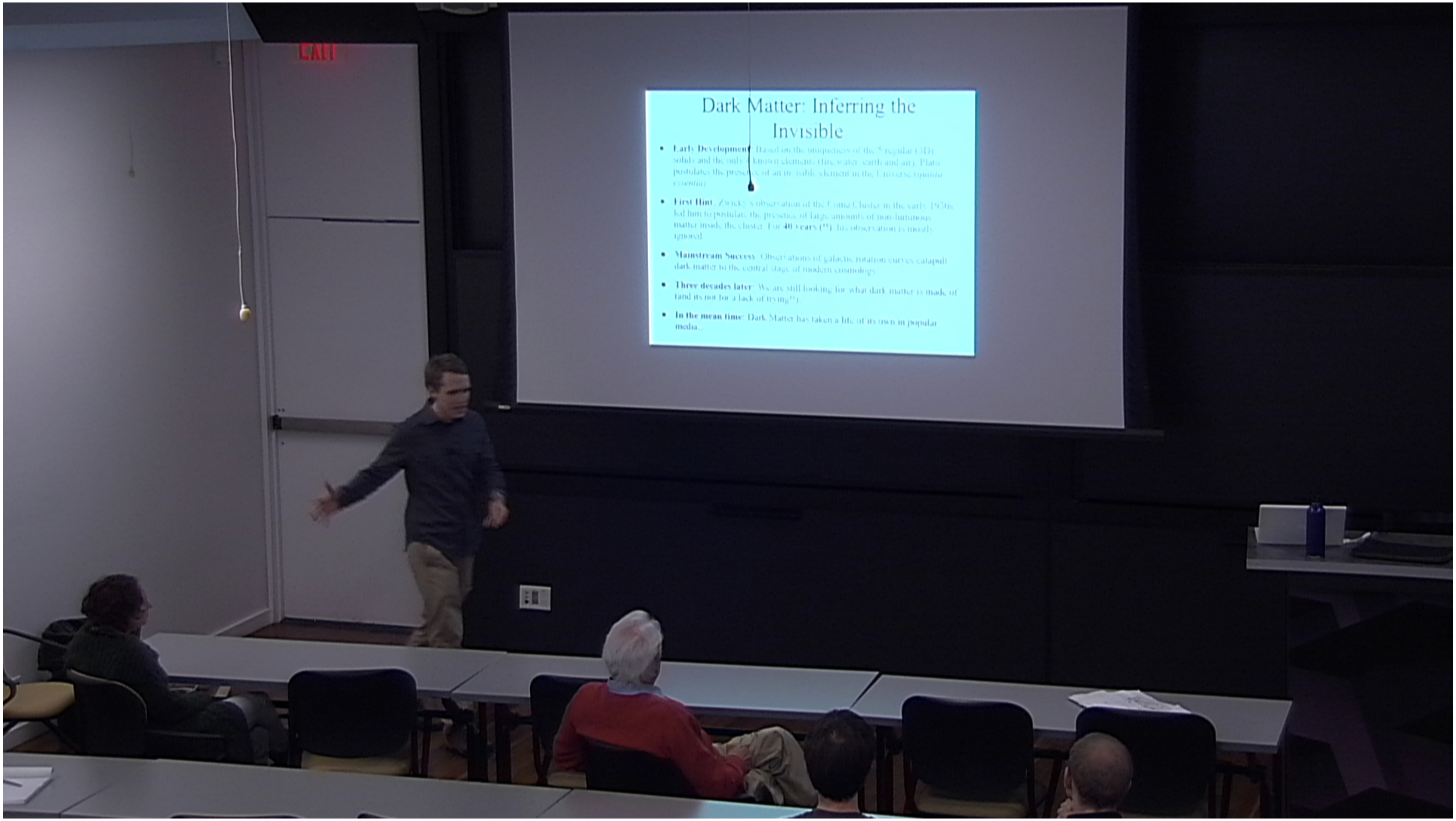
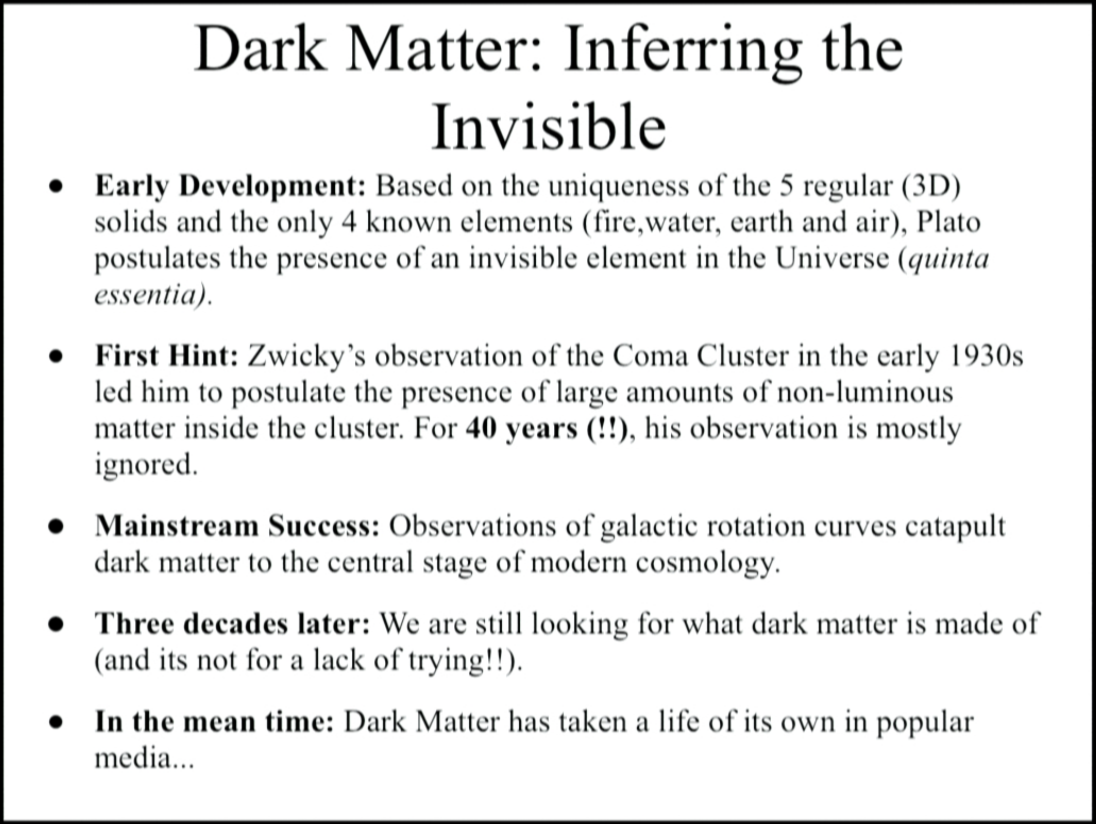
Abstract: Cold dark matter (CDM) is a central pillar of the current cosmological paradigm. While CDM



Dark Matter: Inferring the Invisible

- **Early Development**: Based on the uniqueness of the 5 regular (3D) solids and the only 4 known elements (fire, water, earth and air), Plato postulates the presence of an invisible element in the Universe (*quinta essentia*)
- **First Hint**: Zwicky's observation of the Coma Cluster in the early 1930s led him to postulate the presence of large amounts of non-luminous matter inside the cluster. For **40 years (!!)**, his observation is mostly ignored
- **Mainstream Success**: Observations of galactic rotation curves catapult dark matter to the central stage of modern cosmology
- **Three decades later**: We are still looking for what dark matter is made of (and its not for a lack of trying!!).
- **In the mean time**: Dark Matter has taken a life of its own in popular media..



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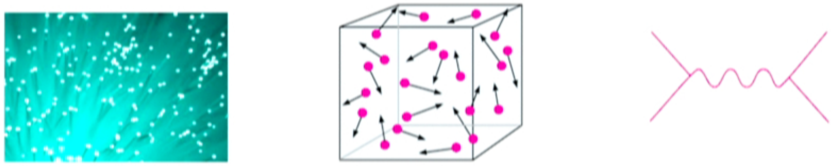
Dark Matter is now part of popular culture...

...Yet we still do not know what it is.

- It comprises about 83% of all matter in the observable Universe.
- We only have observed dark matter through its gravitational interaction (worrying?).

$$\boxed{\text{Modified Gravity ?}} \longrightarrow G_{\mu\nu} = 8\pi G\, T_{\mu\nu} \longleftarrow \boxed{\text{Dark Matter ?}}$$

- It appears cold (negligible free-streaming), collisionless (negligible heat transfer) and non-interacting (neutral).



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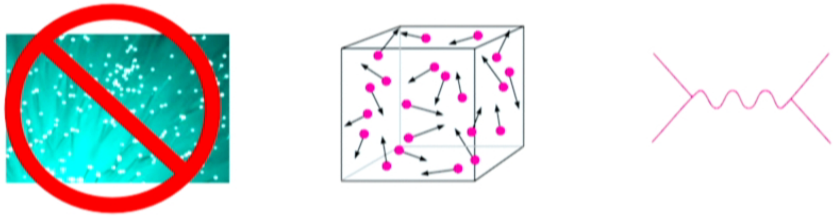

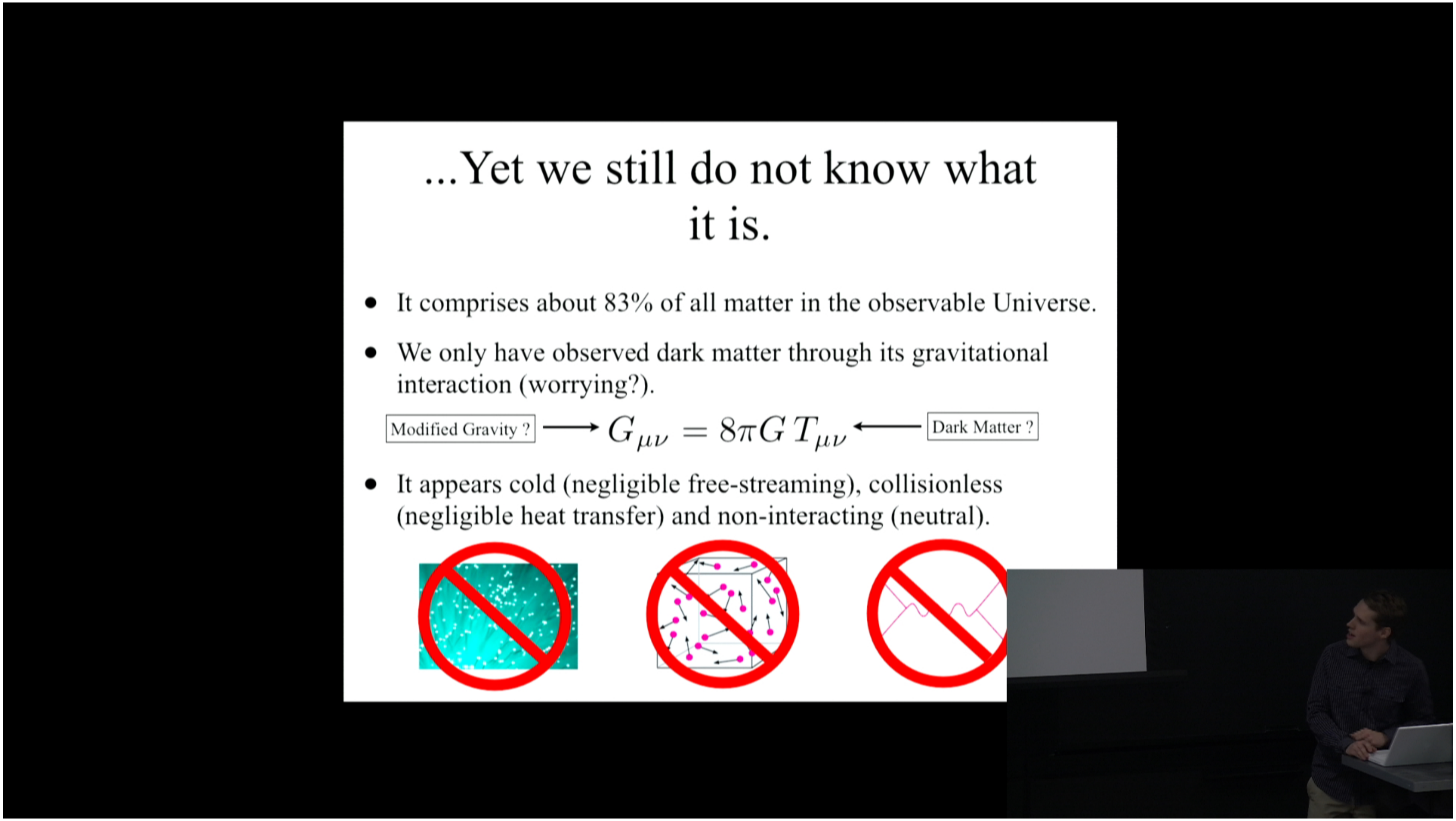

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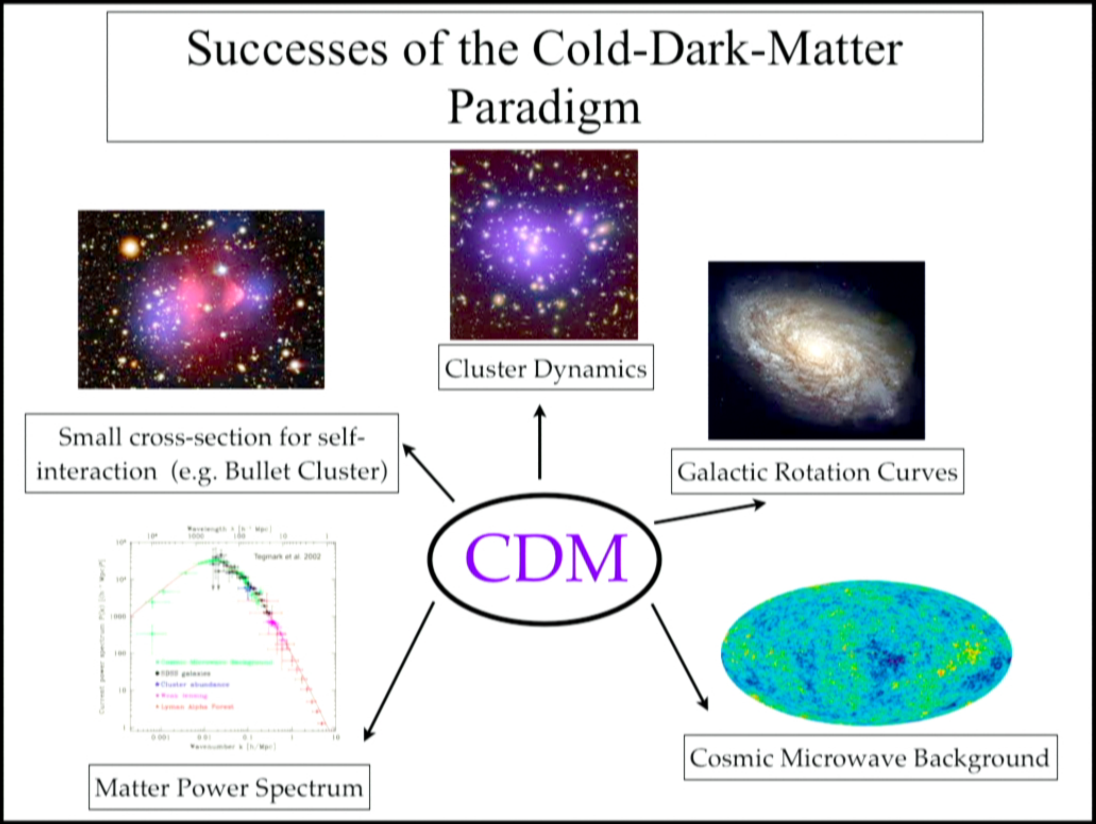


Successes of the Cold-Dark-Matter Paradigm

CDM

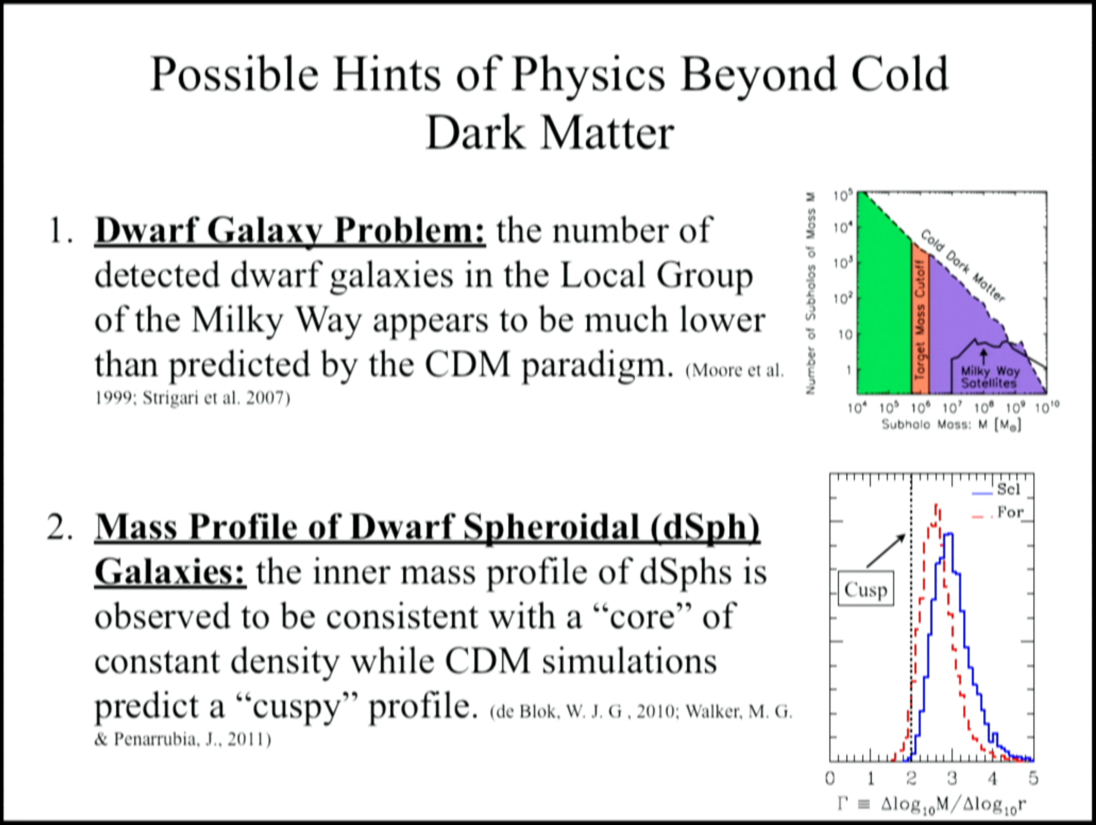
Cluster Dynamics

Small cross-section for self-interaction (e.g. Bullet Cluster)

Galactic Rotation Curves

Matter Power Spectrum

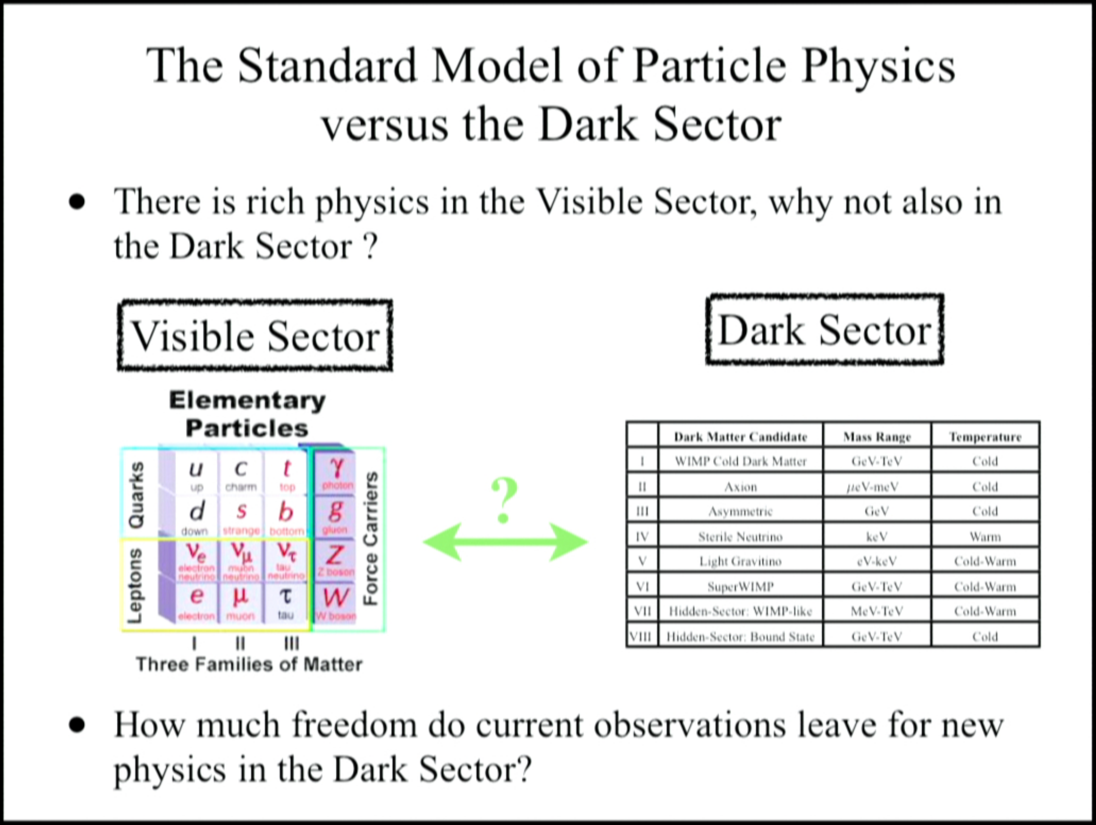
Cosmic Microwave Background



Possible Hints of Physics Beyond Cold Dark Matter

1. **Dwarf Galaxy Problem:** the number of detected dwarf galaxies in the Local Group of the Milky Way appears to be much lower than predicted by the CDM paradigm. (Moore et al. 1999; Strigari et al. 2007)

2. **Mass Profile of Dwarf Spheroidal (dSph) Galaxies:** the inner mass profile of dSphs is observed to be consistent with a "core" of constant density while CDM simulations predict a "cuspy" profile. (de Blok, W. J. G , 2010; Walker, M. G. & Penarrubia, J., 2011)



The Standard Model of Particle Physics versus the Dark Sector

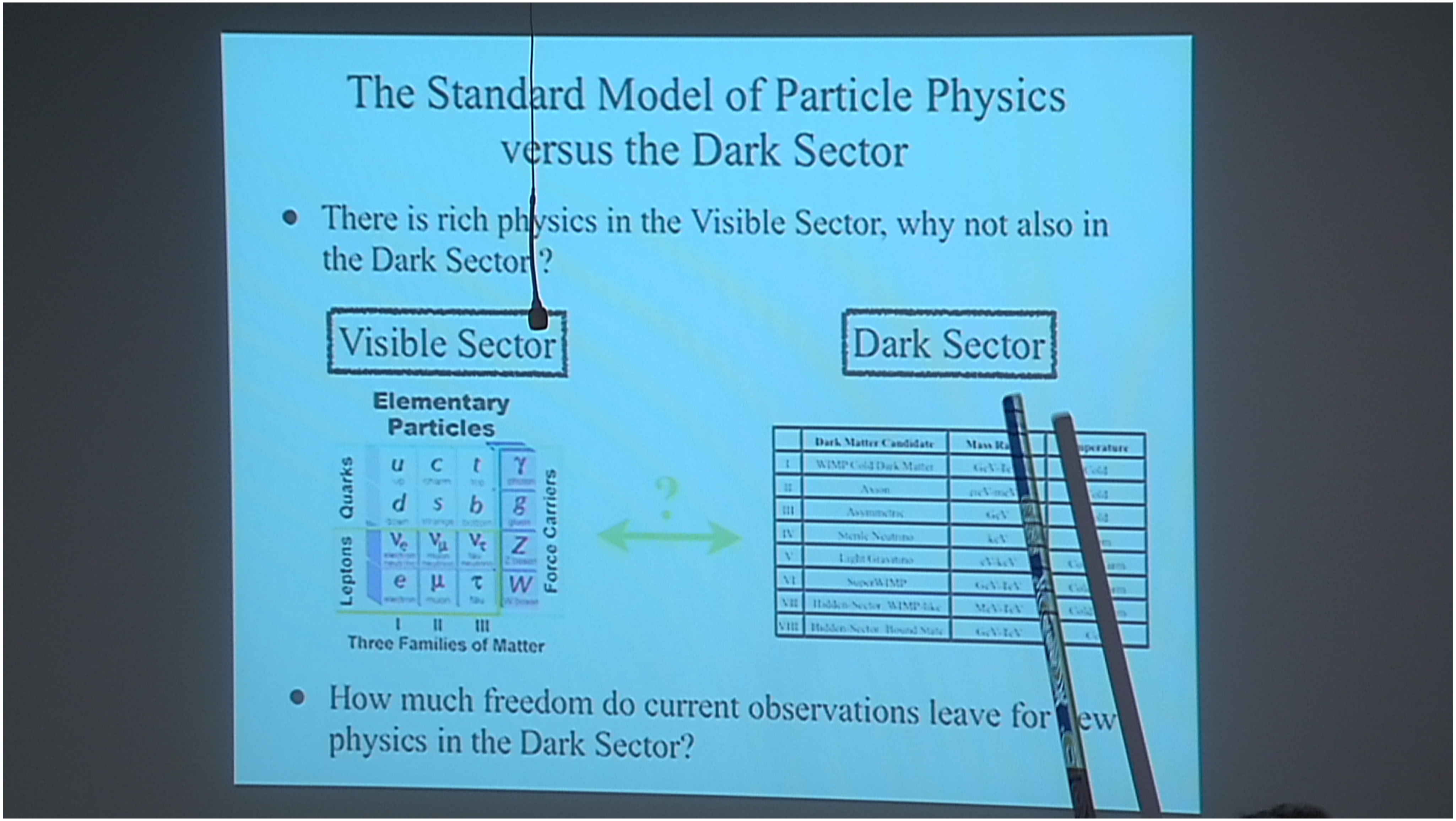
- There is rich physics in the Visible Sector, why not also in the Dark Sector ?

Visible Sector

Dark Sector

	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV-TeV	Cold
II	Axion	μeV-meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV-keV	Cold-Warm
VI	SuperWIMP	GeV-TeV	Cold-Warm
VII	Hidden-Sector: WIMP-like	MeV-TeV	Cold-Warm
VIII	Hidden-Sector: Bound State	GeV-TeV	Cold

- How much freedom do current observations leave for new physics in the Dark Sector?



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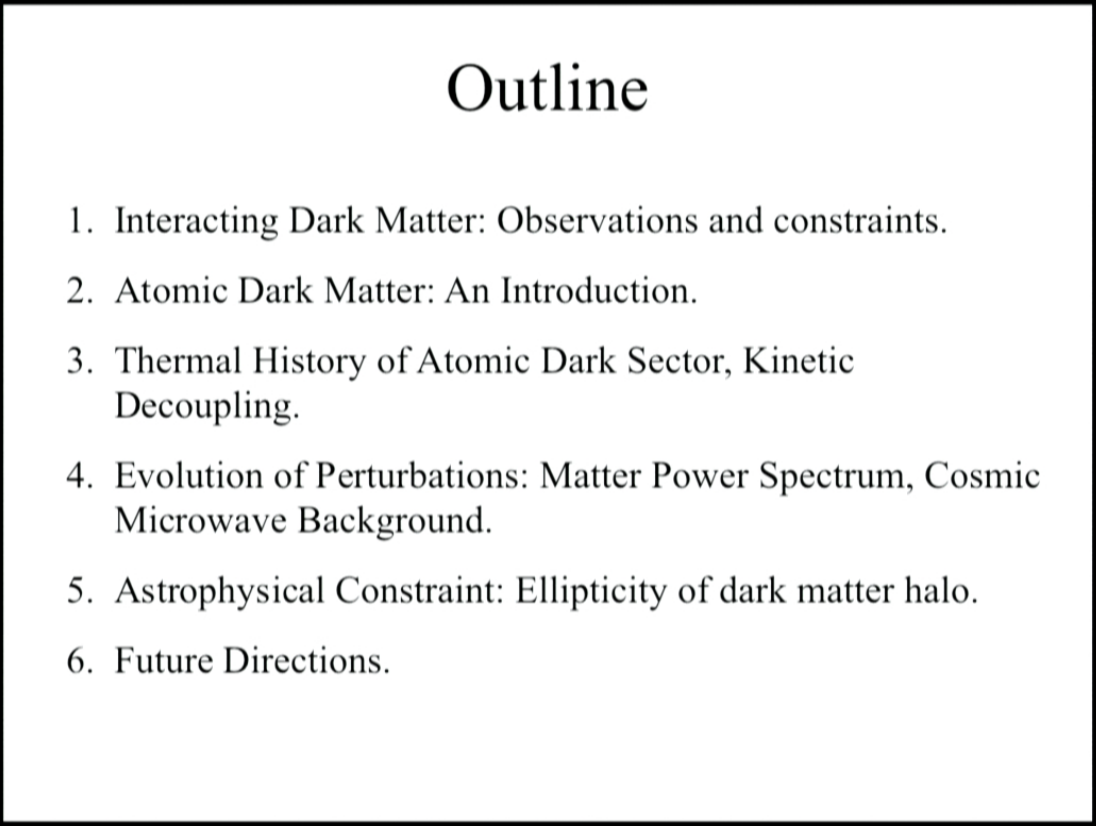
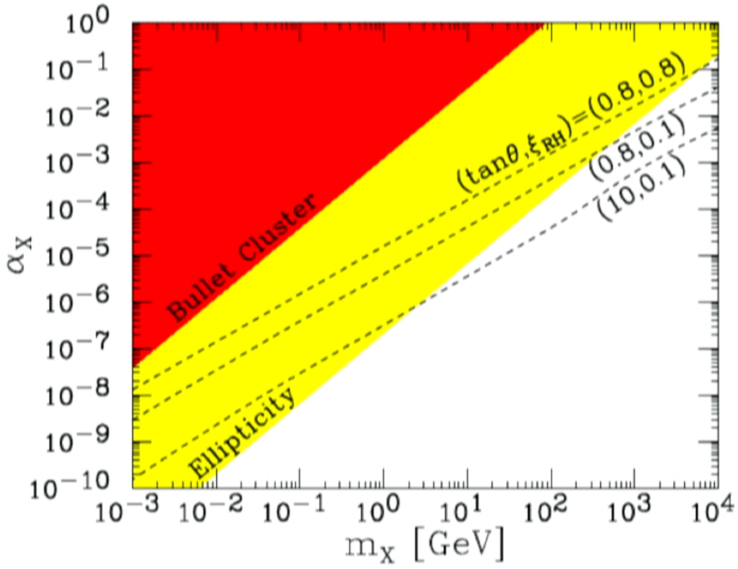


Outline

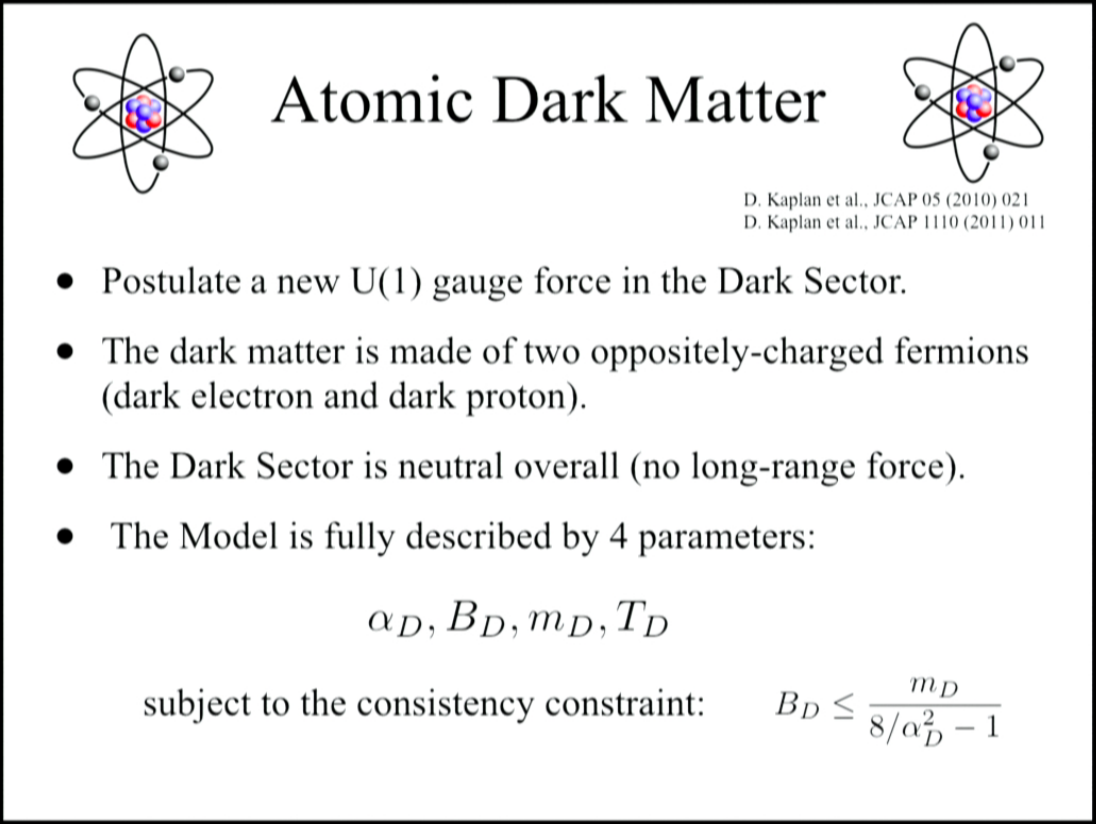
1. Interacting Dark Matter: Observations and constraints.
2. Atomic Dark Matter: An Introduction.
3. Thermal History of Atomic Dark Sector, Kinetic Decoupling.
4. Evolution of Perturbations: Matter Power Spectrum, Cosmic Microwave Background.
5. Astrophysical Constraint: Ellipticity of dark matter halo.
6. Future Directions.

Interacting Dark Matter

Interacting dark matter is viable if it is weakly interacting and has a large mass:



Feng et al. 2009



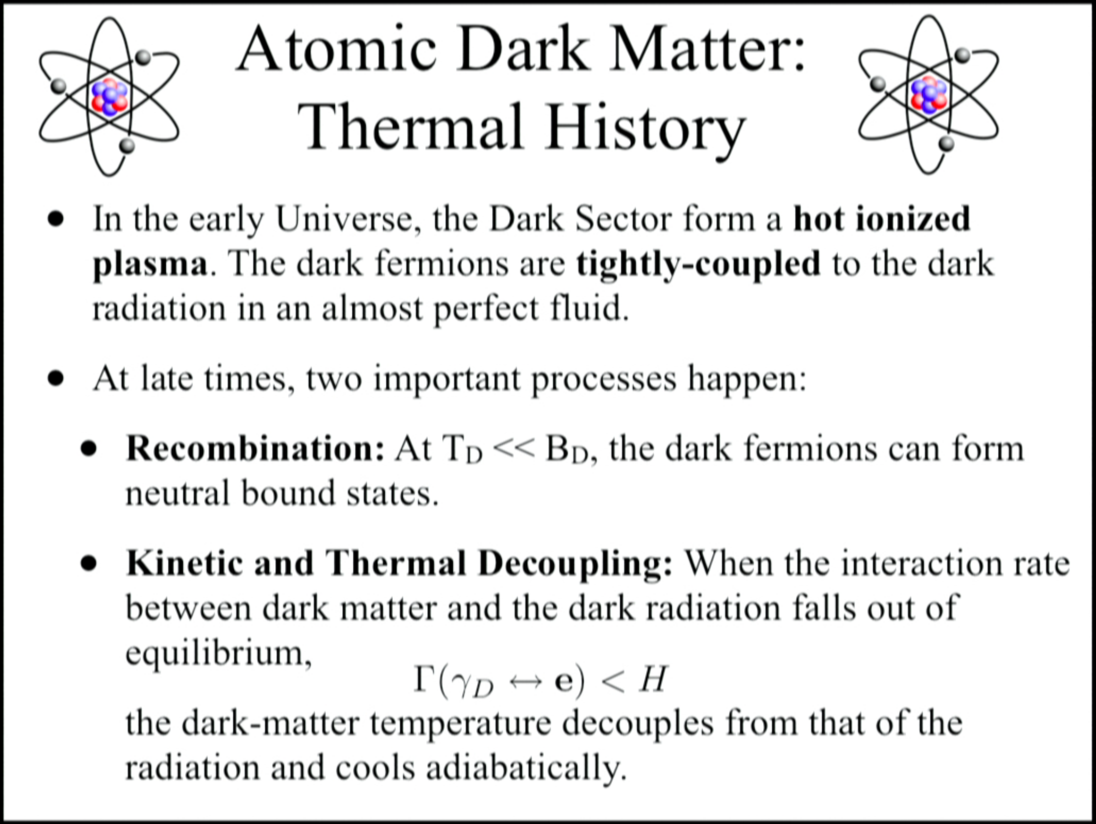
Atomic Dark Matter

D. Kaplan et al., JCAP 05 (2010) 021
D. Kaplan et al., JCAP 1110 (2011) 011

- Postulate a new U(1) gauge force in the Dark Sector.
- The dark matter is made of two oppositely-charged fermions (dark electron and dark proton).
- The Dark Sector is neutral overall (no long-range force).
- The Model is fully described by 4 parameters:

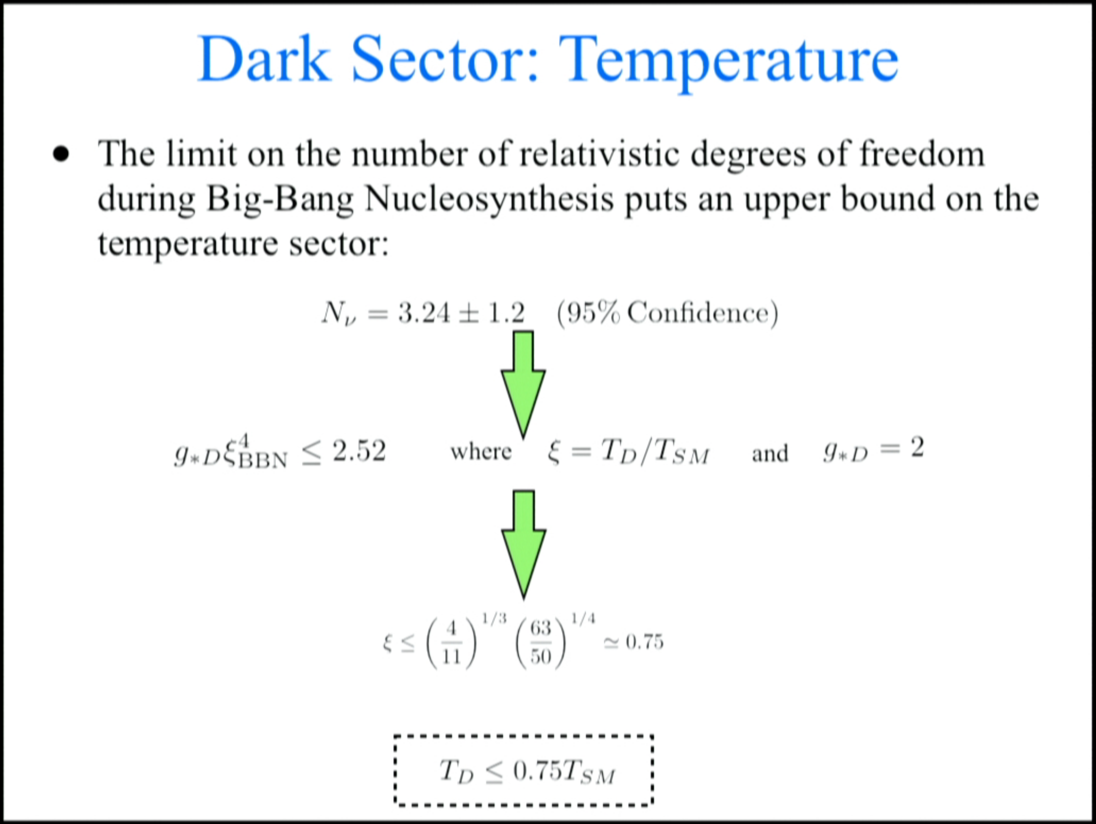
$$\alpha_D, B_D, m_D, T_D$$

subject to the consistency constraint: $B_D \leq \dfrac{m_D}{8/\alpha_D^2 - 1}$



Atomic Dark Matter: Thermal History

- In the early Universe, the Dark Sector form a **hot ionized plasma**. The dark fermions are **tightly-coupled** to the dark radiation in an almost perfect fluid.
- At late times, two important processes happen:
  - **Recombination:** At $T_D << B_D$, the dark fermions can form neutral bound states.
  - **Kinetic and Thermal Decoupling:** When the interaction rate between dark matter and the dark radiation falls out of equilibrium,
  $$\Gamma(\gamma_D \leftrightarrow \mathbf{e}) < H$$
  the dark-matter temperature decouples from that of the radiation and cools adiabatically.



Dark Sector: Temperature

- The limit on the number of relativistic degrees of freedom during Big-Bang Nucleosynthesis puts an upper bound on the temperature sector:

$$N_\nu = 3.24 \pm 1.2 \quad (95\%\ \text{Confidence})$$

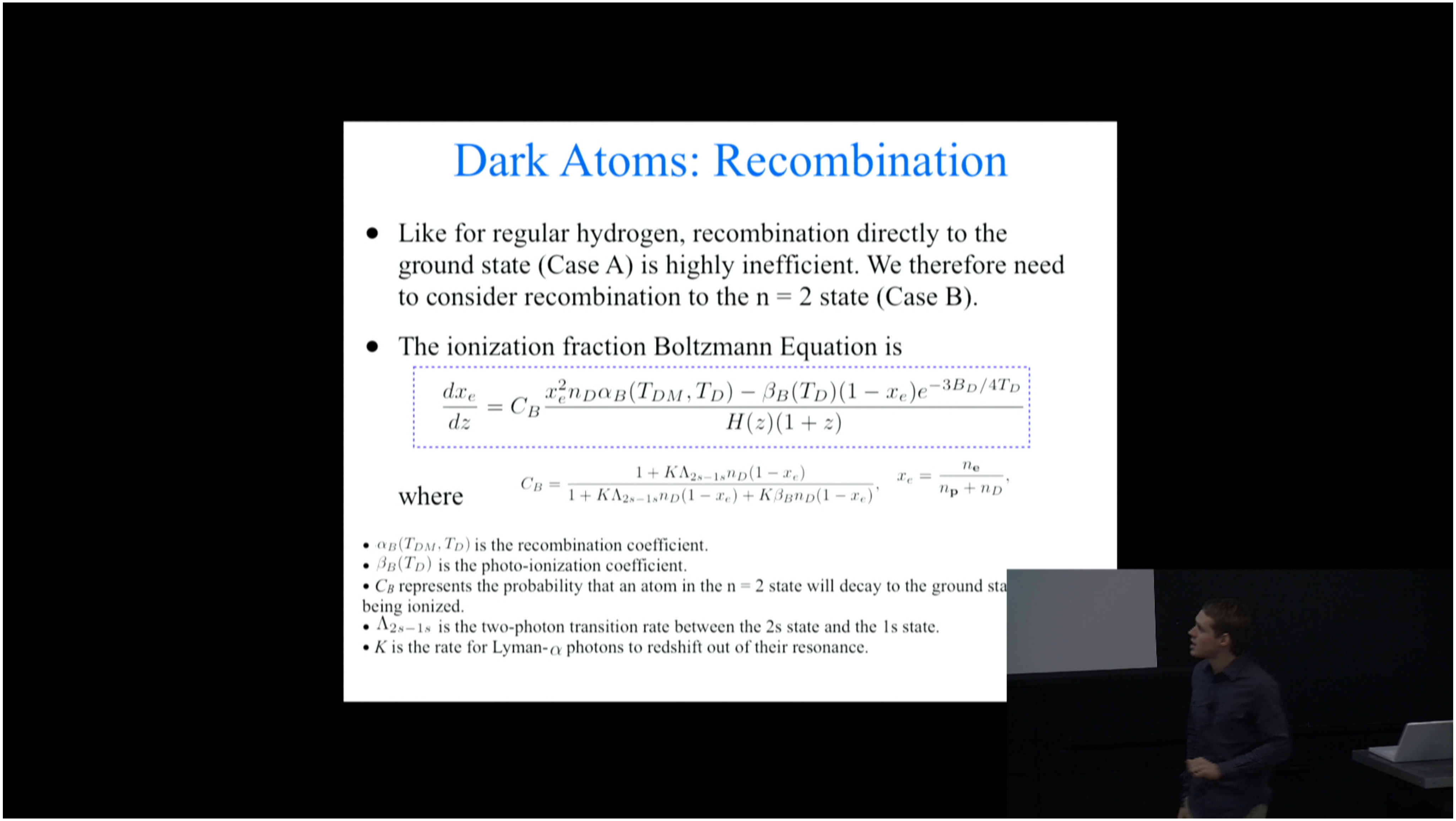
$$\Downarrow$$

$$g_{*D}\xi^4_{\rm BBN} \leq 2.52 \qquad \text{where} \quad \xi = T_D/T_{SM} \quad \text{and} \quad g_{*D} = 2$$

$$\Downarrow$$

$$\xi \leq \left(\frac{4}{11}\right)^{1/3}\left(\frac{63}{50}\right)^{1/4} \simeq 0.75$$

$$\boxed{T_D \leq 0.75 T_{SM}}$$



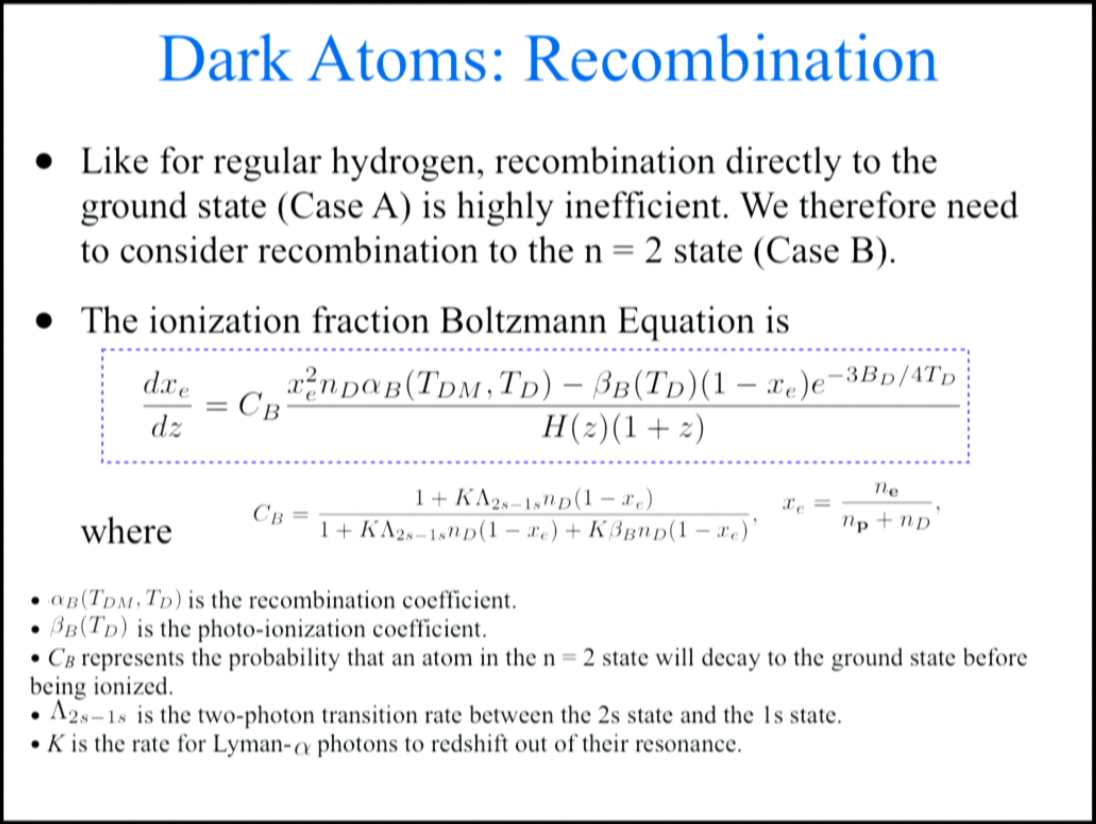
Dark Atoms: Recombination

- Like for regular hydrogen, recombination directly to the ground state (Case A) is highly inefficient. We therefore need to consider recombination to the n = 2 state (Case B).
- The ionization fraction Boltzmann Equation is

$$\boxed{\frac{dx_e}{dz} = C_B \frac{x_e^2 n_D \alpha_B(T_{DM}, T_D) - \beta_B(T_D)(1 - x_e)e^{-3B_D/4T_D}}{H(z)(1+z)}}$$

where $C_B = \frac{1 + K\Lambda_{2s-1s} n_D (1 - x_e)}{1 + K\Lambda_{2s-1s} n_D (1 - x_e) + K\beta_B n_D (1 - x_e)}, \quad x_e = \frac{n_{\mathbf{e}}}{n_{\mathbf{p}} + n_D},$

- $\alpha_B(T_{DM}, T_D)$ is the recombination coefficient.
- $\beta_B(T_D)$ is the photo-ionization coefficient.
- C_B represents the probability that an atom in the n = 2 state will decay to the ground sta being ionized.
- Λ_{2s-1s} is the two-photon transition rate between the 2s state and the 1s state.
- K is the rate for Lyman-α photons to redshift out of their resonance.



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- $\alpha_B(T_{DM}, T_D)$ is the recombination coefficient.
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- C_B represents the probability that an atom in the n = 2 state will decay to the ground state before being ionized.
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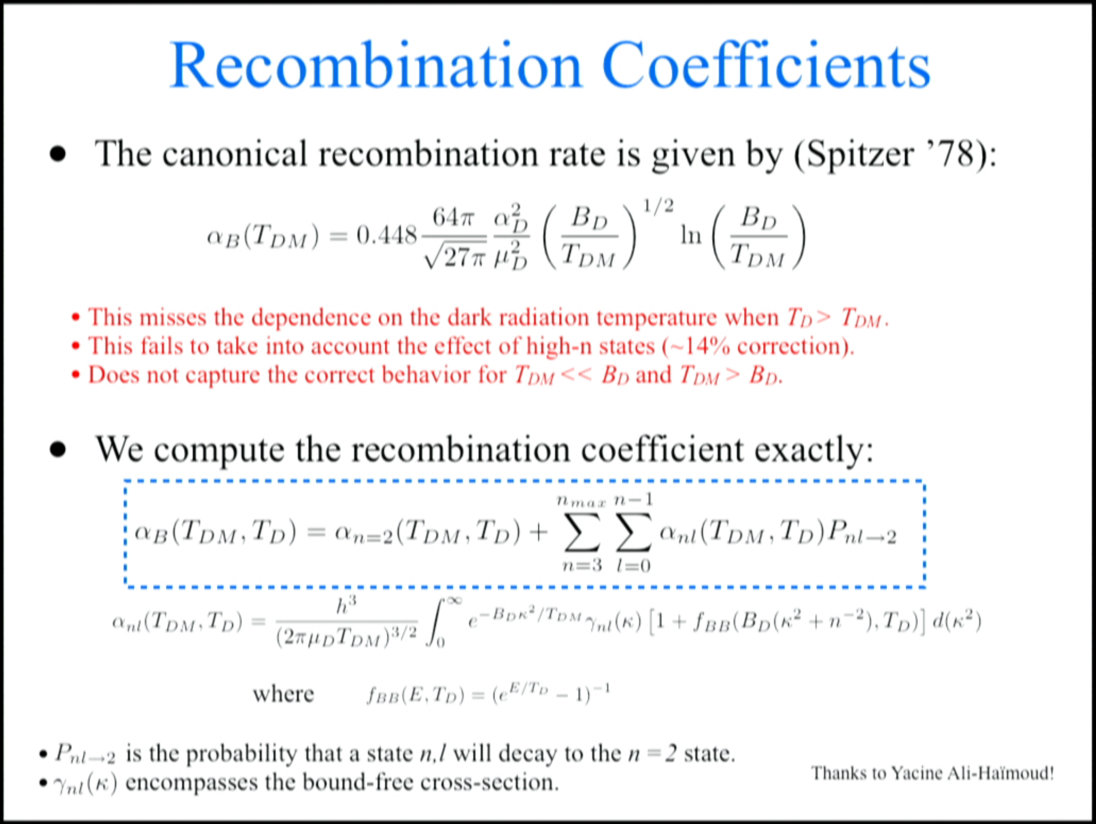


Recombination Coefficients

- The canonical recombination rate is given by (Spitzer '78):

$$\alpha_B(T_{DM}) = 0.448\frac{64\pi}{\sqrt{27\pi}}\frac{\alpha_D^2}{\mu_D^2}\left(\frac{B_D}{T_{DM}}\right)^{1/2}\ln\left(\frac{B_D}{T_{DM}}\right)$$

- This misses the dependence on the dark radiation temperature when $T_D > T_{DM}$.
- This fails to take into account the effect of high-n states (~14% correction).
- Does not capture the correct behavior for $T_{DM} << B_D$ and $T_{DM} > B_D$.

- We compute the recombination coefficient exactly:

$$\boxed{\alpha_B(T_{DM}, T_D) = \alpha_{n=2}(T_{DM}, T_D) + \sum_{n=3}^{n_{max}}\sum_{l=0}^{n-1}\alpha_{nl}(T_{DM}, T_D)P_{nl\to 2}}$$

$$\alpha_{nl}(T_{DM}, T_D) = \frac{h^3}{(2\pi\mu_D T_{DM})^{3/2}}\int_0^\infty e^{-B_D\kappa^2/T_{DM}}\gamma_{nl}(\kappa)\left[1 + f_{BB}(B_D(\kappa^2 + n^{-2}), T_D)\right]d(\kappa^2)$$

where $f_{BB}(E, T_D) = (e^{E/T_D} - 1)^{-1}$

- $P_{nl\to 2}$ is the probability that a state n,l will decay to the $n = 2$ state.
- $\gamma_{nl}(\kappa)$ encompasses the bound-free cross-section.

Thanks to Yacine Ali-Haïmoud!

Recombination Coefficients

- We compute the rate on a grid of T_D/B_D and T_{DM}/T_D up to $n_{max}=200$ and find a fitting formula of the form:

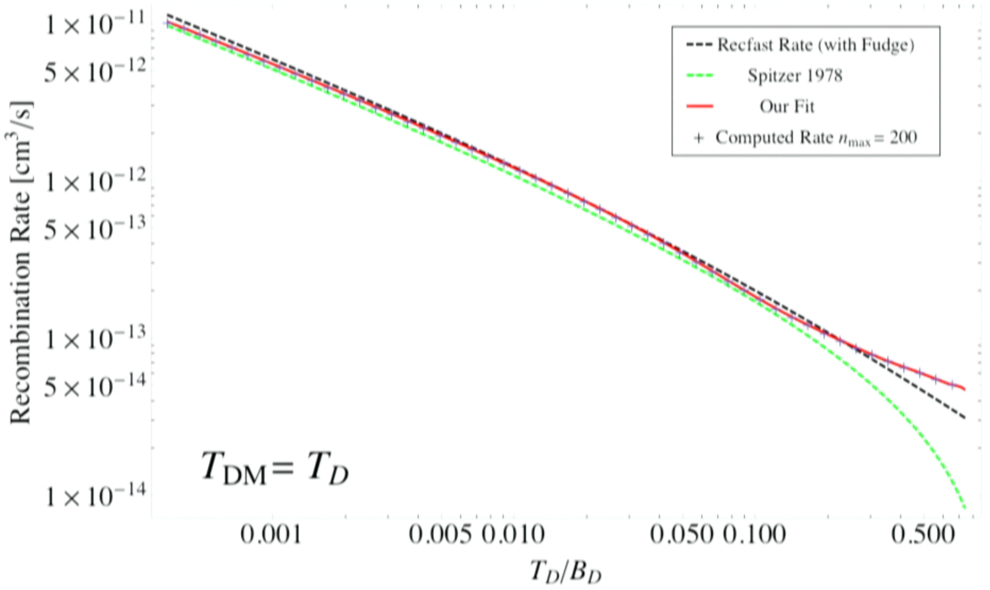
$$\alpha_B(T_{DM},T_D) = \frac{2\alpha_D^3 h^2 c^3}{3(2\pi\mu_D)^{3/2}\sqrt{T_{DM}}} F_{n_{max}}\left(\frac{T_D}{B_D},\frac{T_{DM}}{T_D}\right)$$

Universal dimensionless fitting function

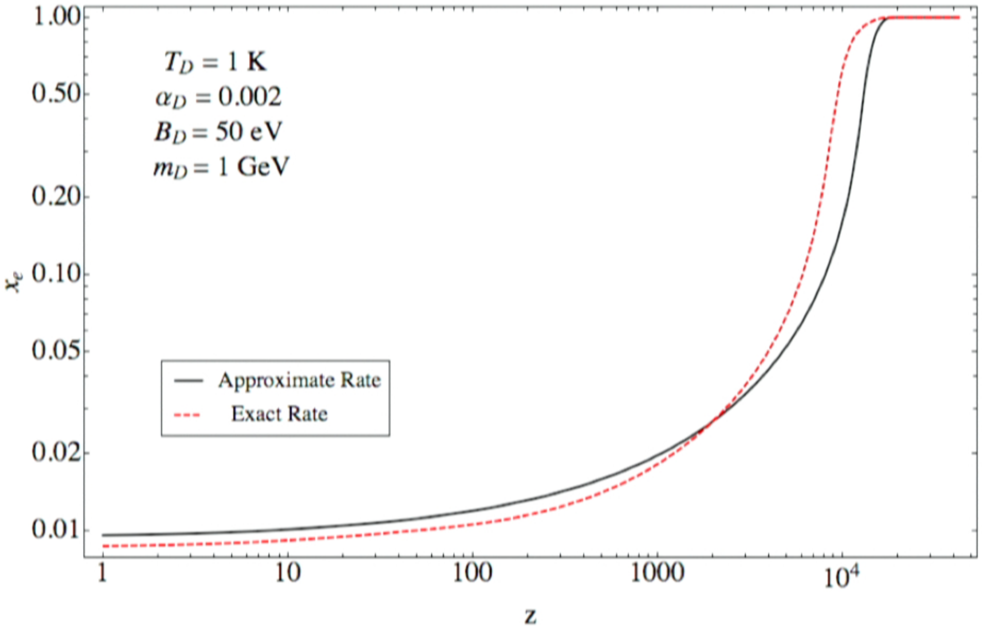
- We obtain the photo-ionization rate through detailed balance:

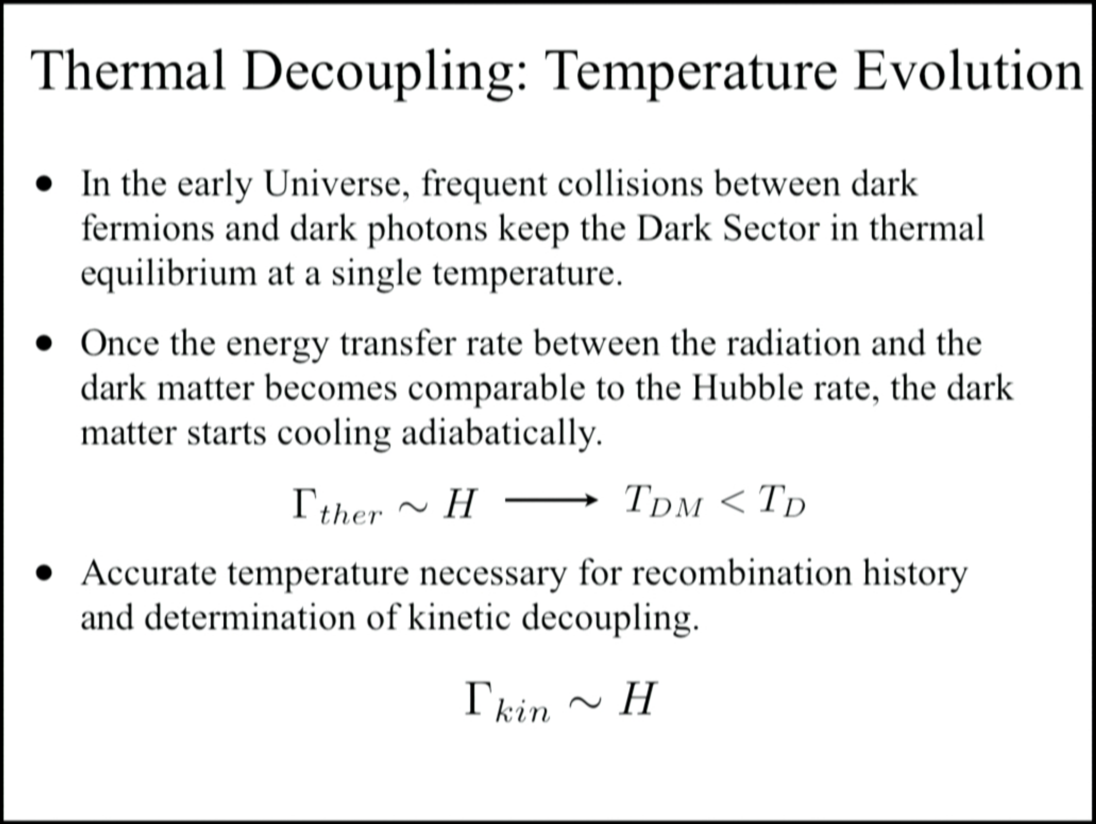
$$\beta_B(T_D) = \left(\frac{2\pi\mu_D T_D}{h^2}\right)^{3/2} e^{-B_D/4T_D}\,\alpha_B(T_{DM}=T_D,T_D)$$

Comparing Recombination Rates



Ionization History: Rate Comparison





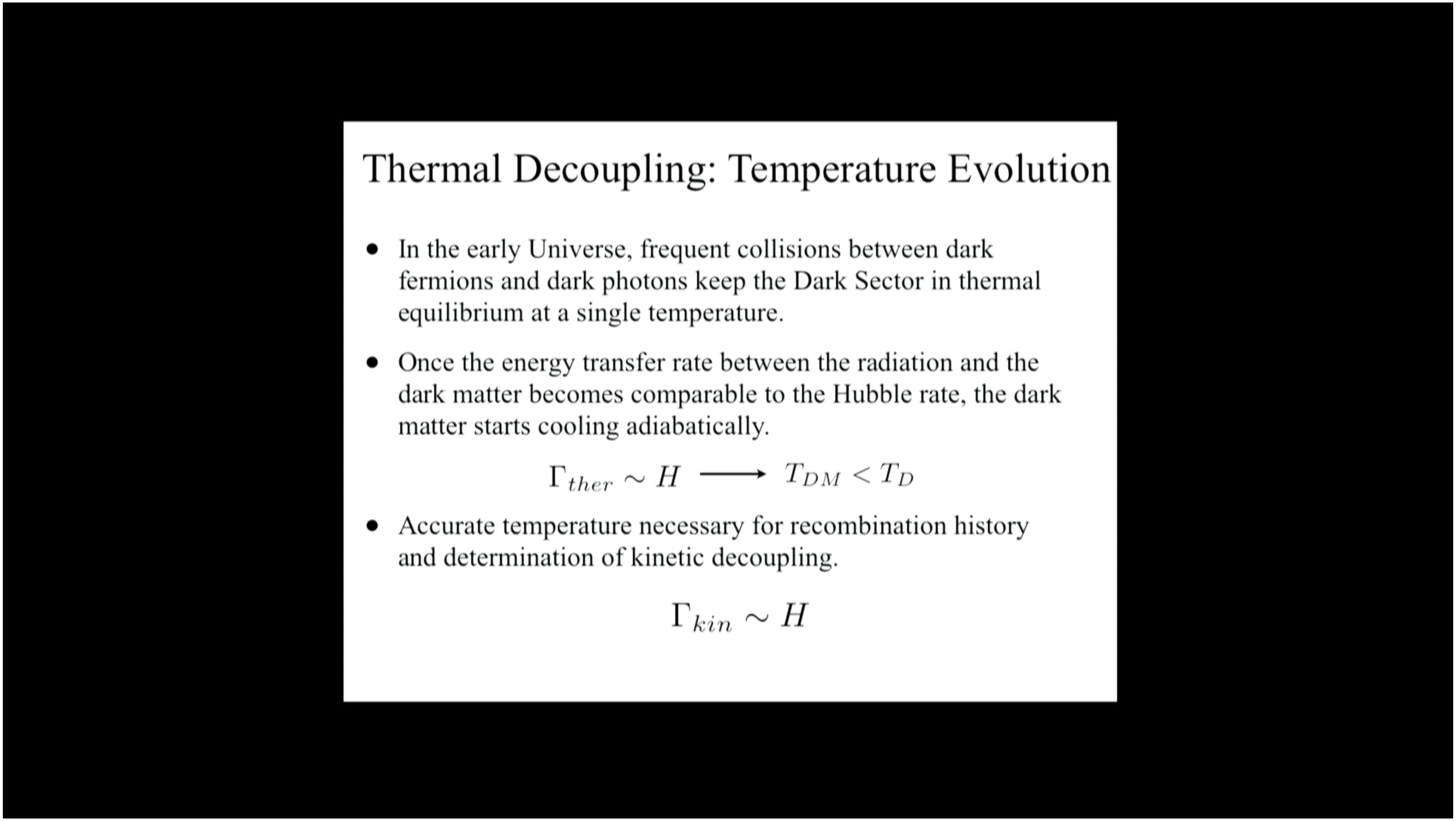
Thermal Decoupling: Temperature Evolution

- In the early Universe, frequent collisions between dark fermions and dark photons keep the Dark Sector in thermal equilibrium at a single temperature.
- Once the energy transfer rate between the radiation and the dark matter becomes comparable to the Hubble rate, the dark matter starts cooling adiabatically.

$$\Gamma_{ther} \sim H \longrightarrow T_{DM} < T_D$$

- Accurate temperature necessary for recombination history and determination of kinetic decoupling.

$$\Gamma_{kin} \sim H$$



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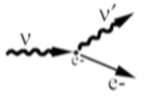
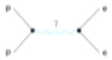
Dark-Sector Temperature

- In the strong coupling regime ($\alpha_D \gtrsim 0.01$), the single most important process to maintain dark matter in thermal equilibrium is Compton Scattering.
- For all interesting cases, Coulomb scattering maintain the dark electrons and dark protons at the same temperature.
- In the weak coupling regime ($\alpha_D \lesssim 0.005$), or for $T_D/T_{SM} \ll 1$, Compton heating is not efficient enough to keep the radiation and the dark matter at the same temperature.


Compton scattering

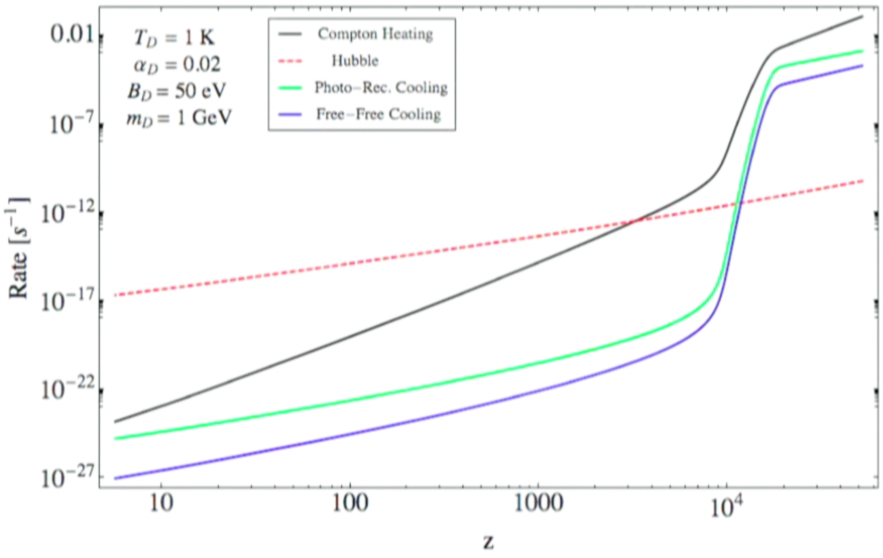
$\nu' < \nu$

Electron is initially at rest
e- gains energy



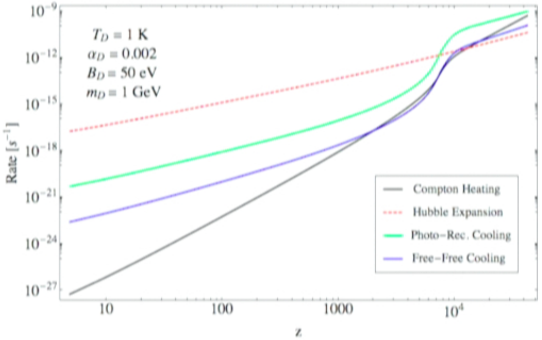
Strong-Coupling Regime

Compton heating determines thermal decoupling:

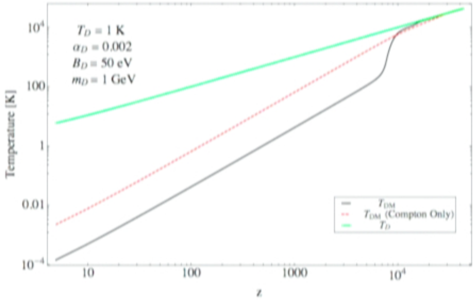


Weak Coupling Regime

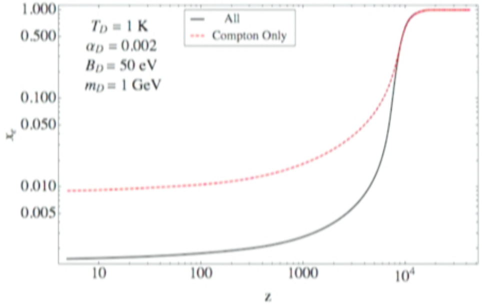
Thermal Rates

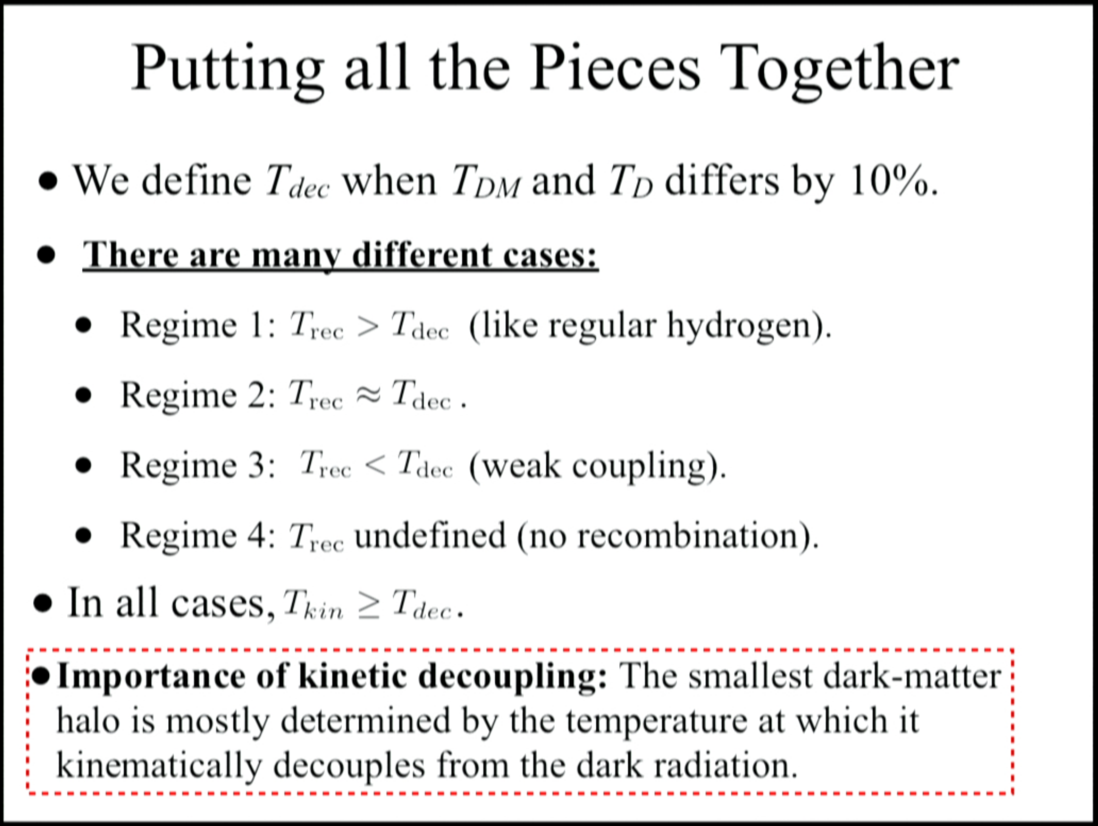


Temperature



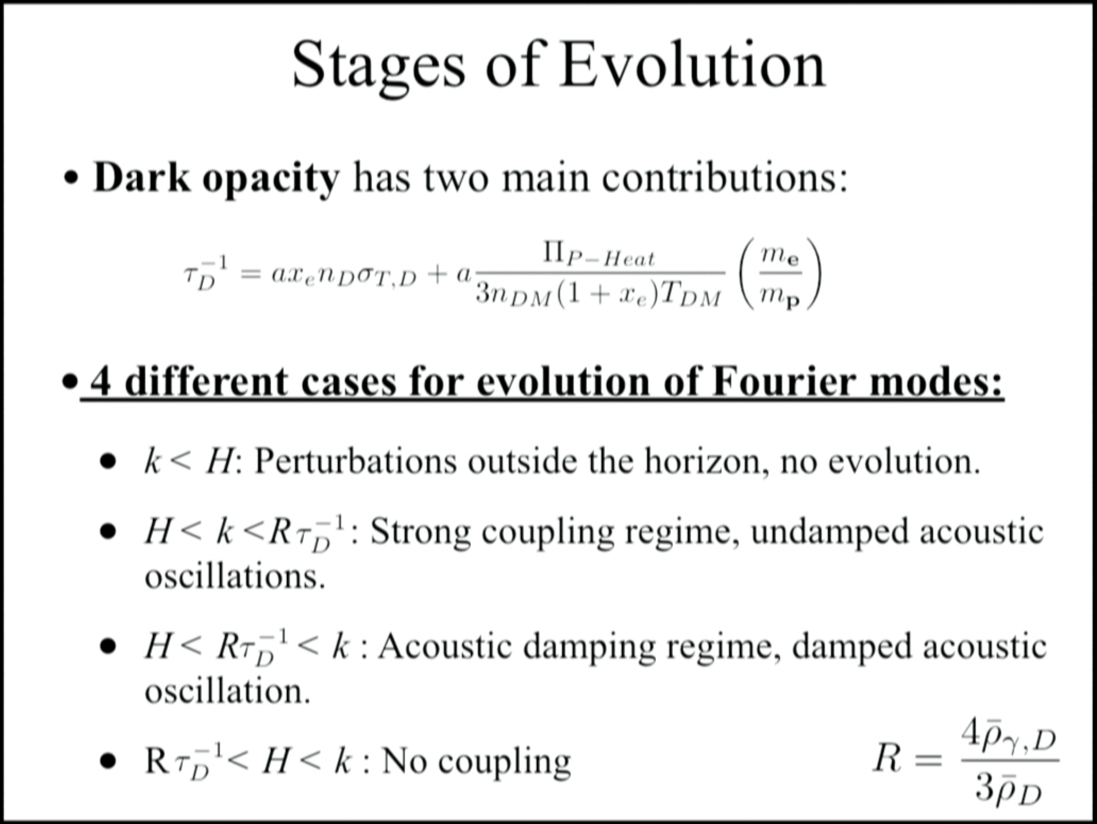
Ionization Fraction





Putting all the Pieces Together

- We define T_{dec} when T_{DM} and T_D differs by 10%.
- **There are many different cases:**
  - Regime 1: $T_{\rm rec} > T_{\rm dec}$ (like regular hydrogen).
  - Regime 2: $T_{\rm rec} \approx T_{\rm dec}$.
  - Regime 3: $T_{\rm rec} < T_{\rm dec}$ (weak coupling).
  - Regime 4: $T_{\rm rec}$ undefined (no recombination).
- In all cases, $T_{kin} \geq T_{dec}$.
- **Importance of kinetic decoupling:** The smallest dark-matter halo is mostly determined by the temperature at which it kinematically decouples from the dark radiation.



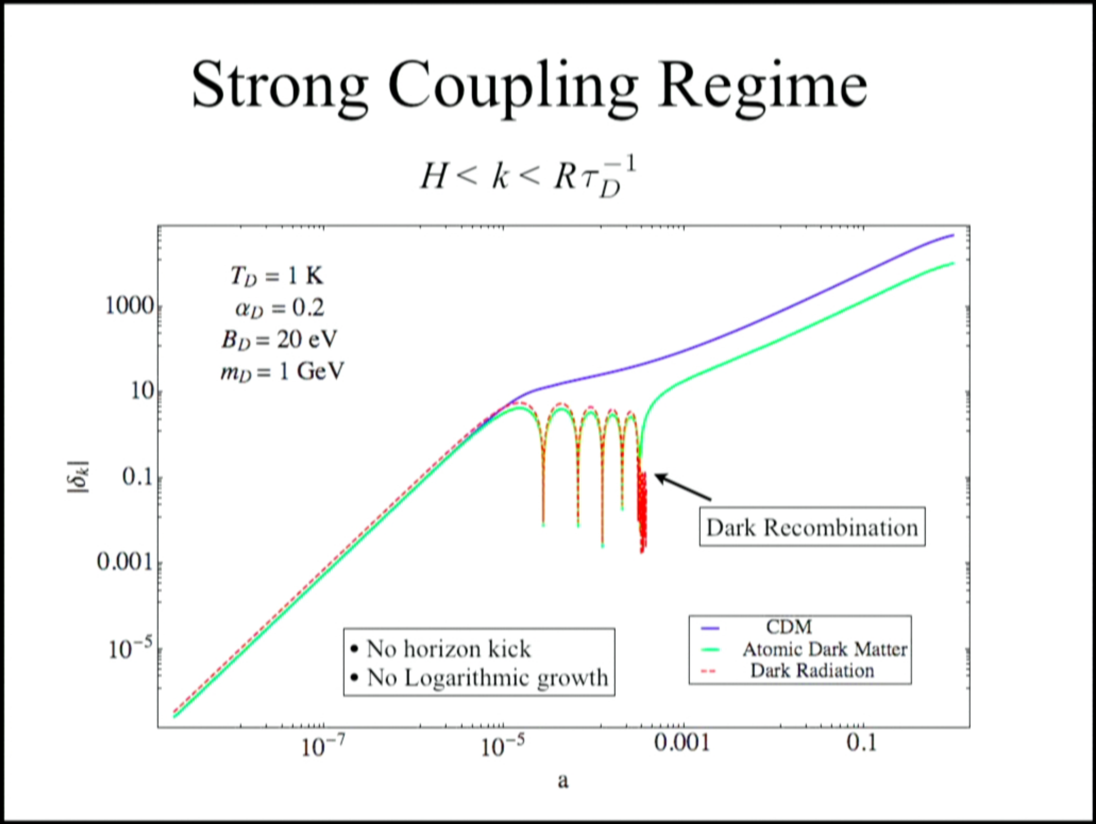
Stages of Evolution

- **Dark opacity** has two main contributions:

$$\tau_D^{-1} = a x_e n_D \sigma_{T,D} + a \frac{\Pi_{P-Heat}}{3 n_{DM}(1+x_e) T_{DM}} \left(\frac{m_{\mathbf{e}}}{m_{\mathbf{p}}}\right)$$

- **4 different cases for evolution of Fourier modes:**
  - $k < H$: Perturbations outside the horizon, no evolution.
  - $H < k < R\tau_D^{-1}$: Strong coupling regime, undamped acoustic oscillations.
  - $H < R\tau_D^{-1} < k$: Acoustic damping regime, damped acoustic oscillation.
  - $R\tau_D^{-1} < H < k$: No coupling

$$R = \frac{4\bar{\rho}_{\gamma,D}}{3\bar{\rho}_D}$$



Strong Coupling Regime

$$H < k < R\tau_D^{-1}$$

$T_D = 1$ K
$\alpha_D = 0.2$
$B_D = 20$ eV
$m_D = 1$ GeV

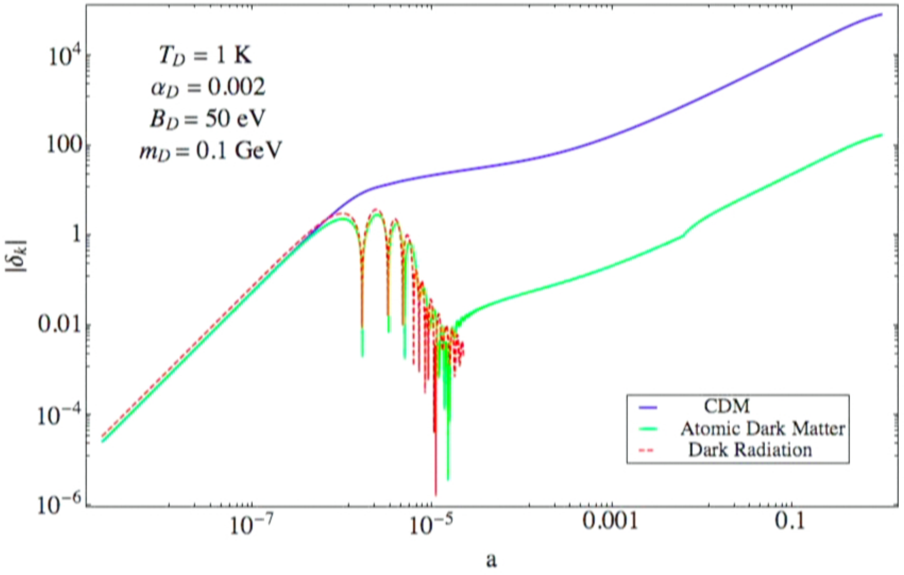
Dark Recombination

- No horizon kick
- No Logarithmic growth

Weak Coupling Regime

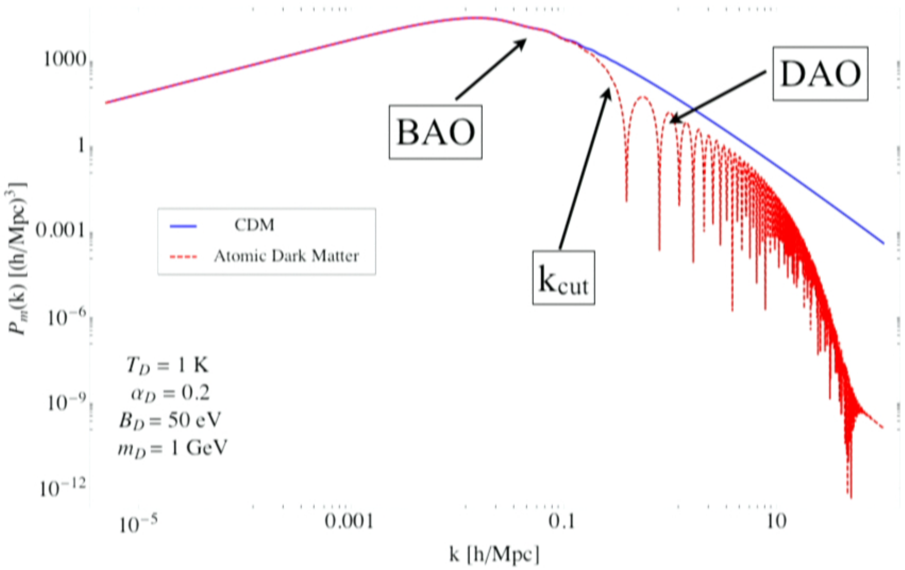
$$H < R\tau_D^{-1} < k$$

- Significant acoustic damping as soon as mode enters horizon:



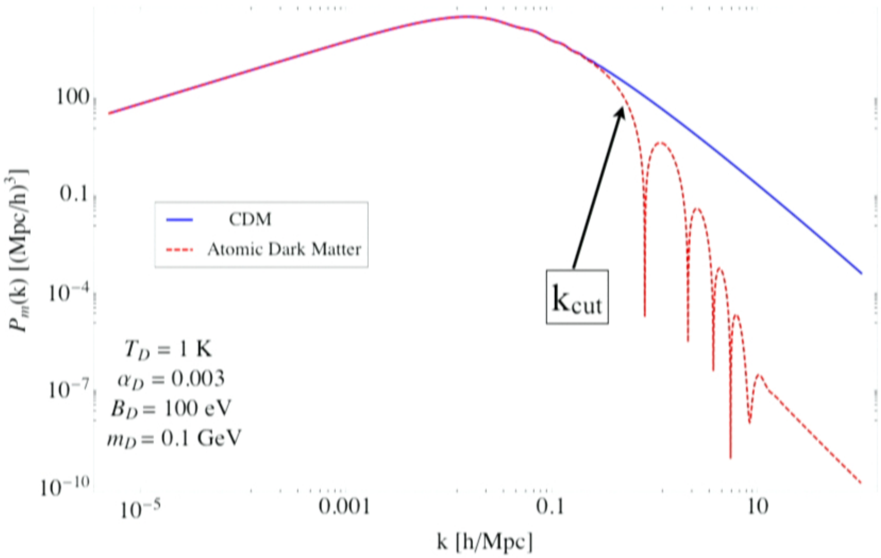
Matter Power Spectrum

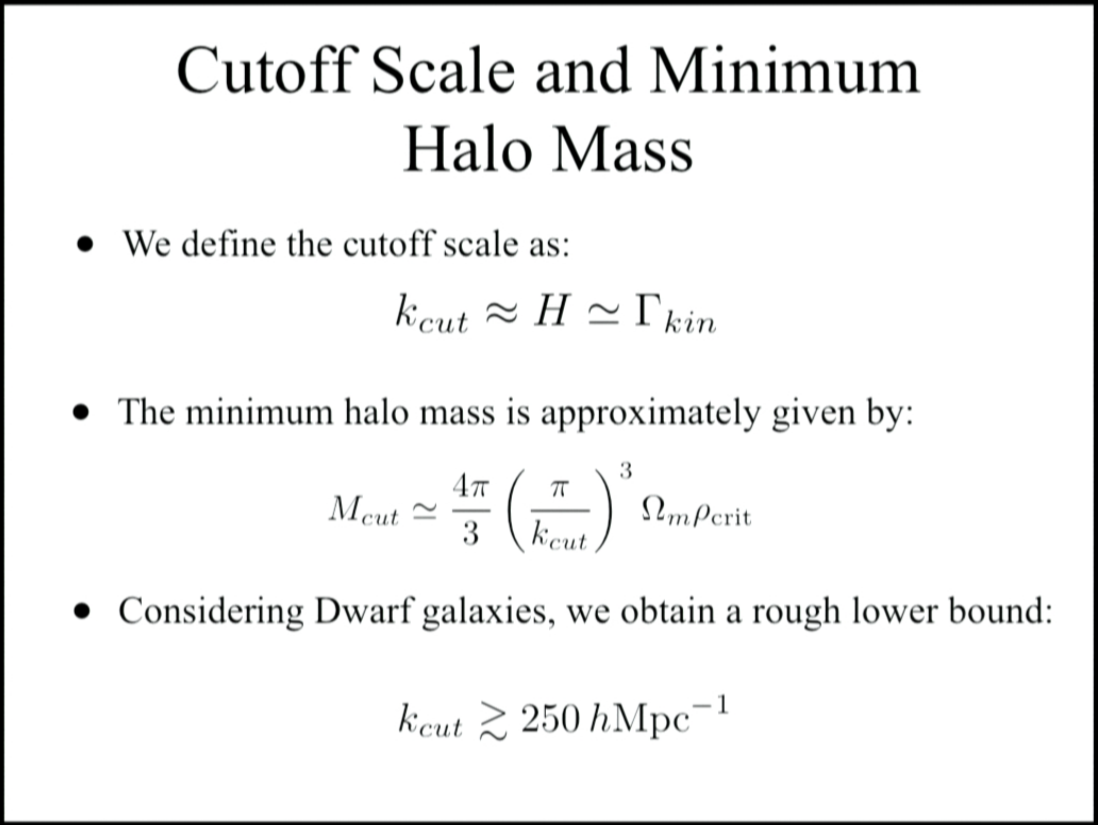
- Strong Coupling Case:



Matter Power Spectrum

- Weak Coupling Case:





Cutoff Scale and Minimum Halo Mass

- We define the cutoff scale as:

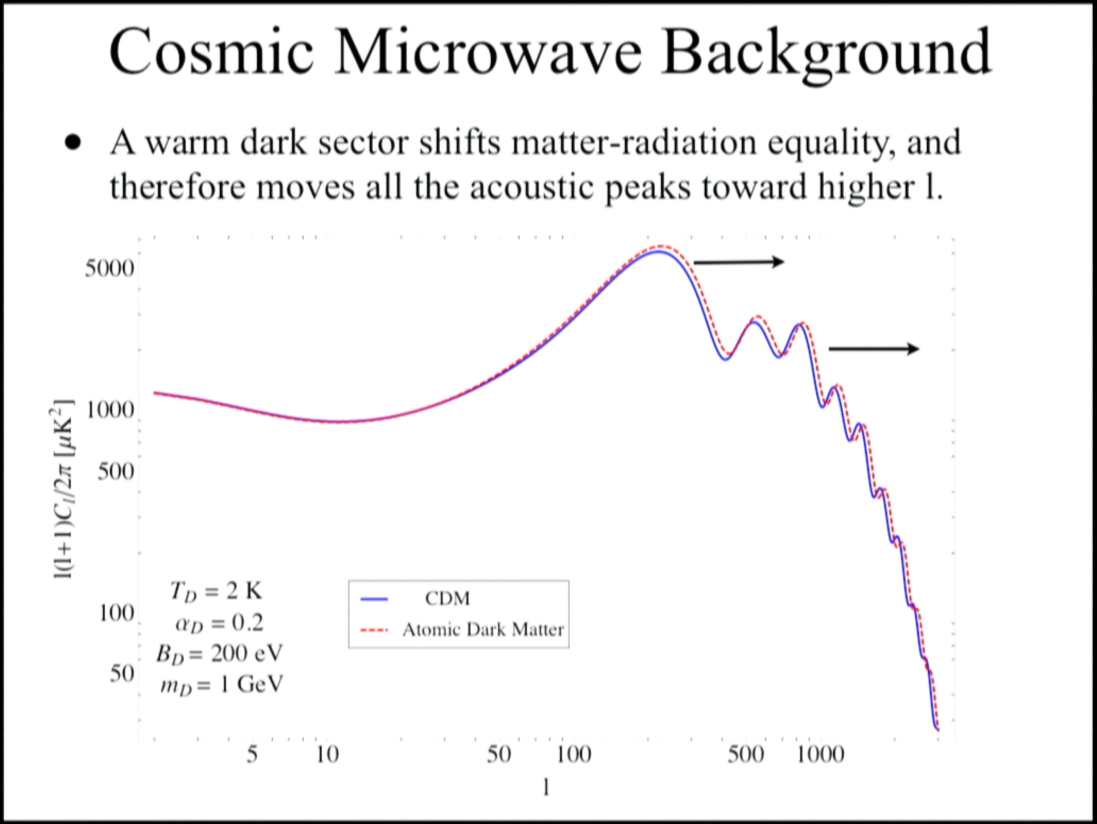
$$k_{cut} \approx H \simeq \Gamma_{kin}$$

- The minimum halo mass is approximately given by:

$$M_{cut} \simeq \frac{4\pi}{3}\left(\frac{\pi}{k_{cut}}\right)^3 \Omega_m \rho_{\rm crit}$$

- Considering Dwarf galaxies, we obtain a rough lower bound:

$$k_{cut} \gtrsim 250\, h\mathrm{Mpc}^{-1}$$



Cosmic Microwave Background

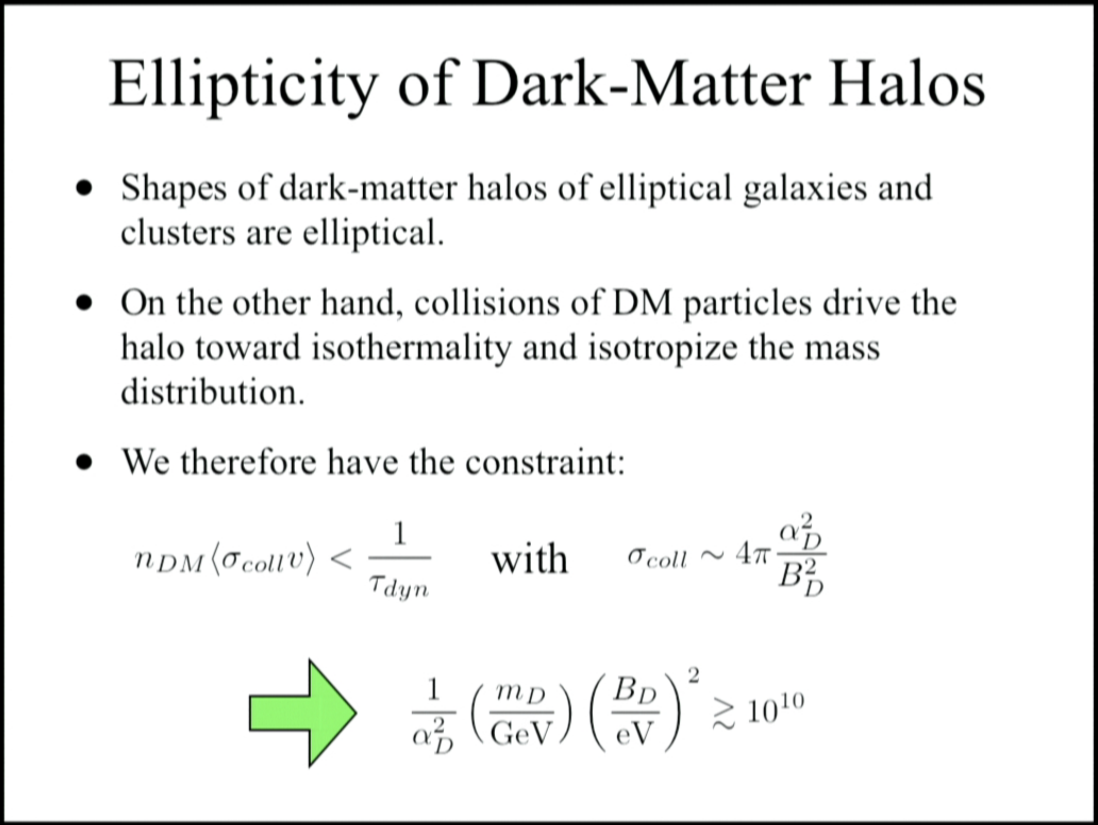
- A warm dark sector shifts matter-radiation equality, and therefore moves all the acoustic peaks toward higher l.

Ellipticity of Dark-Matter Halos

- Shapes of dark-matter halos of elliptical galaxies and clusters are elliptical.
- On the other hand, collisions of DM particles drive the halo toward isothermality and isotropize the mass distribution.
- We therefore have the constraint:

$$n_{DM}\langle \sigma_{coll} v \rangle < \frac{1}{\tau_{dyn}} \quad \text{with} \quad \sigma_{coll} \sim 4\pi \frac{\alpha_D^2}{B_D^2}$$

$$\Rightarrow \quad \frac{1}{\alpha_D^2}\left(\frac{m_D}{\text{GeV}}\right)\left(\frac{B_D}{\text{eV}}\right)^2 \gtrsim 10^{10}$$



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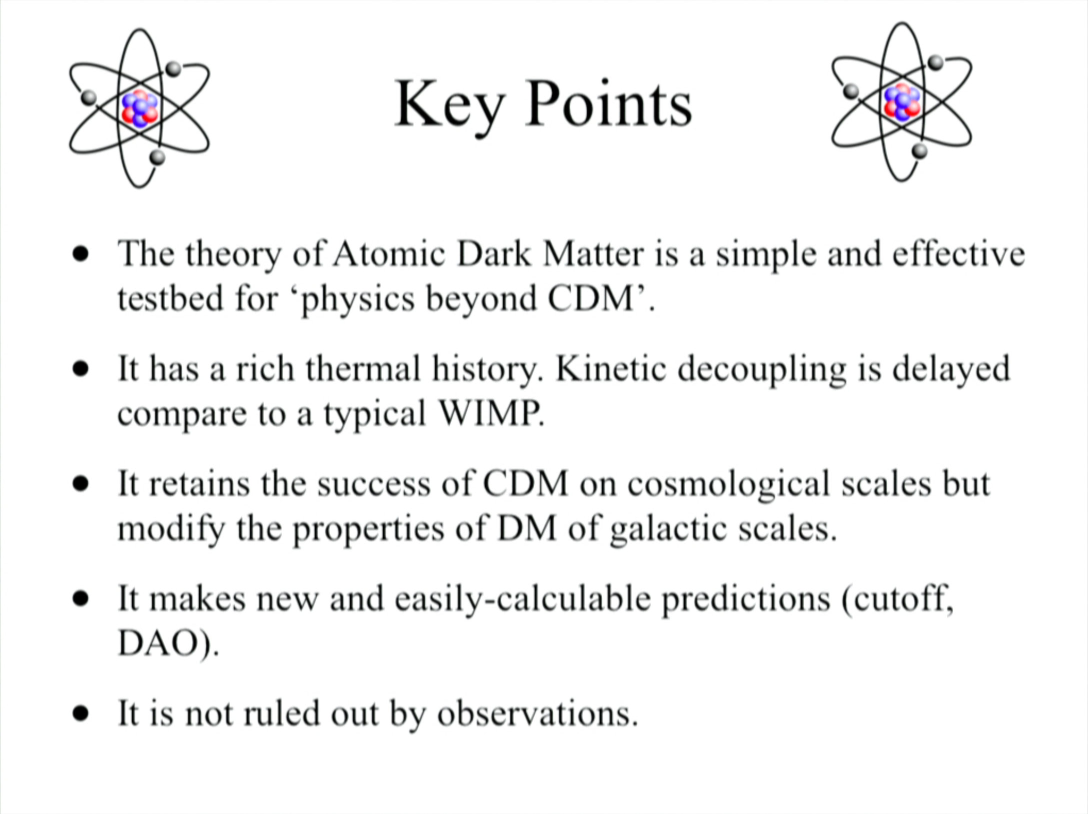
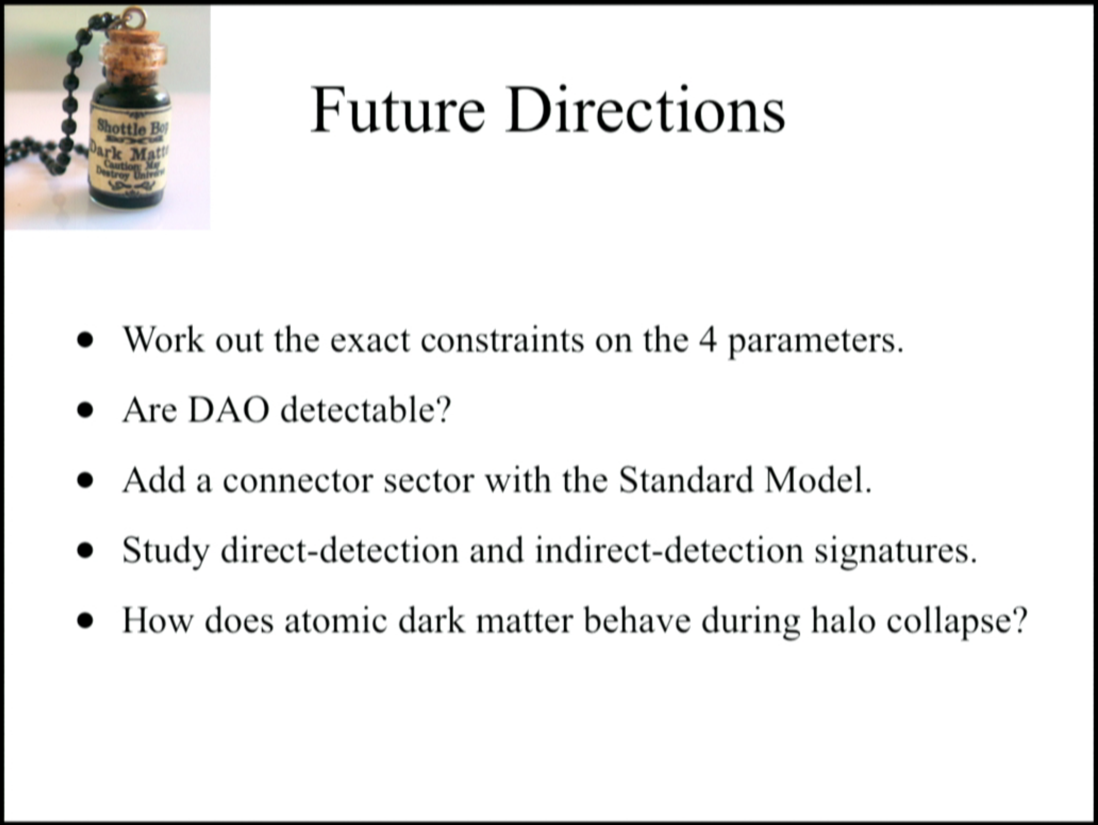


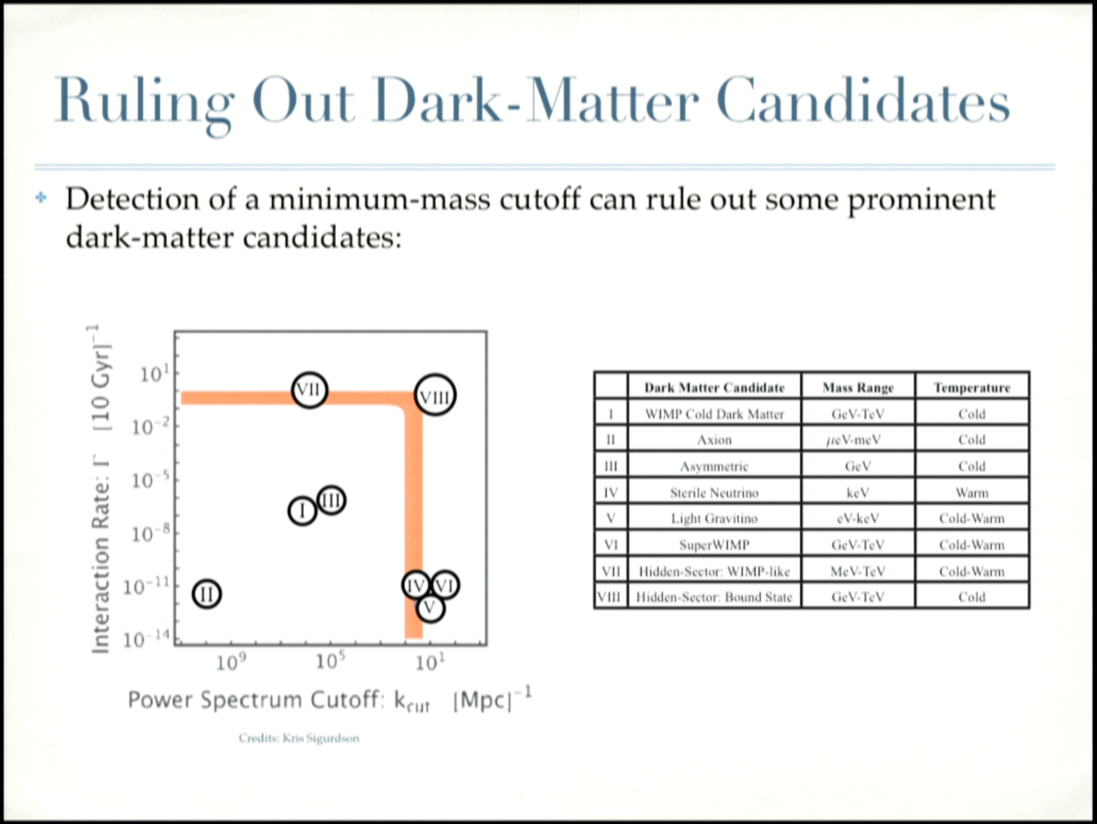
Key Points

- The theory of Atomic Dark Matter is a simple and effective testbed for ‘physics beyond CDM’.
- It has a rich thermal history. Kinetic decoupling is delayed compare to a typical WIMP.
- It retains the success of CDM on cosmological scales but modify the properties of DM of galactic scales.
- It makes new and easily-calculable predictions (cutoff, DAO).
- It is not ruled out by observations.



Future Directions

- Work out the exact constraints on the 4 parameters.
- Are DAO detectable?
- Add a connector sector with the Standard Model.
- Study direct-detection and indirect-detection signatures.
- How does atomic dark matter behave during halo collapse?



Ruling Out Dark-Matter Candidates

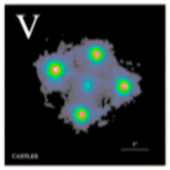
- Detection of a minimum-mass cutoff can rule out some prominent dark-matter candidates:

Credits: Kris Sigurdson

	Dark Matter Candidate	Mass Range	Temperature
I	WIMP Cold Dark Matter	GeV-TeV	Cold
II	Axion	μeV-meV	Cold
III	Asymmetric	GeV	Cold
IV	Sterile Neutrino	keV	Warm
V	Light Gravitino	eV-keV	Cold-Warm
VI	SuperWIMP	GeV-TeV	Cold-Warm
VII	Hidden-Sector: WIMP-like	MeV-TeV	Cold-Warm
VIII	Hidden-Sector: Bound State	GeV-TeV	Cold

Studying Dark-Matter Substructures through Strong Gravitational Lensing

- Strong lenses displaying multiple images of a background source are powerful probes of dark-matter substructures within galactic halos.



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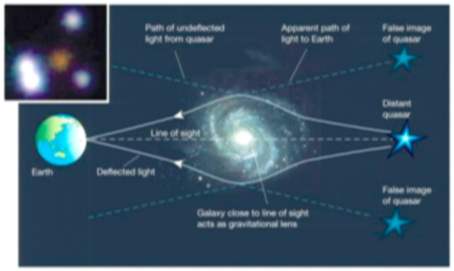

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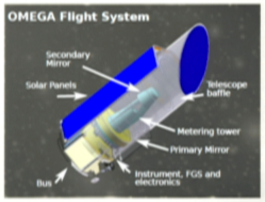
- Needed: precise measurements of gravitational time delays, image positions, and image magnifications.



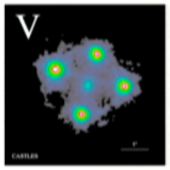
The Calculation

- Would like to compute the Probability Density Function (PDF) of obtaining a given set of lensing observables. For example, the time-delay PDF is:

$$P_\phi(\phi_1, \phi_2, \phi_3) = \int \prod_{j=1}^{N} \{dm_j d^2\mathbf{x}_j P_s(x_j, y_j, m_j)\} \prod_{i=1}^{3} \delta\left(\phi_i - \sum_{k=1}^{N} \frac{m_k}{\pi} \ln \frac{|\mathbf{x}_i - \mathbf{x}_k|}{|\mathbf{x}_0 - \mathbf{x}_k|}\right)$$

- Better Approach: Compute PDF for a single clump.

$$P_1(\phi_1, \phi_2, \phi_3) = \int dm d^2\mathbf{x} P_s(\mathbf{x}, m) \prod_{i=1}^{3} \delta\left(\phi_i - \frac{m}{\pi} \ln \frac{|\mathbf{x}_i - \mathbf{x}|}{|\mathbf{x}_0 - \mathbf{x}|}\right)$$



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- Compute Characteristic Function (Fourier Transform) and use:

$$Q_N(\mathbf{k}) = (q_1(\mathbf{k}))^N.$$