Hylogenesis:

A Unified Origin for Baryonic Visible Matter and Antibaryonic Dark Matter

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with

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[arXiv:1008.2399 [hep-ph]]

U Michigan NCHU Workshop, October 21, 2010

Questions about Baryogenesis

1. Moduli stabilization + Low-Energy Supersymmetry?
   - Motivates moduli oscillation with low reheating.
   - Dark matter can be produced via non-thermal decays.
   - But what about baryogenesis?

2. $\Omega_{DM} \simeq 5\,\Omega_B$?
   - Just an accident?
   - Baryogenesis mechanisms that give this naturally?

A Unified Solution?

- But maybe there is a reason for $\rho_{DM} \sim \rho_B$.
- The DM density could be set by the baryon asymmetry.

  $\rightarrow$ Asymmetric Dark Matter (ADM)

  [Nussinov '85;Kaplan '90; Barr '91; . . . , Luty, Terning, Zurek '08]
- One step further – hidden antibaryons as dark matter.

  [Dodelson+Widrow '90; Farrar+Zaharijas '04;Kitano+Low '04;

  Agashe+Servant '04; An,Chen,Mohapatra,Zhang '09,. . .]
- A Concrete Low-Temperature Mechanism:

  Hylogenesis = Greek for *matter* + *creation*

A Collective Nominal Apology

- Darkogenesis (Ombrogenesis): Shelton+Zurek '10
- Hylogenesis: Davoudiasl,DM,Sigurdson,Tulin '10
- Xogenesis: Buckley+Randall '10
- Baryomorphosis: McDonald '10
- Aidnogenesis: Blennow,Dasgupta,Fernandez-Martinez,Ruis '10
- Related papers with more tasteful titles:

  Gu+Sarkar '09; Matsumoto+Saba '10; Chun '10; Hall,March-Russell,West '10

A Sample Model

- Expand the SM with new hidden particles:
  - X_1, X_2 heavy (TeV) Dirac fermions, $B = +1$
  - Y light (GeV) Dirac fermion, $B = y$
  - Φ light (GeV) complex scalar, $B = -(1+y)$

- Couplings:

$$-\mathcal{L} \supset \frac{\lambda_a}{M^2} X_{L_a} U^c D^c D^c + \zeta_a^* X_a Y \Phi + (h.c.)$$

$\rightarrow$ "neutron portal" coupling

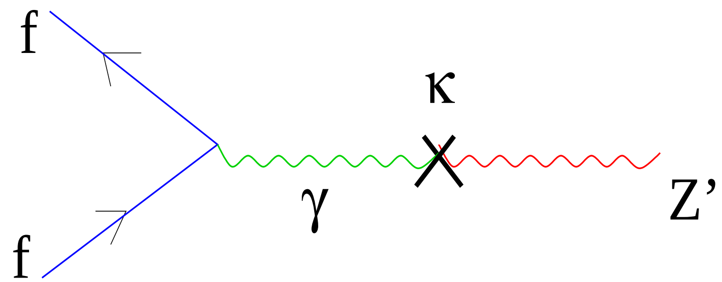
Also used for BG by Kitano,Murayama,Ratz '08; Allahverdi,Dutta,Sinha '10.

- One more ingredient - a new $U(1)'$ gauge symmetry:
  - Higgsed with $m_{Z'} \sim$ GeV
  - SM fields carry no direct $U(1)'$ charge
  - $X_{1,2}$ are neutral
  - Y and Φ have equal and opposite charges.

- Gauge kinetic mixing:

$$\mathcal{L} \supset -\frac{\kappa}{2} B^{\mu\nu} Z'_{\mu\nu}, \qquad |\kappa| \ll 1.$$

Induces a Z' coupling to the SM with strength $e\, Q_{em}\, c_W \kappa$.



Matter Production

- Three Easy Steps:

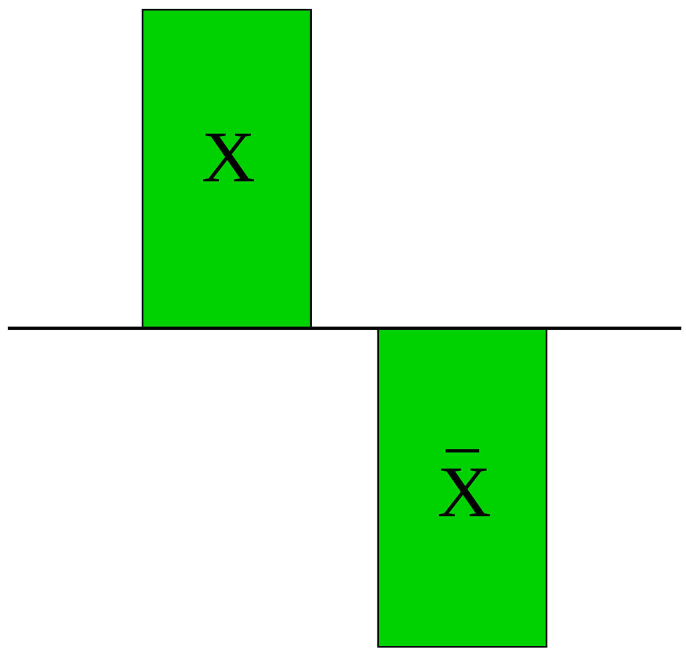
  1. Equal numbers of X_1 and $\bar{X}_1$ are produced non-thermally.
  2. X_1 and $\bar{X}_1$ decay with CP violation into udd and $Y\Phi$.
  3. Non-asymmetric Y and Φ annihilate into Z's.

- Leftover Y and Φ make up the dark matter.

  They carry baryon number and lead to novel DM signals.

Step #1: X Production

- Equal X_1 and $\bar{X}_1$ densities are produced when $T \ll m_{X_1}$.
  e.g. reheating after moduli oscillation, inflation, . . .
- This is the departure from equilibrium ingredient.
- X_1 and $\bar{X}_1$ have $B = \pm 1$, but there is no net B number.



- Minimal non-thermal production: moduli reheating.
- Scalar field φ is displaced, oscillates, and dominates.
- Decays and Reheating (Vanilla):

$$\Gamma_\varphi = \frac{m_\varphi^3}{4\pi\,\Lambda^2}$$

$$T_{RH} \simeq 5\,\text{MeV}\left(\frac{10}{g_*}\right)^{1/4}\left(\frac{M_{\text{Pl}}}{\Lambda}\right)\left(\frac{m_\varphi}{100\,\text{TeV}}\right)^{3/2}$$

- X_1 yield at T_{RH}:

$$\left.\frac{n_X}{s}\right|_{RH} \sim \mathcal{N}_X \frac{T_{RH}}{m_\varphi} \sim \mathcal{N}_X \left(\frac{m_\varphi}{M_{\text{Pl}}}\right)^{1/2}$$

$\mathcal{N}_X$ = average number of X per φ decay.

Step #2: X Decay

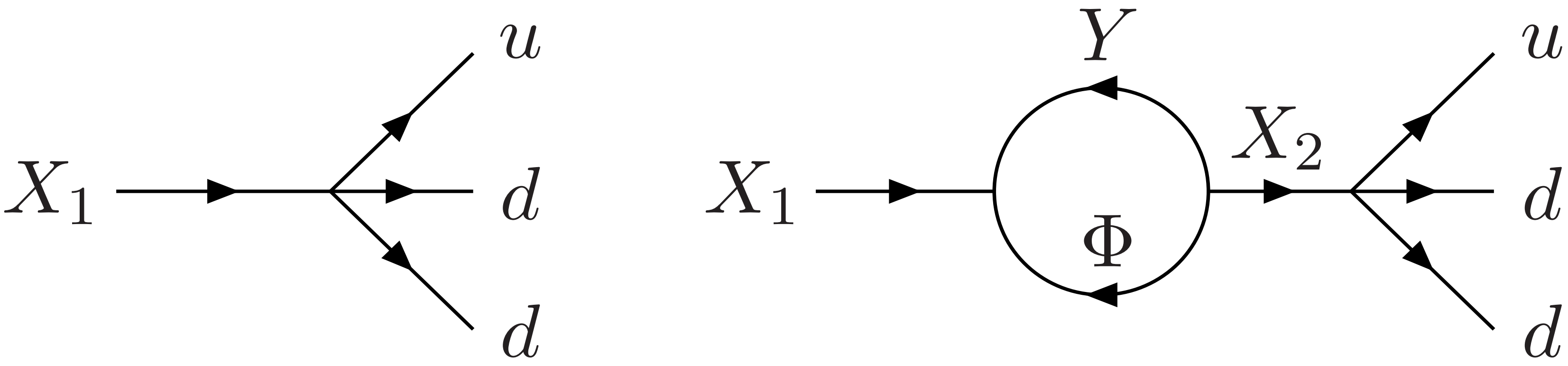
- $X \to udd$ or $\bar{Y}\Phi^*$, $\bar{X} \to \bar{u}\bar{d}\bar{d}$ or $Y\Phi$ instantaneously.

- CP violation alters partial decay widths:

$$\Gamma(X \to 3Q) = \Gamma_{3Q} + \epsilon\,\Gamma_{tot}$$
$$\Gamma(X \to \bar{Y}\bar{\Phi}) = \Gamma_{Y\Phi} - \epsilon\,\Gamma_{tot}$$
$$\Gamma(X \to 3\bar{Q}) = \Gamma_{3Q} - \epsilon\,\Gamma_{tot}$$
$$\Gamma(X \to Y\Phi) = \Gamma_{Y\Phi} + \epsilon\,\Gamma_{tot}$$

CPT requires $\Gamma(X \to all) = \Gamma(\bar{X} \to all)$.

- Asymmetries come from tree-loop interference:

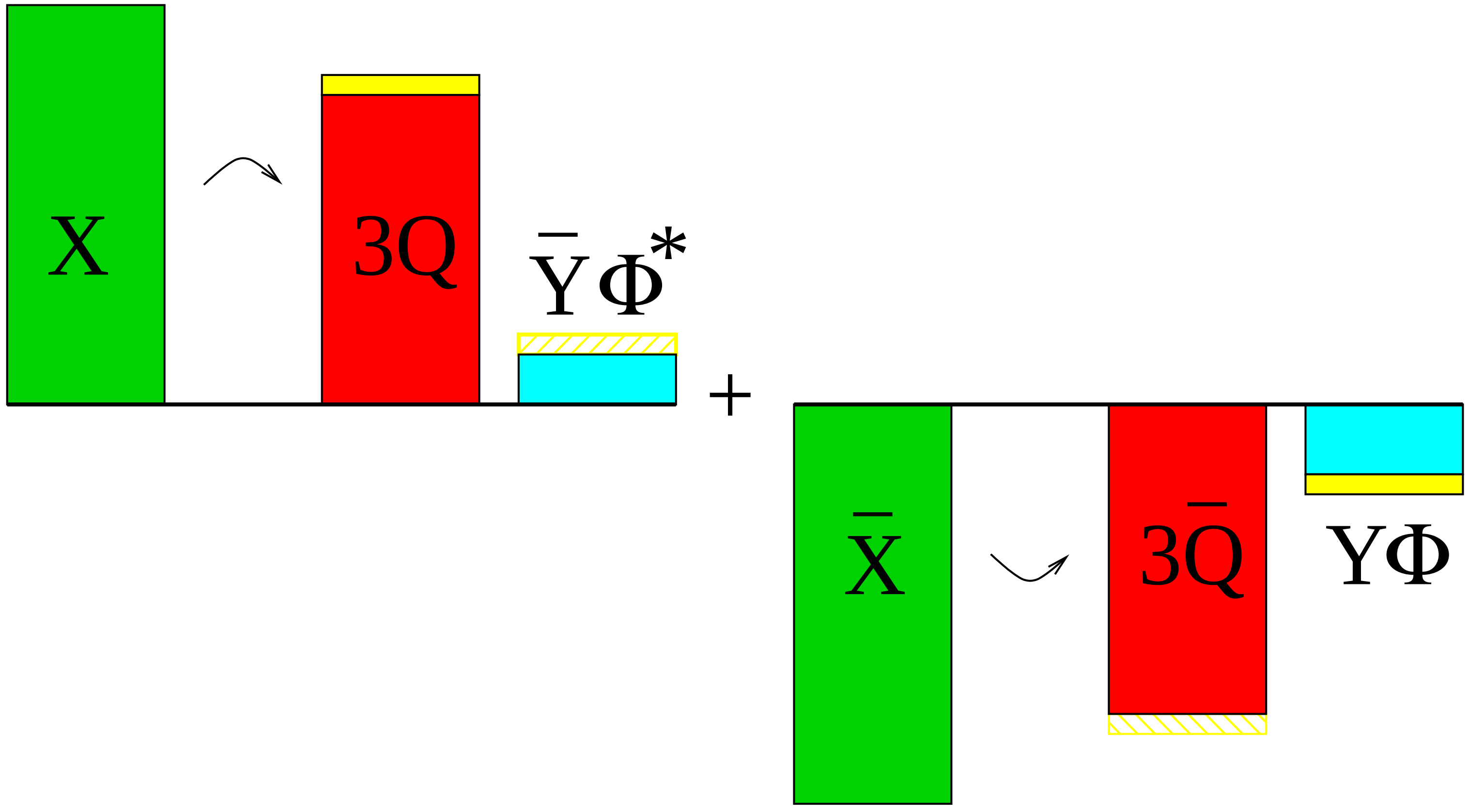


$$\epsilon = \frac{\Gamma(X \to 3Q) - \Gamma(\bar{X} \to 3\bar{Q})}{\Gamma(X \to all) + \Gamma(\bar{X} \to all)}$$

$$\simeq \frac{Im(\lambda_1^* \lambda_2 \zeta_1 \zeta_2^*)}{256\pi^3 |\zeta_1|^2} \frac{m_{X_1}^5}{M^4 m_{X_2}}$$

- Final B Asymmetry: $\frac{n_B}{s} \simeq \epsilon \left.\frac{n_X}{s}\right|_{RH}$.

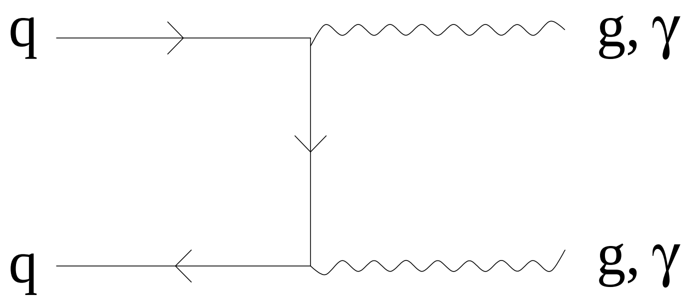
- Asymmetries split B into $3Q$, $Y\Phi$.



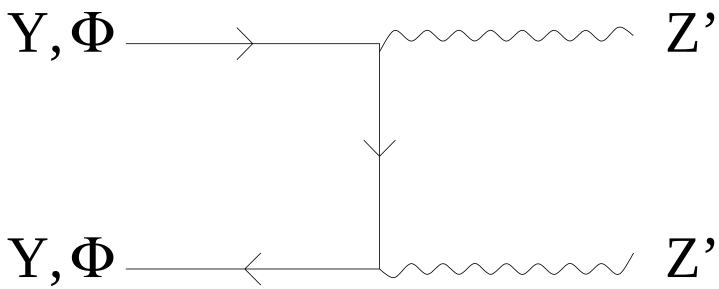
- There is no violation of total B number.

Step #3: Annihilation

- Quarks annihilate until only the asymmetry remains:

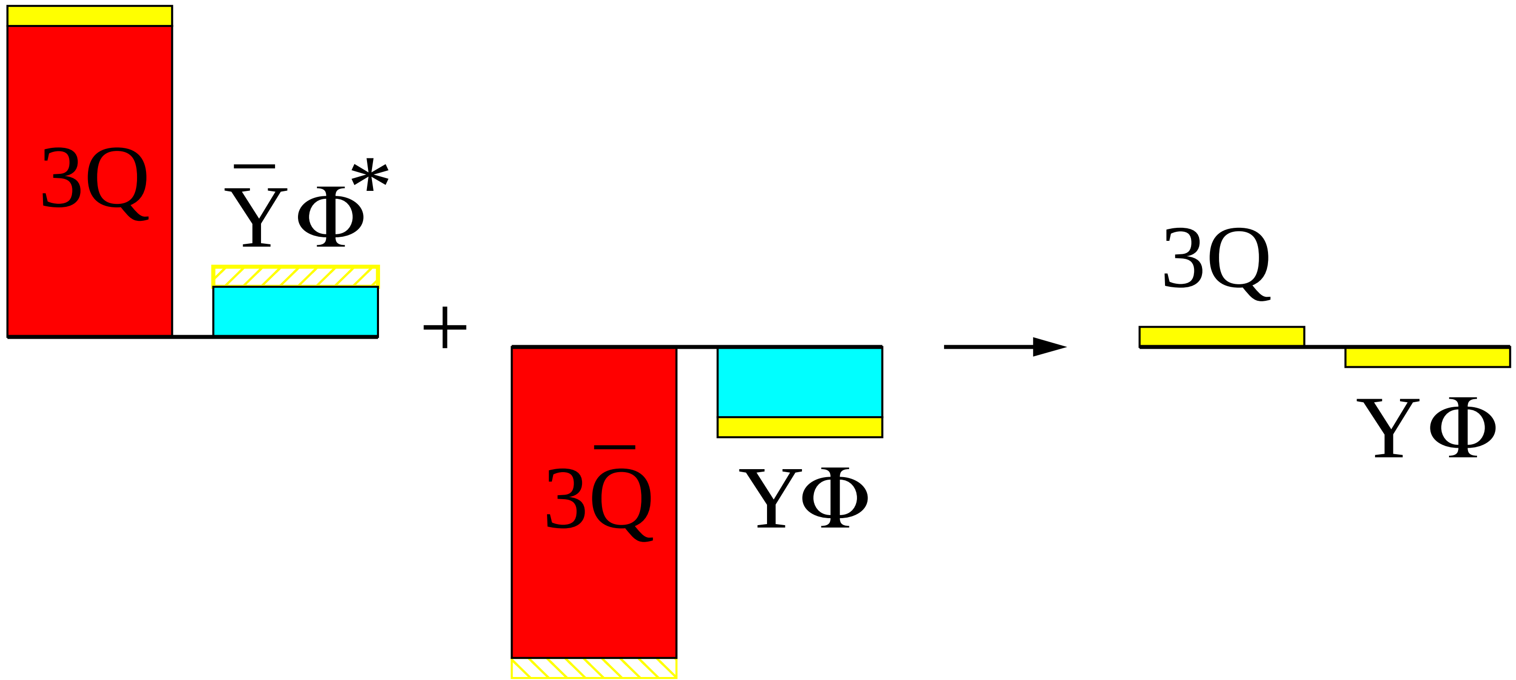


- Y, Φ annihilate to Z' leaving only the asymmetry:



(Requires $m_{Z'} < m_{Y,\Phi}$.)

- All that remains are equal and opposite densities of $3Q$ and $Y\Phi$ set by the decay asymmetry.



- Y and Φ are hidden antibaryons.
- We want them to be stable.

  Hidden antibaryons as dark matter?

Hidden Antibaryonic Dark Matter

- We have $n_Y = n_\Phi = n_B$.

- Both Y and Φ can be stable if:

$$|m_Y - m_\Phi| < (m_p + m_e) < m_Y + m_\Phi$$

- They provide the right DM density if:

$$(m_Y + m_\Phi) = m_p \left(\frac{\rho_{DM}}{\rho_B}\right) \simeq 4.5\,\text{GeV}.$$

- Possible mass ranges: $1.7\,\text{GeV} \lesssim m_{Y,\Phi} \lesssim 2.9\,\text{GeV}$.

  (The Z' should be even lighter than this.)

Signals of Hylogenesis

- Y and Φ together make up the dark matter.

  They both couple to a light Z' vector boson.

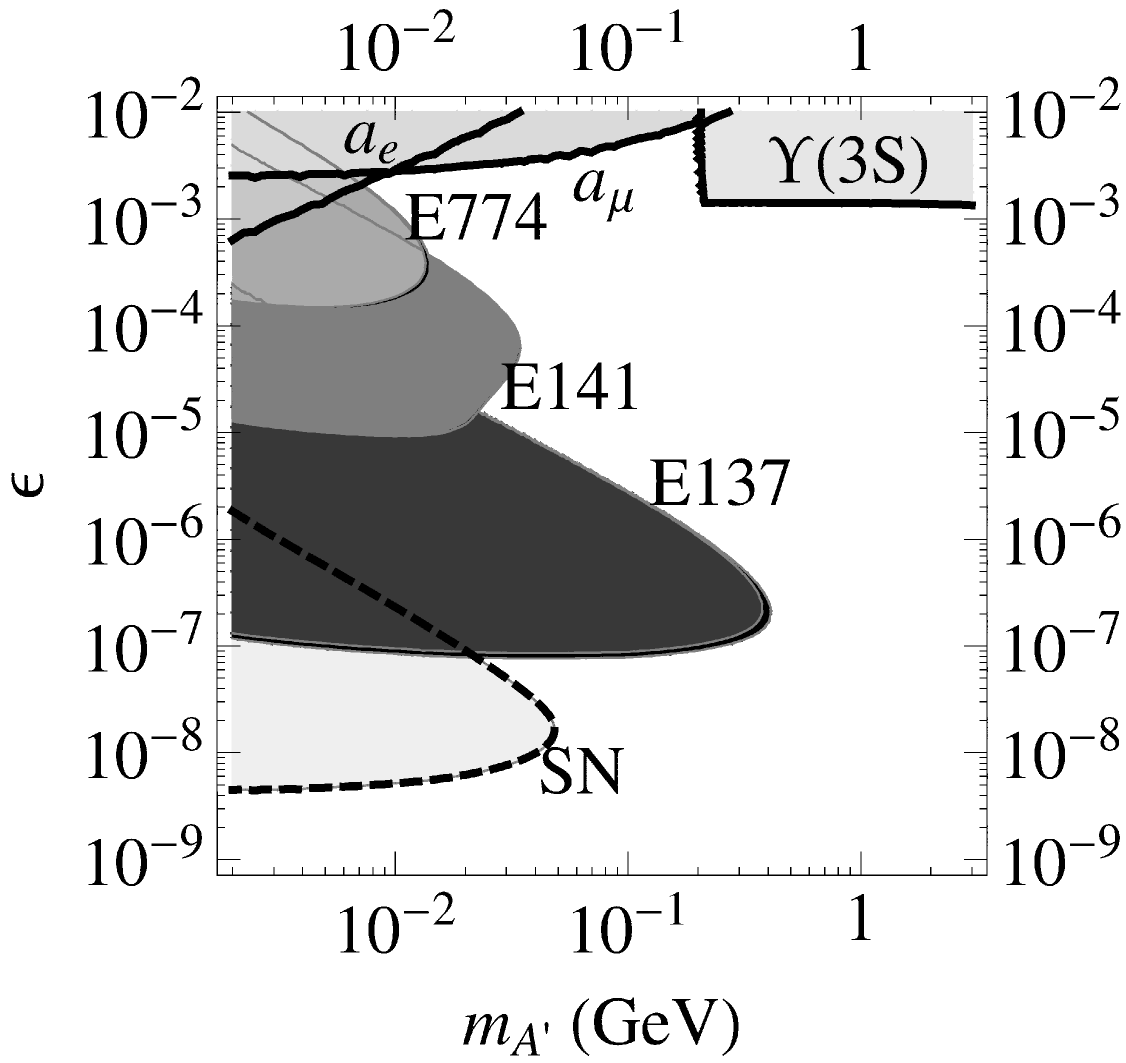
- Potential Signals:
  - Direct Z' effects in colliders, precision experiments.
  - Elastic scattering of Y and Φ off nuclei via Z'.
  - Nucleon destruction from inelastic Y/Φ scattering.
  - Monojets at colliders from $Xudd$, DM production.

- All four types of signals could be observed soon!

Light Z' Effects

- Bounds on a light hidden Z' with kinetic mixing to the SM:

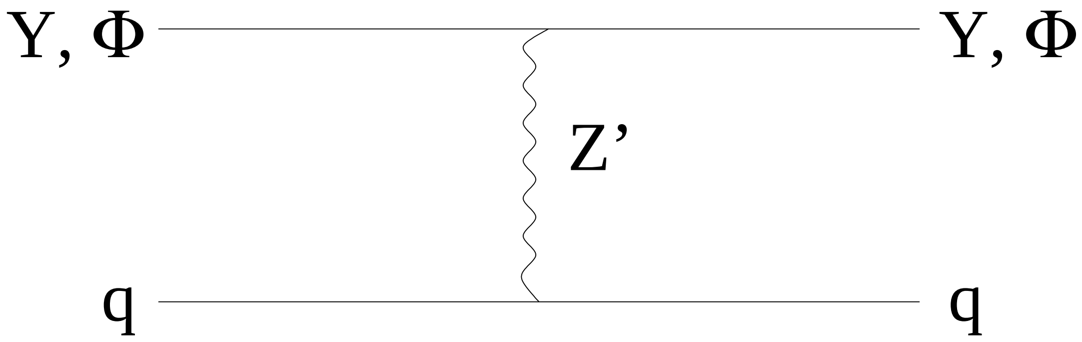
[Pospelov '08; Batell,Pospelov, Ritz '09, Reece+Wang '09; Bjorken *et al.* '09]



[Bjorken *et al.* '09]

DM-Nucleon Elastic Scattering

- Y and Φ can scatter elastically off nuclei via Z'.



- Cross-section per nucleon (spin-independent):

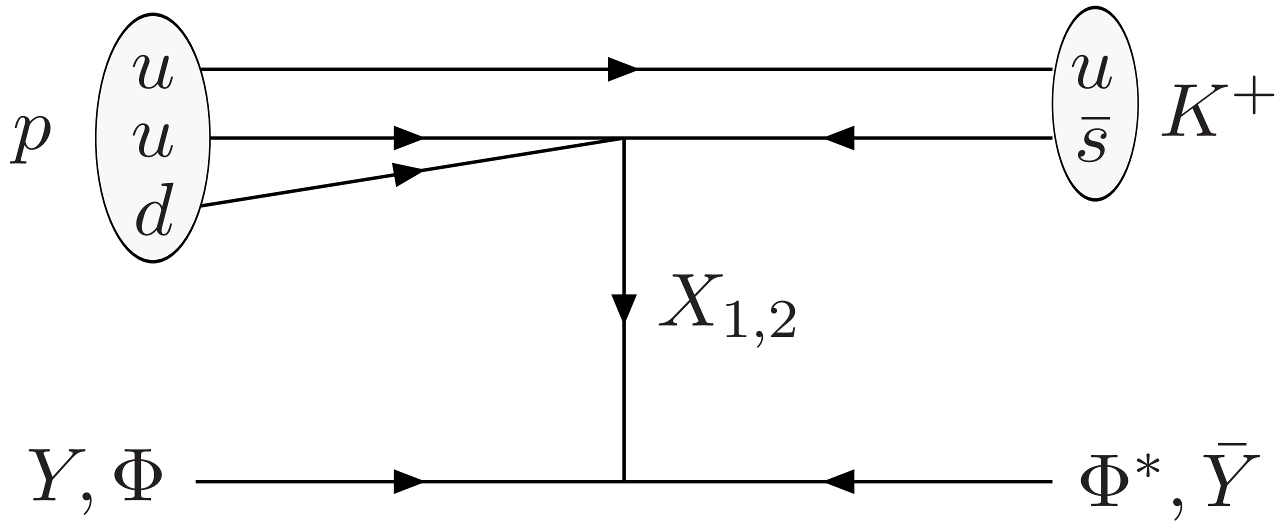
$$\sigma_0^{SI} = (5 \times 10^{-39} cm^2) \left(\frac{2Z}{A}\right)^2 \left(\frac{e'}{0.05}\right)^2 \left(\frac{\kappa}{10^{-5}}\right)^2 \left(\frac{0.1\,\text{GeV}}{m_{Z'}}\right)^4$$

- Current limits are about $10^{-38} cm^2$ for $m_{DM} \sim 3\,\text{GeV}$.
  [CRESST '02]

DM-Nucleon Inelastic Scattering

- DM now carries $B = -1$!
- Y or Φ can scatter inelastically off a nucleon.

e.g.



- A nucleon is destroyed in this process.

$$Y/\Phi + N \to \Phi^*/\bar{Y} + M$$

- Inelastic DM scattering will mimic nucleon decay.

  $\rightarrow$ Induced Nucleon Decay (IND)

- Total event rates in a nucleon decay detector:

$$\begin{aligned} R_{decay} &= \Gamma_{decay} N_{nuc} \\ R_{IND} &= \sigma_{IND} \mathcal{F}_{DM} N_{nuc} \end{aligned}$$

$\mathcal{F}_{DM} =$ local DM flux:

$$\mathcal{F}_{DM} \simeq (4 \times 10^6 cm^{-2} s^{-1}) \left(\frac{2\,\mathrm{GeV}}{m_{DM}} \right) \left(\frac{\rho_{DM}^{loc}}{0.3\,\mathrm{GeV}/cm^3} \right)$$

- Limits on $\Gamma = \tau^{-1}$ translate into limits on $\sigma\mathcal{F} \equiv \tau_{eff}^{-1}$.
- Best current bound: $\tau(p \to K^+\nu) > 2.3 \times 10^{33}\, yr$. [SuperK '05]
- IND gives:

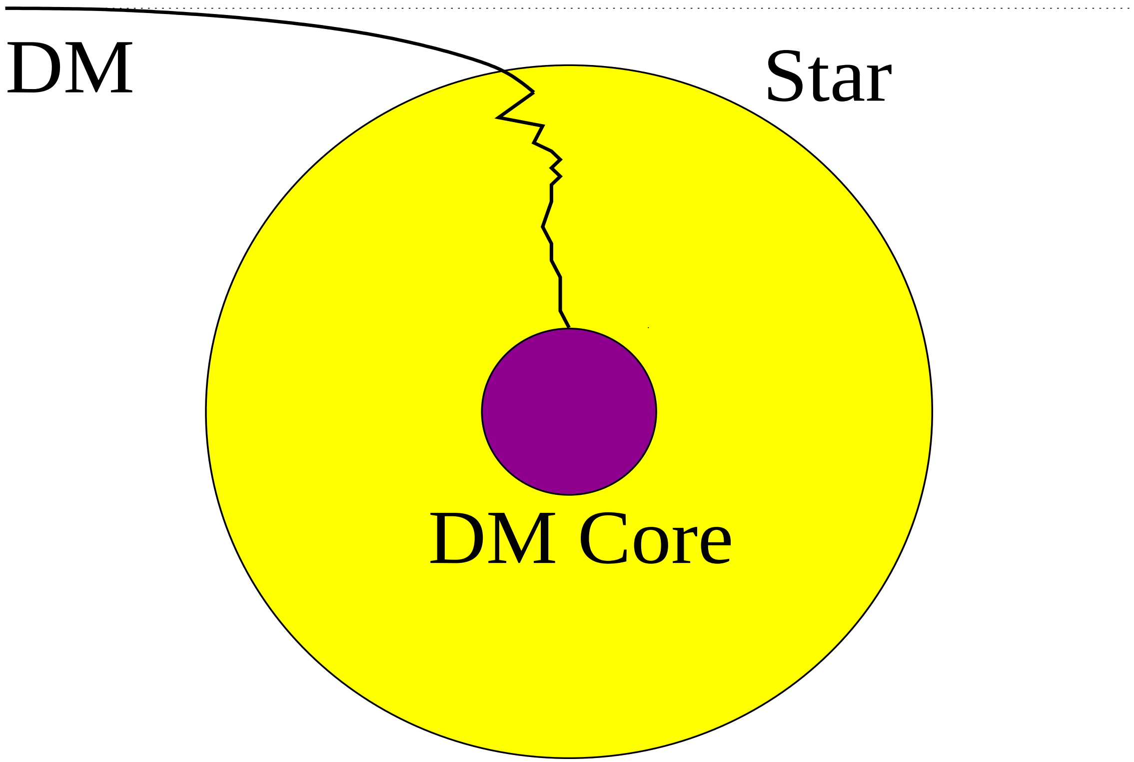
$$\tau_{eff} \simeq 10^{32}\, yr \left| \frac{m_X M^2/\lambda^* \zeta}{\text{TeV}^3} \right|^2$$

- Nucleon decay searches use a meson momentum window. Meson momenta from IND are larger:

Decay mode	p_M^{SND} (MeV)	p_M^{IND} (MeV)
$N \to \pi$	460	800 - 1400
$N \to K$	340	680 - 1360
$N \to \eta$	310	650 - 1340

IND and Stars

- DM can collect in stars and build up a large density.



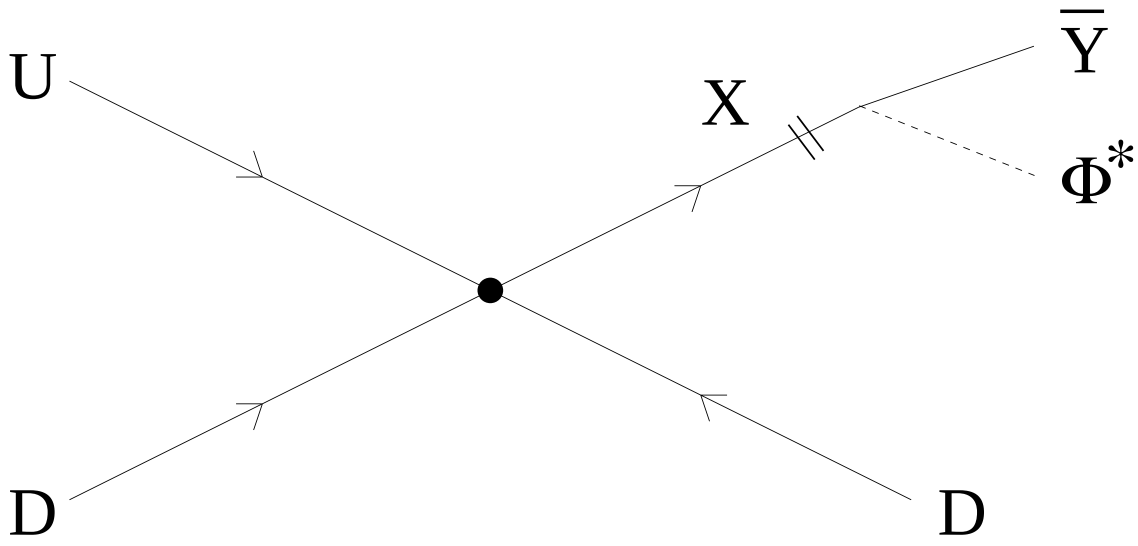
- Regular DM self-annihilates and can heat up a star.
- Y and Φ DM can't self-annihilate, but can yield IND:
  - DM collects in the stellar core by elastic scattering.
  - IND: $Y\,/\,\Phi \;+\; N \;\to\; \Phi^*\,/\,\bar{Y} \;+\; M$
  - Φ^* annihilates with Φ, $\bar{Y}$ annihilates with Y
- Largest effects in dense neutron stars, white dwarfs.

  Main effect is stellar heating, not nucleon destruction.

  [Kouvaris '08; Bertone+Fairbairn '08; McCullogh+Fairbairn '10; Hooper *et al.* '10]
- Solar bounds are weak due to evaporation ($m_{DM} \leq 2.9$ GeV).

Collider Searches

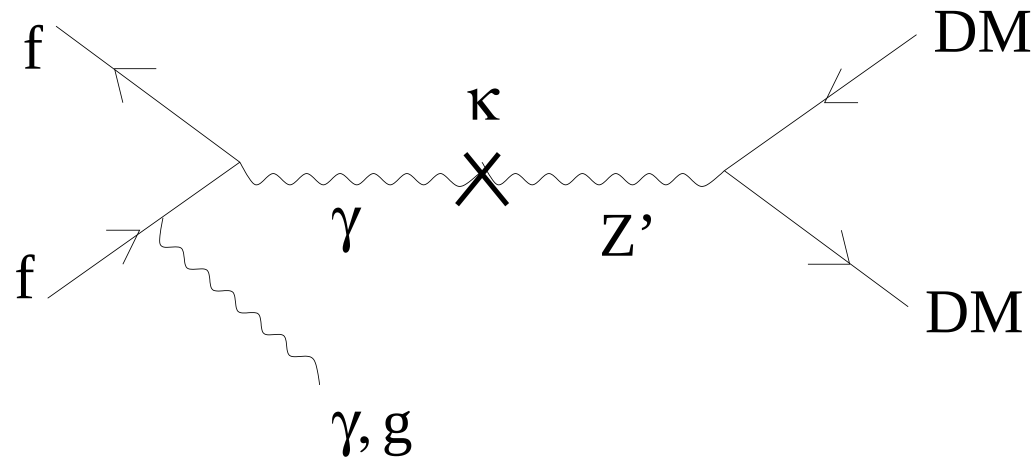
- The operator $\frac{1}{M^2}Xudd$ will produce monojets:



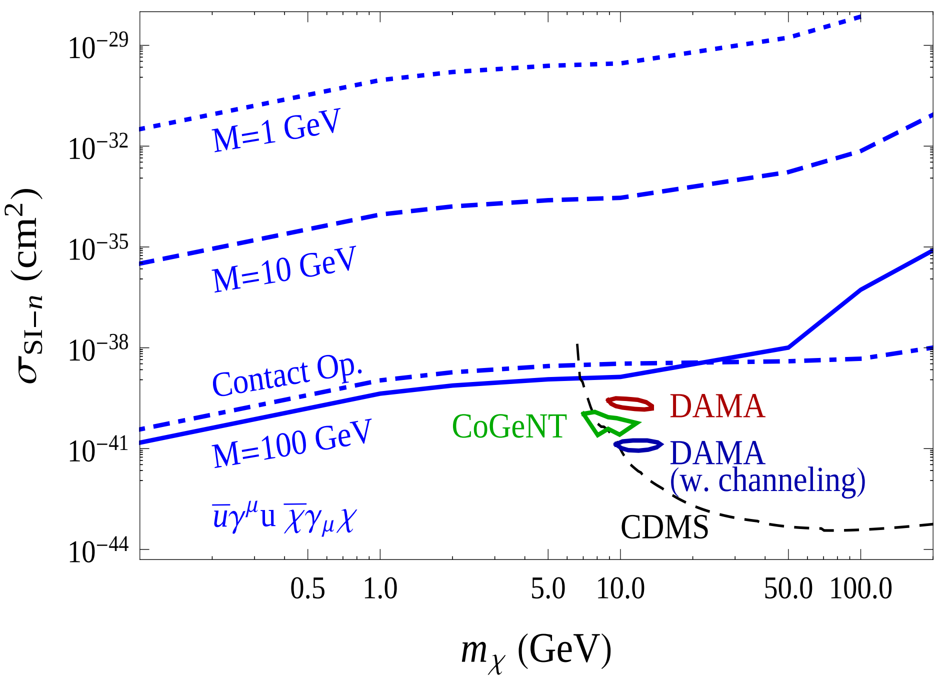
- Consistent with current bounds for $M \gtrsim 300\,\text{GeV}$.

  LHC should increase this to $M \gtrsim 1000\,\text{GeV}$.

- Monojets can also come from Z' Drell-Yan with ISR/FSR:



Could be observable at the LHC: [Bai,Fox,Harnik '10; Goodman '10]



[Bai,Fox,Harnik '10]

Summary

- Hylogenesis realizes DM as hidden antibaryons.

  Explains DM and the baryon asymmetry simultaneously.

- $\rho_{DM} \simeq 5\rho_B \Rightarrow \sum_i m_{DM_i} \simeq 5\, m_p$.

- A distinctive new DM signal is Induced Nucleon Decay.

- The scenario could also be testable at the LHC.

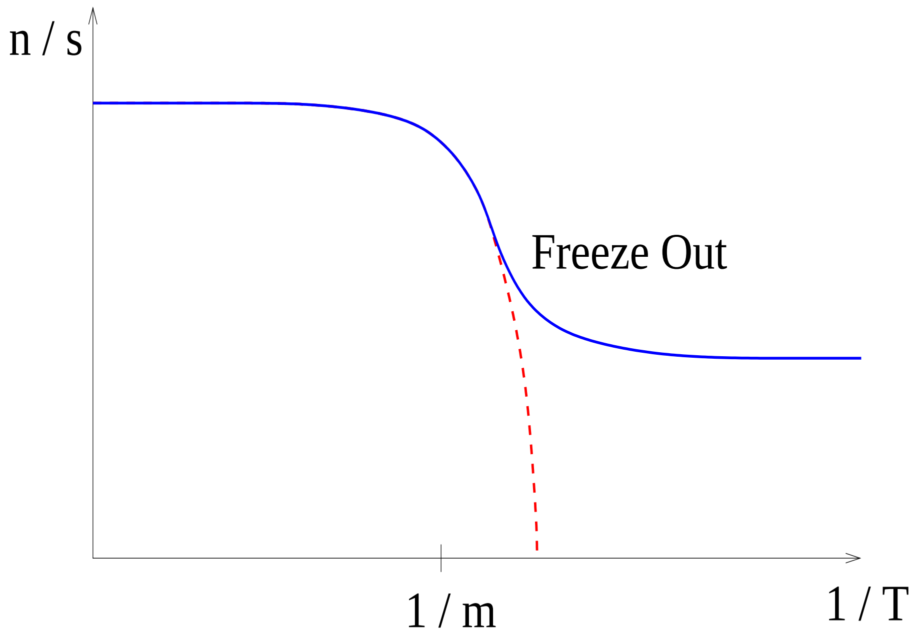
Extra Slides

WIMP Thermal Freeze-Out

- $n_{DM} \propto e^{-m/T}$ for $T < m$ in equilibrium.

- $\Gamma_{ann} = \langle \sigma\, v \rangle_{ann}\, n_{DM}$ falls below H^{-1} at $T = T_{fo}$.

  $\Rightarrow n_{DM}/s$ remains constant for $T < T_{fo}$



Gauge Kinetic Mixing

- Standard Gauge Boson Kinetic Terms:

  $(A = U(1)_{em}, \quad X = U(1)_x)$

  $$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu},$$

  with $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$, $X_{\mu\nu} = \partial_\mu X_\nu - \partial_\nu X_\mu$.

- Gauge Kinetic Mixing:

  $$\mathcal{L} \supset -\frac{1}{2}\epsilon\, F_{\mu\nu}X^{\mu\nu}.$$

- $\epsilon \sim 10^{-4}$–10^{-2} from integrating out heavy states charged under both $U(1)_{em}$ and $U(1)_x$. [Holdom '86]

- Assume DM carries a $U(1)_x$ charge x_{DM}, SM states do not.

- Rotate gauge fields to get canonical kinetic terms:

$$\begin{aligned} A_\mu &\to A_\mu - \epsilon X_\mu + \mathcal{O}(\epsilon^2) \\ X_\mu &\to X_\mu + \mathcal{O}(\epsilon^2) \end{aligned}$$

- This induces a coupling between X_μ and SM states:

$$eQ\, A_\mu\, \bar{f}\gamma^\mu f \to eQ\, A_\mu\, \bar{f}\gamma^\mu f - eQ\epsilon X_\mu\, \bar{f}\gamma^\mu f.$$

SM-$U(1)_x$ coupling strength $= -e\,Q\,\epsilon \ll 1$

DM-$U(1)_x$ coupling strength $= g_x\, x_{DM} \sim 1$

- DM DOES NOT get an electric charge!

Constraints on Light Abelian Sectors

- Breaking $U(1)_x$ near a GeV yields a light Z_x gauge boson.

- Constraints:

  – $(g-2)_{\mu,e}$ [Pospelov '08]

  – $BR(\Upsilon(3s) \to \gamma\,\mu^+\mu^-)$ [Essig *et al* '09, Battell *et al.* '09, Reece *et al.* 09]

  (if Z_x decays mostly to the SM)

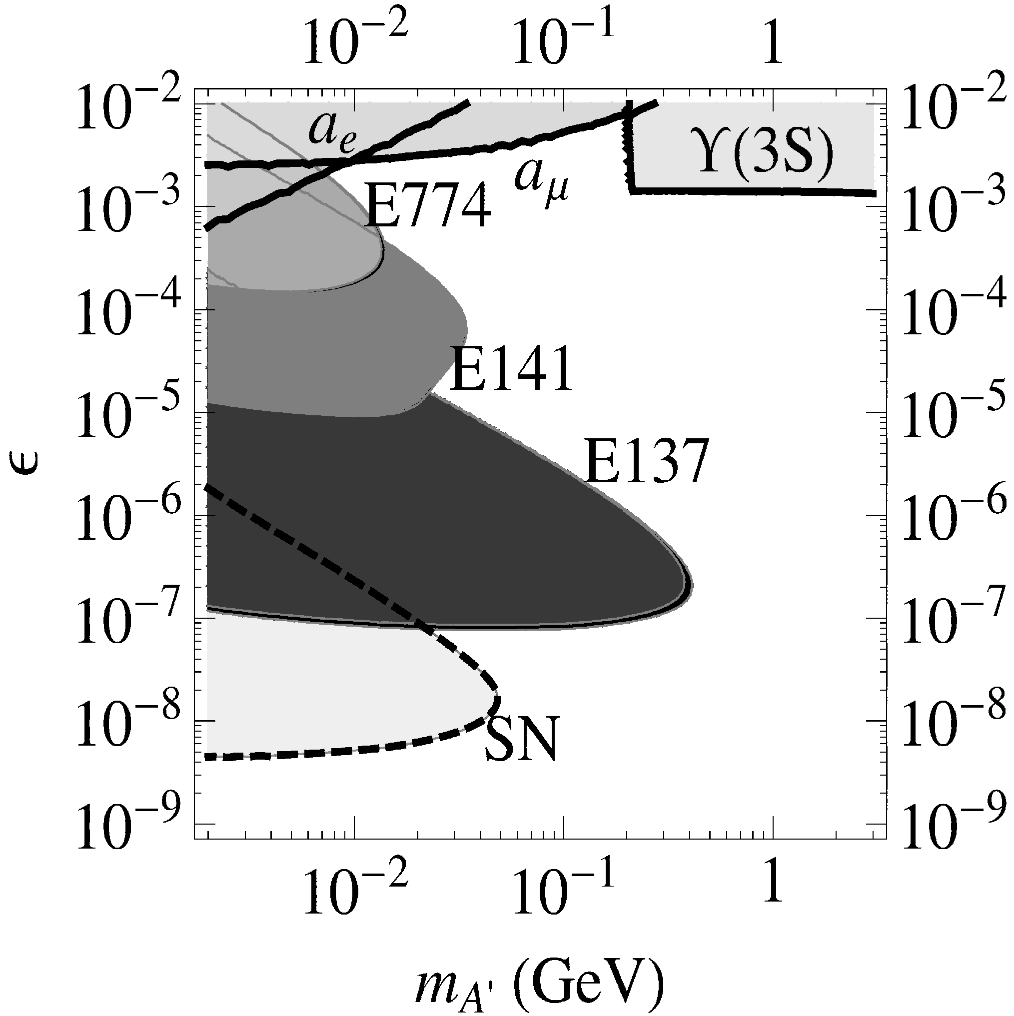
  $BR(\Upsilon(3s) \to \gamma + inv)$ [Essig *et al* '09, Battell *et al.* '09, Reece *et al.* 09]

  (if Z_x decays mostly to hidden stuff)

  – Supernova cooling, beam dumps [Ahlers *et al.* 08, Bjorken *et al.* '09]

  – Neutrino experiments [Battell *et al.* '09]

- ($\Upsilon(3s)$ constraint assumes Z_x decays to SM)



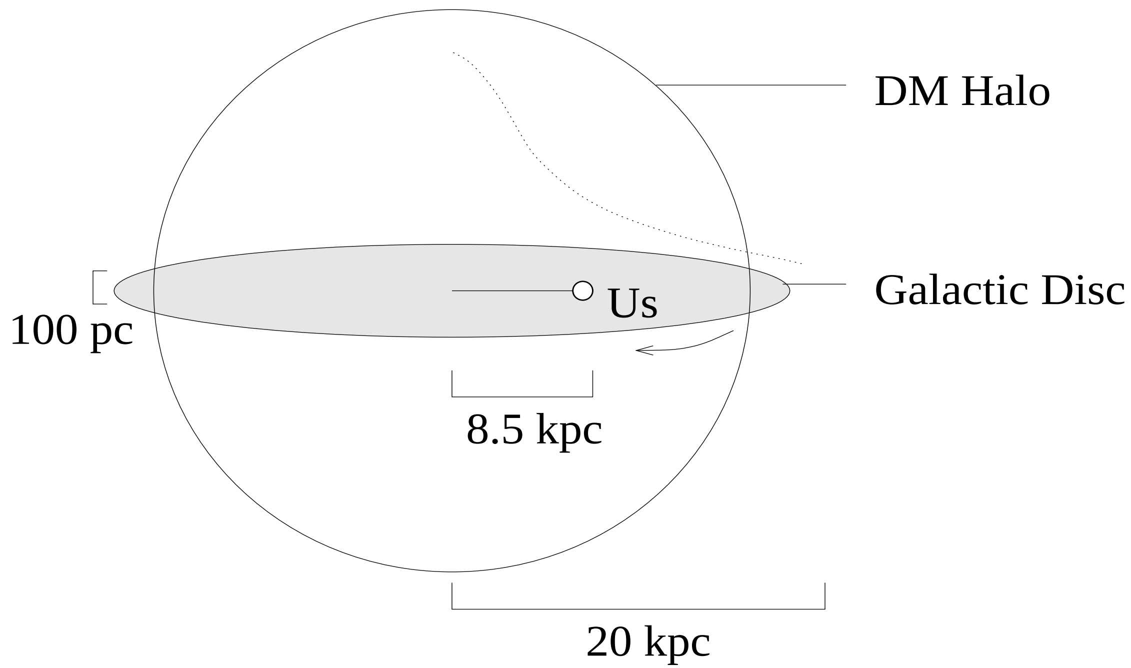
[Bjorken,Essig,Schuster,Toro '09]

- Fixed target experiments can improve these bounds.

[Bjorken *et al.* '09]

Dark Matter in our Galaxy

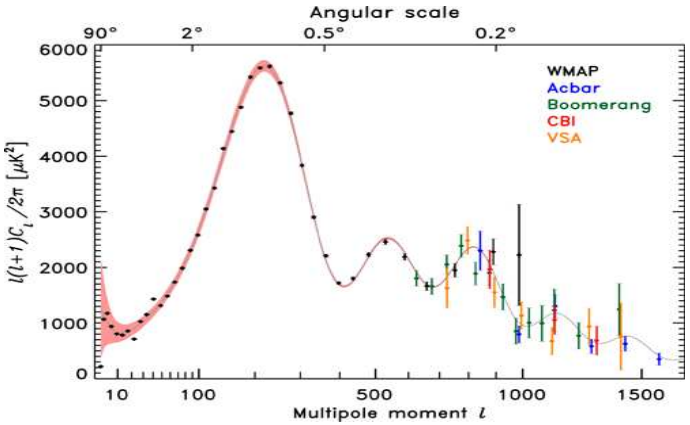
- We encounter a DM "wind" from our galactic motion.

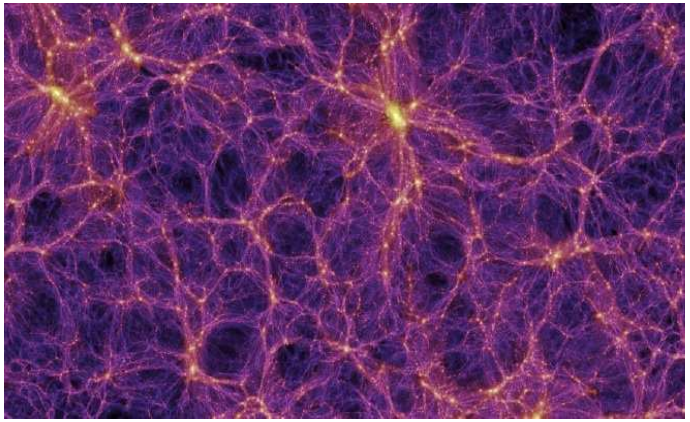


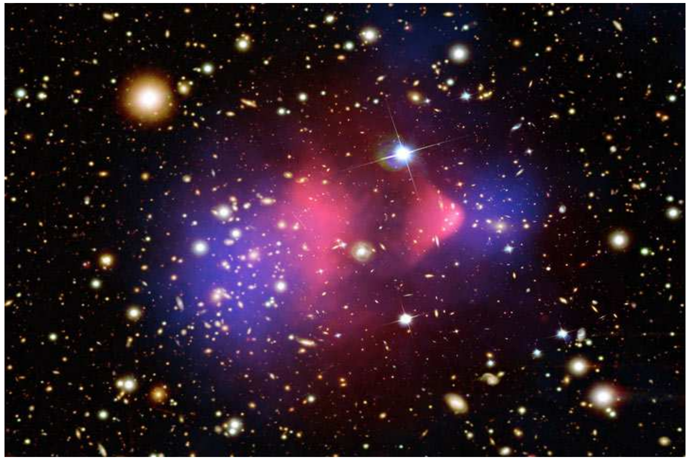
- $v_{us} \simeq (250\, km/s) + (30\, km/s)\,(0.51)\,\cos(2\pi t/yr - June\ 2)$.

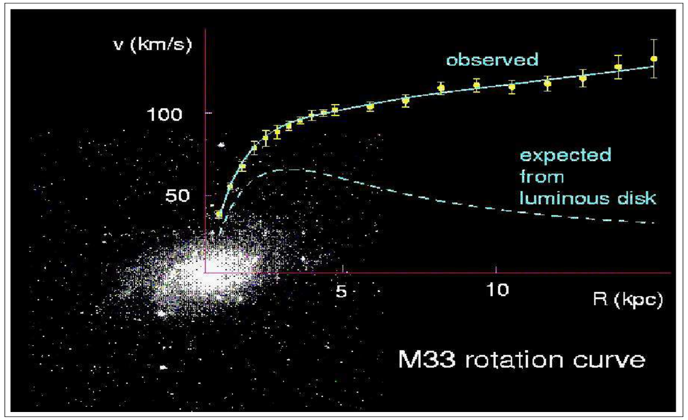
- $v_{DM} \sim$ Maxwell distribution with $\langle v \rangle \simeq 250\, km/s$.

• The presence of DM is deduced by its gravitational effects.









• Combined measurements find: $\rho_{DM}/\rho_{total} = 0.21 \pm 0.01$.