# Changing Dark Matter

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Based on work done in collaboration with

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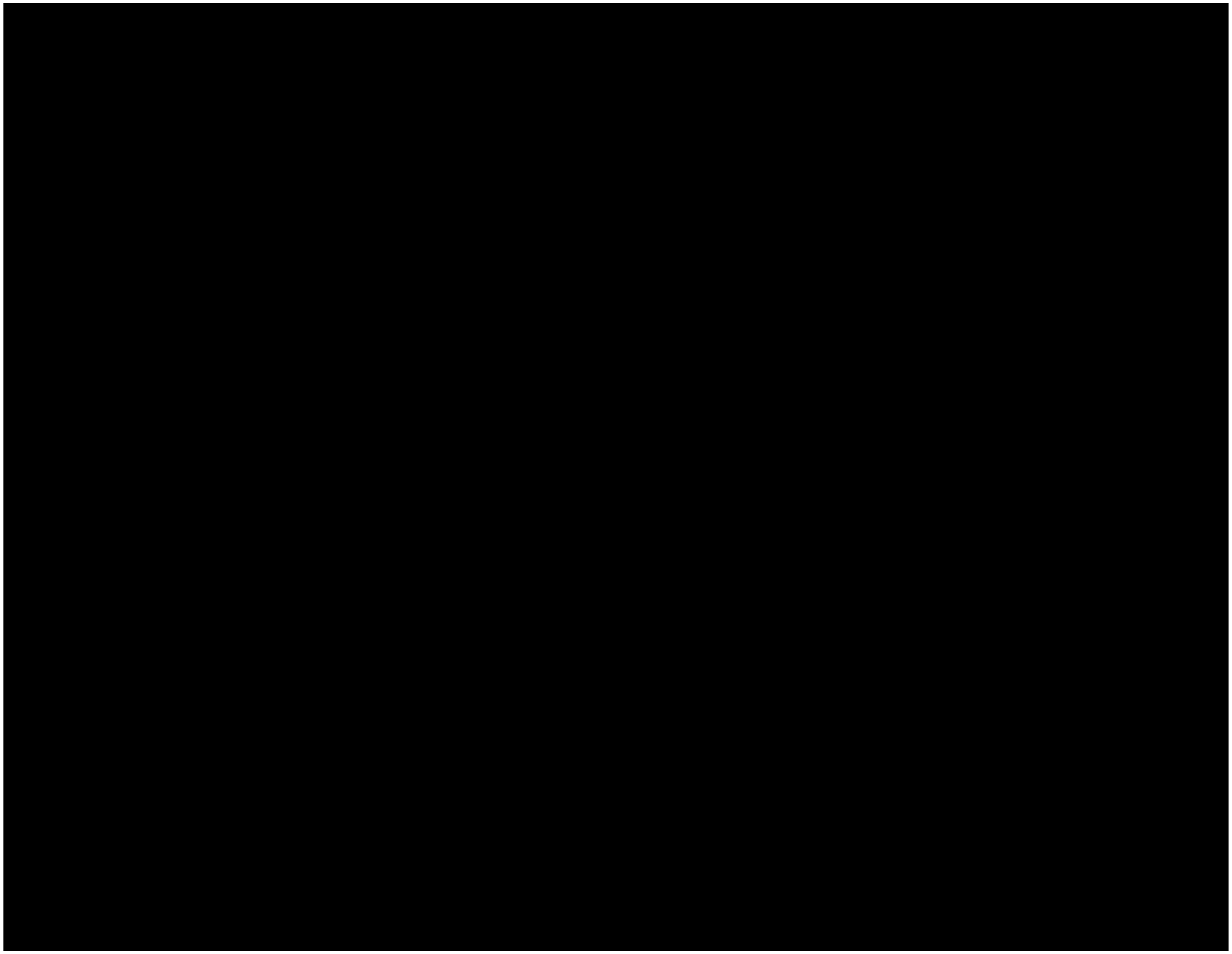
# Outline

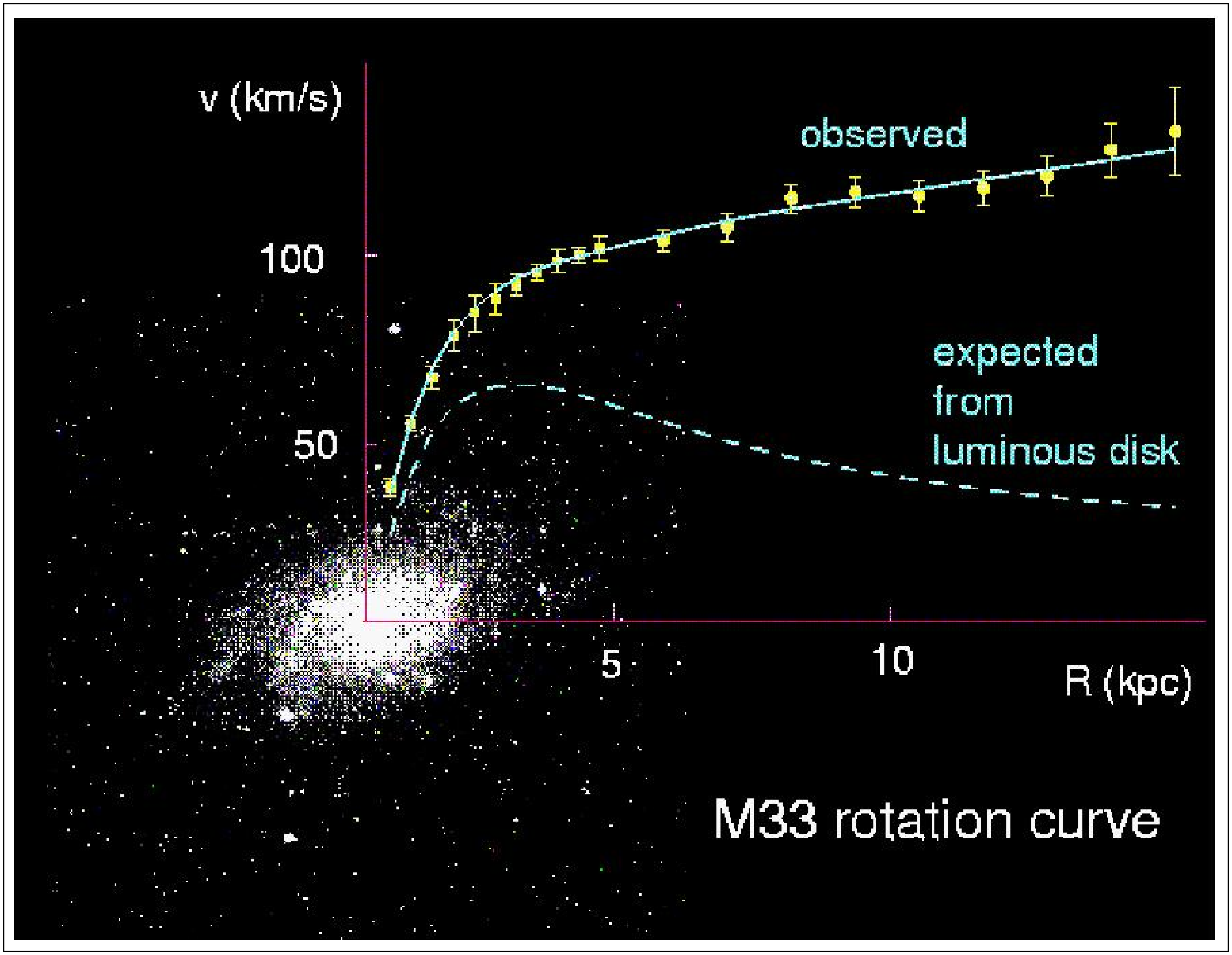
- Evidence and Recent Hints of DM
  - Gravitational Evidence for DM
  - Direct Detection: CDMS, XENON, DAMA,. . .
  - Indirect Detection: PAMELA, ATIC, INTEGRAL,. . .
  - LHC Prospects
- Changing DM
  - A late-time phase transtion after freeze-out
  - Effects on the DM
  - Phenomenology of the PT

# Evidence and Recent Hints of Dark Matter

# Dark Matter . . .



# . . . not so Dark

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[Corbelli *et al.*]

# Dark Matter Evidence from Gravity

- WMAP and other CMB probes have precisely determined the average dark matter density in the universe:

$$\Omega_{DM}h^2 = 0.104^{+0.0073}_{-0.0128}.$$

- This value is consistent with estimates of structure formation and gravitational lensing.

- It is also about what we would expect from the thermal freeze-out of a stable WIMP:

$$\Omega\, h^2 \simeq \left(\frac{T_0}{M_{\rm Pl}}\right)^3 \frac{1}{3H_0^2} \left(\frac{m}{T_{fo}}\right) \frac{1}{\langle\sigma\, v\rangle_{fo}}.$$

# Other Possible Dark Matter Signals

- Dark matter around us can be detected directly by its scattering off nuclei.

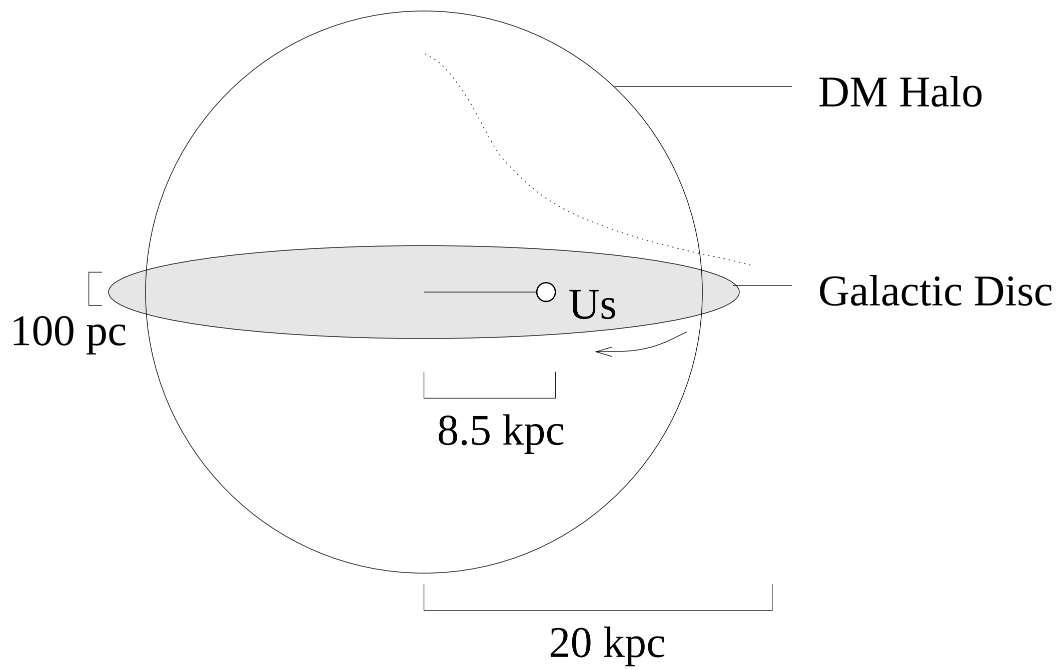
- Dark matter in the galaxy can annihilate producing particle fluxes.

- Dark matter captured in the sun can annihilate and generate a neutrino signal.

- If the DM particle is related to a sector that stabilizes the electroweak scale, we may dicover it at the LHC.

## DM in our Galaxy

- Flat galactic disc surrounded by a spherical DM halo:

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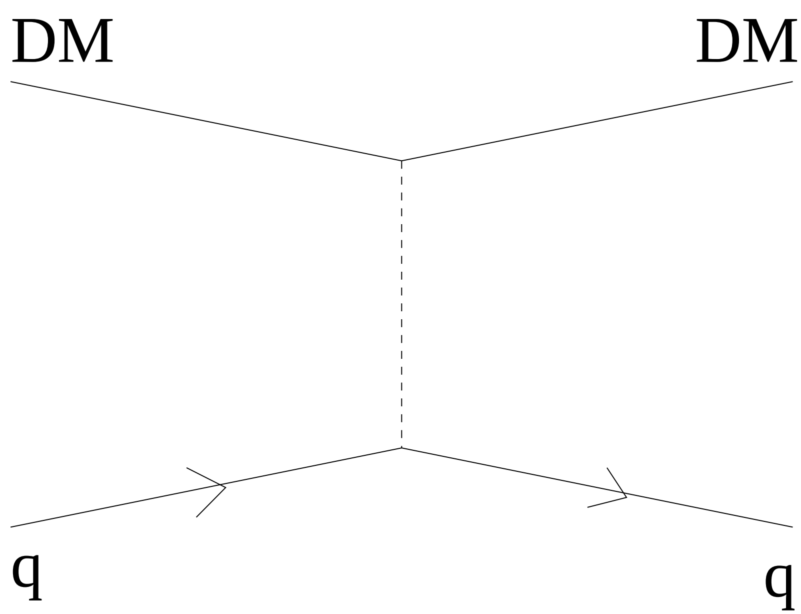
- $v_{us} \simeq (220\,km/s) + (30\,km/s)\,(0.51)\,\cos(2\pi t/yr)$.

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

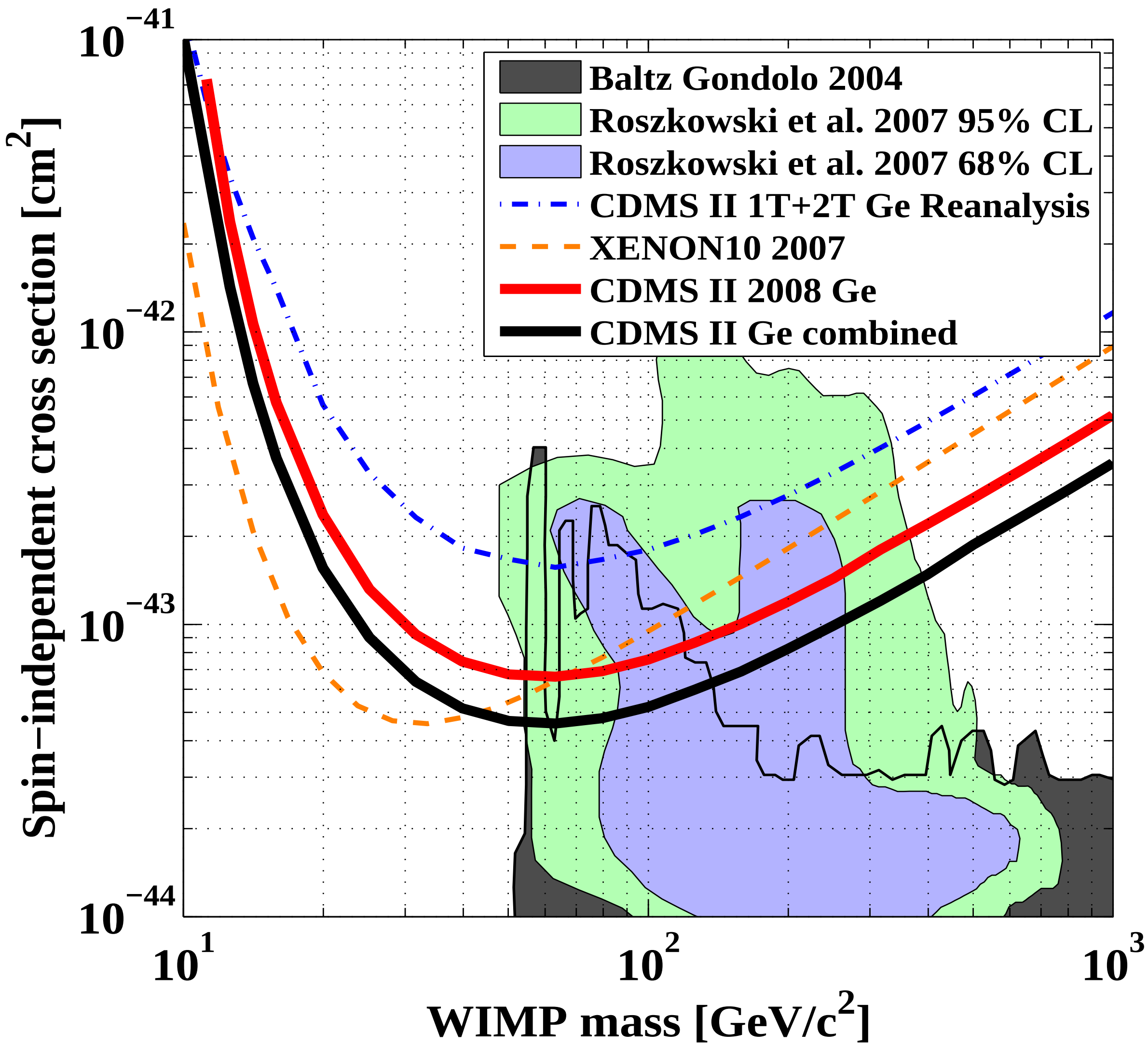
# Direct DM Detection

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

- This DM flux can scatter off nuclei.
  $\longrightarrow$ look for nuclear recoils $\sim 100\,\text{keV}$



# Experimental Limits (Low Background)



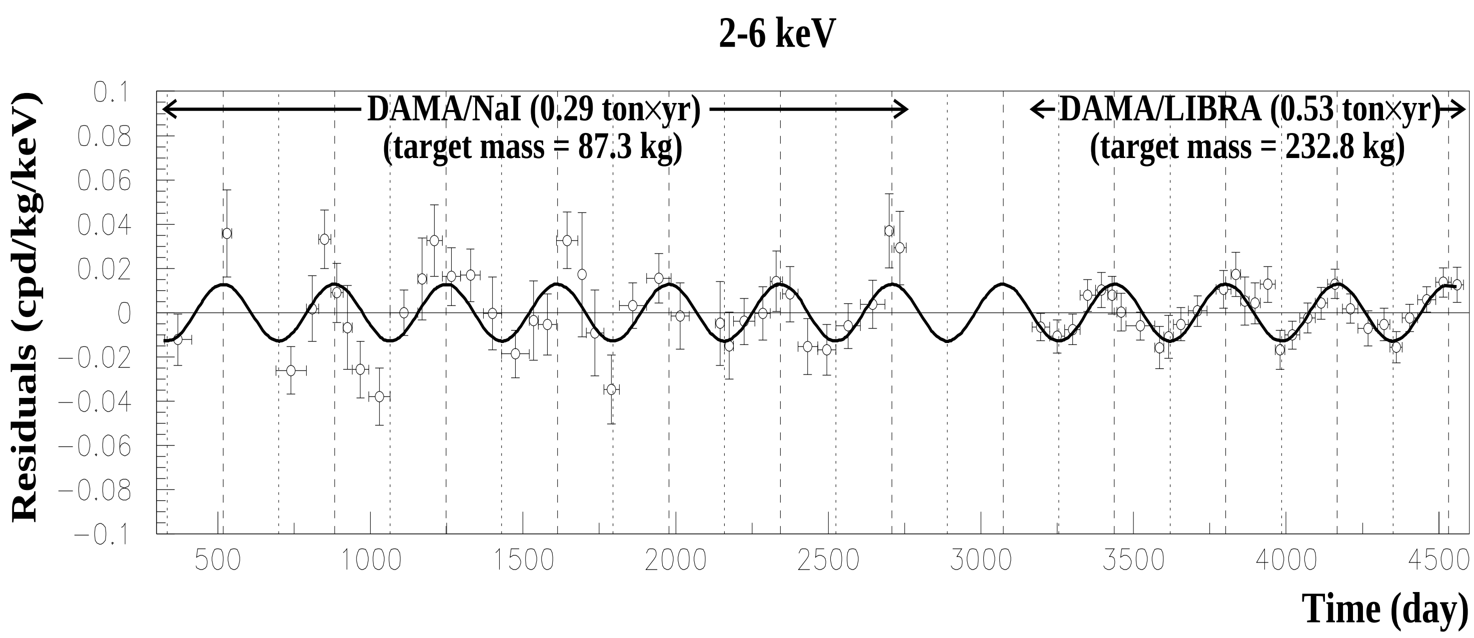

[CDMS '08]

# Annual Modulation - DAMA

- The DM flux changes due to the annual motion of the Earth relative to the galactic rotation.

  [Drukier,Freese,Spergel '86]

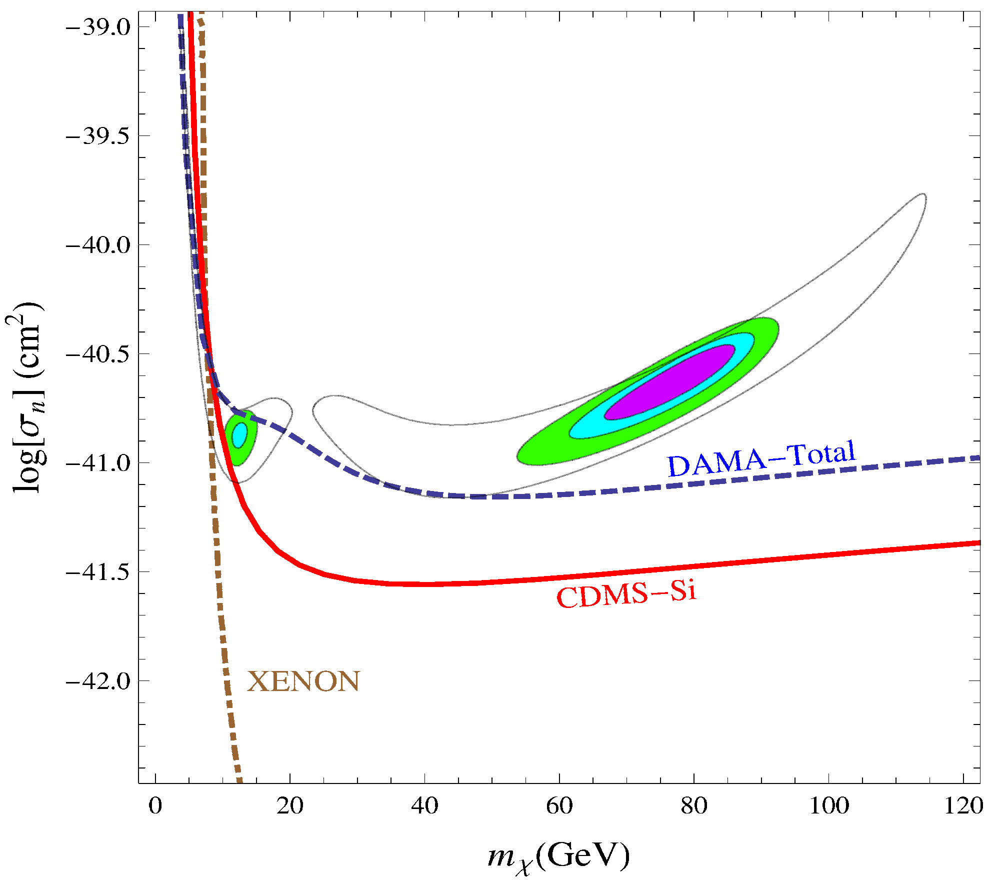
- DAMA looked for scattering off $NaI$ with little background rejection to find an annual modulation signal ($\gtrsim 8\,\sigma$).



# DAMA vs. Other Searches

- DAMA seems to be inconsistent with CDMS, . . . .

  [Chang,Pierce,Weiner '08]




- Non-standard (inelastic) DM can still fit. [Tucker-Smith+Weiner '08]

# Indirect Detection

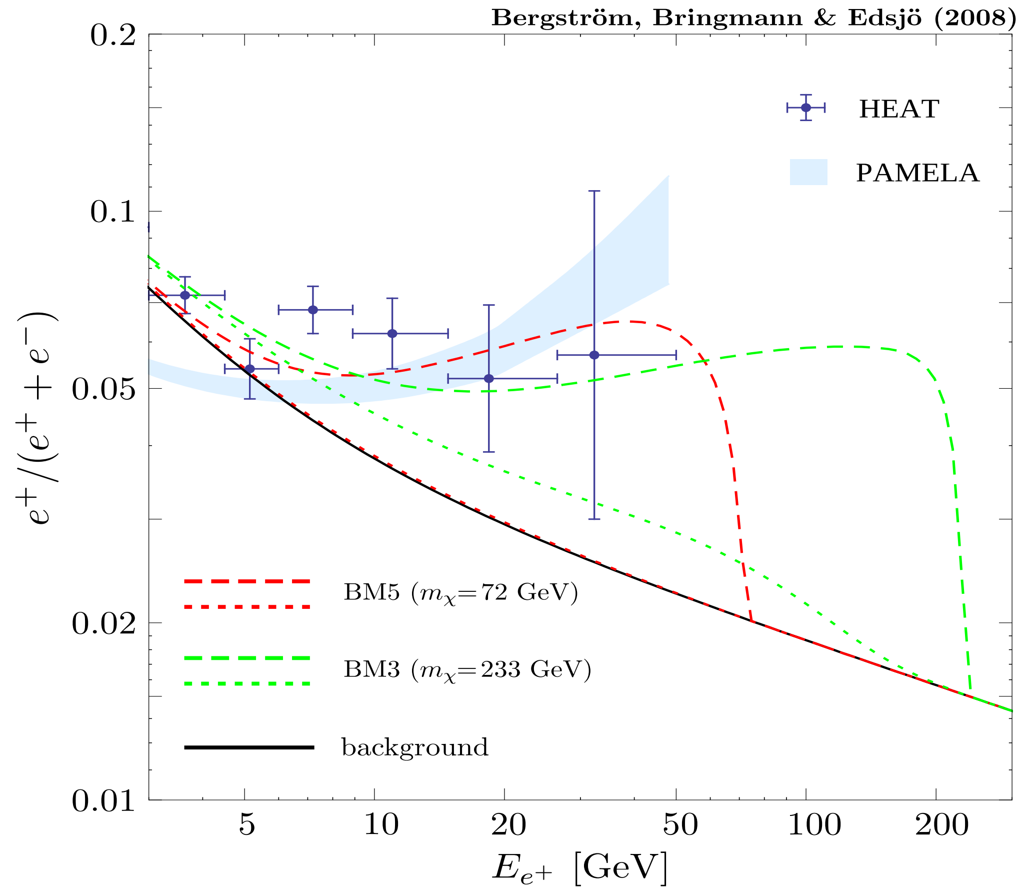
- Dark matter annihilation in our galaxy can give rise to particle fluxes, especially from the galactic center..

- Possible Hints:
  - PAMELA, ATIC, PPB-BETS see an excess $e^+$ and $e^-$.
  - WMAP Haze: too much synchrotron radiation from the galactic center. [Finkbeiner '04]
  - INTEGRAL 511 keV line from around the galactic center.

- Signals from DM annihilating into leptons?

# Excess Cosmic Ray Positrons and Electrons

- PAMELA observes a cosmic ray positron excess.

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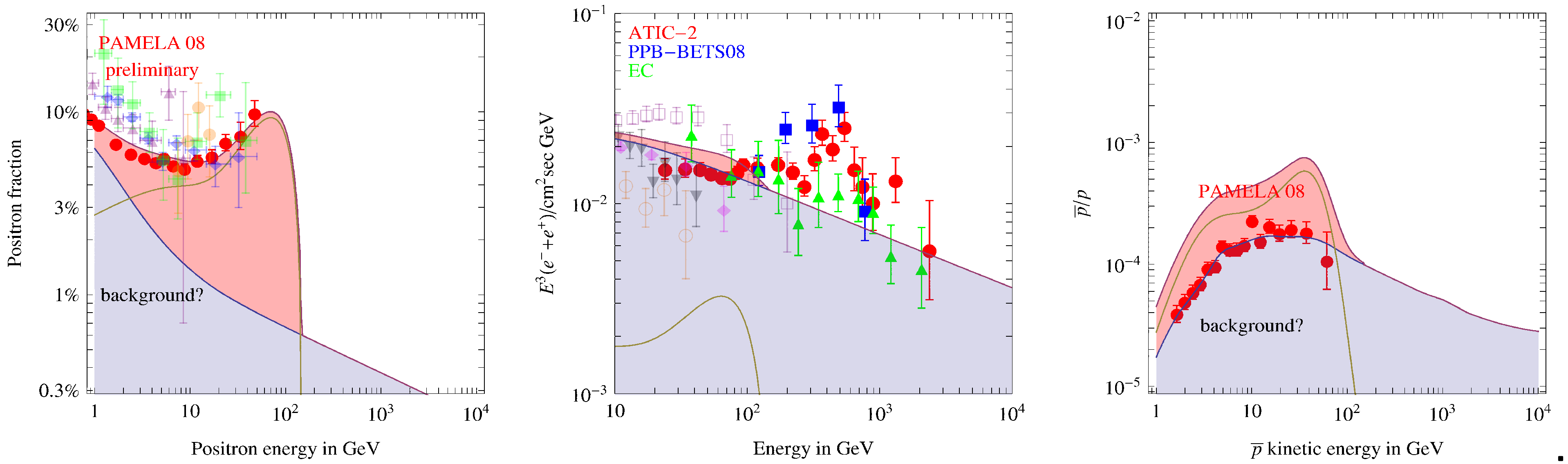
- ATIC, PPB-BETS also see an excess $(e^+ + e^-)$ flux.

- Energies are consistent with DM of mass $\gtrsim 500\,\text{GeV}$.

- Plots from [Cirelli, Kadastik, Raidal, Strumia '08]:

  (Preliminary Data!!!)

DM with $M = 150$ GeV that annihilates into $W^+W^-$



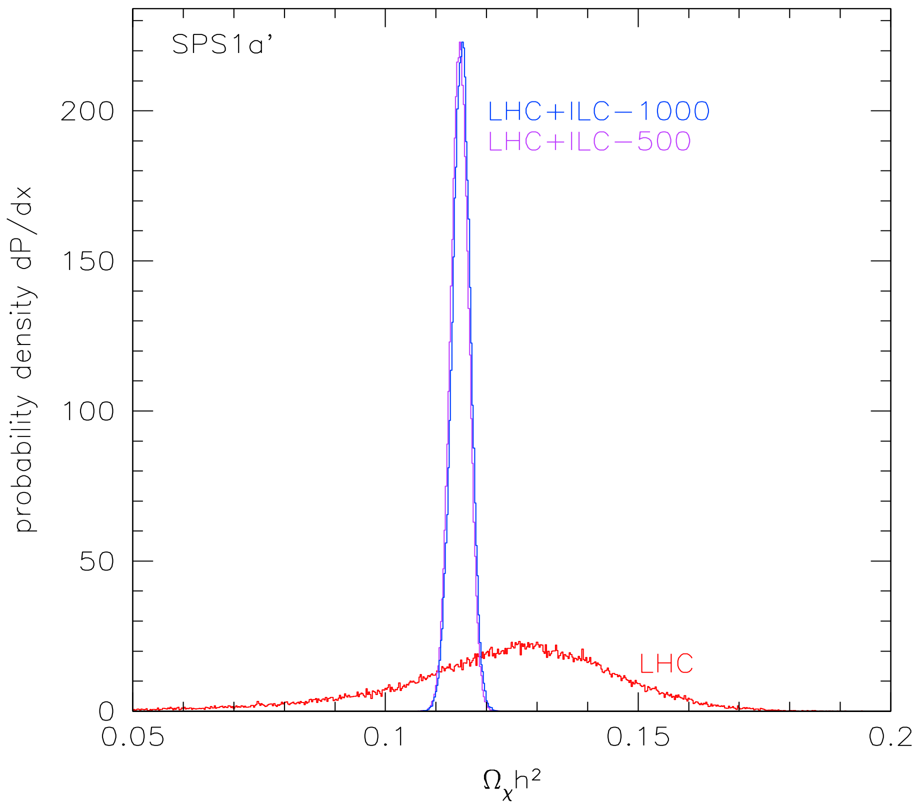
- Injected electrons will circulate in the galactic magnetic field and emit synchrotron radiation.
  → WMAP haze [Finkbeiner '04]

- Soft $e^+$ injected near the galactic center will annihilate.
  → INTEGRAL 511 keV line [Hooper *et al.* '04]

- GLAST/Fermi should test these hints by looking for hard photons from inverse Compton scattering off the CMB.

# DM at the LHC

- DM from new physics stabilizing the electroweak scale?
- It may be possible to deduce the DM mass and couplings from data.




[Baltz *et al.* '06]

# Reconstructing the Relic Density

- If these various probes allow us to deduce the DM mass and couplings we can reconstruct $(\Omega\, h^2)_{obs}$.
  $\rightarrow$ DM relic density assuming a standard thermal history.

- If $(\Omega\, h^2)_{obs} \neq \Omega_{DM} h^2$ we learn about cosmology.

- $(\Omega\, h^2)_{obs} > \Omega_{DM} h^2$
  $\rightarrow$ dilution by entropy production

- $(\Omega\, h^2)_{obs} < \Omega_{DM} h^2$
  $\rightarrow$ non-thermal production, another source of DM, . . .

- Another possibility for either direction is Changing DM.

# Changing Dark Matter

# Changing DM

- All these probes measure DM today.

- What if the DM properties changed since the time its density was formed?

- Idea: a late phase transition that modifies the DM.

- Does this have any generic features?

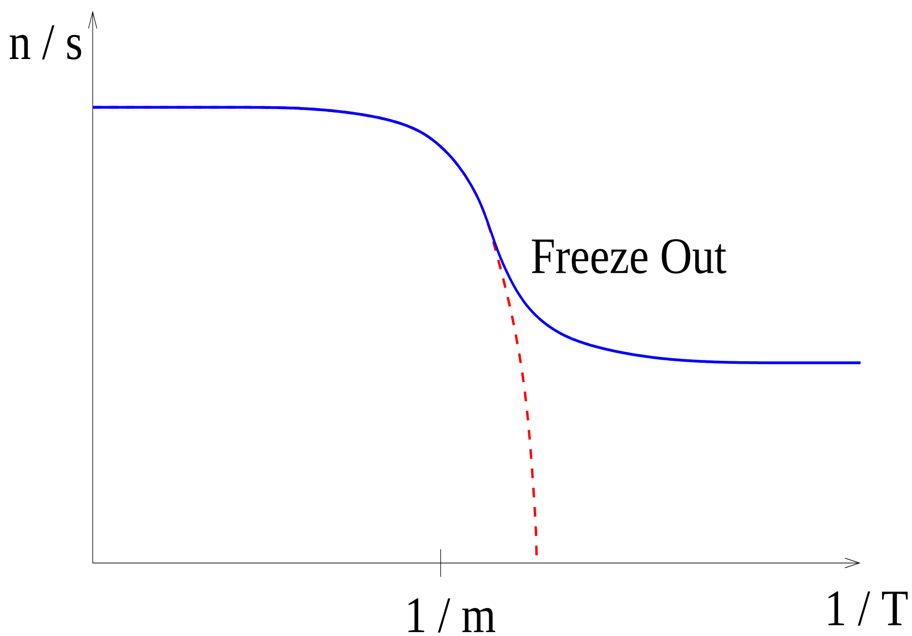
  Is it even possible?

# 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 $T < T_{fo}$



# DM-Changing Phase Transition after Freeze-Out?

- Suppose $P$ develops a VEV at $T_{PT} < T_{fo}$,

  $v_P = \langle P \rangle$ changes the properties of the DM.

- $T_{fo} \lesssim m_{DM}/20$ for WIMP DM.

  We typically want $v_P \sim m_{DM}$ for a large effect.

  $\Rightarrow T_{PT} < T_{fo} \ll v_P \sim m_{DM}$

- Electroweak PT: $v \sim T_{PT}$ with $T_{PT}$ too large.

- QCD PT: $\Lambda_{QCD} \sim T_{PT}$ with $\Lambda_{QCD}$ too small.

# A New Phase Transition Sector (Toy Model)

- New singlet field $P$ with potential

$$V_P = -\frac{1}{2} m_P^2 \, P^2 + \frac{\lambda_P}{4!} P^4$$

$\Rightarrow v_P = \sqrt{6m_P^2/\lambda_P}$

- $N_Q$ sets of massless fermions with $-\mathcal{L} \supset \lambda_{PQ} \, P \, \bar{Q} Q$.

- At finite temperature ($P \sim 0$),

$$V_P \simeq -\frac{1}{2}\left(m_P^2 \, P^2 - \frac{N_Q}{6} \lambda_{PQ} \, T^2\right) + \frac{\lambda_P}{4!} P^4$$

- The $Q$'s trap $P$ at the origin independently of $\lambda_P$.

- At $T = 0$

$$v_P = \sqrt{\frac{6m_P^2}{\lambda_P}}.$$

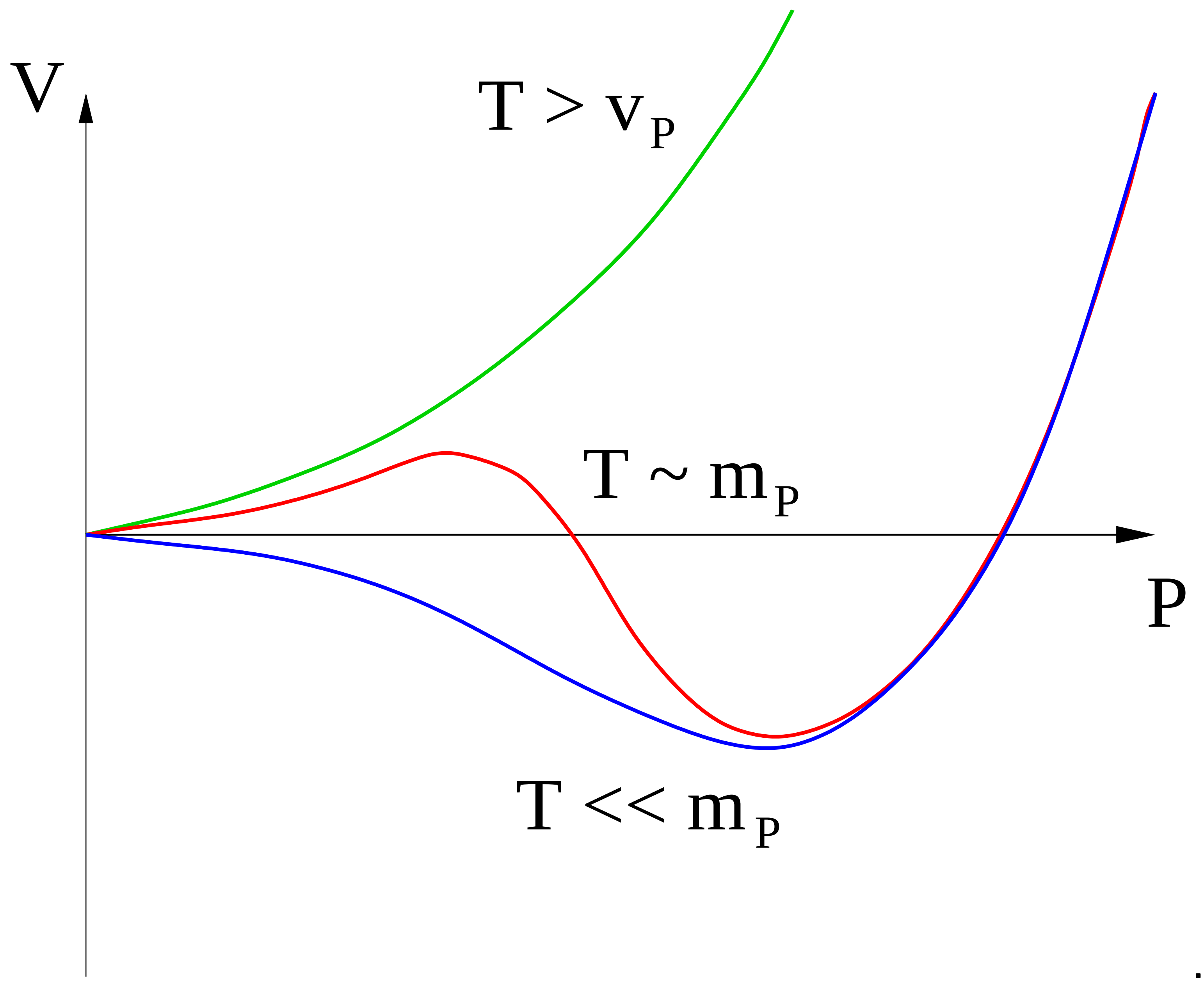
- The phase transition occurs at

$$T_{PT} = \sqrt{\frac{6m_P^2}{N_Q \lambda_{PQ}^2}}.$$

- A hierarchy $v_P \gg T_{PT}$ arises for $N_Q \lambda_{PQ}^2 \gg \lambda_P$.

- Note that $Q$ loops induce

$$\Delta\lambda_P \sim N_Q \frac{\lambda_{PQ}^4}{16\pi^2}.$$


V
T > v_P
T ~ m_P
P
T << m_P

# The Final DM Relic Density

- If this PT changes the DM mass and couplings after freeze-out, the resulting relic density is

$$\Omega_{DM}h^2 = D \left( \frac{m_{DM}^{v_P \neq 0}}{m_{DM}^{v_P = 0}} \right) \Omega_{DM}^{v_P = 0} h^2.$$

$\Omega_{DM}h^2$ is the actual value of the relic density.

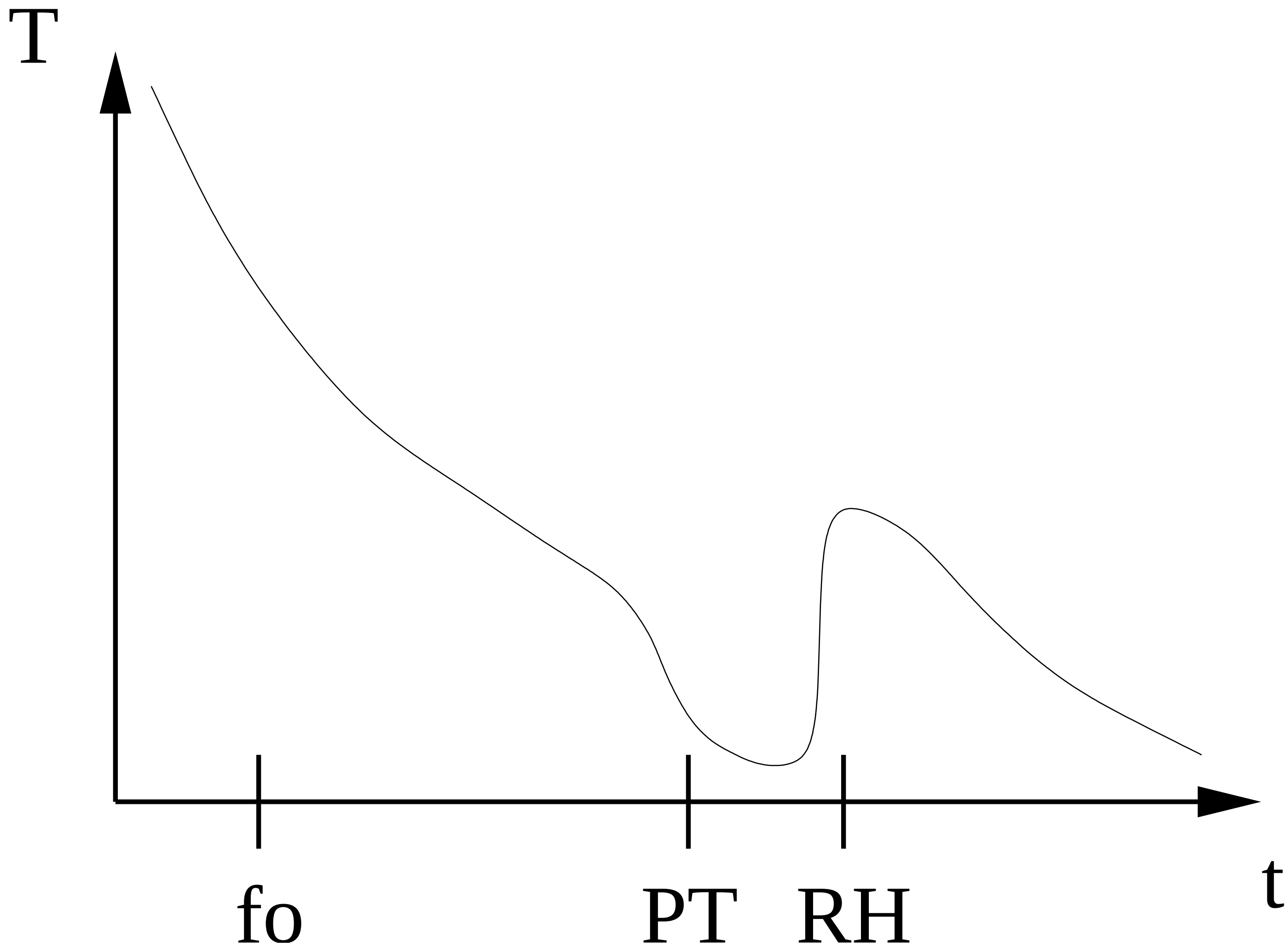
$\Omega_{DM}^{v_P=0}h^2$ is the value obtained without a PT.

$D \leq 1$ is a dilution factor from *thermal inflation*.

$$D = \frac{g_*^{PT}}{g_*^{RH}} \frac{T_{PT}^3}{T_{RH}^3}$$

(We focus on cases where $D \sim 1$.)

# Temperature Timeline



# A Sample Dark Matter Sector

- Higgsino-Singlino system with a $\mathbb{Z}_2$ symmetry:

  $SU(2)_L$ chiral doublets: $\Psi_L, \Psi_{\bar{L}}$

  Singlet chiral fermion: $\Psi_s$

  $-\mathcal{L} \subset \lambda_s\, P\, \Psi_s \Psi_s$

- Neutral Mass Matrix:

$$\mathcal{M} = \begin{pmatrix} 0 & \mu & -\lambda_1 v_H/\sqrt{2} \\ \mu & 0 & \lambda_2 v_H/\sqrt{2} \\ -\lambda_1 v_H/\sqrt{2} & \lambda_2 v_H/\sqrt{2} & 2(\mu_s + \lambda_s\, v_P) \end{pmatrix}$$

- Choose parameters such that the lightest state is:

  $v_P = 0 \Rightarrow$ mostly doublet

  $v_P \neq 0 \Rightarrow$ mostly singlet

# Actual and Apparent Relic Densities

- "Higgsino" DM annihilates into $W^+W^-$ with

$$\Omega_{DM}^{v_P=0}\, h^2 \simeq (0.1)\left(\frac{m_{DM}^{v_P=0}}{\text{TeV}}\right)^2 .$$

- Actual relic density after the phase transition:

$$\Omega_{DM}\, h^2 \simeq (0.1)\left(\frac{m_{DM}^{v_P=0}}{\text{TeV}}\right)^2 D\left(\frac{m_{DM}^{v_P\neq 0}}{m_{DM}^{v_P=0}}\right).$$

- The DM particle at $T = 0$ is mostly singlet.

- If the DM properties at $T = 0$ were measured, the apparent annihilation mode would be through an $s$-channel $P$ to $Q\bar{Q}$:

$$(\Omega\, h^2)_{obs} \simeq \frac{0.05}{N_Q(\lambda_{PQ}\lambda_s)^2}\left(\frac{m_{DM}^{v_P\neq 0}}{\text{TeV}}\right)^2 .$$

- It is easy to obtain $(\Omega\, h^2)_{obs} \gg \Omega_{DM}\, h^2$.

- $s$-channel $P$ exchange also dominates the rate of annihilation in the galaxy today.

- Getting $(\Omega\, h^2)_{obs} \ll \Omega_{DM}\, h^2$ is more difficult.

- Need $\langle \sigma\, v \rangle^{v_P \neq 0} \gg \langle \sigma\, v \rangle^{v_P = 0}$.

  $\rightarrow$ modified $v_P \neq 0$ DM tends to recouple after the PT

- Non-recoupling $\Rightarrow n_{DM}^{PT}\, \langle \sigma\, v \rangle^{v_P \neq 0} \leq 1.66\, (g_*^{RH})^{1/2} \frac{T_{RH}^2}{M_{\mathrm{Pl}}}$.

- Model-independent bound:

$$\frac{(\Omega\, h^2)_{obs}}{\Omega_{DM}\, h^2} \gtrsim \sqrt{\frac{g_*^{RH}}{g_*^{v_P = 0}}} \frac{T_{RH}}{T_{fo}^{v_P \neq 0}}.$$

# Related Phenomenology

- A late phase transition generically requires a light scalar:

$T_{PT} < T_{fo} \lesssim 50\,\text{GeV}\left(\frac{m_{DM}}{\text{TeV}}\right)$

$T_{PT} = \sqrt{m_P^2/N_Q\lambda_{PQ}^2}$

$m_P \sim$ mass of the scalar excitation $\phi_P = P - v_P$.

- "Higgs Portal" mixing:

$$-\mathcal{L} \supset \frac{\lambda_{PH}}{2} P^2 |H|^2$$

- Mixing Angle $\theta$:

$$\tan 2\theta = \frac{\lambda_{PH}\, v_P\, v_H}{\lambda_H^2 v_H^2 - \lambda_P^2 v_P^2}$$

# Bounds on $\phi_P$

- Heavier masses: $m_P \gtrsim 9.5\,\text{GeV}$

  $\Rightarrow \theta < 0.14$ from $Z^0 h^0$ searches at LEP

- Intermediate masses: $5.5\,\text{GeV} \lesssim m_P \lesssim 9.5\,\text{GeV}$

  $\Rightarrow \theta \lesssim 0.3$ from $\Upsilon \to \phi_P \gamma$ with $\phi_P \to \tau\bar{\tau}$

- Lighter masses: $m_P \lesssim 5.5\,\text{GeV}$

  $\Rightarrow \theta \lesssim 10^{-4}$ from $B^0$ decays ($b \to s\phi_P$)

- $h^0\, Z^0 \to \phi_P \phi_P\, Z^0 \to 4b\, Z^0$ at the LHC?

  [Carena,Han,Huang,Wagner '07]

# Other Possibilities

- Our phase transition sector appears to be fairly generic. Use the EW PT by modifying the Higgs sector?

- Other possibilities for the DM sector:
  - Move $m_{DM}$ on or off of an $s$-channel resonance.
  - Change the mass of another particle that coannihilates with the DM.
  - ...

## Summary and Hints

- Lots of gravitational evidence for DM.

  New data may be non-gravitational hints for DM:

  DAMA, PAMELA, INTEGRAL, WMAP haze.

- Current and upcoming experiments stand a good chance of measuring the properties of the DM.

- DM properties can change after freeze-out.

- DM for PAMELA: $\langle \sigma_{ann} v \rangle \simeq 10^{-24} cm^3/s$ with $v \sim 10^{-3}$.

  DM for thermal freeze-out: $\langle \sigma_{ann} v \rangle \simeq 3 \times 10^{-26} cm^3/s$ with $v \simeq 0.05$.