Darkogenesis

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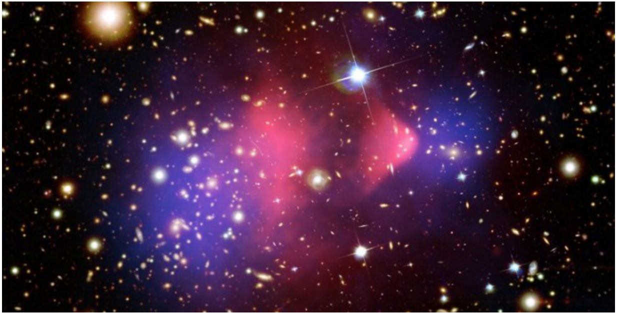
Astrophysics tells us that the Standard Model is incomplete.



- Dark matter makes up almost a quarter of the matter budget of the universe, $\Omega_D = 0.22$
- it's cold,
- it interacts weakly with us,
- and weakly with itself.

The WIMP paradigm

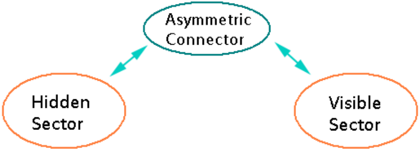
- Dark matter is a Weakly Interacting Massive Particle
- "WIMP Miracle": electroweak-scale masses and SM weak interactions yield approximately the right thermal relic abundance
- Relative equality of baryonic and dark matter densities is a numerical coincidence
- Same cross section governs both freezeout and direct detection.
- Well motivated (EWSB, hierarchy problem) and well studied. But hardly the only way to obtain observed dark matter properties.

Asymmetric dark matter

- Asymmetric Dark Matter: nonthermal relic density set by overdensity of DM relative to anti-DM, as for baryons
- Connecting B and D number directly relates baryonic and dark matter densities
- Direct (and indirect) detection cross sections not directly related to dark matter abundance: nonstandard relations between σ and m
- Motivations? New possibilities for origin of matter

Gelmini, Hall, Lin; Chivukula, Barr, Farhi; Barr; Kaplan; Fujii, Yanagida; Farrar, Zaharijas; Gudnason, Kouvaris, Sannino; Kitano, Low; Kaplan, Luty, Zurek

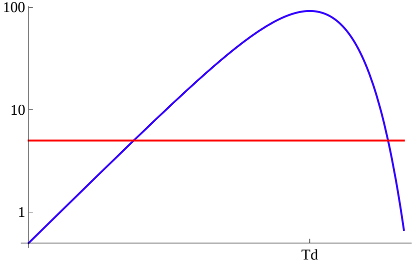
The cosmology of asymmetric dark matter



1. An initial matter-antimatter asymmetry is communicated between the SM and the DM
2. The process responsible for transferring the asymmetry freezes out at T_d
    - May be additional symmetric interactions between the sectors still in equilibrium.
3. The symmetric abundance of dark matter annihilates, leaving only the asymmetric relic density.

Properties of asymmetric dark matter

- Naively, $m_D = (\Omega_D/\Omega_B)m_B \approx 5$ GeV
- More generally, $(n_d - n_{\bar{d}}) \sim \alpha(n_b - n_{\bar{b}})e^{-m_D/T_d}$



Ω_D/Ω_B as a function of m_D

- For fixed decoupling temperature T_d, two mass solutions
- α: exact relation of n_B to n_D depends on transfer mechanism, plasma composition at T_d

Matter Genesis

Generating the matter-antimatter asymmetry: the Sakharov conditions

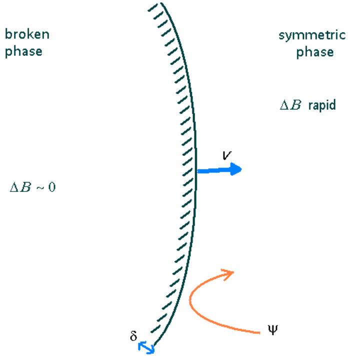
1. Baryon number B must be violated.
2. The discrete symmetries C and CP must be violated.
3. There must be a departure from thermal equilibrium.

Example: Electroweak Baryogenesis

- Electroweak baryogenesis is an elegant realisation of Sakharov criteria.
- In principle, SM contains all necessary ingredients for baryogenesis:
    1. EW sphalerons break *B*
    2. the standard model is chiral, violating *C*, and the Yukawas provide *CP* violation
    3. a first-order electroweak phase transition could provide a local departure from thermal equilibrium
- The properties of the phase transition and the size of the resulting asymmetries depend on the details of the Higgs potential and are calculable.

some reviews: Cohan, Kaplan, Nelson; Riotto, Trodden

Example: Electroweak Baryogenesis



- The bubble wall sweeps through the plasma.
  Passage on timescale $\tau_{wall} \sim v/\delta \ll \tau_{\Delta B}$
- CP-violating interactions of fermions with the wall bias B-violation
- After wall passes, broken phase preserves $\Delta B \neq 0$

Unfortunately...

- Electroweak baryogenesis doesn't work in the Standard Model
  - ... and tiny window in MSSM is rapidly closing (Carena, Quiros, Wagner; Curtin, Jaiswal, Meade; Cohen, Pierce, Morrissey)
- Insufficient *CP* violation:
  - CKM phase is small and enters with additional suppressions from small mixing angles and couplings
- EWSB phase transition insufficiently rapid
  - a sufficiently rapid phase transition: $\lambda \lesssim g^3$
  - Ruled out long ago: needs $m_h \lesssim 42$ GeV
- Can try adding more matter at electroweak scale, or...

  (Menon, Morrissey, Wagner; Das, Fox, Kumar, Wiener; Craig, March-Russell)

Darkogenesis

What if the dark sector is responsible for generating the matter-antimatter asymmetry? (JS, Zurek;

Davoudiasl, Morrissey, Sigurdson, Tulin; Haba, Matsumoto; Blennow, Dasgupta, Fernandez-Martinez, Rius, ...)

- Spectrum in hidden sector far less constrained: easy to arrange a first order transition
- CP violation easy to make large and to sequester from SM observables like EDMs.

A minimal hidden sector

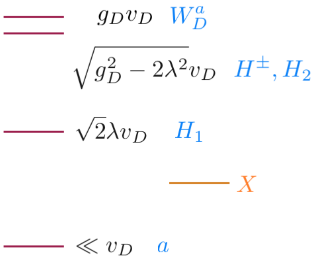
- Consider a weakly coupled hidden sector (for simplicity)
- Then a minimal anomaly-free hidden sector realising darkogenesis is:

	$SU(2)_D$	$U(1)_D$
$H,\ H^c$	2	0
$L_D \times 2$	2	1
$\bar{X}_{1,2} \times 2$	1	-1

(we actually use the supersymmetric version of this model)

- Chiral gauge theory with anomalous global $U(1)_d$
- Two Higgs doublets give CP violation

The dark sector spectrum



Simplified spectrum

- Gauge bosons parametrically heavier than Higgs: first-order
- Yukawa coupling of *X* can be dialed; once mass fixed, all interactions determined
- PNGB *a*: keep light to provide for efficient annihilation of *X*, $\bar{X}$
- Destabilize *a* via small Higgs portal coupling

This minimal hidden sector will be the engine for two explicit models

Asymmetry transfer mechanisms

- Choice of transfer mechanism drives model phenomenology
- Perturbative transfer: obtained by the exchange of some heavy mediator states
  - $\frac{X^2 LH}{\Lambda}$, $\frac{X^2 LLe^c}{\Lambda^2}$, $\frac{X^2 LQd^c}{\Lambda^2}$, $\frac{X^2 LHLH}{\Lambda^3}$
  - $\frac{X^2 u^c d^c d^c}{\Lambda^2}$
- Nonperturbative transfer: add messengers carrying both $SU(2)_L$ and $U(1)_D$.
  - Electroweak sphalerons now violate $B + L + \alpha D$

Model I: Low-scale mediation

- Couple SM to the hidden sector through the B-violating transfer operator $\mathcal{O}_{trans} = \frac{X^2 u^c d^c d^c}{\Lambda^2}$.
- The phase transition in the dark sector can occur below T_{EW}.
    - In our model: phase transition triggered by SUSY-breaking
- Decoupling of transfer operator?
    - Supersymmetric realization: most rapid process involves one SM squark. Boltzmann suppression helps shut off interaction, $T_{EW} > T_d \gg m_D$
- Gives $\frac{B}{D} = \frac{23}{21}$, so $m_D \approx 5$ GeV

Model I: Low-scale mediation

- Direct detection cross sections through the symmetric dark Higgs-visible Higgs coupling.
  - cross section per nucleon: $\sigma \sim 10^{-43}\text{cm}^2$
- While no intrinsic relation to EW scale, model still needs new TeV-scale states:
  - Using supersymmetric realization requires at least one light ($\lesssim 200$ GeV) squark
  - More generally, $\Lambda \lesssim$ few TeV for $T_d < T_{EW}$: new heavy messenger states

Model I: Low-scale mediation

- Leading asymmetric interaction: scattering $pX \to \tilde{X}^*(\pi^+, K^+)$
  - rate $\sim 10^{-30}$/year.
  - *not* constrained by Super-Kamiokande: final state contains only one visible charged particle
  - Interesting signals for future proton decay experiments

    (Davoudiasl, Morrissey, Sigurdson, Tulin)

Model II: Nonperturbative mediation

- Introduce a chiral messenger sector to make electroweak sphalerons violate $B + L + \alpha D$:

	$SU(2)_L$	$U(1)_Y$	$U(1)_D$
$L_M^{\pm}$	2	$\pm\frac{1}{2}$	1
$e_M^{c\ \pm}$	1	∓ 1	-1
X_M^i	1	0	-1

- To avoid fractionally charged states after EWSB, must assign hypercharge; anomaly cancellation then requires vector-like SM charge assignments
- Keep dark sector and messengers in equilibrium with singlet mixing

Model II: Nonperturbative mediation

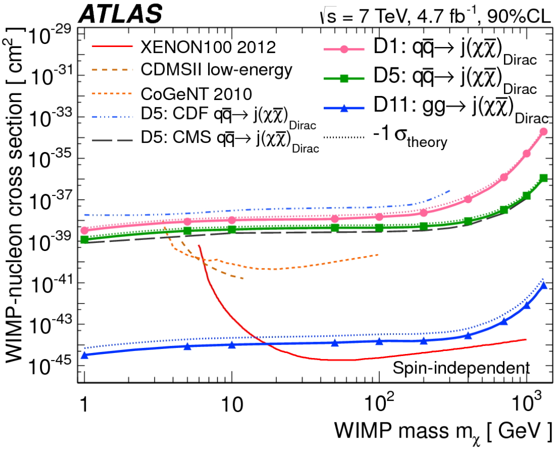
- Electroweak phase transition shuts off the asymmetry transfer
- Mediator states are purely chiral: must live near weak scale
  - PEW constraints are okay
  - Electroweak charged messengers visible at LHC
- Direct detection can now proceed through mixing of the dark matter state with electroweak doublet messengers, $\sigma \lesssim 5 \times 10^{-41}\mathrm{cm}^2 \left(\frac{\chi_{mix}^4}{10^{-3}}\right)^4$
  - Cross section cannot be much larger: Z width constraint $\chi_{mix}^4 < 10^{-3}$

Model II: Nonperturbative mediation

- Dark matter is still GeV-scale: $B = \frac{33}{127} D$ so $m_D \sim 1$ GeV.
- However $T_c > T_{EW} \Rightarrow$ hidden sector mass scale is larger relative to m_D than in low-scale model
- $\Rightarrow$ light dark states interact too weakly to annihilate the symmetric X abundance; must add additional dark sector interactions with a strength unrelated to the symmetry breaking scale.
  - for example: $W_Y = m_Y \bar{Y} Y + Z \bar{X} Y$ lets $X\bar{X} \rightarrow Z\bar{Z}$
  - If Z sufficiently light, cosmologically okay to be stable
- Expect similar results for leptonic transfer models where $T_c > T_{EW}$

Model II: Nonperturbative mediation

- Very light dark matter: possible signals from monojet searches at colliders (Goodman, Ibe, Rajaraman; Bai, Fox, Harnik)



Conclusions

- The dark sector can drive baryogenesis
  - naturally yields light as well as heavy dark matter candidates
  - freedom to choose hidden sector interactions makes it easy to achieve a large matter asymmetry, unlike in SM
  - sequestration of CP violation in hidden sector evades flavor constraints
- Signals determined largely by choice of transfer mechanism:
  - Two example models demonstrate the range of low scale possibilities
- Many novel possibilities for darkogenesis – have only scratched the surface!