Pangenesis in a Baryon-Symmetric Universe: Dark and Visible Matter via the Affleck-Dine Mechanism

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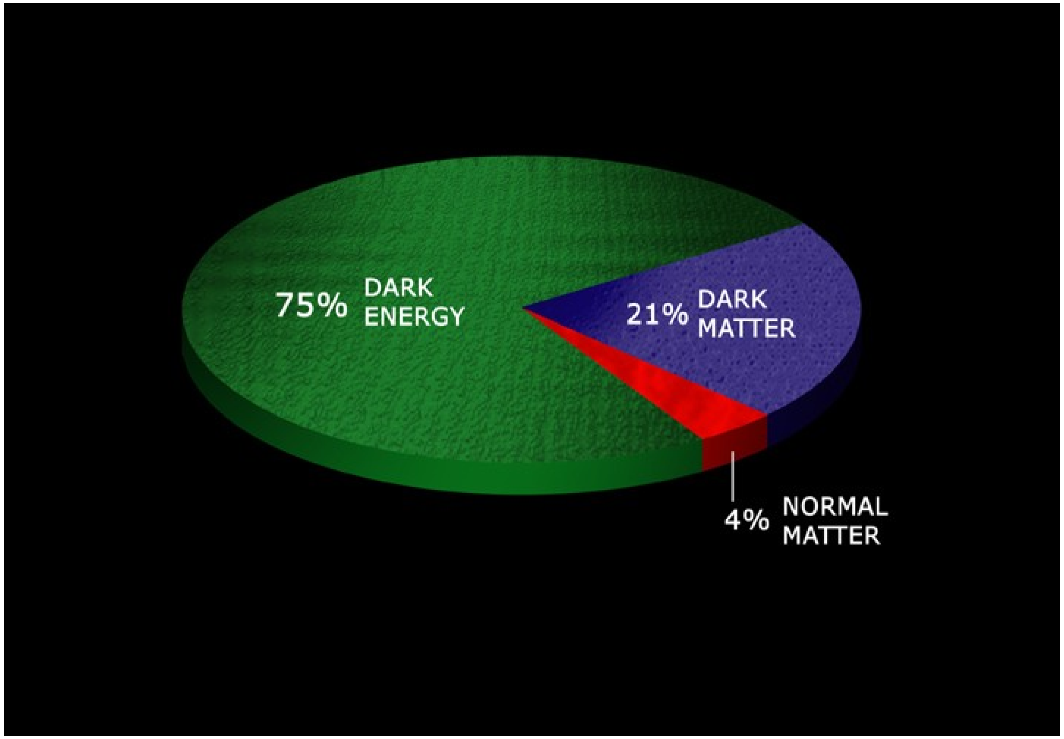
The Content of our Universe



Understanding the relic abundance of *all* components requires physics beyond the Standard Model.

The Visible Matter

- Stability: conserved baryon number B at low energies
- Relic abundance $\Omega_{\rm VM} \sim 0.05$: B asymmetry

$$\eta(B) \equiv \frac{n(B) - n(\bar{B})}{s} \simeq 10^{-10}$$

To make this we need processes which

(i) violate B, at high energies

(ii) violate CP,

(iii) occur out of thermal equilibrium

} $\Omega_{\rm VM}$ depends on M_B, δ_{CP}

The Dark Matter

- Stable (or very long-lived)
- Relic abundance: $\Omega_{\mathrm{DM}} \sim 0.2$
- Not too hot: $\lambda_{\mathrm{fs}} < 1\ \mathrm{Mpc}$
- Hints of direct detection from DAMA, CoGeNT, and now CRESST:

$$m_{\mathrm{DM}} \sim \text{few GeV}$$

many candidates, different parameters.

The Dark Matter

- One approach

Identify a DM candidate within well-motivated extensions of the SM from particle physics, e.g.

  - Hierarchy problem
  - Strong CP problem
  - Neutrino masses

LSP, axion, sterile neutrino

- Another approach

Rely on what we observe about DM *itself*:

$$\Omega_{\rm DM} \sim 0.2, \ \lambda_{\rm fs} < 1 \ {\rm Mpc}$$

and possibly $m_{\rm DM} \sim$ few GeV.

Data may tell us more than just fit model parameters

Cosmic coincidence ...

Cosmic Coincidence

Why $\Omega_{VM} \sim \Omega_{DM}$?

production mechanisms unrelated

relevant parameters different

relic abundances expected to vary greatly.

Related production mechanisms?

Strategy

- Take coincidence seriously:

  generate dark and visible matter simultaneously

- Seek how this can be explained within well-motivated extensions of the SM

Pangenesis in supersymmetric models via the Affleck-Dine mechanism

Bell, KP, Shoemaker, Volkas (2011)

Goal

Both dark and visible matter abundances due to an asymmetry
+
asymmetries related

DM and VM charged under a common symmetry:

Generalization of baryon number

Visible asymmetry compensated by dark asymmetry:

Separation of baryonic — antibaryonic charge.

Symmetry Structure

Symmetry Structure

- Stabilizing $U(1)$ symmetries at low energies

  Visible sector : $\boldsymbol{B_1}$ or $\boldsymbol{(B-L)_1}$

  Dark sector : $\boldsymbol{B_2}$

- Diagonal symmetries

$$\boldsymbol{B-L \equiv (B-L)_1 - B_2}$$
$$\boldsymbol{X \equiv (B-L)_1 + B_2}$$

- Symmetry breaking

  $\boldsymbol{B-L}$: always unbroken

  $\boldsymbol{X}$: broken at high energies, restored at low energies

$$\boldsymbol{(B-L)_1 \times B_2 = (B-L) \times X \xrightarrow{\text{high energies}} B-L}$$

Cosmological evolution

$$B - L \equiv (B-L)_1 - B_2$$
$$X \equiv (B-L)_1 + B_2$$

$$(B-L)_1 \times B_2 = (B-L) \times X \xrightarrow{\text{high energies}} B - L$$

- Early Universe

  explicit X & CP violation generate $X \neq 0$, while $B - L = 0$

  $$\eta((B-L)_1) = \eta(B_2) = \eta(X)/2$$

  Separation of baryonic – antibaryonic charge in visible and dark sectors
  Dodelson, Widrow (1990)

- Late Universe

  - $(B-L)_1$ and B_2 conserved separately to ensure stability of the sectors;
  - asymmetries of the two sectors related.

Separation of baryonic – antibaryonic charge

X asymmetry generation:
standard baryogenesis (and other) techniques, in models with extended particle content

- Decays — Kitano, Low (2006); Davoudiasl *et al.* (2010)
- Asymmetric freeze-out — Farrar, Zaharijas (2004)
- Affleck-Dine — Bell, KP, Shoemaker, Volkas (2011)
- Others...

Each mechanism is operative for different BSM physics and different cosmology.

a note on asymmetric DM scenarios

Models with
an unbroken symmetry
(baryon-symmetric)

- $U(1)_1 \times U(1)_2 \rightarrow U(1)_{\text{diag}}$
- Baryon – antibaryon separation: simultaneous DM and VM genesis
- Possible gauge symmetry → Z' pheno in colliders

Dodelson, Widrow (1990);
Farrar, Zaharijas (2004);
Kitano, Low (2006);
Davoudiasl, *et al.* (2010) : Hylogenesis;
Bell, KP, Shoemaker, Volkas (2011) : Pangenesis.

Models with
no unbroken symmetry

- Baryogenesis in either sector independently
- Sharing of the asymmetry via chemical equilibrium

Nussinov (1985);
many many others ...

a long story: asymmetric DM papers (no unbroken symmetry)

Nussinov (1985);
Barr, Chivukula, Farhi (1990);
Barr (1991);
Kaplan (1992);
Kuzmin (1998);
Foot, Volkas (2003);
Hooper, March-Russell, West (2005);
Cosme, Lopez Honorez, Tytgat (2005);
Suematsu (2006);
Gudnason, Kouvaris, Sannino (2006);
Banks, Echols, Jones (2006);
Kaplan, Luty, Zurek (2009) : Asymmetric DM;
Cai, Luty, Kaplan (2009);
Cohen, Zurek (2010);
Kribs, Roy, Terning, Zurek (2010);
An, Chen, Mohapatra, Zhang (2010);
Gu (2010);
Dulaney, Fileviez Perez, Wise (2011);
Cohen, Phalen, Pierce, Zurek (2010);

Shelton, Zurek (2010) : Darkogenesis;
Buckley Randall, (2010) : Xogenesis;
Gu, Lindner, Sarkar, Zhang, (2010);
Blennow, Dasgupta, Fernandez-Martinez, Rius (2011) : Aidnogenesis;
McDonald (2010) : Baryomorphosis;
Hall, March-Russell, West (2010);
Allahverdi, Dutta, Sinha (2011) : Cladogenesis;
Dutta, Kumar (2010);
Falkowski, Ruderman, Volansky (2011);
Haba, Matsumoto, Sato, (2011);
Chun (2011);
Kang, Li, Li, Liu, Yang (2011)];
Frandsen, Sarkar, Schmidt-Hoberg, (2011);
Kaplan, Krnjaic, Rehermann, Wells, (2011);
Cui, Randall, Shuve, (2011);
March-Russell, McCullough, (2011) : Cogeneration;
Kumar, Ponton (2011);
Graesser, Shoemaker, Vecchi, (2011) : Dark Force

The Affleck-Dine Mechanism

Affleck, Dine (1985); Dine, Randall, Thomas (1996);

The Affleck-Dine Mechanism for generation of an asymmetry

Coherent production of charge
from oscillations of a scalar condensate
when a symmetry is explicitly broken

The Affleck-Dine Mechanism for generation of an asymmetry

Ingredients (toy version) Dine, Kusenko (2004)

- Complex scalar field ϕ carrying a $U(1)$ charge

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2 |\phi|^2 \quad \Rightarrow \quad j^0 = i\left(\phi^* \partial^0 \phi - \phi \partial^0 \phi^*\right)$$

- Small $U(1)$ & CP violating terms in the scalar potential

$$\mathcal{L} = |\partial_\mu \phi|^2 - m^2 |\phi|^2 - \lambda |\phi|^4 - \left[\epsilon \phi^3 \phi^* + \delta \phi^4 + \mathrm{c.c.}\right]$$

ϵ, δ complex

- Large initial field vev $\langle \phi \rangle \neq 0$

The Affleck-Dine Mechanism for generation of an asymmetry

Dynamics

$$\ddot{\phi} + 3H\dot{\phi} + m^2\phi + \lambda\phi^2\phi^* + \epsilon\phi^3 + 3\epsilon^*\phi\phi^{*2} + 4\delta^*\phi^{*3} = 0$$

Initial conditions

$$\langle\phi\rangle \neq 0$$

⇩

Oscillations of ϕ around the minimum.

- ϵ, δ terms generate a time-dependent complex phase for ϕ

$$\phi = \frac{\rho(t)}{\sqrt{2}} e^{[i\theta(t)]} \quad \Rightarrow \quad j^0 = \rho^2\dot{\theta}$$

- ϵ, δ small, so that charge conserved at low energies (small vevs)
- effect of quartic terms amplified by large field vev

The Affleck-Dine Mechanism and particle-physics models

Questions

- Identity of the scalar fields carrying B or L?

- Large vevs in the early universe?

- Smallness of B or L violating quartic terms?

- Asymmetry transfer into ordinary particles?

The Affleck-Dine Mechanism in supersymmetric models

Questions, and the answer: supersymmetry

- Identity of the scalar fields carrying B or L?

  squarks, sleptons, and other scalars in extensions of MSSM.

- Large vevs in the early universe?

  scalar potential of susy theories has *flat directions* with vanishing quartic terms, at the renormalizable level.

- Smallness of B or L violating quartic terms?

  non-renormalizable interactions along flat directions.

- Asymmetry transfer into ordinary particles?

  decay of the scalars, in a B & L preserving way.

Pangenesis

Pangenesis

$$(B-L)_1 \times B_2 \;=\; (B-L)\times X \xrightarrow{\text{high energies}} B-L$$

Pangenesis occurs along flat directions with

$$D_{B-L} \equiv \phi^\dagger T_{B-L}\phi = 0$$

$$D_X \equiv \phi^\dagger T_X \phi \neq 0$$

- $D_{B-L} = 0$ warranted along flat directions if $B-L$ gauged.
- Unbroken $B-L$ makes it natural that it be a gauge symmetry.

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Pangenesis occurs along flat directions with

$$\begin{aligned} D_{B-L} &\equiv \phi^\dagger T_{B-L}\phi &= 0 \leftarrow \begin{cases} T_{B-L}\phi = 0 \\ \text{or} \\ T_{B-L}\phi \neq 0 \end{cases} \\ D_X &\equiv \phi^\dagger T_X \phi &\neq 0 \end{aligned}$$

- $D_{B-L} = 0$ warranted along flat directions if $B-L$ gauged.
- Unbroken $B-L$ makes it natural that it be a gauge symmetry.

A simple model of Pangenesis

Introduce three SM gauge singlet chiral superfields $\Phi_j = (\phi_j, \psi_j, F_j)$ and vector-like partners $\hat{\Phi}_j = \left(\hat{\phi}_j, \hat{\psi}_j, \hat{F}_j\right)$.

Baryoleptonic charge assignments:

	Φ_0	Φ_1	Φ_2
$(B-L)_1$	-1	1	0
B_2	-1	0	1
$B-L$	0	1	-1
X	-2	1	1

At the renormalizable level, impose $B-L$ & X symmetries:

$$\delta W_r = \kappa \Phi_0 \Phi_1 \Phi_2 + \hat{\kappa} \hat{\Phi}_0 \hat{\Phi}_1 \hat{\Phi}_2 + \sum_{j=0}^{2} \mu_j \Phi_j \hat{\Phi}_j$$

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visible sector field; couples to MSSM

dark sector field

connector field with $B-L=0$ & $X \neq 0$

At the renormalizable level, impose $B-L$ & X symmetries:

$$\delta W_r = \kappa \Phi_0 \Phi_1 \Phi_2 + \hat{\kappa} \hat{\Phi}_0 \hat{\Phi}_1 \hat{\Phi}_2 + \sum_{j=0}^{2} \mu_j \Phi_j \hat{\Phi}_j$$

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$$\delta W_r = \kappa \Phi_0 \Phi_1 \Phi_2 + \hat{\kappa} \hat{\Phi}_0 \hat{\Phi}_1 \hat{\Phi}_2 + \sum_{j=0}^{2} \mu_j \Phi_j \hat{\Phi}_j$$

- $\phi_0, \hat{\phi}_0$ are flat directions (no quartic terms) .
- Flat directions lifted by non-renormalizable operators. X-violating interactions included

$$\delta W_{nr} \supset \frac{\lambda}{M} \left\{ \Phi_0^4,\ \Phi_0^3 \hat{\Phi}_0,\ \Phi_0^2 \hat{\Phi}_0^2,\ \Phi_0 \hat{\Phi}_0^3,\ \hat{\Phi}_0^4 \right\}$$

- The Affleck-Dine mechanism along the $\phi_0, \hat{\phi}_0$ manifold generates an X charge.
- The condensate decays into purely visible and purely dark sector fields, via renorm couplings, preserving X .
- Baryonic – antibaryonic charge separated.

A simple model of Pangenesis

Scalar potential along $\phi_0, \hat{\phi}_0$ flat directions

$$V = \left[m_0^2(T) - cH^2\right] |\phi_0|^2 + \left[\hat{m}_0^2(T) - \hat{c}H^2\right] |\hat{\phi}_0|^2$$
$$+ \sum_{k=0}^{4} \frac{(A_k \widetilde{m} + a_k H)\lambda_k}{M} \phi_0^k \hat{\phi}_0^{4-k}$$
$$+ \sum_{k=0}^{3} \sum_{l=0}^{3-k} \frac{\lambda_{kl}^2}{M^2} \left(\phi_0^* \hat{\phi}_0\right)^{3-k-l} |\phi_0|^{2k} |\hat{\phi}_0|^{2l} + \mathrm{c.c.}$$

where $m_0^2(T) \approx \widetilde{m}^2 + \kappa^2 T^2$, H : Hubble parameter

(potential includes: susy non-renormalizable terms; susy-breaking by hidden sector & vacuum energy; thermal corrections)

A simple model of Pangenesis

Scalar potential along $\phi_0, \hat{\phi}_0$ flat directions

large field vev after inflation

$$V = \left[m_0^2(T) - cH^2\right] |\phi_0|^2 + \left[\hat{m}_0^2(T) - \hat{c}H^2\right] |\hat{\phi}_0|^2$$
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X violation

where $m_0^2(T) \approx \widetilde{m}^2 + \kappa^2 T^2$, H : Hubble parameter

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CP violation

X violation

where $m_0^2(T) \approx \widetilde{m}^2 + \kappa^2 T^2$, H : Hubble parameter

(potential includes: susy non-renormalizable terms; susy-breaking by hidden sector & vacuum energy; thermal corrections)

A simple model of Pangenesis

- X asymmetry generated

$$\eta(X) \sim 10^{-10} \left(\frac{\sin\delta}{\lambda}\right) \left(\frac{T_R}{10^9\ \mathrm{GeV}}\right) \frac{M}{M_P}$$

λ: Yukawa couplings of non-renormalizable terms in the superpotential,
δ: effective CP-violating phase

- Visible and Dark sector asymmetries related

$$\eta\left((B-L)_1\right) = \eta\left(B_2\right) = \eta\left(X\right)/2$$

A simple model of Pangenesis

Asymmetry cascade, via X preserving operators

$\Phi_0, \hat{\Phi}_0$

$\kappa \Phi_0 \Phi_1 \Phi_2,$

$\hat{\kappa} \hat{\Phi}_0 \hat{\Phi}_1 \hat{\Phi}_2$

$\Phi_1, \hat{\Phi}_1$ $\Phi_2, \hat{\Phi}_2$

$\Phi_1 L H_u,\ \Phi_1 L L \bar{e},$

$\Phi_1 L Q \bar{d},\ \Phi_1 \bar{u} \bar{d} \bar{d}$

sphaleron transitions, etc

unlimited possibilities

p, n

Lightest

B_2 charged particles

The dark sector of Pangenesis

- Annihilation of the symmetric part of DM:

$$\sigma_{\rm asym\ DM} \gtrsim \sigma_{\rm symm\ thermal\ DM}$$

Graesser, Shoemaker, Vecchi (2011)

Via a dark force into dark-sector radiation
→ possible $U(1)_D$ kinetic mixing to $U(1)_Y$

The dark sector of Pangenesis

- Annihilation of the symmetric part of DM:

$$\sigma_{\text{asym DM}} \gtrsim \sigma_{\text{symm thermal DM}}$$

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Via a dark force into dark-sector radiation
→ possible $U(1)_D$ kinetic mixing to $U(1)_Y$

- Prediction of the dark-matter mass

$$\frac{\Omega_{\text{DM}}}{\Omega_{\text{VM}}} = \frac{m_{\text{DM}}}{m_{\text{VM}}} \frac{q_{\text{DM}}}{q_{\text{VM}}} \frac{\eta(B_2)}{\eta(B_1)}$$

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- Prediction of the dark-matter mass

$$m_{\text{DM}} = \frac{1}{q_{\text{DM}}} \frac{\Omega_{\text{DM}}}{\Omega_{\text{VM}}} \frac{\eta(B_1)}{\eta(B_2)} m_p \sim \mathbf{10\ GeV}$$

  already favoured by DAMA, CoGeNT, CRESST.

The dark sector of Pangenesis

- Dark-matter direct detection
  - via Z'_{B-L}

$$\sigma^{\rm SI}_{B-L} \lesssim (4\times 10^{-44}{\rm cm}^2)\, q^2_{\rm DM} \left(\frac{g_{B-L}}{0.1}\right)^4 \left(\frac{0.7\ {\rm TeV}}{M_{B-L}}\right)^4$$

  just below XENON100 constraints
  - via Z'_D

$$\sigma^{\rm SI}_{D} \approx (10^{-40}{\rm cm}^2) \left(\frac{\epsilon}{10^{-4}}\right)^2 \left(\frac{g_D}{0.1}\right)^2 \left(\frac{1\ {\rm GeV}}{M_D}\right)^4$$

  can explain DAMA, CoGeNT (but can also vary a lot).

Other models of Pangenesis

- Flat direction fields uncharged under generalised $B - L$

$$T_{B-L}\phi = 0; \qquad \phi^\dagger T_X \phi \neq 0$$

$$\text{e.g.} \quad \delta W_{\not X} = \Phi_0^4, \ \hat{\Phi}_0^4$$

- Generalised B-L spontaneously broken along flat directions

$$\begin{aligned} T_{B-L}\phi &\neq 0 \\ \phi^\dagger T_{B-L}\phi &= 0 \end{aligned} \qquad \phi^\dagger T_X \phi \neq 0$$

$$\text{e.g.} \quad \delta W_{\not X} = \ LL\bar{e}\Delta^2, \ LQ\bar{d}\Delta^2, \ \bar{u}\bar{d}\bar{d}\Delta^2, \ \text{etc}$$

$$\text{where for } \Delta : (B-L)_1 = 0, \ B_2 = -1/2;$$

Other models of Pangenesis

- Flat direction fields uncharged under generalised $B - L$

X symmetry impossed at renorm regime

$$T_{B-L}\phi = 0; \qquad \phi^\dagger T_X \phi \neq 0$$

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- Generalised B-L spontaneously broken along flat directions

X symmetry accidental at the renorm regime

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$$\phi^\dagger T_X \phi \neq 0$$

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$$\text{where for } \Delta : (B-L)_1 = 0,\ B_2 = -1/2;$$

Potential evidence for Pangenesis

- Supersymmetry
- $m_{\rm DM} \sim \textbf{few GeV}$
- Gauged $B - L$ with Z'_{B-L} invisible decay width driven by the dark sector (not accounted for by neutrinos)
- Dark $U(1)_D$ force, possibly with kinetic mixing to hypercharge

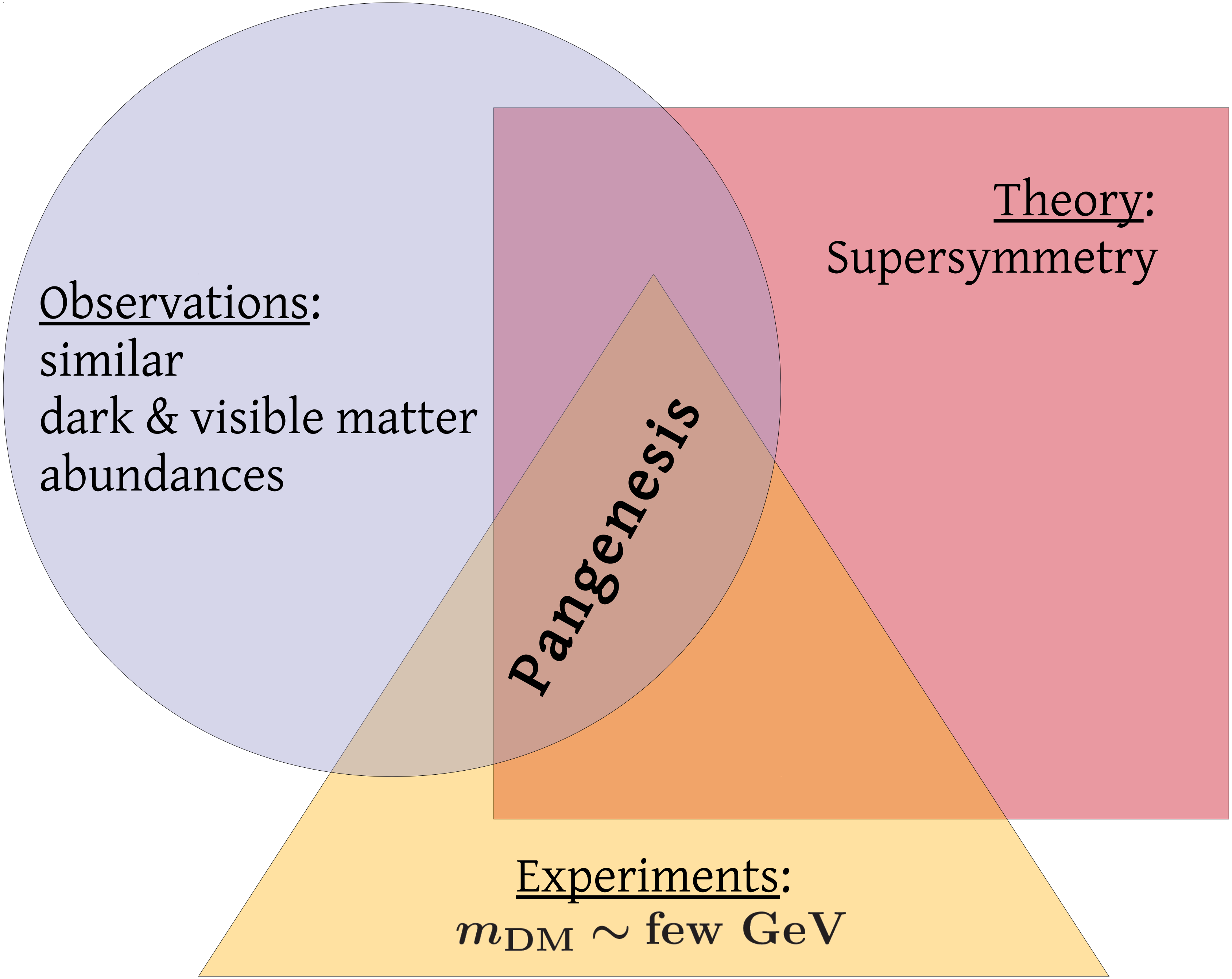
a note on recent literature

Pangenesis or *Cogenesis*

arXiv: 1105.3730
[Bell, KP, Shoemaker, Volkas]

arXiv: 1105.4612
[Cheung, Zurek]

- ✗ Same symmetry structure
  and asymmetry generation mechanism.
- ✗ Different illustrations of the mechanism.


Observations:
similar
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