Theories relating baryon asymmetry and dark matter

In collaboration with S.Boucenna, 1310.1904 published in **Frontiers**

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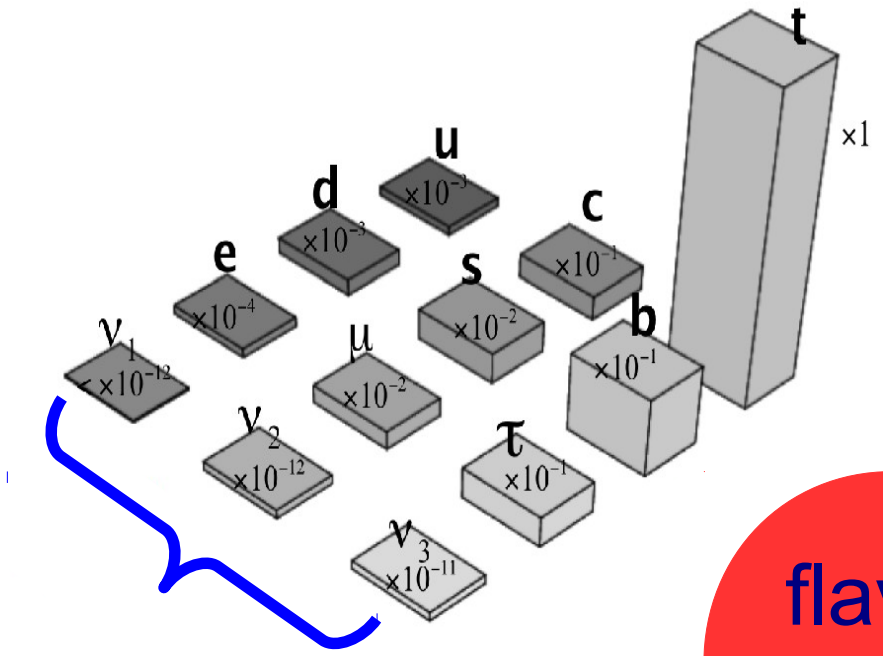
MultiDark
Multimessenger Approach
for Dark Matter Detection

Three major unsolved puzzeles In HEP & COSMO

The flavor problem

The origin and nature of dark matter (DM)

The origin of the baryon asymmetry of the universe (BAU)



*** why fermion mass hierarchies?**

*** why 3 families?**

flavor problem

$$V_{lep} \approx \begin{pmatrix} 0.81 & 0.56 & 0.16 \\ 0.45 & 0.44 & 0.77 \\ 0.36 & 0.70 & 0.61 \end{pmatrix}$$

*** why lep mixing?**

- is CP violated?

$$V_{CKM} \approx \begin{pmatrix} 0.974 & 0.225 & 0.003 \\ 0.225 & 0.973 & 0.041 \\ 0.008 & 0.040 & 0.999 \end{pmatrix}$$

*** why quark mixing?**

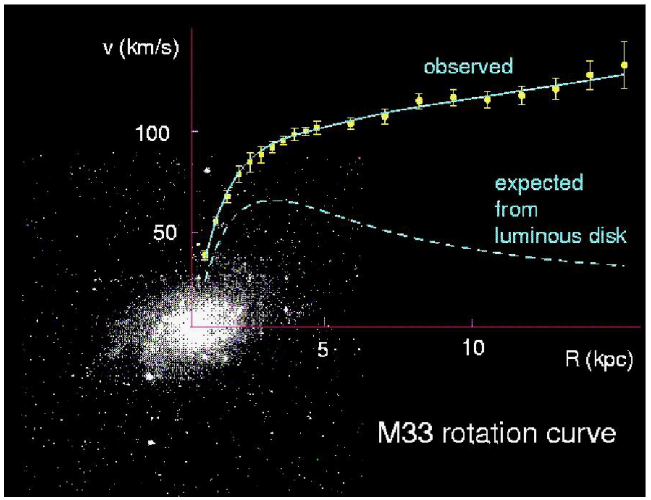
*** why so different?**

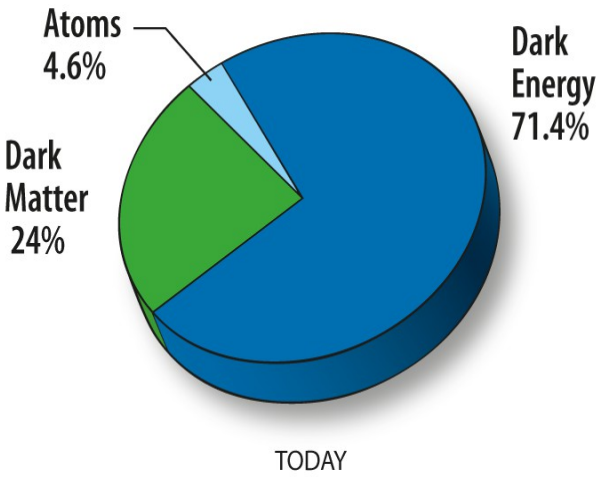
nu mass origin?

- Dirac or Majorana?
- nu absolute scale?
- normal or inverse?
- sterile nu?

Evidence for Dark Matter

Rotational curves of spiral galaxies





Bullet cluster

Evidence for Dark Matter

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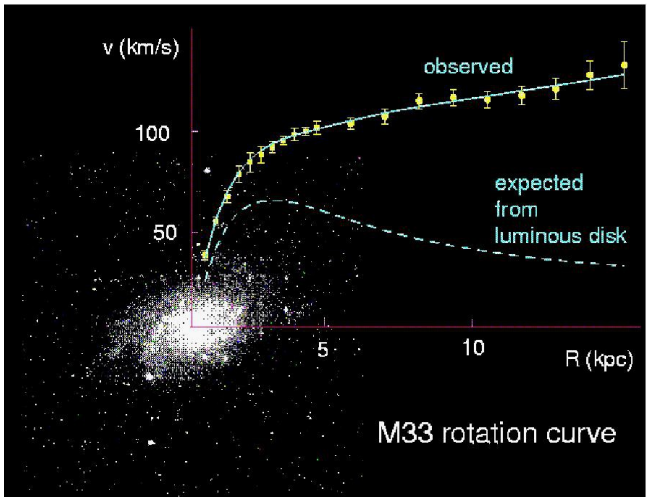
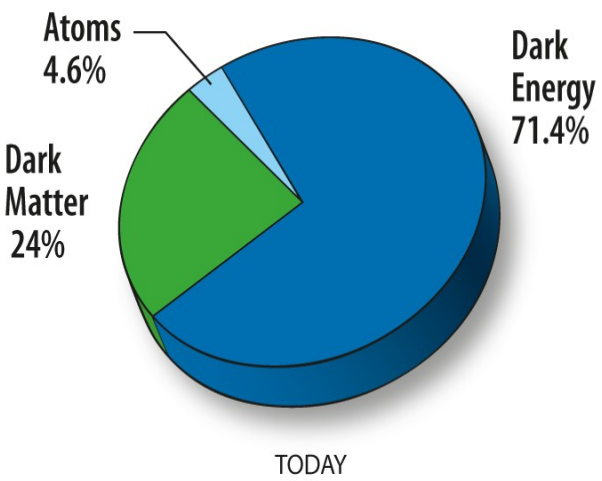




Bullet cluster

Dark Matter Candidates

– stable or very long lived
– electric neutral
– colorless

– production mechanism?
– cold or warm?
– scalar, fermion, vector,...?
– mass scale?
– one or many candidates?
– MOND?

Some DM candidates:

– axions
– sterile neutrino
– asymmetric DM
– WIMPs:
inert scalar
neutralino,…....
– superheavy

Evidence for baryon asymmetry

- antimatter is rare on earth (only accellerators FermiLab, CERN,..)

- antimatter is rare in the solar system

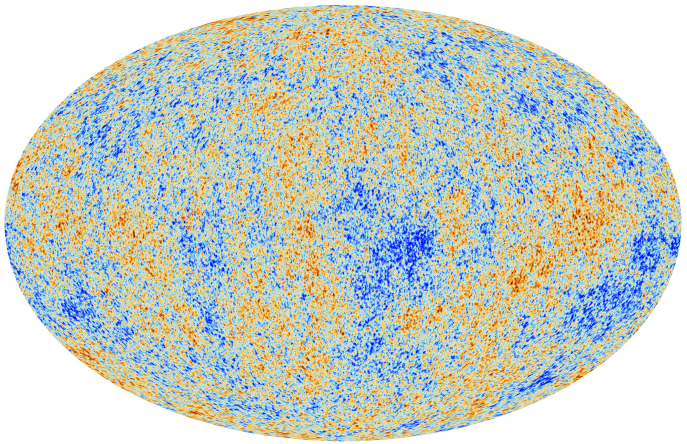
- cosmic rays are almost matter rather than antimatter (< 0.01%) :
  no antimatter from our galaxy and distant galaxies

- no antimatter in cluster of galaxies

If there is a significant amount of antimatter in the Universe
it must be segregated from matter

Evidence for baryon asymmetry

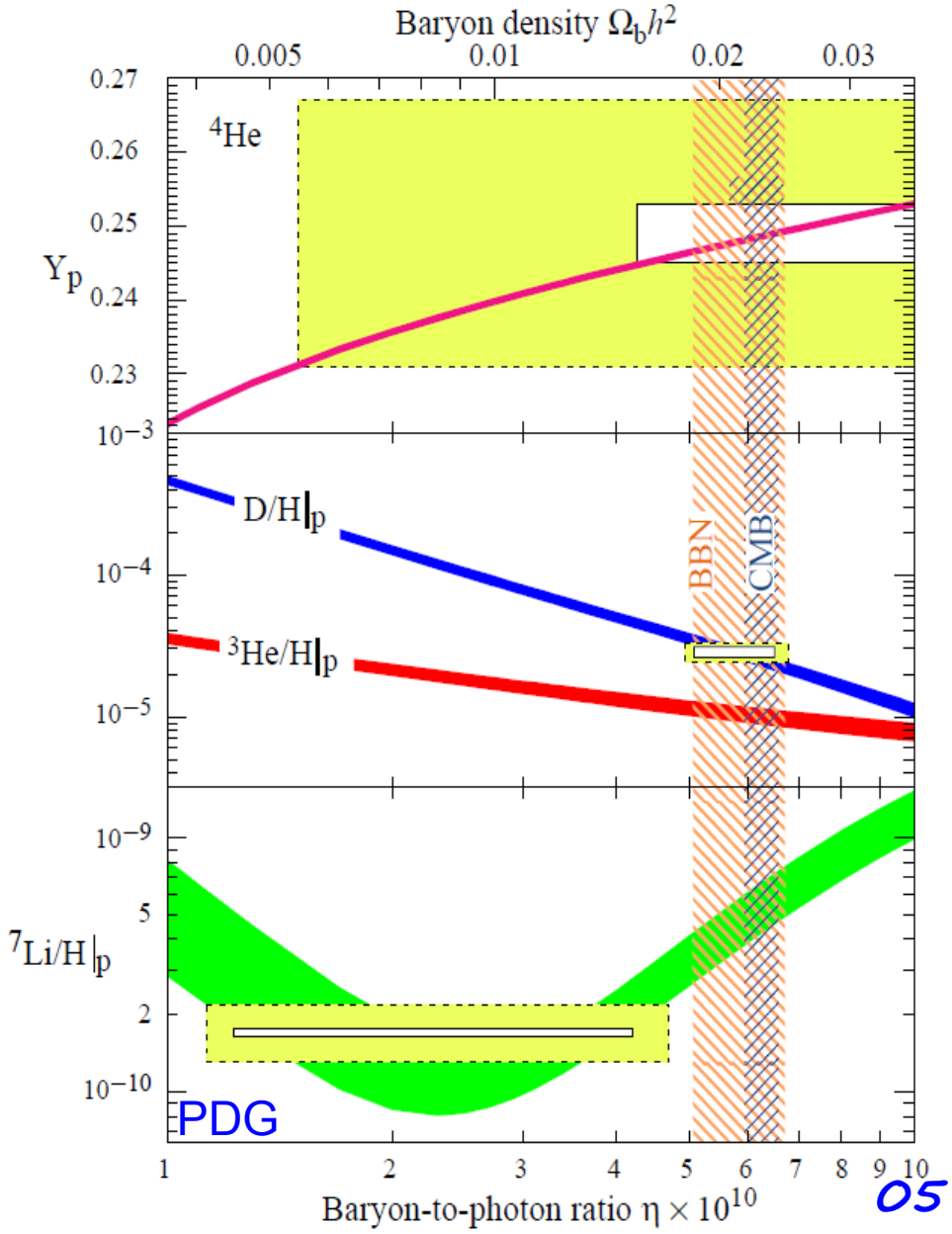
Cosmic Microwave Background rad



Planck Collaboration 1303.5076

$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

Big-Bang Nucleosynthesis



Evidence for baryon asymmetry

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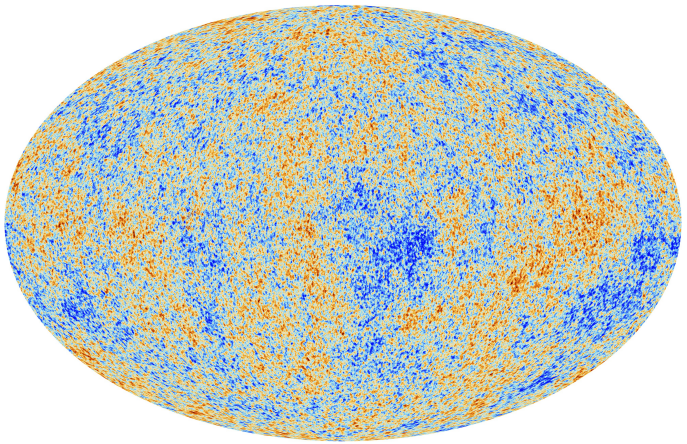


Planck Collaboration 1303.5076

$$\Omega_b h^2 = 0.02205 \pm 0.00028$$

$$\frac{n_b}{s} \simeq (3.81 \times 10^{-9})\,\Omega_b h^2 \simeq 8 \times 10^{-11}$$

– baryon-symmetric Universe

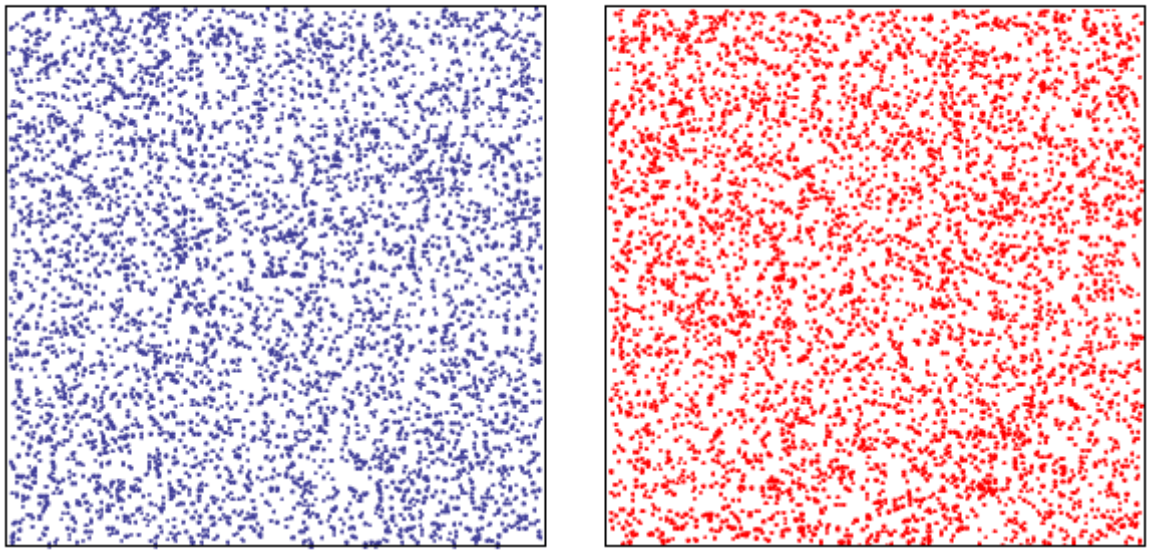
baryon ⟷ anti-baryon (chemical equilibrium) → $\frac{n_b}{s} \simeq 10^{-22}$

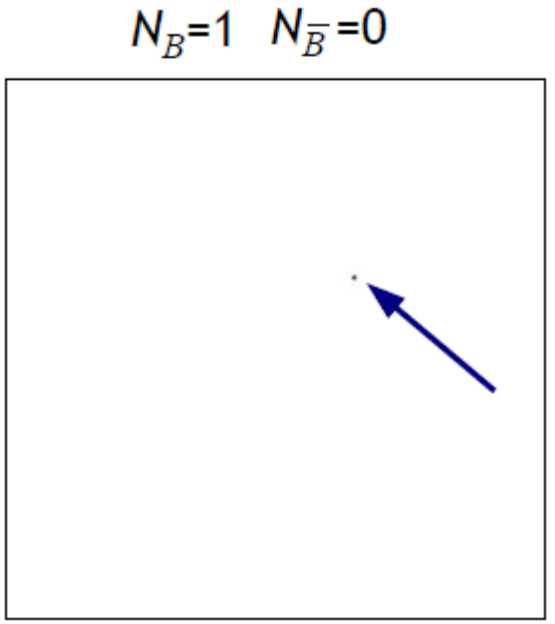
" annihilation catastrophe "

– Early Universe baryon/anti-baryons asymmetry $\frac{n_b - \bar{n}_b}{n_b} \simeq 3 \times 10^{-8}$

tiny b-antib asymmetry at early time

Early Universe





Now

from Ibarra'stalk

baryon asymmetry

Sakharov conditions

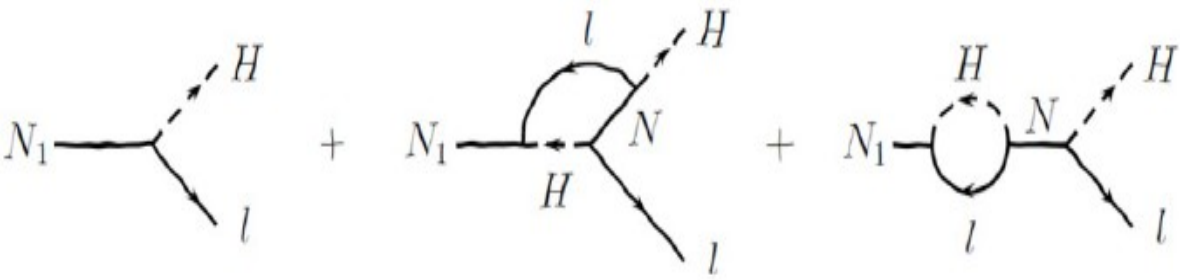
Sakharov JETP Lett6 (67')

(1) B violation

(2) C & CP violation

(3) departure from thermal equil

Some mechanisms:
– GUT baryogenesis
– electroweak baryogenesis
– *leptogenesis*
– Dirac leptogenesis
– Affleck-Dine
– …..

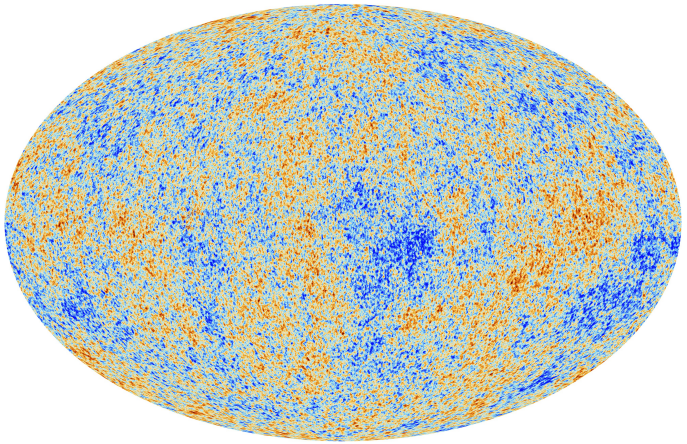


Sphaleron: **B+L** not conserved
B-L conserved

$$\Gamma_N > \mathcal{H}$$

Baryon/DM relic abundance

Cosmic Microwave Background rad

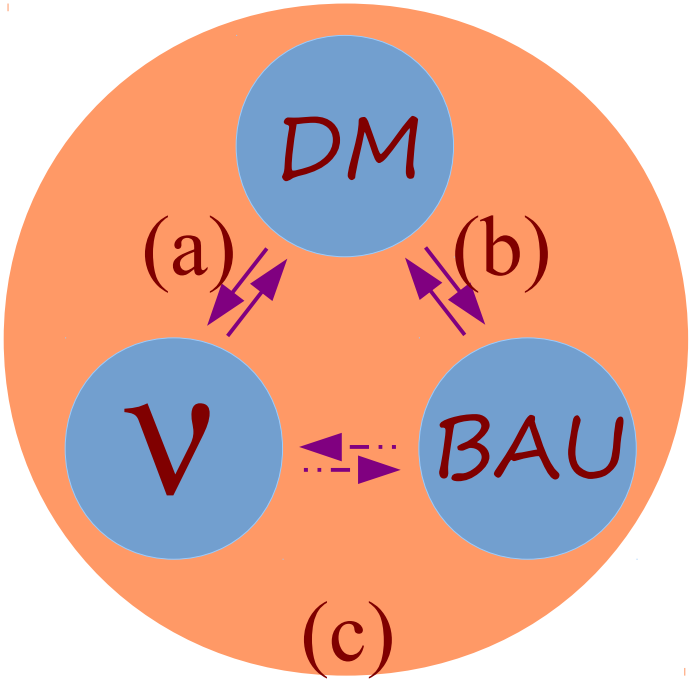


Planck Collaboration 1303.5076

$$\left.\begin{aligned} \Omega_b h^2 &= 0.02205 \pm 0.00028 \\ \Omega_c h^2 &= 0.1199 \pm 0.0027 \end{aligned}\right\} \rightarrow \Omega_{DM} \simeq 5\,\Omega_B$$

Is it a numerical coincidence ?

DM, BAU & neutrino

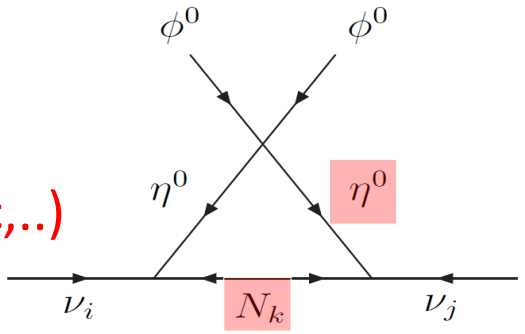


(a) origin of neutrino mass and DM

– sterile neutrino

– radiative nu-mass mech. (scotogenic,..)

– stability of DM from fla-sy (A4 –> Z2 ,..)



(b) origin of DM and BAU

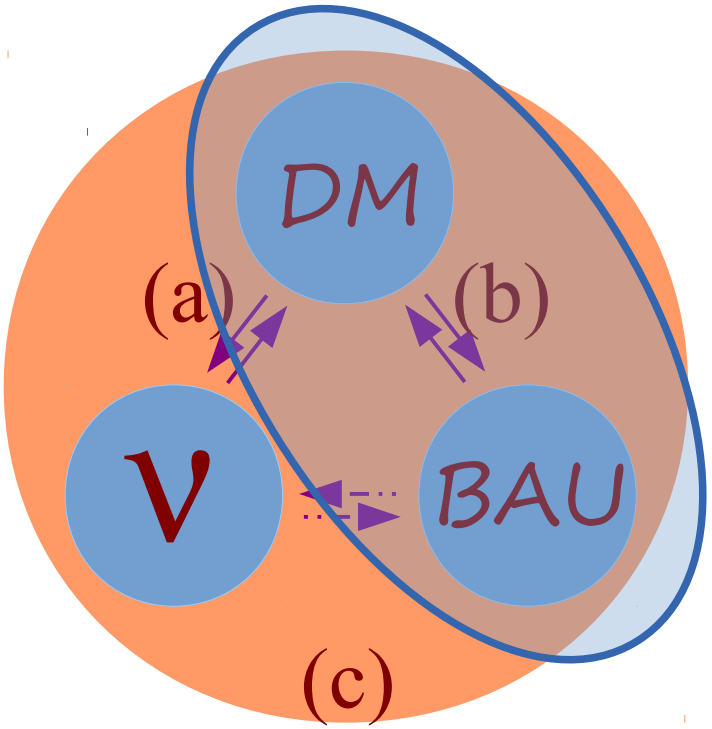
– DM/B densities coincidence

– non-thermal DM-BAU production

(c) unified picture for DM, BAU and neutrino

- neutrino Minimal SM (nMSM) *Asaka, Blanchet, Shaposhnikov*
- Dirac neutrino, inflation, baryogenesis and DM *with a complex scalar*
- non-thermal production and origin of neutrino mass

In this talk



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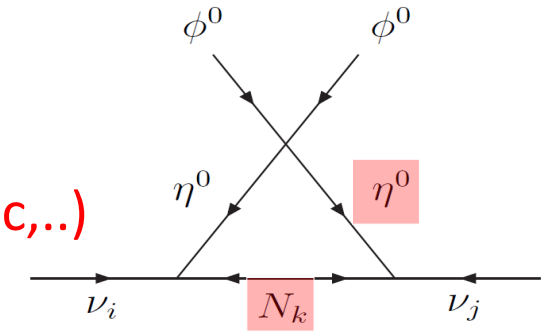

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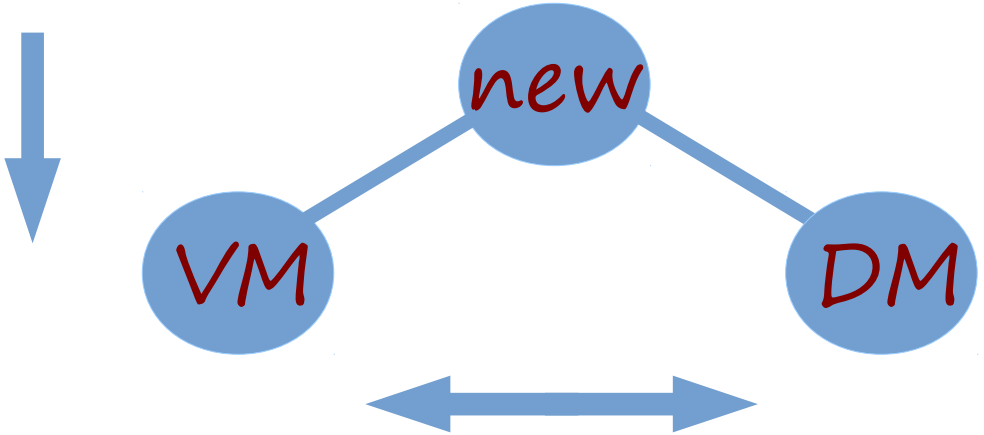
Possible approaches

(1) new sector connecting DM and visible matter (VM)



e.g. Asymmetric DM

S. Nussinov, PLB165 (85')
Petraki, Volkas 1305.4939
Zurek 1308.0338

(2) DM sector as an auxiliary to a successful BaryoGenesis (BG)

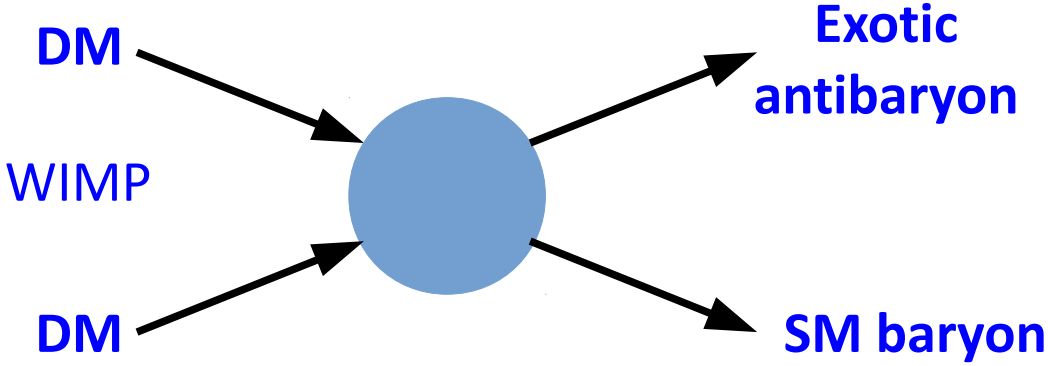
e.g. Electroweak BG

Profumo, Ramsey-Musolf, Shaughnessy
Barger, Paul Langacker, Mathew McCaskey
Ahriche, Nasri; Chowdhury Nemevsek,....

(3) WIMP paradigm as a framework to relate the abundances

e.g. WIMPy BG

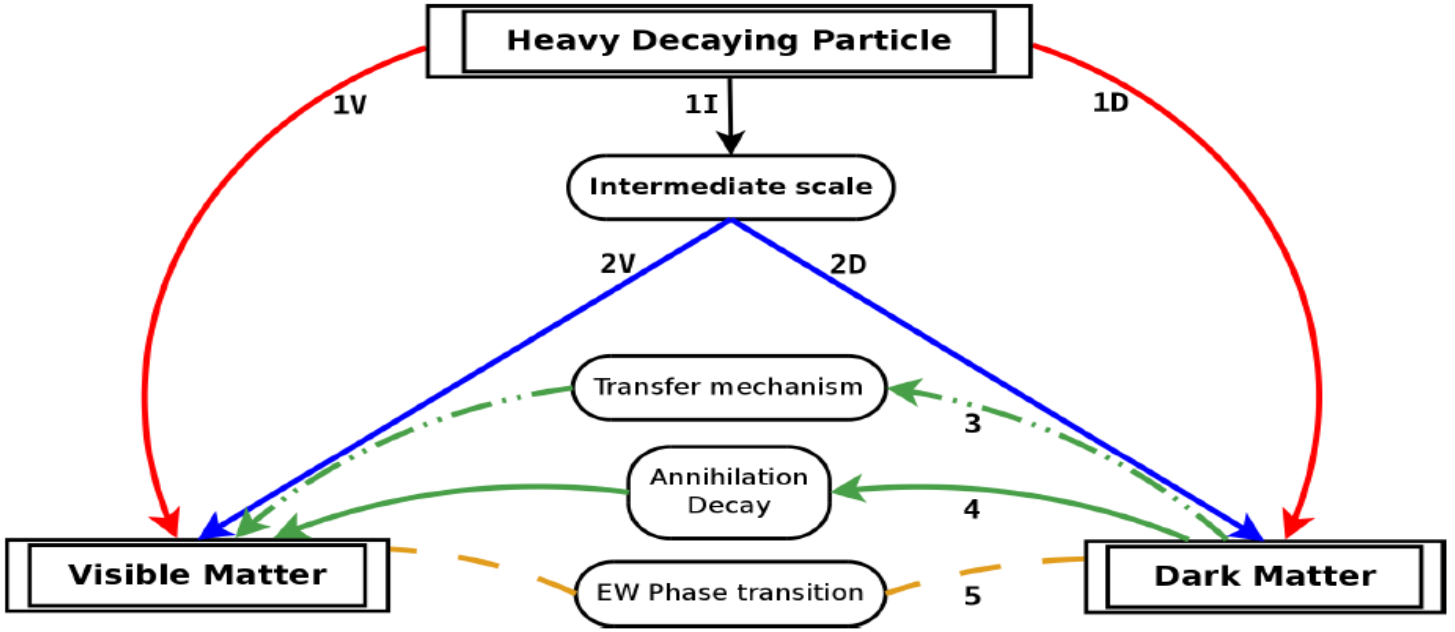
Cui, Randall, Shuve. JHEP (12')



Theories relating baryon asymmetry and dark matter Mini review

arxiv: 1310.1904 published in **Frontiers**

S.M.Boucenna[a1] and S.Morisi[b2]



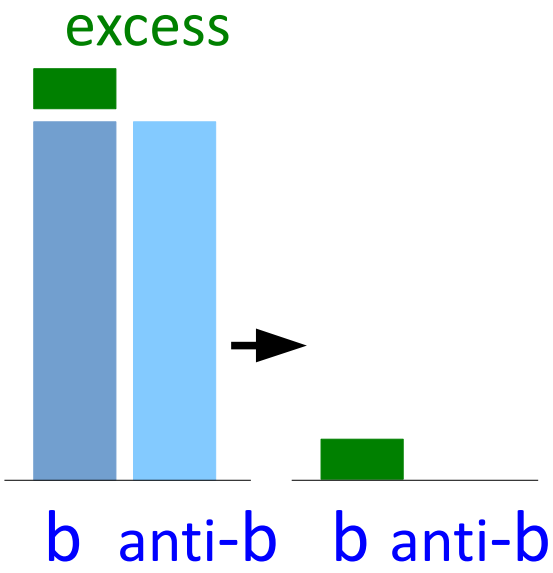
Model	DM	HS	BAU	$\mathcal{O}(M_{DM})$	Signal	Diagram
Two singlets EWBG[9]	$\mathcal{WIMP}$	✗	EWPHT	2 – 225 GeV	DD-ID-CO	5^*
EW cogenesis [53]	$\mathcal{WIMP}$	✗	EWPHT	GeV-TeV	CO	5^*
WIMPy L$^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	TeV	ID-CO	T-4^*
WIMPy Q$^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	500GeV	DD-ID-CO	T-4^*
Meta-stable WIMP[19]	$\mathcal{WIMP}$	✗	DECAY	GeV-TeV	CO	T-4^*
Kitano-Low [26]	$\mathcal{ADM}$	✣	DECAY	GeV	CO	1^*_V-1^*_I-T-2_D
Hylogenesis [42]	$\mathcal{ADM}$	✓	DECAY	5 GeV	IND-DD	1^*_V-1^*_D-T
ADM Leptog [43]	$\mathcal{ADM}$	✓	DECAY	KeV–10 TeV	DD-ID	1^*_V-1^*_D-T
Darkogenesis [49]	$\mathcal{ADM}$	✓	TRANS	5 – 15 GeV	GW	$*$-3-$*$
Baryogenesis from DM [46]	$\mathcal{ADM}$	✓	TRANS	3 GeV	DD-CO	$1_D$$*$-3-$*$
Aidnogenesis [48]	$\mathcal{ADM}$	✓	DECAY	6 GeV	DD-FCNC -CO	1^*_V-$\overline{3}$-$*$-T
Xogenesis [49]	$\mathcal{ADM}$	✓	TRANS	100GeV–TeV	CO	$*$-3-$*$
Pangenesis [38]	$\mathcal{ADM}$	✓	AFDIN	1.6–5 GeV	DD-CO	$*$-1^*_I-T-2_V-2_D
Cladogenesis [51]	$\mathcal{NTDM}$	✣	DECAY	5-500GeV	-	1_I-1_D-2^*_V

Asymmetric DM (ADM) - basic idea

The present-day density of VM is due to BAU

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

The baryon number today constitutes the excess remaining after all the baryon-antibaryon annihilate



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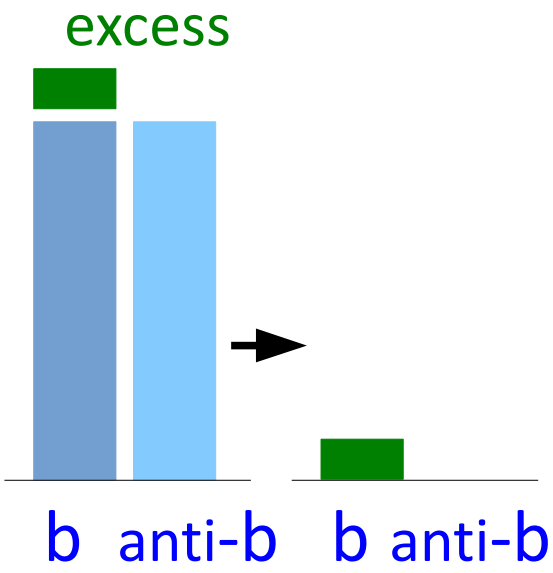

$\Omega_{DM} \simeq 5\,\Omega_B$ The similarity in these densities suggests a common origin

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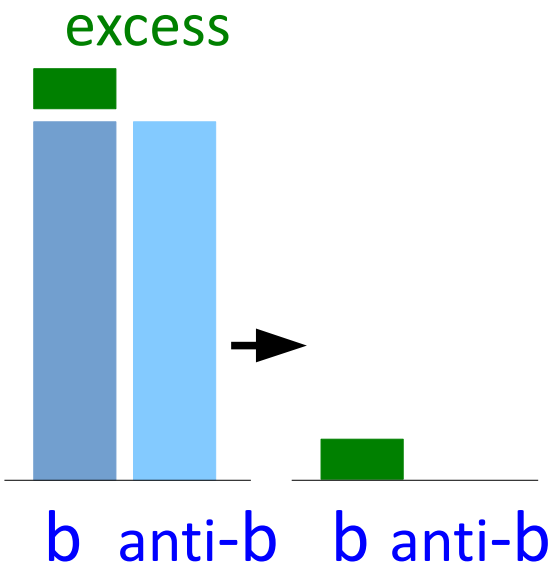

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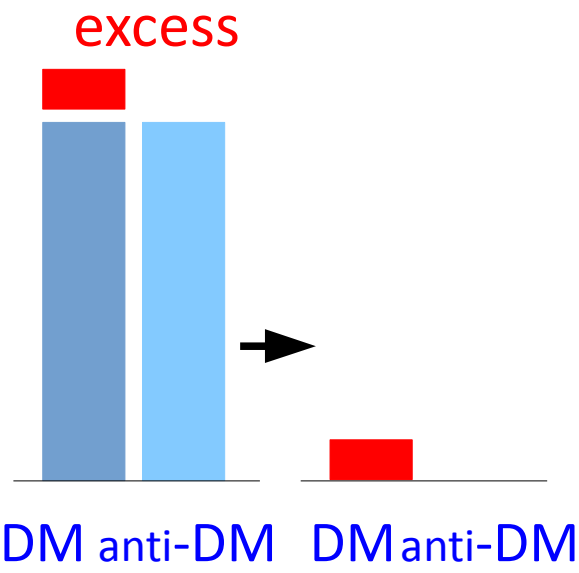
ADM hypotesis:

the DM density is due to
DM particle/antiparticle
asymmetry

$$\eta(B) \sim \eta(DM)$$

$$m_{DM} \sim \frac{\Omega_{DM}}{\Omega_B} m_p$$

$$\eta(DM) \equiv \frac{n_{DM} - \bar{n}_{DM}}{s}$$



Asymmetric DM – basic idea

From Petraki, Volkas 1305.4939

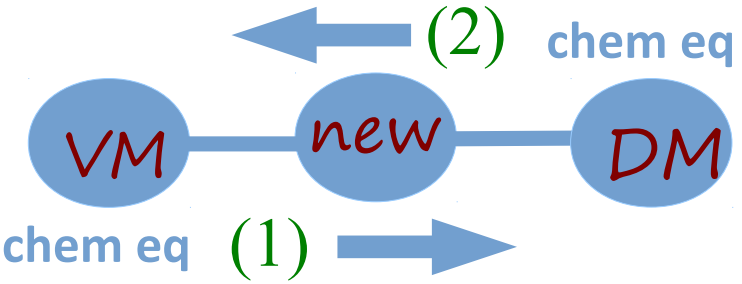
DM may be a stable component of some **gauge group** G_D (**<u>hidden sector</u>**)

$G_V \times G_D$ where G_V contains the SM

B_V B_D Visible Baryon number & Dark Baryon number

(1) B_V is broken and B_D is not broken

(2) B_D is broken and B_V is not broken



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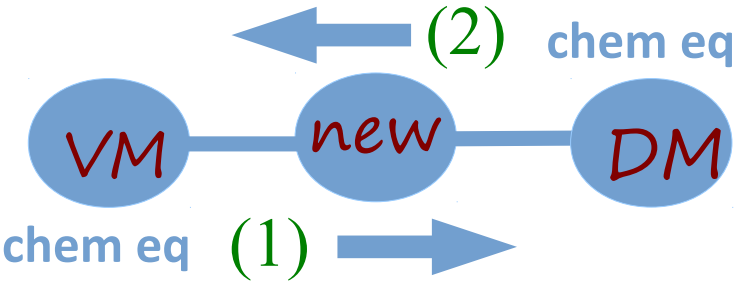

(1) B_V is broken and B_D is not broken

(2) B_D is broken and B_V is not broken

(3) B_V and B_D are broken

the initial asym. could be very different – some interaction is needed
To drive the two asymmetries to equilibration –> i.e. mirror DM

(4) a combination of $B_V - B_D$ is conserved and $B_V + B_D$ is broken

→ the asymmetries in Visible and Dark sectors are *equal*

Hylogenesis (matter-creation: an ADM example)

Davoudiasl,Morrissey,Sigurdson PRL (10')

Hidden Sector

X_1 X_2 Dirac fermions (TeV) B=+1

Y Dirac fermions (GeV) B=y

ϕ Complex scalar(GeV) B=-(1+y)

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

Neutron Portal

Dark sector

Hylogenesis (matter-creation: an ADM example)

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Neutron Portal

Dark sector

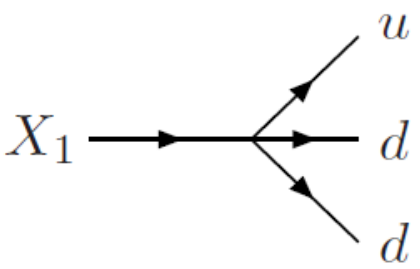
(1) X_1 $\overline{X}_1$ non-thermally produced (inflaton decay,..)

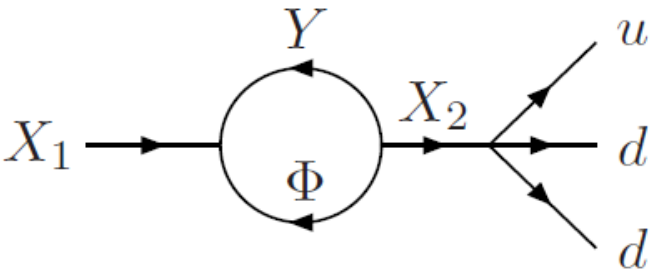
(2) X_1 $\overline{X}_1$ decay with CP violation in the V and D sectors

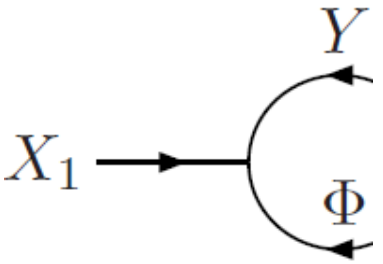
(3) the symmetric components annihilate away

Hylogenesis

from Morrissey's talk







visible sector CP asymmetry

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

dark sector CP asymmetry

$$\frac{n_B}{s} \simeq \epsilon \left.\frac{n_X}{s}\right|_{RH}$$

$$\Gamma(X \to 3Q) = \Gamma_{3Q} + \epsilon_V \Gamma_{tot}$$

$$\Gamma(X \to \bar{Y}\bar{\Phi}) = \Gamma_{Y\Phi} - \epsilon_D \Gamma_{tot}$$

$$\Gamma(\overline{X} \to 3\bar{Q}) = \Gamma_{3Q} - \epsilon_V \Gamma_{tot}$$

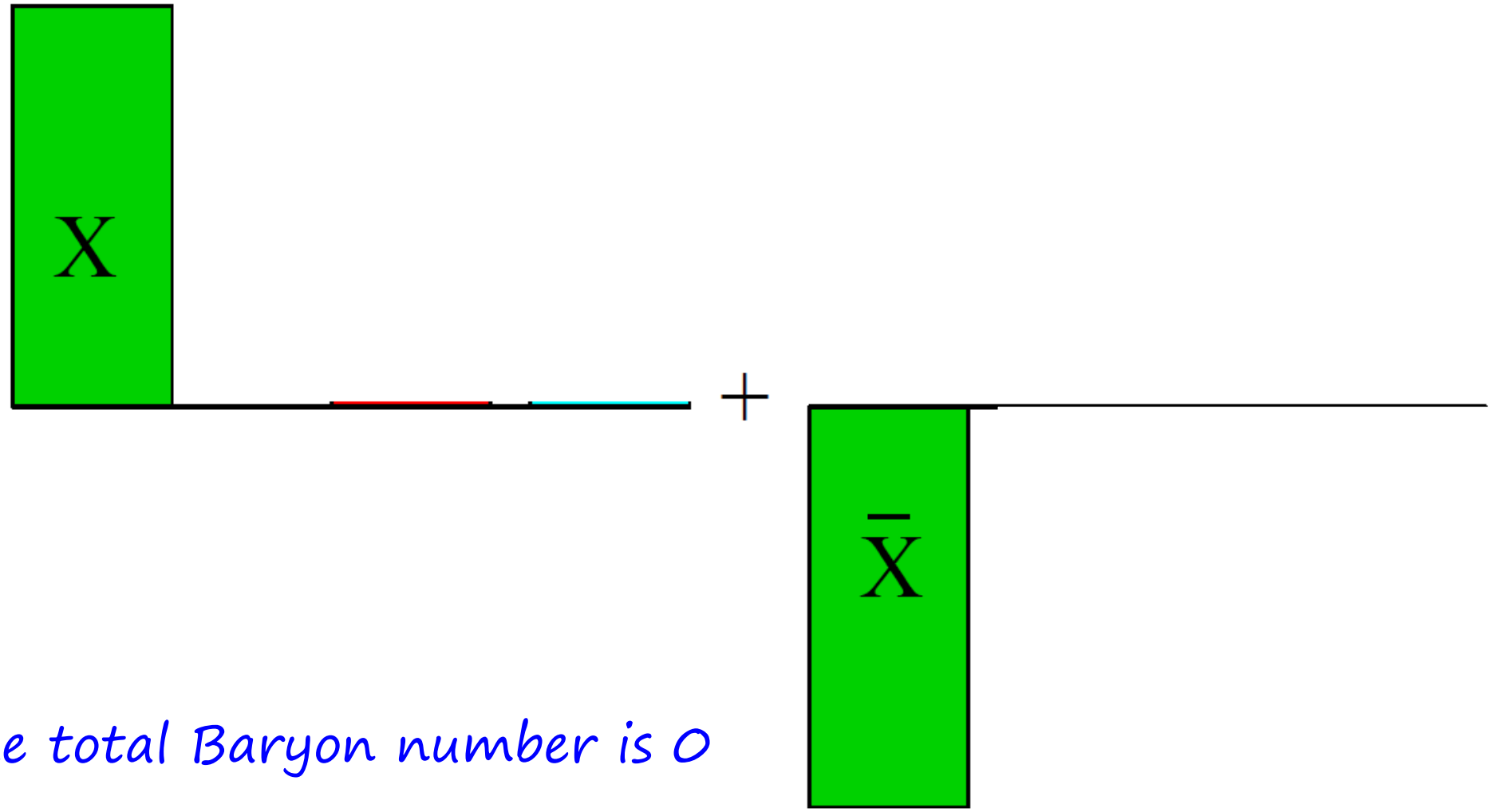
$$\Gamma(\overline{X} \to Y\Phi) = \Gamma_{Y\Phi} + \epsilon_D \Gamma_{tot}$$

CPT $\Gamma(X \to all) = \Gamma(\bar{X} \to all)$ → $|\epsilon_D| = |\epsilon_V|$

Hylogenesis

from Morrissey's talk

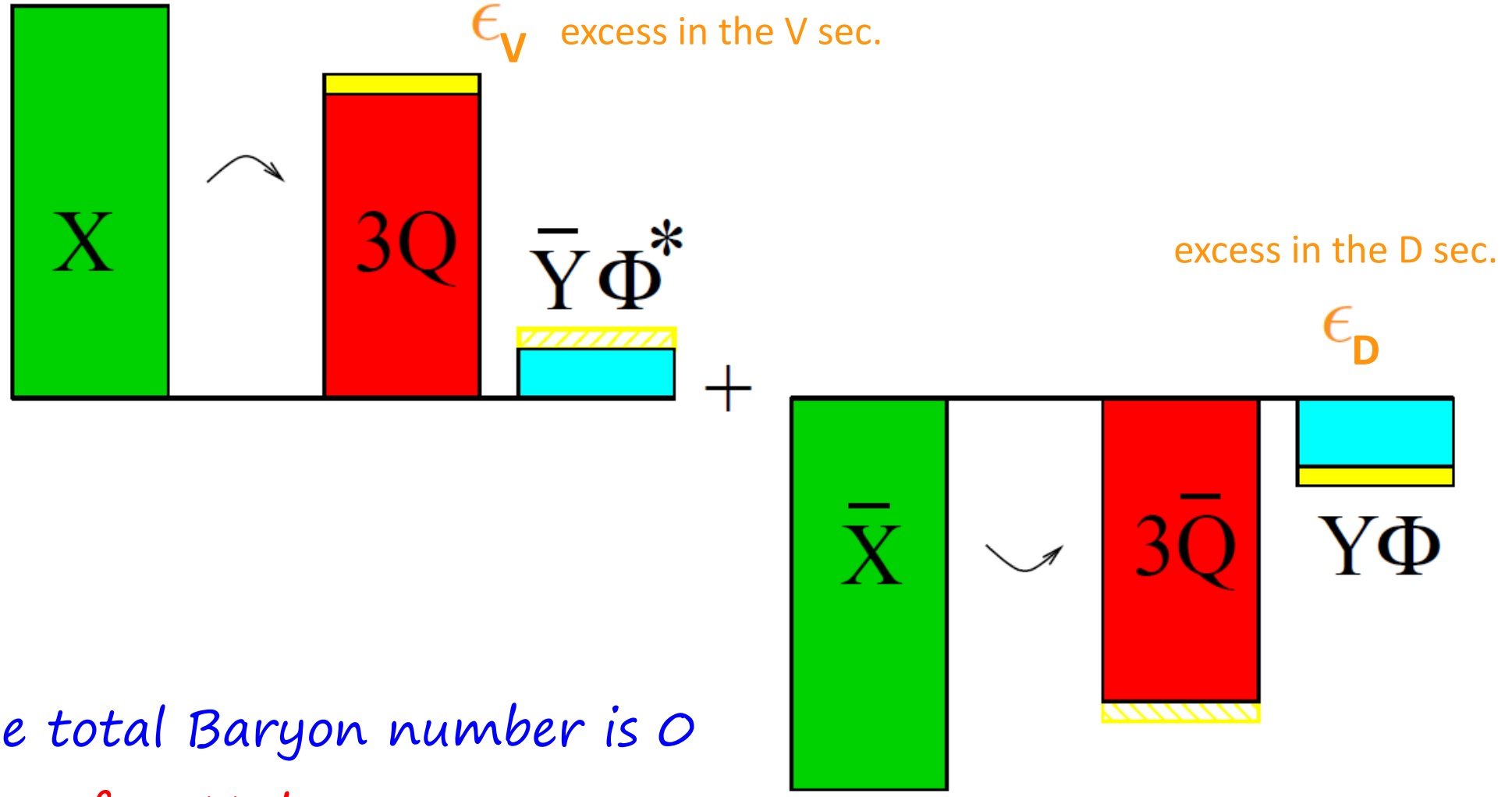
Inflaton decay



the total Baryon number is 0

Hylogenesis

from Morrissey's talk

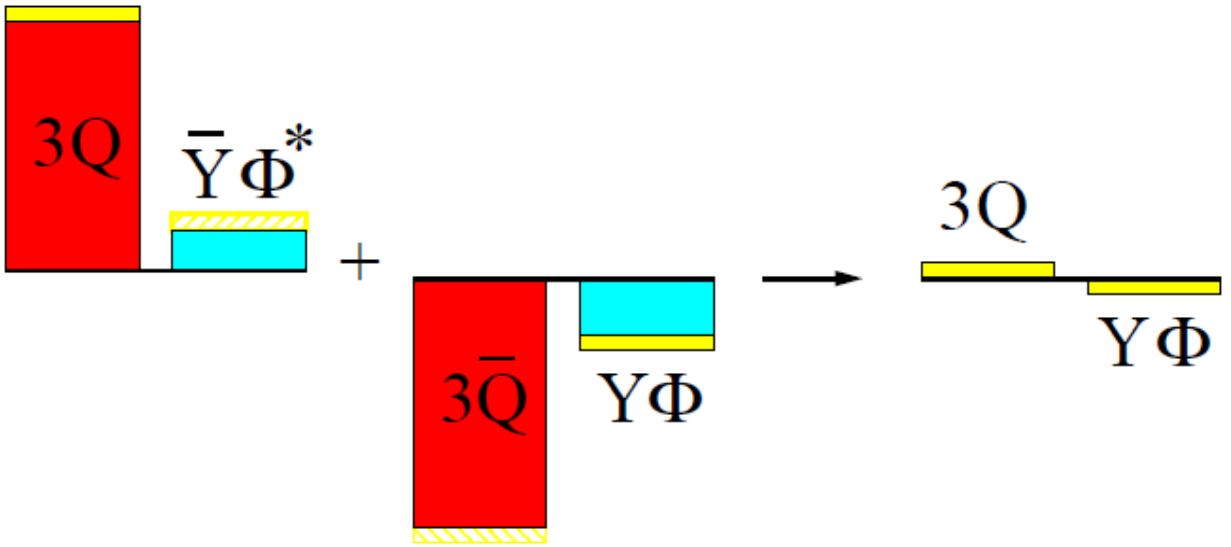


the total Baryon number is 0

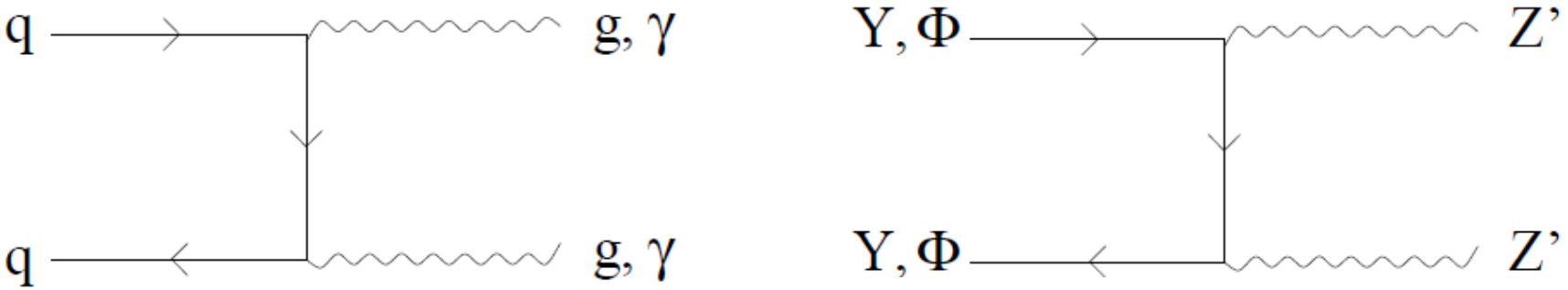
also after X decay

Hylogenesis

from Morrissey's talk



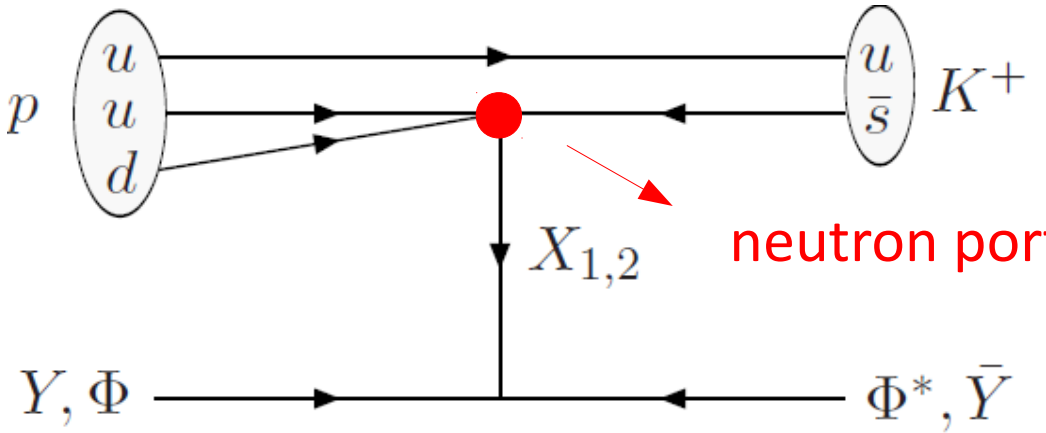
The symmetric part annihilate leaving only the asymmetric one



Extra U'(1) gauged

Dark Force

Hylogenesis: DM signature



Induced nucleon decay

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

Similar to the standard Nucleon Decay

$$N \to M\nu$$

Nucleon to Meson

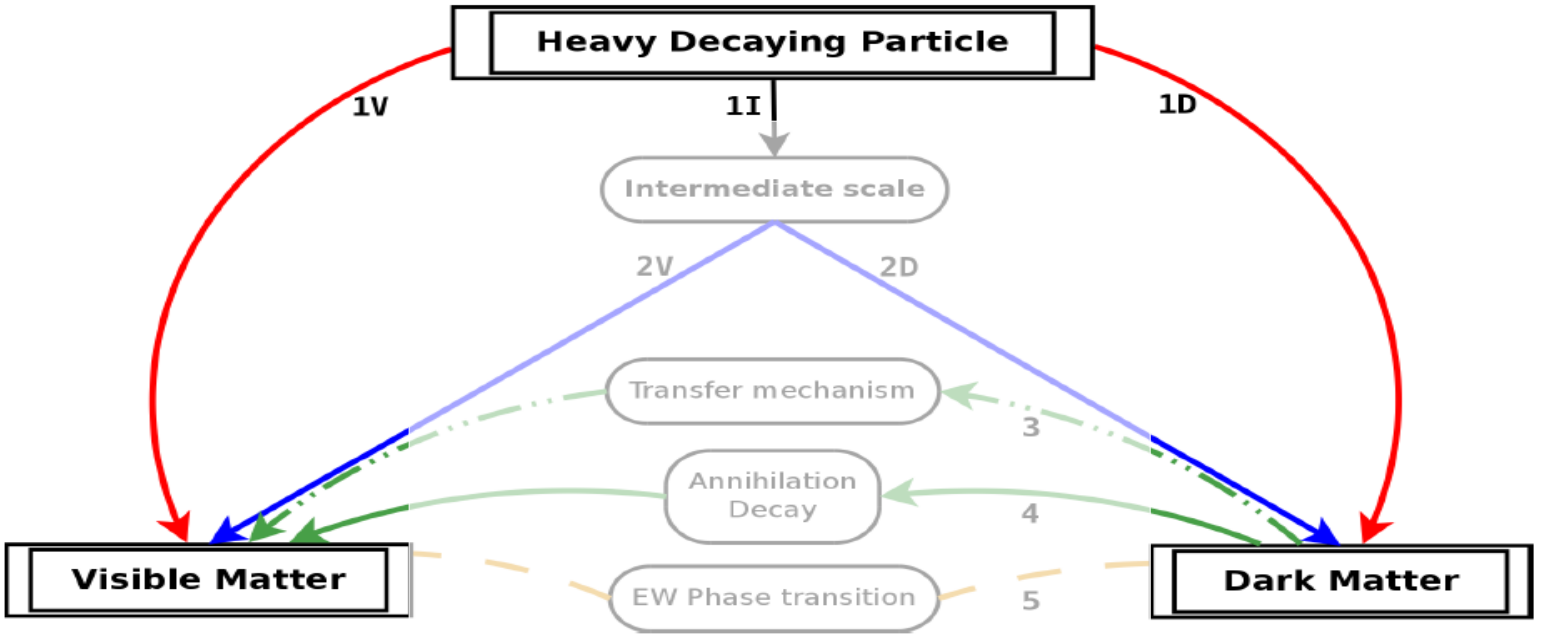
Different kinematic of the daughter meson

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

Hylogenesis

- $X_1 \overline{X}_1$ non-thermally produced (inflaton decay,..)
- $X_1 \overline{X}_1$ decay with CP violation in the V and D sectors
- the symmetric components annihilate away

$$1^*_V\text{-}1^*_D\text{-}T$$



ADM from leptogenesis

Falkowsky, Ruderman,Volansky,JHEO (11')
See also Arina,Sahu NPB(12')

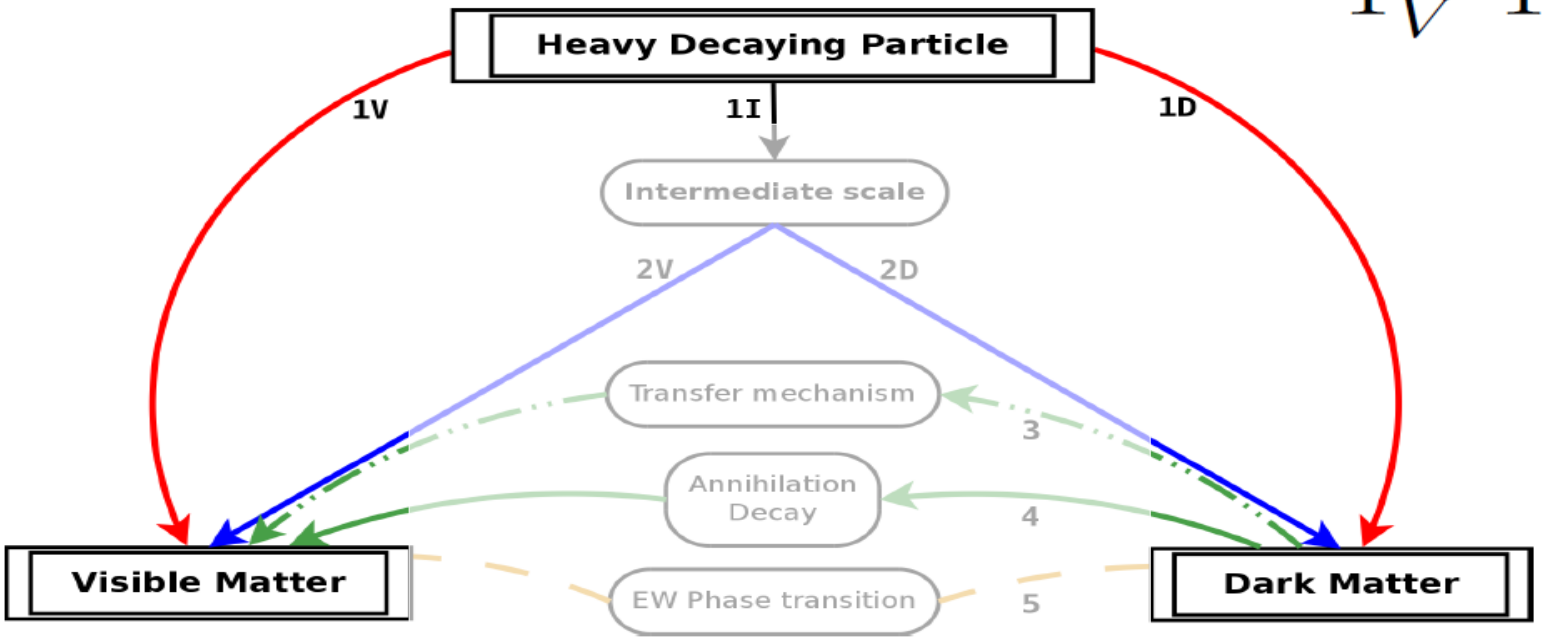
$$N \to LH \qquad N \to Y\phi$$
$$\epsilon_L \qquad \epsilon_{DM}$$

two different and unrelated CP asymmetries

differently from hylogenesis, CPT does not imply $\epsilon_L = \epsilon_{DM}$ because N is Majorana

$$m_{DM} \sim \frac{\Omega_{DM}}{\Omega_B} \frac{\epsilon_L}{\epsilon_{DM}} \frac{\eta_L}{\eta_{DM}} m_p$$ (KeV – 10 TeV)

1^*_V-1^*_D-T



Darkogenesis

Shelton, Zurek, PRD82 (10')

A Dark asymmetry is generated by first order dark phase transition

then is transferred to the visible sector by:

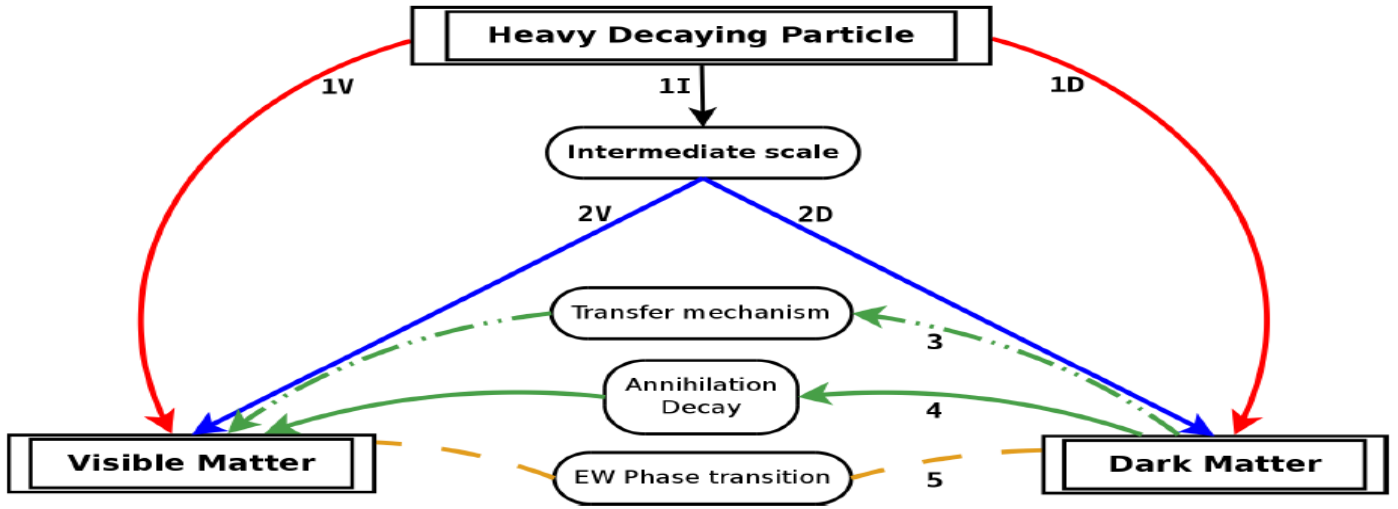
...or different Baryo-mech

Feng,Mazumdar,Nath, PRD88 (13')

- electroweak sphaleron
- higher order transfer op

$$O_d\, LH,\ O_d\, udd,\ O_d\, LLe,\ O_d\, LQd\ \ O_d\, LHLH$$

$$O_d = X,\ X^2$$



$*\_\mathbf{3}\_*$

1^*_V-$\overline{3}$-$*$-T Aidnogenesis

Blennow et al, JHEP (11')

Xogenesis

Buckley, Randall, JHEP (11')

like darkogenesis a Dark asymmetry is transferred to the visible sector

if the DM is not relativistic at the decoupling T of the transfer op
then the DM number density is thermally suppressed allowing heavy DM mass

$$n_i = c_i \mu_i \qquad\qquad c_i = c_i(m_i, T)$$

tranfer op

$$\mu_{DM} \sim \mu_B$$

typically $c_i \sim 1 \longrightarrow n_{\Delta_{DM}} \sim n_{\Delta_B}$

$\frac{m_{DM}}{T} \gg 1 \qquad c_{DM} \sim e^{-\frac{m_{DM}}{T}} \longrightarrow$

Barr,Chivukula,Farhi,PLB(90')

larger DM
mass allowed
100GeV - TeV

Xogenesis

Buckley, Randall, JHEP (11')

X_L $SU(2)_L$ fermionic doublet

$\bar{X}_S^0$ and $\bar{X}_S^-$ $SU(2)_L$ fermionic singlets

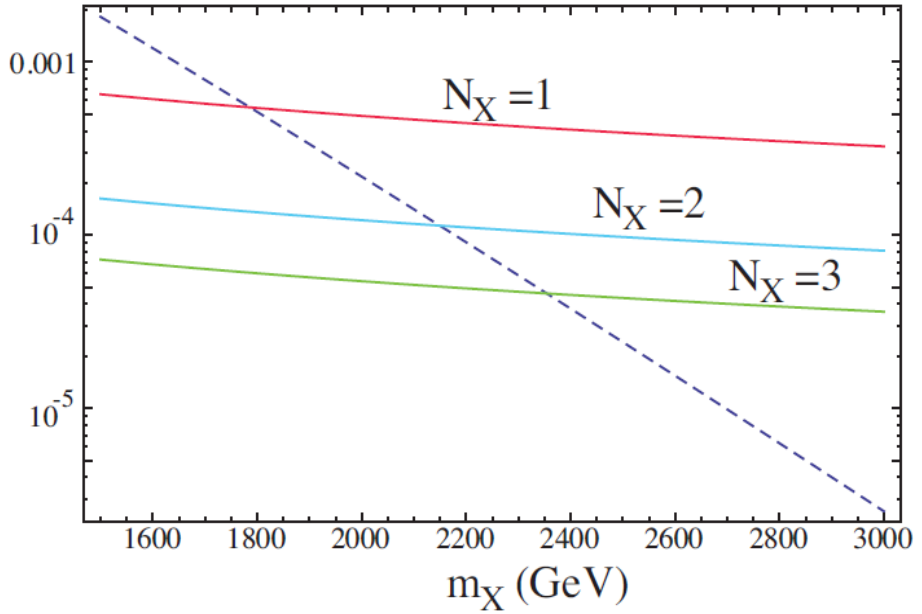
$$\mathcal{L} \supseteq y_X X_L \phi \bar{X}_S^0 + y'_X X_L \phi^* \bar{X}_S^- + m_0 X_S^0 \bar{X}_S^0$$

$B - 3/N_X X$ preserved

the action of the sphaleron enforces chemical eq between DM and quarks

$$\mu_{X_L} = -3N_X \mu_{u_L}$$

$$f(m_X/T_D) = \frac{f(0)}{N_X^2} \frac{\rho_{\rm DM}}{\rho_B} \frac{m_{\rm proton}}{m_X}$$



Xogenesis

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X_L $SU(2)_L$ fermionic doublet

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$$\mathcal{L} \supseteq y_X X_L \phi \bar{X}_S^0 + y'_X X_L \phi^* \bar{X}_S^- + m_0 X_S^0 \bar{X}_S^0$$

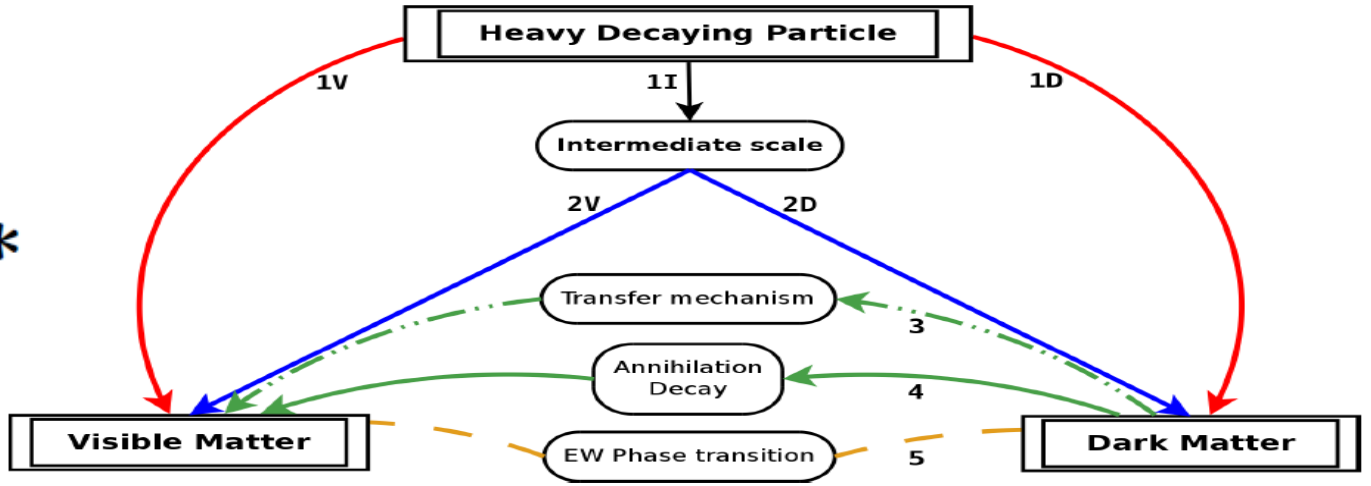
DM ← sphaleron → B, L

$B - 3/N_X X$ preserved

the action of the sphaleron enforces chemical eq between DM and quarks

$$\mu_{X_L} = -3 N_X \mu_{u_L}$$

*_3_*



Non-thermal DM: Cladogenesis

Allahverdi,Bhaskar,Sinha,PRD (11')

the dilution factor due to entropy release by moduli decay
is very close to the observed baryon asymmetry

$$Y_\tau = 3T_{RH}/4M_\tau^4 \sim 10^{-9} - 10^{-7}$$

Any previous DM abbundance (thermally produced)
is suppressed by the same factor

$$\tau \xrightarrow{\mathrm{Br}_N} N \xrightarrow[\text{CP asymmetry}]{\epsilon} \text{SM} \qquad \eta_B \equiv \frac{n_B - n_{\bar{B}}}{s} = Y_\tau \, \mathrm{Br}_N \, \epsilon$$

$$\epsilon \sim 10^{-1} \qquad 10^{-2} \lesssim \mathrm{Br}_N \lesssim 1$$

$$W_{\rm extra} = \lambda_{i\alpha} N_\alpha u_i^c X + \lambda'_{ij} d_i^c d_j^c \overline{X} + \frac{M_\alpha}{2} N_\alpha N_\alpha + M_X X \overline{X}$$

$$\tau \xrightarrow{\mathrm{Br}_\chi} \text{DM} \qquad \frac{n_\chi}{s} = Y_\tau \mathrm{Br}_\chi$$

$$\boxed{\frac{\Omega_{\rm B}}{\Omega_{\rm DM}} \simeq \frac{1\ \mathrm{GeV}}{m_\chi} \times \frac{\epsilon\, \mathrm{Br}_N}{\mathrm{Br}_\chi}}$$

$$\mathrm{Br}_\chi \gtrsim 10^{-3} \quad , \quad 5\ \mathrm{GeV} \lesssim m_\chi \lesssim 500\ \mathrm{GeV}$$

WIMP & BAU

DM in thermal equilibrium in the primordial Universe
The number density frozen-out when the expantion rate drops below the rate of DM annihilation

WIMP miracle

$$\Omega_{CDM}h^2 \simeq \frac{0.3\times 10^{-26} cm^3 s^{-1}}{\langle \sigma v\rangle_{f.o.}}$$

– Meta-stable WIMP

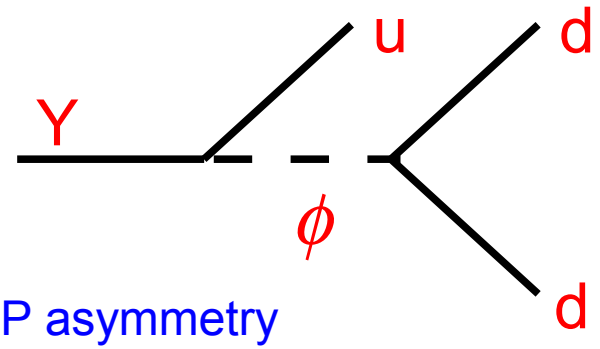
DM/baryon relic densities coincidences preserving the WIMP miracle

Cui,Sundrum, PRD (13')

2 WIMPs:

1 stable & 1 decay after freezeout $\quad Y_{Y_1}(T_f) \approx Y_{Y_2}(T_f) \quad T_f \sim m_Y/20$

$$T_{BBN} < T_{Y_2} < T_f$$



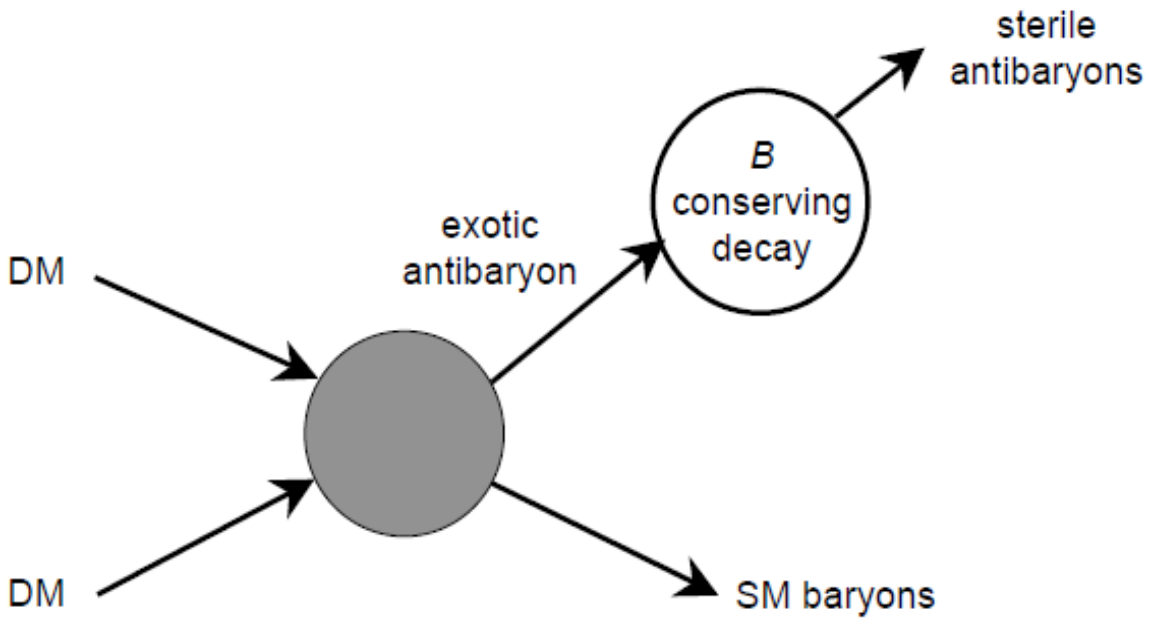
CP asymmetry from interferences with loop diag

$$Y_B(T_0) \approx \epsilon_{CP} Y_{Y_2}(T_f) \qquad Y_Y(T_f) \simeq Y_Y(T_0)$$

$$\Omega_B = \epsilon_{CP}\frac{m_p}{m_{DM}}\Omega_{DM}$$

WIMPy baryogenesis

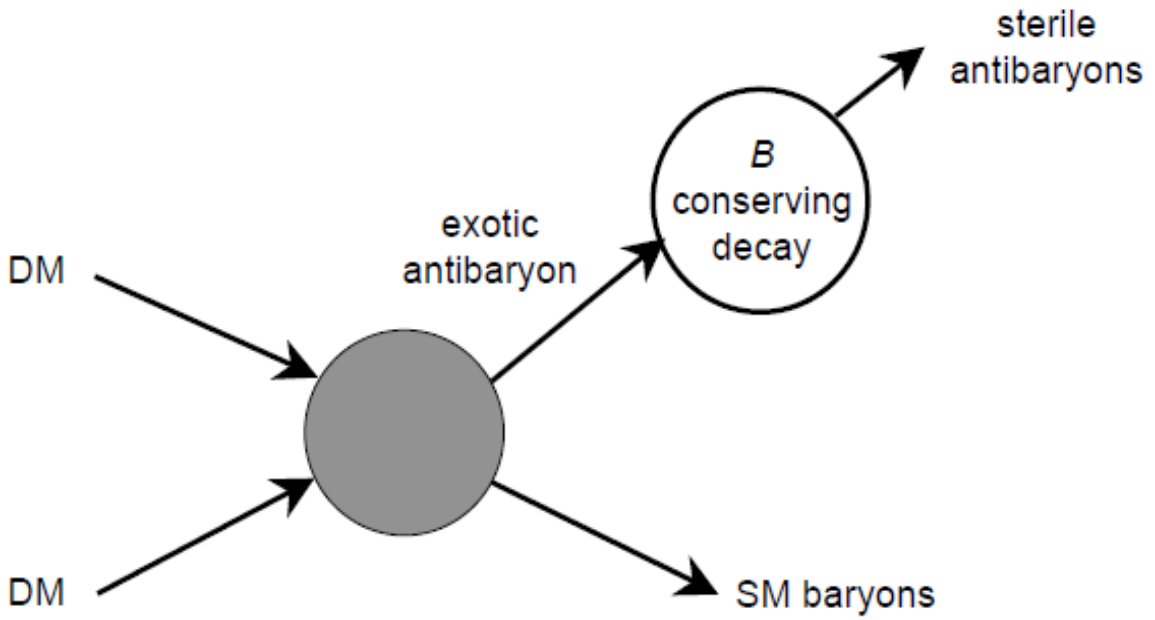
Cui, Randall, Shuve. JHEP (12')



Conventional WIMP annihilation → BAU Can be generated

WIMPy baryogenesis

Cui, Randall, Shuve. JHEP (12')



3-Sakharov conditions in WIMP annihilation

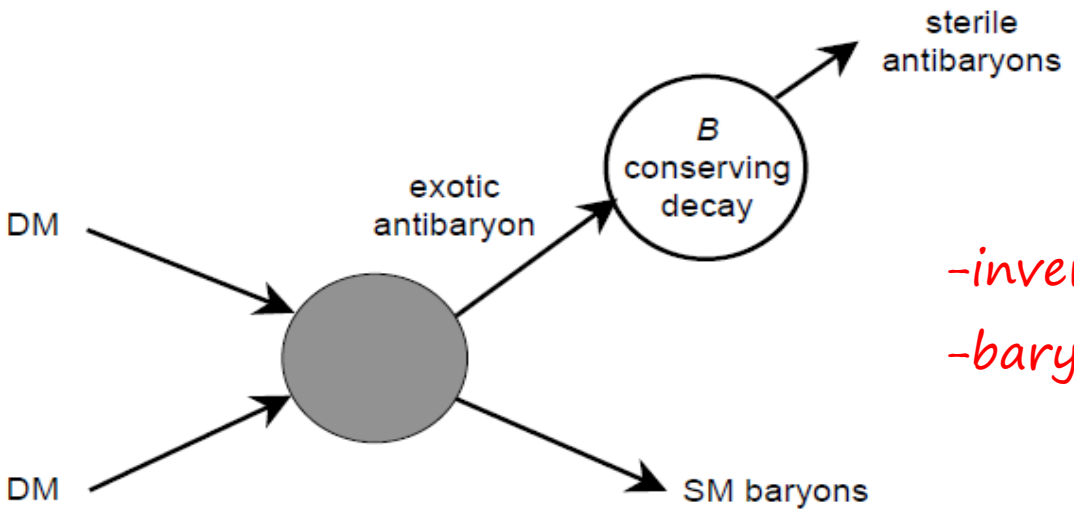
(1) B violation

(2) C & CP violation

(3) departure from T eq

WIMPy baryogenesis

Cui, Randall, Shuve. JHEP (12')



wash out:

-inverse annihilation

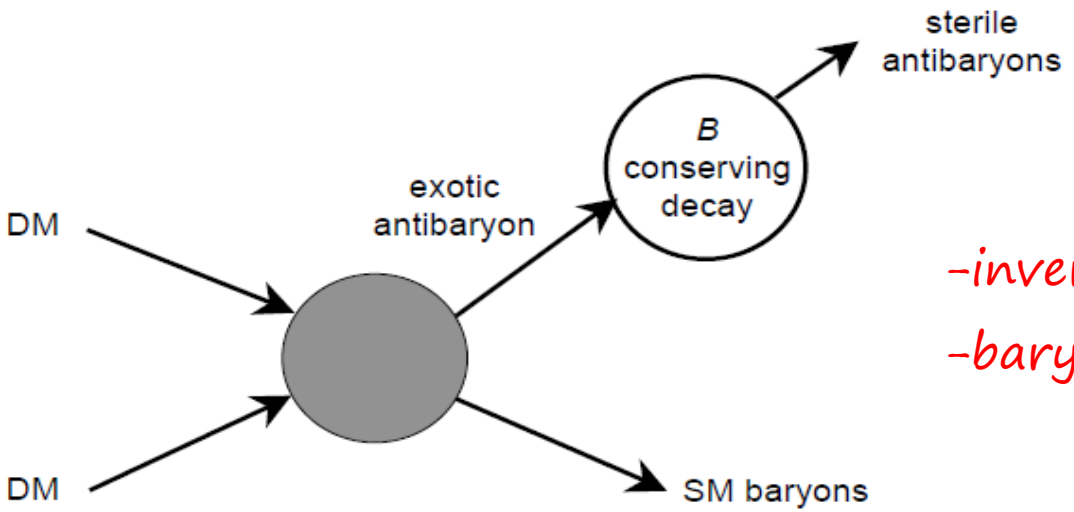
-baryon-to-antibaryon processes

wash out processes must freeze-out before WIMP freeze-out

after wash out freeze out,
then a large BAU may accumulate from DM annihilation

WIMPy baryogenesis

Cui, Randall, Shuve. JHEP (12')



wash out:

-inverse annihilation

-baryon-to-antibaryon processes

wash out processes must freeze-out before WIMP freeze-out

– inverse processes are Boltzmann-Suppressed (BS) for T < MDM

– baryon-antibaryon scattering can remain rapid at T << MDM

But if the exotic antibaryon has a mass > M_{DM} then its abbundance is BS at T < M_{DM}

$$m_{\rm DM} \lesssim m_{\rm exotic\,baryon} \lesssim 2m_{\rm DM}$$

WIMPy baryogenesis

Cui, Randall, Shuve. JHEP (12')

$$\frac{dY_X}{dx} = -\frac{2s(x)}{x\,H(x)}\langle\sigma_{\rm ann}v\rangle\left[Y_X^2 - (Y_X^{\rm eq})^2\right]$$

BE

$$\frac{dY_{\Delta B}}{dx} = \frac{\epsilon\, s(x)}{x\,H(x)}\langle\sigma_{\rm ann}v\rangle\left[Y_X^2 - (Y_X^{\rm eq})^2\right] - \frac{s(x)}{x\,H(x)}\langle\sigma_{\rm washout}v\rangle\frac{Y_{\Delta B}}{2Y_\gamma}\prod_i Y_i^{\rm eq}$$

$$x = m_X/T$$

$$Y_{\Delta B}(x) \approx -\frac{\epsilon}{2}\int_0^x dx'\,\frac{dY_X(x')}{dx'}\,\exp\left[-\int_{x'}^x \frac{dx''}{x''}\,\frac{s(x'')}{2Y_\gamma\,H(x'')}\langle\sigma_{\rm washout}v\rangle\prod_i Y_i^{\rm eq}(x'')\right]$$

CP

source term from DM annihilation

washout term that erase the asymmetry

if it is a rapidly decreasing func it gives a step

$\Gamma_{\rm washout}/H < 1$

$$Y_{\Delta B}(\infty) \approx -\frac{\epsilon}{2}\int_{x_{\rm washout}}^\infty dx'\,\frac{dY_X(x')}{dx} = \frac{\epsilon}{2}\left[Y_X(x_{\rm washout}) - Y_X(\infty)\right]$$

WIMPy baryogenesis

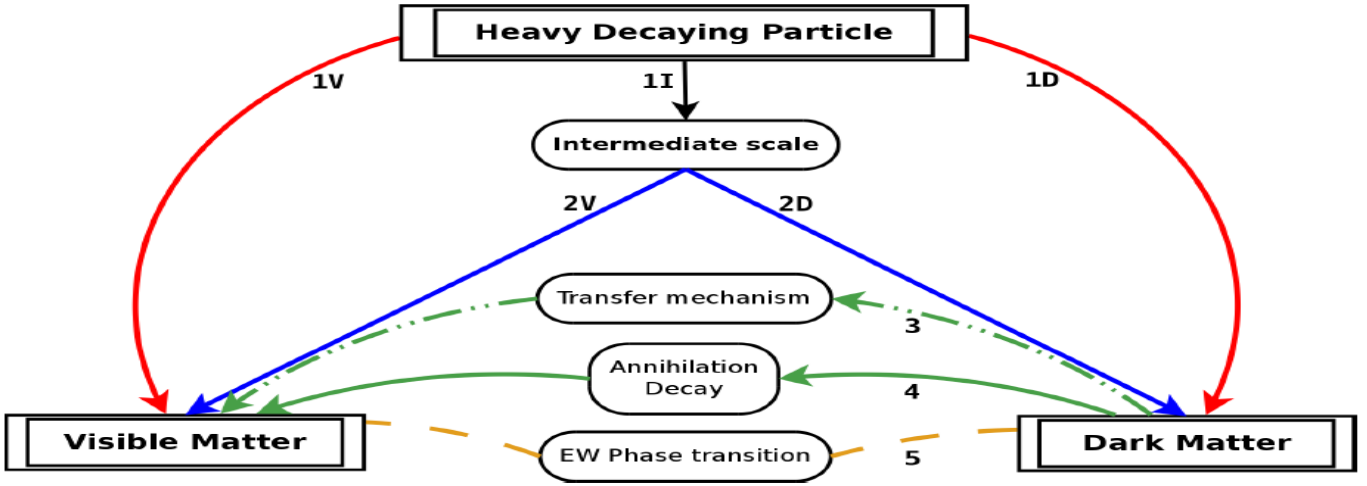
Cui, Randall, Shuve. JHEP (12')

$$Y_{\Delta B}(\infty) \approx -\frac{\epsilon}{2}\int_{x_{\rm washout}}^{\infty} dx' \, \frac{dY_X(x')}{dx} = \frac{\epsilon}{2}\left[Y_X(x_{\rm washout}) - Y_X(\infty)\right]$$

After wash out freeze out,
all subsequent WIMP annihilation
generate a baryon asymmetry with efficiency $\mathcal{E}$

the final BAU from WIMPy baryogenesis
is proportional to
the DM density
at the time when wash out processes freeze out

Summary



Model	DM	HS	BAU	$\mathcal{O}(M_{DM})$	Signal	Diagram
Two singlets EWBG[9]	$\mathcal{WIMP}$	✗	EWPHT	2 – 225 GeV	DD-ID-CO	5^*
EW cogenesis [53]	$\mathcal{WIMP}$	✗	EWPHT	GeV-TeV	CO	5^*
WIMPy $L^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	TeV	ID-CO	T-4^*
WIMPy $Q^{(\dagger)}$[15]	$\mathcal{WIMP}$	✗	ANNIH	500GeV	DD-ID-CO	T-4^*
Meta-stable WIMP[19]	$\mathcal{WIMP}$	✗	DECAY	GeV-TeV	CO	T-4^*
Kitano-Low [26]	$\mathcal{ADM}$	✣	DECAY	GeV	CO	1^*_V-1^*_I-T-2_D
Hylogenesis [42]	$\mathcal{ADM}$	✓	DECAY	5 GeV	IND-DD	1^*_V-1^*_D-T
ADM Leptog [43]	$\mathcal{ADM}$	✓	DECAY	KeV–10 TeV	DD-ID	1^*_V-1^*_D-T
Darkogenesis [49]	$\mathcal{ADM}$	✓	TRANS	5 – 15 GeV	GW	$*$-3-$*$
Baryogenesis from DM [46]	$\mathcal{ADM}$	✓	TRANS	3 GeV	DD-CO	1_D*-3-$*$
Aidnogenesis [48]	$\mathcal{ADM}$	✓	DECAY	6 GeV	DD-FCNC -CO	1^*_V-$\overline{3}$-$*$-T
Xogenesis [49]	$\mathcal{ADM}$	✓	TRANS	100GeV–TeV	CO	$*$-3-$*$
Pangenesis [38]	$\mathcal{ADM}$	✓	AFDIN	1.6–5 GeV	DD-CO	$*$-1^*_I-T-2_V-2_D
Cladogenesis [51]	$\mathcal{NTDM}$	✣	DECAY	5-500GeV	-	1_I-1_D-2^*_V

WIMPy baryogenesis

Cui, Randall, Shuve. JHEP (12')

$$Y_{\Delta B}(\infty) \approx -\frac{\epsilon}{2}\int_{x_{\rm washout}}^{\infty} dx' \frac{dY_X(x')}{dx} = \frac{\epsilon}{2}\left[Y_X(x_{\rm washout}) - Y_X(\infty)\right]$$

After wash out freeze out,

all subsequent WIMP annihilation

generate a baryon asymmetry with efficiency $\mathcal{E}$

$$\Omega_{DM} \simeq 5\,\Omega_B \quad \Longleftrightarrow \quad Y_X(\infty) \approx \frac{(5\ {\rm GeV})\, Y_{\Delta B}(\infty)}{m_X}$$

$$Y_X(x_{\rm washout}) \gg Y_X(\infty)$$

The washout int must become ineffective prior to

XX annihilation freeze-out

In order to generate the observed BAU through WIMPy