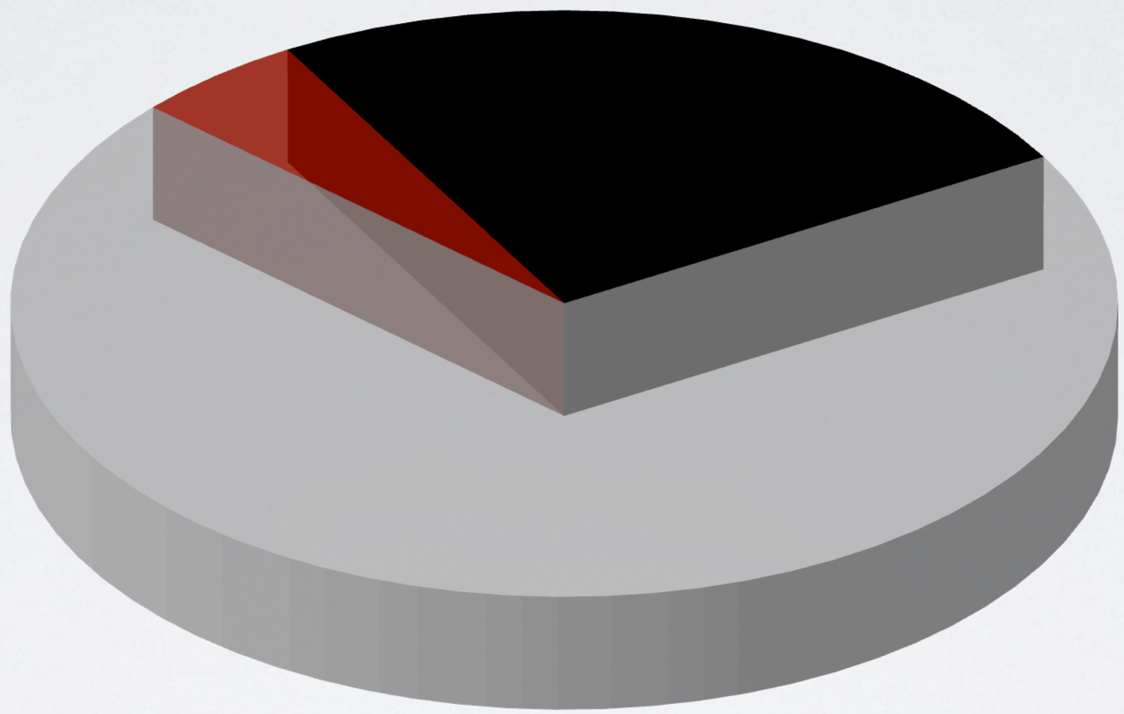
Asymmetric Dark Matter

And the LHC Diphoton Excess



Mads Toudal Frandsen

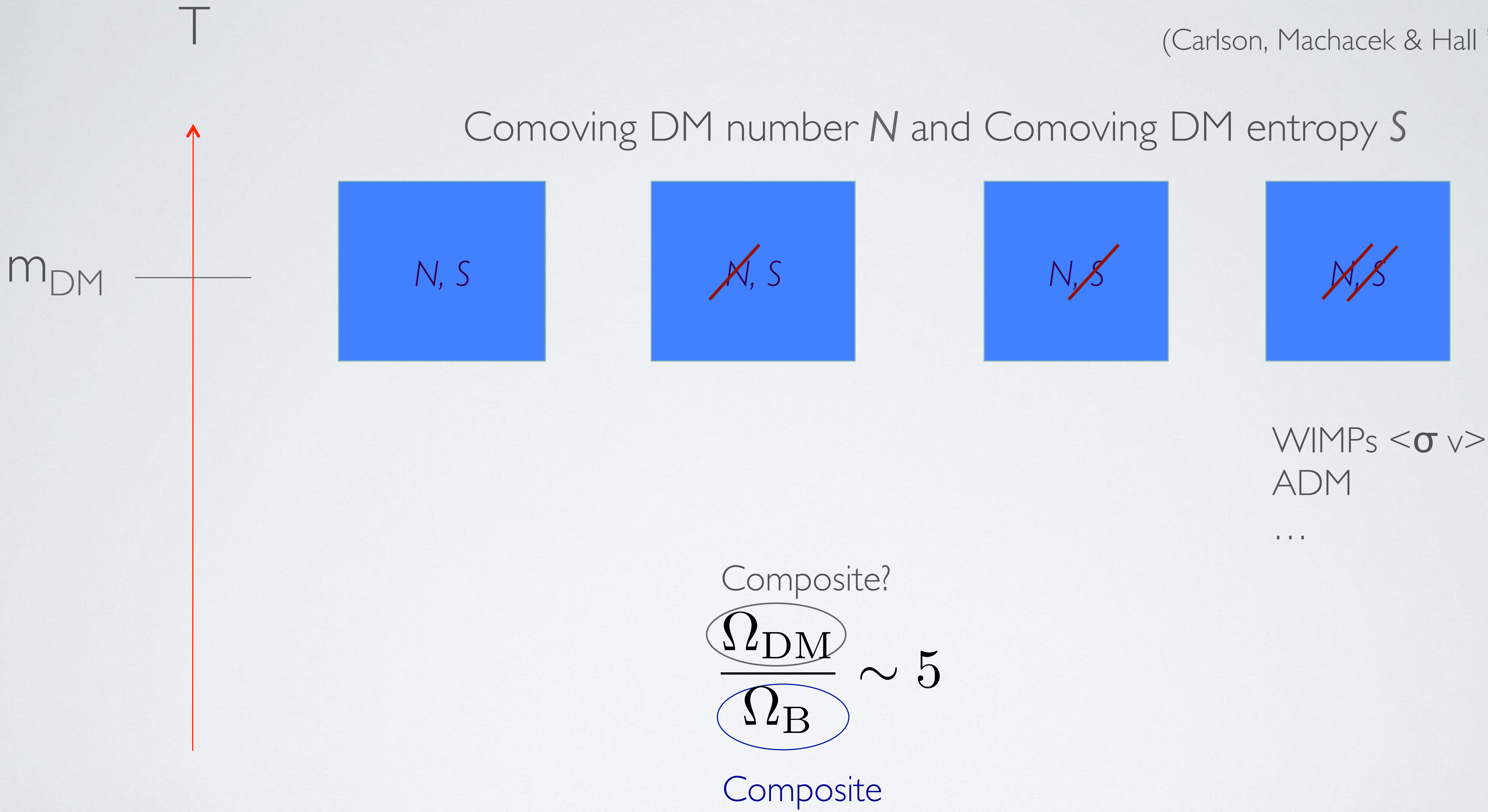
(M.T.F & Sarkar, Phys.Rev.Lett. ’10
M.T.F, Sarkar & Schmidt-Hoberg, PRD ’11
(M.T.F & Shoemaker JCAP ’16)

CP3 Origins
Cosmology & Particle Physics

Origin of the DM relic density

(Carlson, Machacek & Hall '92)

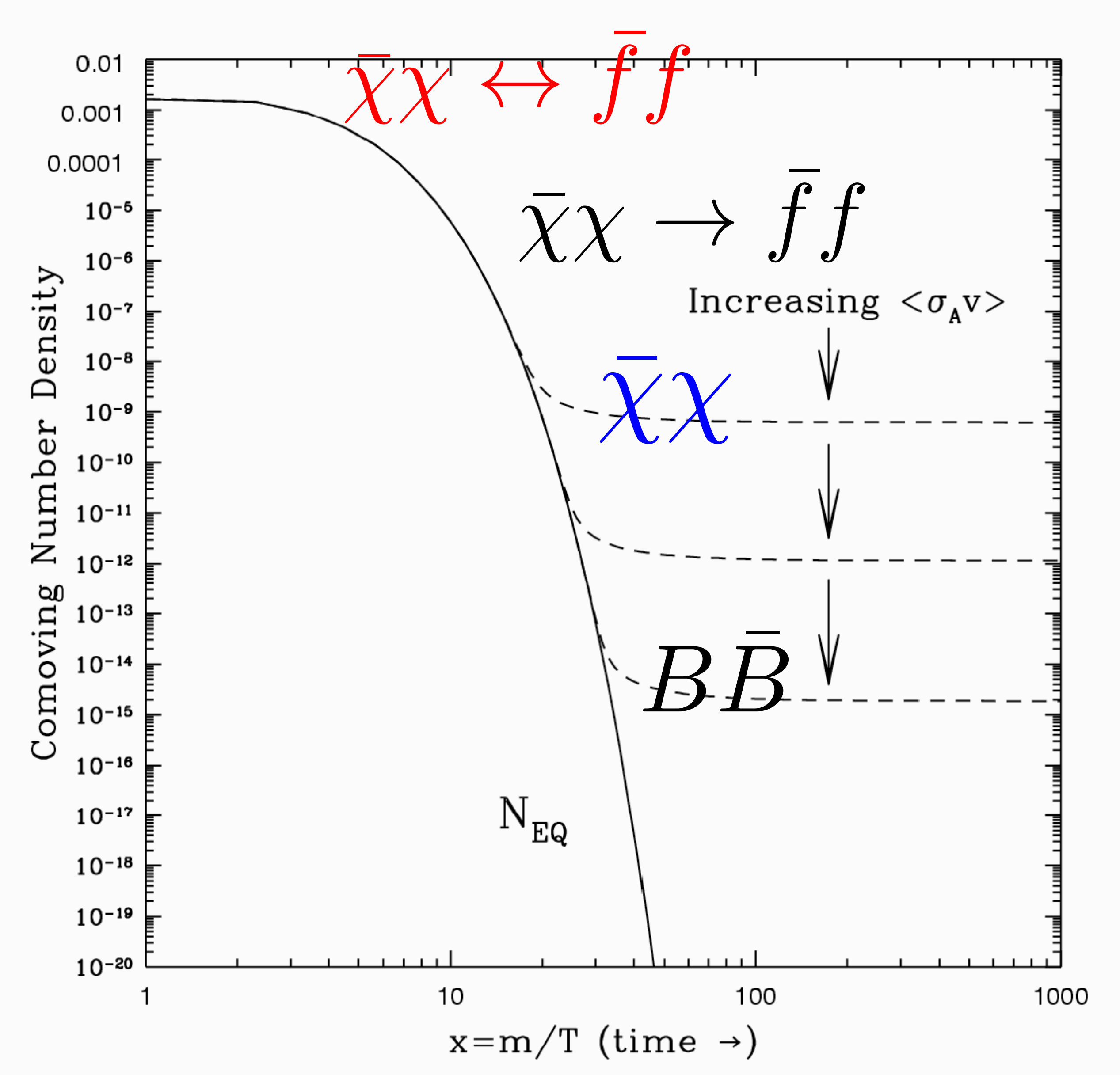
Comoving DM number *N* and Comoving DM entropy *S*



$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} \sim 5$$

Origin of the DM relic density

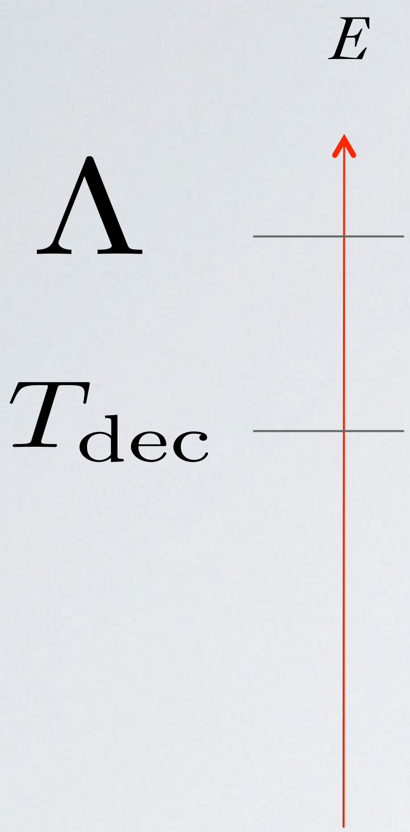
$$\eta_B \equiv \frac{n_B - \bar{n}_B}{n_\gamma} \sim 10^{-9}$$



Asymmetric Dark Matter

- Dynamical EWSB -> TeV Technibaryon ADM (Nussinov ’85)
- Solar neutrino problem -> 5 GeV Cosmion ADM (Gelmini,Hall & Lin ’86)
- Dynamical EWSB & Sphalerons-> TeV Technibaryon ADM (Barr, Chivukula & Farhi ’91)
- Dynamical EWSB & Sphalerons-> 5 GeV ADM (Barr ’91)
- DAMA, GoGENT, Solar composition problemt -> 5 GeV ADM (Kaplan, Luty & Zurek ’09,… Frandsen & Sarkar ’10,…)

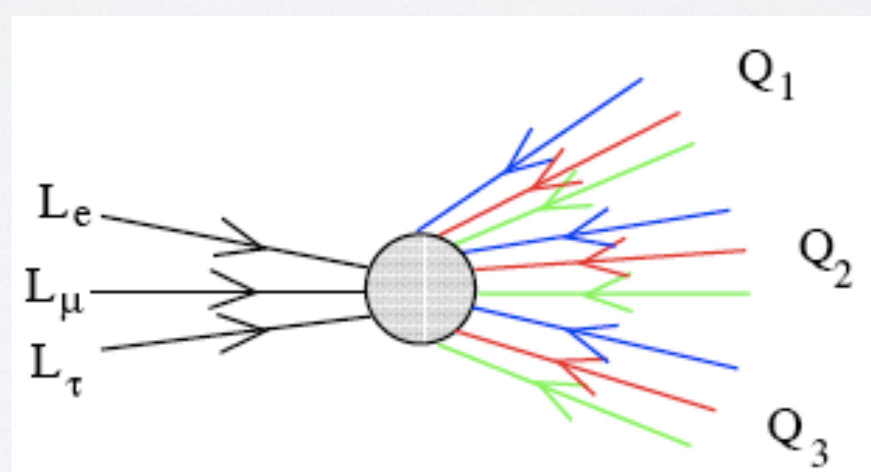
Asymmetry Transfer



- Initial asymmetry in baryons (or DM)
- Asymmetry transferred to DM (or baryons)
- Transfer operator decouples, asymmetric component fixed
- Symmetric component is annihilated away

(Barr, Chivukula & Farhi '91)

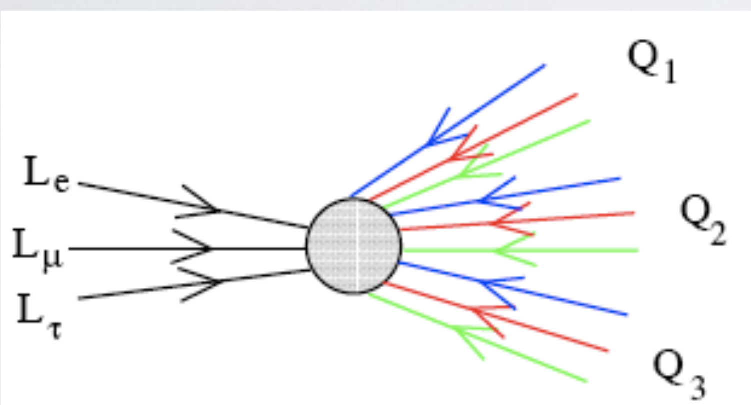
Possible Transfer Operator
Sphalerons



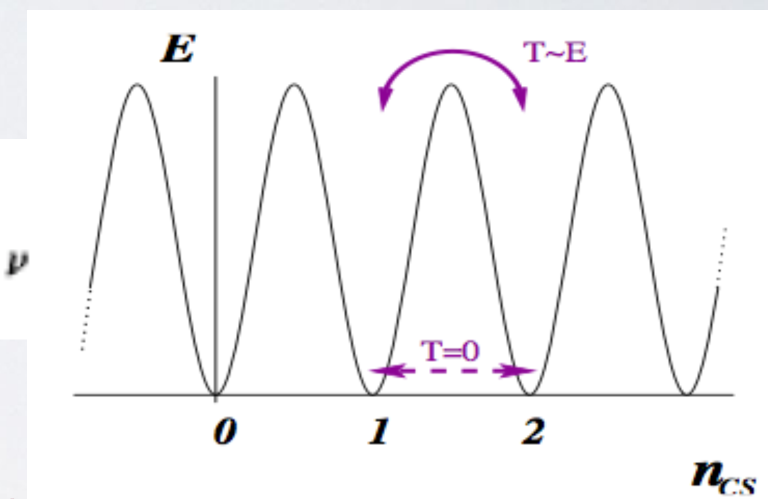
<u>Sakharov conditions for baryogenesis:</u>

1. Baryon number violation
2. C and CP violation
3. Departure from thermal equilibrium

When T> m_W baryon number is also violated in the SM through sphaleron-mediated processes that preserve B – L, but violate B + L …



$$\partial_\mu j_i^\mu = \partial_\mu(\bar{\psi}^i \gamma^\mu \psi^i) = \frac{g^2}{8\pi} W^{a\mu\nu} \tilde{W}^a_{\mu\nu}$$



…CP-violation is too weak (and the electroweak phase transition is a 'cross-over')

The matter we know originated non-thermally in the early universe

ADM via Sphalerons

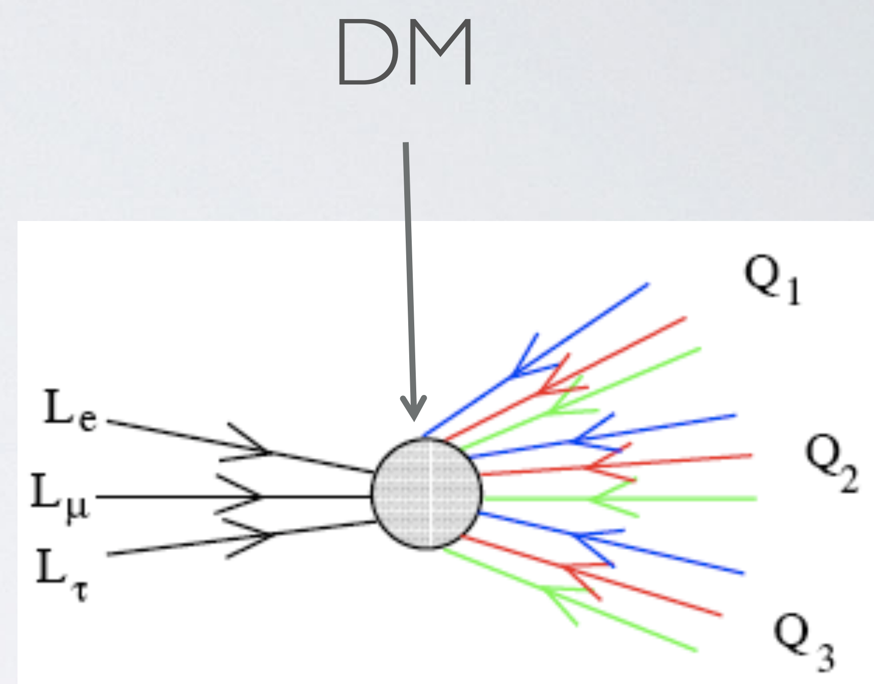
(Barr, Chivukula and Farhi 90)

E

Λ — η_B

$m_{\rm DM}$ — $\eta_B \sim \eta_{\rm DM}$

$T_{\rm Sph}$ — $\eta_{\rm DM} \sim \eta_{\rm B} e^{-\frac{m_{\rm DM}}{T_{\rm Sph}}}$



Dark Sector

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} = \frac{m_{\rm DM}}{m_{\rm B}} \frac{\eta_{\rm DM}}{\eta_{\rm B}}$$

Weak sector - Sphalerons

Strong sector

ADM via Sphalerons

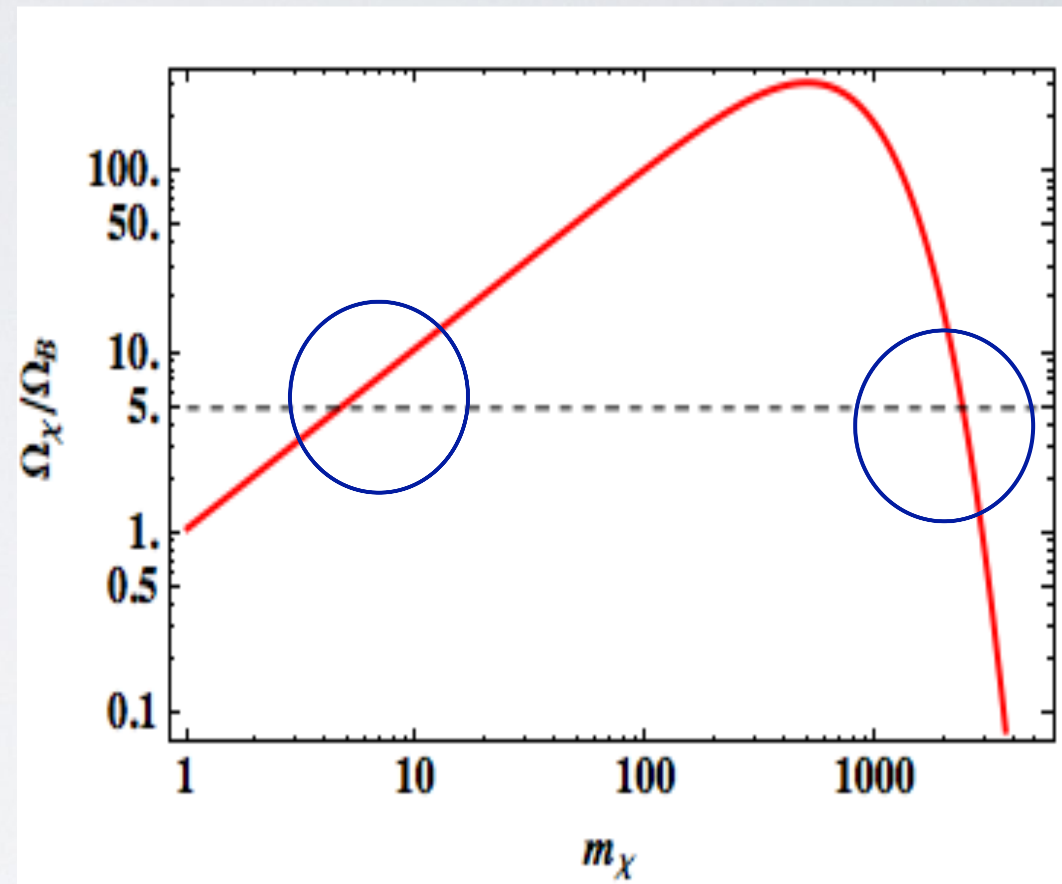
(Barr, Chivukula and Farhi 90)

E

Λ — η_B

$m_{\rm DM}$ — $\eta_B \sim \eta_{\rm DM}$

$T_{\rm Sph}$ — $\eta_{\rm DM} \sim \eta_{\rm B} e^{-\frac{m_{\rm DM}}{T_{\rm Sph}}}$



Dark Sector

$$\frac{\Omega_{\rm DM}}{\Omega_{\rm B}} = \frac{m_{\rm DM}}{m_{\rm B}} \frac{\eta_{\rm DM}}{\eta_{\rm B}}$$

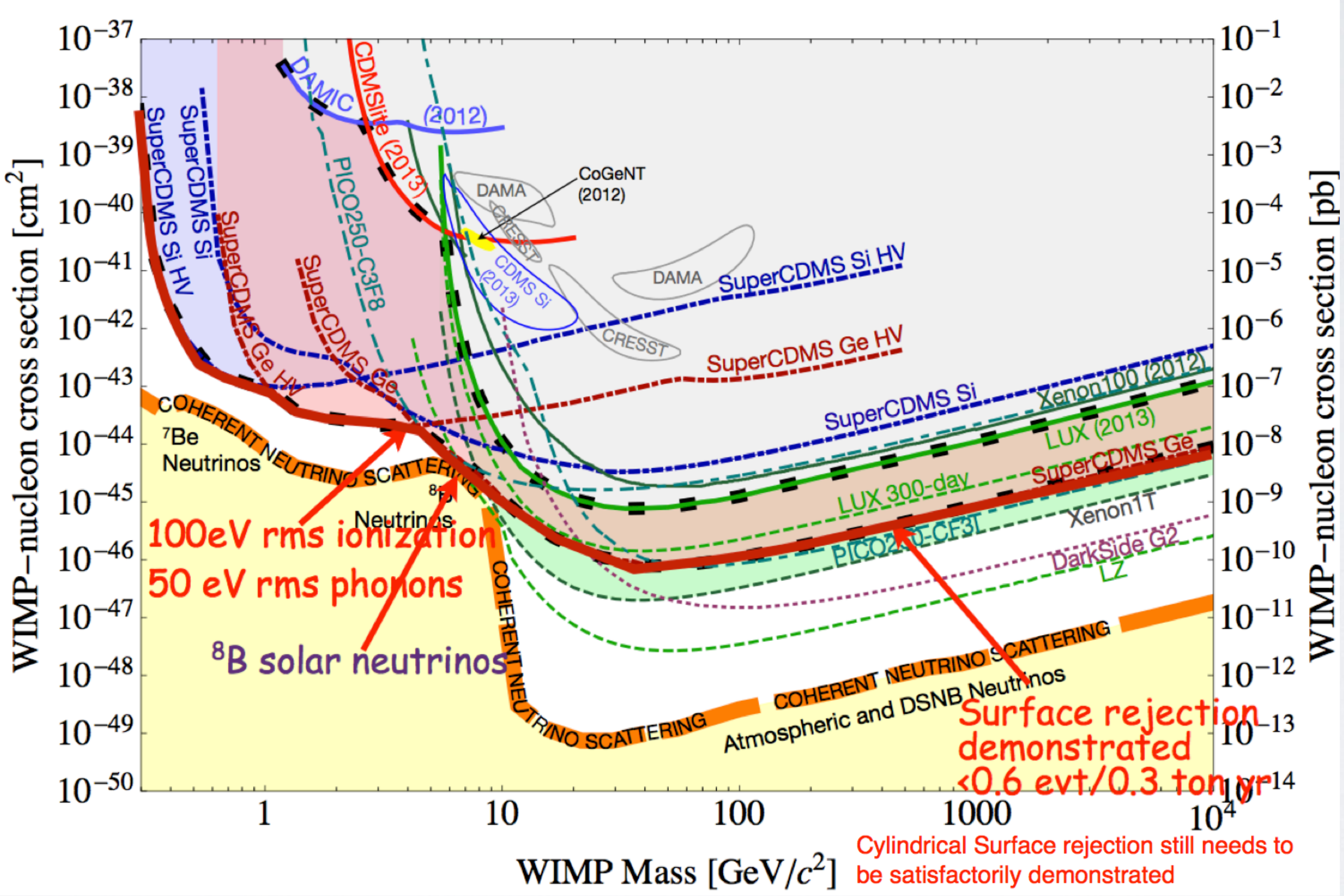
Strong sector

Weak sector
Sphalerons

Direct Detection

(Drukier & Stodolsky '85
Goodman and Witten '85)

Weak scale scattering cross-section ruled out from GeV - TeV



Solution I: Composite DM

(Barr, Chivukula and Farhi 90)

'Hide' weak quantum numbers (weak) neutral composite states

Solution I: Composite DM

(Barr, Chivukula and Farhi 90)

'Hide' weak quantum numbers (weak) neutral composite states

Minimal Technicolor: 2 Dirac Flavors. No QCD charges.

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \; , \quad U_R^{+1/2} \; , \; D_R^{-1/2} \; .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

'TIMP'

- $\mathcal{R}$ pseudo-real
- $T^0 \sim U_L D_L$
- SM singlet GB
- $M^2_{T^0} \sim -g^2\, F^2_\Pi$

(Gudnason, Kouvaris & Sannino 05; MTF & Sannino 09; …)

(Barr, chivukula & Farhi 90)

(Ryttov and Sannino 09)

Solution I: Composite DM

(Barr, Chivukula and Farhi 90)

‘Hide’ weak quantum numbers (weak) neutral composite states

Natural setting for diphoton resonances…

Minimal Technicolor: 2 Dirac Flavors. No QCD charges.

$$Q_L = \left(U_L^{+1/2}, D_L^{-1/2}\right)^T \; , \quad U_R^{+1/2} \; , \; D_R^{-1/2} \; .$$

'iTIMP'

- $\mathcal{R}$ real
- $T^0 \sim U_L D_L$
- Iso-singlet GB
- $M_{T^0} \sim g\, F_\Pi$

(Gudnason, Kouvaris & Sannino 05; MTF & Sannino 09; …)

'TIMP'

- 4 of $SU(4)$
- $U_L D_L U_L D_L$
- SM singlet
- $M_T \sim N_{TC}^{3/2} F_\Pi$

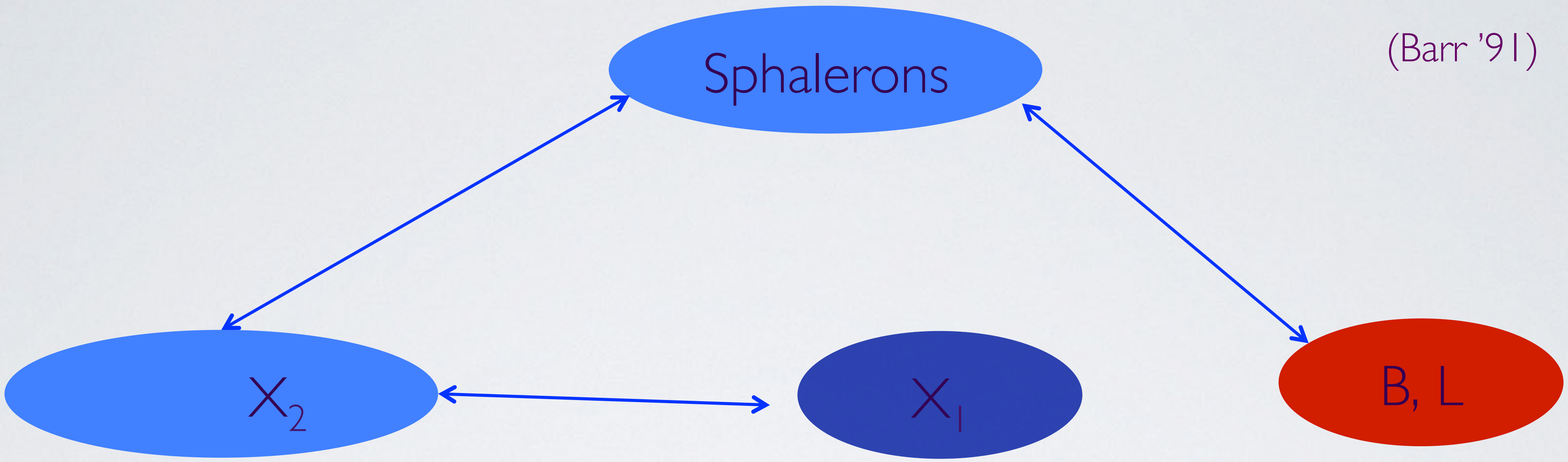
(Barr, chivukula & Farhi 90)

'TIMP'

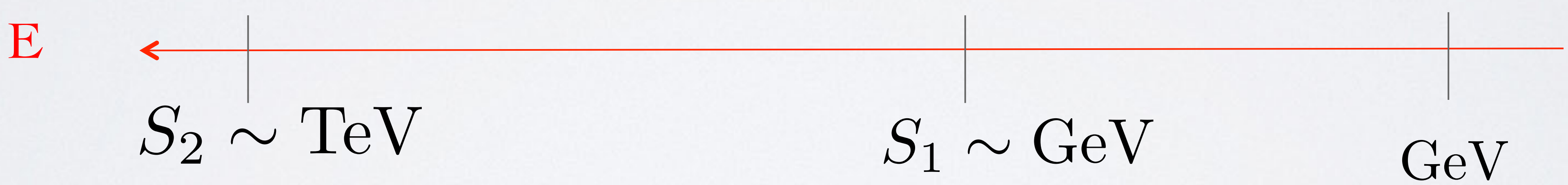
- $\mathcal{R}$ pseudo-real
- $T^0 \sim U_L D_L$
- SM singlet GB
- $M_{T^0}^2 \sim -g^2\, F_\Pi^2$

(Ryttov and Sannino 09)

Solution II: Decays to singlets



$$\Phi X_2 X_1$$



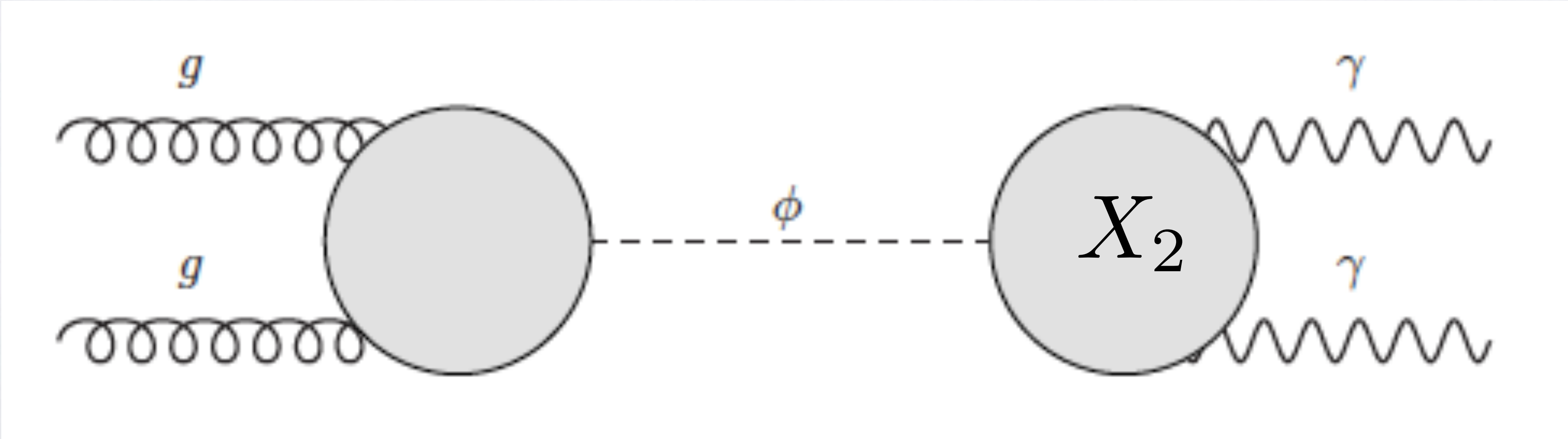
S_1 X_2 , Φ (constituents) carry weak charges and are connected to sphalerons

S_2 X_1 (constituents) is singlet

Diphotons

(Frandsen & Shoemaker '16)

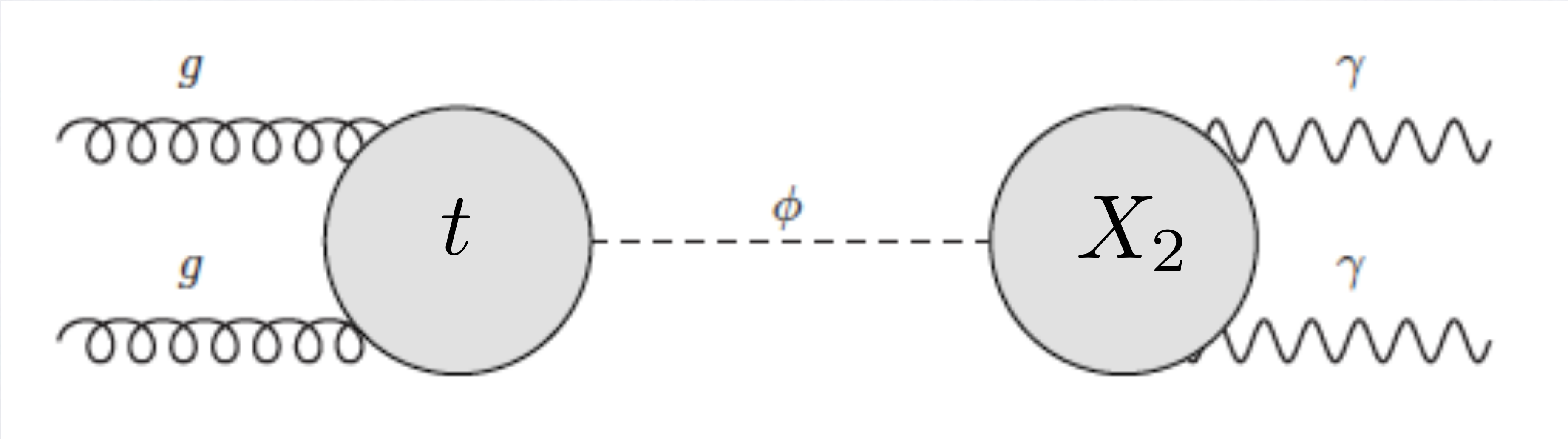
- New weak charged fermions X_2 – asymmetry transfer to dark sector
- New scalars – decay of X_2 to DM.
- Basic ingredients for a new resonance in diphoton searches



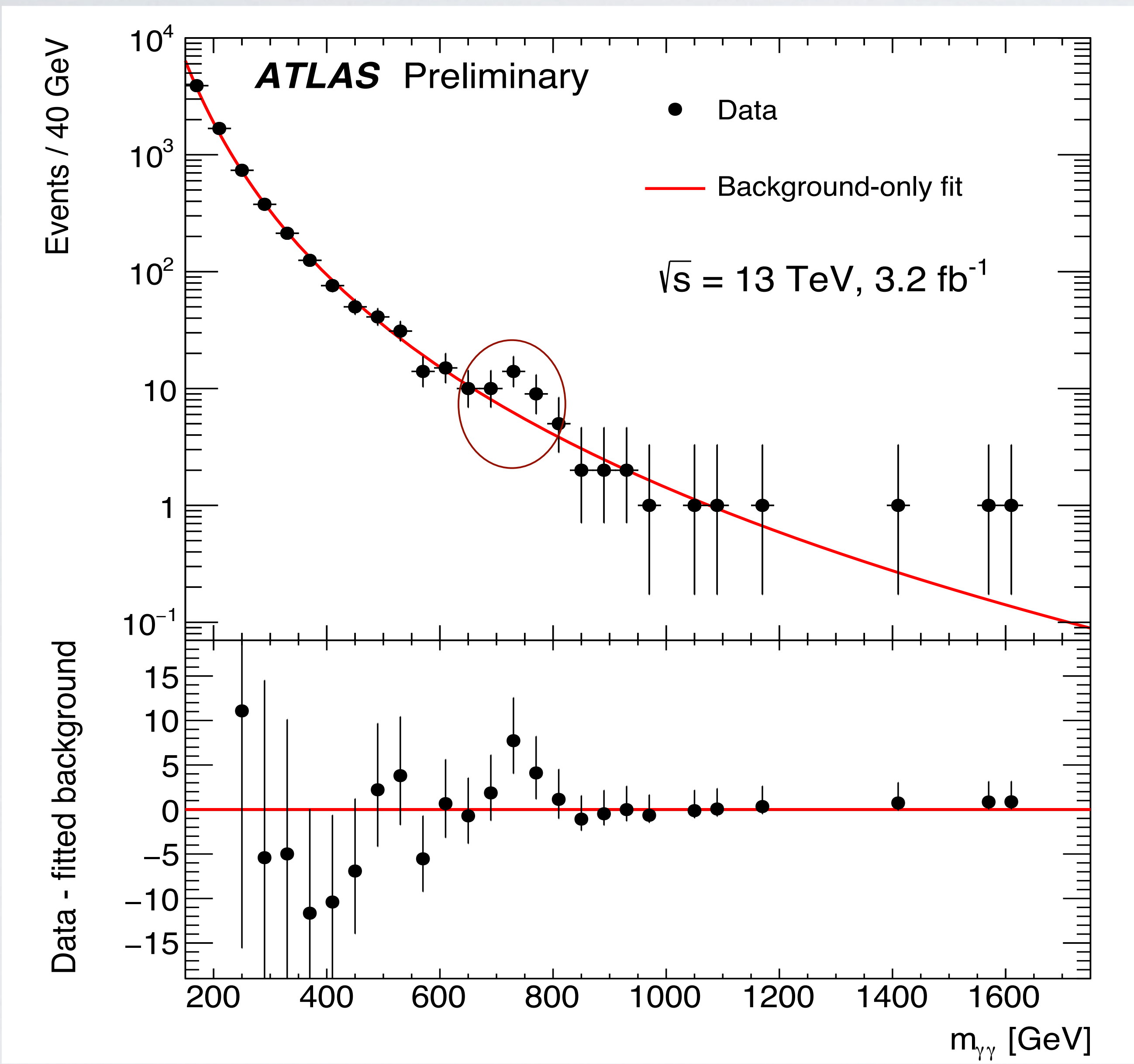
Diphotons

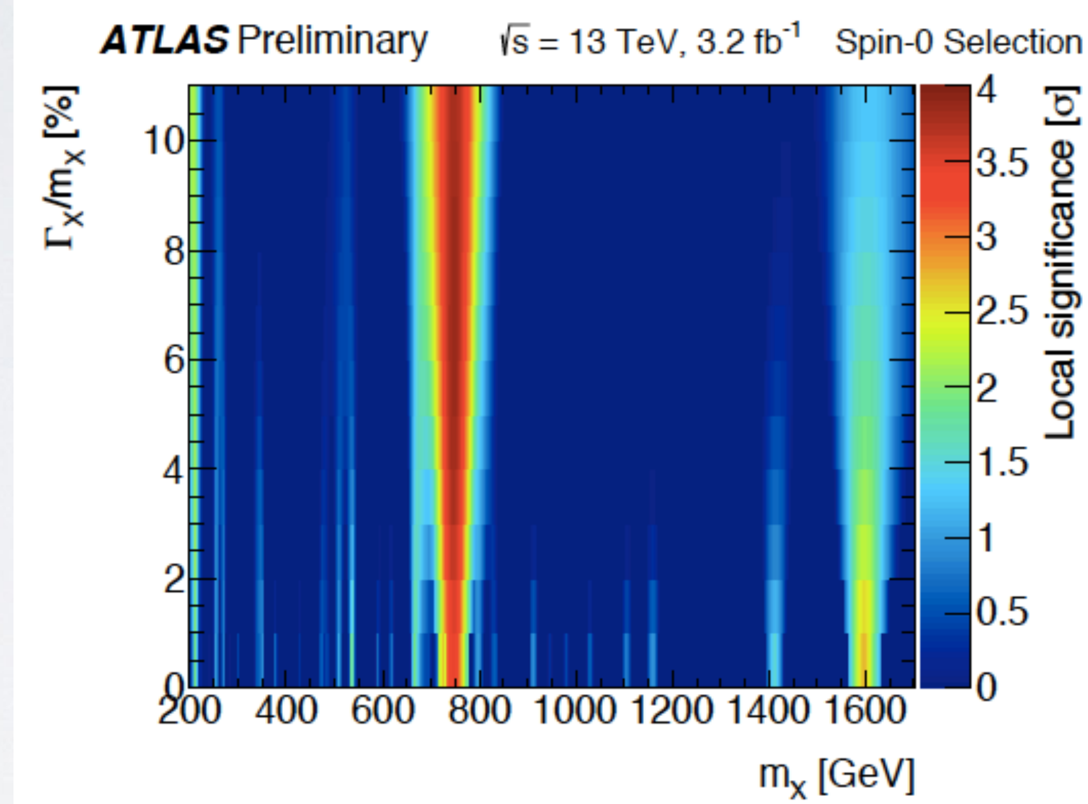
(Frandsen & Shoemaker '16)

- New weak charged fermions X_2 – asymmetry transfer to dark sector
- New scalars – decay of X_2 to DM.
- Basic ingredients for a new resonance in diphoton searches



LHC Diphoton Excess

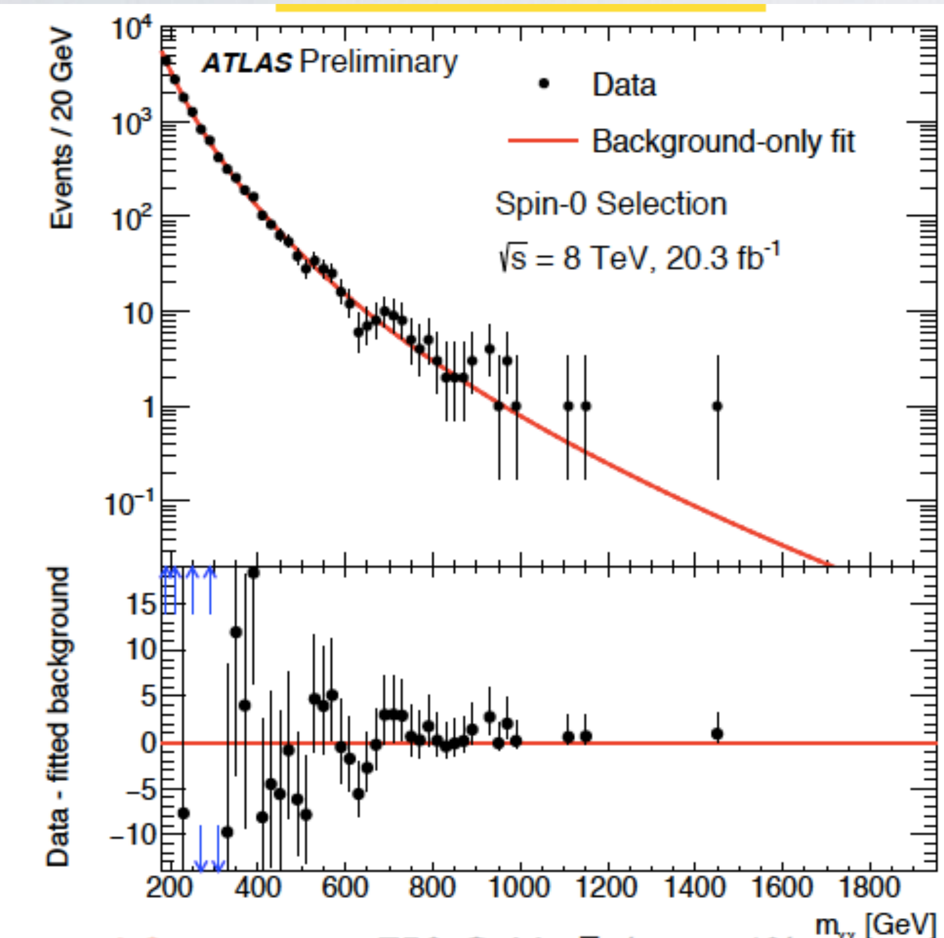




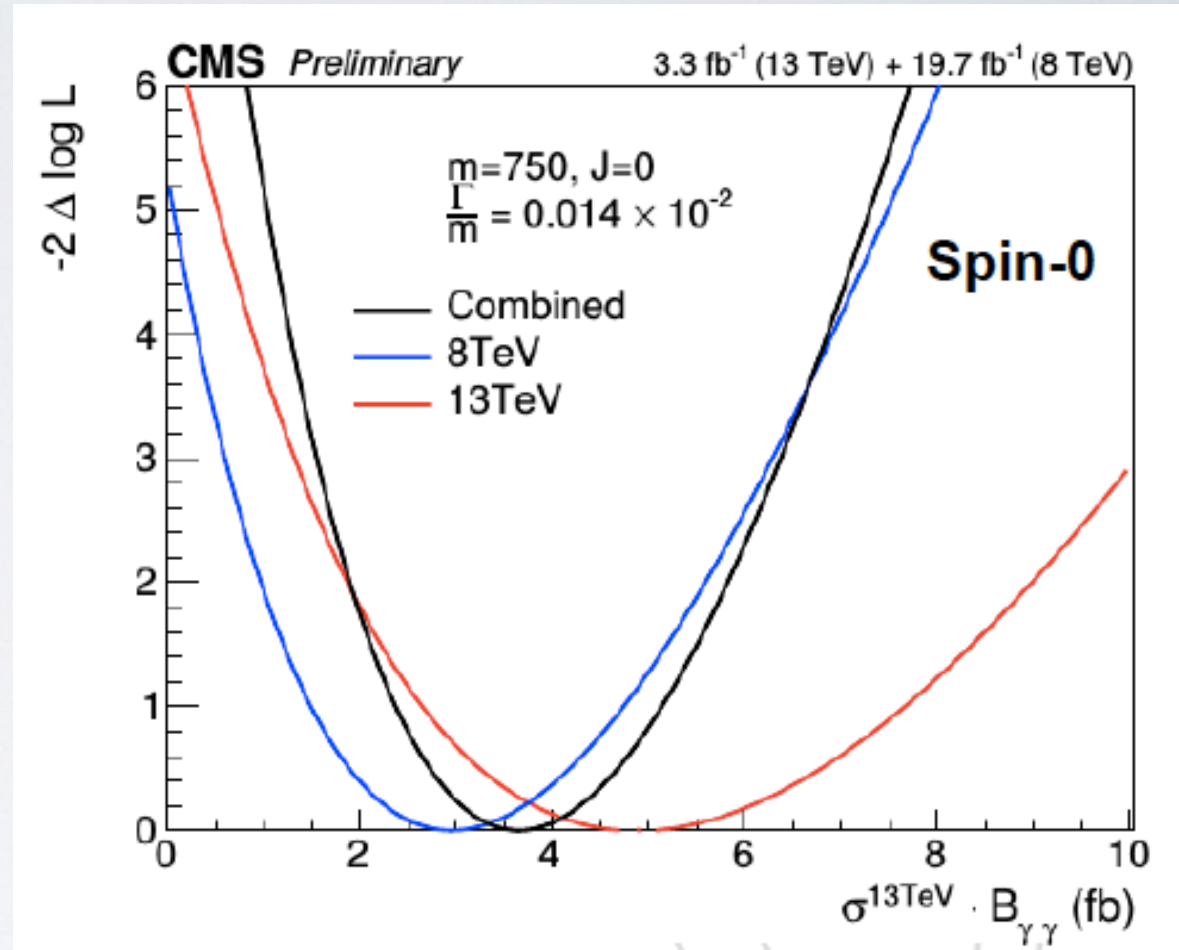
- Largest deviation from B-only hypothesis
  - ✓ $m_X \sim 750$ GeV, $\Gamma_X \sim 45$ GeV (6%)
  - ✓ Local Z = **3.9 σ**
  - ✓ Global Z = **2.0 σ**
    - m_X = [200 GeV - 2 TeV]
    - Γ_X/m_X = [1% - 10%]

(From M. Delmastro and P. Musella, Moriond '16)

LHC Diphoton Excess



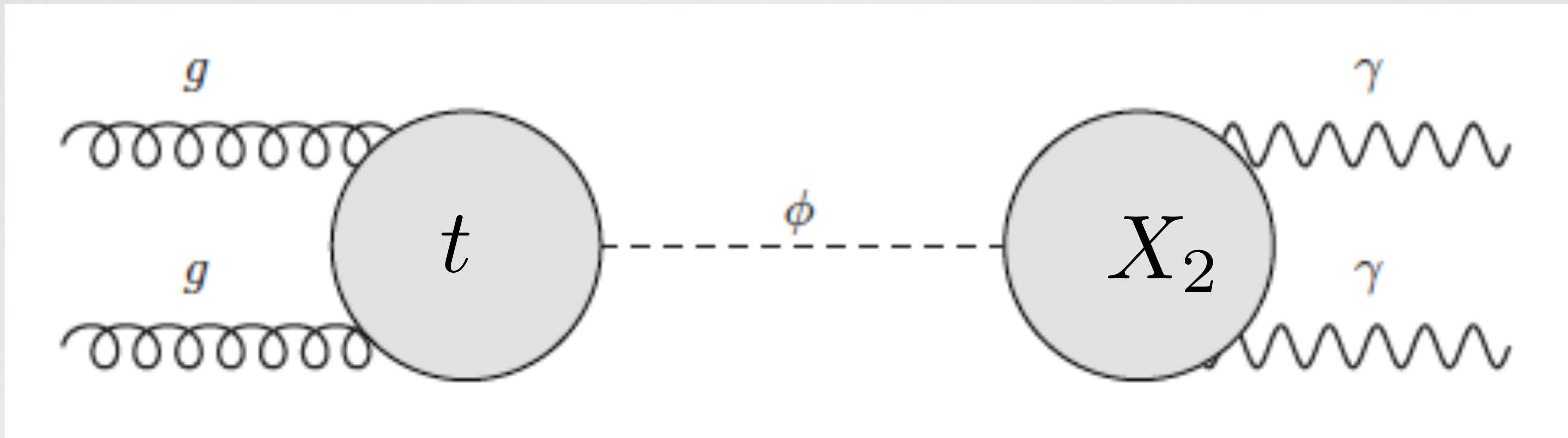
- 1.9 σ at m_X = 750 GeV , Γ_X/m_X = 6%
- Compatibility with 13 TeV scalar
  - ✓ gg (scaling: 4.7) → compatibility: 1.2 σ
  - ✓ qq (scaling: 2.7) → compatibility: 2.1 σ



- Atlas diphoton cross section ~10 fb

(From M. Delmastro and P. Musella, Moriond '16)

Pseudoscalar Diphoton Resonance



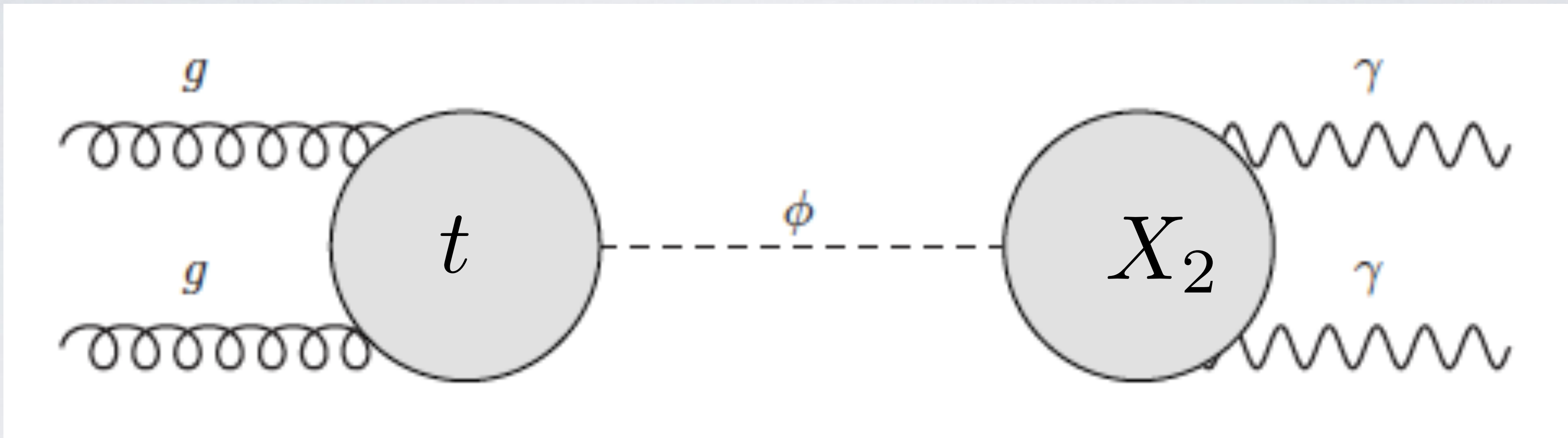
Pseudoscalar diphoton cross-section at 14 TeV from gluon/photon-fusion

$$\sigma_{\gamma\gamma} \simeq \left(\sigma_{gg\to P,0}\, y_{Pt}^2 + \sigma_{\gamma\gamma\to P,0}\frac{\Gamma_{P\to\gamma\gamma}}{\Gamma_{\gamma\gamma,0}}\right) \times \frac{\Gamma_{P\to\gamma\gamma}}{\Gamma_{P\to\gamma\gamma}+\Gamma_{P\to VV}+\Gamma_{P\to tt}}\,,$$

Normalized to top-Yukawa of 1

$$\sigma_{gg\to P,0} = 1.9 \text{ pb}$$

Pseudoscalar Diphoton Resonance



Pseudoscalar diphoton cross-section at 14 TeV from gluon/photon-fusion

$$\sigma_{\gamma\gamma} \simeq (\sigma_{gg\to P,0}\, y_{Pt}^2 + \sigma_{\gamma\gamma\to P,0}\frac{\Gamma_{P\to\gamma\gamma}}{\Gamma_{\gamma\gamma,0}}) \times \frac{\Gamma_{P\to\gamma\gamma}}{\Gamma_{P\to\gamma\gamma} + \Gamma_{P\to VV} + \Gamma_{P\to tt}}\,,$$

$$\sigma_{gg\to P,0} = 1.9 \text{ pb}$$

Need very large diphoton partial width

$$\Gamma_{P,S\to ff} \simeq \frac{N_c(f)}{8\pi} y_{P,Sf}^2\, m_P$$

$$\Gamma_{P\to\gamma\gamma}/m_P \gtrsim 3 - 6\times 10^{-4}$$

Pseudoscalar Diphoton Resonance

Realized in CP conserving 2HDM $\Phi_{1,2}, X_{1,2}$

$$\begin{aligned}\mathcal{V} &= m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - [m_{12}^2\Phi_1^\dagger\Phi_2 + \text{h.c.}] \\ &+\frac{1}{2}\lambda_1(\Phi_1^\dagger\Phi_1)^2 + \frac{1}{2}\lambda_2(\Phi_2^\dagger\Phi_2)^2 + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) \\ &+\left\{\frac{1}{2}\lambda_5(\Phi_1^\dagger\Phi_2)^2 + [\lambda_6(\Phi_1^\dagger\Phi_1) + \lambda_7(\Phi_2^\dagger\Phi_2)]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} .\end{aligned}$$

With new fermions and type-I Yukawa interactions

$$\mathcal{L} \sim -y_X X X \Phi_1 - y_f f f \Phi_2$$

Pseudoscalar Diphoton Resonance

(Frandsen & Shoemaker '16)

Two angles define the scalar sector:

$$t_\beta \equiv \tan\beta \equiv \frac{v_2}{v_1}$$

$$\begin{aligned}
\Phi_1^\pm &= c_\beta G^\pm - s_\beta H^\pm\,,\\
\Phi_2^\pm &= s_\beta G^\pm + c_\beta H^\pm\,,\\
\Phi_1^0 &= \tfrac{1}{\sqrt{2}}\left[v_1 + c_\alpha H - s_\alpha h + i c_\beta G - i s_\beta A\right]\\
\Phi_2^0 &= \tfrac{1}{\sqrt{2}}\left[v_2 + s_\alpha H + c_\alpha h + i s_\beta G + i c_\beta A\right]
\end{aligned}$$

2 new (pseudo-) scalar resonances: $\Phi_{1,2} \to h, H, A$

Decoupling limit controlled by: $\delta \equiv \beta - \alpha - \pi/2$

Couplings of new scalars:

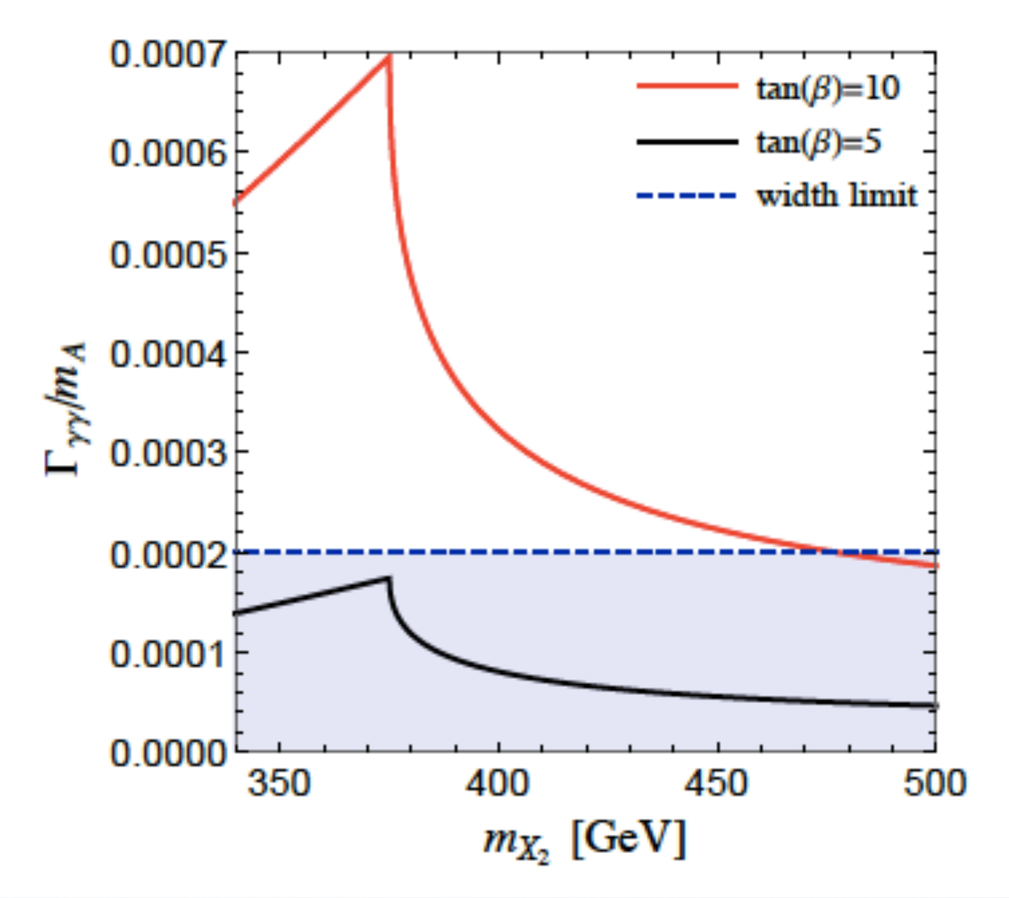
$$\begin{aligned}
c_{AX_2} &= -i\tan\beta\\
c_{HX_2} &= c_\alpha/c_\beta \simeq \tan\beta - \delta\\
c_{hX_2} &= -s_\alpha/c_\beta \simeq 1 + \delta\,\tan\beta
\end{aligned}$$

$$\begin{aligned}
c_{Hf} &= s_\alpha/s_\beta \simeq -\delta - \cot\beta\\
c_{HV} &= c_{\beta-\alpha} \simeq -\delta\\
c_{Af} &= i c_\beta/s_\beta = i\cot_\beta\ .
\end{aligned}$$

ADM and Diphotons

Diphoton width large near threshold
For large tanβ

$$\Gamma_{A\gamma\gamma} \simeq \frac{\alpha^2 G_F}{32\sqrt{2}\pi^3} \tan\beta^2 m_A^3 \left|A^A_{X_2}(\tau_{X_2})\right|^2$$



(Frandsen & Shoemaker '16)

Can get sufficient cross-section
from top-induced gluon fusion

$$\sigma_{\gamma\gamma} \simeq \left((5-8)\frac{\tan\beta^2}{10^2} + (1-2)\frac{\tan\beta^6}{10^6}\right) \times \frac{1}{1+5\times 10^{-5}\tan\beta^4}\,\text{fb}\,.$$

Model has composite interpretation:

(Frandsen, Sarkar & Schmidt-Hoberg '10)

Summary

- Dark and bright matter densities of the same order
- May be adressed in models of Asymmetric Dark Matter
- Possible to address the current LHC diphoton excess.