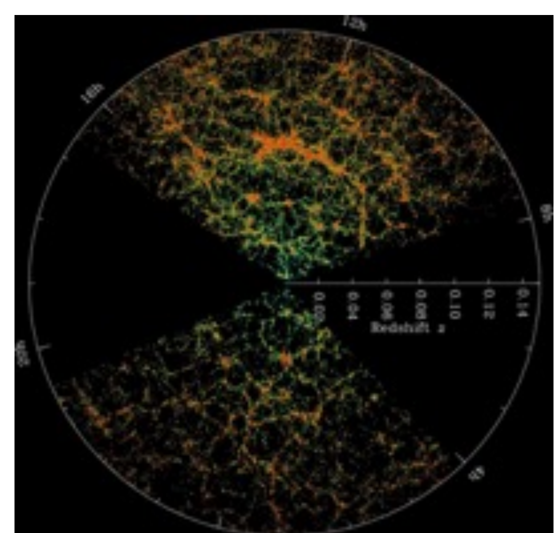
Collider & Cosmological Signatures of Hidden Naturalness QCD

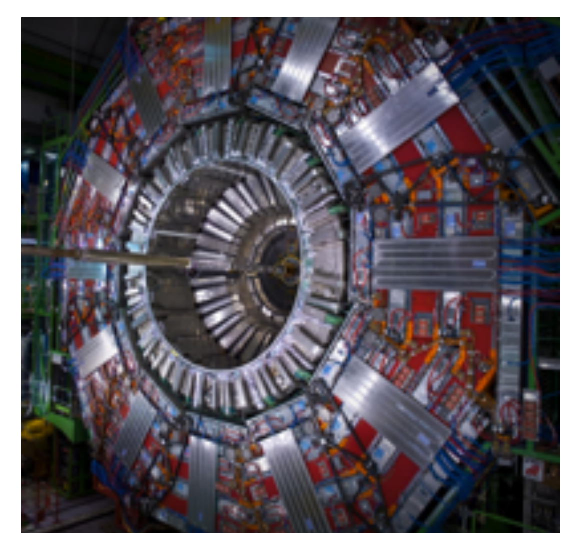
Yuhsin Tsai

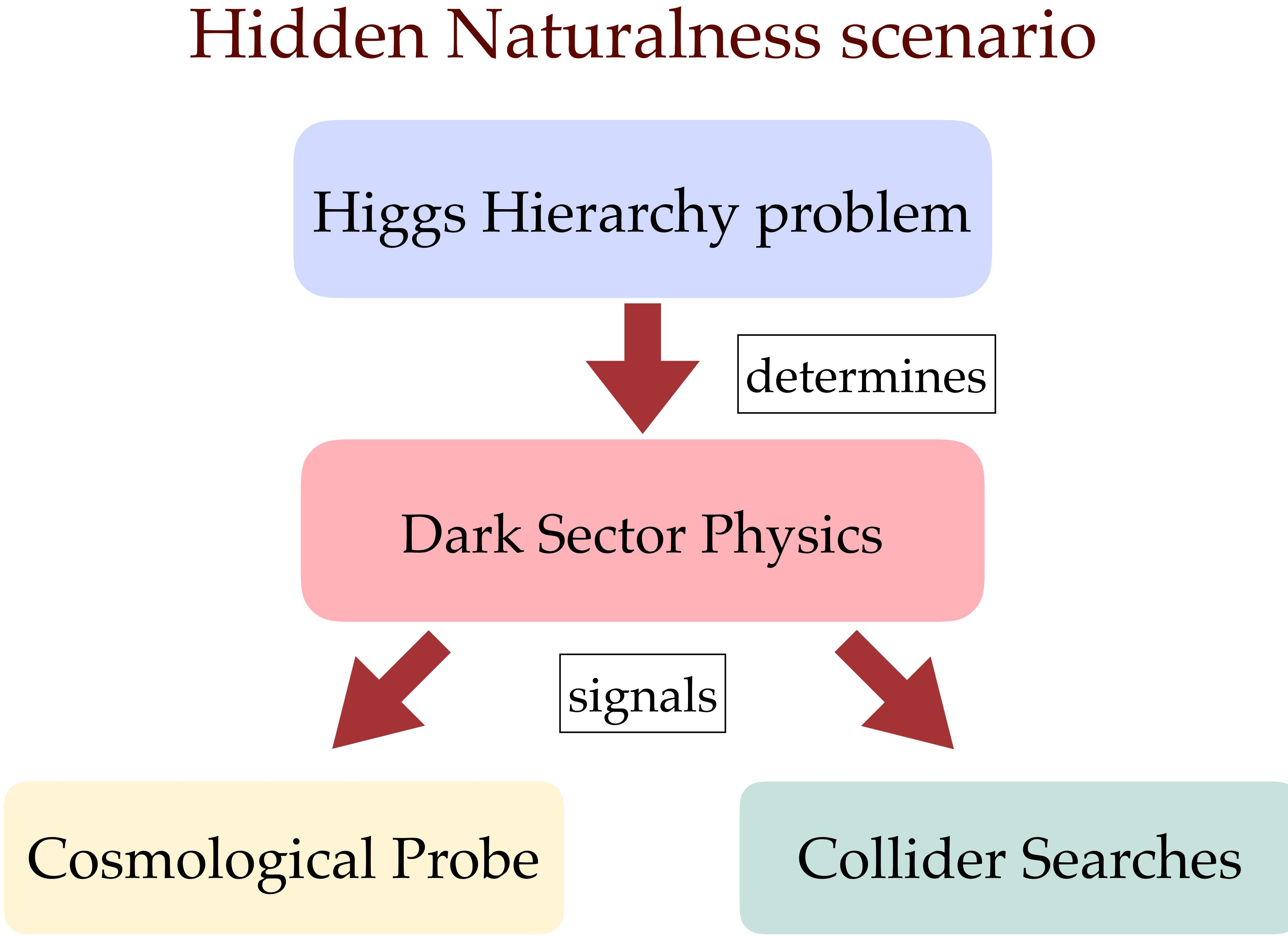
University of Maryland

Lattice for BSM, April 5, 2018

h



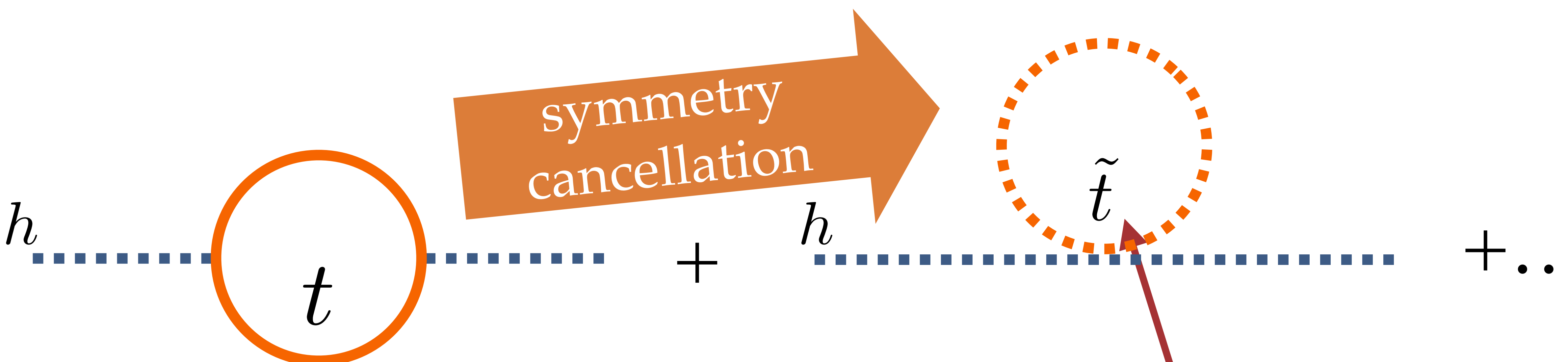




Hidden Naturalness scenario
Higgs Hierarchy problem
determines
Dark Sector Physics
signals
Cosmological Probe
Collider Searches

One solution to the hierarchy problem:
Supersymmetry

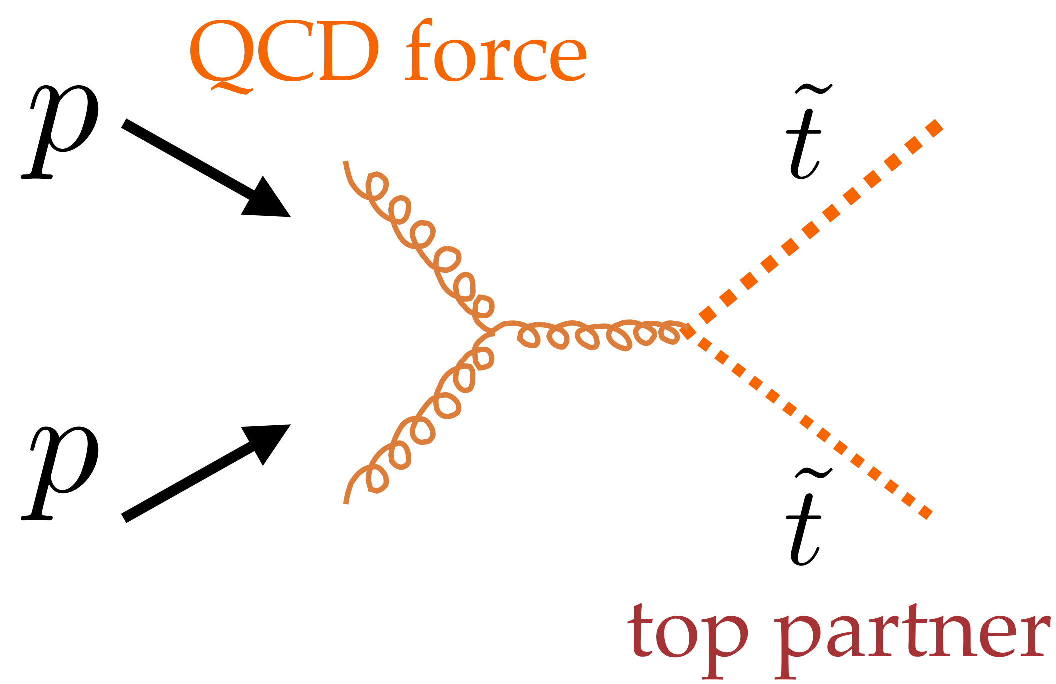
Super particle loops cancel the divergence



top quark
carry SM QCD charge

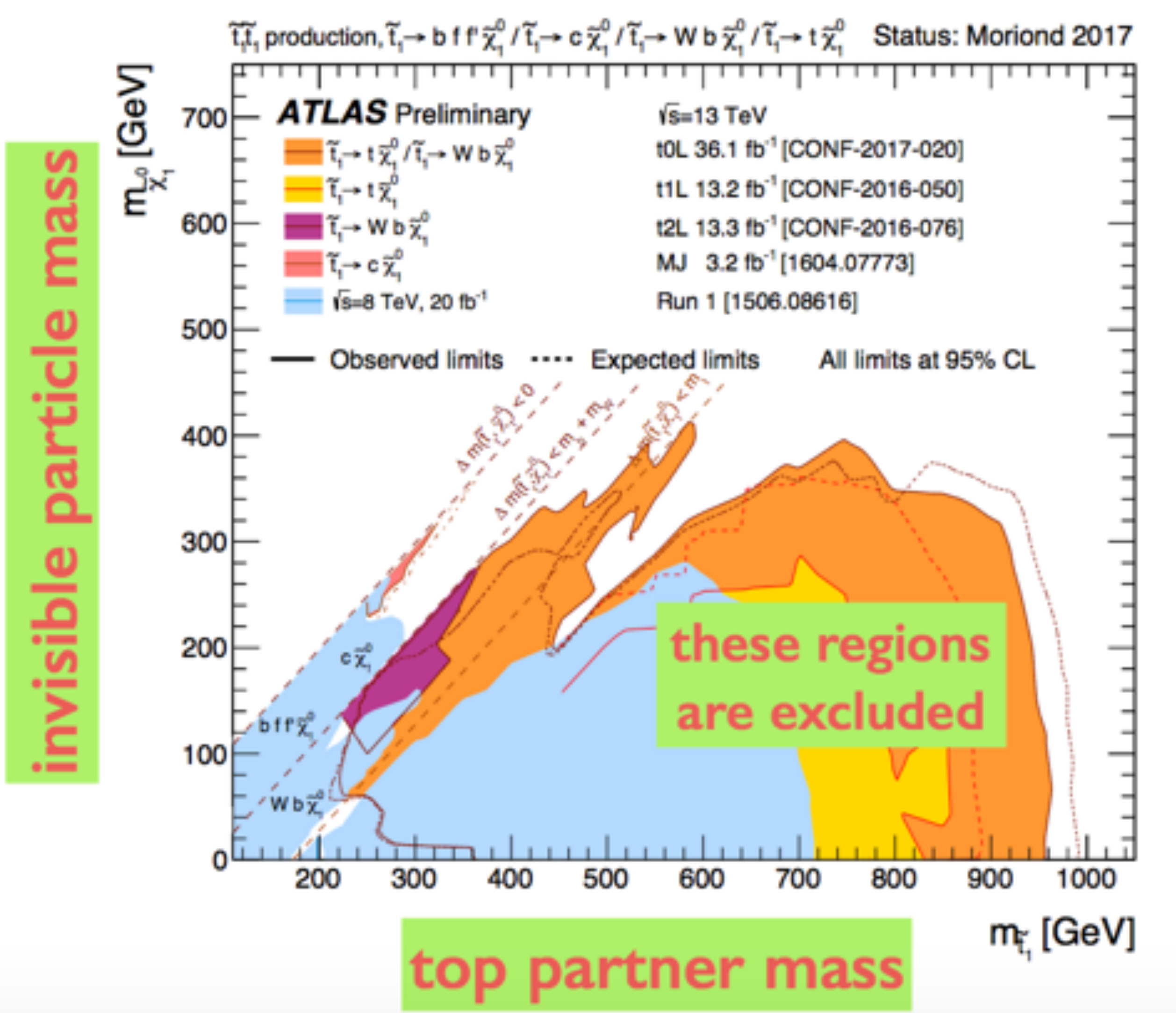
Top Partner
carry SM QCD charge

symmetry



collider signal

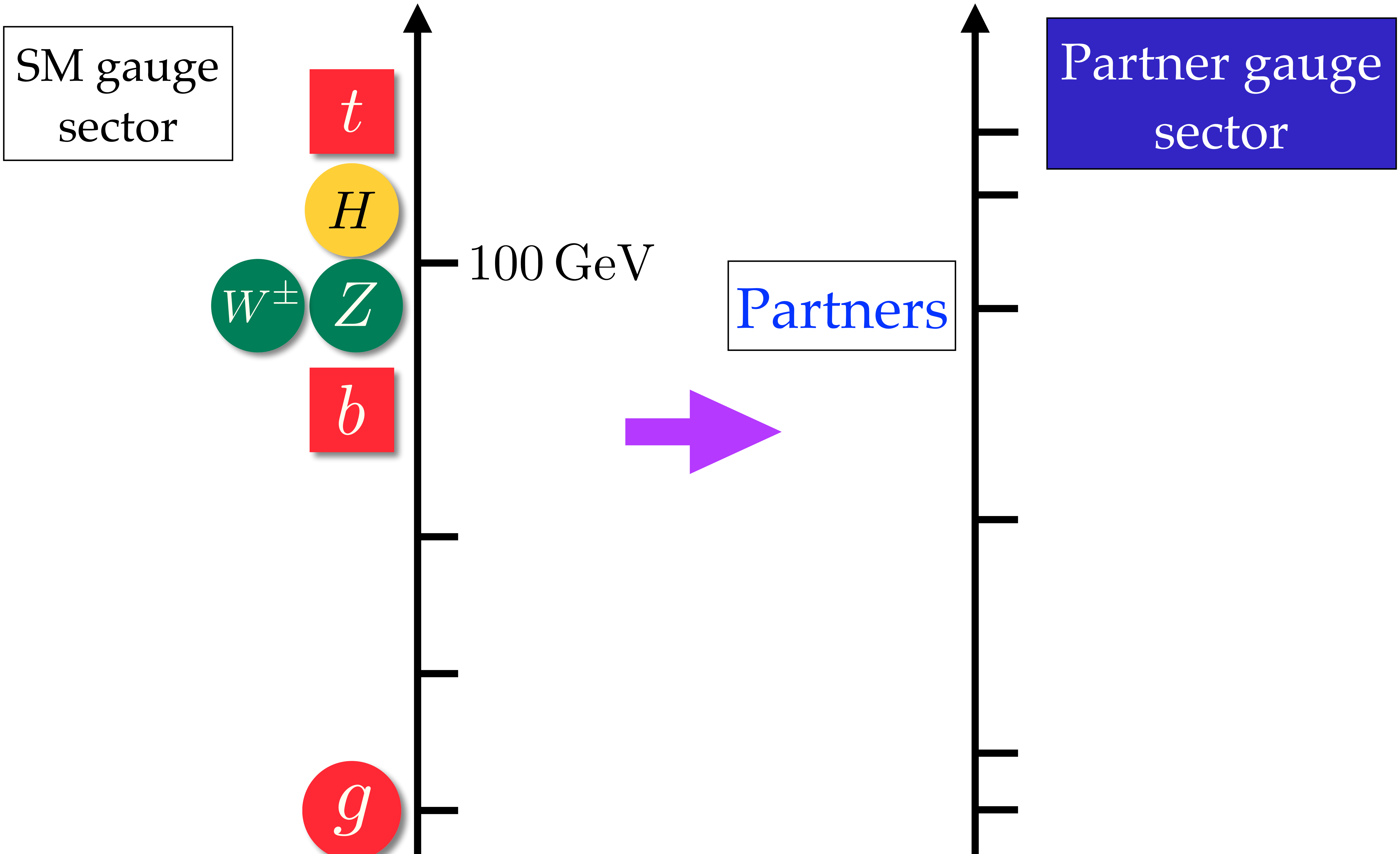
No SUSY so far…



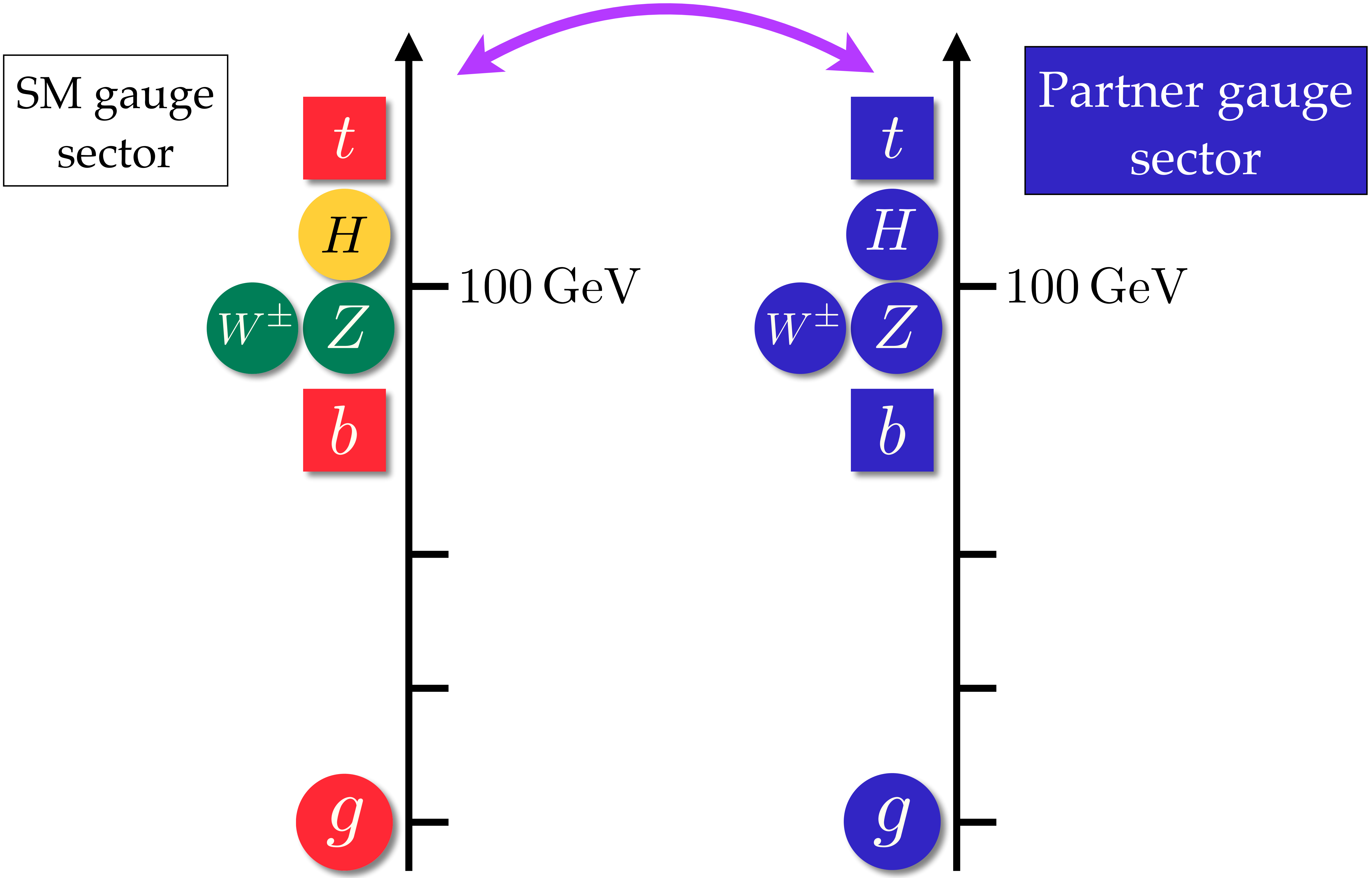
$$m_{\tilde{t}} \gg m_t$$

The hope for symmetry cancellation is fading…

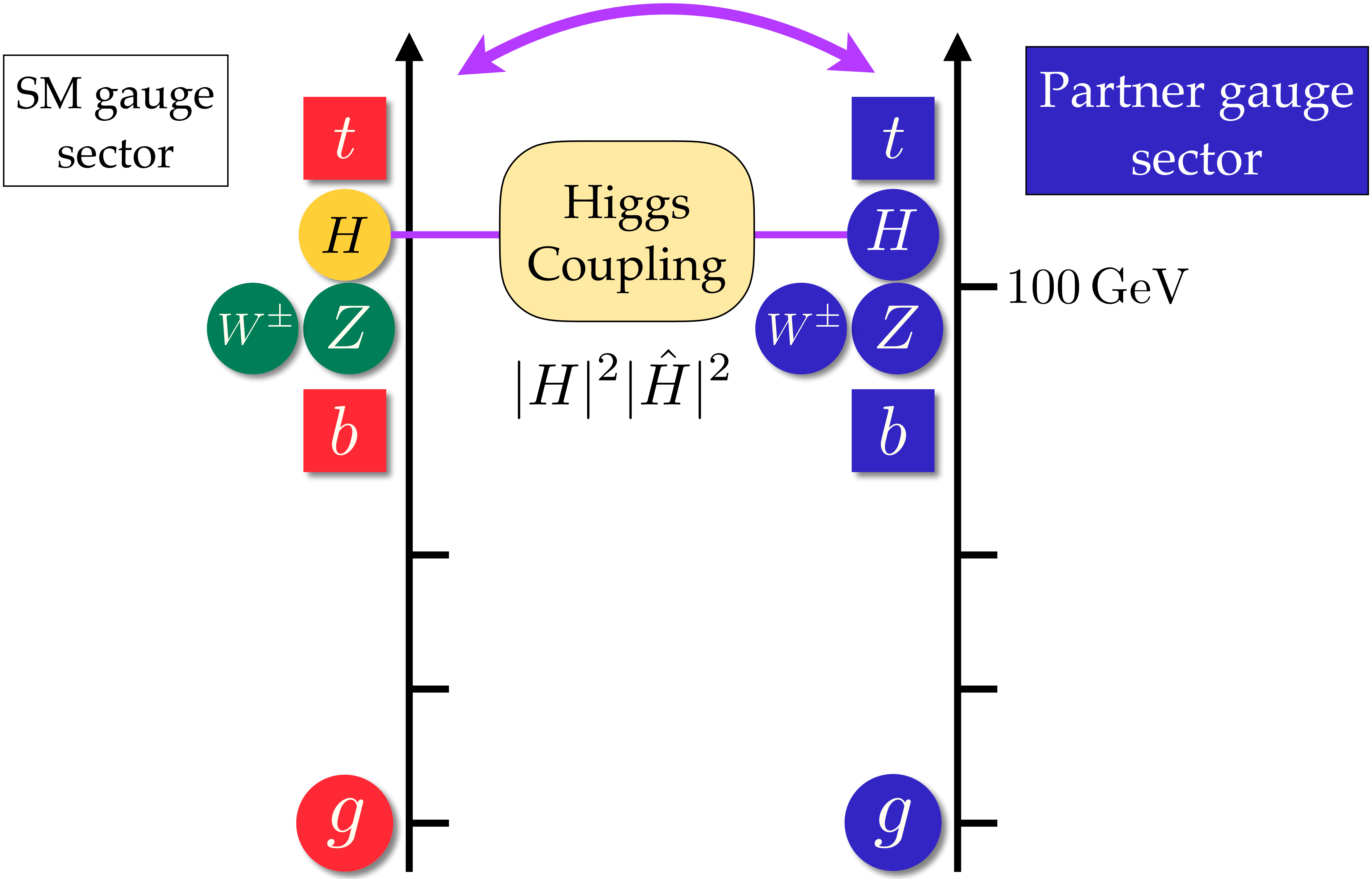
Partner fields in a different gauge sector



Related by a **Mirror Symmetry** Z_2

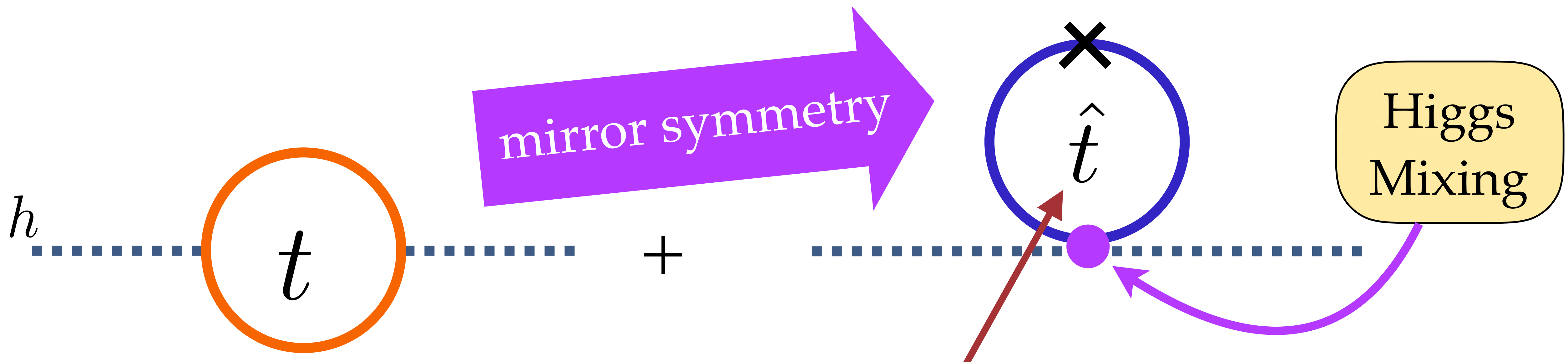


Related by a **Mirror Symmetry** Z_2



A concrete example: Twin Higgs

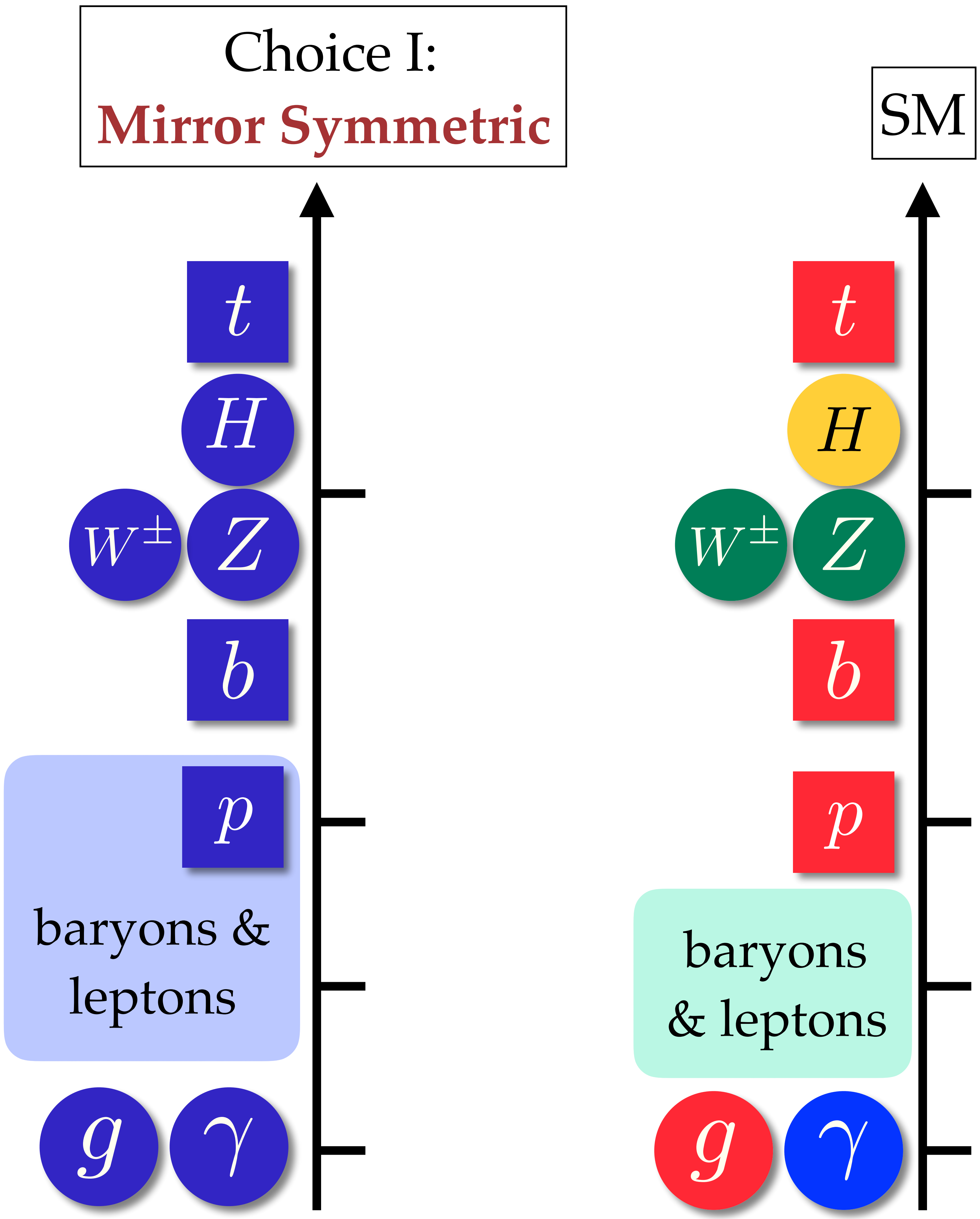
Chacko, Goh, Harnik (2005)



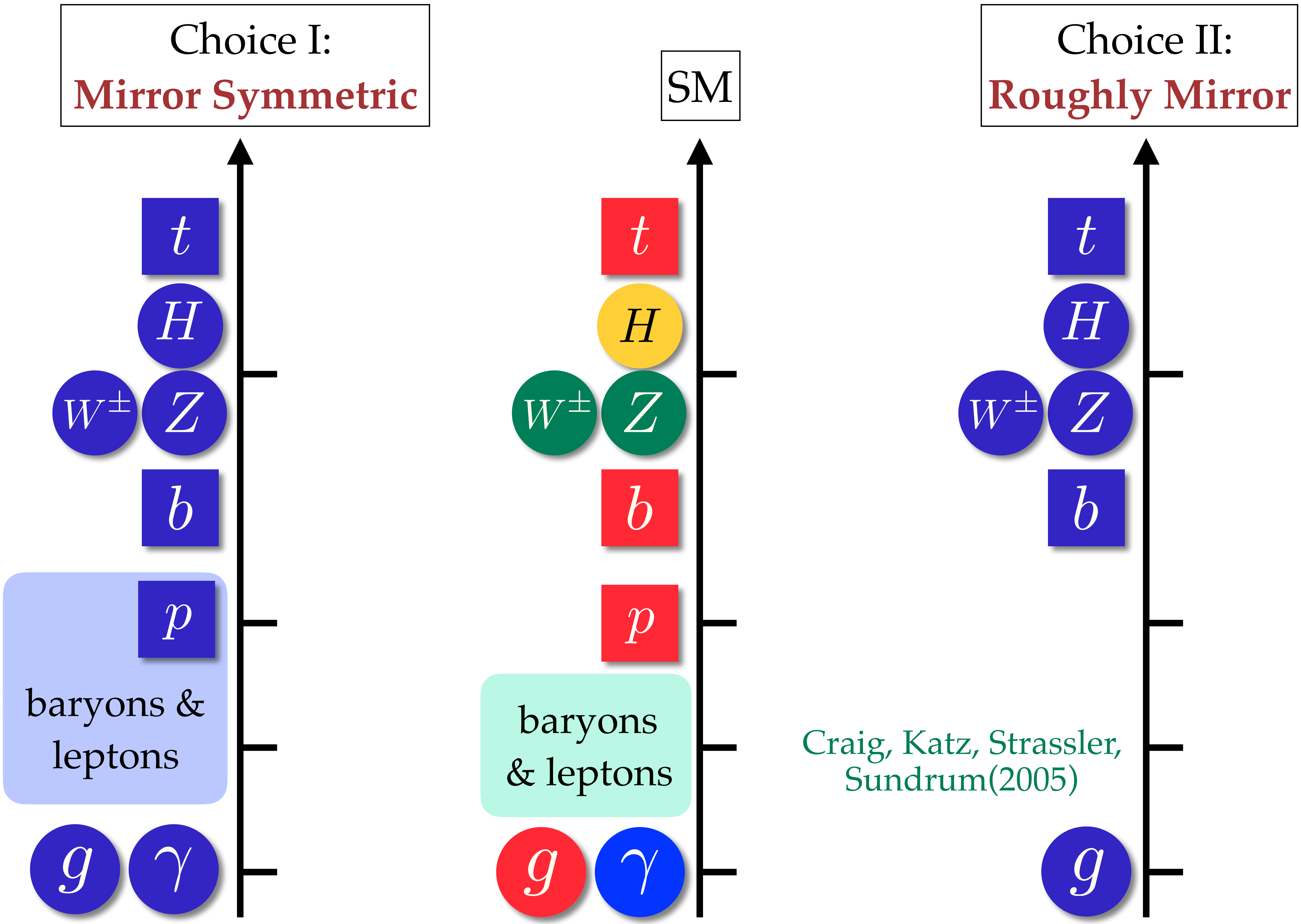
Top
carries SM gauge charges

Mirror top
carries **mirror gauge** charges

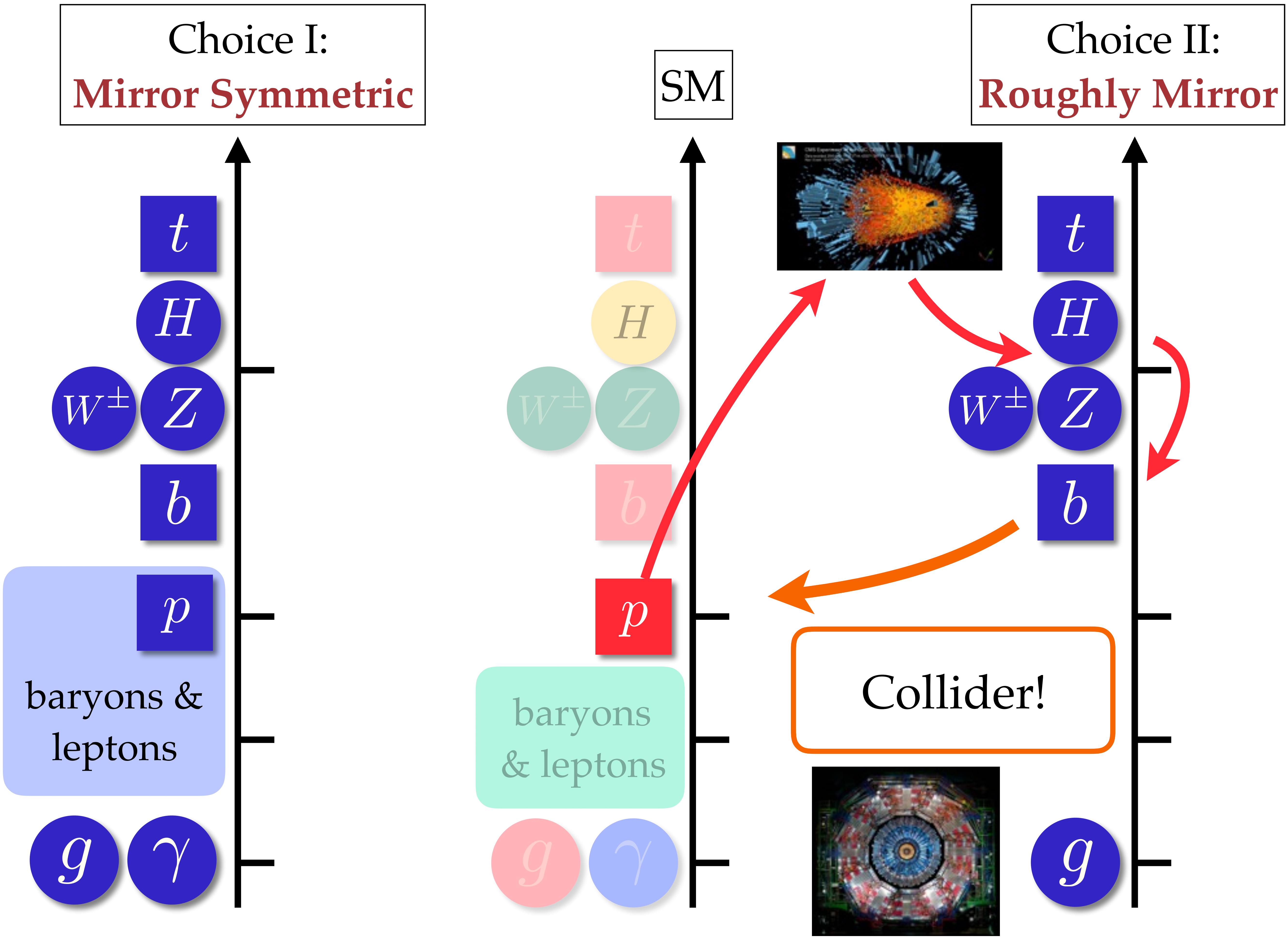
Mirror copy of the relevant particles



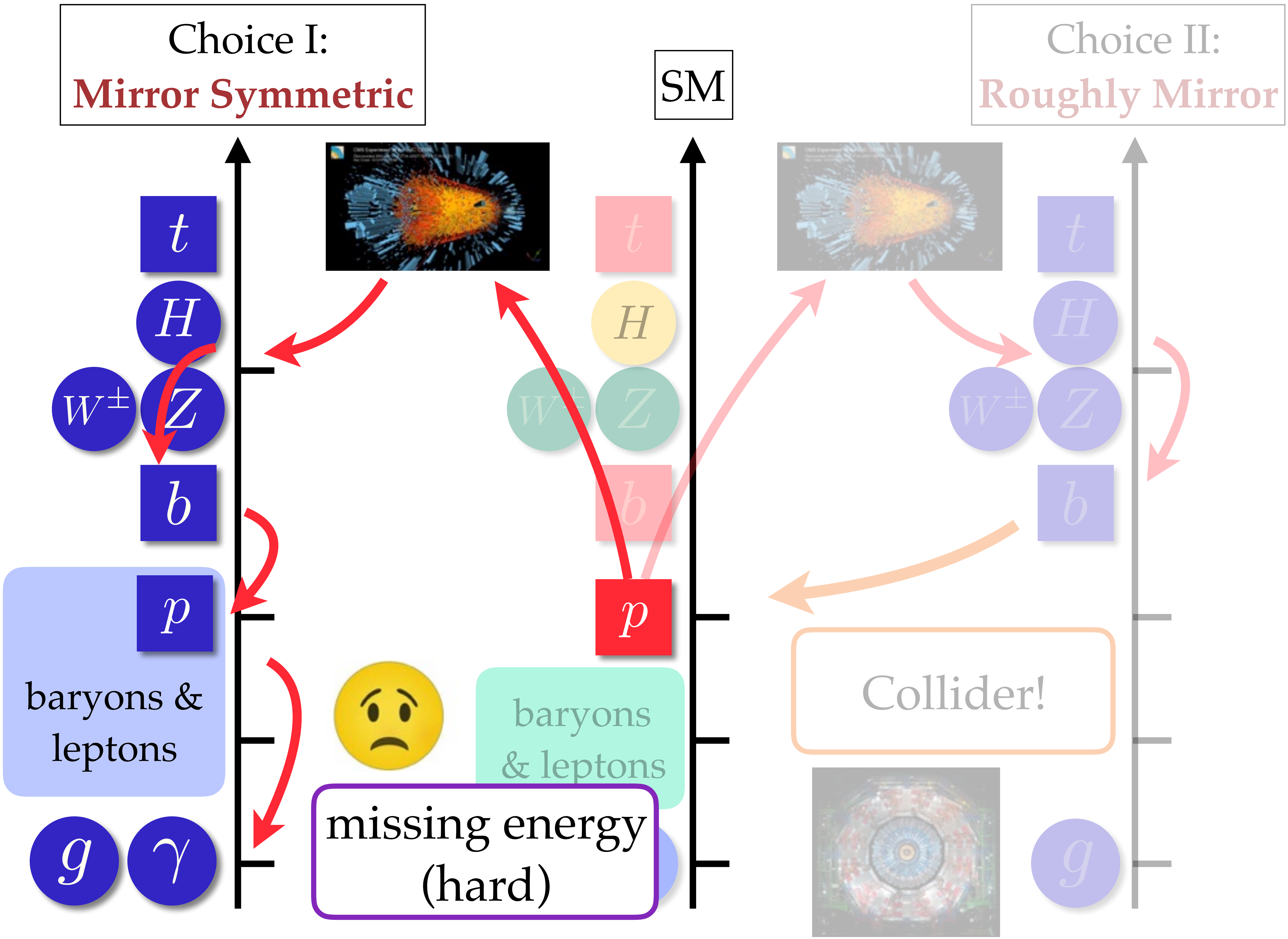
Choice I:
Mirror Symmetric
SM
t
H
$W^{\pm}$
Z
b
p
baryons & leptons
g
γ
t
H
$W^{\pm}$
Z
b
p
baryons & leptons
g
γ



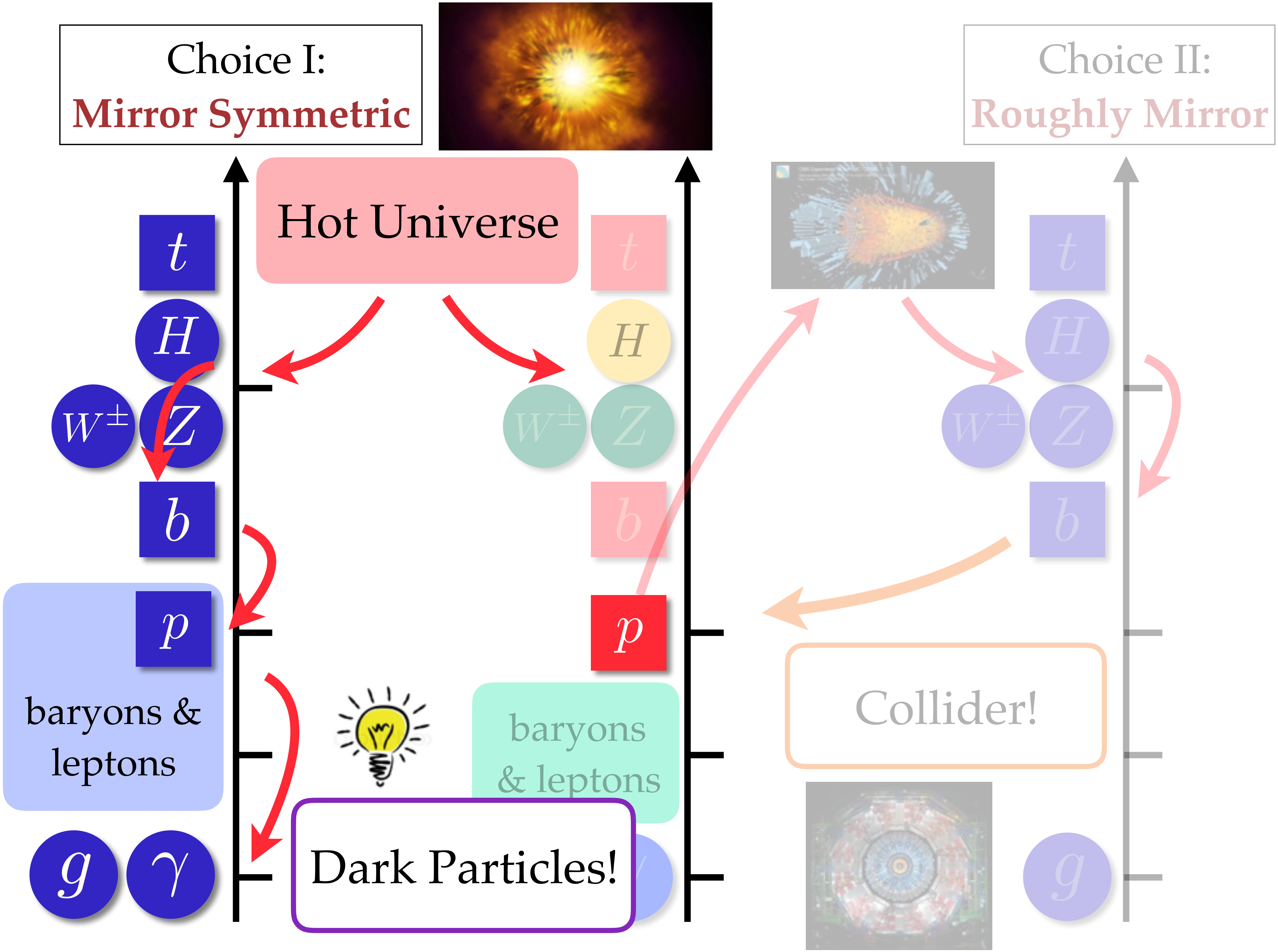
Choice I:
Mirror Symmetric
SM
Choice II:
Roughly Mirror
t
H
W±
Z
b
p
baryons & leptons
g
γ
t
H
W±
Z
b
p
baryons & leptons
g
γ
t
H
W±
Z
b
Craig, Katz, Strassler, Sundrum(2005)
g



Choice I:
Mirror Symmetric
SM
Choice II:
Roughly Mirror
t
H
$W^{\pm}$
Z
b
p
baryons & leptons
g
γ
t
H
$W^{\pm}$
Z
b
p
baryons & leptons
g
γ
t
H
$W^{\pm}$
Z
b
Collider!
g

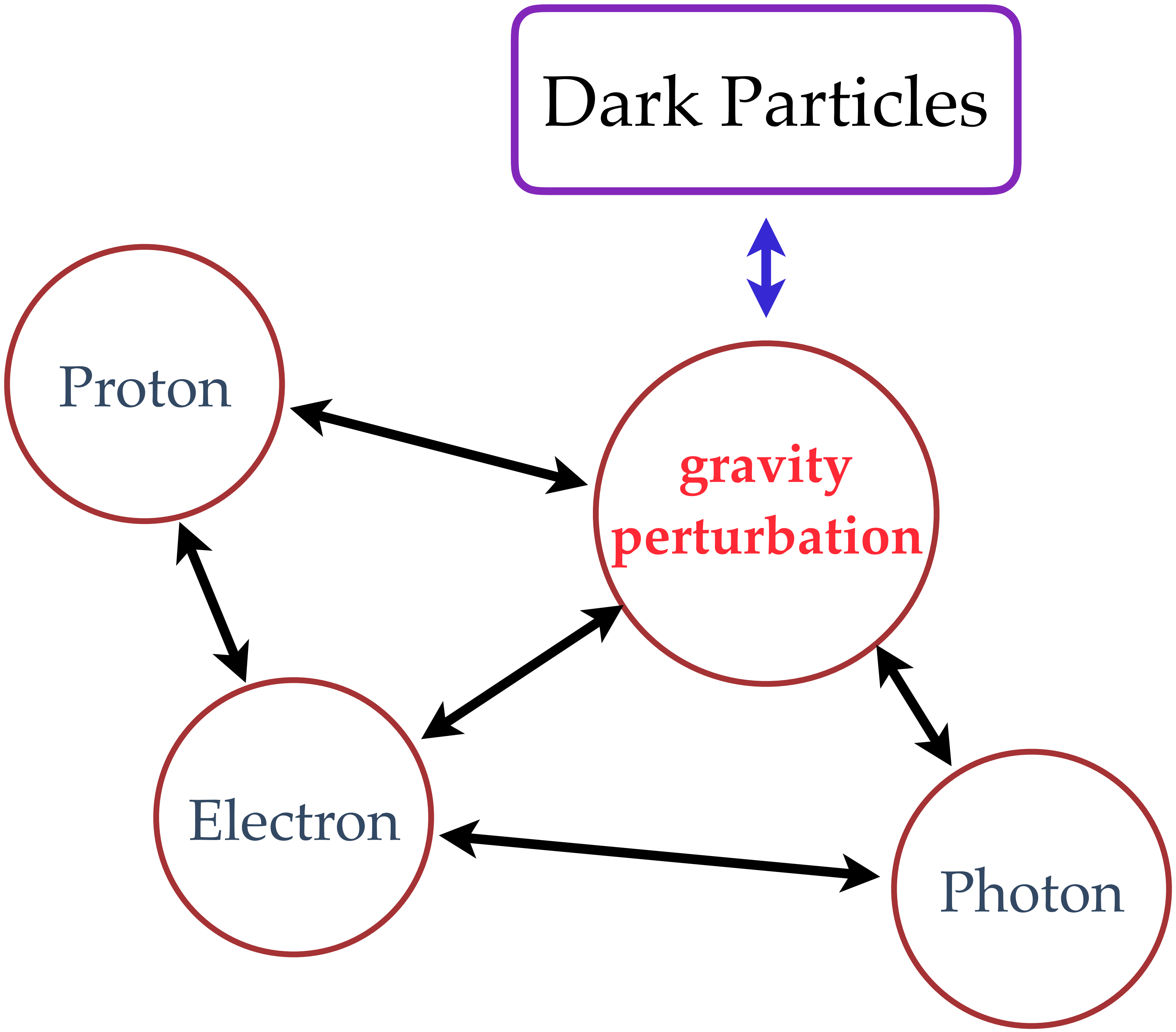


Choice I:
Mirror Symmetric
SM
Choice II:
Roughly Mirror
t
H
W±
Z
b
p
baryons & leptons
g
γ
baryons & leptons
missing energy (hard)
Collider!

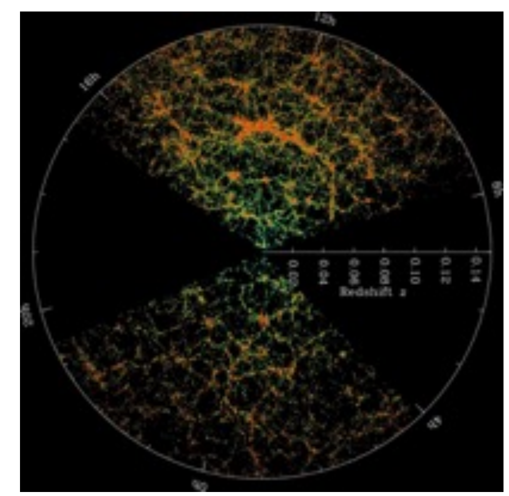


Choice I:
Mirror Symmetric
Choice II:
Roughly Mirror
Hot Universe
t
H
W±
Z
b
p
baryons & leptons
g
γ
t
H
W±
Z
b
p
baryons & leptons
Dark Particles!
t
H
W±
Z
b
Collider!
g

Study Dark Particles through gravity perturbation

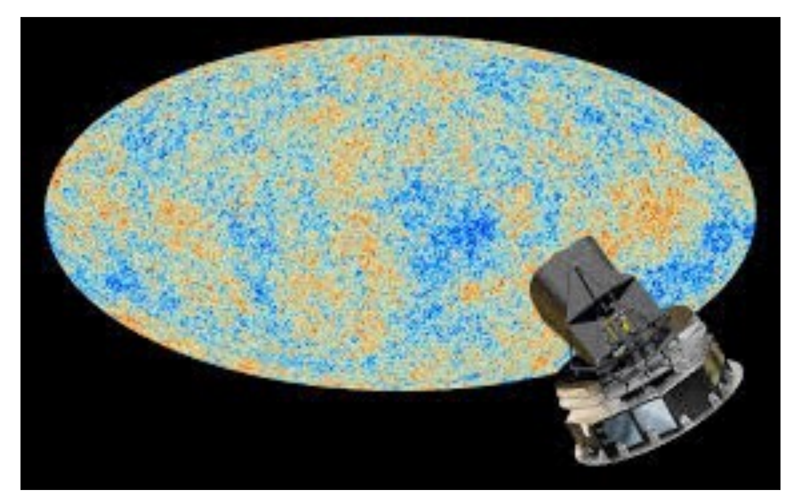


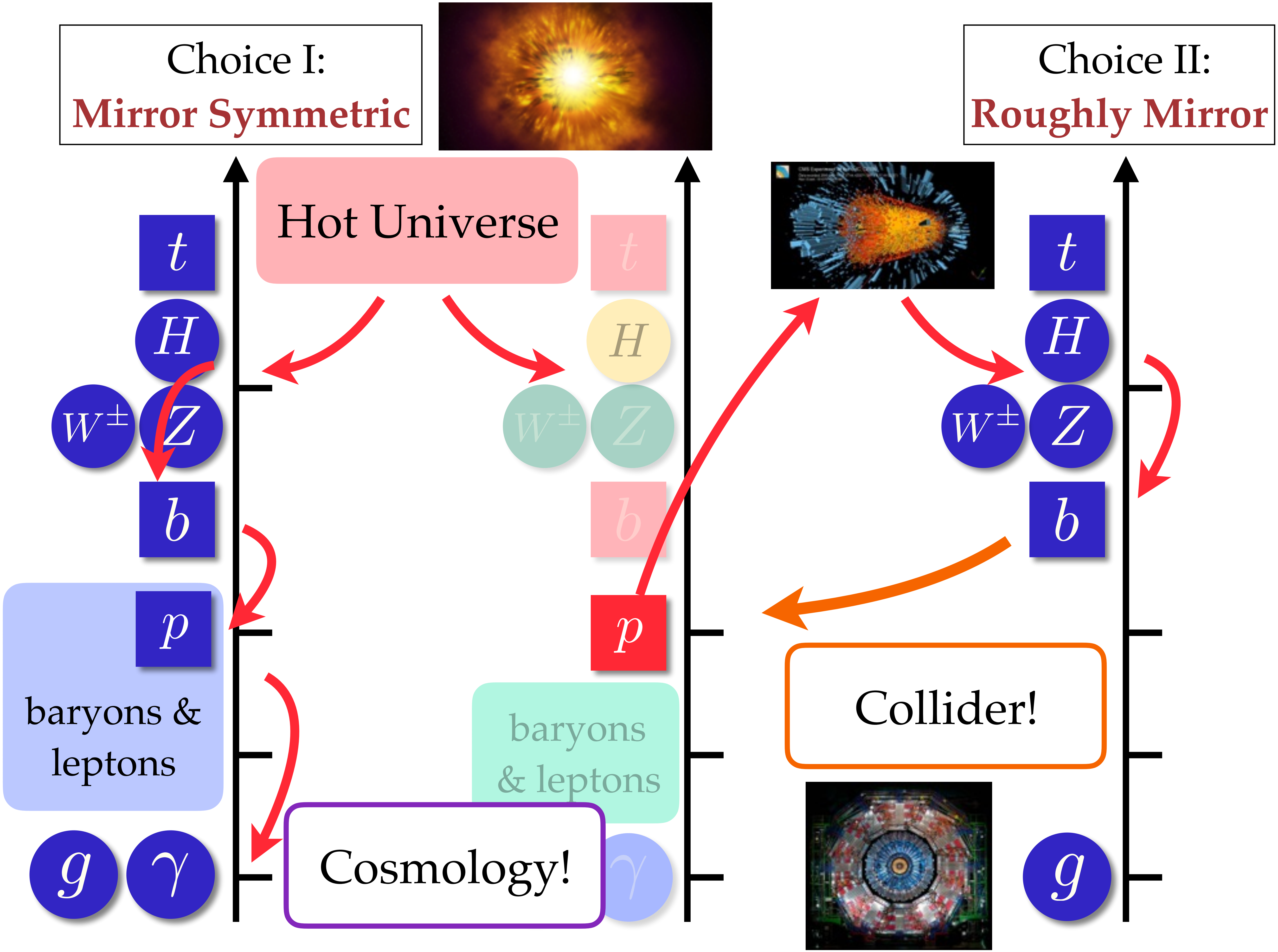
galaxy structure



Large scale structure

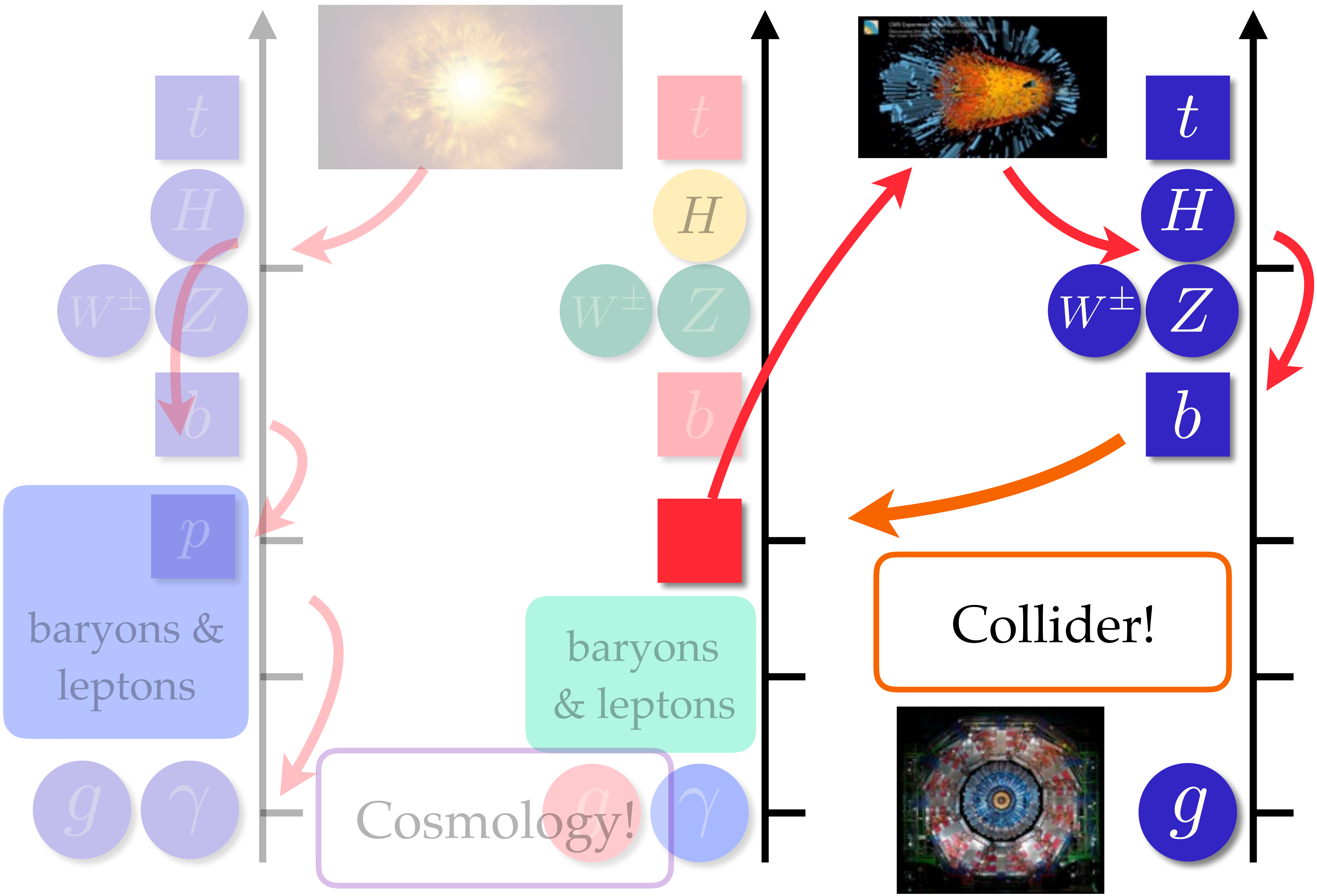
CMB



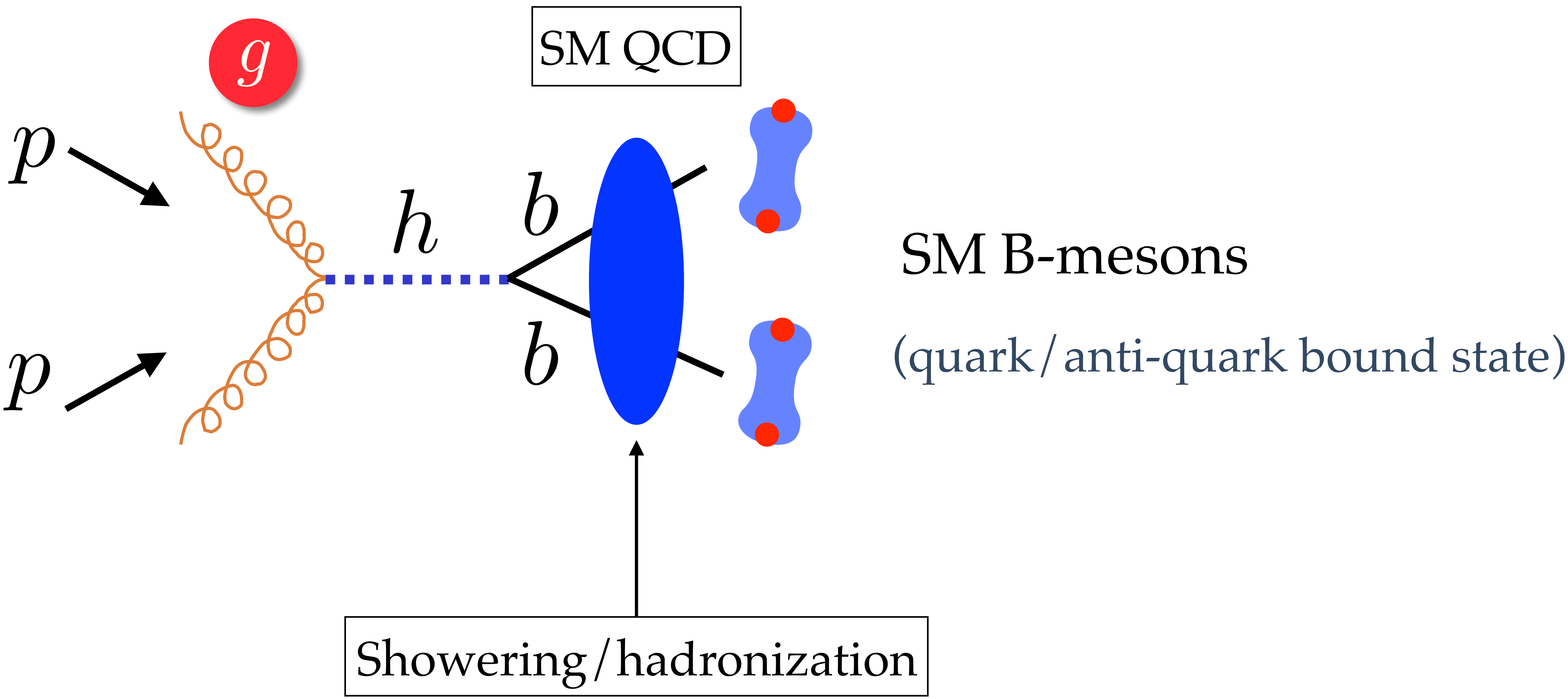


Choice I:
Mirror Symmetric
Choice II:
Roughly Mirror
Hot Universe
t
H
$W^\pm$
Z
b
p
baryons & leptons
g
γ
t
H
$W^\pm$
Z
b
p
baryons & leptons
γ
Cosmology!
Collider!
t
H
$W^\pm$
Z
b
g

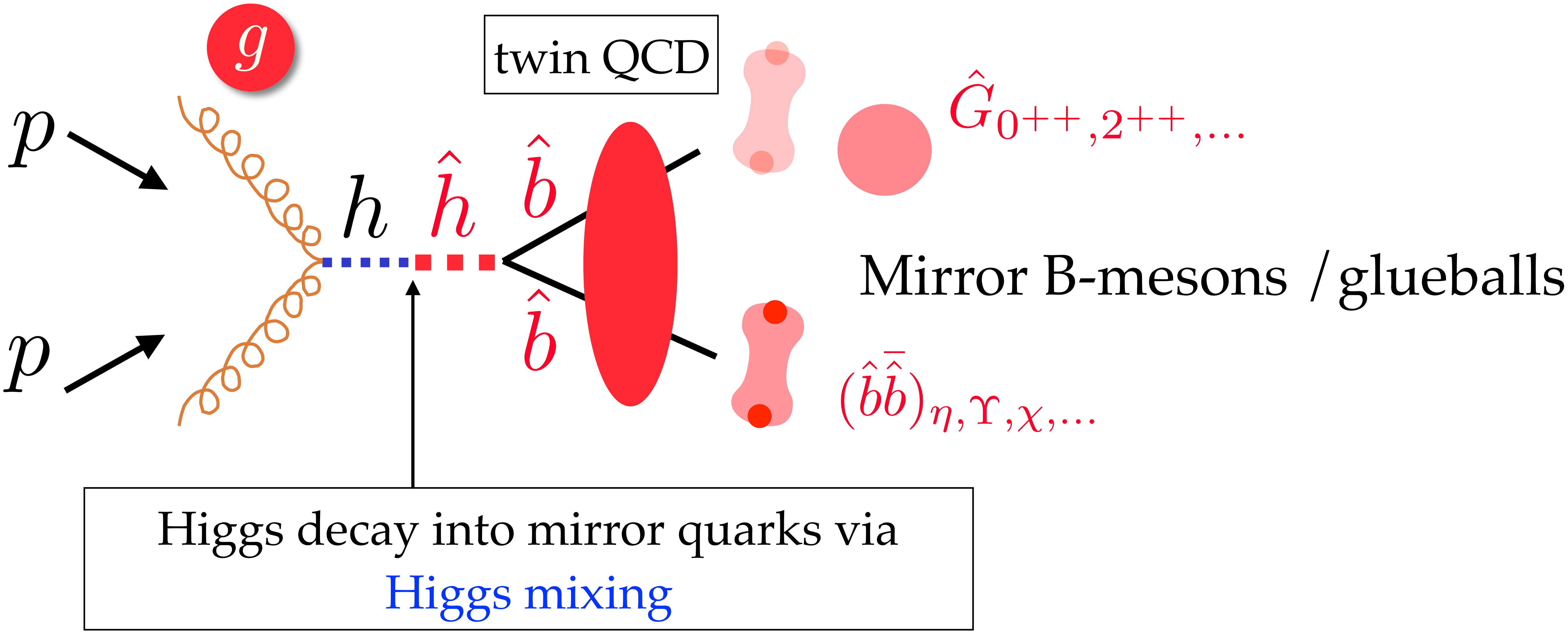
Collider Signature from Hidden Naturalness



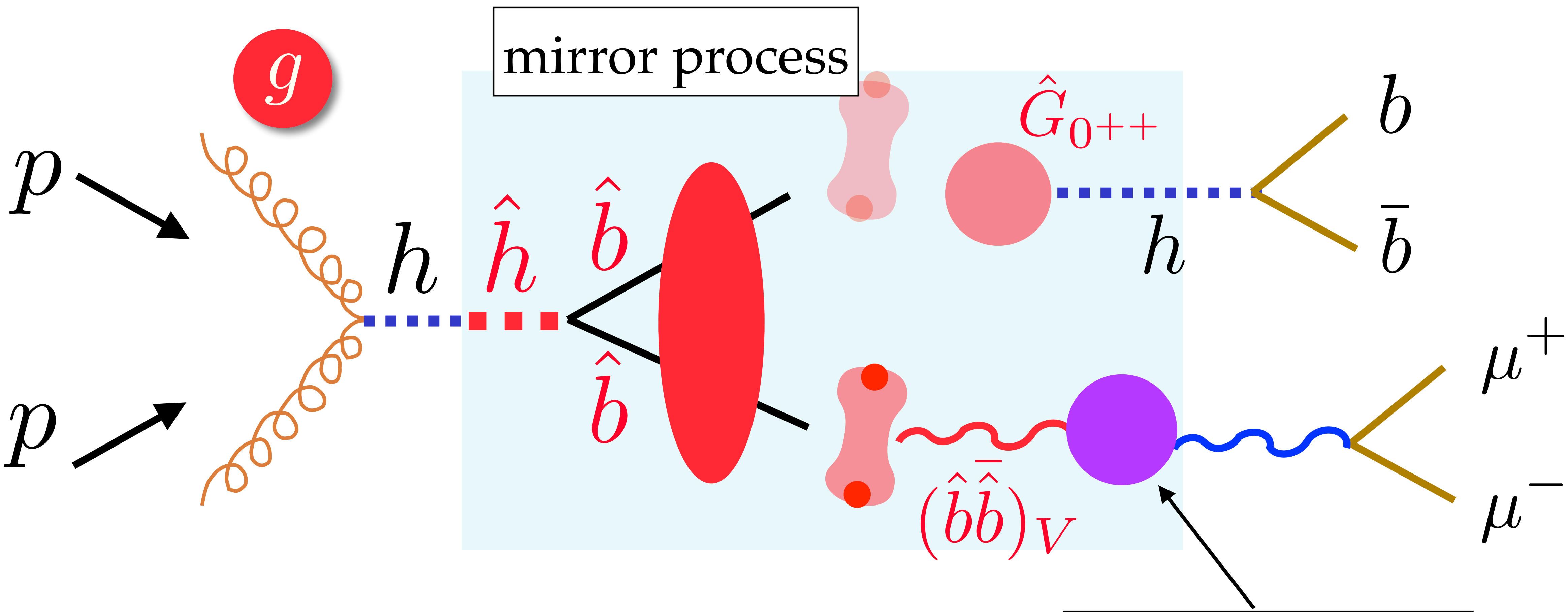
Production & decay of SM Higgs @ LHC



Higgs decay into mirror particles



Higgs decay into mirror particles



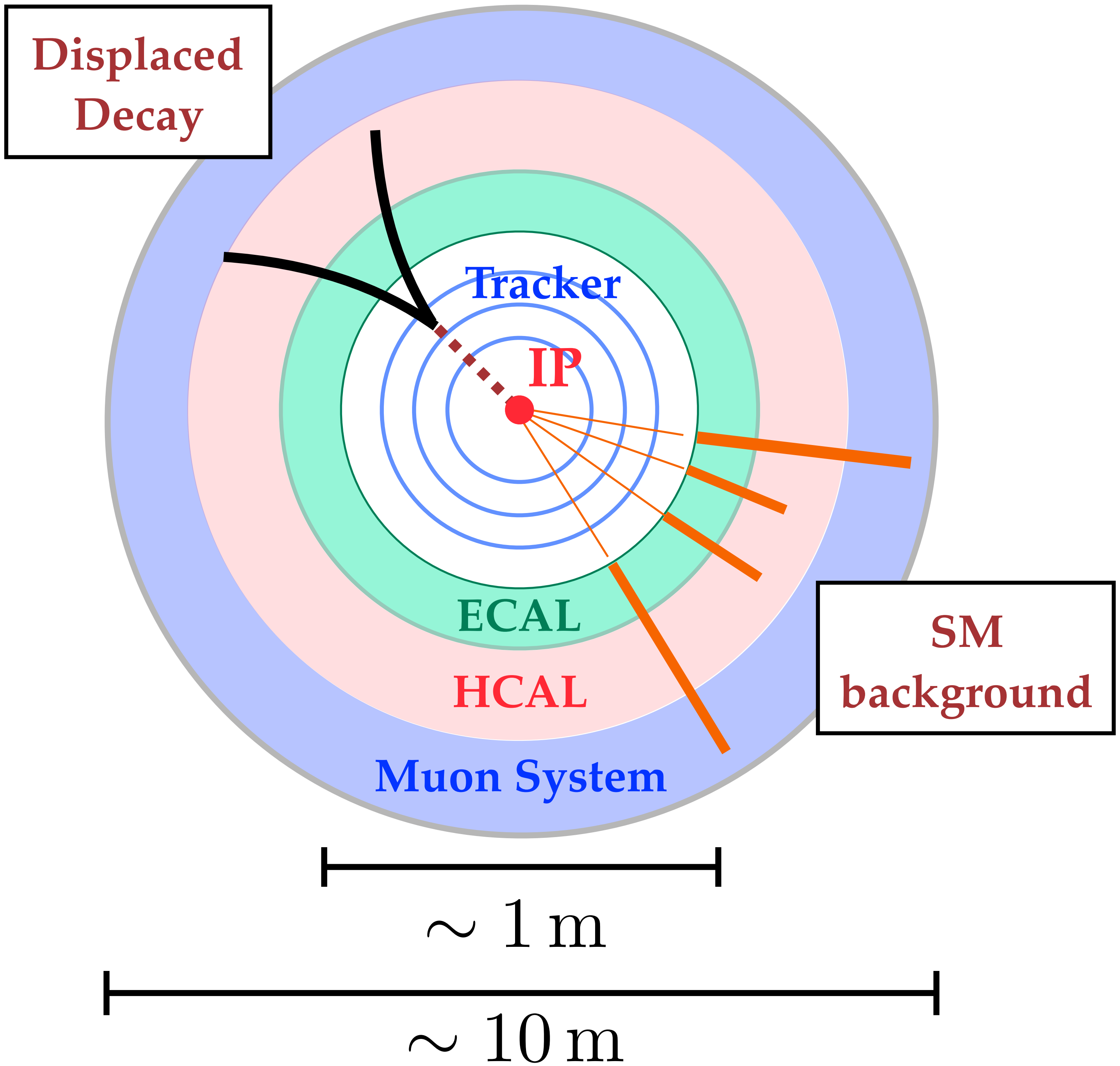
Craig, Katz, Strassler, Sundrum (2015)
Curtin, Verhaaren (2015)
Chacko, Curtin, Verhaaren (2015)

Cheng, Jung, Salvioni, YT (2015)

Pierce, Shakya, YT, Zhao (2017)

Twin hadrons **SLOWLY** decay into SM particles

If the coupling is so small => Long-lived particles



``Naturalness" predicts twin particle masses

- Twin sector has the same gauge/top yukawa couplings

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- satisfy Higgs coupling constraint while remaining natural (better than 10% tuning) $3 \leq v_{\rm twin}/v_{\rm SM} \leq 5$

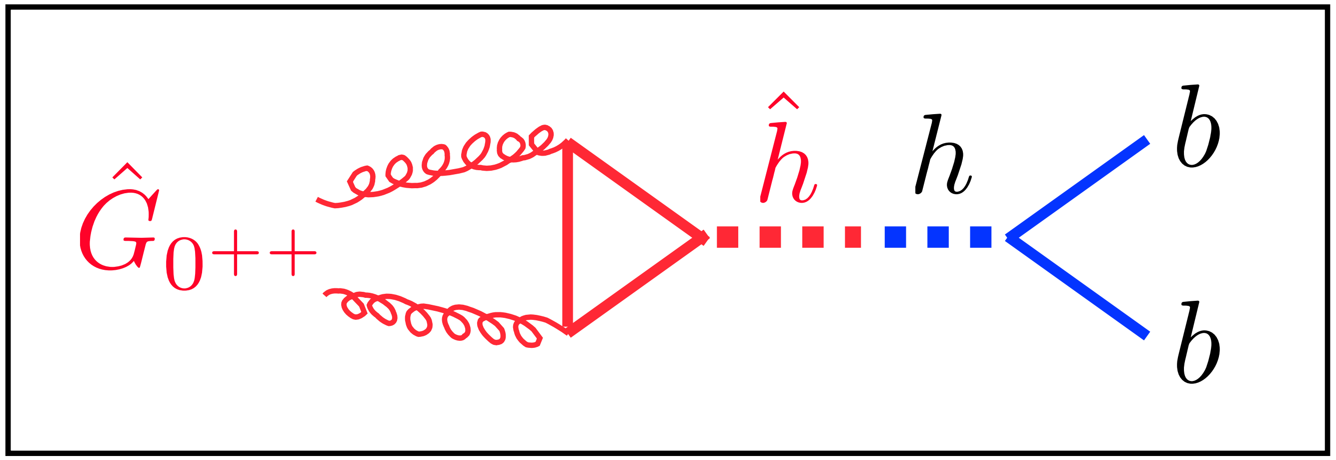
``Naturalness" predicts twin particle masses

- Twin sector has the same gauge/top yukawa couplings
- satisfy Higgs coupling constraint while remaining natural (better than 10% tuning) $3 \leq v_{\rm twin}/v_{\rm SM} \leq 5$
- can estimate the confinement scale from RG running (~ 5 GeV minimal TH)

$$m_{\hat{G}_{0++}} \approx 6.8\,\hat{\Lambda}_3 \qquad m_{(\hat{b}\bar{\hat{b}})} \approx 2m_{\hat{b}} + \mathcal{O}(1)\,\hat{\Lambda}_3$$

Morningstar, Peardon (1999)
Chen, Alexandru, Dong, Draper, Horvath (2006)

However, need more precise number for twin hadron decay



$$\left(\frac{\hat{\alpha}_{\rm QCD}}{6\pi}\frac{v_{\rm SM}}{v_{\rm twin}^2}\right) h\, \hat{G}^a_{\mu\nu}\hat{G}^{\mu\nu}_a$$

$$\sim \left(\frac{\hat{\alpha}_{\rm QCD}}{6\pi}\frac{v_{\rm SM}}{v_{\rm twin}^2}\right) h\, f_0\, \hat{G}_{0^{++}}$$

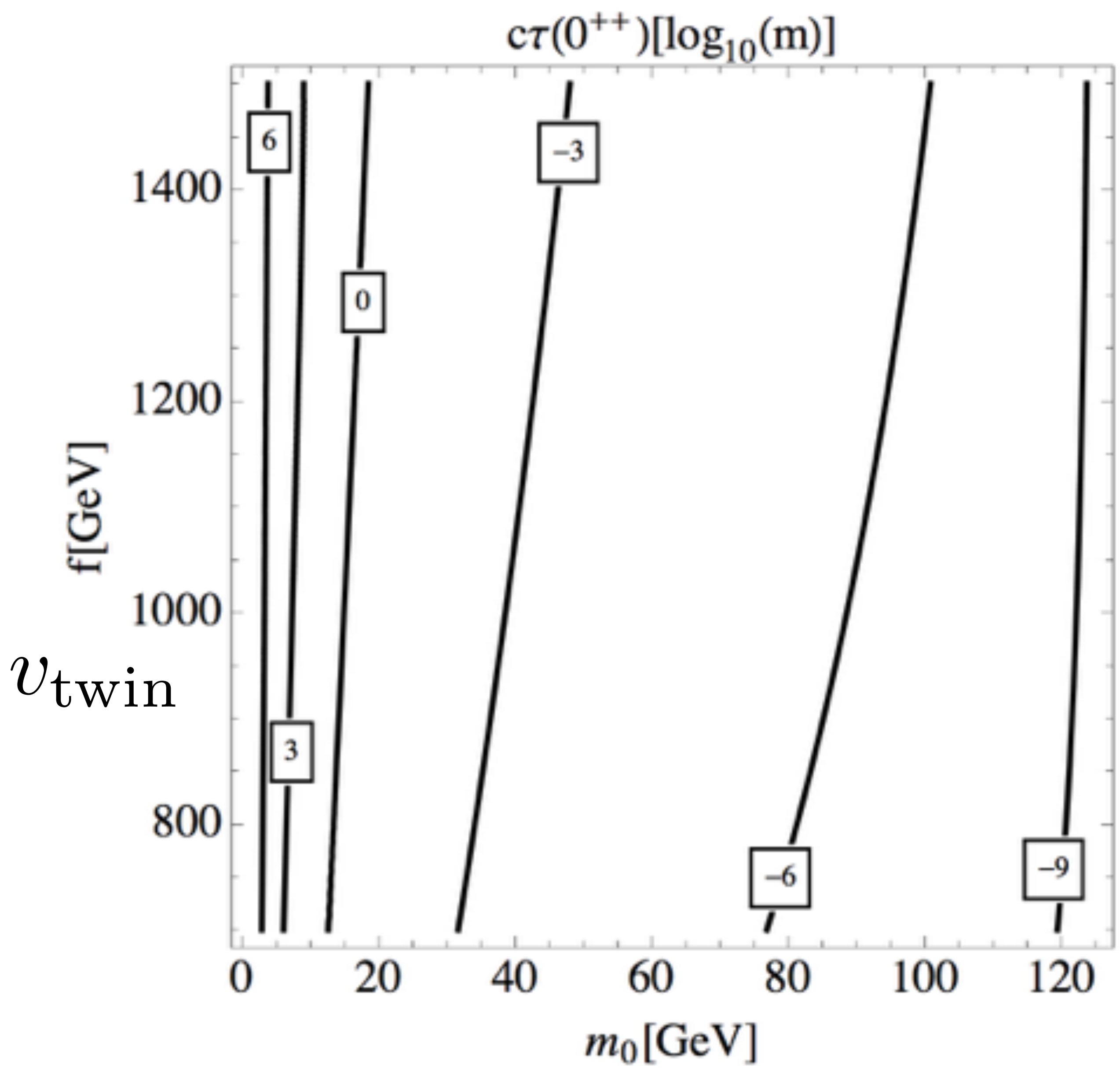
$$c\tau_{0^{++}} \sim 18\,{\rm m} \times \left(\frac{10\,{\rm GeV}}{m_{0^{++}}}\right)^7 \left(\frac{v_{\rm twin}}{750\,{\rm GeV}}\right)^4$$

$$4\pi\,\hat{\alpha}_{\rm QCD}\, f_0 = 3.06\, m^3_{0^{++}}$$

Chen et al. (2006)

The result is extremely sensitive to glueball mass / decay constant!

Lattice result determines if we can see collider signals or not



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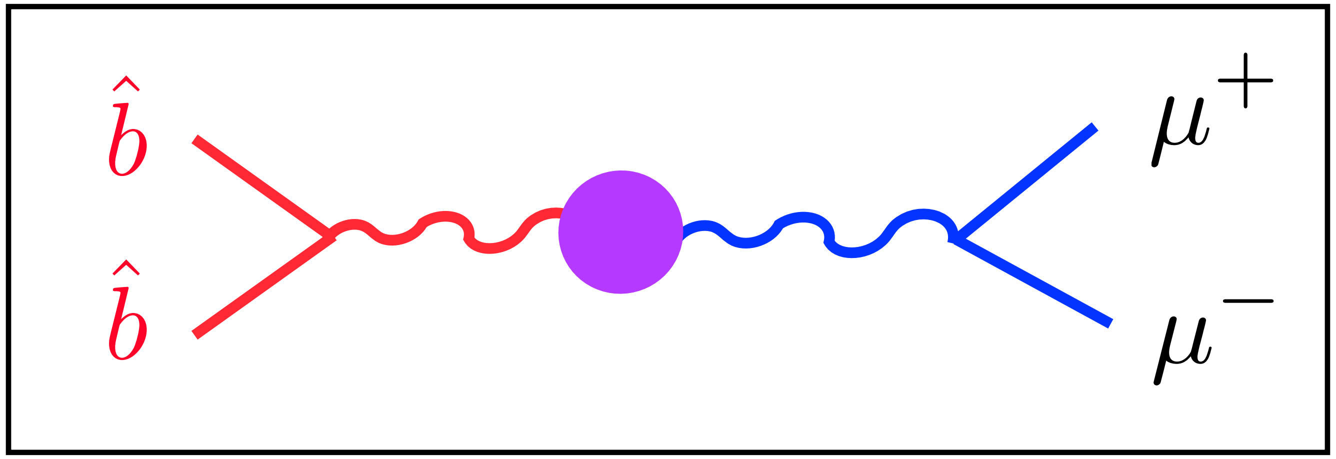
$$4\pi\,\hat{\alpha}_{\rm QCD}\,f_0 = 3.06\,m^3_{0^{++}}$$

Craig, Katz, Strassler, Sundrum (2015)

Similarly for bottomonium decay

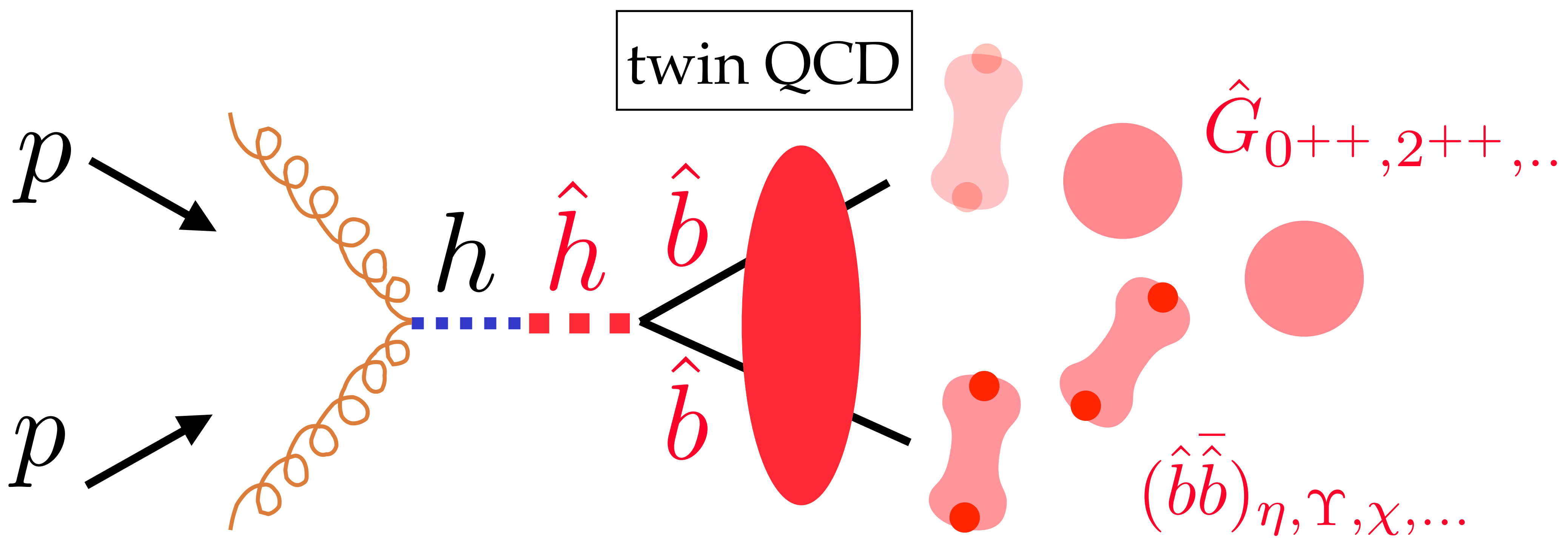


$$c\tau_{\hat{\Upsilon}} \simeq 1.5\,\mathrm{cm}\left(\frac{m_b}{m_{\hat{b}}}\right)^3\left(\frac{m_{\hat{A}}}{100\,\mathrm{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{5\,\mathrm{GeV}}{\Lambda}\right)^2\left[\left(\frac{\sqrt{s}}{3m_{\hat{b}}}\right)^2+\frac{2}{9}\right]^{-1} \quad (m_{\hat{b}} \gg \Lambda),$$

$$c\tau_{\hat{\Upsilon}} \simeq 1.3\,\mathrm{cm}\left(\frac{m_{\hat{A}}}{100\,\mathrm{GeV}}\right)^4\left(\frac{10^{-3}}{\epsilon}\right)^2\left(\frac{5\,\mathrm{GeV}}{\Lambda}\right)^5\left(\frac{\sqrt{s}}{3\Lambda}\right)^{-2} \quad (m_{\hat{b}} \ll \Lambda),$$

Cheng, Jung, Salvioni, YT (2015)

Other uncertainty, showering & hadronization

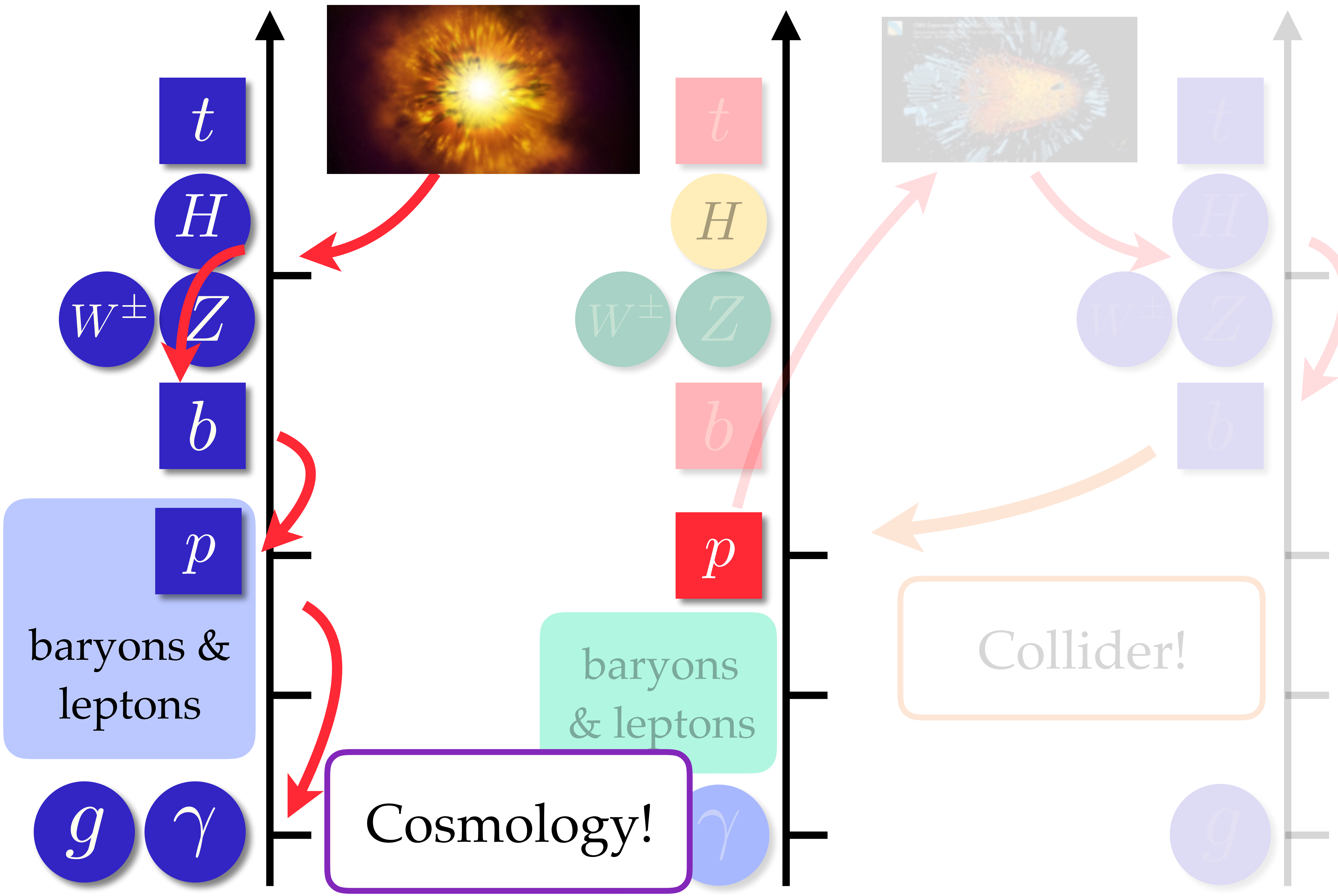


Twin hadron multiplicity?

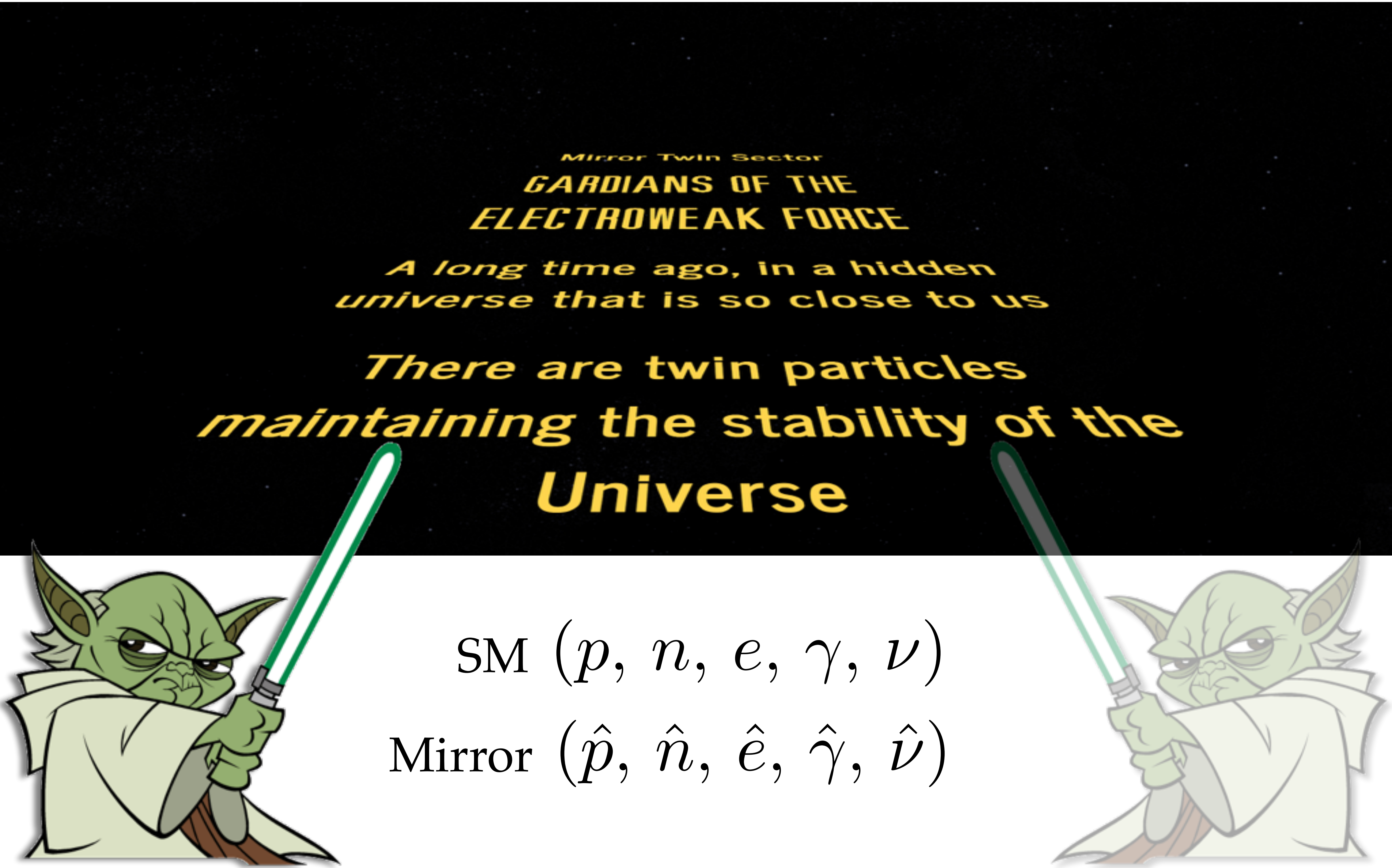
Relative number between different hadrons?

Energy distribution? …

Cosmological Signature from Hidden Naturalness



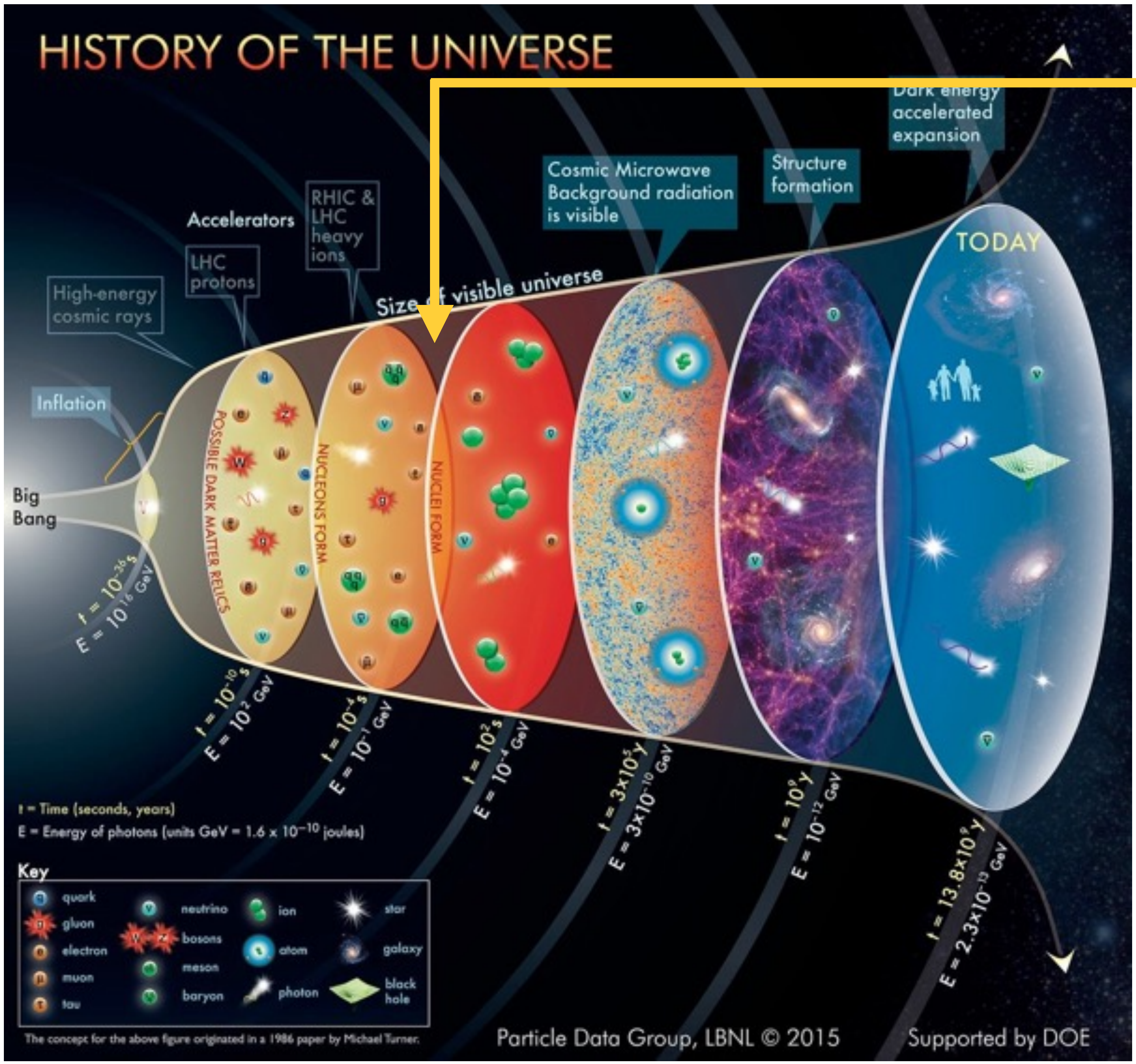
A long time ago, when T ~ MeV (~1 sec)



SM $(p,\, n,\, e,\, \gamma,\, \nu)$

Mirror $(\hat{p},\, \hat{n},\, \hat{e},\, \hat{\gamma},\, \hat{\nu})$

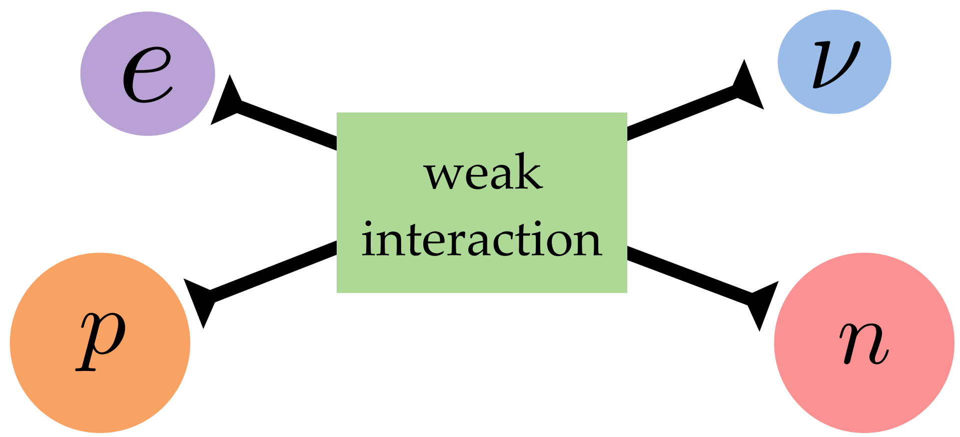
Big-bang Nucleosynthesis (~1 sec, T ~ MeV)



Nucleosynthesis

Two important BBN processes

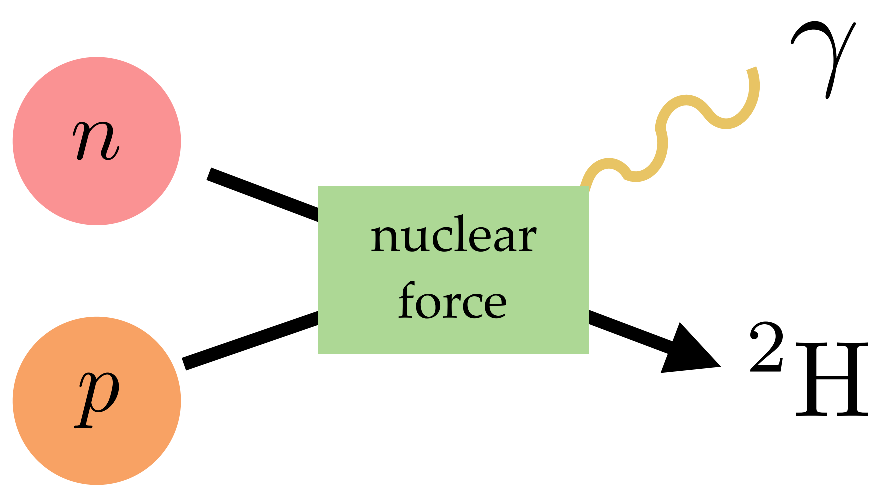
neutron / proton freeze out



twin neutron / proton mass splitting?

$$\left(\frac{n}{p}\right) \sim e^{-\frac{\Delta M_{np}}{T_F}}$$

Deuterium Bottleneck



twin deuterium binding energy?

Cosmology is very sensitive to twin baryon masses!

A rough estimation of twin baryon masses

twin neutron/proton mass splitting?

$$\frac{m_{\hat{p}}}{m_p} \approx \frac{m_{\hat{n}}}{m_n} \approx \frac{\Lambda_{QCD_B}}{\Lambda_{QCD_A}} \approx 0.68 + 0.41 \log(1.32 + v_B/v_A)$$

from RGE

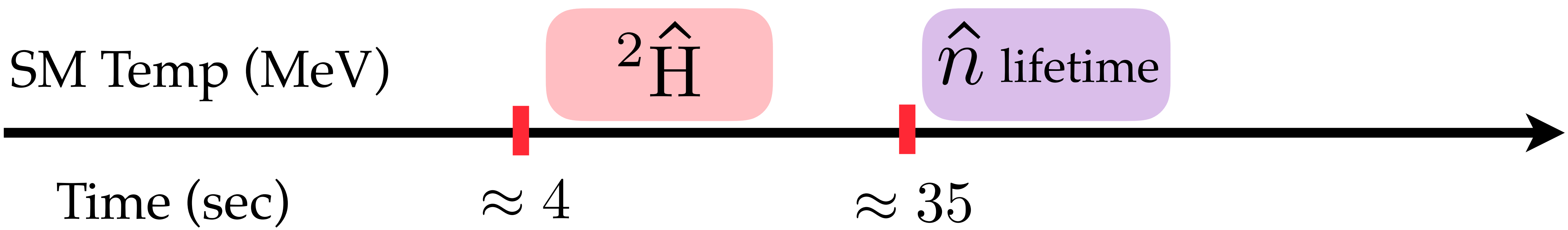
twin deuterium binding energy?

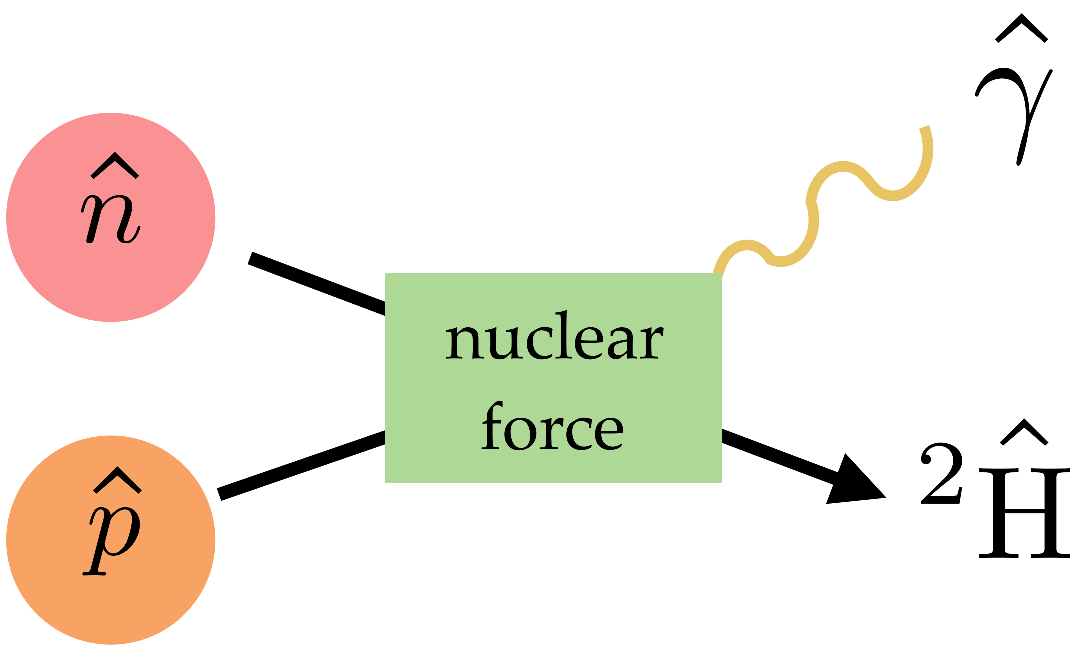
$$\frac{\Delta M_{\hat{n}\hat{p}}}{\Delta M_{np}} \approx 1.68 v_B/v_A - 0.68, \qquad \Delta M_{np} = 1.29\,\mathbf{MeV}.$$

from lattice result, Borsanyi et al. (2014)

For $v_B/v_A = 3$, twin proton ~ 30% heavier than SM proton
twin neutron/proton splitting ~ 5.6 MeV

Mirror Deuterium Bottleneck





$$\frac{t_{^2\hat{\mathrm{H}}}}{t_{\hat{n}\ \mathrm{decay}}} \approx \frac{t_{^2\mathrm{H}}}{t_{n\ \mathrm{decay}}}$$

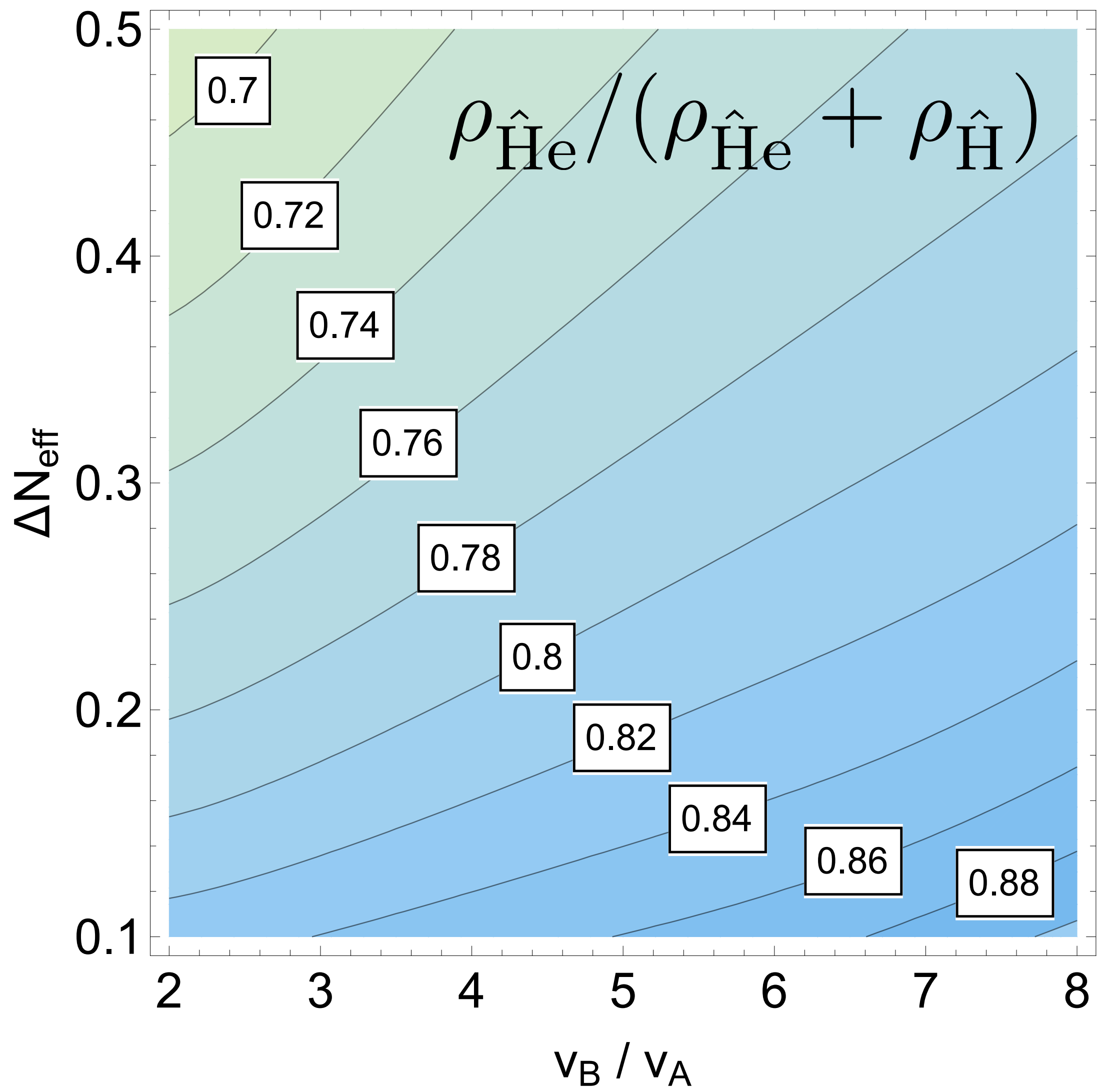
Estimate twin ^{2}H binding energy from lattice calculation

Orginos et al. (2015)

Mirror deuterium/helium can form

Mirror helium dominates twin matter density

Chacko, Curtin, Geller, YT (*1803.03263*)

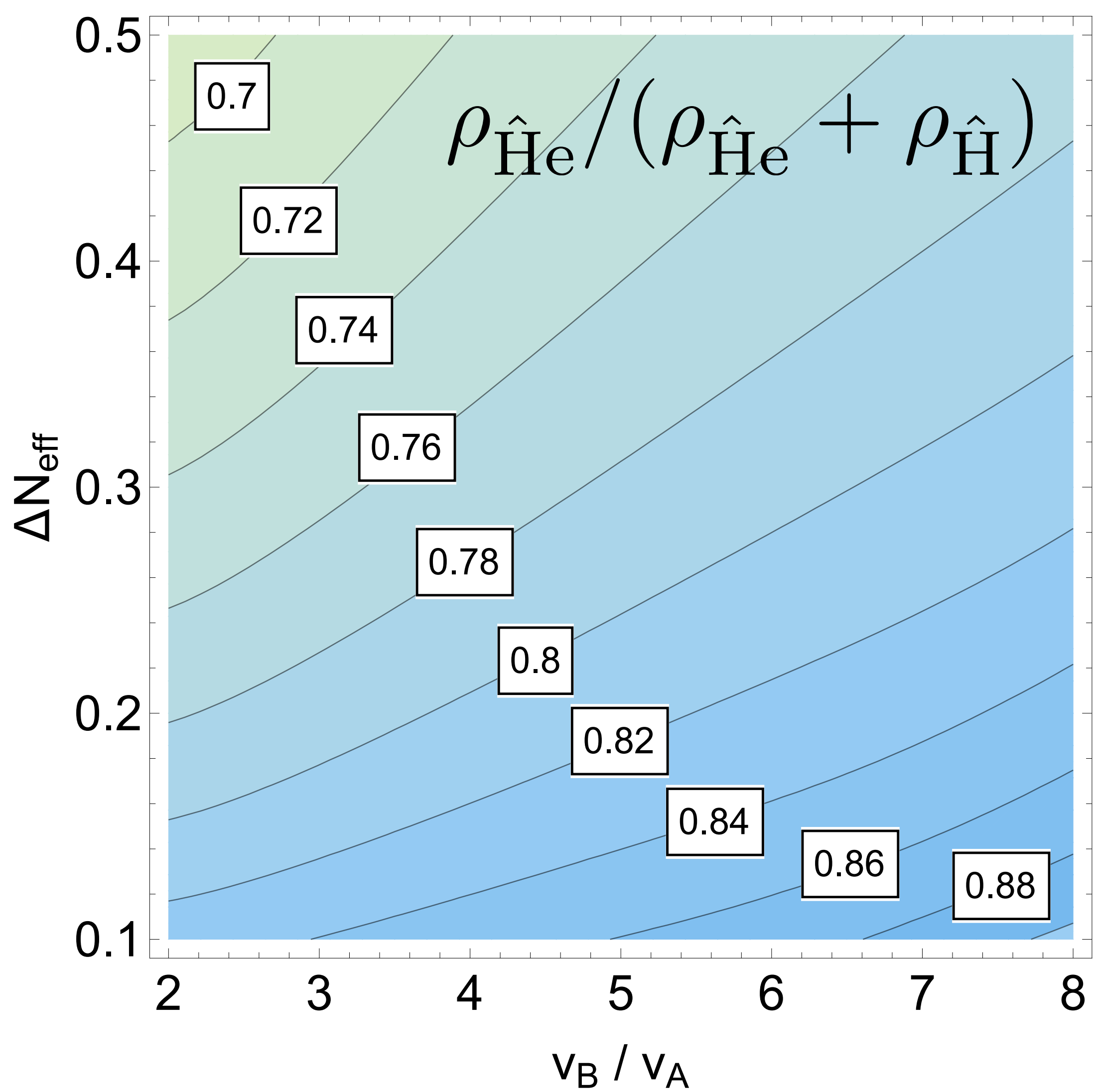


Mirror: ~ 75% mass is in **mirror He**

SM: ~ 75% mass is in **Hydrogen**

Mirror helium dominates twin matter density

Chacko, Curtin, Geller, YT (*1803.03263*)

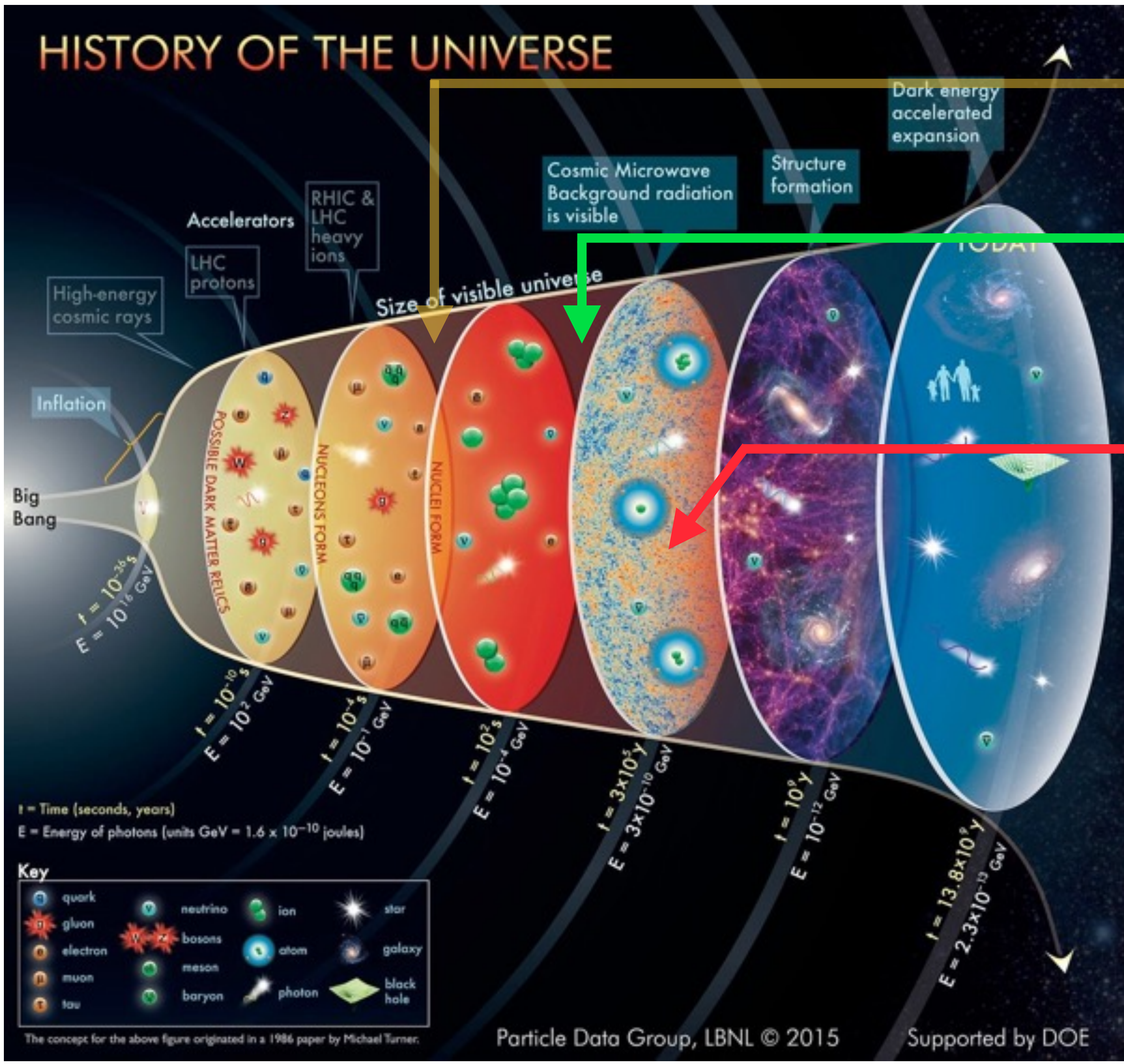


Mirror: ~ 75% mass is in **mirror He**

SM: ~ 75% mass is in **Hydrogen**

The result will determine the
Large Scale Structure of Universe

Era for the Large Scale Structure & CMB

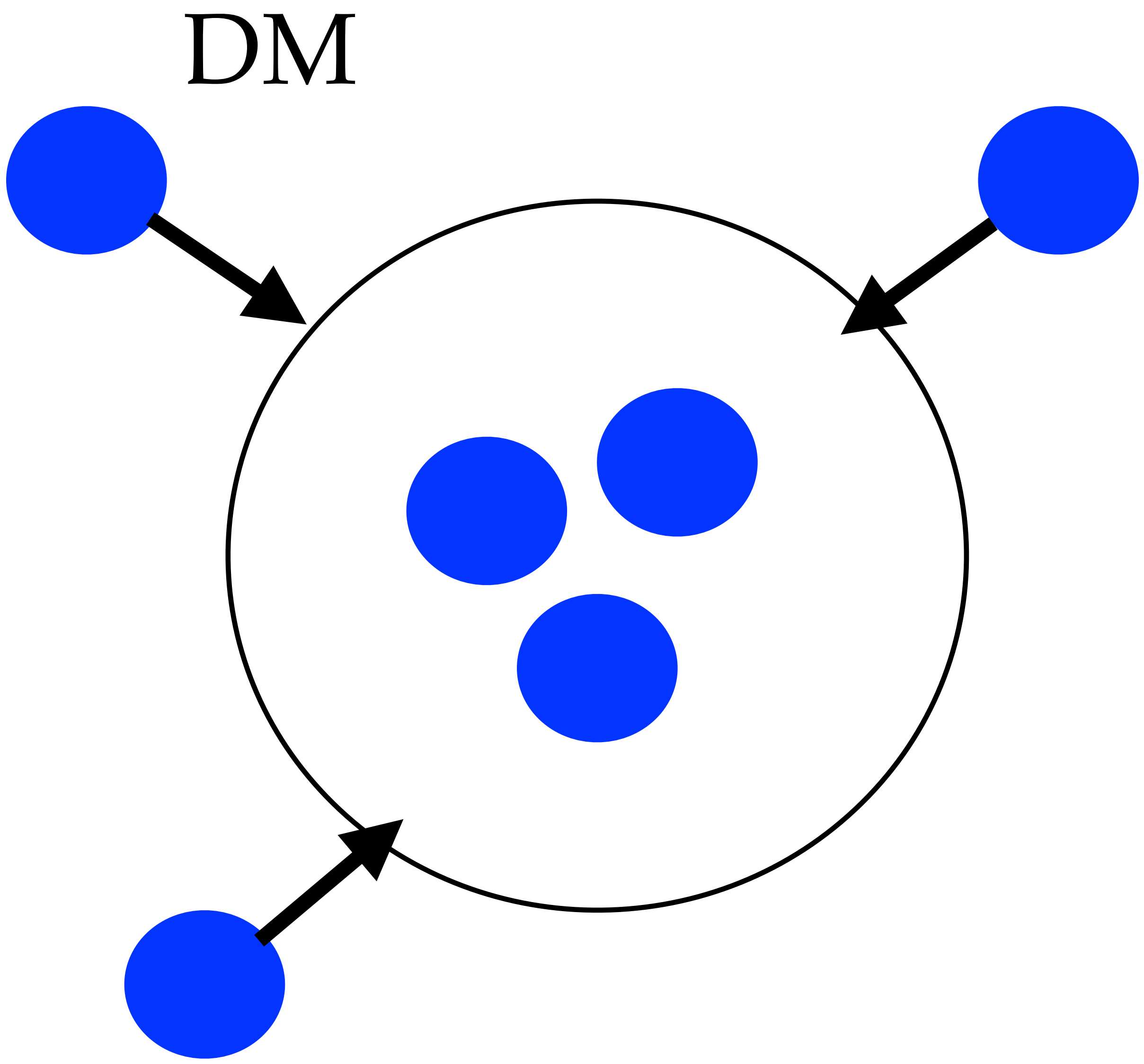


Nucleosynthesis

Matter-radiation equilibrium

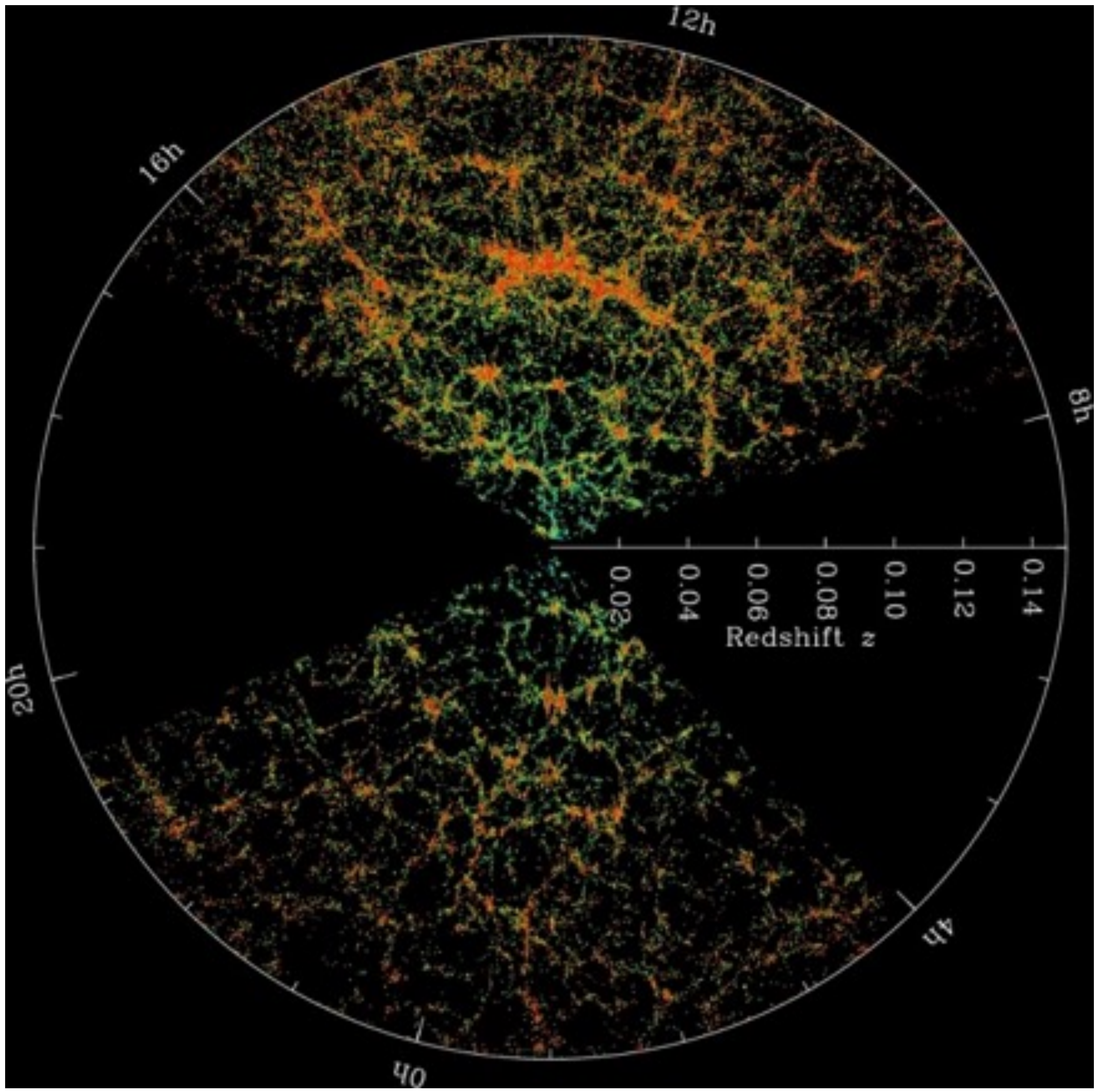
Large Scale Structure

Structure formation of collision-less DM



higher density -> larger gravity -> even higher density…

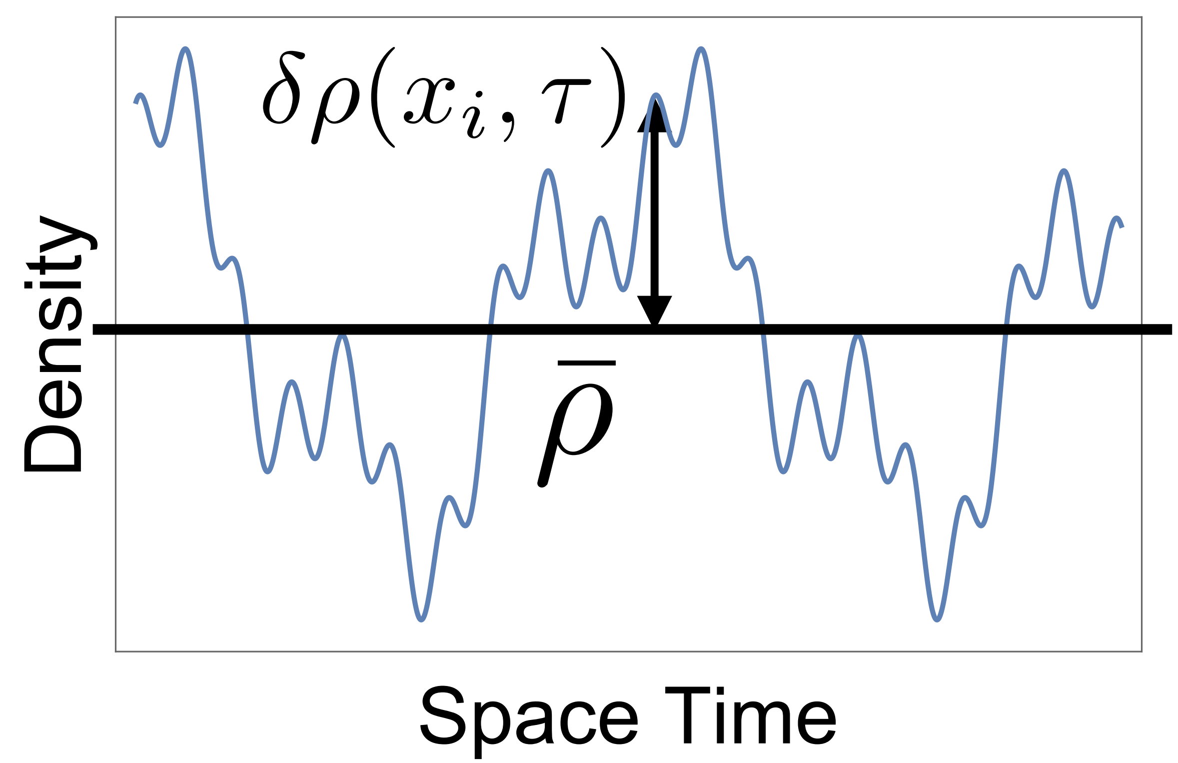
Large Scale Structure of the Universe



SDSS

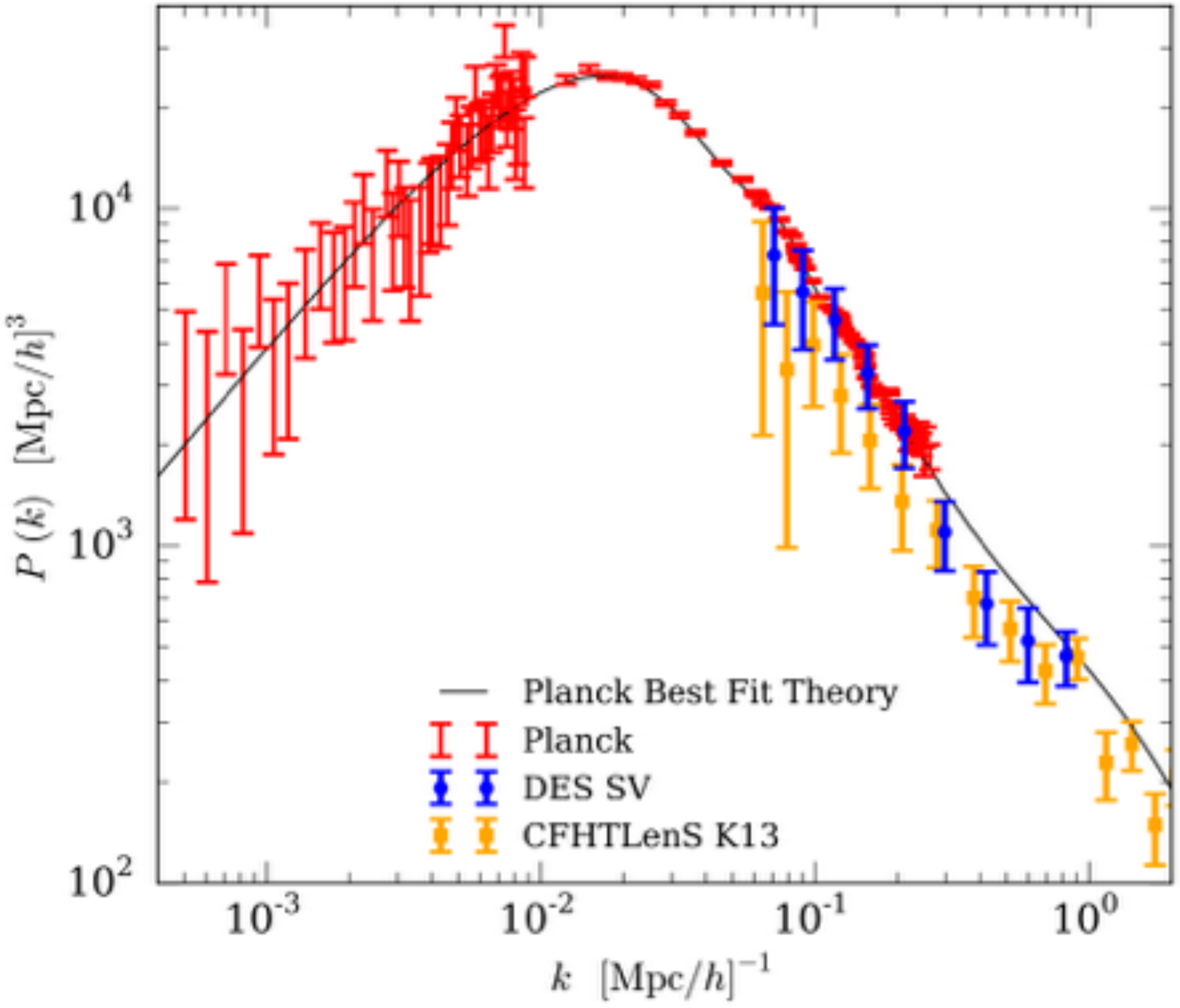
Density Perturbation

$$\delta_i \equiv \frac{\delta\rho_i}{\bar{\rho}_i} \qquad i = \mathrm{DM},\ \gamma,\ b,\ \nu$$



Matter power spectrum of the Universe

$$P(k)_s \propto k^{-3}\langle \delta_s(k,a)^2 \rangle$$



DES: 1507.05552

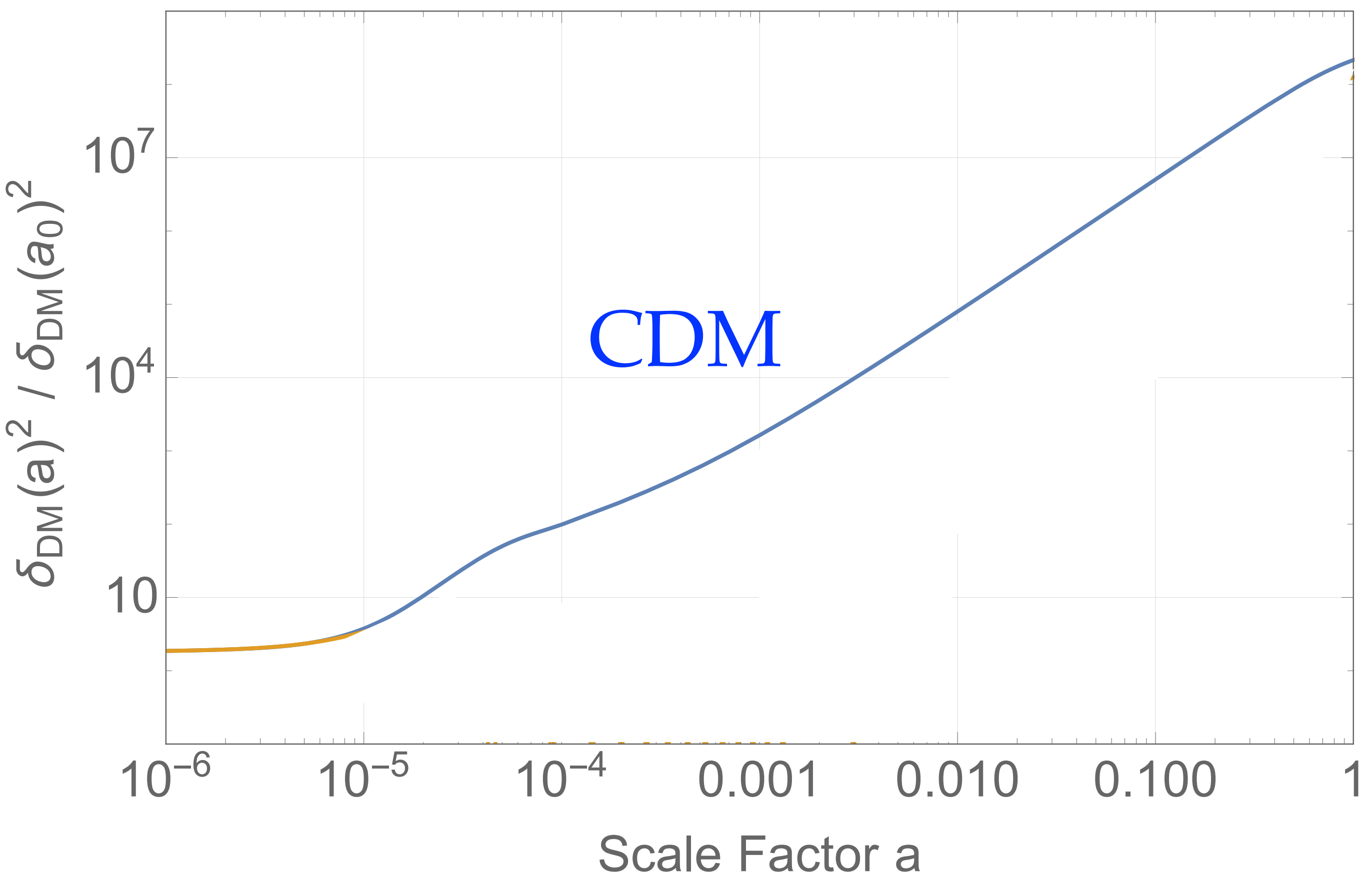
Density Perturbation

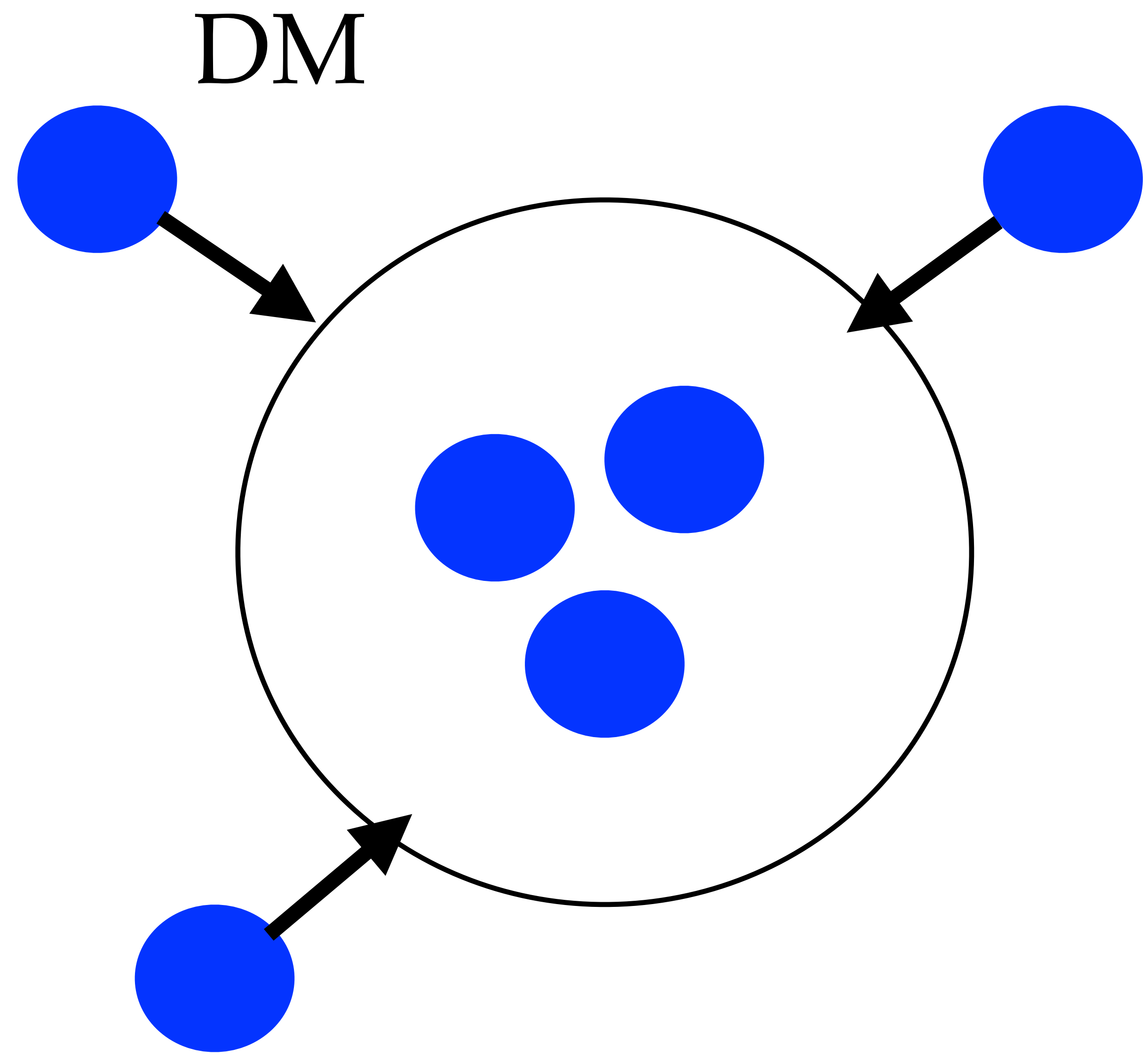
$$\delta_i \equiv \frac{\delta\rho_i}{\bar{\rho}_i} \quad i = \mathrm{DM},\, \gamma,\, b,\, \nu$$

Fourier transform into frequency modes

$$\delta_i(x,a) \to \delta_i(k,a)$$

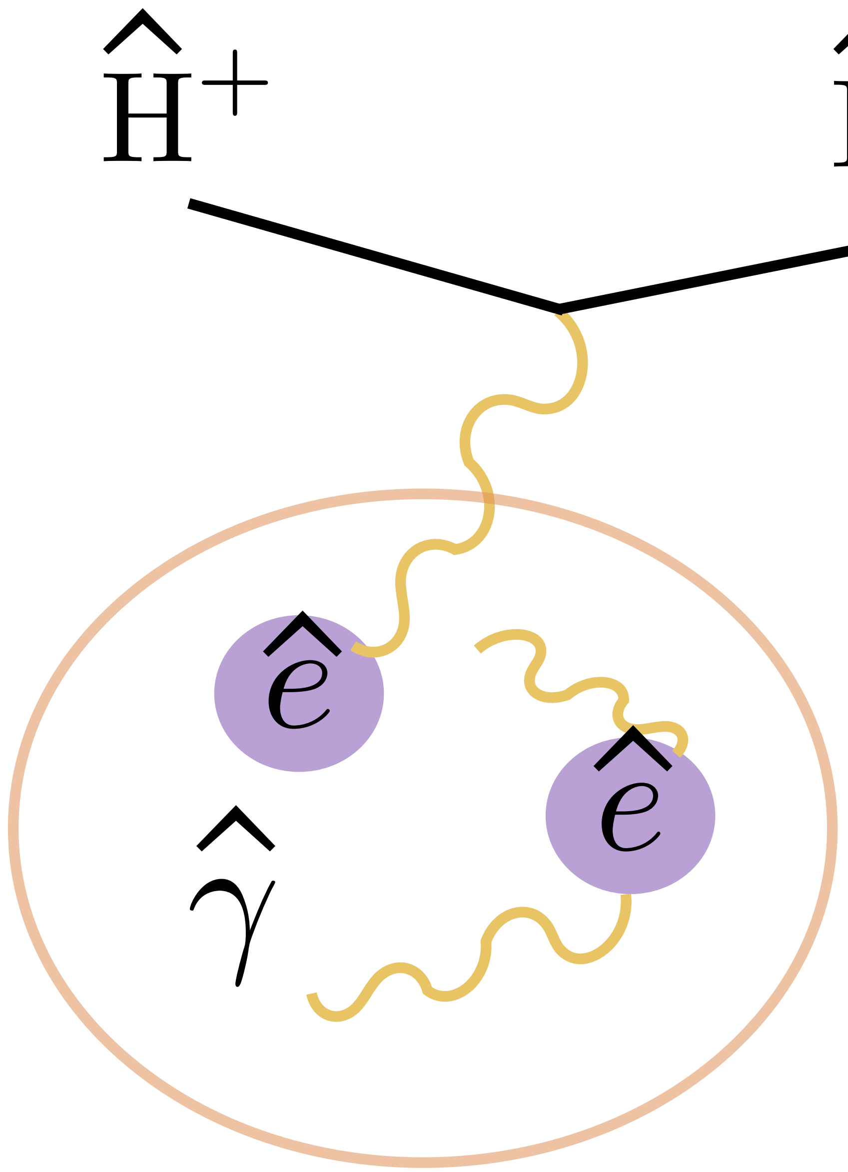
Structure formation of collision-less DM



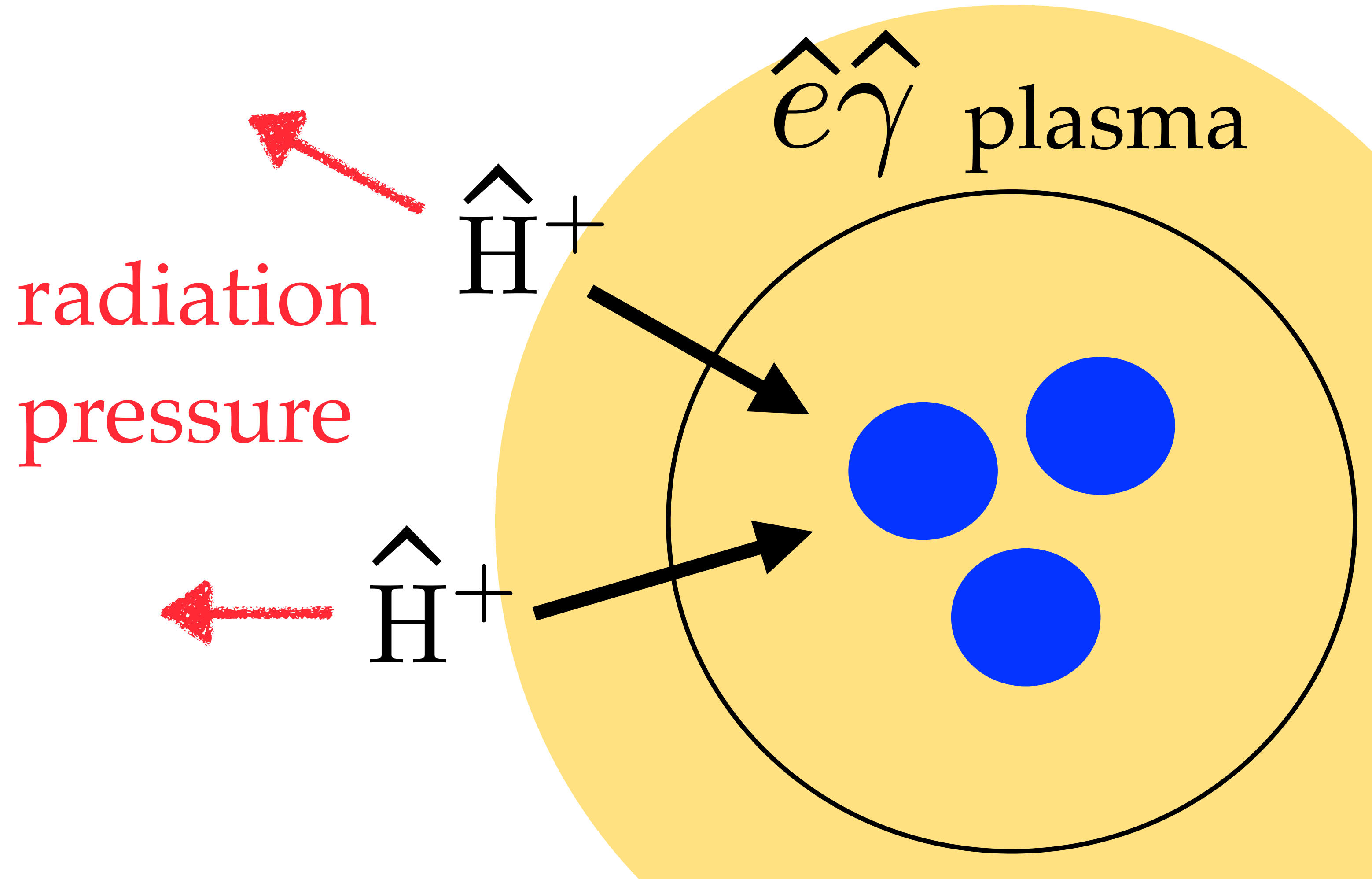


higher density -> larger gravity -> even higher density…

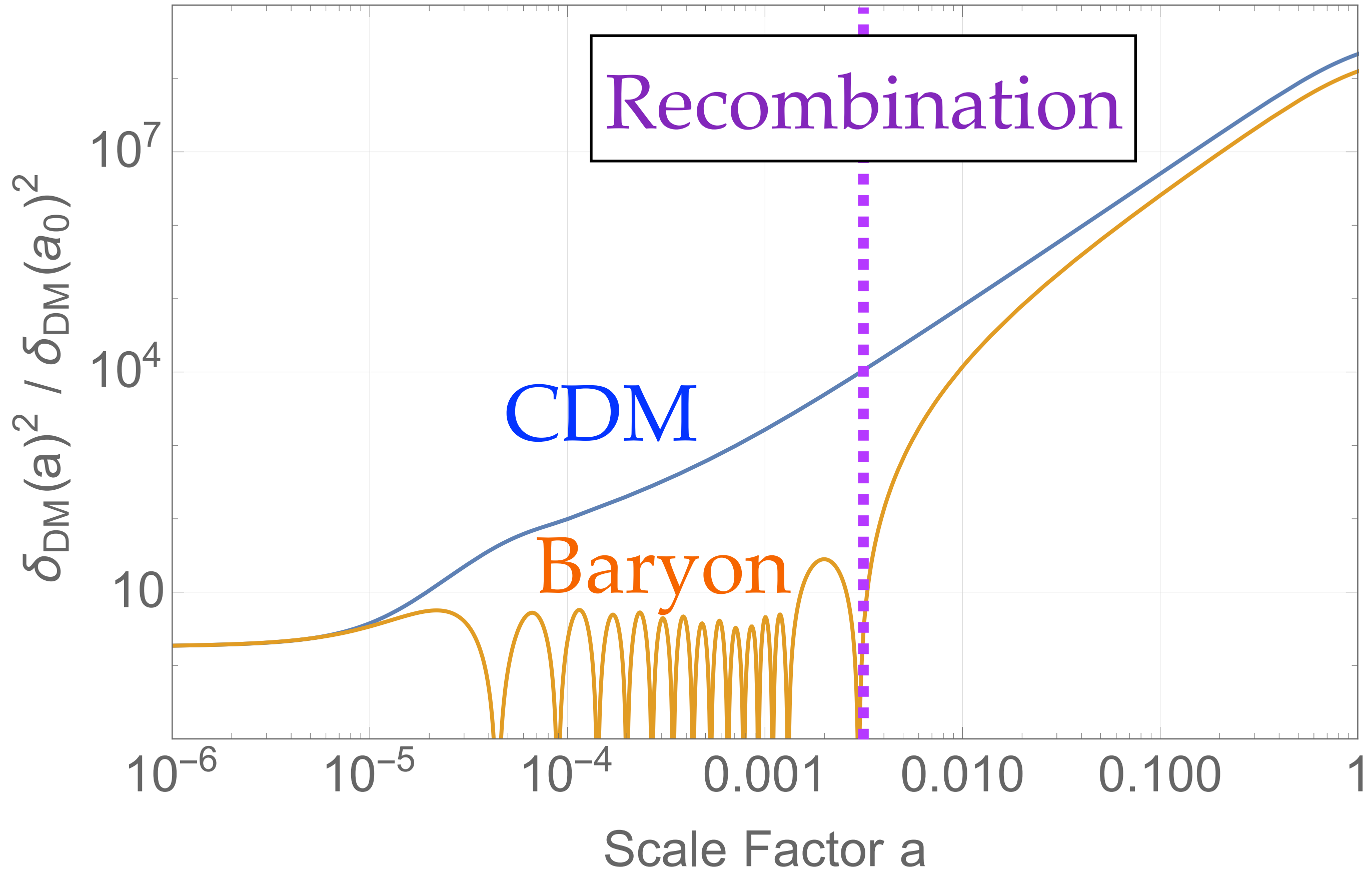
Structure formation of mirror baryons



The scattering forbids mirror baryons to form structure



Twin baryon acoustic oscillations (TBAO) suppress matter density perturbation



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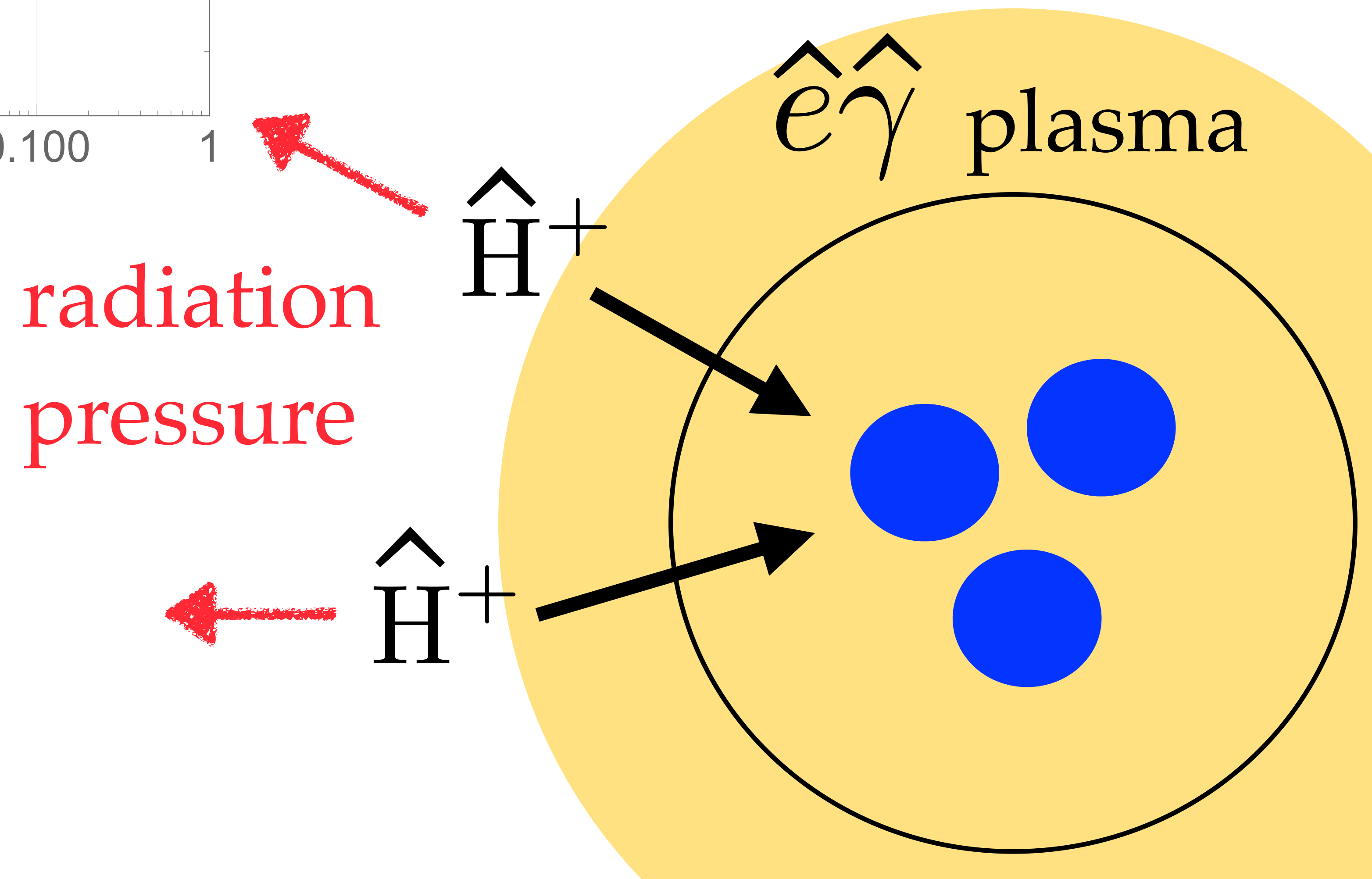


Quantify the suppression of matter structure

$$\delta_{tot}(k) = \sum_{i=\chi,\hat{b},p} (\Omega_i/\Omega_m)\, \delta_i(k),$$

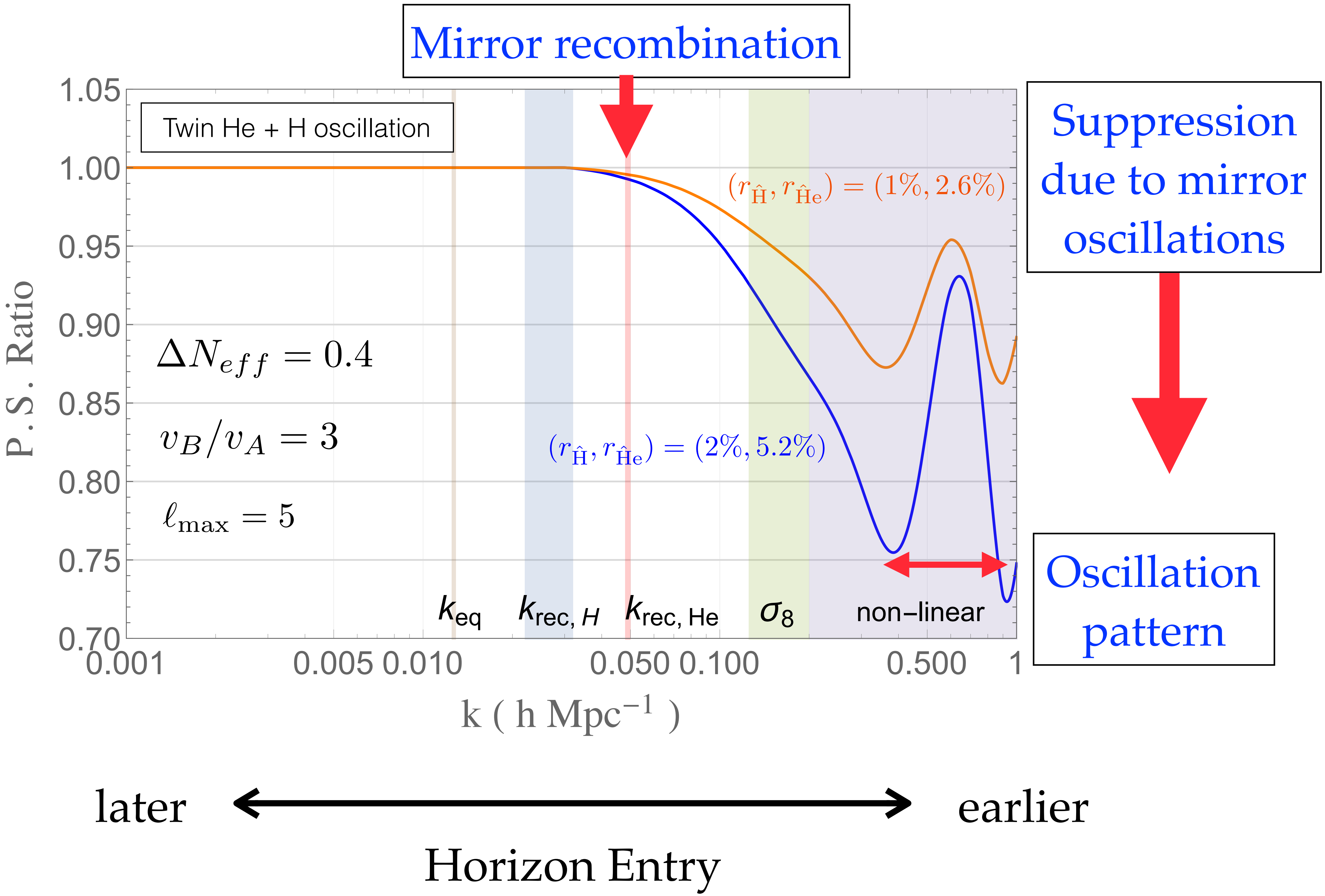
With mirror oscillations

$$\text{P.S. Ratio}(k) \equiv \frac{\delta^2_{tot}(k)\Big|_{\Lambda\text{CDM+MTH}}}{\delta^2_{tot}(k)\Big|_{\Lambda\text{CDM+DR}}}$$

Without mirror oscillations

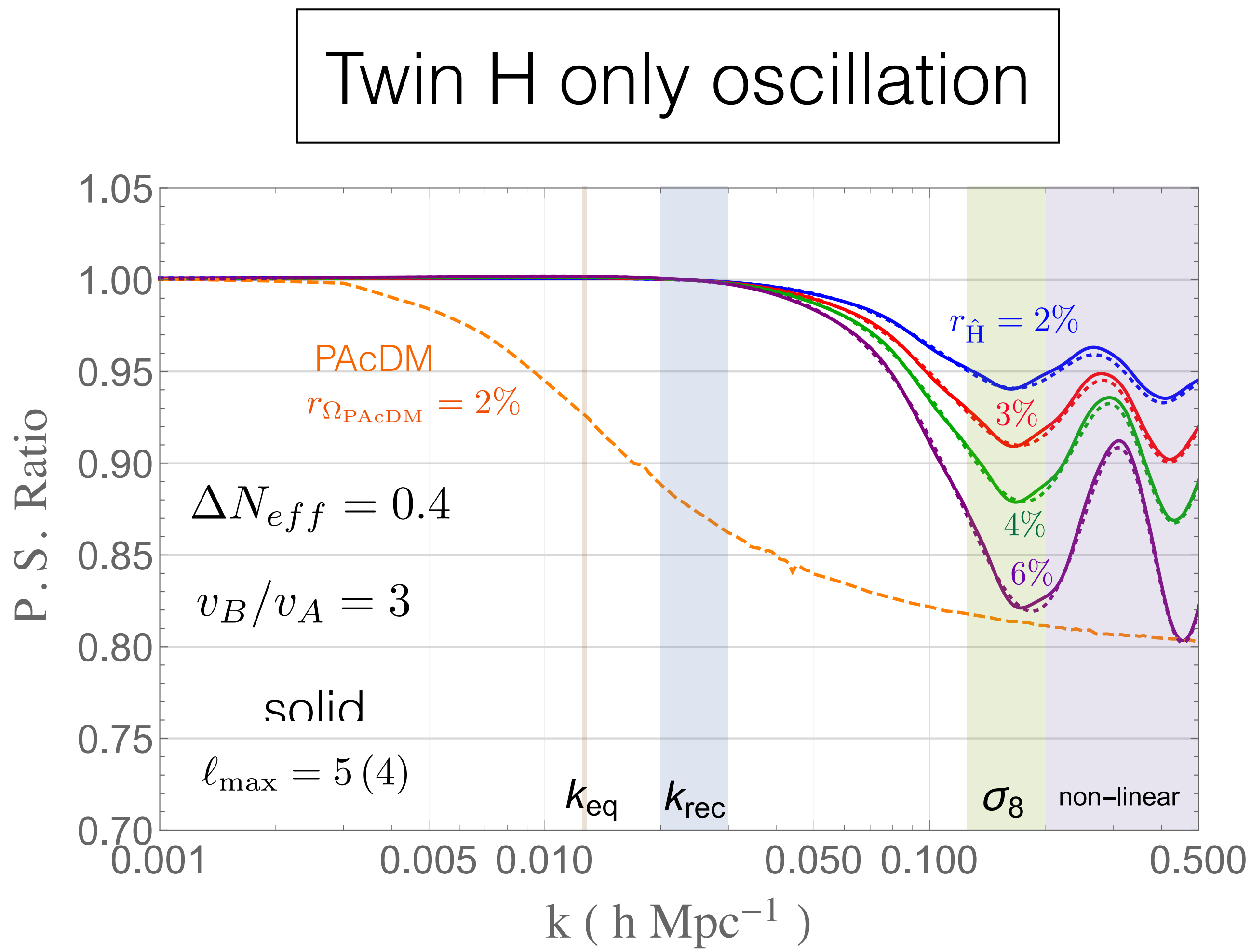
Twin acoustic oscillations → P.S. Ratio < 1

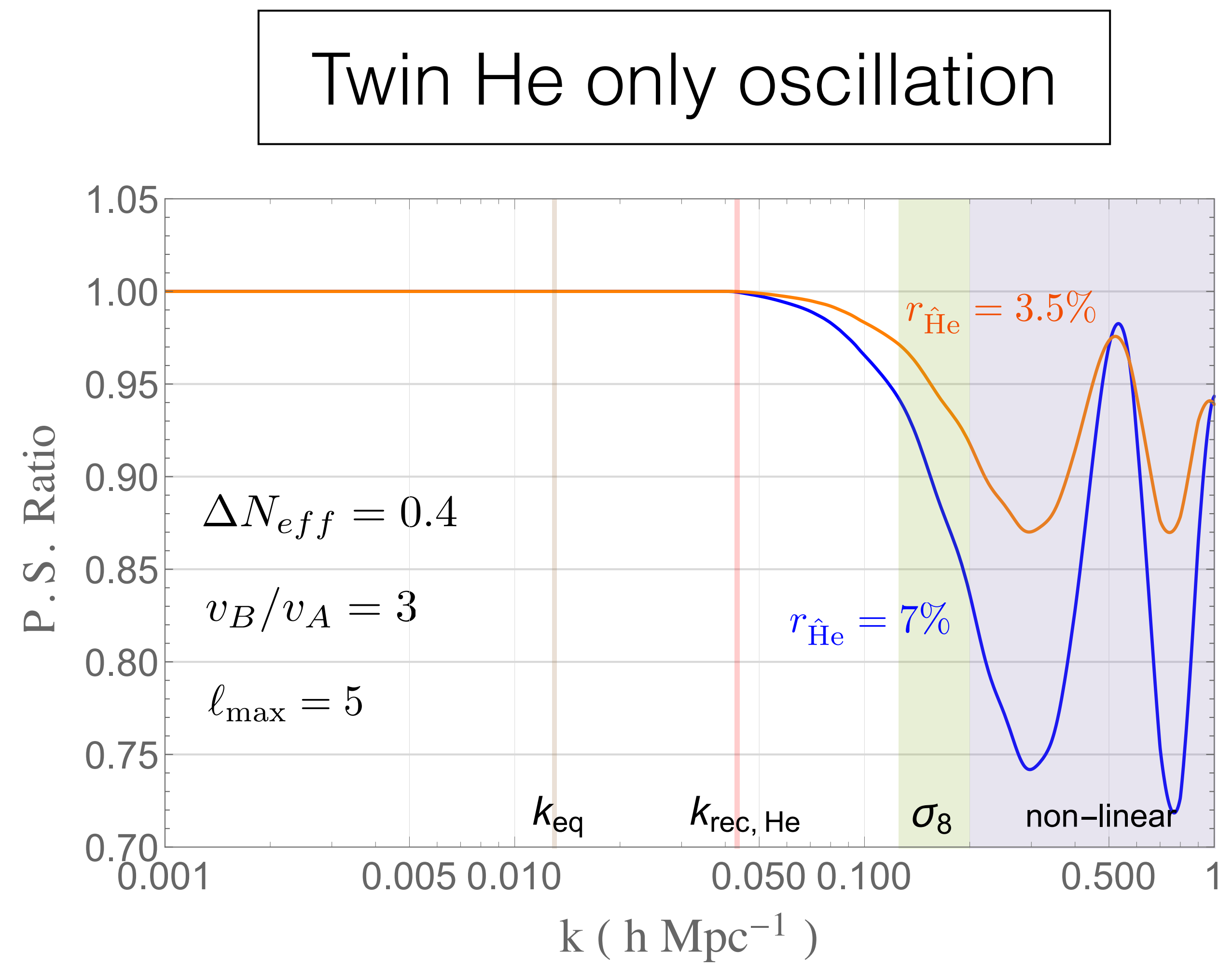
Suppression of the Large Scale Structure



Chacko, Curtin, Geller, YT (*1803.03263*)

Effect is sensitive to baryon composition

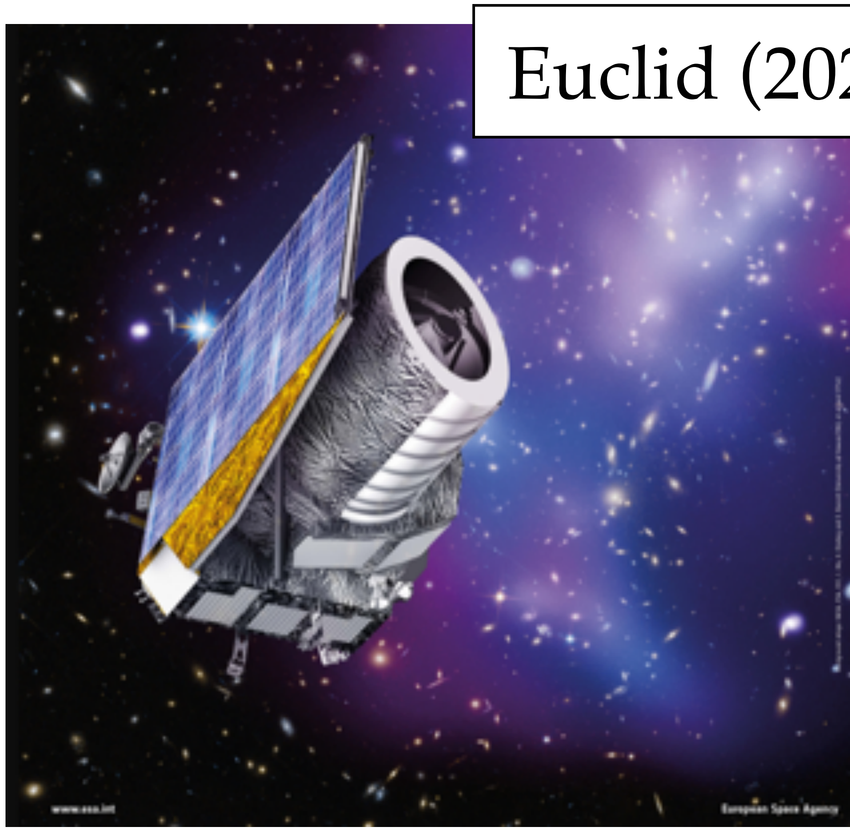




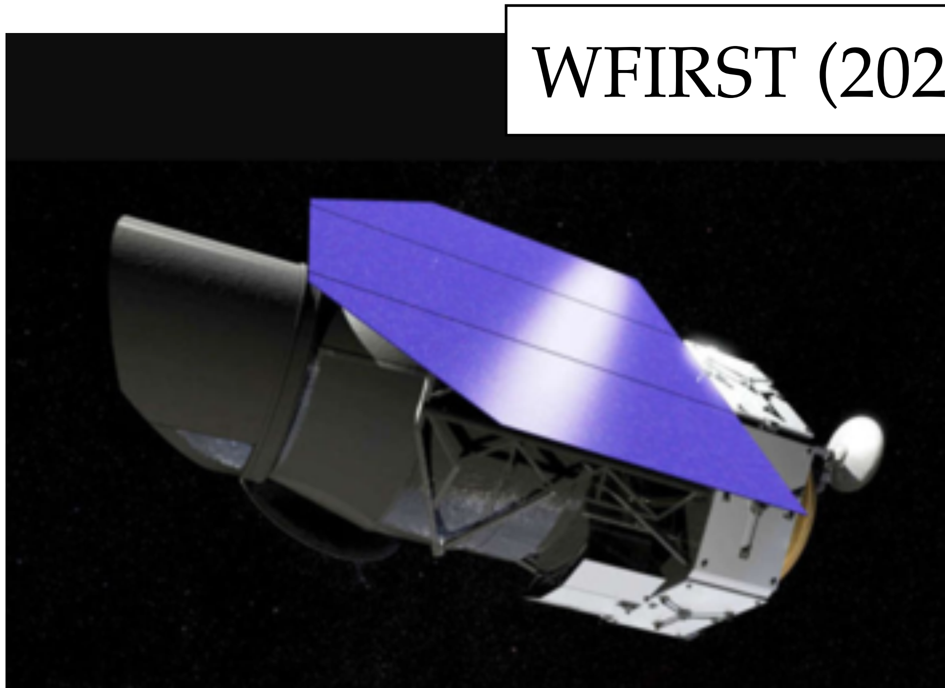
Chacko, Curtin, Geller, YT (*1803.03263*)

Precision measurement of the LSS

Euclid (2020)

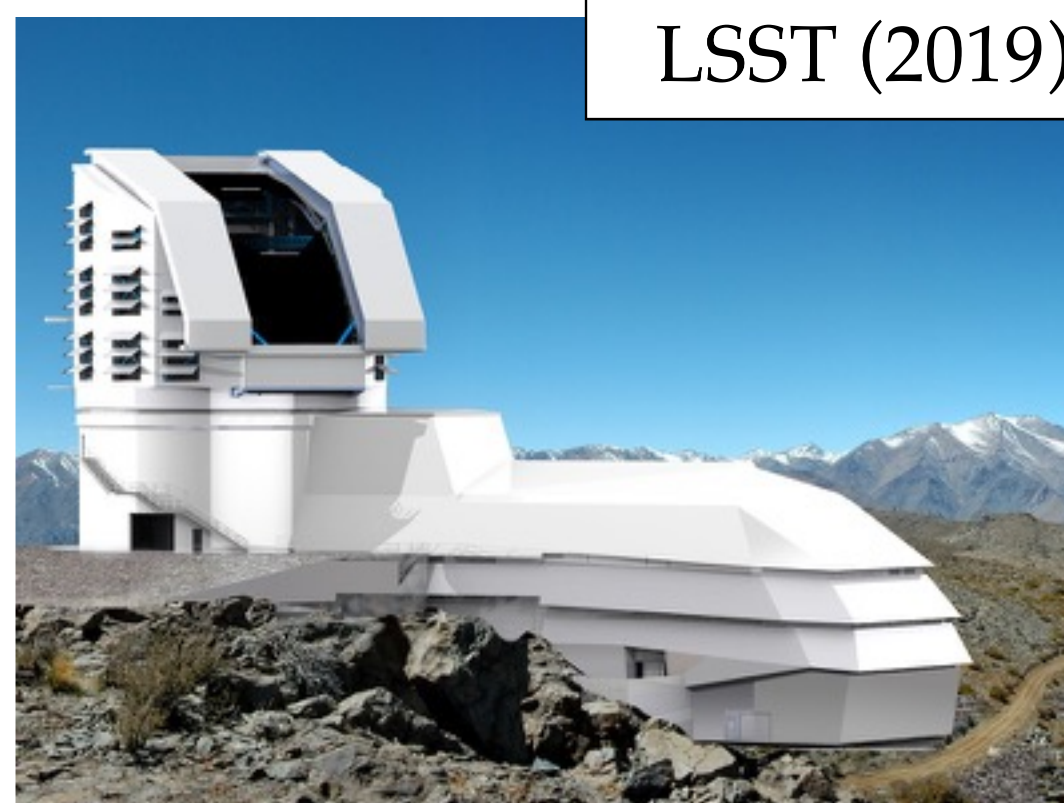


WFIRST (2020)

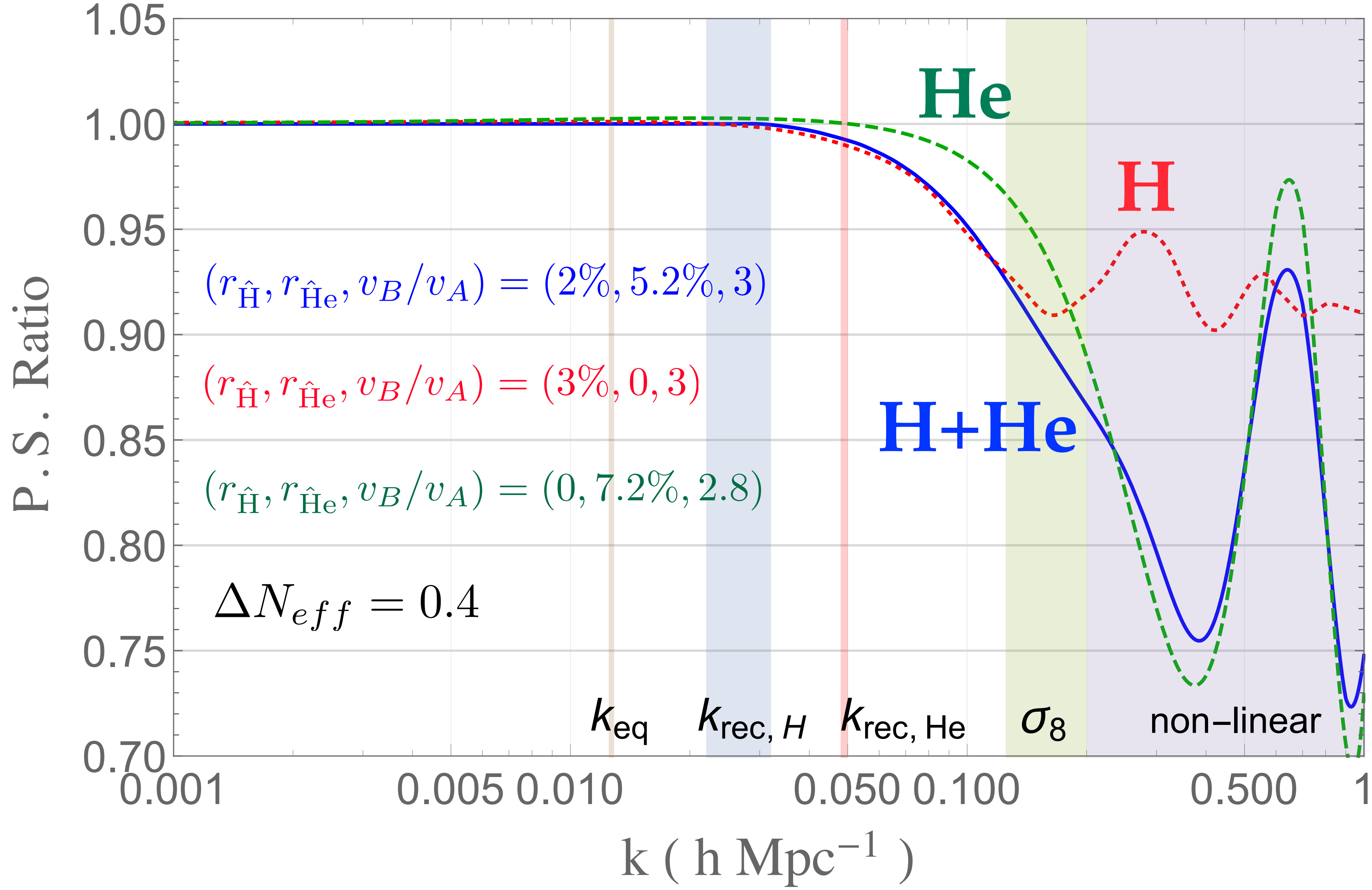


Precent level precision
in ~ 10 years

LSST (2019)



Large Scale Structure as dark atom spectroscopy



later ⟷ earlier

Horizon entry

Chacko, Curtin, Geller, YT (*1803.03263*)

Conclusion

- **Hidden Naturalness** scenarios solve the hierarchy problem and provide non-trivial DM model with a dark QCD
- We can use **cosmological data** to examine the idea, or design **Long-lived Particle searches at colliders** to look for twin hadrons
- Both of the cosmology & collider signatures are highly sensitive to **hidden hadron mass/decay constant** from lattice calculations