Embracing The Dark Side

Hidden Naturalness in Colliders & Cosmology

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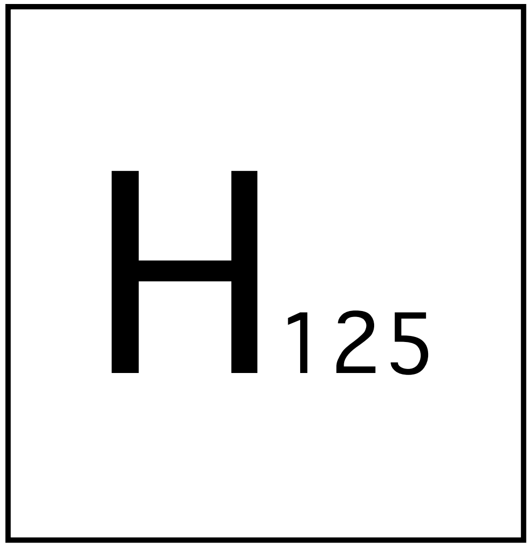
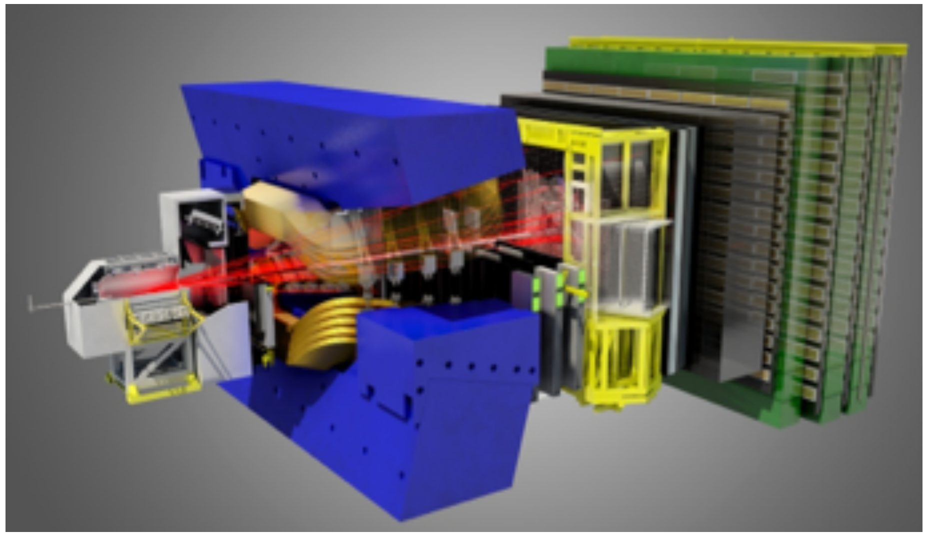
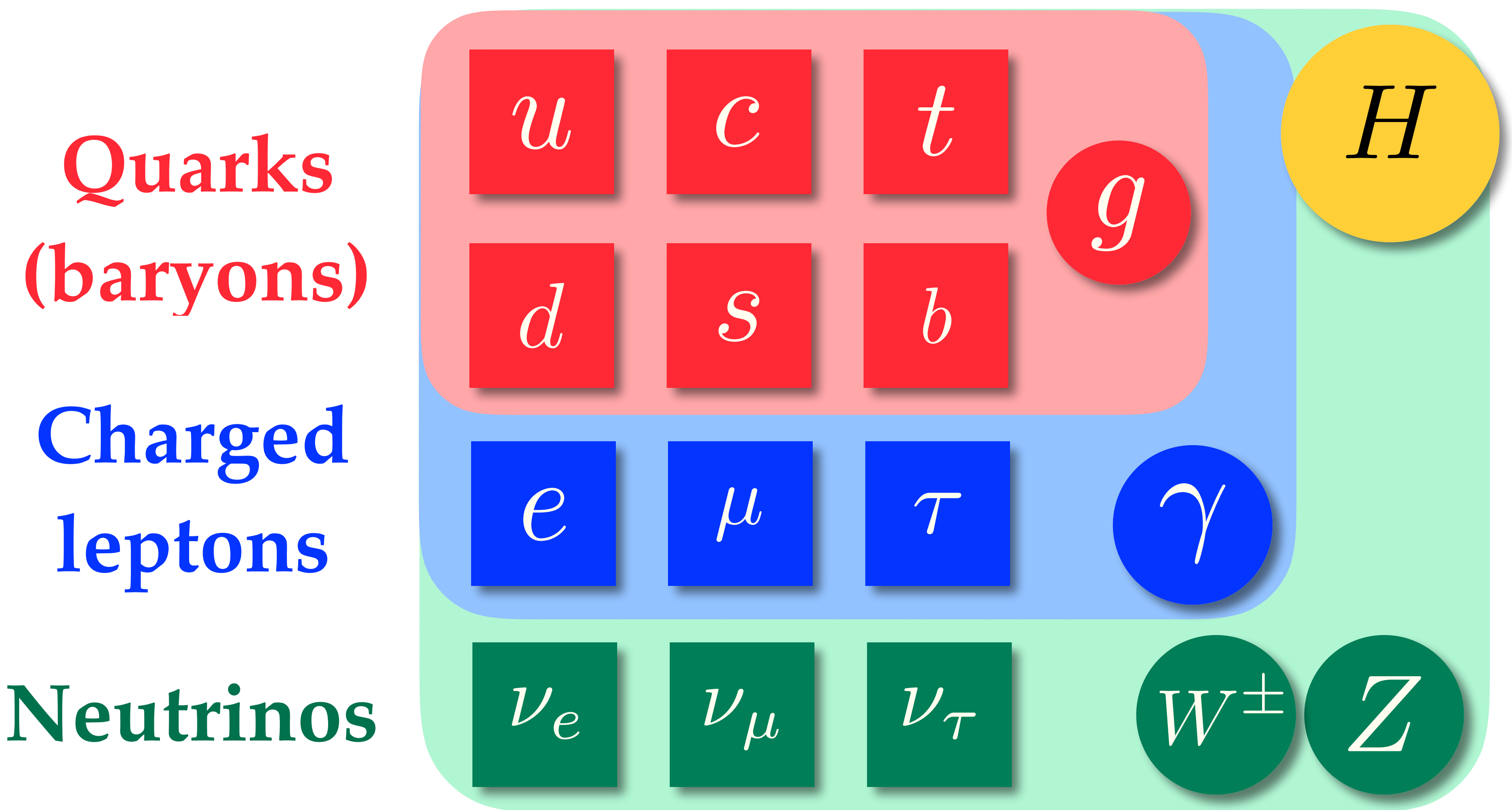
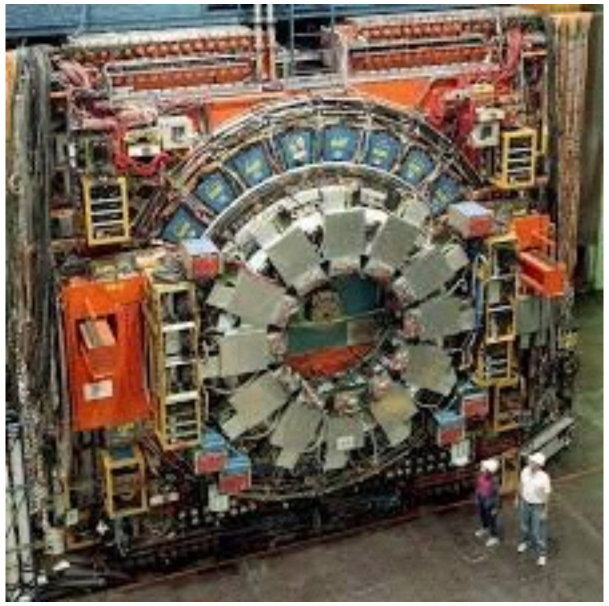
University of Toronto, Jan 24, 2018

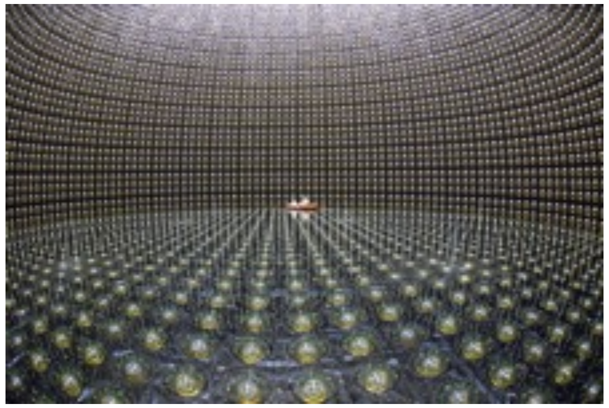




The Standard Model (SM)







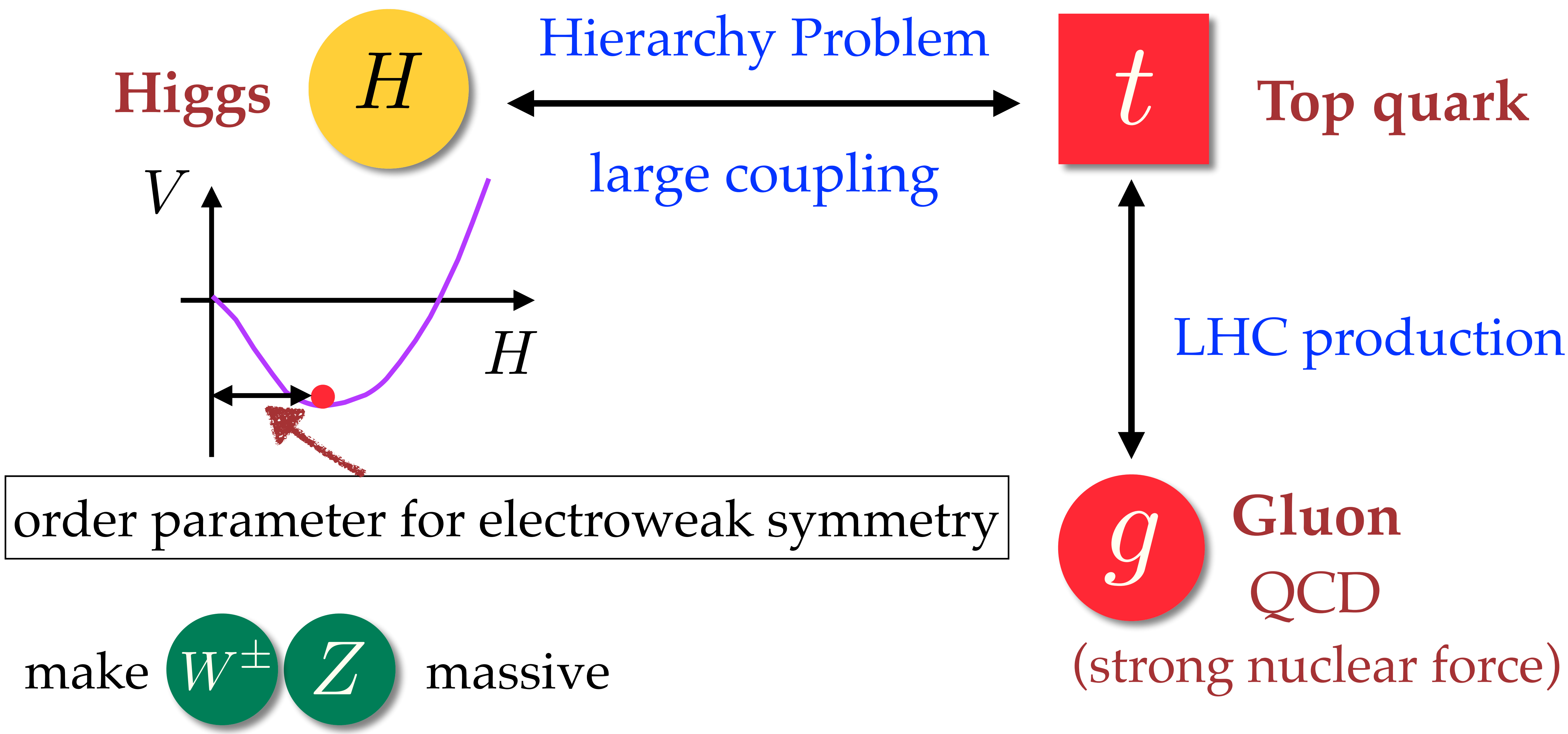
g gluon, **SU(3)c** color force

H Higgs

$W^\pm$ Z **SU(2)** weak force

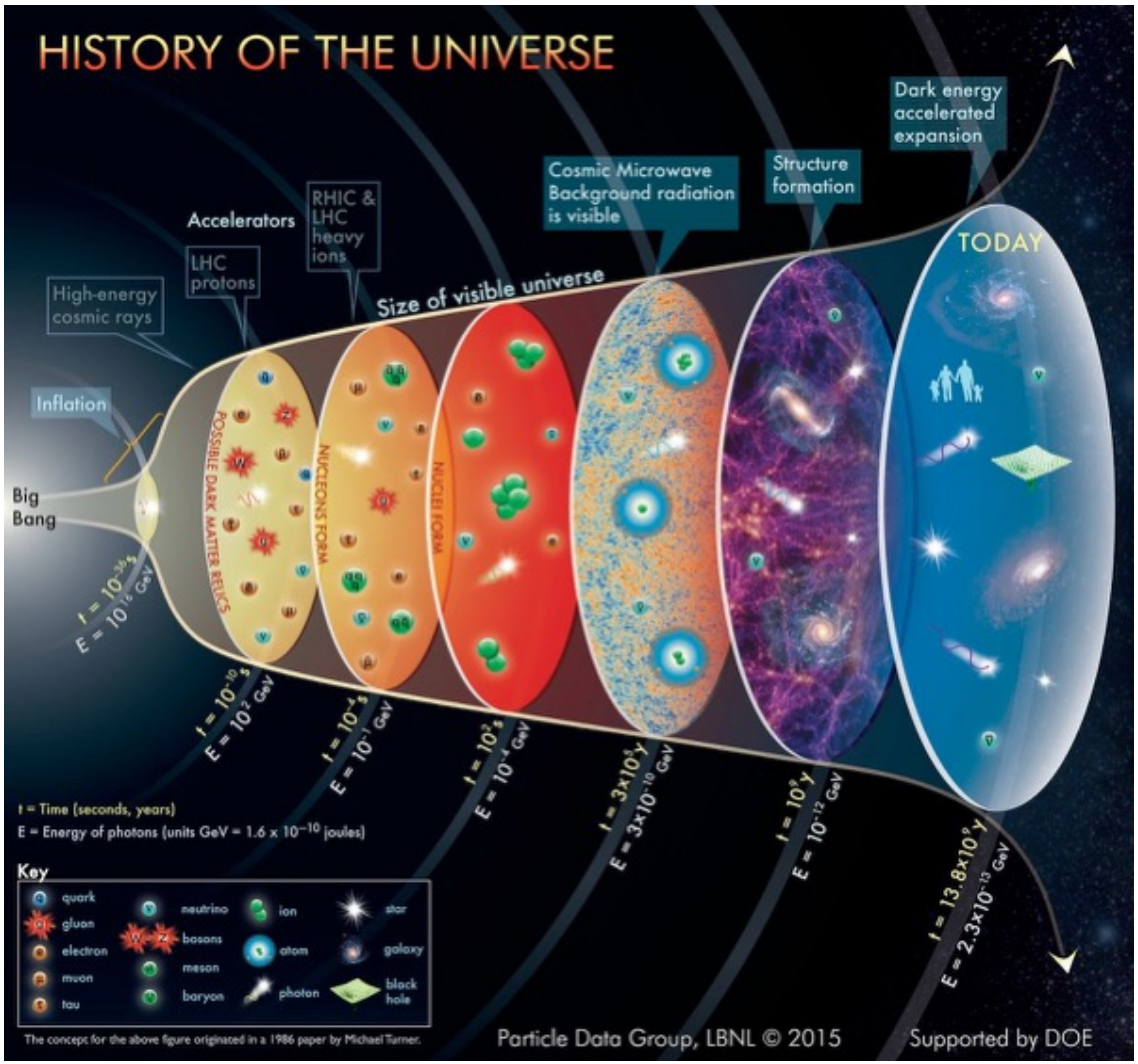
γ photon, **U(1)**

Some important particles to remember



give mass to fundamental fermions $y_f H \bar{f}_L f_R$

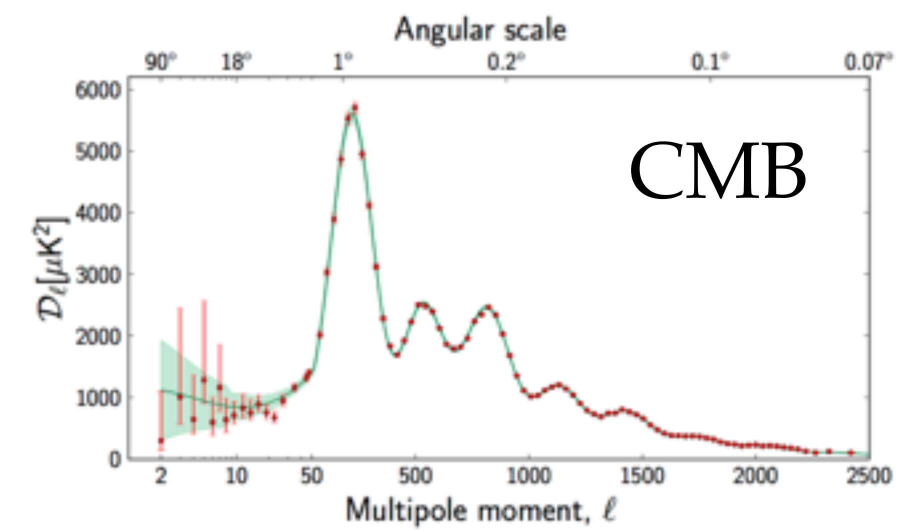
The Standard Cosmology: ΛCDM

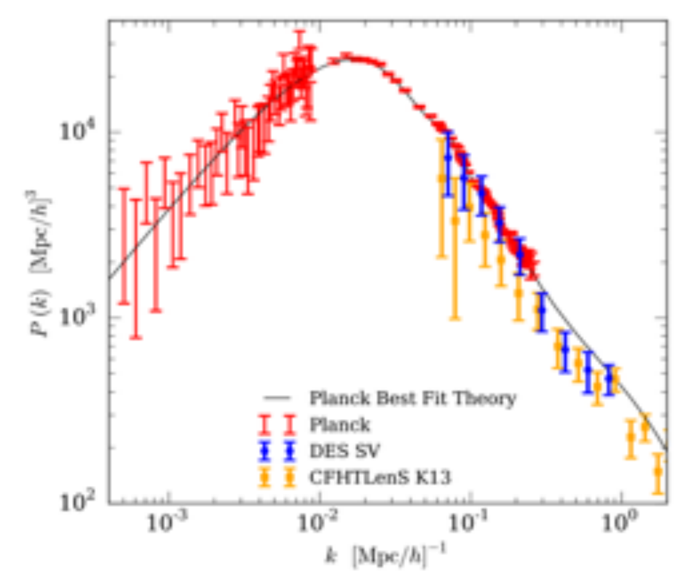


Cold Dark Matter

+

Cosmological Constant





LSS

We know enough to be confused…

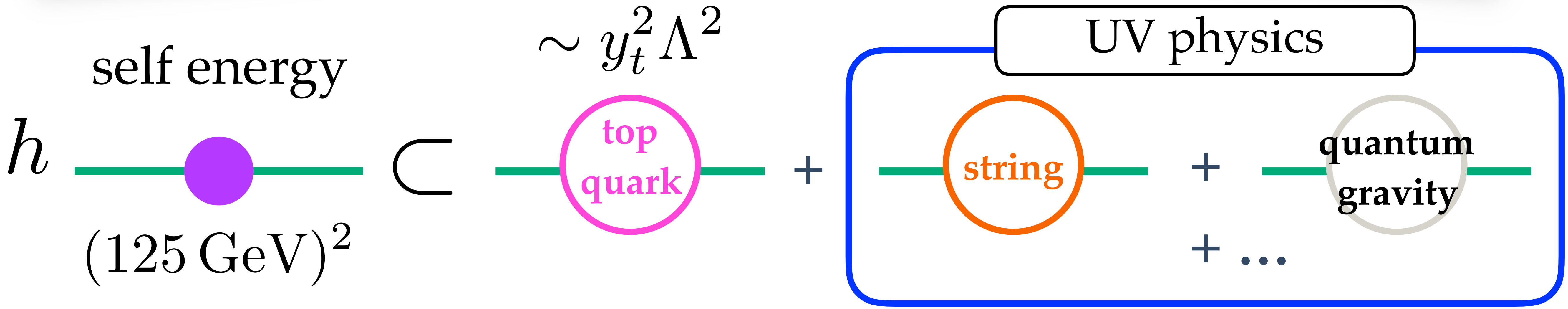
Higgs Hierarchy problem

What is dark matter?

The solution of these puzzles will likely bind collider physics and cosmology

Higgs Hierarchy Problem

We run into trouble when ***calculating*** the Higgs mass

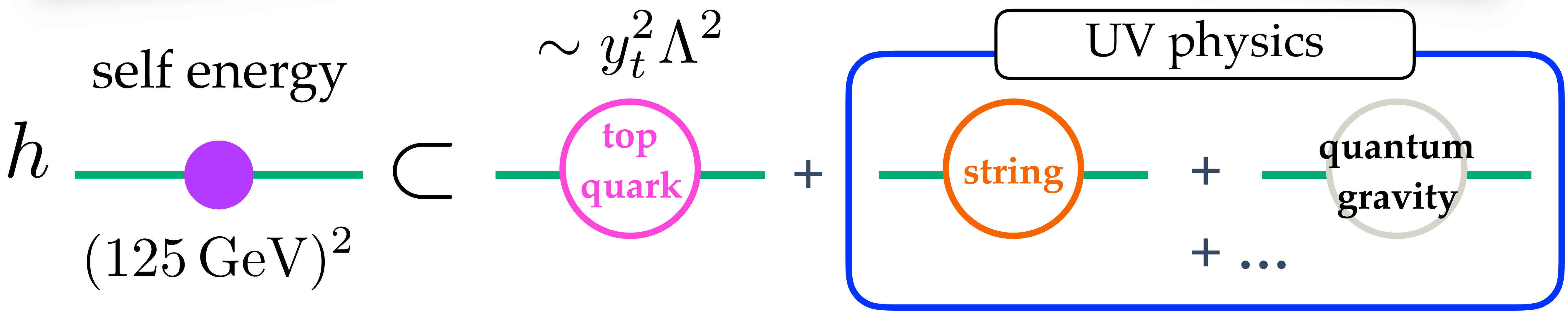


Electroweak scale is extremely sensitive to the UV correction

If SM works up to the Planck scale ~ 10^{19} GeV,
the cancellation for needs to be extremely tuned!

Higgs Hierarchy Problem

We run into trouble when *calculating* the Higgs mass



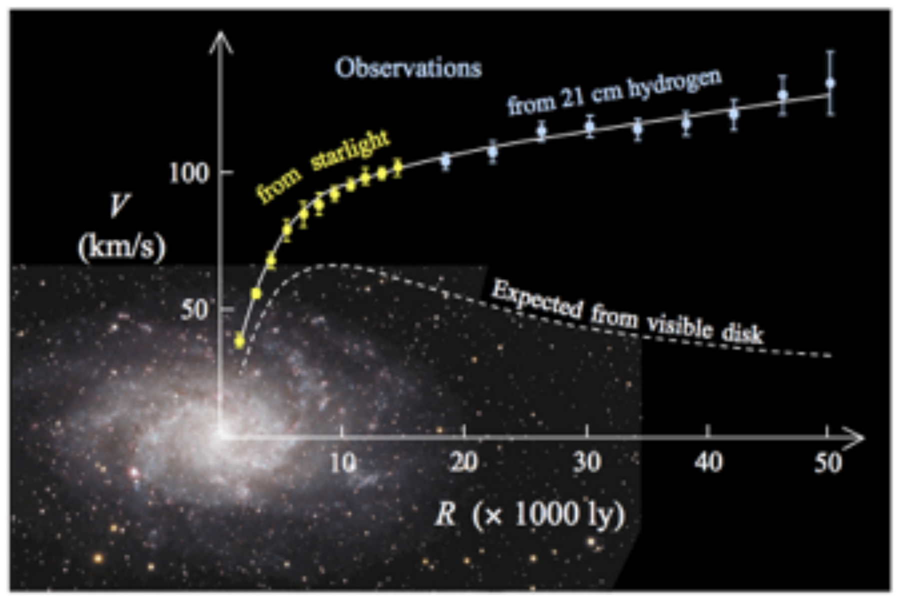
SM is only tested up to ~ TeV scale

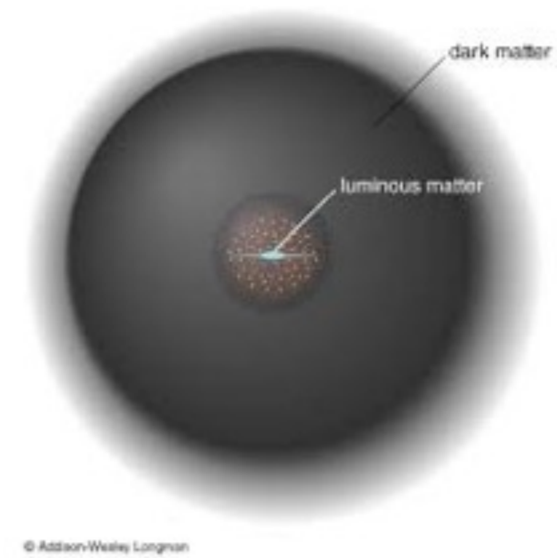
New physics may be waiting beyond that scale!

What is Dark Matter?

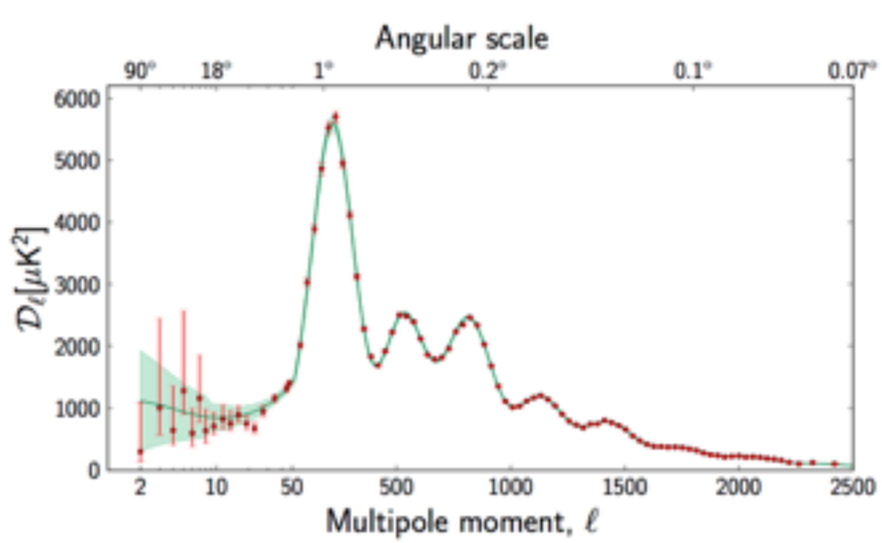
DM is there doing important things!

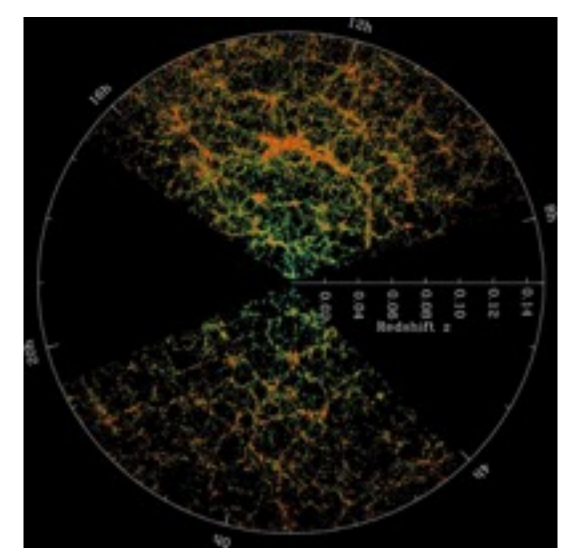
Small Scale Structure
~< 10 lyrs





Large Scale Structure
>~ 10 lyrs





What is Dark Matter?

But we don’t know its detailed property

What’s the mass of DM particles?

Single species, or a whole zoo of dark particles?

Non-gravitational interaction?

How do they obtain their relic density?

What is Dark Matter?

Also, we see weird things in cosmological signatures

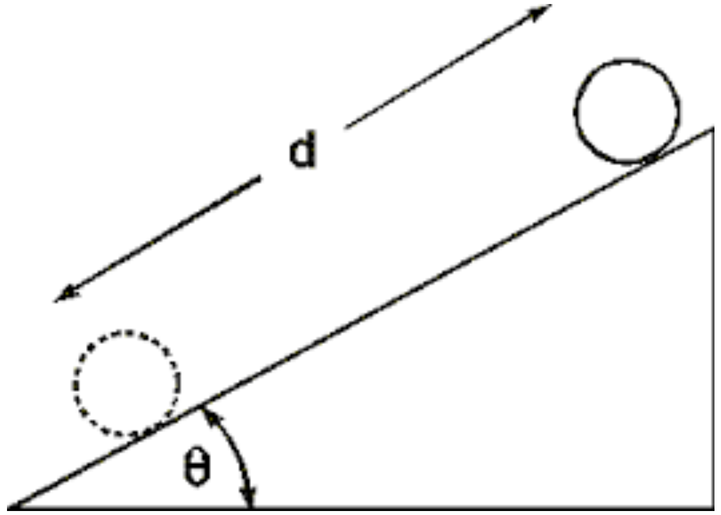
Mass deficit problem in Small Scale Structure

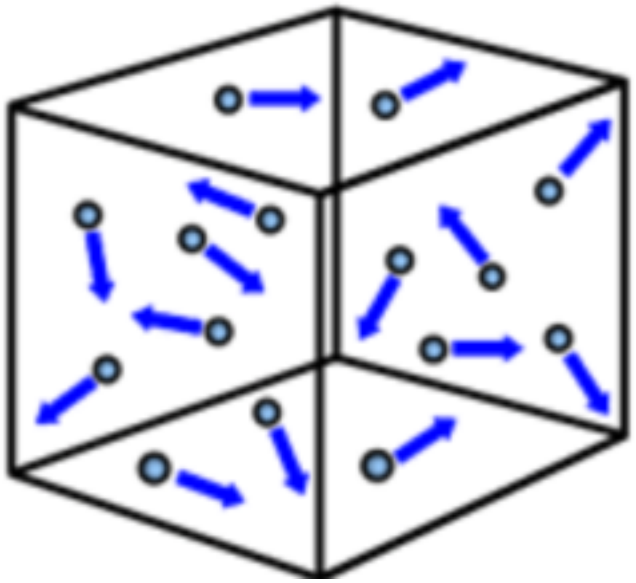
$(\sigma_8,\ H_0)$ problem in Large Scale Structure

Possible signals from indirect detection experiments

Suggest a more complicated dark sector

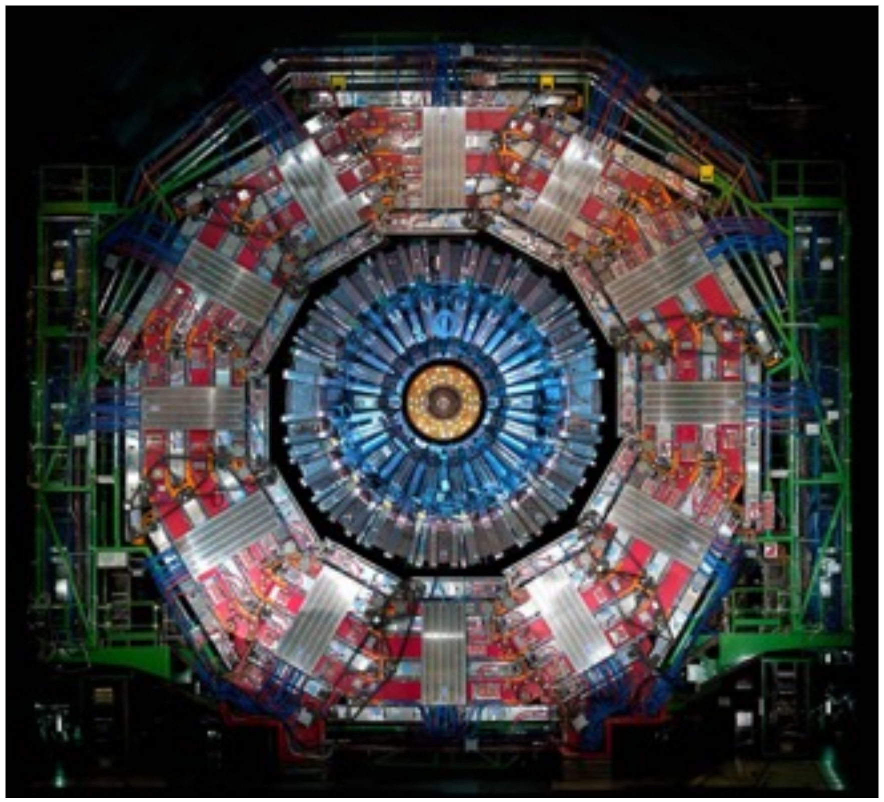
How are we going to study these?

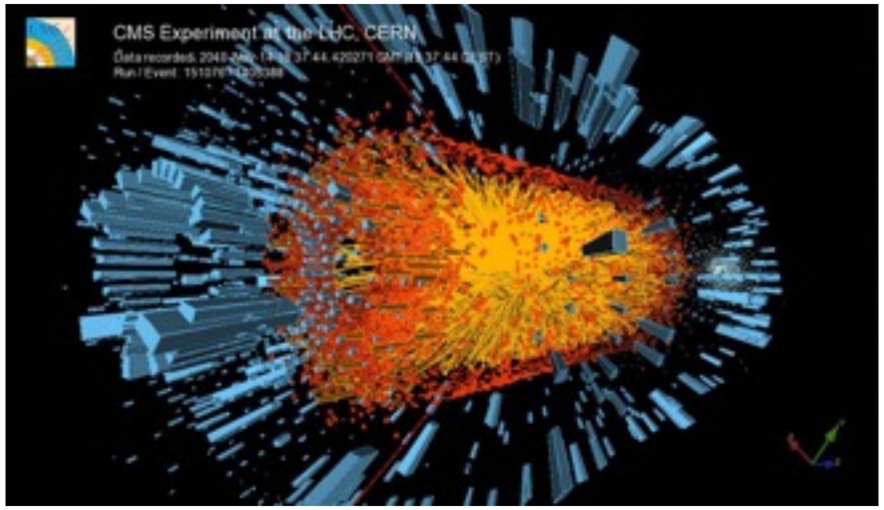




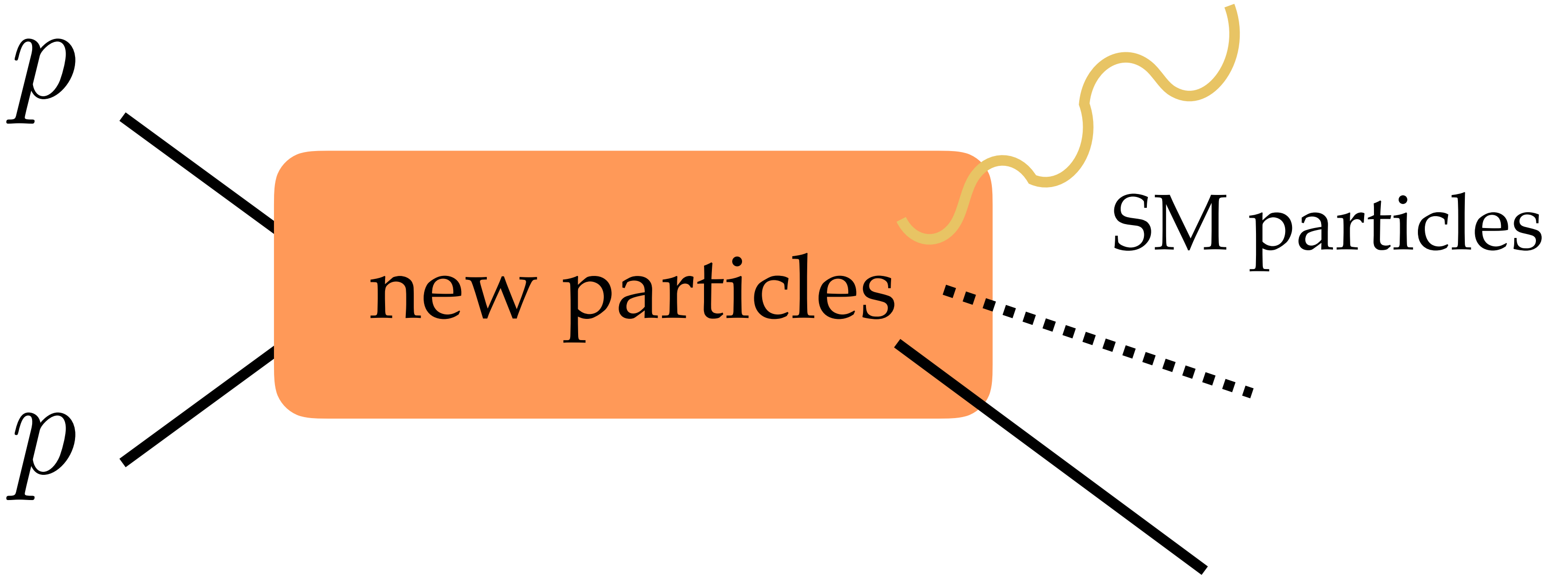
How are we going to study these?

High energy collider, sensitive detectors





Can identify new particles if they couple to us



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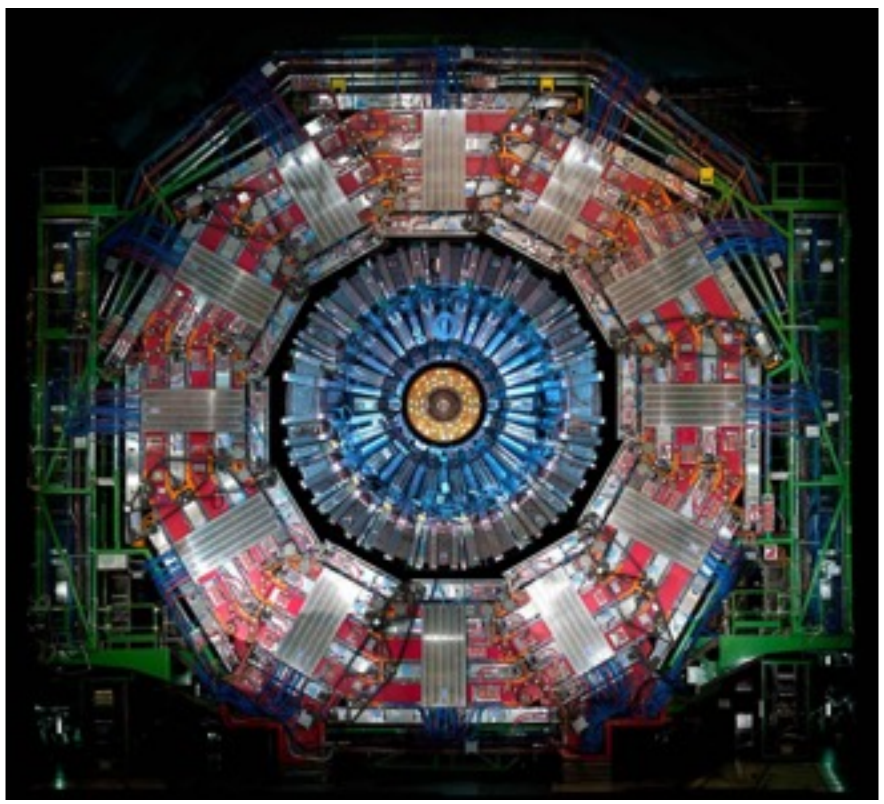

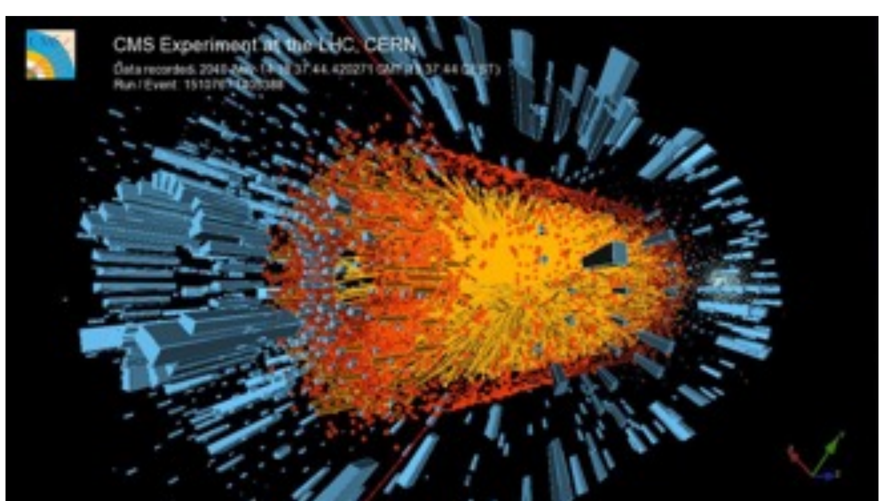

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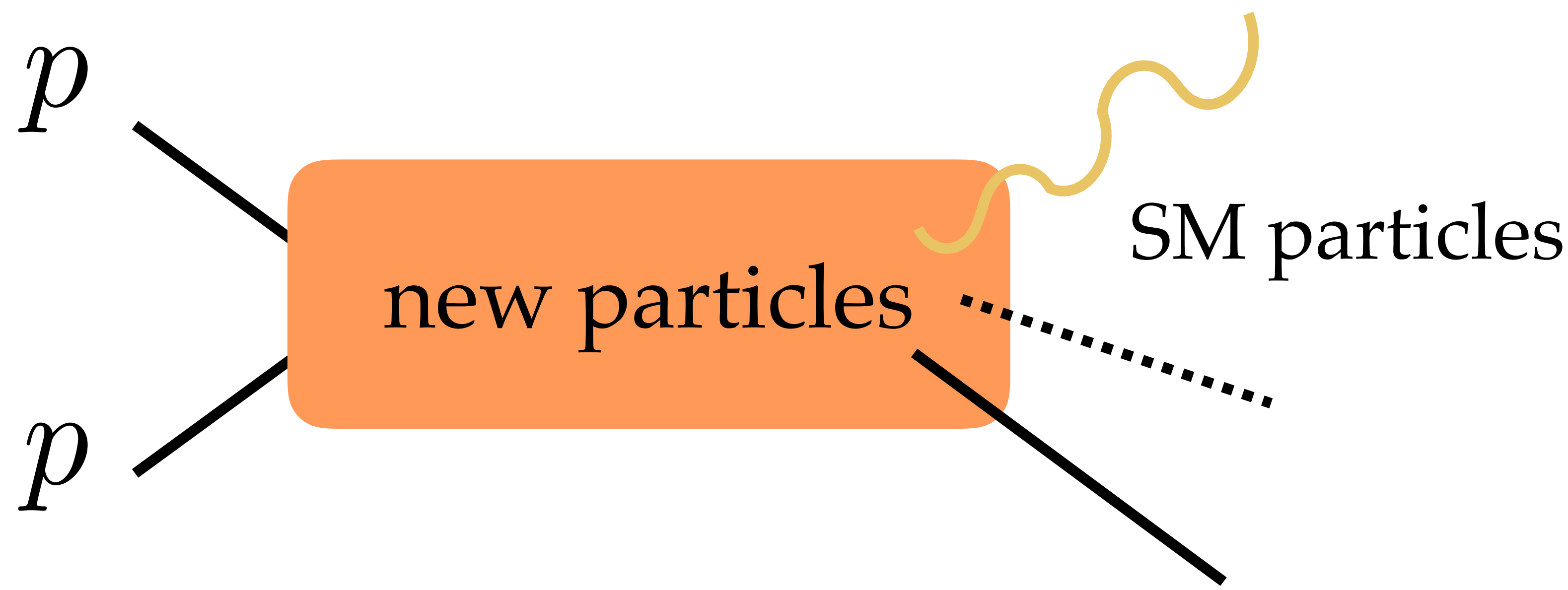
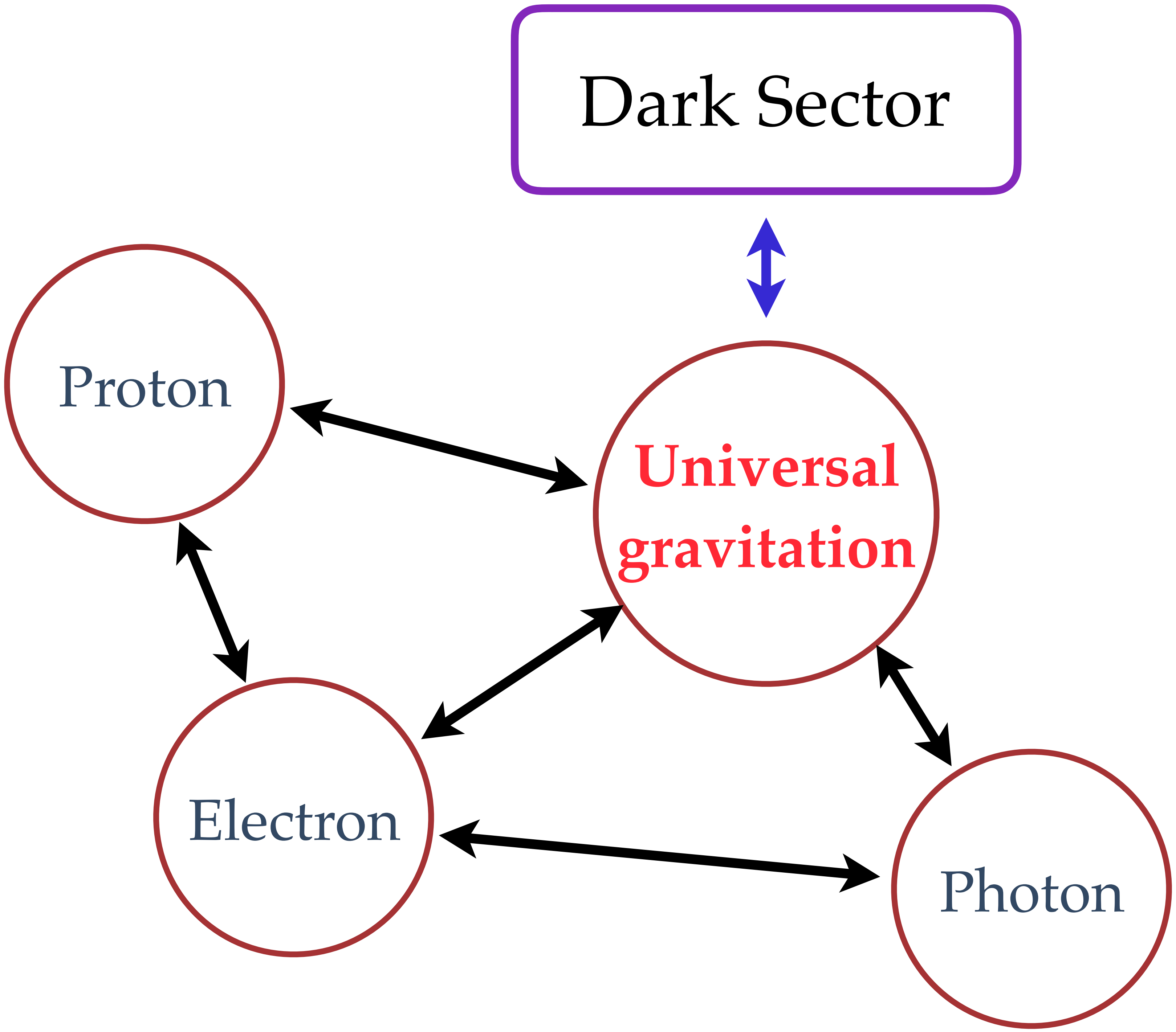
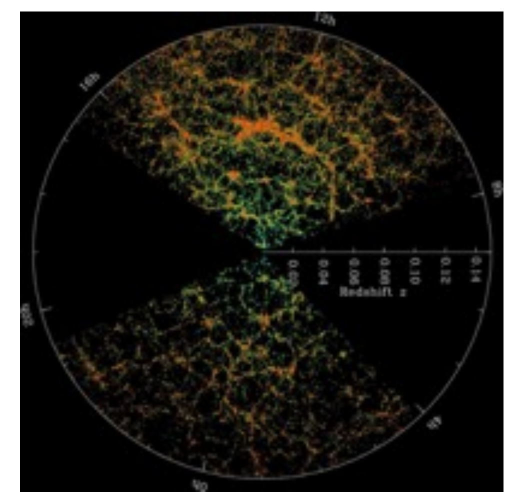


but what if they don't couple to us, or if the coupling is tiny?

Cosmological signatures

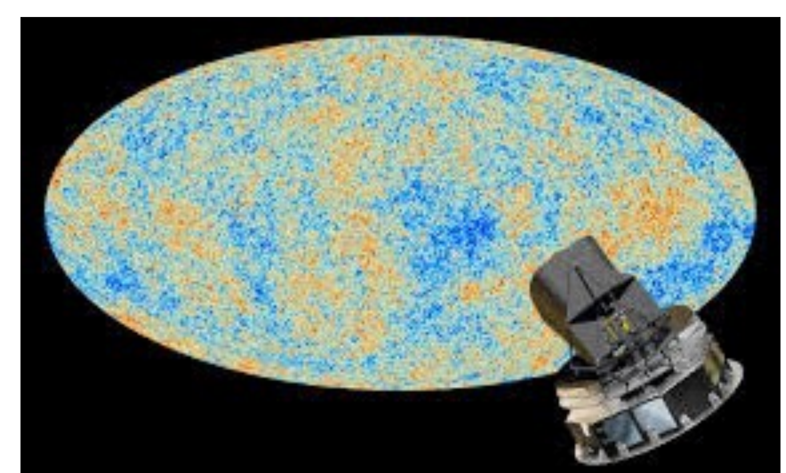


galaxy structure

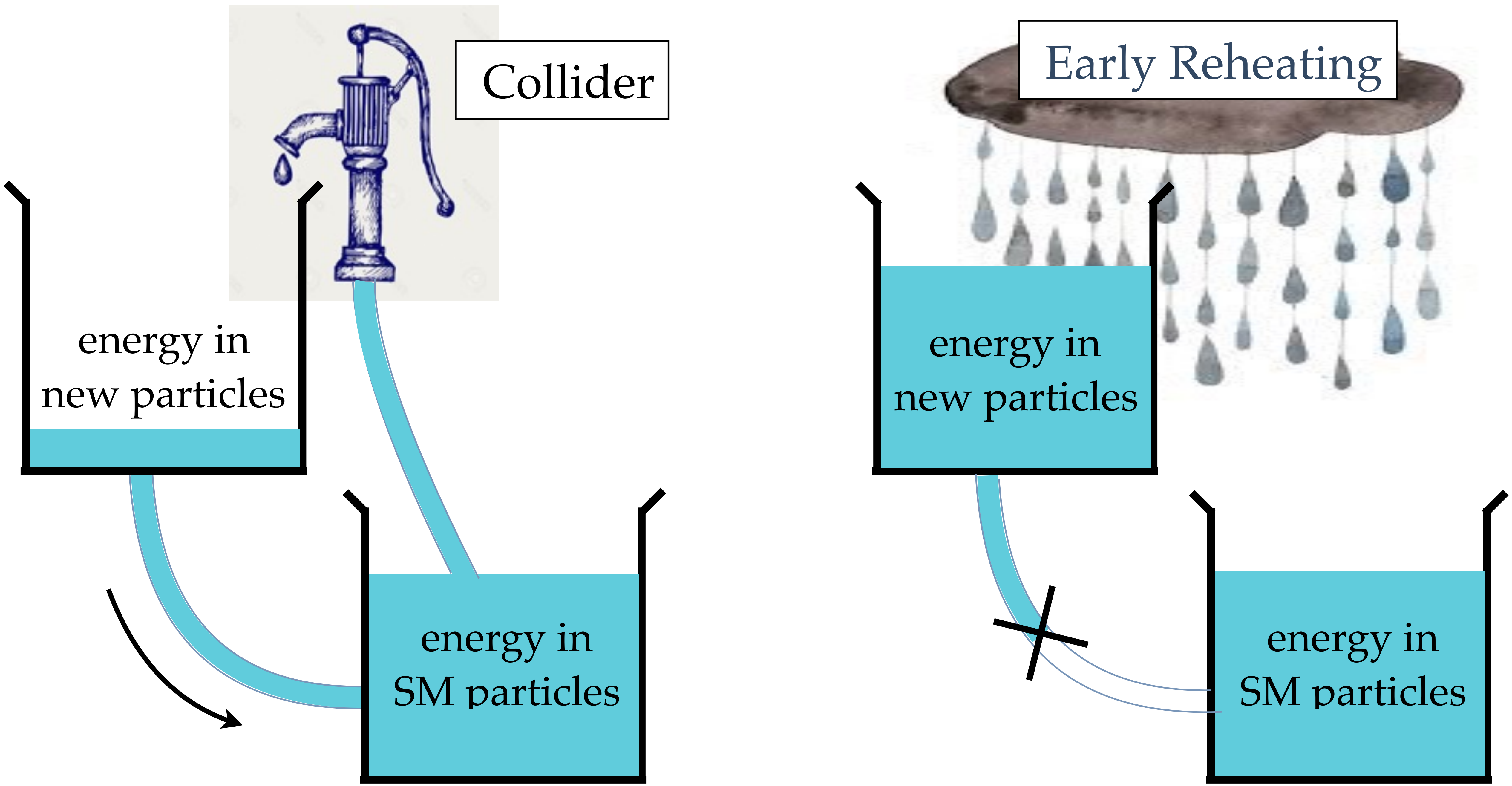


Large scale structure

CMB



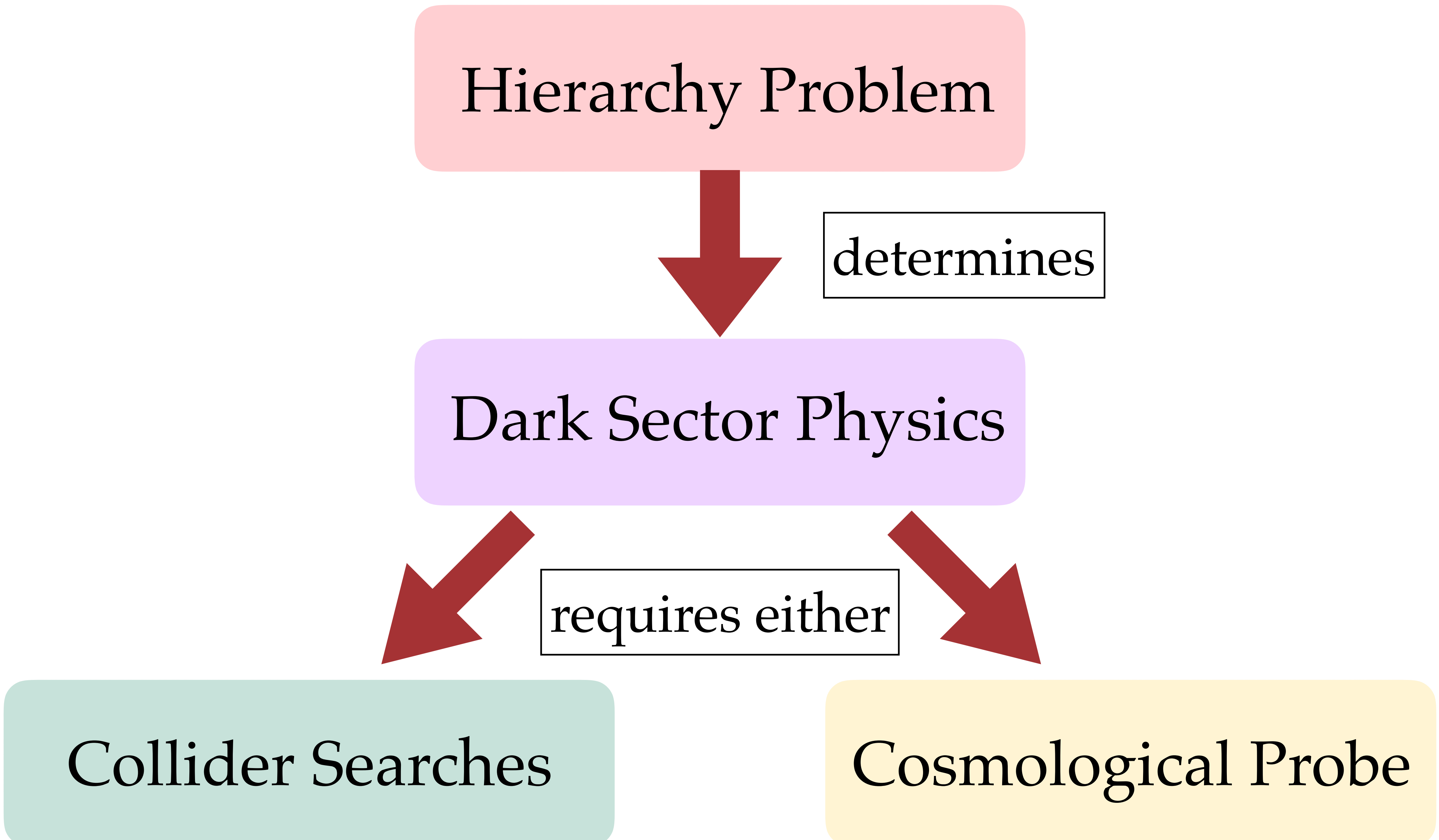
The Collider <-> Cosmology Interplay



energy leak back into SM
seeing collider signals

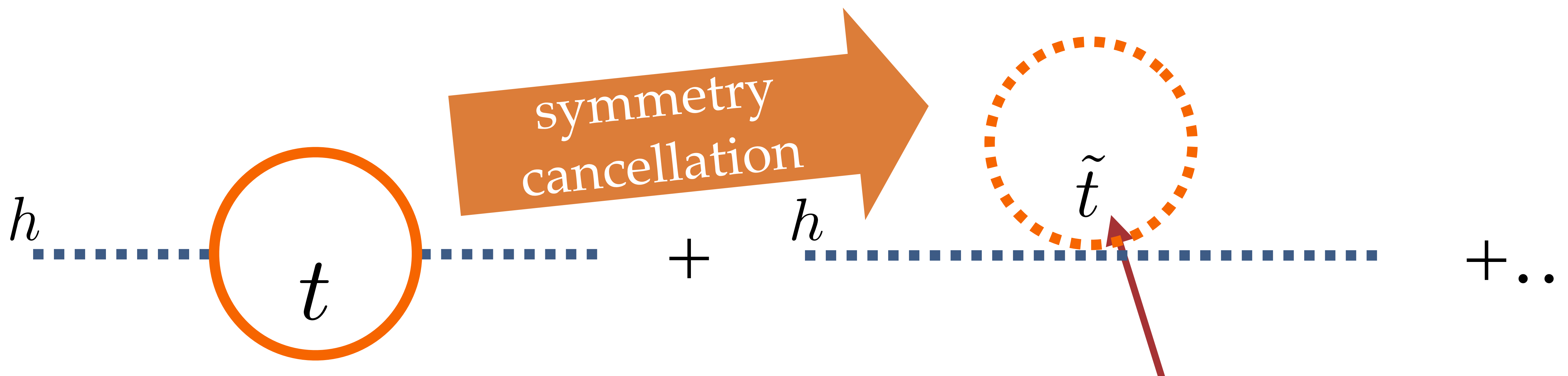
lots of energy in new particles
change the cosmology

Example: Neutral Naturalness scenarios



One solution to the hierarchy problem:
Supersymmetry

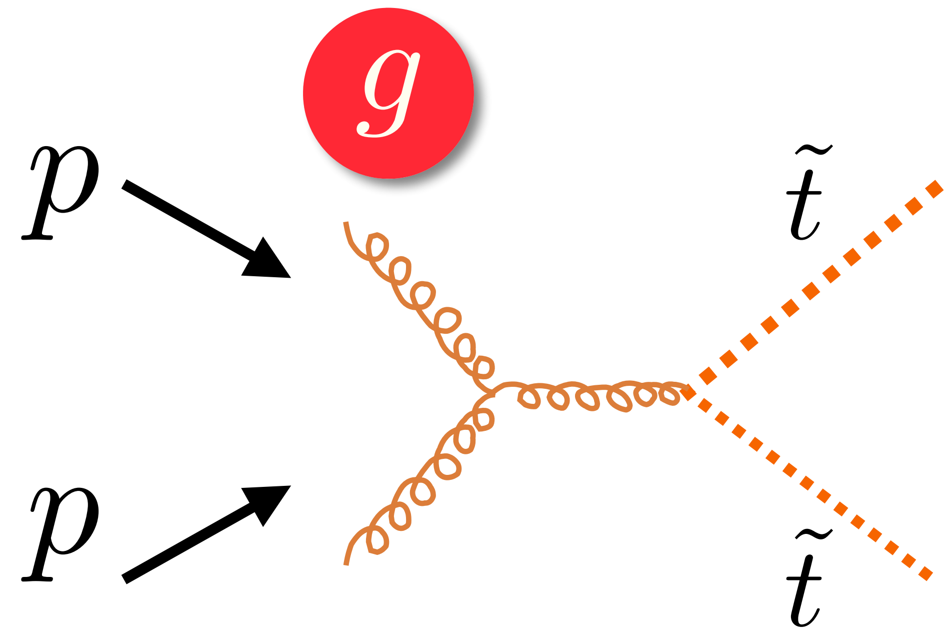
Super particle loops cancel the divergence

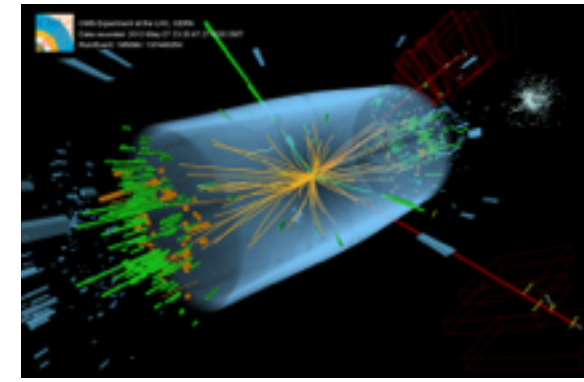


top quark
carry SM QCD charge

Top Partner
carry SM QCD charge

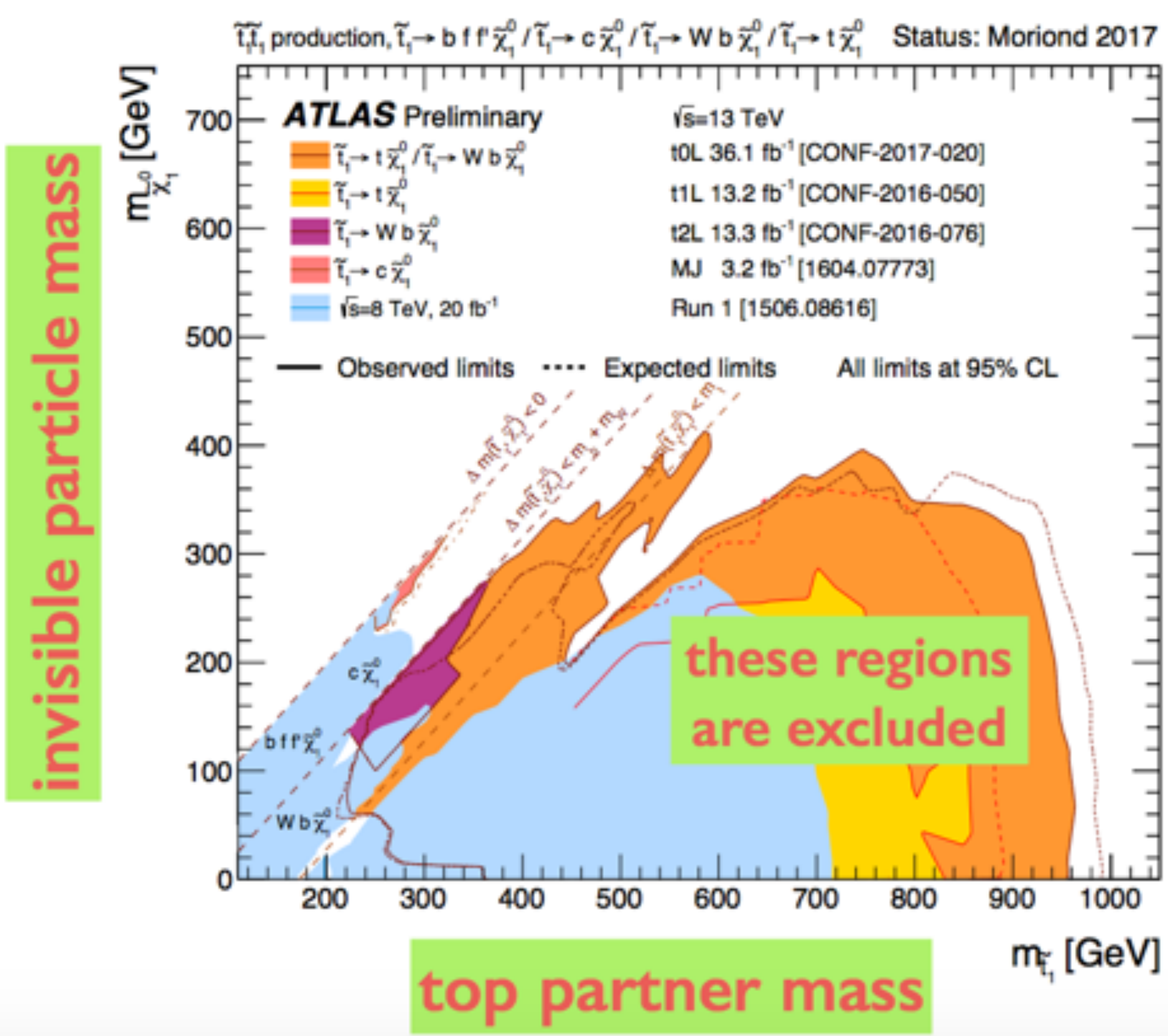
symmetry





collider signal

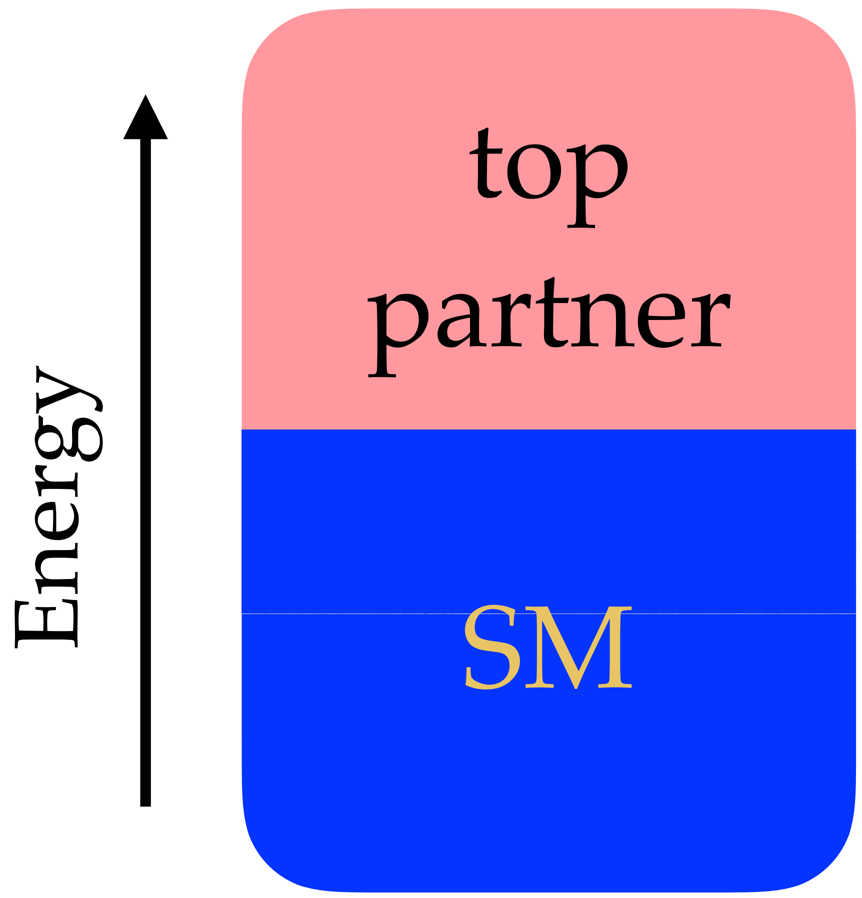
No SUSY so far…



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

The hope for symmetry cancellation is fading…

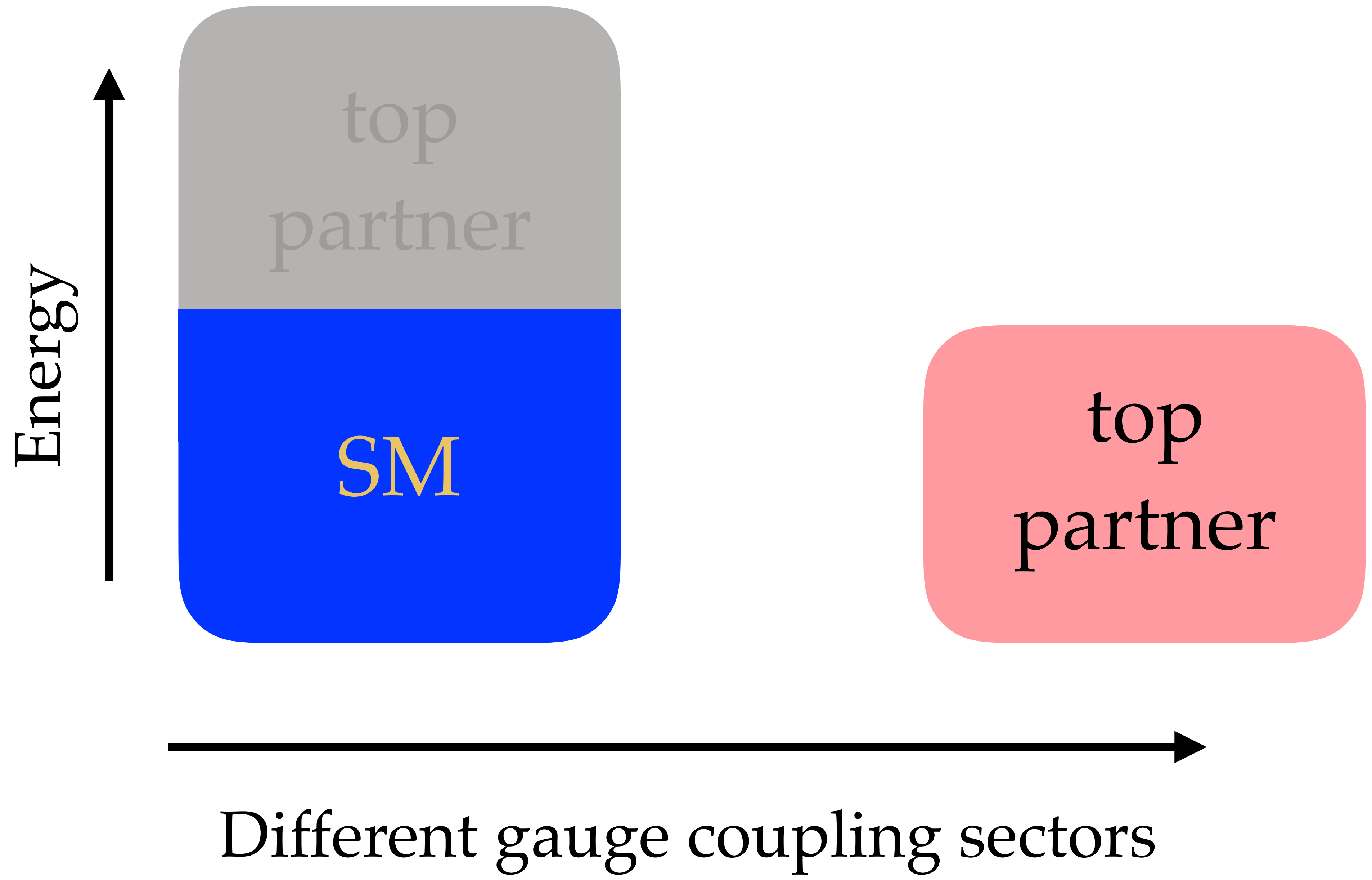
The standard structure of top partner



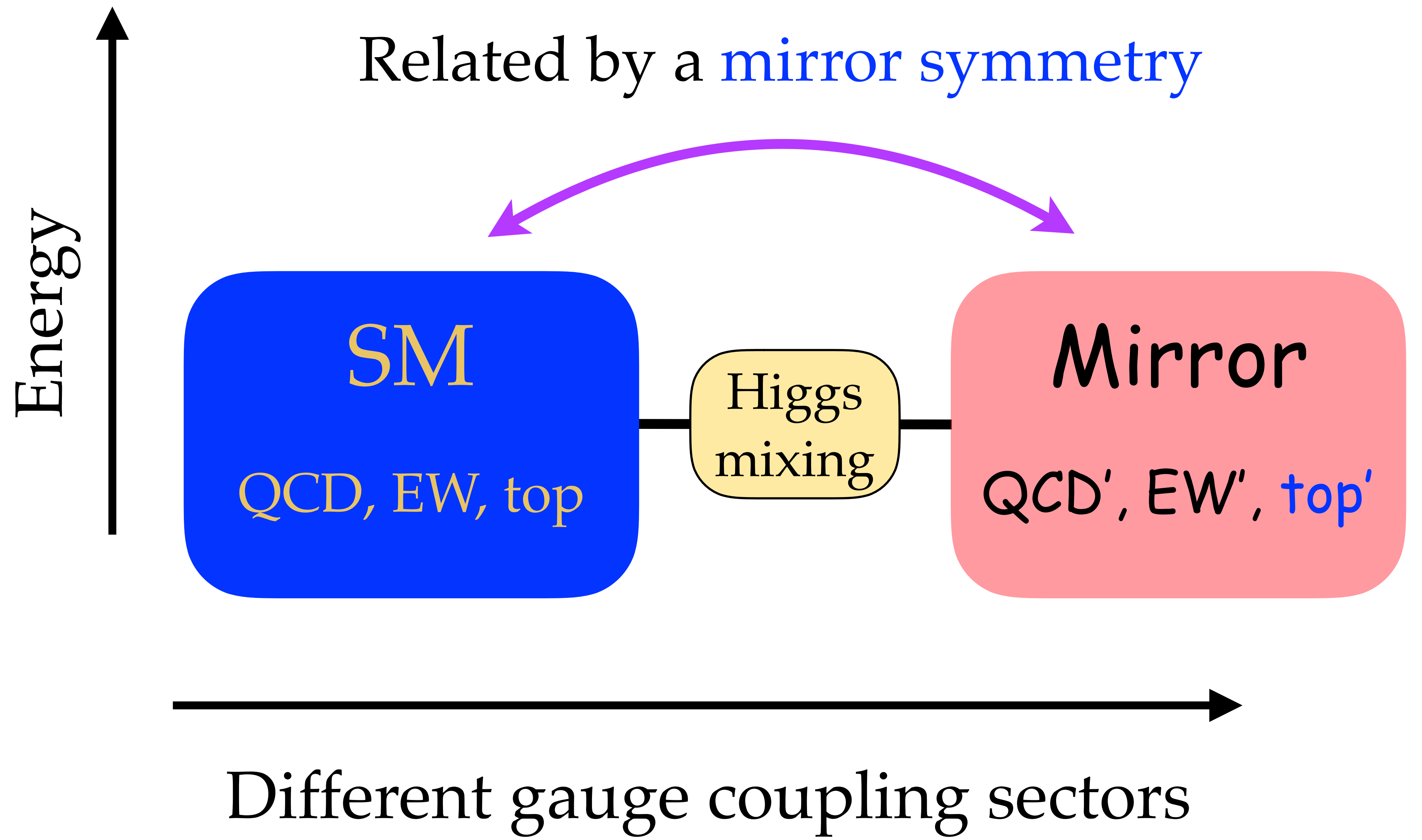
top partner at high mass carry
the same SM top couplings

(e.g., QCD for collider production)

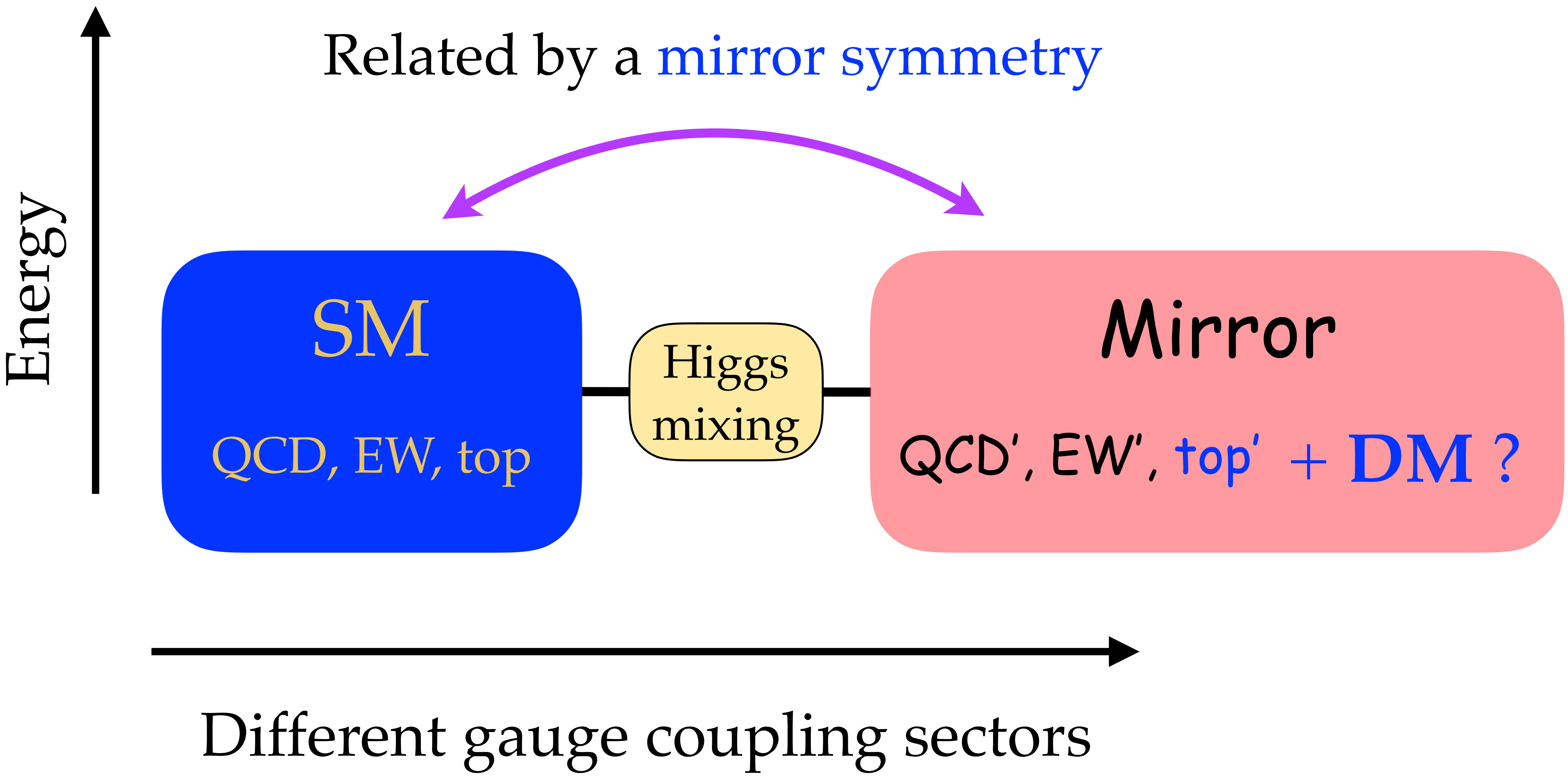
Motivated by collider constraints



Hidden Naturalness solution to the Hierarchy Problem

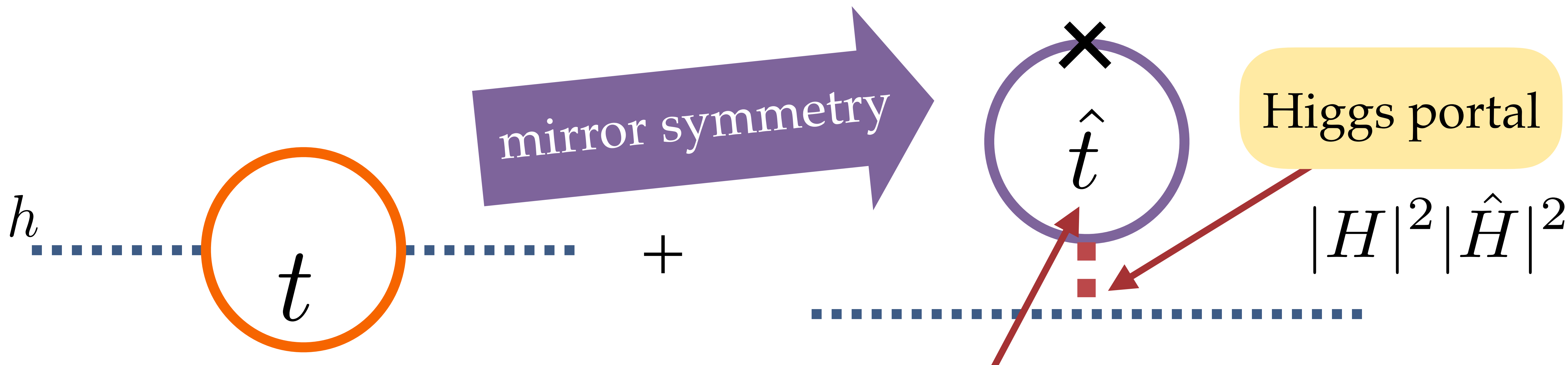


A nice structure for Dark Matter too!



A concrete example: Twin Higgs

Chacko, Goh, Harnik (05')



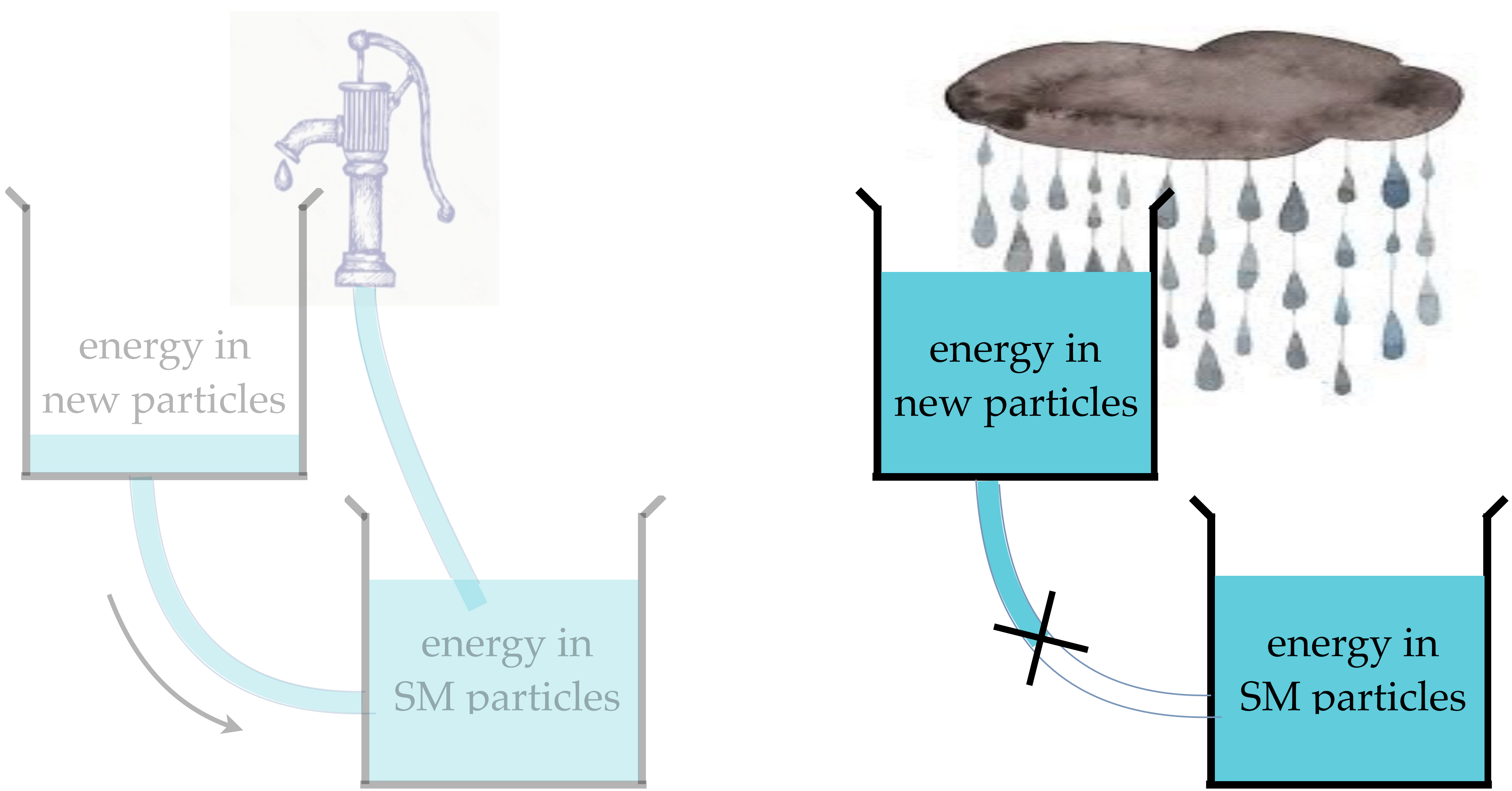
Top
carry SM gauge charges

Mirror top
carry mirror gauge charges

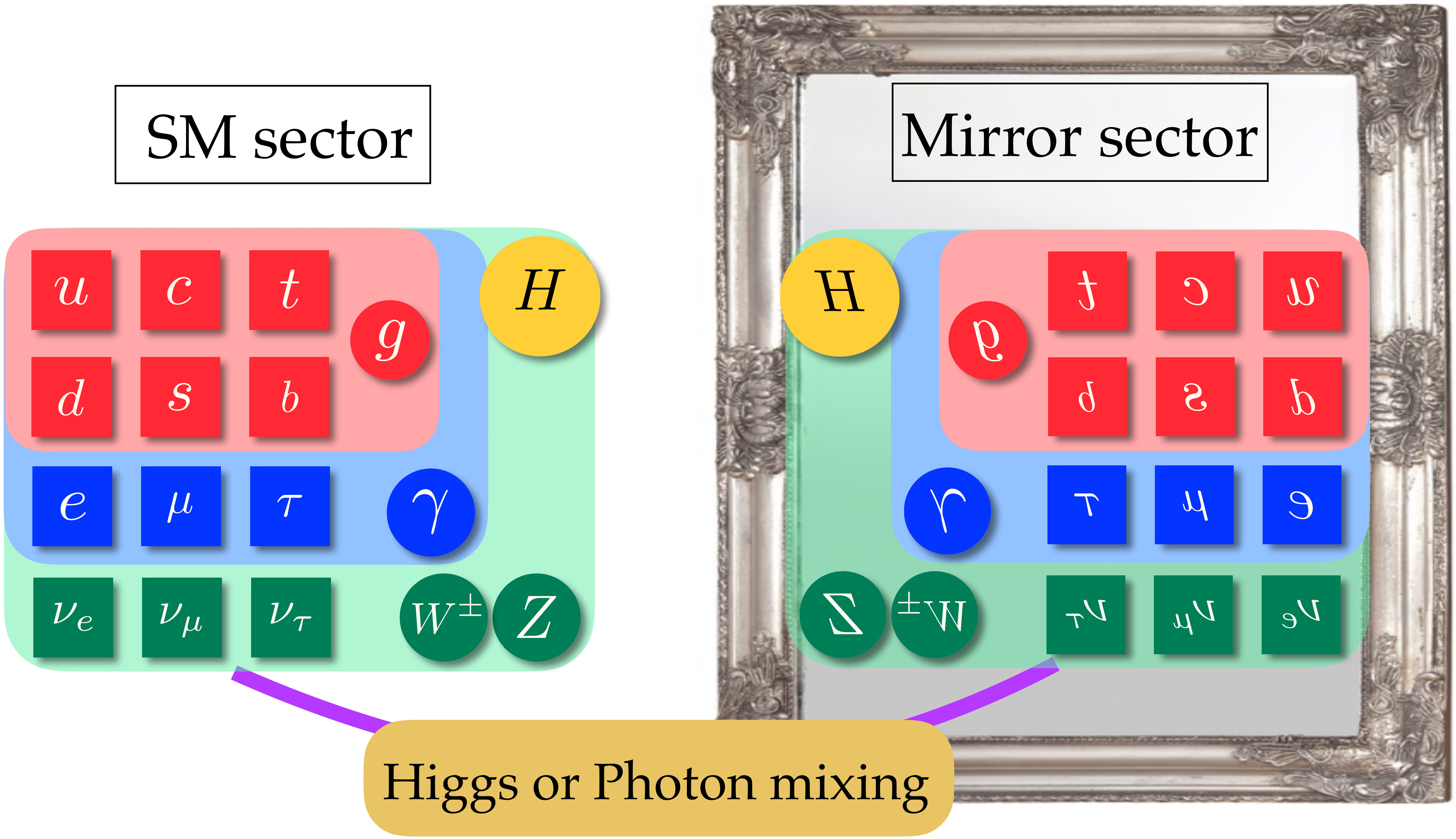
Mirror copy of the relevant particles

Part I.

Cosmological Signatures from Mirror Twin Higgs



Mirror Symmetric Twin Higgs

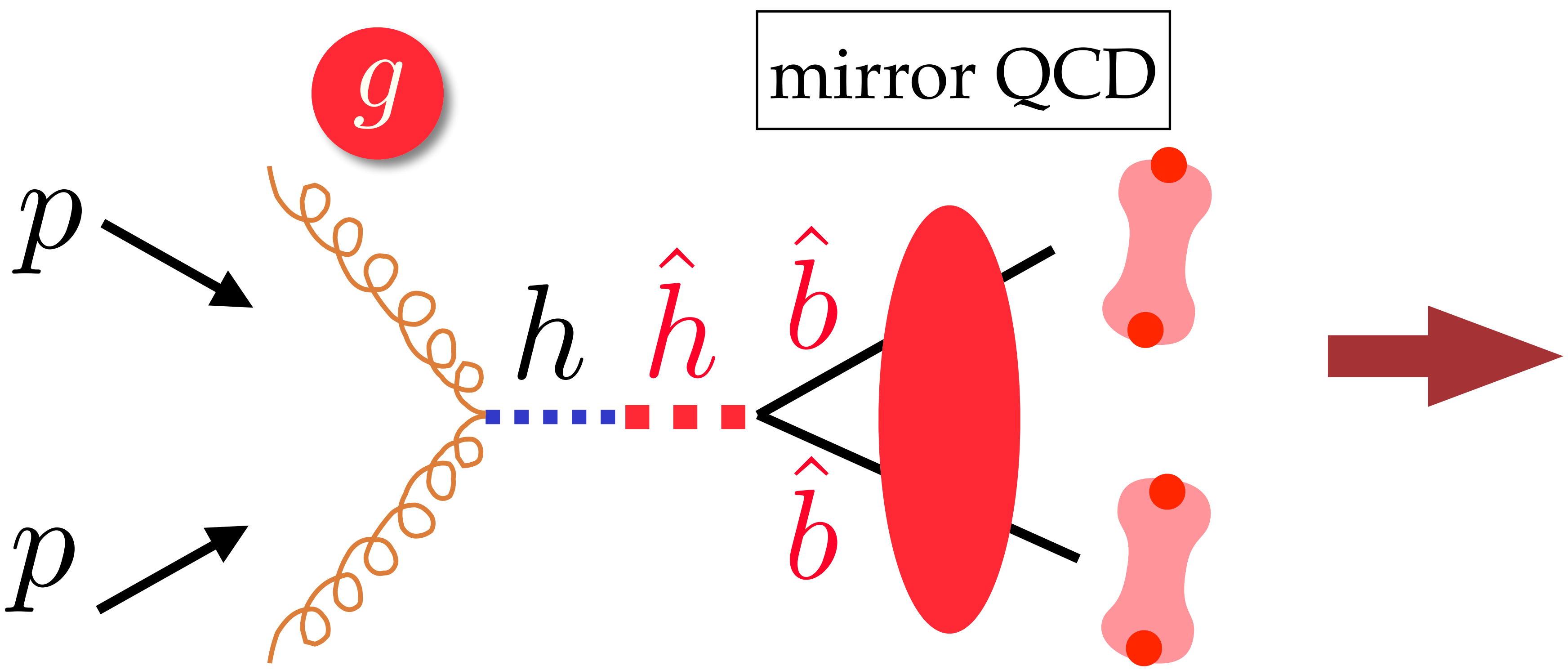


$$v_B/v_A \geq 3$$

Easier to UV-complete

Higgs coupling measurement

Collider Search? It's hard…



Decay into light twin particles & remain invisible

This is why we need to look into Twin Cosmology

Lots of interesting things in Twin cosmology

Cosmological Signatures of a Mirror Twin Higgs

Chacko, Curtin, Geller, YT (*in progress, 18'*)

Solving small scale structure puzzles

Prilepina, YT (17')

Addressing large scale structure puzzles

Prilepina, YT (17')

Galactic center gamma ray excess

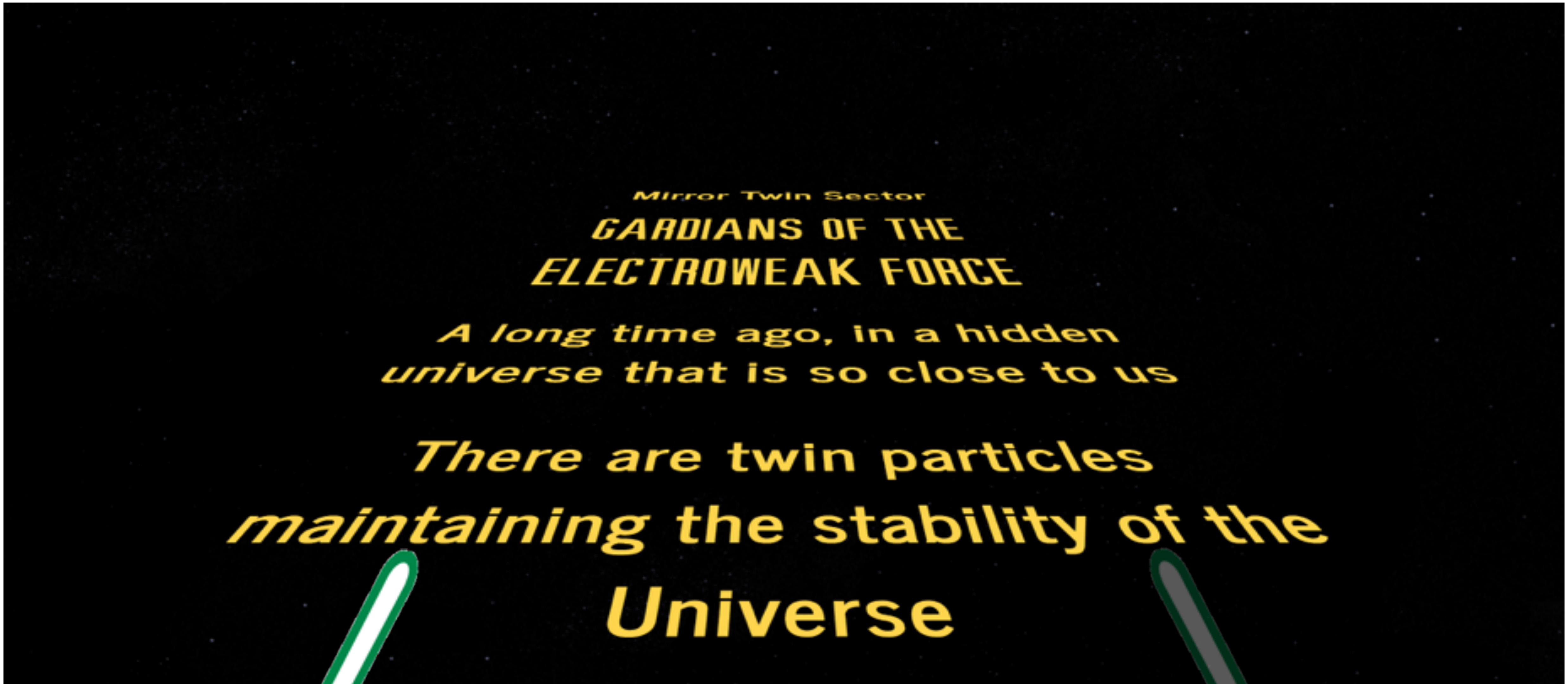
Freytsis, Knapen, Robinson, YT(16')

Cosmological constraint on twin meson lifetime

Cheng, Jung, Salvioni, YT (15')

Here I will only discuss the effect of Twin sector on **Large Scale Structure**

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

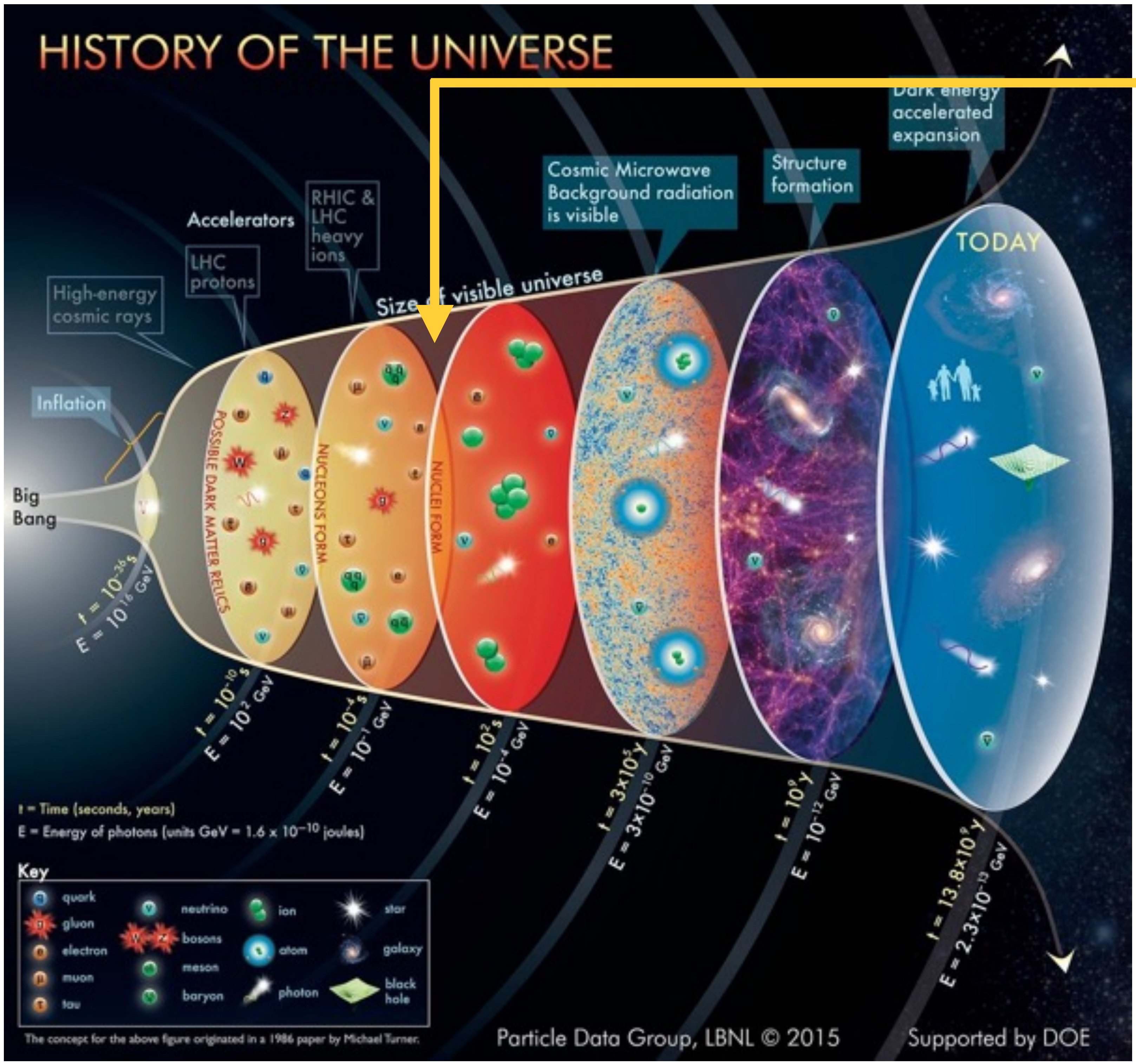


SM $(p,\ n,\ e,\ \gamma,\ \nu)$

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

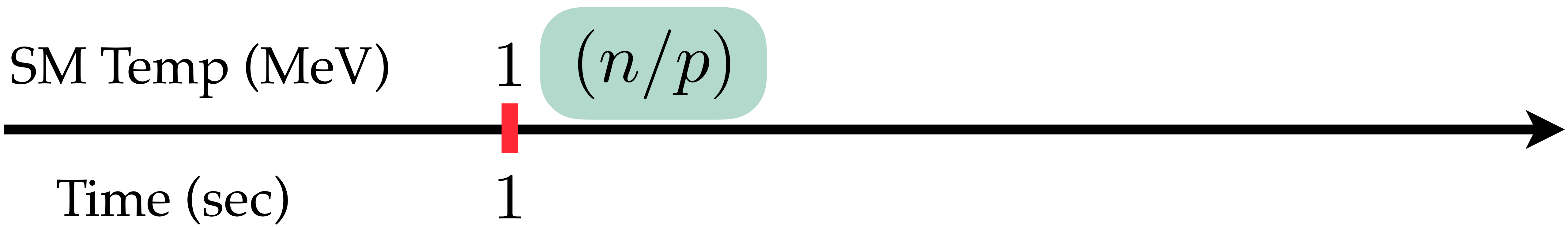
+ Cold DM

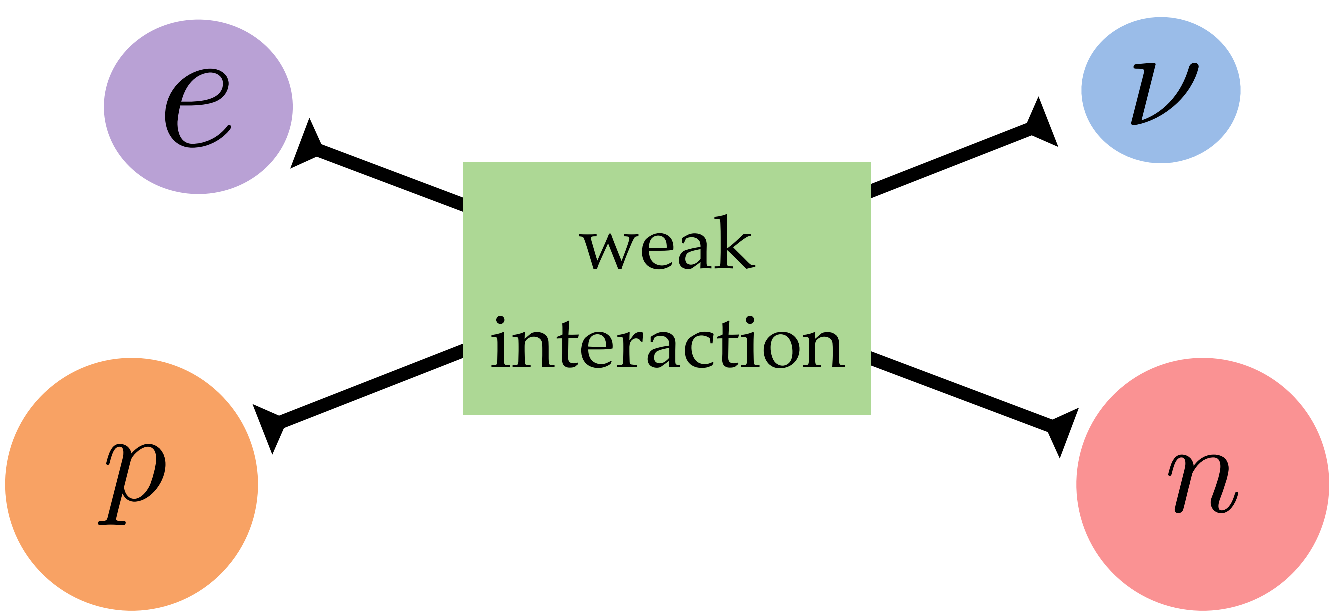
Big-bang Nucleosynthesis (~1 sec, T ~ MeV)



Nucleosynthesis
nuclei formation

(neutron / proton) freeze out



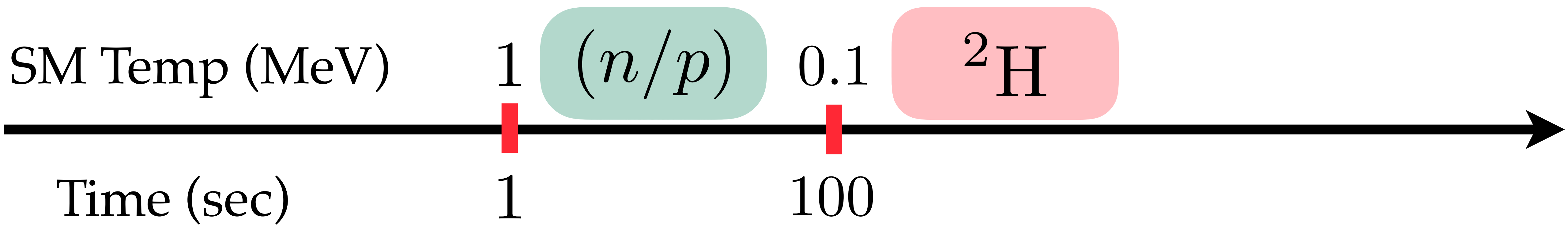


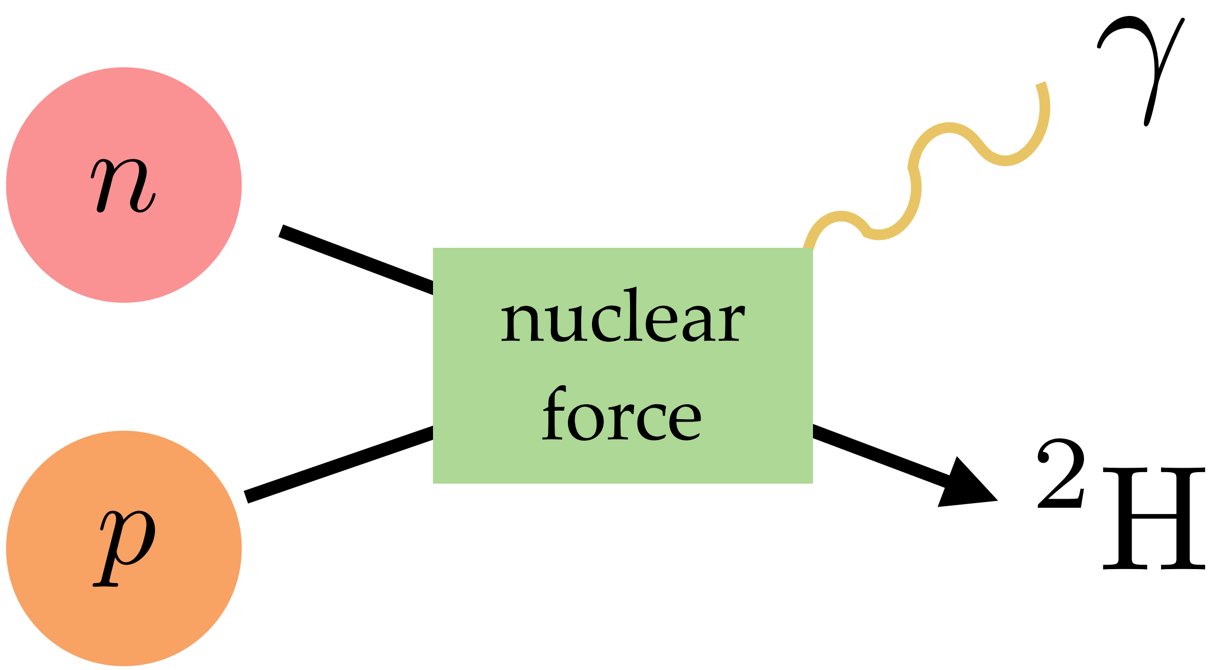
Out of equilibrium when
T < $T_F \sim 0.8\,\text{MeV}$

neutron / proton number
ratio ~ 14%

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

Deuterium Bottleneck





Inverse process stops when

$$n_\gamma \, e^{-B(^2\mathrm{H})/T} < n_p$$

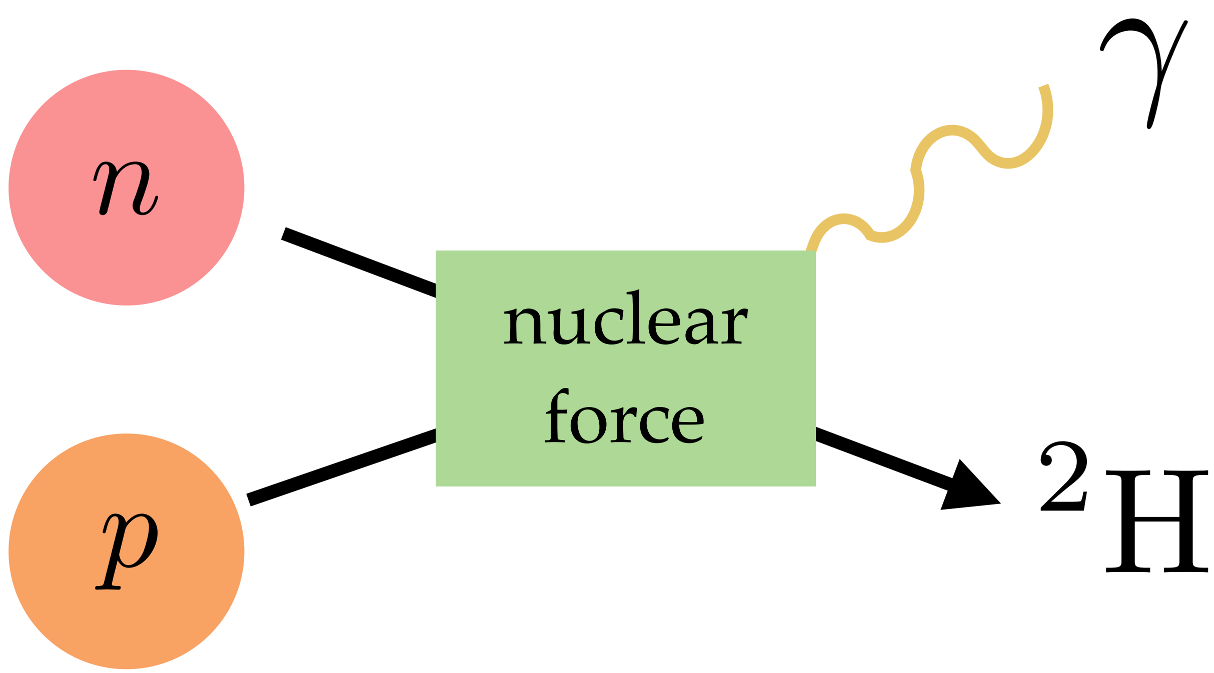
$$B(^2\mathrm{H}) = 2.2\,\mathrm{MeV}$$

Deuterium forms when $T \lesssim 0.1\,\mathrm{MeV}$

Deuterium Bottleneck

SM Temp (MeV) 1 (n/p) 0.1 ^{2}H 0.03 n lifetime

Time (sec) 1 100 880



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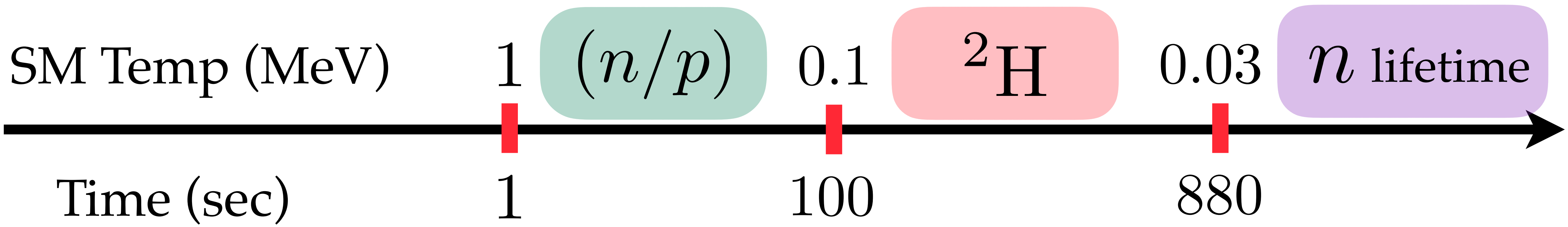
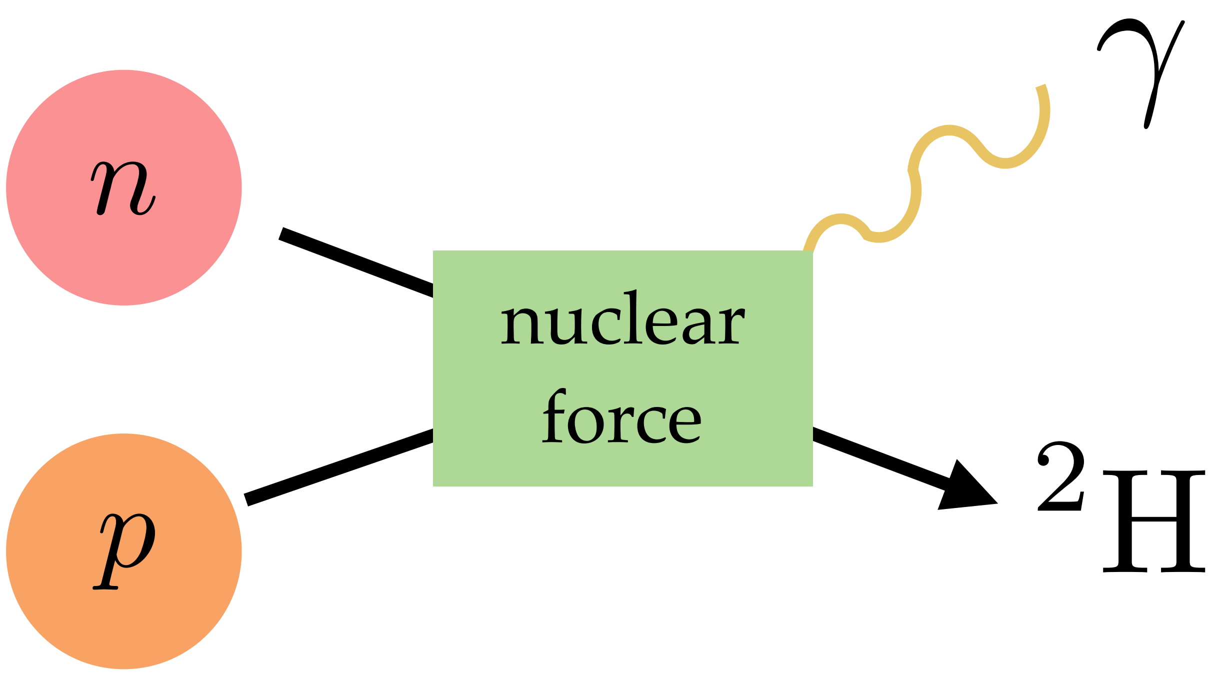
Deuterium forms when $T \lesssim 0.1\,\mathrm{MeV}$

Luckily, this happens ``before'' neutron decays

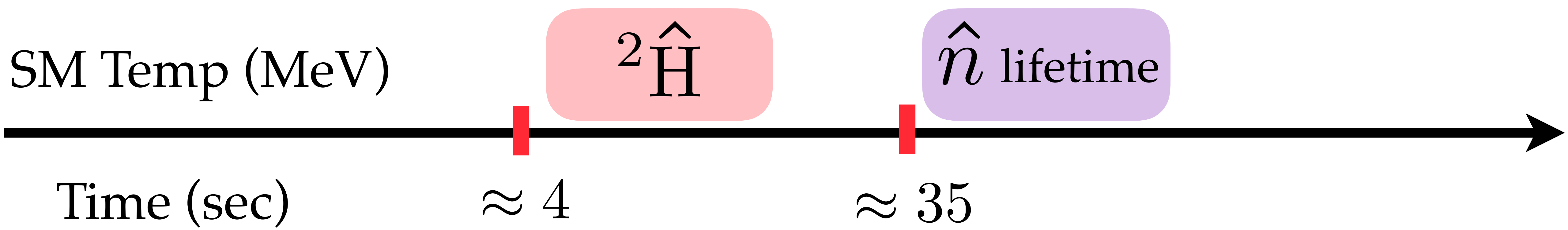
Deuterium Bottleneck

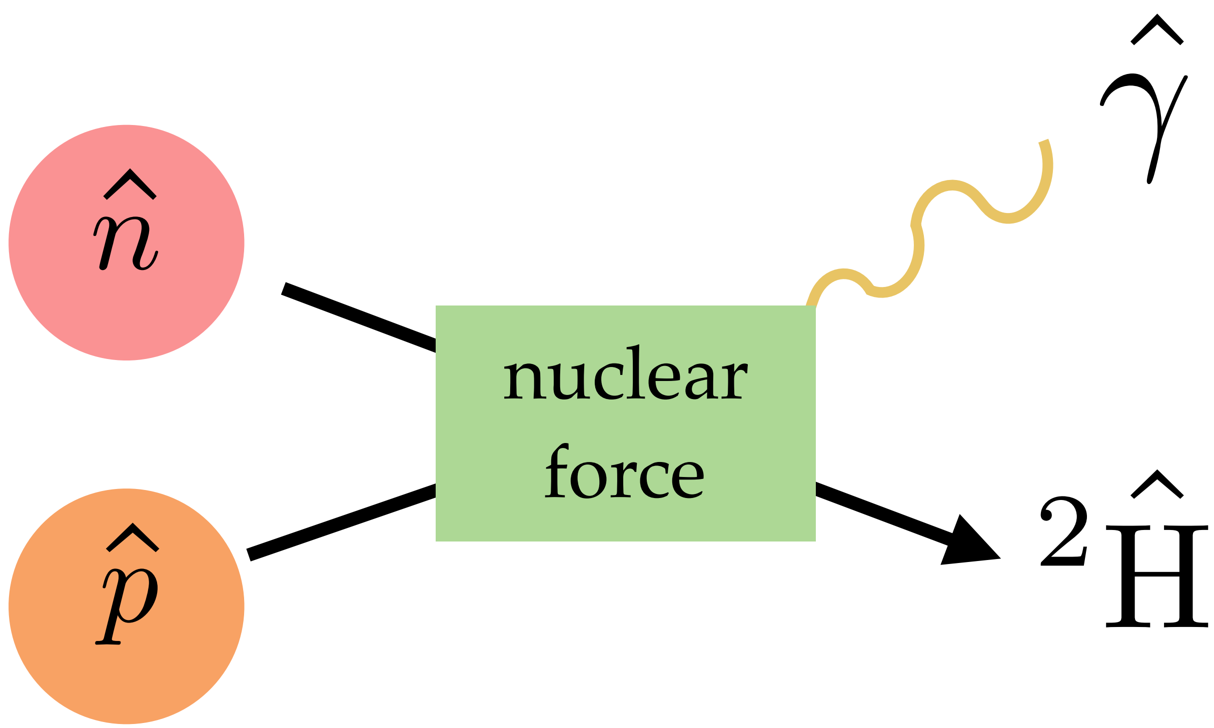




$$p + n \rightarrow {}^2\mathrm{H} + \gamma$$
$$p + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + \gamma$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{He} + n$$
$${}^2\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^3\mathrm{H} + p$$
$${}^3\mathrm{He} + {}^2\mathrm{H} \rightarrow {}^4\mathrm{He} + p$$
$${}^3\mathrm{H} + {}^2\mathrm{H} \rightarrow {}^4\mathrm{He} + n$$

Let's first check Twin Deuterium Bottleneck





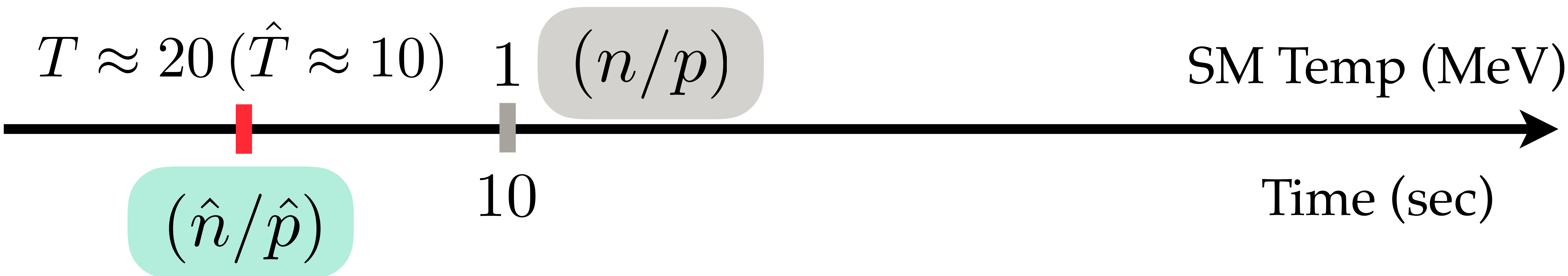
$$\frac{t_{^2\hat{\mathrm{H}}}}{t_{\hat{n}\ \mathrm{decay}}} \approx \frac{t_{^2\mathrm{H}}}{t_{n\ \mathrm{decay}}}$$

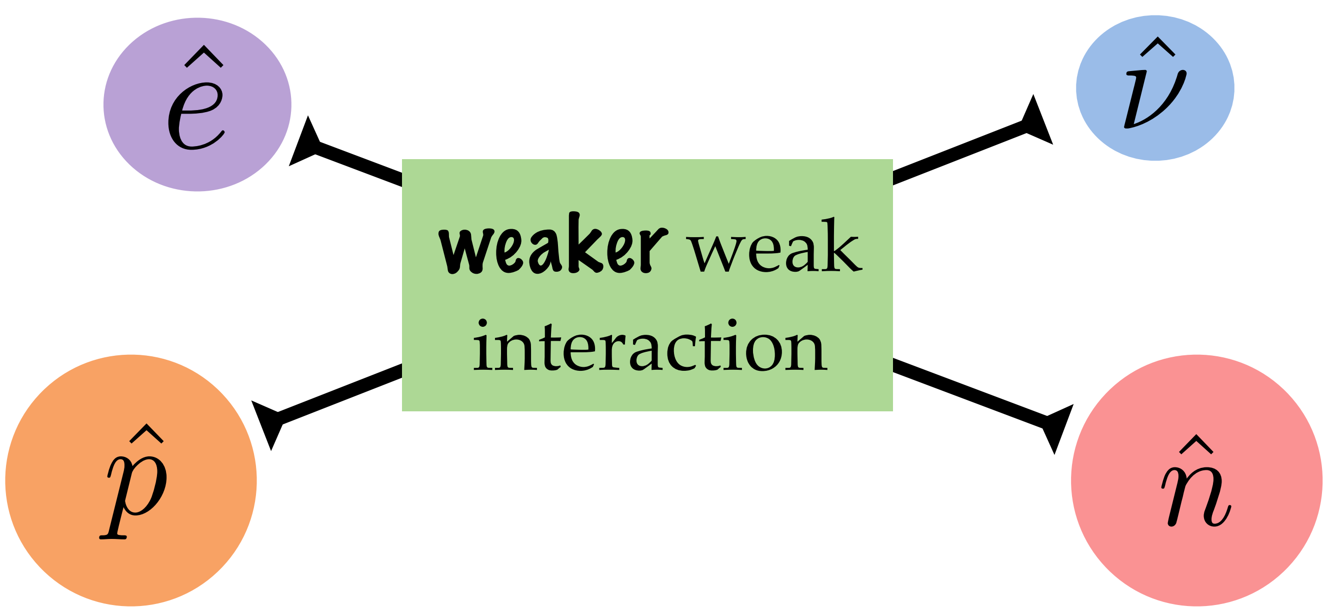
Estimate twin ^{2}H binding energy from lattice calculation

1508.07583

Twin deuterium also forms before twin neutron decay

Twin (neutron / proton) freeze out earlier





Lower n <-> p rate

Process stops at a higher temperature!

$$\left(\frac{\hat{n}}{\hat{p}}\right) \sim e^{-\frac{\Delta M_{\hat{n}\hat{p}}}{\hat{T}_F}}$$

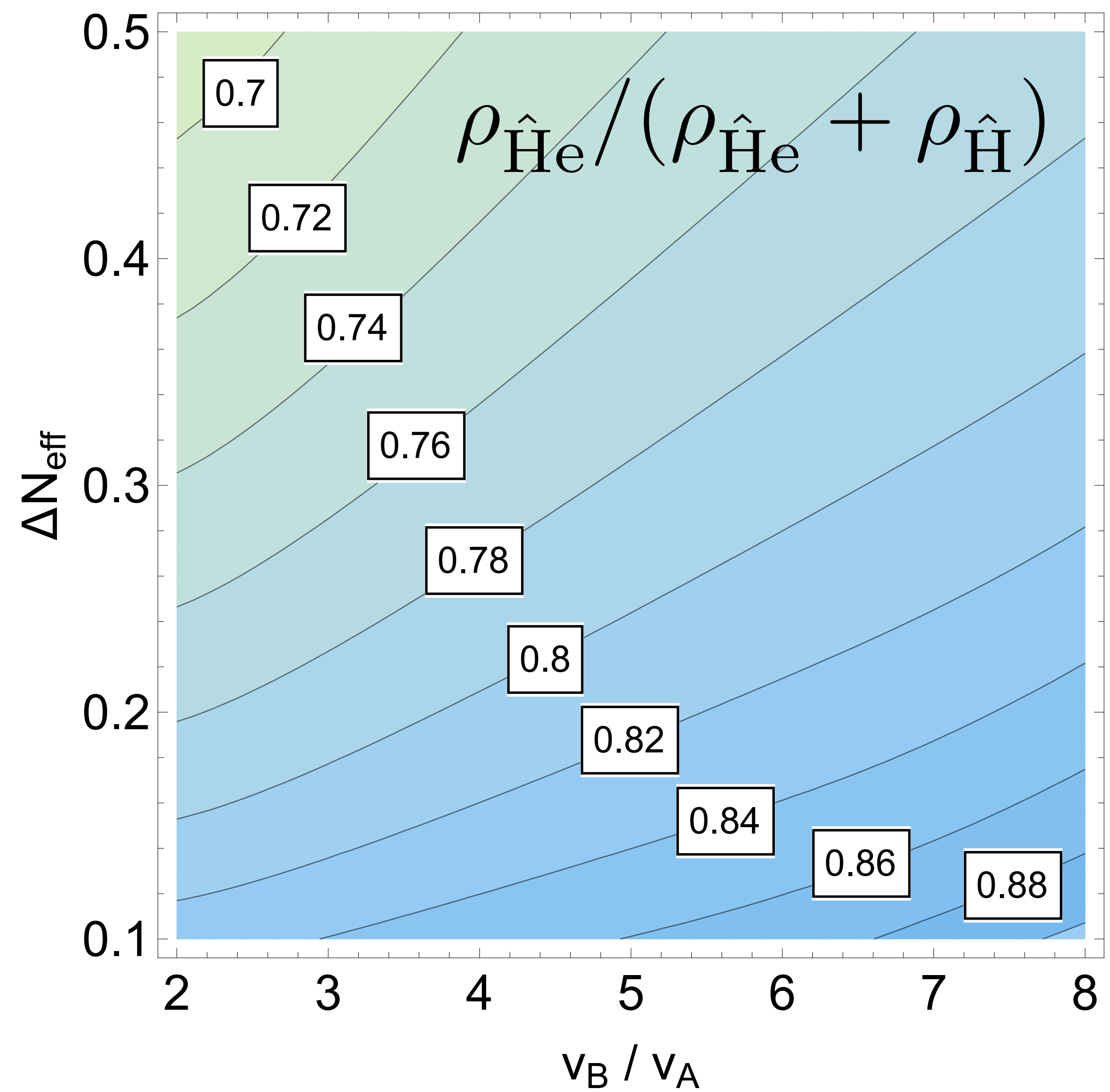
$$\Delta M_{\hat{n}\hat{p}} \sim 5\,\Delta M_{np}$$

Twin helium dominates twin matter density

Chacko, Curtin, Geller, YT (*in progress, 18'*)

Twin: ~ 75% mass is in twin Helium

SM: ~ 25% mass is in Helium



from solving the Boltzmann eqs

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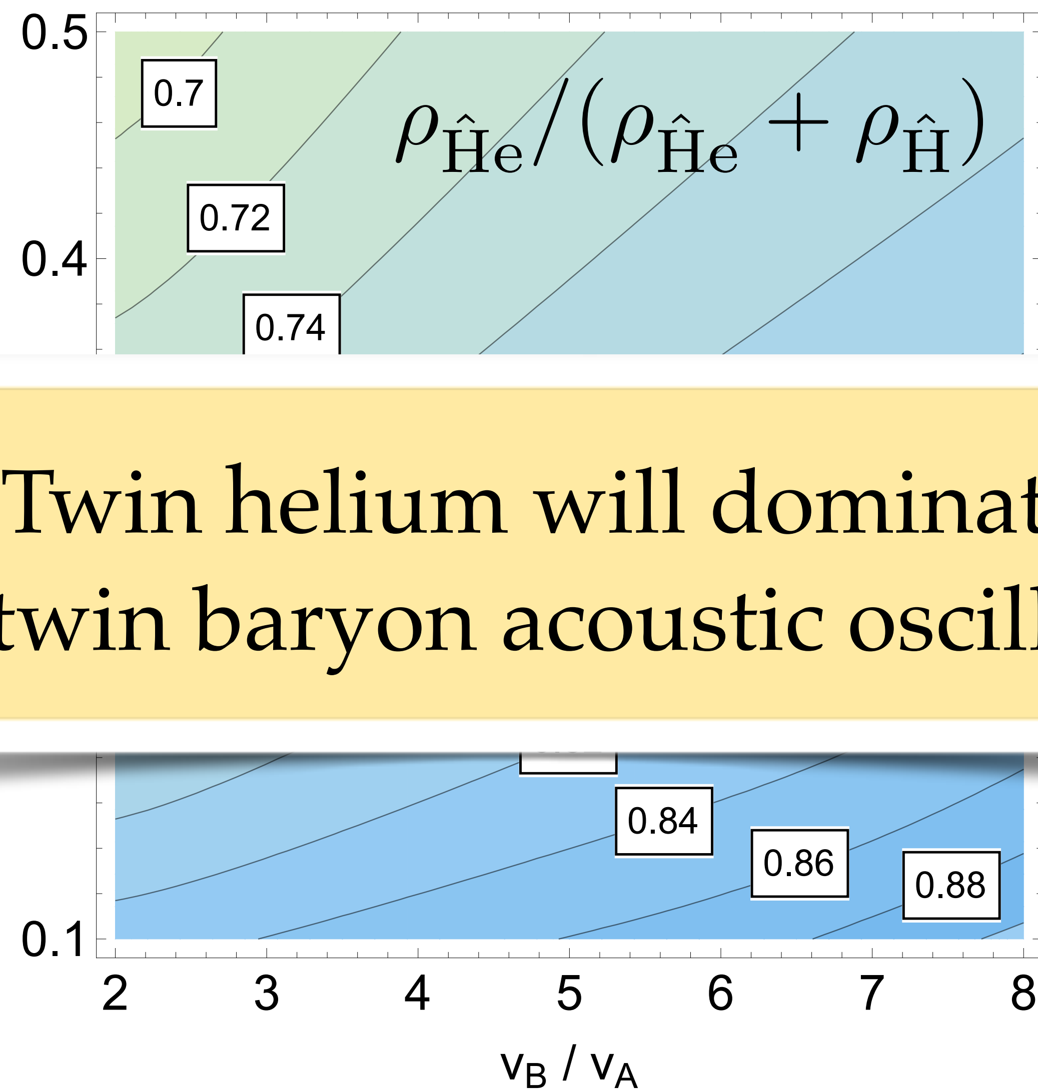
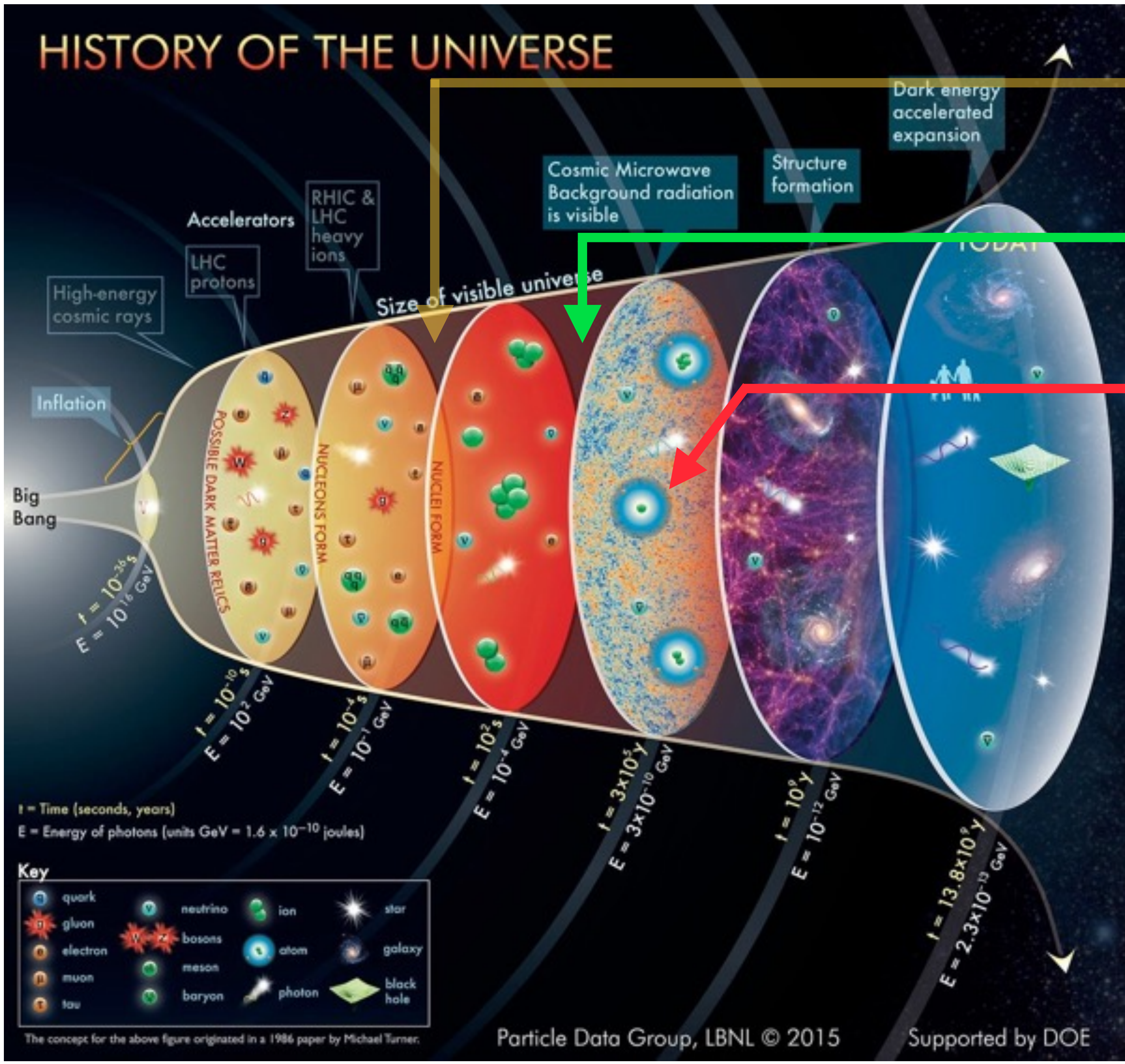


Twin helium will dominate the twin baryon acoustic oscillation

from solving the Boltzmann eqs

Era for the Large Scale Structure & CMB

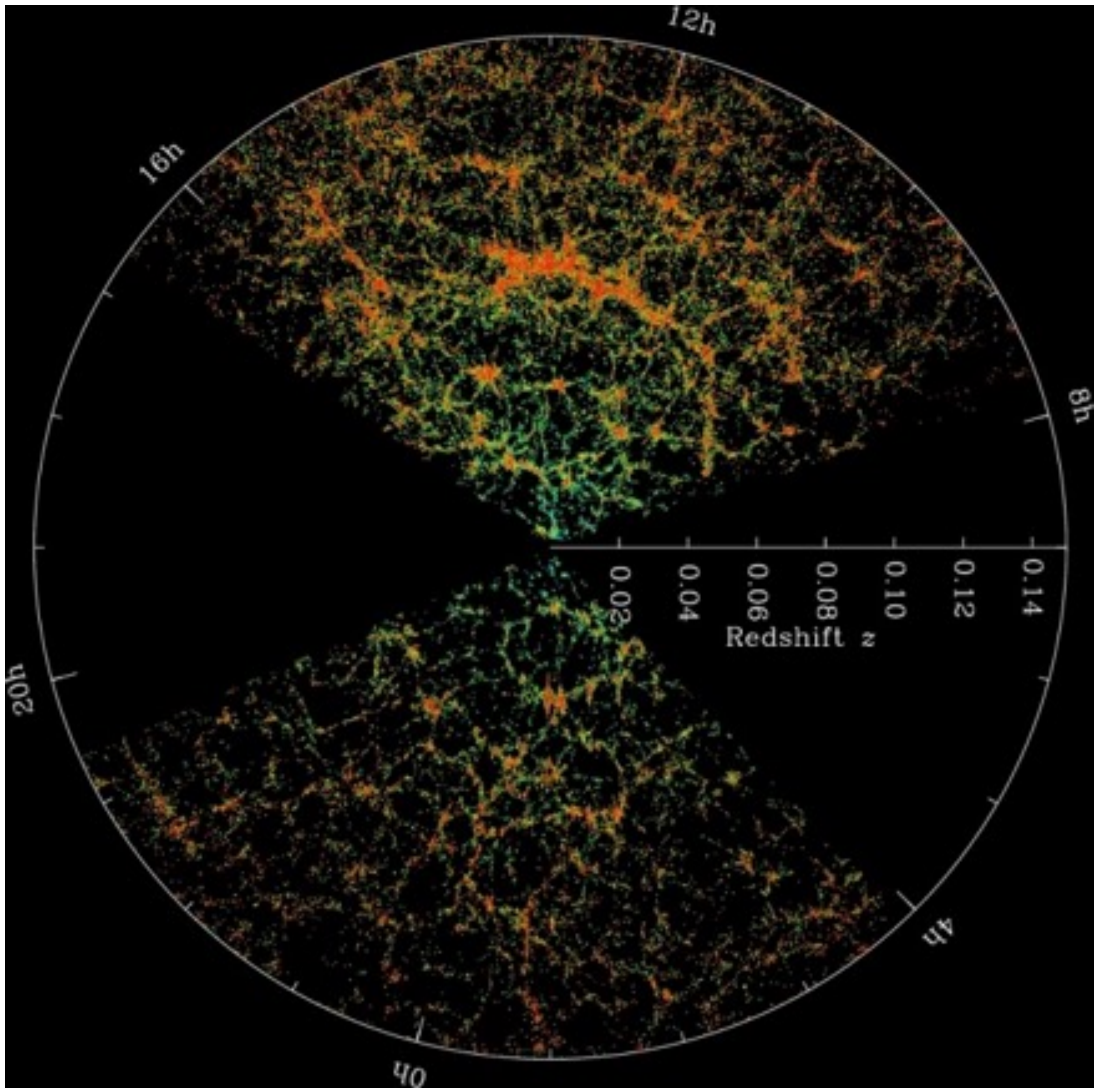


Nucleosynthesis
nuclei formation

Matter-radiation equilibrium
structure formation speeds up

Recombination
Ions become neutral atoms,
baryon structure begins,
CMB photons escape

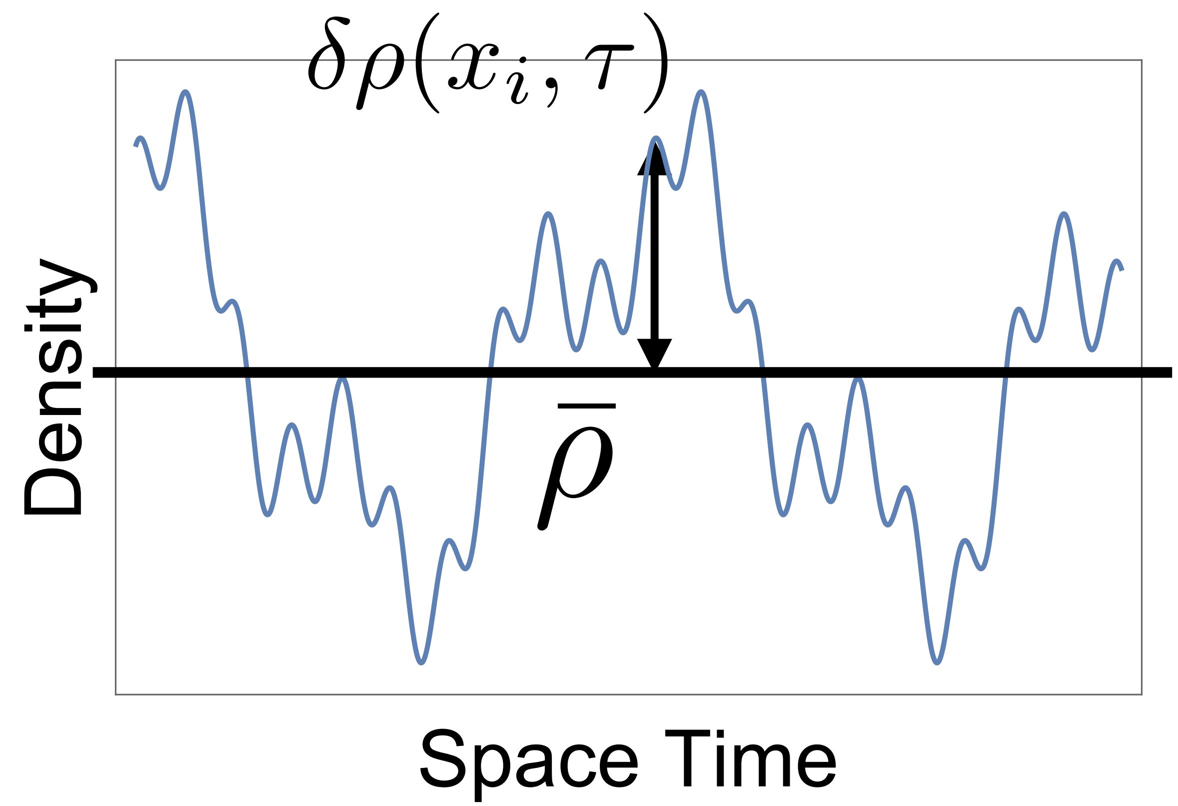
Large Scale Structure of the Universe



SDSS

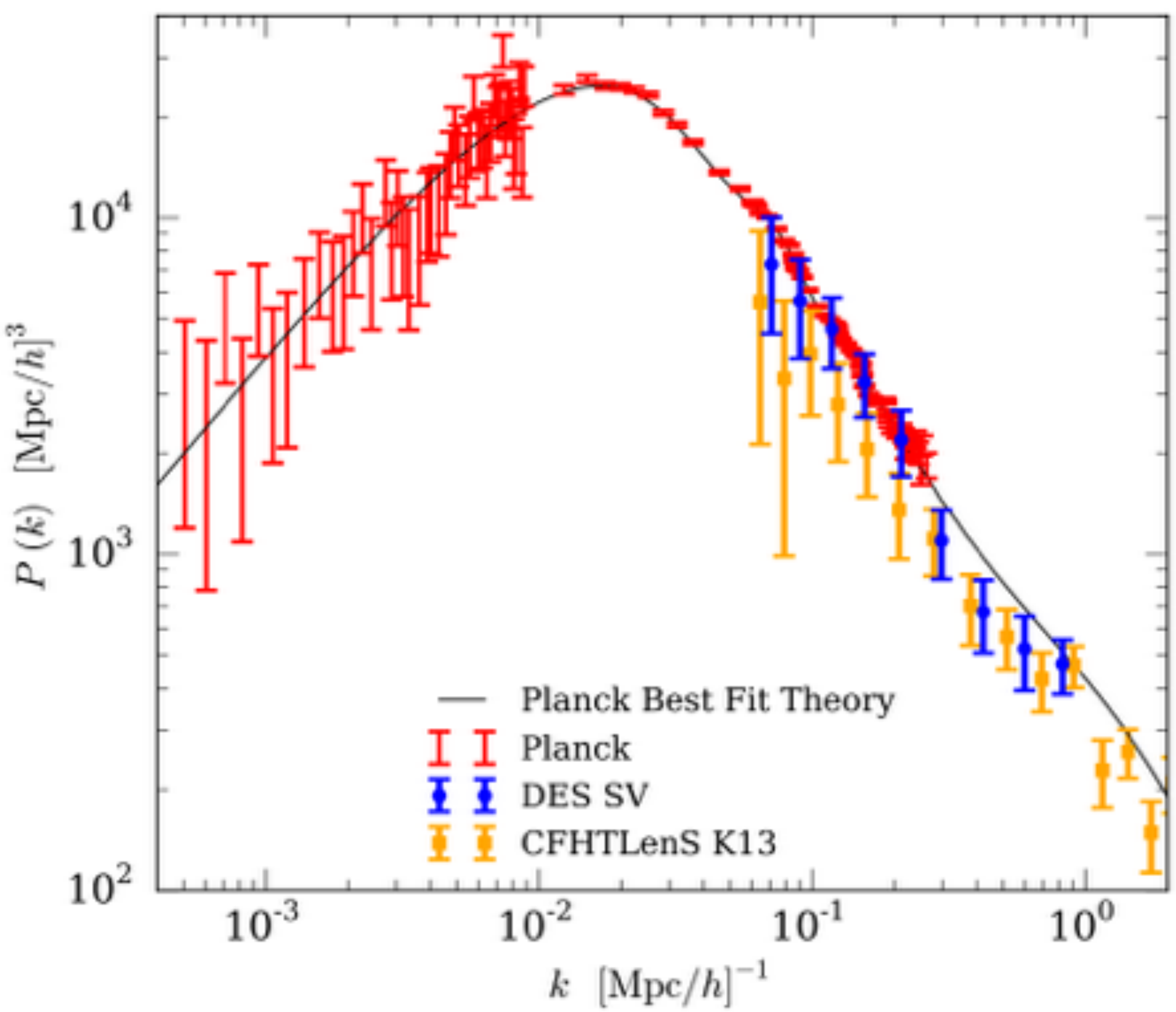
Density Perturbation

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



Large Scale Structure of the Universe

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



DES: 1507.05552

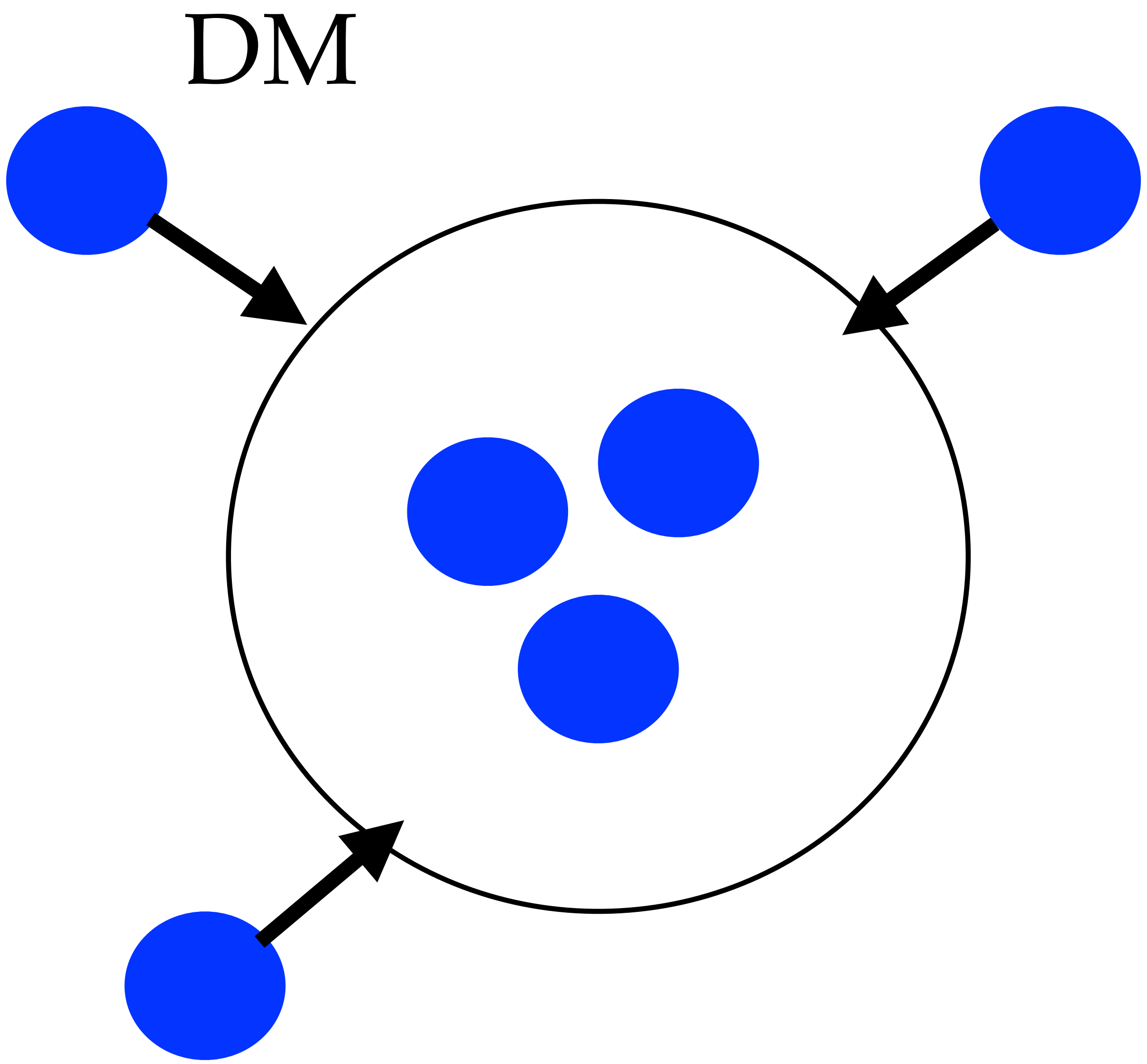
Density Perturbation

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

Fourier transform into frequency in space

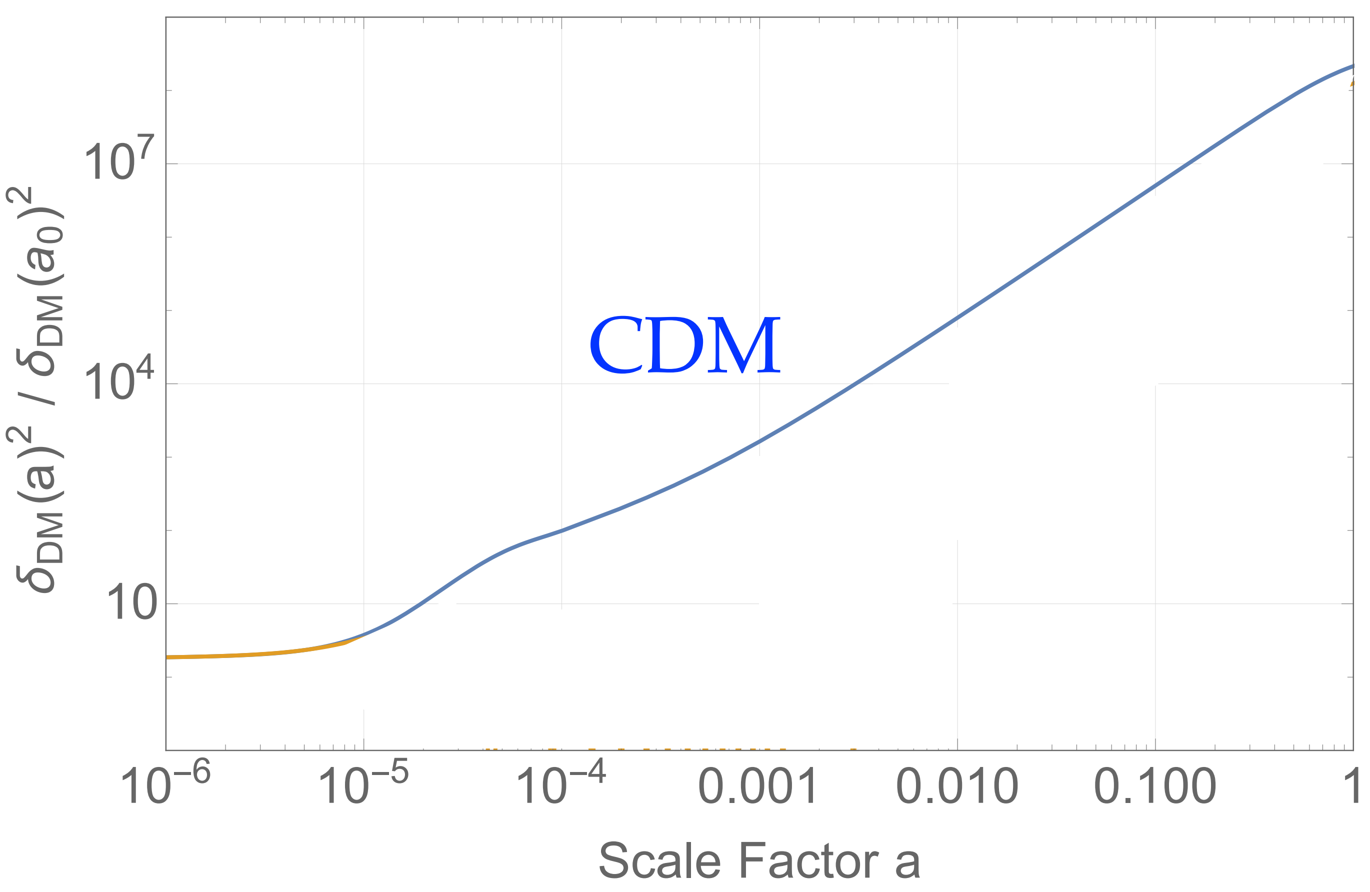
$$\delta_i(x,a) \rightarrow \delta_i(k,a)$$

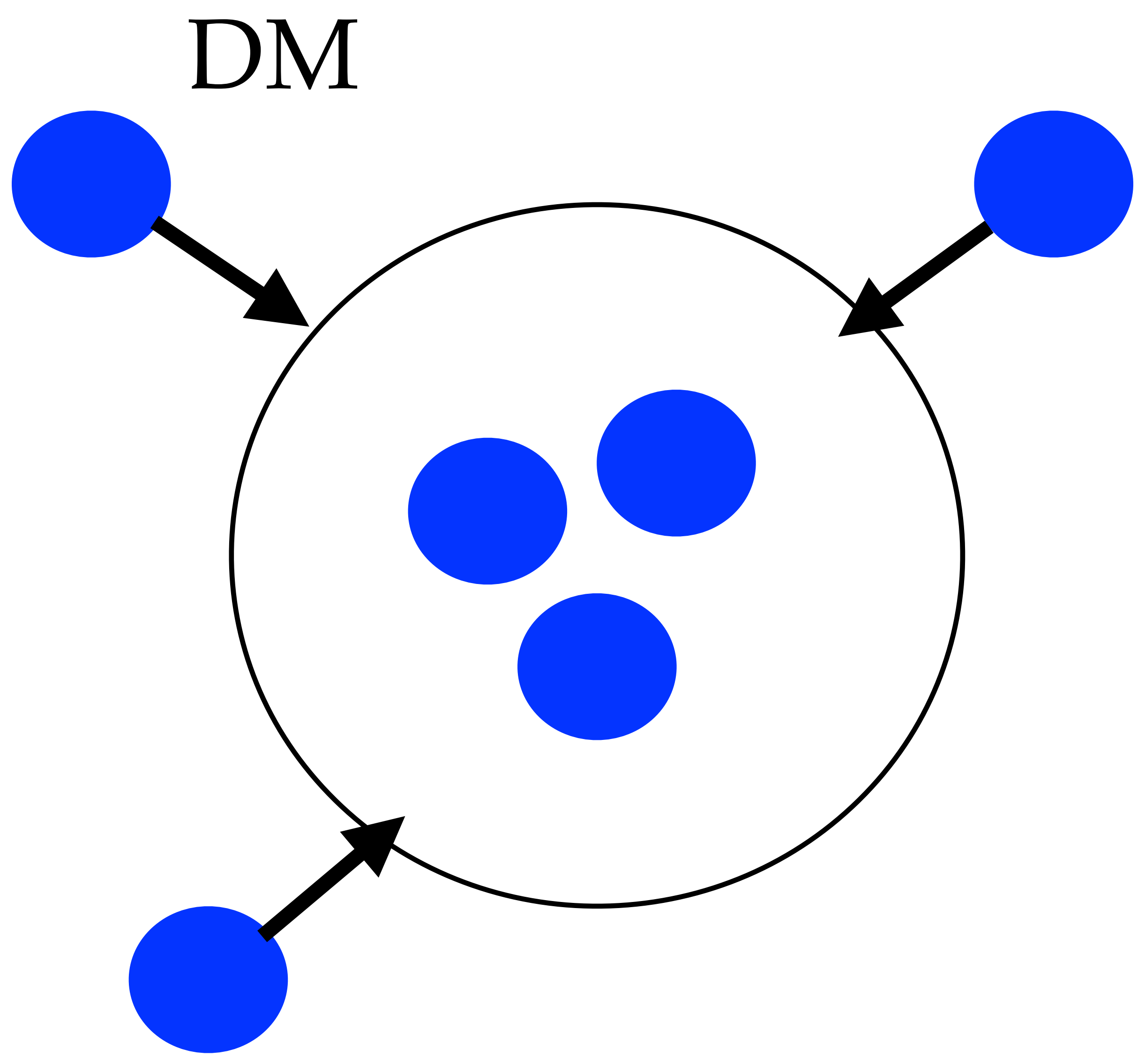
Structure formation of collision-less DM



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

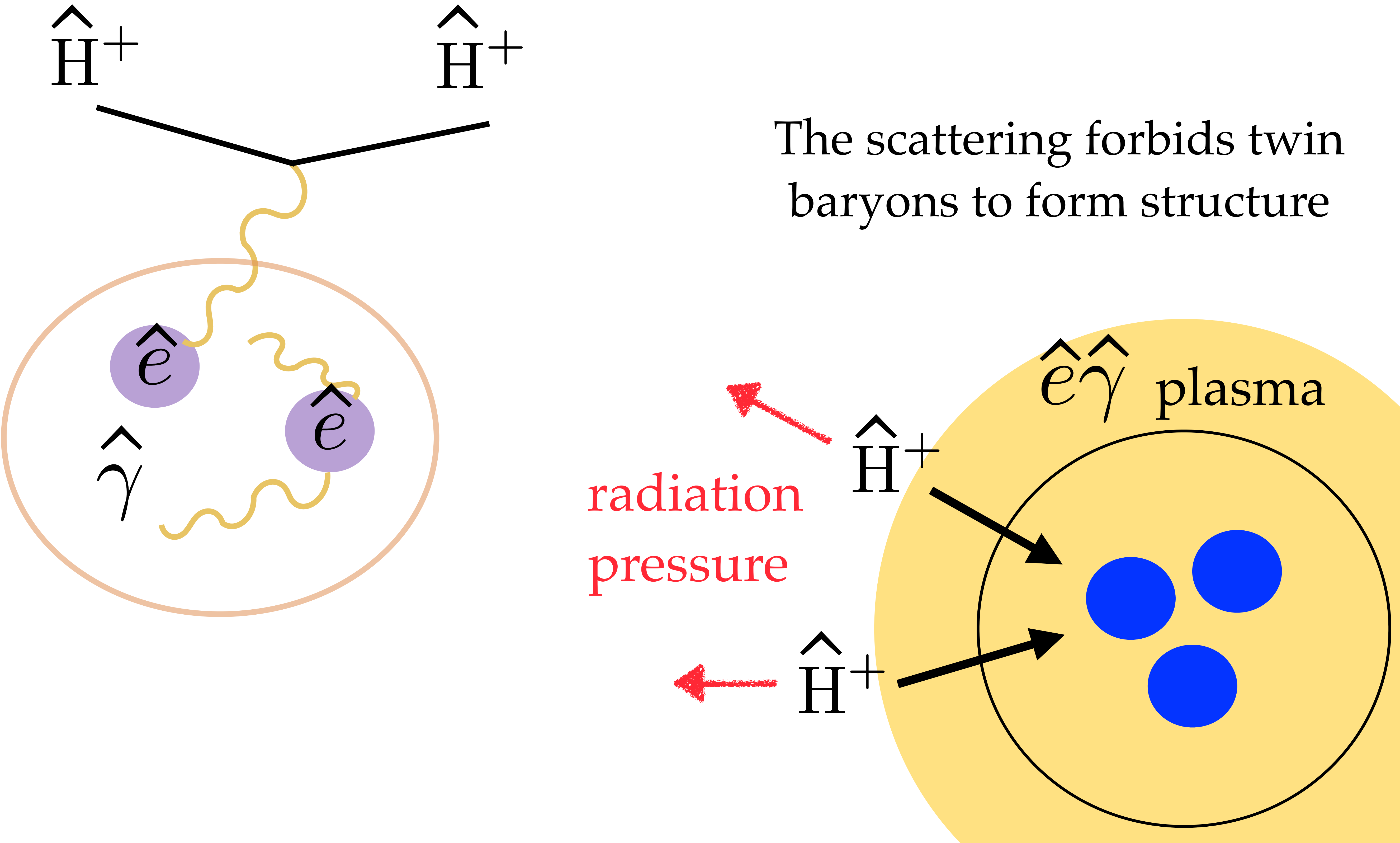
Structure formation of collision-less DM





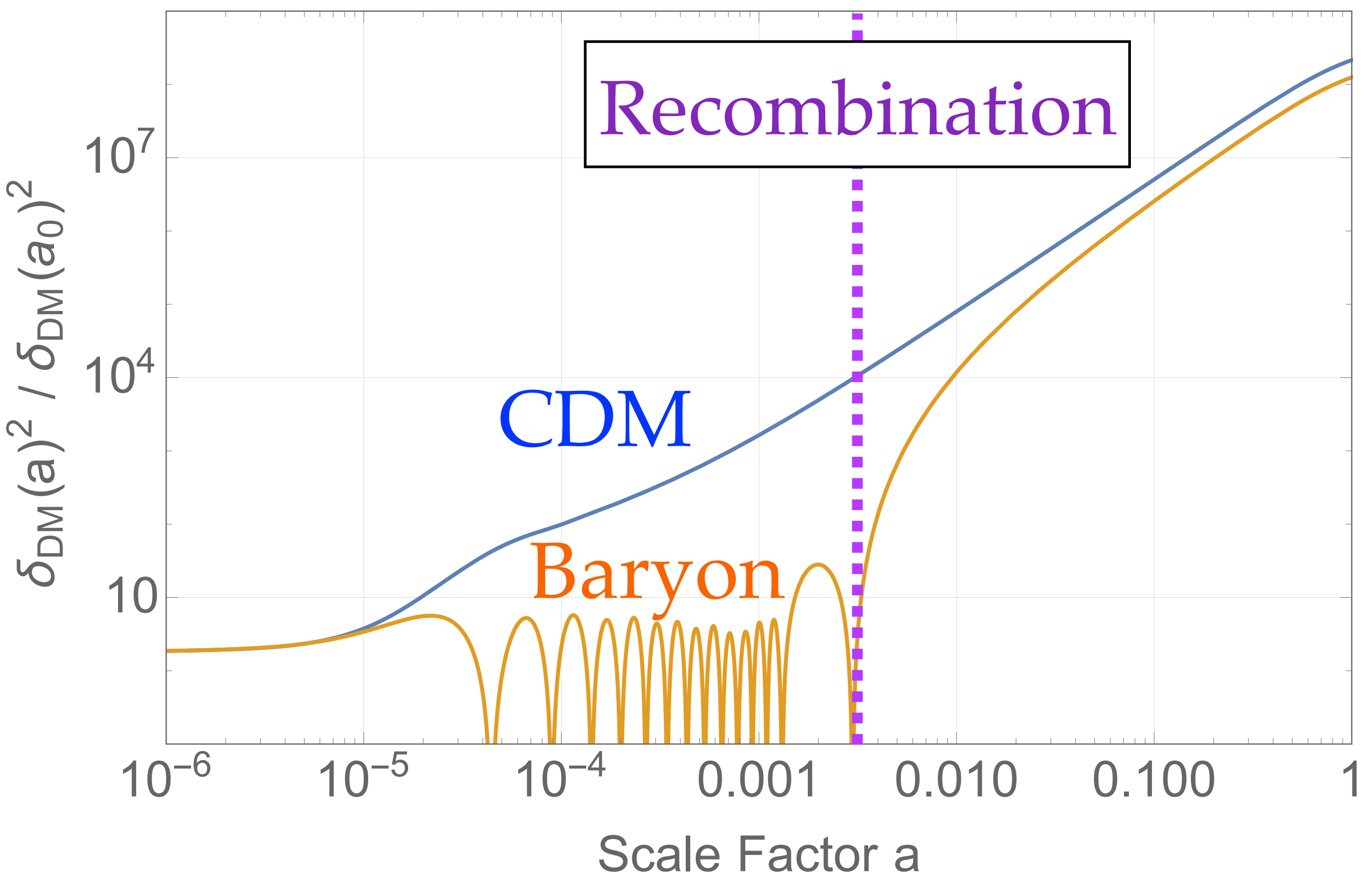
higher density -> larger gravity -> even higher density…

Structure formation of twin baryons

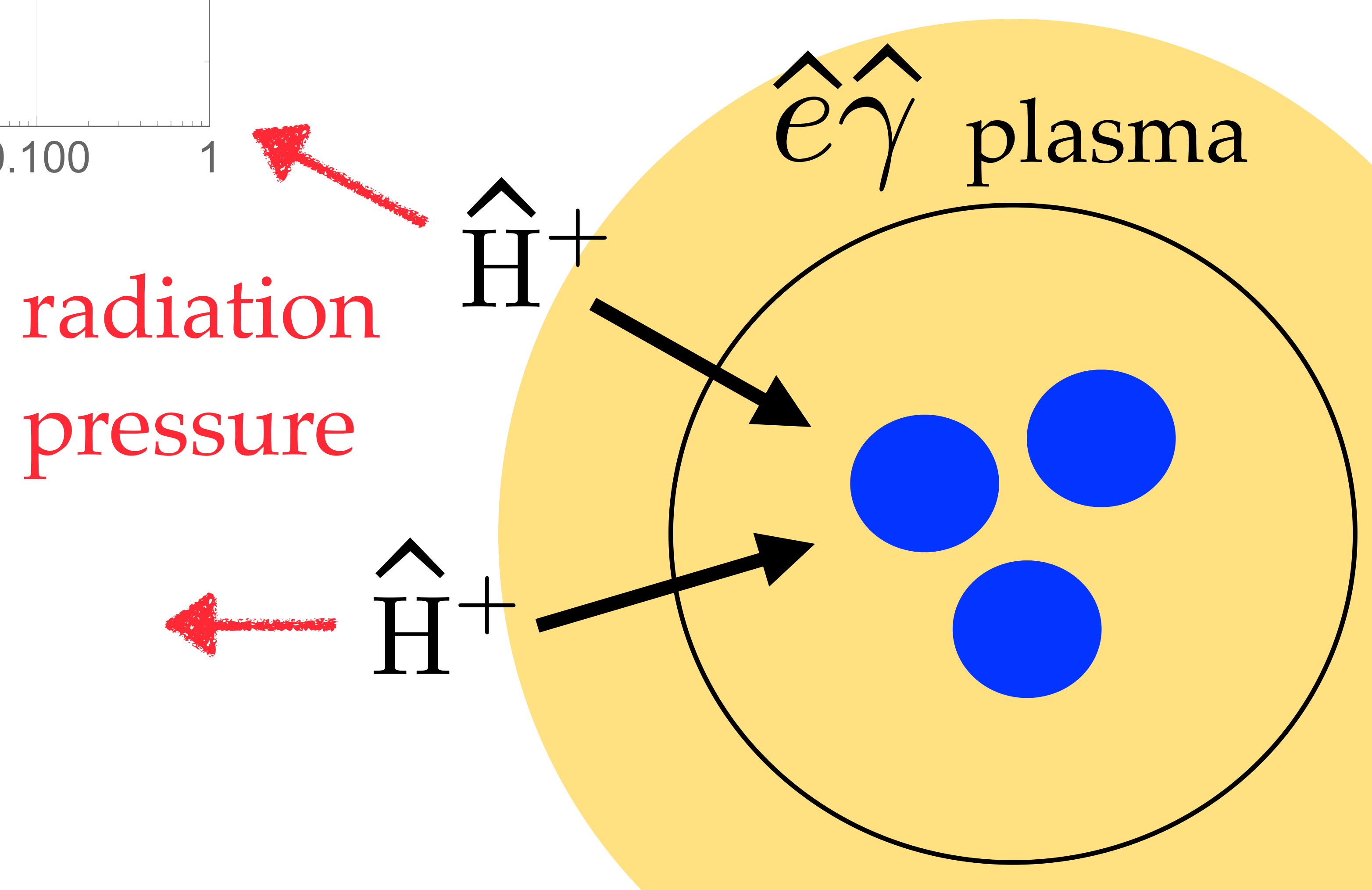


The scattering forbids twin baryons to form structure

Baryon Acoustic Oscillation (BAO)



The scattering forbids twin baryons to form structure

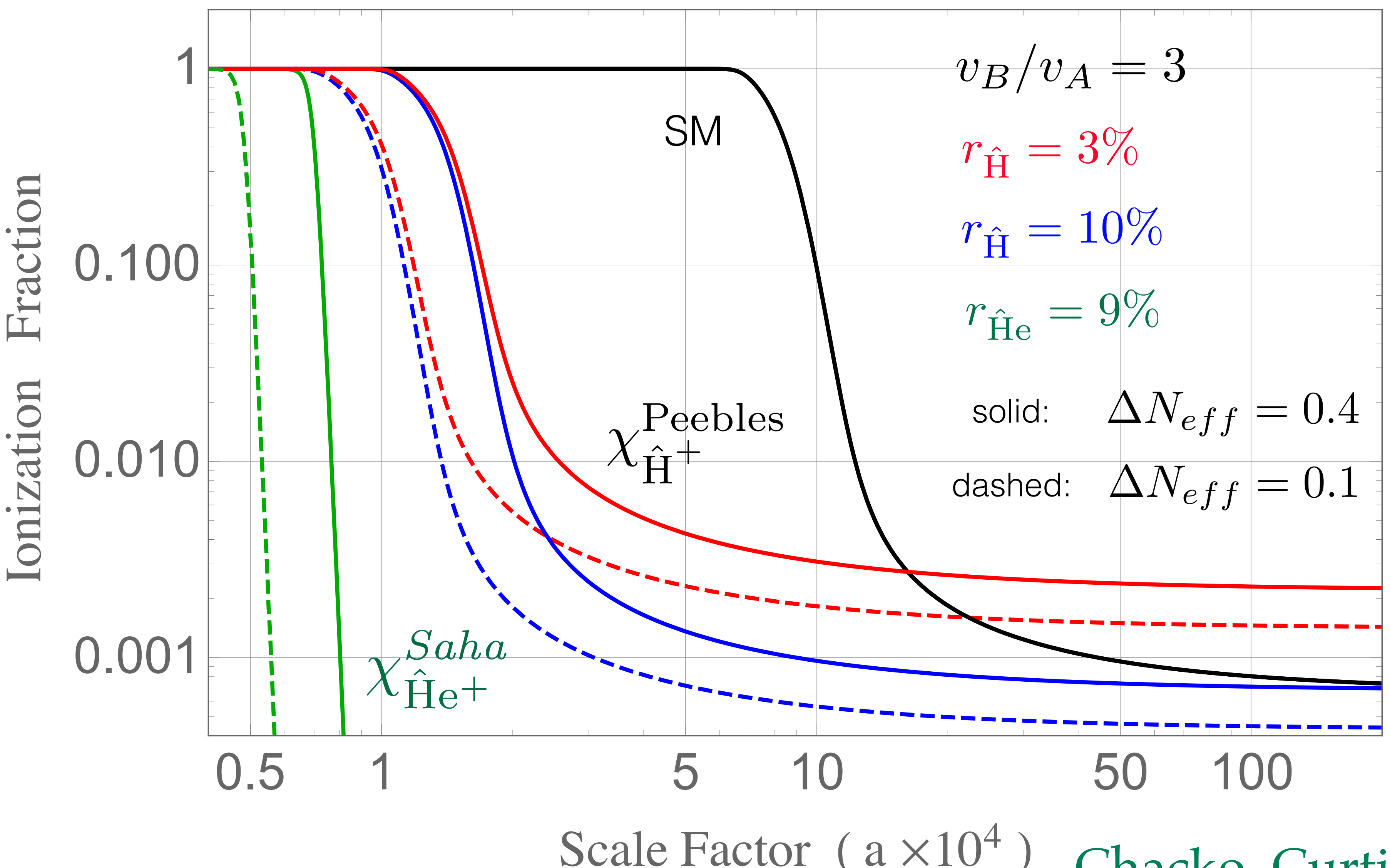


$$\ddot{\delta}_b + \frac{k^2}{3(1+R)}\,\delta_b \simeq -k^2\psi$$

$$R \equiv \frac{3\rho_b}{4\rho_R} \ll 1$$

Oscillation stops after recombination

$$H^+ + e^- \to H^0 + \gamma + (\gamma) \qquad \frac{n_{H^+}\, n_{e^-}}{n_{H^0}} \sim \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\frac{13.6\,\mathrm{eV}}{T}}$$



taking more precise energy transitions into account (Peebles)

Chacko, Curtin, Geller, YT (*in progress, 18'*)

Twin BAO suppresses the density perturbation

See also Chacko, Cui, Hong, Okui, YT (16')

How much mirror baryon density can we have?

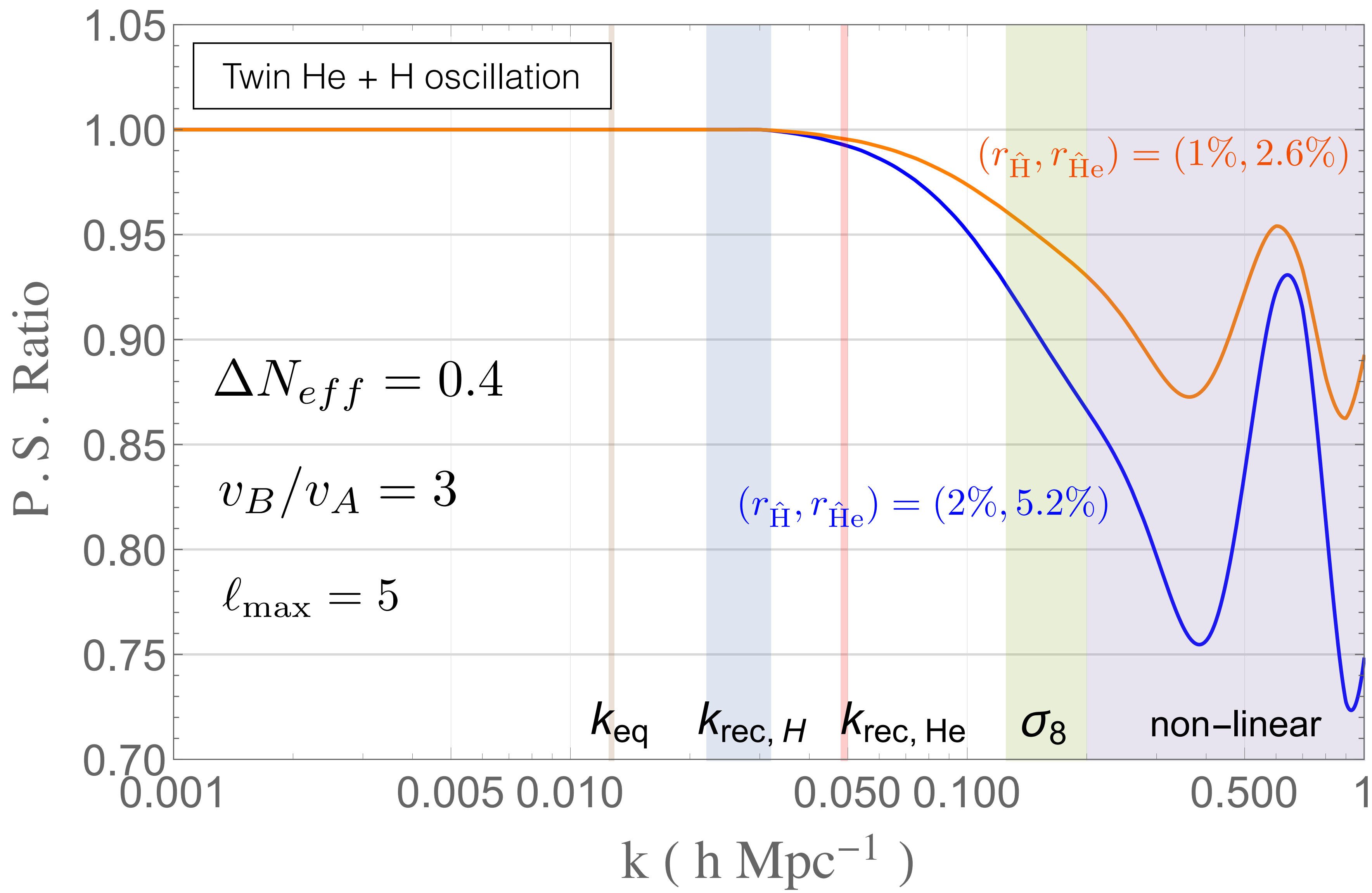
$$r_{\hat{\mathrm{H}}} = \Omega_{\hat{\mathrm{H}}}/\Omega_{\mathrm{DM}}, \qquad r_{\hat{\mathrm{He}}} = \Omega_{\hat{\mathrm{He}}}/\Omega_{\mathrm{DM}}$$

Quantify the suppression of density perturbation with ratio

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

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

TBBN -> Twin Helium -> Imprints on LSS!

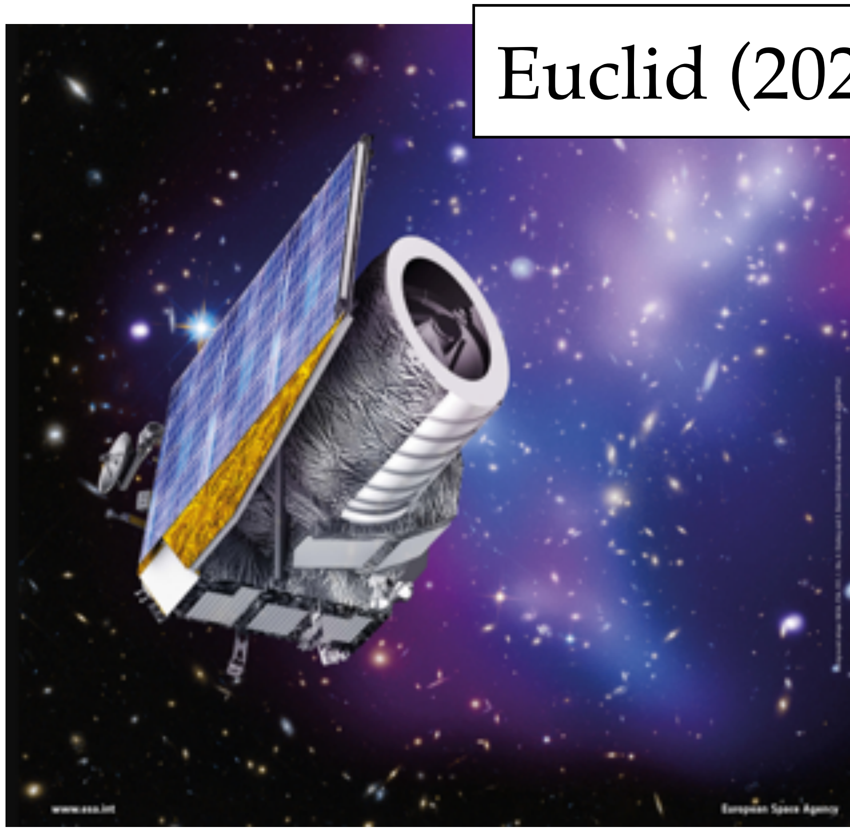


later ⟷ earlier

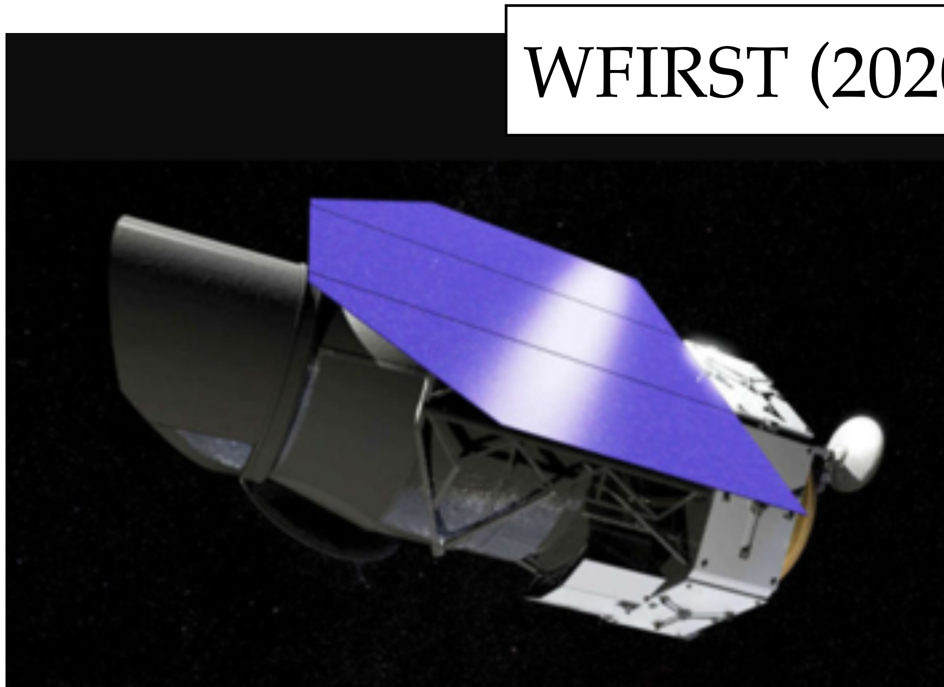
Horizon entry

Precision measurement of the LSS

Euclid (2020′)

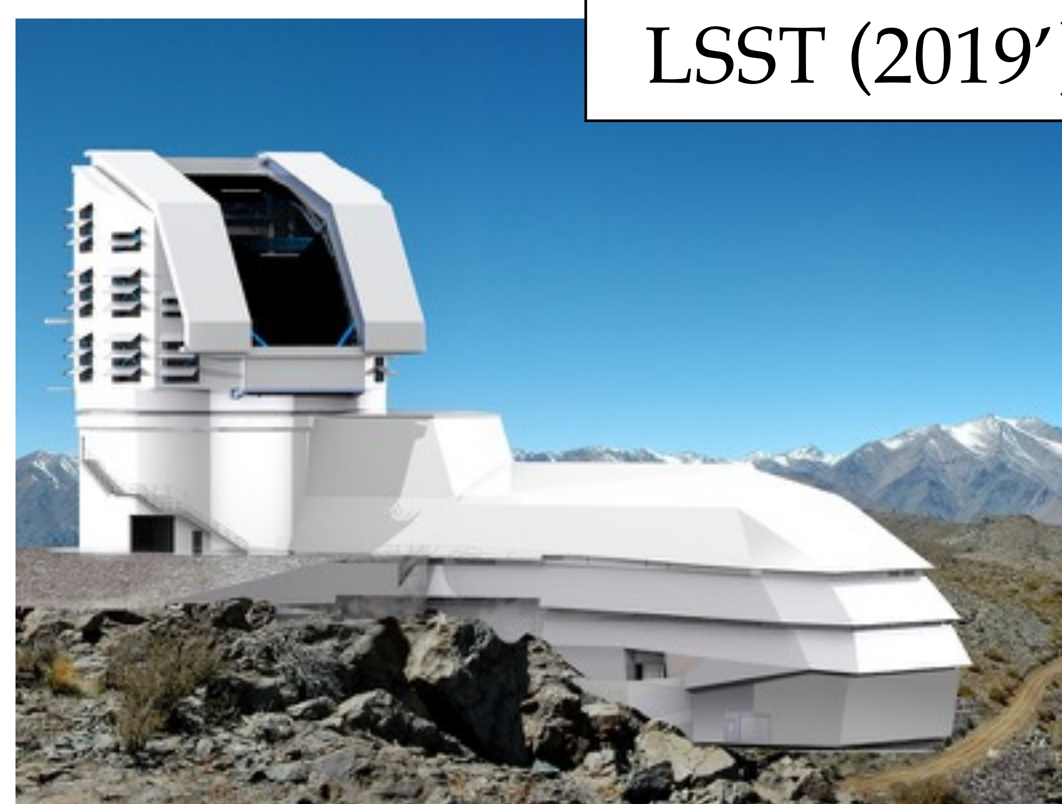


WFIRST (2020′)

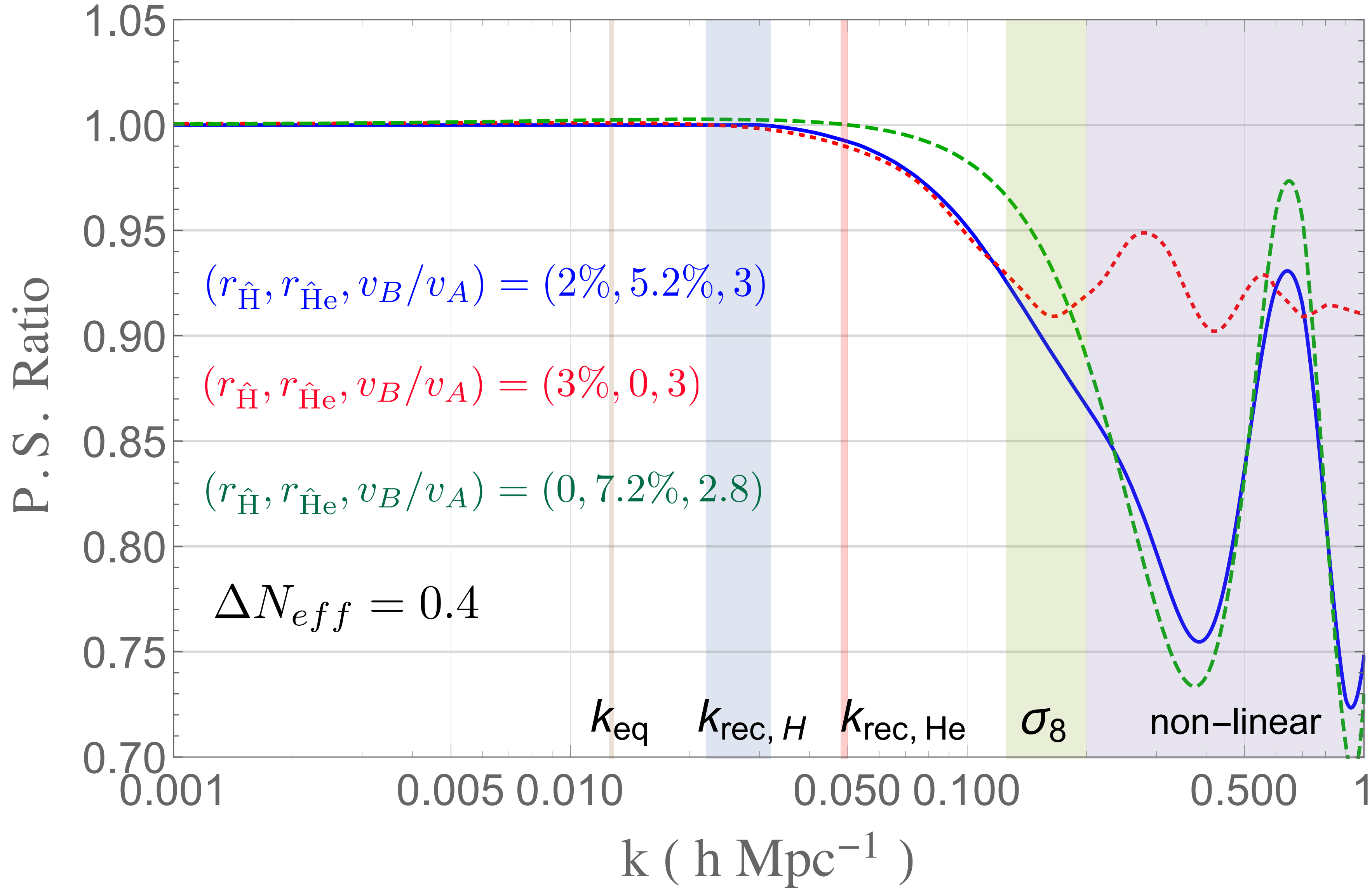


Precent level precision
in ~ 10 years

LSST (2019′)



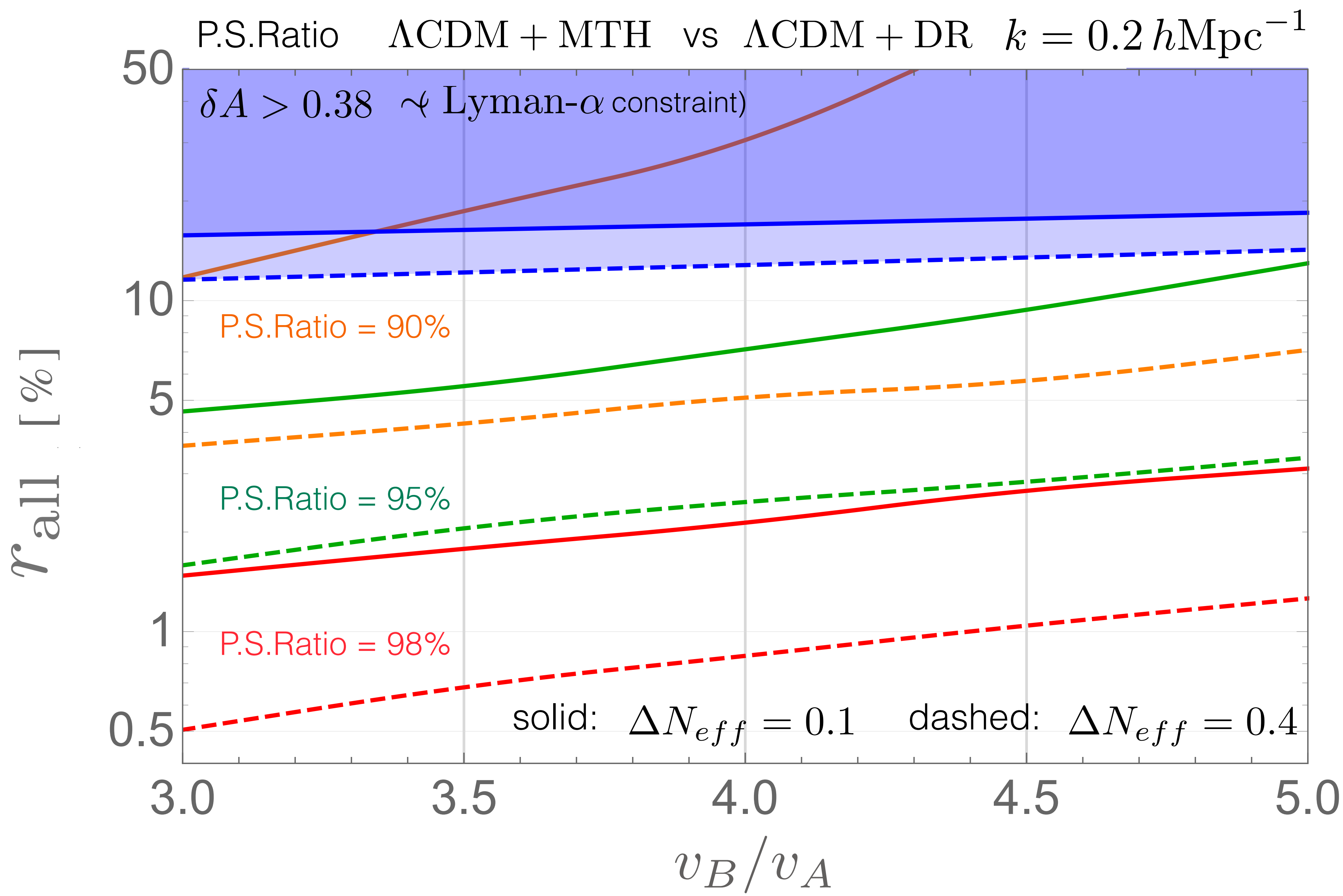
Can see the effect from both H & He



later ⟷ earlier

Horizon entry

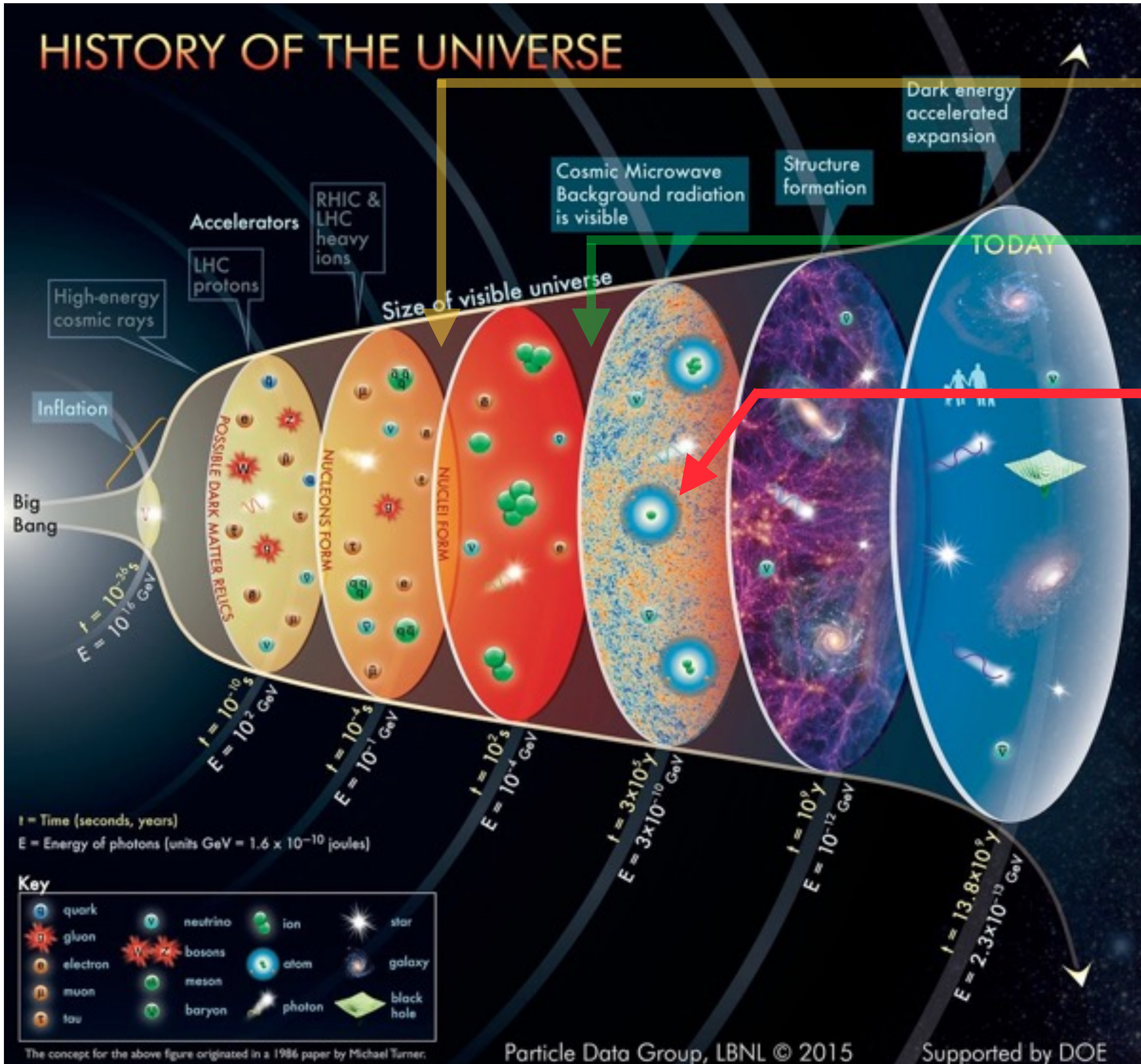
LSS constraint on mirror particle density



Current bound allows $\Omega_{\hat{b}}/\Omega_{\mathrm{DM}} < 10\%$

Future constraint will be $< 1\ \%$

Cosmic Microwave Background



Nucleosynthesis
nuclei formation

Matter-radiation equilibrium
structure formation speeds up

Recombination
Ions become neutral atoms,
baryon structure begins,
CMB photons escape

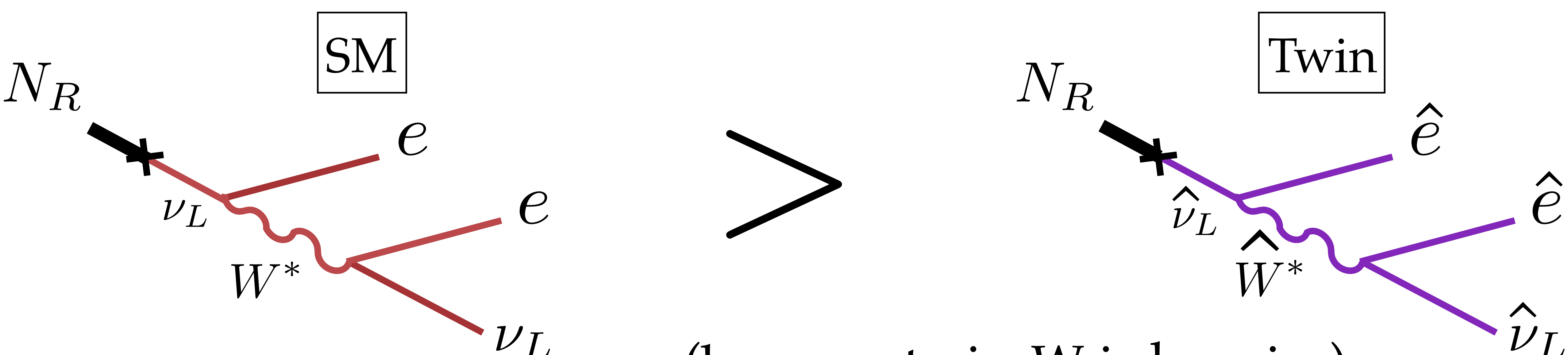
Dark radiation, asymmetric reheating

$\hat{\gamma}$ $\hat{\nu}$

give too much radiation density $\Delta N_{eff} = 5.7$

while the current bound $\Delta N_{eff} < 0.45\,(2\sigma)$ ☹

Idea: heavy neutrinos decay suppresses ΔN_{eff}



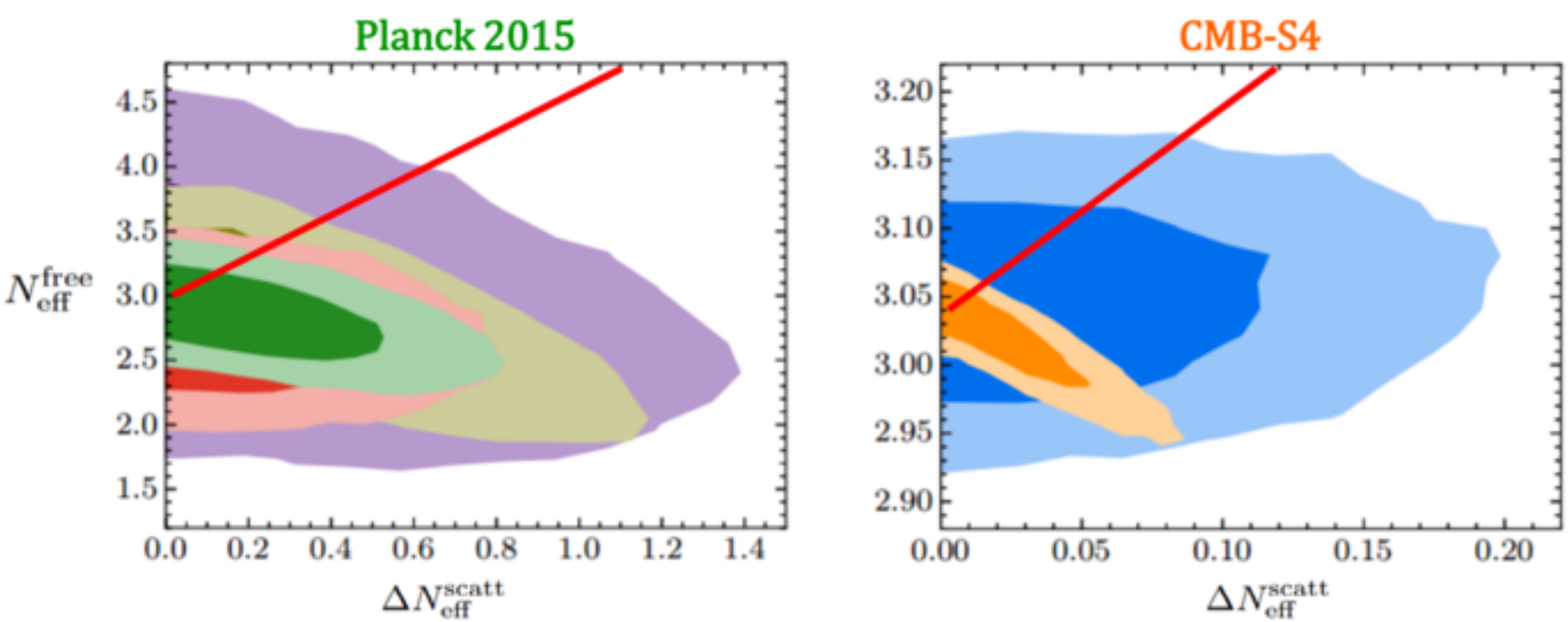
(because twin-W is heavier)

Chacko, Craig, Harnik (17')

Cosmic Microwave Background (CMB)

Different signals from free streaming / scattering radiation

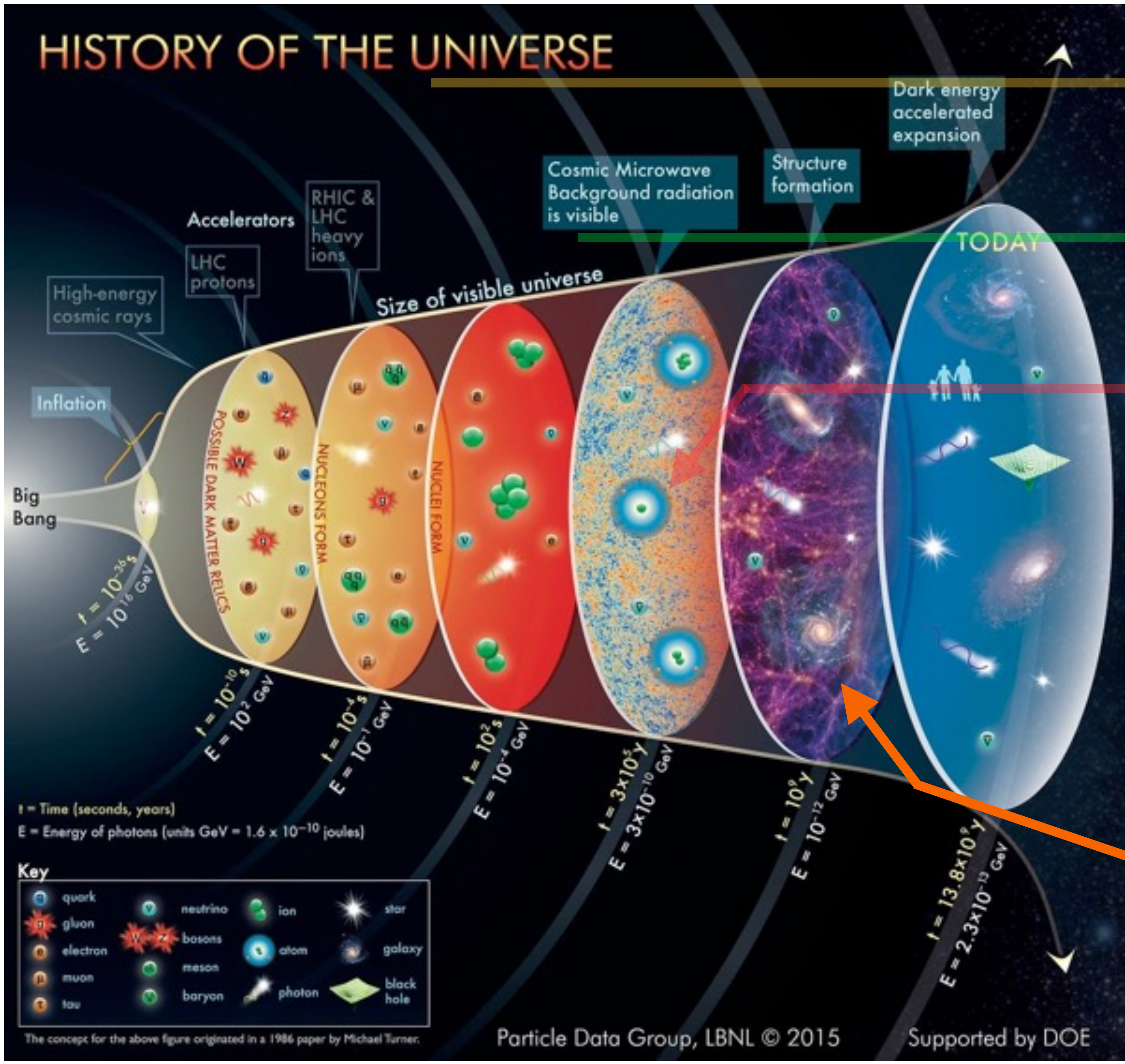
$\hat{\gamma}$ scatters before twin recombination $$\frac{\Delta N_{eff}^{free}}{\Delta N_{eff}^{scatt}} = \frac{\Delta N_{eff}^{\hat{\nu}}}{\Delta N_{eff}^{\hat{\gamma}}} = \frac{3}{4.4}$$



CMB S-4 may test the radiation composition in MTH

Baumann et. al. 1508.06342

Formation of the small scale structures



Nucleosynthesis

nuclei formation

Matter-radiation equilibrium

structure formation speeds up

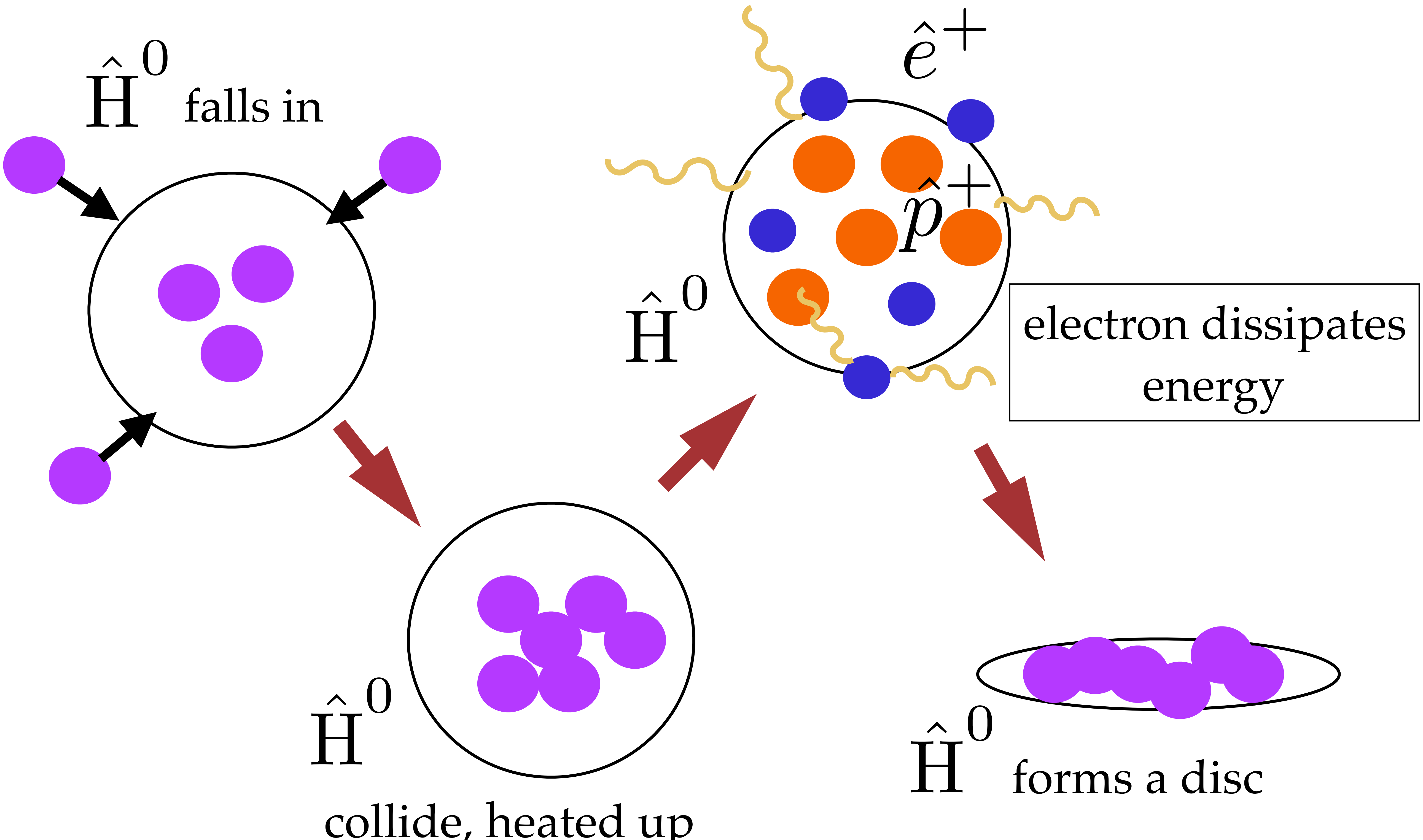
Recombination

Ions become neutral atoms, baryon structure begins, CMB photons escape

Galaxy formation

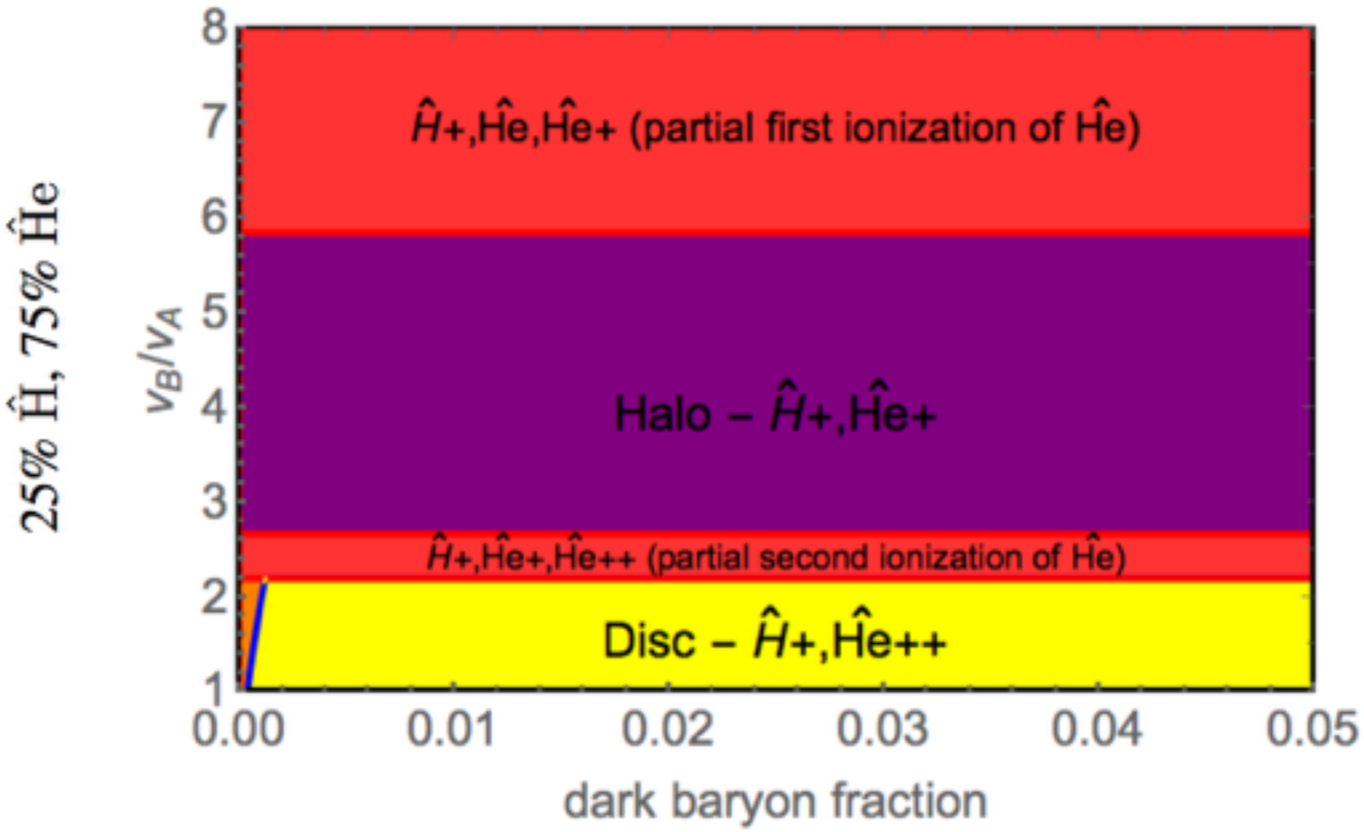
Falling-in baryons scatter & re-ionized, later cools down forming a disc

Re-ionization of twin atoms

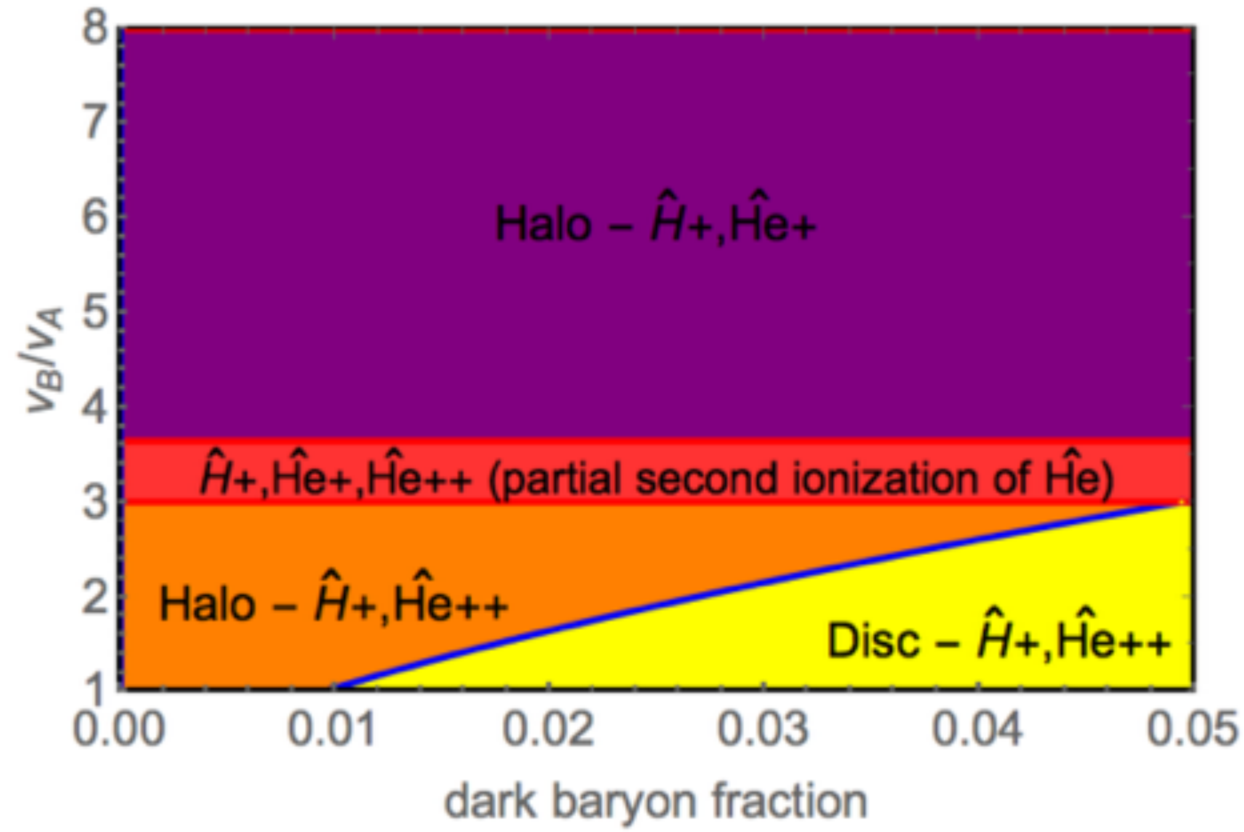


Small scale structure, mirror disc?

NFW profile



Uniform DM distribution



There is a chance to form a Twin disc

Gaia survey only allows 1% of DM forming a disc

More study is needed to see if Twin disc can form

Upshot

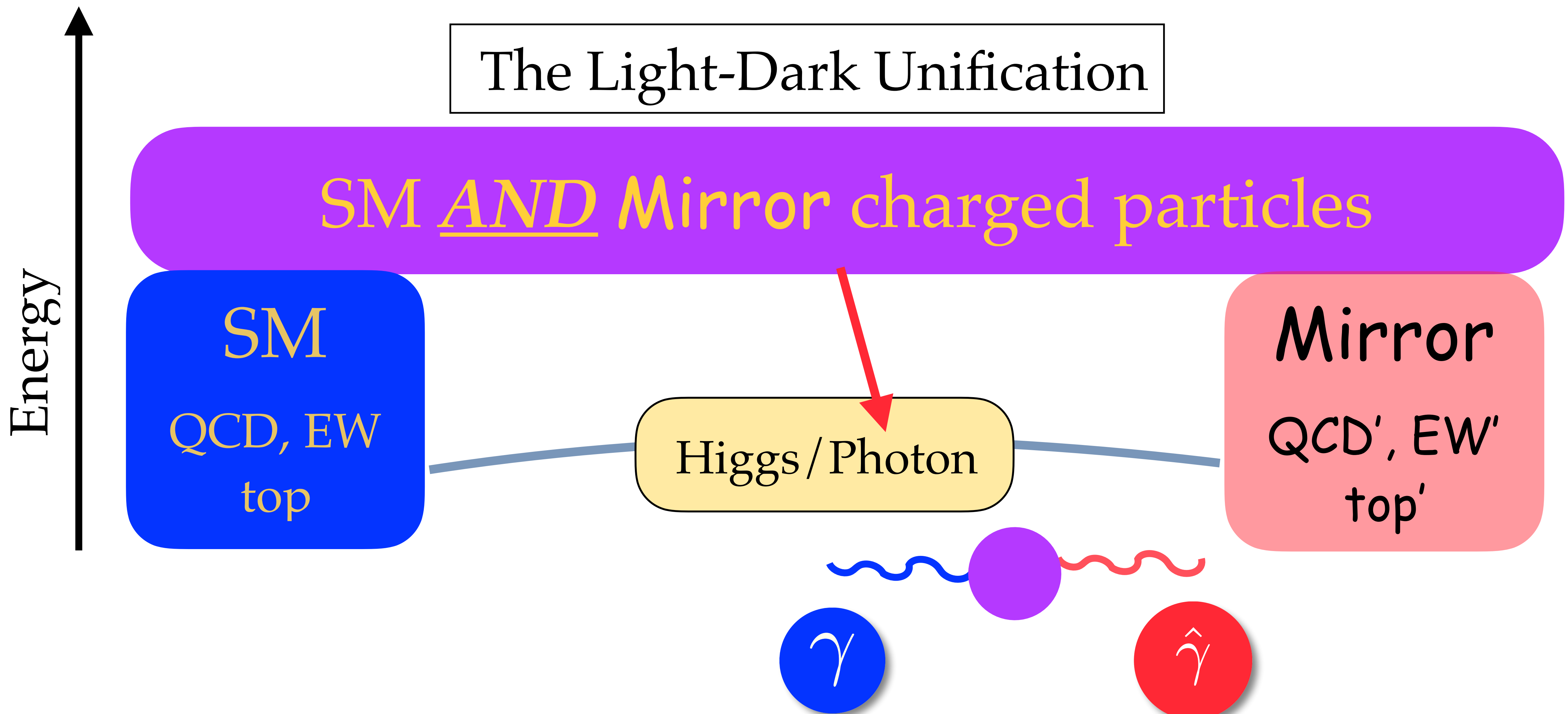
Cosmology depends on various **``details"** (mass, coupling,…)

We can give concrete predictions to Twin Cosmology
because the **Naturalness requirement** gives us these details

These LSS and CMB signals only scratch the surface:

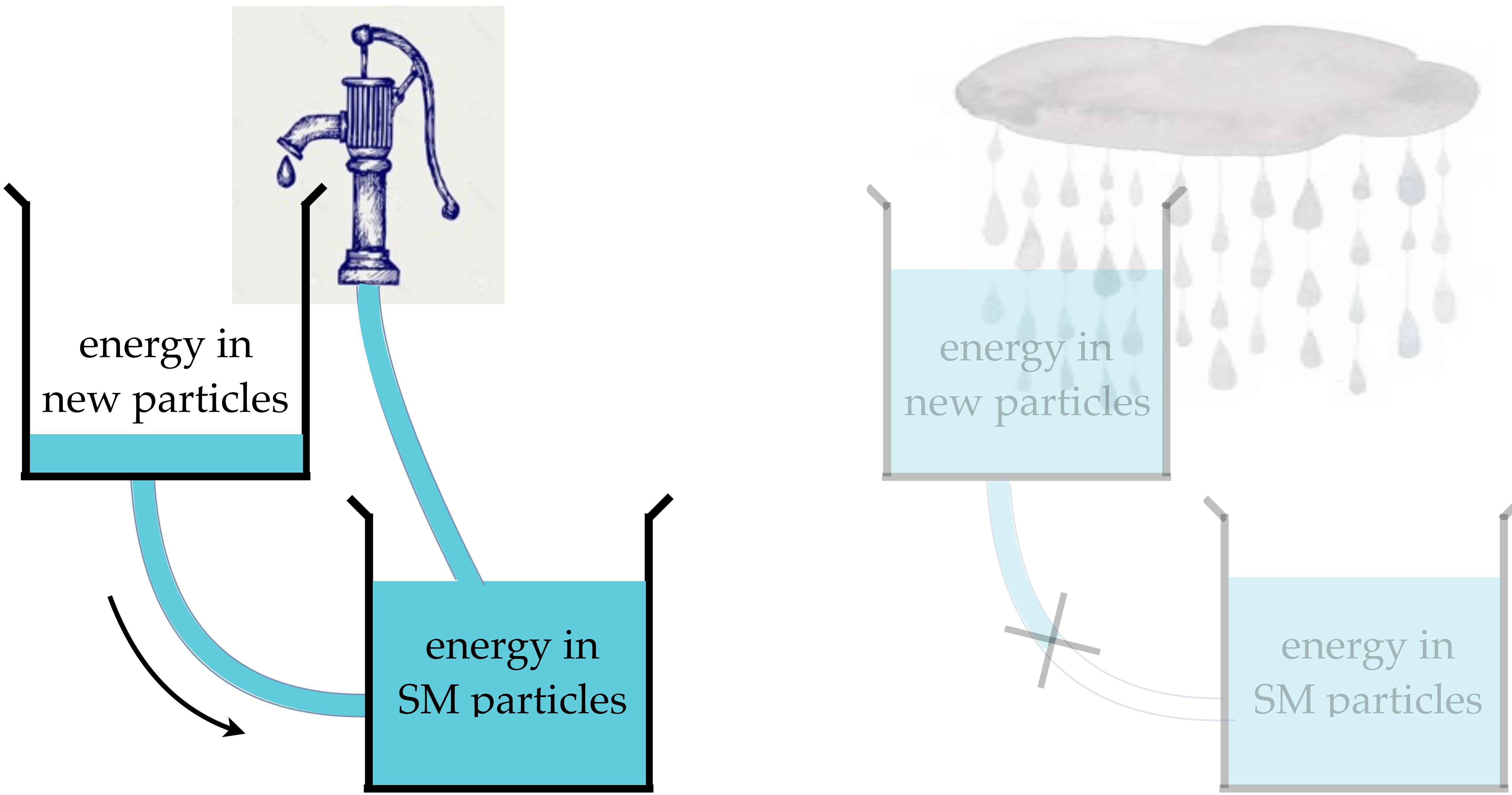
more on
Direct Detection
Astrophysics
…

Mirror symmetry generates new phenomenology

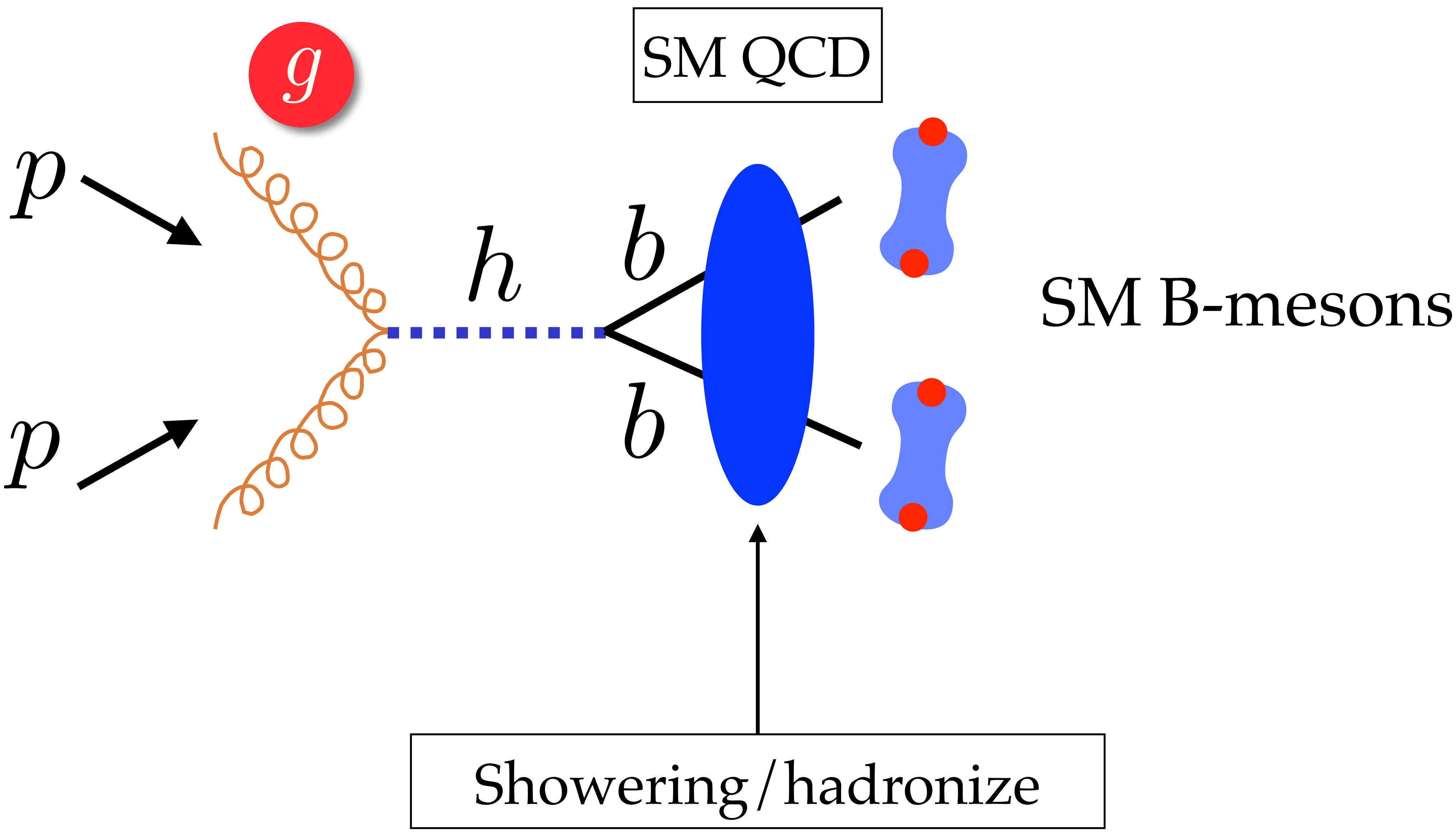


Part I.

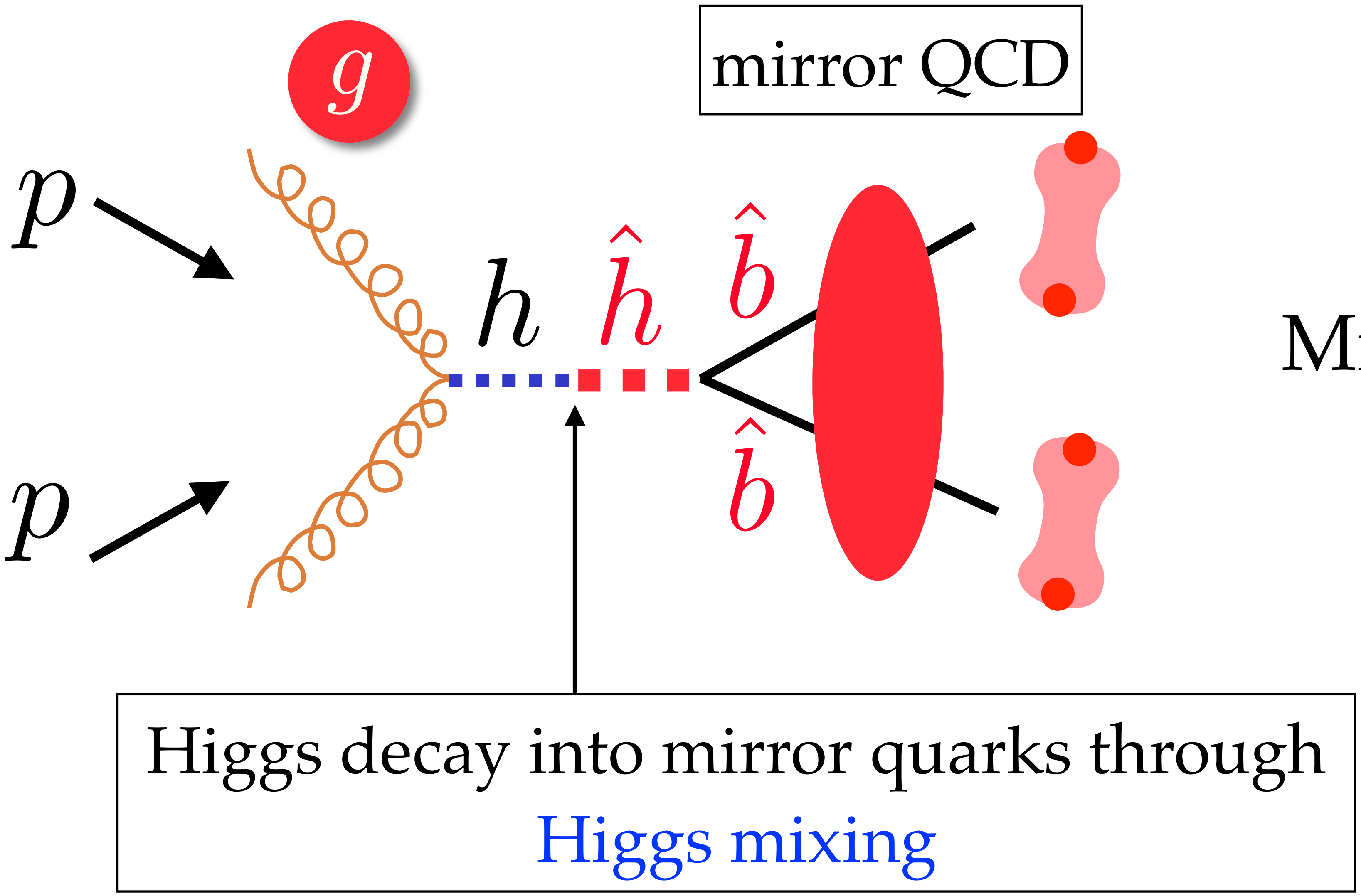
Collider Signatures from Hidden Naturalness



Production & decay of SM Higgs @ LHC



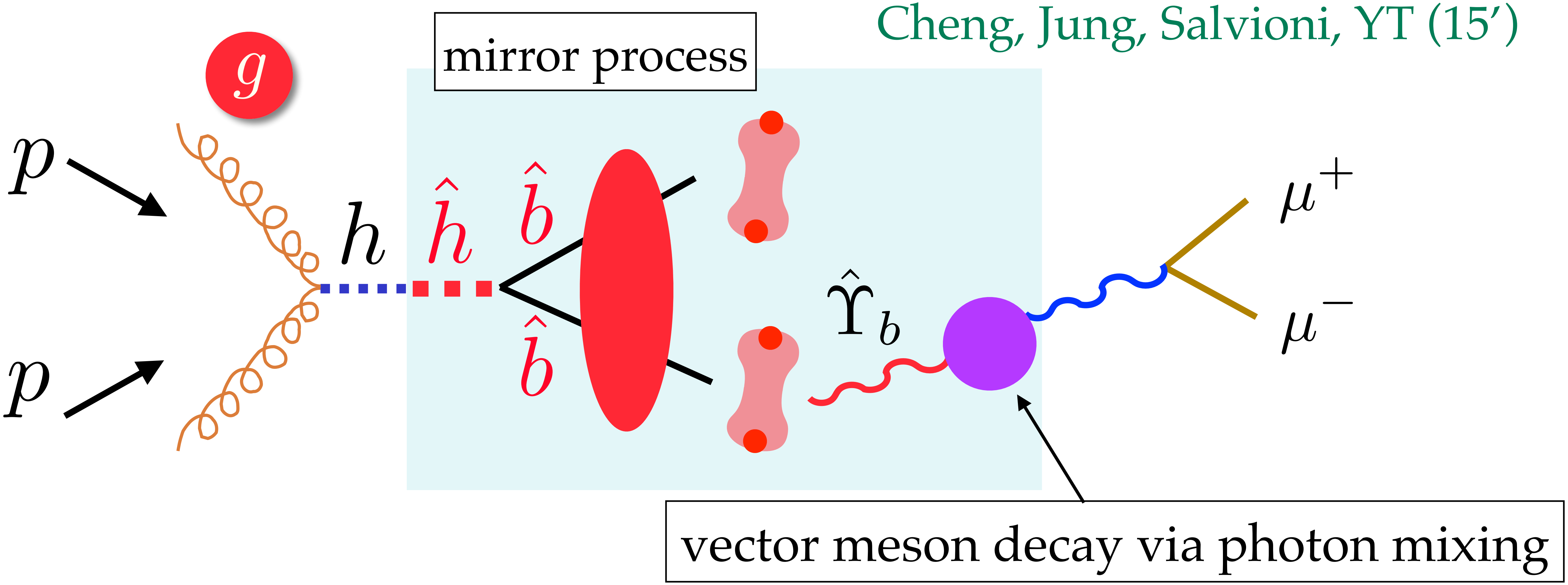
Higgs decay into mirror particles



Mirror B-mesons

Higgs decay into mirror particles

Cheng, Jung, Salvioni, YT (15')

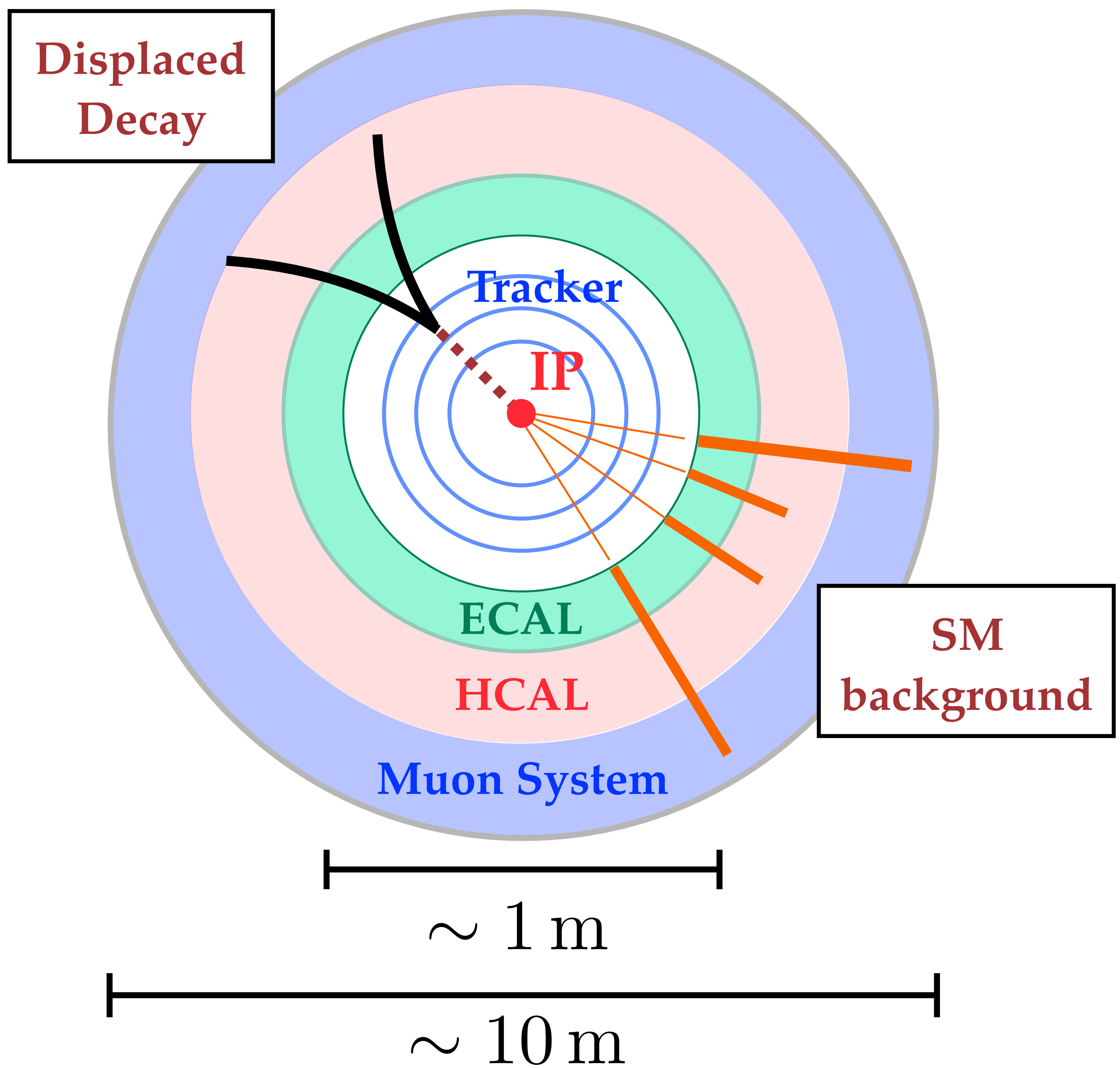


When there's no lighter mirror particles to decay into

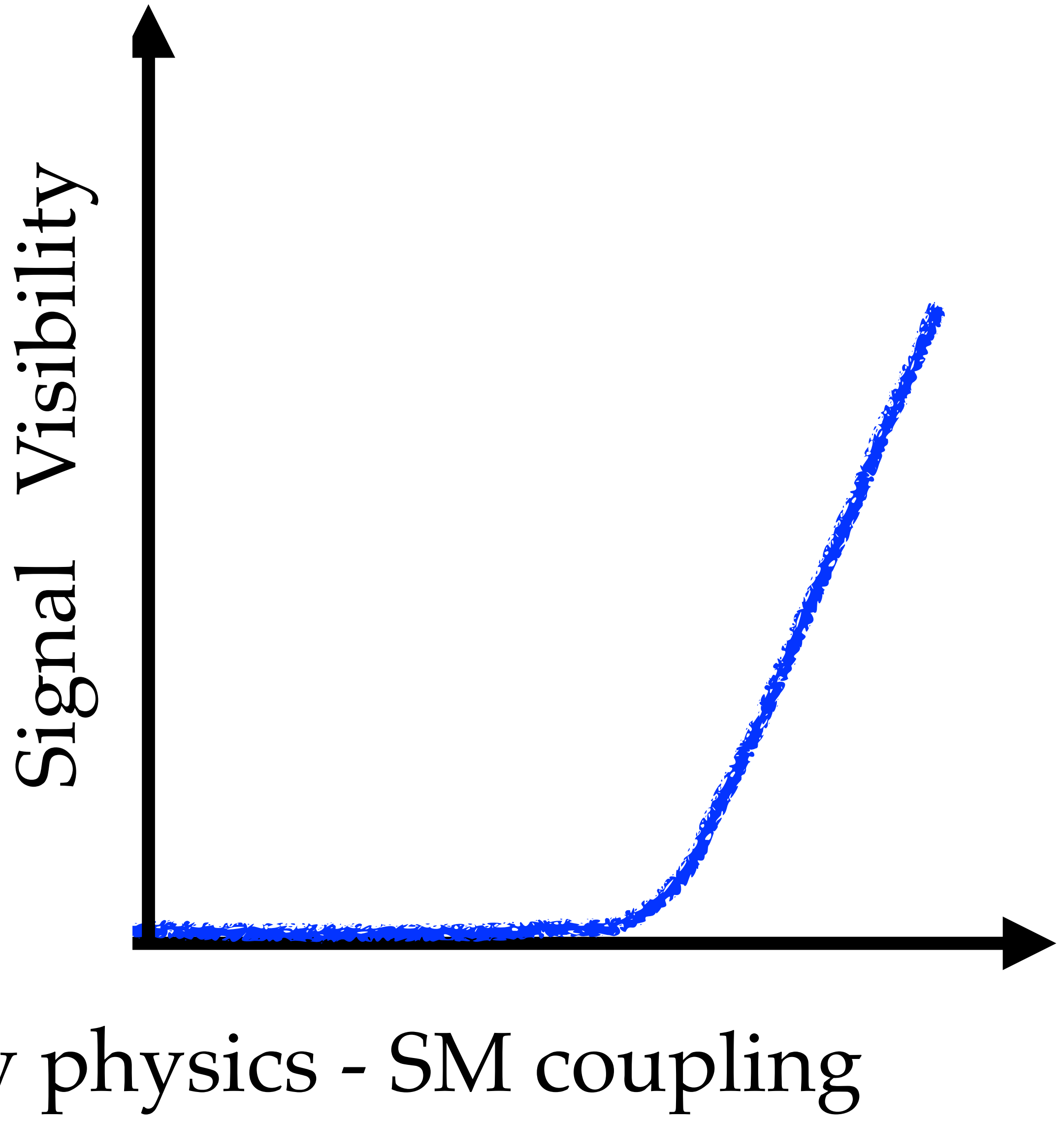
(since we only need heavier mirror particles for Naturalness)

Mirror hadrons **SLOWLY** decay back to SM particles

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



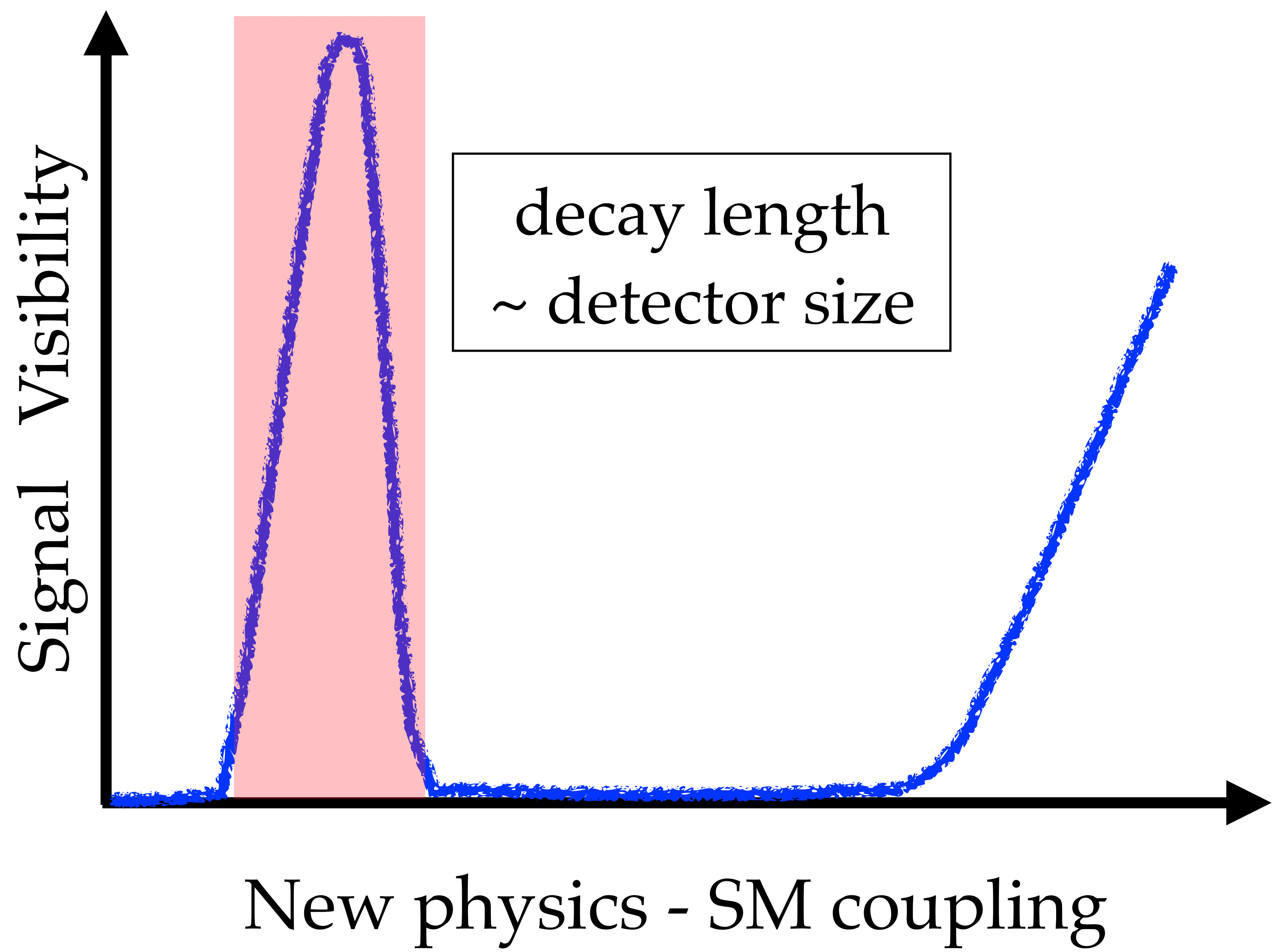
Normal story: smaller coupling => bad

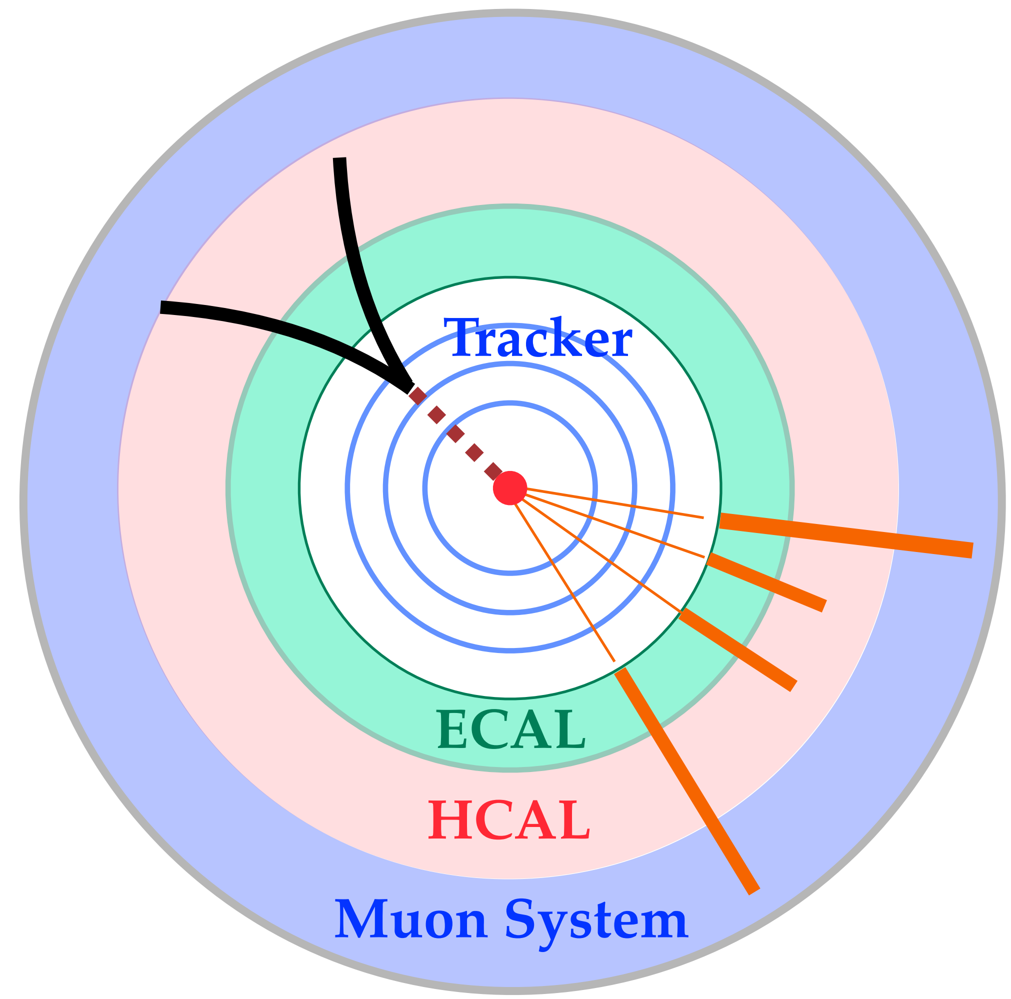


Long-lived Particle (LLP) search

NEGLECTED SO FAR

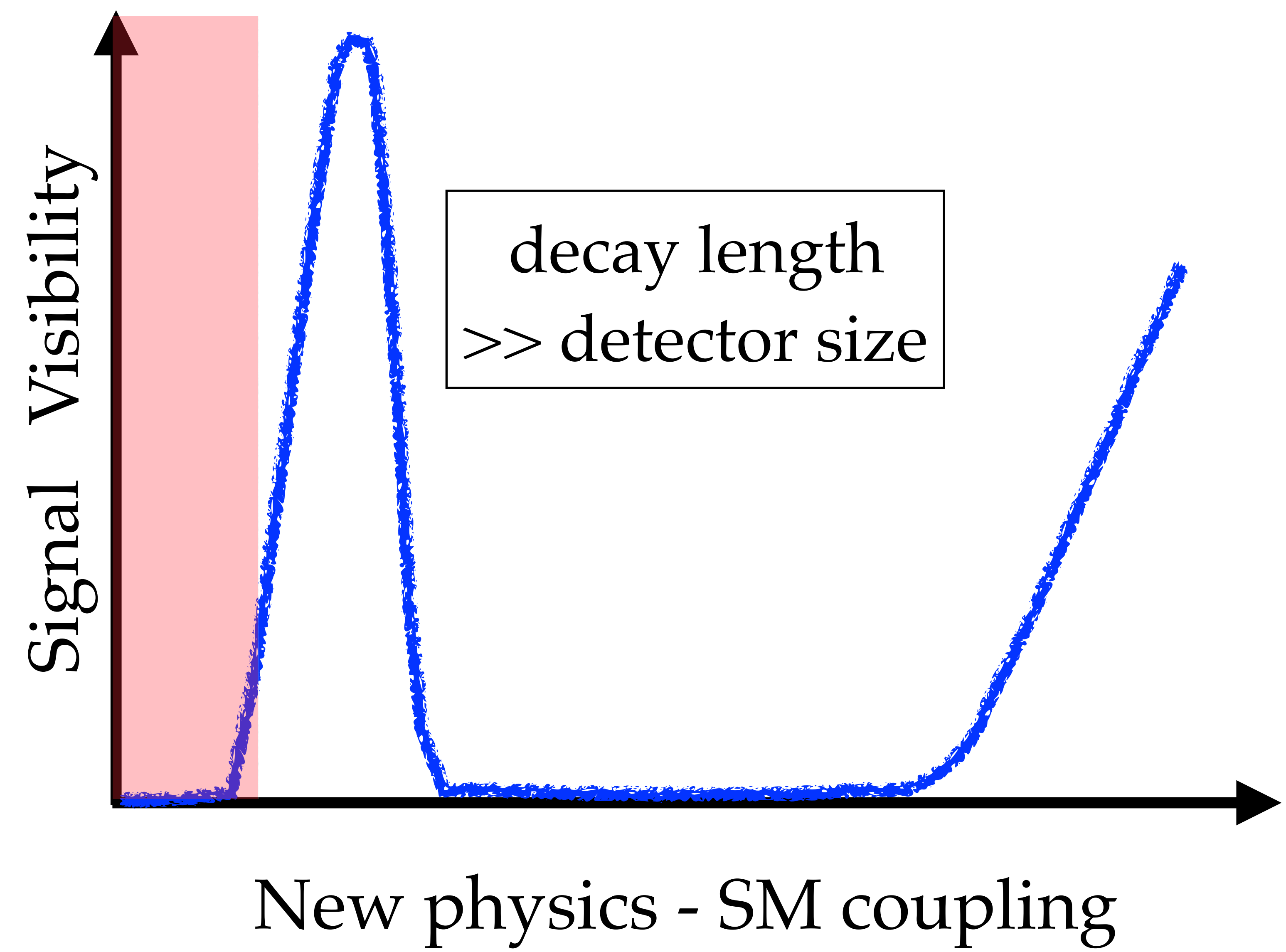
but increasingly being studied!

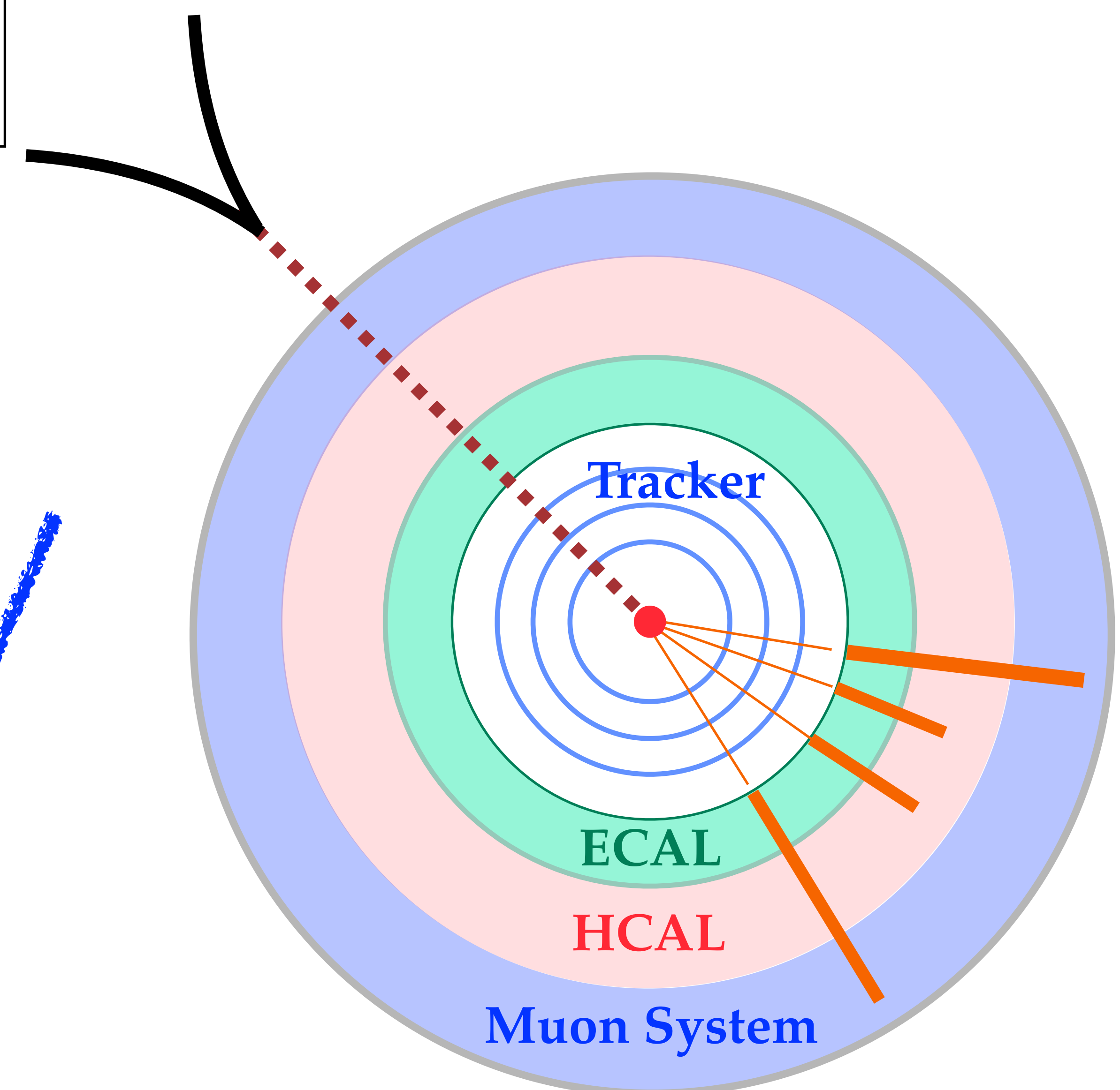




But if it's tooo long-lived

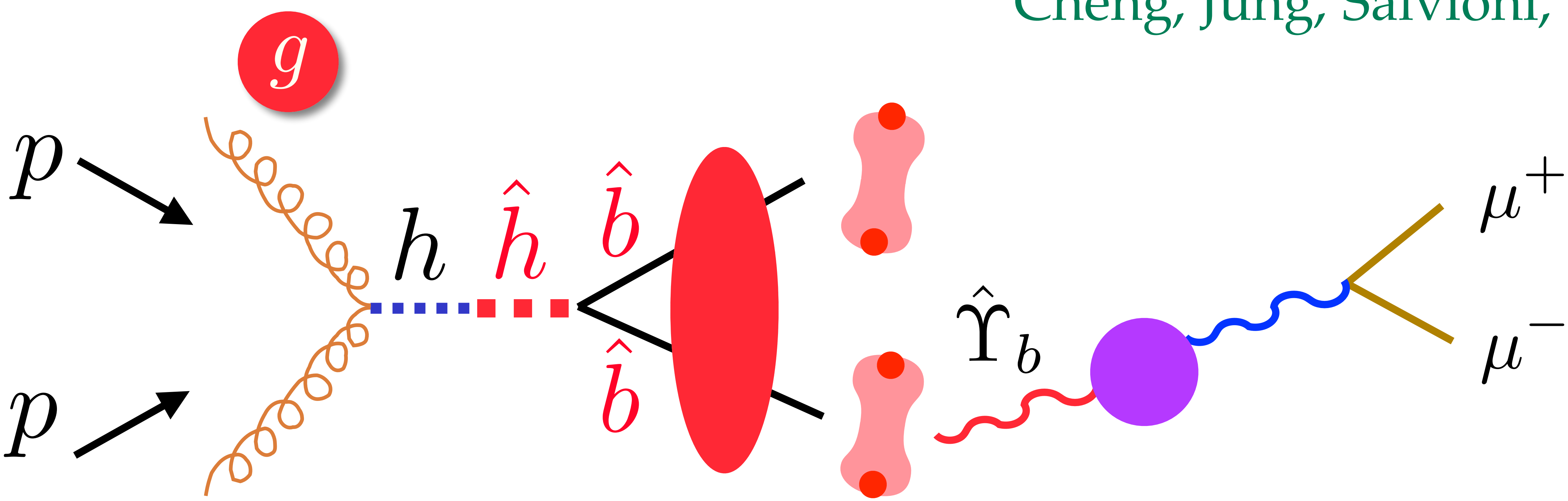
NEGLECTED SO FAR
but increasingly being studied!





Max decay length from cosmological constraint

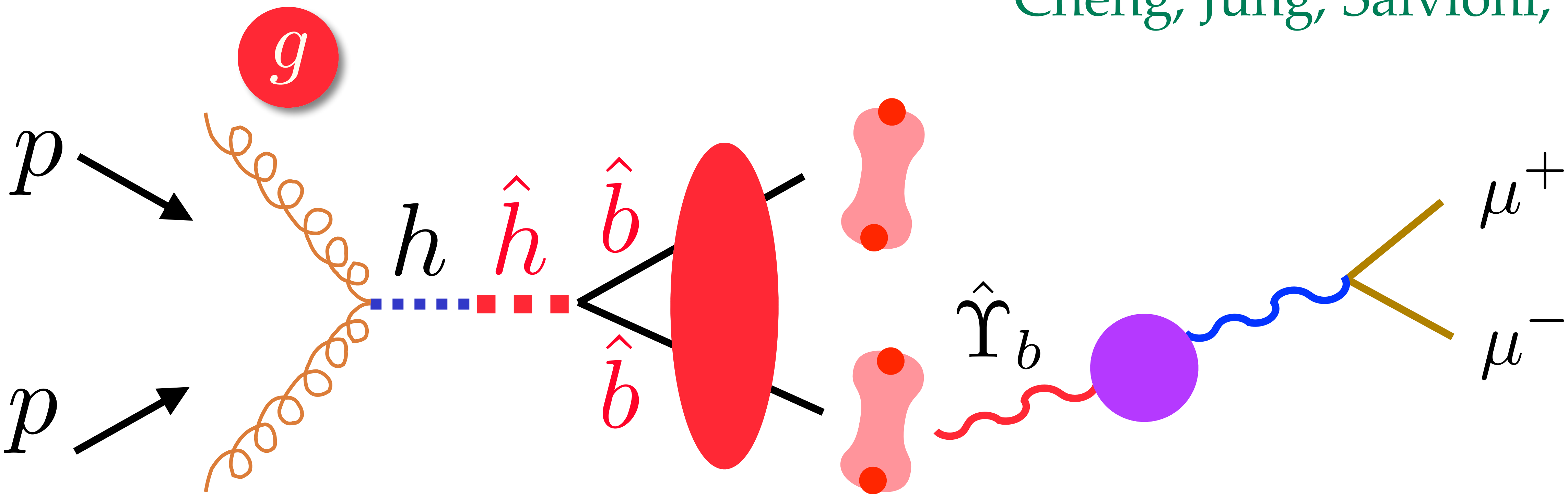
Cheng, Jung, Salvioni, YT (15')

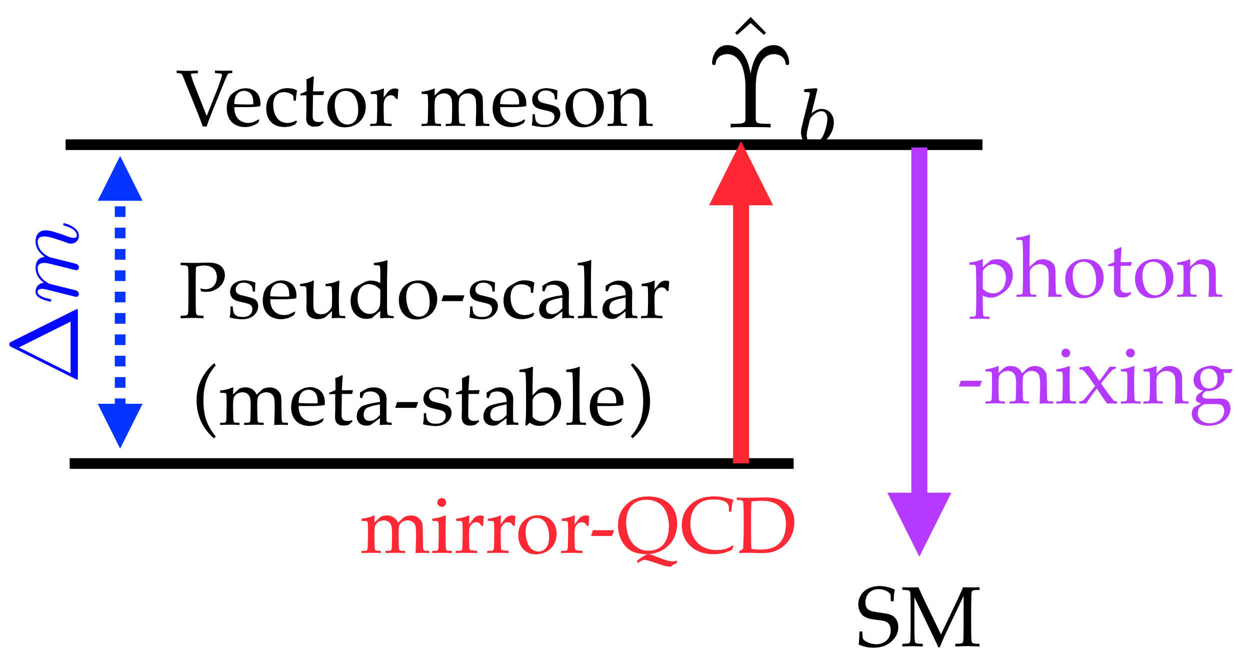


If mirror mesons have mass ~ GeV are the lightest mirror particles, and if there're only couple through Higgs/Photon portals, vector meson should decay ~< 1 m to avoid BBN constraint

Max decay length from cosmological constraint

Cheng, Jung, Salvioni, YT (15')





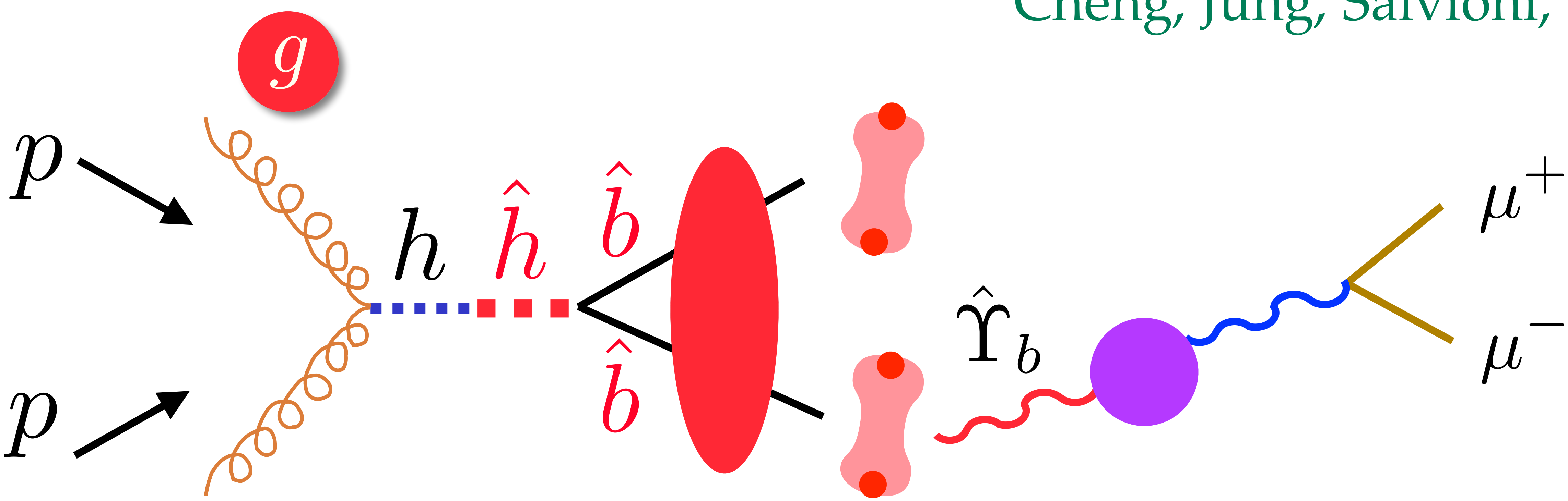
Pseudo-scalar is meta-stable and overly abundant. An easy way to dump them is to have

$$\Gamma_{\hat{\Upsilon}_b} > H(T \simeq \Delta m)$$

=> decay length ~< 1 m

Max decay length from cosmological constraint

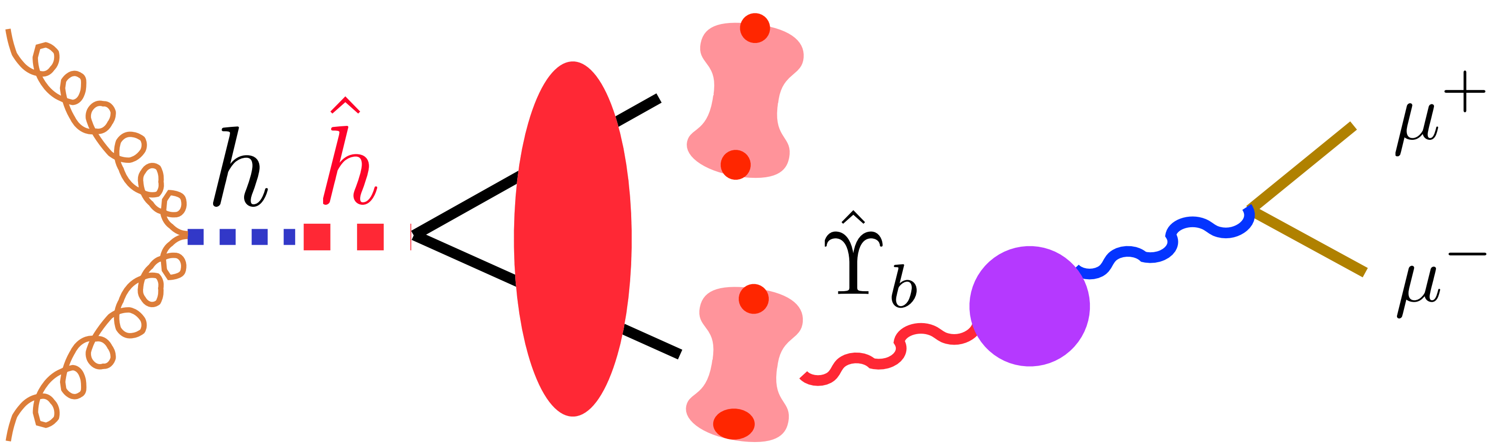
Cheng, Jung, Salvioni, YT (15')



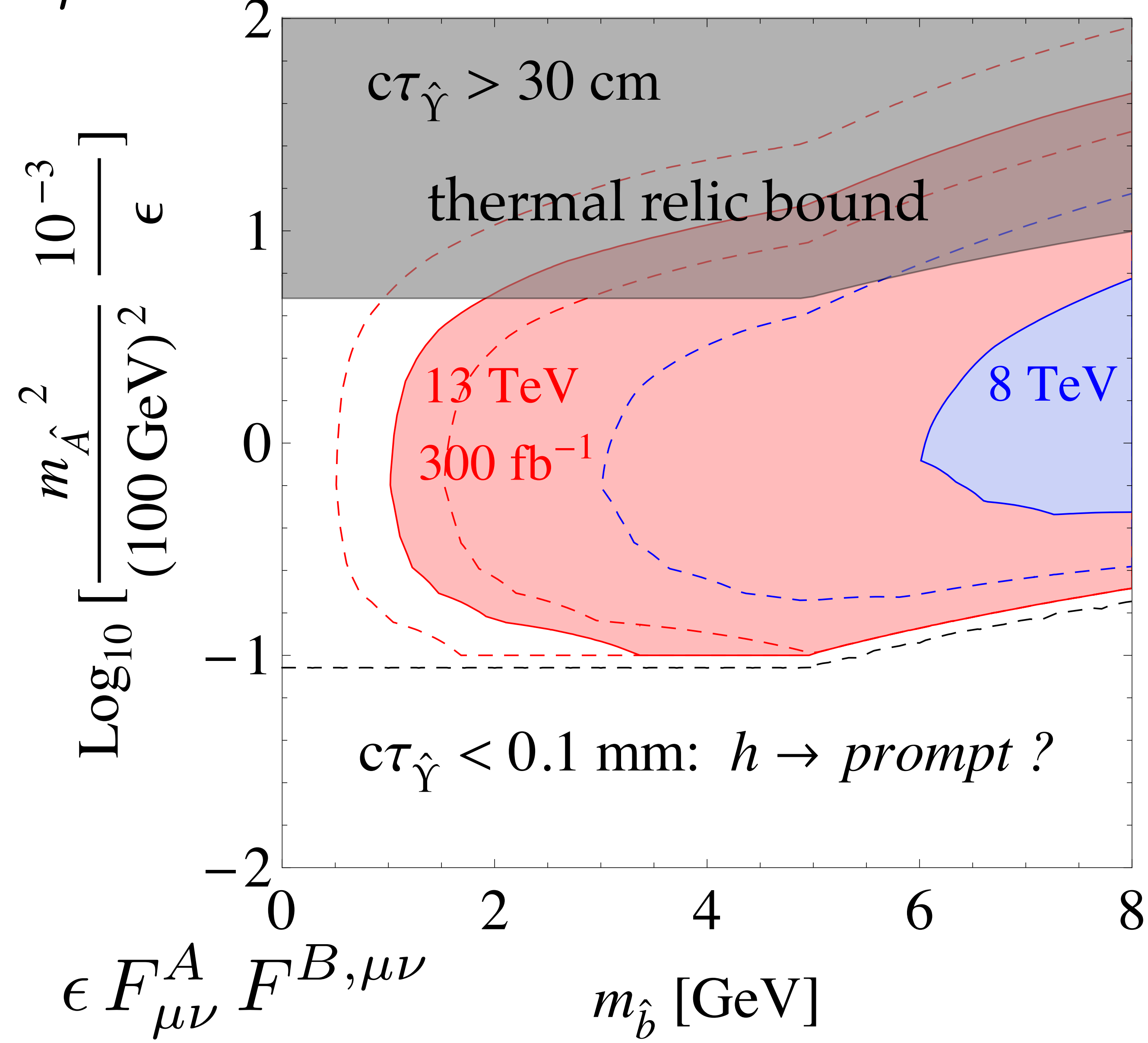
The decay will likely happen inside the detector in the simplest mirror meson scenario

LHC search of displaced muon pairs

Cheng, Jung, Salvioni, YT (15′)



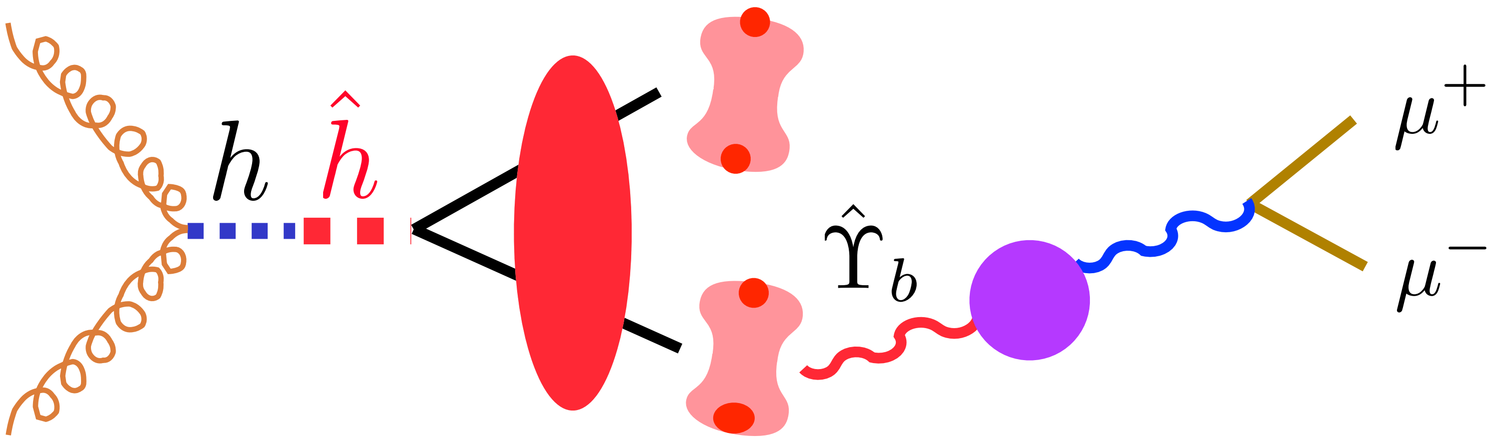
Using result from the CMS displaced di-muon search (1411.6977)



$\epsilon\, F^{A}_{\mu\nu}\, F^{B,\mu\nu}$

LHC search of displaced muon pairs

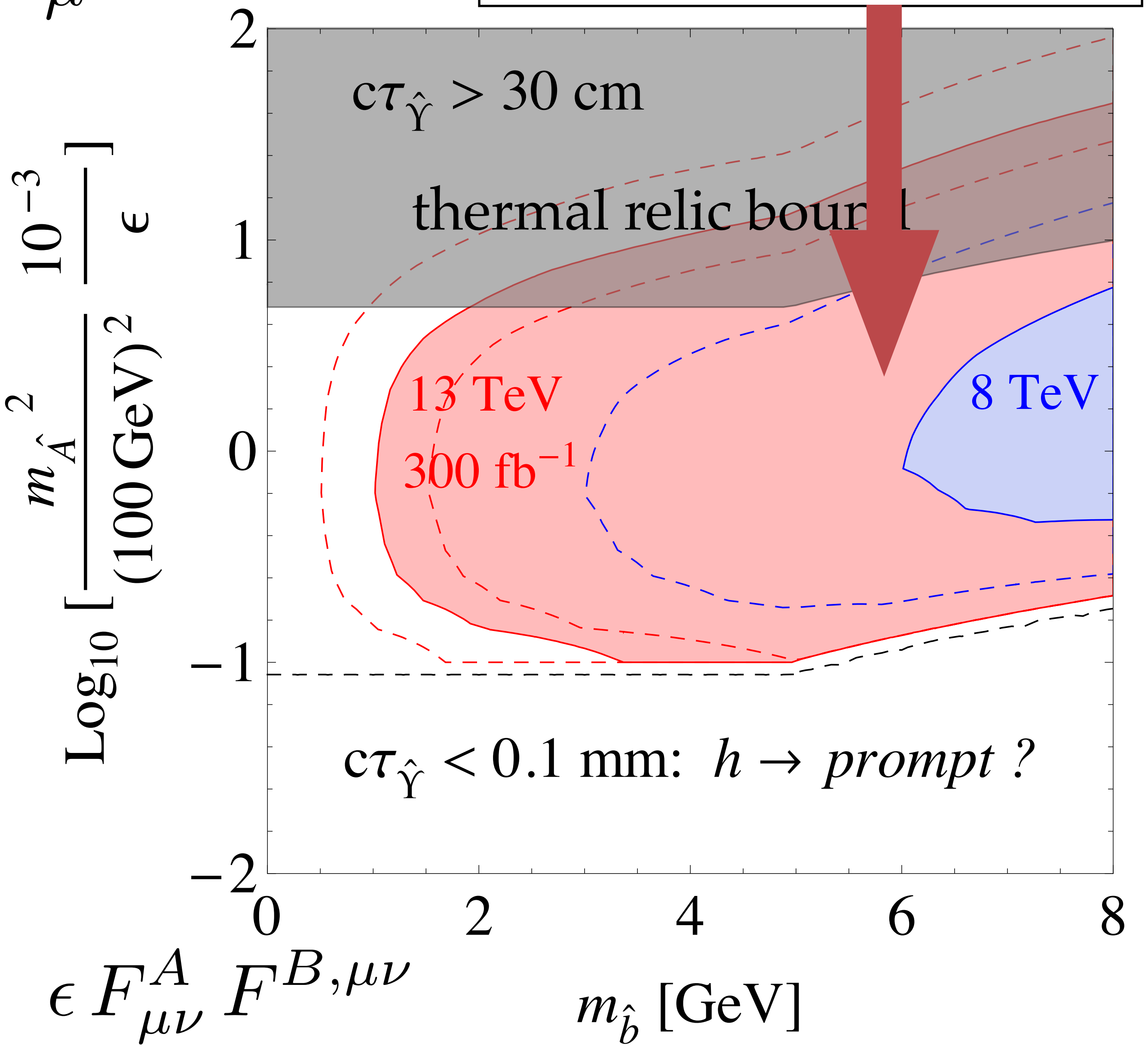
Cheng, Jung, Salvioni, YT (15′)



Using result from the CMS displaced di-muon search (1411.6977)

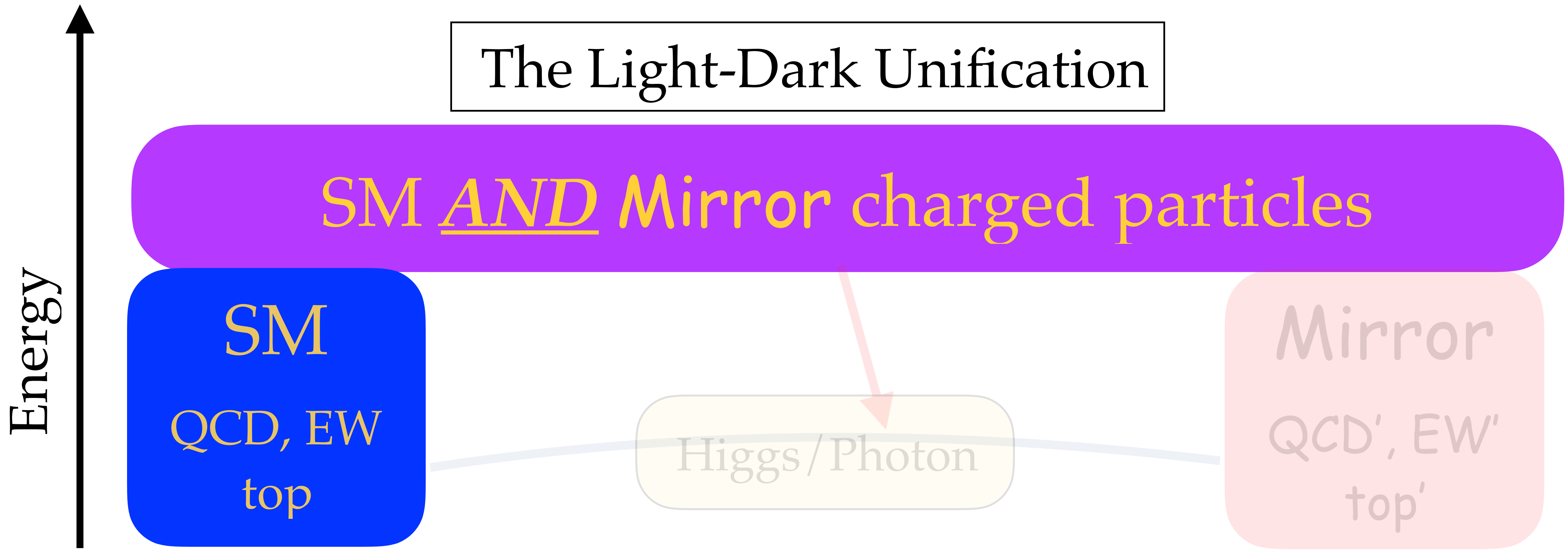
Probe mirror quark coupling
~ 1000x weaker than
the SM Weak interaction

We showed the whole param-space is accessible!

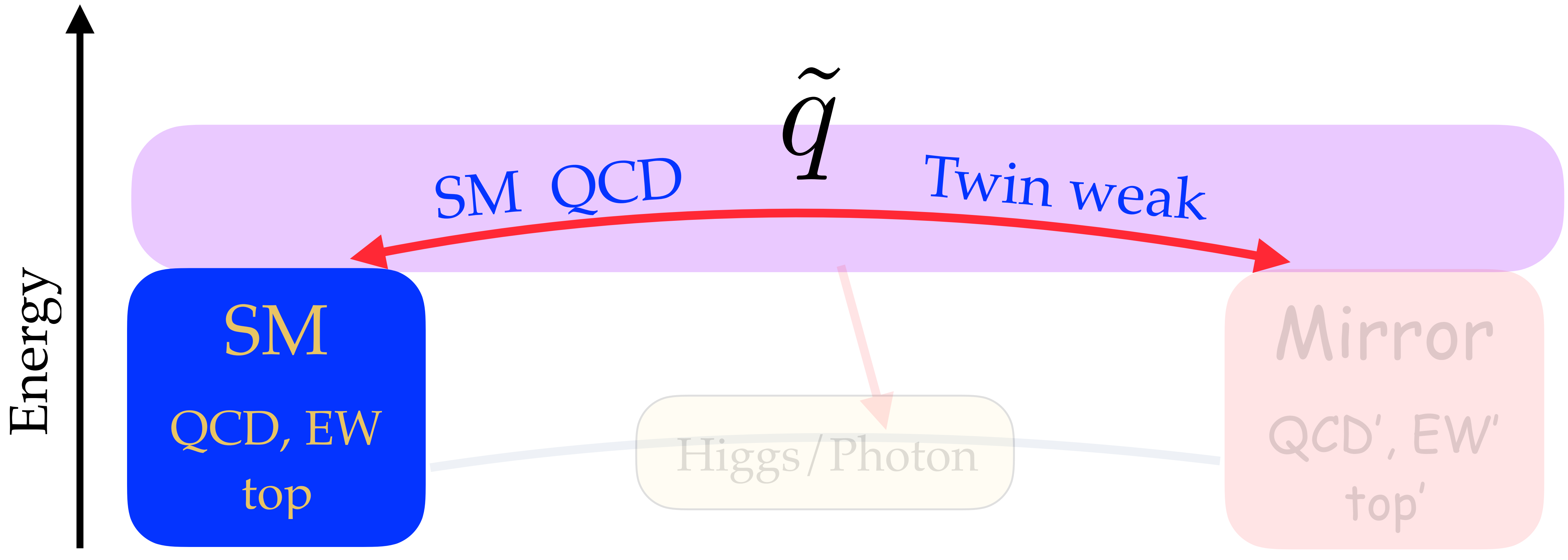


$\epsilon F^A_{\mu\nu} F^{B,\mu\nu}$

Probing the Light-Dark unification!

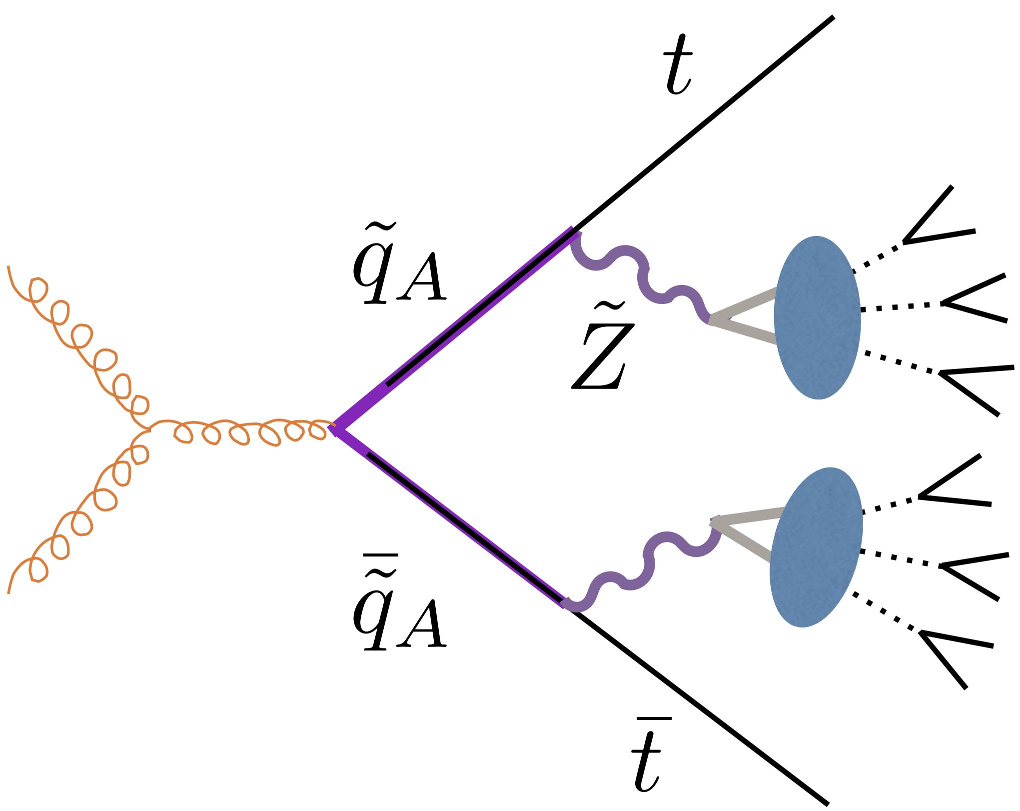


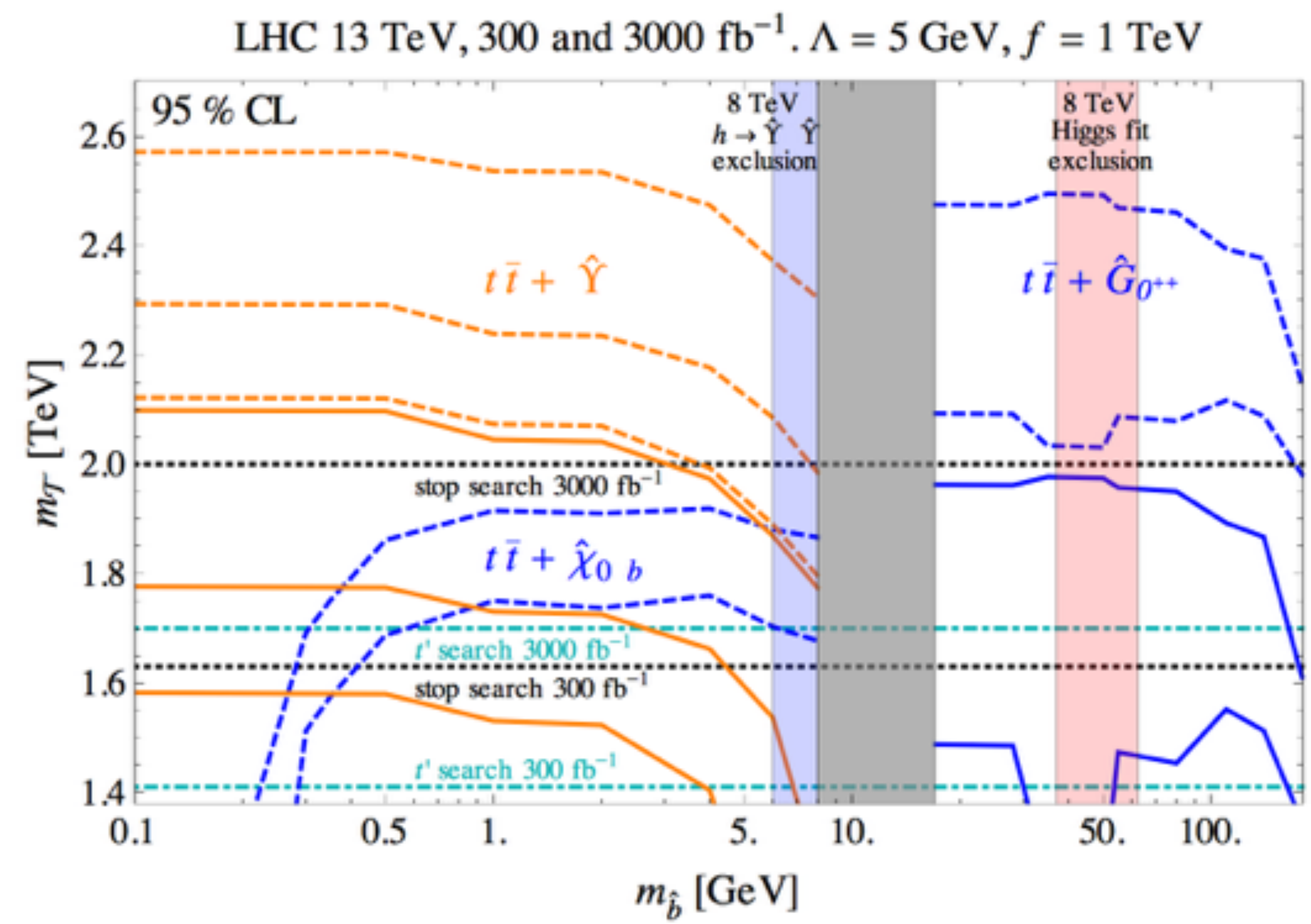
Probing the Light-Dark unification!



Probe the UV structure of Twin Higgs

DV into bb or muons + lepton (pT > 100)





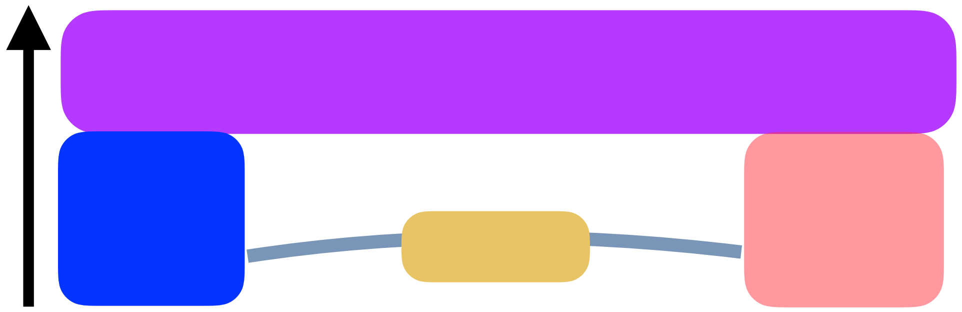
Cheng, Jung, Salvioni, YT (15', 16')

Li, Salvioni, YT, Zhang (17')

Can probe the structure of
Hidden sector up to few TeV scale!

What does this mean?

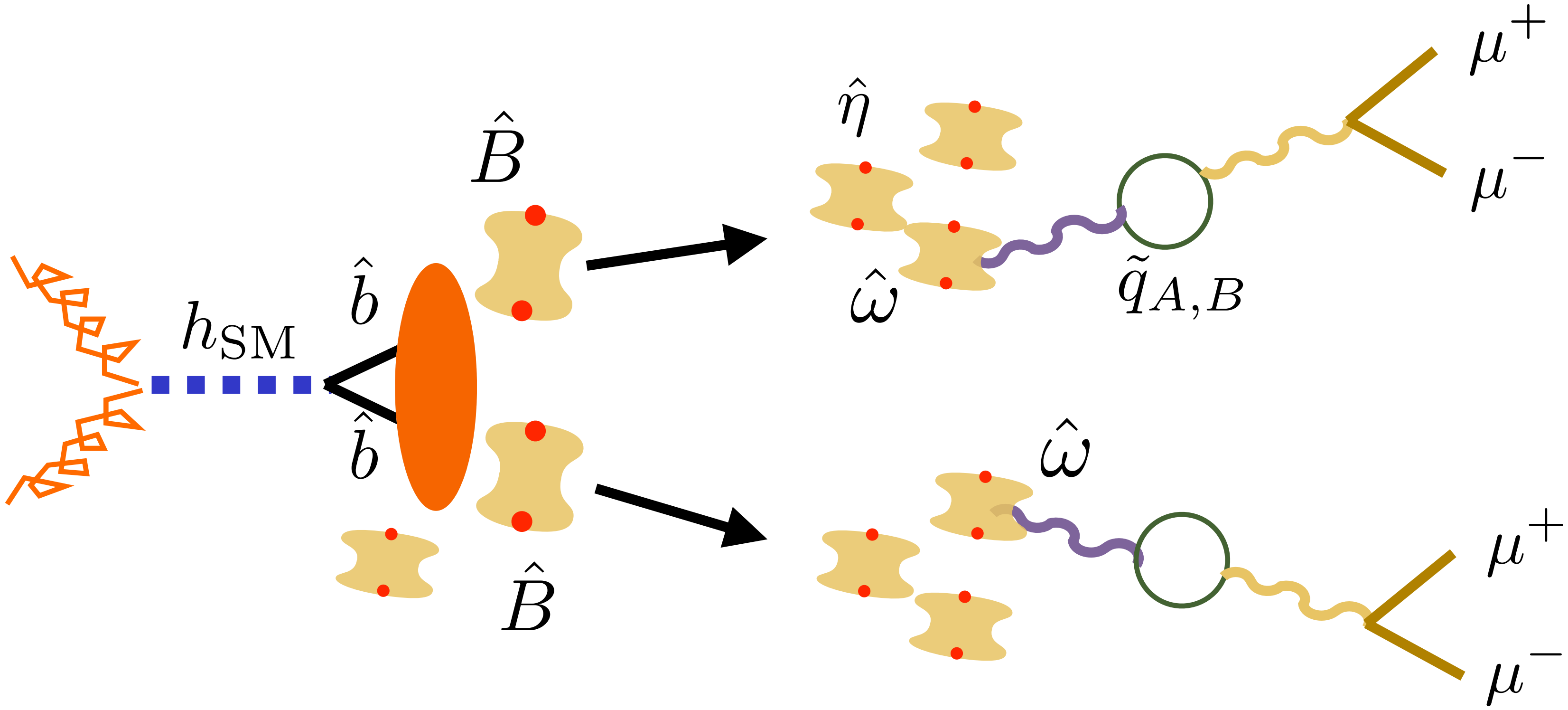
The **Long-lived particle** search is very powerful.
We can study both **low energy portal** and
high energy structure of the hidden sector

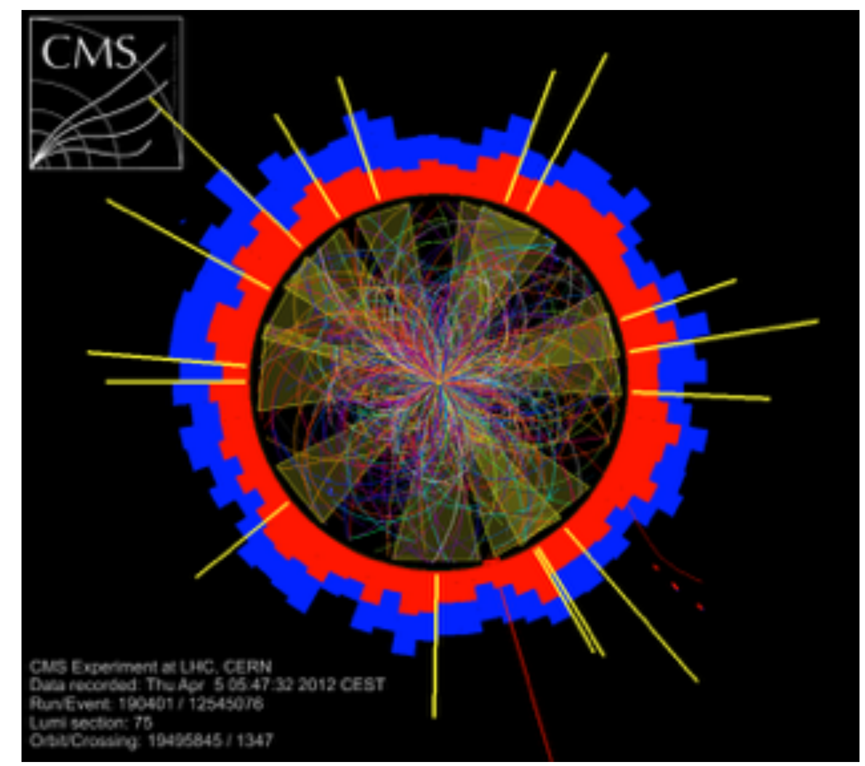


Since the LLP search is so important,
we need to probe every corner of that signature space

Challenge: LLP with low mass and energy

Twin hadrons can be light & have low energy



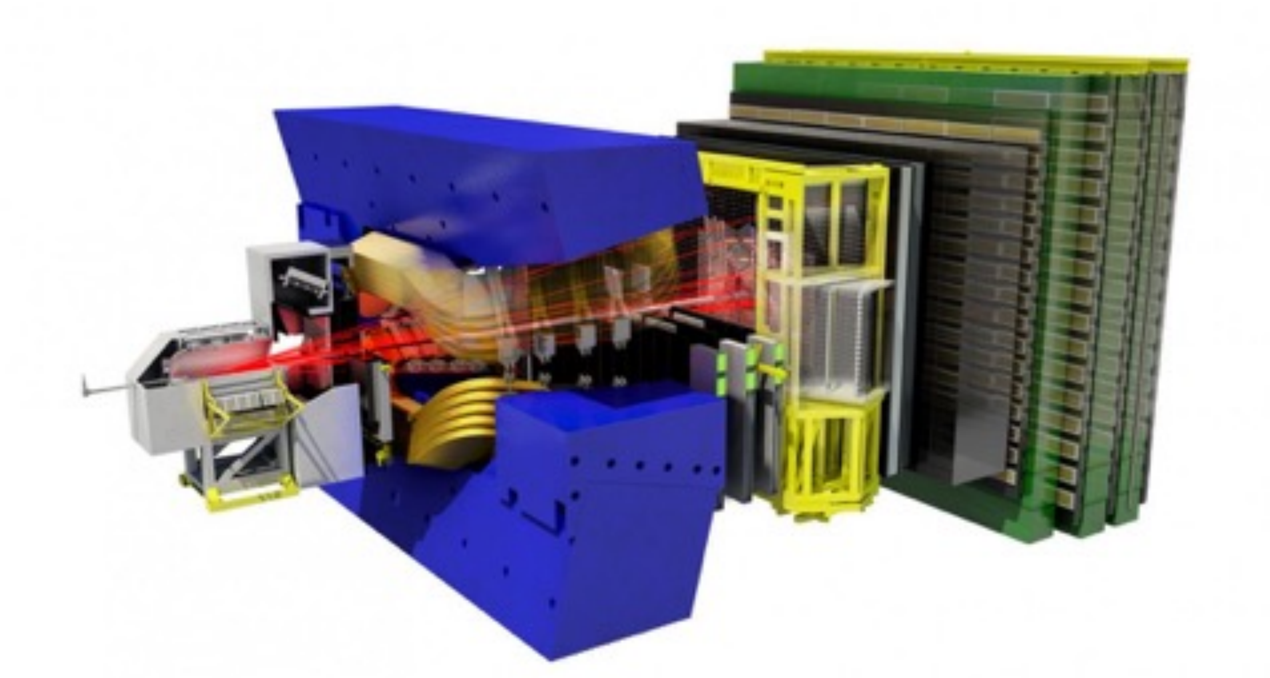


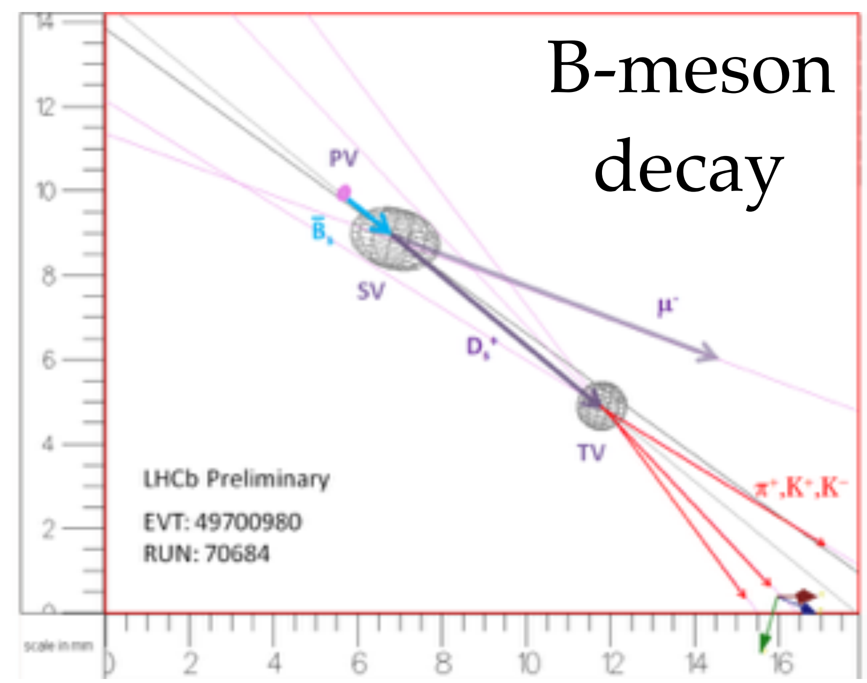
>6 LLPs with muon pT < 10 GeV

hard to distinguish signal from background

Solution: using the flavor physics machine

LHCb detector is designed to see rare SM meson decays





It turns out it’salso powerful for the LLP search!

Pierce, Shakya, YT, Zhao (17’)

Why LHCb?

In order to look for rare SM meson decays, LHCb has

Good vertex resolution (10 μm)

Low pileup background (~< 5 at Run 3)

Good particle identification (pion fake rate for muons $\epsilon_\pi^2 \approx 10^{-6}$)

Low pT requirement (charge track >~ 0.5 GeV)

e.g., Multi-muon trigger in CMS/ ATLAS usually
require >~ 6 - 10 GeV muons (x3 muons)

Why LHCb?

In order to look for rare SM meson decays, LHCb has

Good vertex resolution (10 μm)

Low pileup background (~< 5 at Run 3)

Good particle identification (pion fake rate for muons $\epsilon_\pi^2 \approx 10^{-6}$)

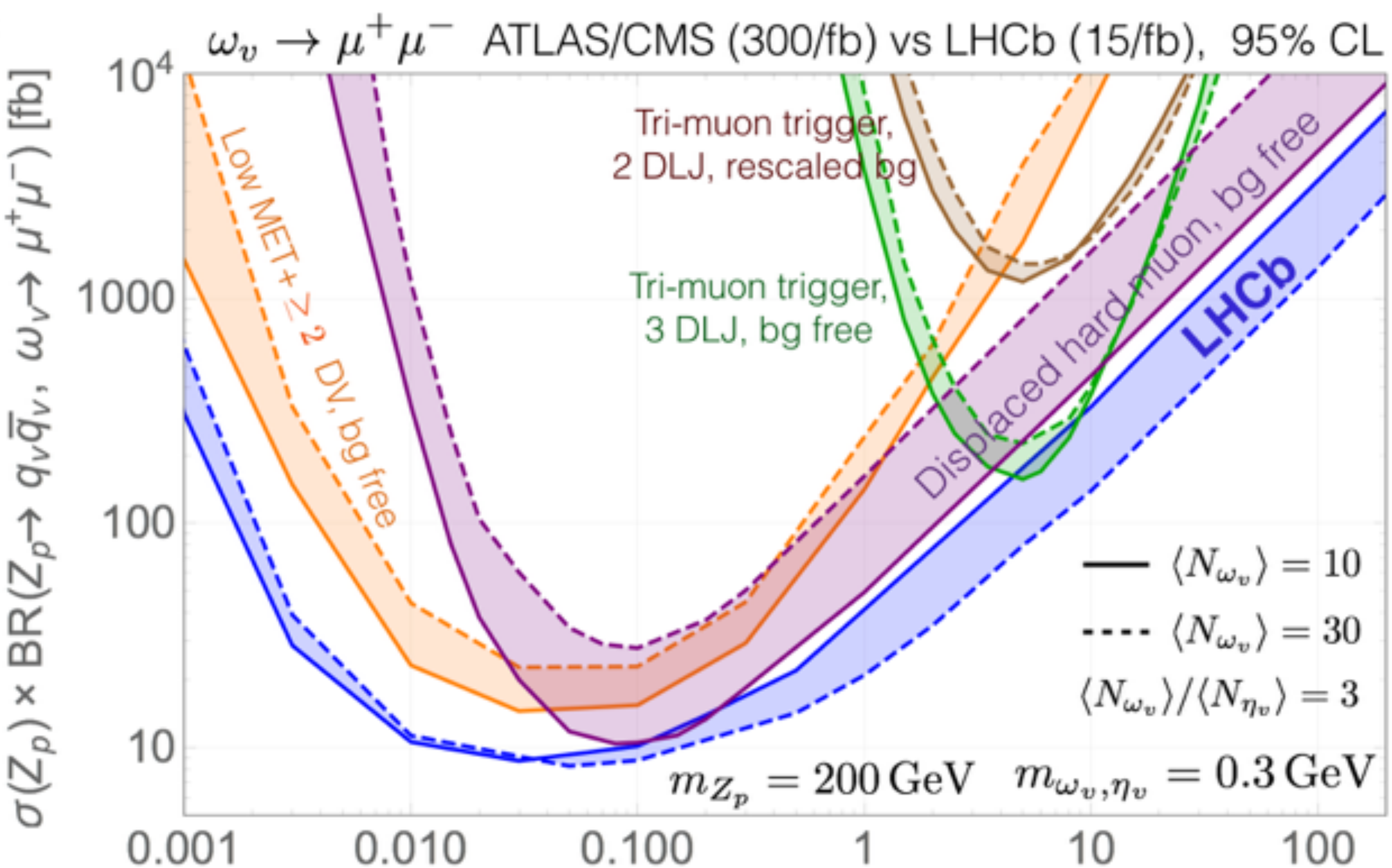
Low pT requirement (charge track >~ 0.5 GeV)

We can see the soft LLP events at the LHCb

Light & soft LLP search at LHCb

Example: 200 GeV Z′ decays into 10-20 sub-GeV hidden mesons

Signal Production Rate



Average Decay Length (cm)

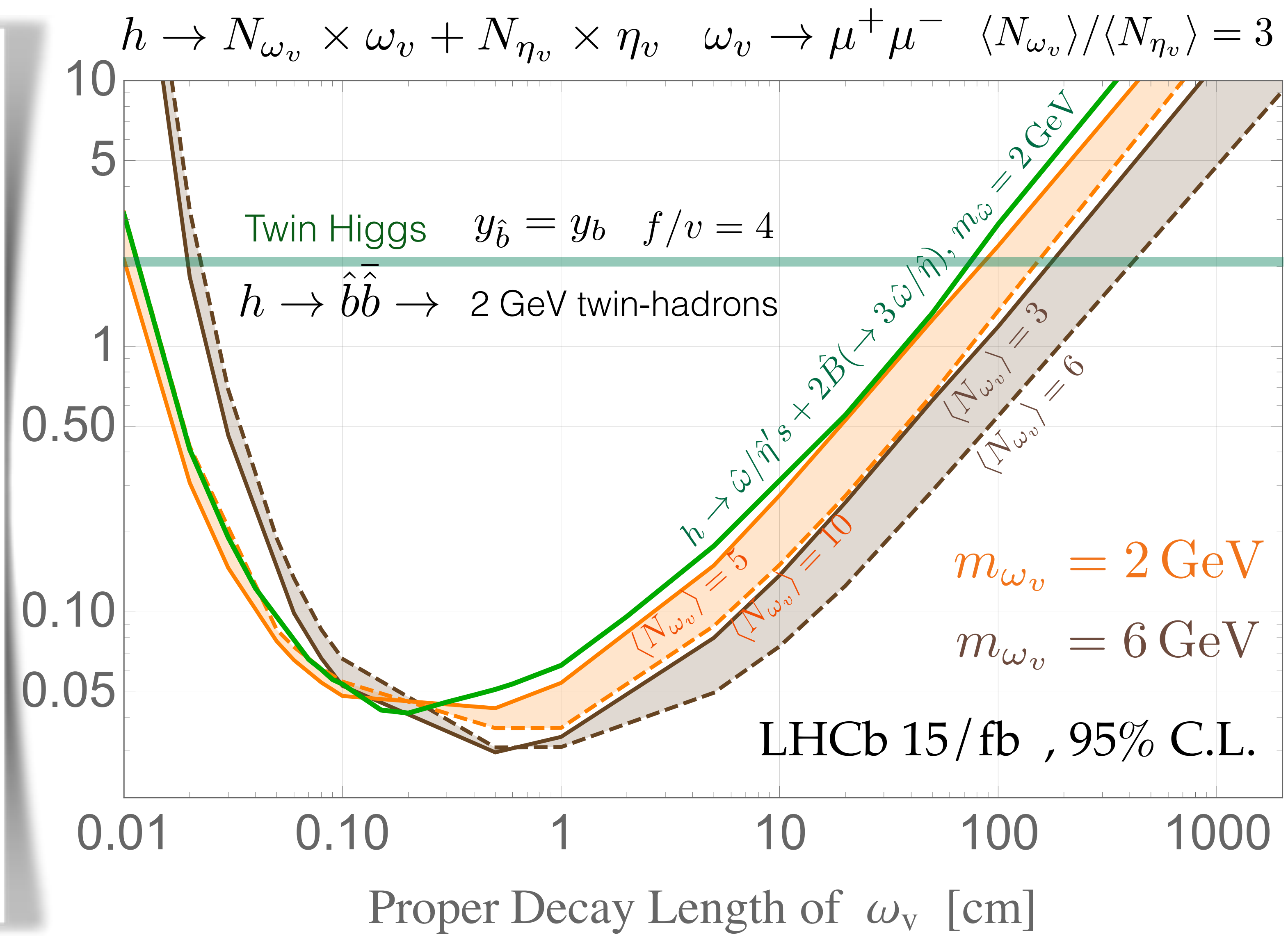
LHCb is good at identifying soft particles

Pierce, Shakya, YT, Zhao (17′)

LHCb constraint on the exotic Higgs decay

Pierce, Shakya, YT, Zhao (17')

Probability of Higgs Decay into Mirror Mesons

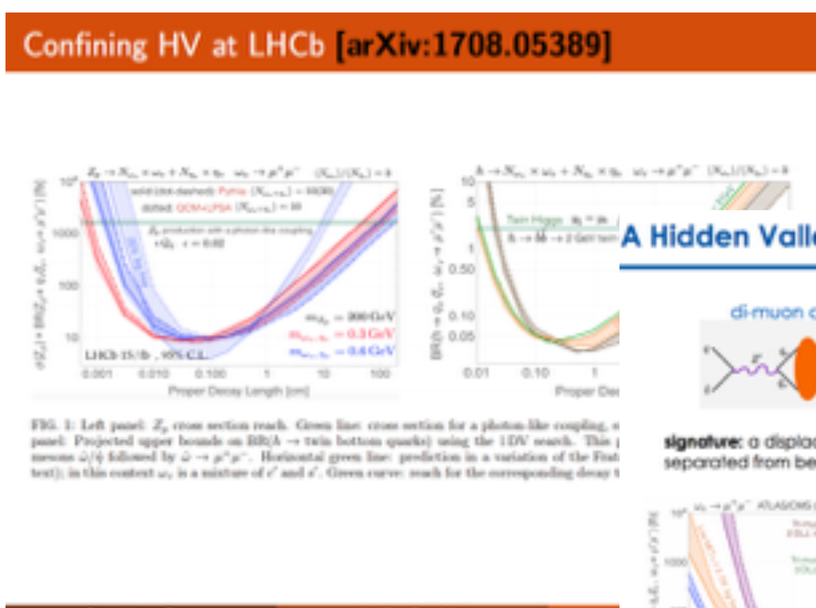


Average Decay Length

We showed this much FTH parameter space only accessible at LHCb!

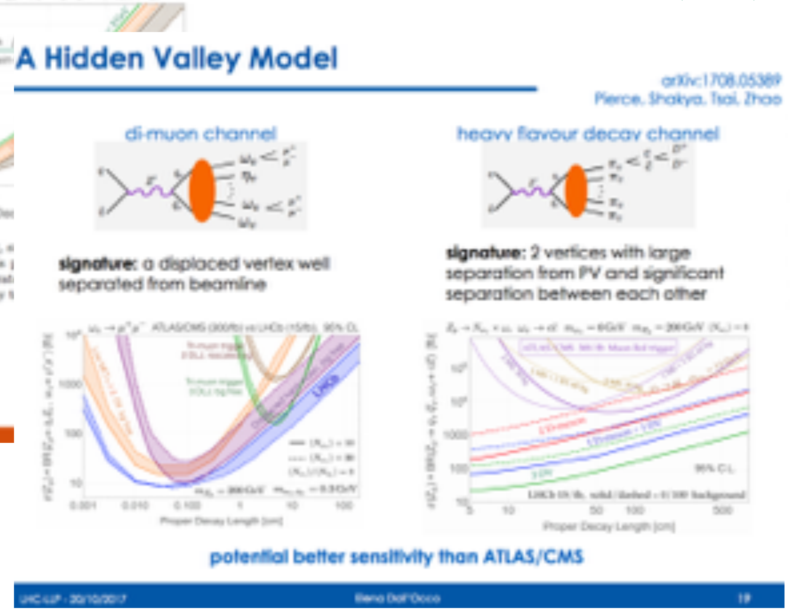
LHCb was not designed to look for new particles

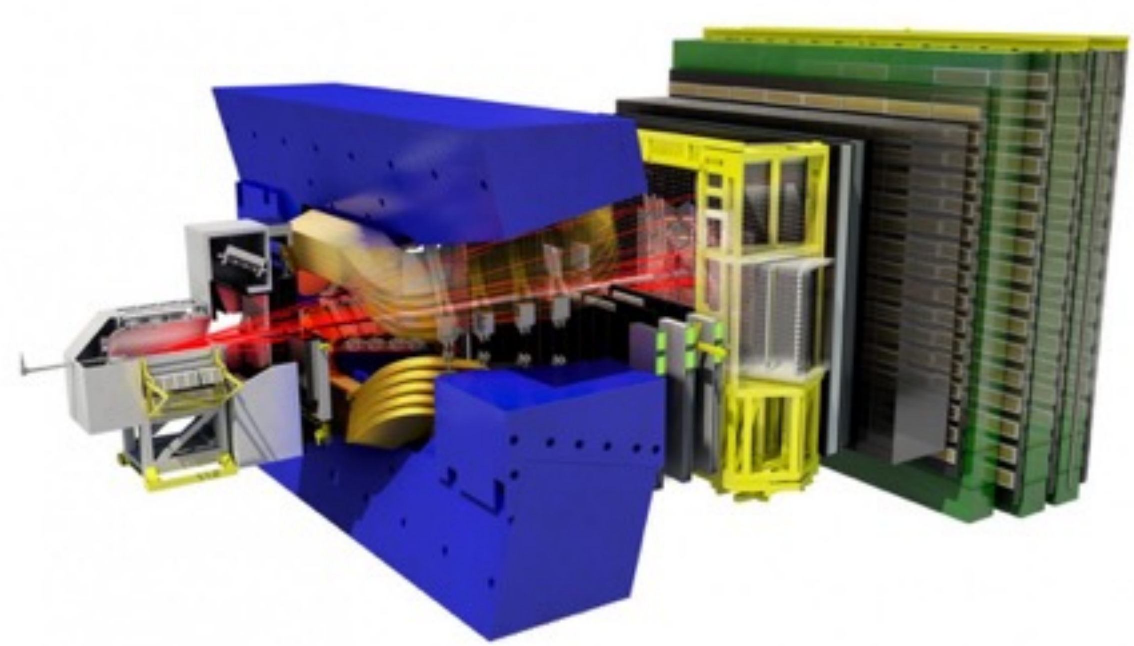
But its precision capabilities are proving vital in the search for hidden sectors and naturalness



Vazquez-Sierra (17′)

Dall′Occo (17′)





Conclusion

An important interplay between **Collider** <-> **Cosmology**
when solving the physics puzzles

Neutral Naturalness gives a concrete example to solve
the **Higgs Hierarchy Problem** by **Hidden Sector physics,**
which leads to exciting cosmological signatures

Many experimental efforts have been put to improve
both **collider** & **cosmological** searches
It it vital to combine these data for solving the puzzles