What is Beyond the SM ?

Tensions in the Standard Model

B Decay anomalies	~2.5 sigma
Muon’s g-2 anomaly	~3.5 sigma
H_0 tension	~ 4 sigma
Dark matter	
Dark energy	

The Dark Matter Seems the Most Robust Problem

Who Orders Dark Matter ?

Tsutomu Yanagida

(TDLI, Shanghai Jiao Tong University)

BLV 2019 in Madrid

What is the Dark Matter ?

?????

10^{-22} eV 10^{+47} GeV

Too many possibilities

Never Threw a Dice !

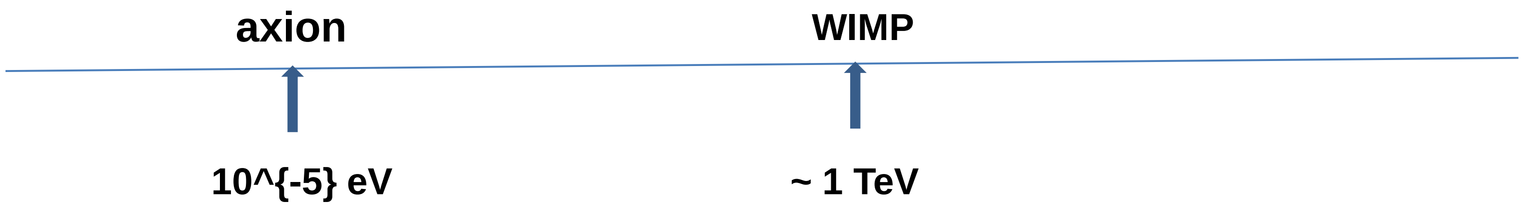
Who Orders the Dark Matter ?

A Solution to the Strong CP Problem in QCD

→ ***The Axion***

A Solution to the Hierarchy Problem

→ ***SUSY WIMP***



Only Two Candidates !!!

Do We Have Another Candidate ?

Yes !

Unification in Dark Sector

Unification in Our Sector ?

SO(10) !!!

A Key Point is Neutrino Masses

Discovery of the Seesaw Mechanism

A Puzzle in the Weinberg-Salam model:

Gauge group = SU(3)xSU(2)xU(1)

1. U(1) hypercharges ?

$$q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \text{(1/6)} \qquad u_R^i \text{ (2/3)} \qquad d_R^i \text{ (-1/3)}$$

$$l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \text{(-1/2)} \qquad e_R^i \text{ (-1)}$$

The theory is anomaly free with these awkward charges !

An example; 6x(1/6)^3 + 3x(-2/3)^3 + 3x(1/3)^3 +2x(-1/2)^3 +(+1)^3 =0

The hypercharges are naturally explained in a grand unification

SU(3)xSU(2)xU(1) is embedded in **SU(5)**

Georgi, Glashow (1974)

All quarks and leptons belong to **5* + 10** of the SU(5) !
The hypercharges are given by an SU(5) generator

But, the quarks and leptons are not completely unified

SO(10) contains the SU(5) and is more attractive, since it unifies all quarks and leptons in 16

$$\mathbf{16} = \quad q_L^i = \begin{pmatrix} u \\ d \end{pmatrix}_L^i \quad \begin{matrix} u_R^i \\ d_R^i \end{matrix} \quad ; \quad l_L^i = \begin{pmatrix} \nu \\ e \end{pmatrix}_L^i \quad e_R^i \quad \nu_R^i$$

We had a big problem

The neutrino has a large Dirac mass

$$y_\nu \bar{\nu}_R l_L \langle H \rangle \quad ; \quad y_t \bar{t}_R q_L \langle H \rangle$$

$y_\nu = y_t$ → m(neutrino) = m(top) ???

But, we found the right-handed neutrino get a huge Majorana mass when the SO(10) breaks down to the Standard Model

$$\frac{1}{2} M \bar{\nu}_R^C \nu_R$$

The neutrino mass becomes $m_\nu \simeq \dfrac{m^2}{M}$; $M_N \simeq M$

Yanagida (1979)
Gell-Mann, Ramond, Slansky (1979)

Seesaw Mechanism

All Quarks and Leptons are Unified in 16 of SO(10)

SO(10) → SU(5) x U(1)

16 → 5* + 10 + N(1)

→ SU(3) x SU(2) x U(1)

quarks, leptons , heavy right-handed neutrino N

SO(10) GUT !!!

Quarks / Leptons are unified in 16 !

We have only three 16's

VERY BEAUTIFUL

Dark Sector Unification

Kamada, Yamada, Yanagida (2019)
at TDLI

SO(10)

All Dark Matter is Unified in a 16 Chiral Fermion of SO(10) as in Our SO(10) GUT

SO(10) → SU(5) x U(1)_{B-L}

16 → X(5*) + Y(10) + N(1)

We consider the SU(5) is not broken till present

The SU(5) gauge interaction becomes strong at lower energies and the quarks X(5*) and Y(10) are confined

We have two anomalous global U(1) symmetries, but a combination of them is non anomalous and hence it is an exact symmetry

We should have massless composite fermions to satisfy the *t'Hooft* anomaly matching condition

t' Hooft (1979)

What are those bound-state baryons ?

A Massless Baryon → $Z \sim \{X(5^*)\, X(5^*)\, Y(10)\}$!

U(1) charges: Z(-5) ; X(-3), Y(+1)

The t'Hooft anomaly matching condition is satisfied by only the composite baryon Z Dimopoulos, Raby, Susskind (1980)

The U(1) is nothing but the gauged $U(1)_{\{B-L\}}$

→ The U(1) charge of N is +5 !

Z and N form a Dirac fermion pair !!!

t'Hooft anomaly matching condition is satisfied

- U(1) charges: X(-3), Y(+1) ; Z(XXY)=(-5)
- {U(1)}^3 anomalies:

  Elementary; (-3)^3x5 +(+1)^3x10=-135+10

  =-125

  Composite; (-5)^3x1=-125

- {U(1)}{graviton}^2 anomalies:

  Elementary; (-3)x5 + (+1)x10 =-5

  Composite; (-5)x1=-5

Gauge invariant operator =

$$(1/M_{PL})^2 \{XXY\} N$$

Mass of Z and N ; $M(ZN) = (\Lambda)^3/(M_{PL})^2$

$M(ZN) \sim O(1)$ TeV

For $\Lambda \sim 10^{13}$ GeV

Z and N are charged under the dark U(1)_{B-L} and hence they are completely stable as long as the dark B-L symmetry is not broken

We call the Dirac Fermion Z and N as a Darkly Charged DM

Consistent with Observations ?

Ellipticity of Galaxies

Dark photon exchange generates a long rage force between DM's which can wipe out deviations from isotropy (the DM velocity distribution is randomized by the self-interaction)

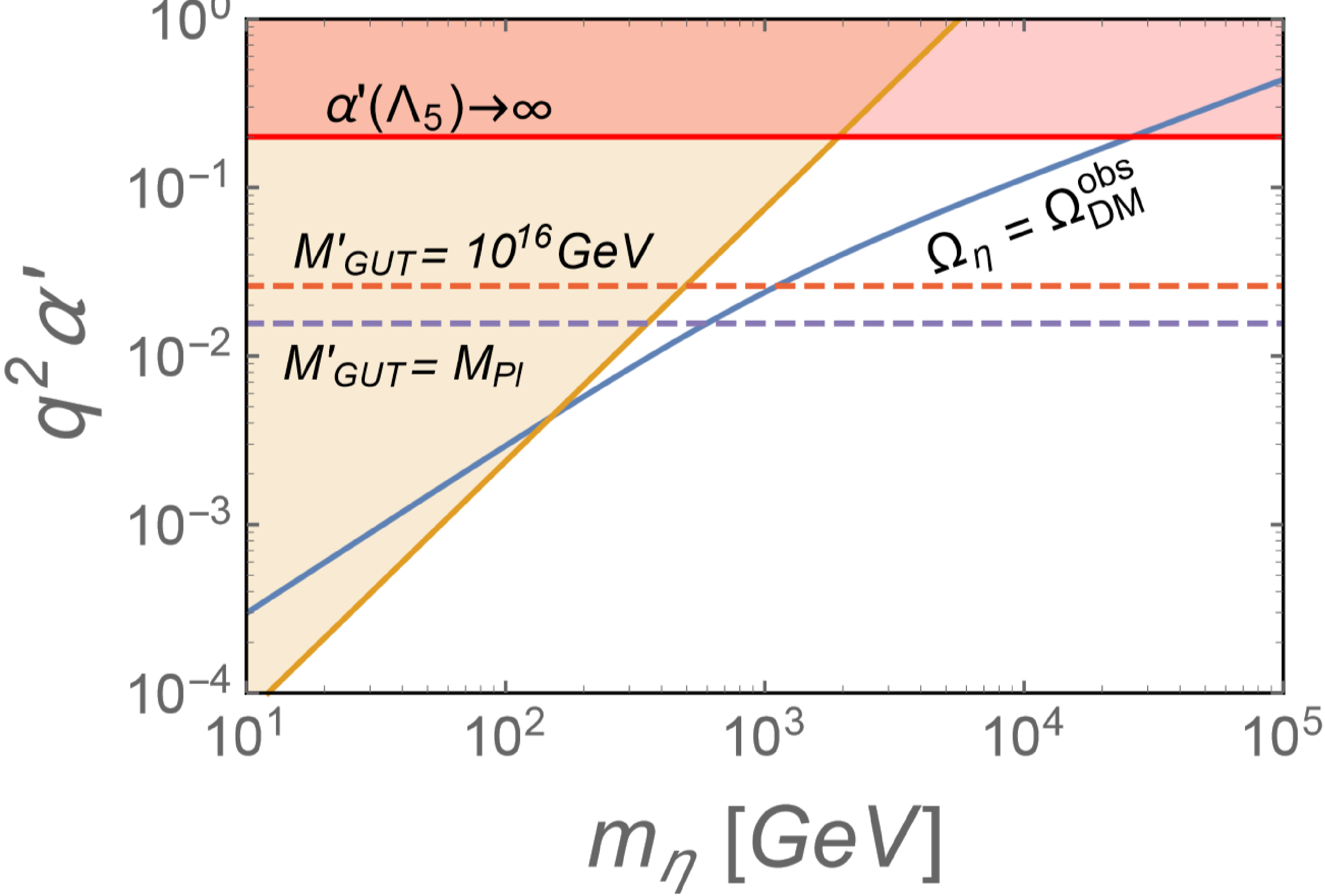
Measured non-zero ellipticity of NGC720 gives us a strong constraint on the coupling constant and the DM mass

Agrawal, Cyr-Racine, Randall, Scholtz (2017)

Dwarf Galaxy Survival

With too strong interaction, dwarf galaxies will be stripped as they pass through a halo

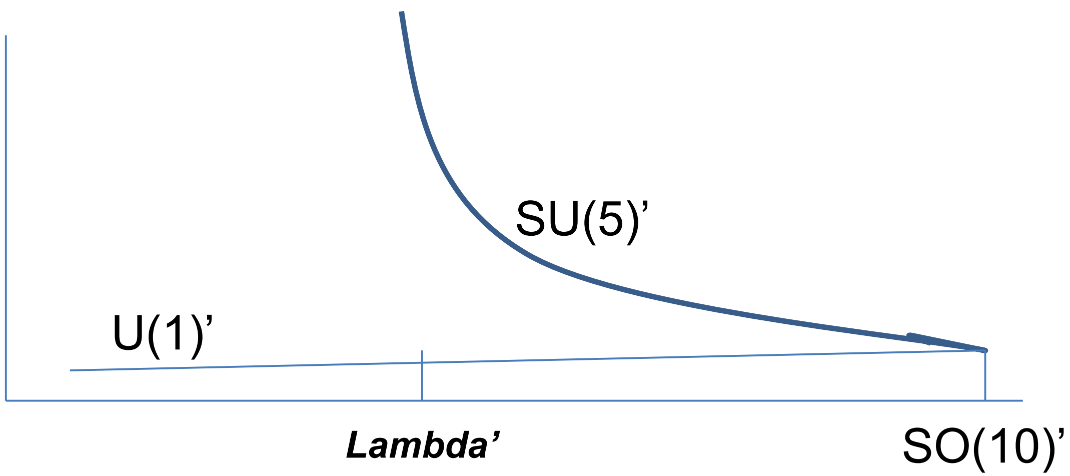
Kahlhoefer, Schmidt-Hoberg, Kummer, Sarker (2014)

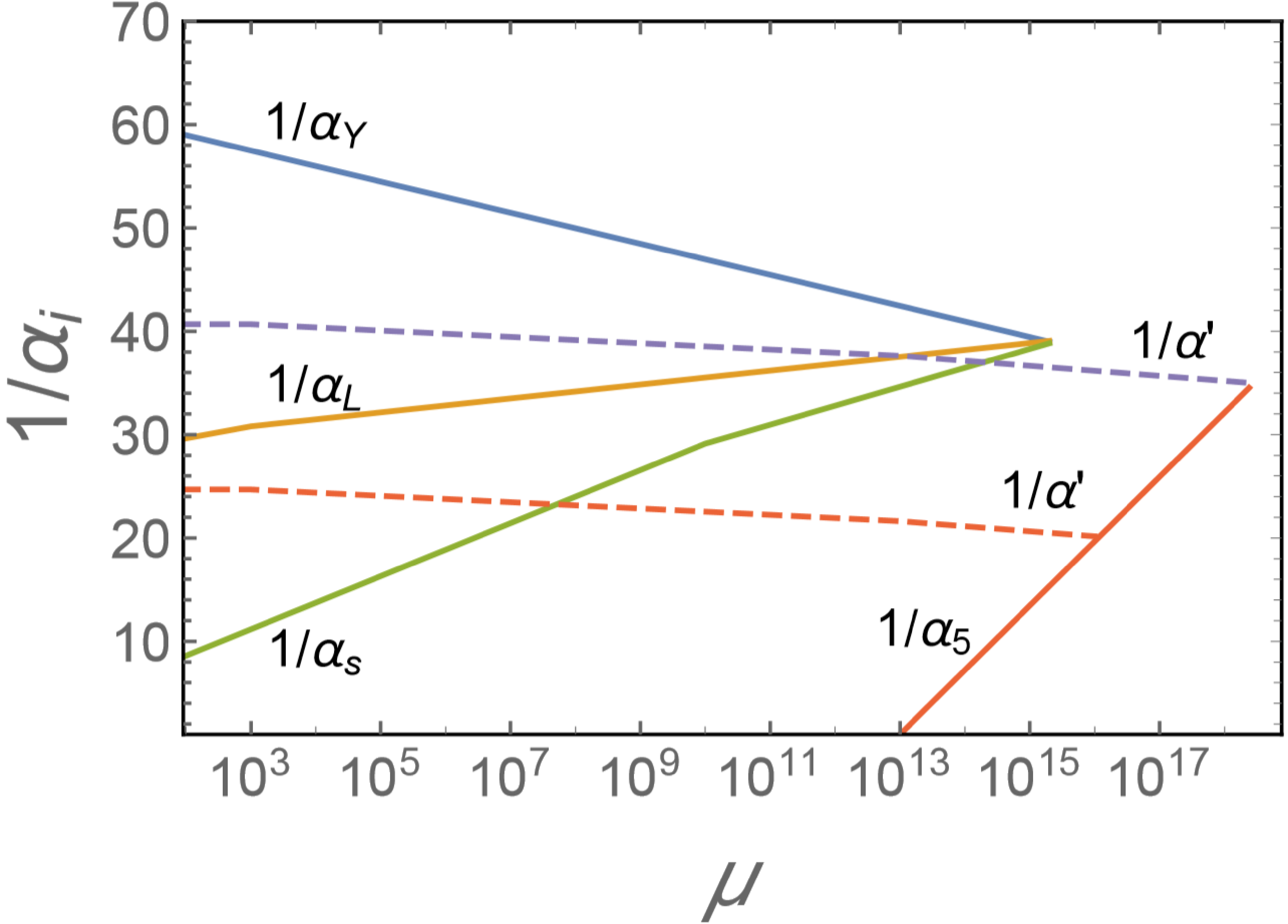


$\alpha'(\Lambda_5)\to\infty$
$M'_{GUT} = 10^{16}$ GeV
$\Omega_\eta = \Omega_{DM}^{obs}$
$M'_{GUT} = M_{Pl}$
$q^2\alpha'$
m_η [GeV]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^1
10^2
10^3
10^4
10^5

Gauge Coupling Unification in the Dark Sector

SO(10)' → SU(5)' x U(1)'





70
60
50
40
30
20
10
$1/\alpha_i$
$1/\alpha_Y$
$1/\alpha'$
$1/\alpha_L$
$1/\alpha'$
$1/\alpha_5$
$1/\alpha_s$
10^3
10^5
10^7
10^9
10^{11}
10^{13}
10^{15}
10^{17}
μ

We predict

¥alpha’ = (2.5-4.2)x10^{-2) ; m(DM) = 0.6-1.1 TeV

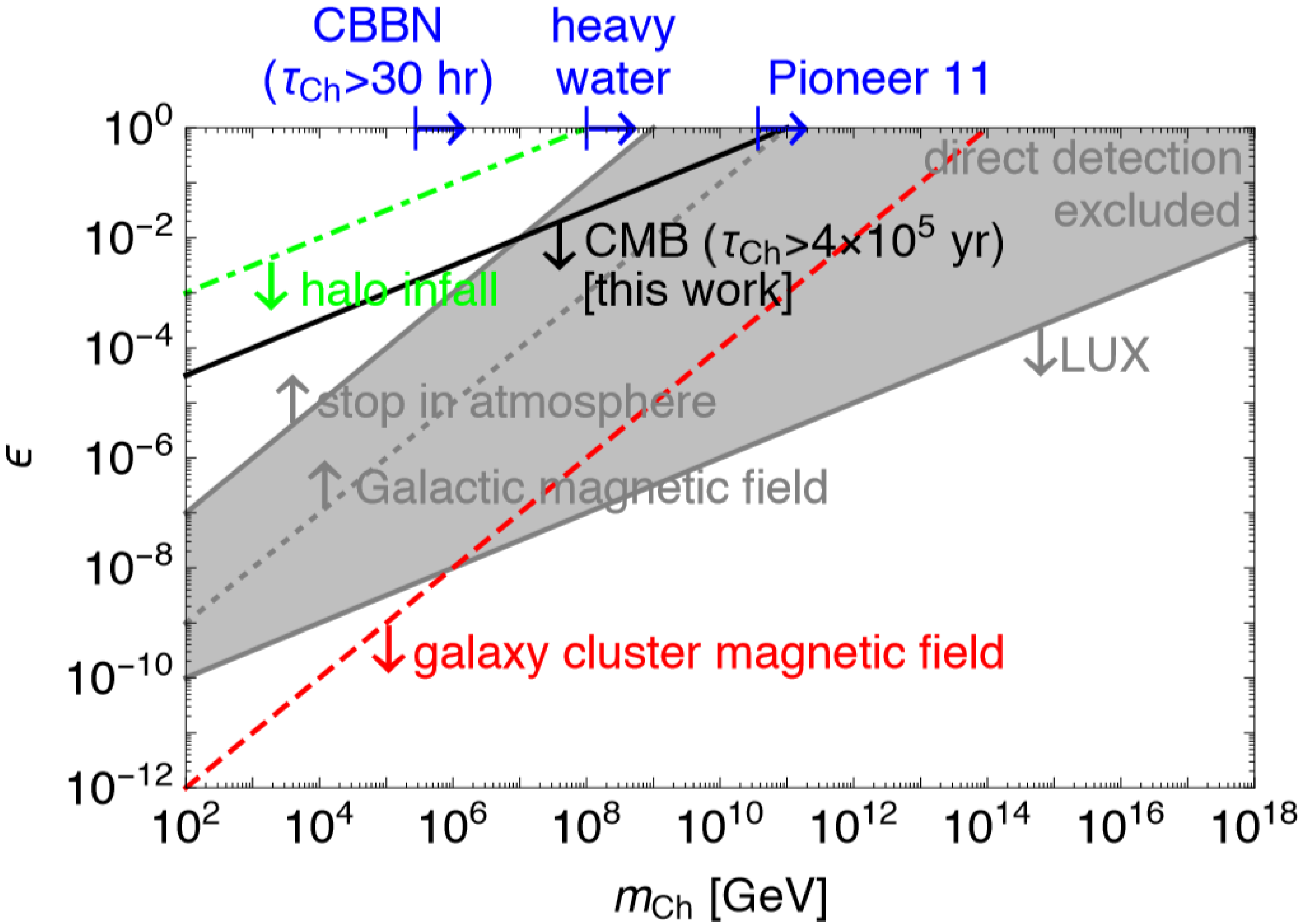
How to Test It ?

Photon-Dark Photon Mixing

$$k F^{ij} F'_{ij}$$

photon *dark photon*

We have strong constraints from LUX, XENON and Panda X


CBBN
(τ_{Ch}>30 hr)
heavy
water
Pioneer 11
direct detection
excluded
CMB (τ_{Ch}>4×10^5 yr)
[this work]
halo infall
LUX
stop in atmosphere
Galactic magnetic field
galaxy cluster magnetic field
ϵ
m_{Ch} [GeV]

Beautiful Unification

SO(10) x SO(10)'

↑

SO(10) x SO(10) x SO(10) x SO(10)'

16 **16** **16** **16**

1st generation — 2nd generation — 3d generation — DM

Conclusions

- **Unification** was a **Light House** in Past Physics
- GUT explains the charge quantization
- **SO(10)** is very successful .

  All quarks and leptons are unified in 16 of SO(10)

  The small neutrino masses are explained

  Universe's baryon asymmetry is explained

- We propose SO(10) in the dark sector

  The light (100 GeV) DM is predicted

  It is a darkly charged Dirac fermion

  The DM seems consistent with observations

I hope that it will be tested in future observations

Onion Unification !!!

1st Skin….1st Family

2nd Skin….2nd Family

…………

4th Skin….The DM Family

……….

…………