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Minimal Mirror Twin Higgs

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with

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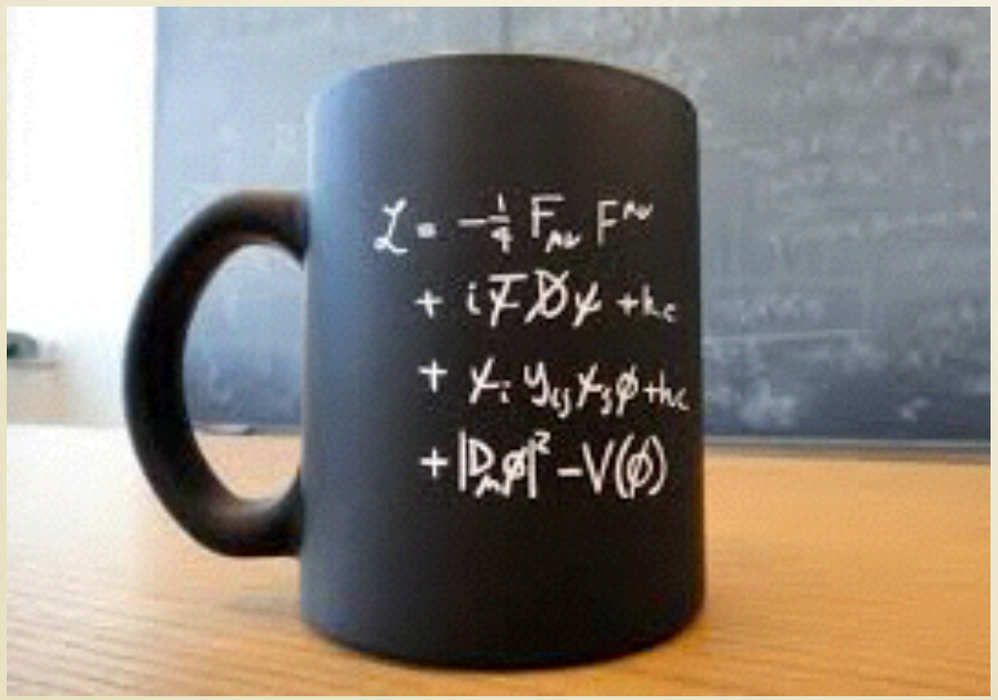
1609.05589, 1706.xxxx

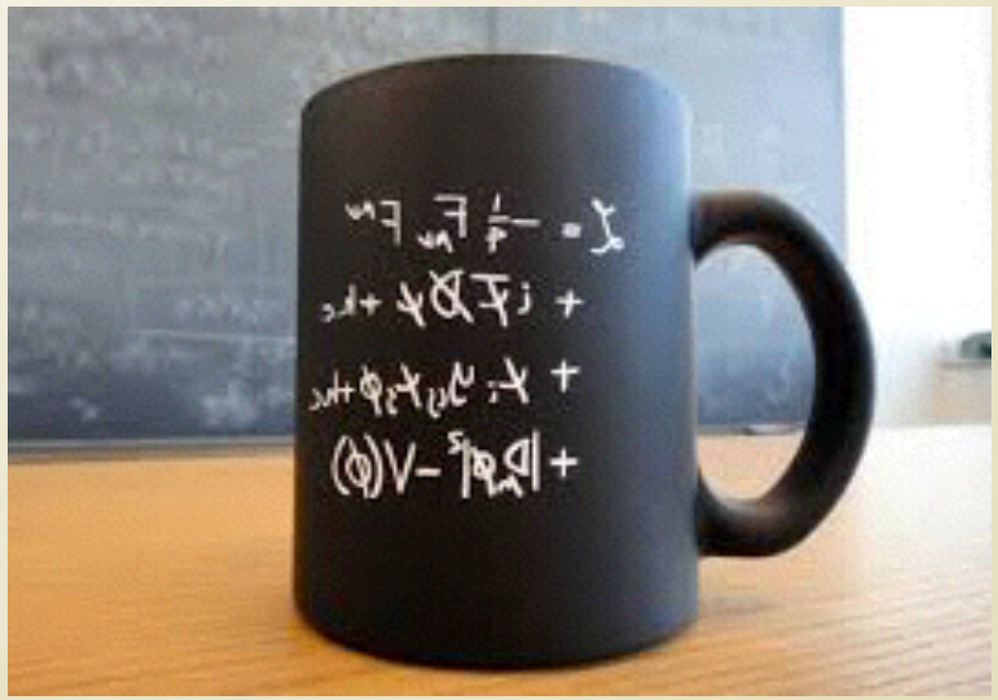
Mirror World

Parity SM ↔SM'

- Provide dark matter candidates
- Solve the hierarchy problem with uncolored new state at low energy

Lee and Yang (1956)
Kobrazev, Okun and Pomeranchuk (1966)





Mirror World

Parity SM ↔SM'

- Provide dark matter candidates
- Solve the hierarchy problem with uncolored new state at low energy

Goldberg and Hall (1986)

$$B',\ e'$$

$$\Omega_{\rm baryon} \sim \Omega_{\rm DM}$$

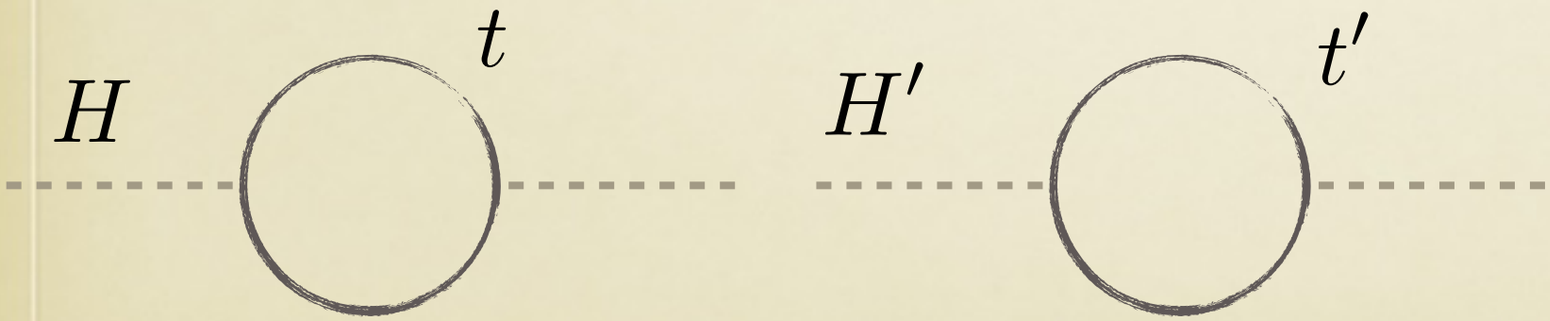
Mirror World

Parity SM ↔SM'

- Provide dark matter candidates
- Solve the hierarchy problem with uncolored new state at low energy (Twin Higgs)

Chacko, Goh and Harnik (2006)

$$H + H' = \mathbf{4} \text{ of } SU(4) \to SU(3) \text{ via } < H' > \neq 0$$



$$\sim \frac{\Lambda^2}{16\pi^2} y_t^2 (|H|^2 + |H'|^2$$

I will talk about..

- What is/Why MMTH ?
- Higgs signal
- Dark matter phenomenology
- Dark radiation

Minimal Mirror Twin Higgs

Problems of unbroken mirror

- Too small Higgs signal
- Too large dark radiation
- Too large self interaction of DM

1. Higgs signal

$$V(H,H') = \lambda(|H|^2 + |H'|^2 - M^2)^2 + \delta\lambda(|H|^2 + |H'|^2)$$

SU(4) symmetric

explicit SU(4) breaking
Z2 symmetric
(top loop, EW D term, etc)

$$v = v'$$

$$h_{125\ \mathrm{GeV}} = \frac{1}{\sqrt{2}}(h_{\mathrm{SM}} + h'_{\mathrm{SM}})$$

factor of two smaller higgs signal

1. Higgs signal

$$V(H,H') = \lambda(|H|^2 + |H'|^2 - M^2)^2 + \delta\lambda(|H|^2 + |H'|^2)$$

$$\Delta V = \Delta m_H^2 |H^2|$$

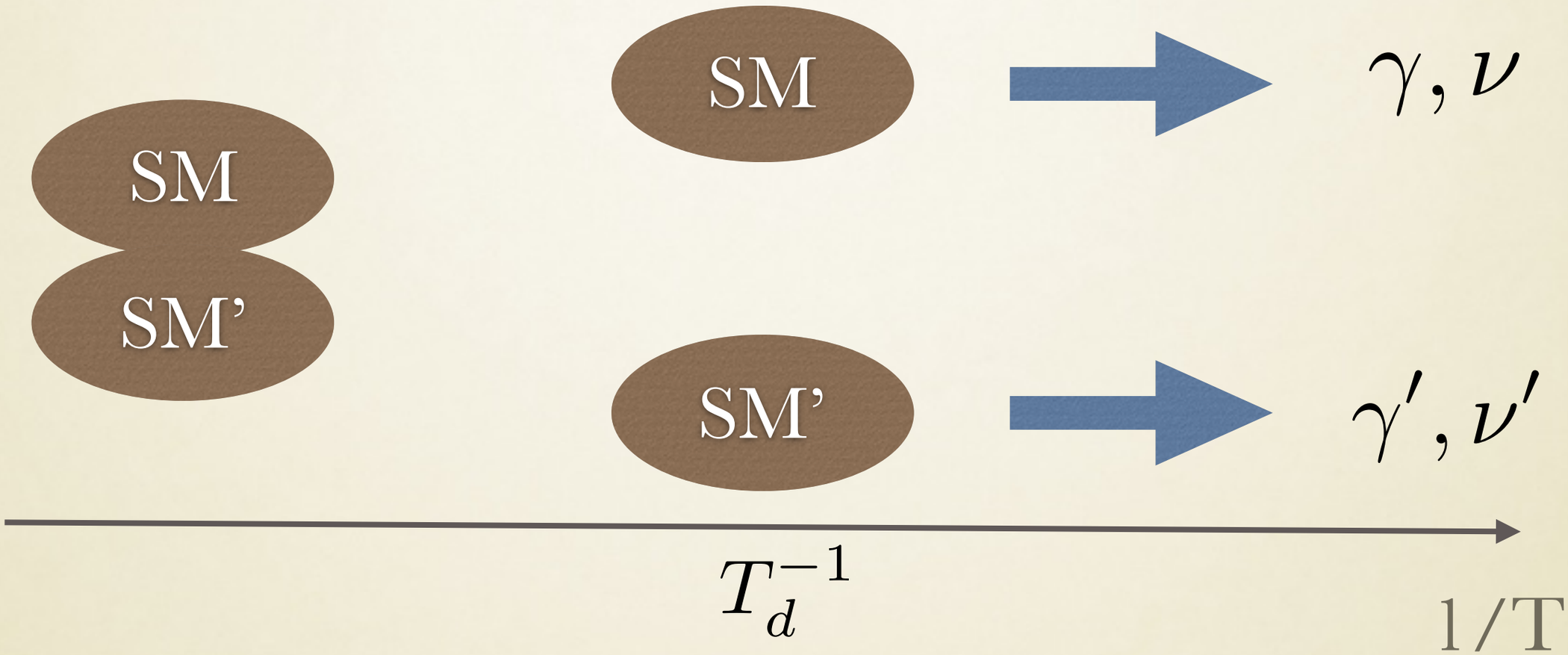
$$v < v'$$

suppressed mixing

$$\Delta \equiv \left| \frac{\partial \ln v^2}{\partial \ln \Delta m_H^2} \right| \simeq \frac{1}{2} \frac{v'^2}{v^2}$$

What is the origin of the Z2 symmetry breaking?

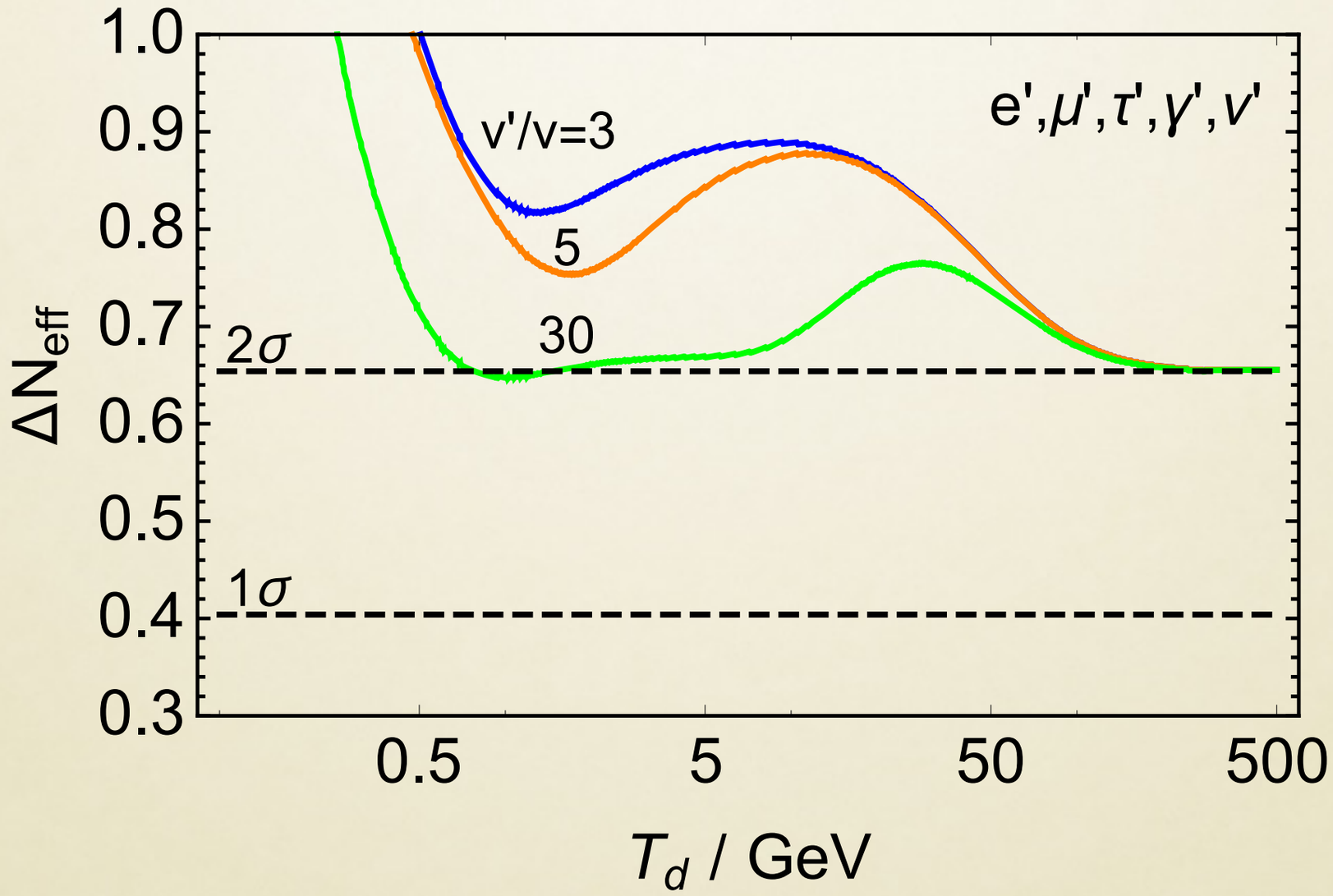
2.Dark radiation



γ', ν' are observed as dark radiation

2.Dark radiation

$$y_l = y'_l$$

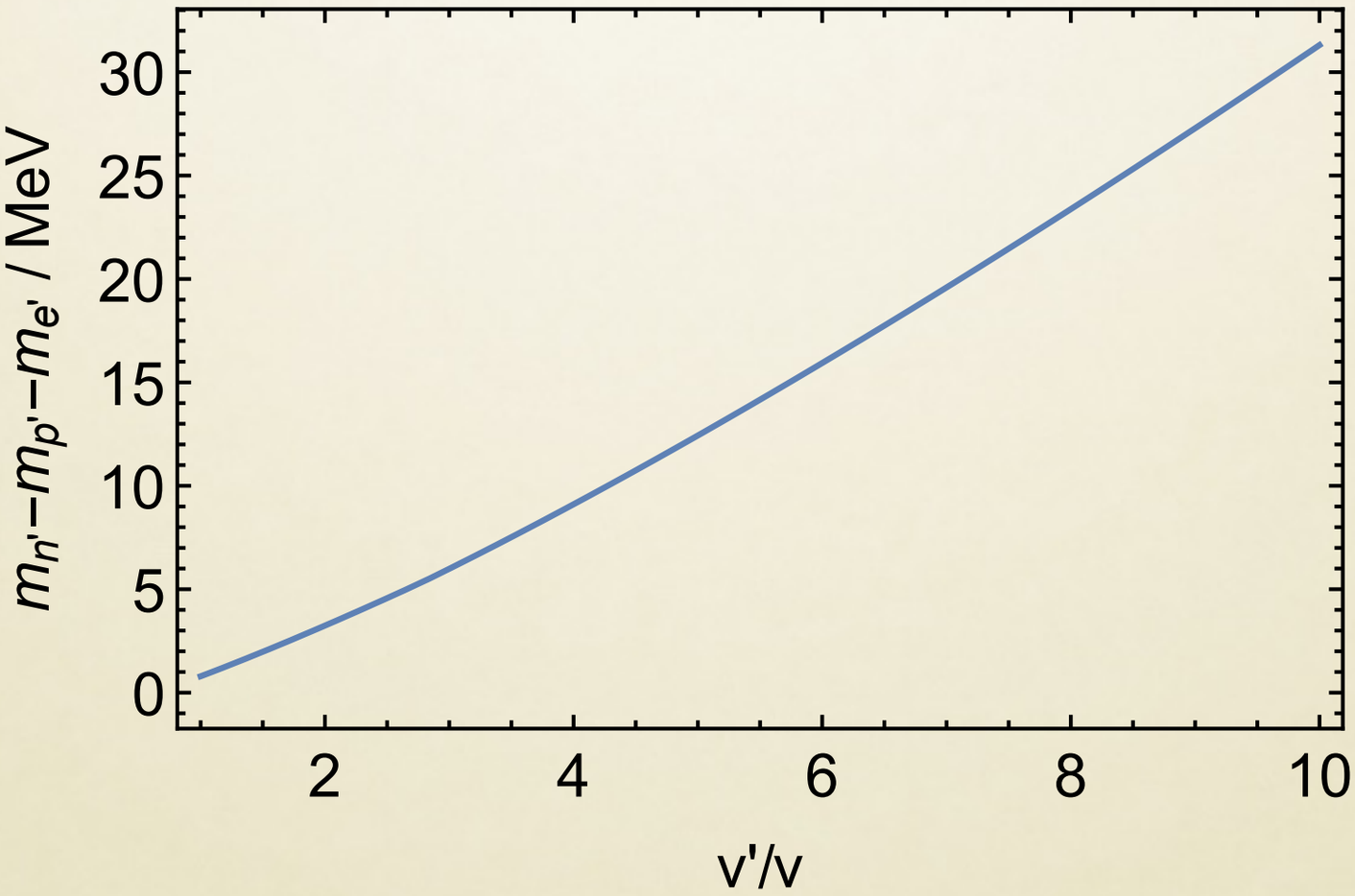


excessive fine-tuning

3.Dark matter

Assume dark matter from mirror matter asymmetry

explain $\Omega_{\rm baryon} \sim \Omega_{\rm DM}$



mirror neutron is unstable, mirror hydrogen dark matter

3.Dark matter

Self interaction of mirror hydrogen is large,

$$\frac{\sigma}{m_{\rm DM}} = \frac{100}{(m_{e'}\alpha)^2}\frac{1}{m_{p'}} \gg 10{\rm cm}^2/{\rm g}$$

Problems of Z2-symmetric case

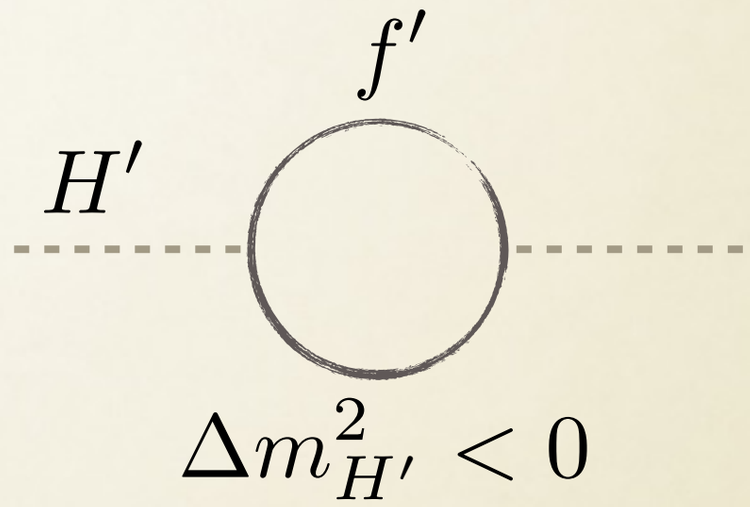
- Too small Higgs signal
- Too large dark radiation
- Too large self interaction of DM

All of them can be solved by $y'_f \neq y_f$

Minimal Mirror Twin Higgs

Problems of Z2-symmetric case

- Too small Higgs signal
- Too large dark radiation
- Too large self interaction of DM



Minimal Mirror Twin Higgs

Problems of Z2-symmetric case

- Too small Higgs signal
- Too large dark radiation

larger f' mass
non-relativistic

- Too large self interaction of DM

Minimal Mirror Twin Higgs

Problems of Z2-symmetric case

- Too small Higgs signal
- Too large dark radiation → larger f' mass
- Too large self interaction of DM

Minimal Mirror Twin Higgs

Realization of MMTH

$$\frac{|y_t - y_{t'}|}{y_t} \lesssim O(1-10)\ \%$$ to avoid too large Δm^2_H

while $y'_{\rm others} \gg y_{\rm others}$

Natural framework in flavor hierarchy:

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^6 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \qquad \epsilon' > \epsilon$$

Realization of MMTH

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^6 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix} \qquad \epsilon' > \epsilon$$

Floggatt-Nielsen $\quad \epsilon = \dfrac{<\phi>}{M}, \;\; <\phi'> \neq <\phi>$

Extra dimension $\quad \epsilon = e^{-m_{\rm bulk} L}, \;\; L \neq L'$

Kaplan and Tait (2001)

Ex: SU(5) motivated FN model

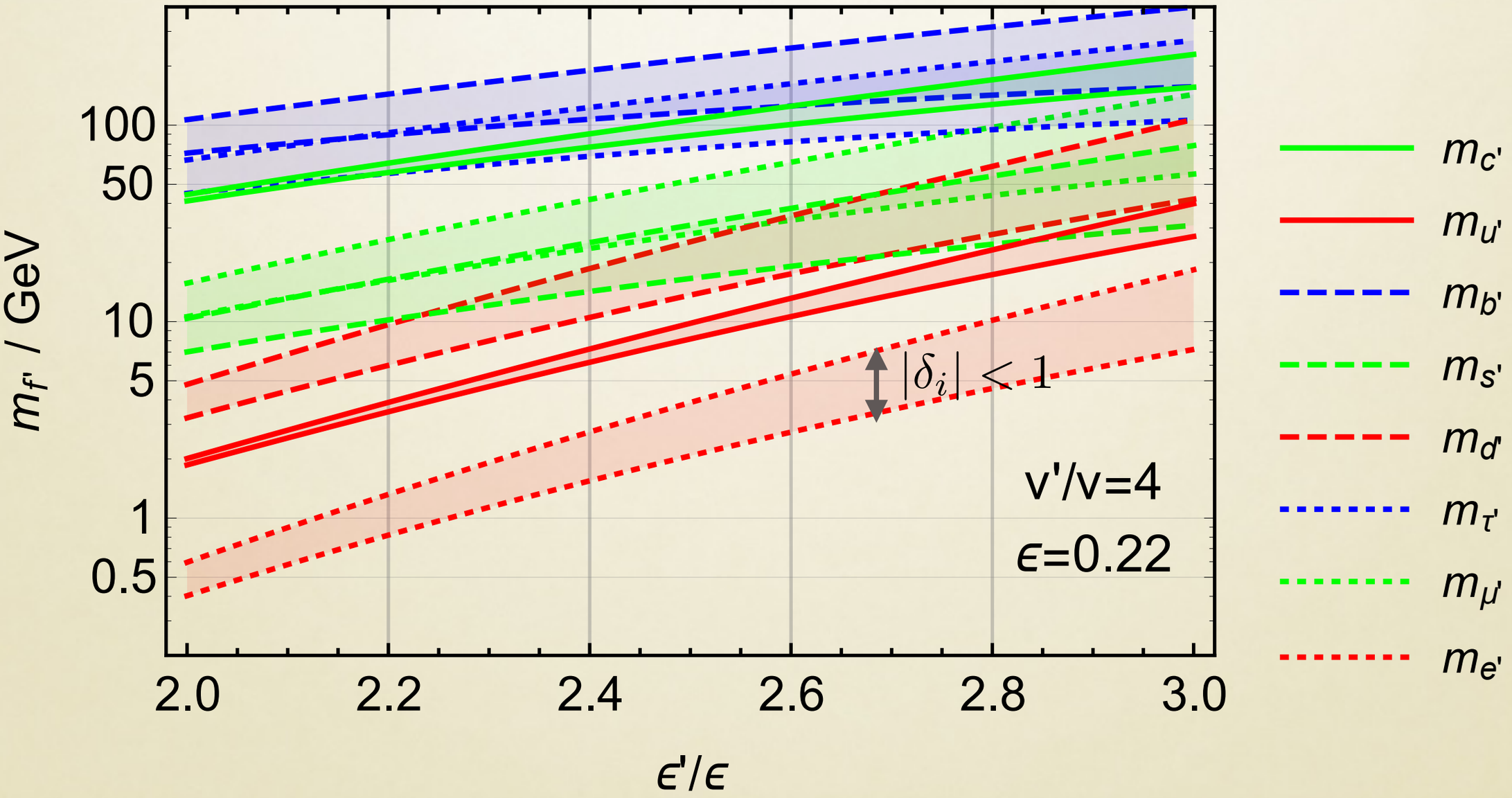
$$Q, \bar{u}, \bar{e}: \ (4,2,0), \quad \bar{d}, L: \ (4,3,3)$$

$$Y_u \sim \begin{pmatrix} \epsilon^8 & \epsilon^6 & \epsilon^4 \\ \epsilon^6 & \epsilon^4 & \epsilon^2 \\ \epsilon^4 & \epsilon^2 & 1 \end{pmatrix}$$

$$\begin{aligned} y_t &\sim \ 1 + \delta_t \epsilon^4, \\ y_c &\sim \ \epsilon^4 \left(1 + \delta_c \epsilon^4\right), \\ y_u &\sim \ \epsilon^8 \left(1 + \delta_u \epsilon^4\right) \end{aligned}$$

$\delta_{t,u,c}$: mixing effect

Ex: SU(5) motivated FN model



Phenomenology

- Higgs signal
- Dark Matter
- Dark Radiation

Higgs signal

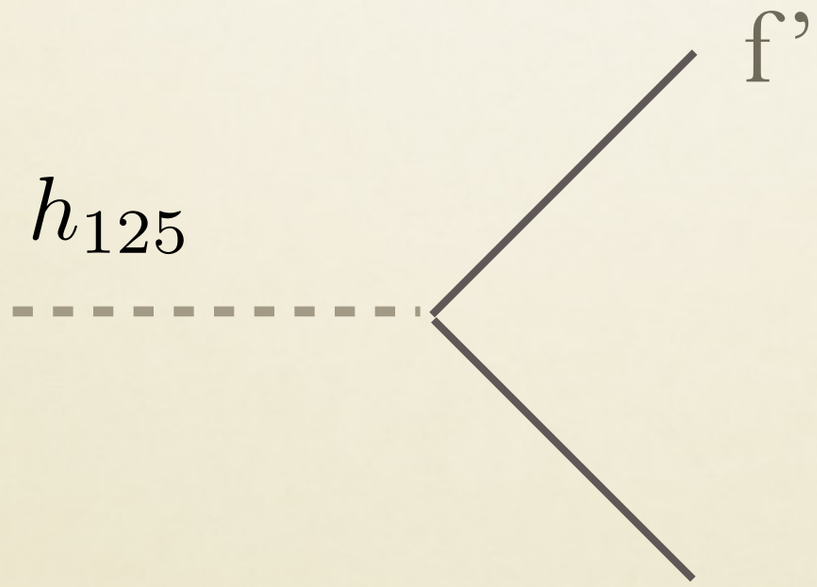
Reduction of production

$$h_{125} \simeq (1 - \frac{v^2}{v'^2})h + \frac{v}{v'}h'$$

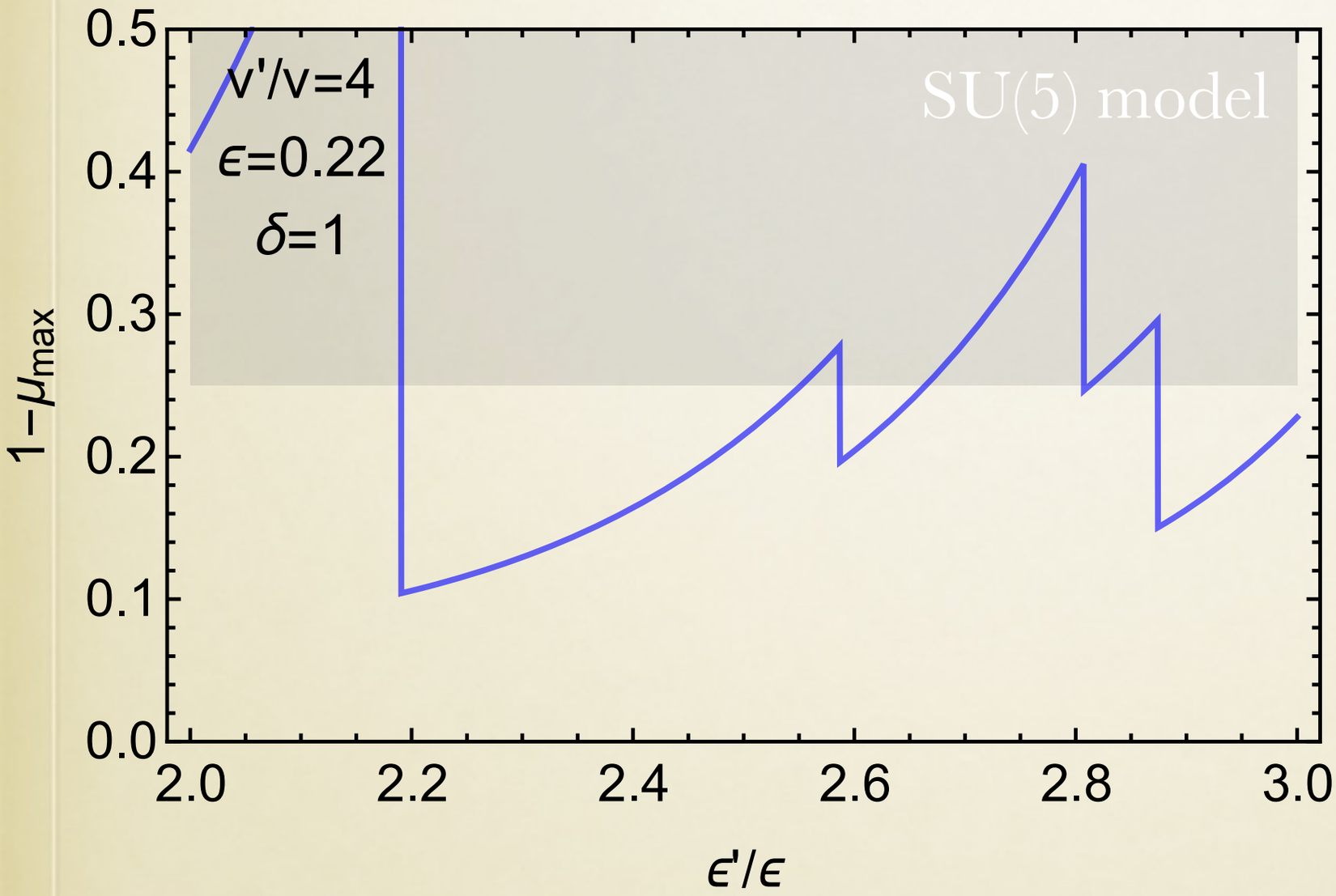
$$\frac{\sigma}{\sigma_{\rm th}} \simeq (1 - \frac{v^2}{v'^2})^2$$

Invisible decay

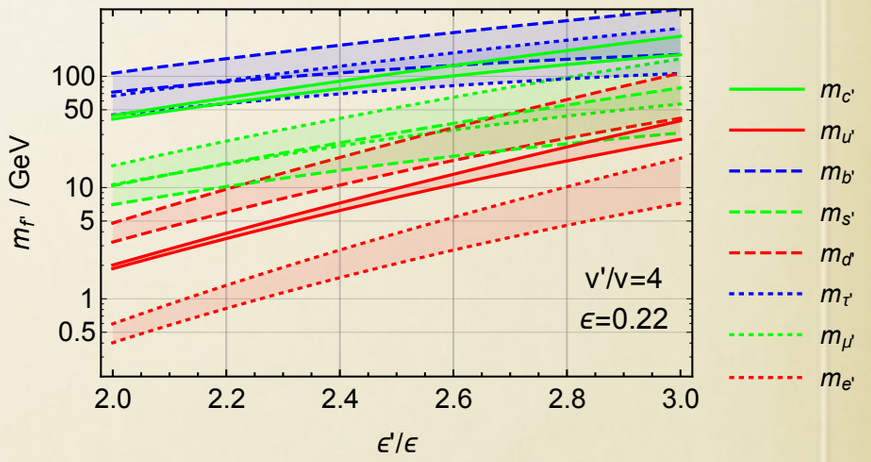
$$h_{125} \simeq (1 - \frac{v^2}{v'^2})h + \frac{v}{v'}h'$$



Signal strength



$$y_t \sim 1 + \delta_t \epsilon^4,$$
$$y_c \sim \epsilon^4 \left(1 + \delta_c \epsilon^4\right),$$
$$y_u \sim \epsilon^8 \left(1 + \delta_u \epsilon^4\right)$$



δ_f chosen to minimize inv.decay

Dark matter

Dark baryon DM

dark matter is composed of u', d' and e'

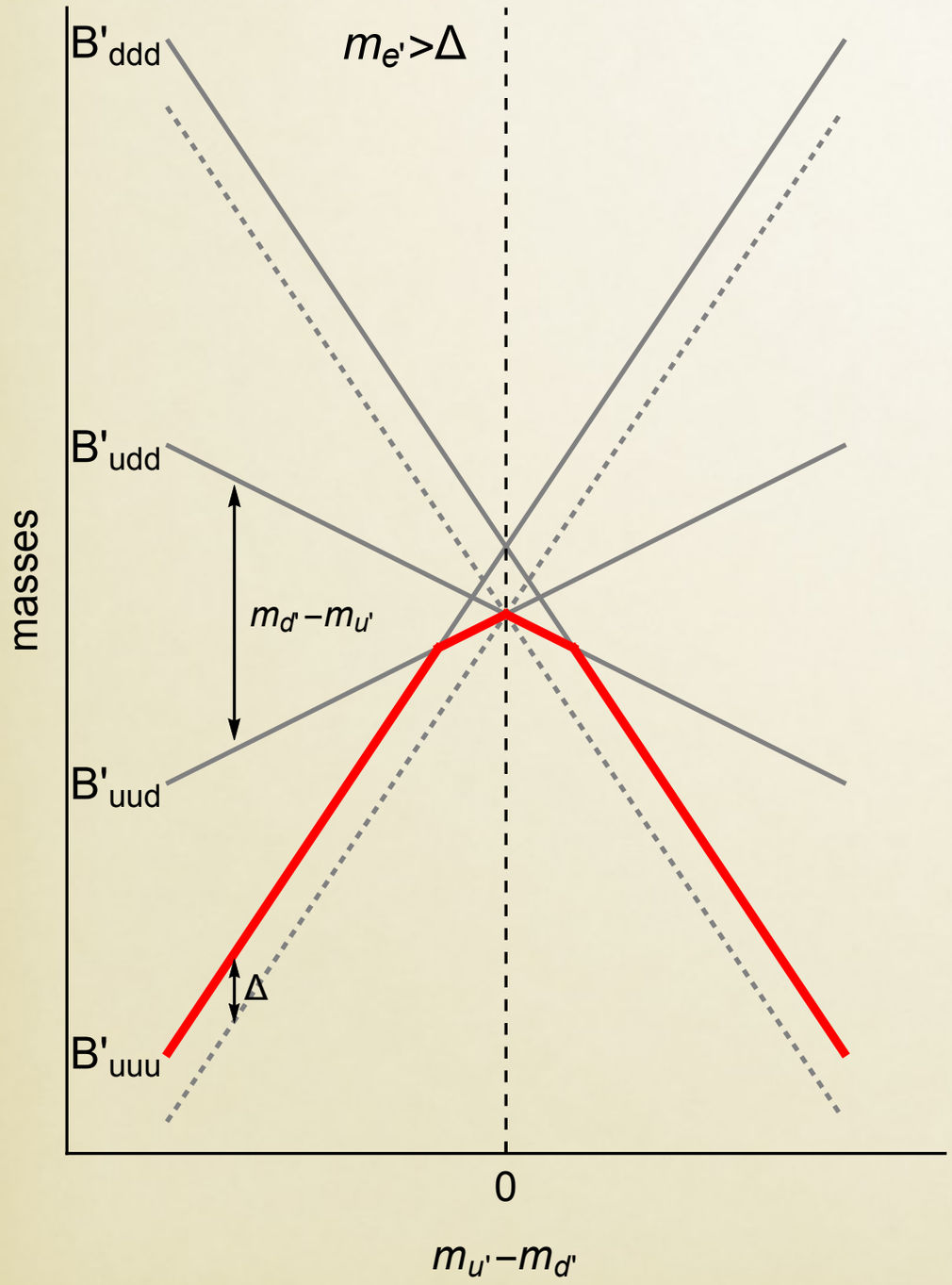
$$B'_{uuu},\ B'_{uud},\ B'_{udd},\ B'_{ddd},\ e'$$

$$p' \qquad n'$$

Q : +2 +1 0 -1 -1

Mirror matter asymmetry is stored in them
Relative abundance?

Thermal evolution

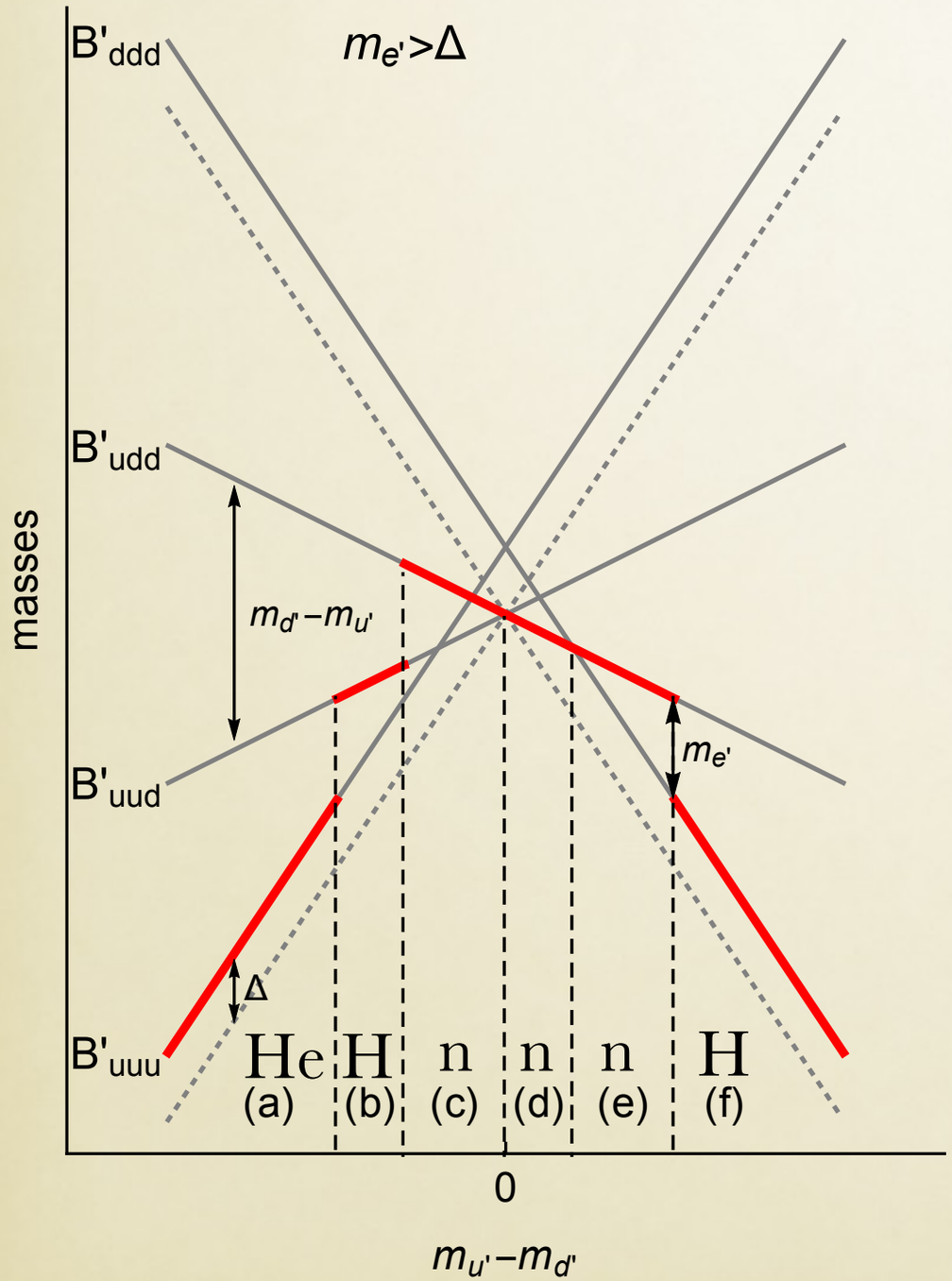


Around $T \simeq m_{e'}/20$
the CC interaction decouples

$$e.g.\ \ p' + e' \leftrightarrow n' + \nu'$$

$$n_{B1}/n_{B2} \propto \exp(-\frac{m_{B1} - m_{B2}}{T})$$

Dark baryon DM



Around $T < m_{e'}\alpha^2$
the recombination occurs

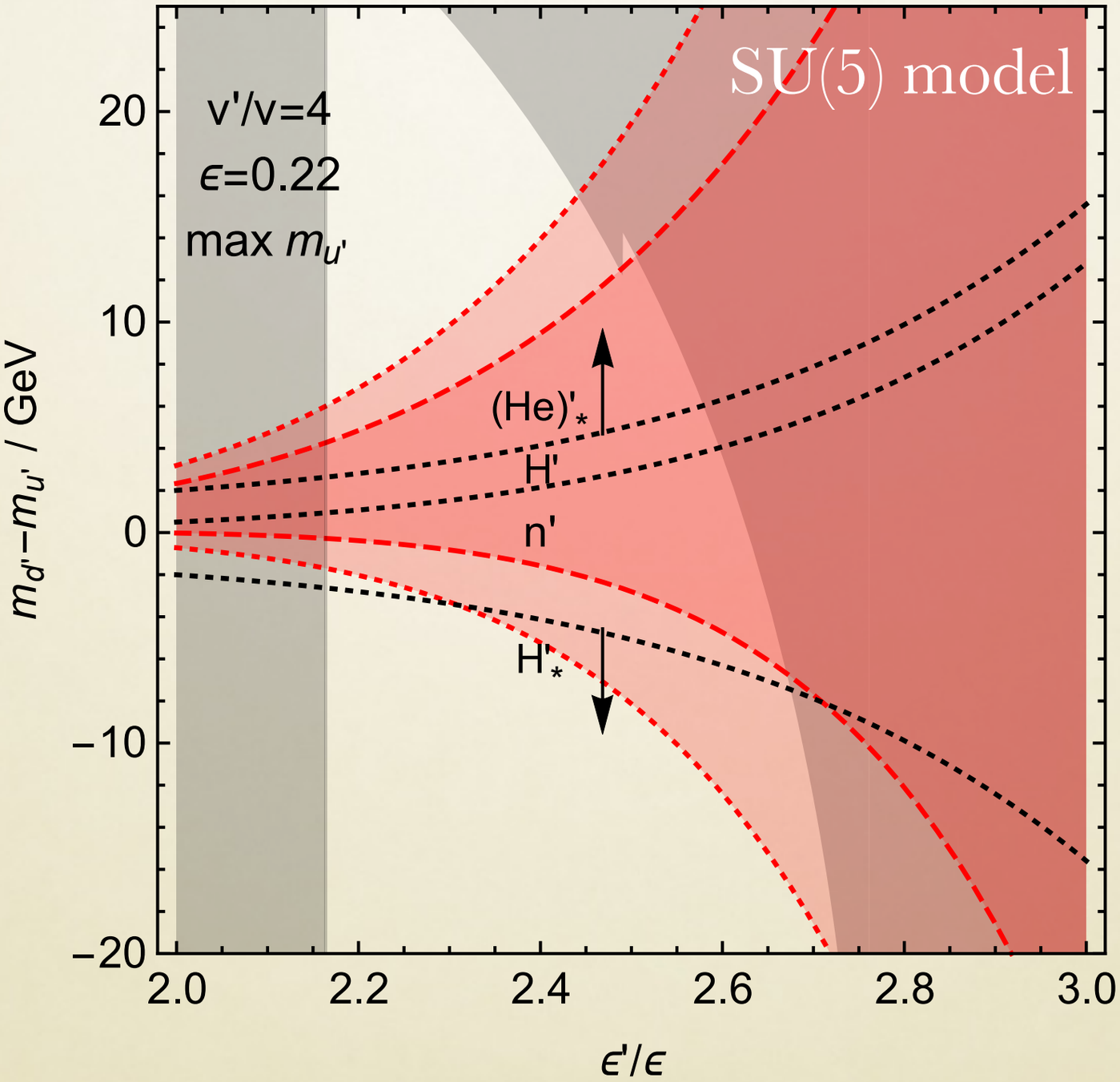
$$e.g.\ \ p' + e' \to H'(1s) + \gamma'$$

electron capture may occurs

$$H'(1s) \to n' + \nu'$$

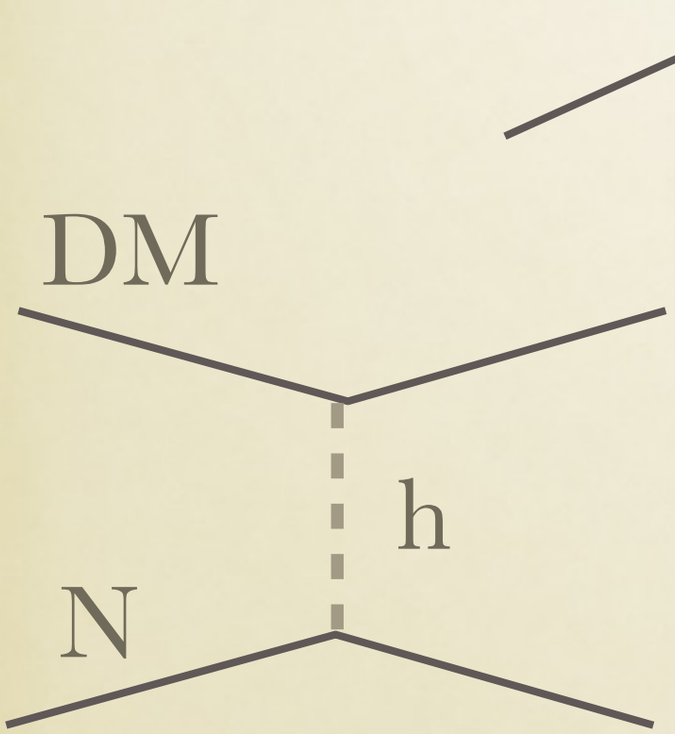
$$\delta m < m_{e'}$$

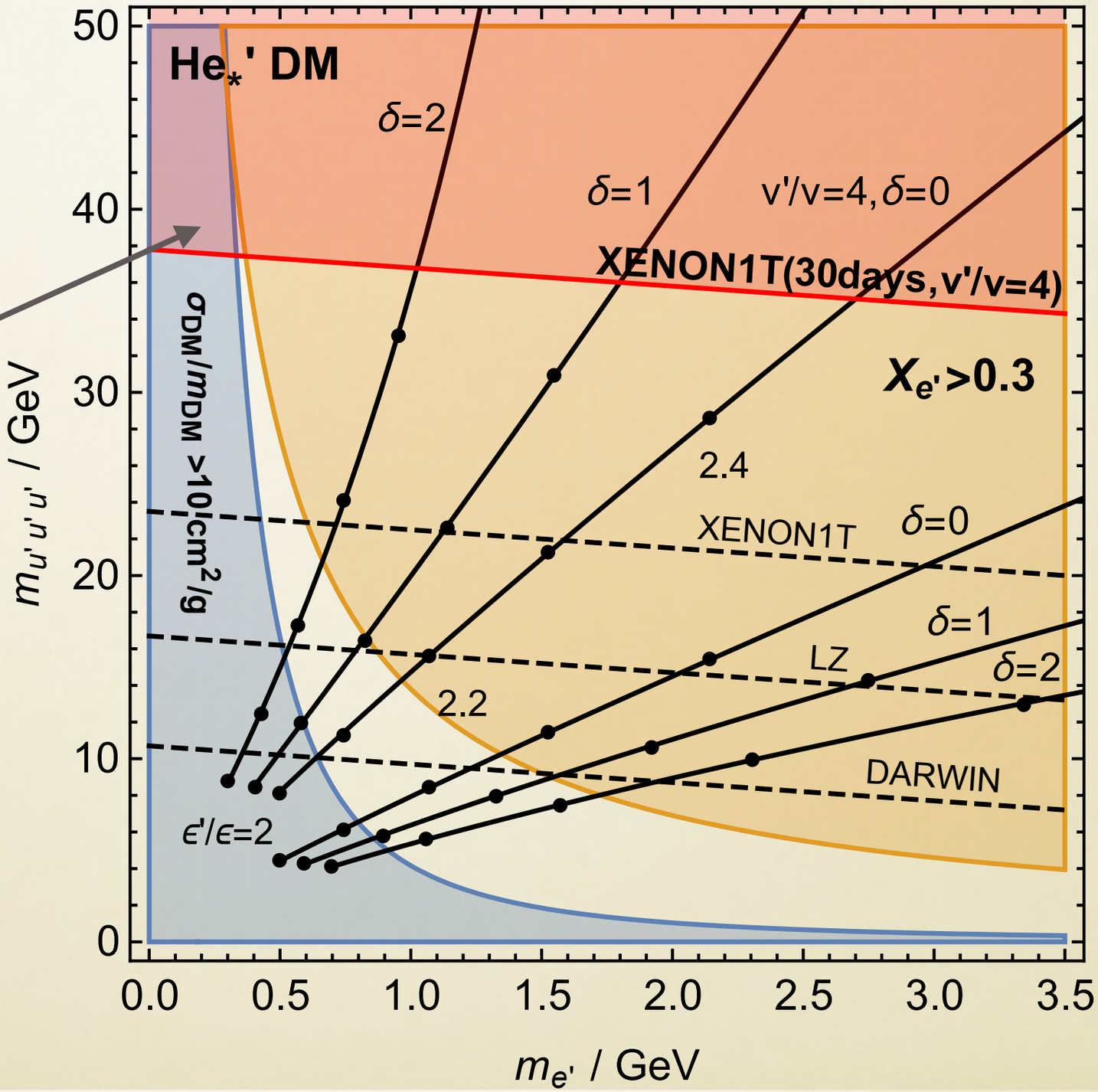
Dark baryon DM



Mirror Heliumoid

$B'_{uuu} + 2e$



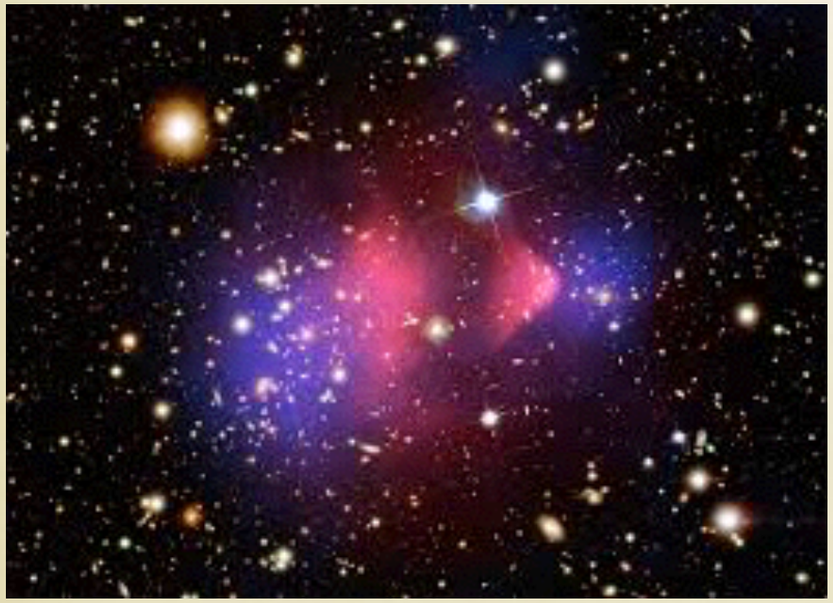


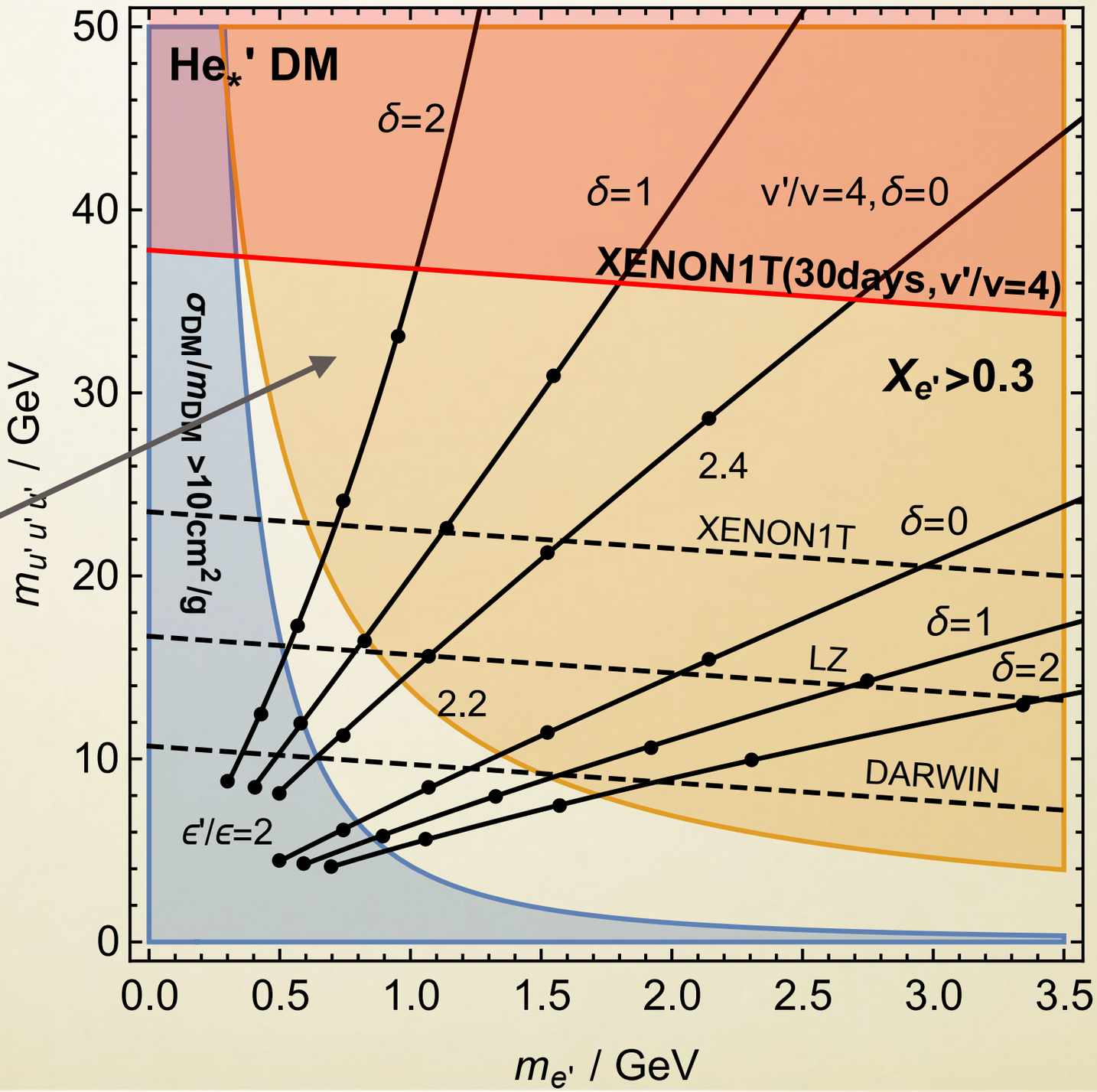
Mirror Heliumoid

$B'_{uuu} + 2e$

Plasma DM

Talk by Spethmann(Wed.)



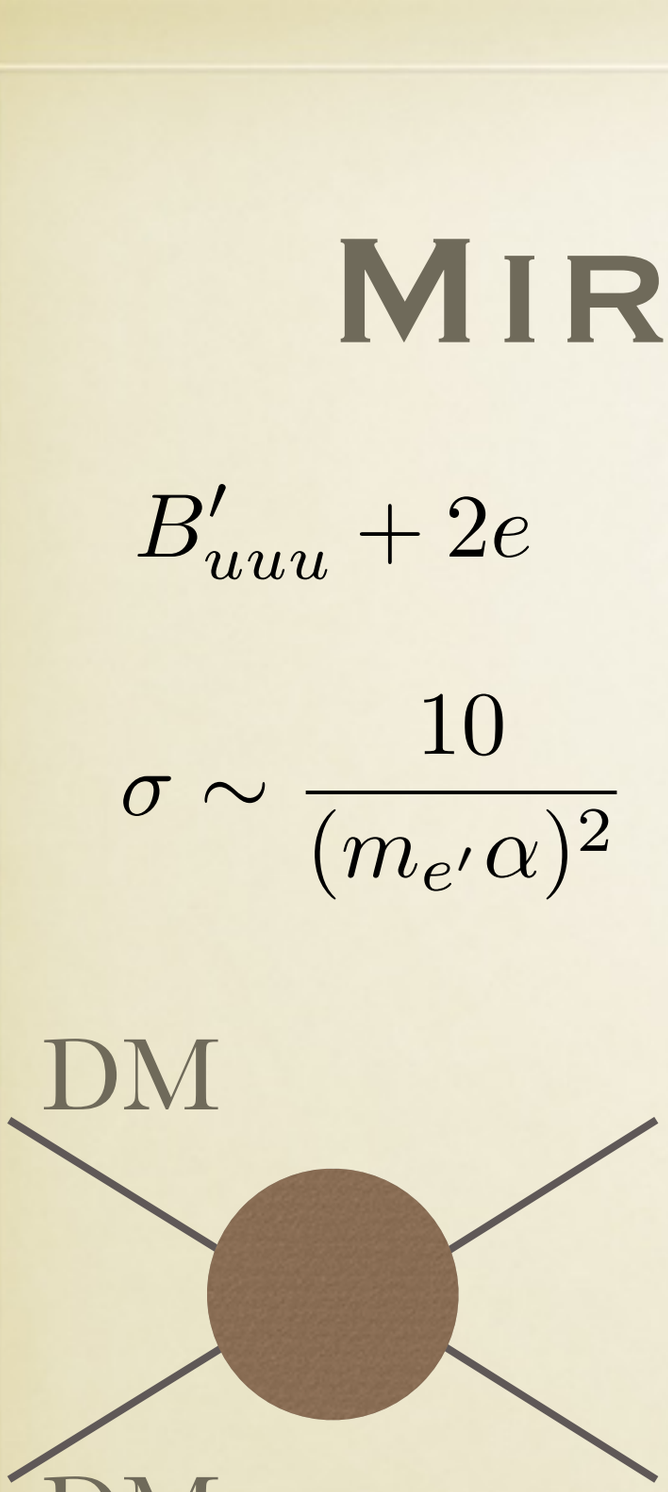


Mirror Heliumoid

$$B'_{uuu} + 2e$$

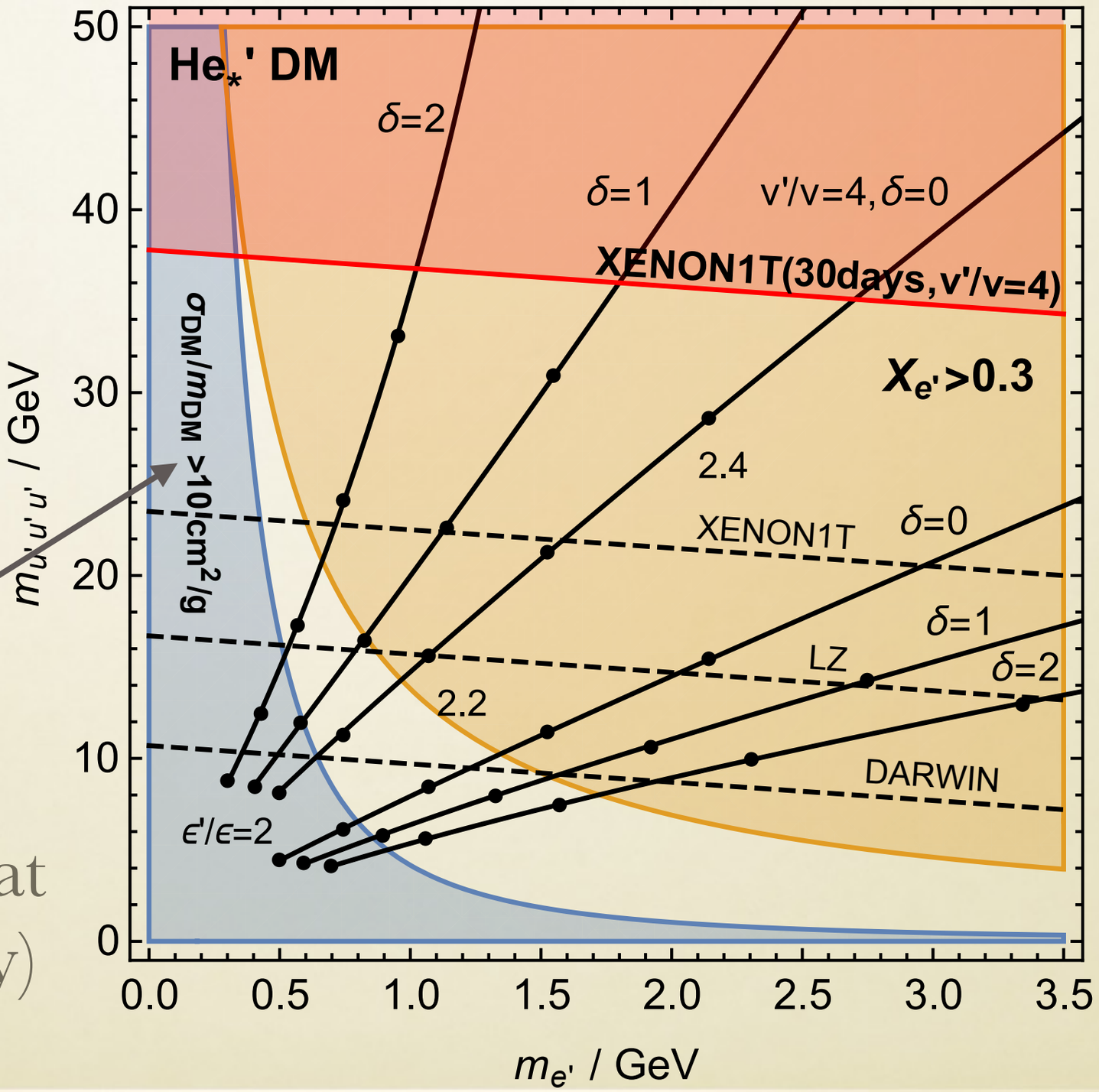
$$\sigma \sim \frac{10}{(m_{e'}\alpha)^2}$$

DM



DM

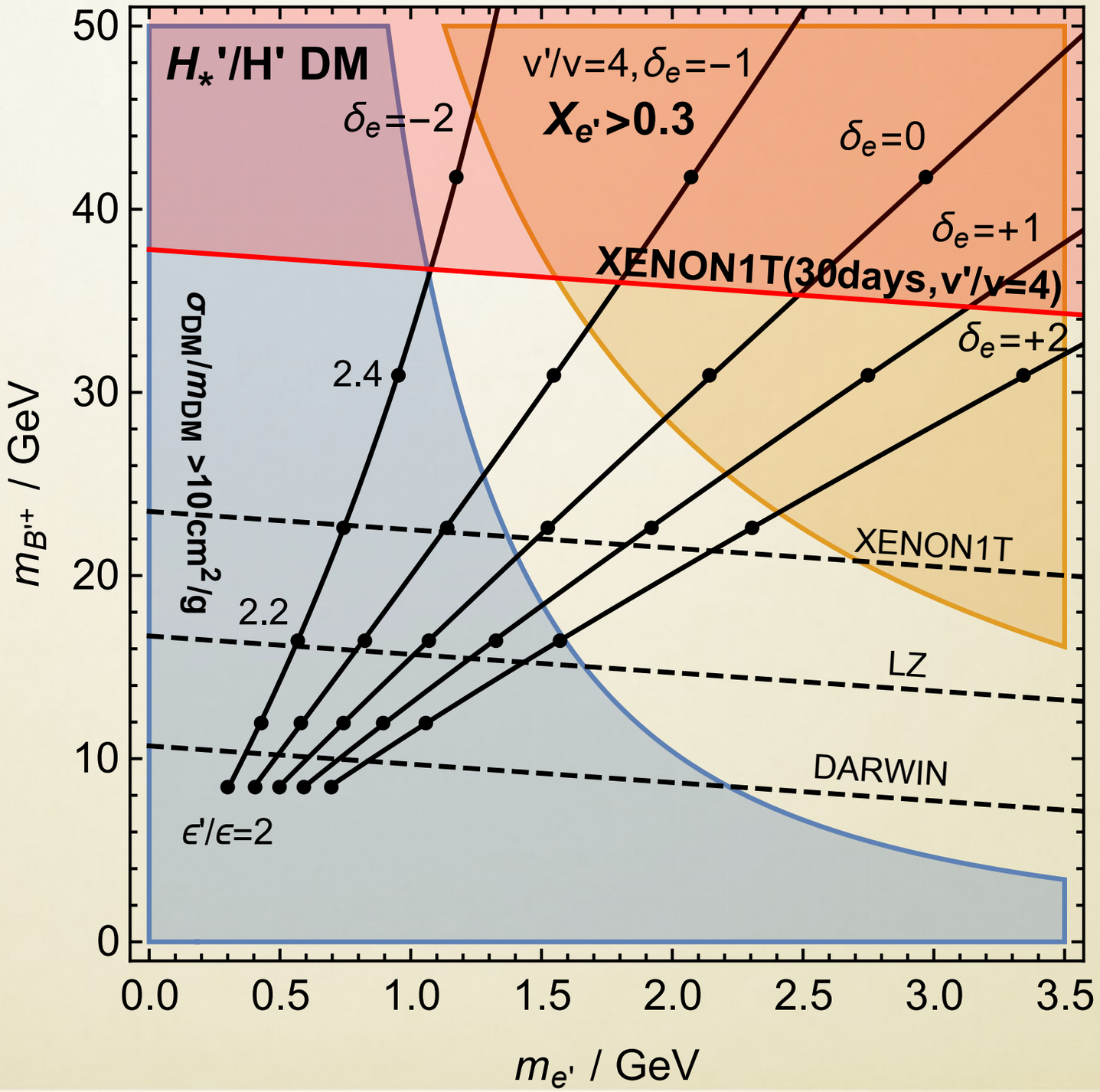
(suppressed at high velocity)



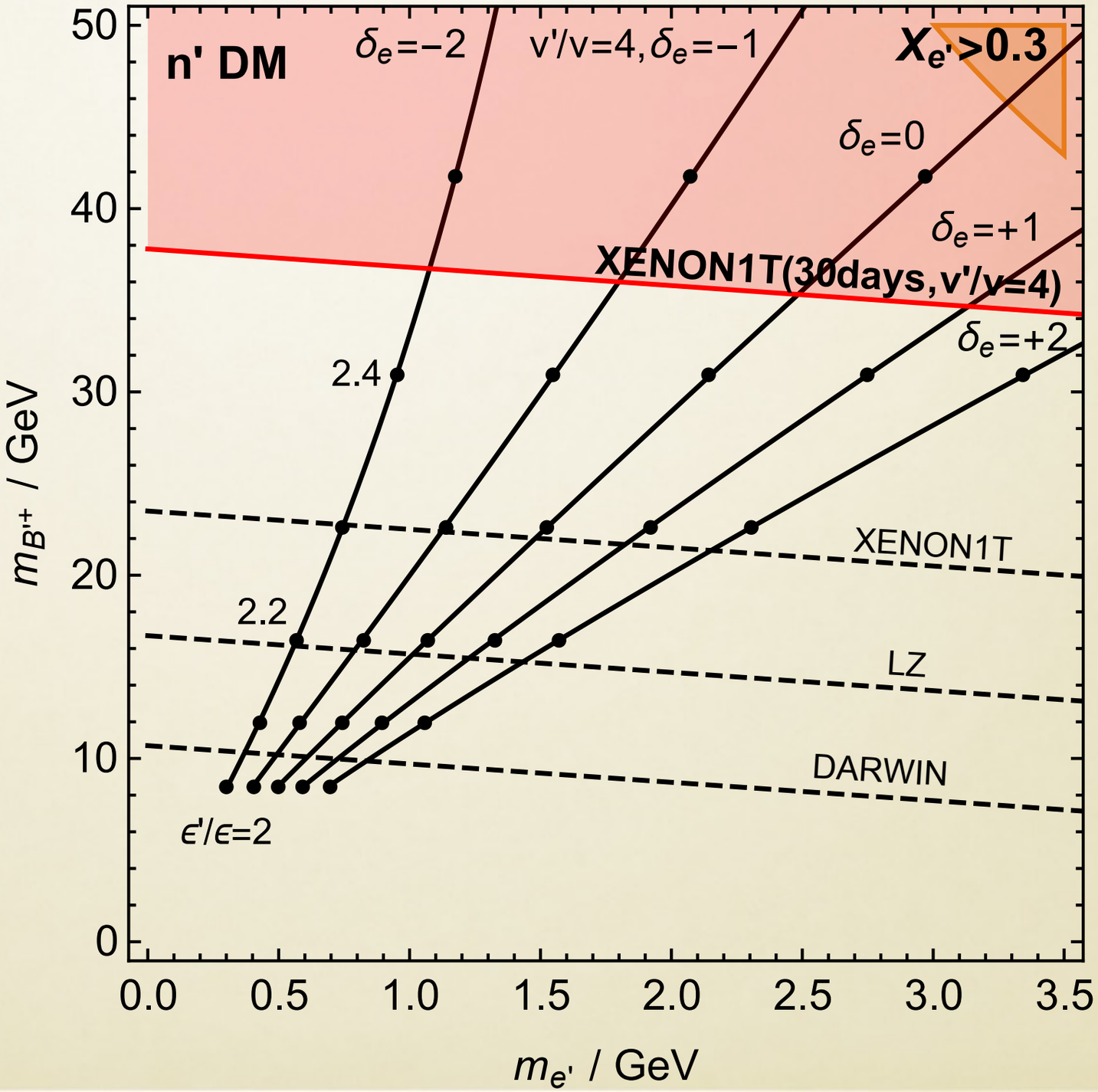
Mirror Hydrogen

$$B'_{uud} + e$$

$$B'_{ddd} + e^+$$

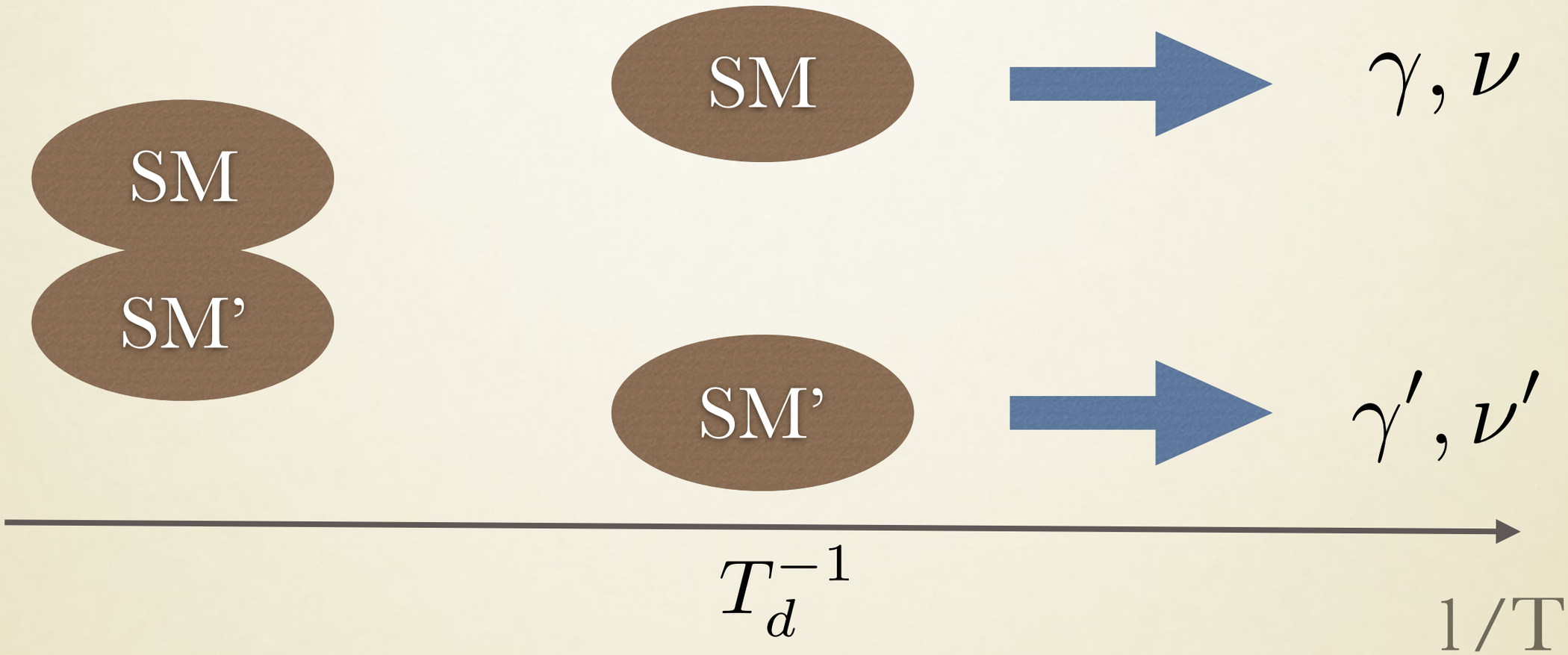


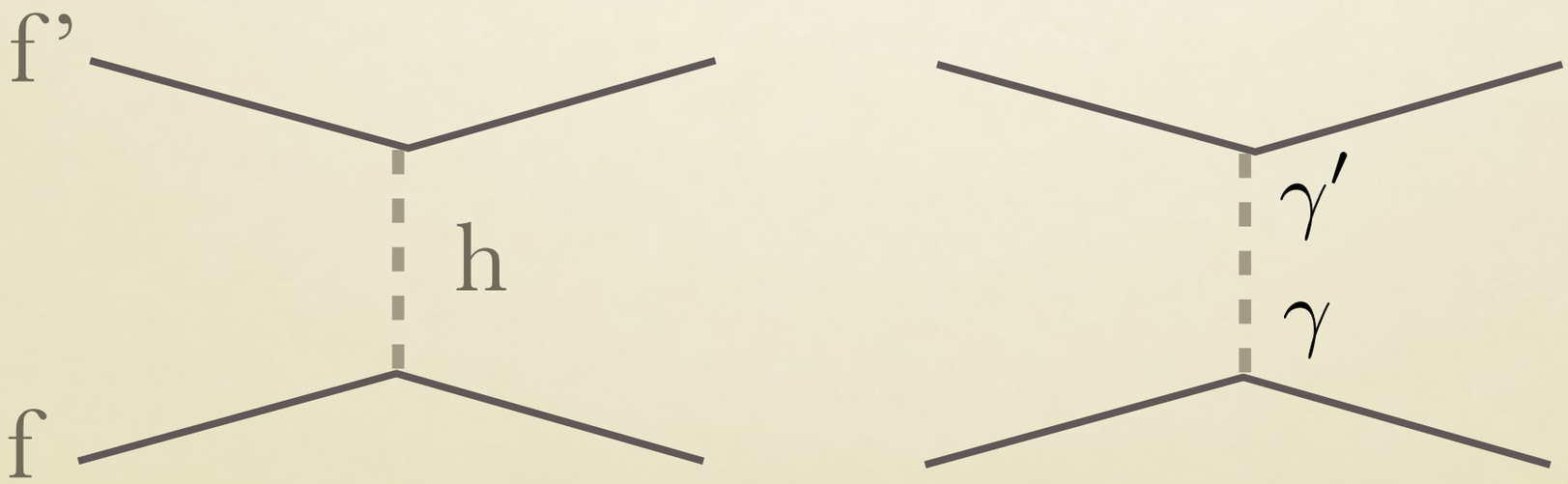
Mirror neutron



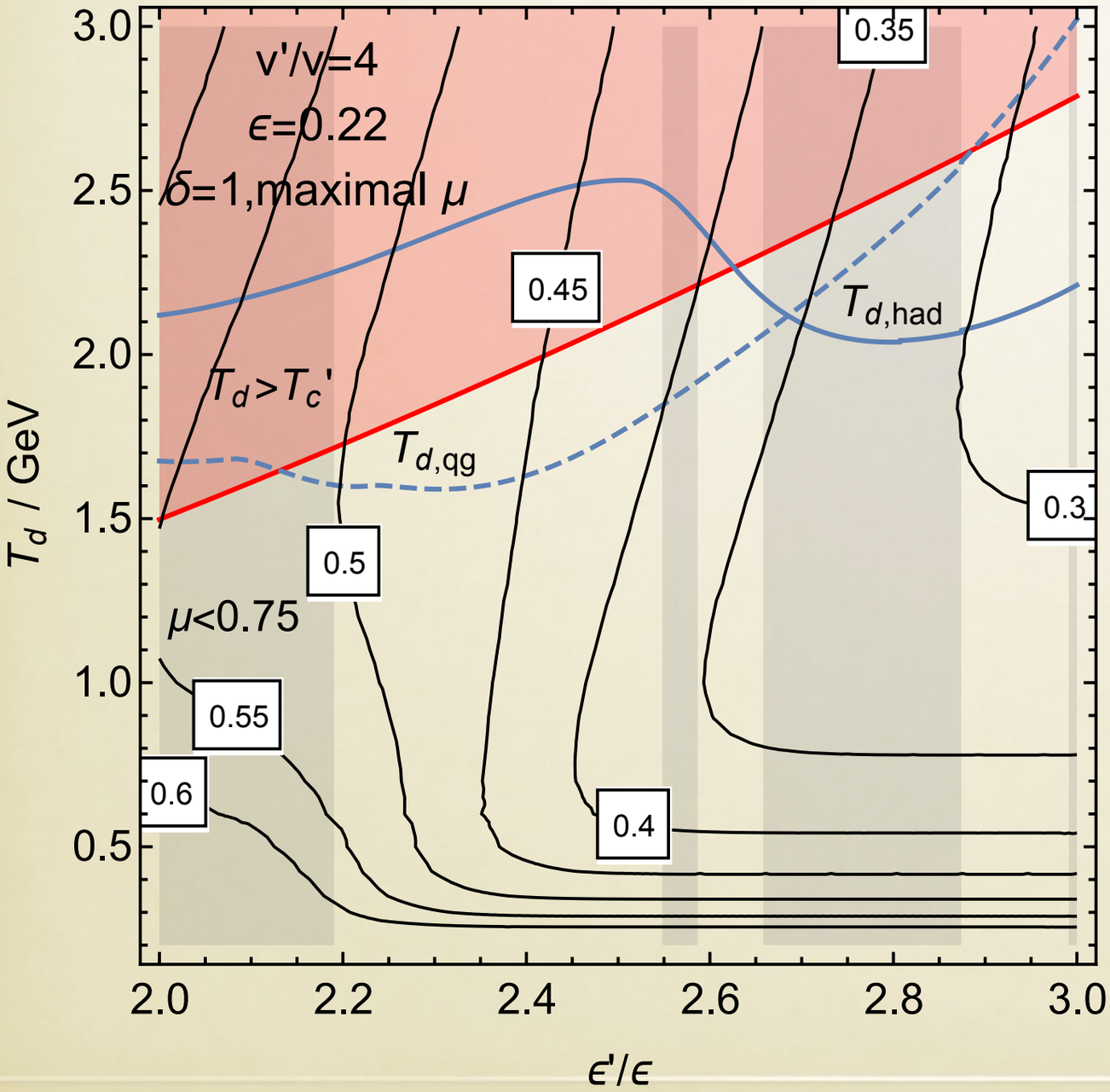
Dark radiation

Dark radiation

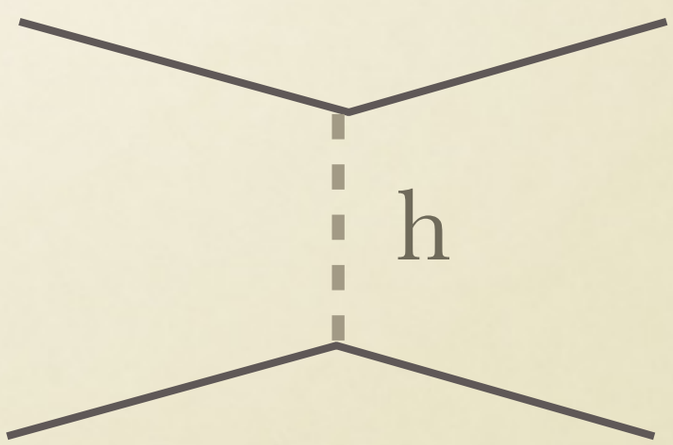




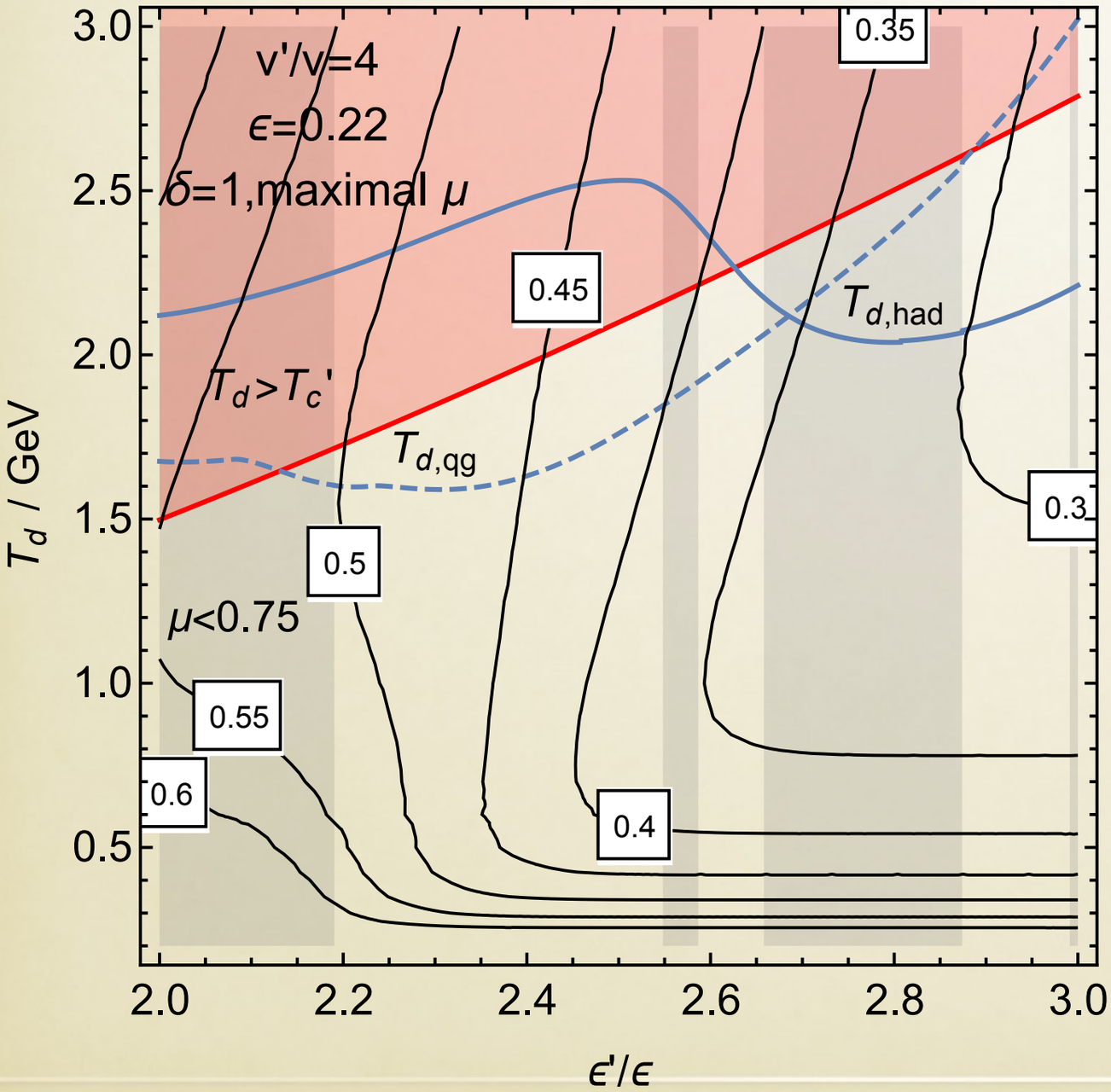
Higgs exchange



Uncertainty in Higgs exchange from mirror QCD



Kinetic mixing



Mirror electron
is important
for kinetic mixing

$$m_{e'} < m_{\text{others}}$$

$$\text{mixing} \sim 10^{-6}$$

mirror atom DM
is excluded
by direct detection

Other option(s)

- SM-mirror Neutrino Mixing

Csaki, Kuffik and Lombardo(2017)

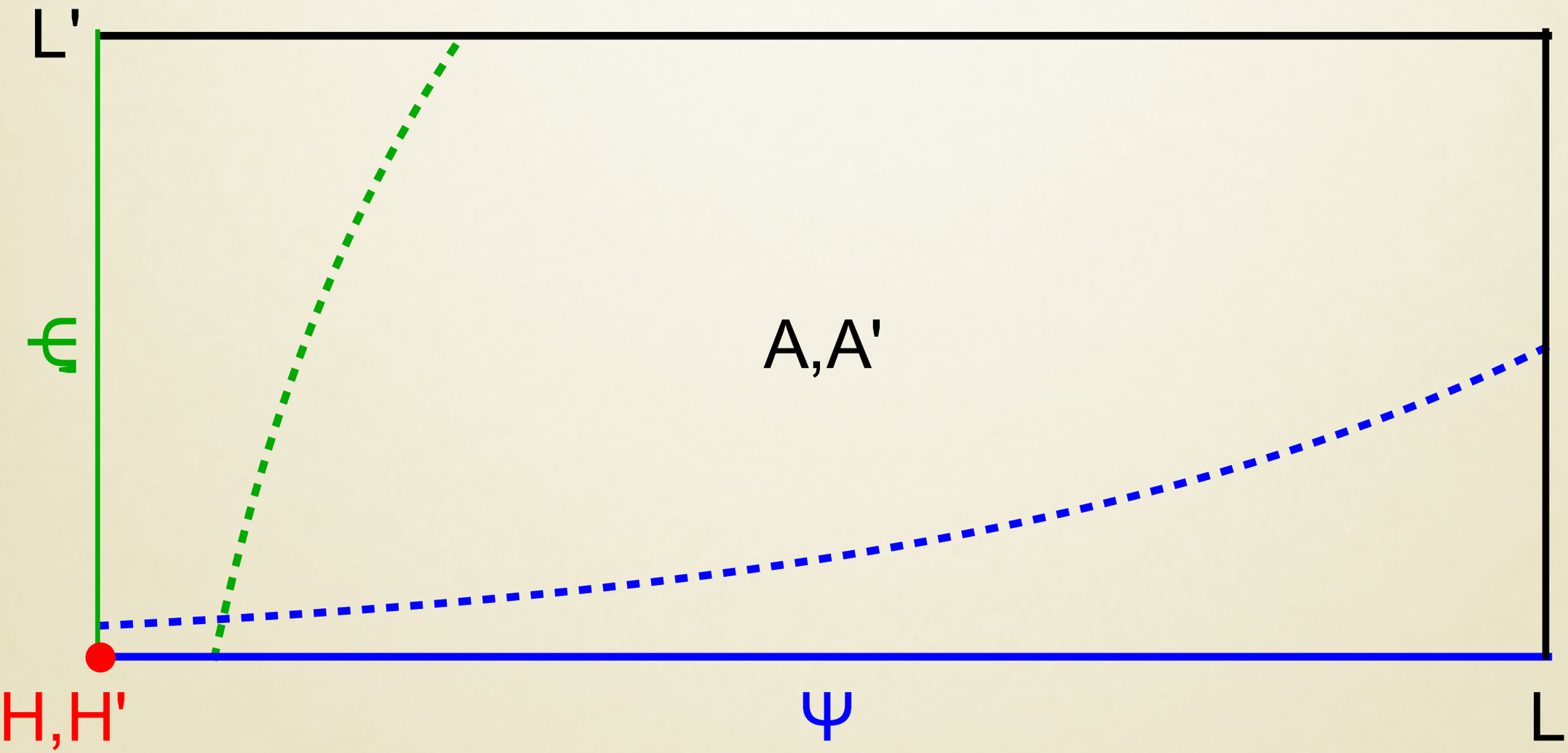
- Others?

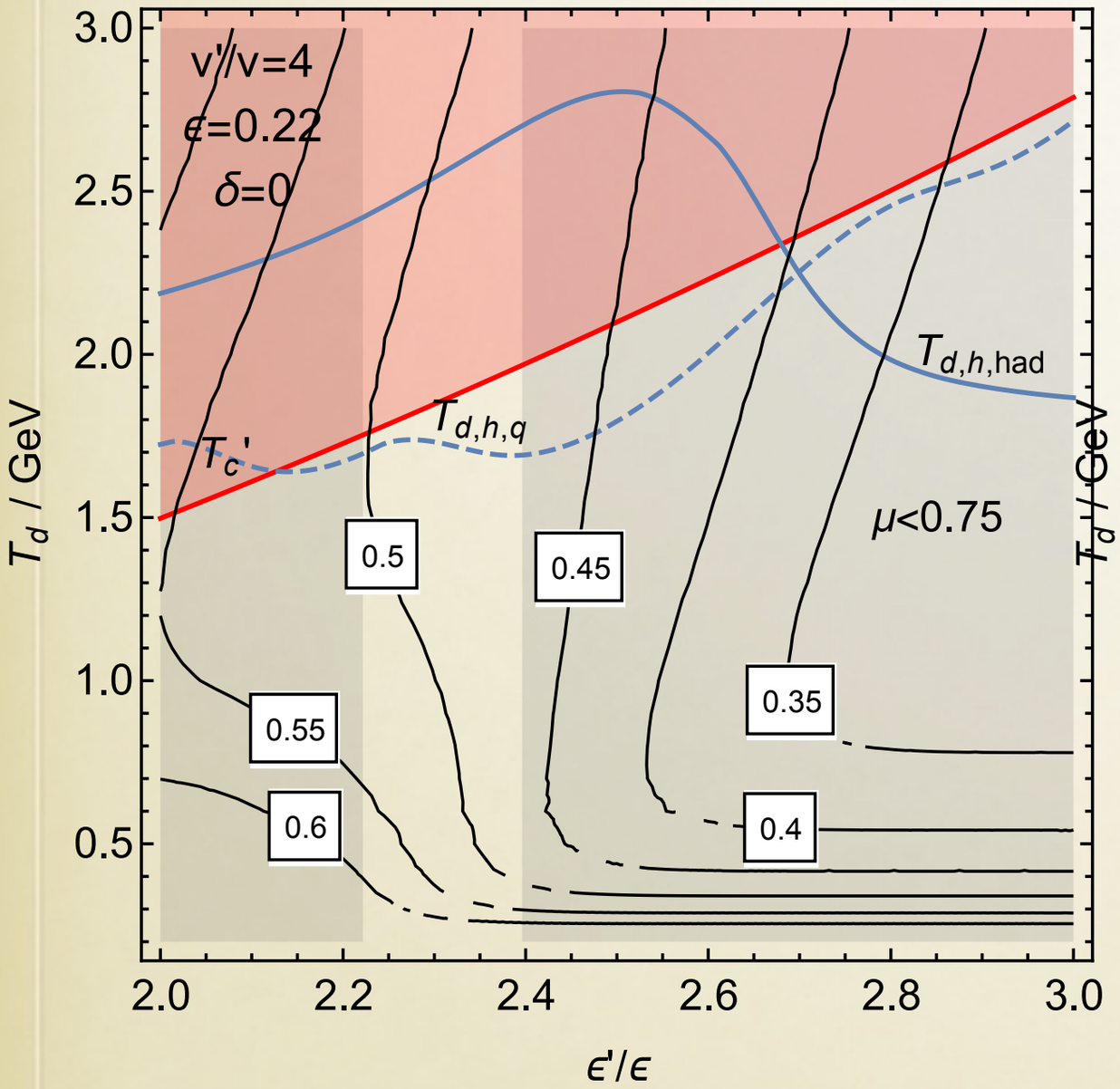
Summary

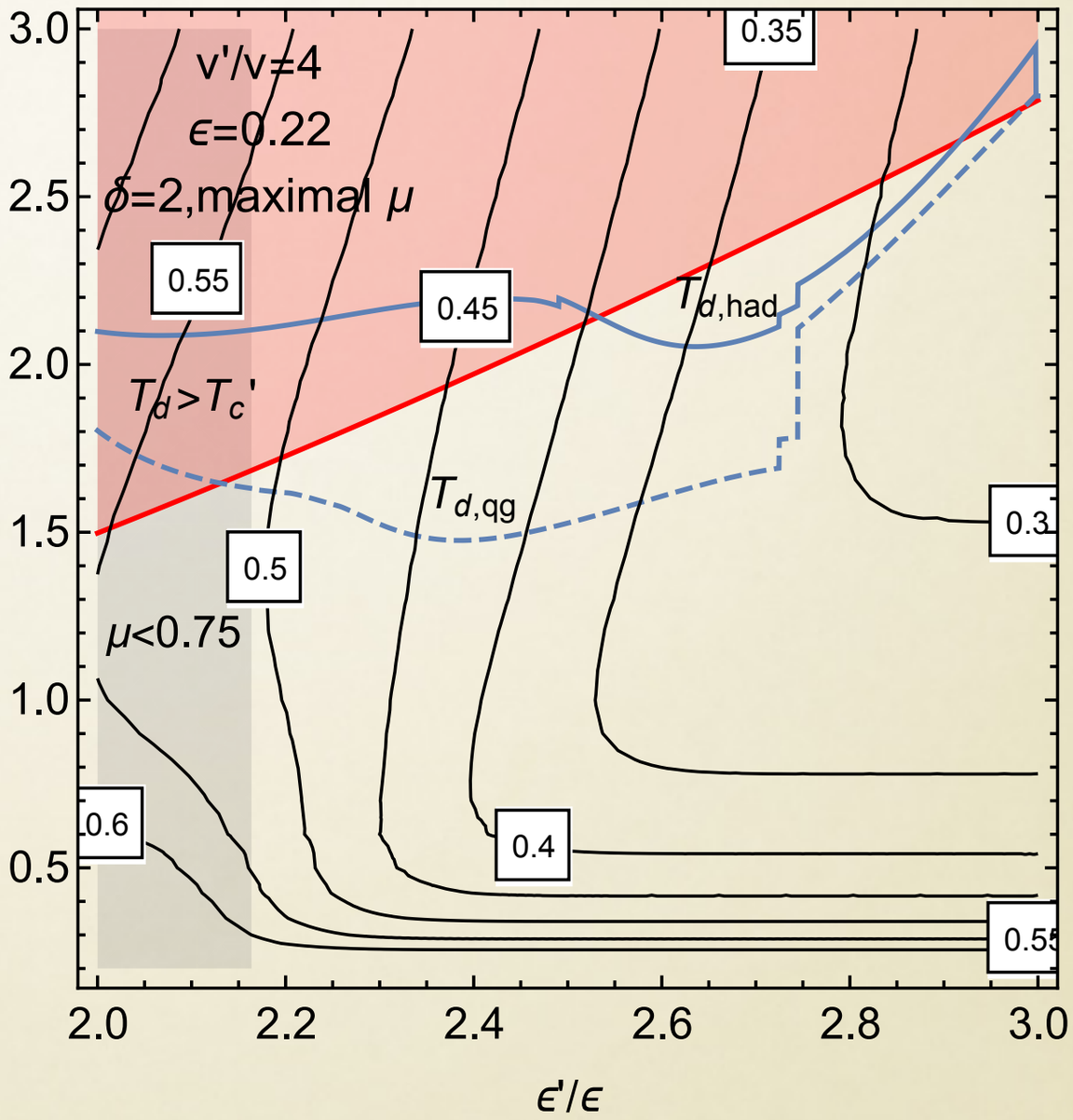
- Twin Higgs solves the hierarchy problem and provided dark matter candidates
- Several problems are simultaneously solved in MMTH
- Rich dark matter phenomenology
- Higgs signal is affected
- Observable dark radiation

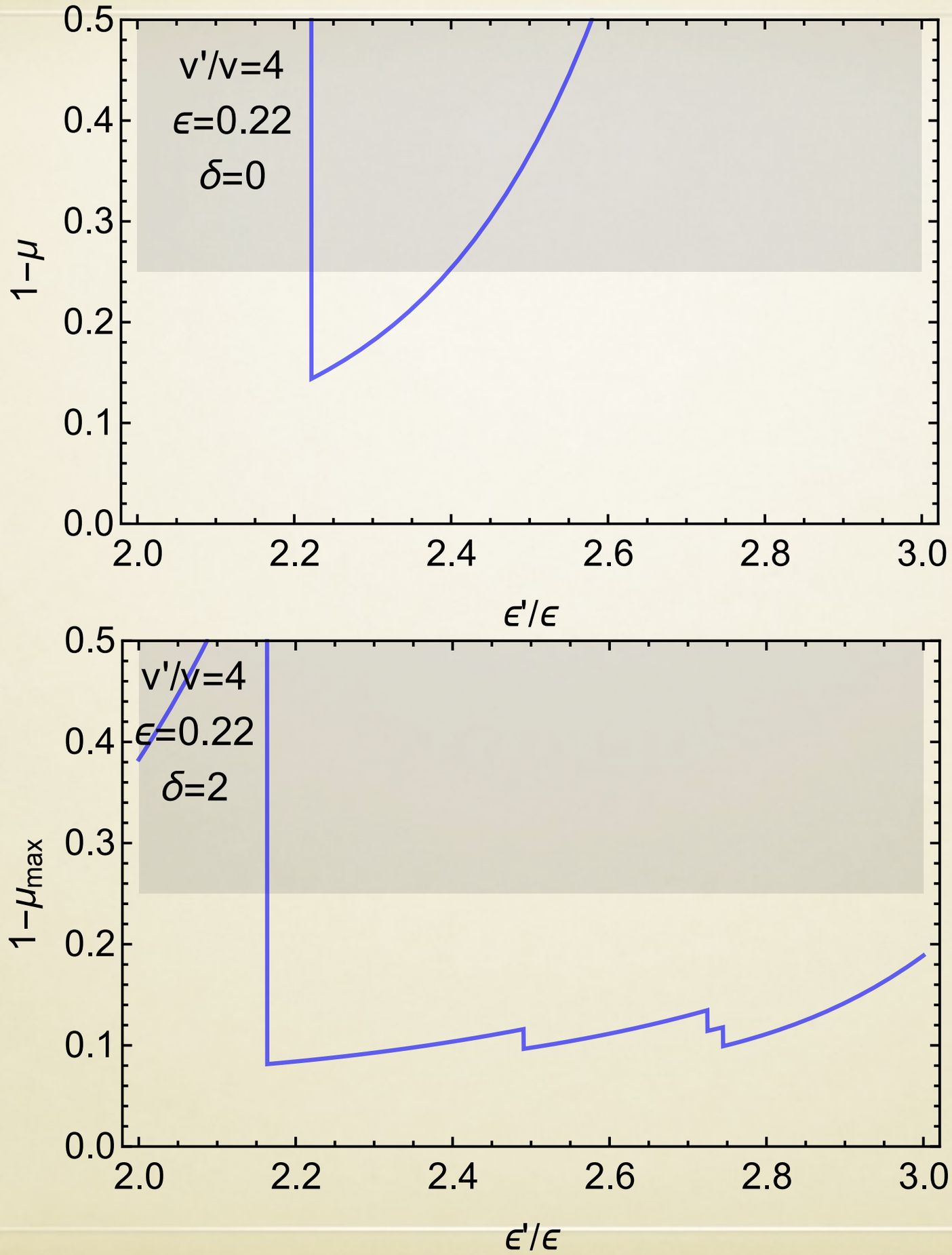
Backups

Extra dimensional model




v'/v=4
ϵ=0.22
δ=0
T_d / GeV
T_c'
$T_{d,h,q}$
$T_{d,h,\mathrm{had}}$
μ<0.75
0.5
0.45
0.55
0.35
0.6
0.4
3.0
2.5
2.0
1.5
1.0
0.5
2.0
2.2
2.4
2.6
2.8
3.0
ϵ'/ϵ


v'/v=4
ϵ=0.22
δ=2,maximal μ
T_d>T_c'
$T_{d,\mathrm{had}}$
$T_{d,qg}$
μ<0.75
0.55
0.45
0.35
0.5
0.6
0.4
0.3
0.55
3.0
2.5
2.0
1.5
1.0
0.5
2.0
2.2
2.4
2.6
2.8
3.0
ϵ'/ϵ


v'/v=4
ϵ=0.22
δ=0
1−μ
0.0
0.1
0.2
0.3
0.4
0.5
2.0
2.2
2.4
2.6
2.8
3.0
ϵ'/ϵ
v'/v=4
ϵ=0.22
δ=2
1−μmax
0.0
0.1
0.2
0.3
0.4
0.5
2.0
2.2
2.4
2.6
2.8
3.0
ϵ'/ϵ

Recombinasion