Collider Probes of Dark Matter Genesis

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dark matter facts

We know that dark matter is

- dark (electrically neutral)
- around (cosmologically stable)
- abundant ($\Omega h^2 = 0.11$)

WIMP miracle

The present day abundance of dark matter,

$$\Omega h^2 \simeq \frac{1\ \mathrm{pb}}{\langle \sigma v \rangle}$$

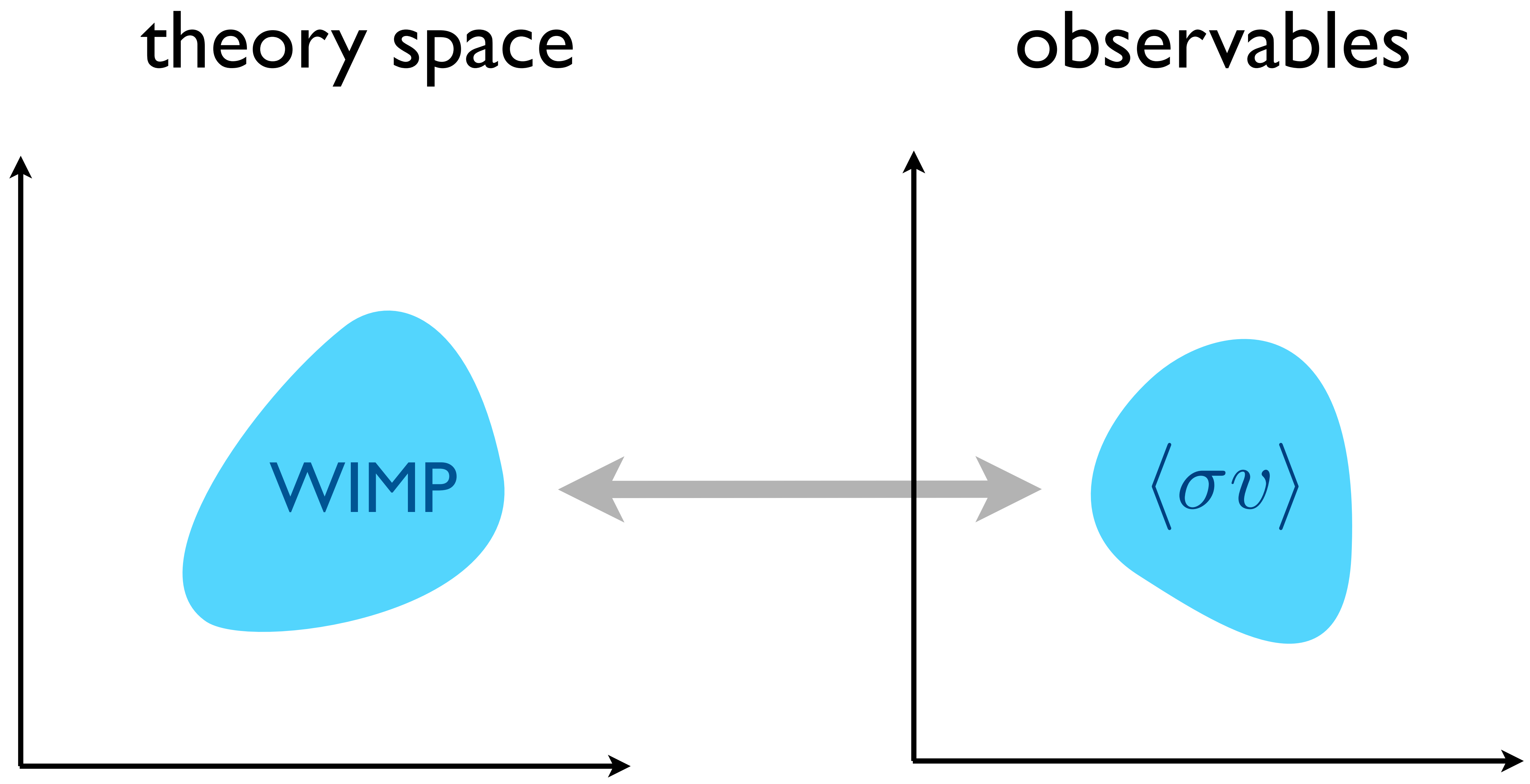
is more or less correct given a weak-scale annihilation cross-section.

Solving hierarchy problem yields dark matter!

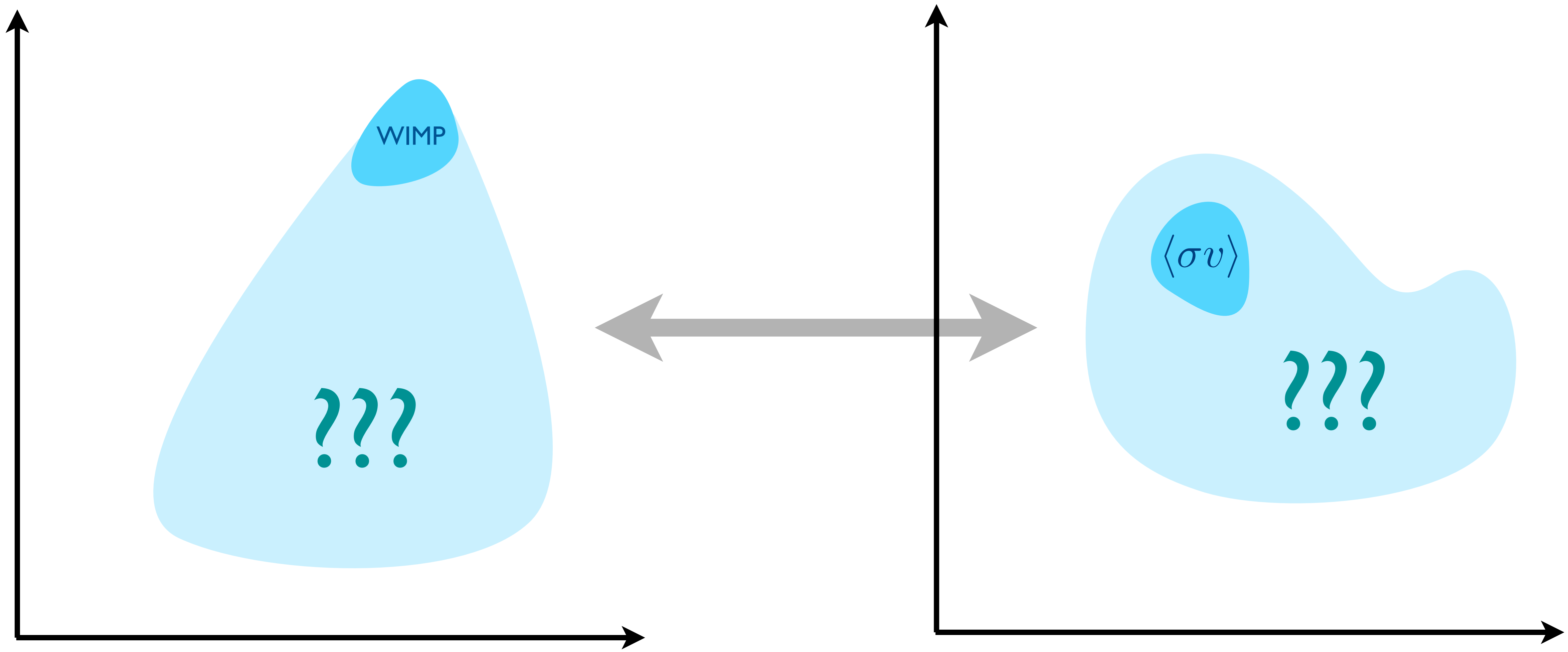
theory	Z_2
Supersymmetry	R-parity
Extra Dimensions	KK-parity
Little Higgs	T-parity

WIMP miracle is a well-motivated and highly predictive framework which

- links dark matter to the hierarchy problem.
- implies signals for direct detection & LHC.


theory space
observables
WIMP
$\langle \sigma v \rangle$

theory space | observables



The WIMP is just the tip of the iceberg!

The WIMP miracle *requires* :

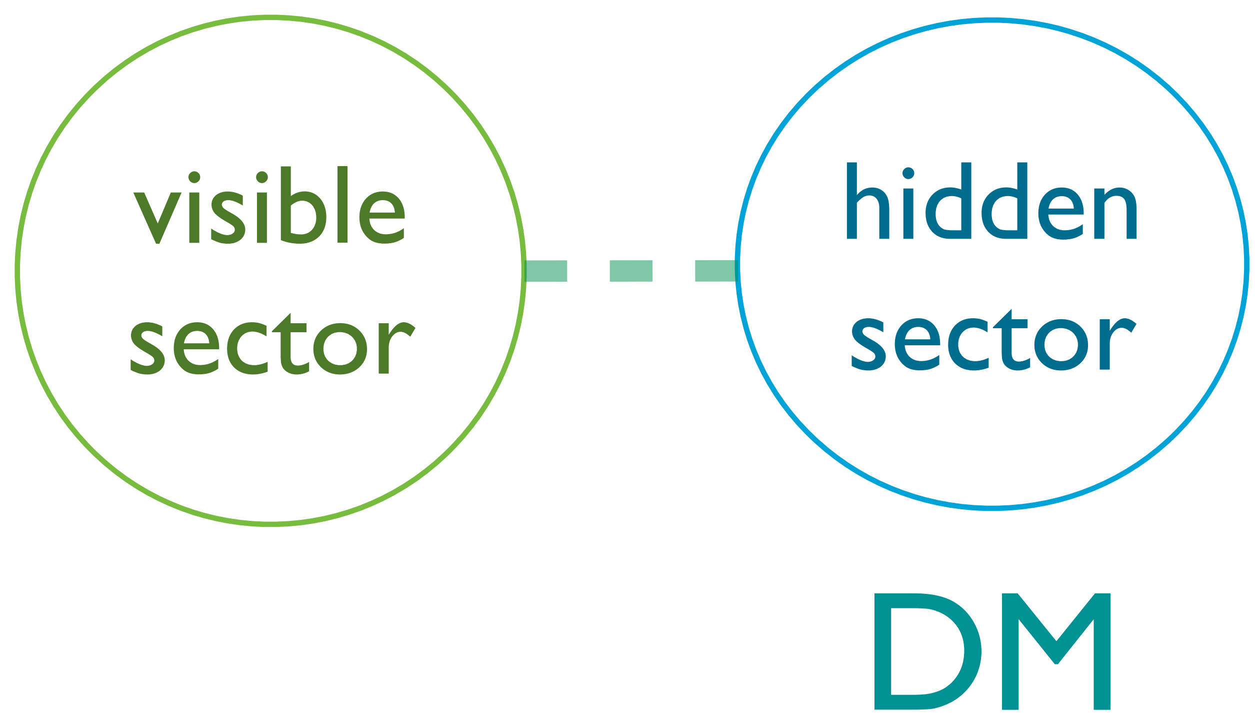
Dark matter thermalized with SM
at temperatures of order its mass.

Let us consider the *complementary* space :

Dark matter NOT thermalized with SM
at temperatures of order its mass.

1 sector :

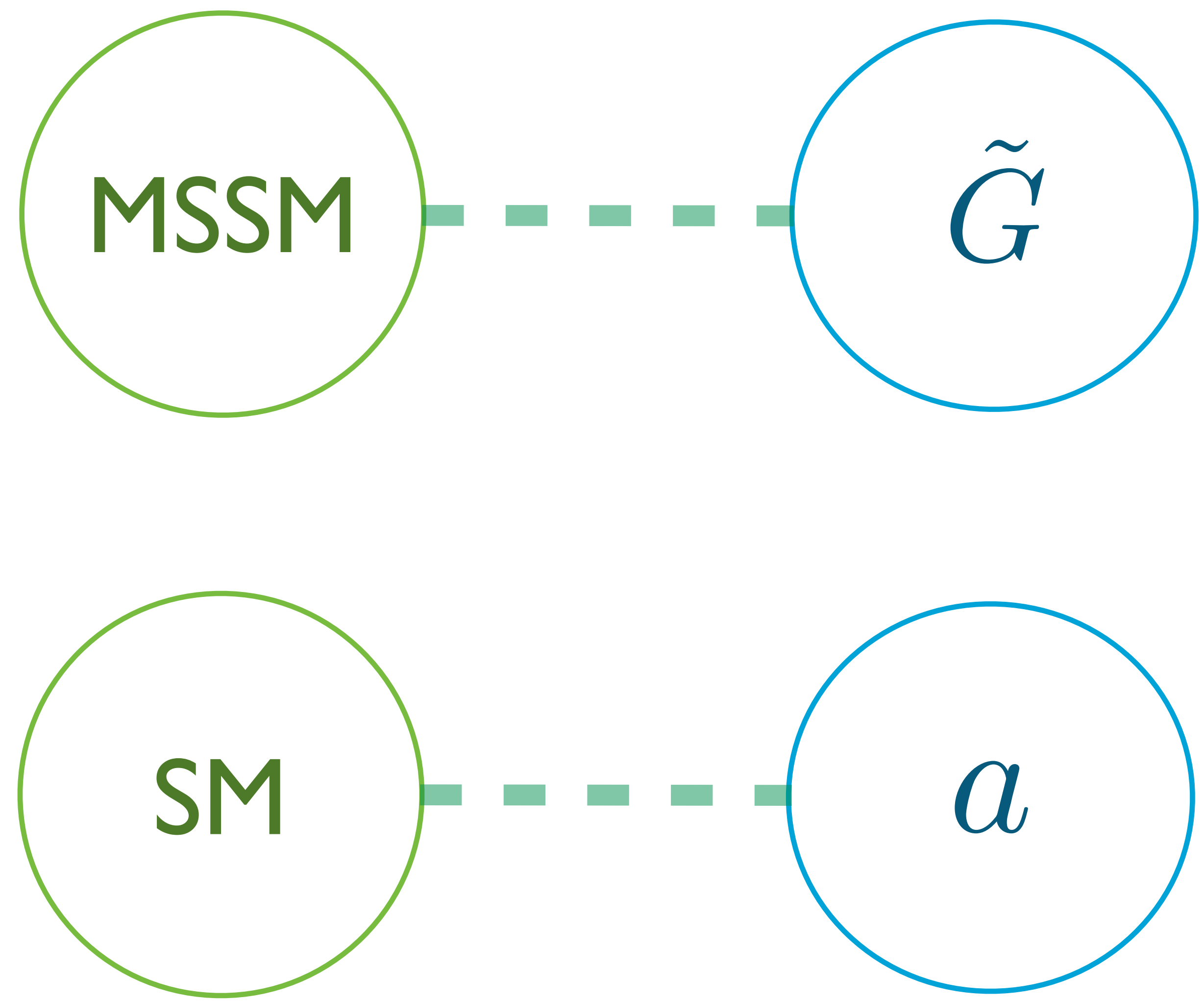
2 sectors :



This setup is actually quite familiar.

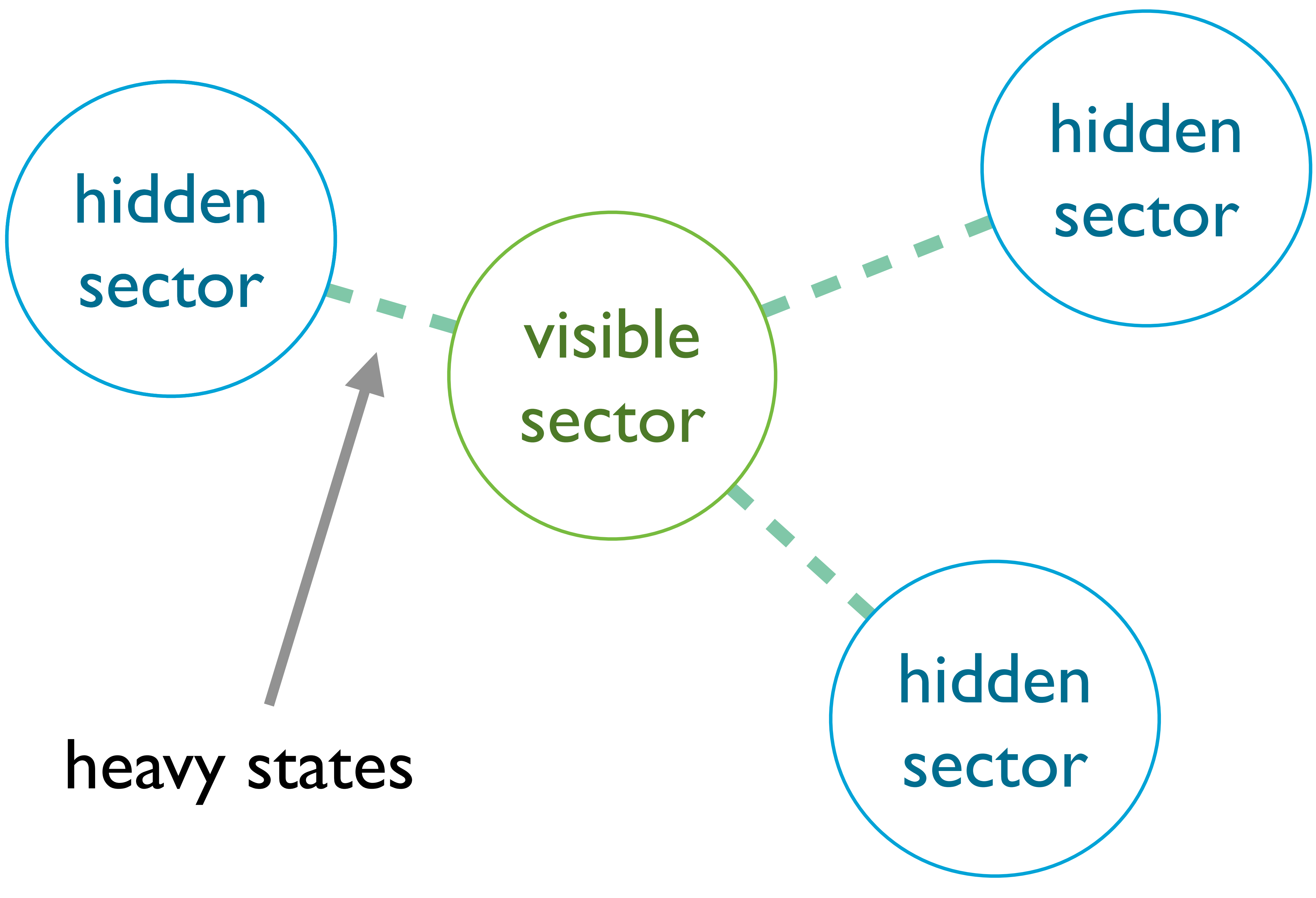
gravitino:

axion:

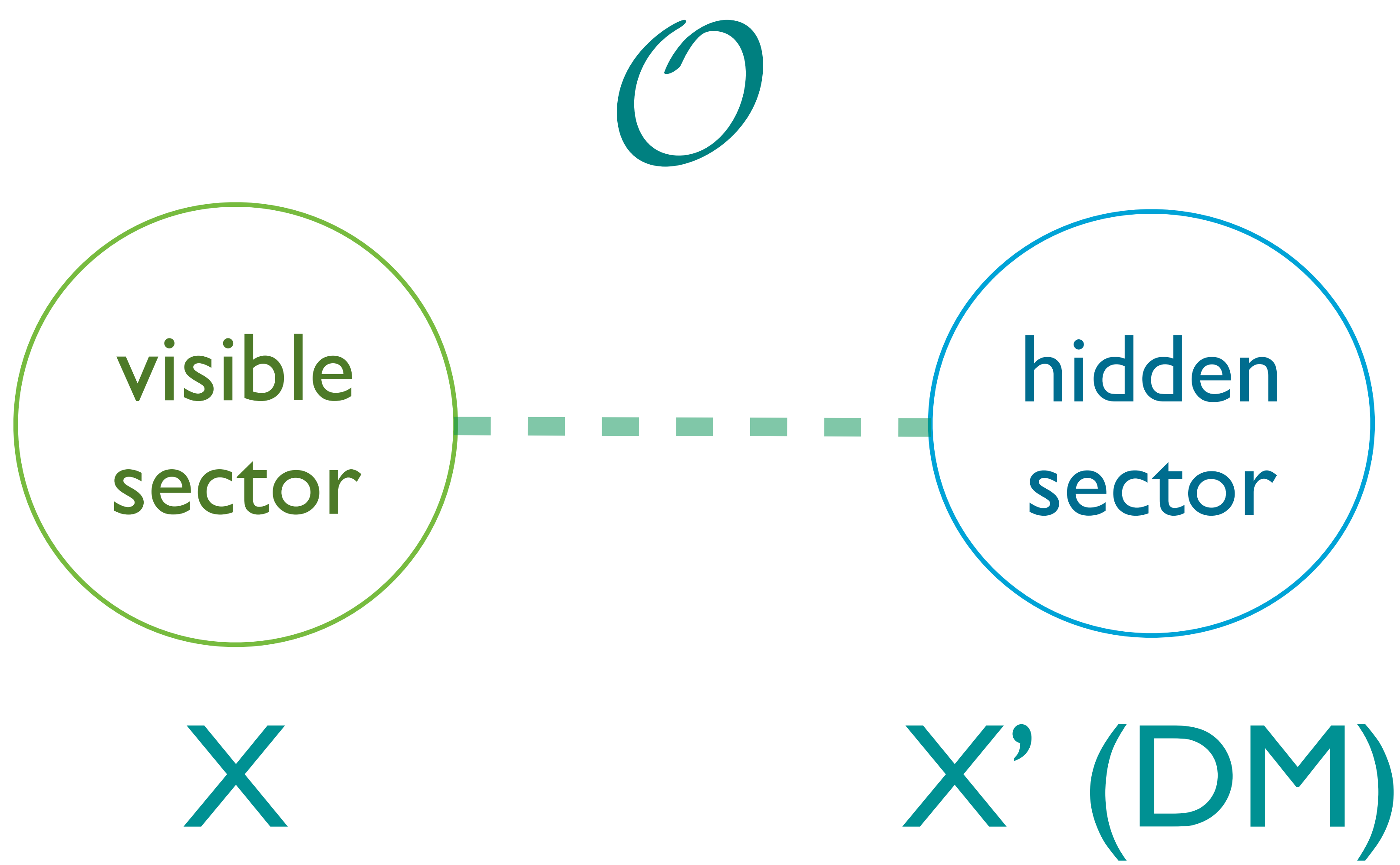


Are there other motivations for this setup?

hidden worlds?



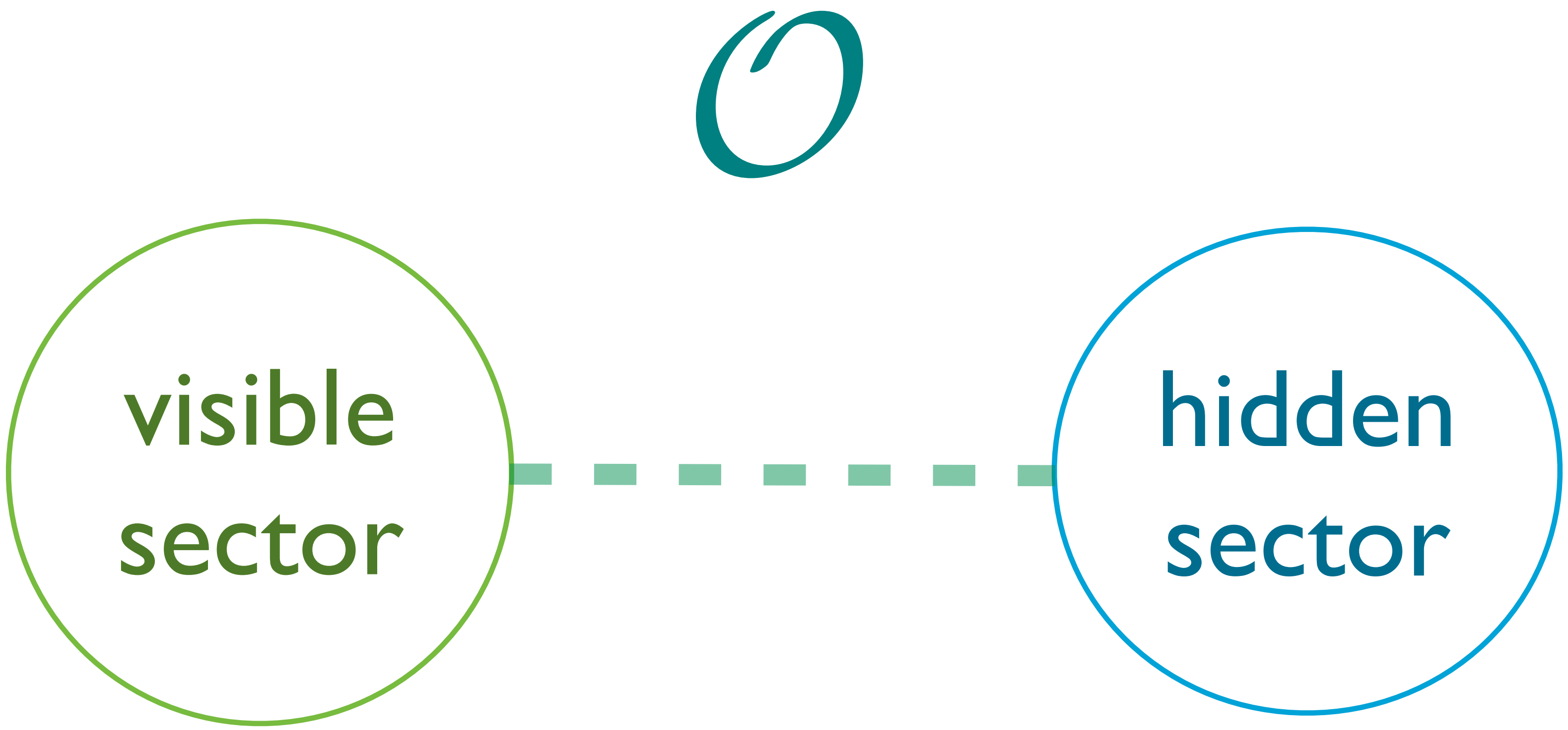
Consider the following general setup.



X, X' = Z_2 odd

m, m' = weak-scale

example : gravity mediation + R-parity



X (NLSP) X’ (LSP)

X, X’ = R odd m, m’ = weak-scale

decays to dark matter

Since m > m' the portal mediates the decay

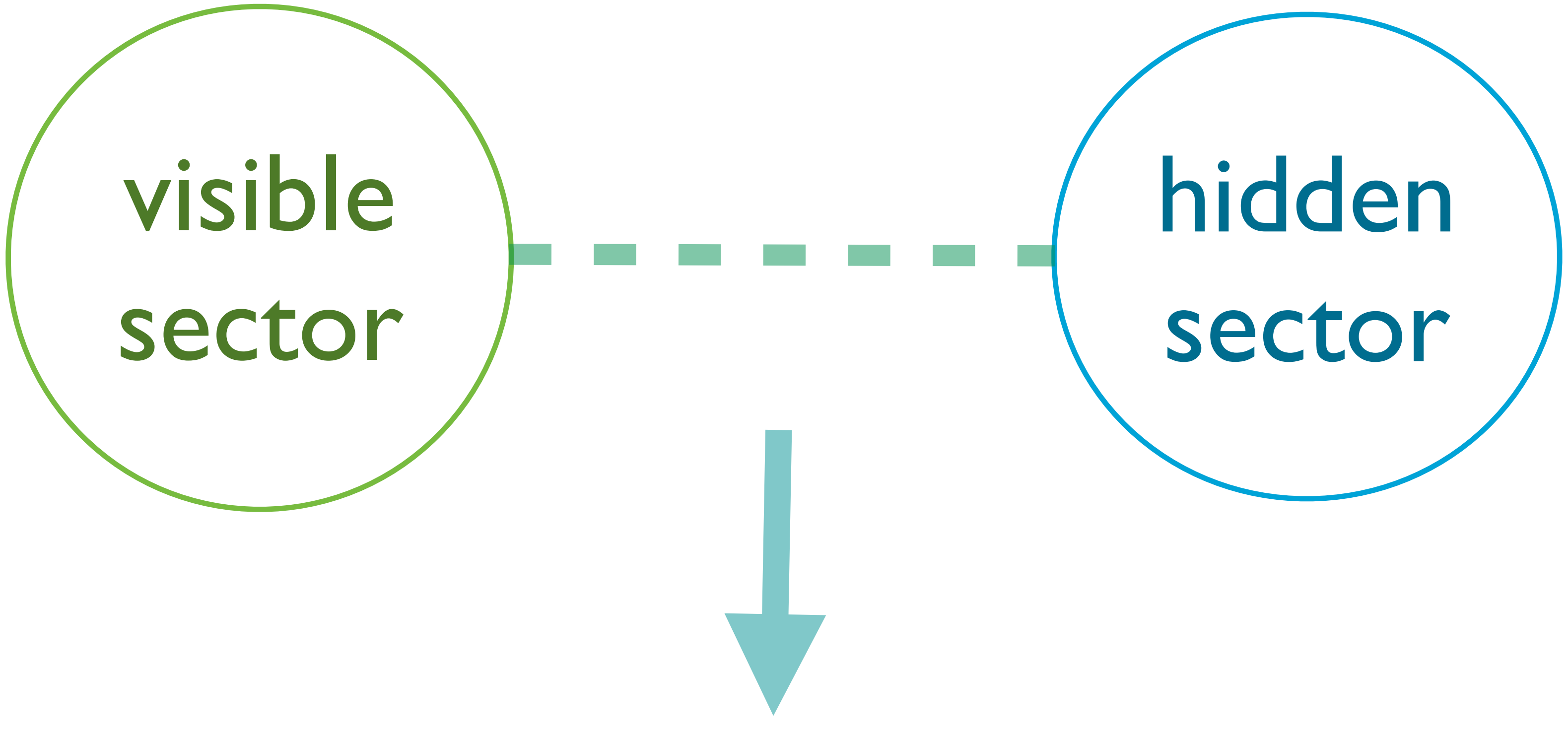
$$X \to X' + \ldots$$

We are interested in
10^{-13} sec < τ < 1 sec.

May contain SM fields.

sector equilibration

initially, two heat baths



ultimately, one heat bath

Only a handful of parameters fix Ω:

1 sector : $\langle \sigma v \rangle$

2 sector : $\xi = T'/T$

τ

$m, \langle \sigma v \rangle$

$m', \langle \sigma v \rangle'$

Only a handful of parameters fix Ω:

1 sector : $\langle \sigma v \rangle$ ← accessible at colliders

2 sector : $\xi = T'/T$

τ

$m, \langle \sigma v \rangle$

$m', \langle \sigma v \rangle'$

Only a handful of parameters fix Ω:

1 sector : $\langle \sigma v \rangle$ ← accessible at colliders

2 sector : $\xi = T'/T$

accessible at colliders → τ, $m, \langle \sigma v \rangle$, $m', \langle \sigma v \rangle'$

$$\tau$$

$$m, \langle \sigma v \rangle$$

$$m', \langle \sigma v \rangle'$$

lifetime range

The cosmological history varies substantially as a function of the lifetime:

lifetime range

The cosmological history varies substantially as a function of the lifetime:

outline

- general setup
- two sector cosmology
- cosmological phase diagram
- collider signals
- neutrinos

two sector cosmology

bath + bath'

visible sector

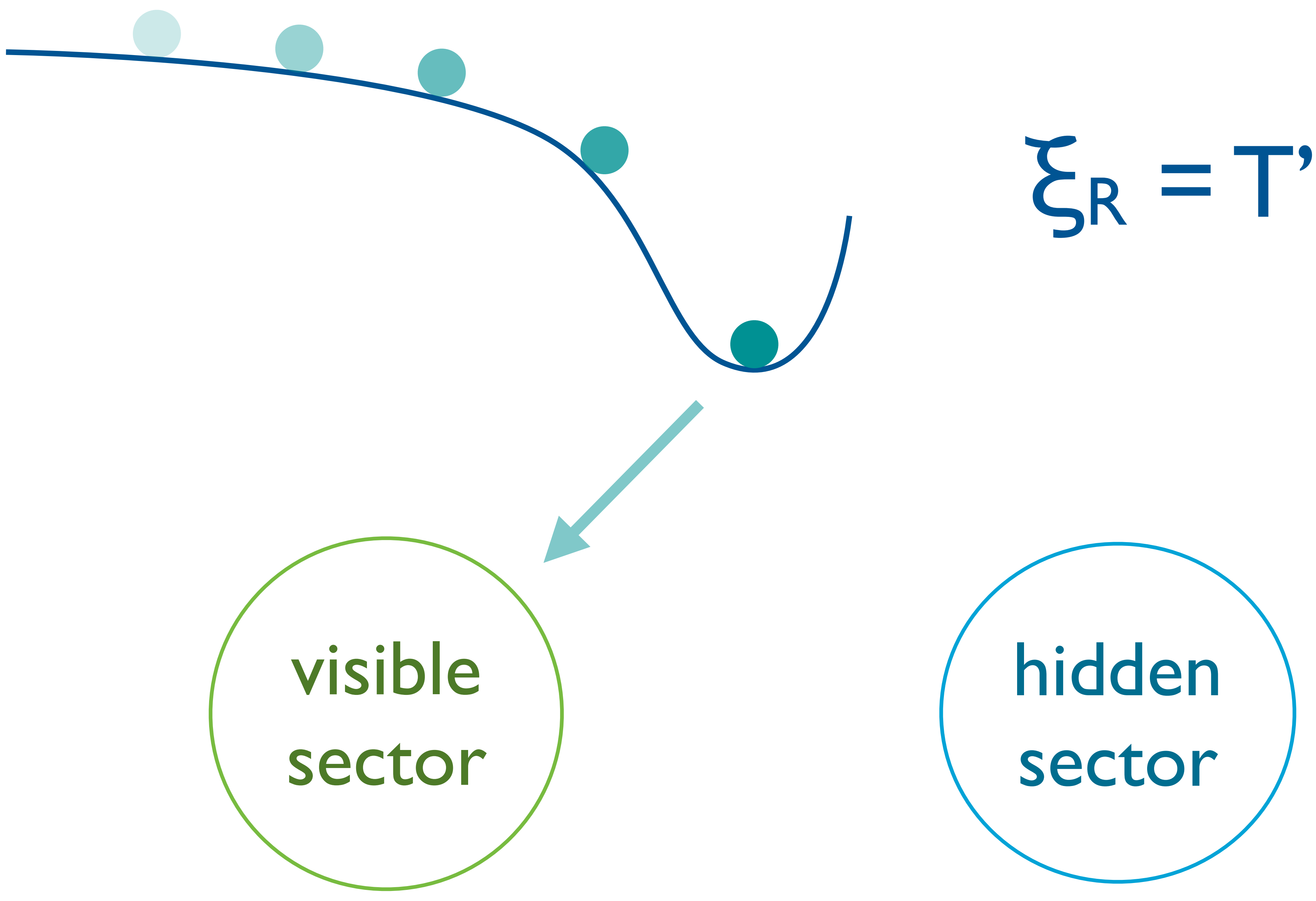
T

hidden sector

T'

Define the ratio $\xi = T' / T$.

Inflaton may dominantly decay into and reheat the visible sector!



$\xi_R = T'_R / T_R$

degrees of freedom

Assuming conserved entropy in each sector,

$$\xi(T) \propto \left(\frac{g_{*s}(T)}{g'_{*s}(T)} \right)^{1/3}$$

where g_{*s} and g'_{*s} are the number of degrees of freedom in each sector.

energy budgets

The effective number of relativistic species at BBN is bounded by

$$\Delta N_\nu = \frac{4}{7} g'_*(T_{\rm BBN}) \xi(T_{\rm BBN})^4$$

$$< 1.4$$

Colder hidden sectors are safe!

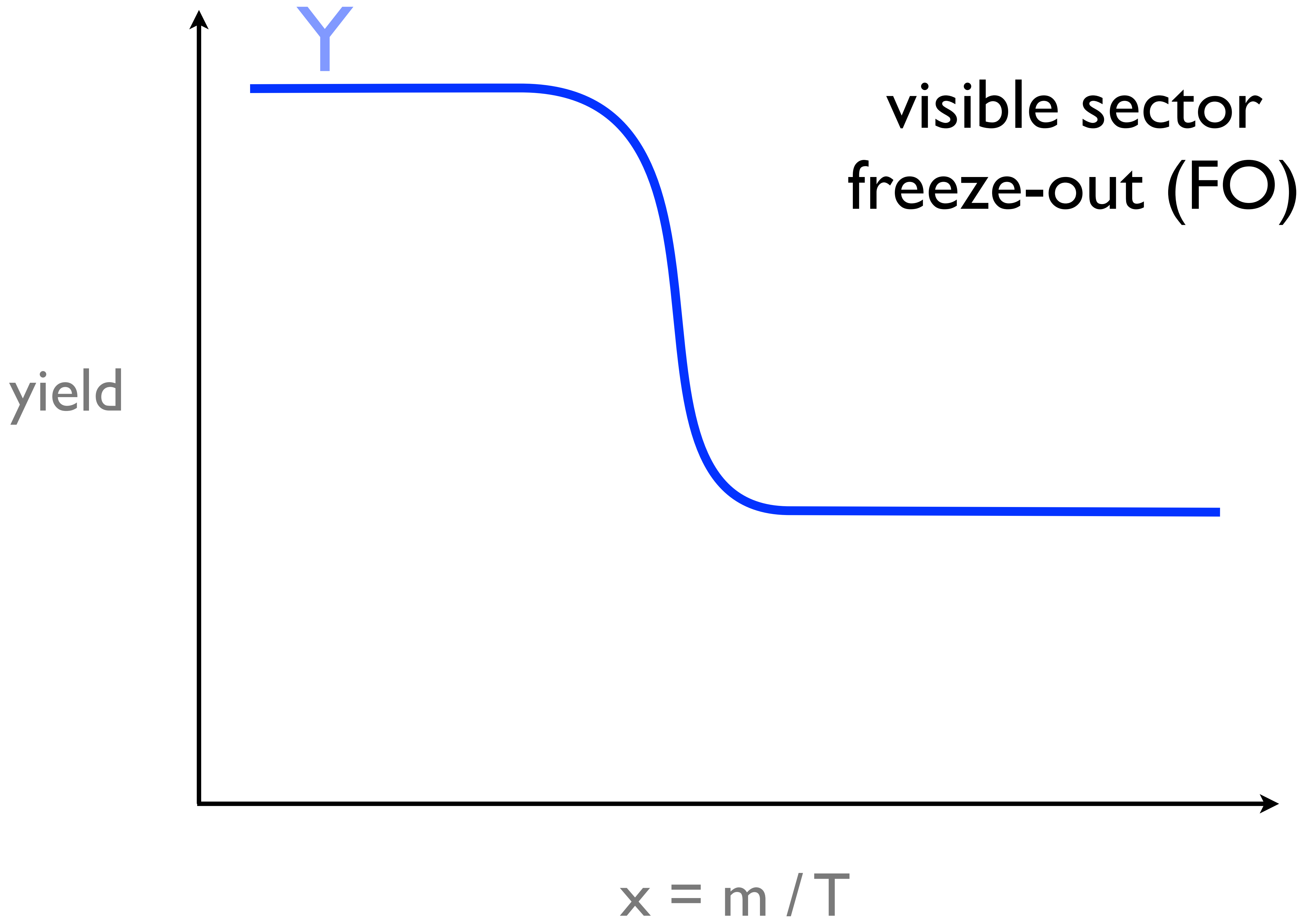
yield variables

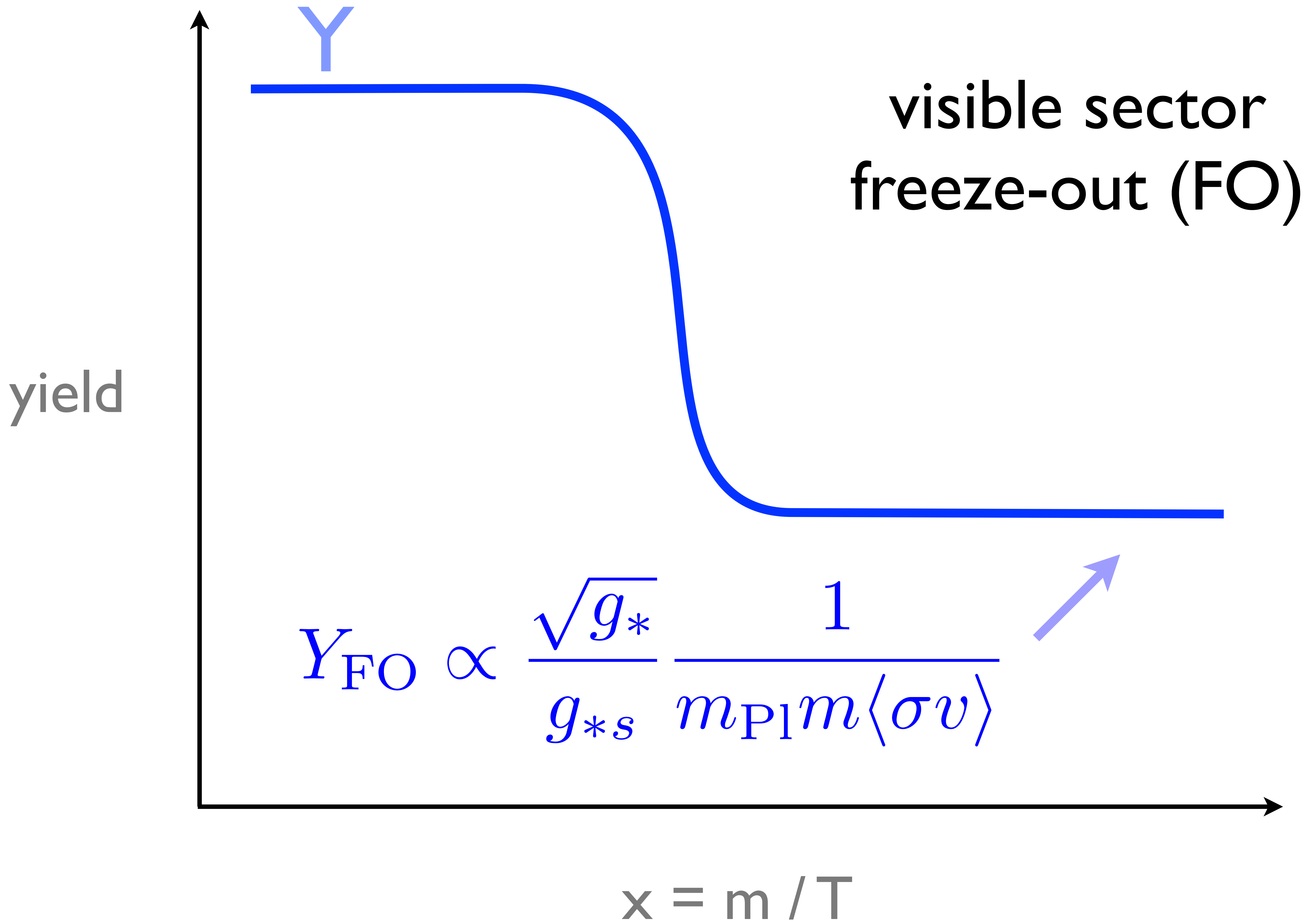
The yield of X is defined to be

$$Y = \frac{n}{s}$$

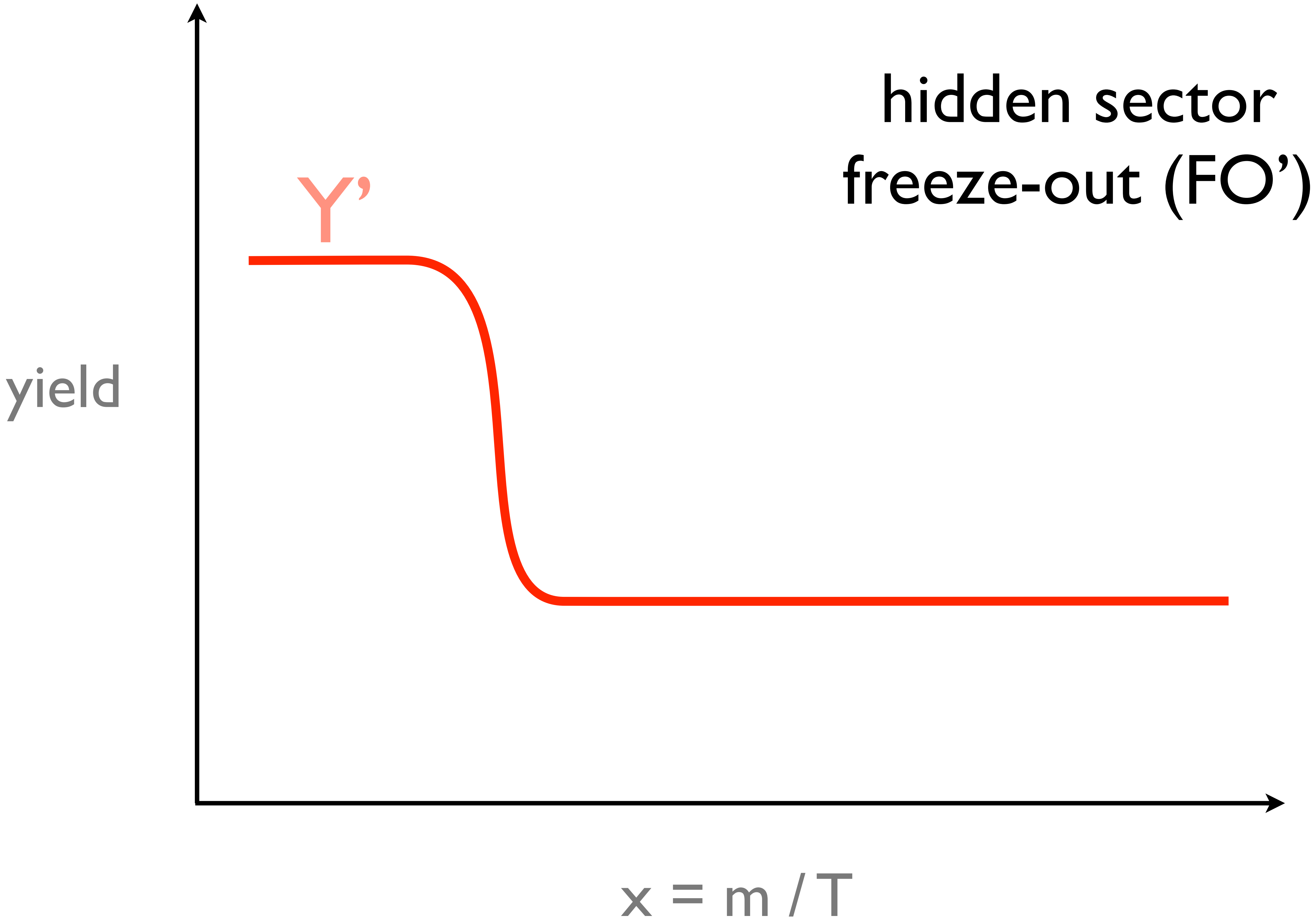
The yield of X' is defined to be

$$Y' = \frac{n'}{s}$$


Y
visible sector
freeze-out (FO)
yield
x = m / T

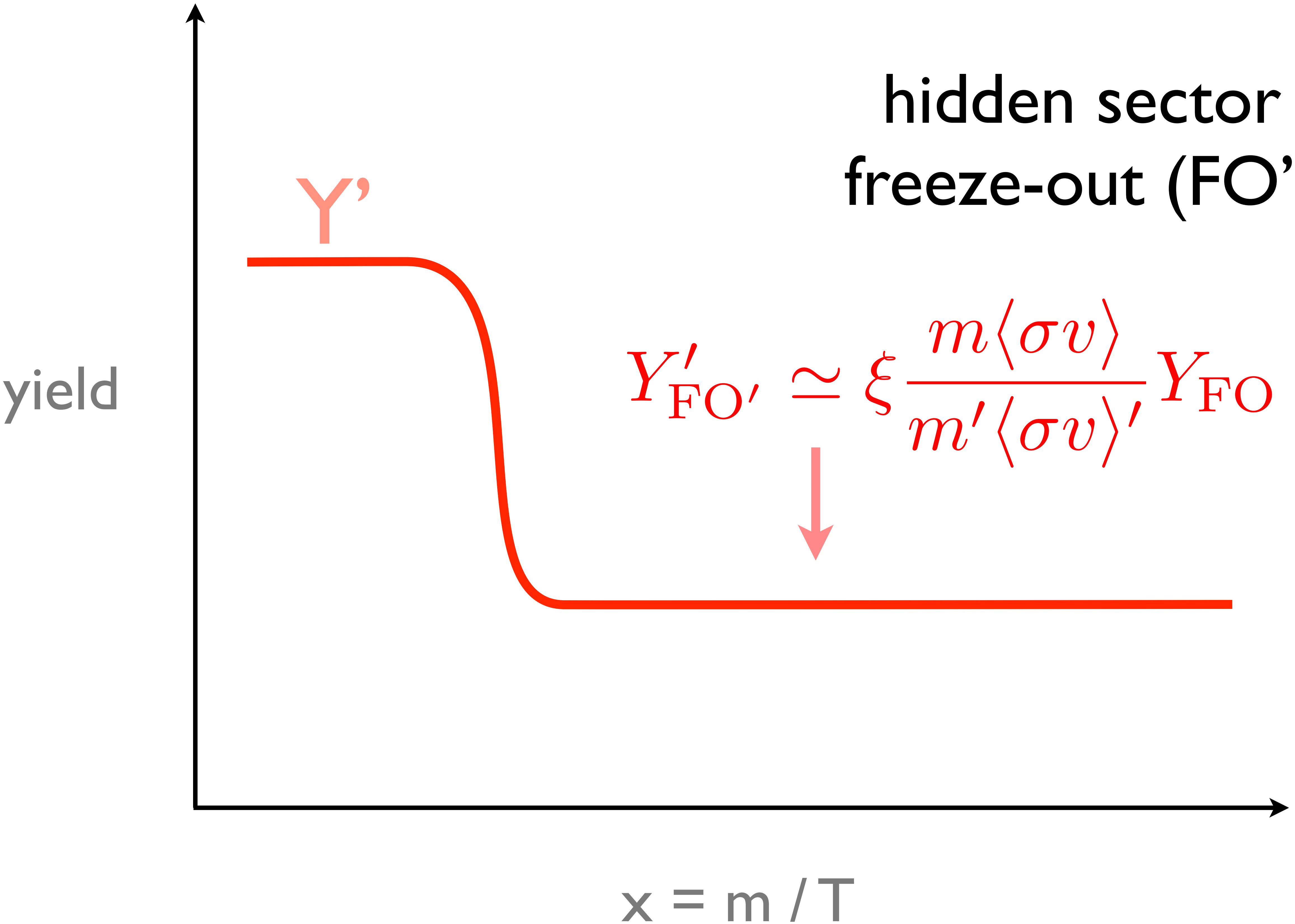


Y
visible sector
freeze-out (FO)
yield
$Y_{\mathrm{FO}} \propto \frac{\sqrt{g_*}}{g_{*s}} \frac{1}{m_{\mathrm{Pl}} m \langle \sigma v \rangle}$
x = m / T

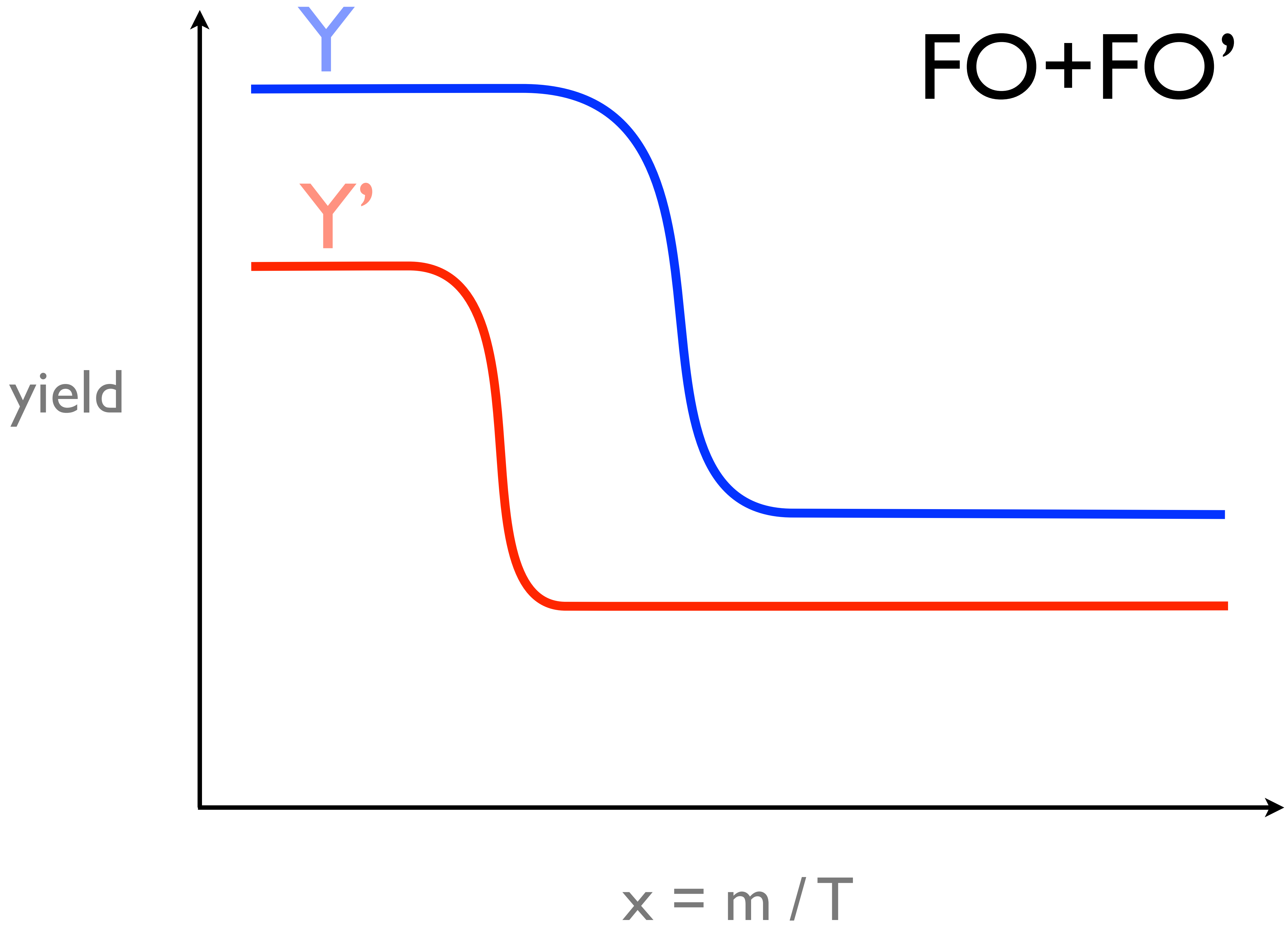


hidden sector
freeze-out (FO')
Y'
yield
x = m / T

hidden sector freeze-out (FO')

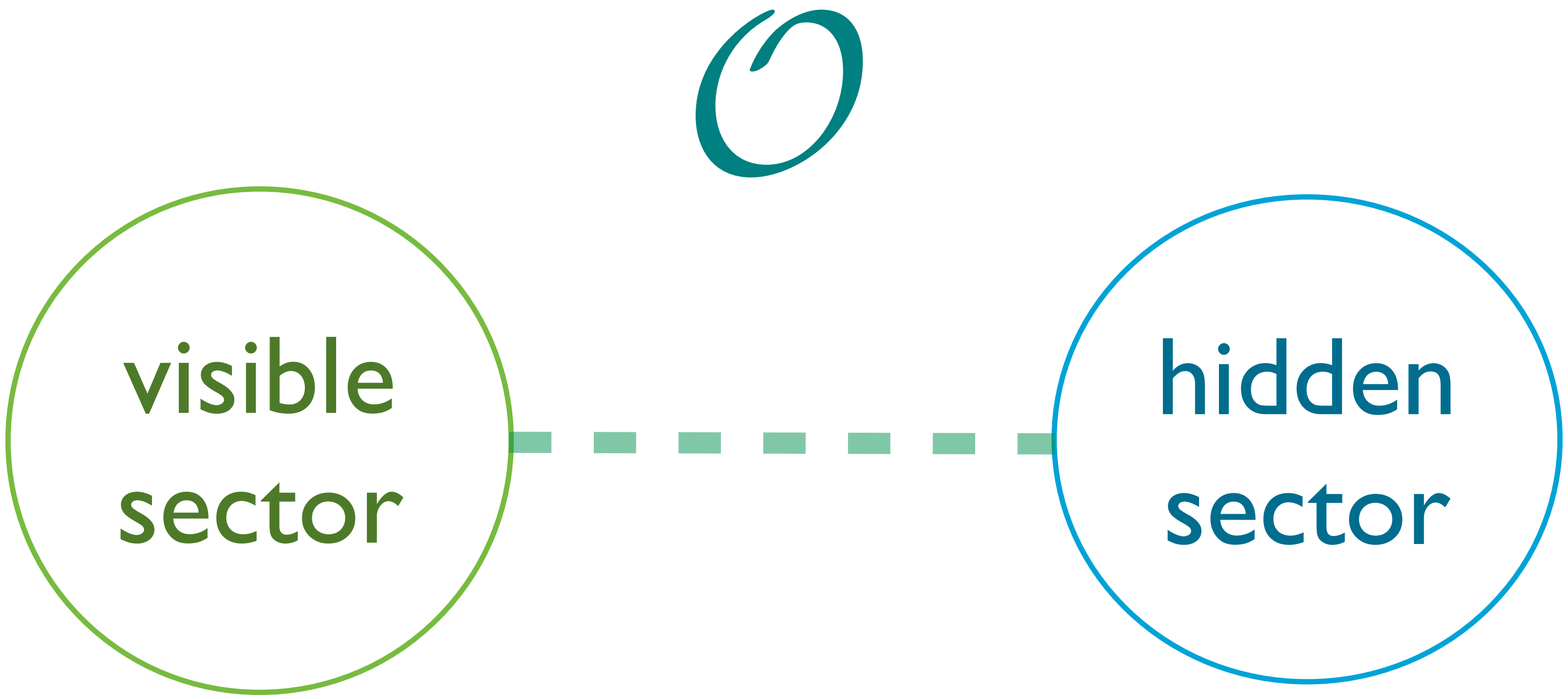


$$Y'_{\mathrm{FO}'} \simeq \xi \frac{m \langle \sigma v \rangle}{m' \langle \sigma v \rangle'} Y_{\mathrm{FO}}$$

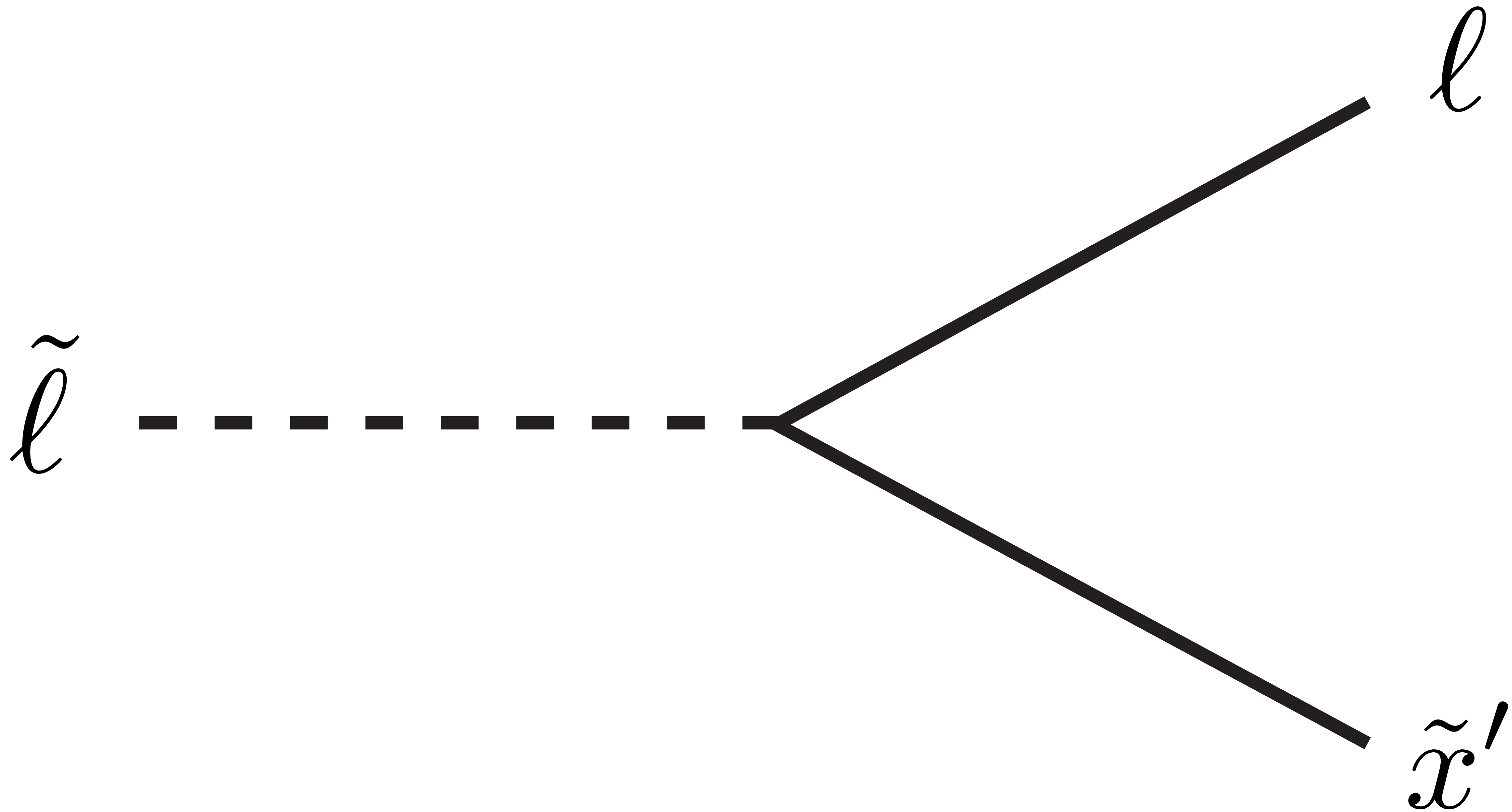


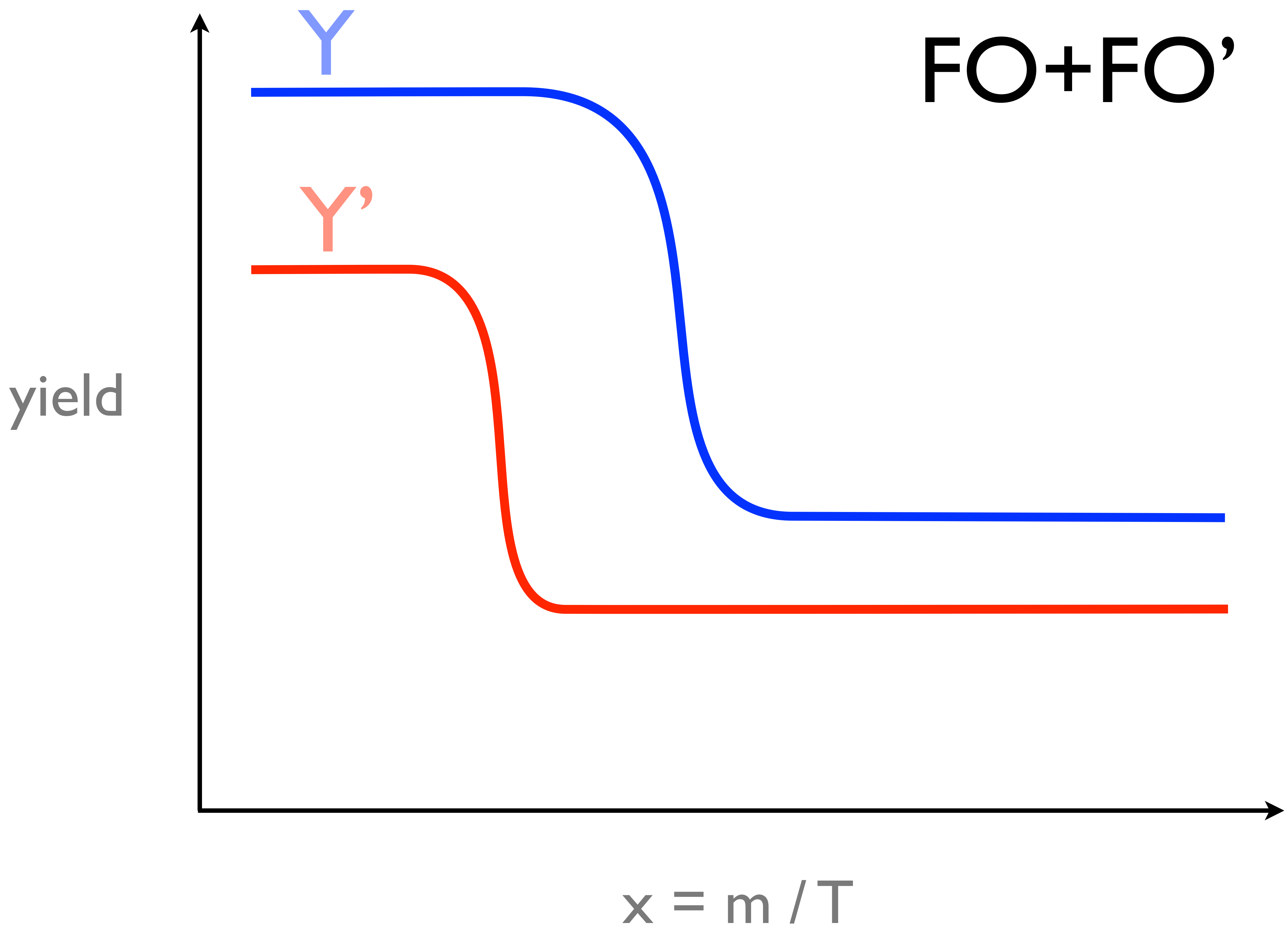
Y
FO+FO'
Y'
yield
x = m / T

portal operator

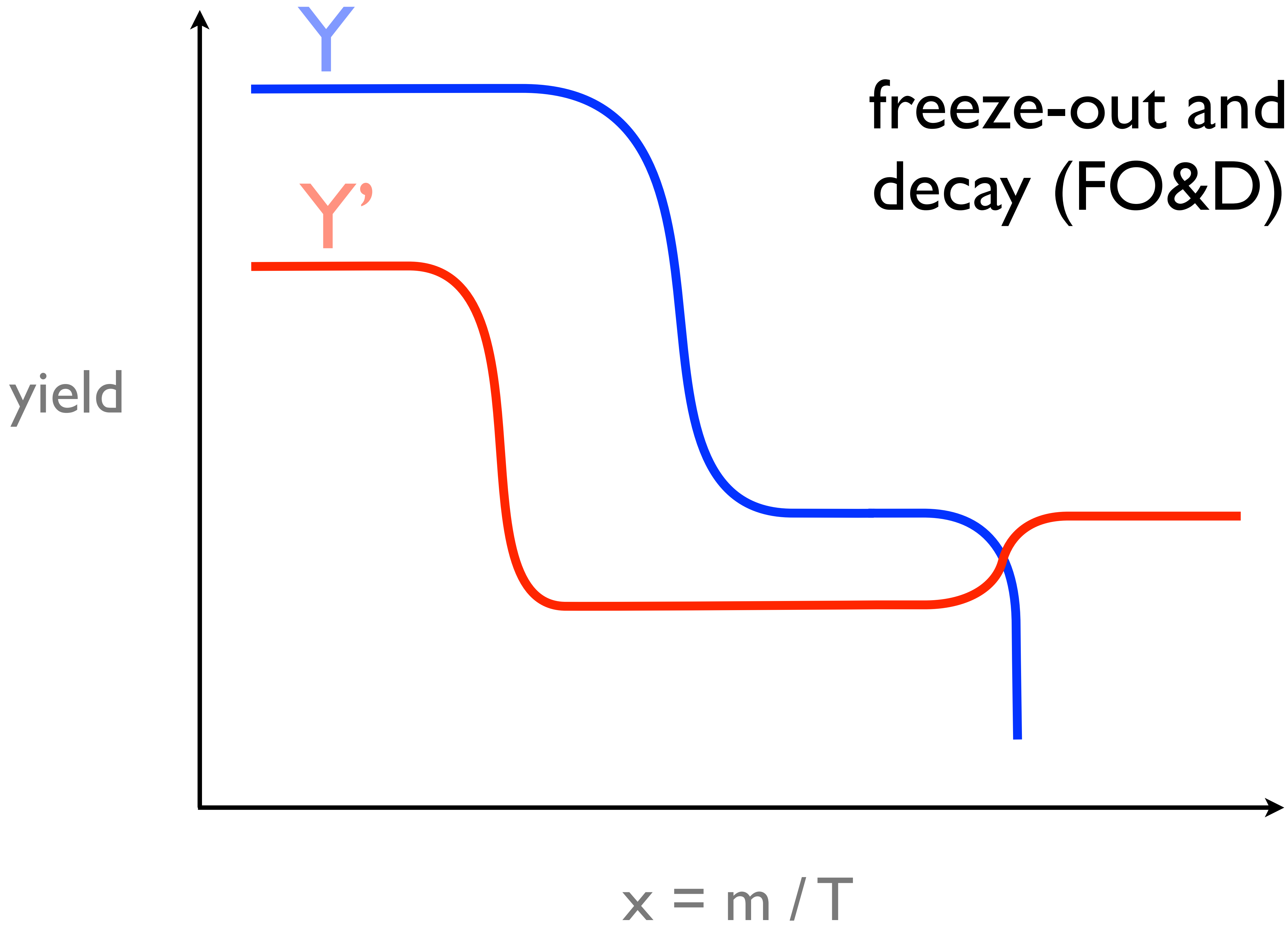


e.g. $\mathcal{O} = [L^\dagger L X']_D$

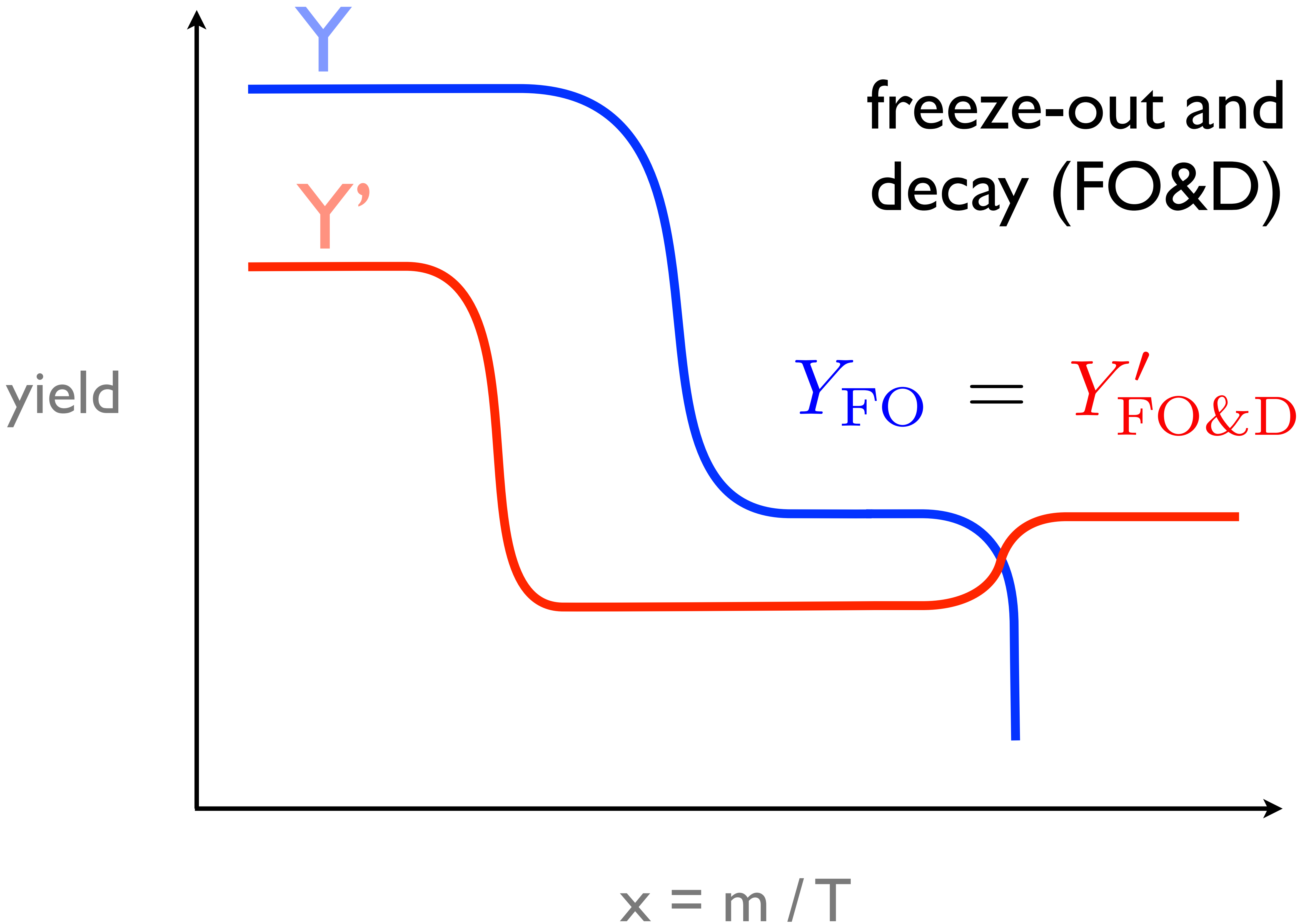

$\tilde{\ell}$
ℓ
$\tilde{x}'$



Y
FO+FO'
Y'
yield
x = m / T

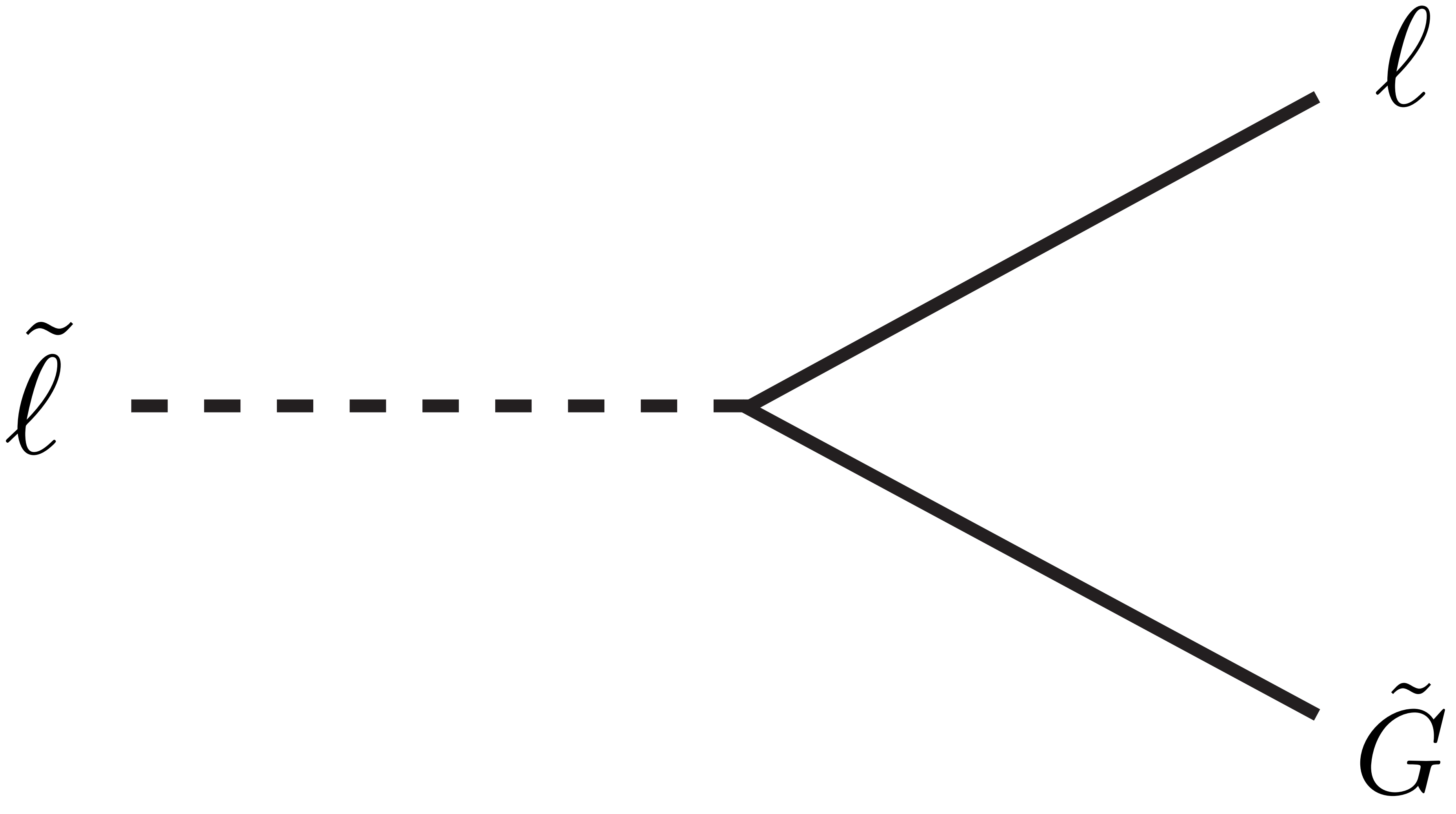


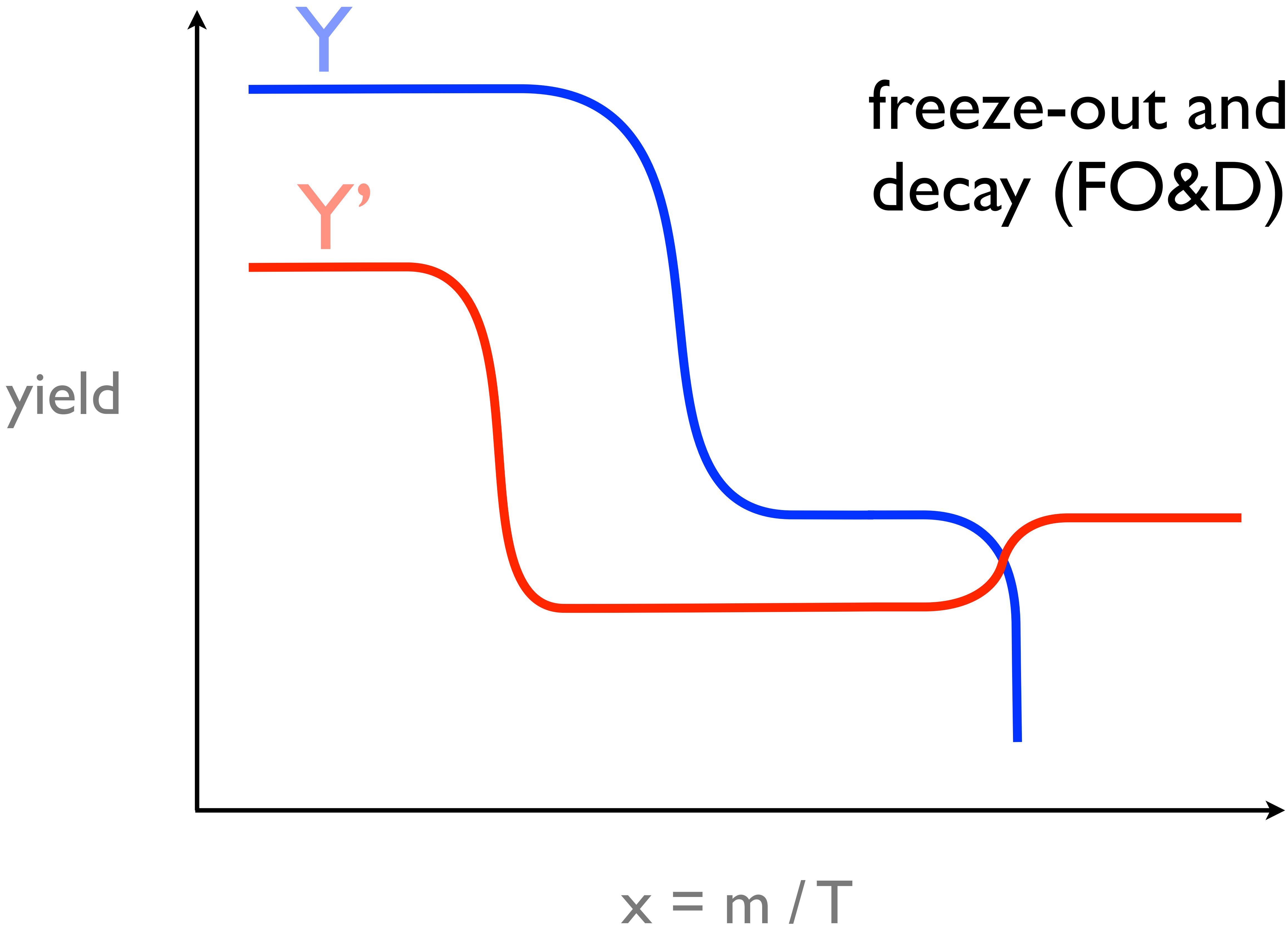
Y
Y'
freeze-out and
decay (FO&D)
yield
x = m / T


Y
Y'
freeze-out and decay (FO&D)
$Y_{\mathrm{FO}} = Y'_{\mathrm{FO\&D}}$
yield
x = m / T

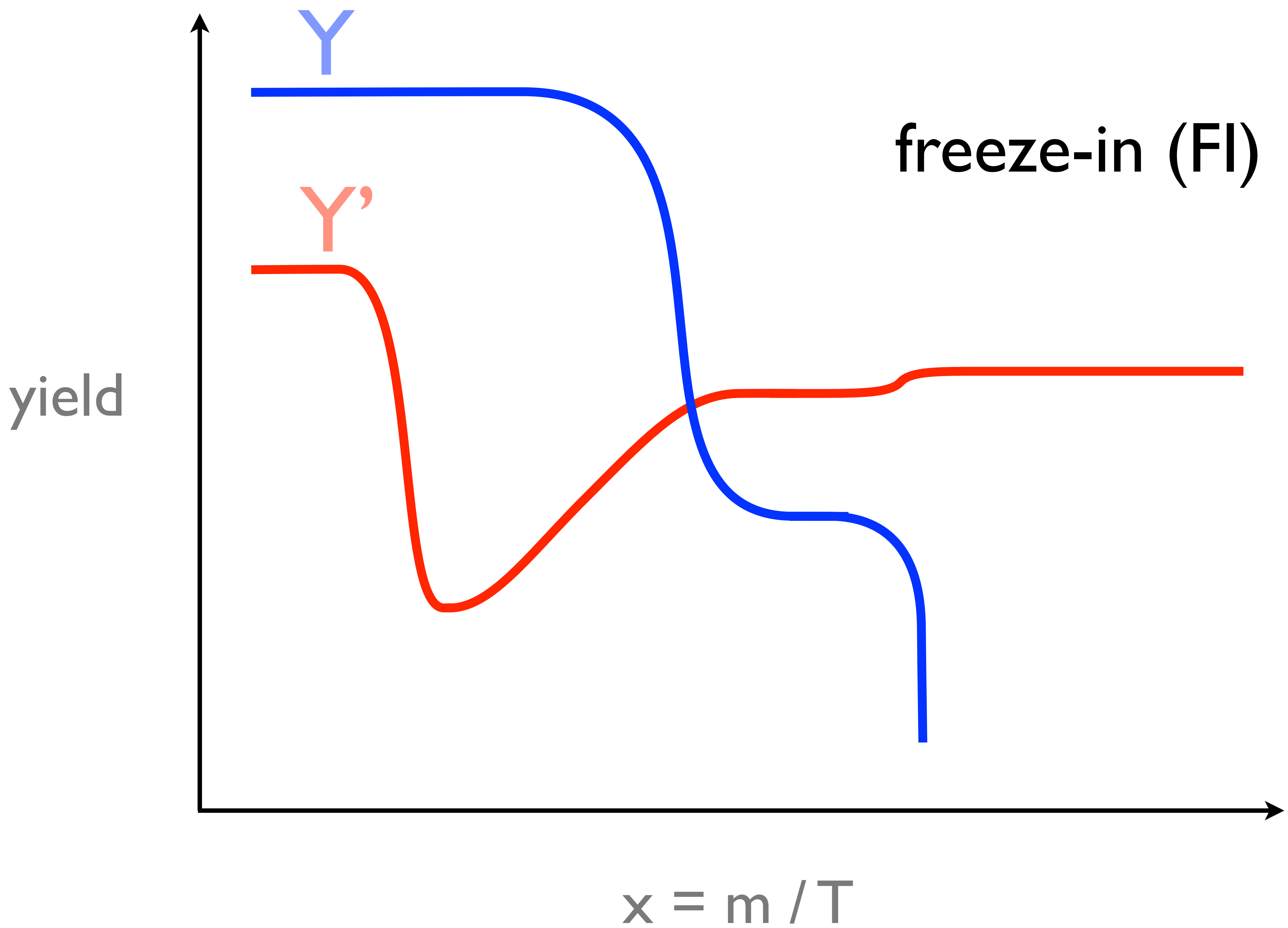
superWIMPs

FO&D is actually familiar from Feng et al.

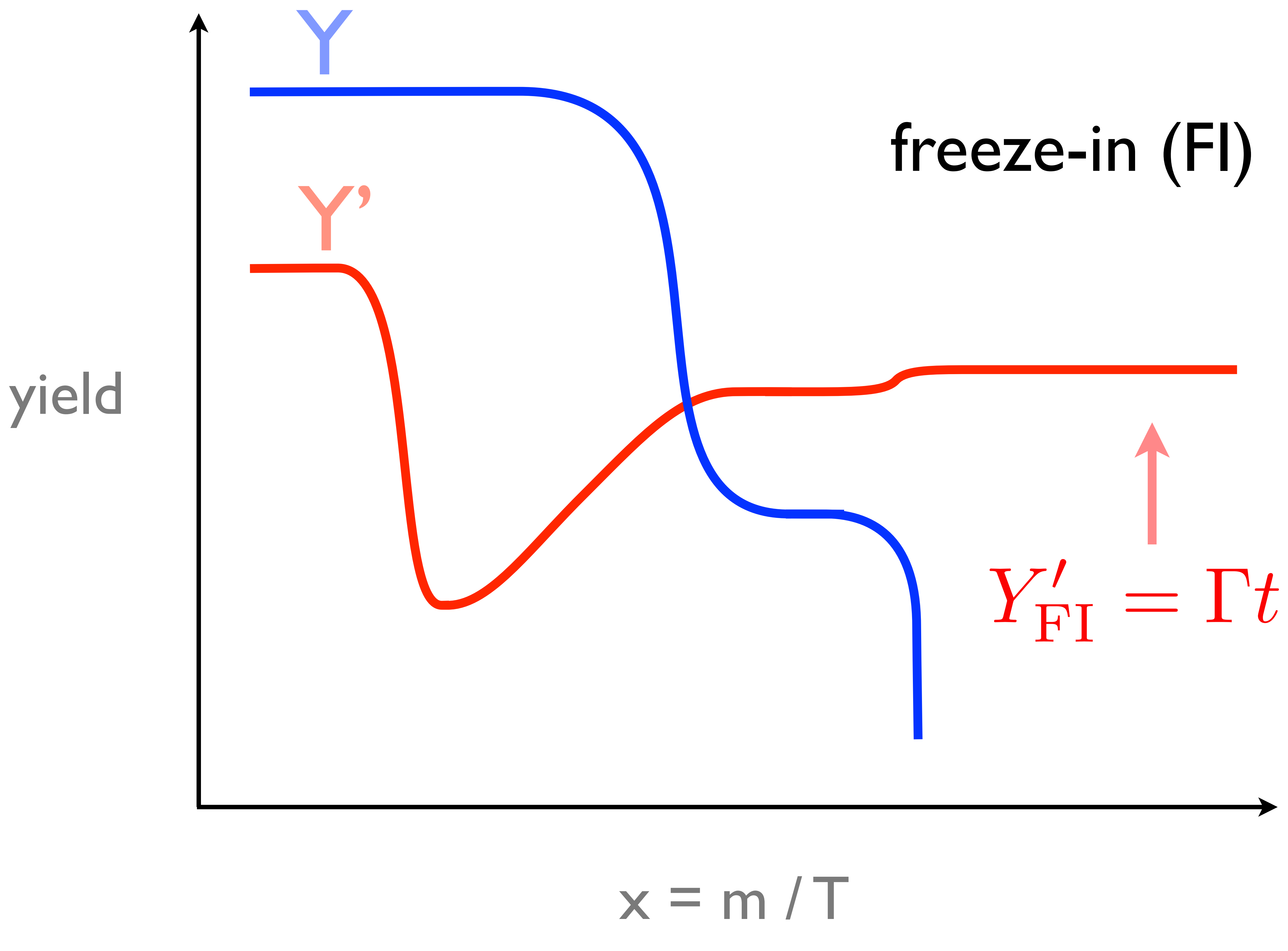




Y
Y'
freeze-out and decay (FO&D)
yield
x = m / T



Y
freeze-in (FI)
Y'
yield
x = m / T


Y
Y'
freeze-in (FI)
yield
$Y'_{\rm FI} = \Gamma t$
x = m / T

freeze-in

Since $t \propto 1/H$ at the time when X becomes non-relativistic, the final yield of X' is

$$Y'_{\rm FI} \propto \frac{\Gamma m_{\rm Pl}}{m^2}$$

fast decays, small masses → more!

re-annihilation

If the yield of X' exceeds a critical value,

$$n' \langle \sigma v \rangle' > H$$

then X' will begin to (re-)annihilate and in turn deplete the abundance.

re-annihilation

For each mode of dark matter genesis is a "re-annihilated" variant:

$$\mathrm{FO\&D} \rightarrow \mathrm{FO\&D}_r$$

$$\mathrm{FI} \rightarrow \mathrm{FI}_r$$

cosmological phase diagram

Some of the parameters which dictate the cosmological history can be measured.

accessible	inaccessible
τ	ξ
$m, \langle \sigma v \rangle$	$\langle \sigma v \rangle'$
m'	

Plot "phase diagram" of dominant mode of dark matter genesis, subject to $\Omega h^2 = 0.11$.

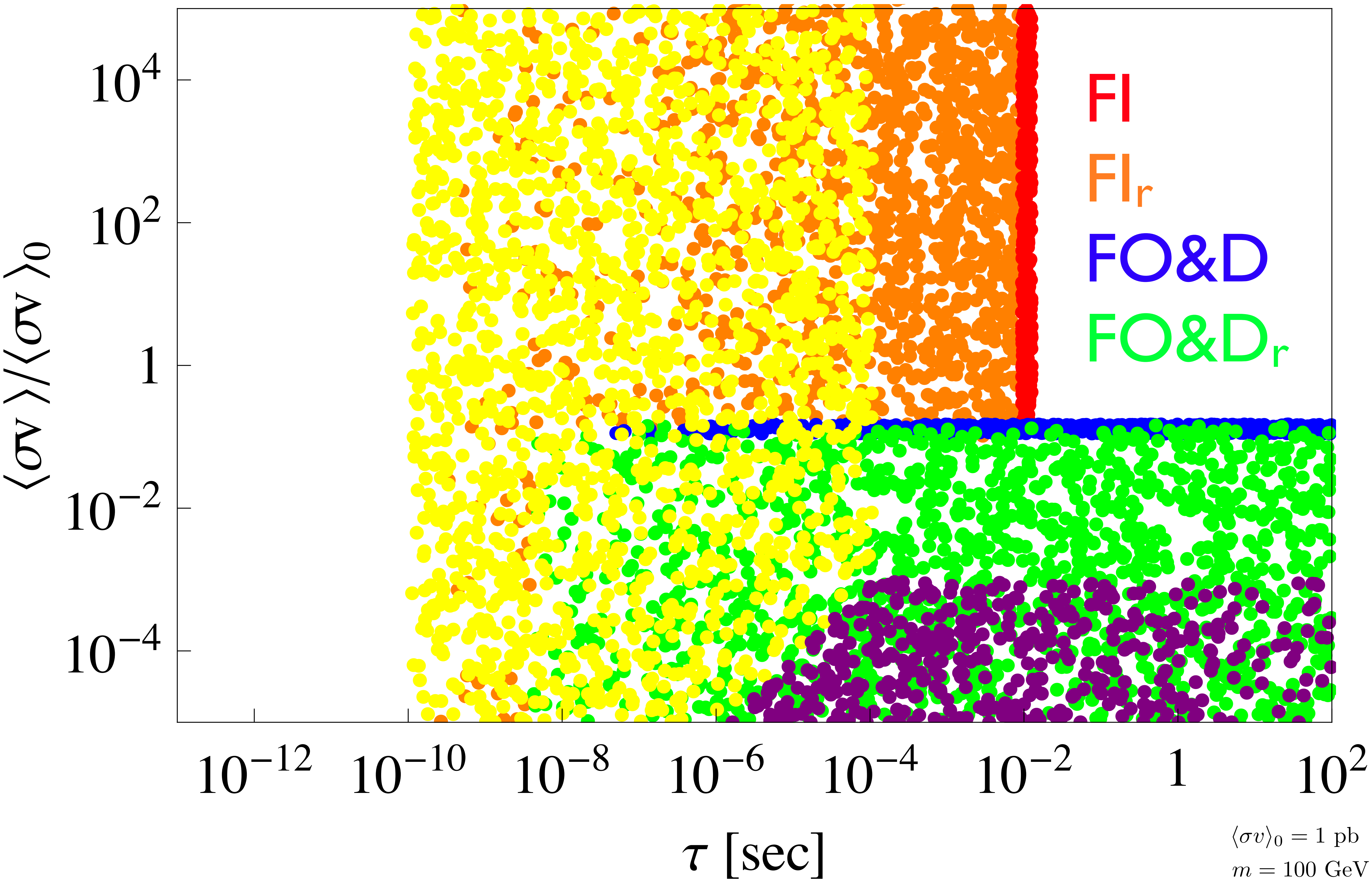
Inaccessible parameters scanned inclusively :

$$10^{-3} < \xi < 10^{-1}$$

$$10^{-5}\ \mathrm{pb} < \langle \sigma v \rangle' < 10^{5}\ \mathrm{pb}$$

and accessible parameters are the axes.

Cosmology imprints observables!



$\langle \sigma v \rangle_0 = 1$ pb

$m = 100$ GeV

$1/4 < m'/m < 1/3$

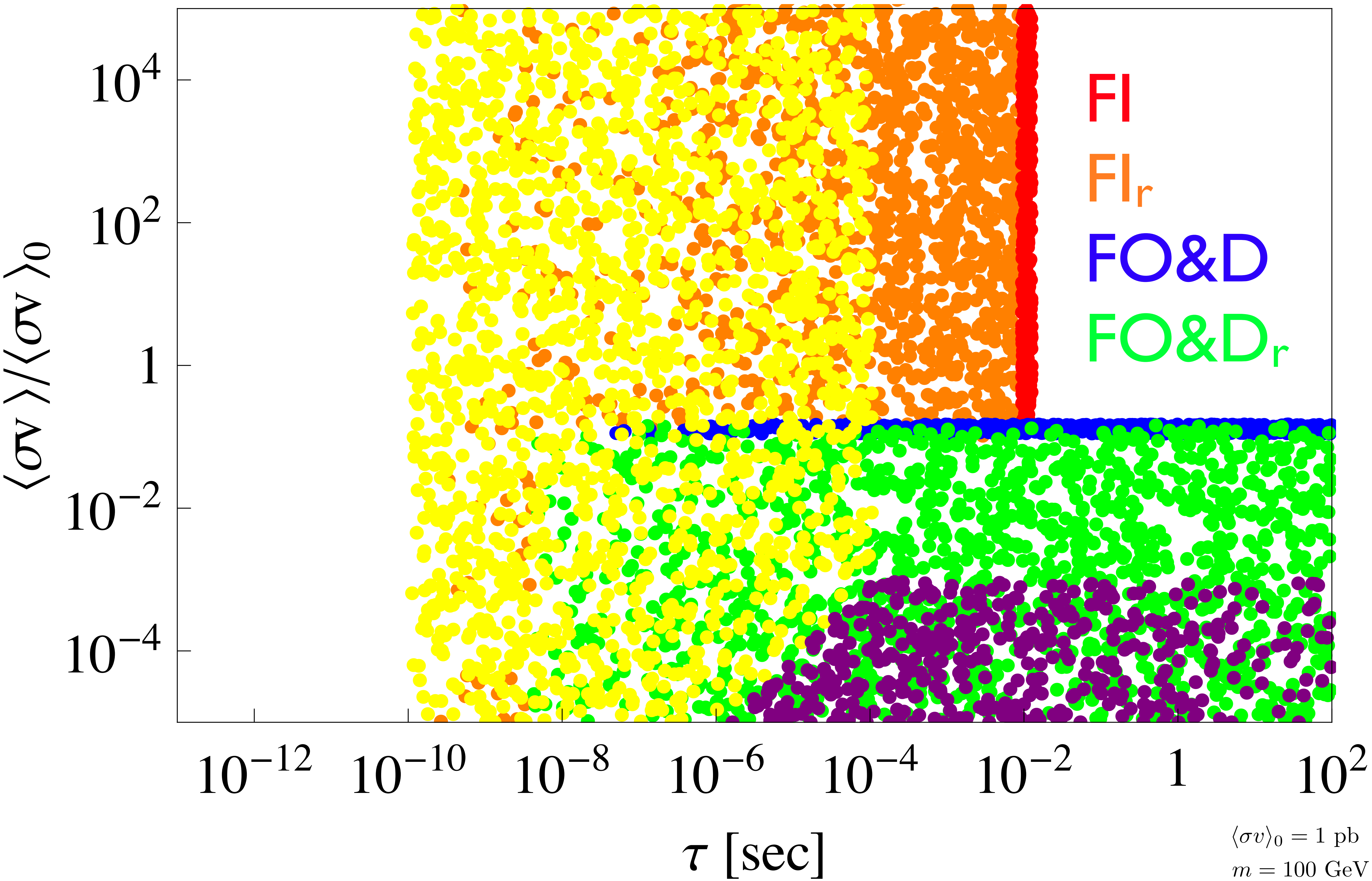
What are there phenomenological signals for these cosmological scenarios?

- Direct detection is a lost cause.

- How about X decays at LHC?

$$X \to X' + \ldots$$

Hidden sectors imply long lifetimes.



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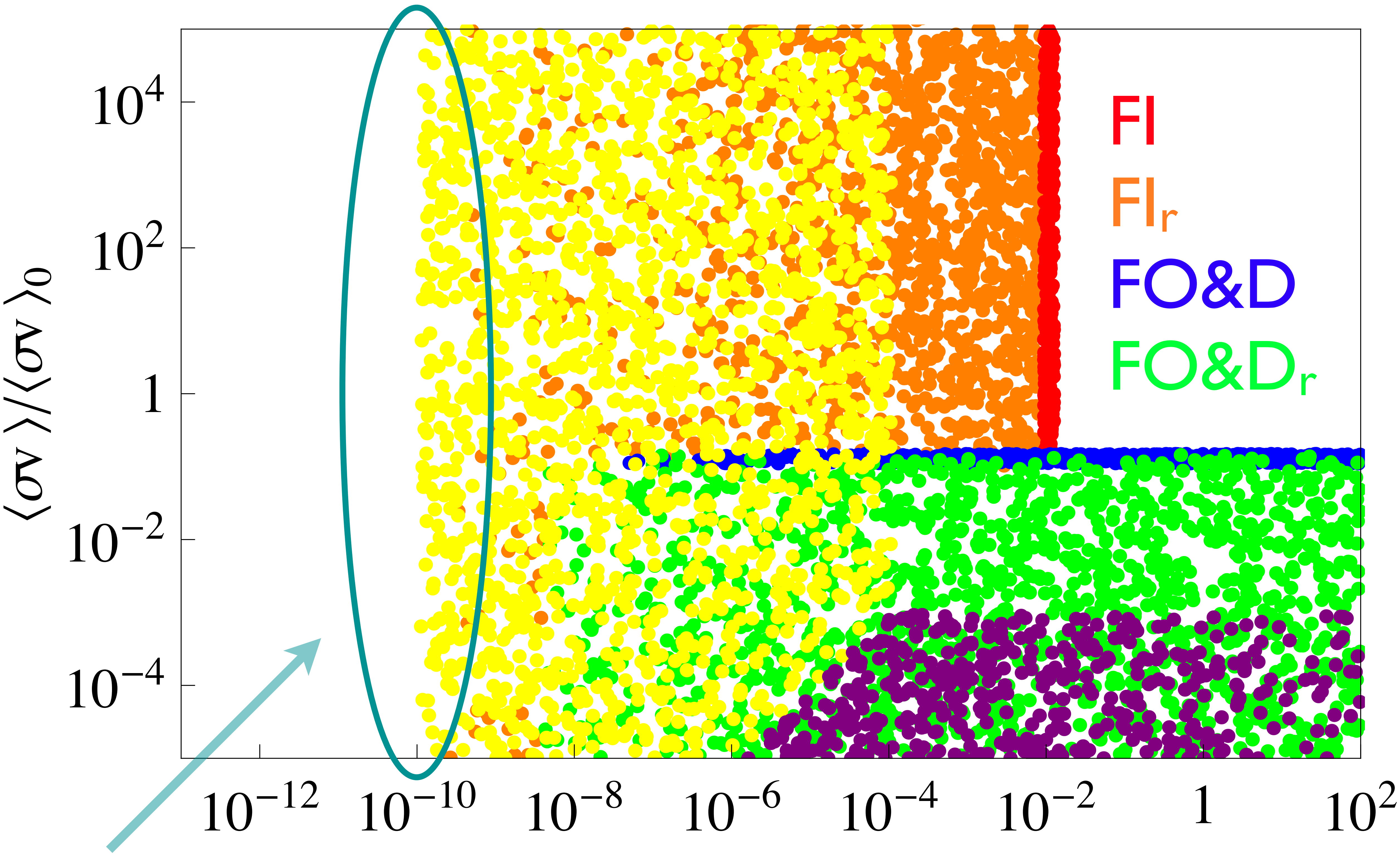


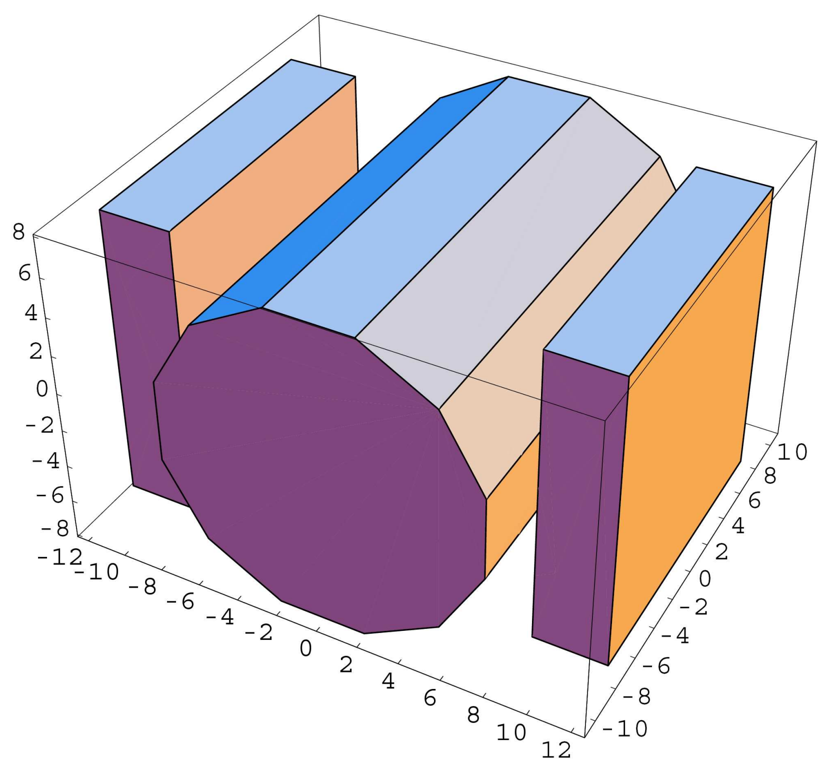
~ cm displaced vertex

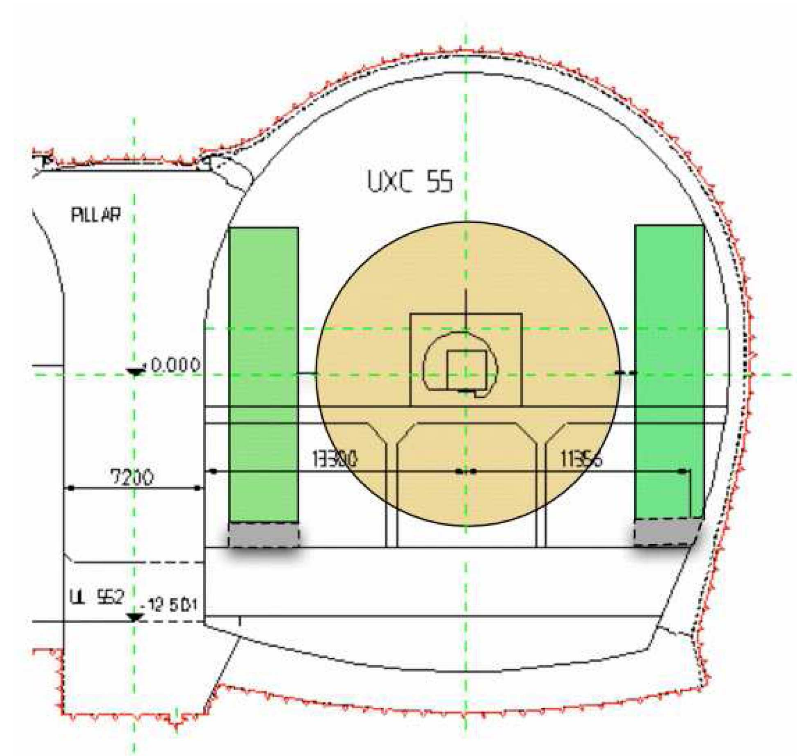
$\langle \sigma v \rangle_0 = 1$ pb
$m = 100$ GeV
$1/4 < m'/m < 1/3$

collider signals

long-lived CHAMPs

If X is charged or colored, it may be stopped!





hep-ph/0612060 (Hamuguchi, Nojiri, de Roeck)
hep-ph/0506246 (Arvanitaki, Dimopoulos, Pierce, Rajendran, Wacker)
hep-ph/0409278 (Feng, Smith)
hep-ph/0409248 (Hamaguchi, Kuno, Nakaya, Nojiri)

Search for Stopped Gluinos in pp collisions at $\sqrt{s} = 7$ TeV

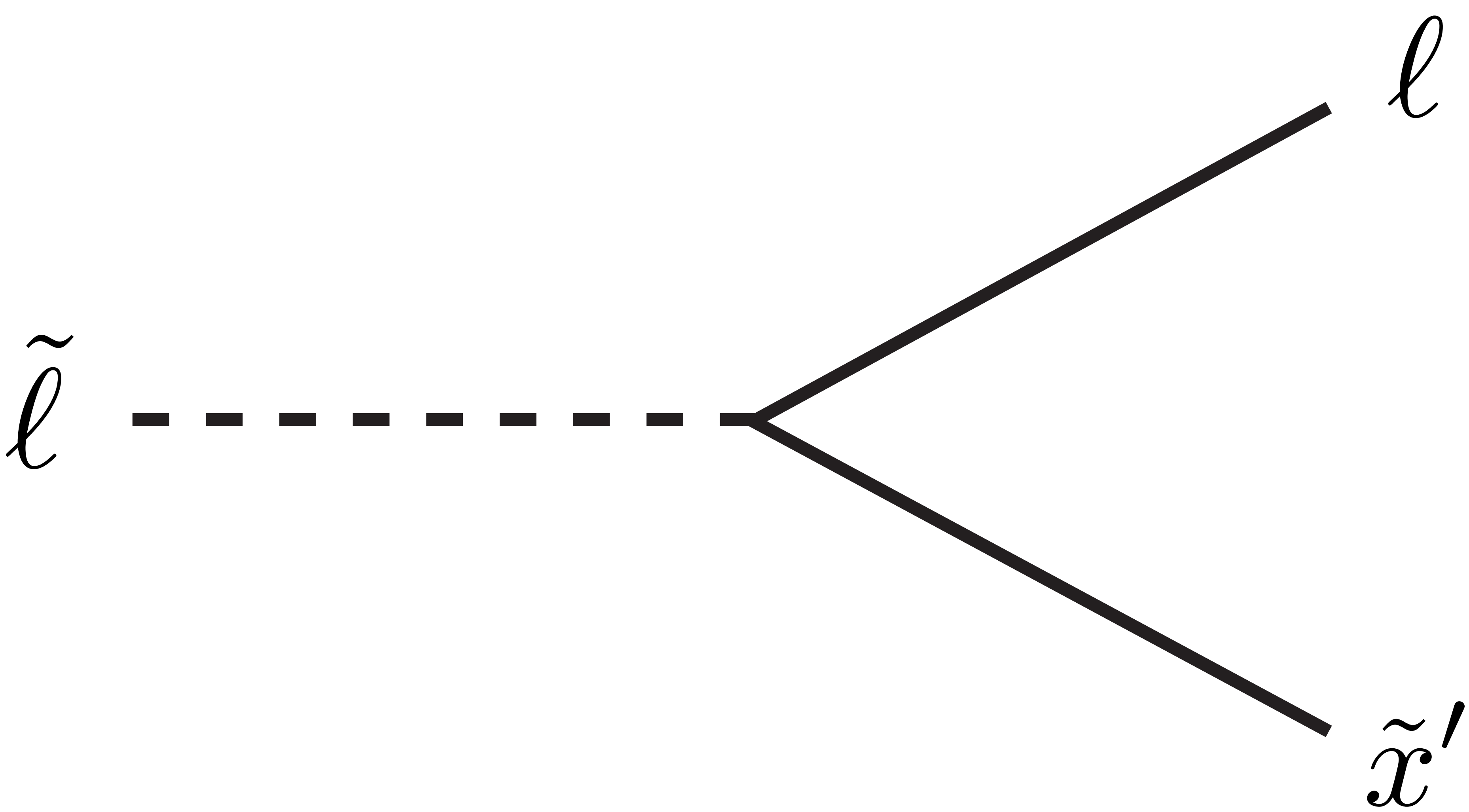
The CMS Collaboration*

Abstract

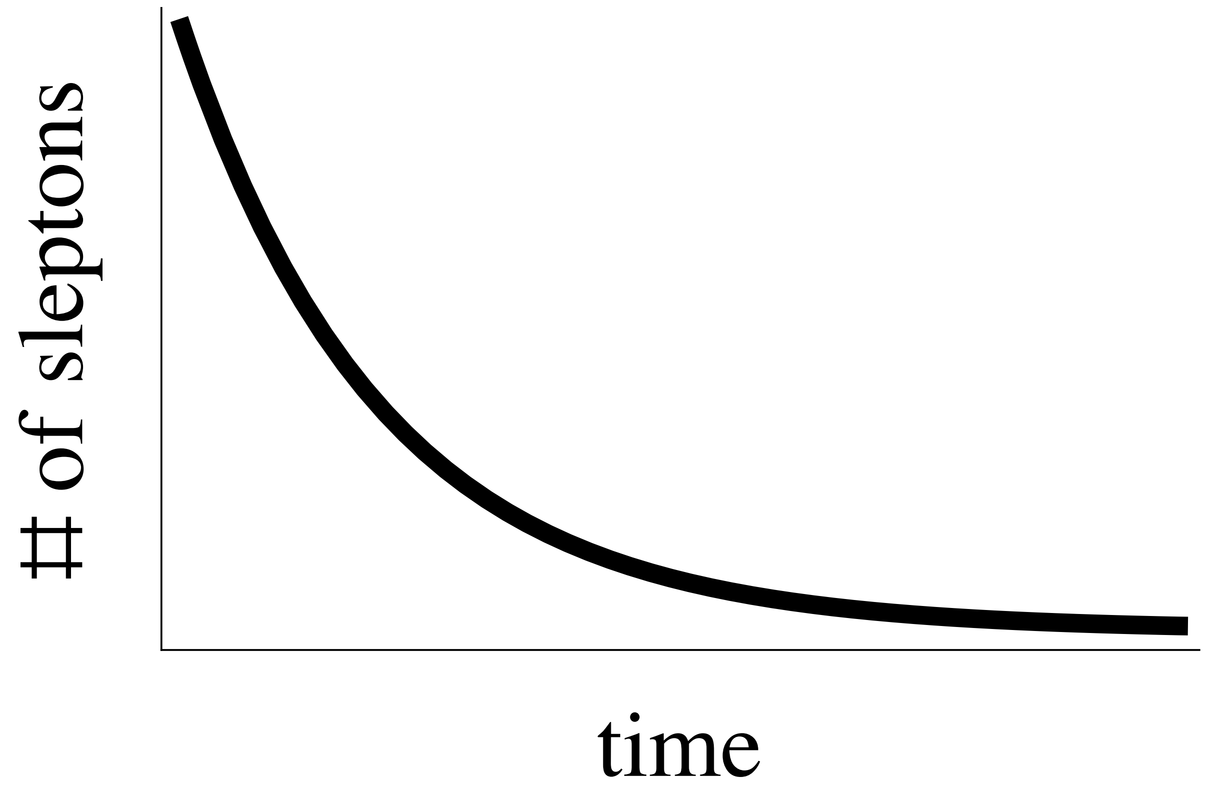
The results of the first search for long-lived gluinos produced in 7 TeV pp collisions at the CERN Large Hadron Collider are presented. The search looks for evidence of long-lived particles that stop in the CMS detector and decay in the quiescent periods between beam crossings. In a dataset with a peak instantaneous luminosity of 1×10^{32} cm^{-2}s^{-1}, an integrated luminosity of 10 pb^{-1}, and a search interval corresponding to 62 hours of LHC operation, no significant excess above background was observed. Limits at the 95% confidence level on gluino pair production over 13 orders of magnitude of gluino lifetime are set. For a mass difference $m_{\tilde{g}} - m_{\tilde{\chi}_1^0} > 100\ \mathrm{GeV}/c^2$, and assuming BR($\tilde{g} \rightarrow g\tilde{\chi}_1^0$) = 100%, $m_{\tilde{g}} < 370\ \mathrm{GeV}/c^2$ are excluded for lifetimes from 10 μs to 1000 s.

an example

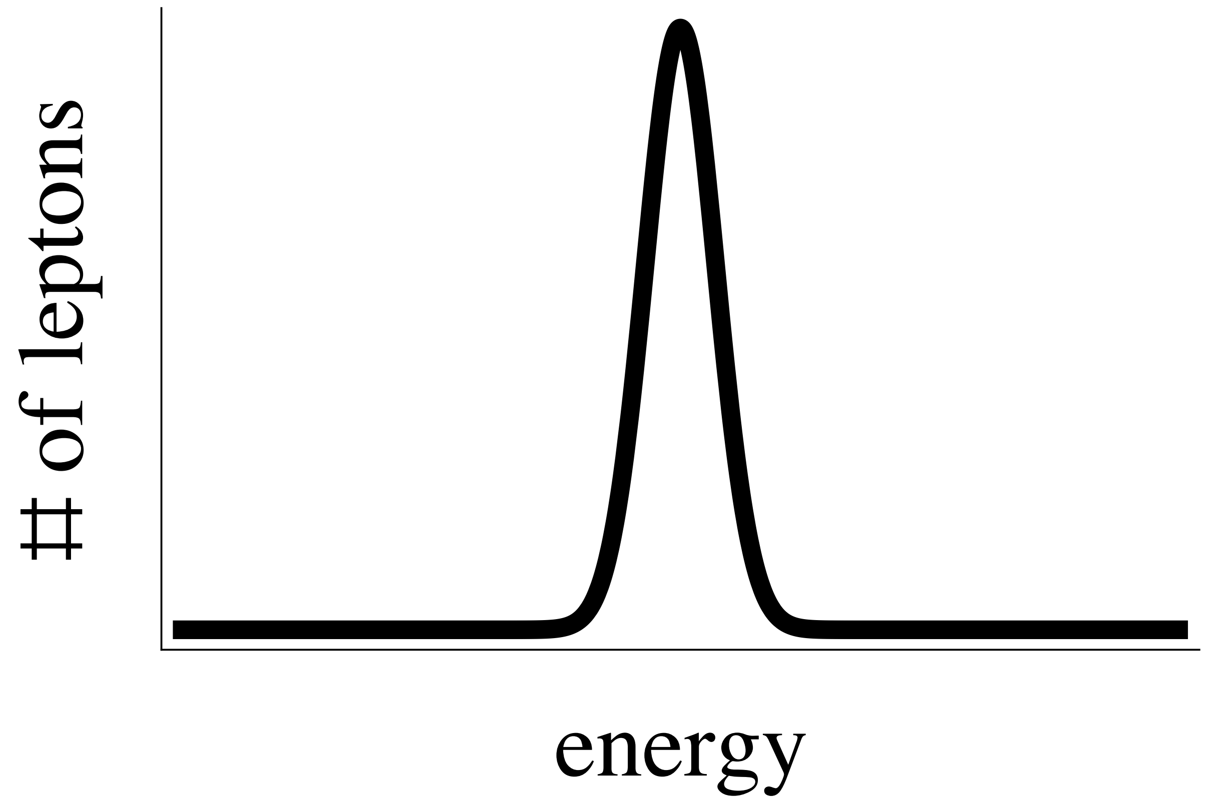
Consider the example $\mathcal{O} = [L^\dagger L X']_D$.



lifetime (τ) measurement



mass (m') measurement



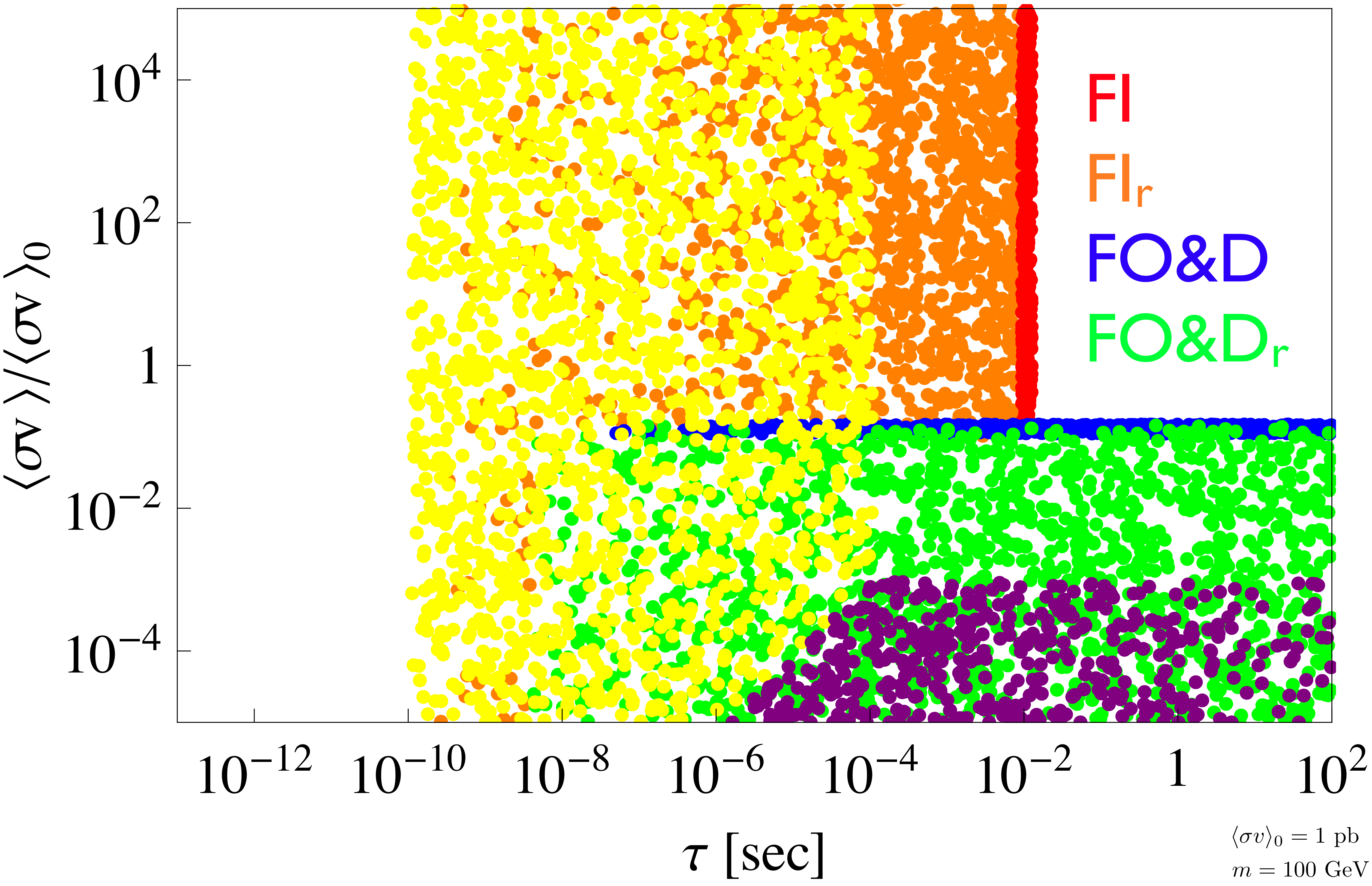
By ascertaining the lifetime of extremely long-lived CHAMPs we can extend LHC reach.

τ = 1 sec $\qquad \mathcal{O}/m_{\mathrm{GUT}}$

τ = 3 hrs $\qquad \mathcal{O}/m_{\mathrm{Pl}}$

LHC can probe the GUT scale!

We can verify the origin of dark matter!

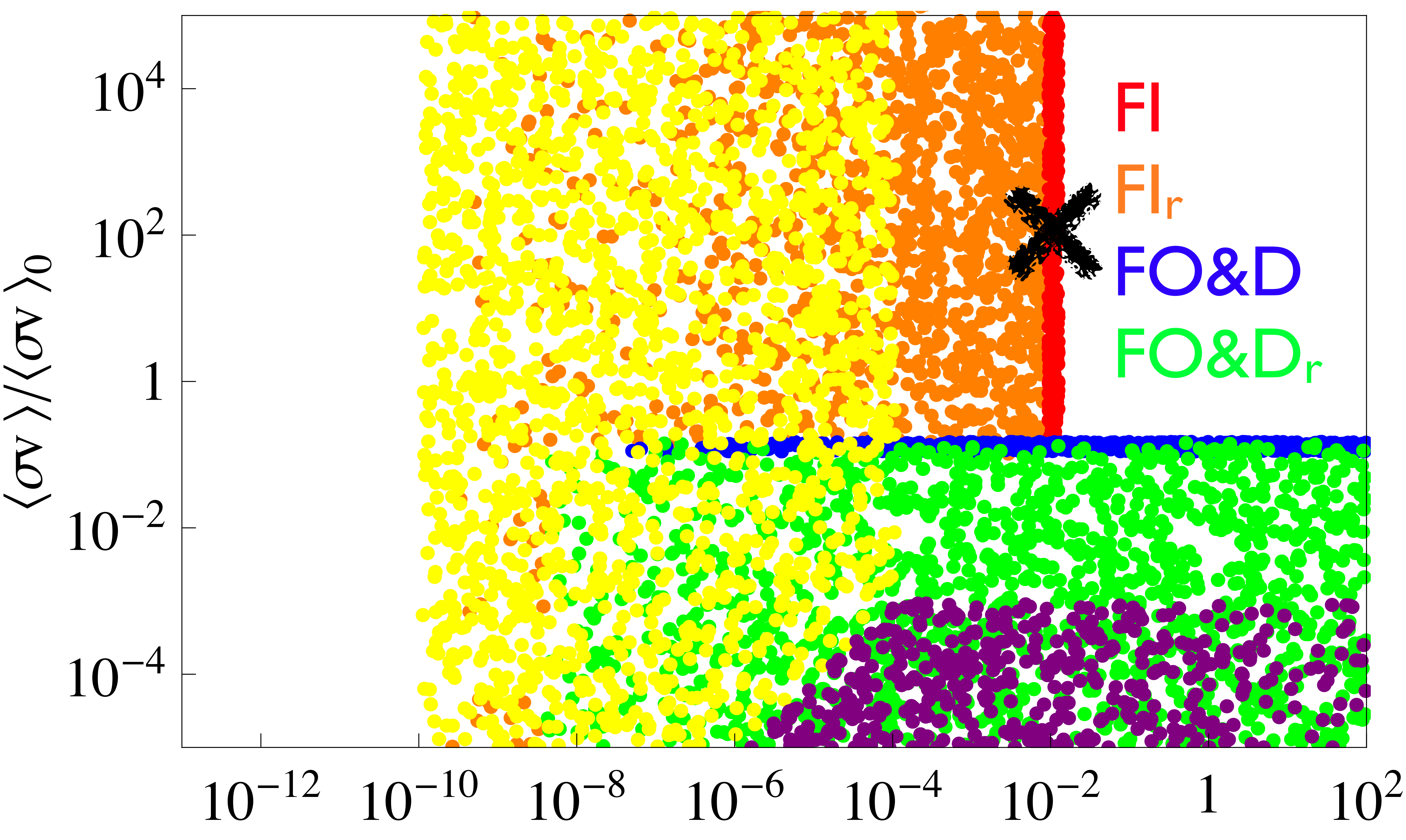


$\langle \sigma v \rangle_0 = 1$ pb

$m = 100$ GeV

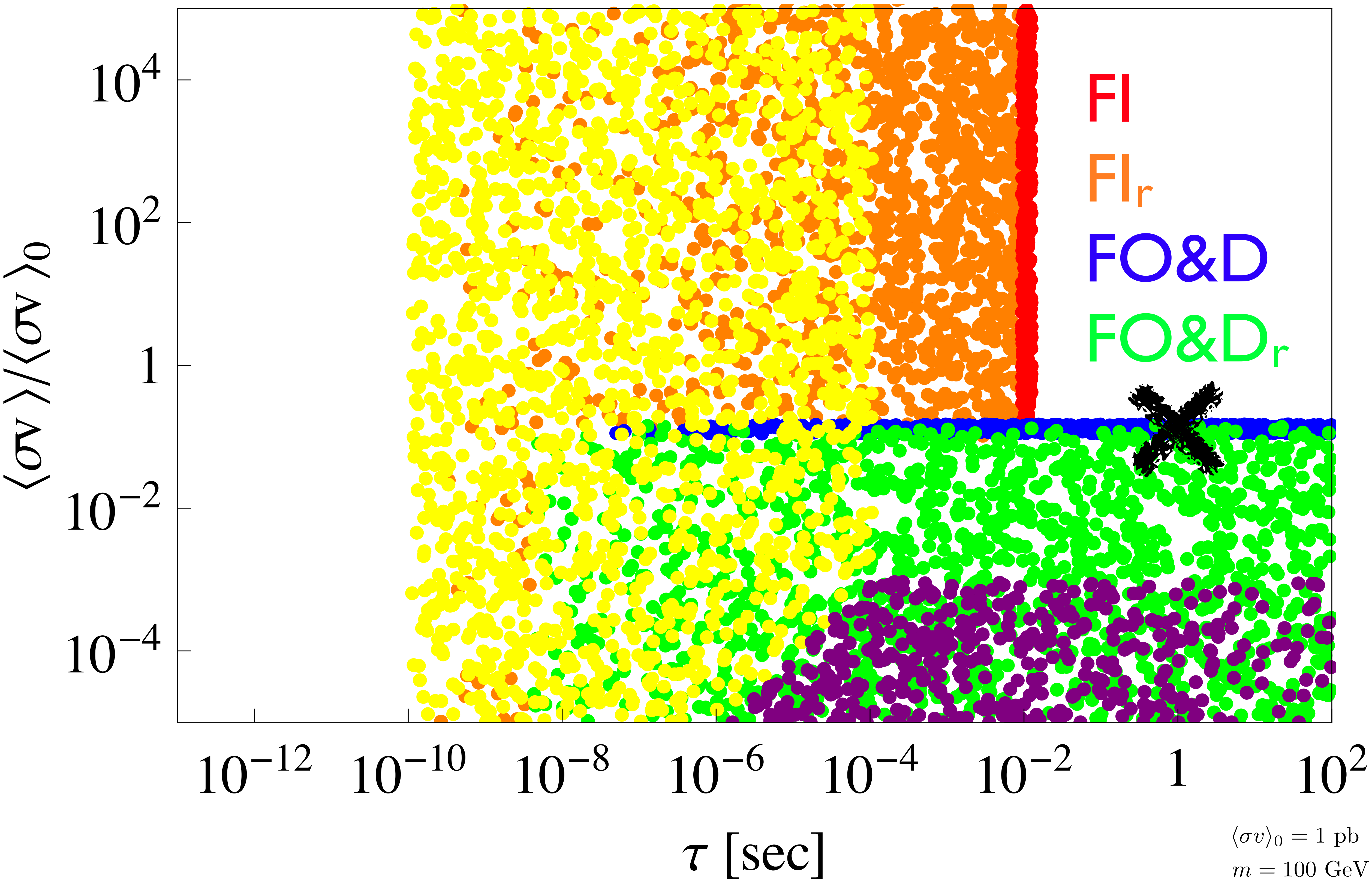
$1/4 < m'/m < 1/3$

Dark matter from freeze-in.



$\langle\sigma v\rangle_0 = 1$ pb
$m = 100$ GeV
$1/4 < m'/m < 1/3$

Dark matter from freeze-out and decay.



$\langle \sigma v \rangle_0 = 1$ pb

$m = 100$ GeV

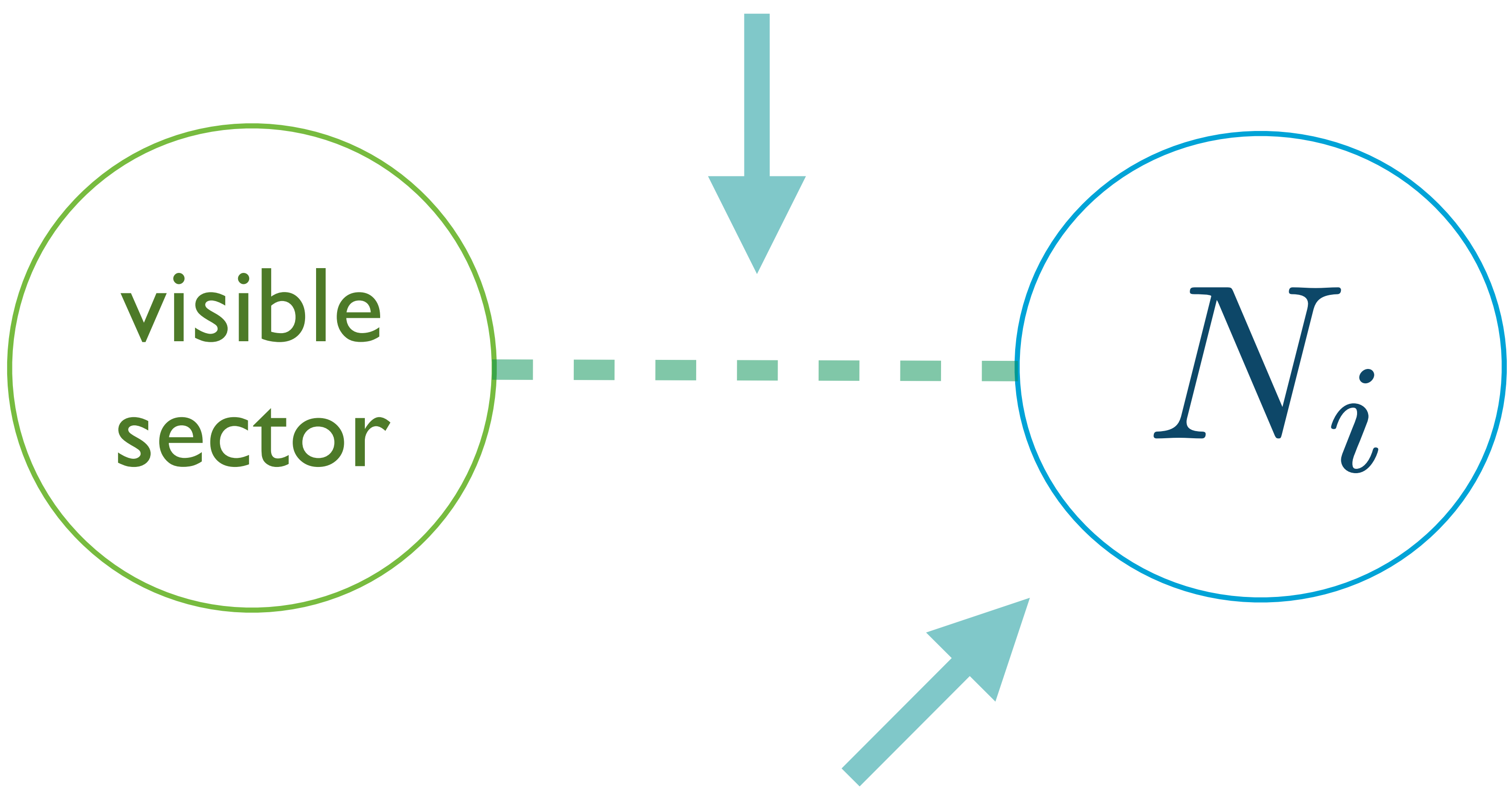
$1/4 < m'/m < 1/3$

Now, onwards to a well-known example...

...neutrinos!

The see-saw is a hidden sector “in disguise”.

$$\lambda_{ij}[L_i N_j H_u]_F$$



$$[M_i N_i N_i]_F$$

neutrino see-saw

Integrating out the sterile neutrinos yields the active neutrino masses :

$$m_{ij} = v_u^2 \left(\lambda M^{-1} \lambda^T\right)_{ij}$$

probed experimentally to be $m_{ij} \lesssim 0.1$ eV.

Since m_{ij} is constrained, M_i and λ_{ij} are related.
The neutrino see-saw can be :

high-scale **or** low-scale

$$M_i \sim 10^{14}\ \mathrm{GeV} \qquad M_i \sim 100\ \mathrm{GeV}$$

$$\lambda_{ij} \sim 1 \qquad \lambda_{ij} \sim 10^{-6}$$

Since m_{ij} is constrained, M_i and λ_{ij} are related.
The neutrino see-saw can be :

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$$\lambda_{ij} \sim 1 \qquad\qquad \lambda_{ij} \sim 10^{-6}$$

Small Yukawas are okay by me! (e.g. electron)

In the low-scale supersymmetric see-saw,

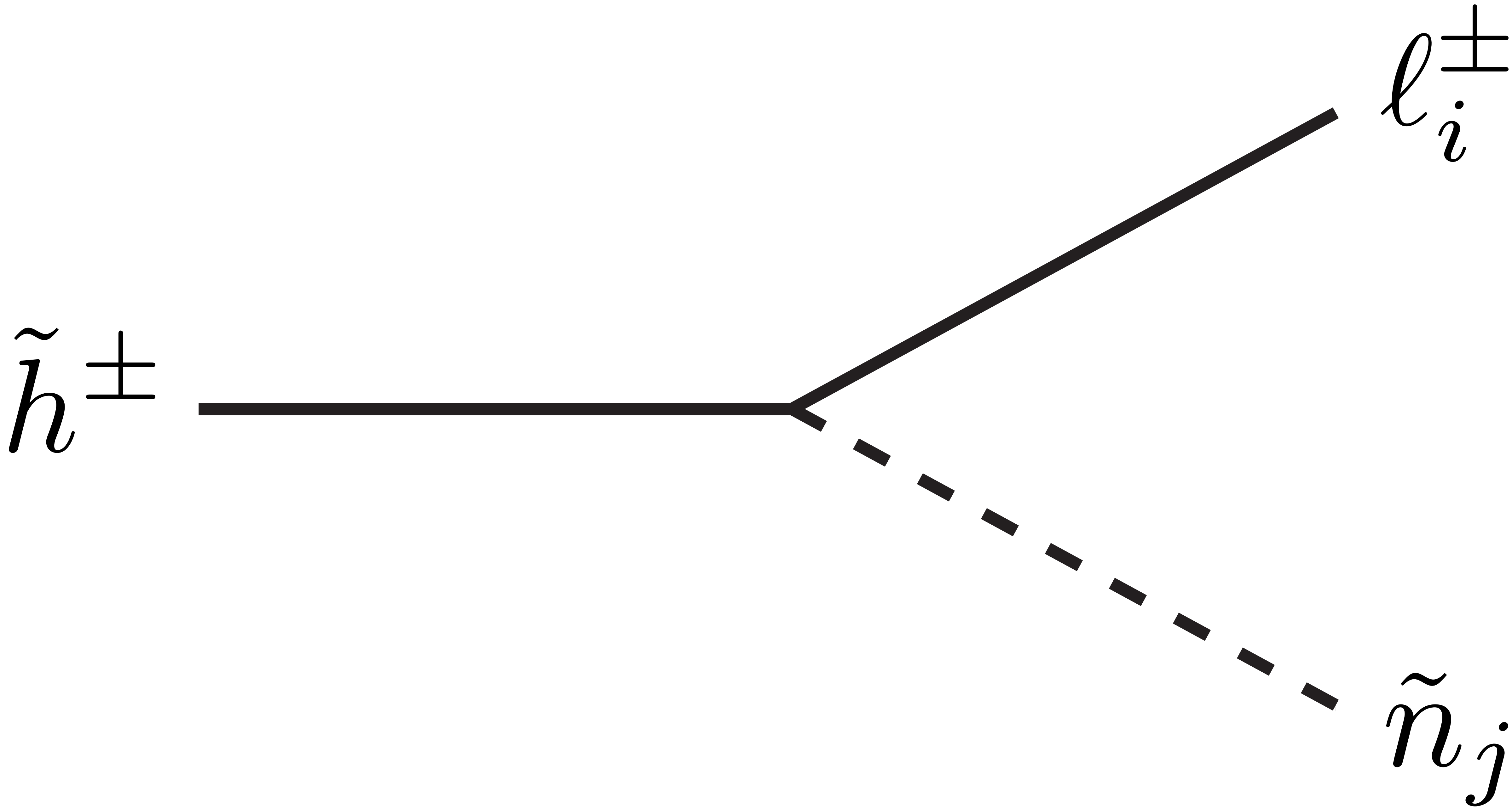
$$\lambda_{ij} \sim 10^{-6}$$

and sectors are very weakly coupled.

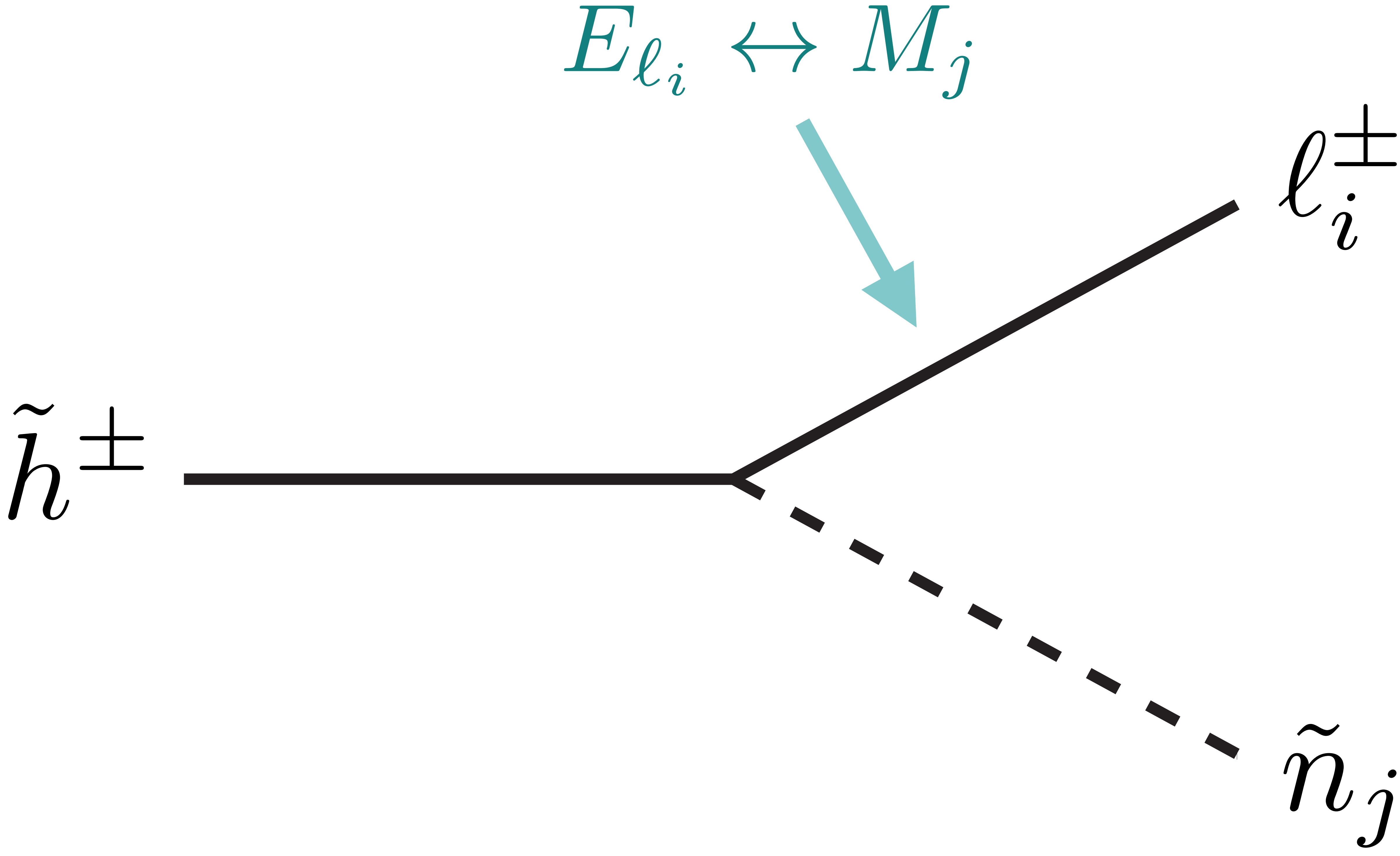
Claim : despite the tiny coupling, we can probe the see-saw directly at colliders!

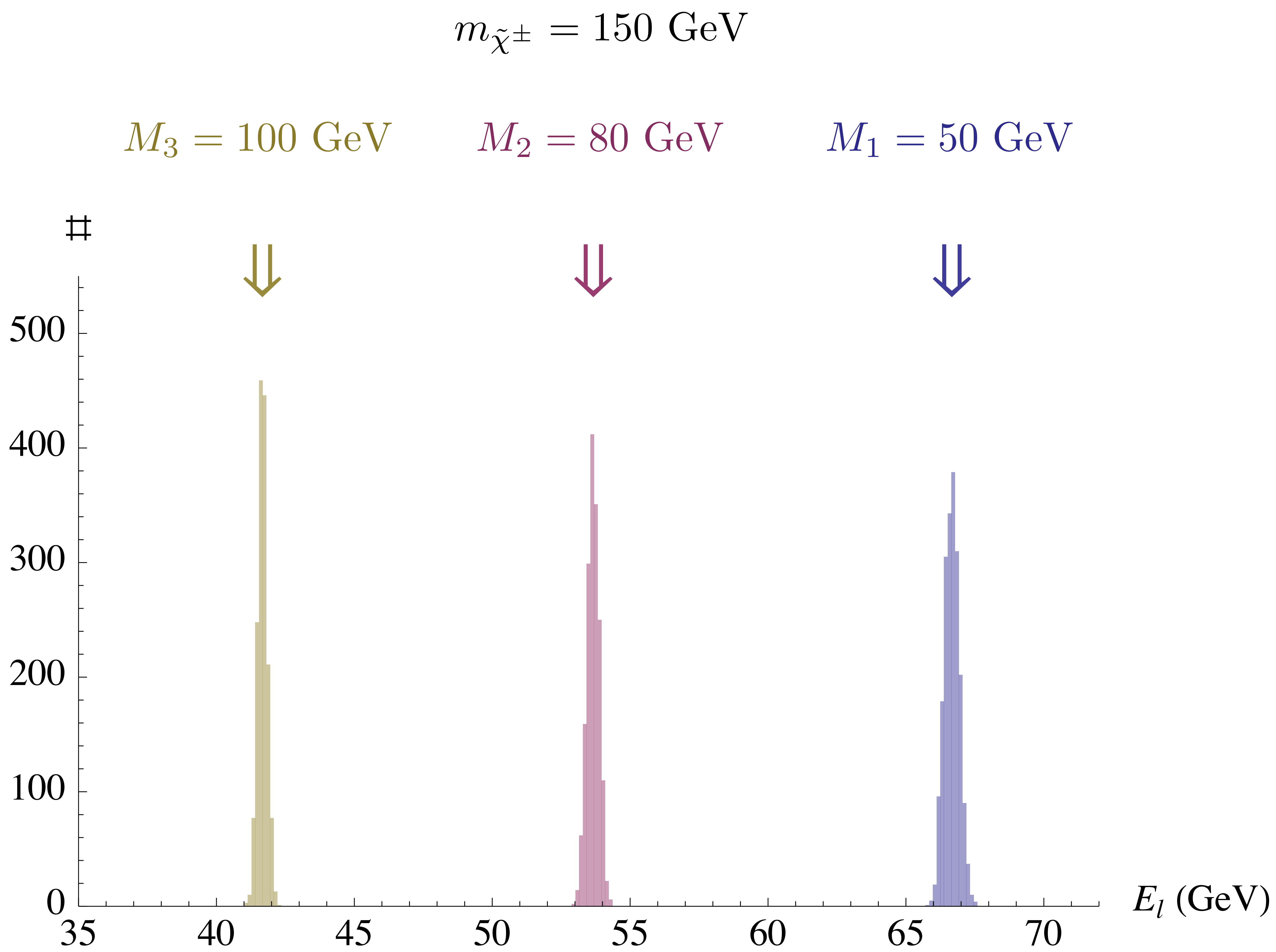
See-saw can be verified at LHC if :

- LSP = sterile sneutrino
- NLSP = charged
- degenerate masses, $M_i \approx \tilde{M}_i$

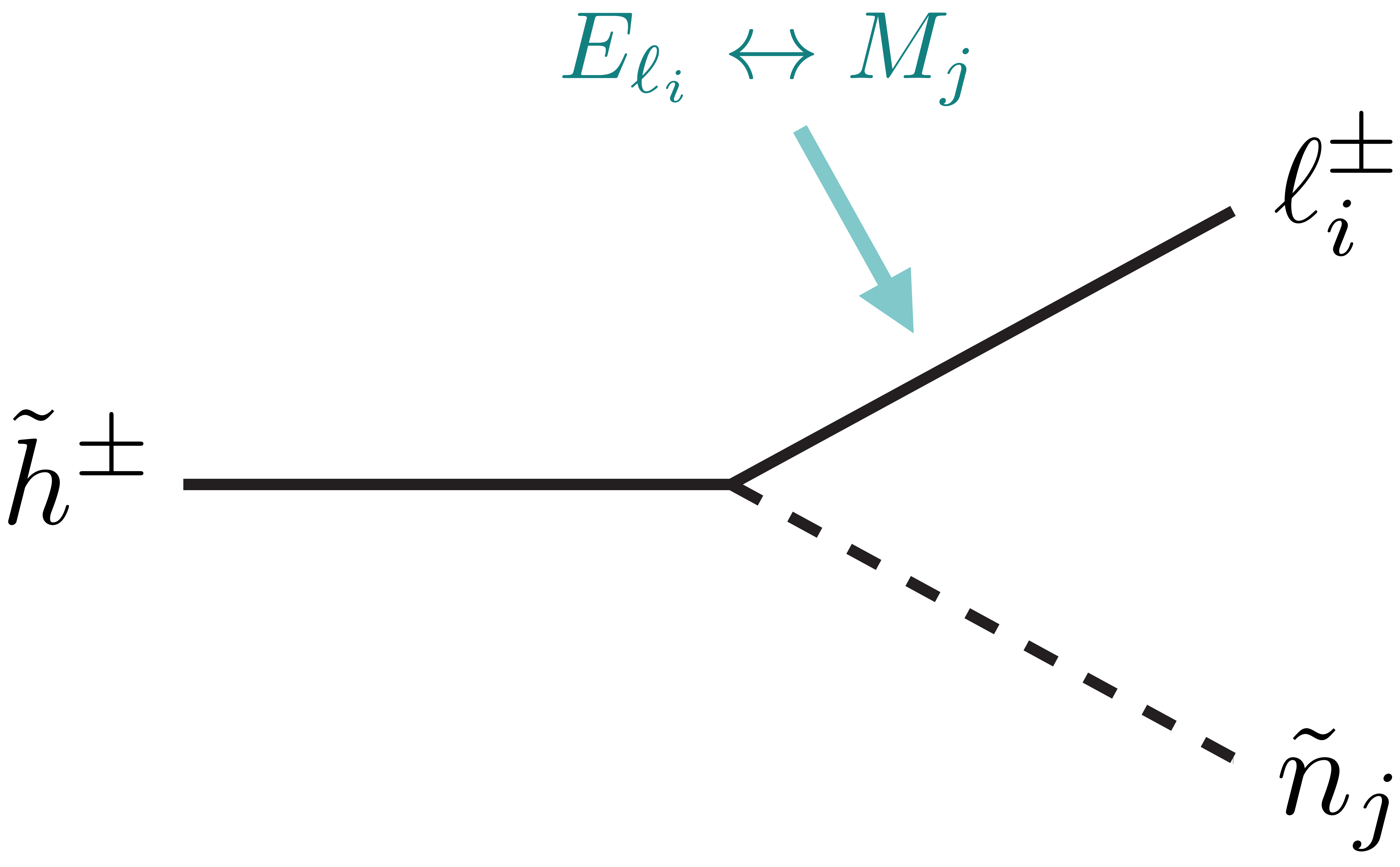


$\tilde{h}^{\pm}$
$\ell_i^{\pm}$
$\tilde{n}_j$

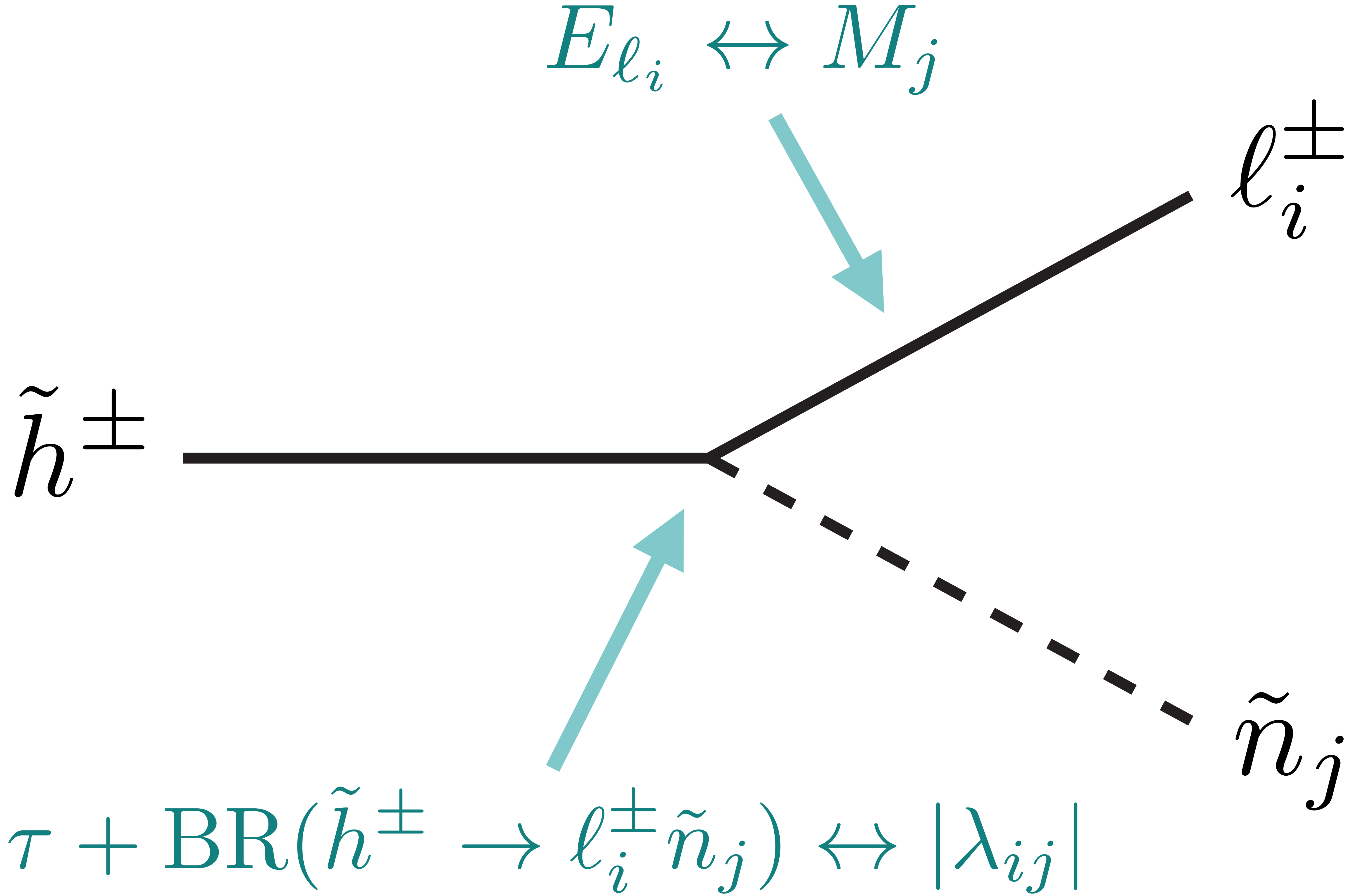

$E_{\ell_i} \leftrightarrow M_j$
$\ell_i^\pm$
$\tilde{h}^\pm$
$\tilde{n}_j$



$m_{\tilde{\chi}^{\pm}} = 150$ GeV
$M_3 = 100$ GeV
$M_2 = 80$ GeV
$M_1 = 50$ GeV
#
500
400
300
200
100
0
35
40
45
50
55
60
65
70
E_l (GeV)



$E_{\ell_i} \leftrightarrow M_j$
$\tilde{h}^{\pm}$
$\ell_i^{\pm}$
$\tilde{n}_j$



$E_{\ell_i} \leftrightarrow M_j$
$\ell_i^\pm$
$\tilde{h}^\pm$
$\tilde{n}_j$
$\tau + \mathrm{BR}(\tilde{h}^\pm \to \ell_i^\pm \tilde{n}_j) \leftrightarrow |\lambda_{ij}|$

See-saw spectroscopy at the LHC!

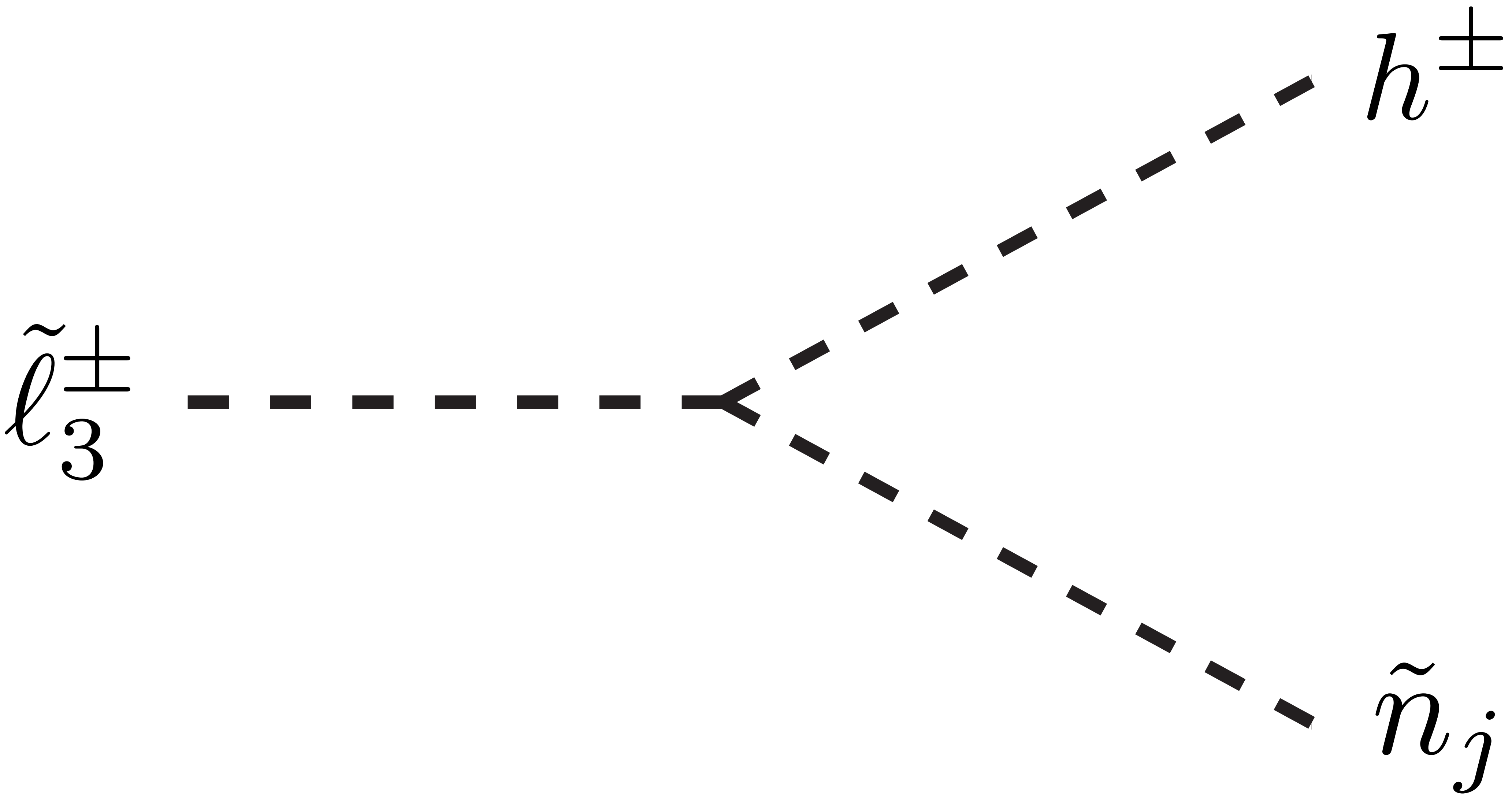
$$M_j + |\lambda_{ij}| =$$

order of mag. verification?

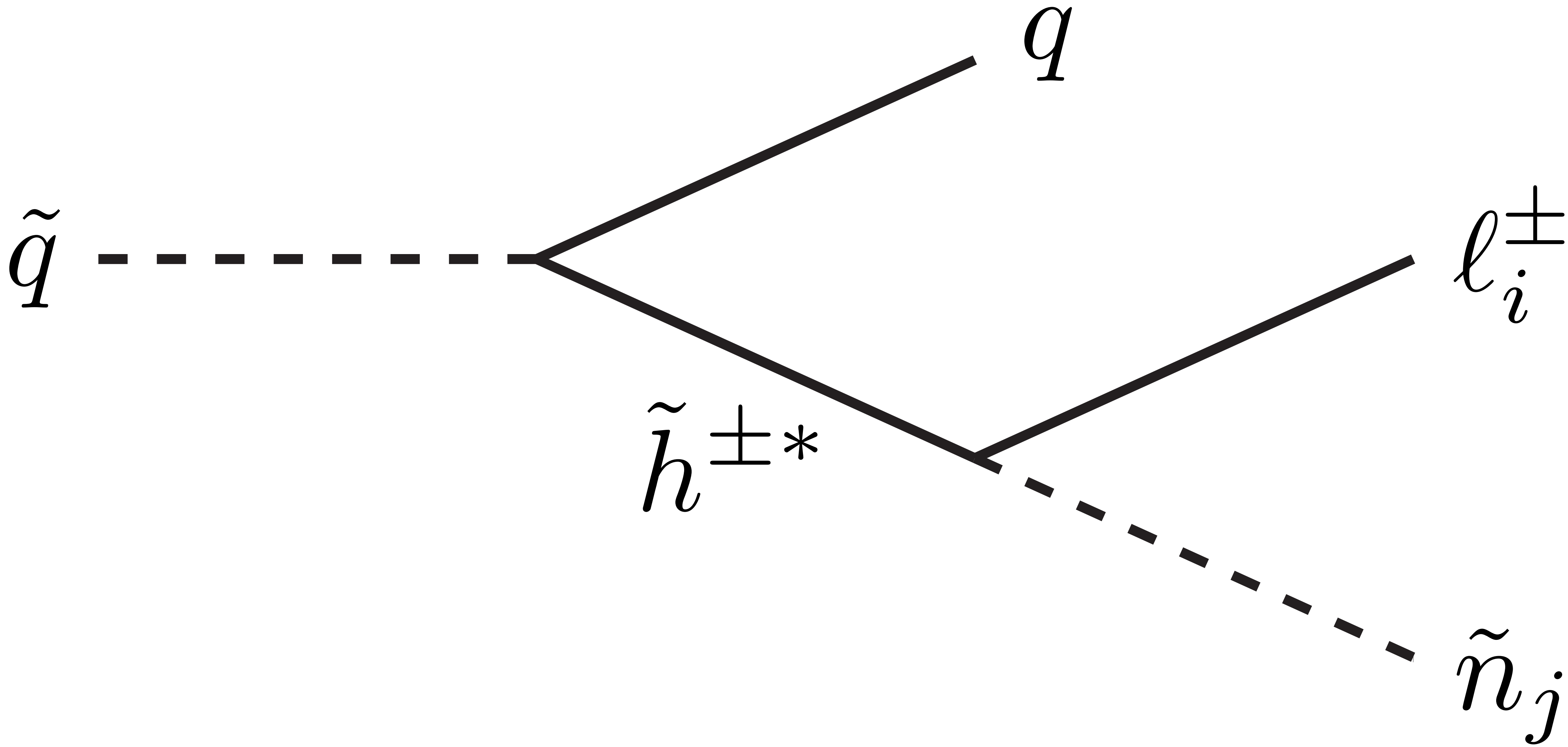
large mixing angles?

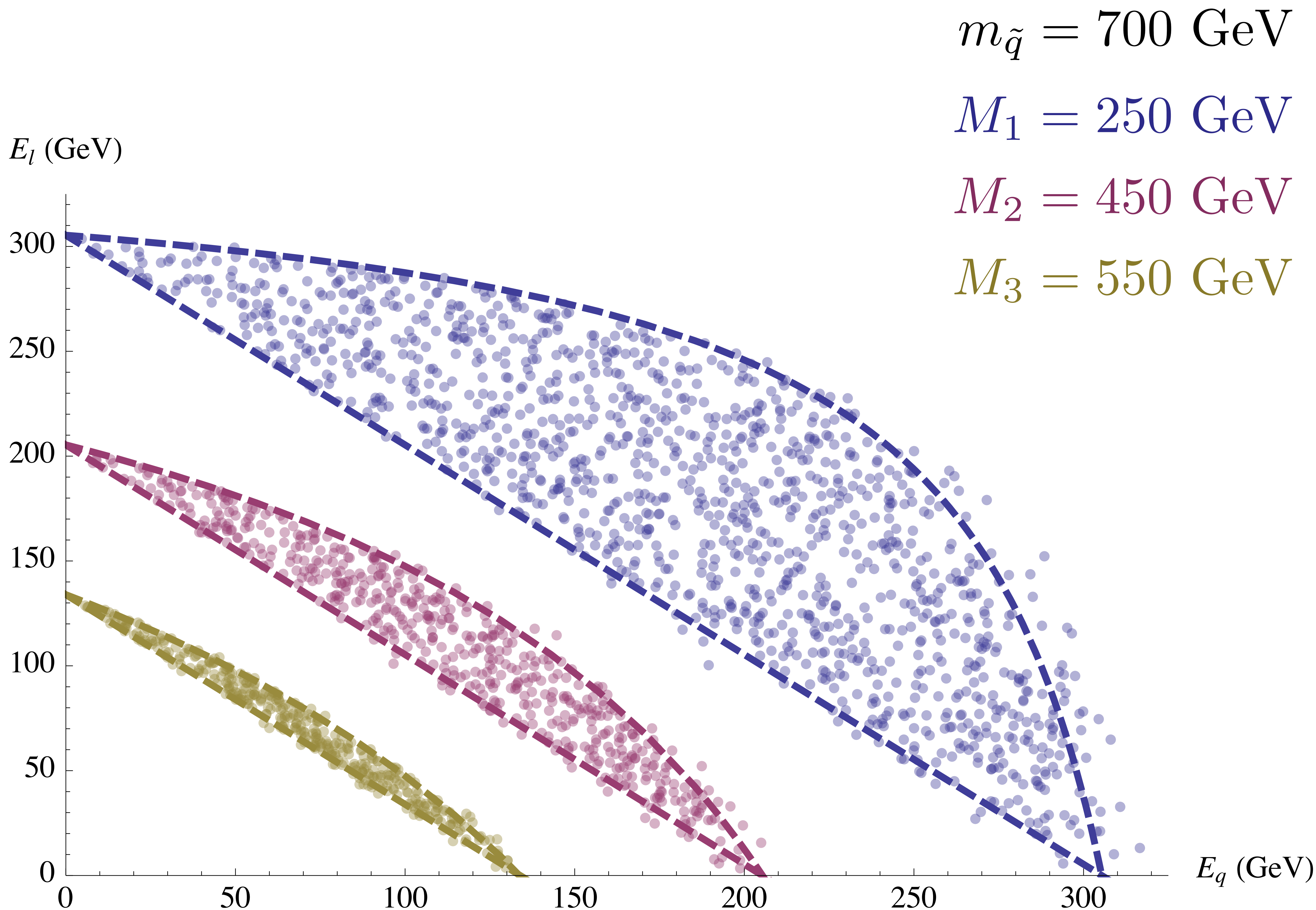
inverted hierarchy?

NLSP = stau $\longleftrightarrow$ measure λ_{3j} and M_i only



NLSP = squark ⟷ measure λ_{ij} and M_i





$m_{\tilde{q}} = 700$ GeV
$M_1 = 250$ GeV
$M_2 = 450$ GeV
$M_3 = 550$ GeV
E_l (GeV)
E_q (GeV)
0
50
100
150
200
250
300

conclusions

- There exists a rich array of alternatives to the WIMP paradigm of dark matter genesis.

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- CHAMPS offer a unique opportunity for probing high-scale / weakly coupled physics.

- We may be able to reconstruct the origin of dark matter at colliders!

thanks!

Boltzmann equations

Cosmological history is determined by

$$\frac{dn}{dt} + 3Hn = -(n^2 - n_{\rm eq}^2)\langle\sigma v\rangle - \Gamma(n - n_{\rm eq})$$

$$\frac{dn'}{dt} + 3Hn' = -(n'^2 - n'^2_{\rm eq})\langle\sigma v\rangle' + \Gamma(n' - n'_{\rm eq})$$

where $n^{(')}$ is the number density of $X^{(')}$.

sector equilibration

Since FI produces $\Delta\rho = Y'_{FI} T^4 = T'^4$ energy in the hidden sector, this yields a temperature

$$\xi = (Y'_{\rm FI})^{1/4}$$

so demanding $\xi < 1$ bounds $\tau > \tau_{min}$.

sector equilibration

There is a minimum lifetime given by

$$\tau_{\min} \simeq 10^{-13}\ \mathrm{s} \ \left(\frac{100\ \mathrm{GeV}}{m}\right)^2 \left(\frac{100}{g'_*(T \simeq m)/g_X}\right)$$

at which the two sectors thermalize.

2 to 2 scattering

If $\mathcal{O}$ is a higher dimension operator then X' particles are produced via 2 to 2 scattering

$$Y'_{\rm scatt} \propto m_{\rm Pl} T_{\rm R} \langle \sigma v \rangle_{\rm scatt}$$

Y'_{scatt} can be neglected for low T_R or if there is substantial re-annihilation.