Dark Photons from the Early Universe to LHCb

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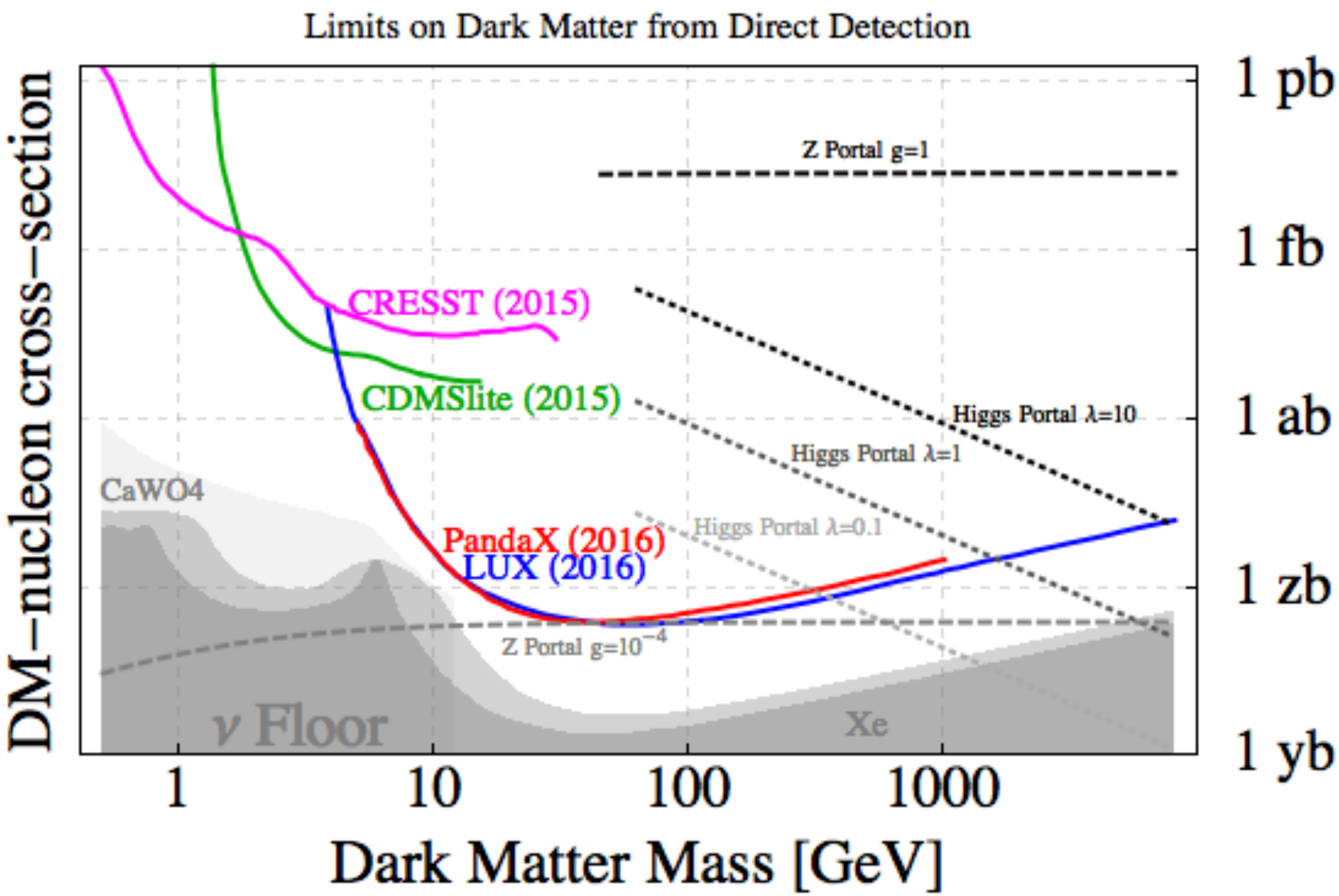
MIT

March 21, 2017
Winter Aspen

WIMP in Direct Detection



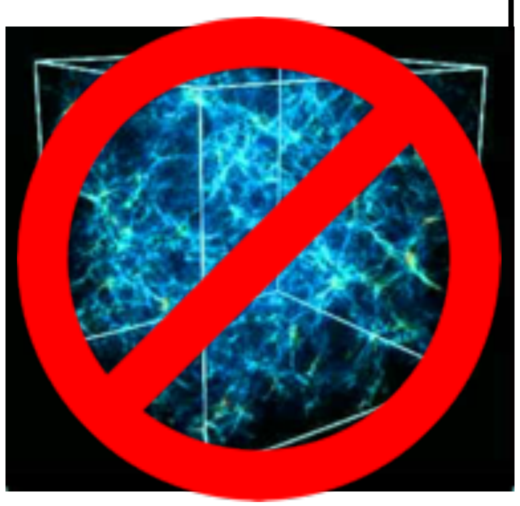
Thermal Dark Matter

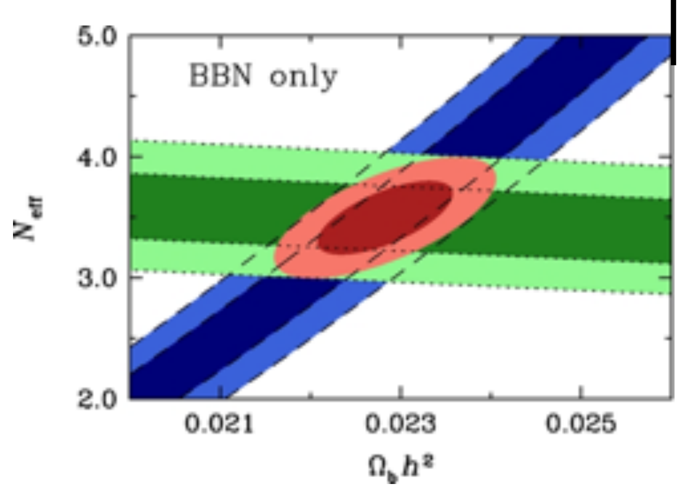
- Why thermal dark matter? initial condition

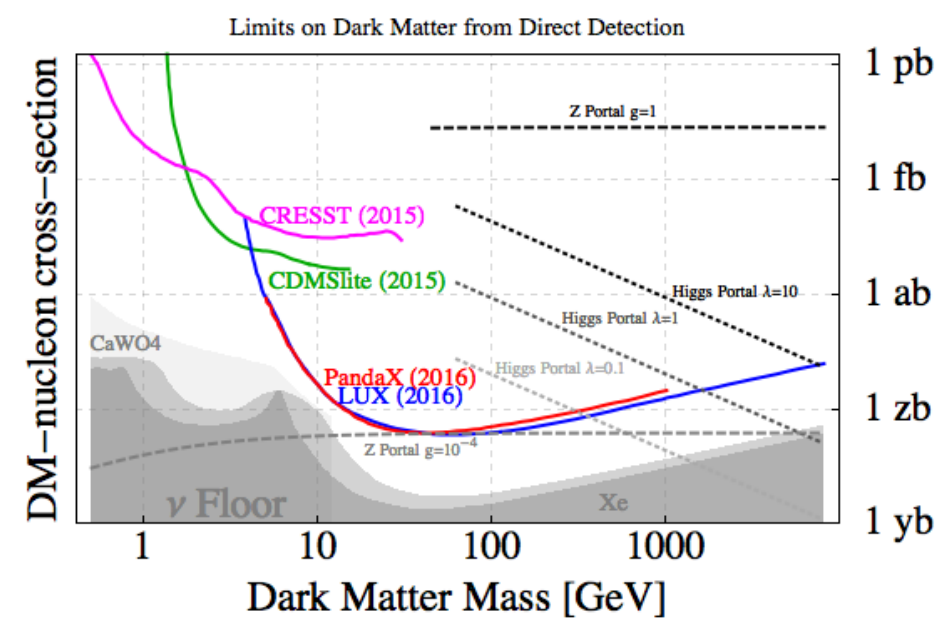
?

keV MeV GeV TeV

unitarity bound







Plan

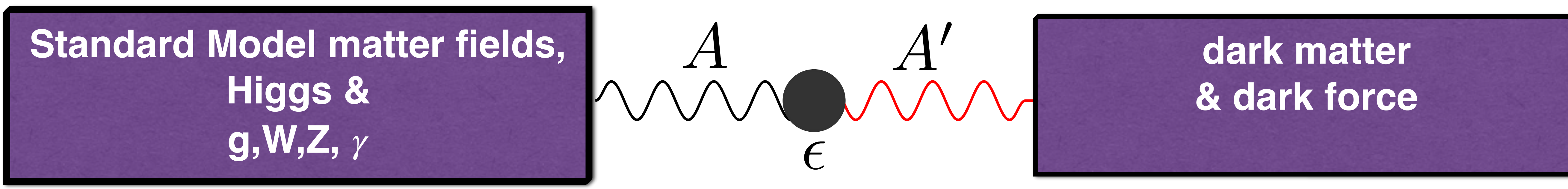
- MeV - GeV dark matter in the early universe
  - Not-Forbidden Dark Matter (NFDM)
    - dark photon + dark matter model

      *[J. Cline, H. Liu, T. Slatyer, **WX** arXiv : 1702.07716]*

- dark photons at LHCb
  - meson decay
    - *[P. Ilten, J. Thaler, M. Williams, **WX** arXiv : 1509.0676, PRD]*
  - inclusive di-muon
    - *[P. Ilten, Y. Soreq, J. Thaler, M. Williams, **WX** arXiv : 1603.08926, PRL]*
- conclusion

One of the Simplest Models
vector portal dark matter

- U(1)' dark photon can kinetically mix with photon



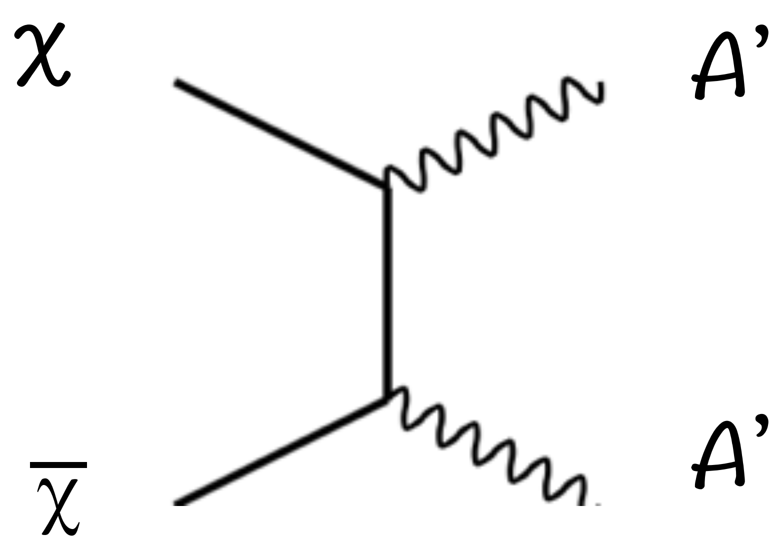
$$\frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

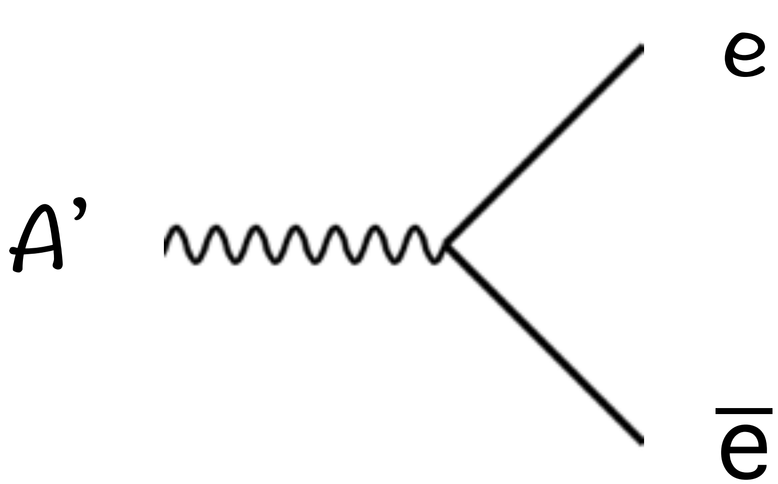
- effective Lagrangian (dark matter + dark photon)

$$\mathcal{L} = \bar{\chi}(i\not{D} - m_\chi)\chi + \frac{1}{2} m_{A'}^2 A'_\mu A'^\mu + e\epsilon A'_\mu J^\mu_{EM}$$

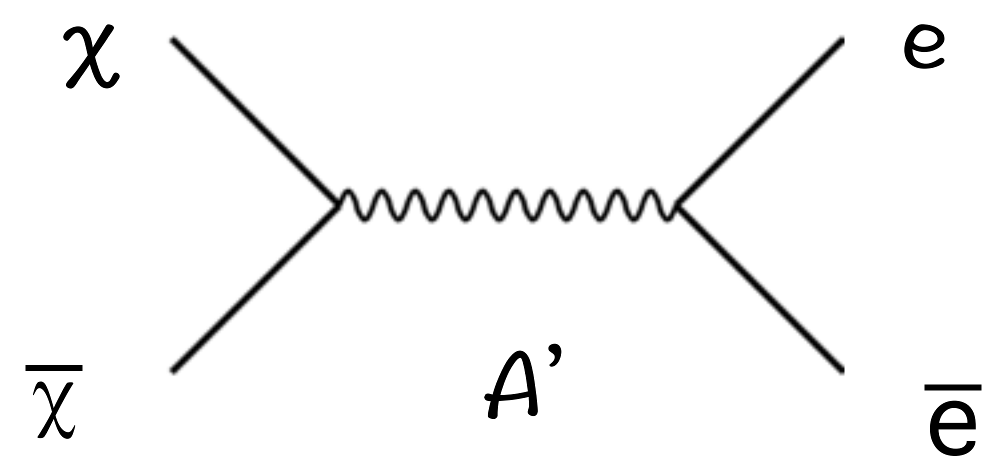
Vector Portal Dark Matter

$m_\chi > m_{A'}$



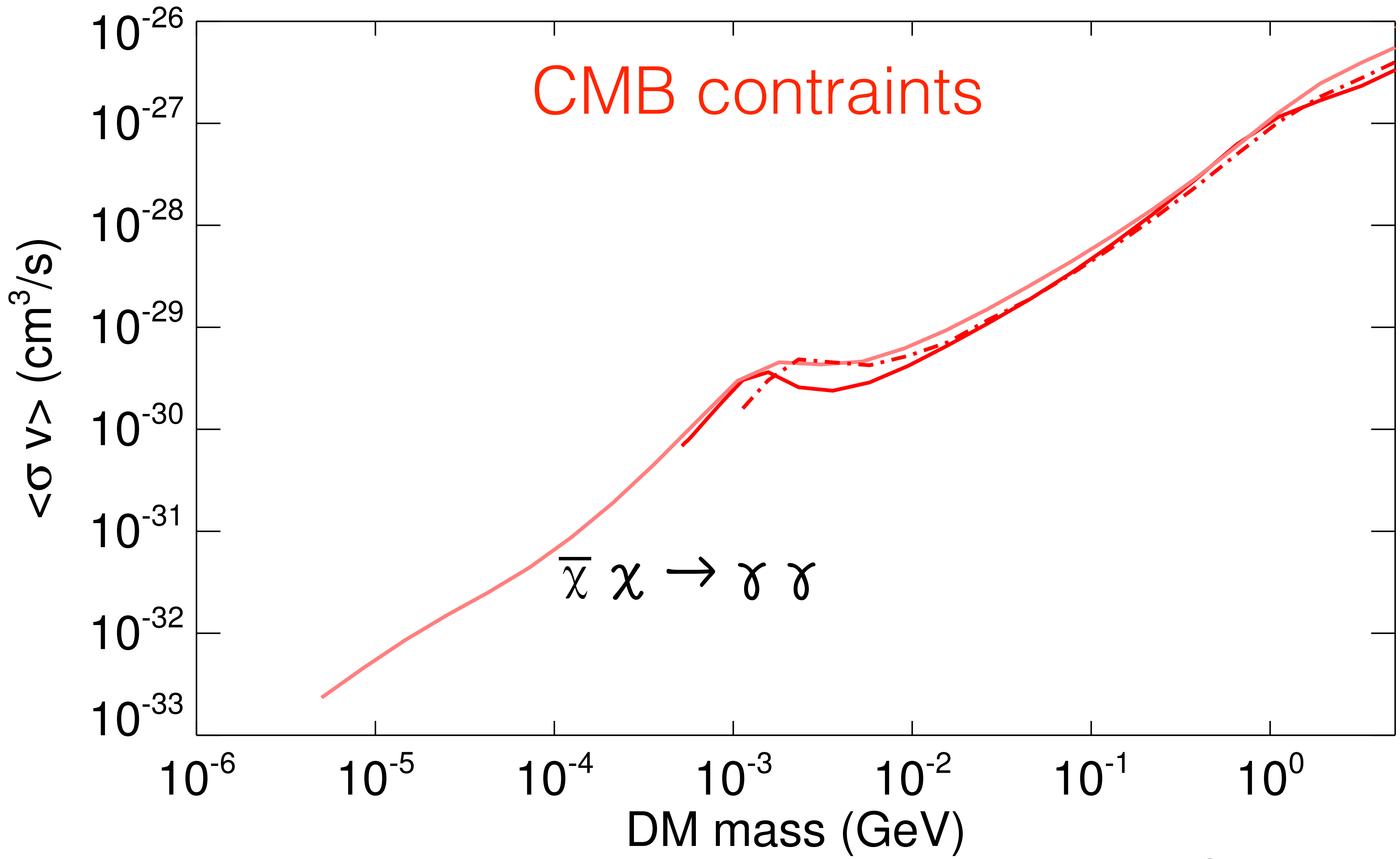


$m_\chi < m_{A'}$



Challenges for MeV-GeV Dark Matter

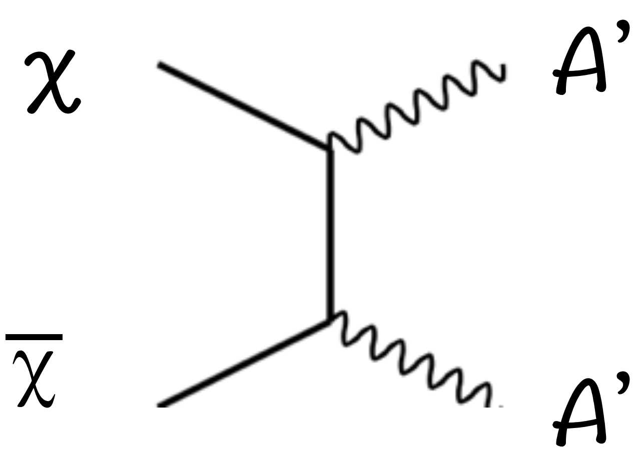
thermal cross section $\langle\sigma v\rangle \sim 3 \times 10^{-26}\ \mathrm{cm^3/s}$



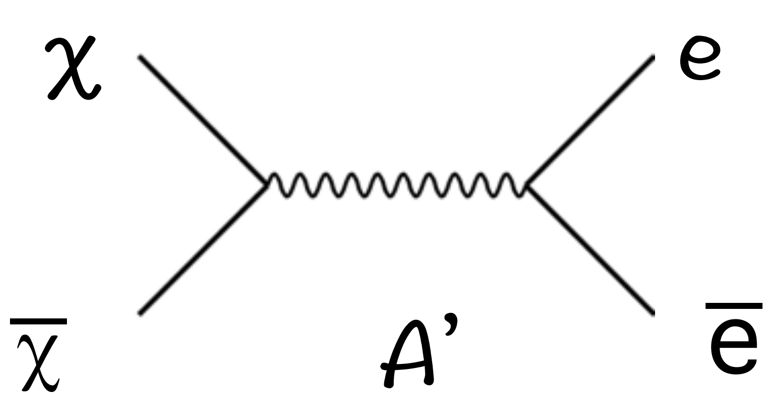
[T. Slatyer, 1506.03811]

Vector Portal Dark Matter

$m_\chi > m_{A'}$



$m_\chi < m_{A'}$

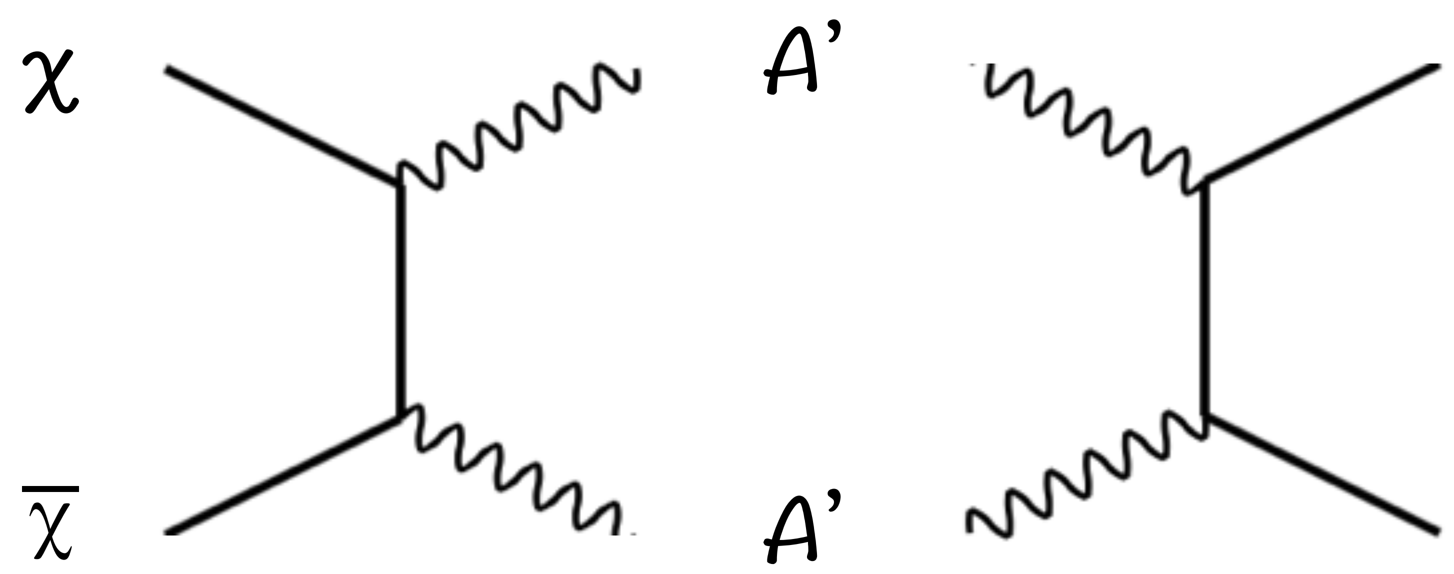


$m_\chi \sim m_{A'}$

Forbidden Dark Matter

$m_\chi \sim m_{A'}$ and $m_\chi < m_{A'}$

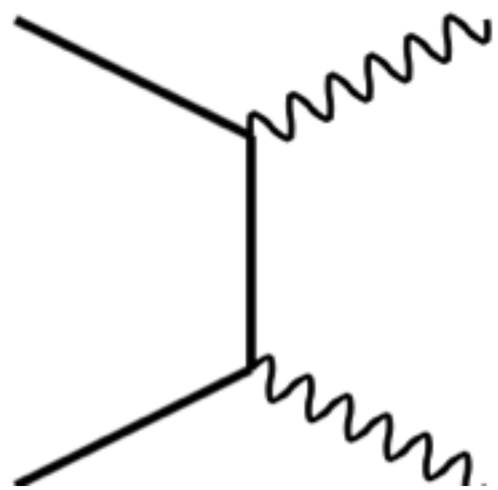
$2 \leftrightarrow 2$

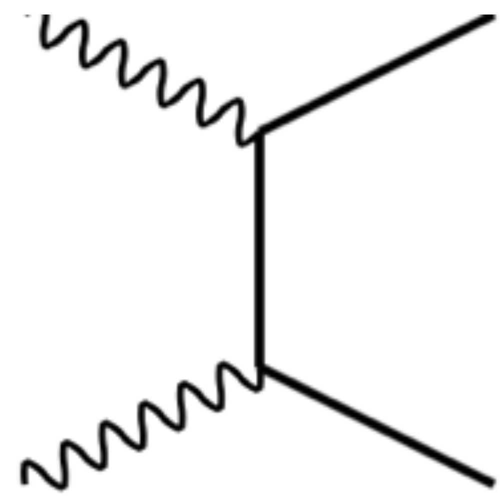


Not Forbidden Dark Matter

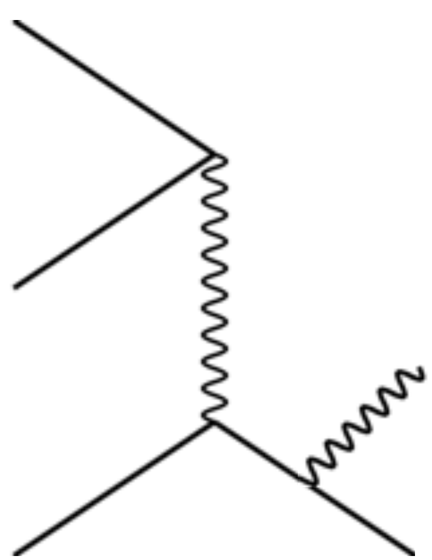
$m_\chi \sim m_{A'}$ and $m_\chi < m_{A'}$

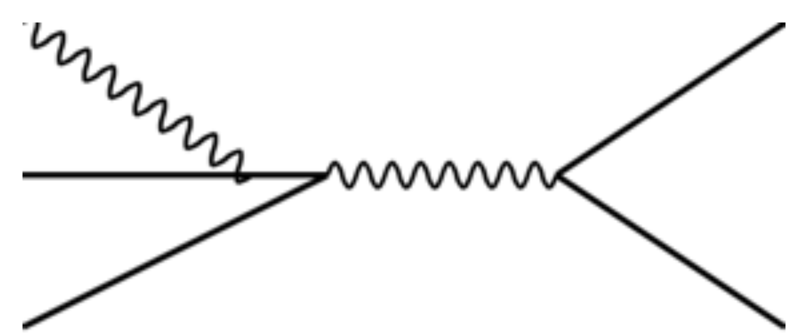
$2 \leftrightarrow 2$





$3 \leftrightarrow 2$





Why 3↔2? Not-Forbidden DM

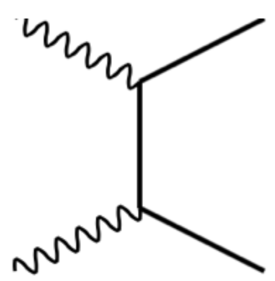
- In the early universe, dark matter density is pretty high

- Boltzmann distribution

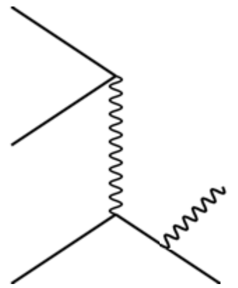
$$n_0 = (mT)^{3/2} \exp(-x)\ ,\ n_{A0} = (m_A T)^{3/2} \exp(-r\,x)$$

- $\chi\,\bar{\chi} \to A'\,A'$ is forbidden ($x \equiv m_\chi/T$, $r \equiv m_A/m_\chi$)

$$\text{Rate}\,(2 \to 2) \sim n_A{}^2 / n_\chi \langle\sigma v\rangle$$
$$\sim \exp\,[-\,(2r-1)\,x]\,\langle\sigma v\rangle$$



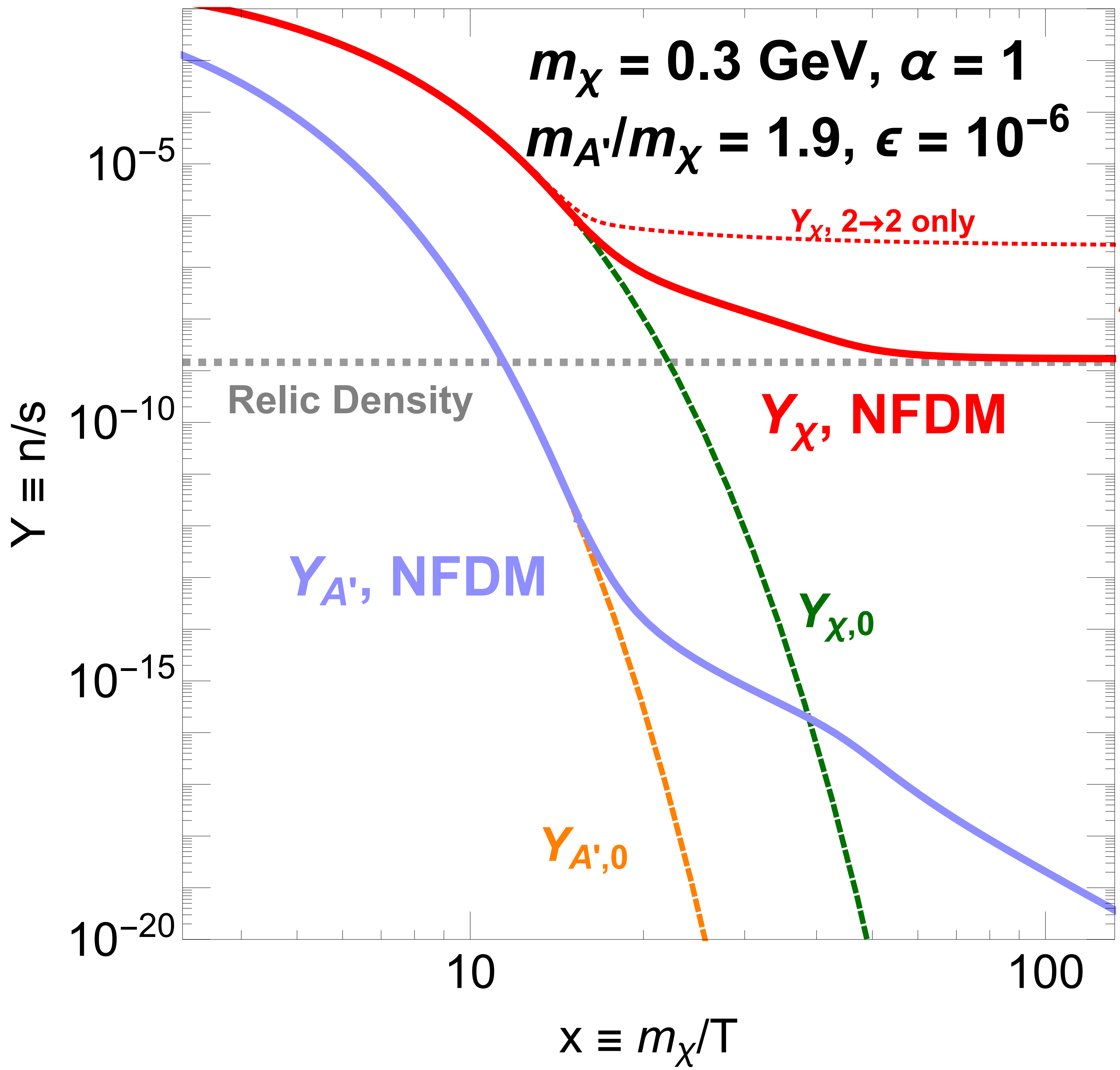
$$\text{Rate}\,(3 \to 2) \sim n_\chi{}^2 \langle\sigma v^2\rangle \sim \exp\,(-2x)\,\langle\sigma v^2\rangle$$



- $r \gtrsim 1.5$

$$\text{Rate}\,(3 \to 2) \gtrsim \text{Rate}\,(2 \to 2)$$

r (≡ m_A/m_χ) ≳ 1.5



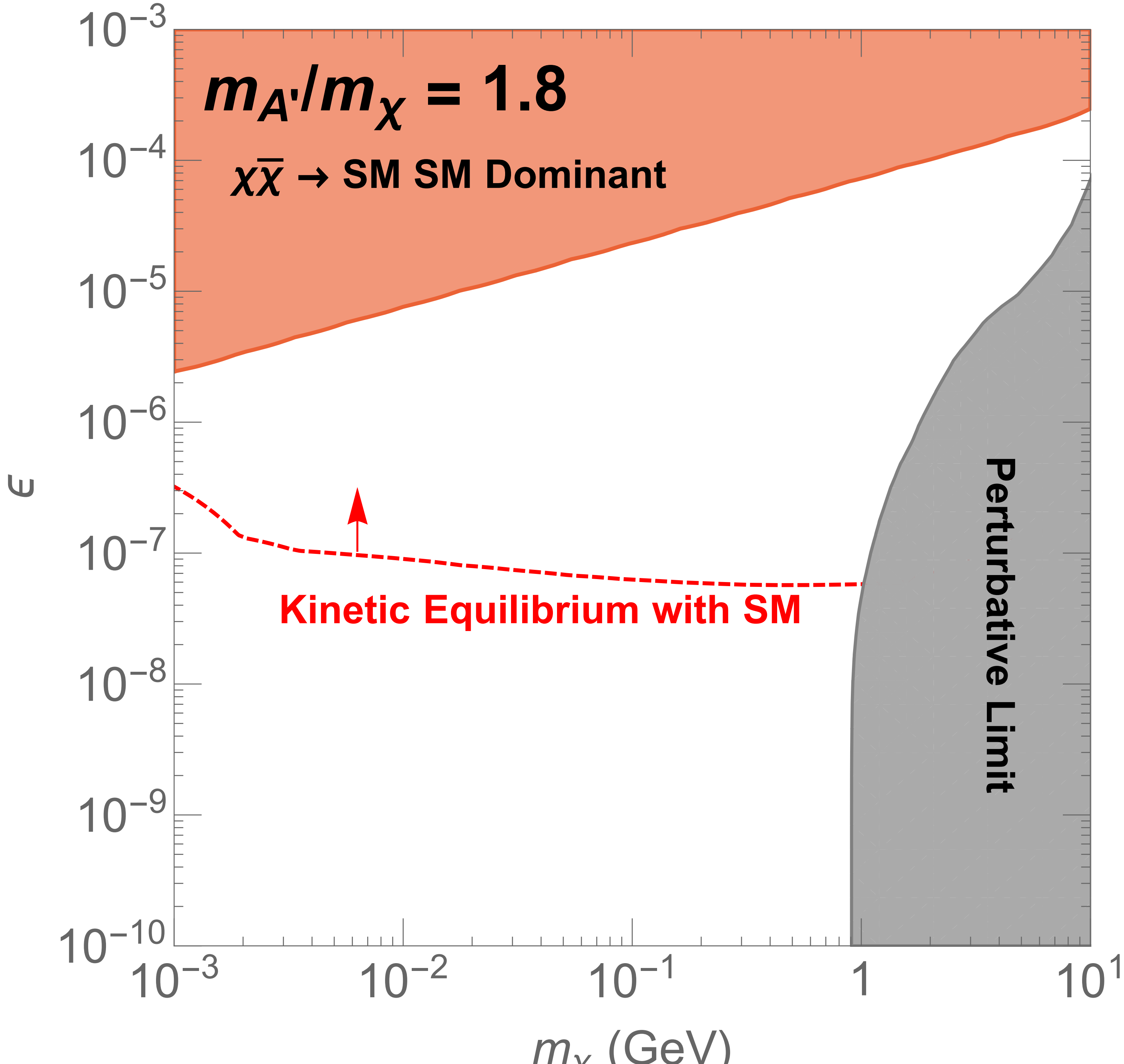
3→2 longer freeze-out

$n_A \neq n_{A0}$ even $\Gamma_A \gg H$

Constraints and Signatures

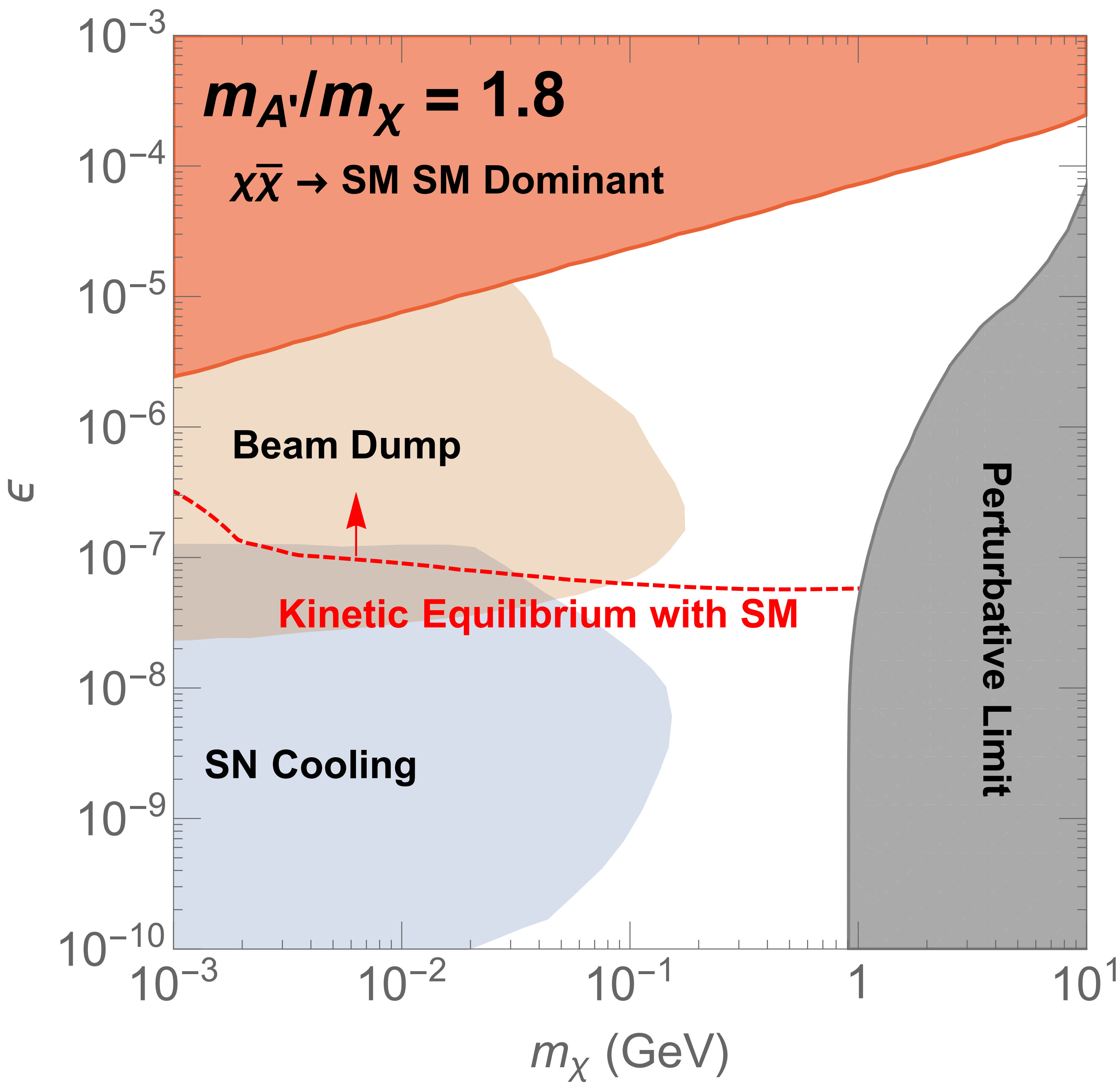
NFDM parameter space

- observed thermal relic



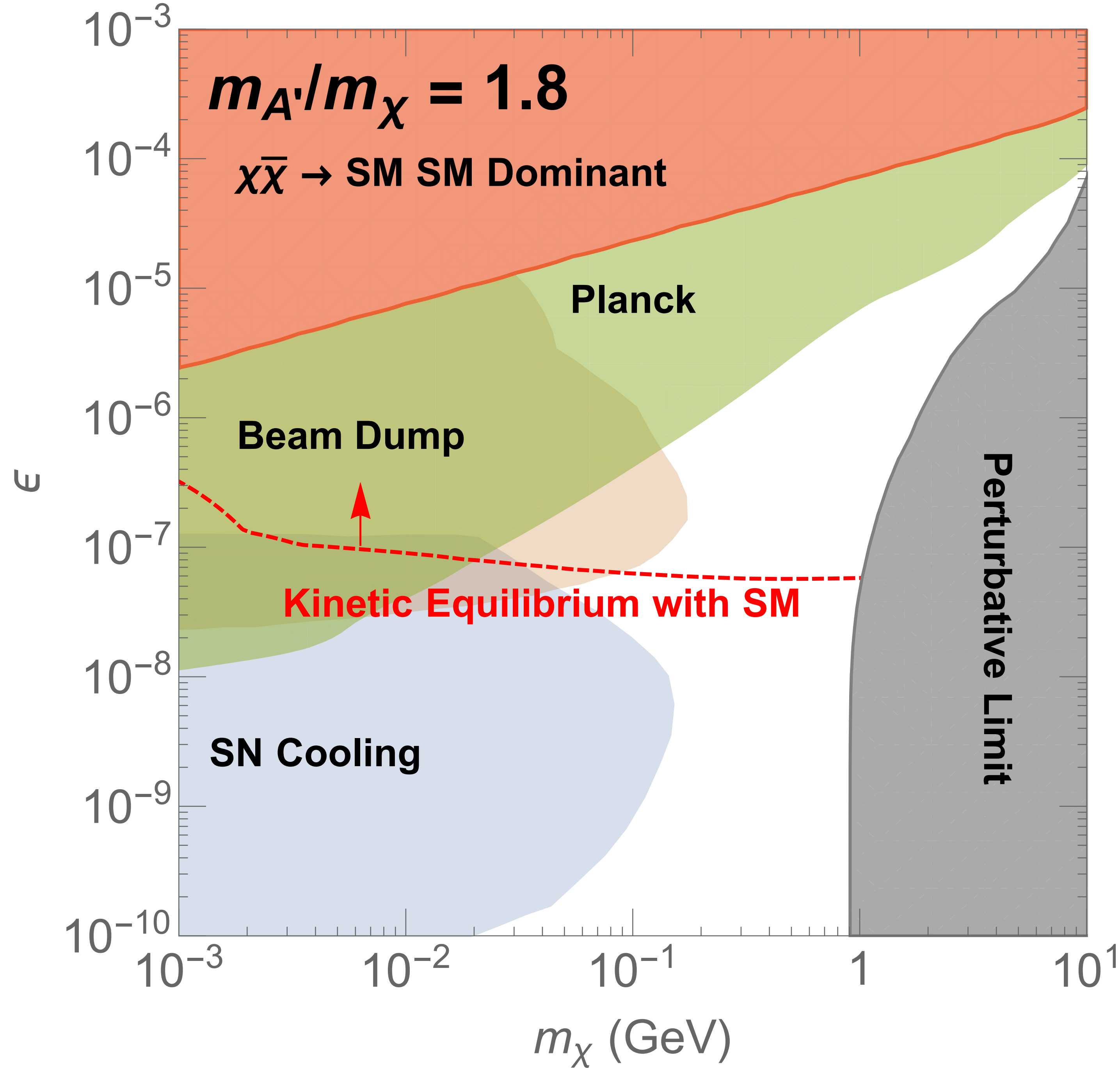
Dark Photon Constraints

- predictive dark photon mass



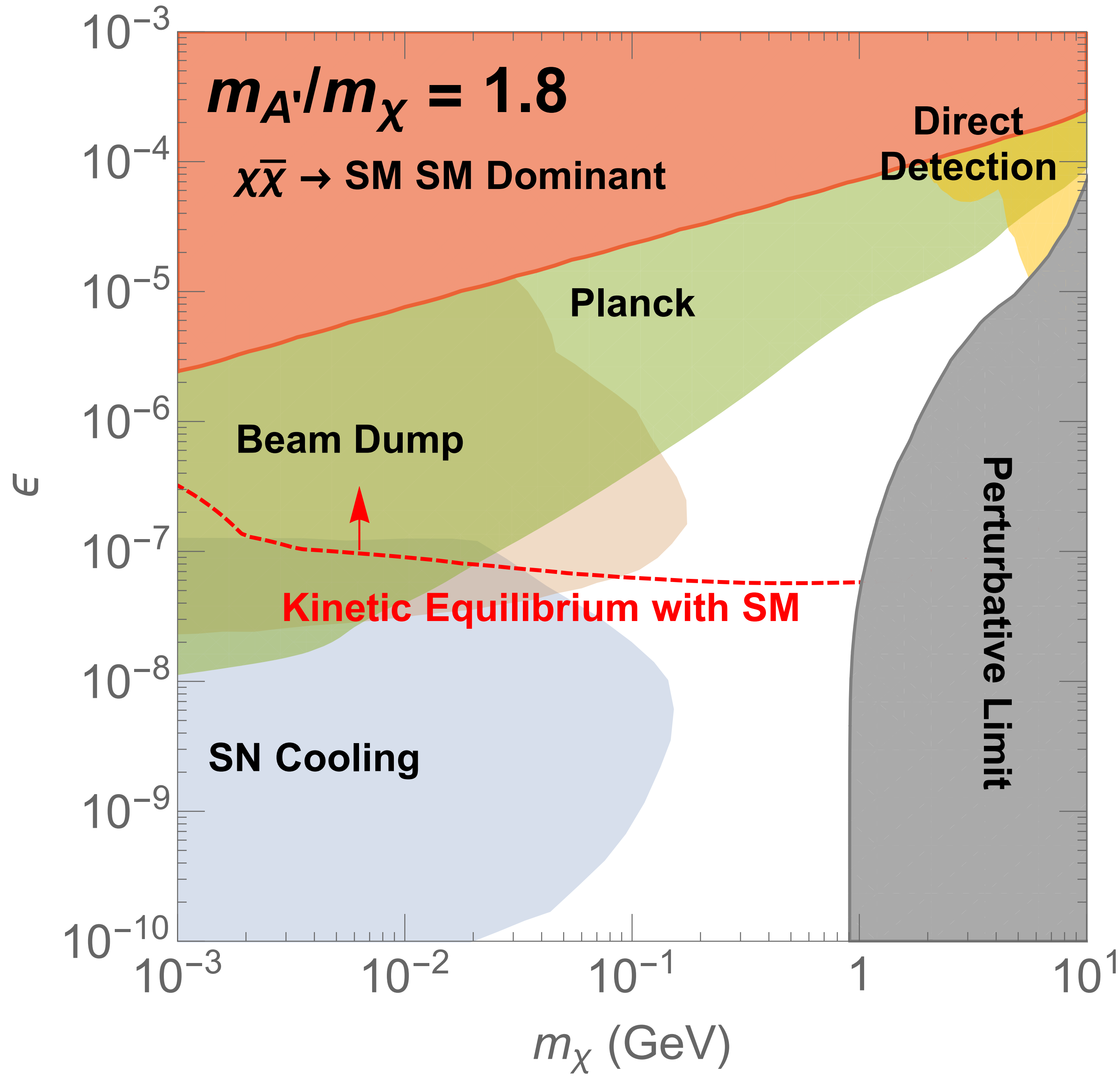
CMB Constraints

- pretty strong constraints.
  set limits on many MeV- GeV dark matter models



Direct Detection Constraints

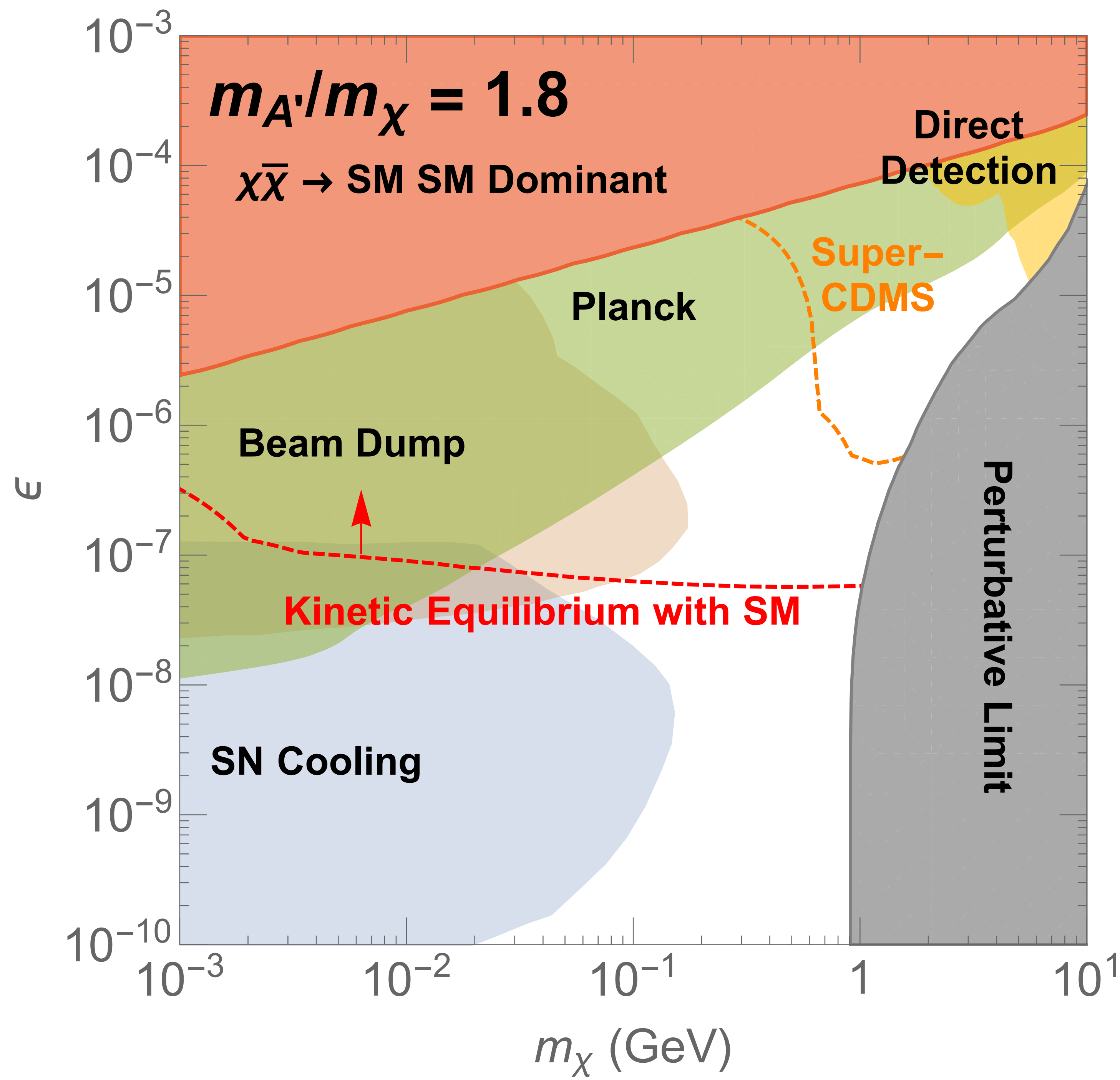
- LUX, PandaX, CDMSlite ~ 10 GeV



Future Direct Detection

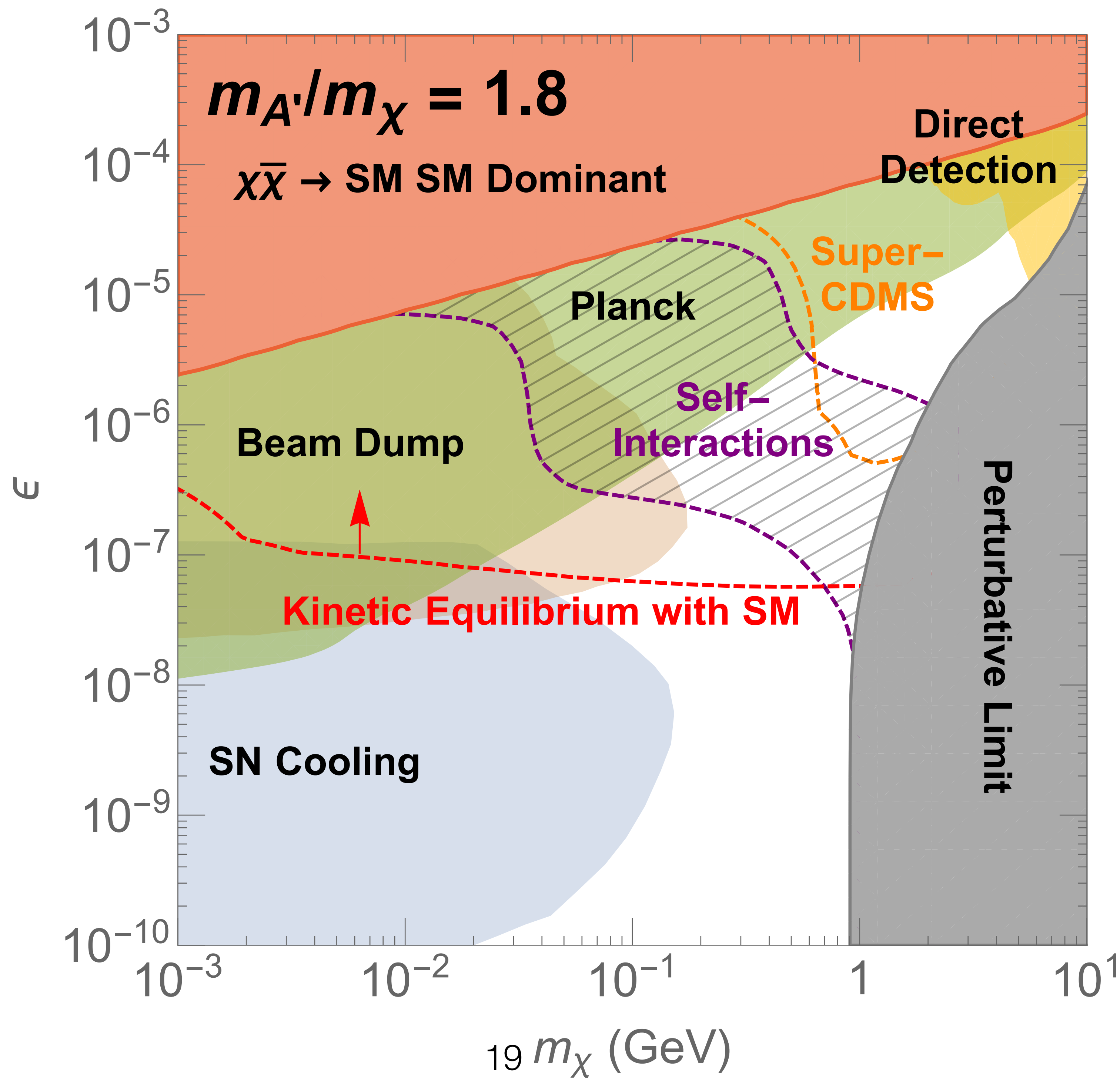
- superCDMS

…



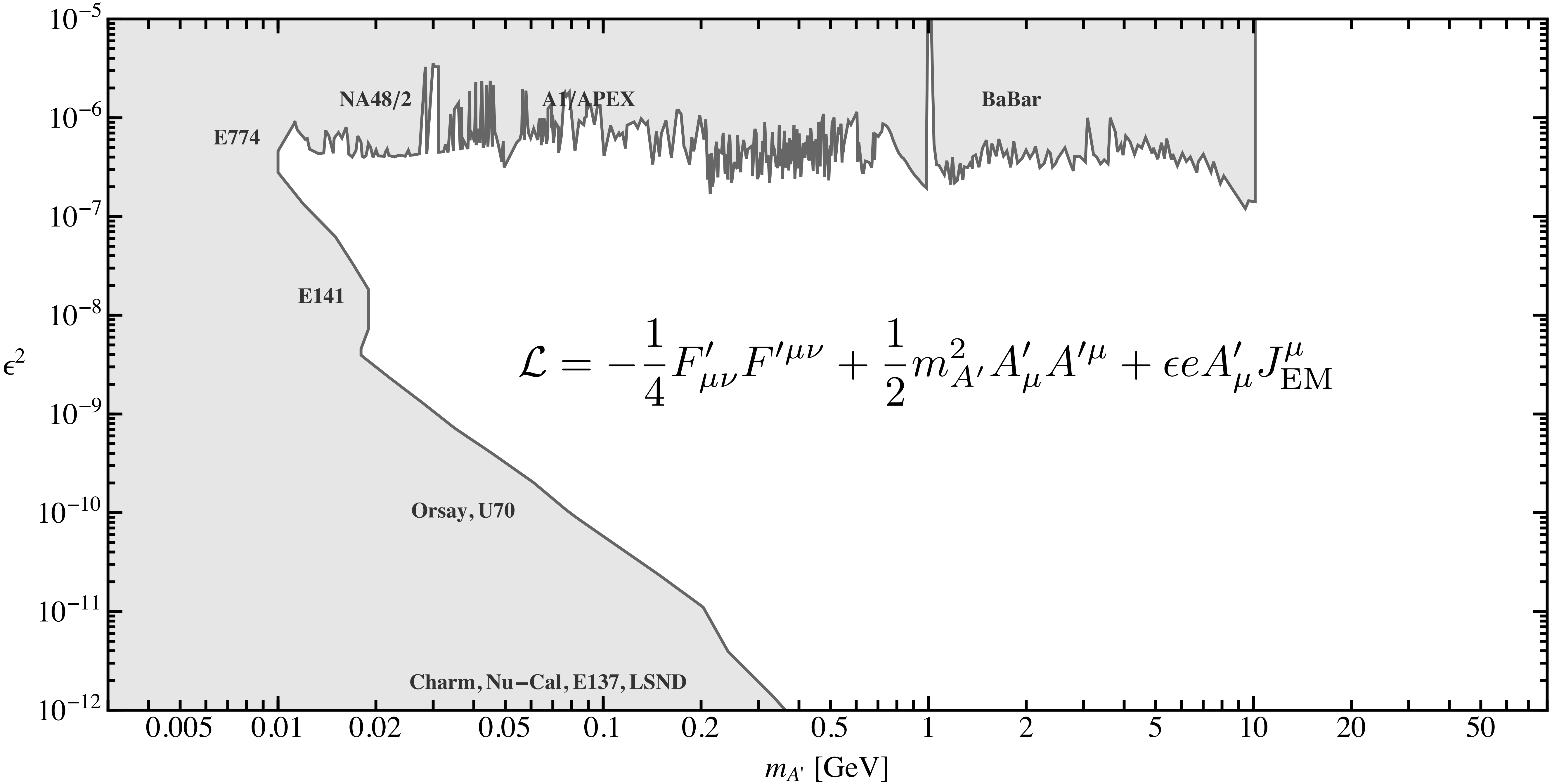
Cusp/Core Problem

- $0.1 \lesssim \sigma/m \lesssim 1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$



When we search for dark matter,

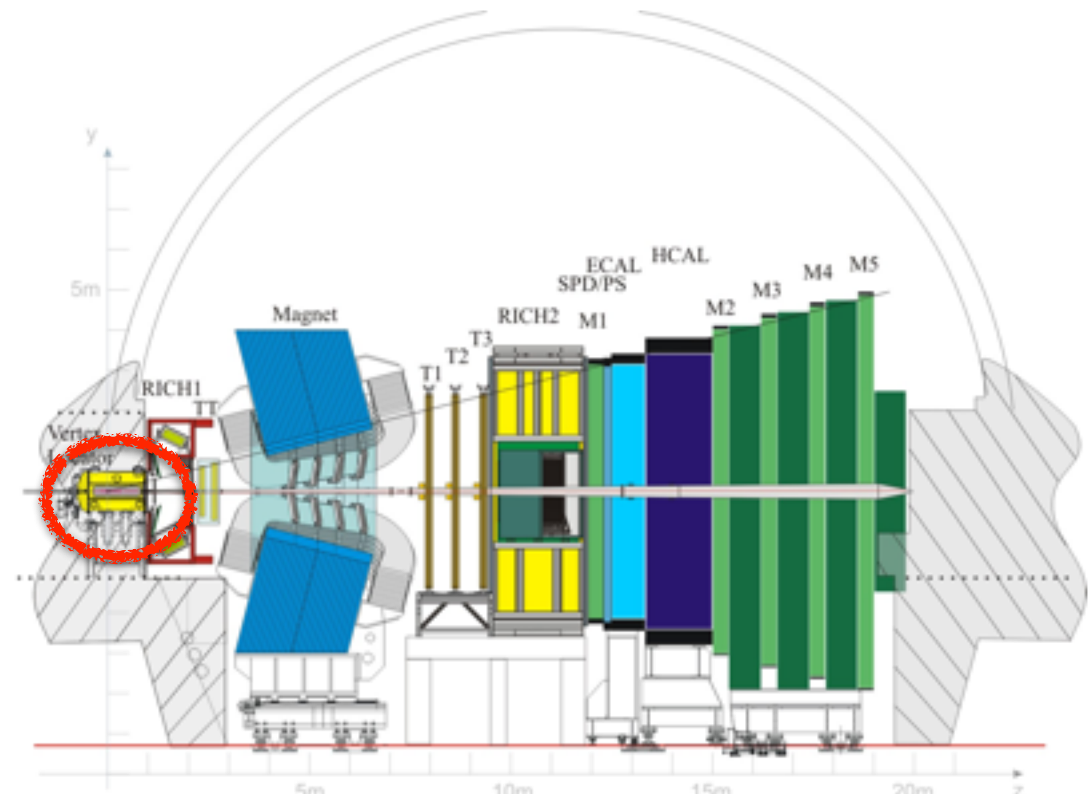
…

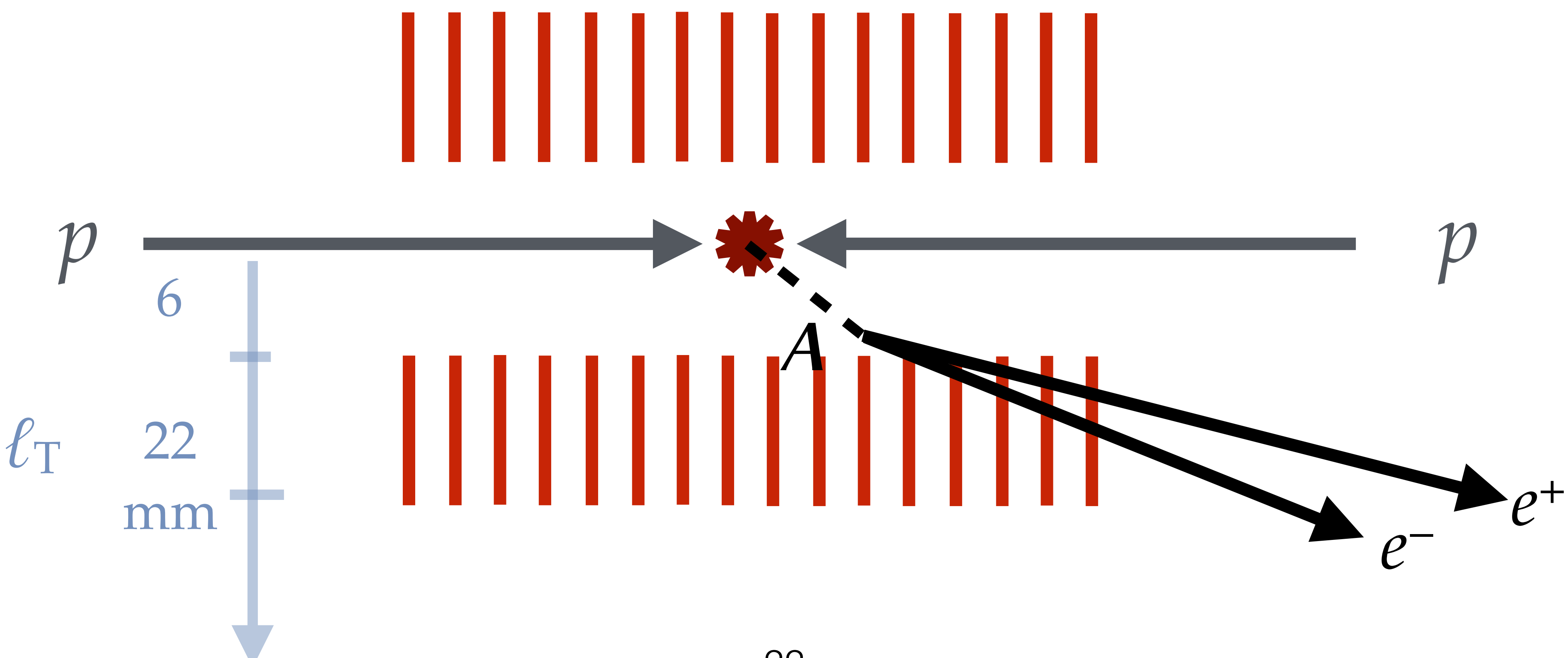


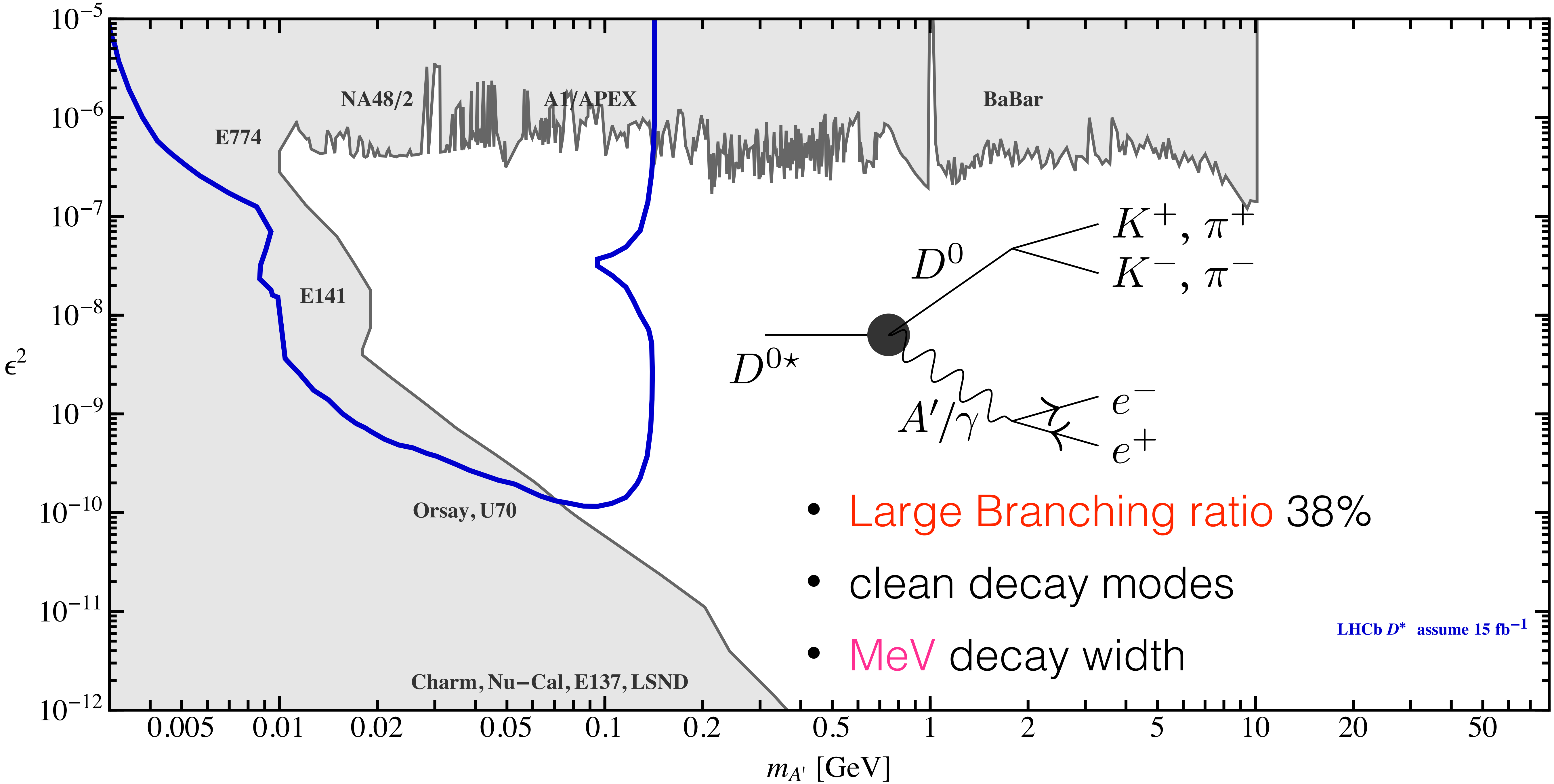
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
ϵ^2
NA48/2
A1/APEX
BaBar
E774
E141
Orsay, U70
Charm, Nu-Cal, E137, LSND
$$\mathcal{L} = -\frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m^2_{A'}A'_\mu A'^\mu + \epsilon e A'_\mu J^\mu_{\rm EM}$$
0.005
0.01
0.02
0.05
0.1
0.2
0.5
1
2
5
10
20
50
$m_{A'}$ [GeV]

Why LHCb

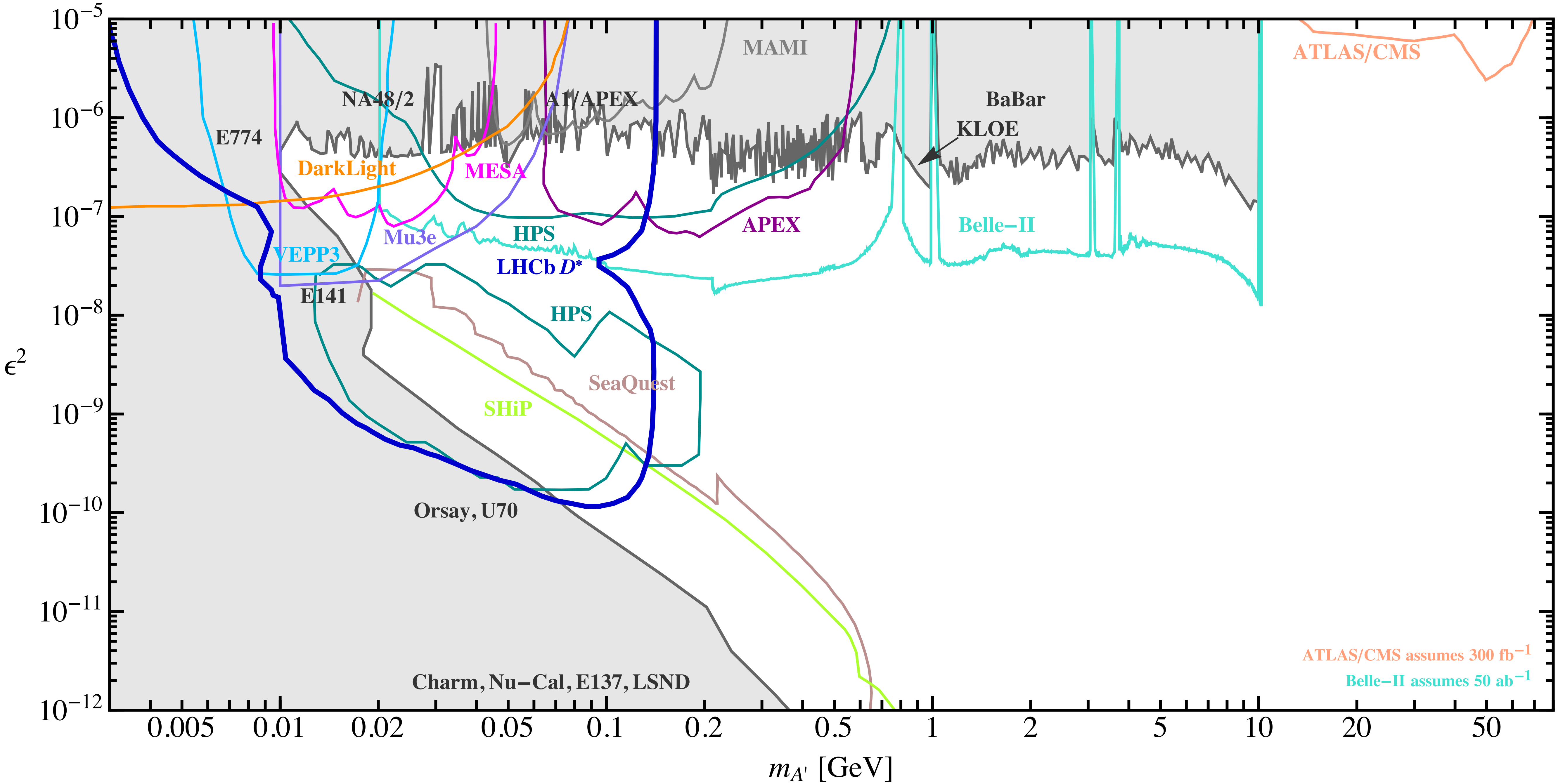
- no pile-up (Run 1 and 2)
- good vertexing :VELO detector (10 μm)
- good invariant mass resolution (**O**(MeV))
- triggerless readout (Run 3)



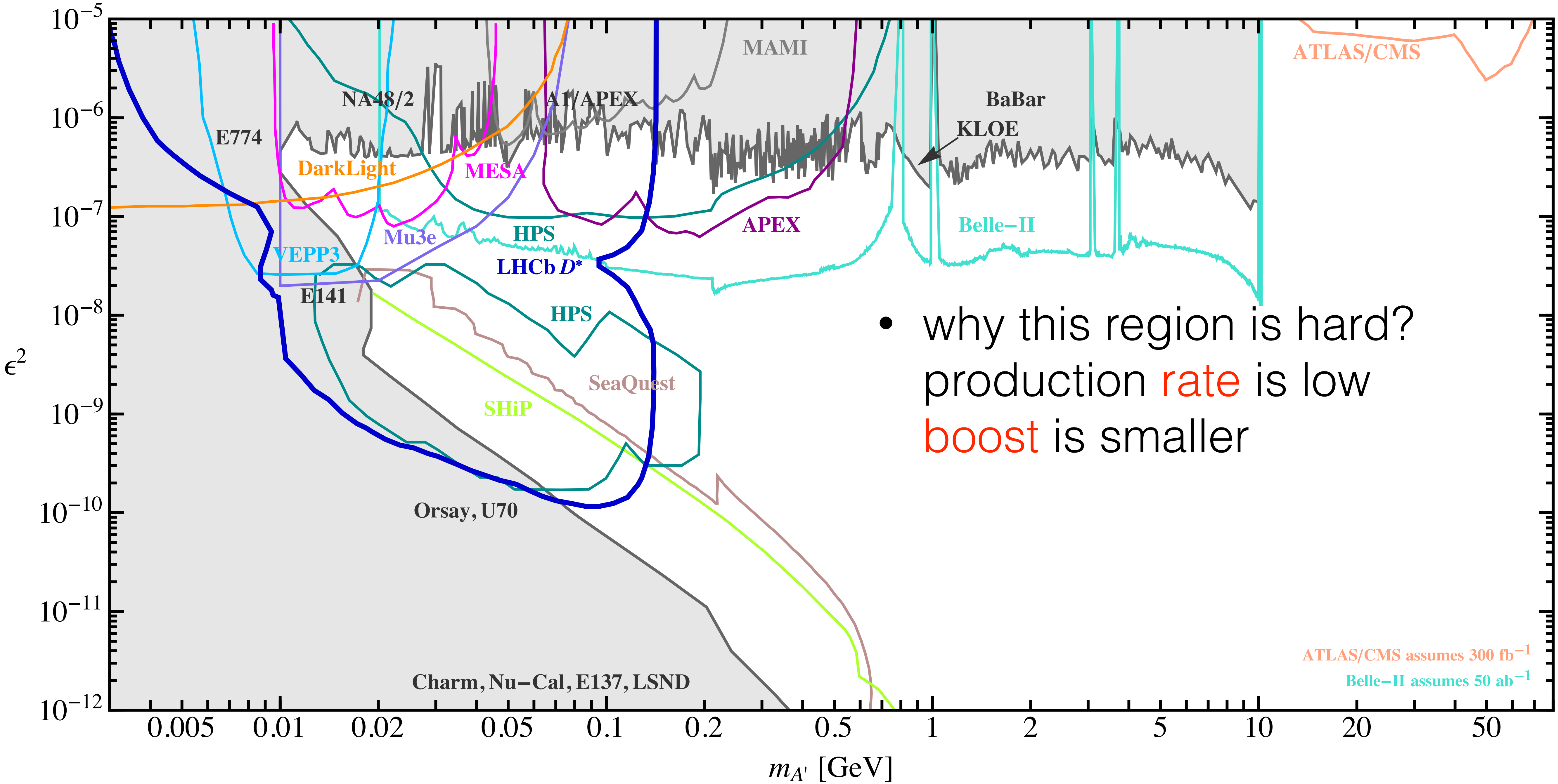




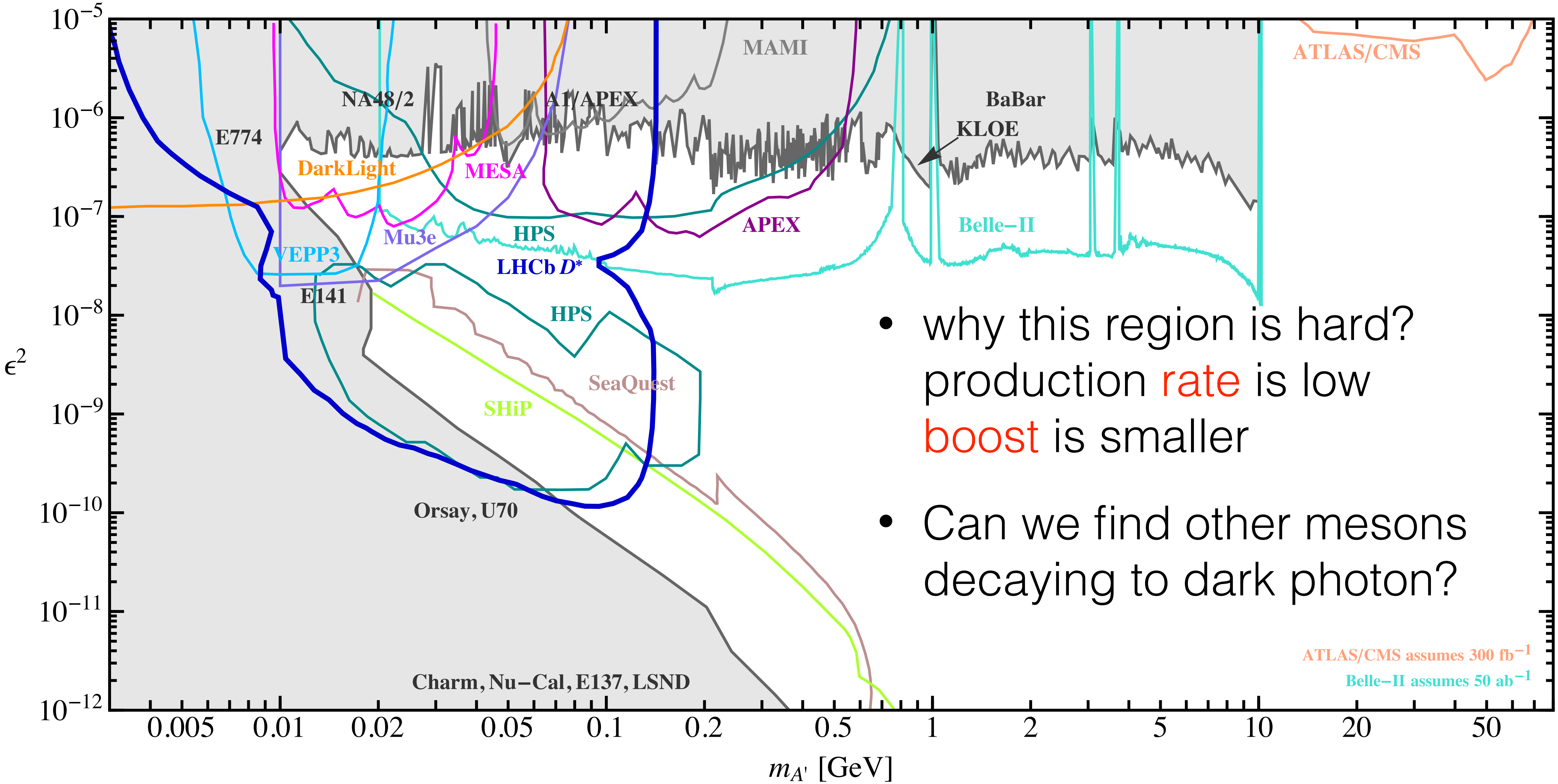
NA48/2
A1/APEX
BaBar
E774
E141
Orsay, U70
Charm, Nu-Cal, E137, LSND
D^0
K^+, π^+
K^-, π^-
$D^{0\star}$
A'/γ
e^-
e^+
• Large Branching ratio 38%
• clean decay modes
• MeV decay width
LHCb D^* assume 15 fb^{-1}
ϵ^2
$m_{A'}$ [GeV]



MAMI
ATLAS/CMS
NA48/2
A1/APEX
BaBar
KLOE
E774
DarkLight
MESA
APEX
Belle−II
HPS
Mu3e
VEPP3
LHCb D^*
E141
HPS
SeaQuest
SHiP
Orsay, U70
Charm, Nu−Cal, E137, LSND
ATLAS/CMS assumes 300 fb^{-1}
Belle−II assumes 50 ab^{-1}
ϵ^2
$m_{A'}$ [GeV]



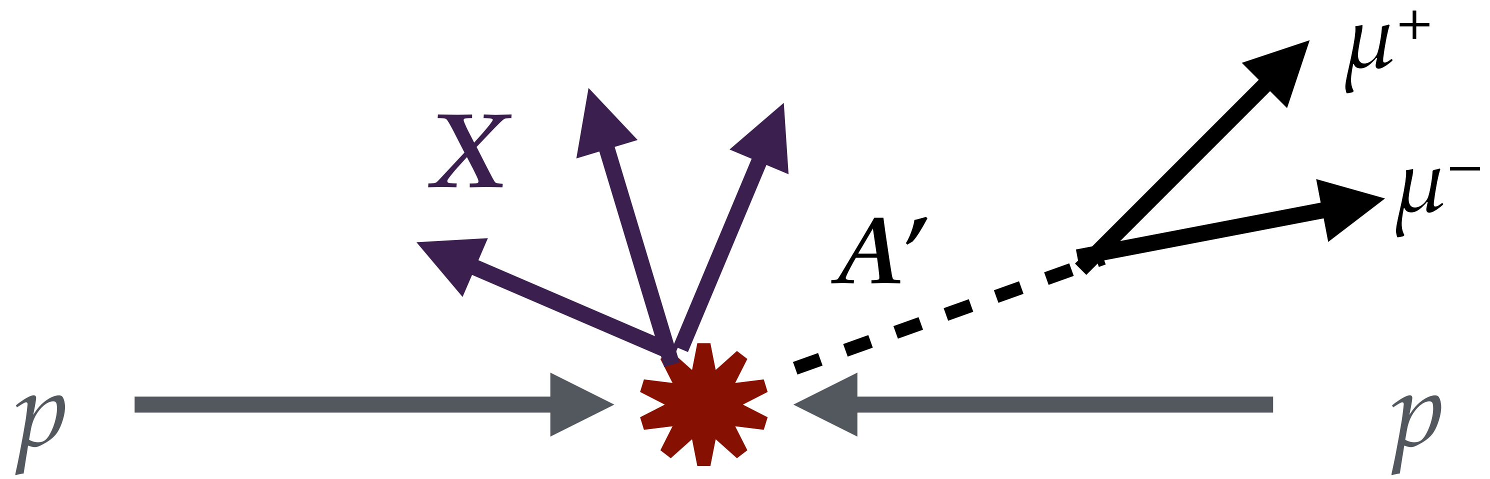
- why this region is hard?
  production rate is low
  boost is smaller



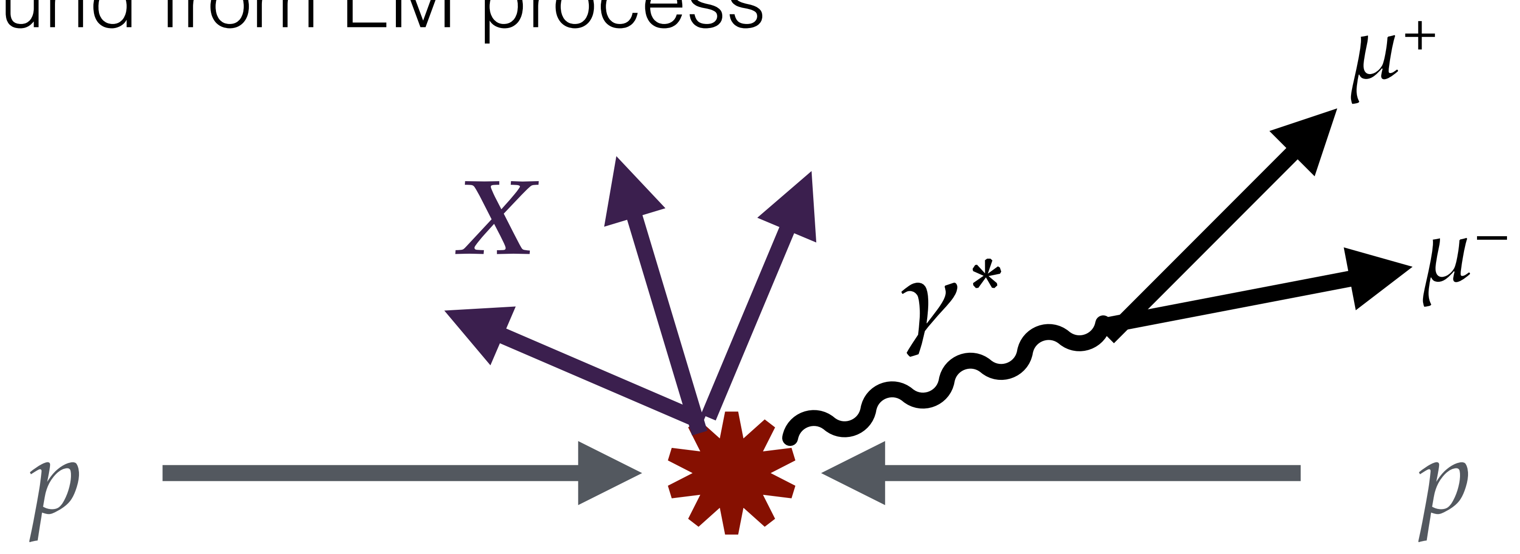
- why this region is hard?
  production rate is low
  boost is smaller
- Can we find other mesons decaying to dark photon?

inclusive dimuon search

- dark photon mix with photon and also vector mesons



- Background from EM process



Data driven method

- ratio (form factor are cancelled)

$$\frac{d\sigma_{pp\to XA'\to X\mu^+\mu^-}}{d\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4 \frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2 - m_{A'}^2)^2 + \Gamma_{A'}^2 m_{A'}^2}$$

- per mass bin

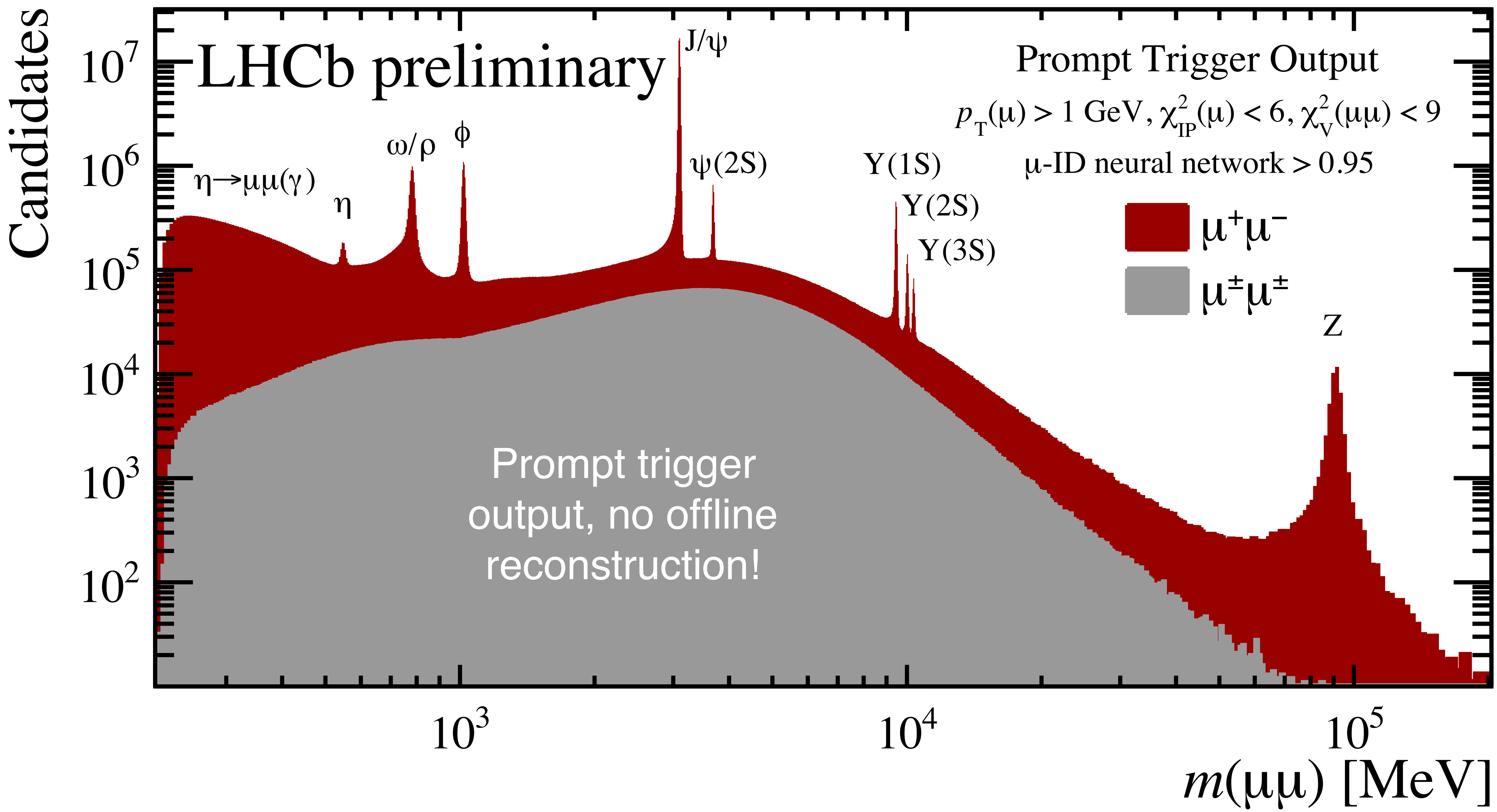
$$\frac{S}{B_{\rm EM}} \approx \epsilon^4 \frac{\pi}{8} \frac{m_{A'}^2}{\Gamma_{A'}\sigma_{m_{\mu\mu}}} \approx \frac{3\pi}{8} \frac{m_{A'}}{\sigma_{m_{\mu\mu}}} \frac{\epsilon^2}{\alpha_{\rm EM}(N_\ell + \mathcal{R}_\mu)}$$

number of leptons with mass below $m_{A'}$

$$\frac{\sigma_{e^+e^-\to \rm hadrons}}{\sigma_{e^+e^-\to\mu^+\mu^-}}$$

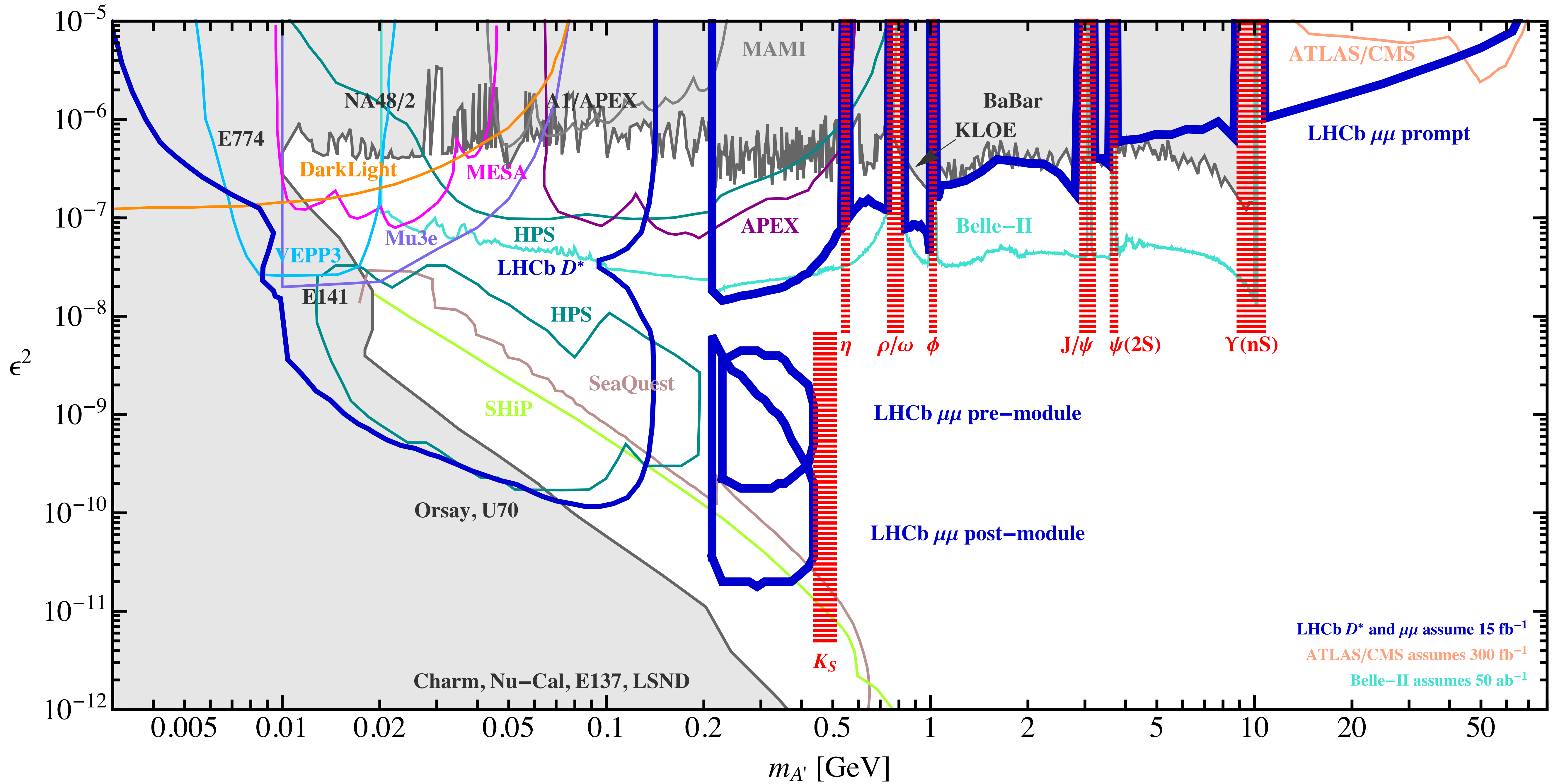
- the continuous dimuon spectrum that LHC have is the background

Measured Di-muon Spectrum

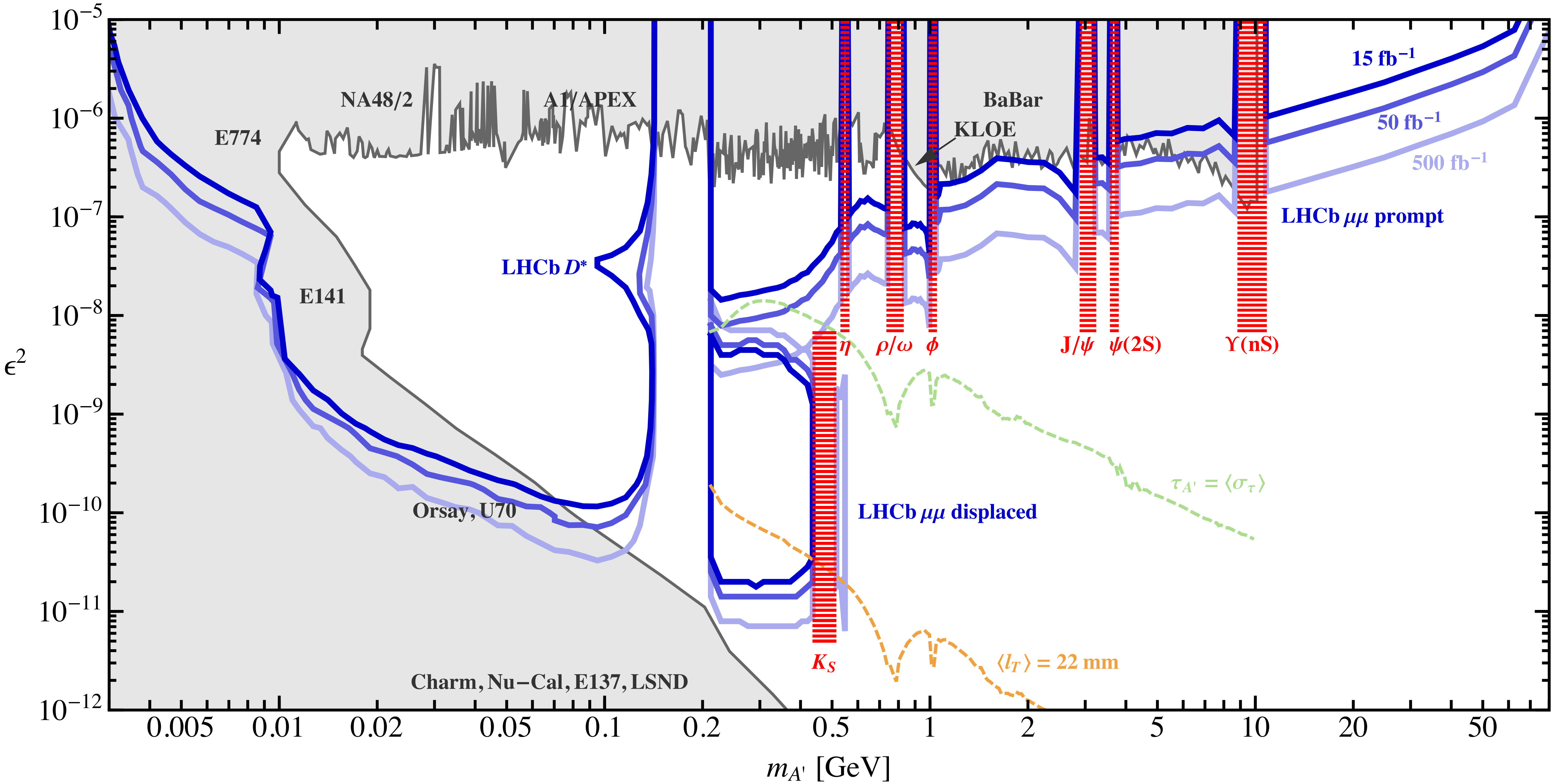


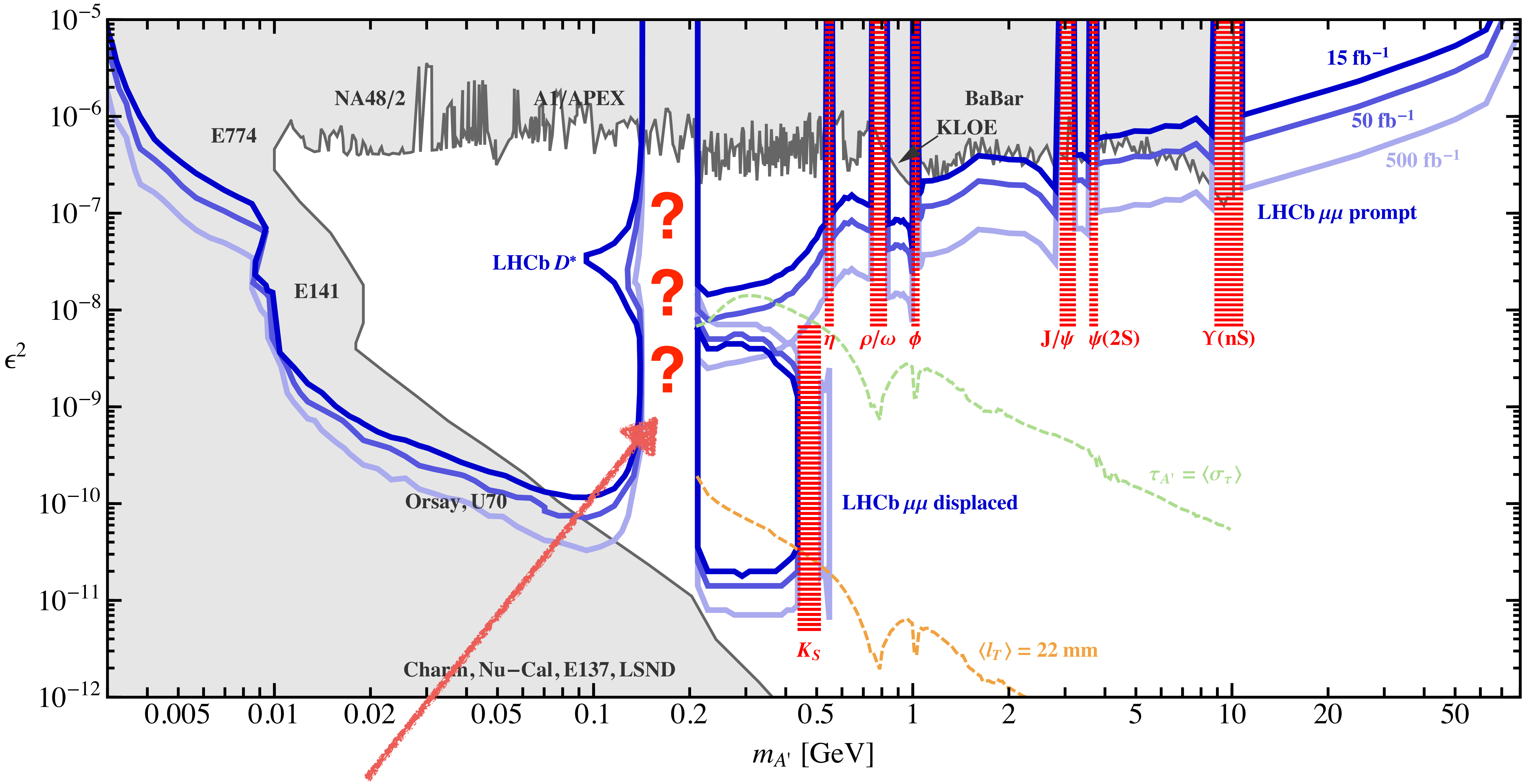
M. Williams' talk

Future Dark Photon Search



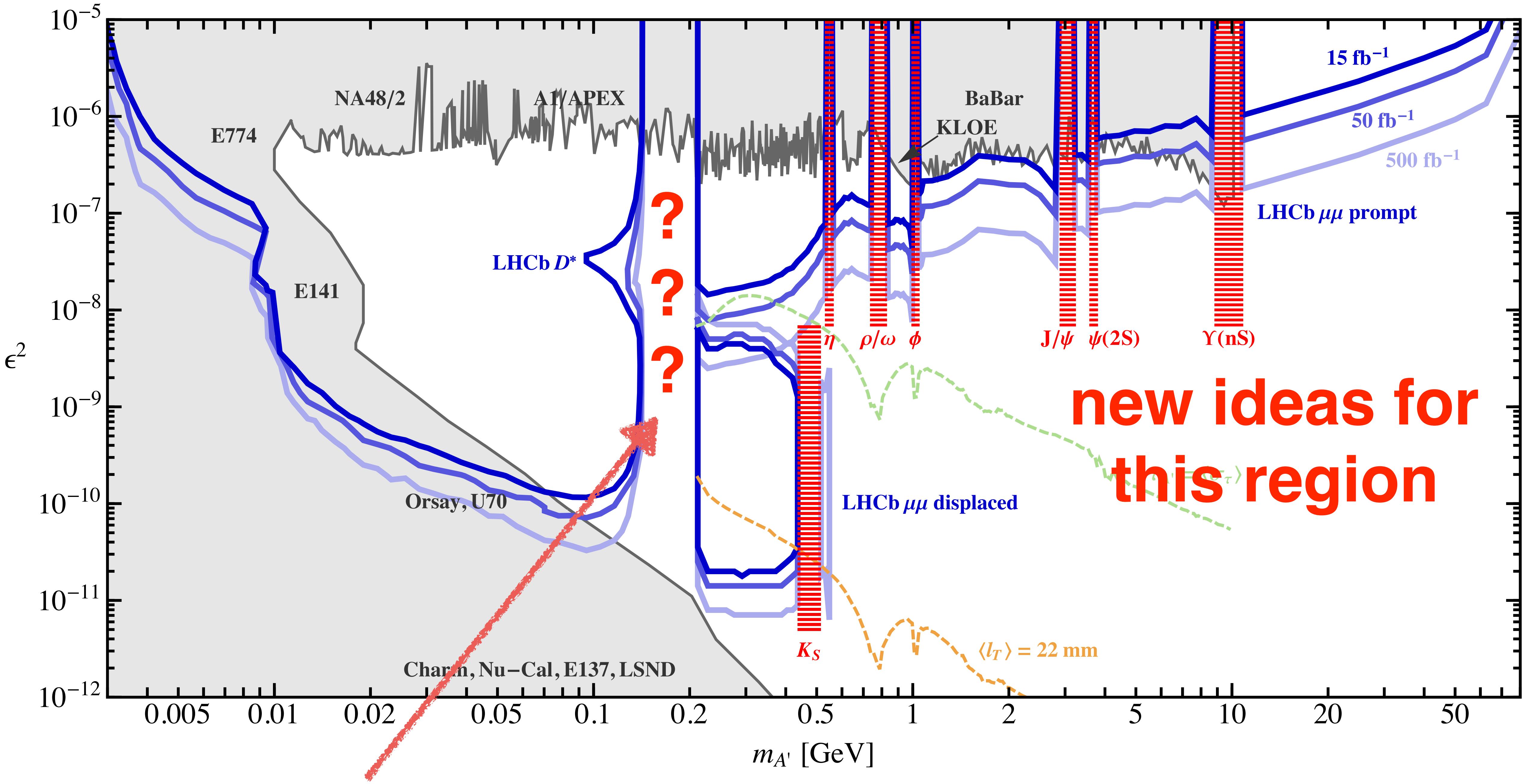
Possible improvement





NA48/2
A1/APEX
BaBar
KLOE
E774
E141
LHCb D*
15 fb⁻¹
50 fb⁻¹
500 fb⁻¹
LHCb μμ prompt
η
ρ/ω
φ
J/ψ
ψ(2S)
Υ(nS)
LHCb μμ displaced
Orsay, U70
Charm, Nu-Cal, E137, LSND
K_S
⟨l_T⟩ = 22 mm
τ_A' = ⟨σ_τ⟩
ϵ²
m_A' [GeV]

?η → A' + … ?



NA48/2
A1/APEX
BaBar
KLOE
E774
E141
LHCb D*
15 fb−1
50 fb−1
500 fb−1
LHCb μμ prompt
η
ρ/ω
ϕ
J/ψ
ψ(2S)
Υ(nS)
new ideas for this region
LHCb μμ displaced
Orsay, U70
K_S
⟨l_T⟩ = 22 mm
Charm, Nu−Cal, E137, LSND
ϵ²
m_A' [GeV]
?
?
?

?η → A' + … ?

Conclusion

- MeV - GeV dark matter is our future target
- NOT-forbidden dark matter
  $3 \to 2$ process cannot be neglected for $m_A \sim m_\chi$
- dark photon searches in the future
  $D^{0*} \to D^0 + \gamma$ and inclusive search
  the (di-muon) data-drive method can be applied to other experiments

Thank you

Background and Signal Rate

- amplitude generating dark photon

$$i\mathcal{M}_{X\to YA'} = i\epsilon e\langle Y|J^{\mu}_{\rm EM}|X\rangle\epsilon(k)_{\mu}$$

- amplitude generating off-shell photon

$$i\mathcal{M}_{X\to Y\ell^+\ell^-} = ie^2\langle Y|J^{\mu}_{\rm EM}|X\rangle\frac{-ig_{\mu\nu}}{(k_1+k_2)^2}\bar{u}(k_1)\gamma^{\nu}v(k_2)$$

- ratio (form factor are cancelled)

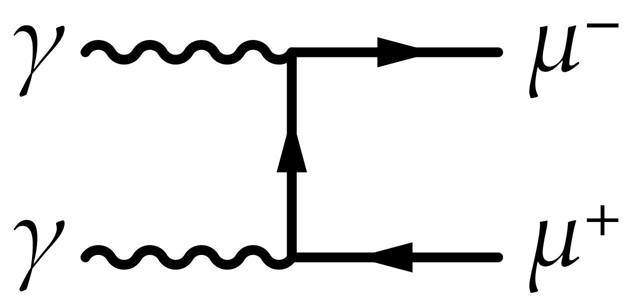
$$\frac{\mathrm{d}\sigma_{pp\to XA'\to X\mu^+\mu^-}}{\mathrm{d}\sigma_{pp\to X\gamma^*\to X\mu^+\mu^-}} = \epsilon^4\frac{m_{\mu\mu}^4}{(m_{\mu\mu}^2-m_{A'}^2)^2+\Gamma_{A'}^2 m_{A'}^2}$$

Prompt Search

- "good" Background
  proportional to EM currents
  Mesons, FSR/DY

- "bad" Background

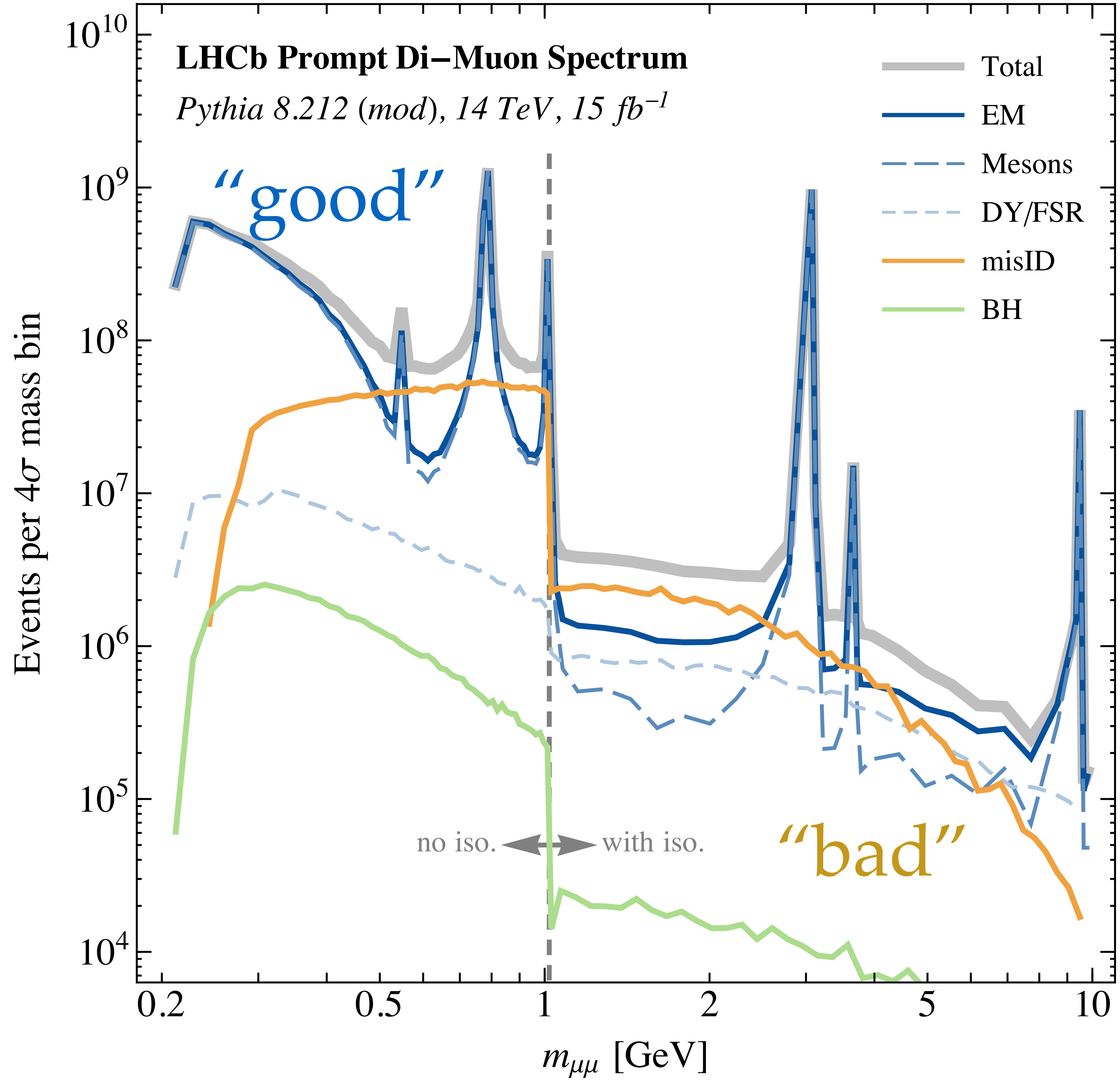
  - Beith-Heitler, subdominant, small photon PDF



  - mis-identified pions (fake rate ~ 10^{-3}):
    $B^{\pi\pi}$ - two pions are misidentified
    $B^{\pi\mu}$ - one pion is misidentified and one real muon
    subtract them in a data-driven way (same-sign dimuon)

selections:

- $2<\eta(\mu^{\pm})<5$
- $p(\mu^{\pm})>10$GeV
- $p_T(\mu^{\pm})>0.5$GeV
- $p_T(A')>1.0$GeV
- μ isolation: $m_{A'}>m_{\phi}\sim1$ GeV



$$B_{\text{prompt}} = \underbrace{B_M + B_{\text{FSR}} + B_{\text{DY}}}_{B_{\text{EM}}} + \underbrace{B^{\pi\pi}_{\text{misID}} + B^{\pi\mu}_{\text{misID}}}_{B_{\text{misID}}}$$

"good" scales as signal

"bad" does not scale as signal

Displaced Search Background

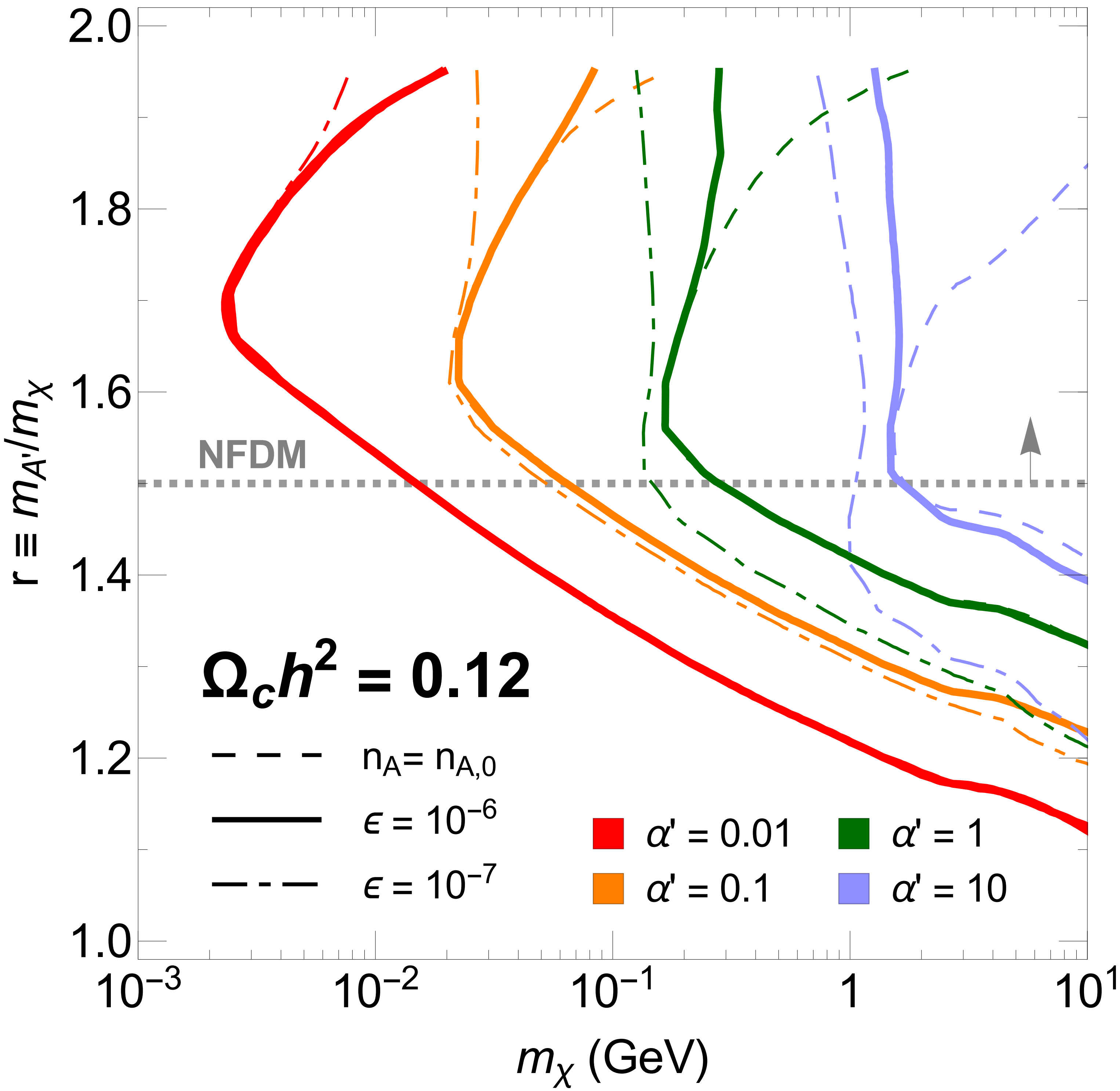
- pre-module : semi-leptonic heavy meson decays
  $b \to c\,\mu^{\pm} X$, $c \to \mu^{\pm} Y$
  10^4 events per $\pm\, 2\,\sigma$ inv mass bin

- post-module : $\tau_A \gg \tau_{D,B}$
  mostly material interactions.
  25 events per mass bin
  (rescaled from $K_s \to \mu^+ \mu^-$ search)

Why LHCb 2)

- Run 3 triggerless readout:
  - removing the first-level hardware trigger
  - realtime calibration
  - no hardware limited
    only disk space limitation
  - triggerless readout opens new possibilities for particle physics search in Run3
  - we should test it right now!

Relic Density



Simplified Example I

A' Prompt decay

$$n_A = n_{A0} \quad (\Gamma \to \infty)$$

One Boltzmann Equation

- set $n_A = n_{A0}$ (ε large)
  two Boltzmann equations are reduced to one

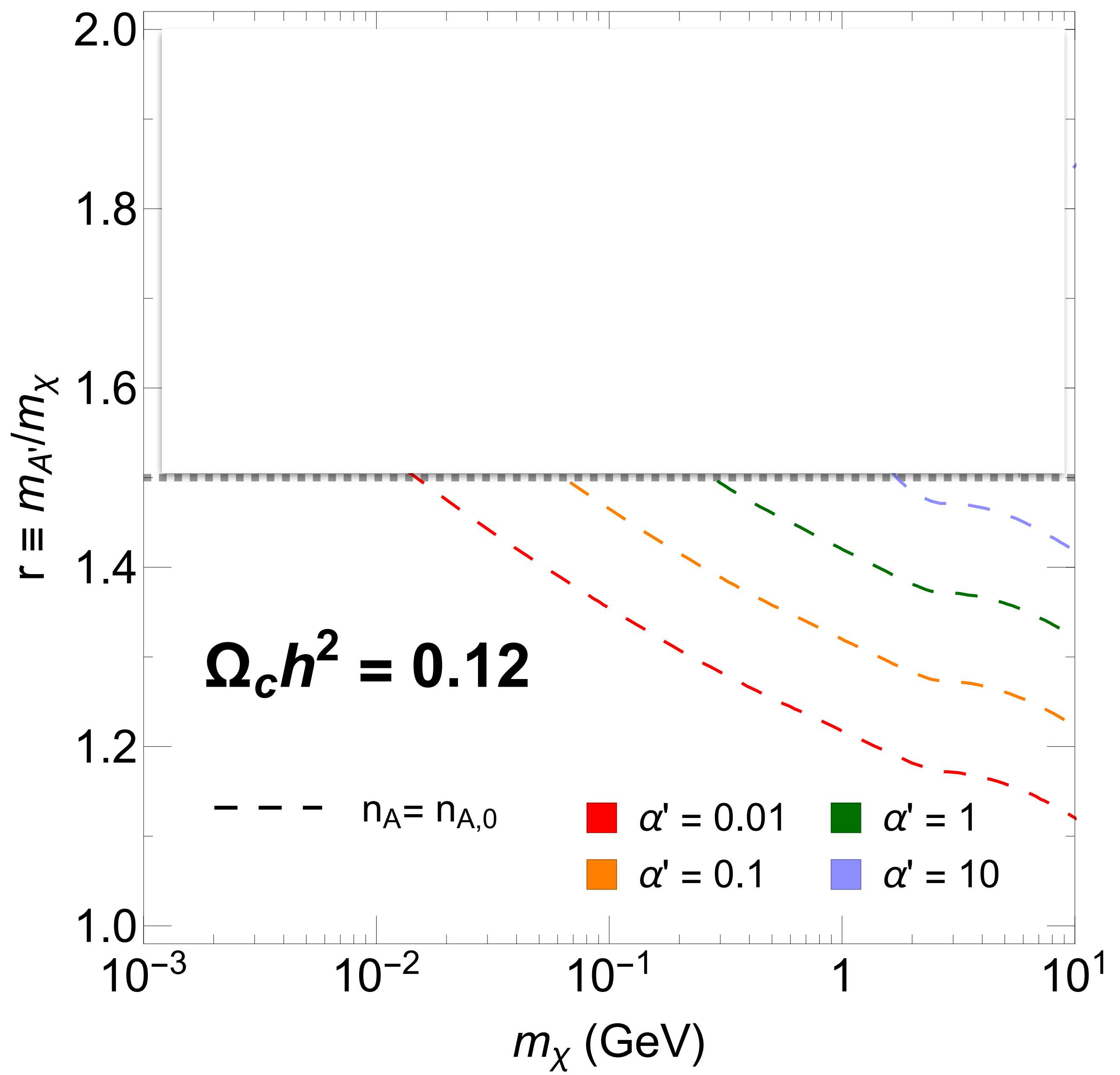
$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\frac{1}{4}\langle\sigma v^2\rangle_{\chi\chi\bar{\chi}\to\chi A'}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi\right) + \langle\sigma v\rangle_{A'A'\to\bar{\chi}\chi}\left(n_{A',0}^2 - n_{A',0}^2\frac{n_\chi^2}{n_{\chi,0}^2}\right)$$

- the stronger process matters
  when the weaker process rate ~ Hubble, $n_\chi = n_{\chi 0}$
  When the stronger process rate ~ Hubble , n_χ deviates from $n_{\chi 0}$

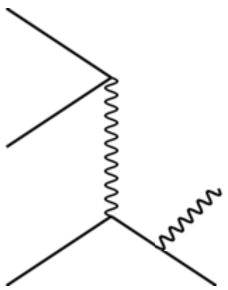
$r\ (\equiv m_A/m_\chi) \lesssim 1.5$ (Simplified)

- dominant process is 2→2
  this process is forbidden
  $\langle \sigma v \rangle (\chi\bar{\chi} \to AA) \simeq \langle \sigma v \rangle n_A^2/n_\chi^2 \quad \propto \exp[-(2r-2)x_f]\ \alpha^2/m_\chi^2$
  freeze-out happens at $x_f = m/T_f$

- Relic density
  $\Omega h^2 \propto 1/\langle \sigma v \rangle (\chi\bar{\chi} \to AA)$

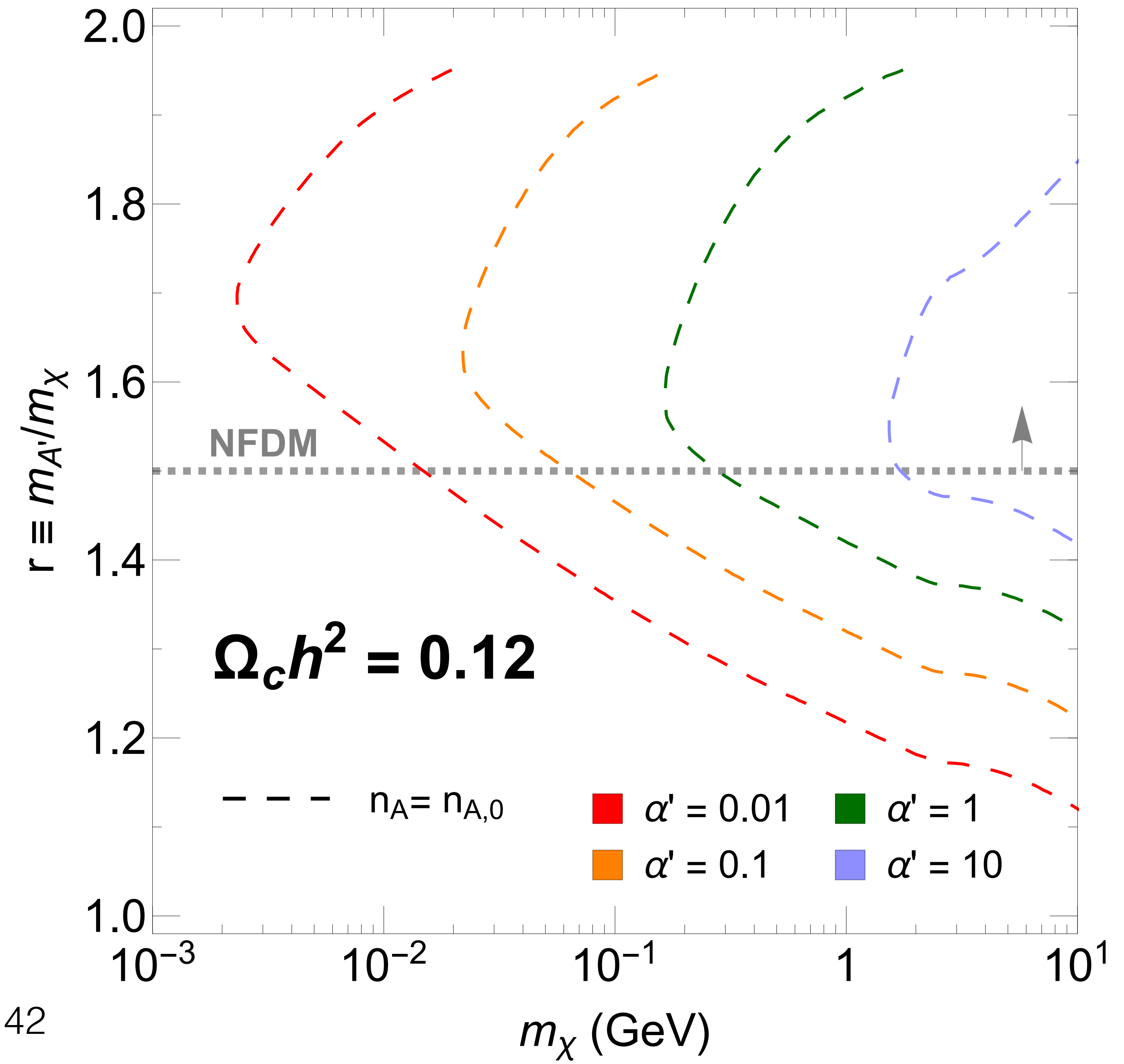


$r\ (\equiv m_A/m_\chi) \gtrsim 1.5$ (Simplified)



- dominant process is $3 \to 2$
  $\Gamma(3 \to 2)\ n \simeq \langle \sigma v^2 \rangle n_\chi^3$,
  r-dependence $\langle \sigma v^2 \rangle \propto \alpha^3/m^5\ (r-2)^{-7/2}$

- Relic density
  $\Omega h^2 \propto 1/\langle \sigma v^2 \rangle^{1/2}$



Two Coupled Boltzmann Equations

- Boltzmann equations

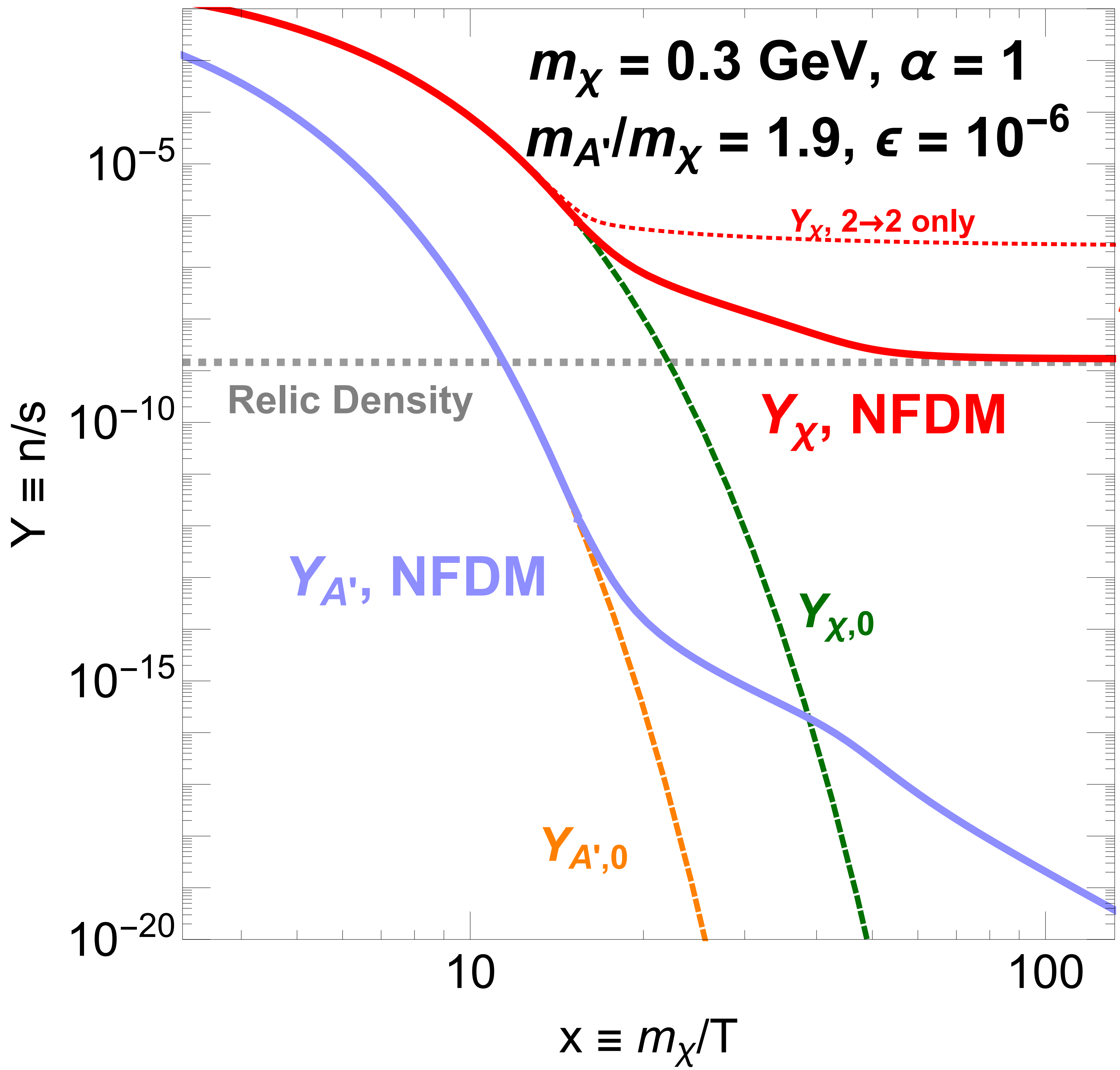
$$\frac{dn}{dt} + 3Hn = -\frac{1}{4}\langle\sigma v^2\rangle_{\chi\chi\bar{\chi}\to\chi A'}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) \quad +\langle\sigma v\rangle_{A'A'\to\bar{\chi}\chi}\left(n_{A'}^2 - n_{A',0}^2\frac{n_\chi^2}{n_{\chi,0}^2}\right)$$

$$\frac{dn_{A'}}{dt} + 3Hn_{A'} = \frac{1}{8}\langle\sigma v^2\rangle_{\chi\chi\bar{\chi}\to\chi A'}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right) \quad -\langle\sigma v\rangle_{A'A'\to\bar{\chi}\chi}\left(n_{A'}^2 - n_{A',0}^2\frac{n_\chi^2}{n_{\chi,0}^2}\right)$$

- $n_A = n_{A0}$ and $n_\chi = n_{\chi 0}$

- the second strongest process matters
  when the 3rd strongest process rate ~ Hubble, $n_\chi = n_{\chi 0}$
  when the 2nd strongest process rate ~ Hubble , n_χ deviates from $n_{\chi 0}$

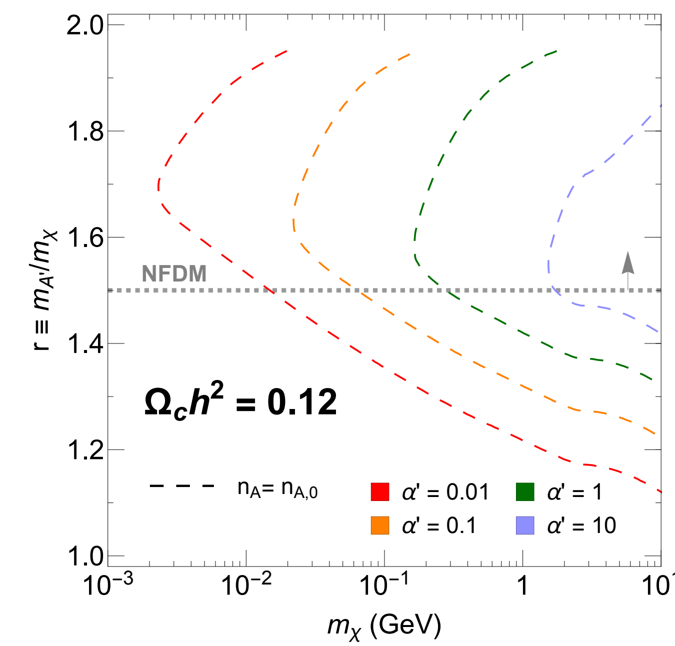
r (≡ m_A/m_χ) ≳ 1.5

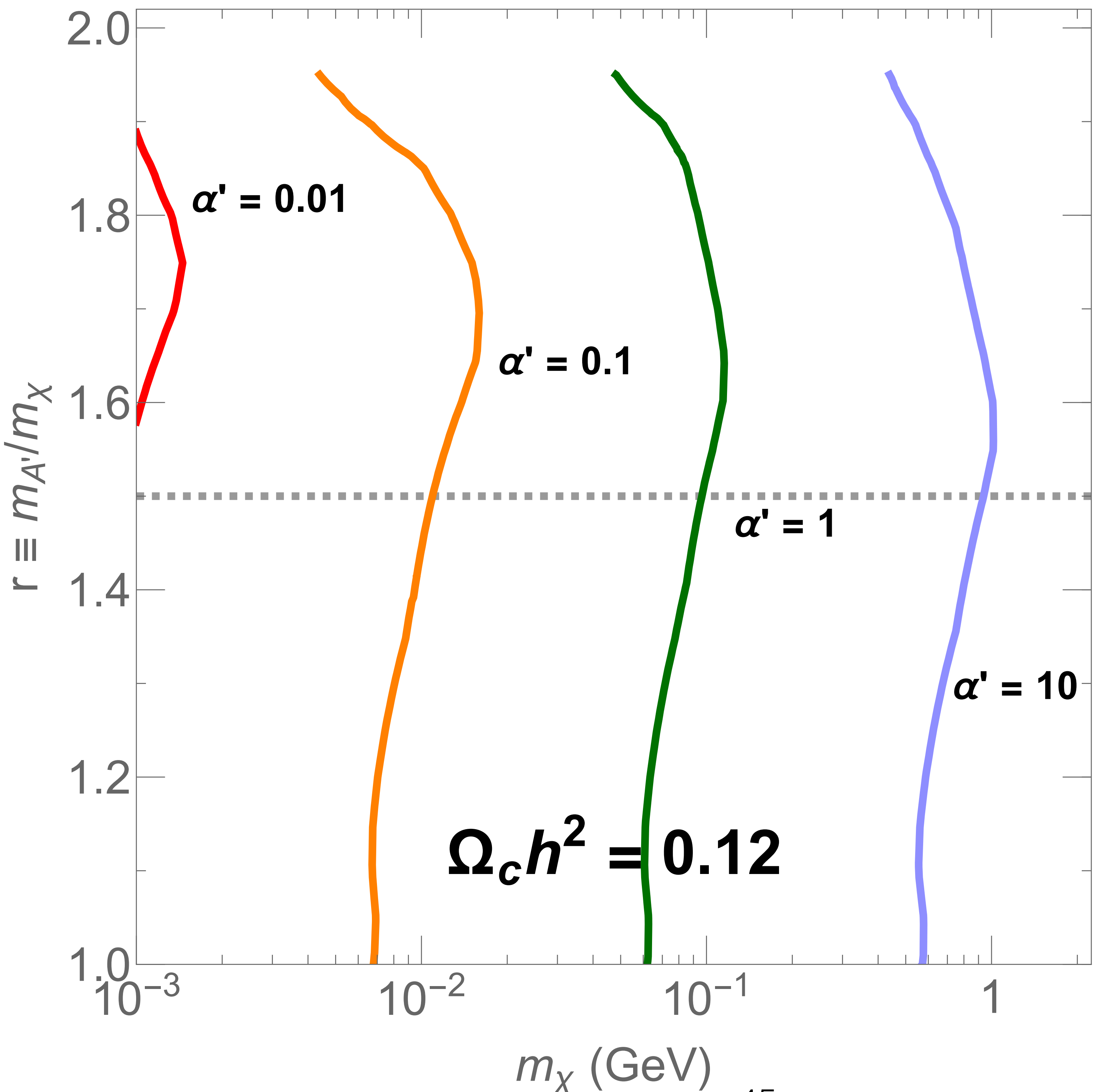


3→2 longer freeze-out

$n_A \neq n_{A0}$
even $\Gamma_A \gg H$

Thermal Relic Contours

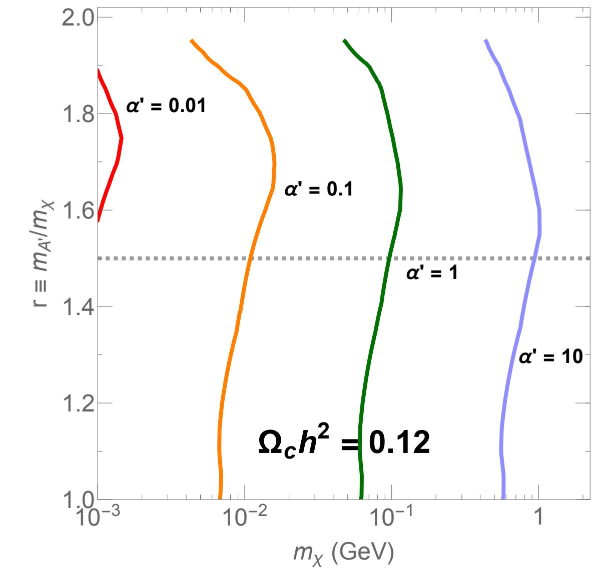


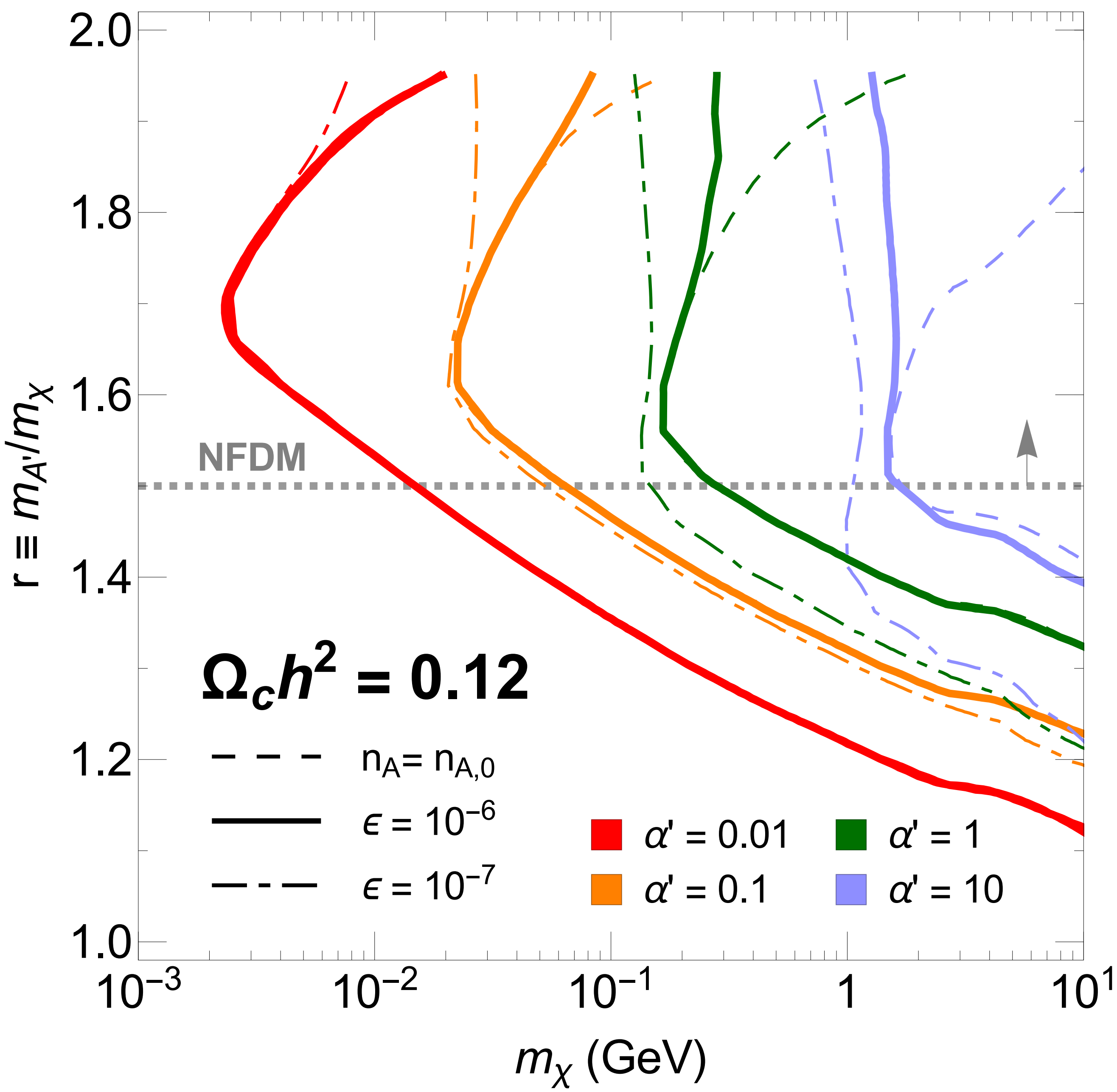


2→2 initializes freeze-out

3→2 initializes freeze-out

Relic Density



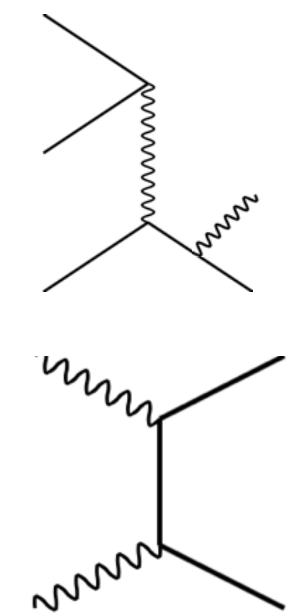


Coupled Boltzmann Equations

dark matter χ

$$\frac{dn}{dt} + 3Hn = -\frac{1}{4}\langle \sigma v^2 \rangle_{\chi\chi\bar{\chi}\to\chi A'}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right)$$

$$+\langle \sigma v \rangle_{A'A'\to\bar{\chi}\chi}\left(n_{A'}^2 - n_{A',0}^2 \frac{n_\chi^2}{n_{\chi,0}^2}\right)$$



dark photon A'

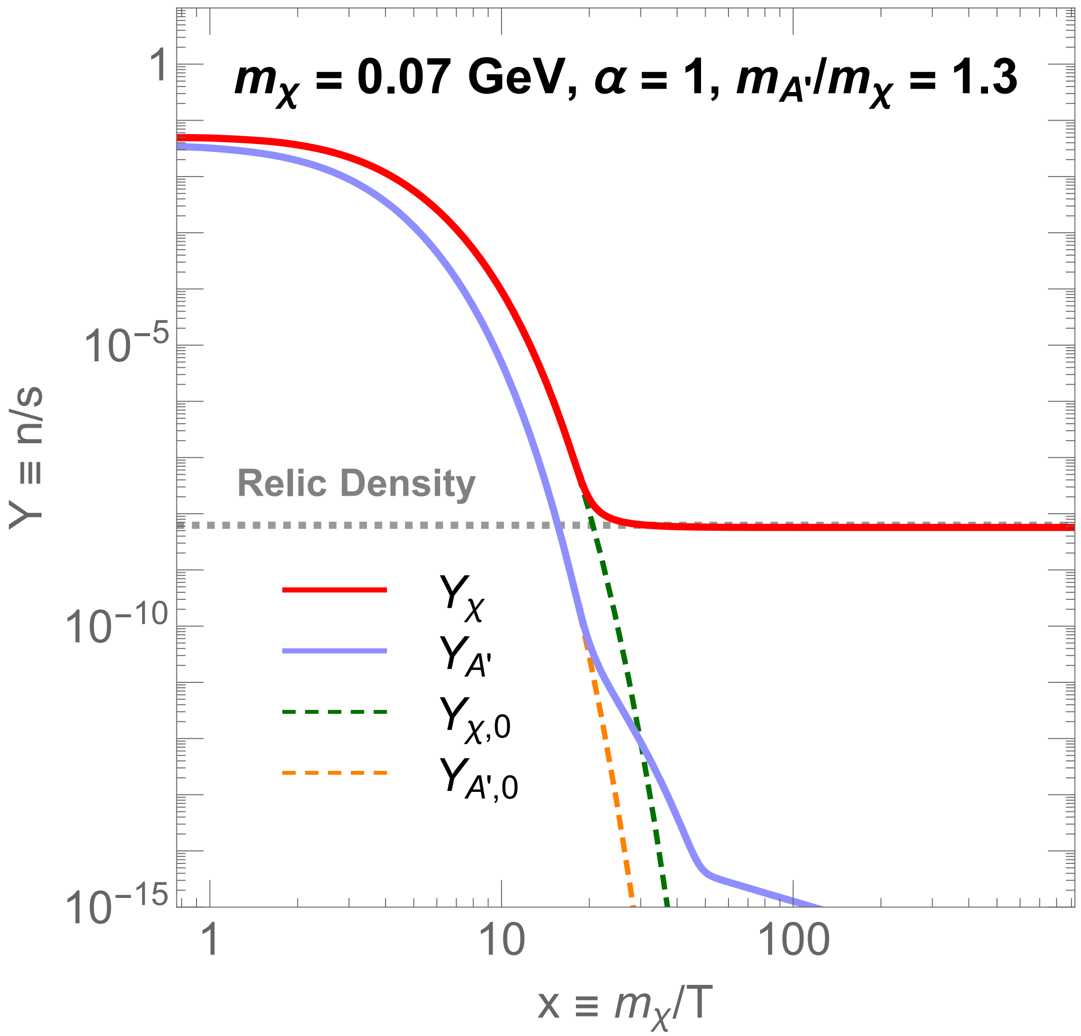
$$\frac{dn_{A'}}{dt} + 3Hn_{A'} = \frac{1}{8}\langle \sigma v^2 \rangle_{\chi\chi\bar{\chi}\to\chi A'}\left(n_\chi^3 - n_{\chi,0}^2 n_\chi \frac{n_{A'}}{n_{A',0}}\right)$$

$$-\langle \sigma v \rangle_{A'A'\to\bar{\chi}\chi}\left(n_{A'}^2 - n_{A',0}^2 \frac{n_\chi^2}{n_{\chi,0}^2}\right) - \Gamma_{A'\to f\bar{f}}\left(n_{A'} - n_{A',0}\right)$$

Short vs Long Freeze-out

$r \lesssim 1.5$

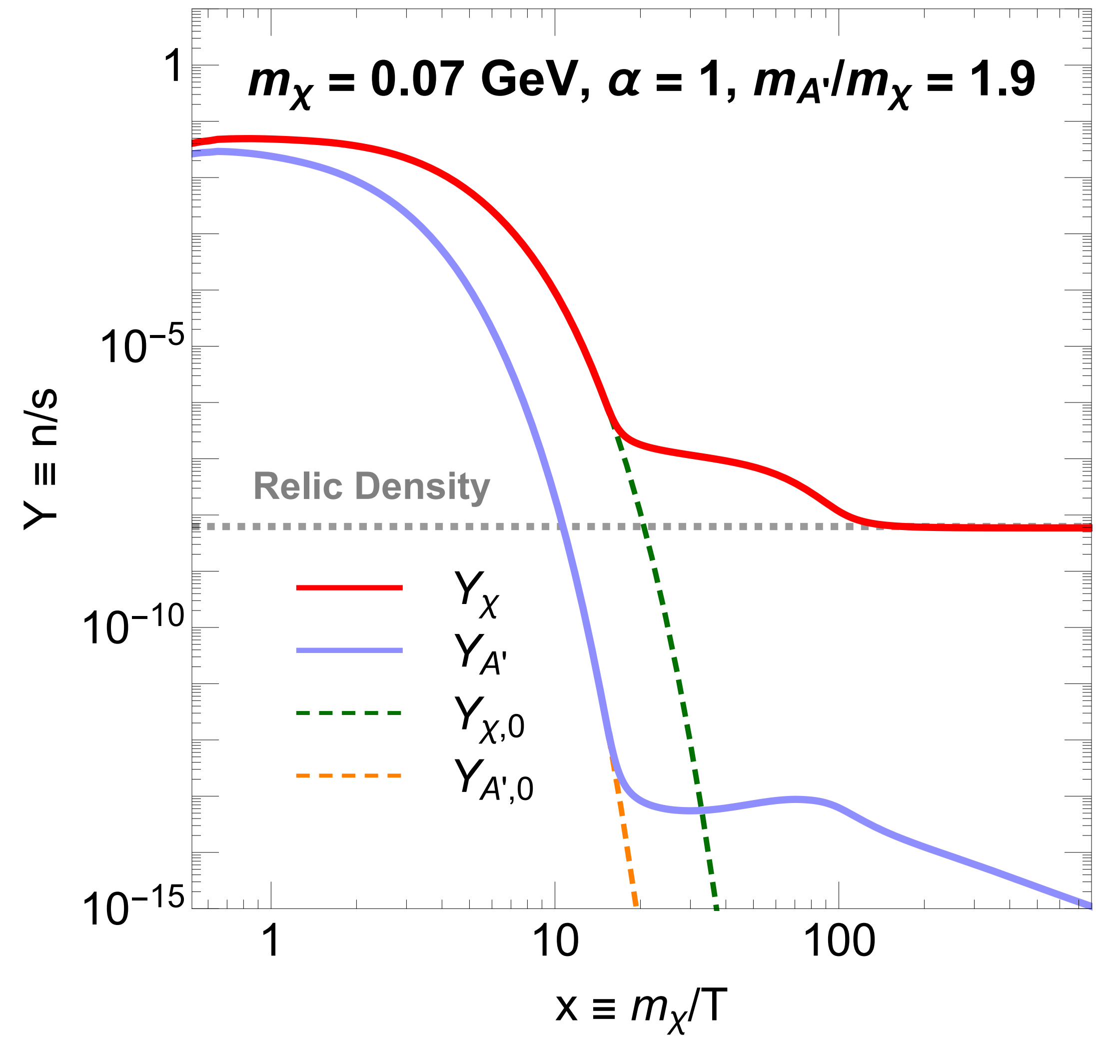
$\Gamma(3 \to 2) \simeq \langle \sigma v^2 \rangle n_\chi^2$

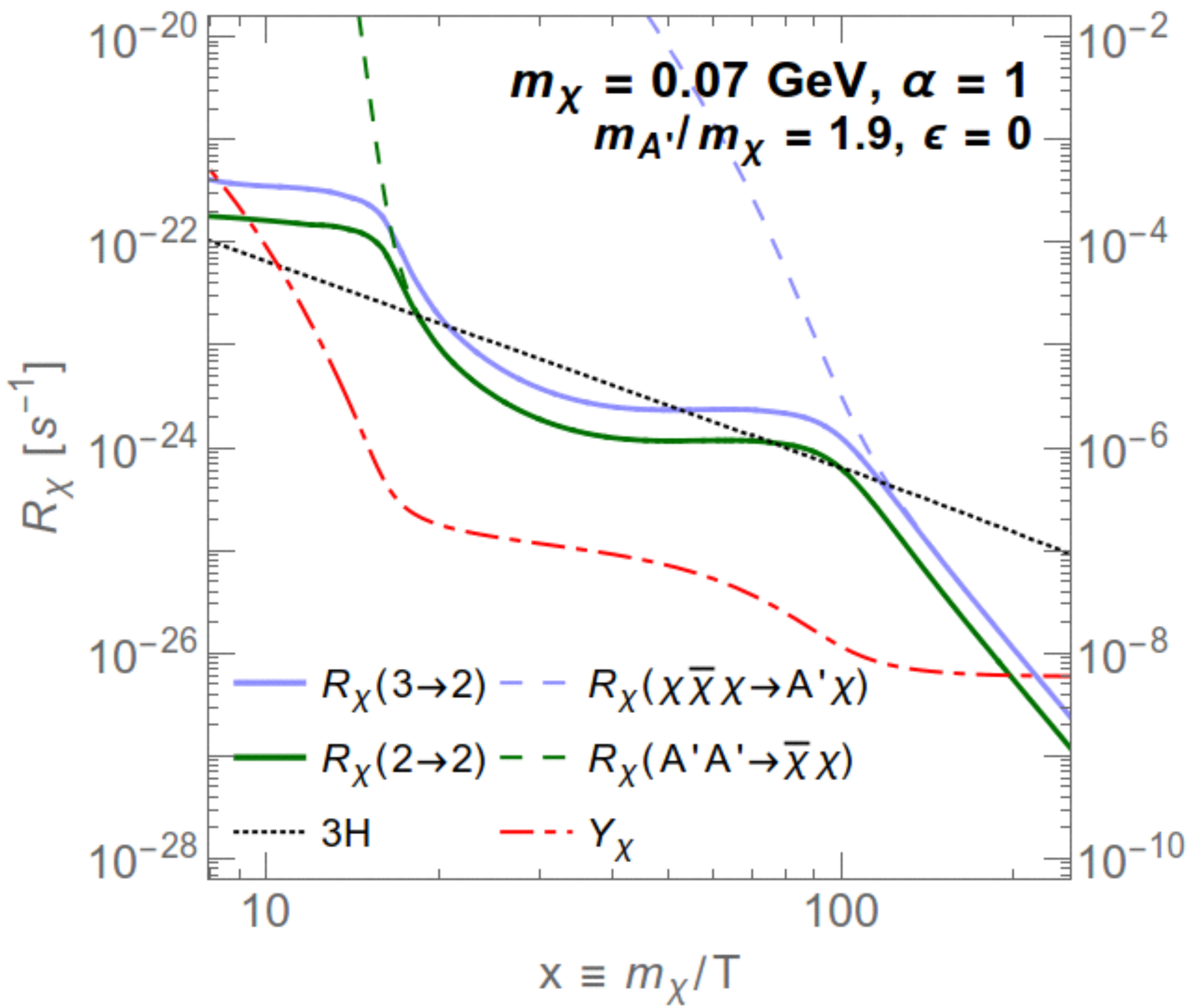


$r \gtrsim 1.5$

$\Gamma(2 \to 2) \simeq \langle \sigma v \rangle n_A^2 / n_\chi$

$n_A = n_{A0}\, n^2 / n_{\chi 0}^2 \propto \exp[-(r-2)x]\, n^2$





m_χ = 0.07 GeV, α = 1
$m_{A'}/m_\chi$ = 1.9, ϵ = 0
$R_\chi(3\to2)$
$R_\chi(\chi\bar{\chi}\chi\to A'\chi)$
$R_\chi(2\to2)$
$R_\chi(A'A'\to\bar{\chi}\chi)$
3H
Y_χ
R_χ [s^{-1}]
$Y_\chi \equiv n_\chi/s$
$x \equiv m_\chi/T$
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10
100