Inelastic DM (iDM) Constraints and Viable Scenarios

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Light Dark World 2025

Sept 18th, 2025 - Madrid

IFUSP
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DFMA
IFUSP

Many Evidences of Dark Matter

But only Gravitational

1930s - Fritz Zwicky noticed a problem with the mass of the Coma Cluster of galaxies

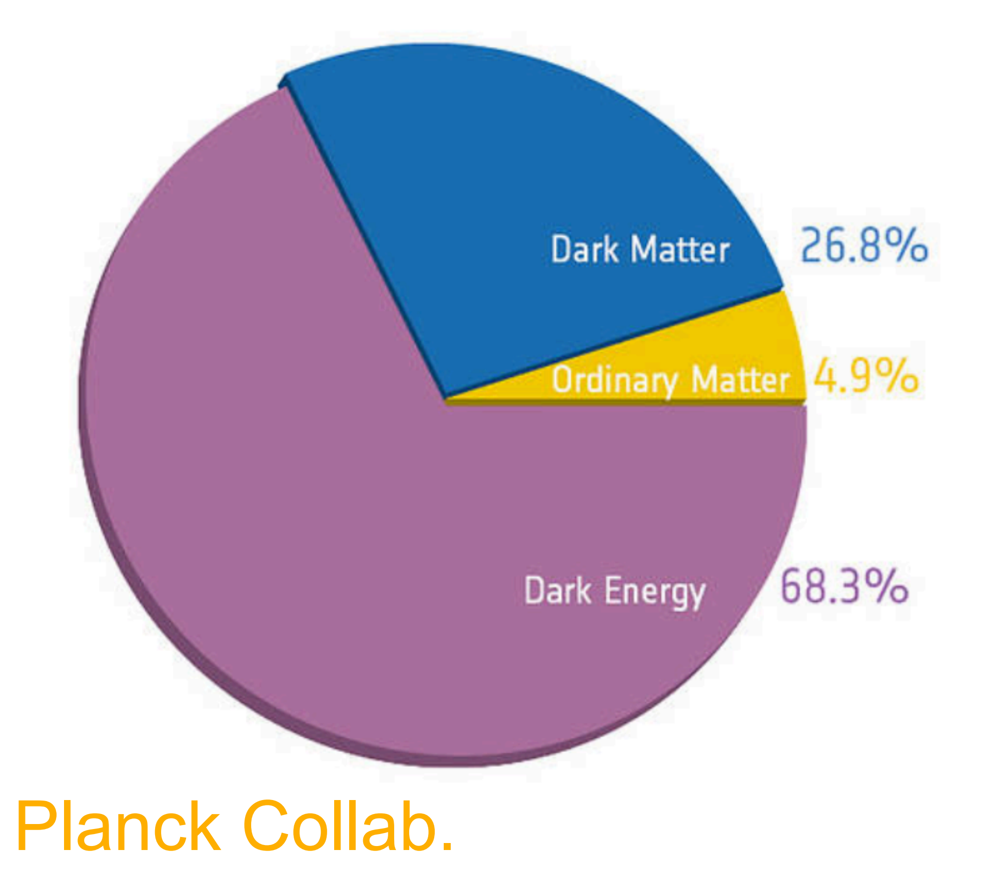
“If this would be confirmed, we would get the surprising result that dark matter is present in much greater amount than luminous matter”

1970s - Vera Rubin provided more compelling evidence of DM by studying the rotation curves of spiral galaxies

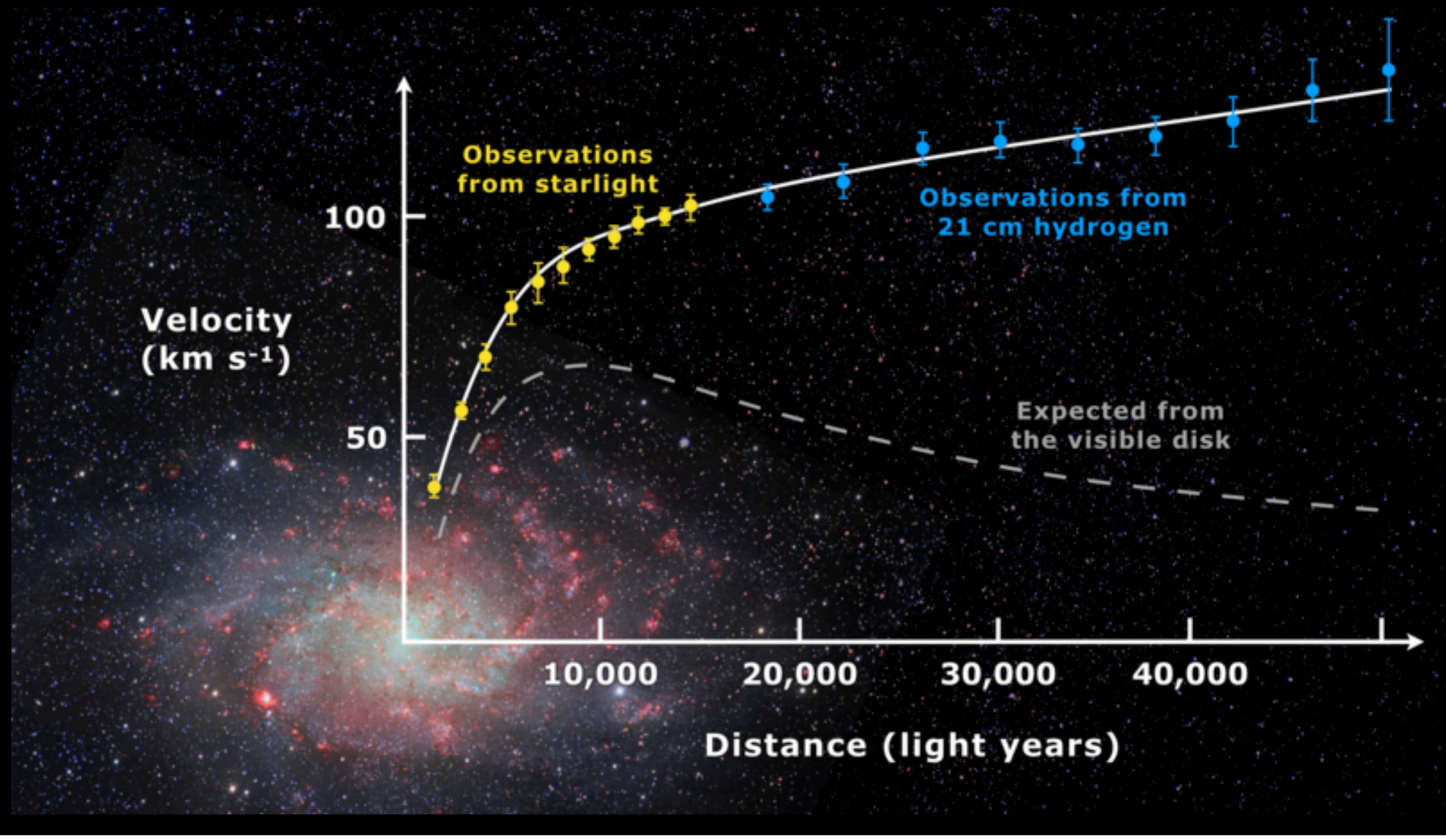
Motion of Galaxies in the Coma Cluster **Rotation Curves of Spiral Galaxies**

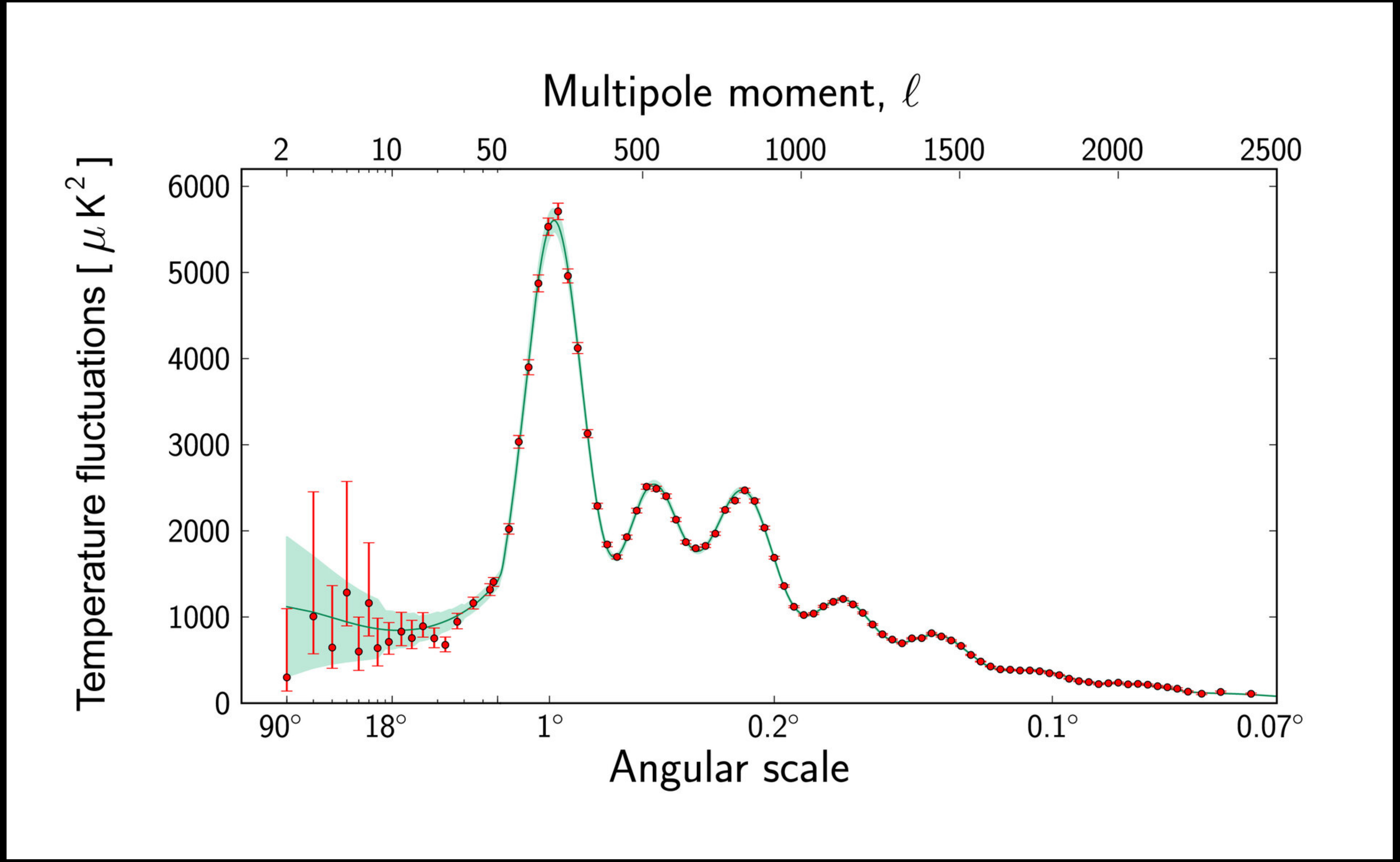
The Bullet Cluster **The Cosmic Microwave Background Radiation**

Gravitational Lensing Data **Large Scale Structure**



Planck Collab.





What have we learned about DM?

After +3 decades of scientific efforts

Cosmologically stable

DARK

COLD or WARM

Almost collisionless

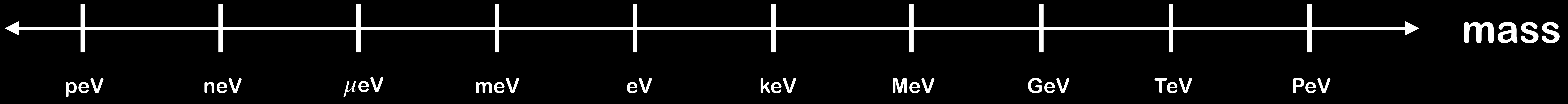
No viable SM Candidate

WIMP Largely Excluded

Evaded All DD/ID/Accelerator Searches so far

So what is DM?

Things we still don’t know



Boson ? Fermion ?

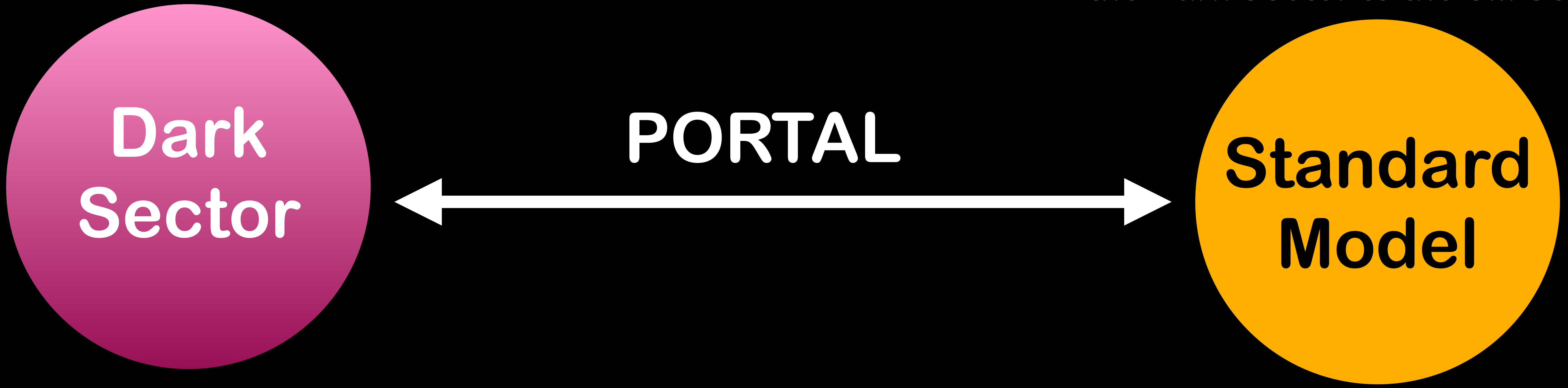
How the relic abundance is produced ?

How many species in the Dark Sector ?

How does DM connect to the SM?

A plausible portal

Need an efficient way to transfer energy density from the Dark Sector to the SM Sector via a Portal (Mediator)

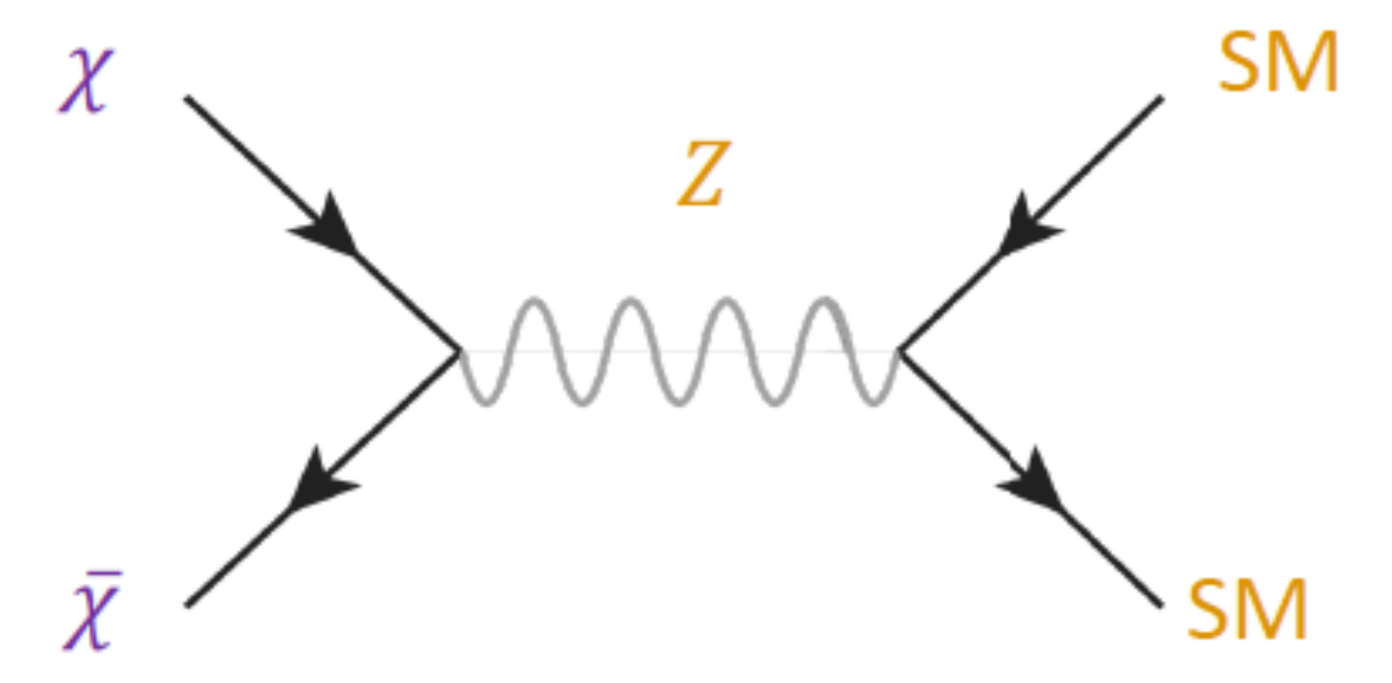


Dark Sector

PORTAL

Standard Model

Natural possibility: couple to SM via weak interactions



$$\langle \sigma v \rangle \simeq \frac{m_\chi^2}{m_Z^4}$$

Can provide the correct observed abundance via thermal freeze-out but

$$m_\chi \gtrsim 2 \text{ GeV}$$

[Lee,Weinberg (1977)]

Inelastic Dark Matter

iDM Main Ideas

Minimal Dark Sector

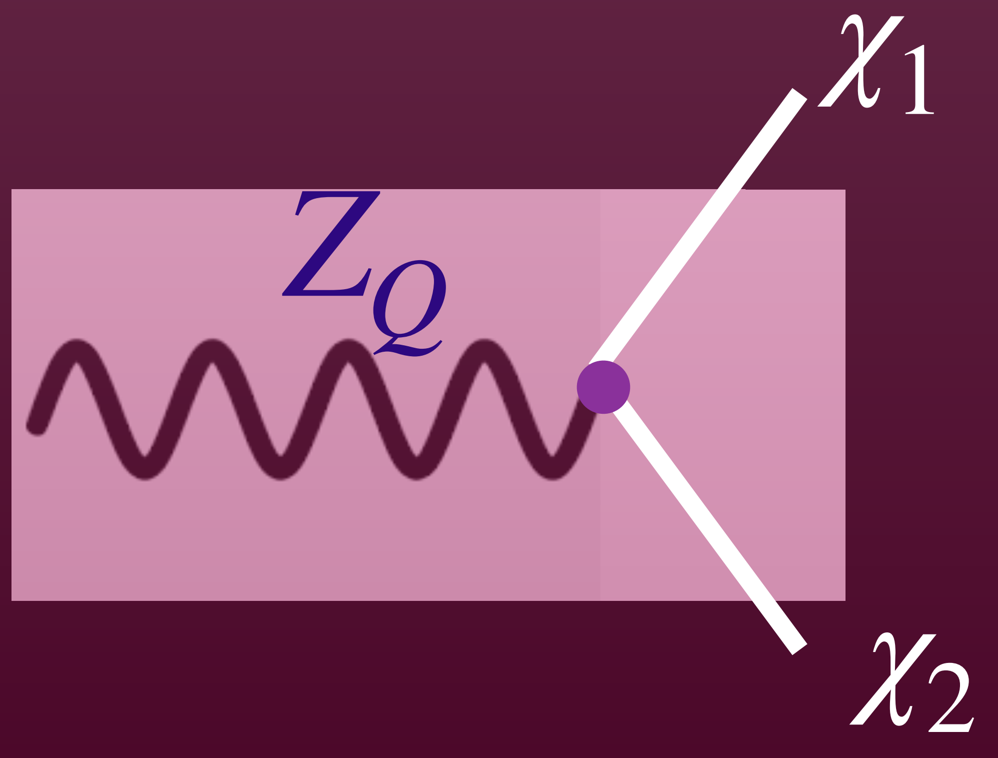
- Pseudo-Dirac fermion pair

[Smith,Weiner (2001)]

$$m_2 - m_1 \ll m_1$$

Small Mass Splitting

- A vector current that is purely off-diagonal



Inelastic Dark Matter

Motivations

- **Thermal relics:** DM abundance can be computed via thermal freeze-out

- **Evades direct detection bounds:**

$\chi_1 + N \rightarrow \chi_1 + N$ **Elastic Scattering** loop suppressed + scattering predominately off nucleons i.e. no Z^4 enhancement from coherent scattering

[Izaguirre, Krnjaic, Shuve (2015)]

$\chi_1 + N \rightarrow \chi_2 + N$ **Inelastic Scattering** only allowed if $\Delta < \dfrac{\beta^2 m_N}{2(m_\chi + m_N)} \sim 10^{-6}$

- **Evades indirect direct signals**

χ_2 abundance negligible after DM freeze-out

no present-day population of χ_2 to co-annihilate with DM

Inelastic Dark Matter

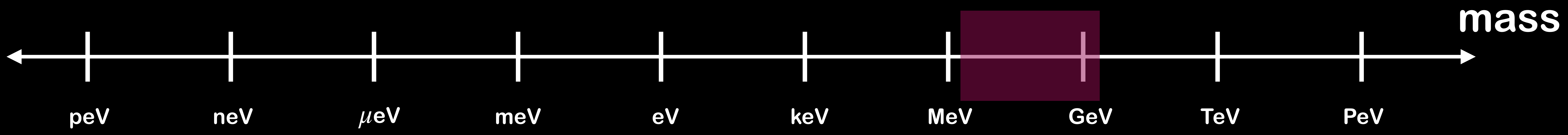
Motivations

- **Evades stringent CMB limits** [Planck Collab. (2020)]

  the abundance of χ_2 is already negligible during recombination era (co-annihilation that would inject energy into the plasma is suppressed)

- **The Light Dark Sector can be produced @ high intensity accelerators**

  the unstable χ_2 can be probed in current and future facilities (testable @ Earth!)



Inelastic Dark Matter

Theoretical Description

$\psi_{1,2}$ are the Weyl components of a Dirac spinor charged under U(1)$_Q$ Abelian gauge symmetry

$$\mathscr{L} \supset q_D\, g_Q\, Z_{Q\mu}(\psi_1^\dagger \bar{\sigma}^\mu \psi_1 - \psi_2^\dagger \bar{\sigma}^\mu \psi_2) \longrightarrow \mathscr{L}^{\mathrm{D}}_{\mathrm{int}} = i g_D Z_{Q\mu}\overline{\chi_2}\gamma^\mu \chi_1 + \mathrm{h.c.}$$

After the gauge symmetry is spontaneously broken these components can acquire a Majorana Mass

$$\mathscr{L} \supset -\underbrace{m_D \psi_1 \psi_2}_{\text{Dirac}} - \underbrace{\frac{1}{2}(\delta_1\, \psi_1^2 + \delta_2\, \psi_2^2)}_{\text{Majorana}} + \mathrm{h.c.} \qquad \delta_1 \sim \delta_2 \ll m_D$$

Mass Eigenstates

χ_2

χ_1

pseudo-Dirac pair with nearly degenerate masses

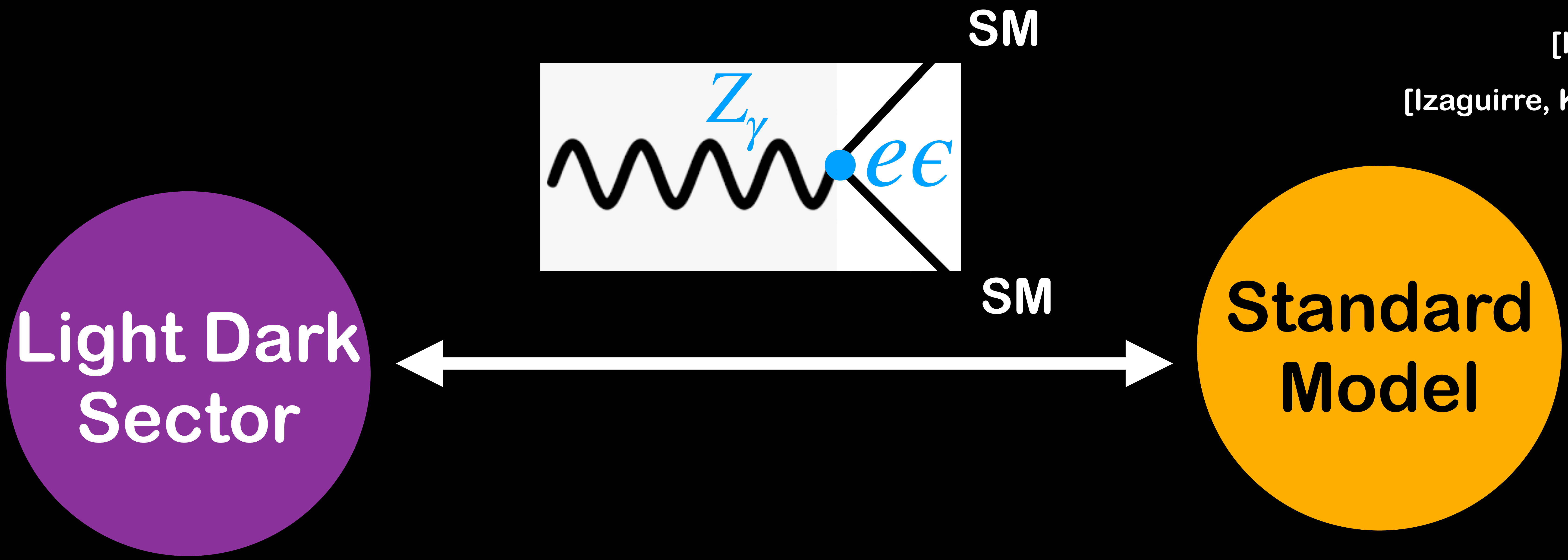
$$\Delta := \frac{m_2 - m_1}{m_1} = \frac{\delta_1 + \delta_2}{m_1} < 1$$

χ_1, χ_2 are odd under a global Z_2 symmetry
χ_1 is lightest state charged under this symmetry
i.e. stable on cosmological scale

Inelastic Dark Matter

Vanilla Case

$$\mathscr{L}^{\mathrm{SM}}_{\mathrm{int}} = e\epsilon J^{\mu}_{\mathrm{em}} Z_{\gamma\mu}$$



[Izaguirre, Krnjaic, Shuve (2015)]

[Izaguirre, Kahn, Krnjaic, Moschella (2017)]

[Belin, Kling (2019)]

[Belin, Krnjaic, Pinetti (2023)]

[Jodlowski (2023)]

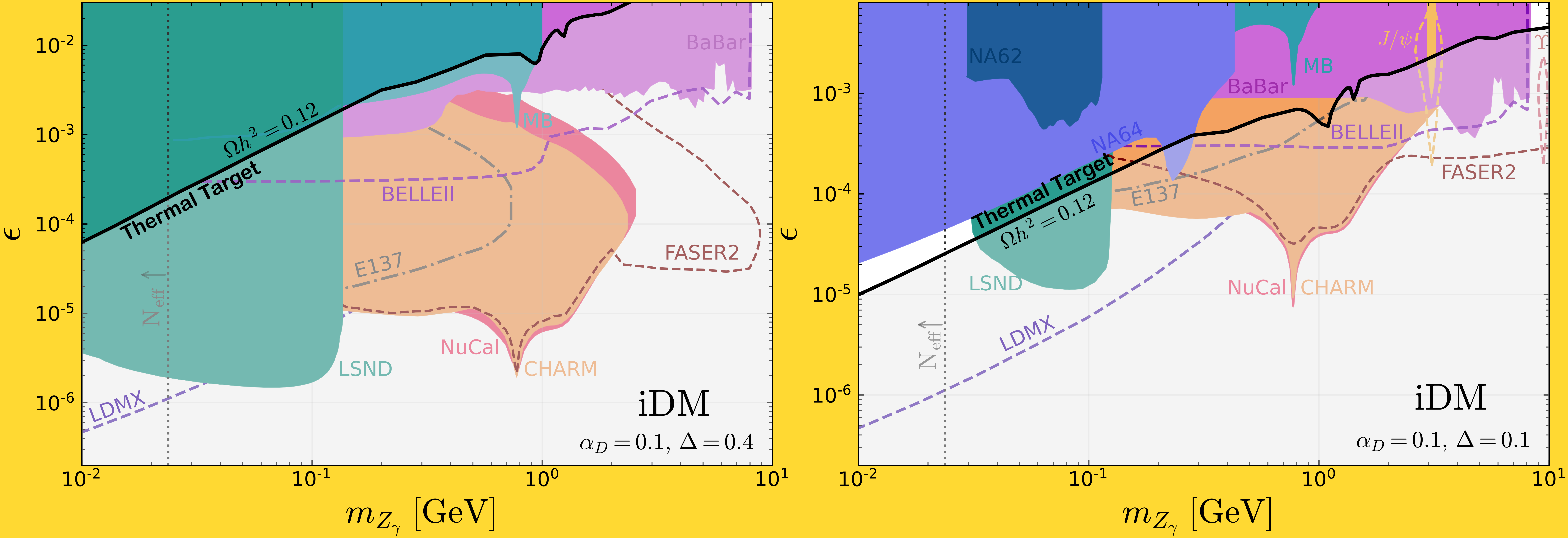
Vanilla iDM = dark photon portal

Inelastic Dark Matter

Vanilla Case

See also Sara Bianco, Victor Martín Lozano @LDW2025

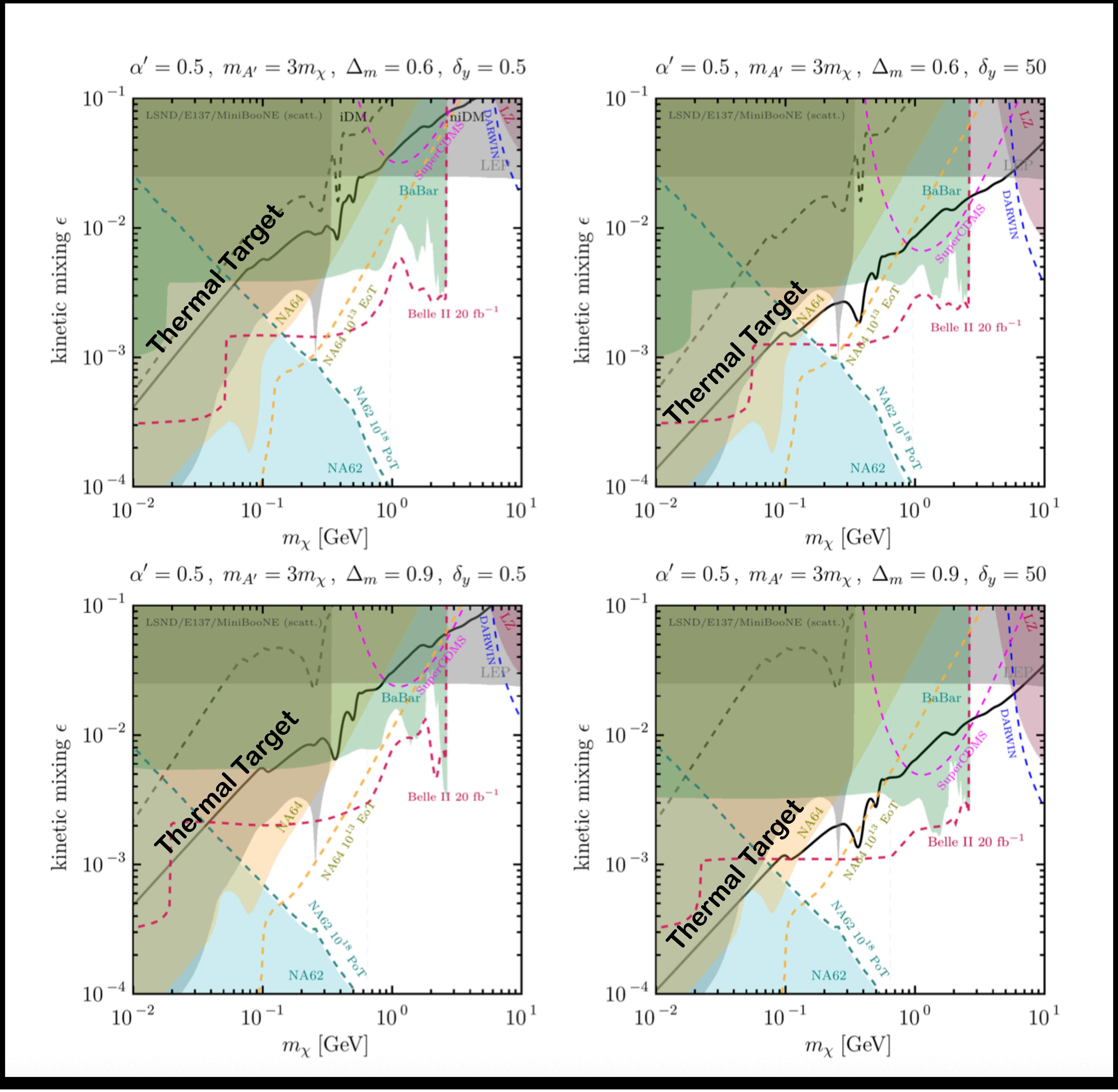
nearly ruled out by experiments



No-so-inelastic Dark Matter

$\delta_1 \neq \delta_2$

[G. Garcia+ (2025)]



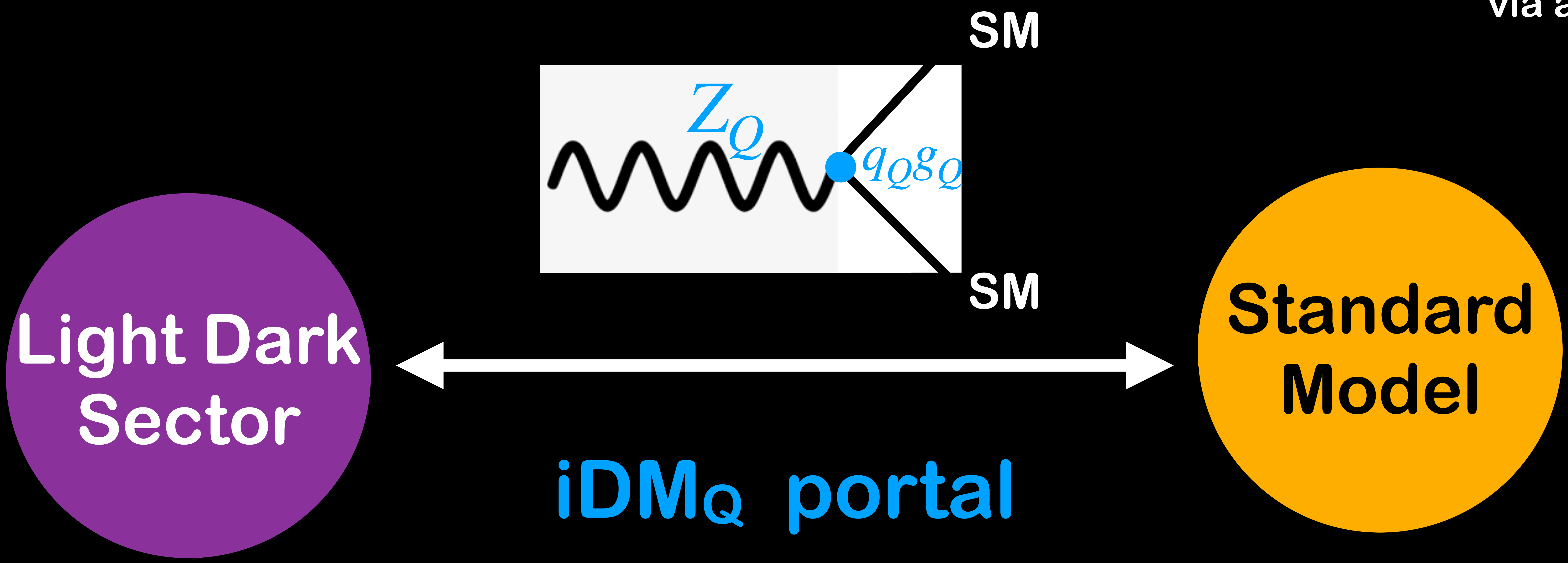
Inelastic Dark Matter

Generic iDM$_Q$ - case of a generic U(1)$_Q$

[Foguel, Reimitz, RZF (2025)]

Dark mediator couples to the SM via a direct term

$$\mathscr{L}^{\rm SM}_{\rm int} = g_Q J^\mu_Q Z_{Q\mu}$$



SM

SM

Light Dark Sector

Standard Model

iDM$_Q$ portal

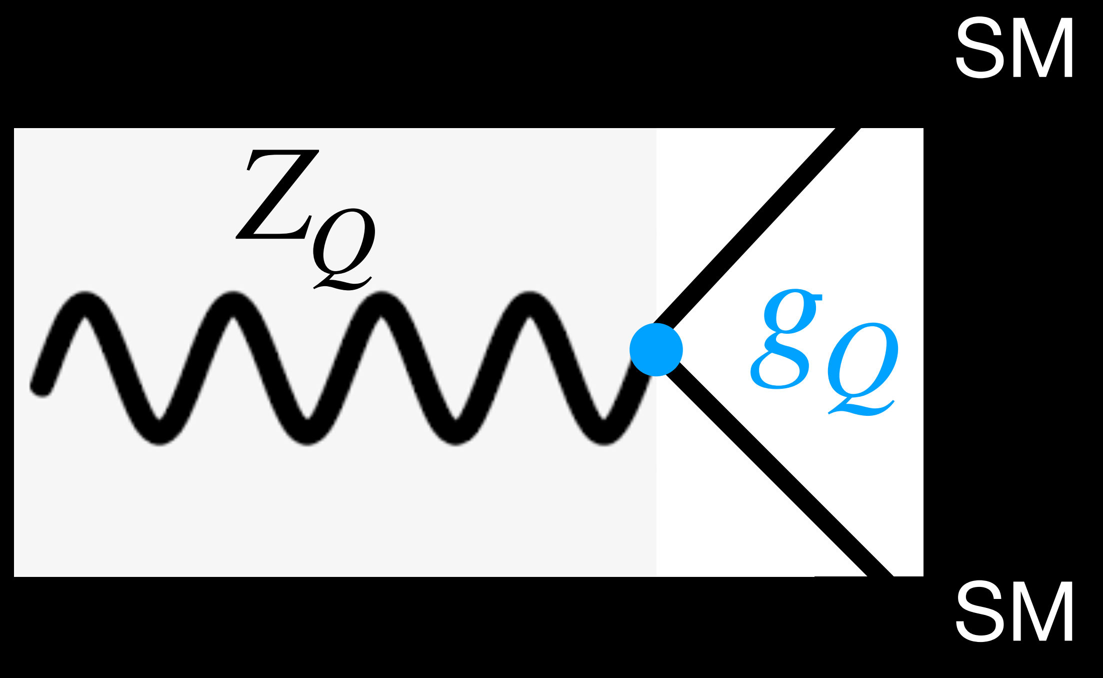
$$J^\mu_Q = \sum_f q^f_Q \bar f \gamma^\mu f + \sum_{\ell=e,\mu,\tau} q^{\nu_\ell}_Q \bar\nu_\ell \gamma^\mu P_L \nu_\ell$$

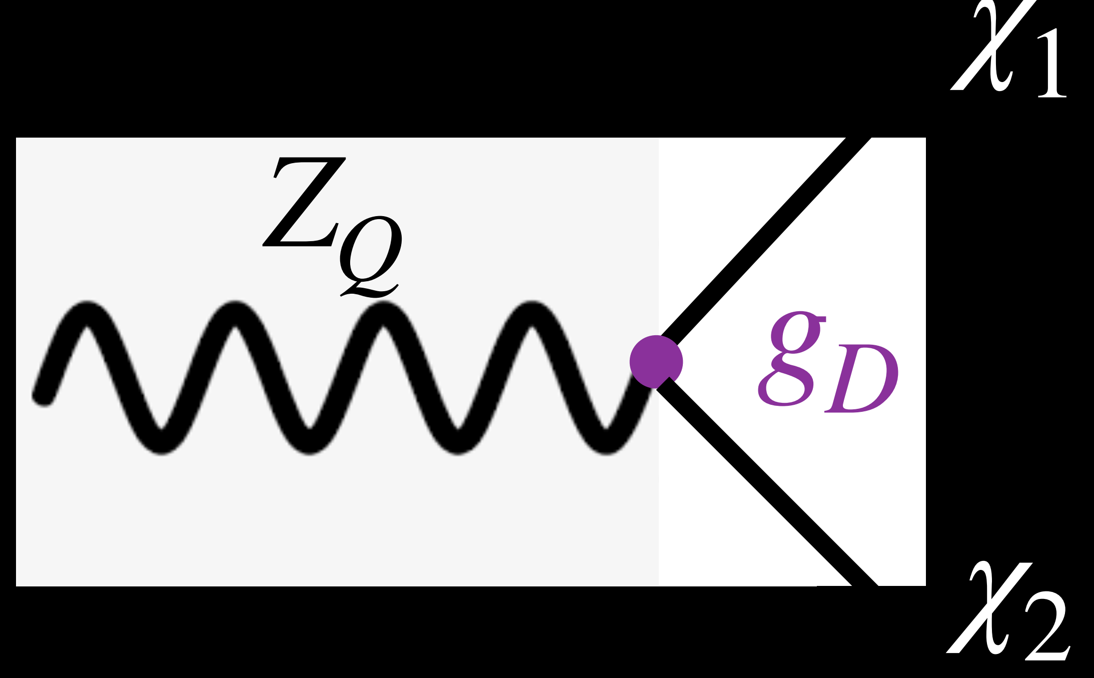
$$\text{e.g.}, Q = B - L, B - 3L_\tau, L_\mu - L_\tau$$

depending on the choice of charge

IDM$_Q$ Models

Free Parameters Choice





$$U(1)_Q \qquad m_{Z_Q} \qquad \Delta \qquad g_Q \qquad \alpha_D \equiv \frac{g_D^2}{4\pi} \qquad R \equiv \frac{m_{Z_Q}}{m_1}$$

$$\epsilon \ll g_Q \qquad 10^{-2} < \frac{m_{Z_Q}}{\mathrm{GeV}} < 10 \qquad \Delta = 0.1\ (0.4) \qquad R = 3$$

Light Dark Sector

on-shell

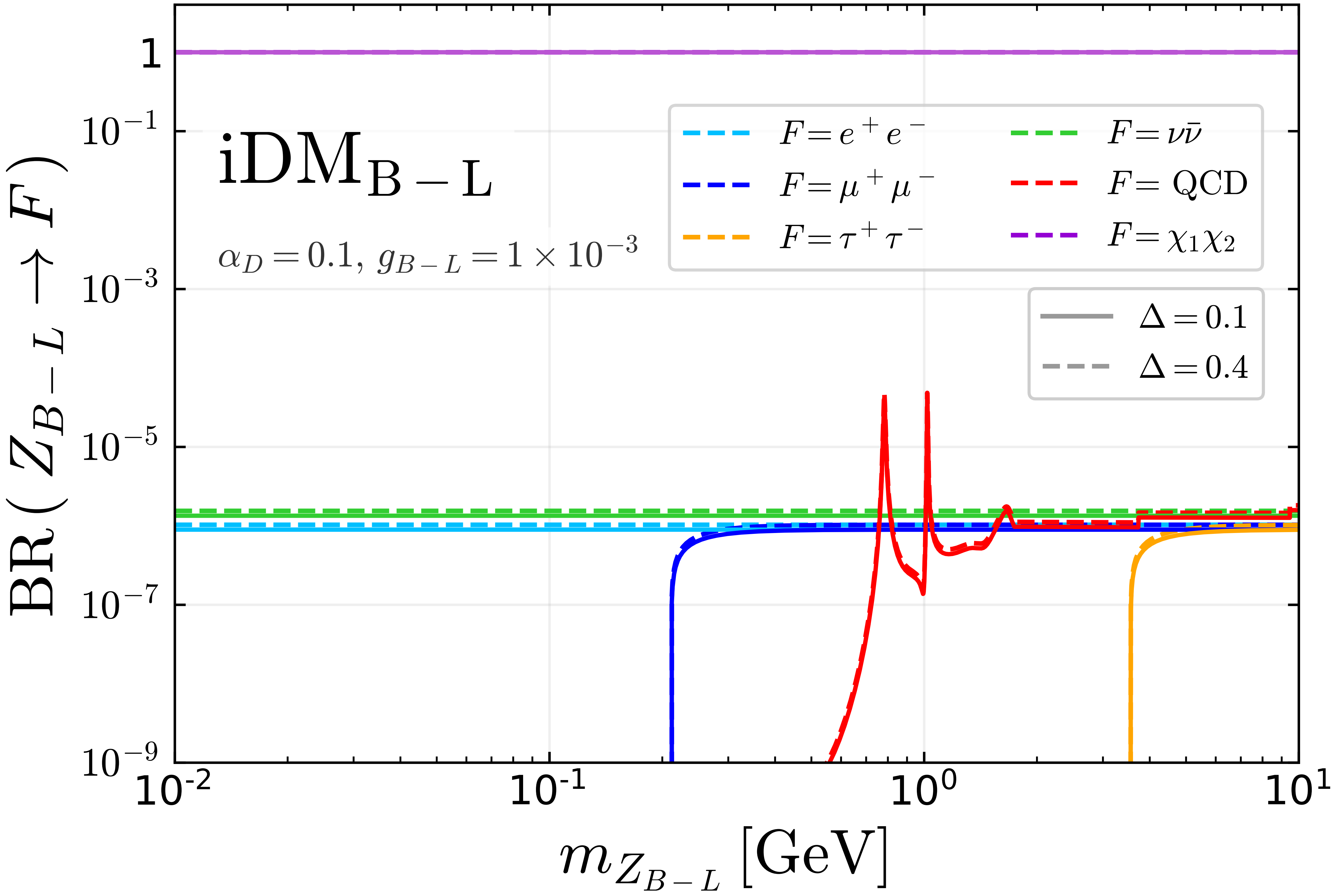
$Z_Q \rightarrow \chi_1 + \chi_2$

IDM$_Q$ Models

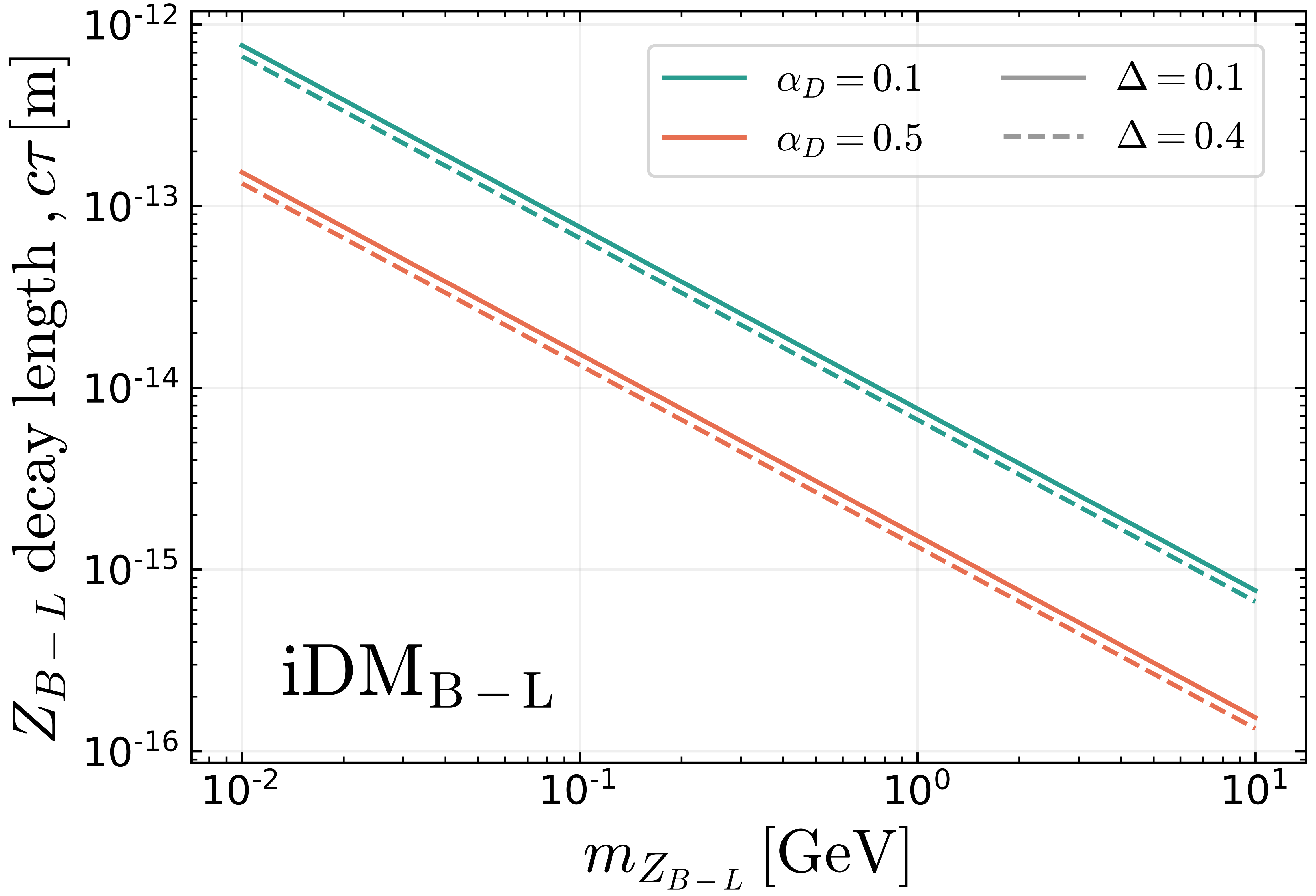
Z$_Q$ Decay Rates

$R = 3$

$$Z_{B-L} \rightarrow \chi_1 + \chi_2$$

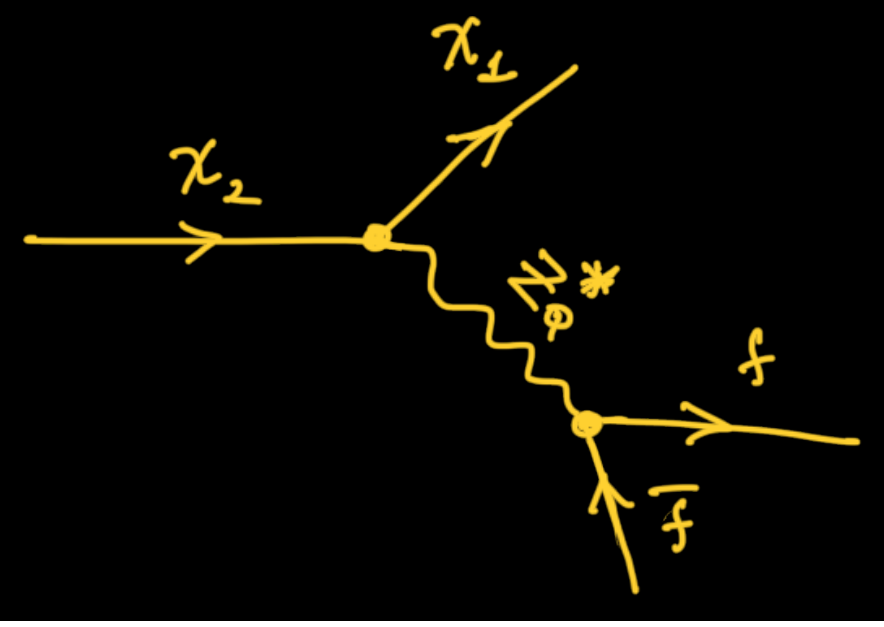


Prompt Decay

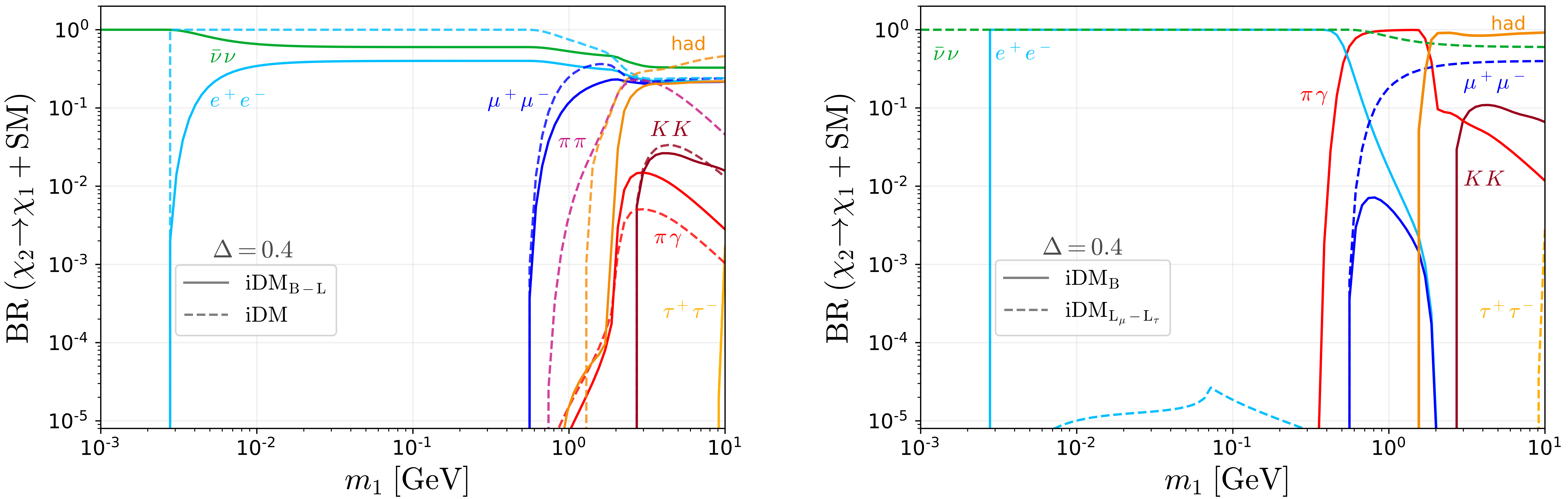


IDM$_Q$ Models

χ_2 Decay Rates

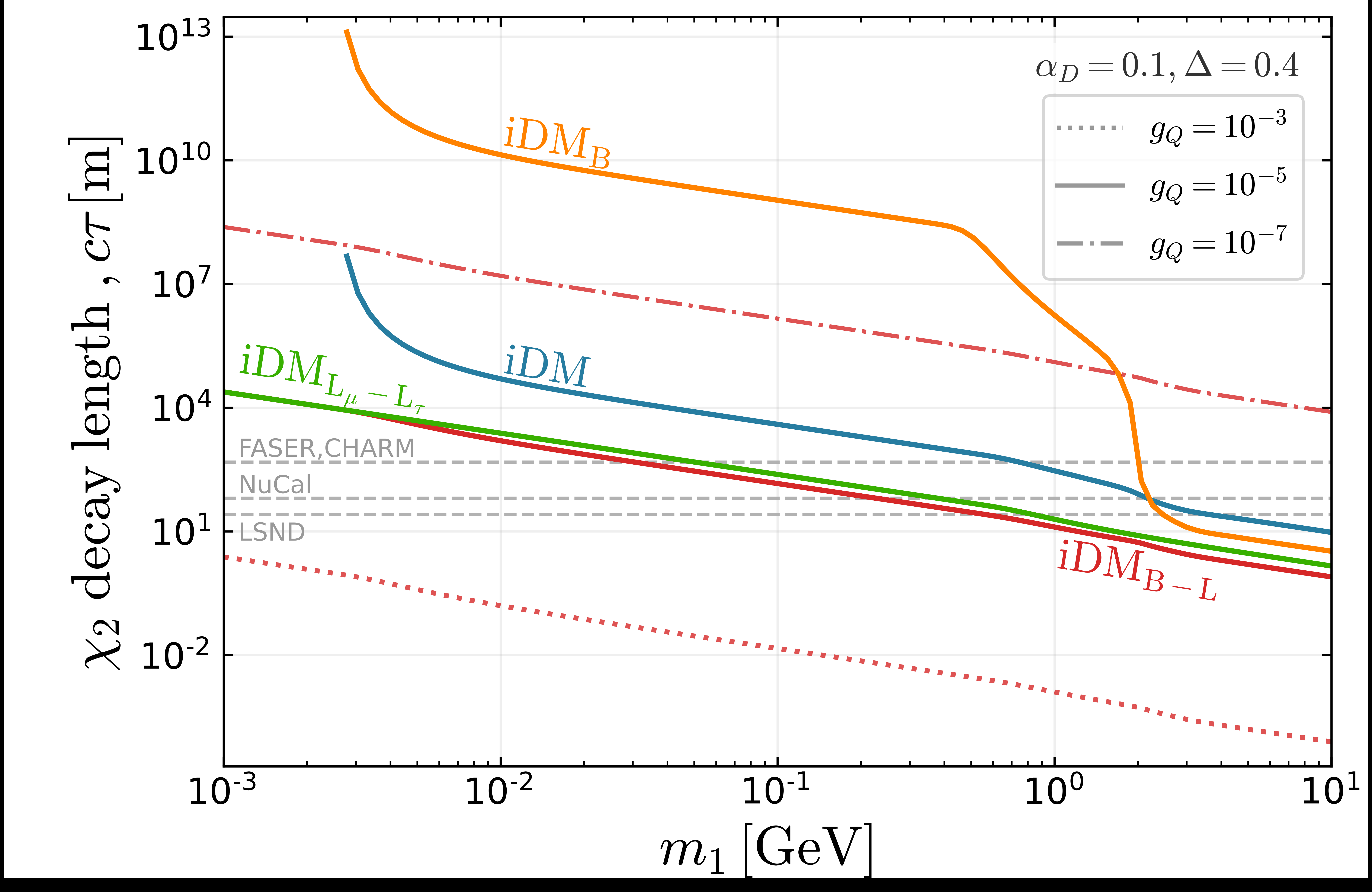


$$\Gamma(\chi_2 \to \chi_1 \bar{f} f) \simeq \frac{4\,\alpha_Q\,\alpha_D\,\Delta^5\,m_{Z_Q}}{15\pi R^5}$$



IDM$_Q$ Models

χ_2 Decay Rates



IDM$_Q$ Models

Relic Density Calculation

evolution parameter

$$x \equiv \frac{m_2}{T}$$

SM bath temperature

co-moving number density

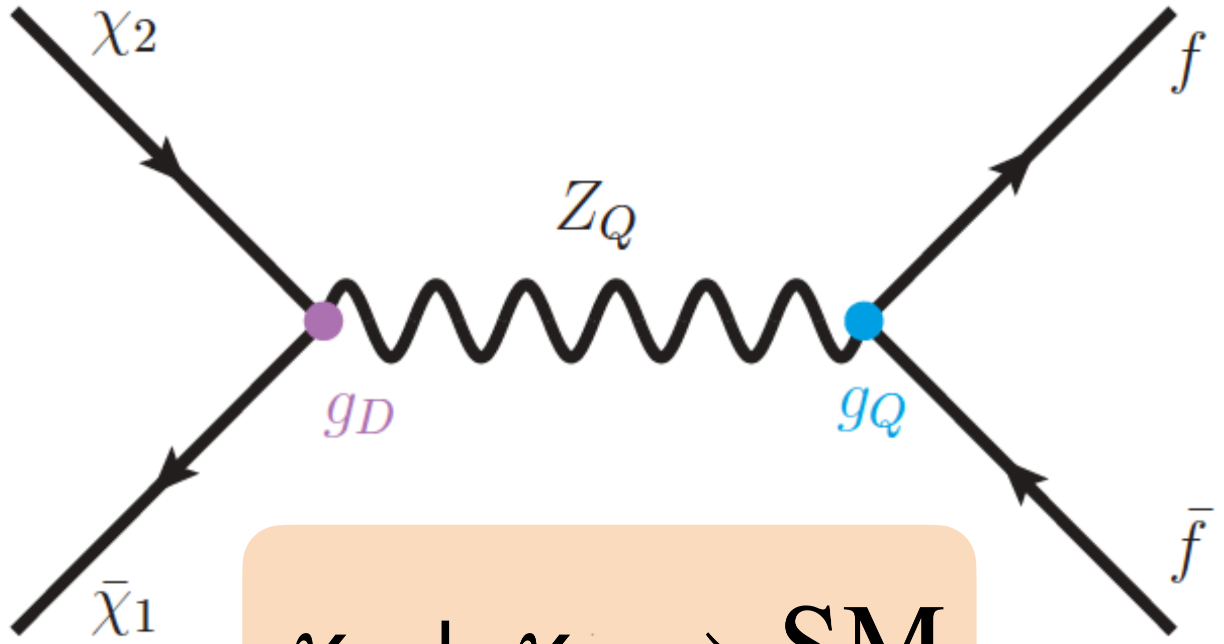
$$Y_{1,2} \equiv \frac{n_{1,2}}{s}$$

entropy density

Boltzmann Equations

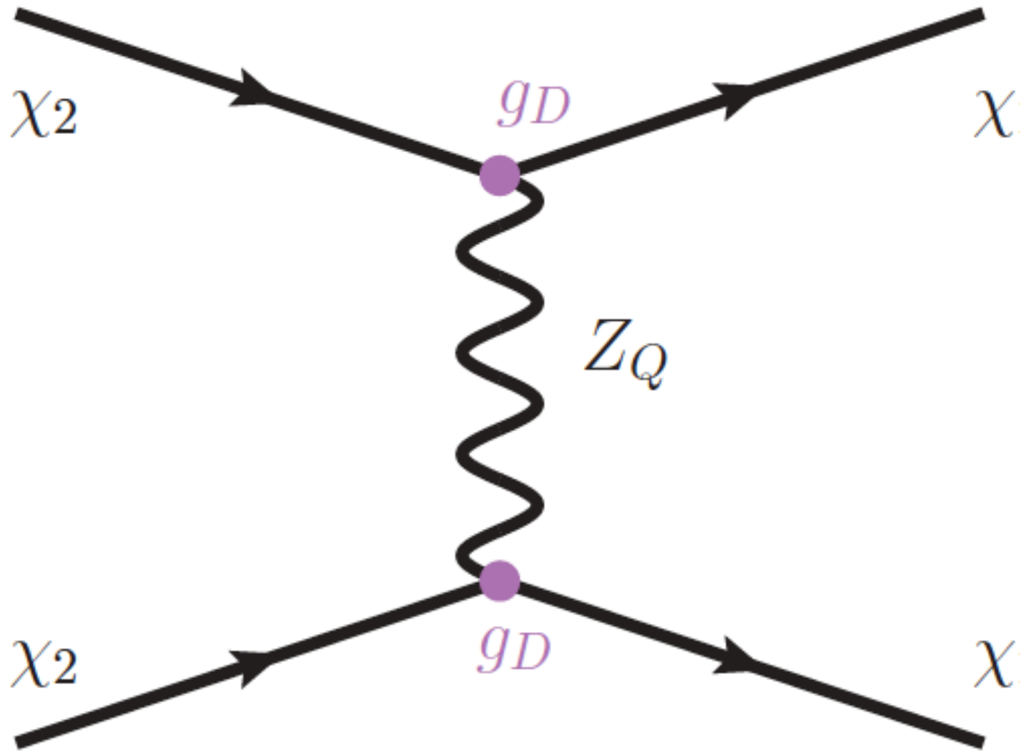
$$\frac{dY_{1,2}}{dx} = \frac{s}{Hx}\left[-\langle\sigma v\rangle_{12\to ff}(Y_1Y_2 - Y_1^{\rm eq}Y_2^{\rm eq}) \pm 2\langle\sigma v\rangle_{22\to 11}\left((Y_2)^2 - (Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}})^2\right) \pm \left(\langle\sigma v\rangle_{2f\to 1f}Y_f^{\rm eq} + \frac{1}{s}\langle\Gamma\rangle_{2\to 1ff}\right)\left(Y_2 - Y_1\frac{Y_2^{\rm eq}}{Y_1^{\rm eq}}\right)\right]$$

main contribution to set abundance



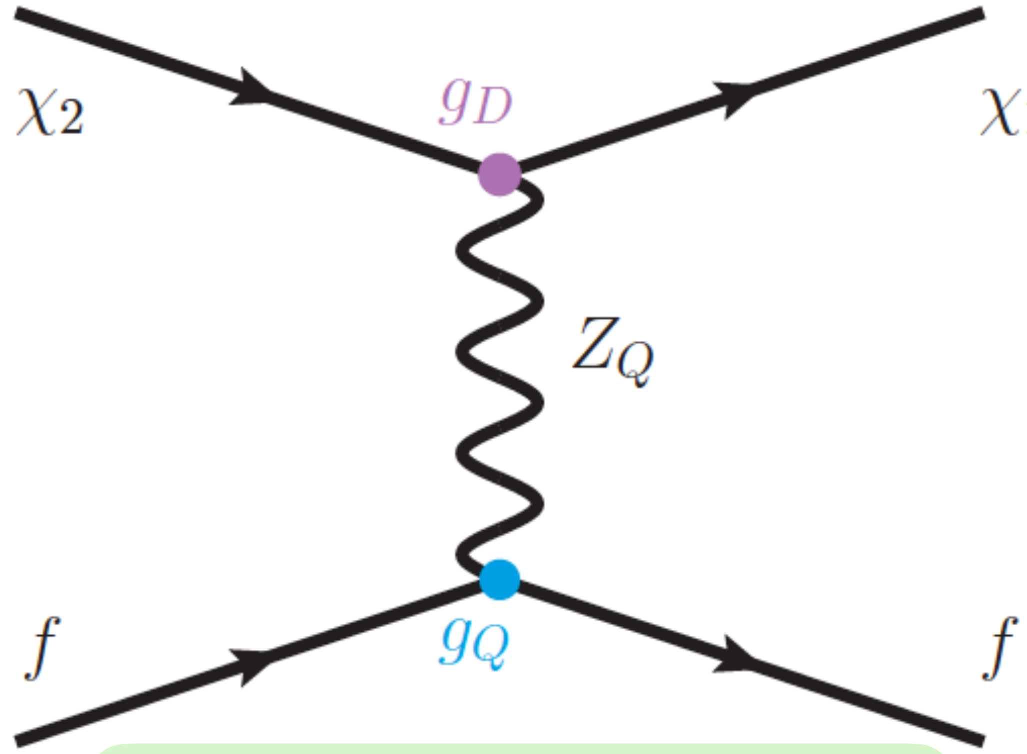
$$\chi_2 + \chi_1 \to \text{SM}$$

co-annihilation



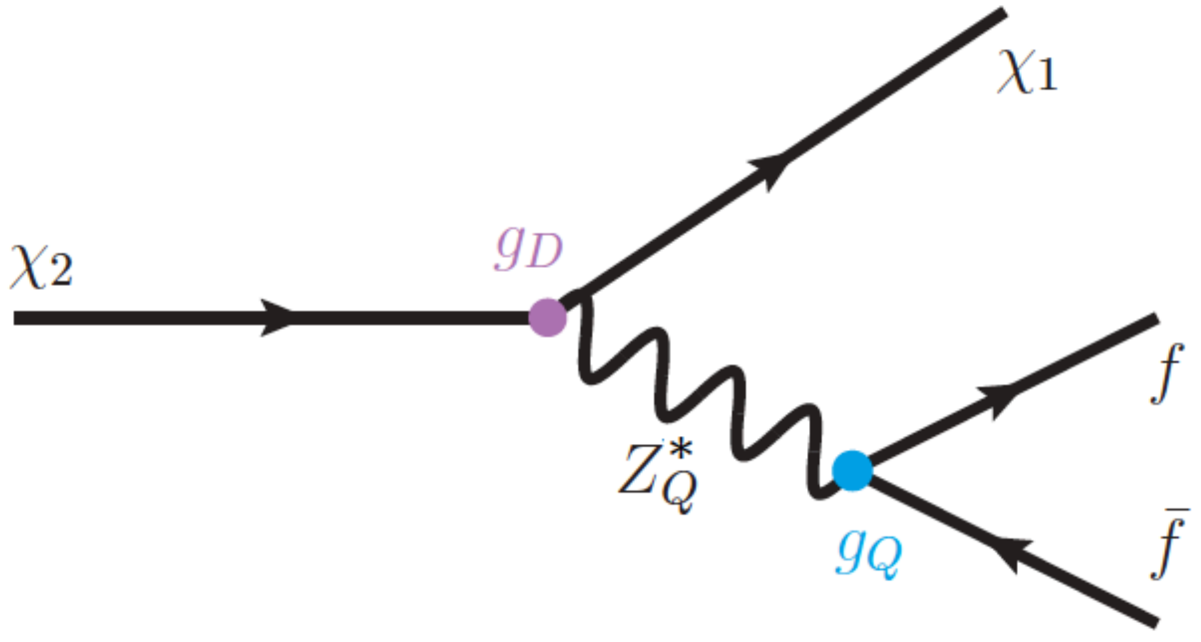
$$\chi_2 + \chi_2 \to \chi_1 + \chi_1$$

$\chi_2 - \chi_1$ scattering



$$\chi_2 + f \to \chi_1 + f$$

$\chi_2 - f$ inelastic scattering



$$\chi_2 \to \chi_1 + \text{SM}$$

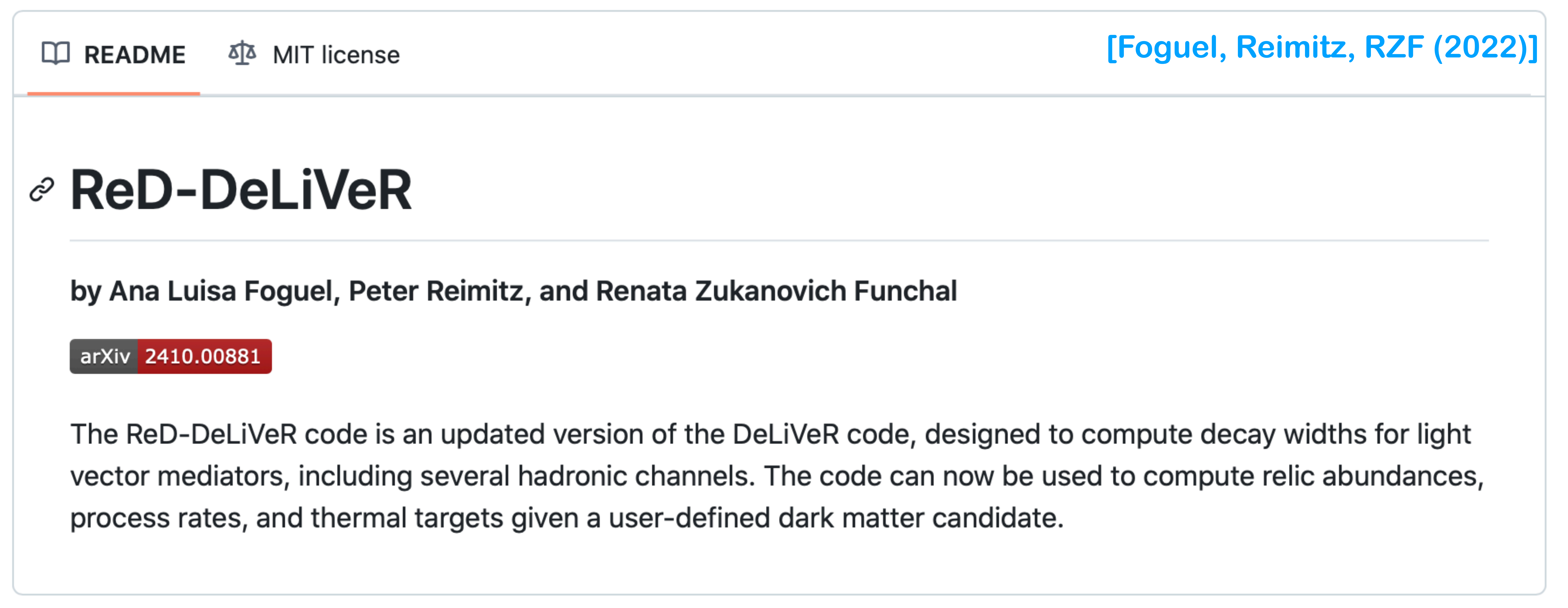
χ_2 decay

IDM$_Q$ Models

Python package ReD-DeLiVeR (Relic Density with DeLiVeR)

http://github.com/preimitz/DeLiVeR

Designed to numerically solve the Boltzmann Equations and evaluate the relic density curves and thermal targets for simplified DM models and the iDMQ scenario



[Foguel, Reimitz, RZF (2022)]

ReD-DeLiVeR

by Ana Luisa Foguel, Peter Reimitz, and Renata Zukanovich Funchal

arXiv 2410.00881

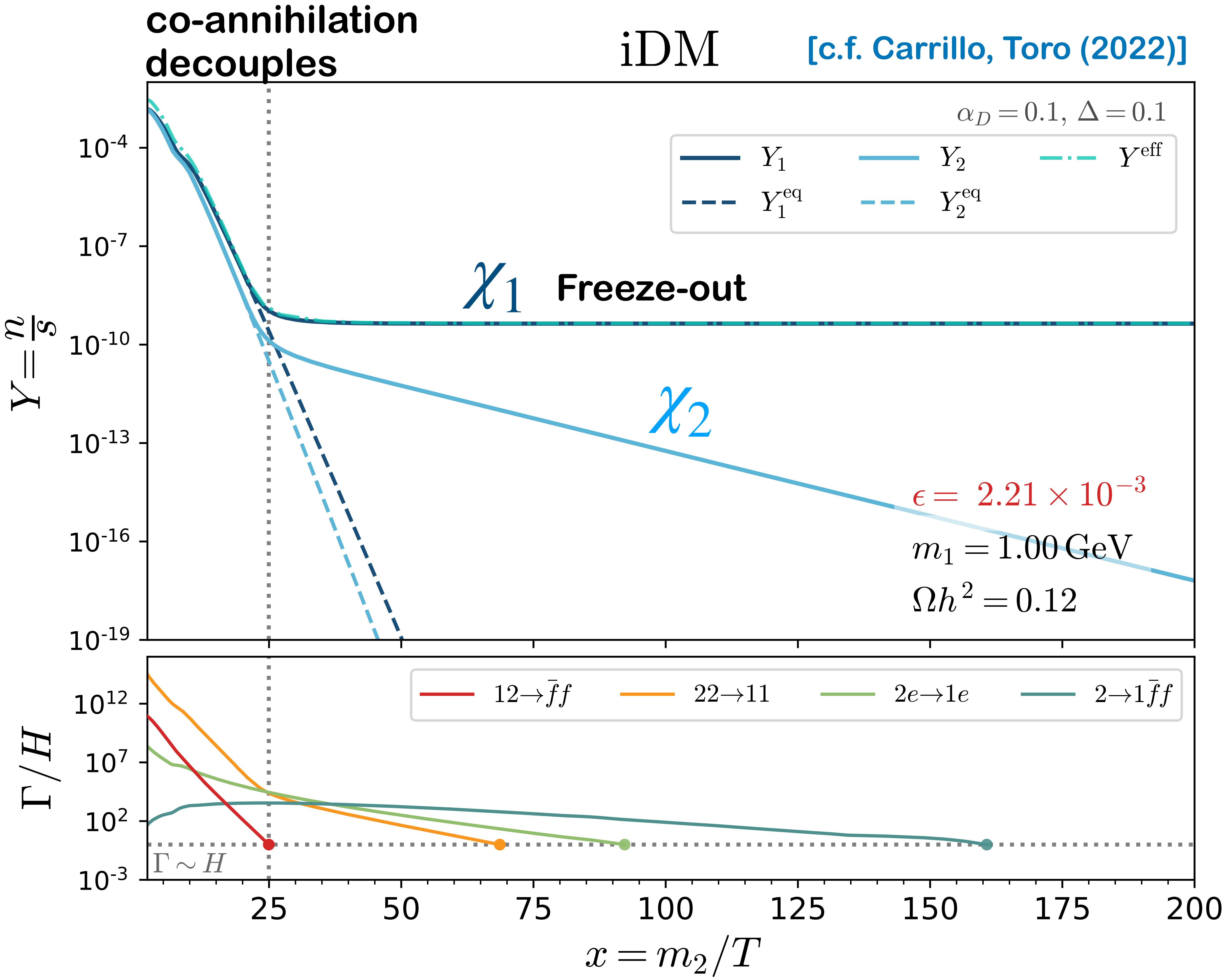
The ReD-DeLiVeR code is an updated version of the DeLiVeR code, designed to compute decay widths for light vector mediators, including several hadronic channels. The code can now be used to compute relic abundances, process rates, and thermal targets given a user-defined dark matter candidate.

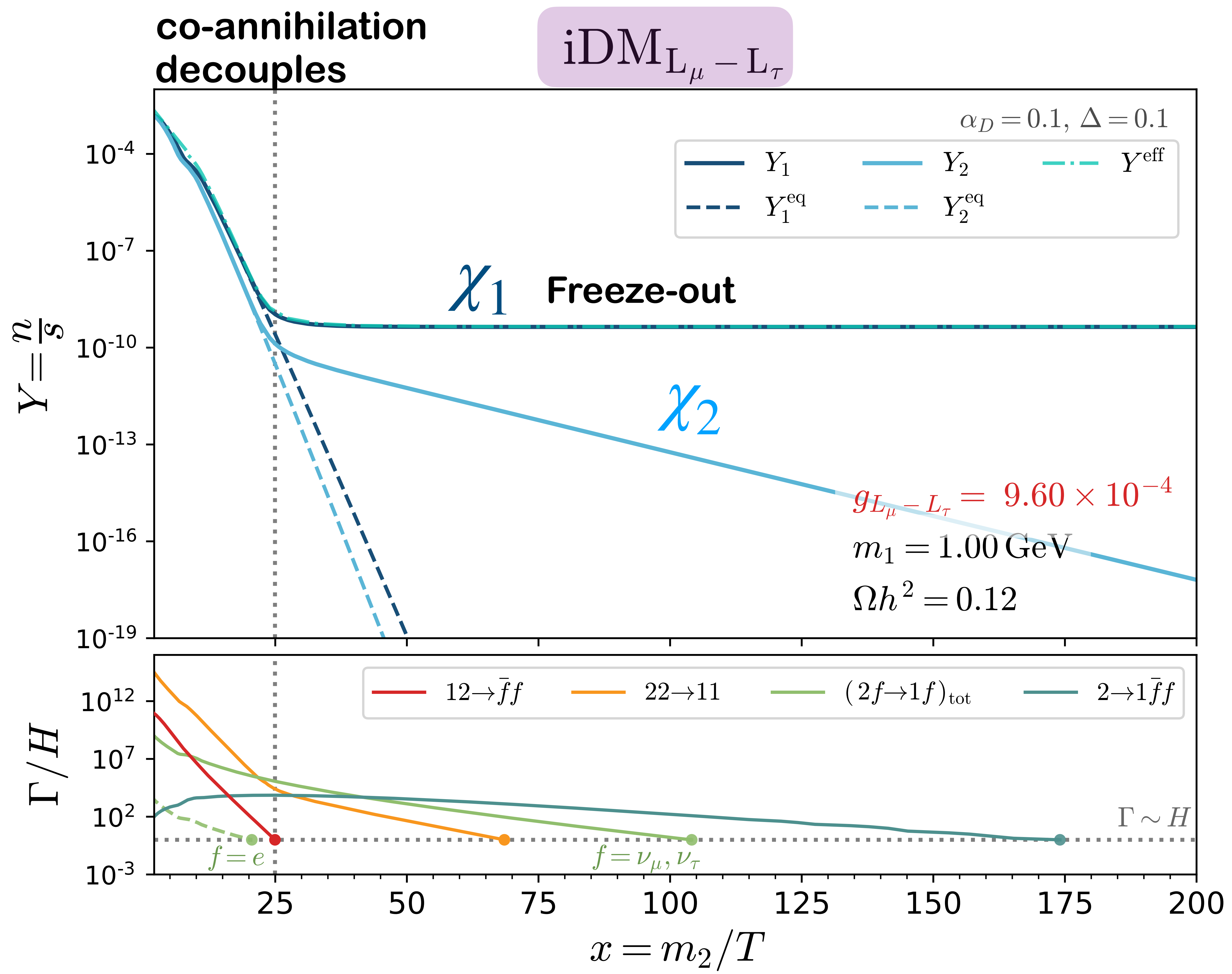
$\mathrm{IDM_Q}$ Models

Relic Density Freeze-out

$$\alpha_D \uparrow \Rightarrow \ g_Q \downarrow$$

$$\langle \sigma v \rangle_{12 \to ff} \propto \Delta^{-1} \Rightarrow \Delta \downarrow \ g_Q \downarrow$$

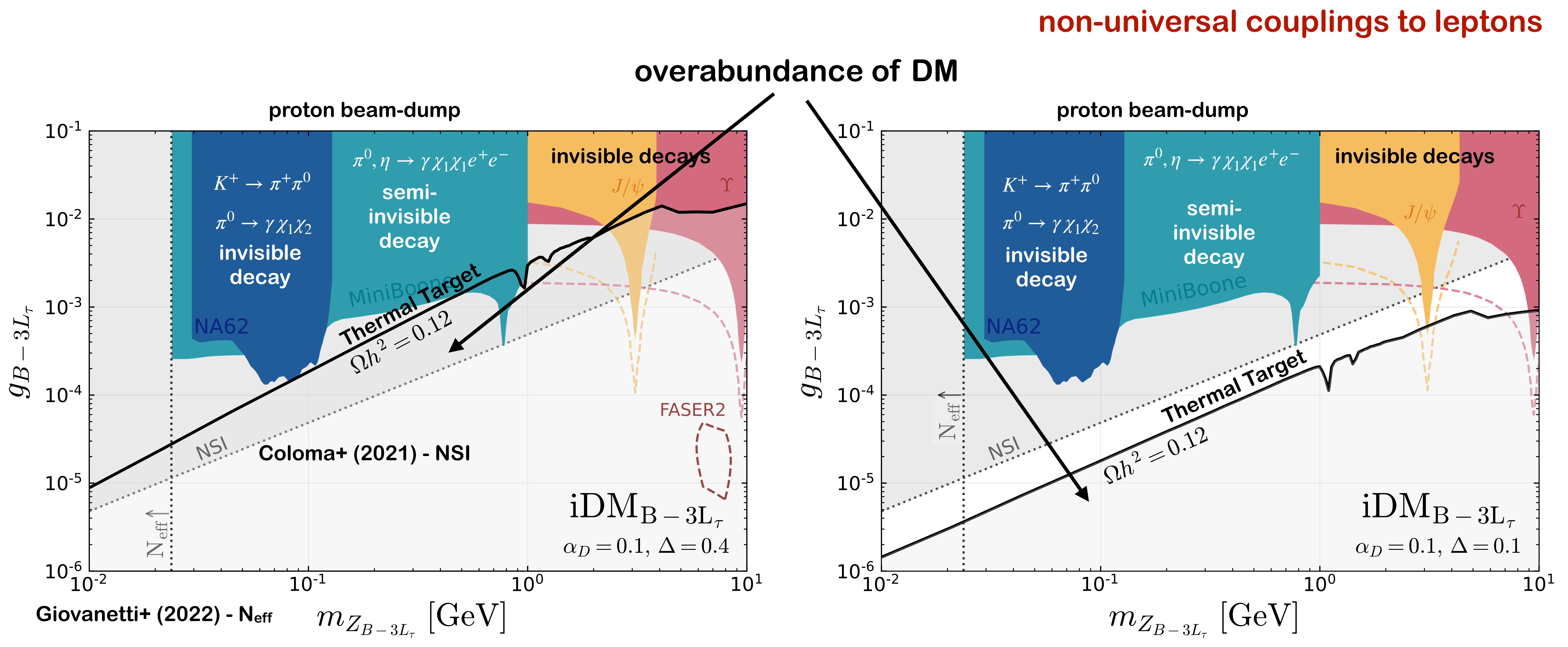




Some Viable Models

iDM$_{B-3L_\tau}$

[Foguel, Reimitz, RZF (2025)]


non-universal couplings to leptons

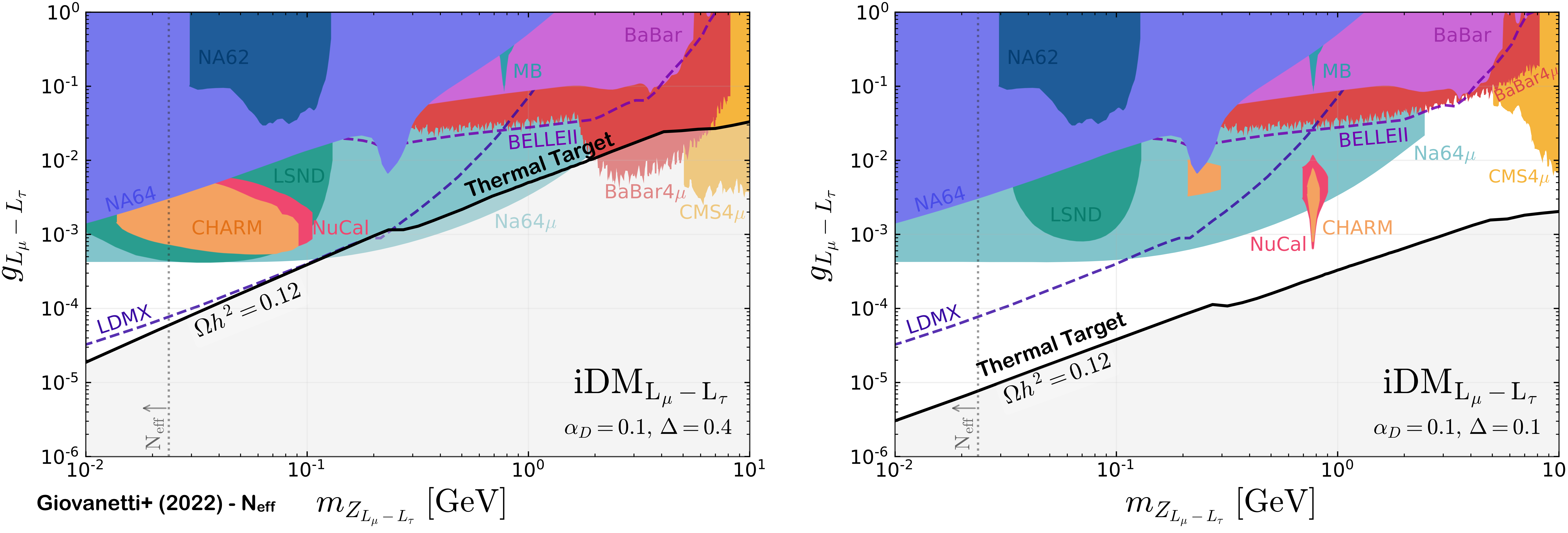
overabundance of DM

Some Viable Models

iDM$_{L_\mu - L_\tau}$

[Foguel, Reimitz, RZF (2025)]

non-universal couplings to leptons



Giovanetti+ (2022) - N$_{\rm eff}$

Final Conclusions

What is my message?

- iDM scenario is an interesting theoretical proposal naturally evading direct, indirect detection bounds and cosmological constraints while yielding the observed relic abundance by the freeze-out mechanism

- The light [10 MeV - 10 GeV] dark sector of iDM can be produced in accelerators ⇒ the vanilla iDM parameter space is largely ruled out

✦ We have extended iDM to include generic charges Q and shown that this significantly modify the phenomenology

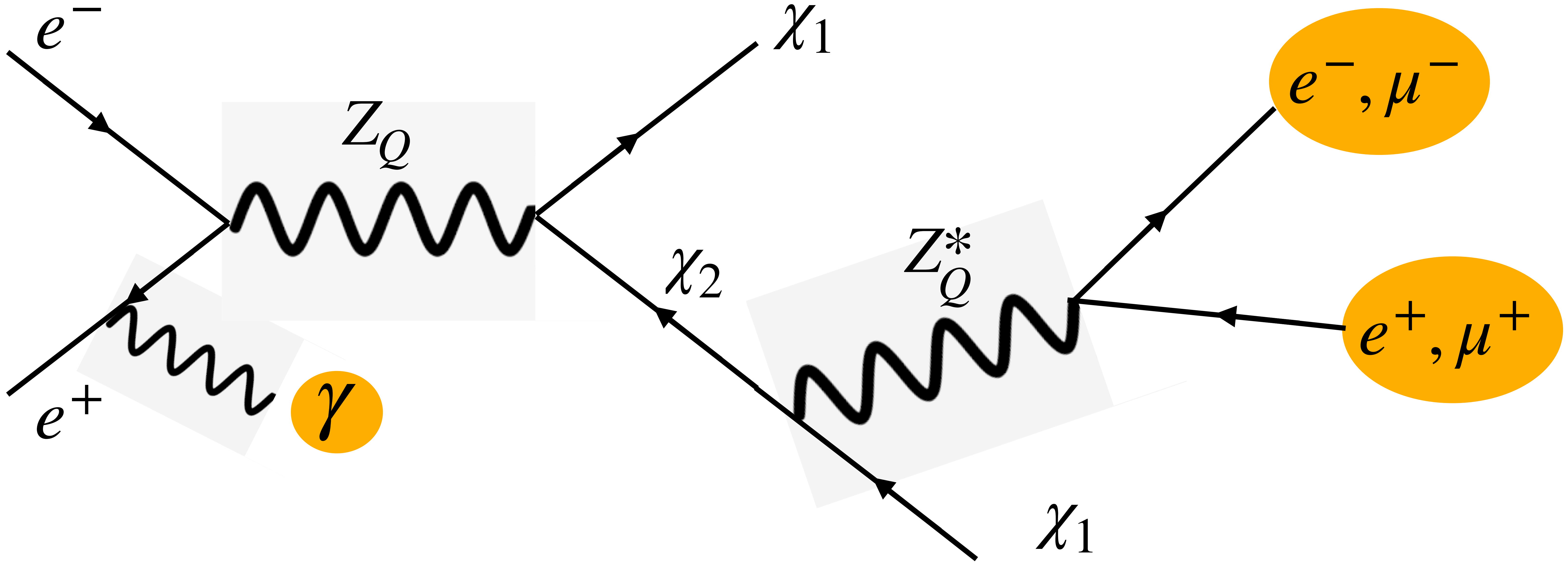
✦ We have found models that couple non-universally to leptons and have unconstrained regions where χ_1 can still be a viable DM candidate

✦ This shows that cosmologically viable $\mathrm{iDM_Q}$ models can provide new windows to be explored by future experiments

Thank you !

Backup

e^+e^- Colliders



- BaBar
- BES II
- Belle II

Invisible

$$e^+e^- \to \gamma\chi_1\chi_2$$

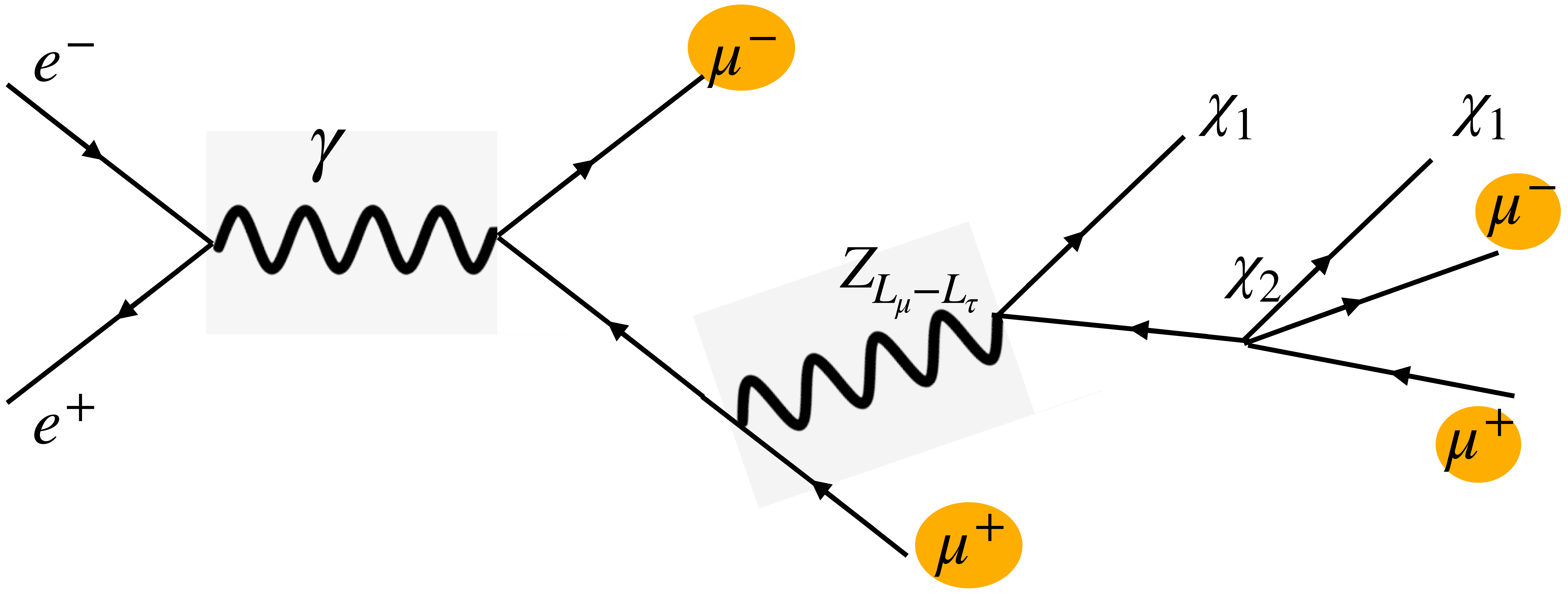
mono-photon

Semi-visible

$$e^+e^- \to \gamma\chi_1\chi_1\ell^+\ell^-$$

photon +displaced signature

e^+e^- Colliders



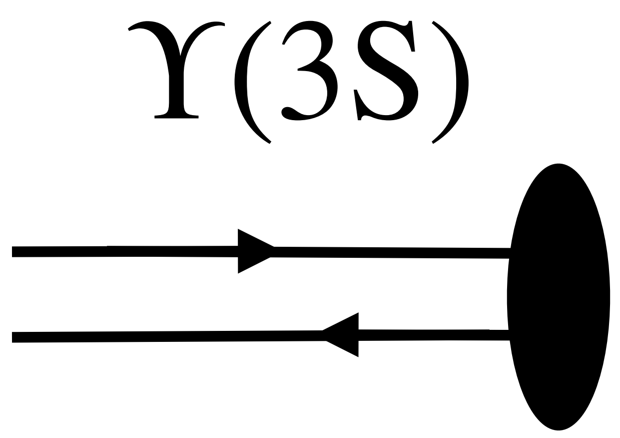
- BaBar

Semi-visible

$$e^+e^- \to \mu^+\mu^-\chi_1\chi_1\mu^+\mu^-$$

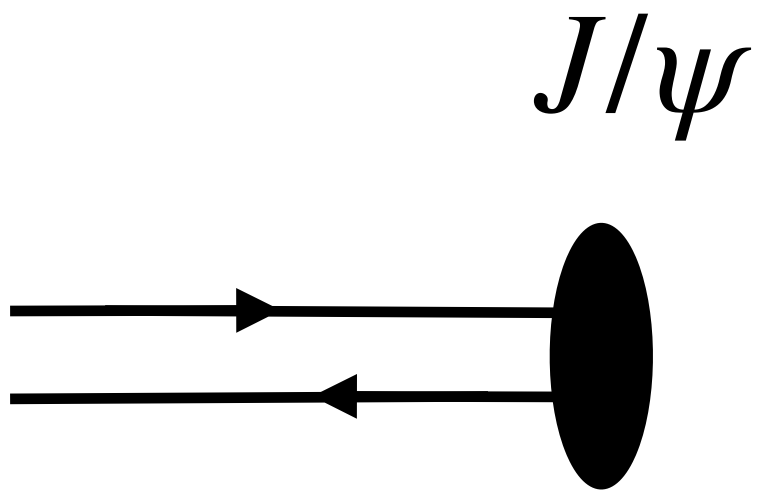
4-muon searches

e^+e^- Colliders - Heavy Meson Decay



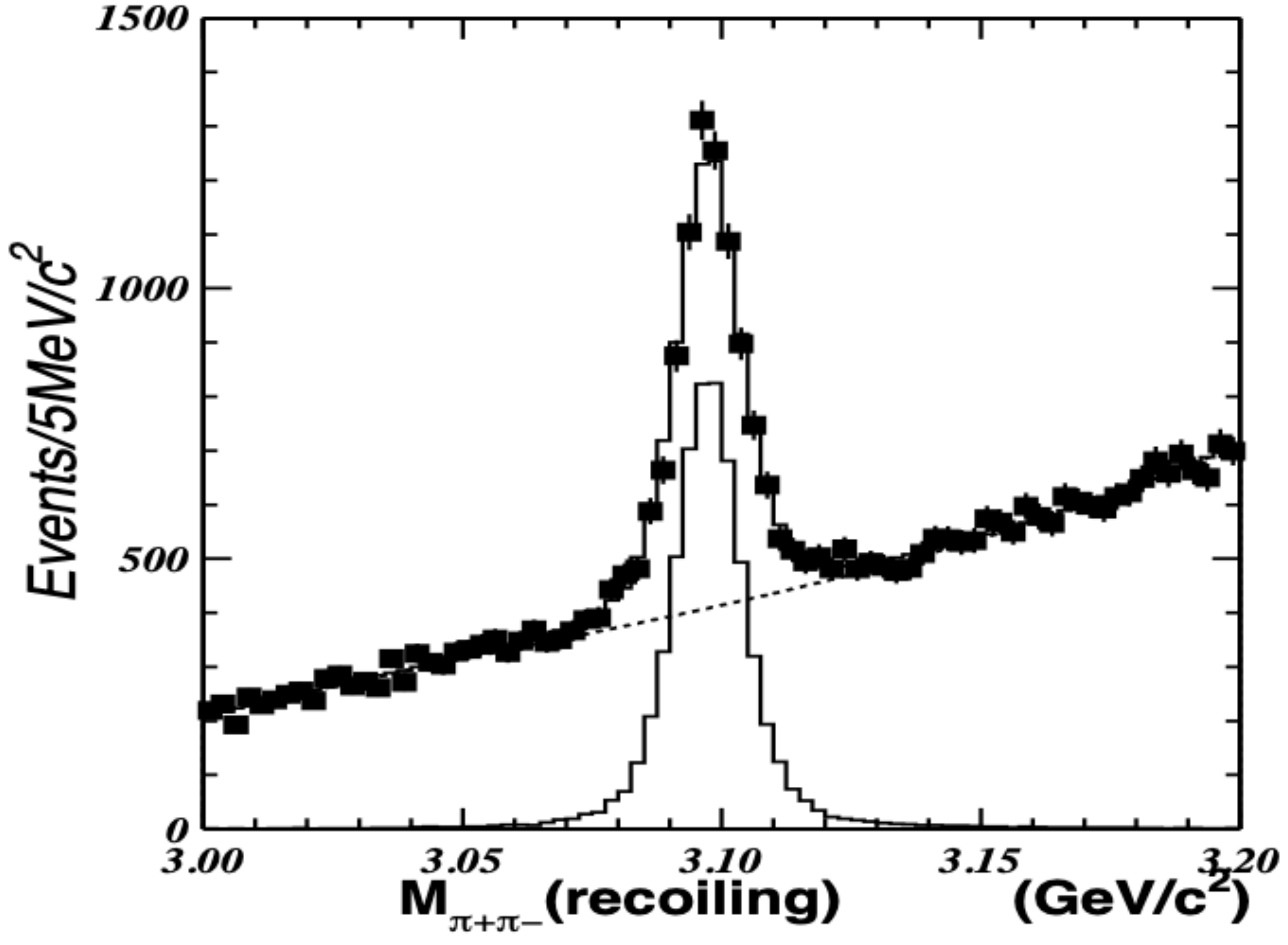
- **BaBar**

$$m_{Z_Q} \simeq m_{\Upsilon(1S)}$$



- **BES II**

$$m_{Z_Q} \simeq m_{J/\psi}$$



Invisible

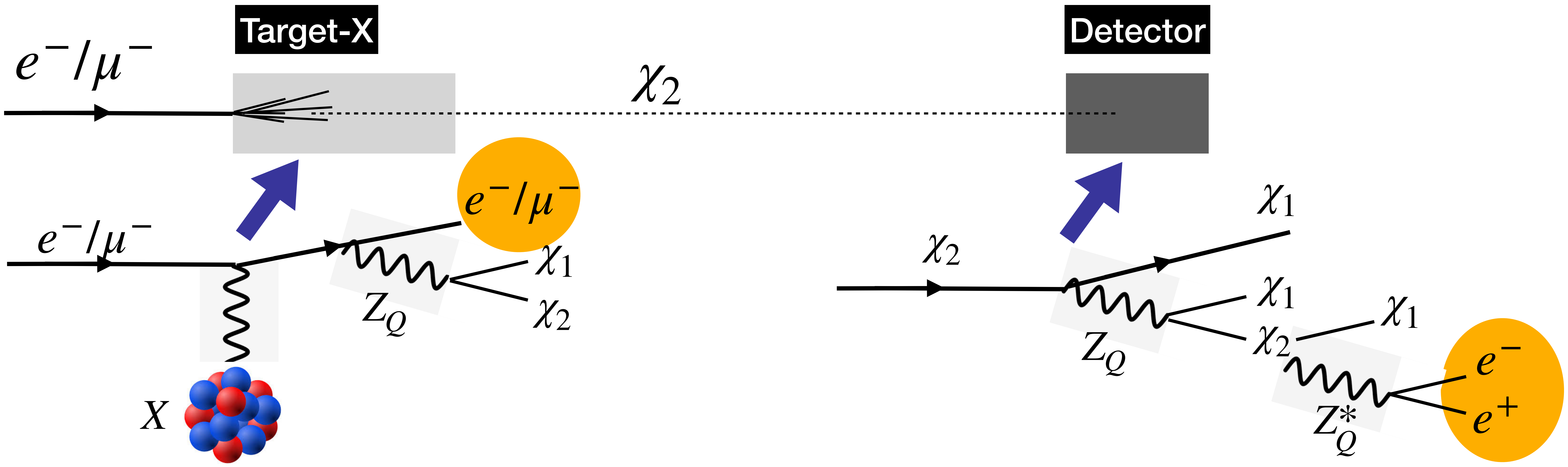
BR(Υ(1S) → invisible)

$$\Upsilon(3S) \rightarrow \Upsilon(1S) + \pi^+\pi^-$$
$$\Upsilon(1S) \rightarrow \chi_1\chi_2$$

BR(Jψ → invisible)

$$\psi(2S) \rightarrow J/\psi + \pi^+\pi^-$$
$$J/\psi \rightarrow \chi_1\chi_2$$

ℓ^- Beam Dump Experiments



- NA64-e
- NA64-μ
- E137

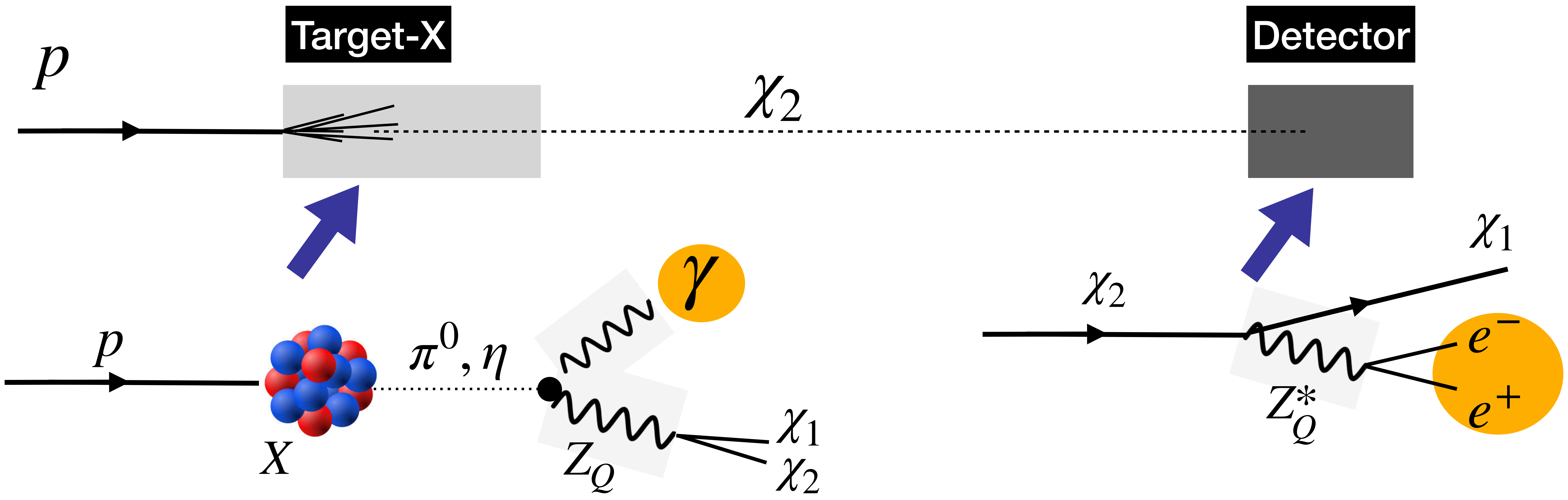
Invisible missing energy

$$\ell^- X \to \ell^- X Z_Q$$
$$Z_Q \to \chi_1 \chi_2$$

Semi-visible tagging

$$\ell^- X \to \ell^- X Z_Q$$
$$Z_Q \to \chi_1 \chi_1 e^+ e^-$$

Proton Beam Dump Experiments

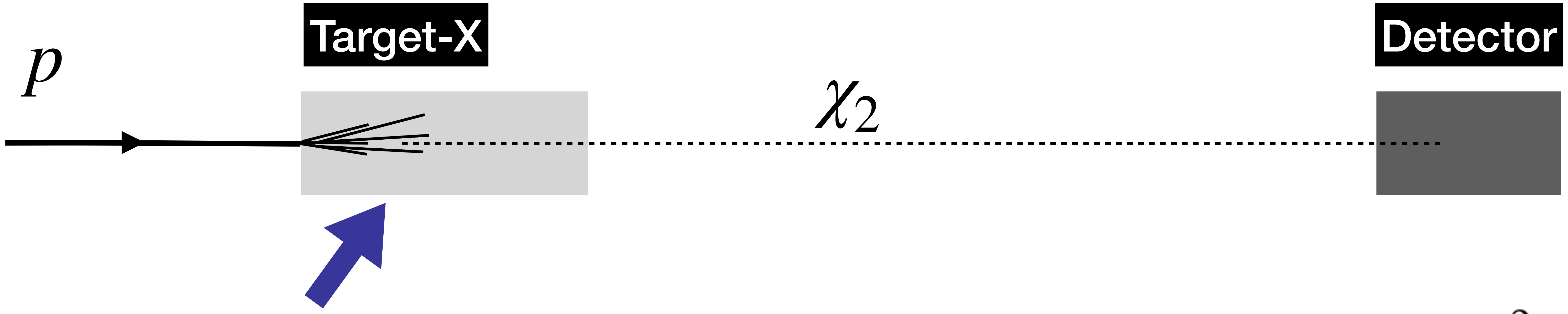


- **CHARM**
- **NuCal**
- **MiniBooNE**
- **LSND**
- **NA62**

Semi-visible

$$\pi^0, \eta \rightarrow \gamma Z_Q$$
$$Z_Q \rightarrow \chi_1 \chi_1 e^+ e^-$$

Proton Beam Dump Experiments

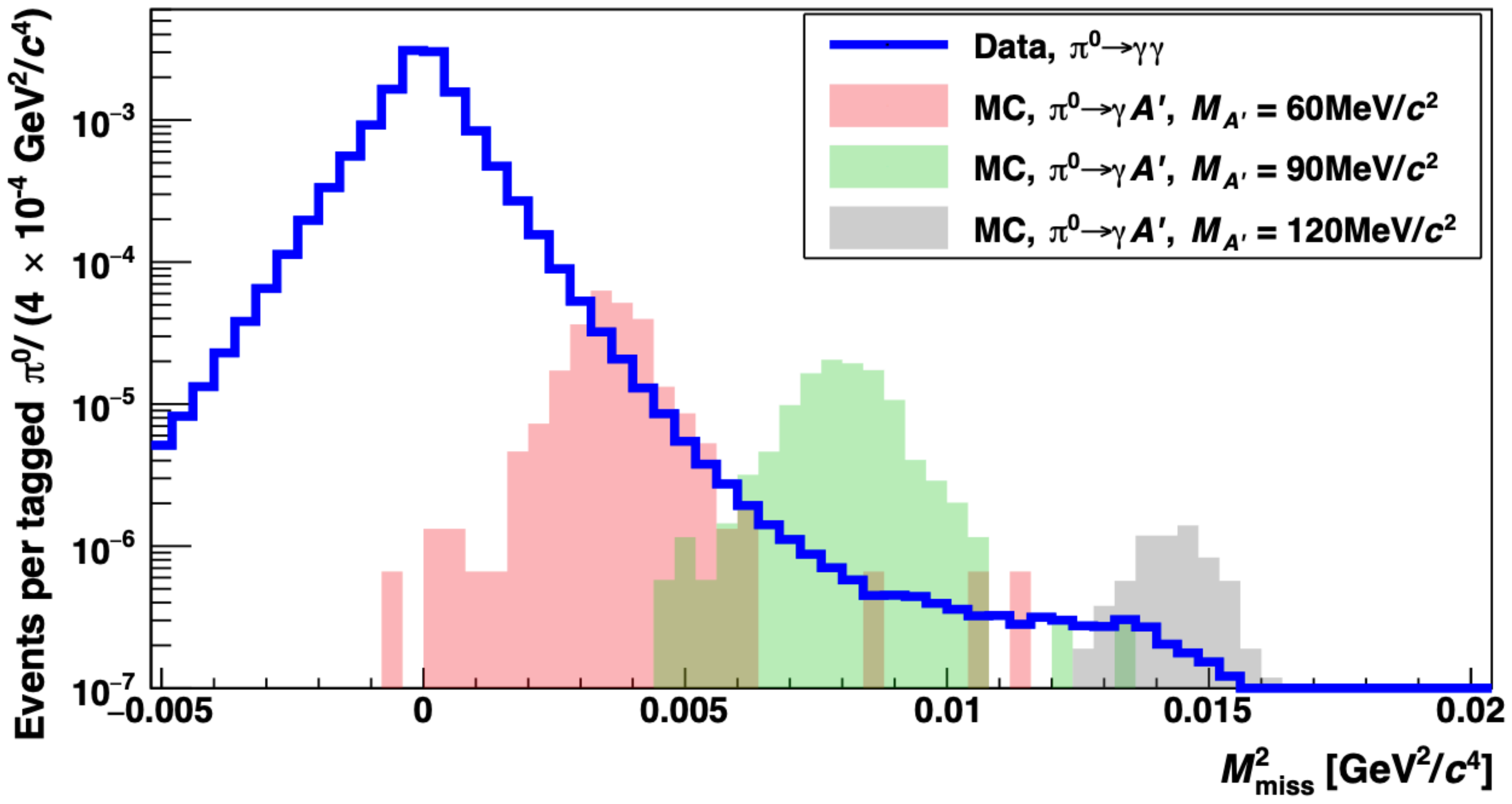


- **NA62**

$K^+ \to \pi^+\pi^0$

$\pi^0 \to \gamma\, Z_Q$

$$M^2_{\text{miss}} = (P_K - P_\pi - P_\gamma)^2$$



Invisible

$$\pi^0 \to \gamma Z_Q$$

$$Z_Q \to \chi_1\chi_2$$

Hadron Colliders

Invisible

- **CDF**

$$p\bar{p} \to \chi_1\chi_2 + \text{jet}$$

missing E_T

mono-jets

Semi-visible • **LHCb**

$$pp \to X + Z_{L_\mu - L_\tau}$$

$$Z_{L_\mu - L_\tau} \to \chi_1\chi_1\mu^+\mu^-$$

Inclusive search

Semi-visible • **CMS**

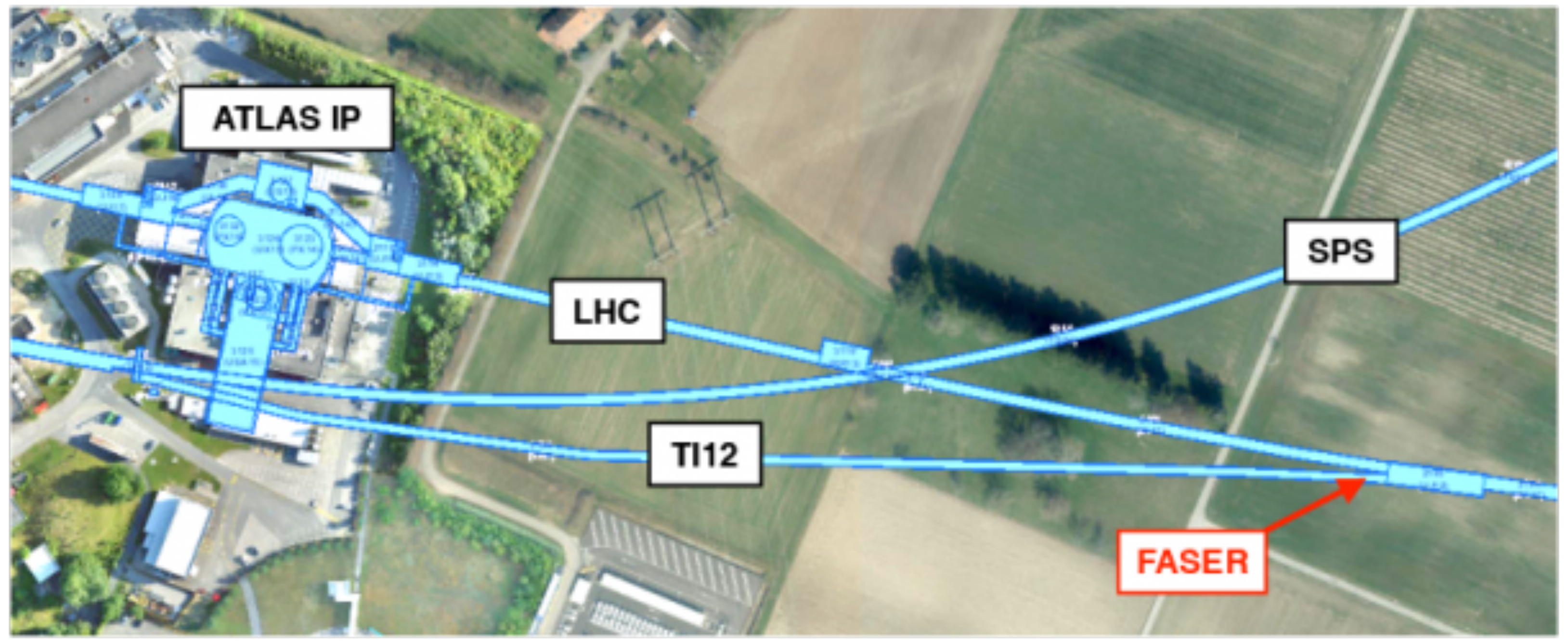
$$pp \to \mu^+\mu^- Z_{L_\mu - L_\tau}$$

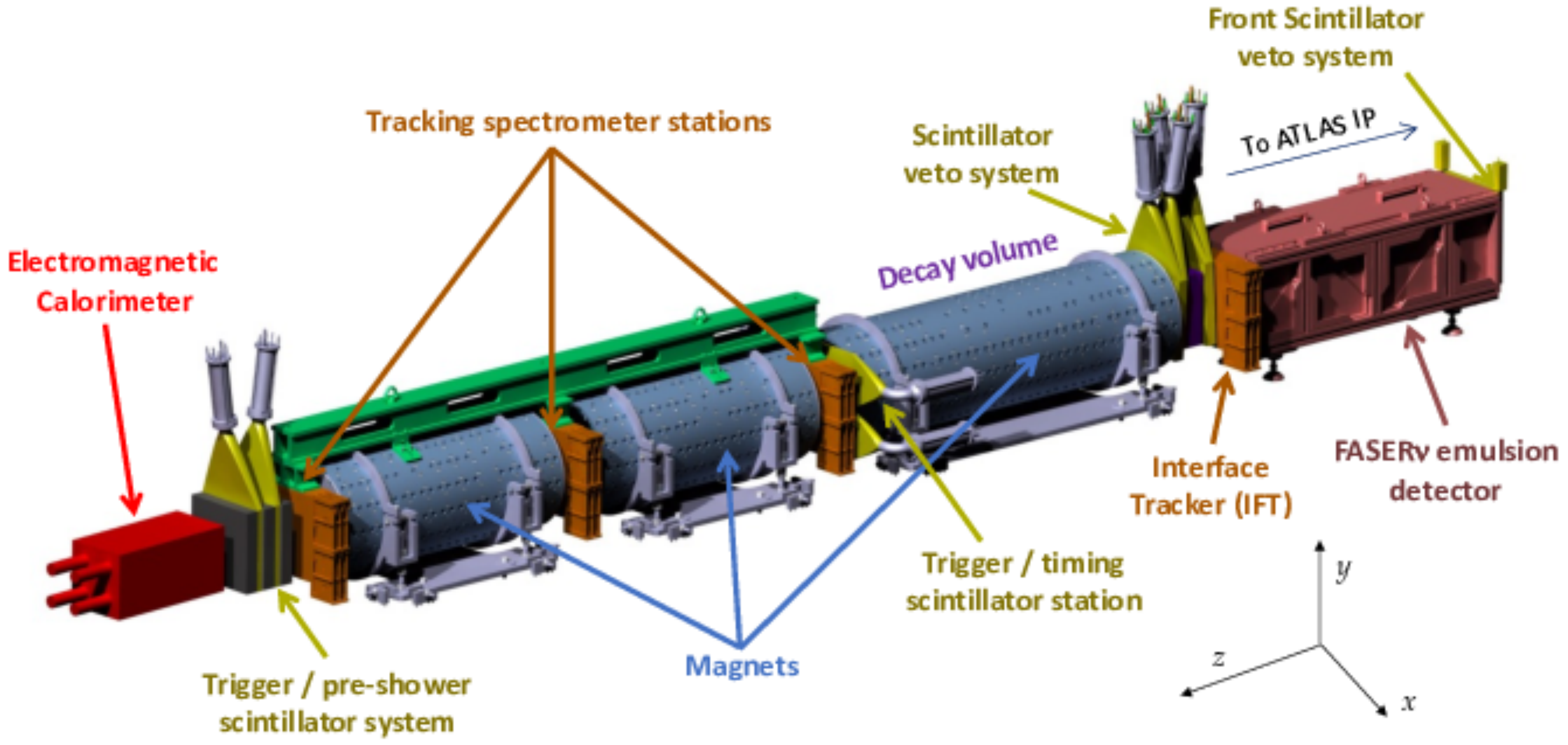
$$Z_{L_\mu - L_\tau} \to \chi_1\chi_1\mu^+\mu^-$$

4-muon events

missing E_T

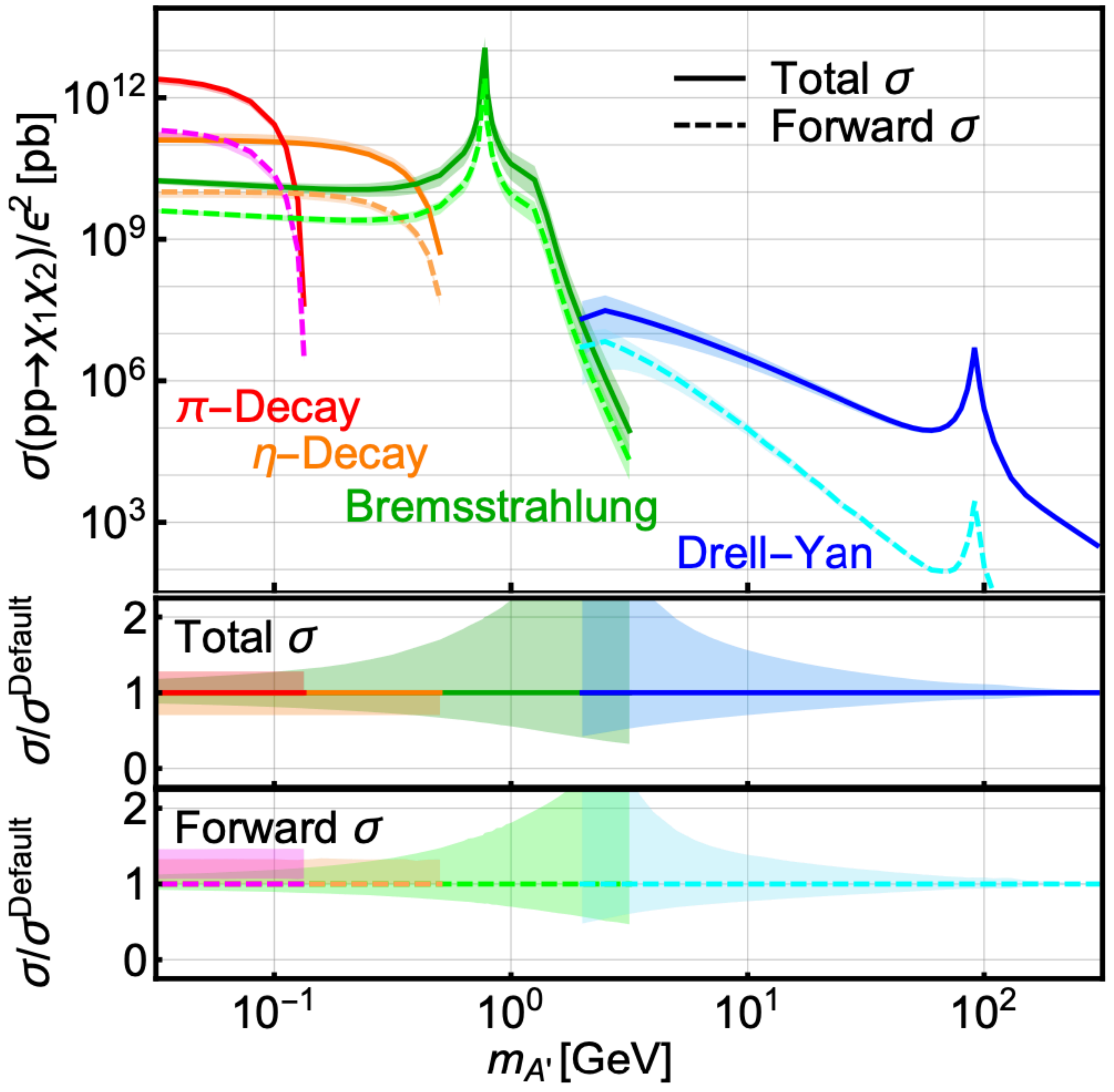
Hadron Colliders





- **FASER**
- **FASER2**

[Belin, Kling (2019)]



Semi-visible

$$\pi^0, \eta \to \gamma Z_Q$$

bremsstrahlung

$$Z_Q \to \chi_1 \chi_1 e^+ e^-$$

$$q\bar{q} \to Z_Q$$

Current Limits & Future Sensitivities

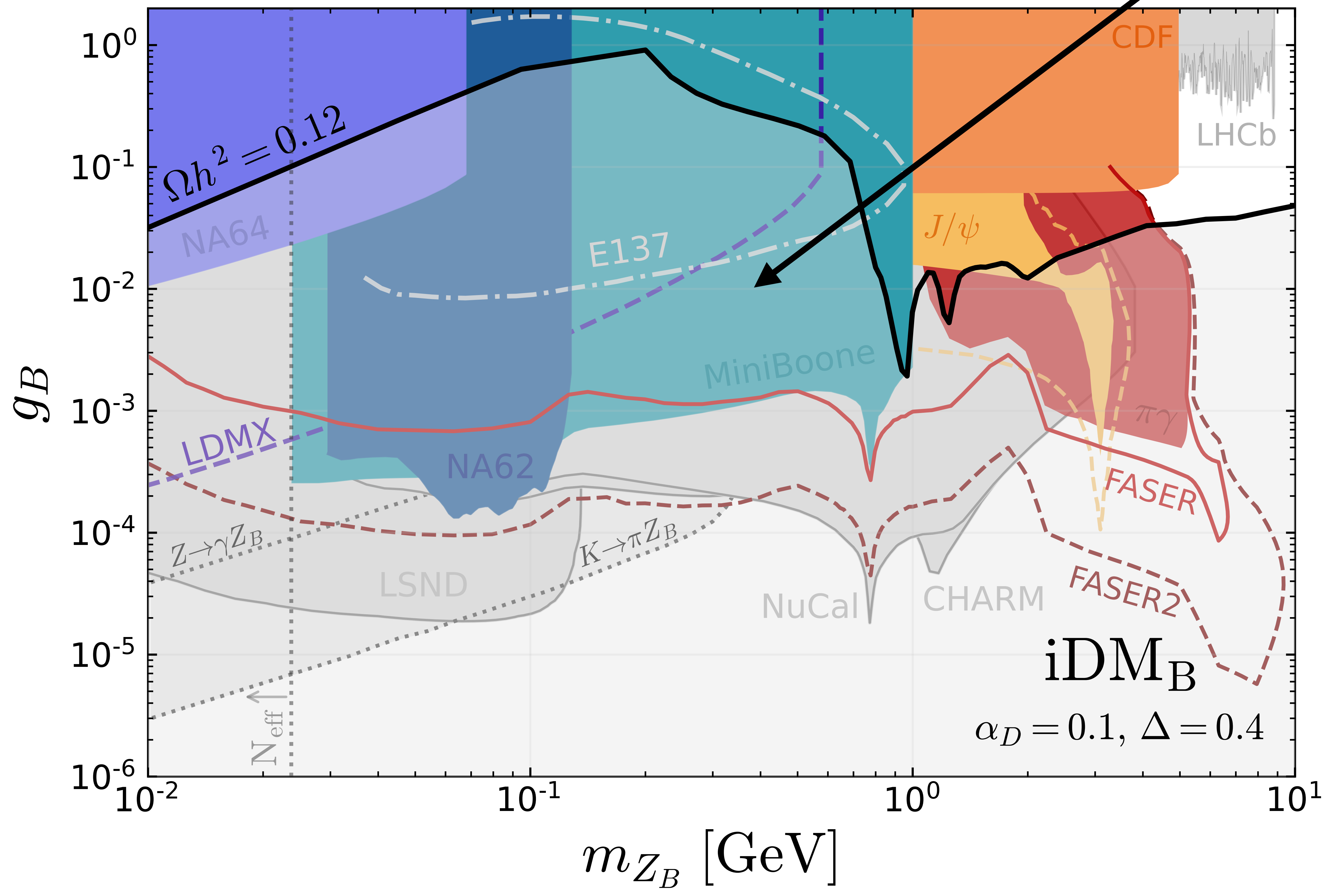
$\mathrm{iDM_B}$

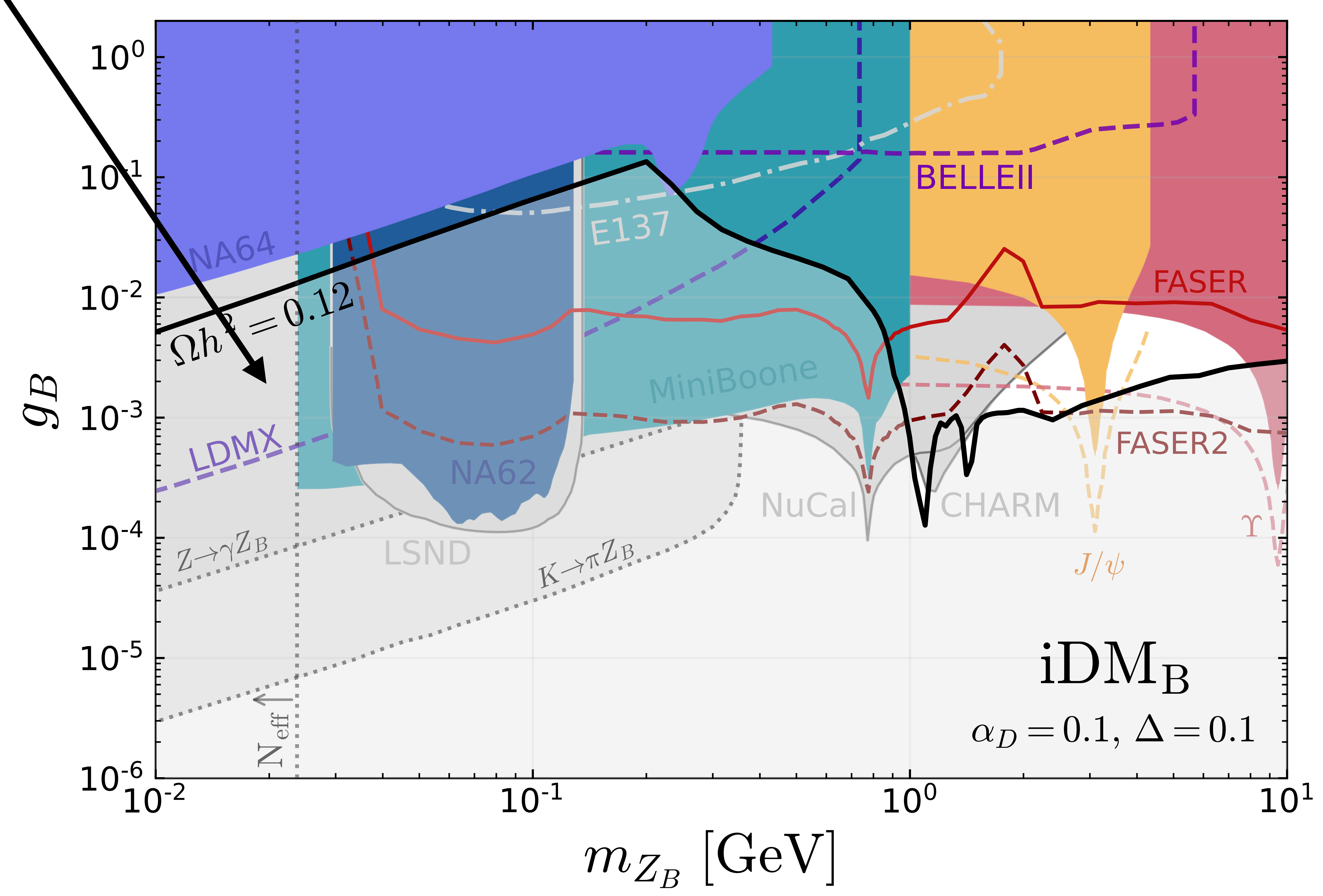
universal couplings to leptons

[Dror, Lasenby, Pospelov (2017)]

[Giovanetti, Lisanti, Liu, Ruderman (2022)]

overabundance of DM





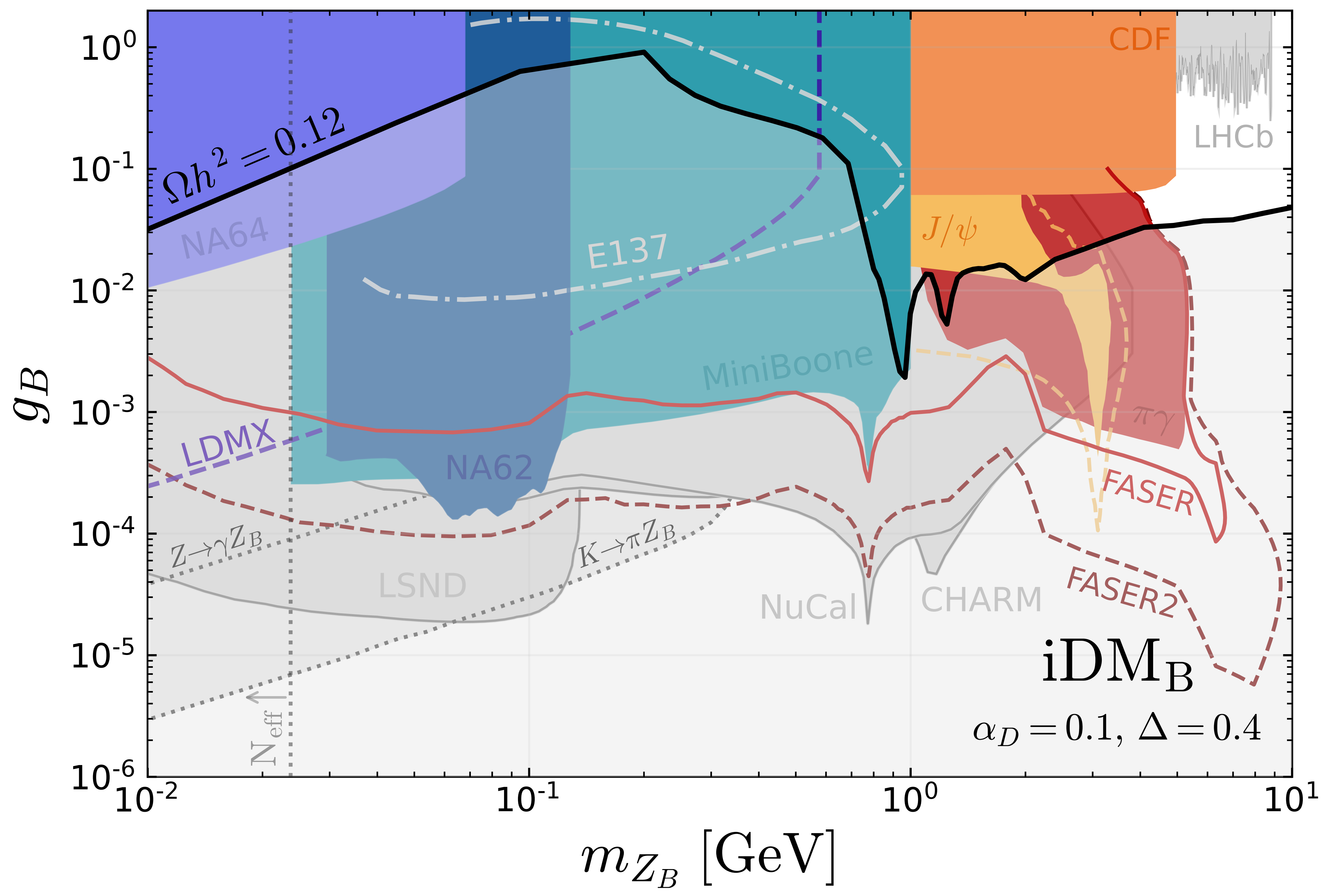
Current Limits & Future Sensitivities

iDM$_B$

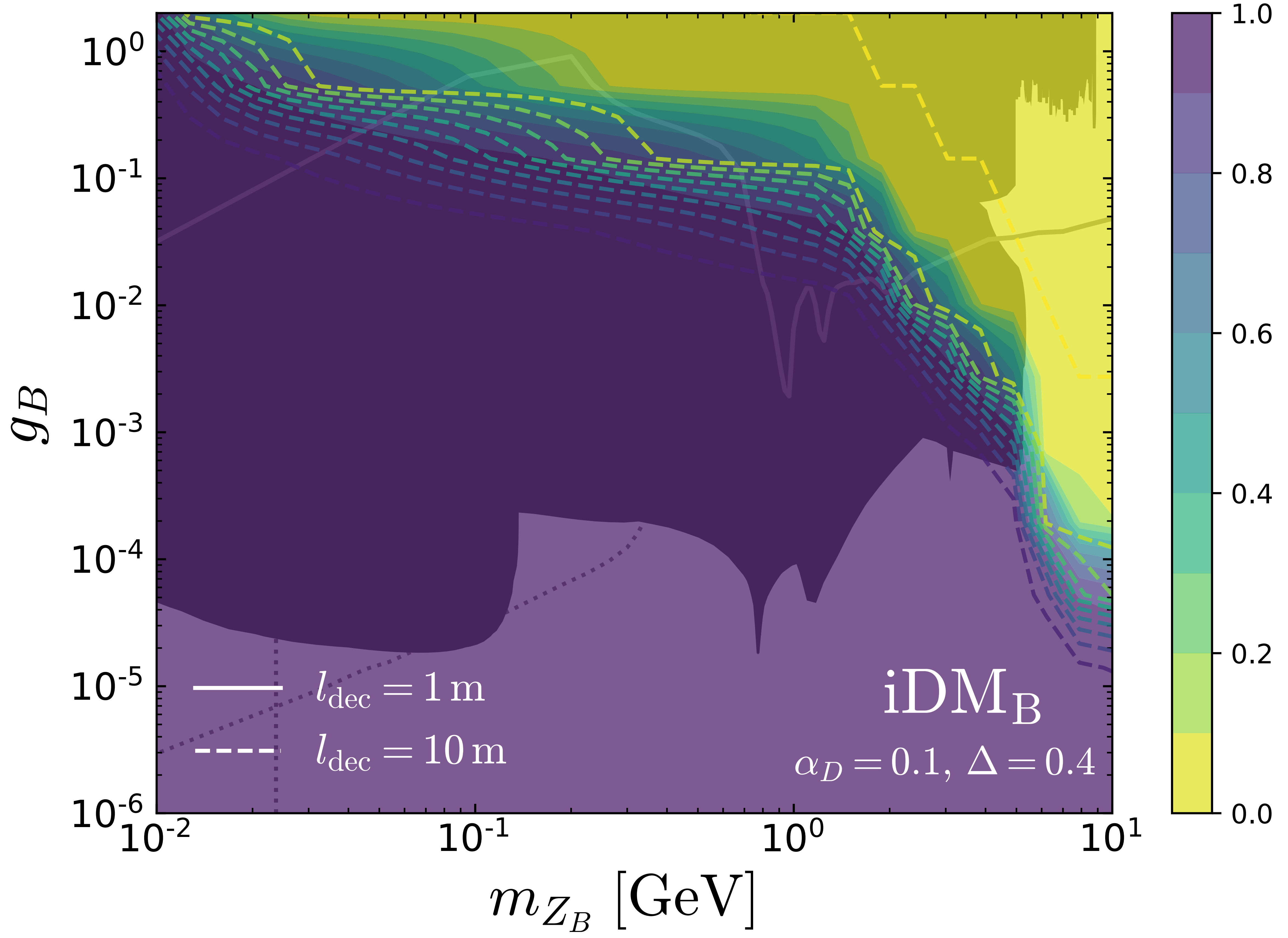
universal couplings to leptons

[Dror, Lasenby, Pospelov (2017)]

[Giovanetti, Lisanti, Liu, Ruderman (2022)]



Invisible Decay Probability



Current Limits & Future Sensitivities

iDM$_{B-3L_\tau}$

non-universal couplings to leptons

[Coloma, Gonzalez-Garcia, Maltoni (2021)]

[Giovanetti, Lisanti, Liu, Ruderman (2022)]