MeV-GeV Dark Matter
FIP Physics Center Approach

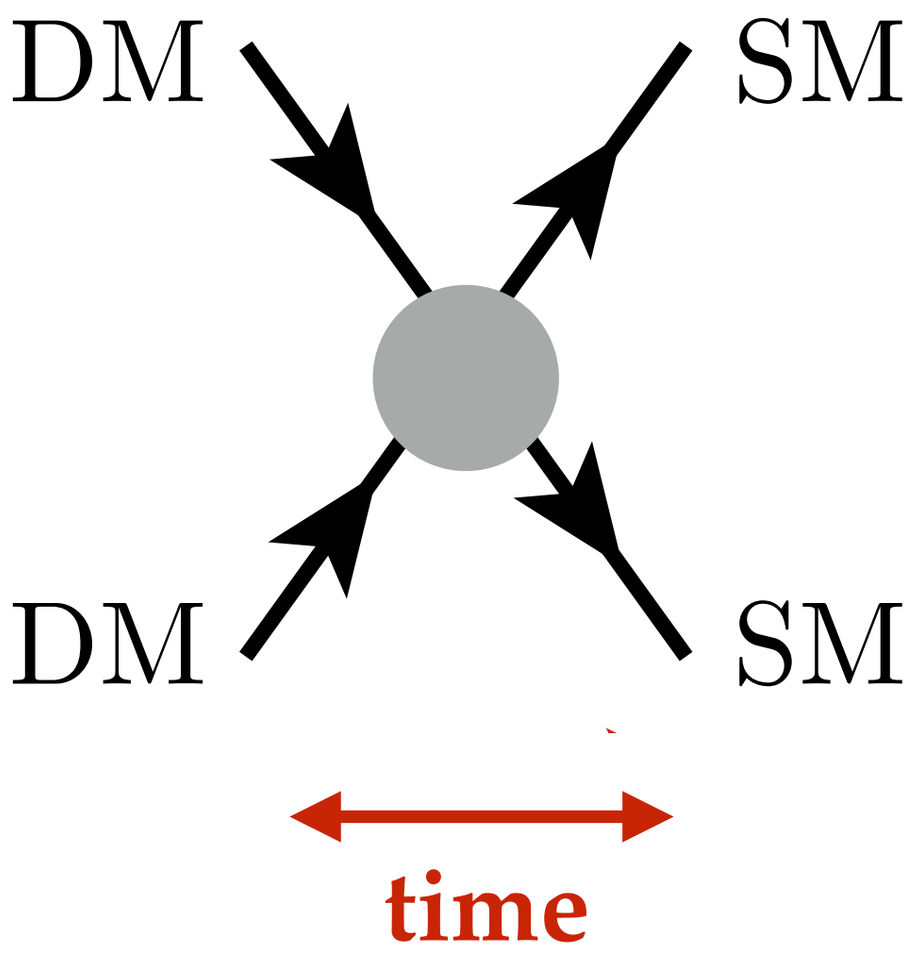
Gordan Krnjaic

Fermilab & University of Chicago

FIPS 2022 Workshop @ CERN, Oct 20, 2022

Image: Volker Springel

Was DM ever in equilibrium with SM?



Recall Natalia Toro's talk

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

Was DM ever in equilibrium with SM?

NO

How was it populated?

Was DM ever in equilibrium with SM?

NO

How was it populated?

Initial conditions

Axion / ALP
WIMPzilla
Primordial Black Holes
⋮

Rarely predictive

Was DM ever in equilibrium with SM?

NO

How was it populated?

Feeble coupling to us

Sterile Neutrino
Freeze In
SuperWIMP
⋮

Very hard to test
[few known examples]

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Stays there

Today we have measured that

$$\rho_\chi \sim 10^3\,\mathrm{eV\,cm^{-3}}$$

Equilibrium predicts DM mass

$$m_\chi \sim 10\,\mathrm{eV}$$

Too hot for large scale structure

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Stable dark states

Heavy

too much stuff

$\sum \Omega_{\rm dark} > \Omega_{\rm DM}$

Light

$N_{\rm eff} > 3$ spoils

CMB/BBN/LSS

Requires nonstandard cosmology

See Celine Boehm's talk

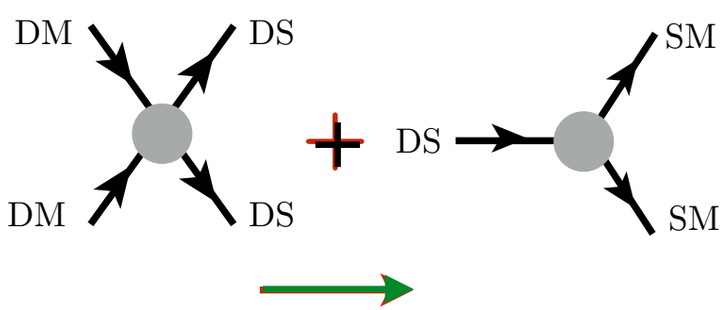
Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

Where did its density go?

Visible matter

"Secluded" Annihilation



Lighter mediator decays to SM
Wide range of visible couplings

Motivates new force searches

Was DM ever in equilibrium with SM?

YES $n_\chi \sim n_\gamma \sim T^3$

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Visible matter

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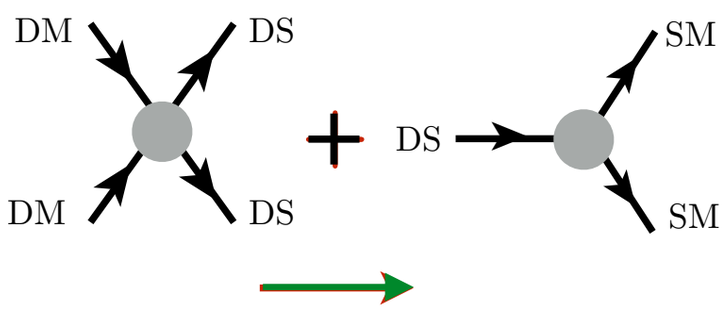
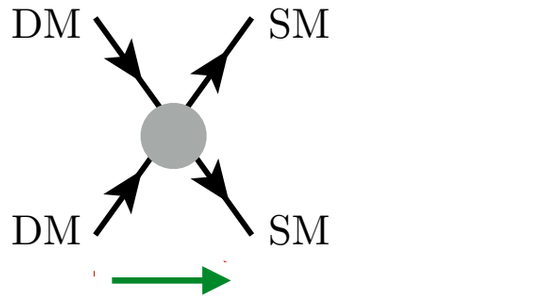


Lighter mediator decays to SM
Wide range of visible couplings

Motivates new force searches

Direct Annihilation



Heavier mediator decays to DM
Predictive production targets

Motivates beam dumps + missing E

Q: What's so great about equilibrium?

A: Generic and easily achieved

Compare interaction rate to expansion rate

$$\mathcal{L}_{\rm eff} = \frac{g^2}{\Lambda^2}(\bar{\chi}\gamma^\mu\chi)(\bar{f}\gamma_\mu f)$$

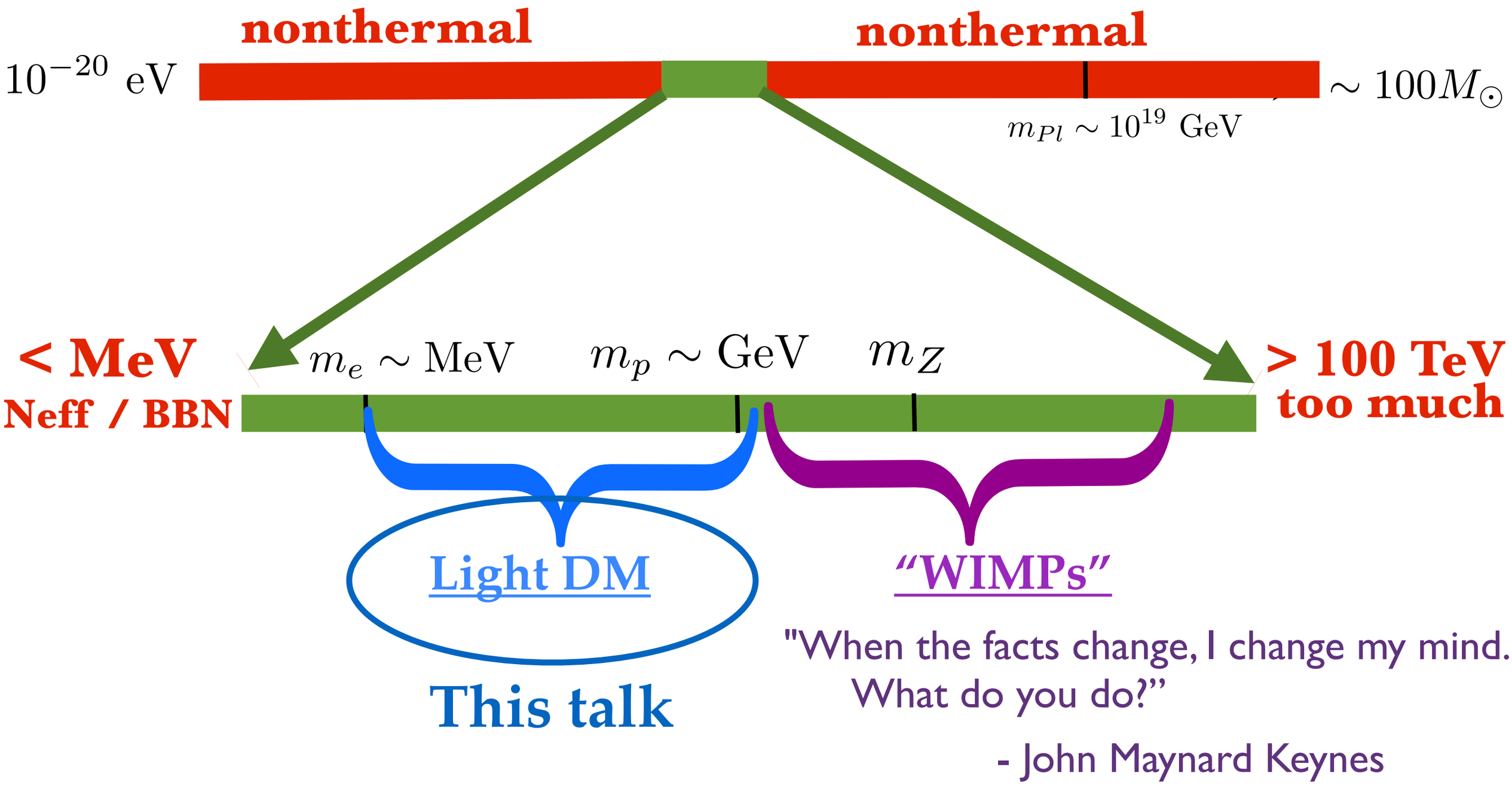
$$H \sim n\sigma v \quad \Longrightarrow \quad \frac{T^2}{m_{Pl}} \sim \frac{g^2 T^5}{\Lambda^4}\Bigg|_{T=m_\chi}$$

Equilibrium condition

$$g \gtrsim 10^{-8}\left(\frac{\Lambda}{10\,\mathrm{GeV}}\right)^2\left(\frac{\mathrm{GeV}}{m_\chi}\right)^{3/2}$$

All* models testable @ accelerators were once in equilibrium

Equilibrium Narrows Mass Range!



"When the facts change, I change my mind.
What do you do?"

- John Maynard Keynes

FIP Physics Center Continues PBC Discussion

Physics Beyond Colliders at CERN
Beyond the Standard Model Working Group Report

J. Beacham[1], C. Burrage[2,*], D. Curtin[3], A. De Roeck[4], J. Evans[5], J. L. Feng[6], C. Gatto[7], S. Gninenko[8], A. Hartin[9], I. Irastorza[10], J. Jaeckel[11], K. Jungmann[12,*], K. Kirch[13,*], F. Kling[6], S. Knapen[14], M. Lamont[4], G. Lanfranchi[4,15,*,**], C. Lazzeroni[16], A. Lindner[17], F. Martinez-Vidal[18], M. Moulson[15], N. Neri[19], M. Papucci[4,20], I. Pedraza[21], K. Petridis[22], M. Pospelov[23,*], A. Rozanov[24,*], G. Ruoso[25,*], P. Schuster[26], Y. Semertzidis[27], T. Spadaro[15], C. Vallée[24], and G. Wilkinson[28].

PBC report 1901.09966

Review of PBC Benchmarks

Categories organized around portal couplings for DM Mediators

Vector portal $F'_{\mu\nu}F^{\mu\nu}$

Scalar portal $\phi H^\dagger H$ $\phi^2 H^\dagger H$

Neutrino portal LHN

Axion portal $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$

Motivated as mediators to DM or as minimal extensions to SM

Review of PBC Benchmarks

Lots of compatibility with US Snowmass perspective (RF6)

See Stefania Gori's talk

PBC report 1901.09966

Review of PBC Benchmarks

Lots of compatibility with US Snowmass perspective (RF6)

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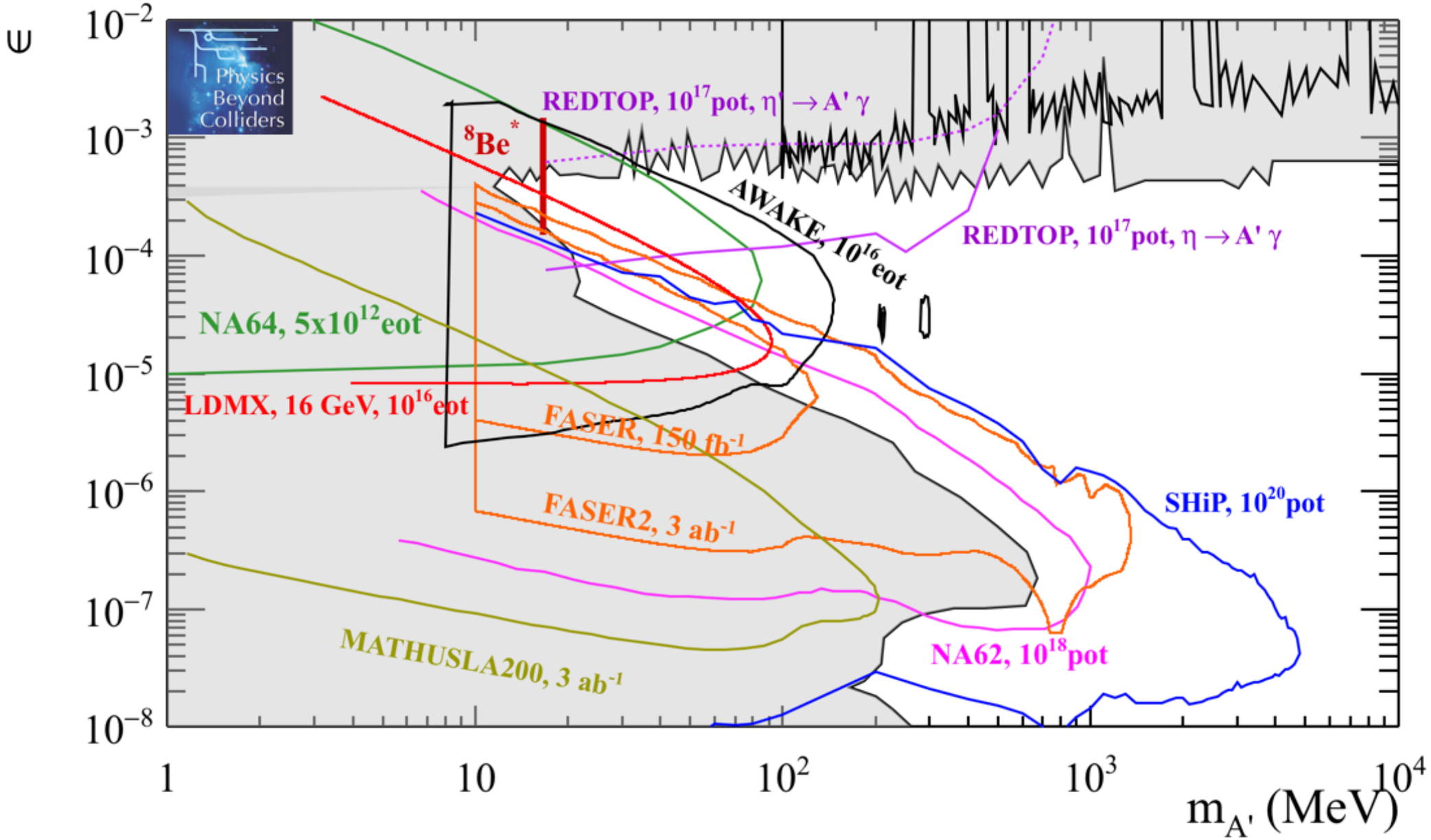
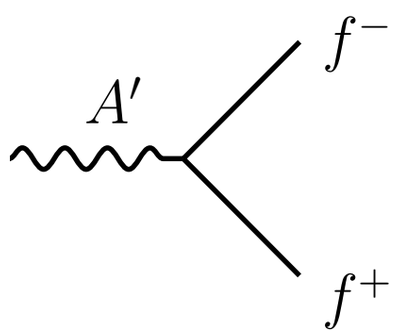
PBC report 1901.09966

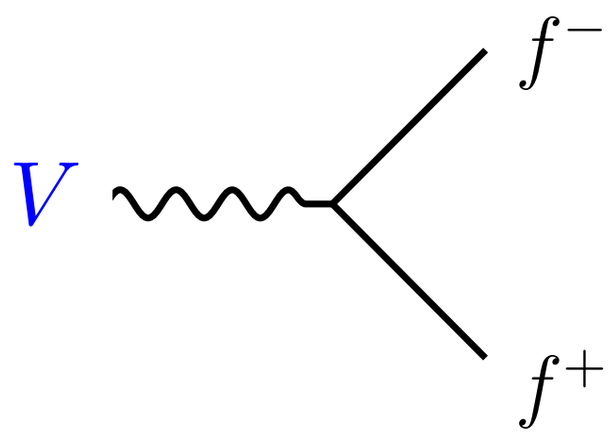
BC1 Benchmark: **visibly** decaying dark photon

$F'_{\mu\nu}F^{\mu\nu}$





FPC Generalize BC1 : **visibly** decaying anomaly free U(1) gauge bosons



$$\mathcal{L} \supset \quad V_\mu J^\mu_{\rm SM}$$

Charge SM directly under new 5th force

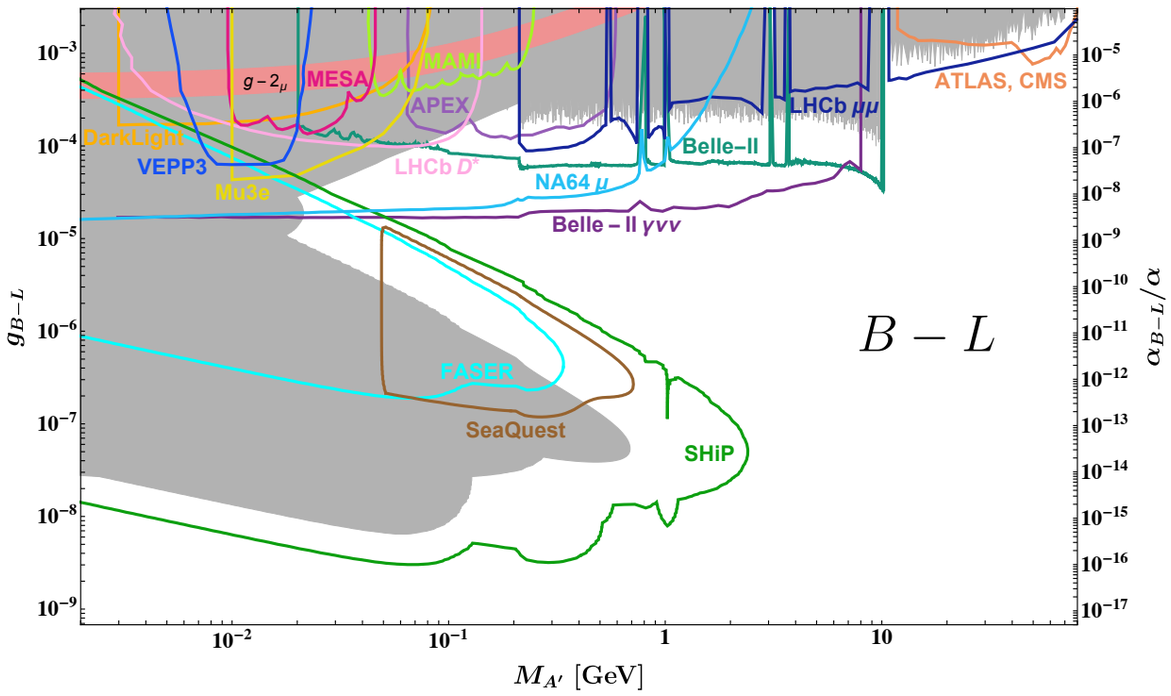
Gauge a combination of global SM quantum numbers

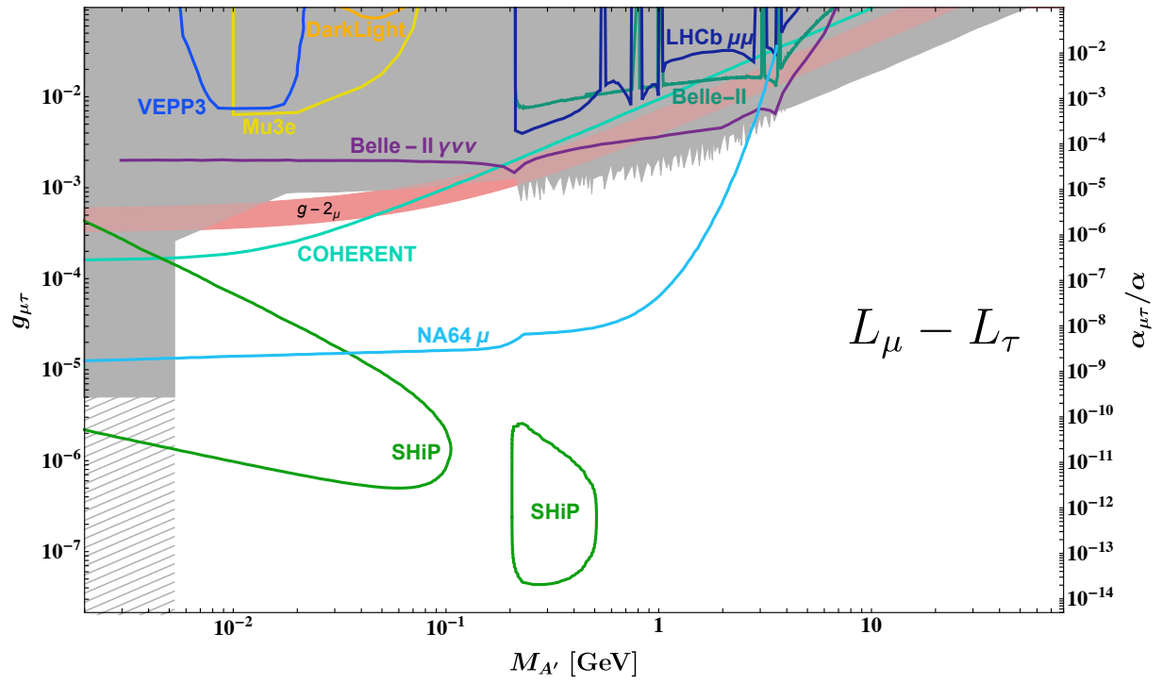
$U(1)_{B-L}$ $U(1)_{B-3L_i}$ $U(1)_{L_i-L_j}$

Finite set of consistent anomaly-free options

See Patrick Foldenauer's talk

FPC Generalize BC1 : **visibly** decaying anomaly free U(1) mediators





Different currents relative to minimal kinetic mixing

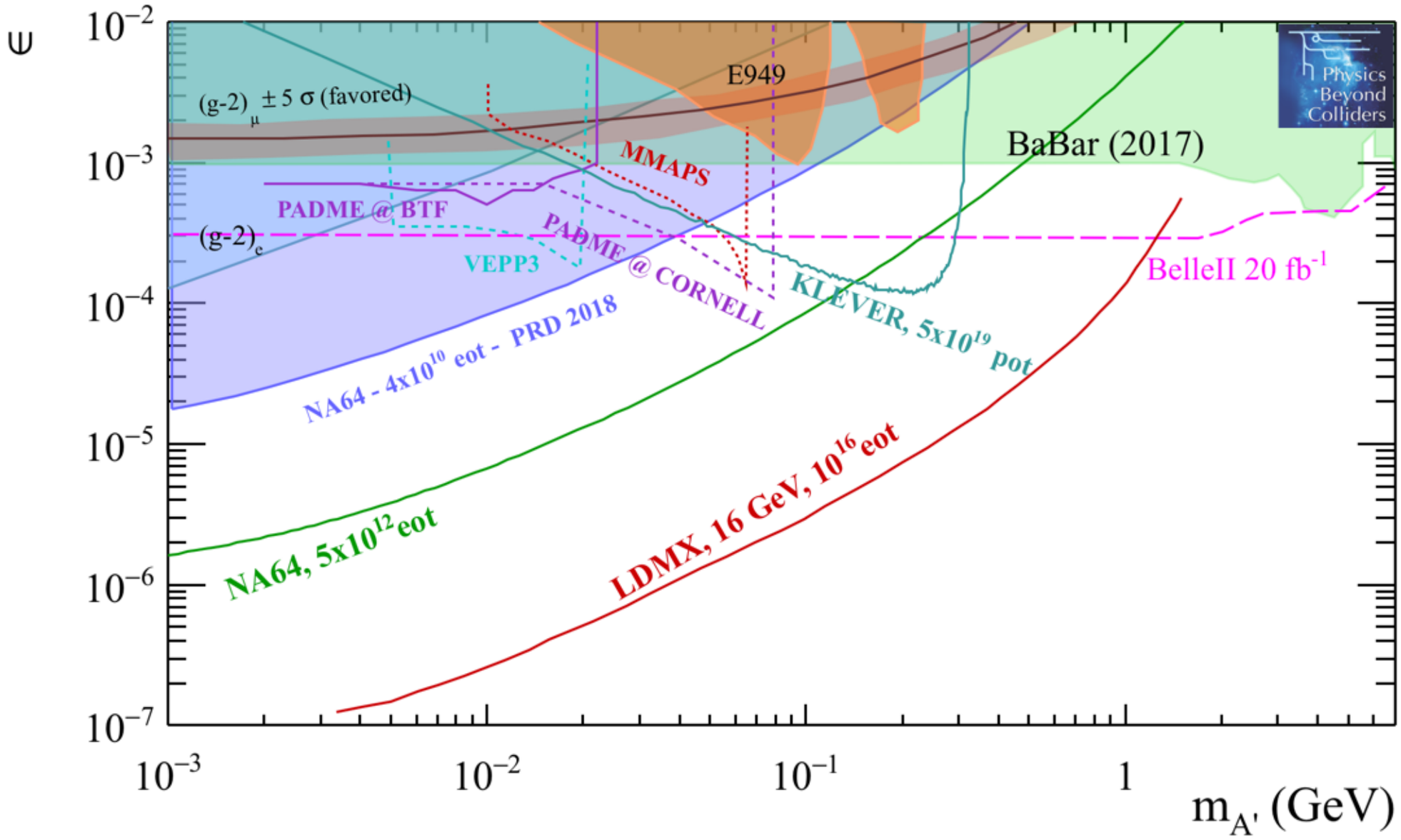
Generically coupled to neutrinos

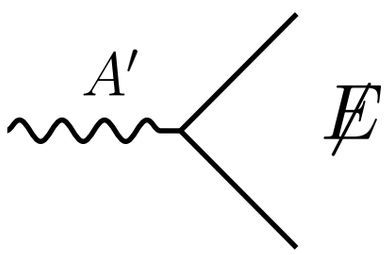
Last remaining solution to muon g-2 with light new vector*

Bauer, Foldenauer, Jaeckel 1803.05466

BC2 Benchmark: **invisibly** decaying dark photon

$F'_{\mu\nu}F^{\mu\nu}$

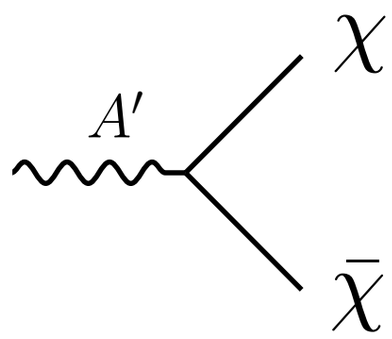




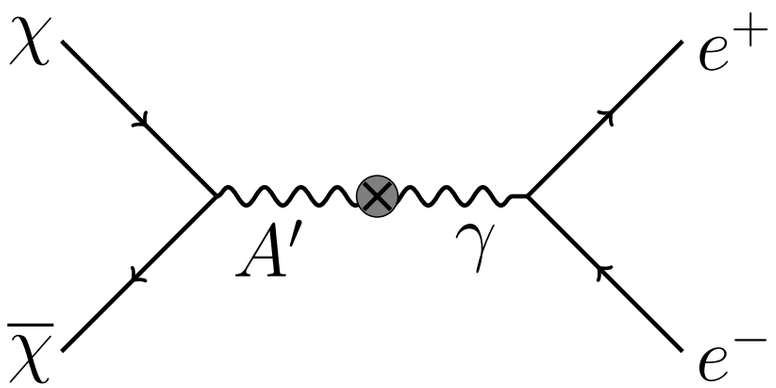
Interpret agnostically as invisibly decaying particle

BC2 Benchmark: **invisibly** decaying dark photon $F'_{\mu\nu}F^{\mu\nu}$

Interpret visible decay as dark matter production at accelerators



Mediates direct DM annihilation to SM particles

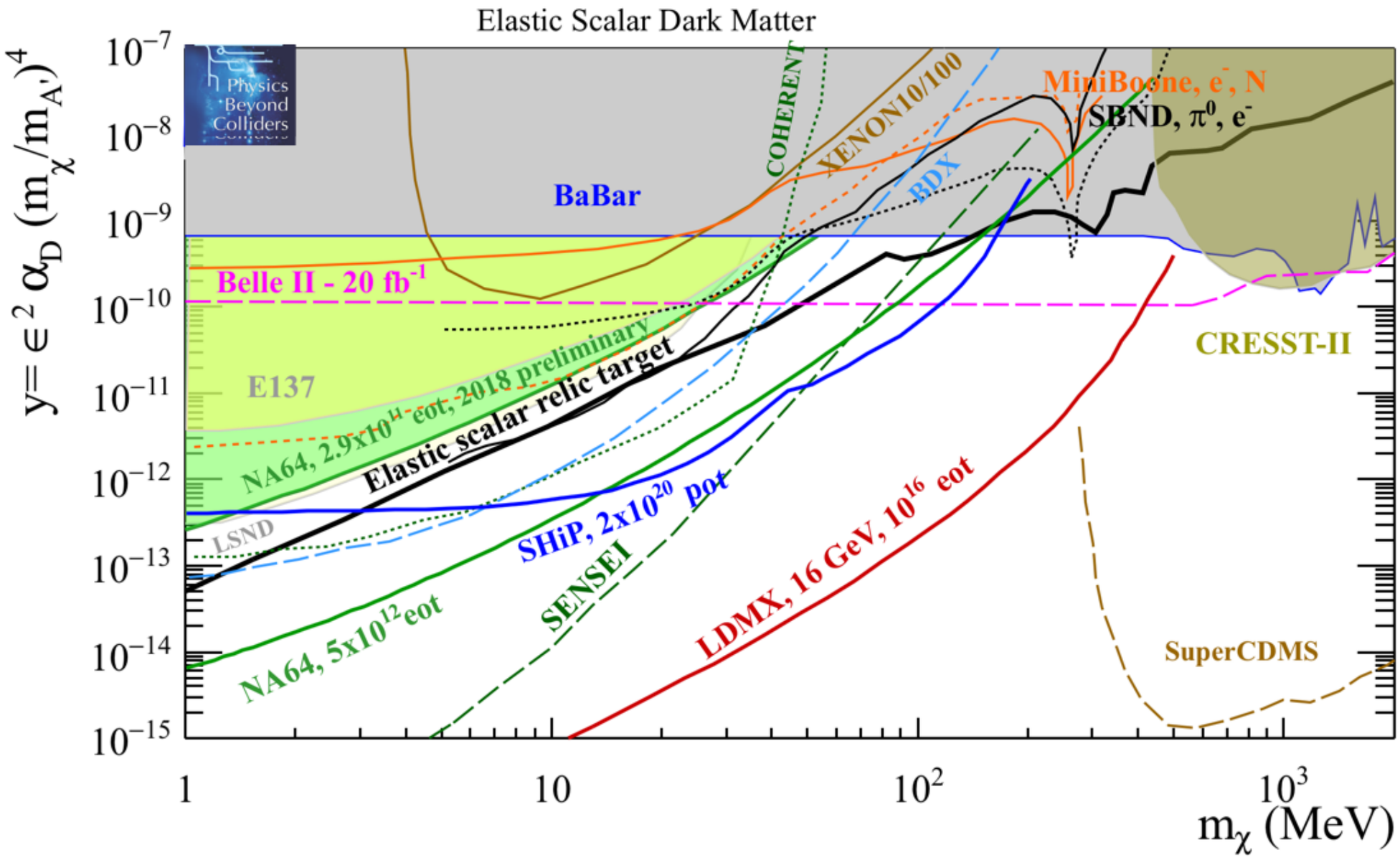


$$\sigma v \propto \epsilon^2 \alpha_D \left(\frac{m_\chi}{m_{A'}}\right)^4 \equiv y$$

Predictive thermal target for DM freeze-out in the early universe

BC2 Benchmark: **invisibly** decaying dark photon

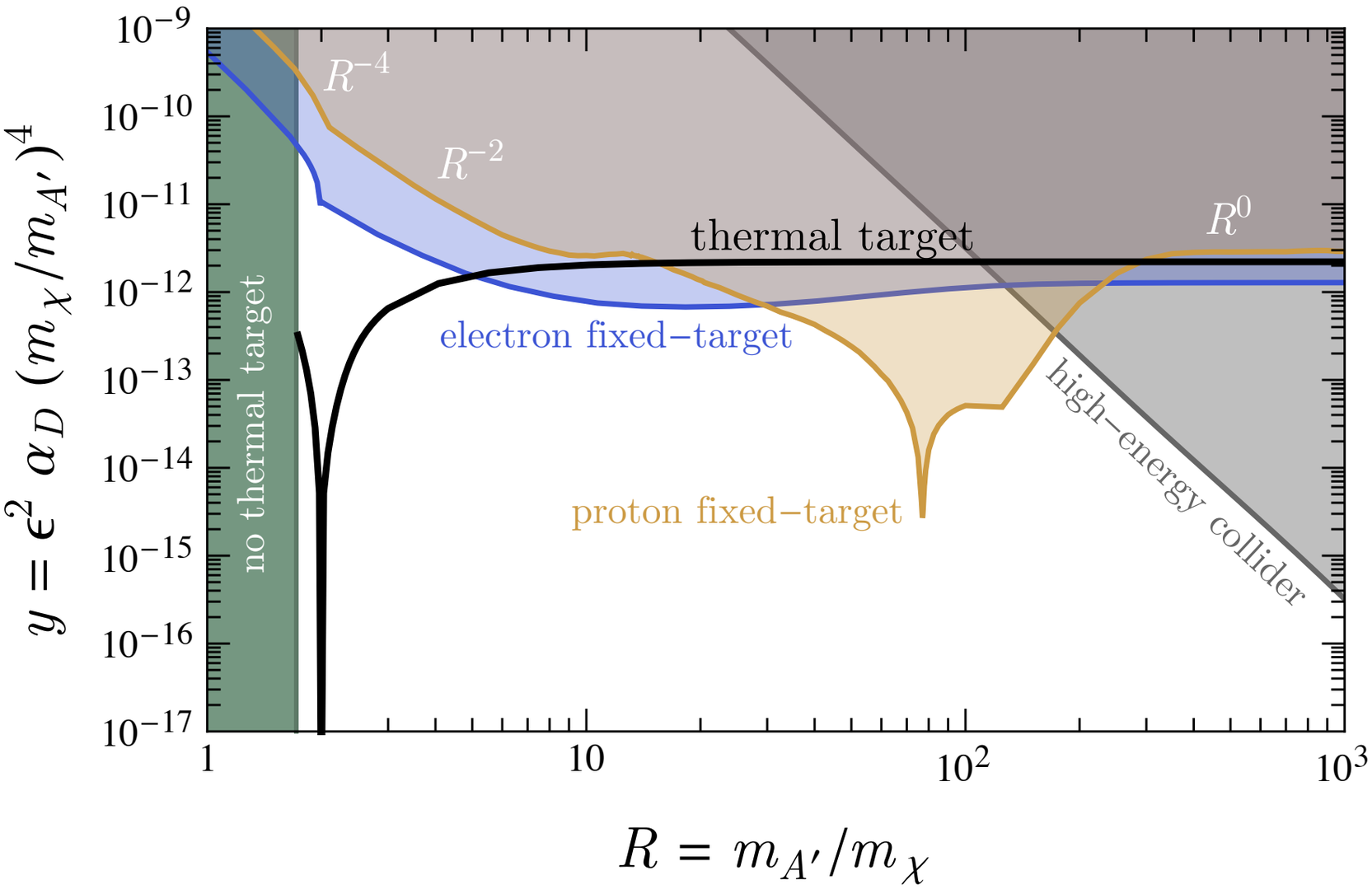
$$F'_{\mu\nu}F^{\mu\nu}$$



Interpreted as mediator to dark matter $\alpha_D = 0.1\ ,\ m_{A'}/m_\chi = 3$

BC2 Benchmark: **invisibly** decaying dark photon

$F'_{\mu\nu}F^{\mu\nu}$

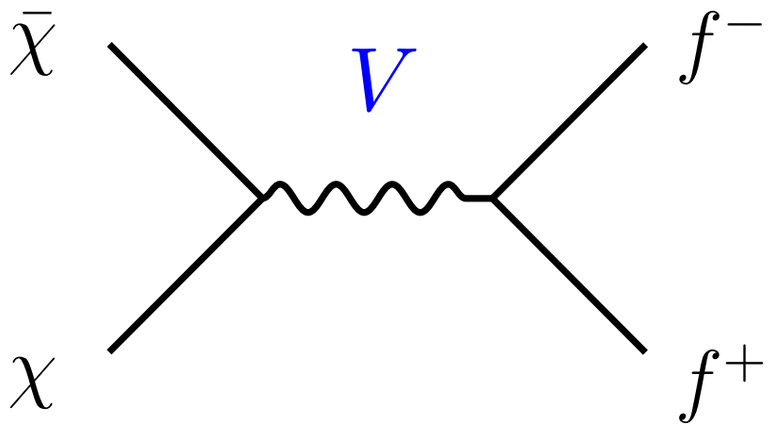


$m_{A'}/m_\chi = 3$ benchmark chosen to target viable parameter space

Thermal targets insensitive to ratio except at resonance $m_{A'} = 2m_\chi$

Berlin, deNiverville, Ritz, Schuster, Toro, 2003.03379

FIP Generalize BC2 : **invisibly** decaying anomaly free U(1) mediators



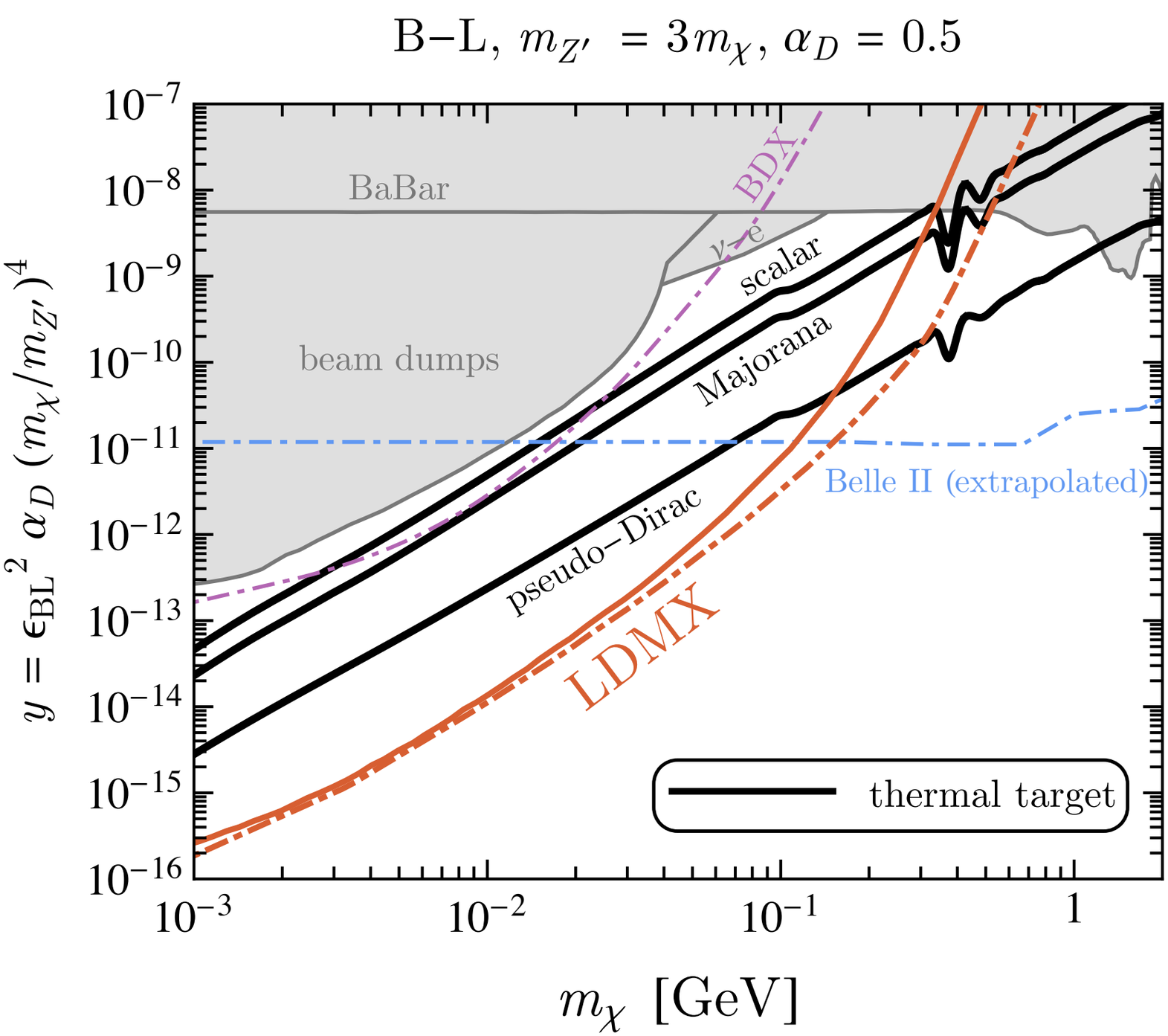
$$\mathcal{L} \supset \quad V_\mu J^\mu_{\rm SM}$$

Larger coupling to light DM yields mainly invisible decays

Again gauge a combination of global SM quantum numbers

$U(1)_{B-L}$ $U(1)_{B-3L_i}$ $U(1)_{L_i-L_j}$

FIPS Generalize BC2 : **invisibly** decaying anomaly free U(1) mediators



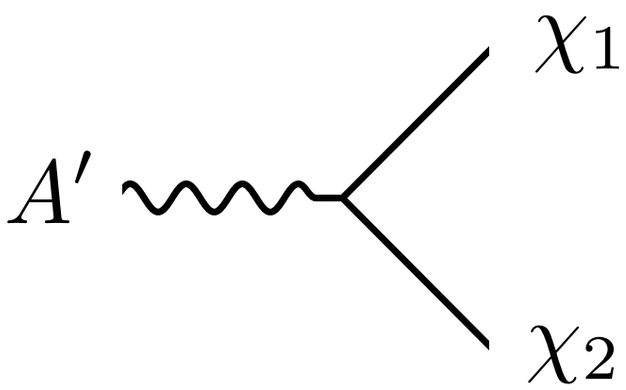
Interpreted as mediator to DM

Berlin, Blinov GK, Schuster, Toro arXiv: 1807.01730

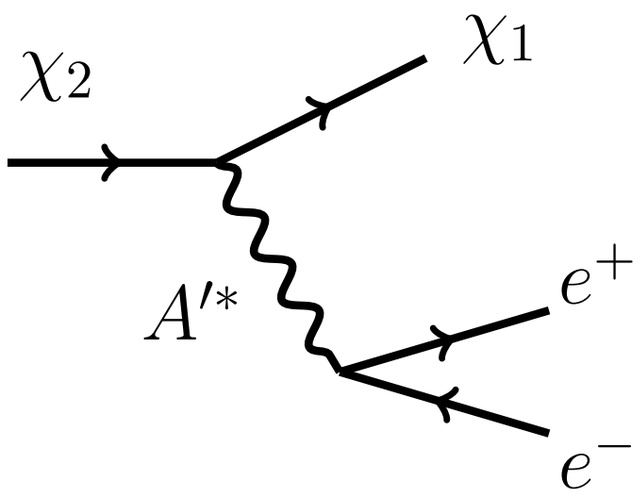
FIPS Generalize BC2 : **inelastic** dark matter

Dark sector is 2-level system
with mass splitting

$$\Delta \equiv \frac{m_2 - m_1}{m_1}$$



Mediator couples off-diagonally

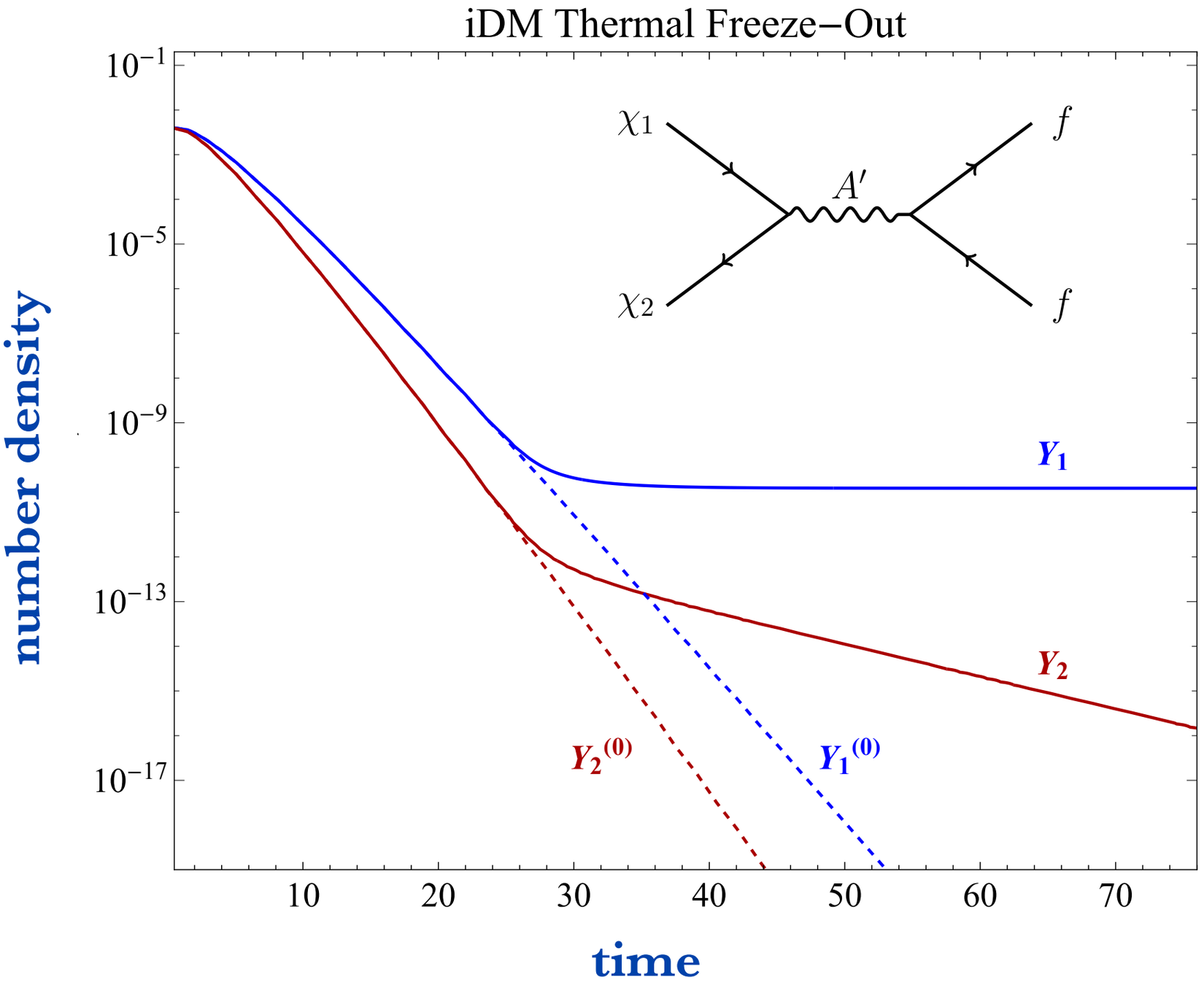


Excited state decays semi-visibly

Izaguirre, GK, Shuve 1508.03050

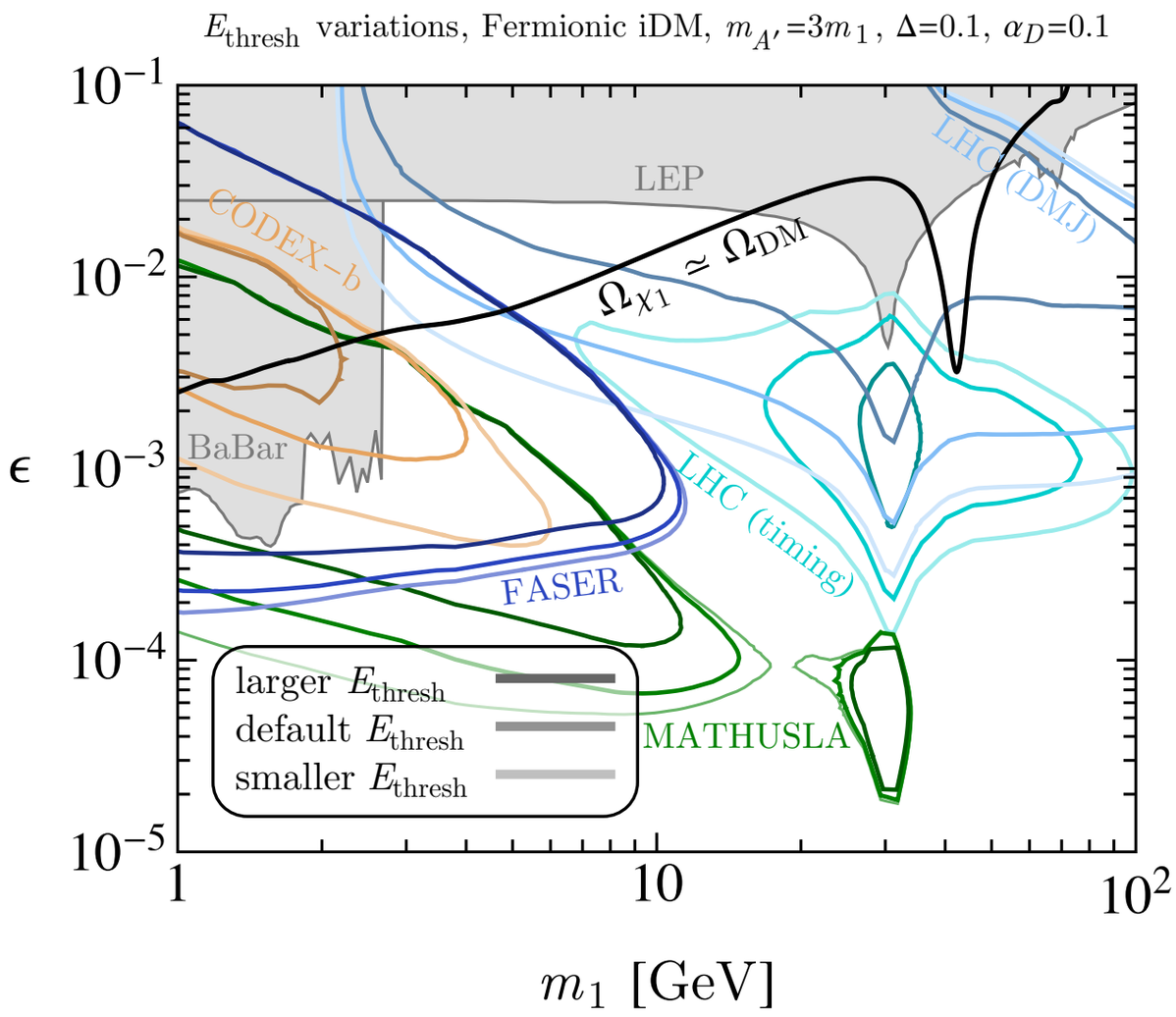
Also see Sam Junius's talk

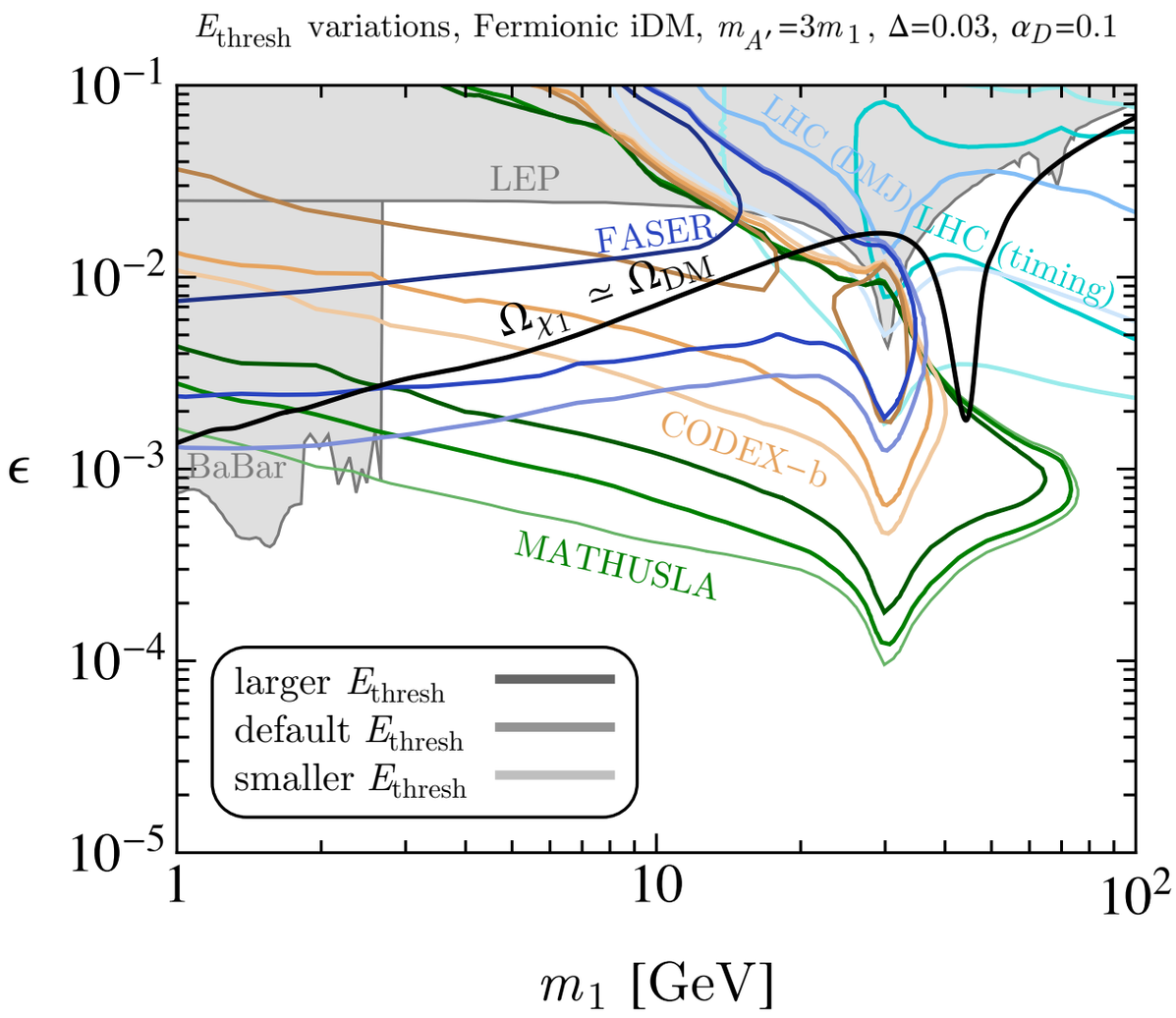
FIPS Generalize BC2 : **inelastic** dark matter



Heavier state feels Boltzmann suppression earlier
Thermal target depends on mass splitting

FIPS Generalize BC2 : **inelastic** dark matter





Large splittings: relic abundance requires larger couplings

Qualitative difference in strategy by including decays

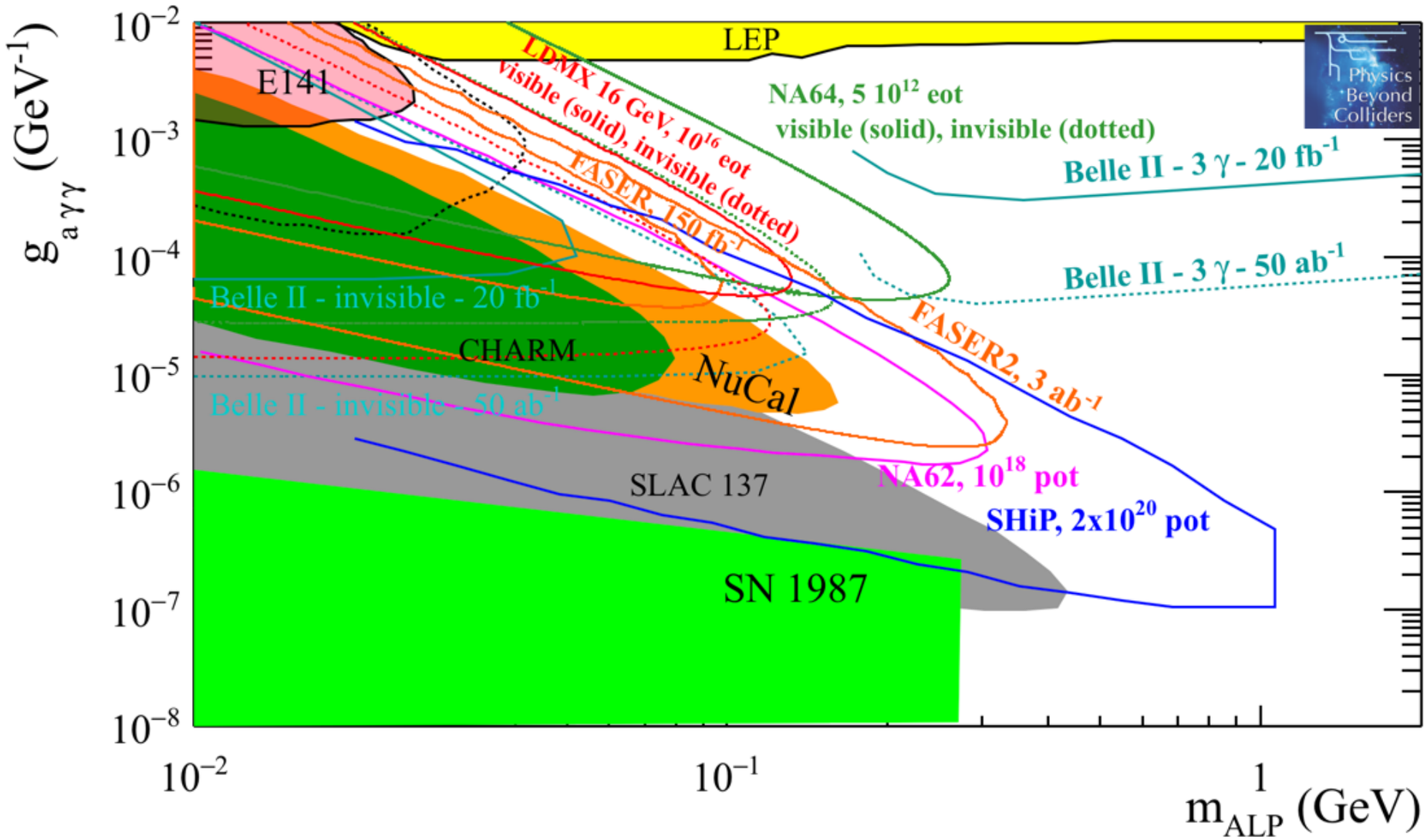
Berlin, Kling: 1810.01879

Review of PBC Benchmarks

PBC report 1901.09966

PBC Benchmark BC9: ALP w/ photon couplings, **visible** decays

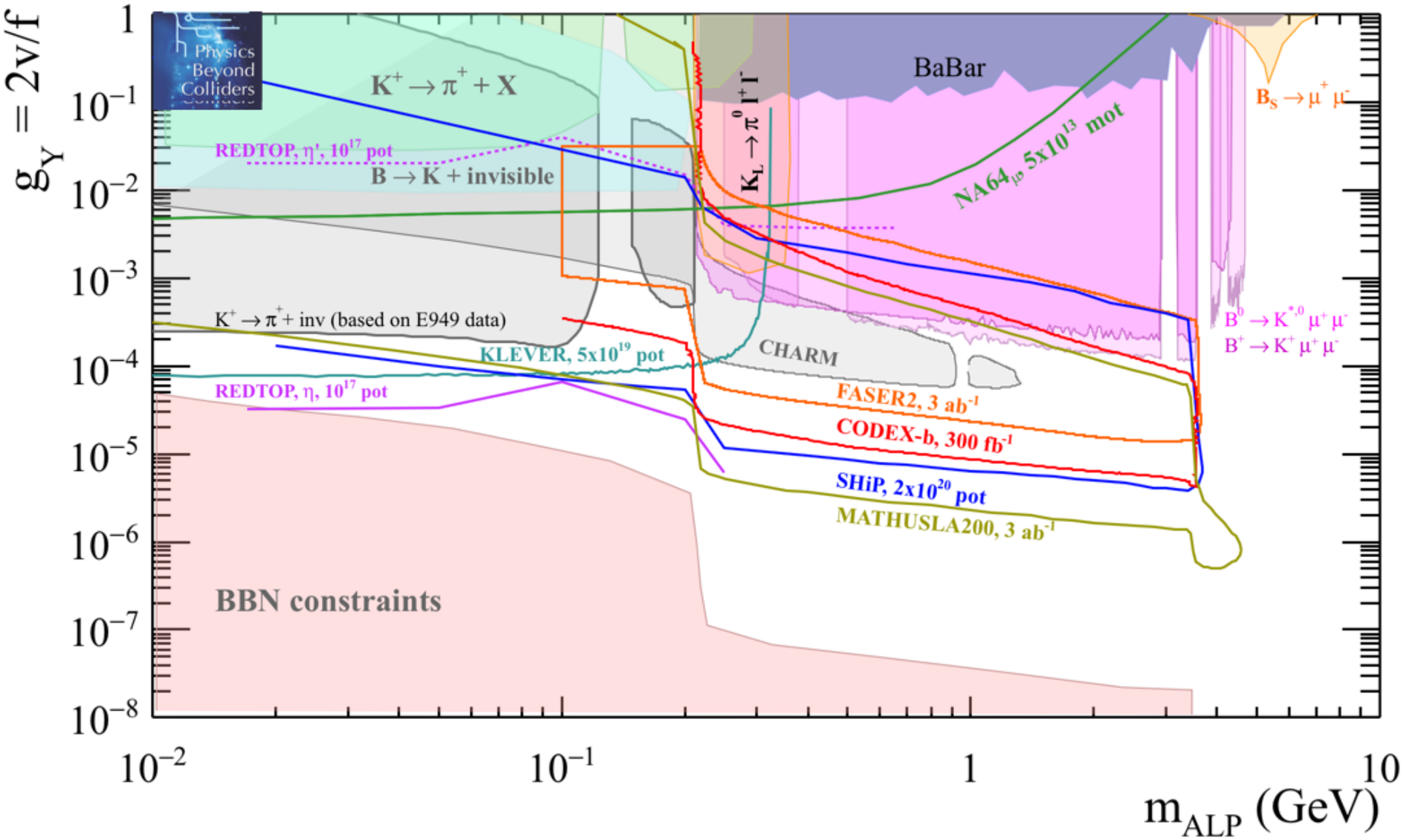
$$\mathcal{L} \supset \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}$$



PBC report 1901.09966

PBC Benchmark BC10: ALP w/ fermion couplings, **visible** decays

$$\frac{\partial_\mu a}{f_l}\sum_\alpha \bar{l}_\alpha\gamma_\mu\gamma_5 l_\alpha + \frac{\partial_\mu a}{f_q}\sum_\beta \bar{q}_\beta\gamma_\mu\gamma_5 q_\beta$$

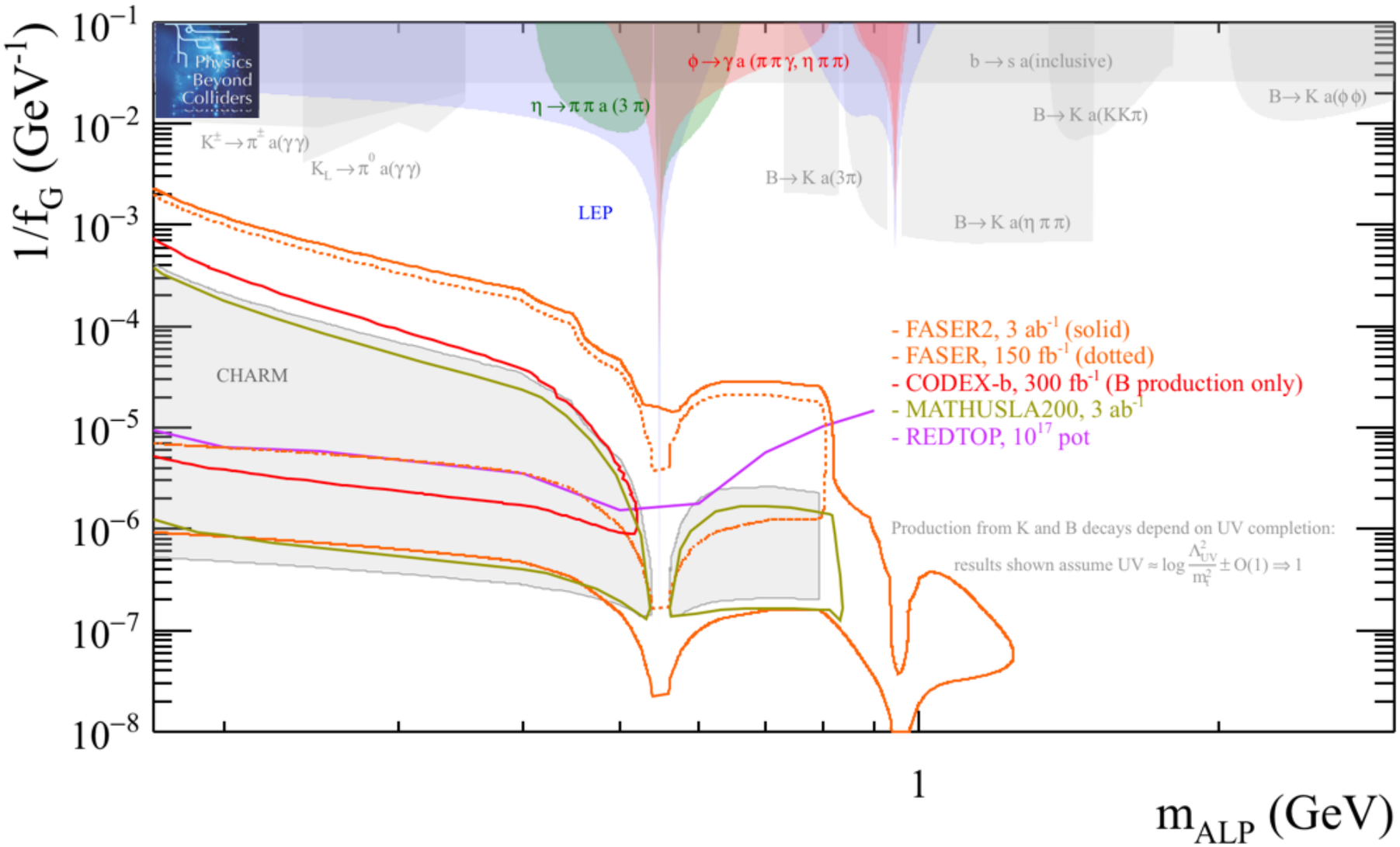


PBC report 1901.09966

Mass weighted couplings per flavor

PBC Benchmark BC10: ALP w/ gluon couplings, **visible** decays

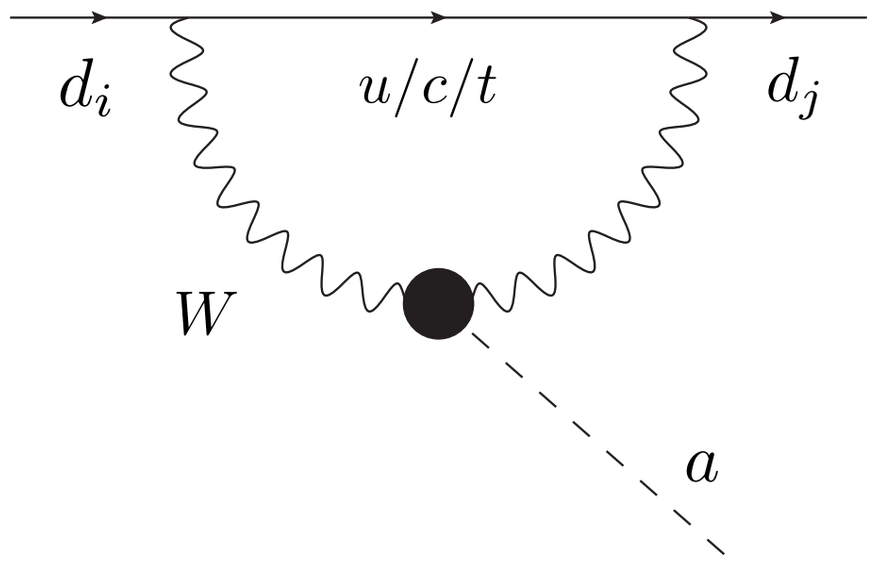
$$\mathcal{L} = \mathcal{L}_{\mathcal{SM}} + \mathcal{L}_{\mathcal{DS}} + a\frac{g_s^2}{8f_G}G^b_{\mu\nu}\tilde{G^b}^{\mu\nu}$$



PBC report 1901.09966

FPS Generalization: ALP w/ dominantly W couplings

$$\mathcal{L} = (\partial_\mu a)^2 - \frac{1}{2} M_a^2 a^2 - \frac{g_{aW}}{4}\, a\, W^a_{\mu\nu} \tilde{W}^{a\mu\nu},$$



Enhanced ALP production in loops

EWSB induces diphoton decays

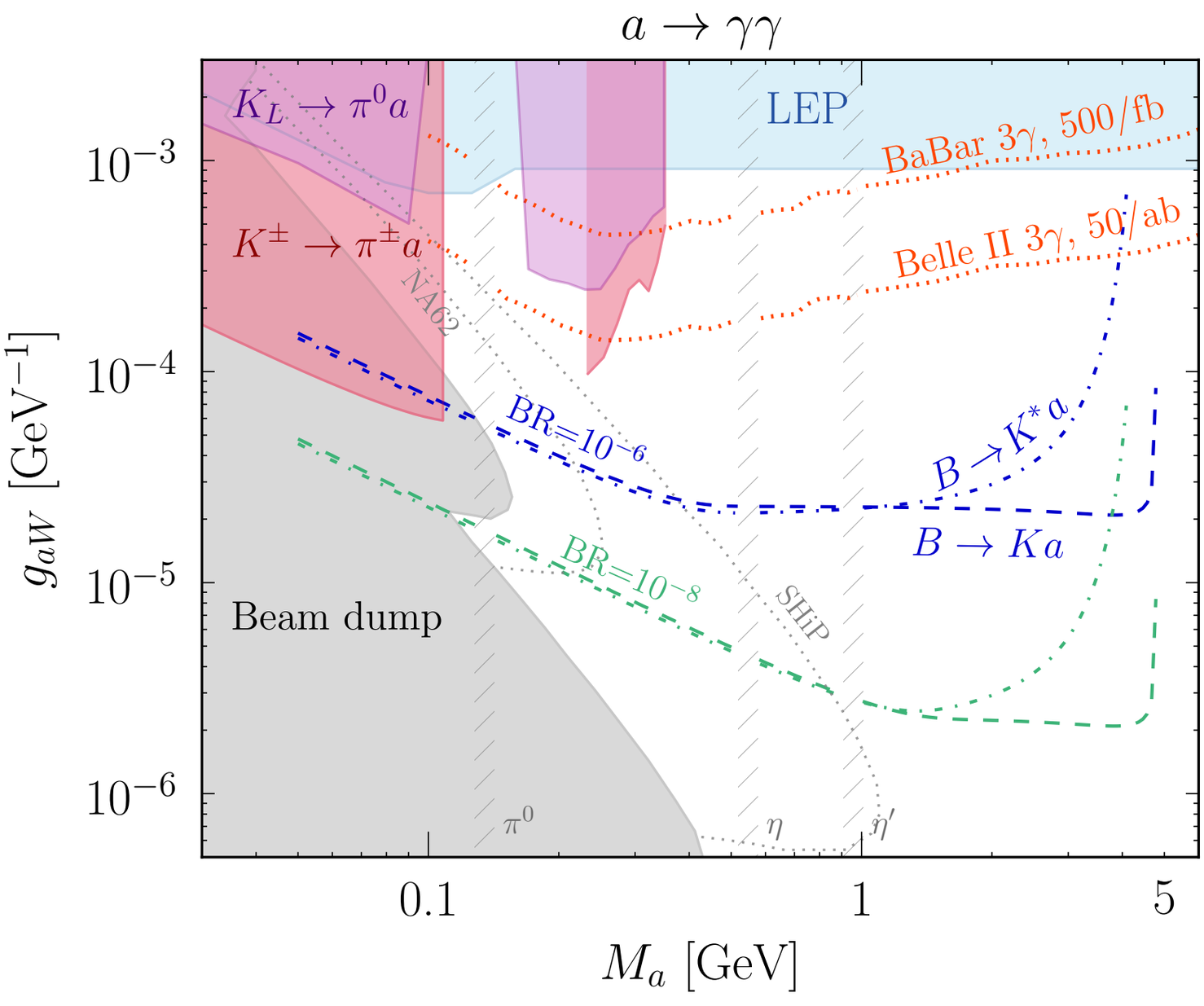
$$a \to \gamma\gamma$$

Can also consider invisible decays

$$a \to \not{E}$$

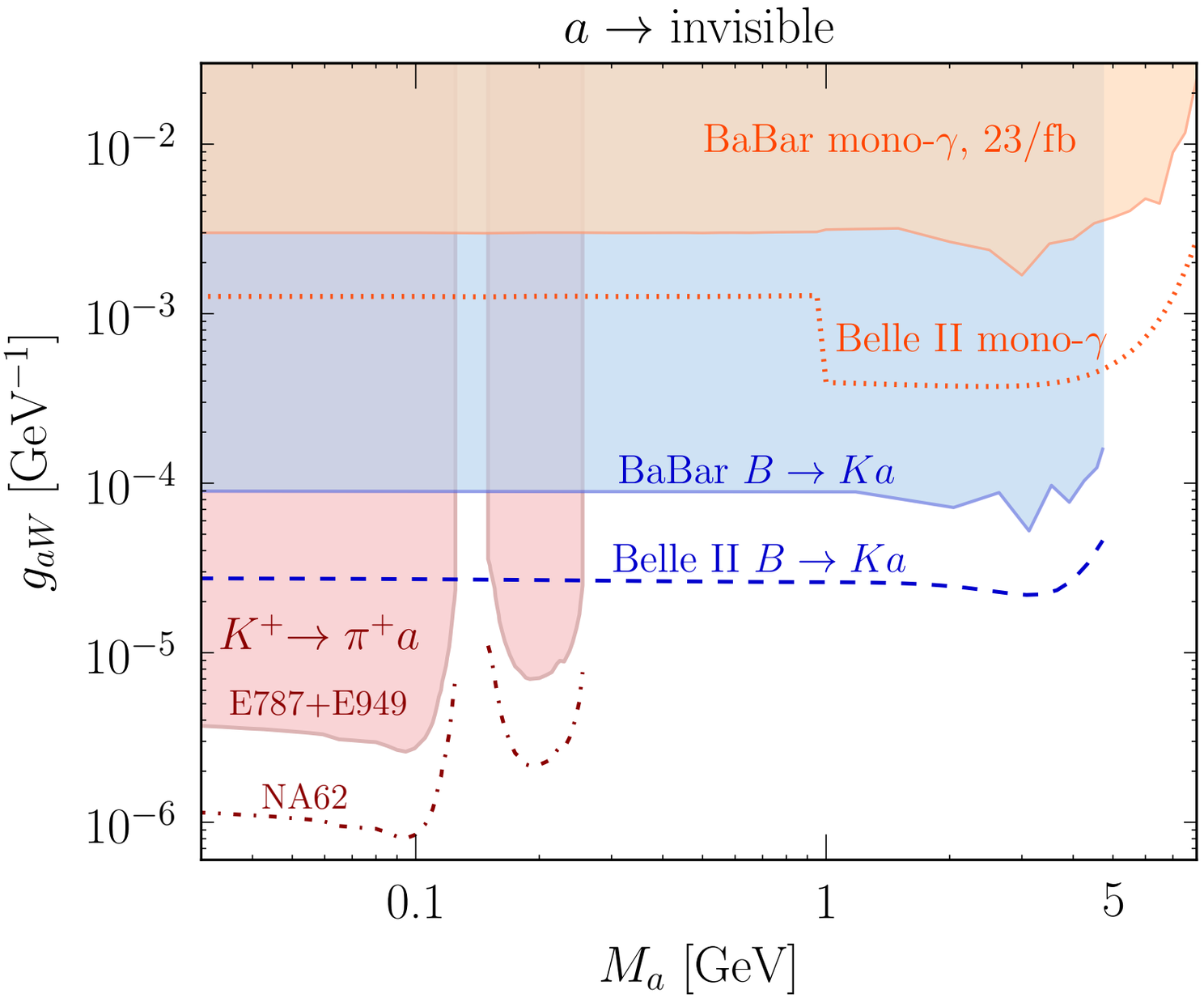
Izaguirre, Lin, Shuve 1611.09355

FPS Generalization: ALP w/ W couplings



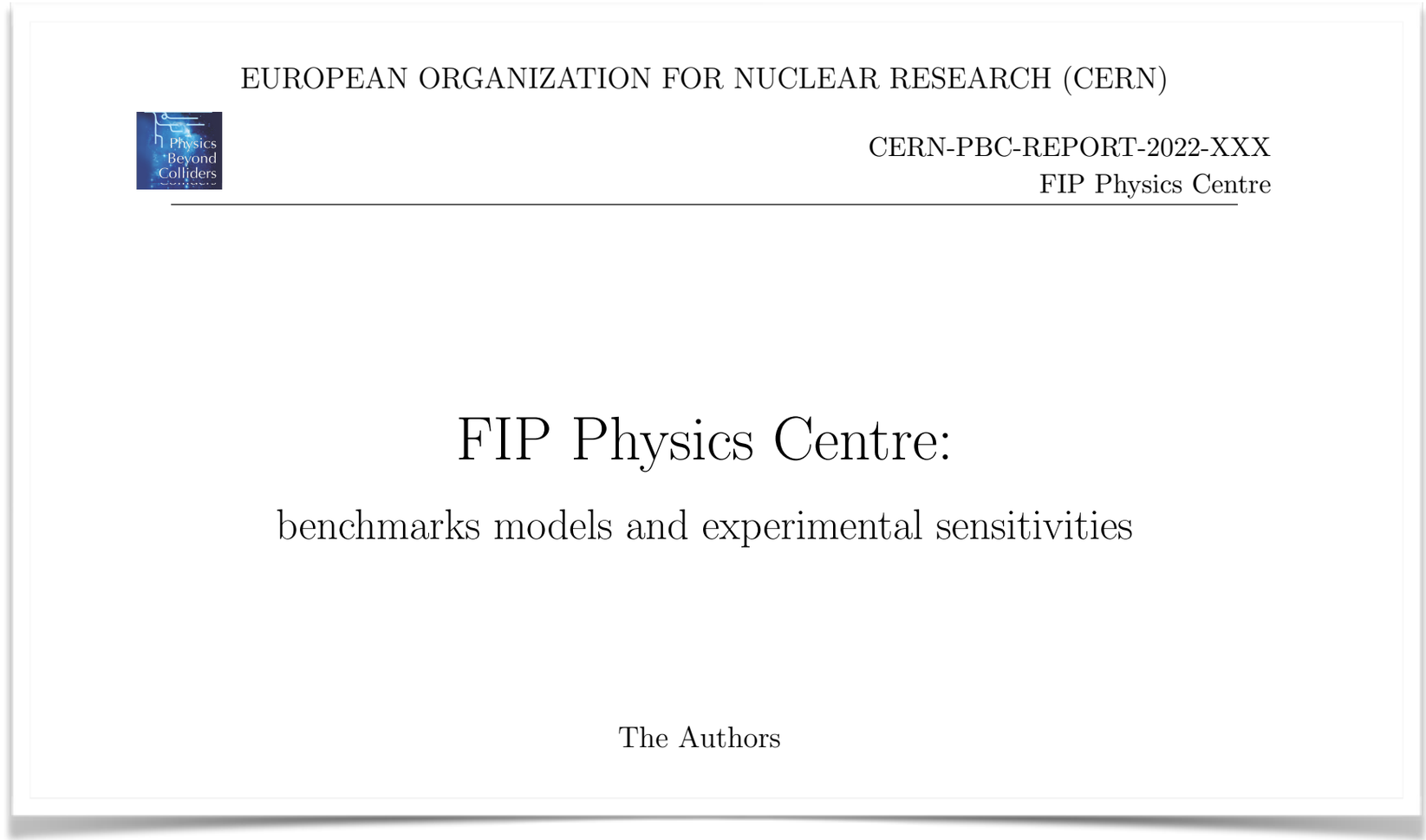
Izaguirre, Lin, Shuve 1611.09355

FPS Generalization: ALP w/ W couplings



Izaguirre, Lin, Shuve 1611.09355

Conclusion



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

Physics Beyond Colliders

CERN-PBC-REPORT-2022-XXX
FIP Physics Centre

FIP Physics Centre:

benchmarks models and experimental sensitivities

The Authors

FPC Physics Centre approach organized around mediator portals

Generalize PBC benchmarks — new vectors, inelastic DM, ALP flavor

Variety of targets and projections for visible/invisible decays

Document soon…