Sub-GeV Scalar Dark Matter — Hints and Probes

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Particle Physics Seminar, 15.01.2021

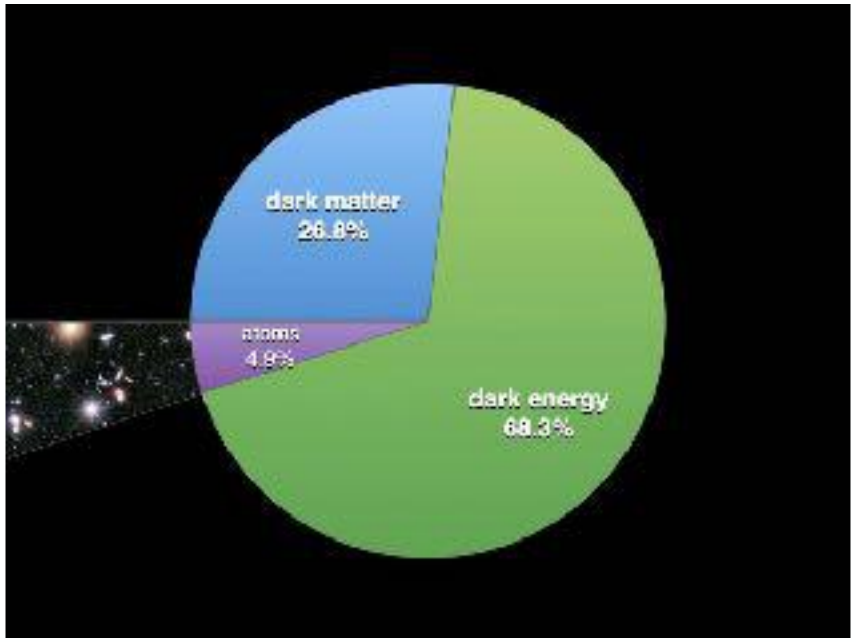
Based on arXiv:2010.02954

In collaboration with
Celine Bohem, Xiaoyong Chu and Josef Pradler

Outline

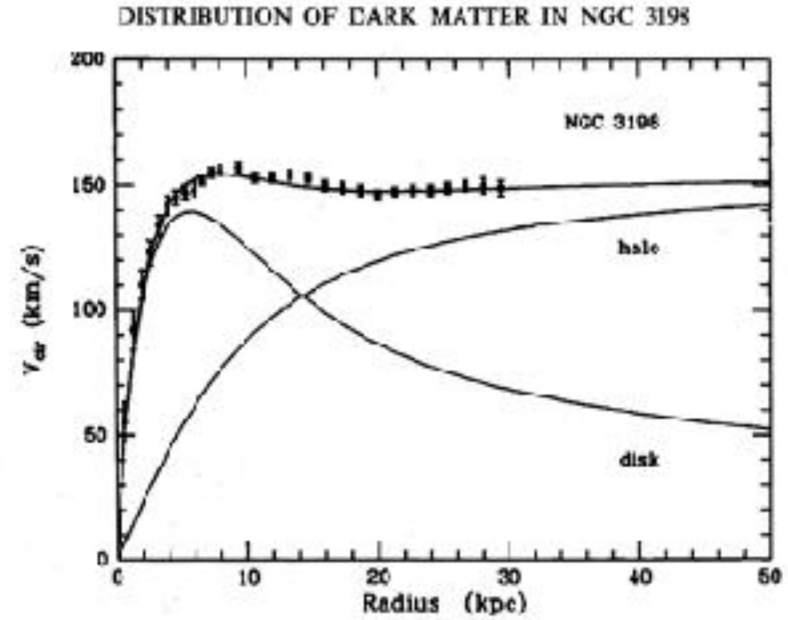
- Motivation and Hints
- Particle Model
- Intensity Frontier
- Precision Frontier and LEP
- Direct Detection and astro/cosmo constraints
- Summary

Motivation and Hints



Credit: Katie Mack

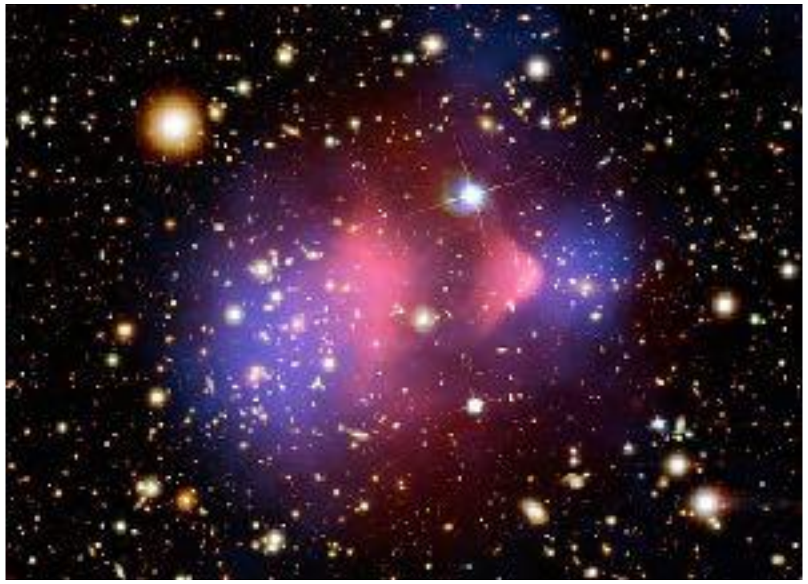
Galaxy Rotation Curves



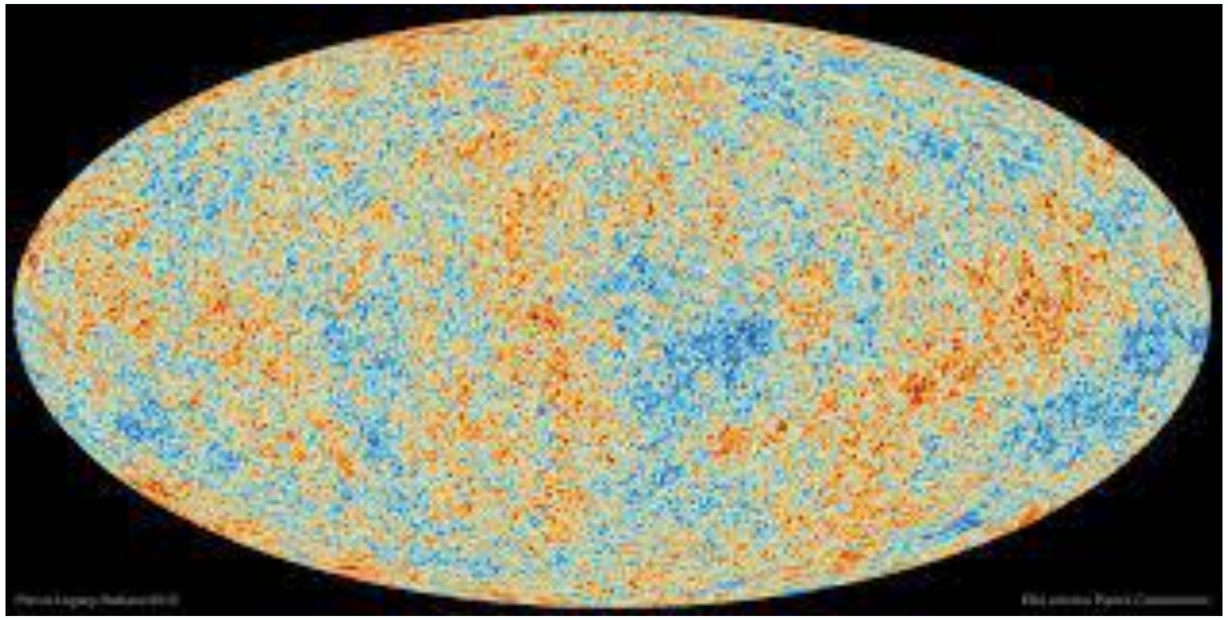
Credit: Physics and Universe

Bullet Cluster

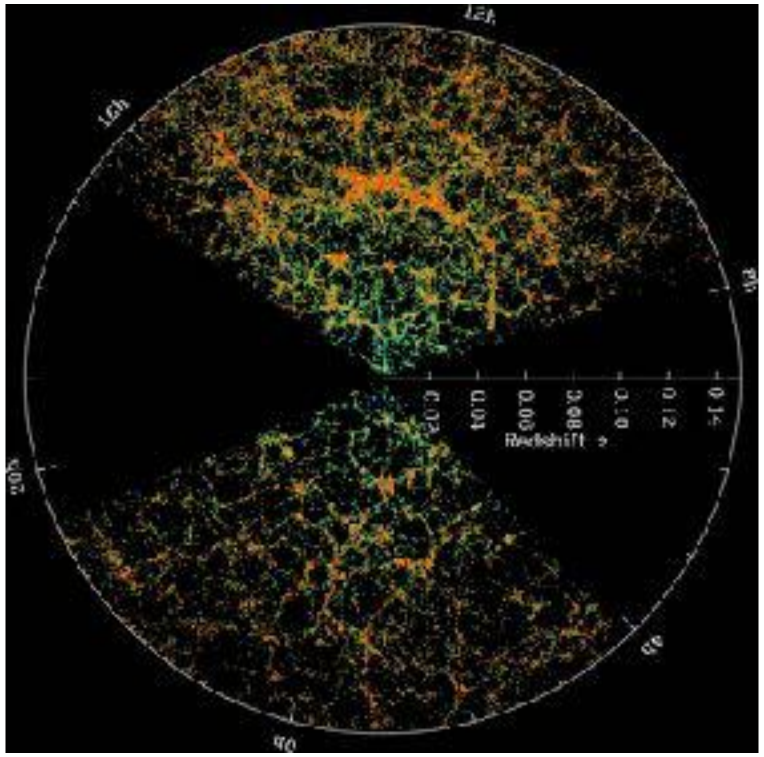
Credit: NASA



CMB



Credit: Planck



Large-scale Structure

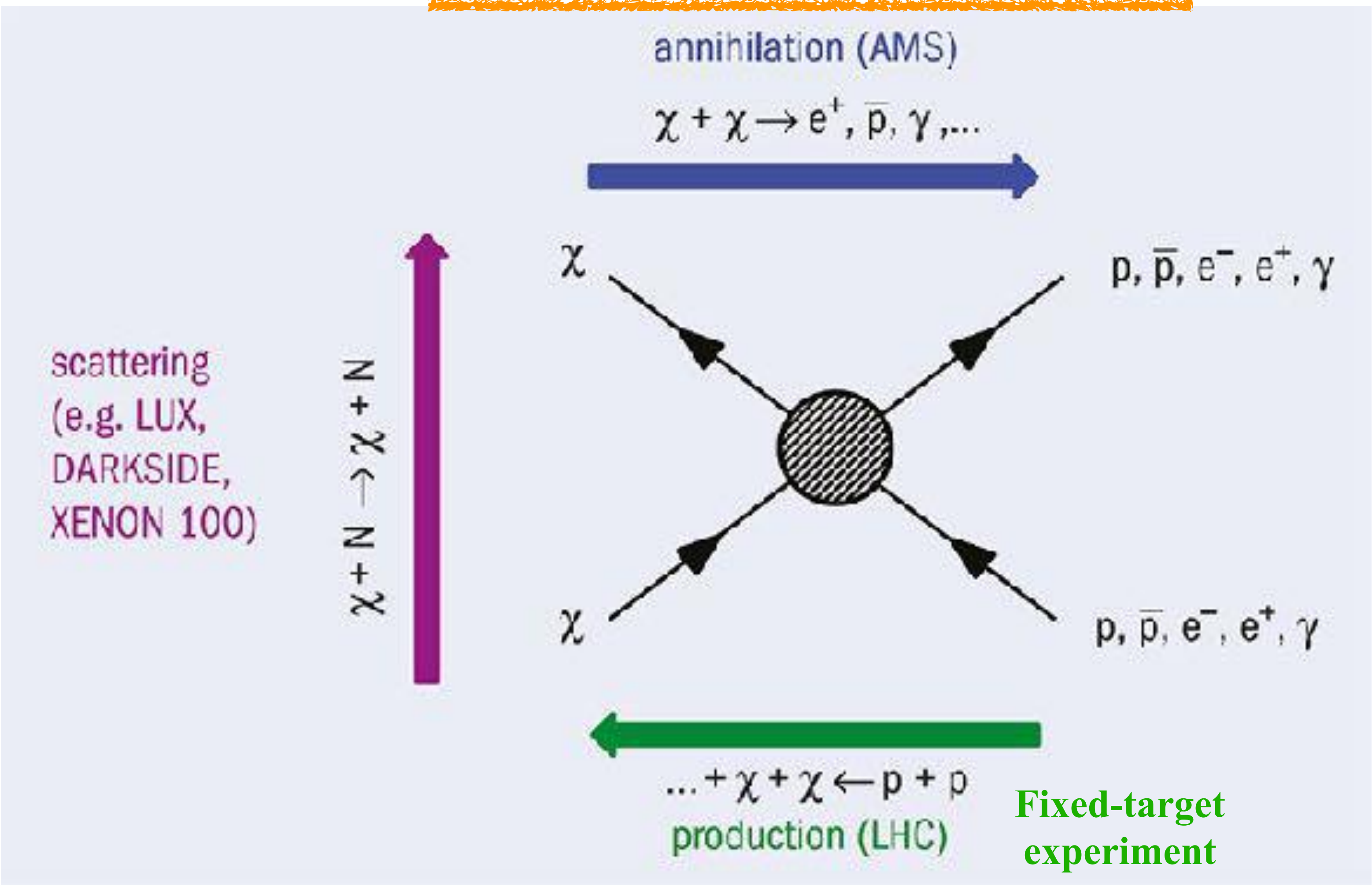
Credit: SDSS

Motivation and Hints

- How to probe dark sector?

Indirect detection

Direct detection

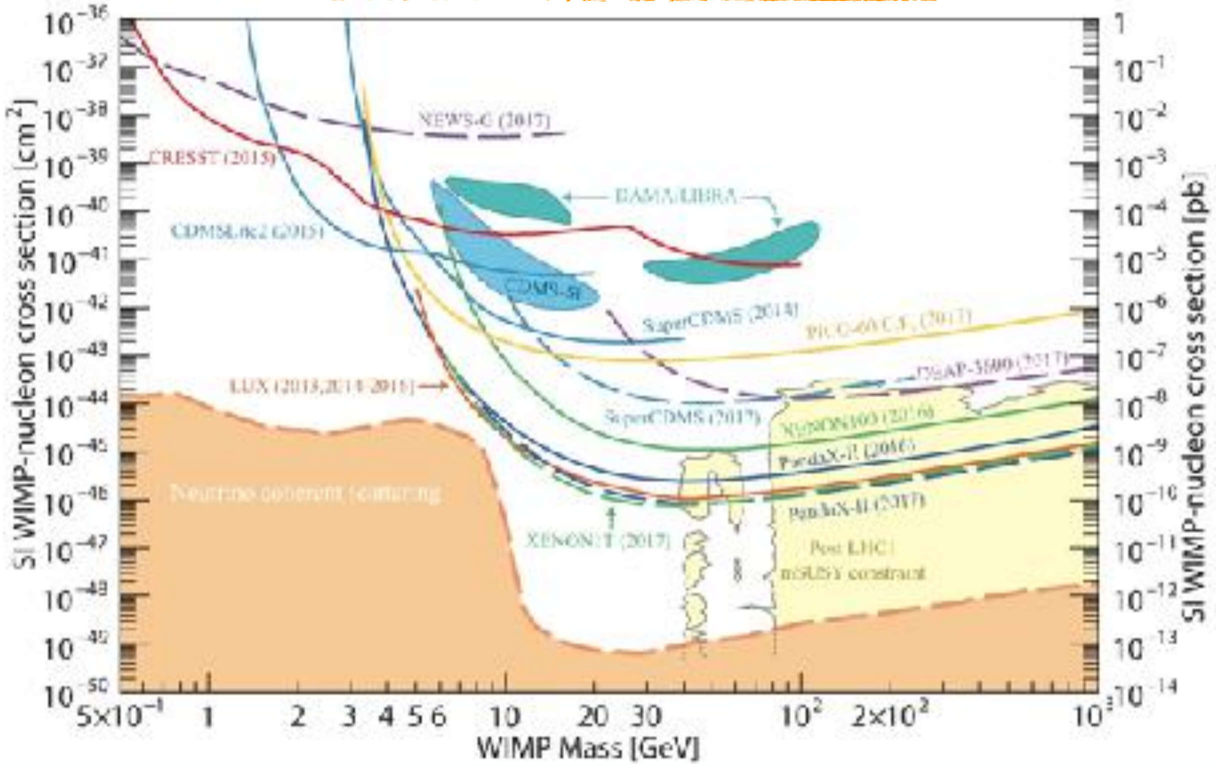


Credit: CERN Courier

e.g. Production in colliders (heavy DM) or stars (light DM)

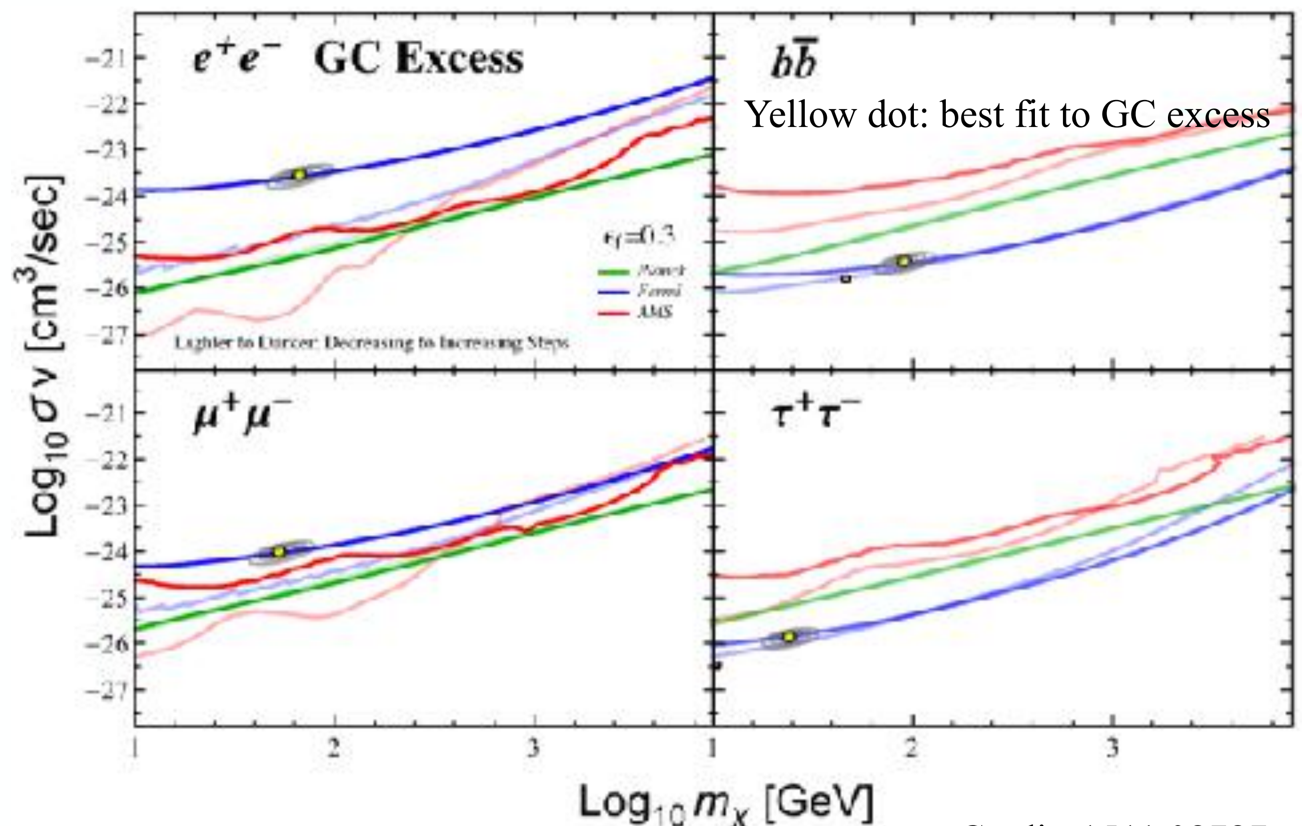
Motivation and Hints

Direct detection



Credit: 1901.05658

Indirect detection



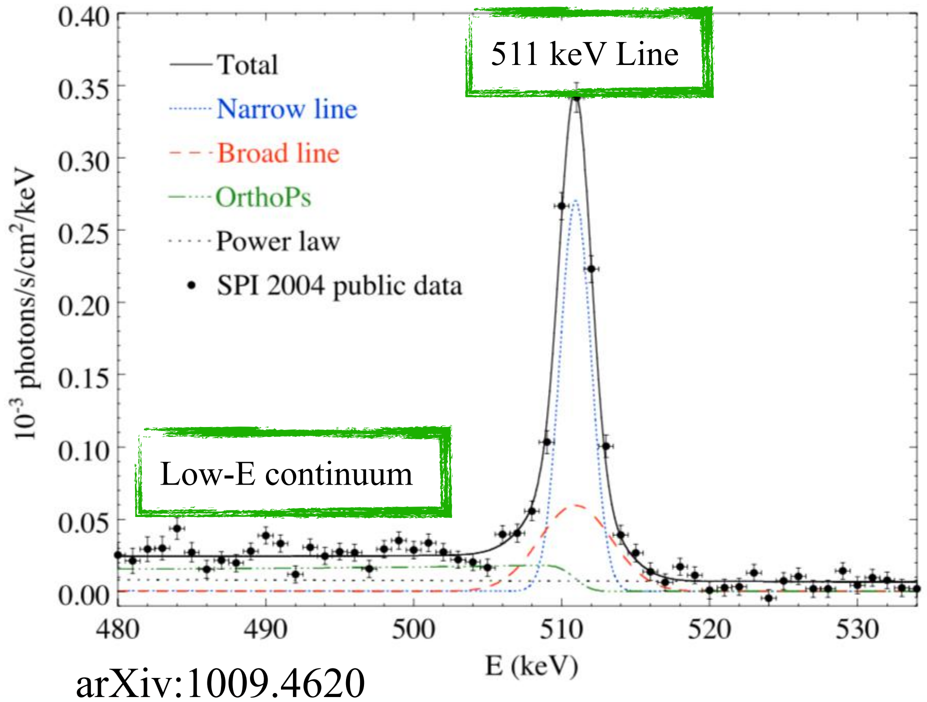
Credit: 1511.08787

Minimal WIMP model is excluded!

→ A light dark sector (< GeV — TeV) possible?

Motivation and Hints

- 511 keV line measured by INTEGRAL/SPI



arXiv:1009.4620

Origin: electron-positron annihilation after positronium formation

Jean et. al (2003), Knodlseder et. al (2003), Prantzos et. al (2010) and Siegert et. al (2015)

Low-energy positron source?
Astrophysics: seems not viable

Prantzos et. al (2010) and Panther et. al (2017)

Positrons from the annihilation of light dark matter!?

Boehm et. al (2003)

$$\sigma_{\rm ann} v = a + b v^2$$

s-wave $a \simeq 2.2 \times 10^{-31} \left(\frac{m_\phi}{\rm MeV}\right)^2 \ {\rm cm}^3\,{\rm s}^{-1}$

p-wave $b \simeq 3.4 \times 10^{-25} \left(\frac{m_\phi}{\rm MeV}\right)^2 \ {\rm cm}^3\,{\rm s}^{-1}$

Motivation and Hints

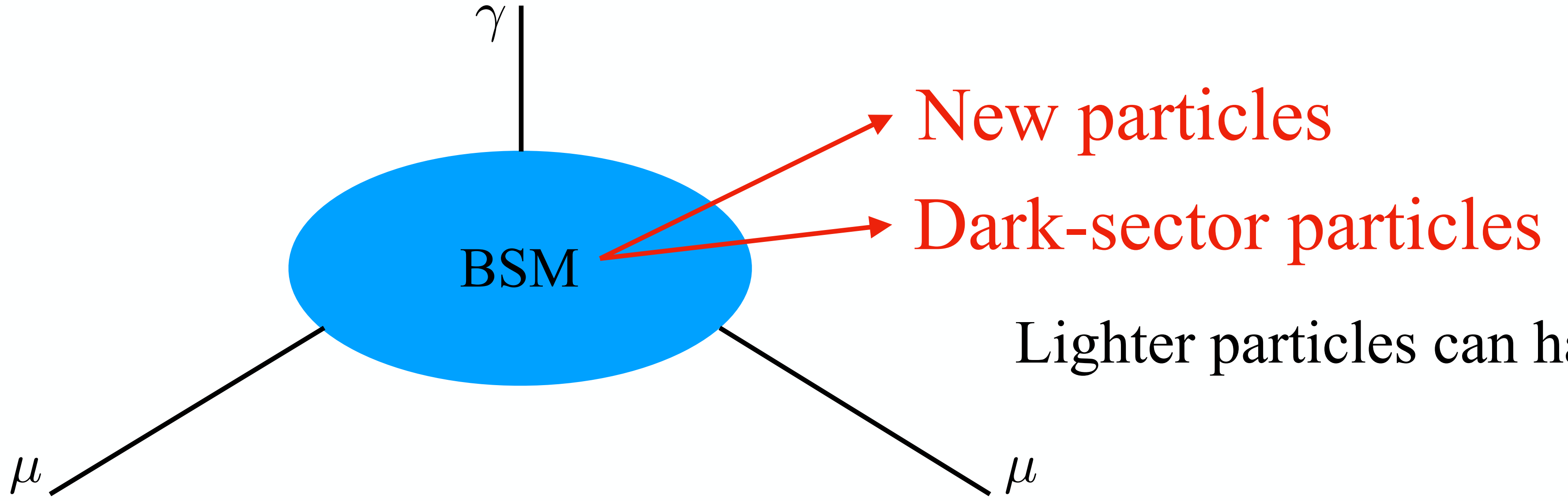
- Muon g-2 anomaly

$$a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (290 \pm 90) \times 10^{-11}$$ Bennett et. al (2006)

3-sigma deviation from SM prediction

Precise calculation of SM contribution (QED, EW and hadronic)

Indication of contribution from new physics? (maybe)



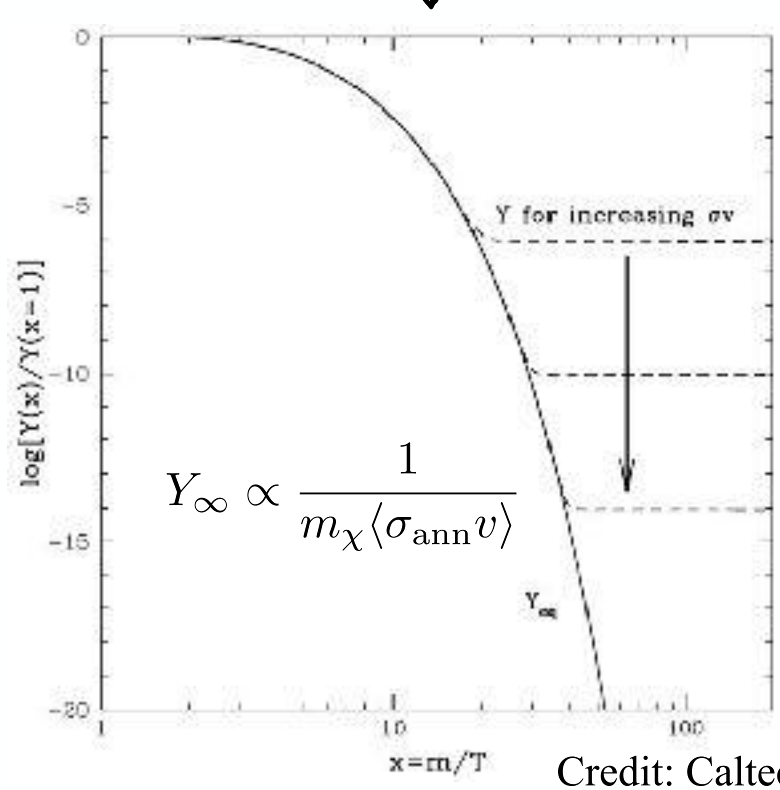
Lighter particles can have larger contribution

Motivation and Hints (3)

- DM relic density

CMB and large-scale structure measurements constrain the abundance of dark matter

Straightforward scenario: thermal freeze-out



$$Y_\infty \propto \frac{1}{m_\chi \langle \sigma_{\rm ann} v \rangle}$$

Credit: Caltech

Works for conventional WIMP (GeV-TeV)

Also possible for light DM (sub-GeV) !

Exist other production mechanism such as freeze-in scenario

Particle Model

- Sub-GeV Dark Matter is motivated suggested by previous hints

Scalar Dark Matter Candidates Boehm and Fayet (2003)

➡ Pioneering work on sub-GeV DM

1. Fermion portal

$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\phi\bar{F}^0 P_L\nu_l + h.c.$$

Yukawa-type interaction
If only 1 generation of F, LFV is possible

2. Vector portal

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu\phi^*\phi - ig_\phi Z'_\mu\left[\phi^*(\partial^\mu\phi) - (\partial^\mu\phi^*)\phi\right] - iZ'_\mu\bar{l}\gamma^\mu(g_L P_L + g_R P_R)l.$$

scalar-QED like interaction

QED-like interaction,
but chiral interaction is possible

Successfully address the hints (INTEGRAL 511 keV line, muon g-2, thermal freeze-out) Boehm and Fayet (2003)

Particle Model

At that time (2003), no data can constrain aforementioned models!

Intensity frontier (low-E colliders, fixed-target/ beam-dump exp.)

LEP and High-E colliders   BSM charged particle needs to be heavier than ~ O(800) GeV

Precision tests of SM

DM direct detection by scattering with bound electrons

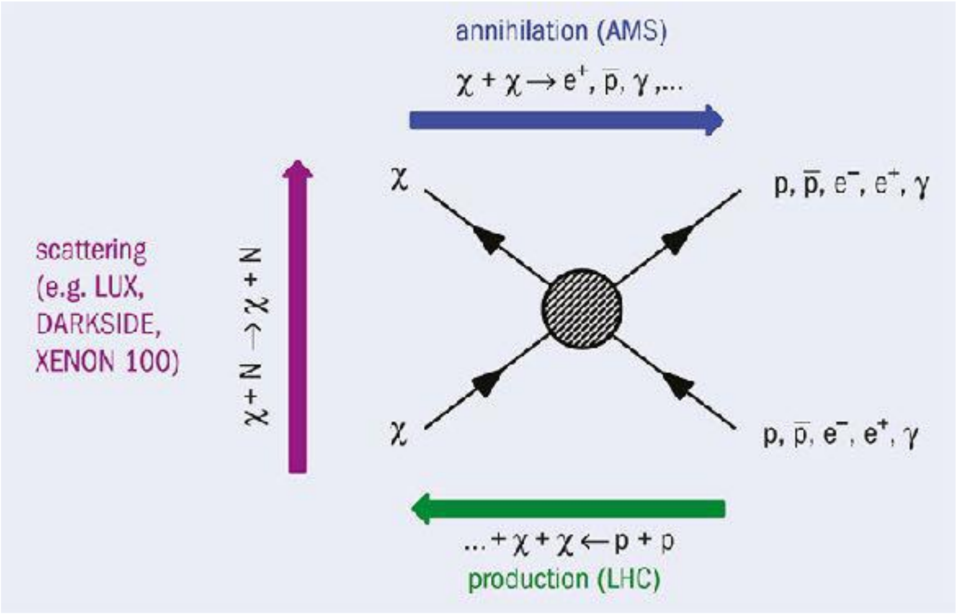
Updated Astro./ Cosmo. Constraints on new physics

Still no plausible positron source for the 511 keV line

Now: time for revisiting these models with two decades of data

Particle Model

- To probe a 'light' dark sector



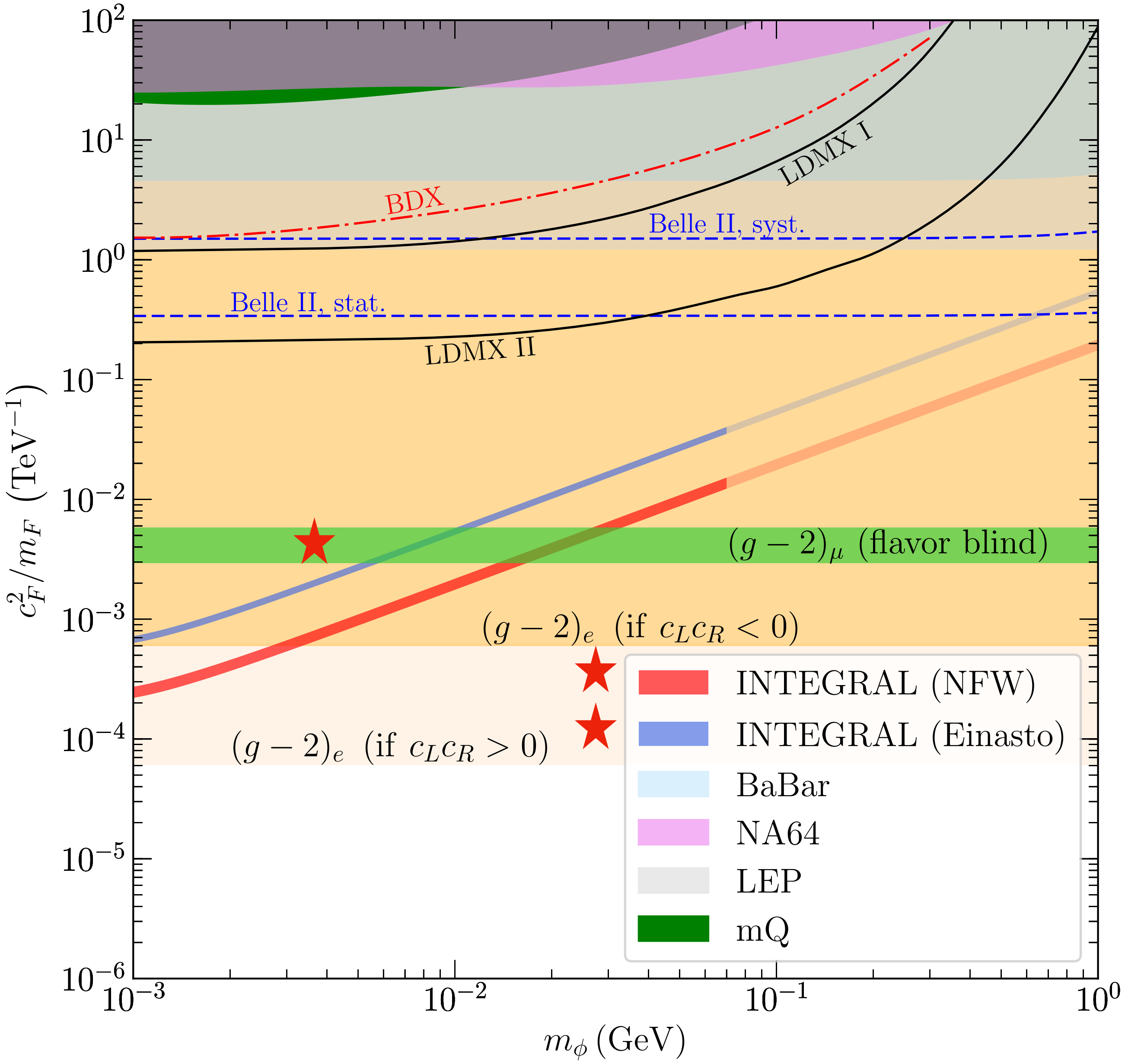
The physical picture is still the same!

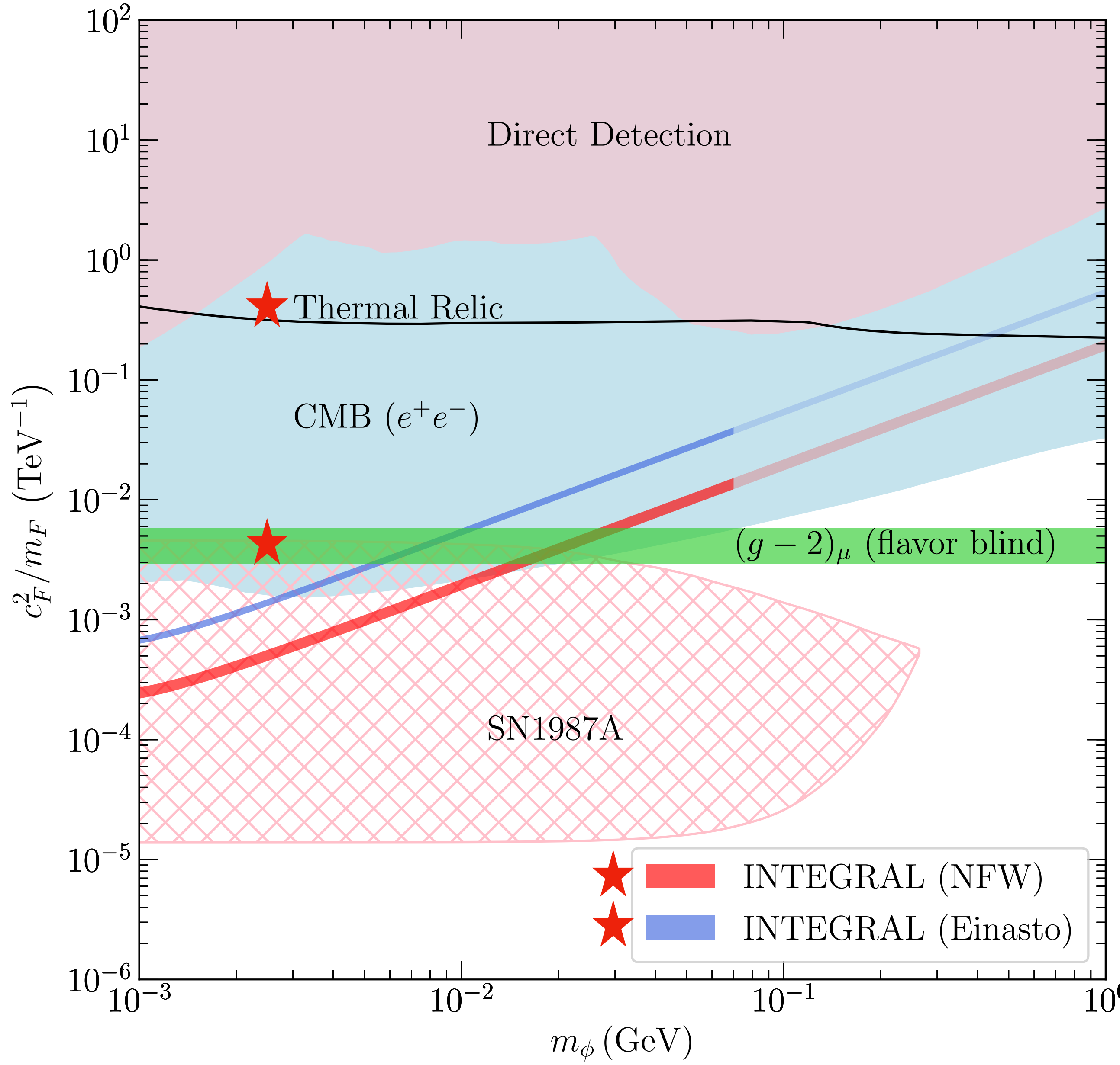
High intensity: low-energy colliders, fixed-target experiment and beam-dump experiments

High precision: SM precision observables

Low threshold: stellar emission and direct detection

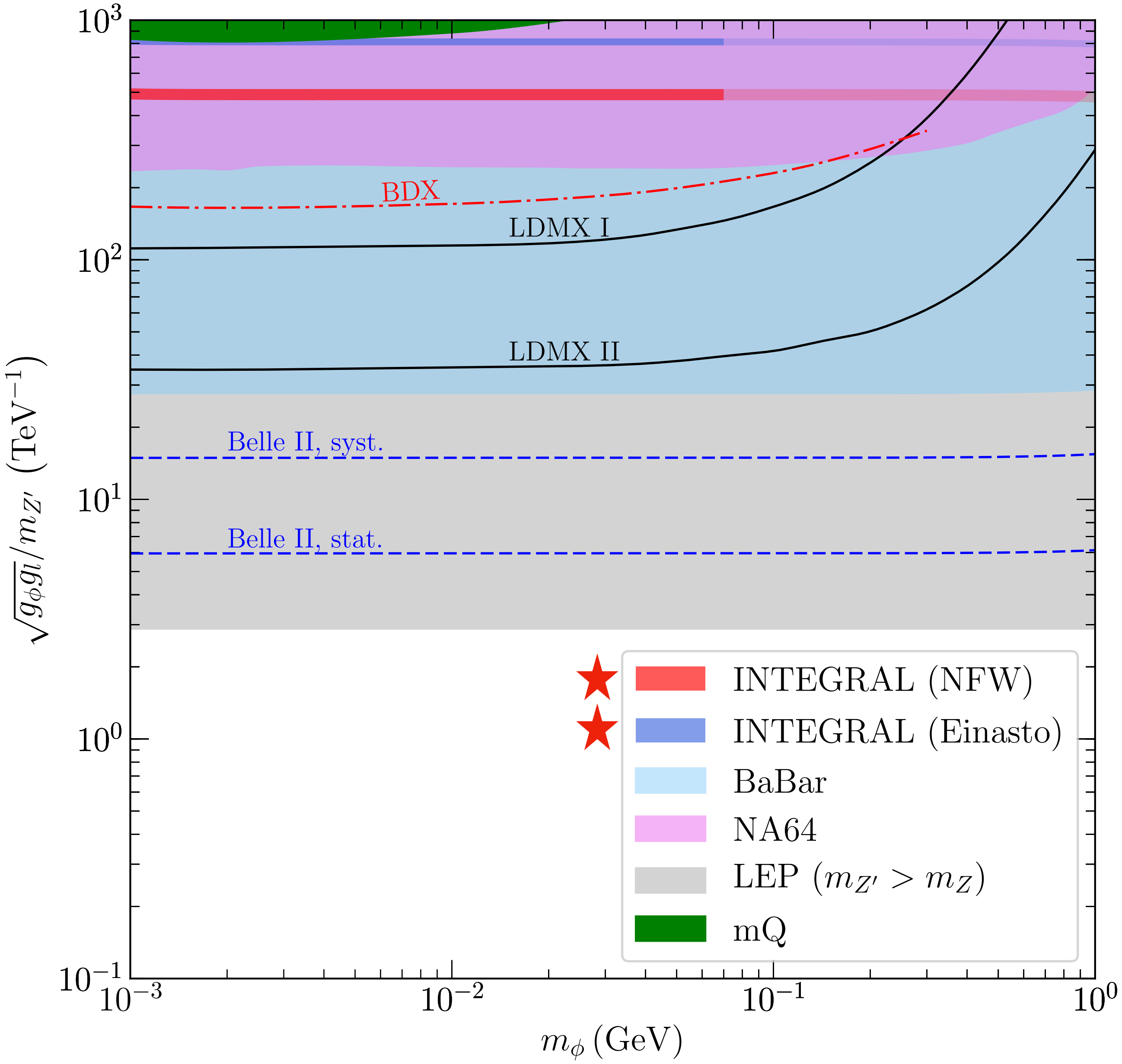
Overview of Parameter Space: F

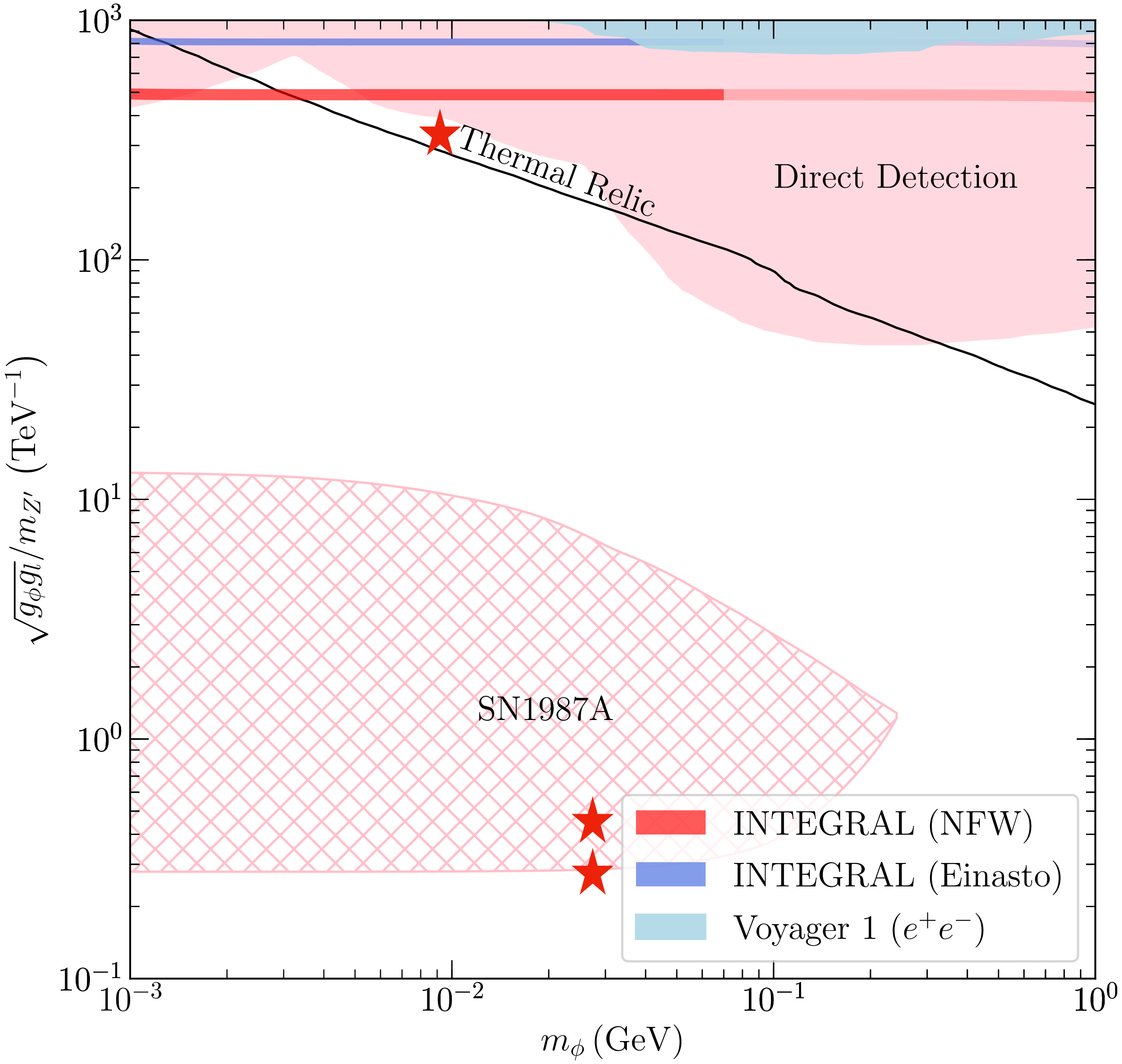




$$\mathcal{L}_F = -c_L^l \, \phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

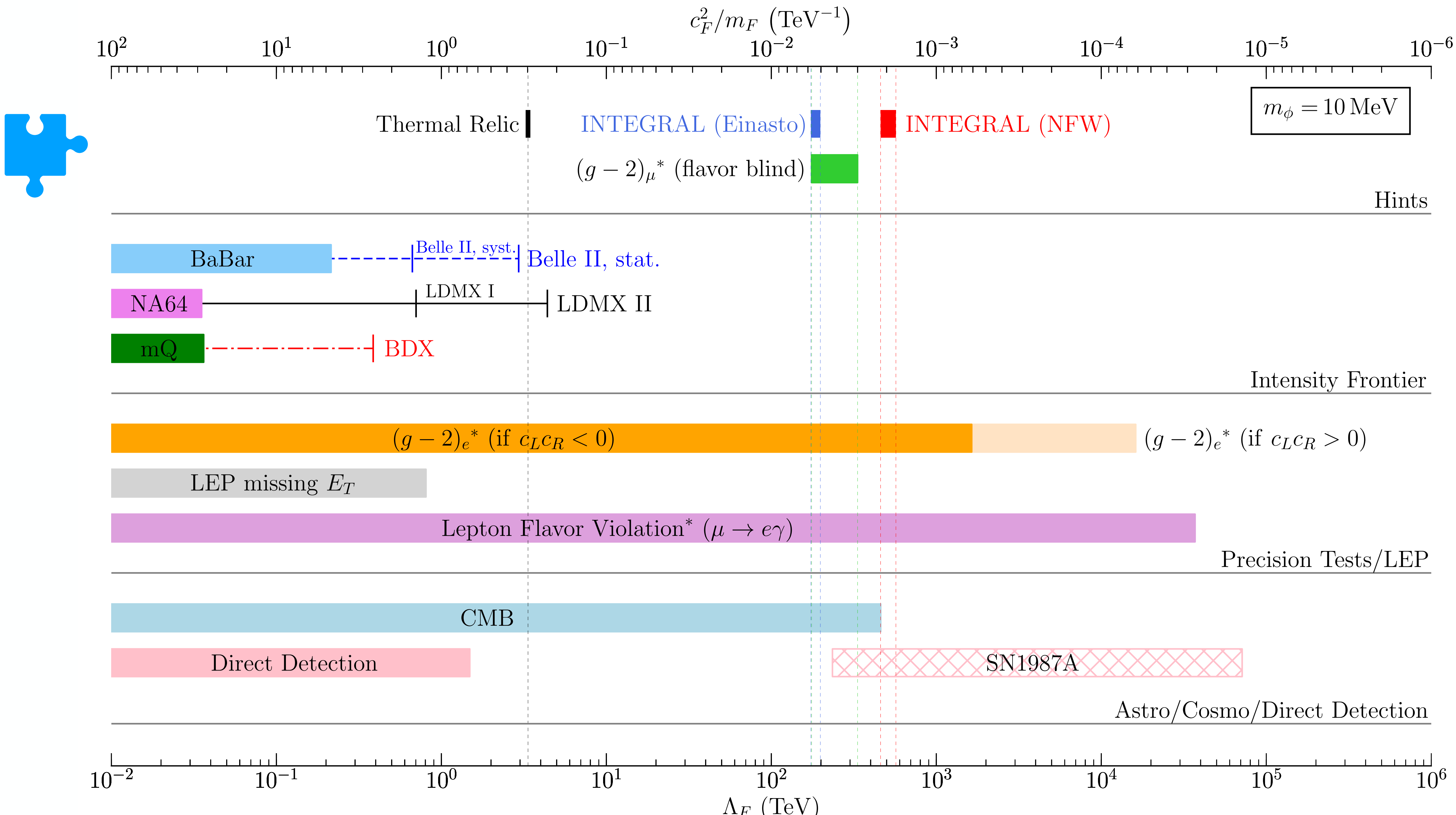
Overview of Parameter Space: Z'





$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

Check List



$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\phi\bar{F}^0 P_L\nu_l + h.c.$$

Intensity Frontier

Pros

- Very high intensity: integrated luminosity could be larger than that from collider

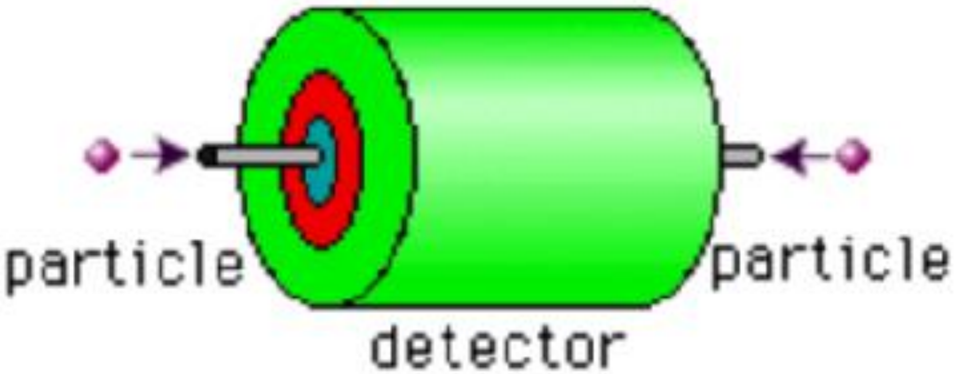
Cons

- Difficulties in handling the neutrino background

Intensity frontier exp.

Produce light particles

High-energy collider exp.

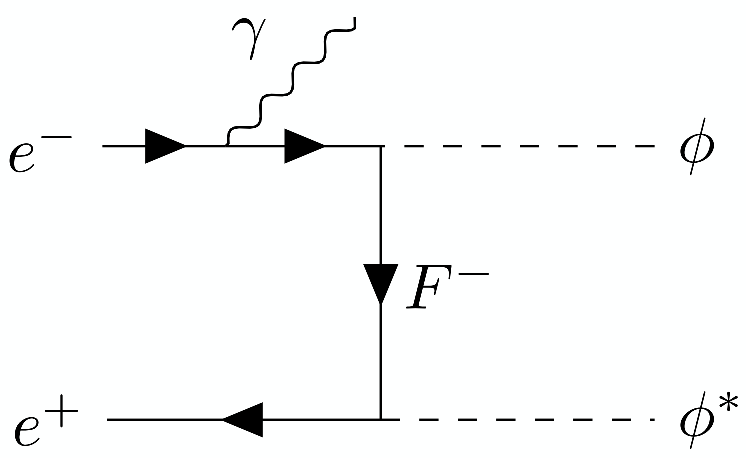


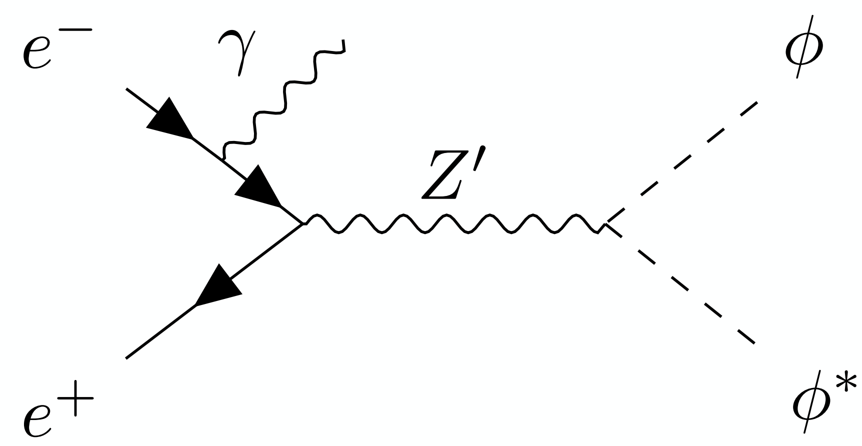
Produce heavy particles

Intensity Frontier

- Low-energy electron-positron collider (BaBar and Belle II)

Process: electron-positron annihilation with initial-state radiation





$$\mathcal{L}_F = -c^l_L\, \phi \bar{F} P_L l - c^l_R \phi \bar{F} P_R l - c^l_L \phi \bar{F}^0 P_L \nu_l + h.c.$$

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*)\phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

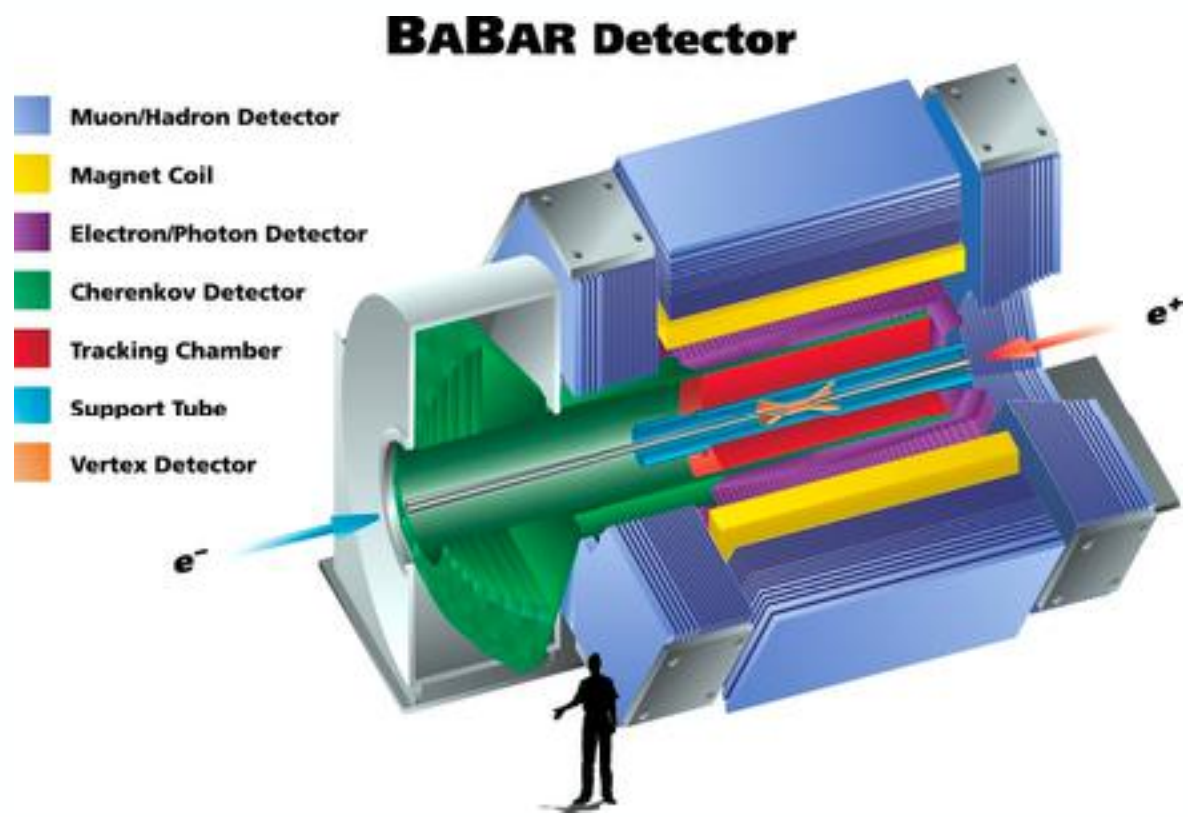
Signal: missing transverse E/p + mono-photon

SM background: $e^+e^- \to \gamma\not{\gamma}$ (peak), $e^+e^- \to \gamma \not{e}^+ \not{e}^-$ or $\gamma\not{\gamma}\not{\gamma}$ (continuum)

Intensity Frontier

- Low-energy electron-positron collider

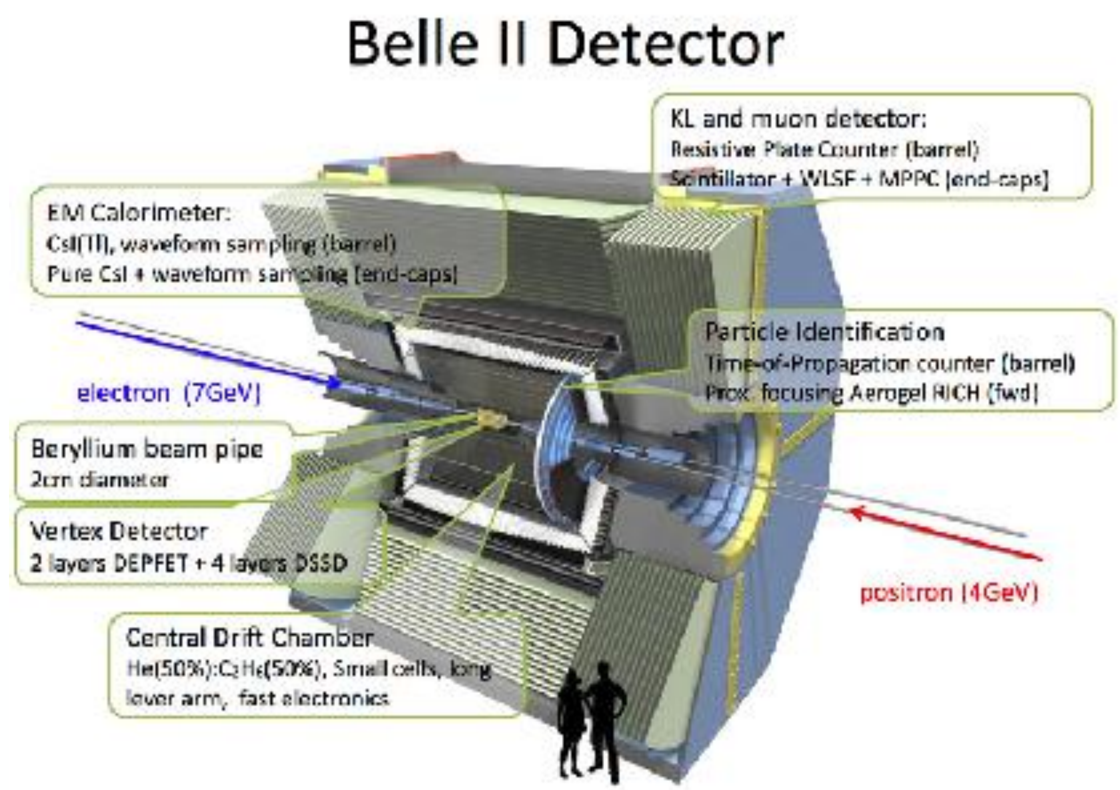
Current: BaBar



$$E_{\mathrm{CM}} = 10.35\,\mathrm{GeV}$$

$$\mathcal{L} = 19\,\mathrm{fb}^{-1}(\text{low } E_\gamma) \text{ and } 28\,\mathrm{fb}^{-1}(\text{high } E_\gamma)$$

Future: Belle II

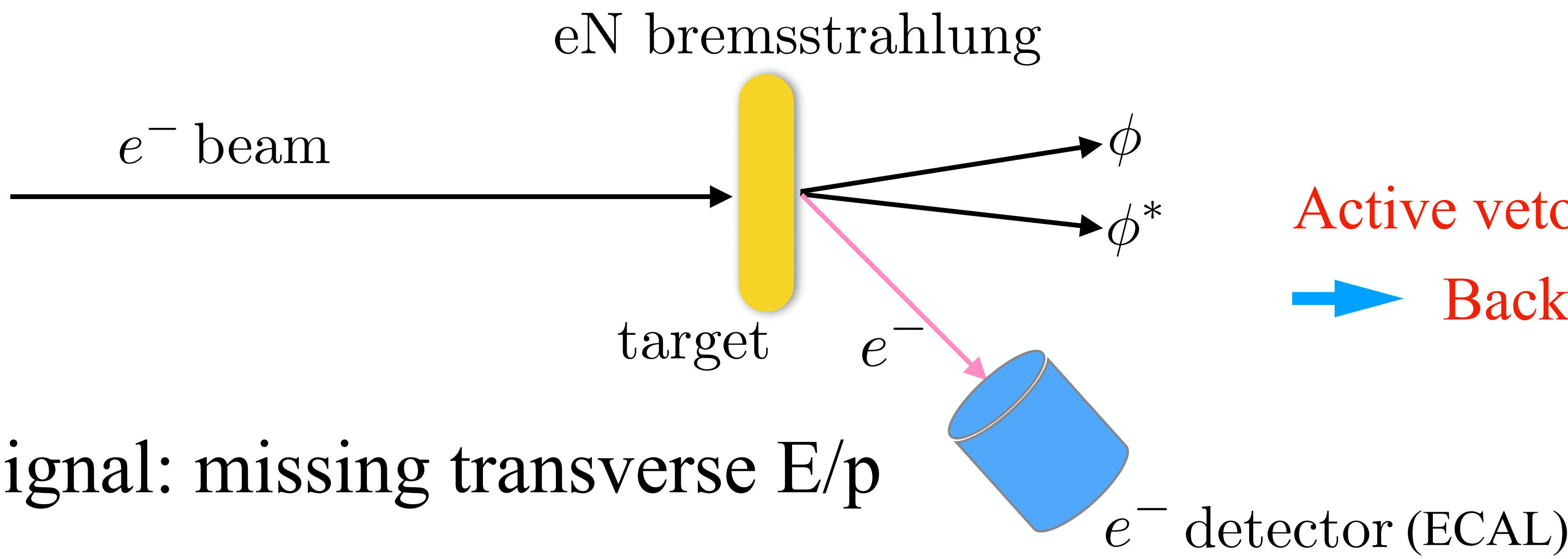


$$E_{\mathrm{CM}} = 10.57\,\mathrm{GeV}$$

$$\mathcal{L} = 50\,\mathrm{ab}^{-1}$$

Intensity Frontier

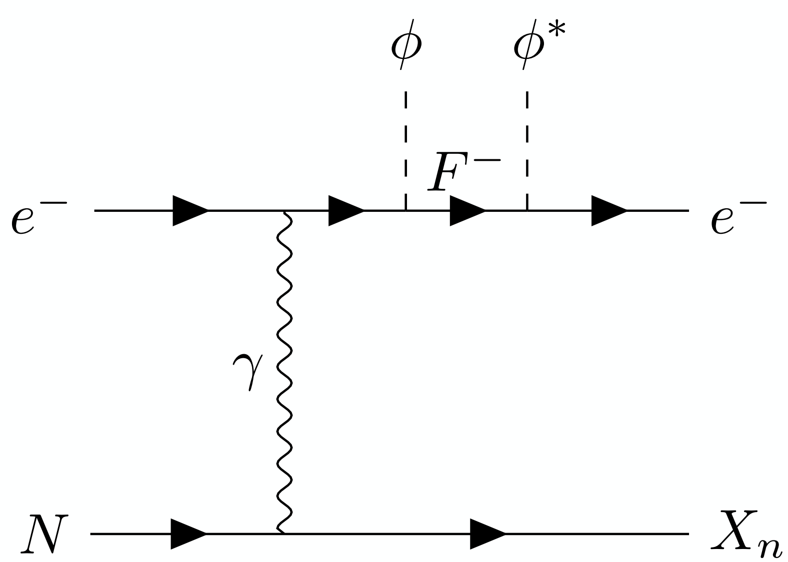
- Electron fixed-target experiments (NA64 and LDMX)

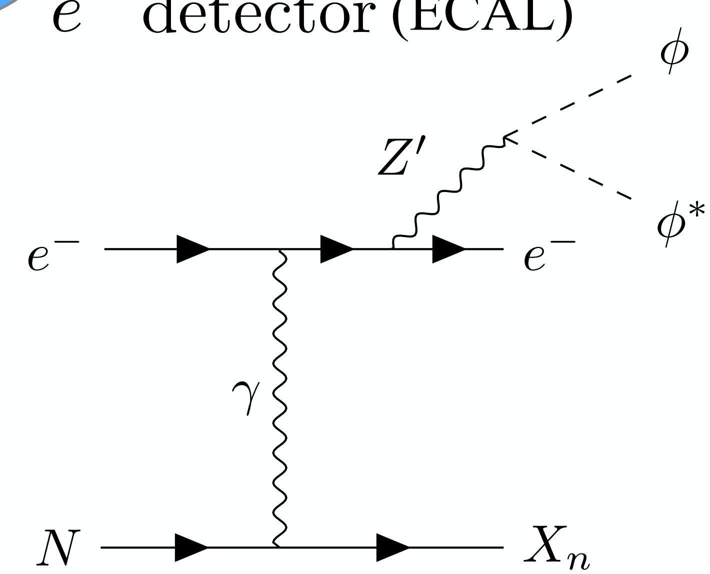


Active veto system and cuts

→ Background free!

Signal: missing transverse E/p





$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\phi\bar{F}^0 P_L \nu_l + h.c.$$

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^*\phi - ig_\phi Z'_\mu\left[\phi^*(\partial^\mu\phi) - (\partial^\mu\phi^*)\phi\right] - iZ'_\mu\bar{l}\gamma^\mu(g_L P_L + g_R P_R)l.$$

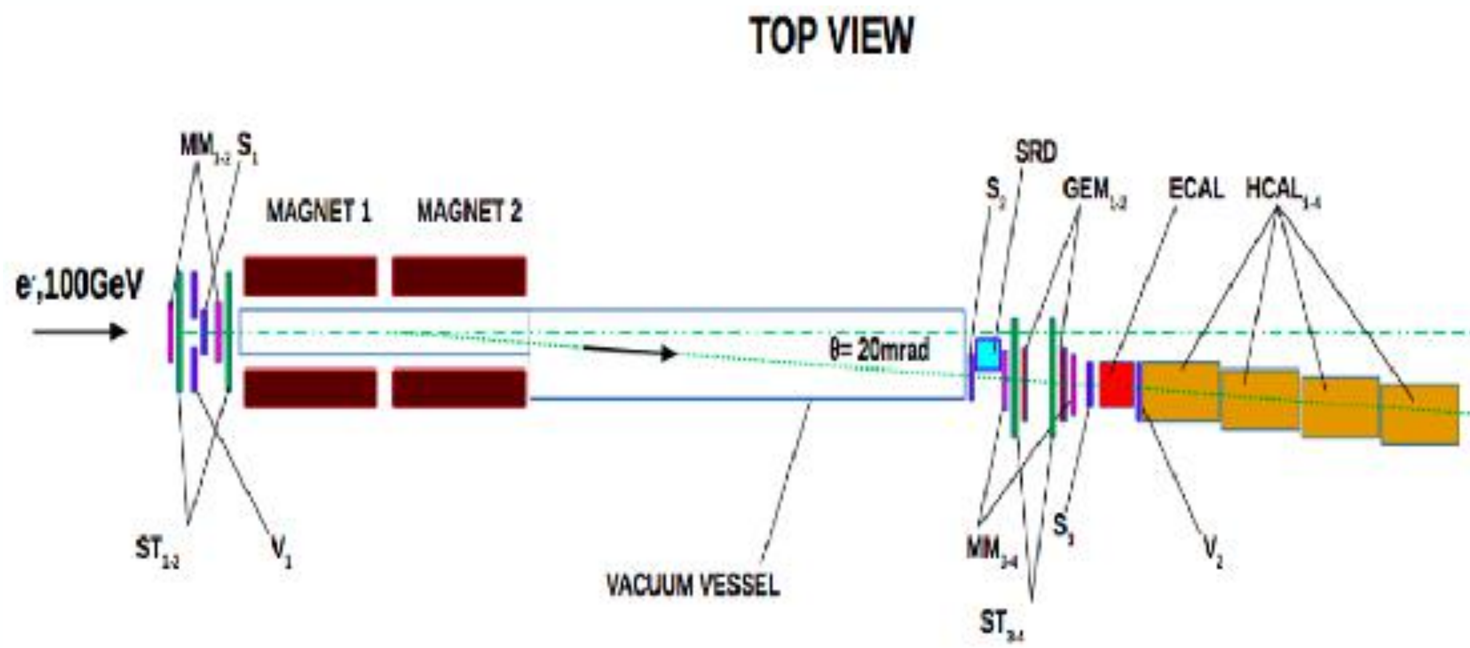
Intensity Frontier

- Electron fixed-target experiments

Current: NA64

$$E_{\text{beam}} = 100\,\text{GeV}$$

$$N_{\text{EOT}} = 4.3 \times 10^{10}$$



Future: LDMX

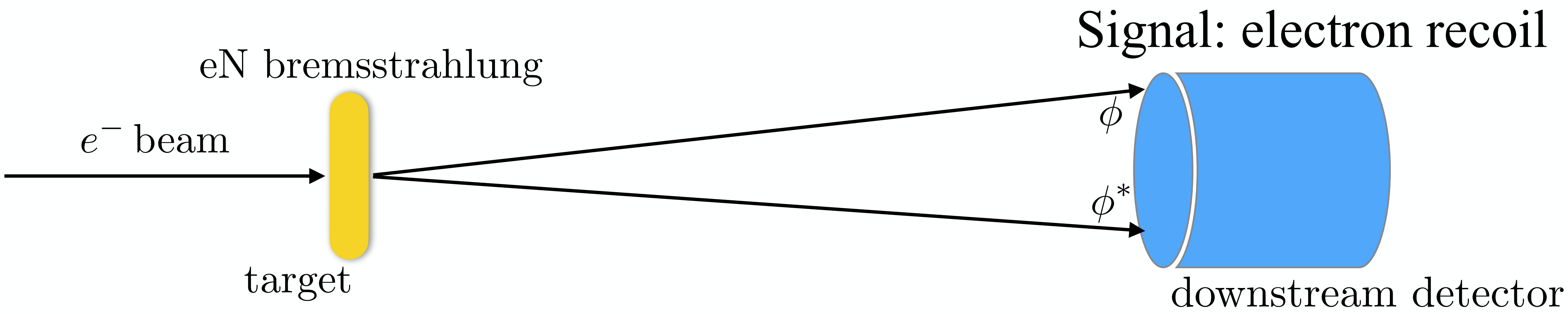
Similar setup with NA64 ...

$$E_{\text{beam}} = 4\,\text{GeV (phase-I)} \quad \text{and} \quad 8\,\text{GeV (phase-II)}$$

$$N_{\text{EOT}} = 4 \times 10^{14}\,\text{(phase-I)} \quad \text{and} \quad 3.2 \times 10^{15}\,\text{(phase-II)}$$

Intensity Frontier

- Electron beam-dump experiments (mQ, BDX)



Background: neutrino

Production:

$$\frac{dN_\phi}{dE_\phi} = 2N_{\mathrm{EOT}}\frac{\rho_{\mathrm{target}}}{m_N}X_0\int_{E_\phi}^{E_{\mathrm{beam}}} dE \times \int_{\cos\theta_\phi^{\min}}^{\cos\theta_\phi^{\max}} d\cos\theta_\phi\, I(E)\frac{d\sigma_{2\to4}}{dE_\phi\, d\cos\theta_\phi}$$

detector acceptance

electron propagation in (thick) target

Detection:

$$N_{\mathrm{sig}} = n_e L_{\mathrm{det}}\int_{m_\phi}^{E_\phi^{\max}}\int_{E_R^{\mathrm{th}}}^{E_R^{\max}} dE_R\,\epsilon_{\mathrm{eff}}(E_R)\frac{dN_\phi}{dE_\phi}\frac{d\sigma_{\phi\text{-}e}}{dE_R}$$

Intensity Frontier

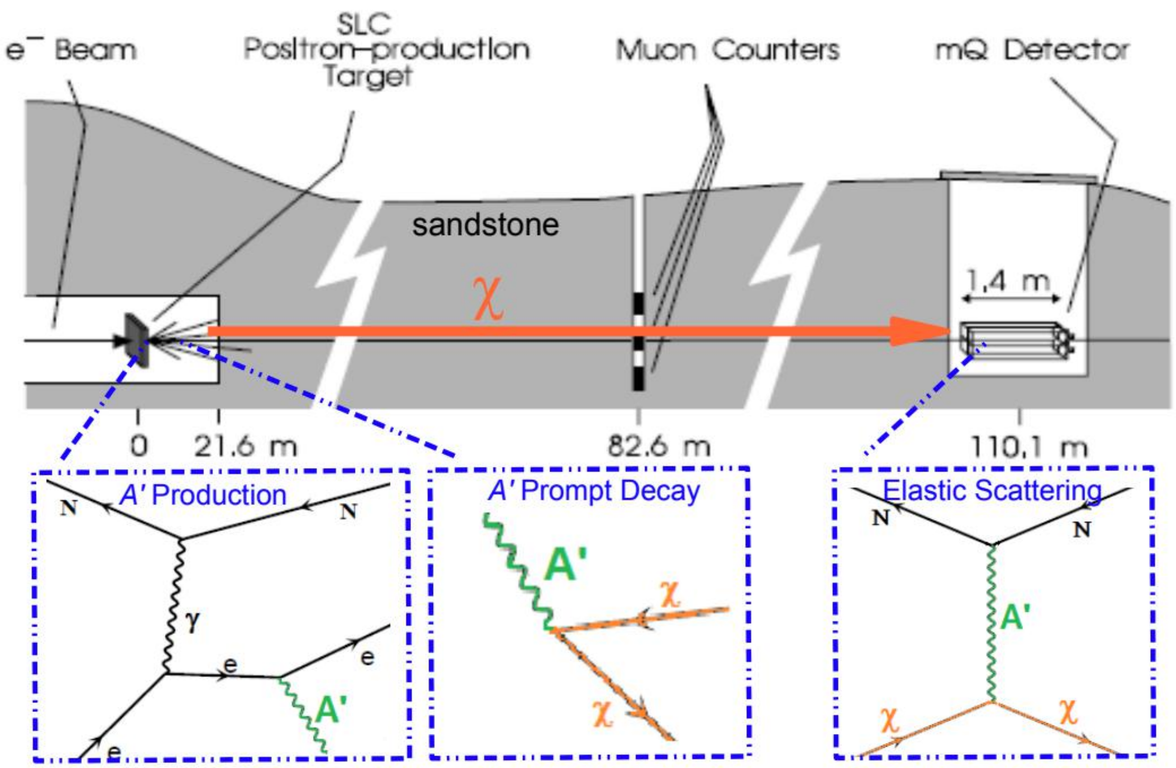
- Electron beam-dump experiments

arXiv:1307.6861

Current: mQ

$$E_{\text{beam}} = 29.5\,\text{GeV}$$

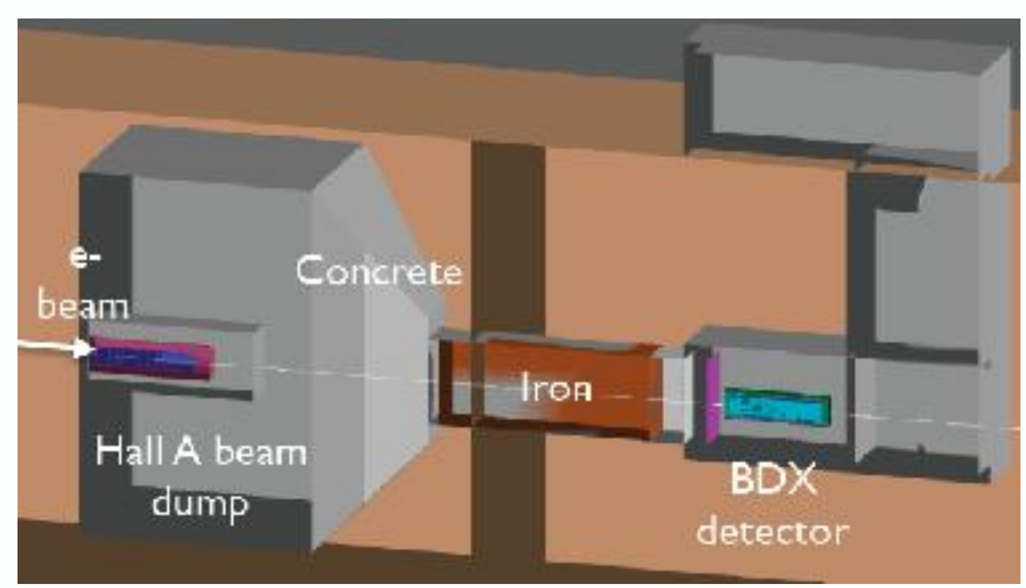
$$N_{\text{EOT}} = 8.4 \times 10^{18}$$



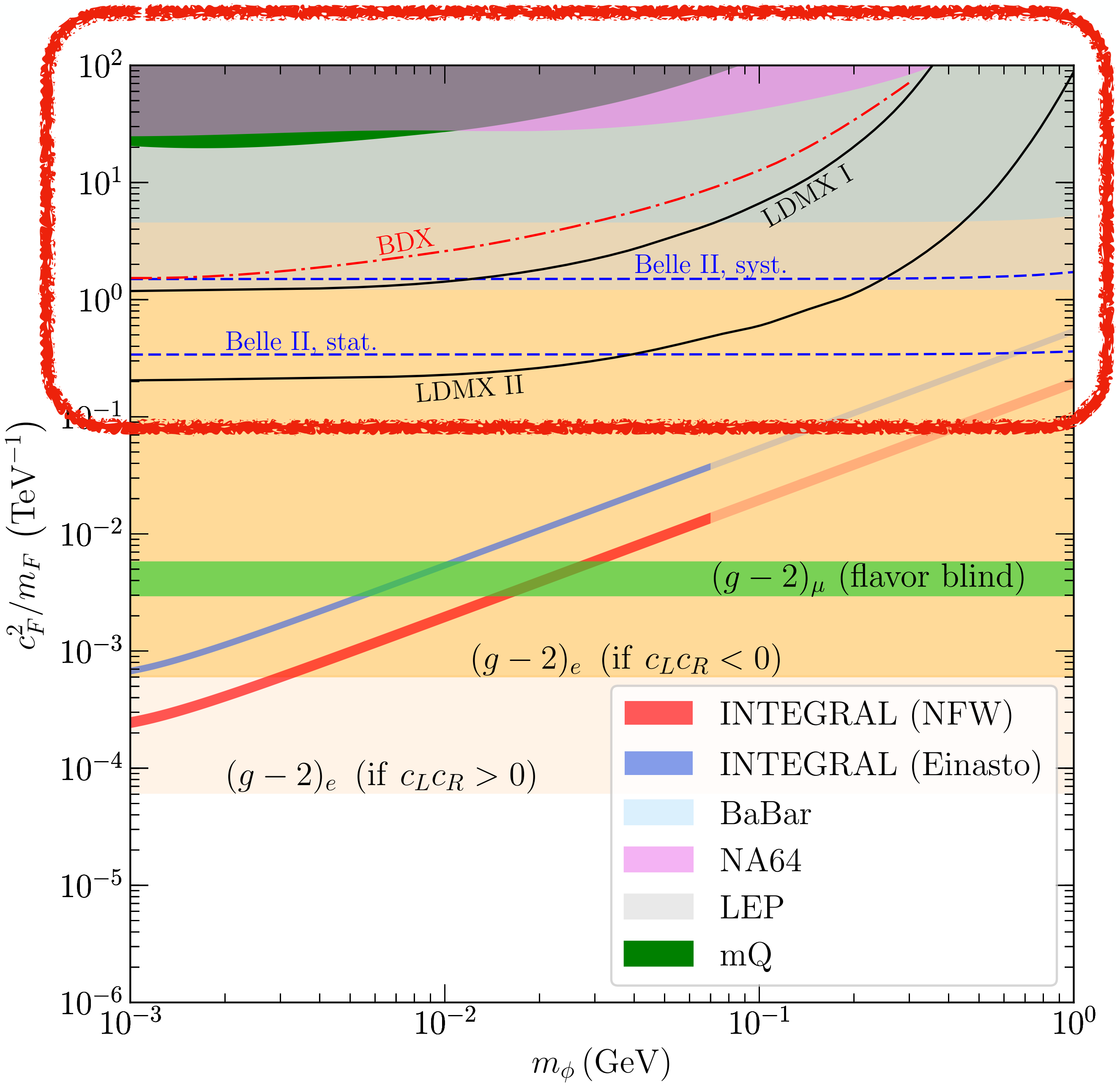
Future: BDX

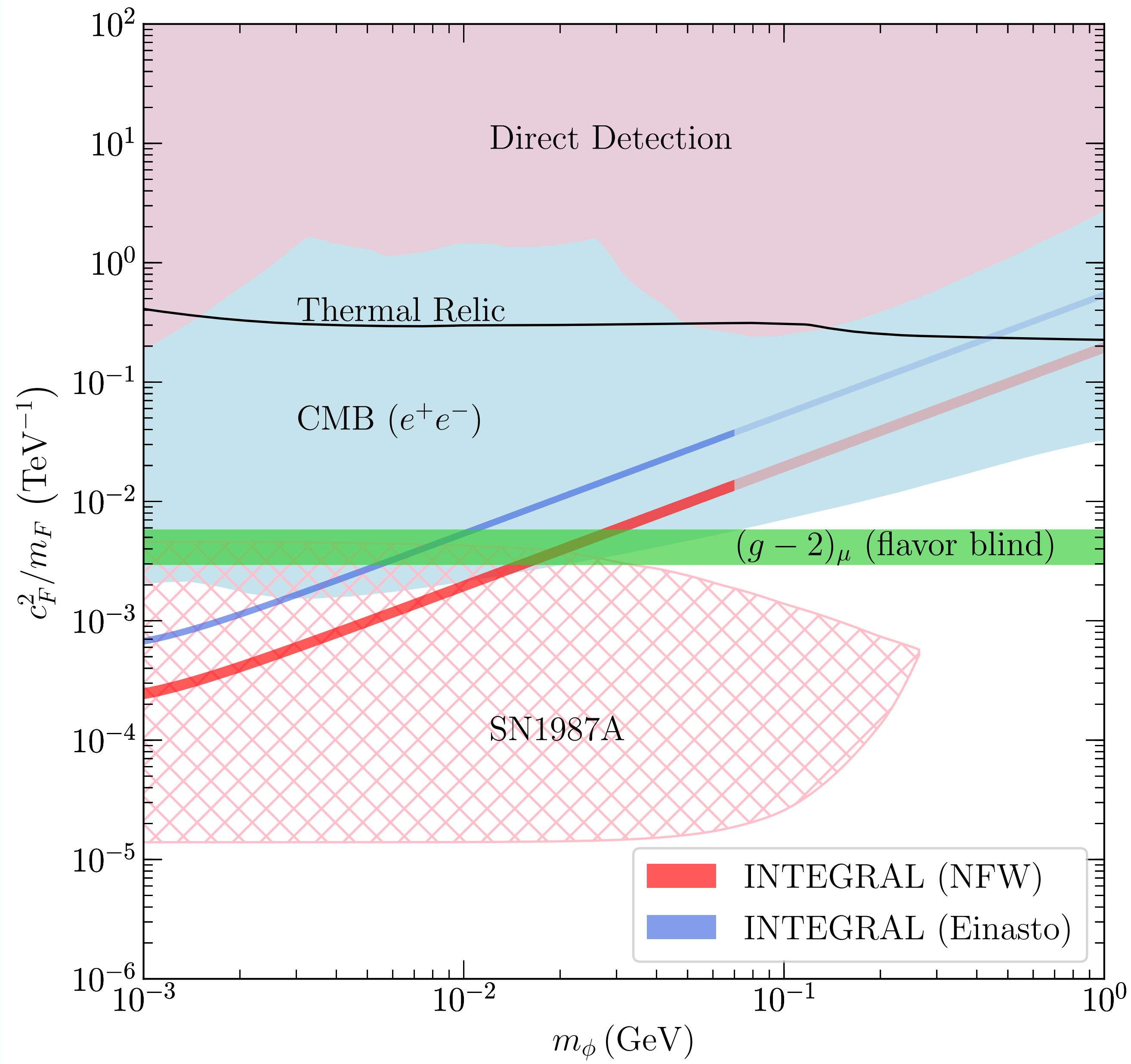
$$E_{\text{beam}} = 11\,\text{GeV}$$

$$N_{\text{EOT}} = 10^{22}$$



Overview of Parameter Space: F





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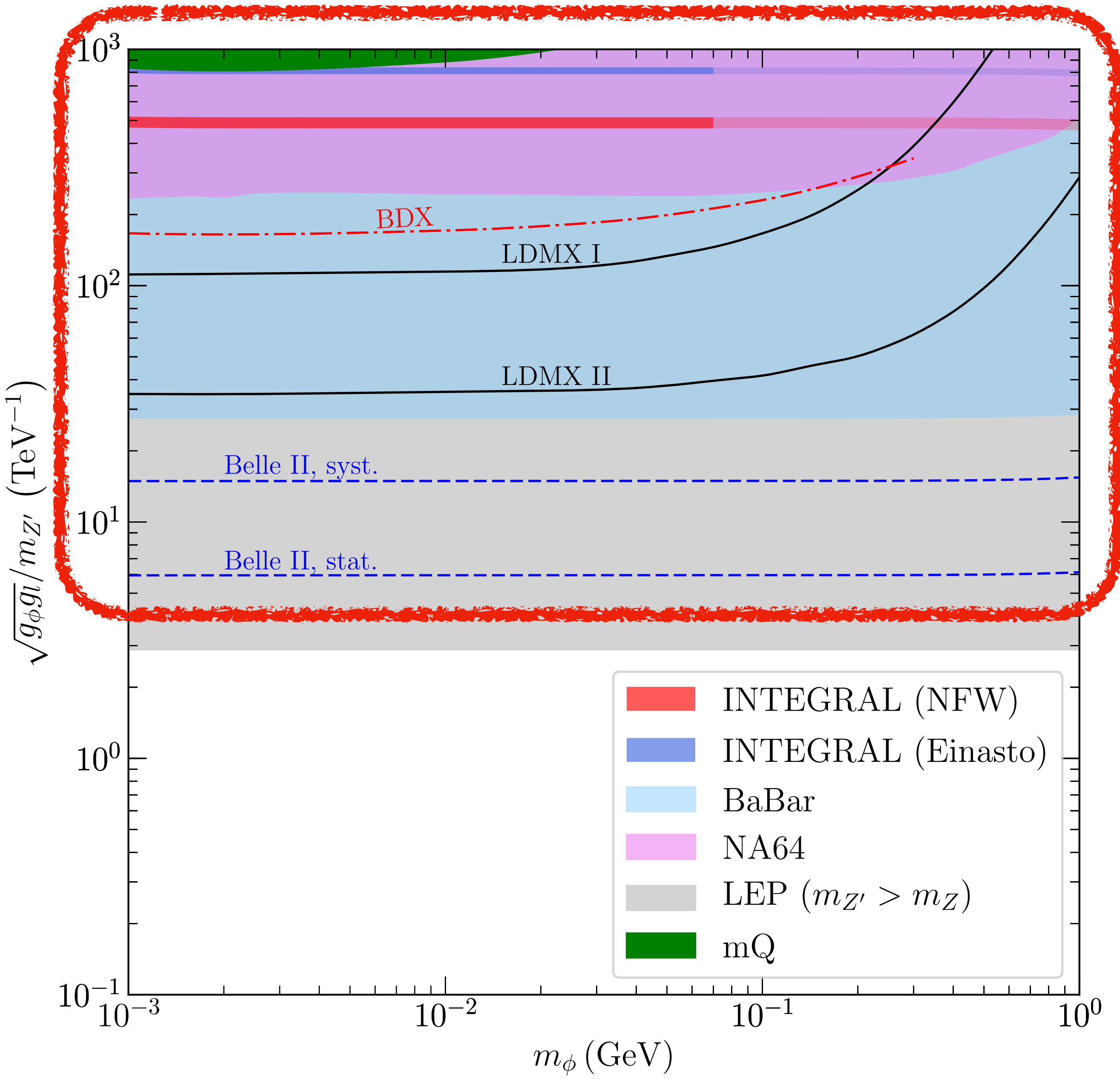
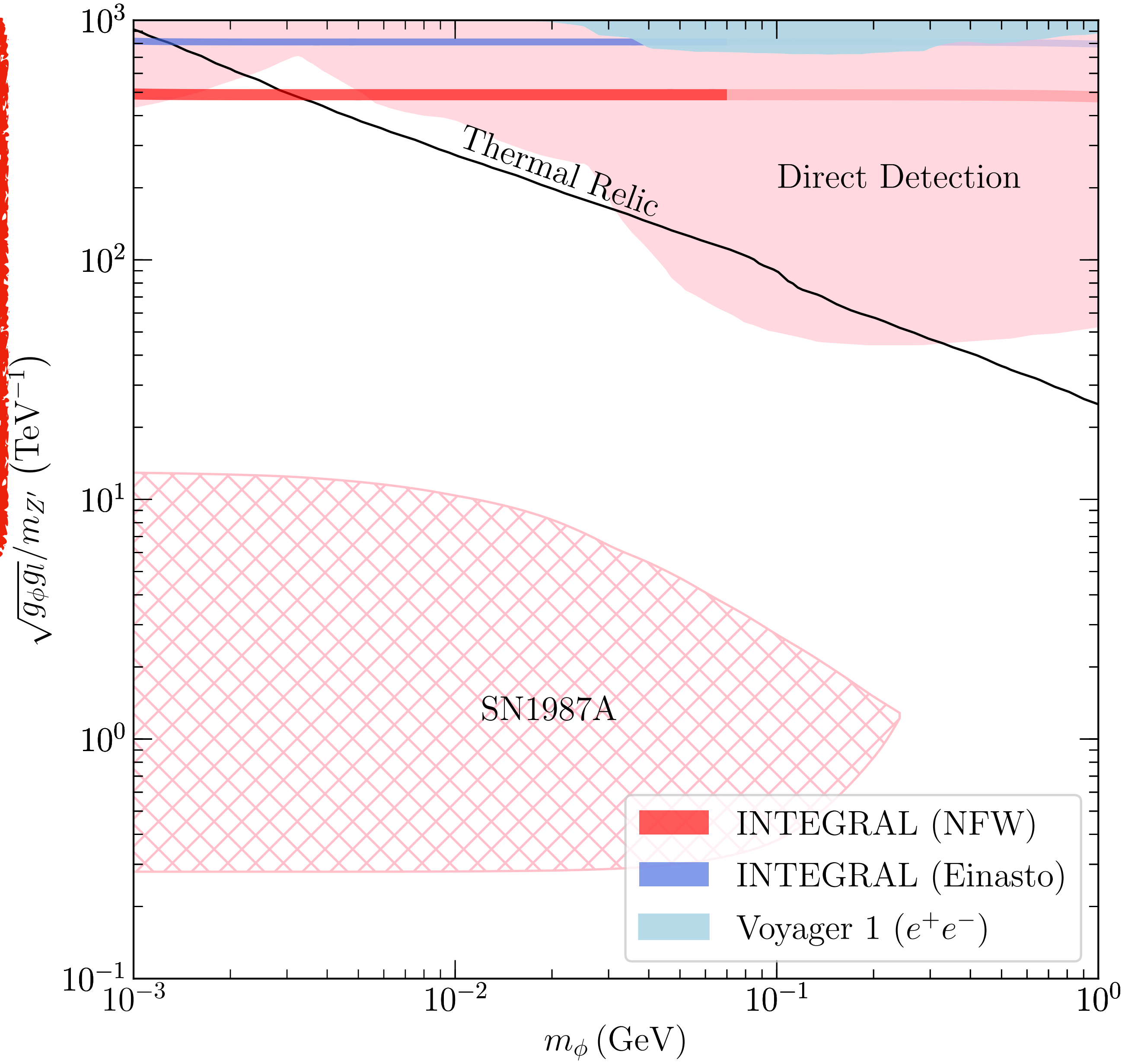
Overview of Parameter Space: Z'

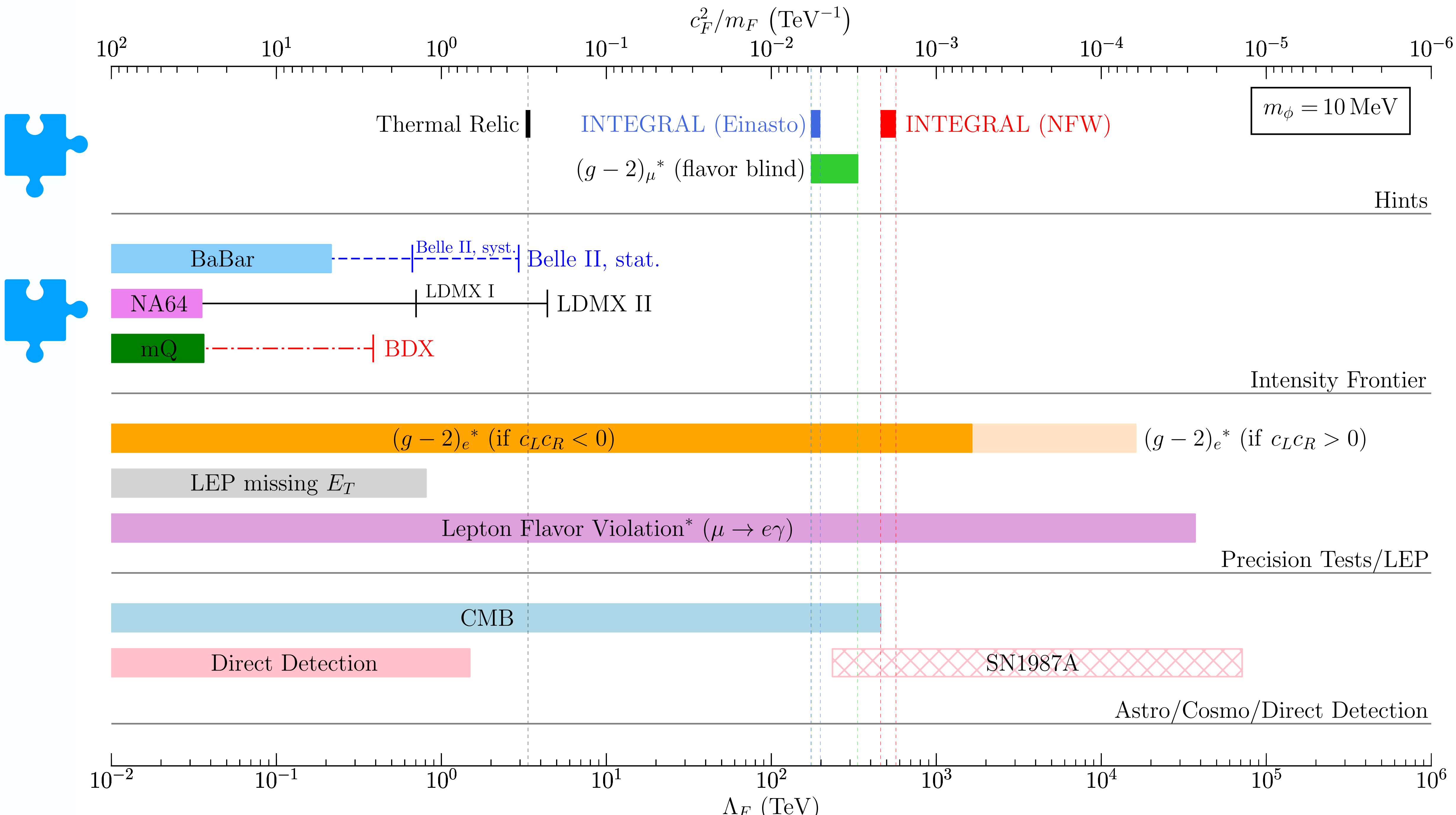




- Intensity frontier constraints are important (rule out INTEGRAL favoured region)

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^*\phi - i g_\phi Z'_\mu \left[\phi^*(\partial^\mu\phi) - (\partial^\mu\phi^*)\phi\right] - i Z'_\mu \bar{l}\gamma^\mu(g_L P_L + g_R P_R)l.$$

Check List



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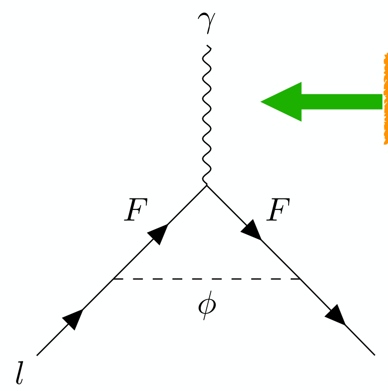
Precision Frontier

- Electron g-2



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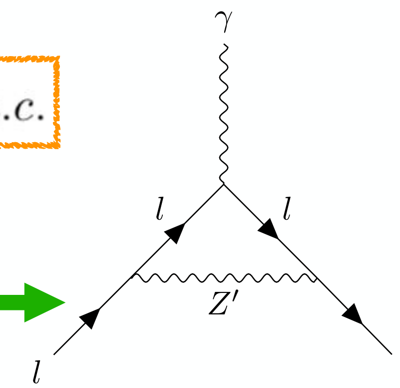


New measurement of α from Cs atom interferometer

Parker et. al (2018)

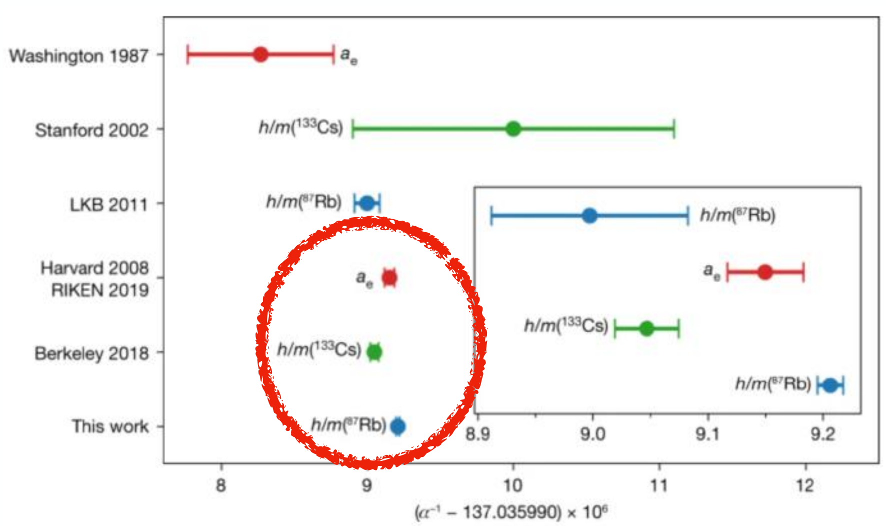
➡ 2.5σ between $a_e^{(\text{meas.})}$ and $a_e^{(\text{Cs})}$

➡ $\Delta a_e^{\text{BSM}} \in (-0.88 \pm 3 \times 0.36) \times 10^{-12} = [-1.96, 0.30] \times 10^{-12}$

Can also be recasted into α tension

Caveat: allow new physics contribution of both signs!

Update:



New measurement of α from the recoil velocity of a Rb atom that absorbs a photon using matter-wave interferometry

Morel et. al, Nature (Dec. 02, 2020)

Precision Frontier

$$\mathcal{L}_F = -c_L^l\,\phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

- Z-invisible decay

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

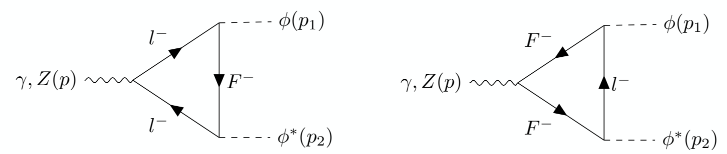
$$\Gamma(Z \to \text{inv})_{\text{new}} \lesssim 0.56\,\text{MeV} \quad \text{at } 95\%\ \text{C.L.}$$

Measurement: missing energy at the Z-pole (LEP)

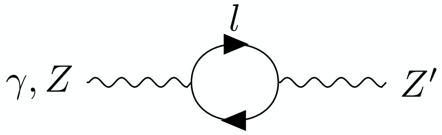
SM contribution: Z decays into neutrinos

BSM contribution: Z decays into scalar DM

- Via triangle loop containing F



- Via kinetic mixing between Z and Z’



Also in F case: effective charge-radius operator (triangle loop)

Bai and Berger (2014) and Hamze et. al (2015)

and running of fine-structure constant (vacuum polarisation)

Precision Frontier

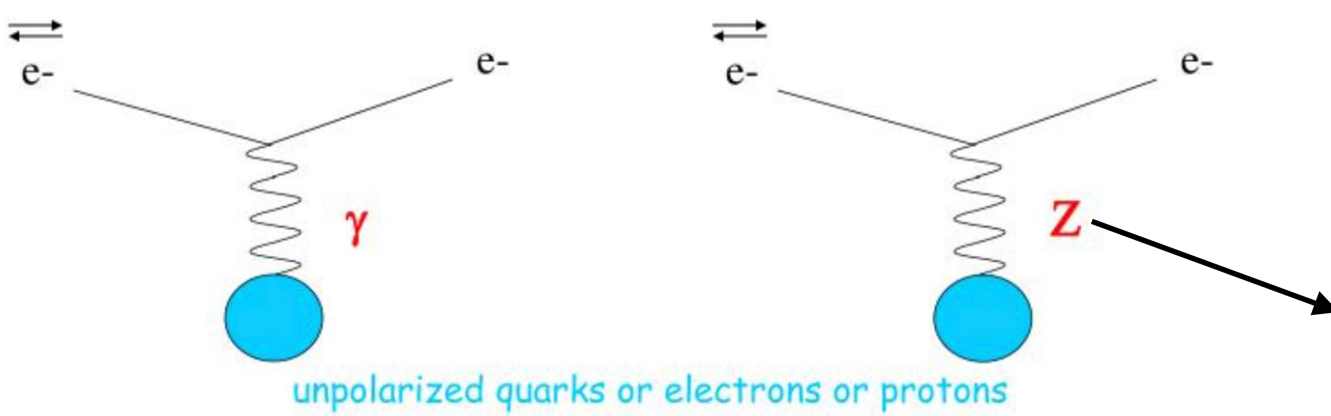
- Parity violation

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

SM contribution: weak interaction

Measurement: asymmetry in polarisized Moller scattering

Czarnecki and Marciano (2000)



Z' can be here!

Credit: Jewel Garcia

$$A_{LR} = \frac{d\sigma_{e_R e} - d\sigma_{e_L e}}{d\sigma_{e_R e} + d\sigma_{e_L e}}$$

Two extreme cases for Z' : $g_L = 0$ and $g_R = 0$

(No tree-level electron-electron scattering for F model)

Current: E158 at SLAC SLAC E158 Collaboration (2005)

Future: MOLLER and P2 at MESA MOLLER Collaboration (2014) and Becker et. al (2018)

Precision Frontier

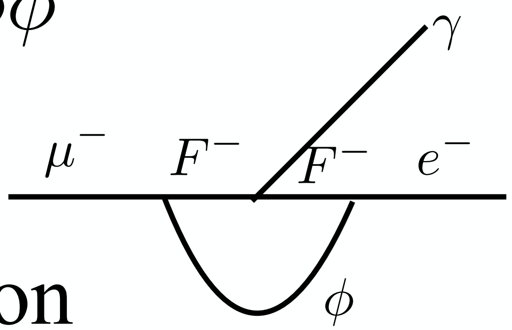
- Lepton-flavor violation (LFV)

$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\,\phi\bar{F}^0 P_L \nu_l + h.c.$$

When we only have 1 flavour of F …

Measurement: LFV decay such as $\mu \to e\gamma$ and $\mu \to e\phi\phi^*$

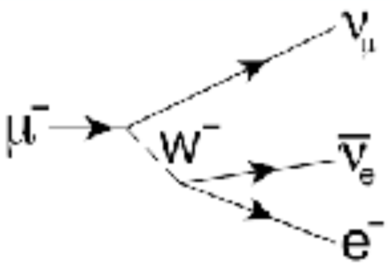
1. $\mu \to e\gamma$



Via the loop-induced effective magnetic dipole interaction

$\mathrm{Br}_{\mu\to e\gamma} < 4.2 \times 10^{-13}$ MEG collaboration (2016)

2. $\mu \to e\phi\phi^*$ (If kinematic allows)



SM process

Michel parameters

$$\frac{\Gamma_{e\phi\phi}}{\Gamma_{e\bar{\nu}_e\nu_\mu}} \sim \frac{m_W^4}{m_\mu^2 m_F^2} \quad \text{or} \quad \frac{m_W^4}{m_F^4}$$

for $(c_L^\mu c_R^e)^2 + (c_R^\mu c_L^e)^2 \neq 0$ or $(c_L^\mu c_R^e)^2 + (c_R^\mu c_L^e)^2 = 0$

Observable: distortion in the electron spectrum See review, Renga (2016)

➡ Constrain flavour structure of F model

LEP constraint

Heavy new particles remain unconstrained by LEP (F, Z')

Missing energy search at Z-pole L3 collaboration (2004)

→ constrain sub-GeV dark sector particles production

Future: dark sector particles production by Drell-Yan processes in high-luminosity LHC and ILC

Caveat: constraint for Z' model

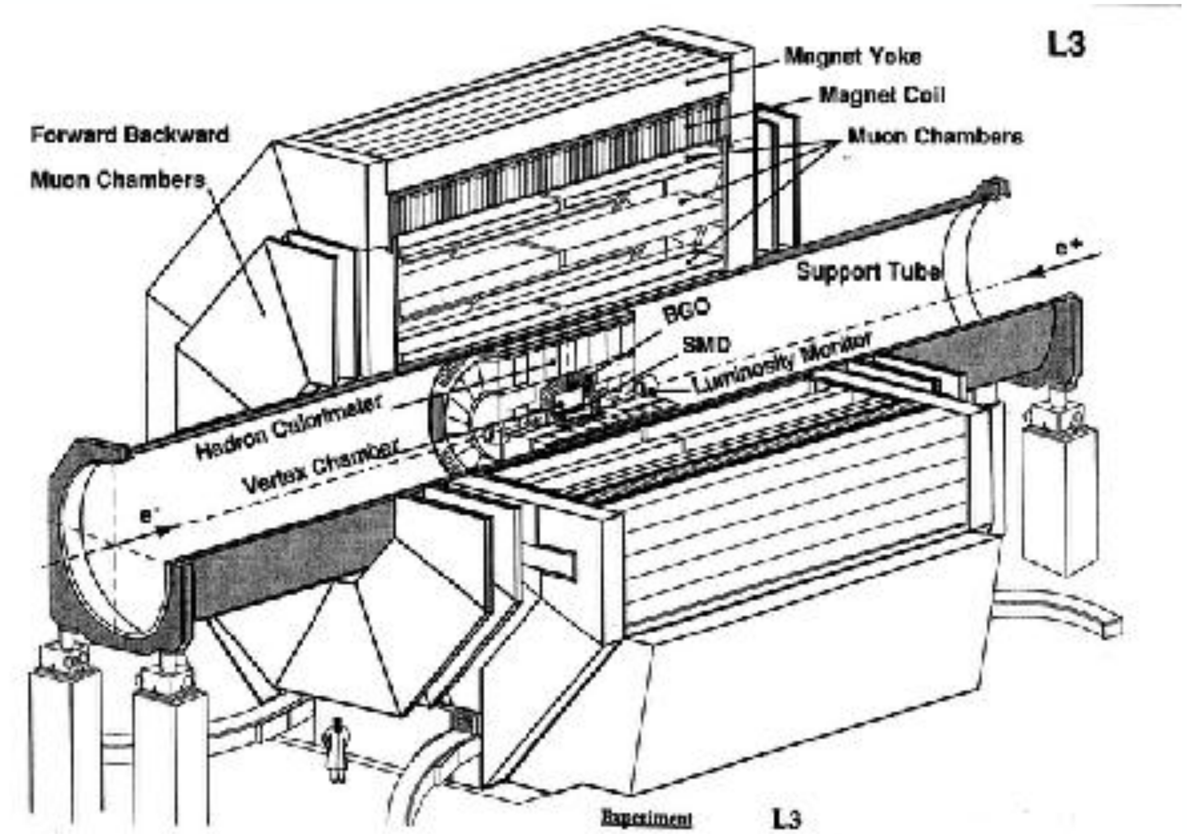
$m_{Z'} > m_Z$: Z' is always off-shell

→ constraint on $g_\phi g_l$

Fox et. al (2011) and Cheung et. al (2012)

$m_{Z'} < m_Z$: Z' can be produced on-shell

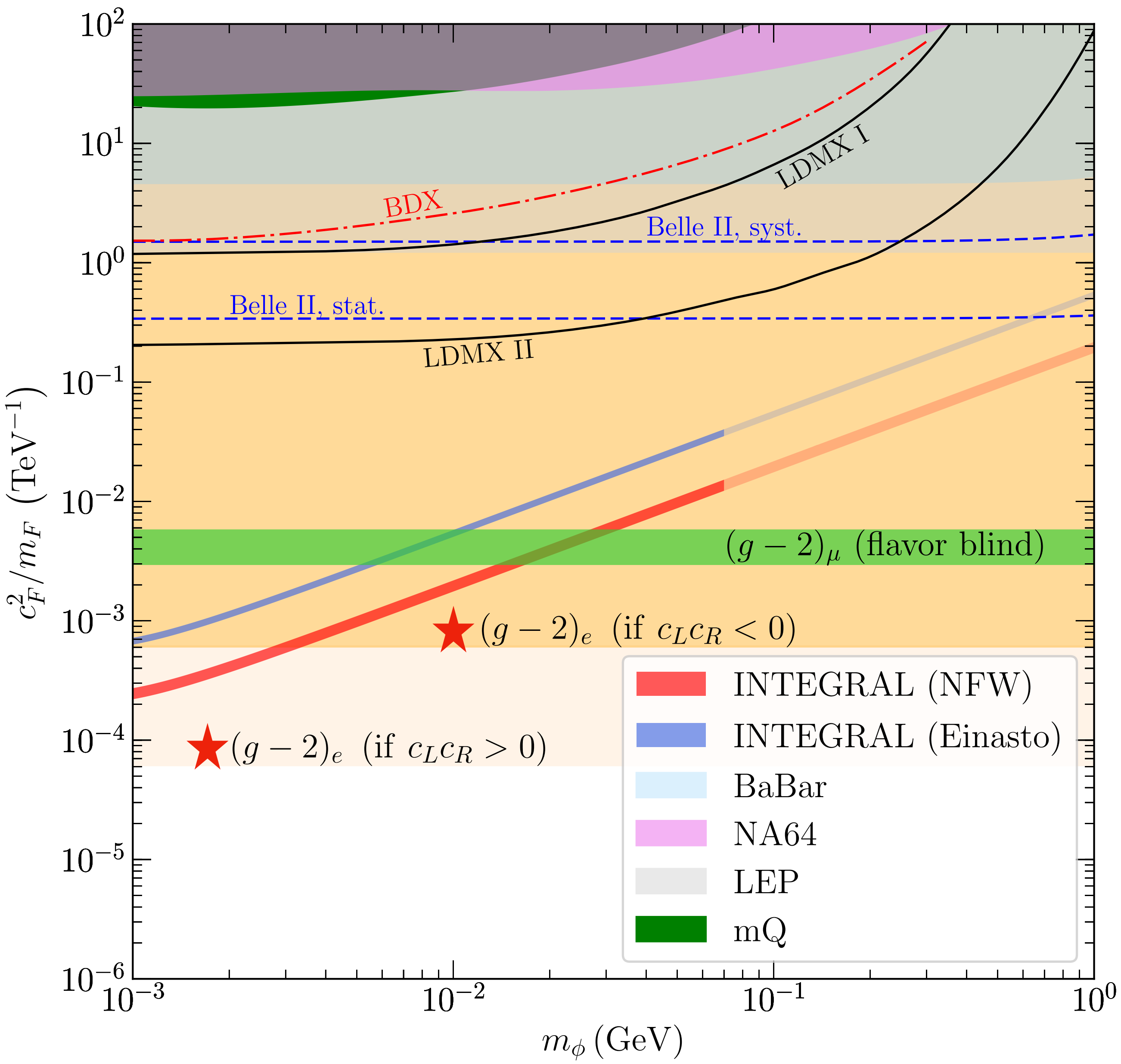
→ constraint on g_l Ilten et. al (2018)

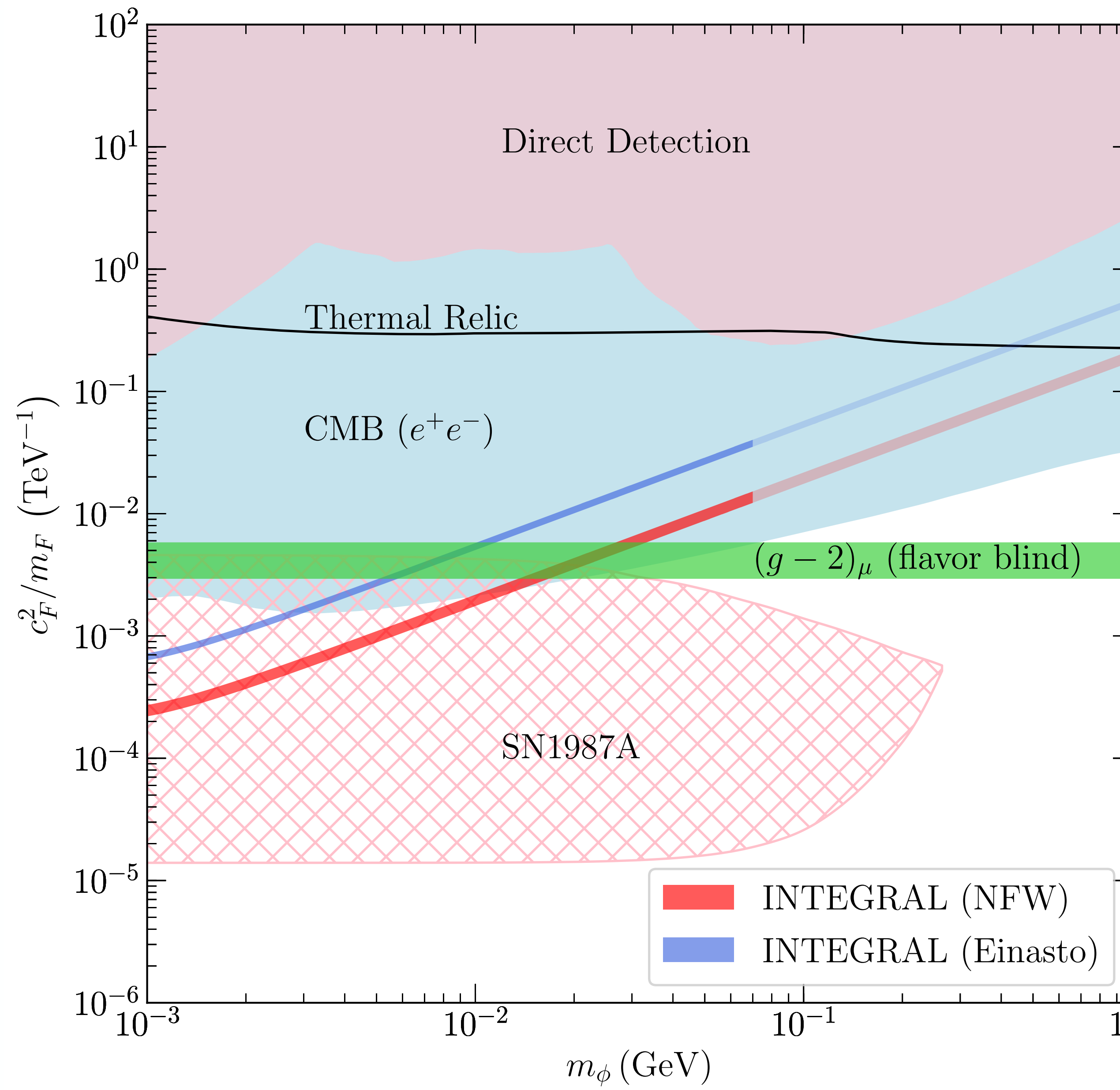


$$\mathcal{L}_F = -c^l_L \phi \bar{F} P_L l - c^l_R \phi \bar{F} P_R l - c^l_L \phi \bar{F}^0 P_L \nu_l + h.c.$$

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*)\phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

Overview of Parameter Space: F

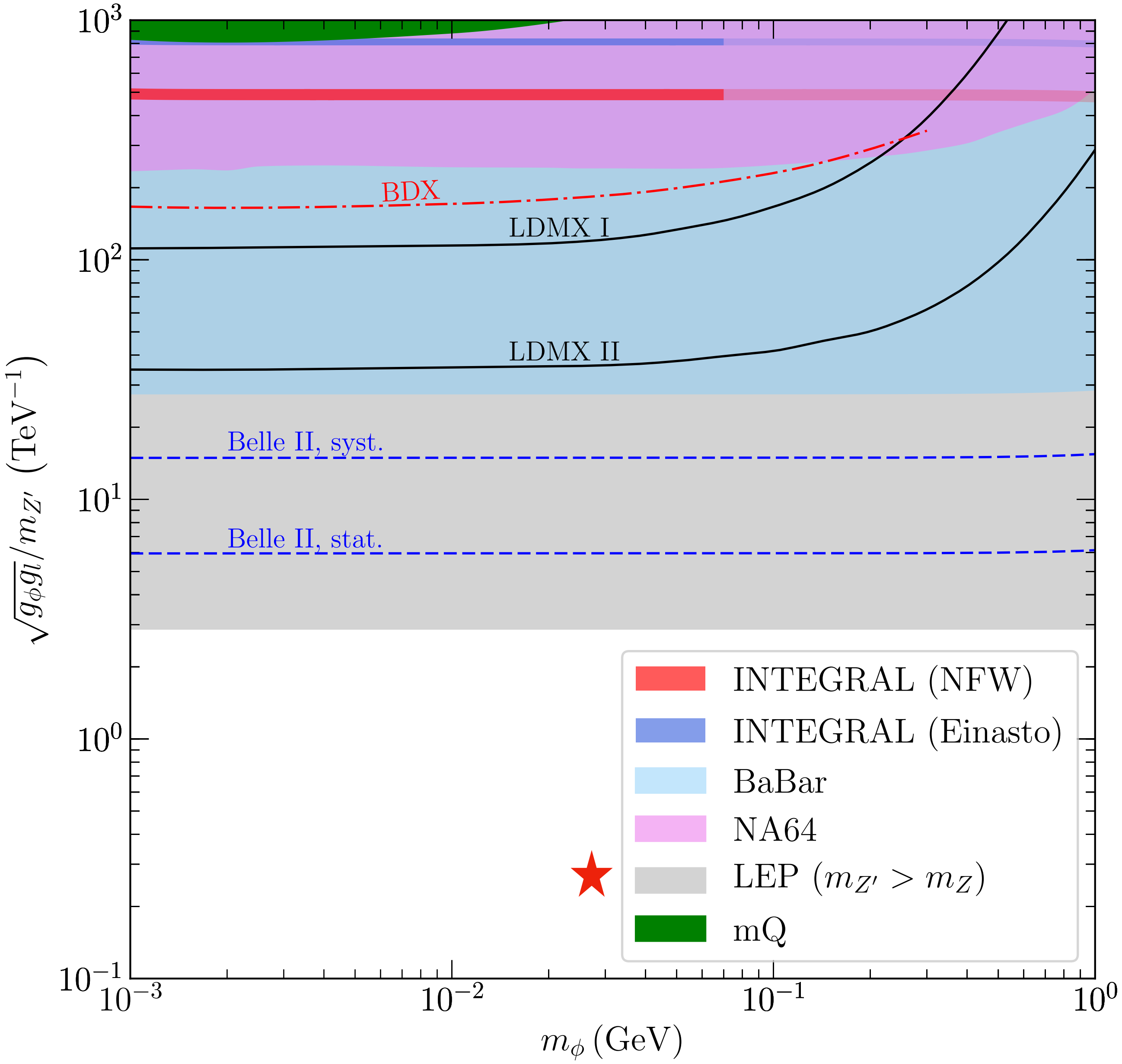


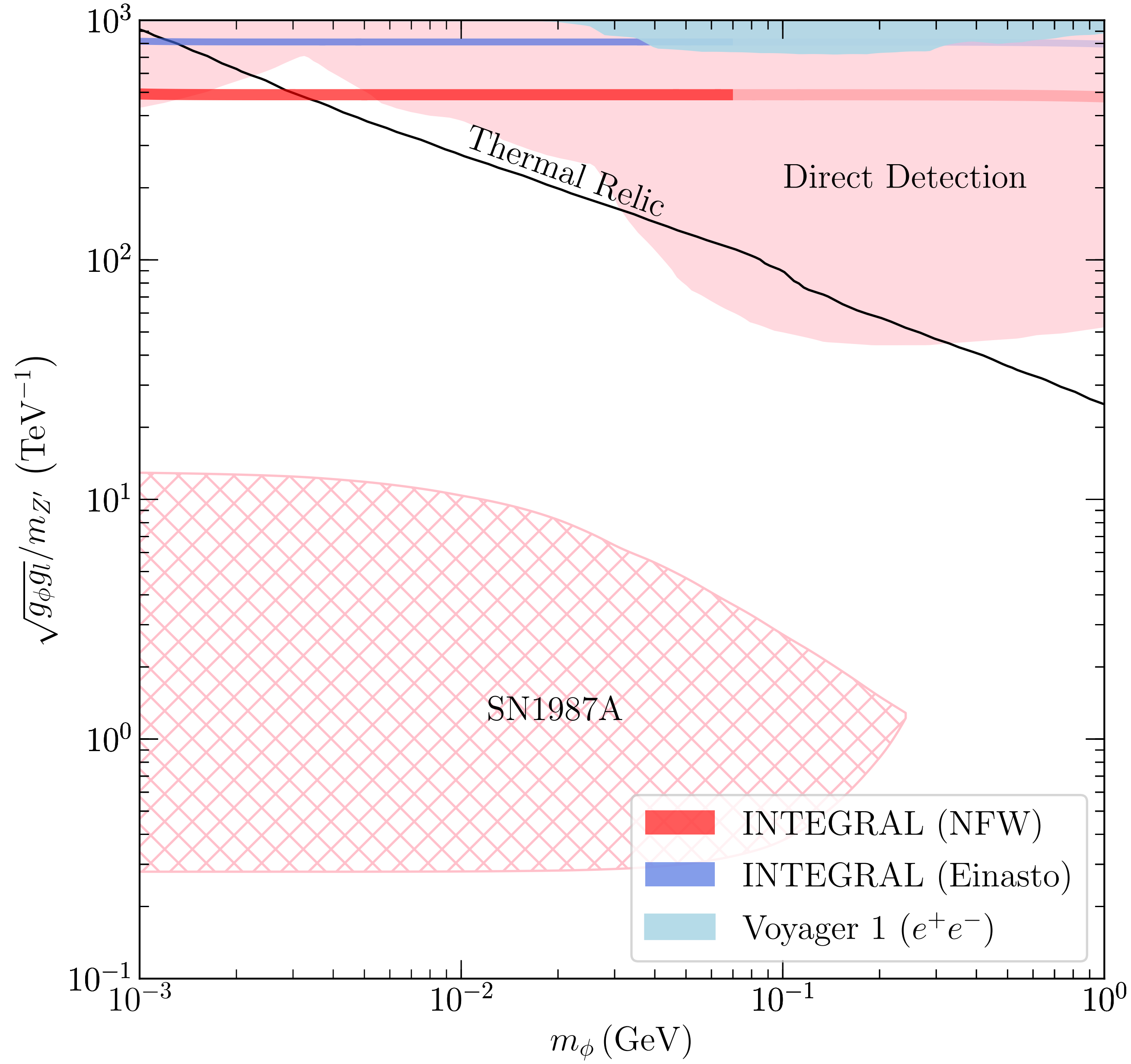


- Electron g-2 gives strong constraint

$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\phi\bar{F}^0 P_L\nu_l + h.c.$$

Overview of Parameter Space: Z'

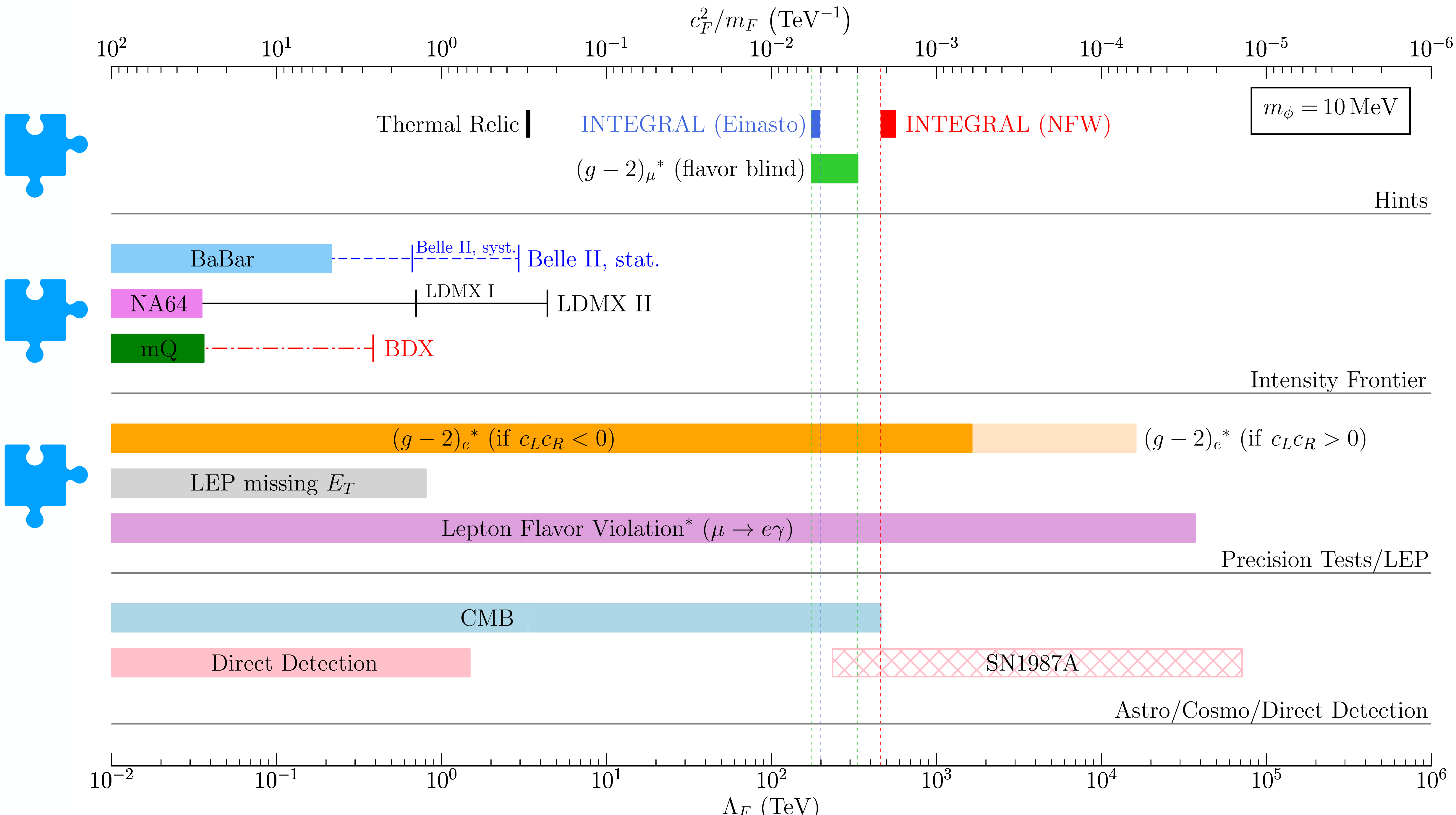




- LEP is the strongest terrestrial bound

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

Check List

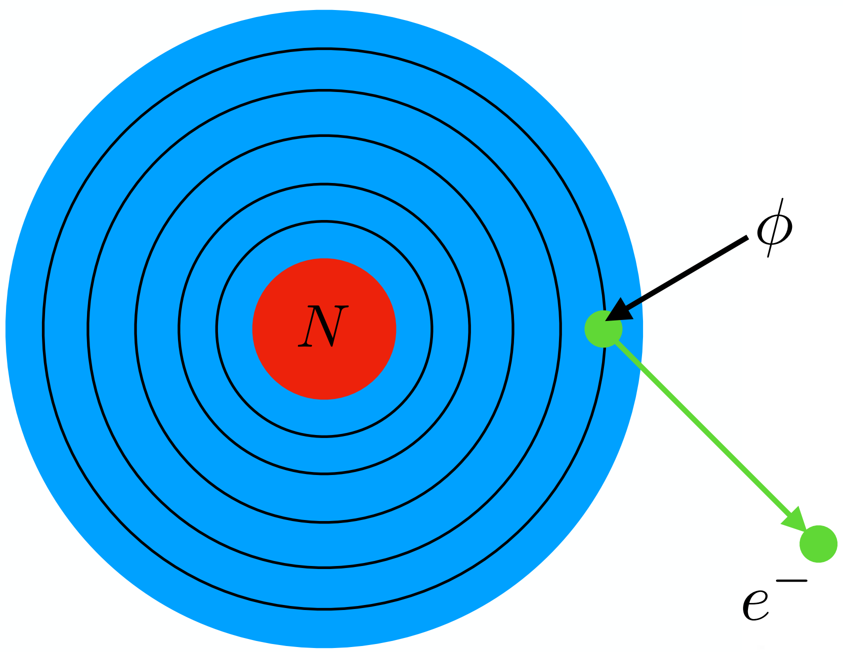


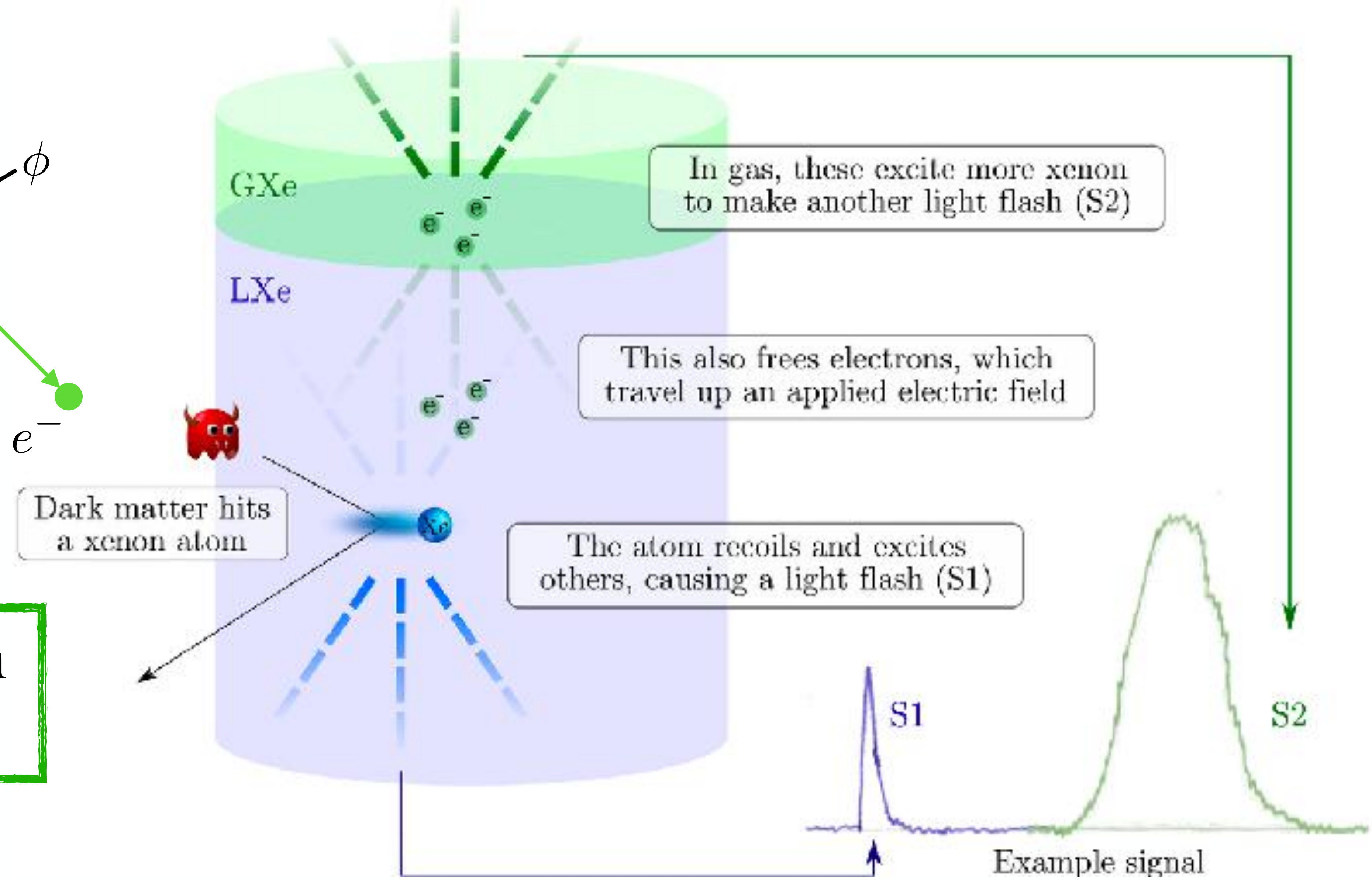
$$\mathcal{L}_F = -c_L^l\, \phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

Direct Detection

- Scattering with bound electron

Last year: XENON1T low-energy excess!?





Lower threshold than nuclear recoil!

Direct Detection

- Scattering with bound electron

Lower threshold: desirable for sub-GeV DM

$$\bar{\sigma}_e = \frac{1}{16\pi(m_e + m_\phi)^2} \overline{|\mathcal{M}_{\phi\text{-}e}(q)|}^2_{q^2=\alpha^2 m_e^2}$$

$$F(q) \equiv \overline{|\mathcal{M}(q)|}^2 / \overline{|\mathcal{M}(q)|}^2_{q^2=\alpha^2 m_e^2}$$ encode q-dependence

Both models: const. dark form factor (indep. of momentum transfer)

Combined constraints from SENSEI, XENON10, XENON1T + (solar reflection flux)

SENSEI collaboration (2020), Essig et. al (2012), Essig et. al (2017), XENON collaboration (2019), An et. al (2018)

$$\mathcal{L}_F = -c_L^l\, \phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*)\phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

Astro./Cosmo. Probes

Signal from DM annihilation

- CMB bound (early universe)

$$\mathcal{L}_F = -c_L^l\, \phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

Relevant for F model: s-wave annihilation

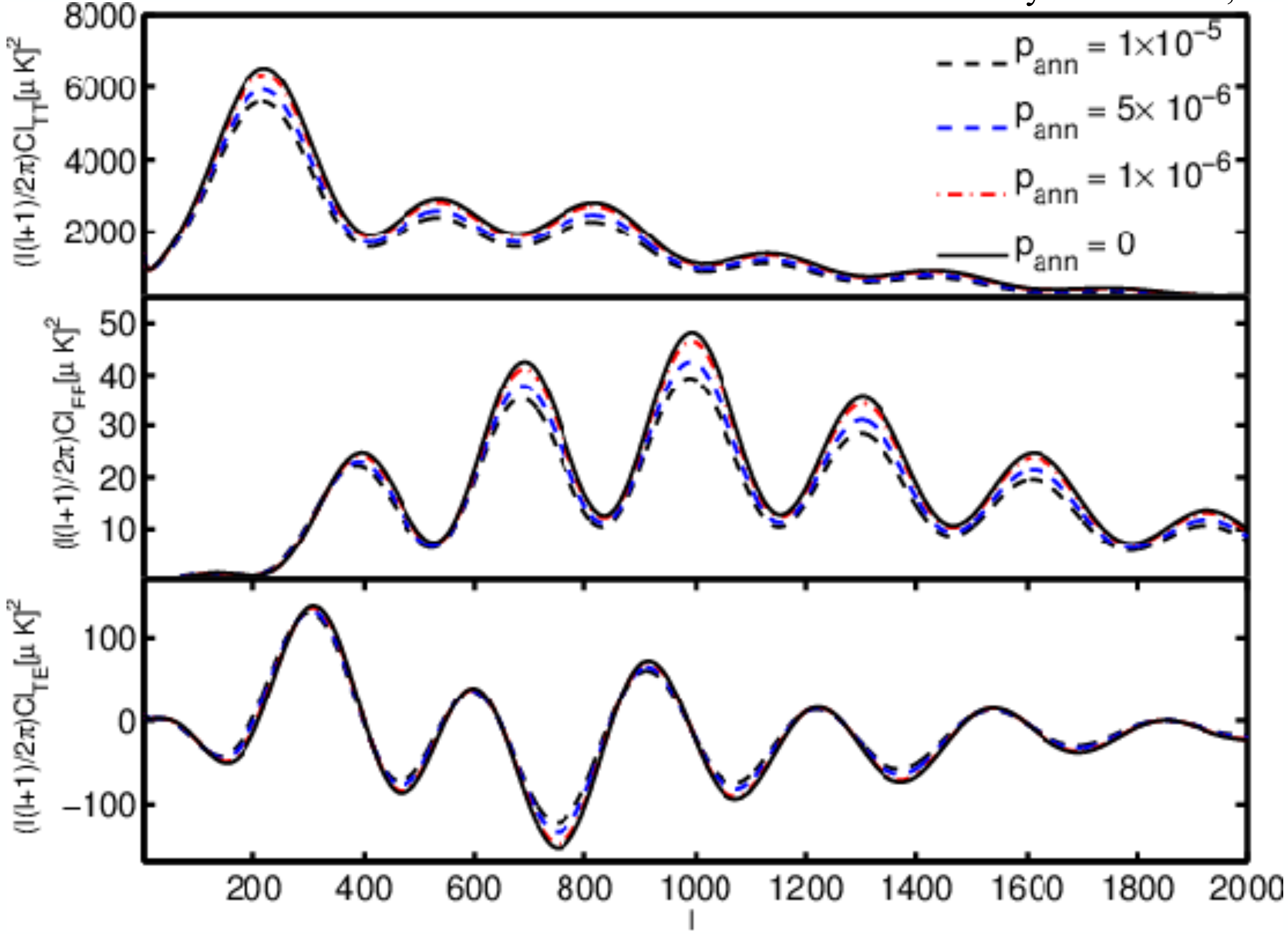
p-wave annihilation is velocity suppressed!

Energy injection from DM annihilation

↓ Heating, Ionization

Observable: distortion in CMB power spectrum

Credit: Phys. Rev. D 80, 023505



Astro./Cosmo. Probes

Signal from DM annihilation

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

- Indirect search (late universe)

  Relevant for Z' model: p-wave annihilation

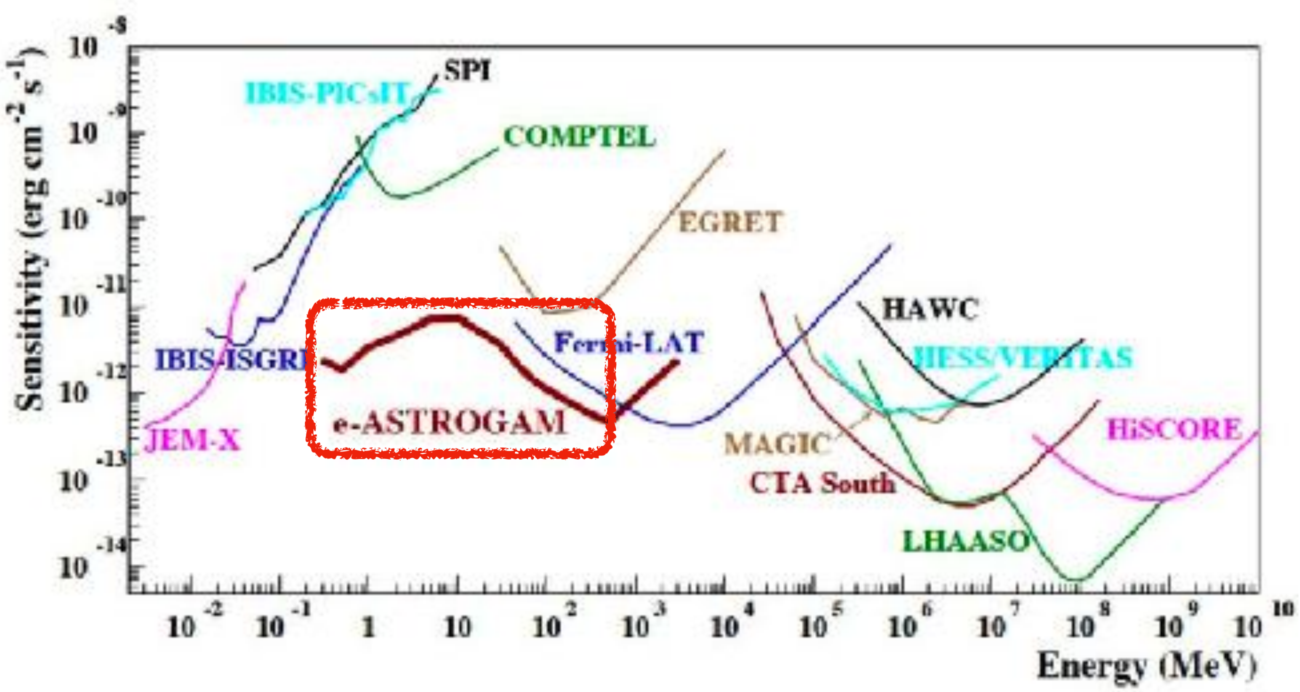
  p-wave annihilation receives enhancement from clustering

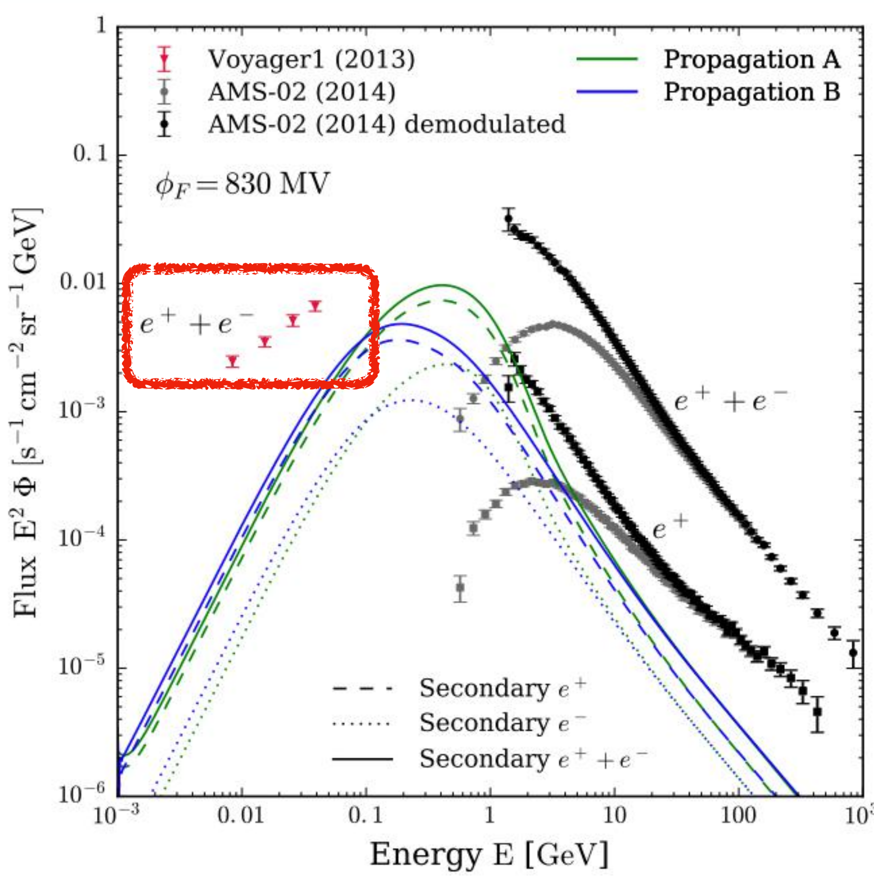
Observable: extra anti-matter or gamma ray lines

Credit: 1612.07698

Data: Voyager 1 Stone et. al (2013)

Future: e-ASTROGAM and AMEGO





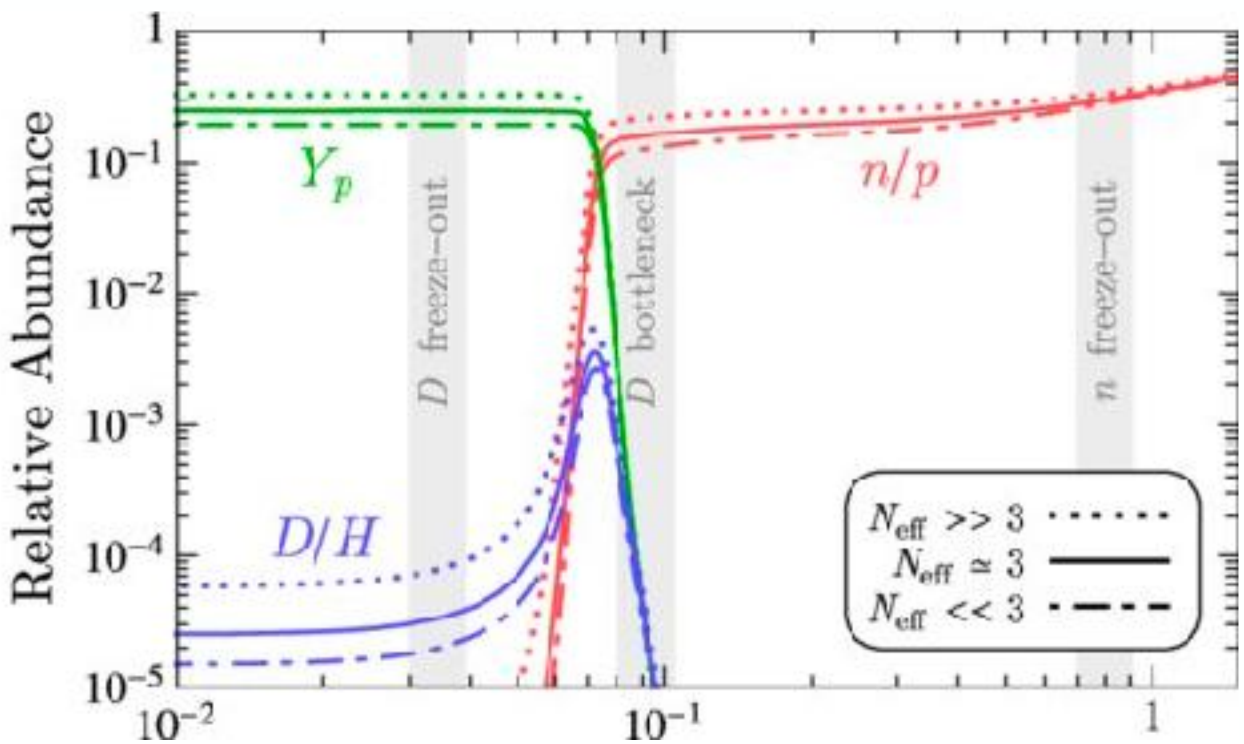
Astro./Cosmo. Probes

- BBN/CMB $N_{\rm eff}$ bounds

Thermalized MeV scalar DM can contribute to the relativistic degrees of freedom in the early universe

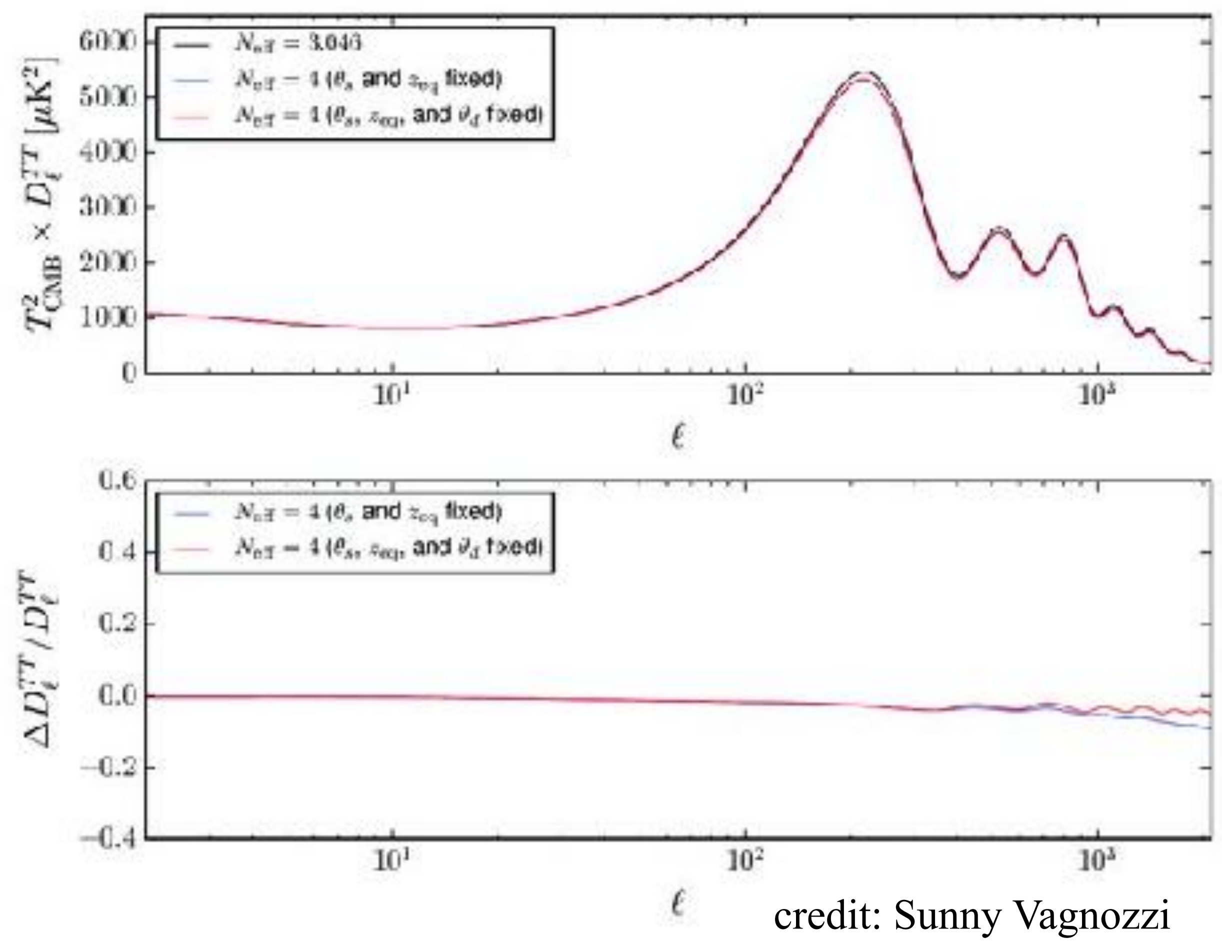
Constraint: $m_\phi \geq 2\,\mathrm{MeV}$

At BBN



Phys. Rev. D 100, 015038

At CMB



credit: Sunny Vagnozzi

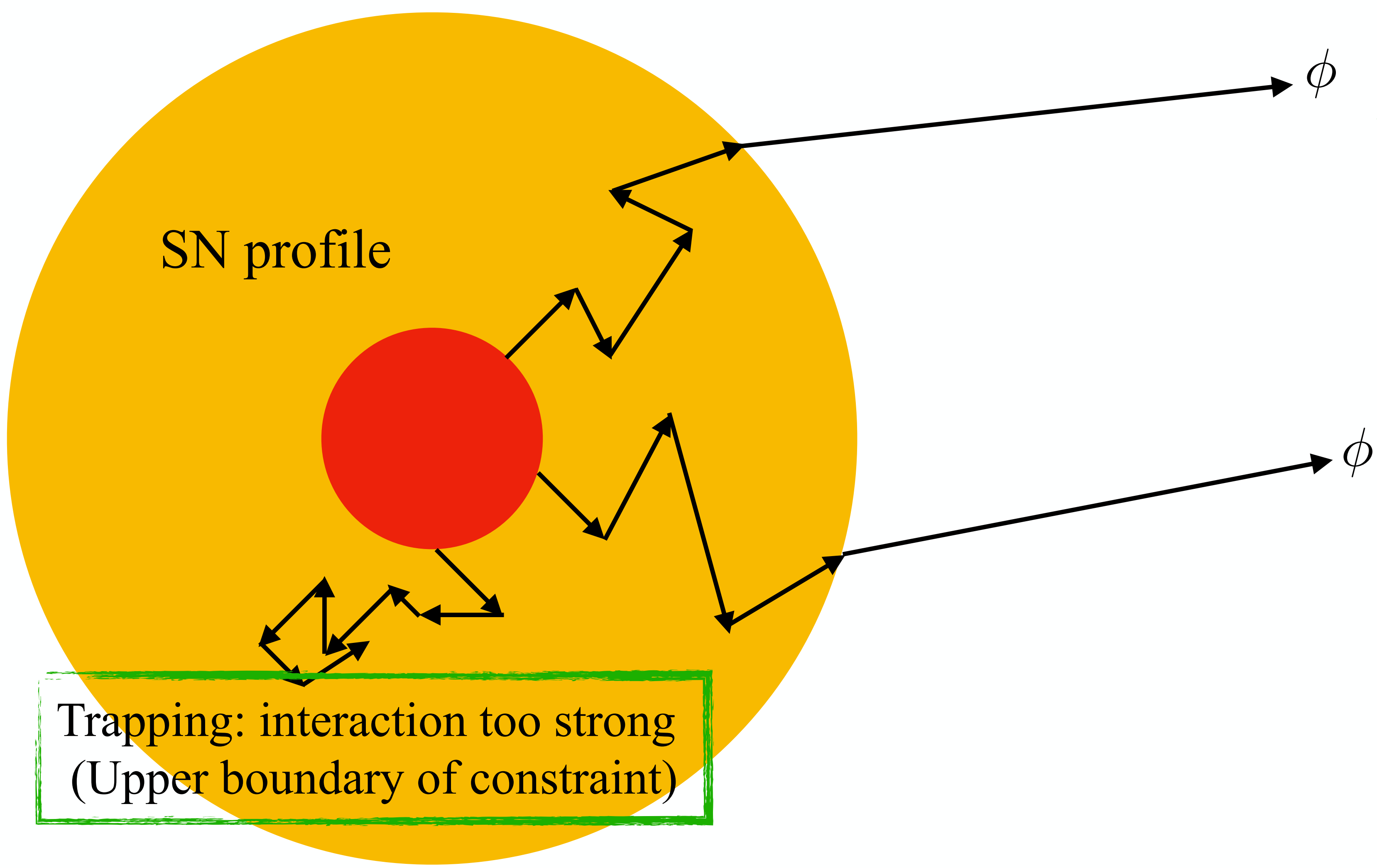
Astro./Cosmo. Probes

- SN1987A We observe few neutrinos from it!

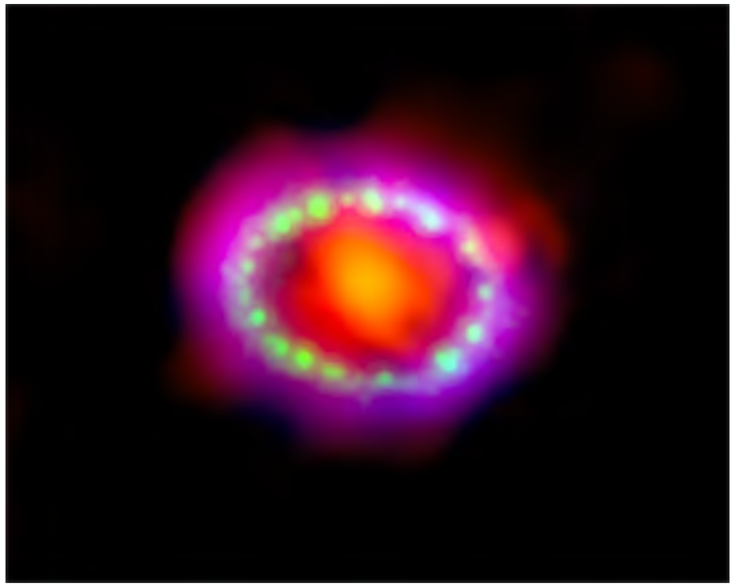
MeV scalar DM can also be produced in supernova (T ~ MeV)

➡ Anomalous energy loss alters the cooling rate of the proto-neutron star

Constraint: $\mathcal{L}_\phi \leq \mathcal{L}_\nu = 3 \times 10^{52}\,\mathrm{erg/s}$ Raffelt (1996)

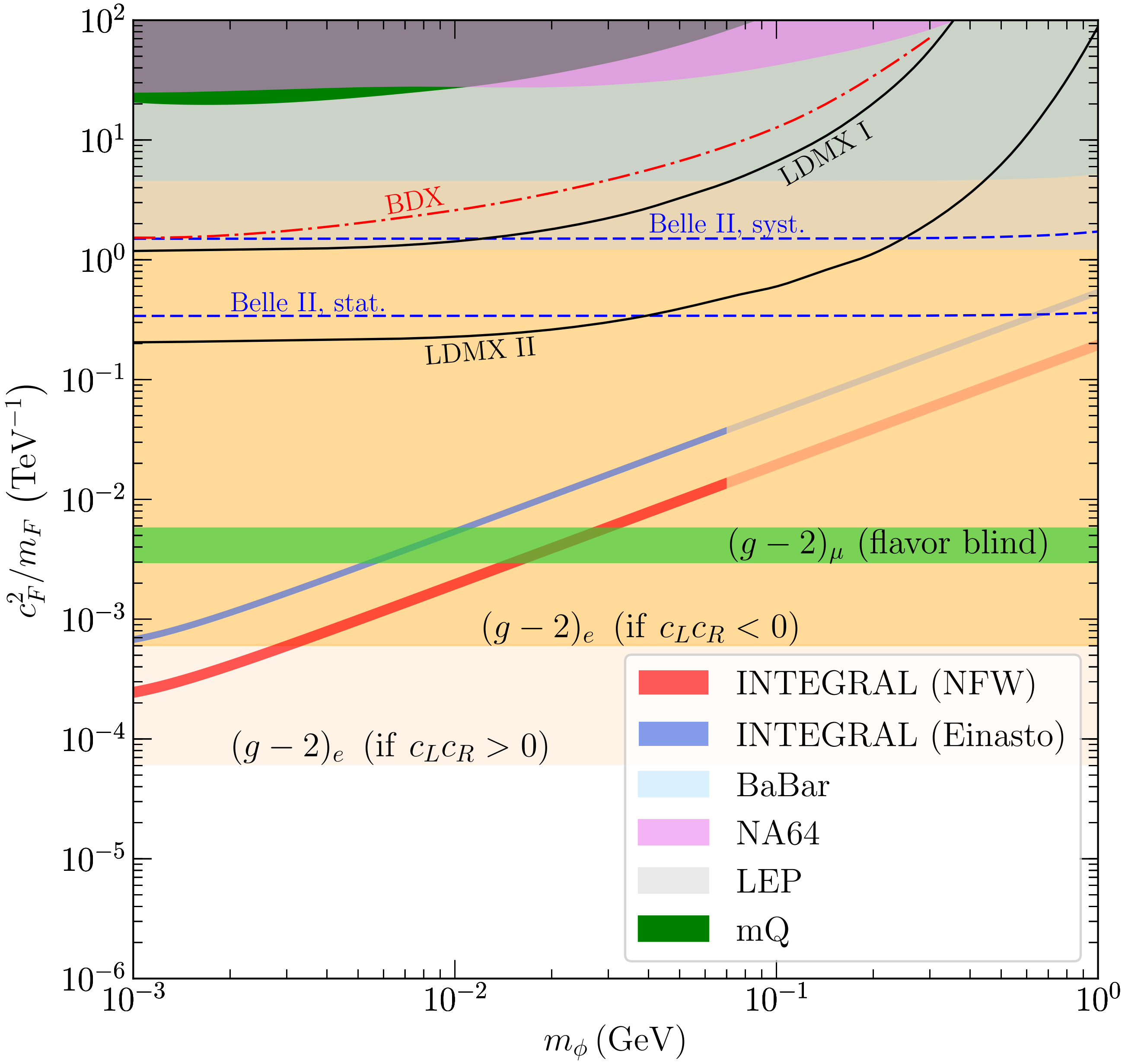


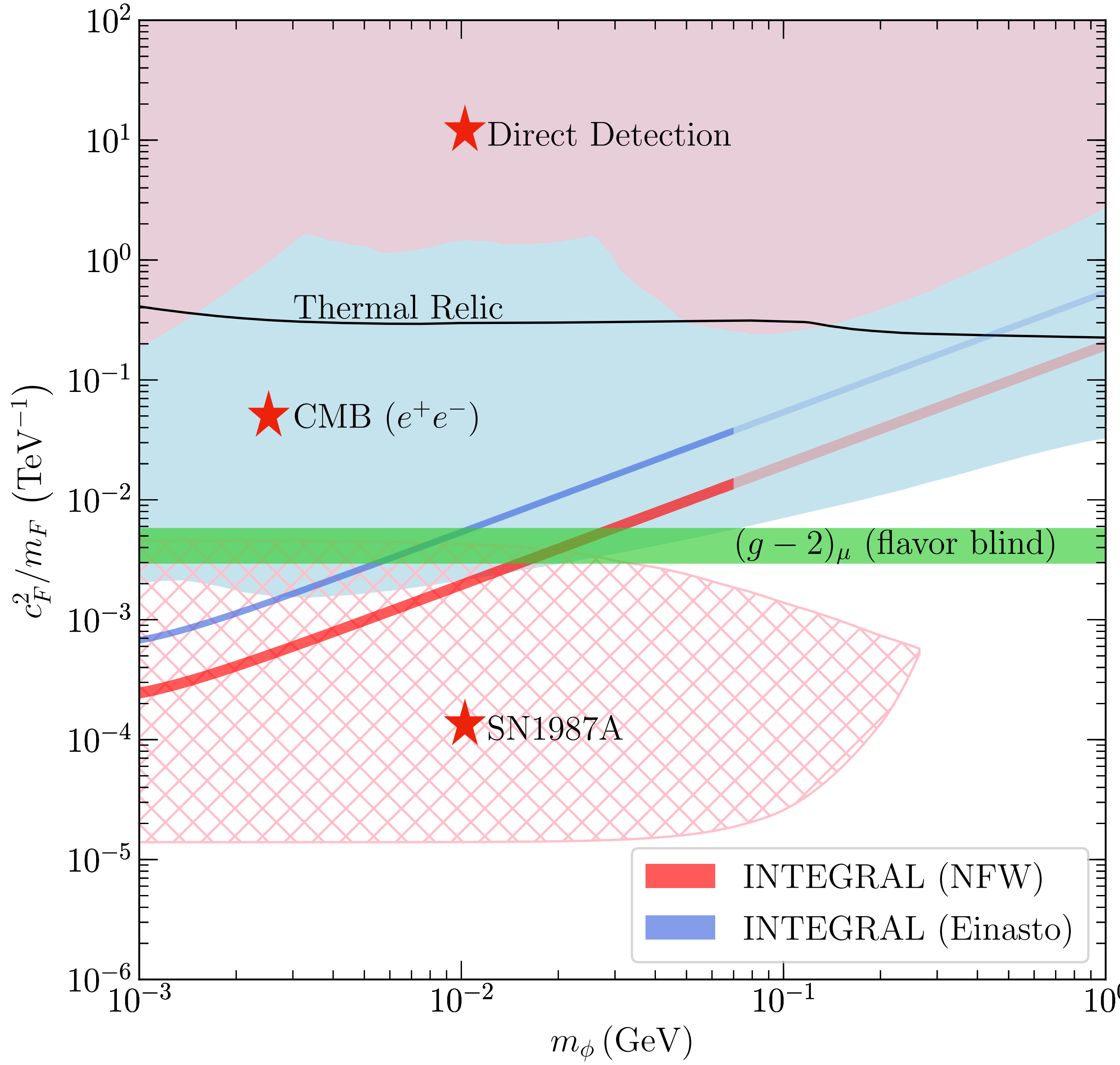
Anomalous energy loss
(Lower boundary of constraint)



credit: Chandra X-ray Observatory

Overview of Parameter Space: F

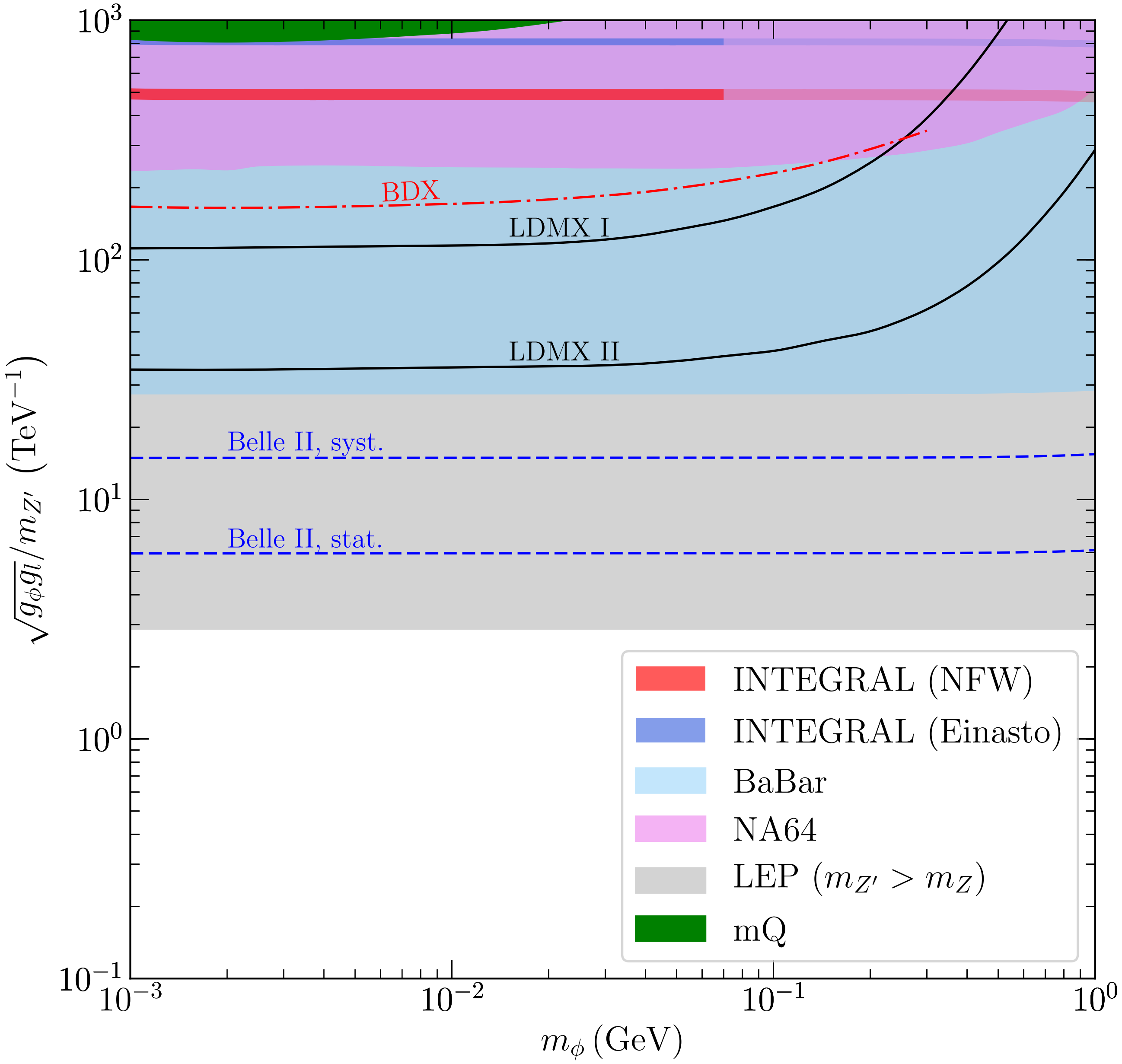


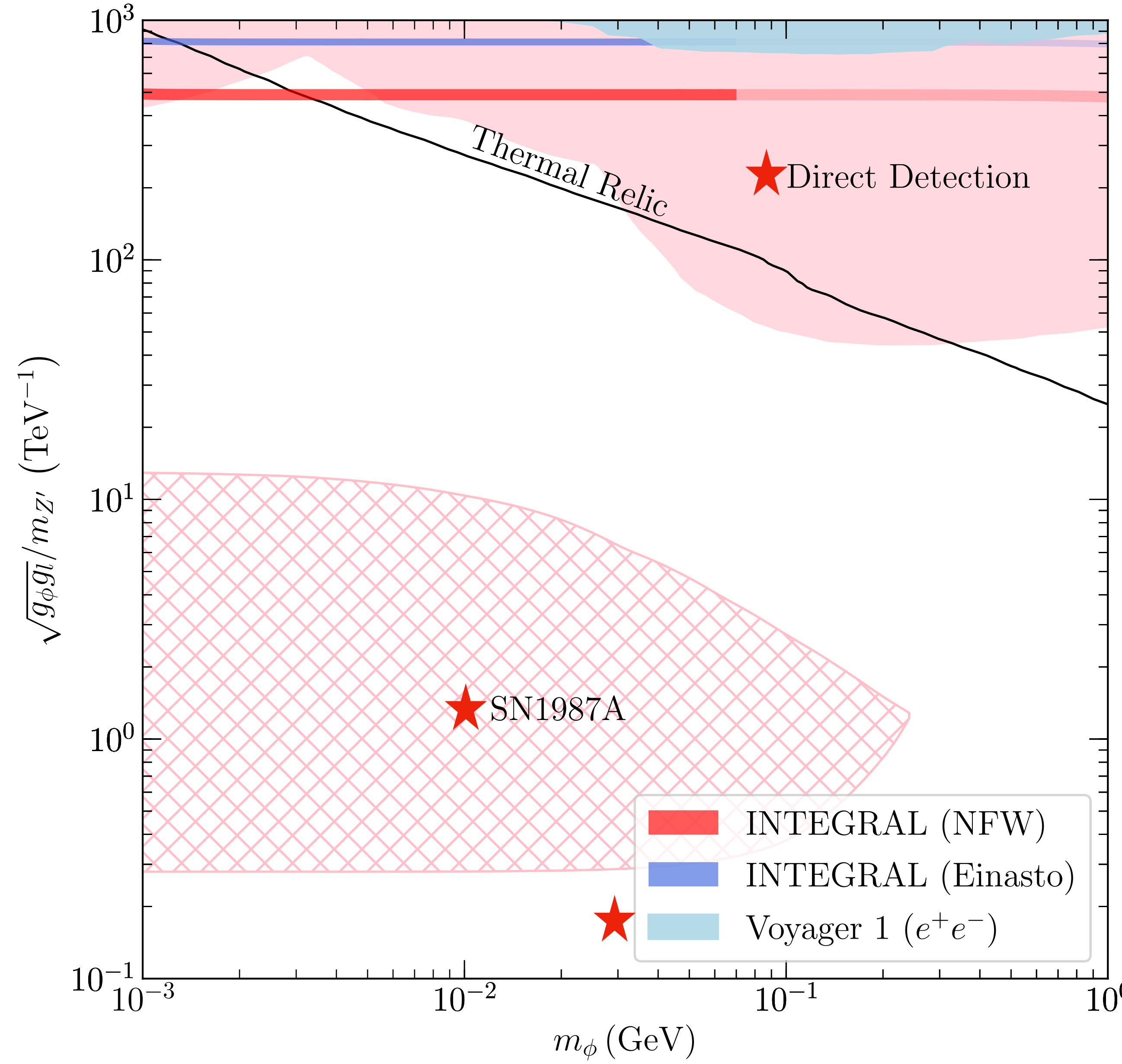


- SN1987A has best sensitivity

$$\mathcal{L}_F = -c_L^l\,\phi\bar{F}P_L l - c_R^l\phi\bar{F}P_R l - c_L^l\phi\bar{F}^0 P_L\nu_l + h.c.$$

Overview of Parameter Space: Z'

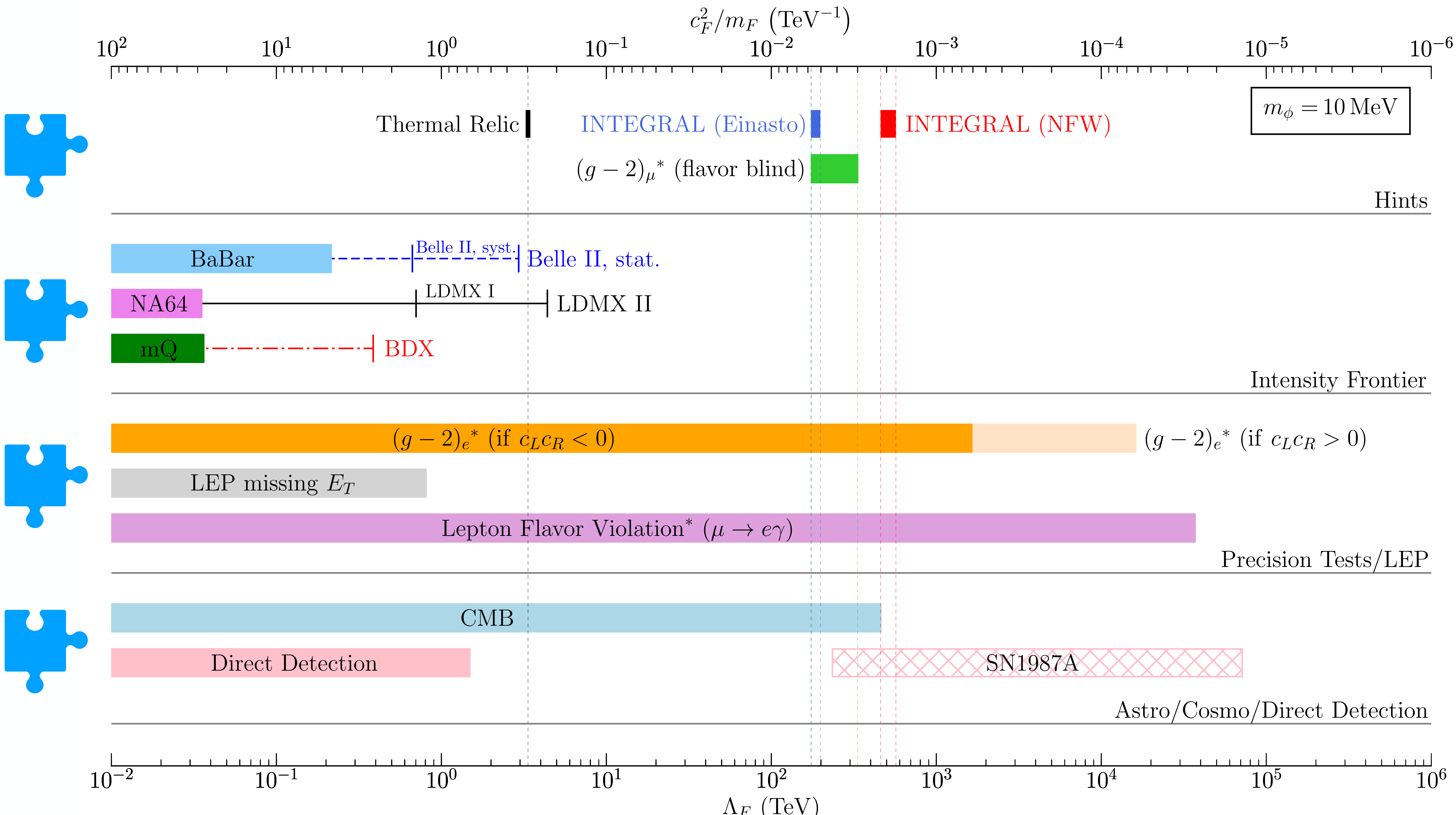




- SN1987A has best sensitivity

$$\mathcal{L}_{Z'} = g_\phi^2 Z'_\mu Z'^\mu \phi^* \phi - i g_\phi Z'_\mu \left[\phi^* (\partial^\mu \phi) - (\partial^\mu \phi^*) \phi\right] - i Z'_\mu \bar{l} \gamma^\mu (g_L P_L + g_R P_R) l.$$

Check List

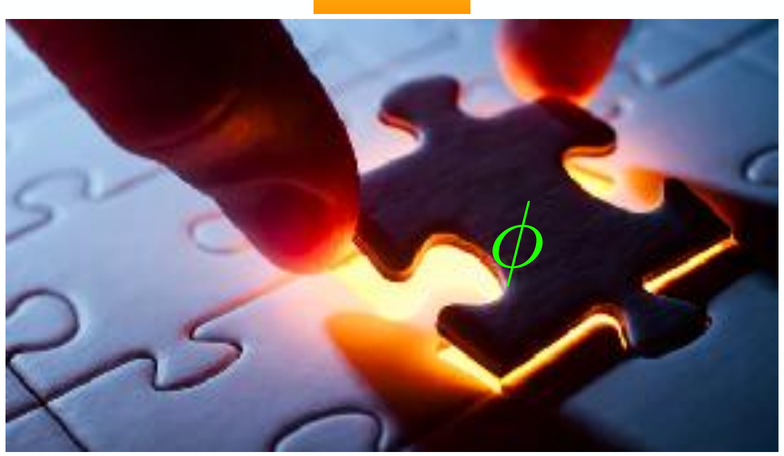


$$\mathcal{L}_F = -c_L^l\, \phi \bar{F} P_L l - c_R^l \phi \bar{F} P_R l - c_L^l \phi \bar{F}^0 P_L \nu_l + h.c.$$

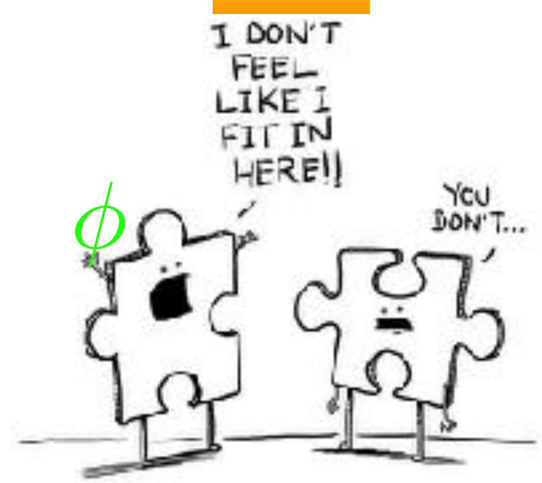
Summary

- Future intensity frontier experiments can have better sensitivity on a light dark sector
- Precision tests of SM are sensitive to the flavour and chiral structure of the dark sector
- Electron g-2 puts strong constraints on BSM physics but with caveat
- Stellar environments such as SN1987A has the best sensitivity for MeV scale dark sector particles
- The INTEGRAL (both NFW and Einasto) and thermal freeze-out favoured parameter space are ruled out for both models

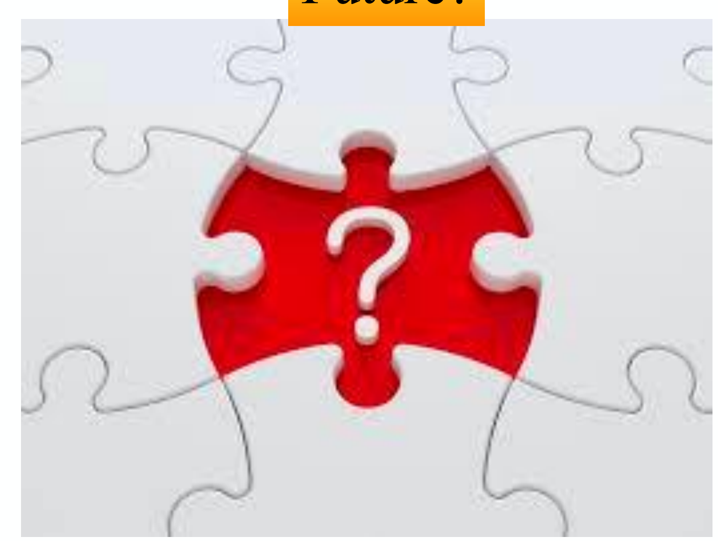
2003



2020



Future?



Backup

Electron-Positron Annihilation

- Direct annihilation of stopped electron and positron

  Single 511 keV line

- Annihilation after positronium formation

  Single 511 keV line

  Lower energy continuum

  INTEGRAL signal preferred

511 keV line

- Morphology

  The Einasto profile seems fit better than the NFW profile

  Vincent et. al (2012)

- INTEGRAL X-ray data Cirelli et. al (2020)

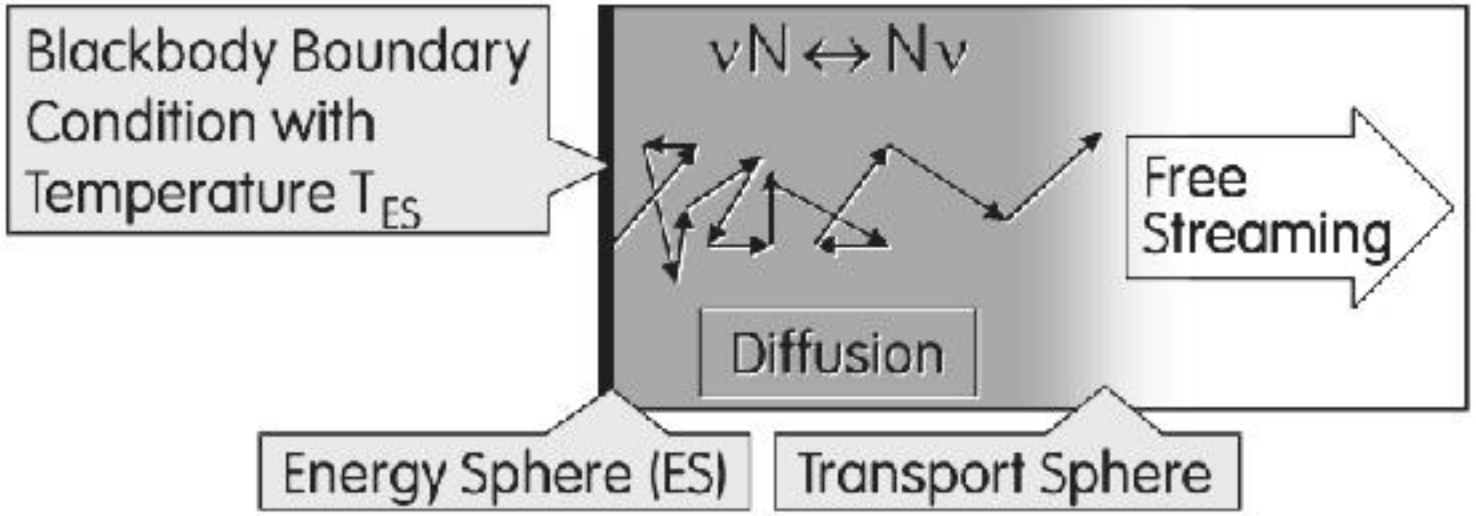
  Rule out scalar DM with mass larger than 70 MeV to be the explanation

Limit on DM energy loss

- Trapping of dark states in SN

Once the dark states are produced, they engage in random walk by scattering with charged particles in the environment

When the coupling is too large, the dark states cannot escape the stellar profile due to frequent scattering and are trapped inside, rendering the energy loss argument ineffective → upper boundary of the constraint



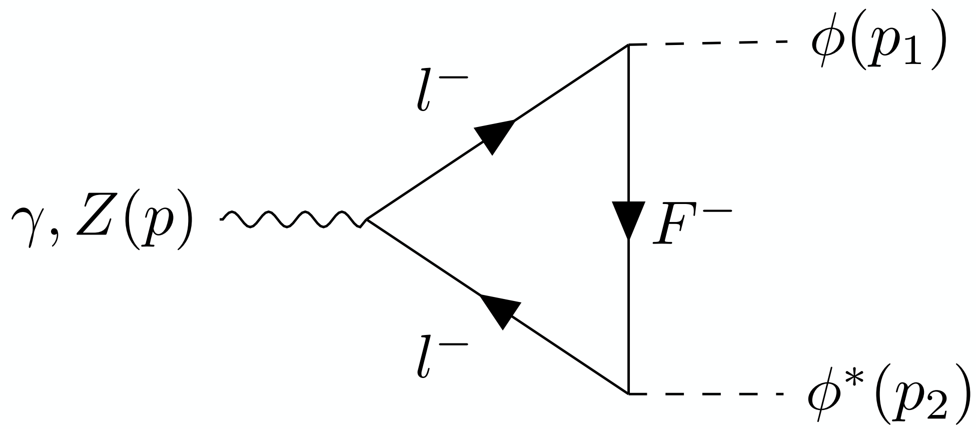
Neutrino analogue

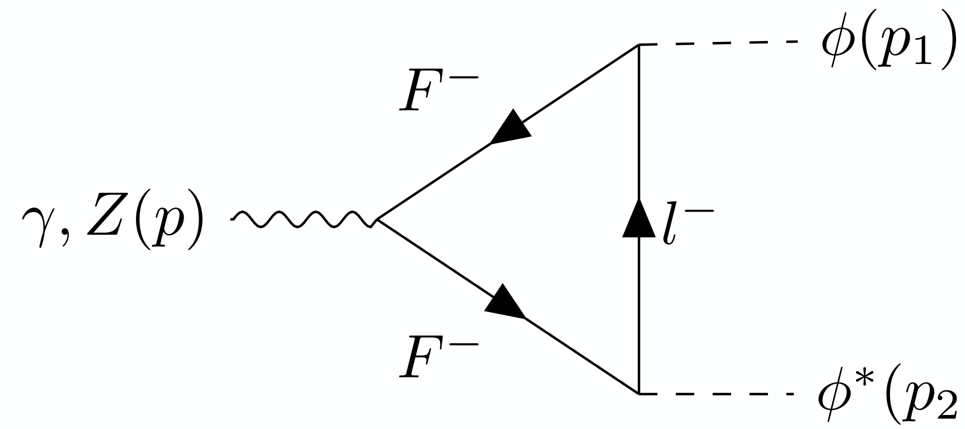
(Raffelt 2001)

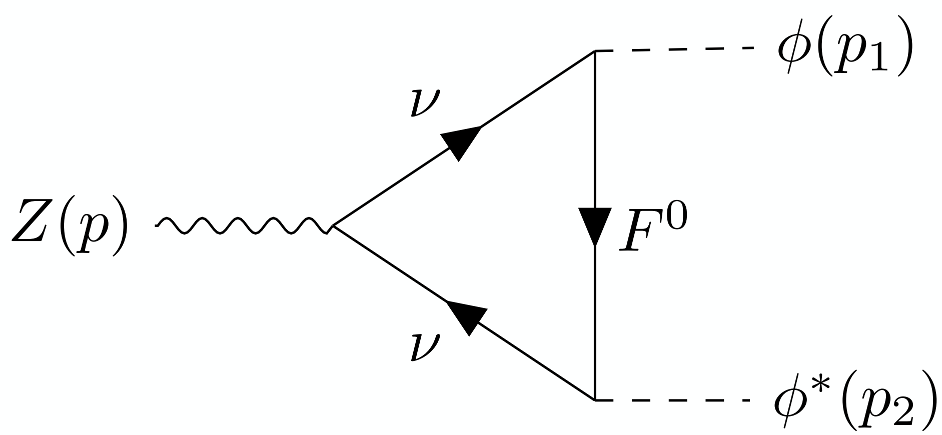
Credit: astro-ph/0105250

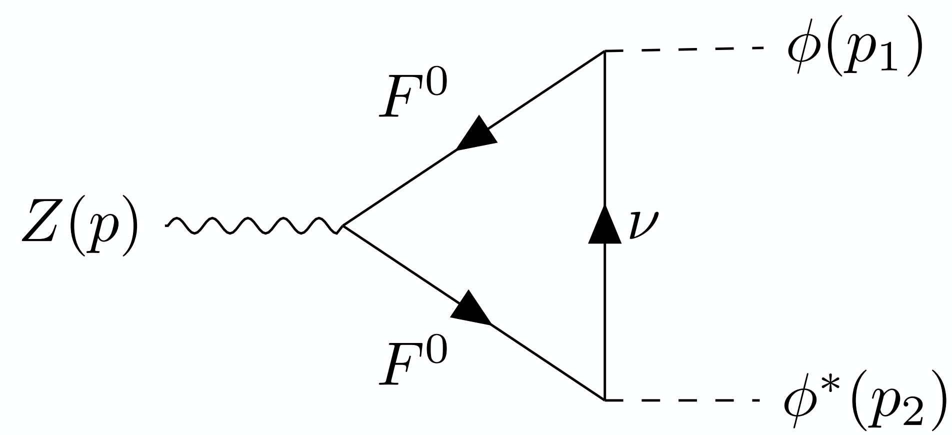
Z-invisible decay diagram (1)

- Contribution to Z-invisible decay: F-loop



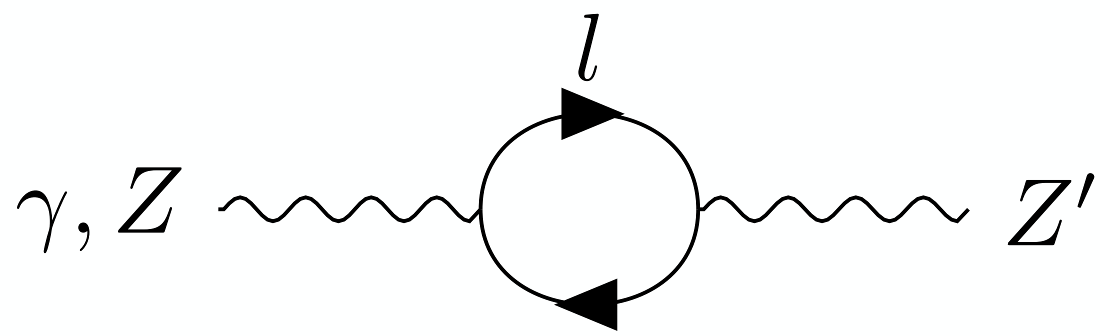






Z-invisible decay diagram (2)

- Contribution to Z-invisible decay: kinetic mixing

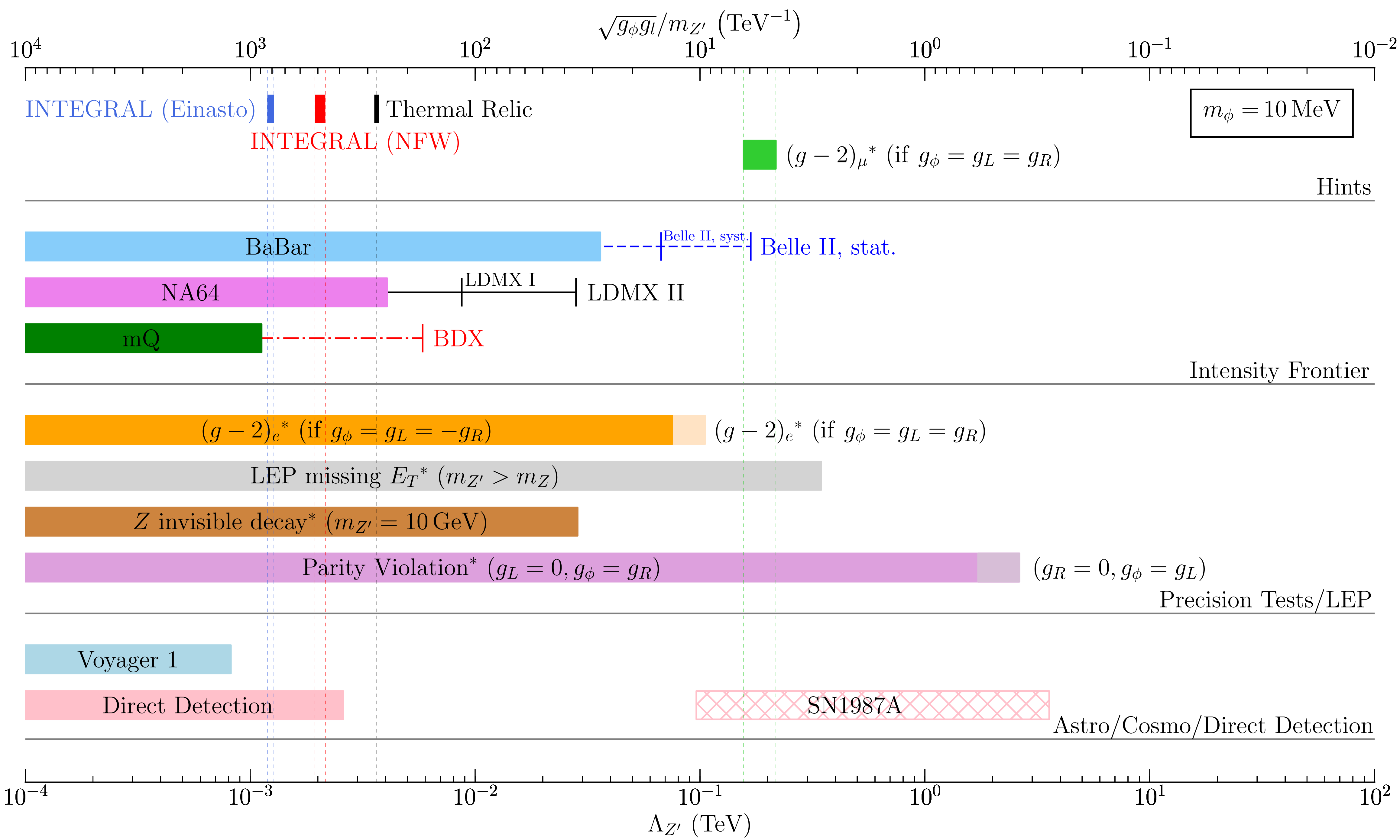


$$i\Pi^{\mu\nu} = i\left(p^2 g^{\mu\nu} - p^\mu p^\nu\right)\Pi(p^2)$$

$$\Pi(p^2) = -\frac{e g_l}{2\pi^2}\int_0^1 dx\, x(1-x)\left[\frac{2}{\epsilon} + \ln\frac{\tilde{\mu}^2}{\Delta} + \mathcal{O}(\epsilon)\right]$$

The ensuing constraint is fully covered by LEP bound

Particle Model (4)



Low mass Z' (1)

$m_{Z'} < 10\,\mathrm{GeV}$: Z' can be on-shell in intensity frontier experiments

➡ Cannot use effective operator!

➡ Model parameters: $g_l, g_\phi, m_{Z'}, m_\phi$

1. Fix g_ϕ by cluster bound or saturate the perturbativity bound

$\sigma_{\mathrm{SI}}/m_\phi \leq 0.5\,\mathrm{cm}^2/\mathrm{g}$ Harvey et. al (2015), Bondarenko et. al (2018), and Harvey et. al (2019) $\alpha_D \equiv g_\phi^2/(4\pi) < 10$

2. Solve for $m_{Z'}$ for each (m_ϕ, g_l) to fulfil

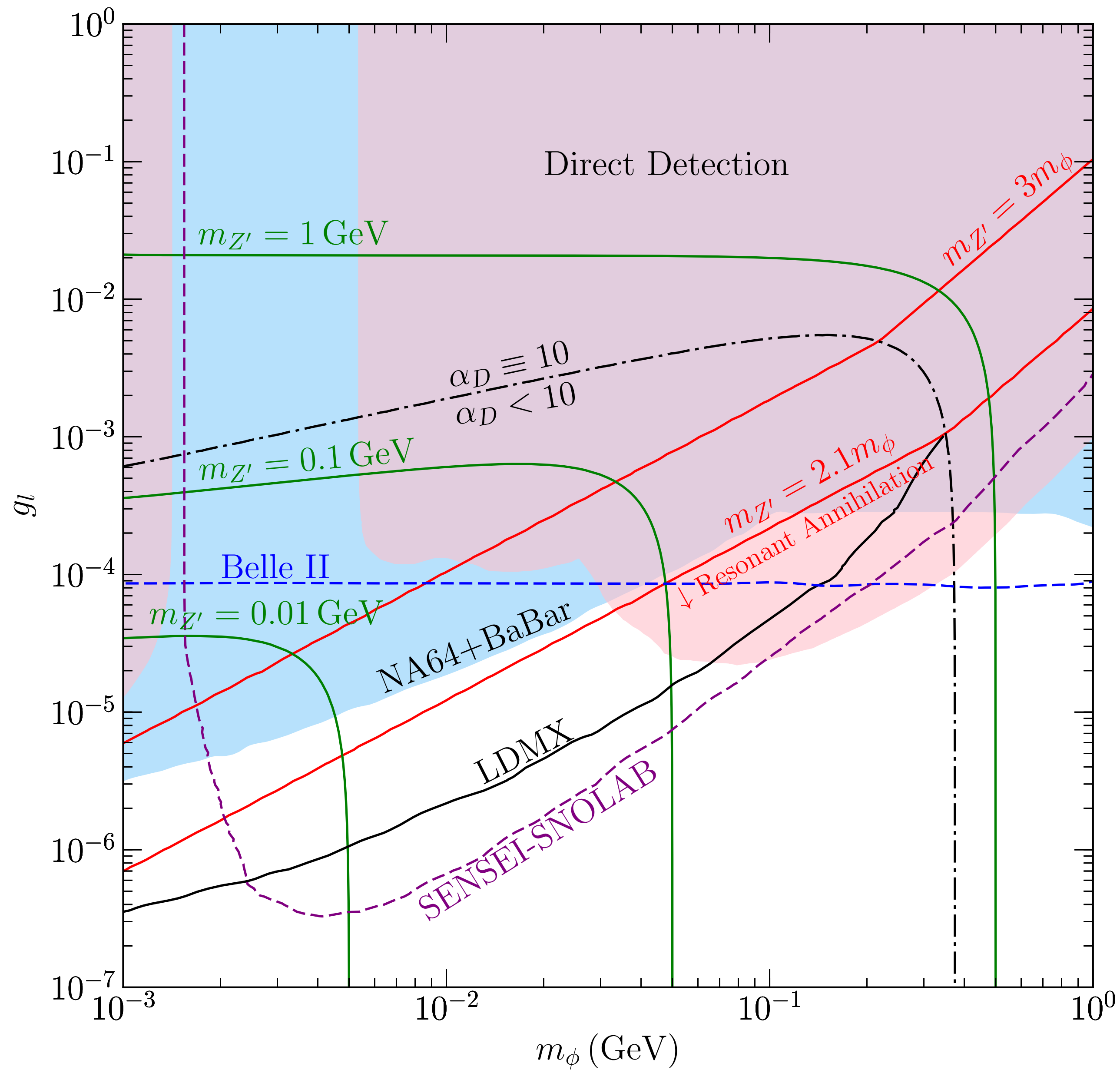
- Annihilation xsec for INTEGRAL 511 keV line
- Annihilation xsec for thermal freeze-out

Caveat: resonant annihilation $\phi\phi^* \to Z'$ at $m_{Z'} \leq 2m_\phi$

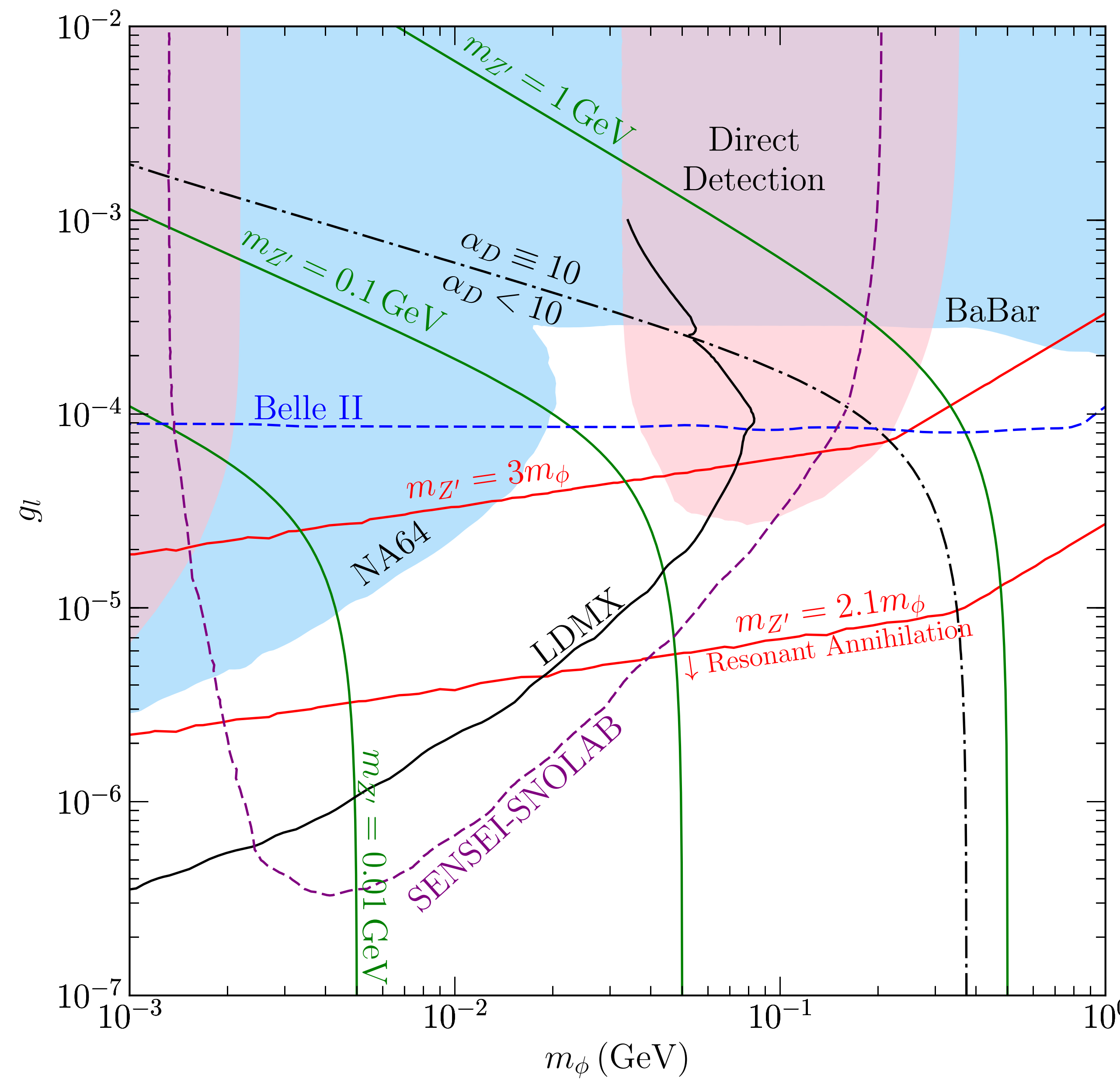
➡ Additional velocity dependence in annihilation xsec

Low mass Z' (2)

xsec: INTEGRAL 511 keV line



xsec: thermal freeze-out



Intensity frontier: invisibly decaying Z' See review, Beacham et. al (1996)