Dark matter, on and off the beaten track

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Outline

1. Dark Matter and WIMP
   A. Short reminder and upcoming bounds
2. Sub-Gev Dark Matter and dark sector
   A. How and why of sub-GeV Dark Matter
   B. Dark photon mass and dark Higgs
   C. Dark Higgs: signals and constraints

Dark Matter and WIMP

The golden path: WIMP

- Weakly Interacting Massive Particle
  - →Mass roughly between 10 GeV and few TeV
  - →Cross-section of approximately the weak interaction's one

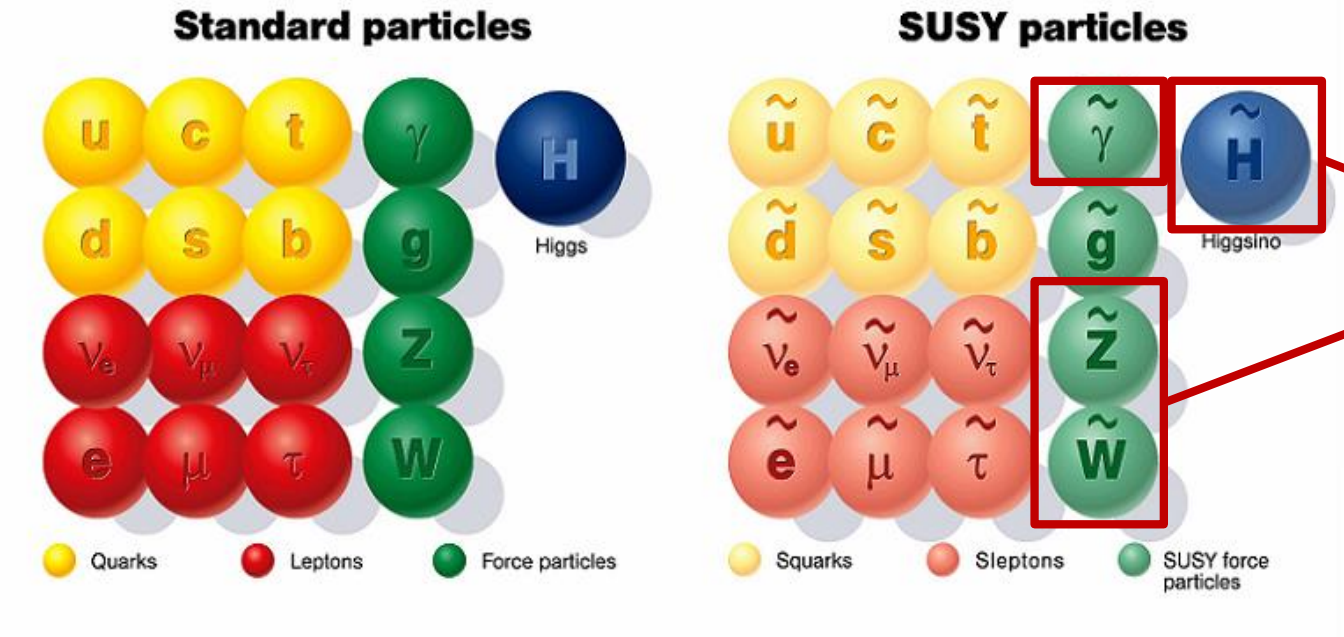
- Works perfectly for interactions mediated by the weak force

$$\Omega h_\chi^2 \simeq \frac{10^{-37} cm^2}{\langle \sigma v \rangle_{anni}} \simeq 0.119 \qquad \langle \sigma v \rangle \sim 10^{-36} \mathrm{cm}^2 y^4 \left(\frac{m}{400\mathrm{GeV}} \right)^2 \left(\frac{2\mathrm{TeV}}{m_\Phi} \right)^4$$

- Include new physics at the scale searched for at LHC experiments

In particular SUSY-WIMP

- Supersymmetry introduces several good WIMP candidate



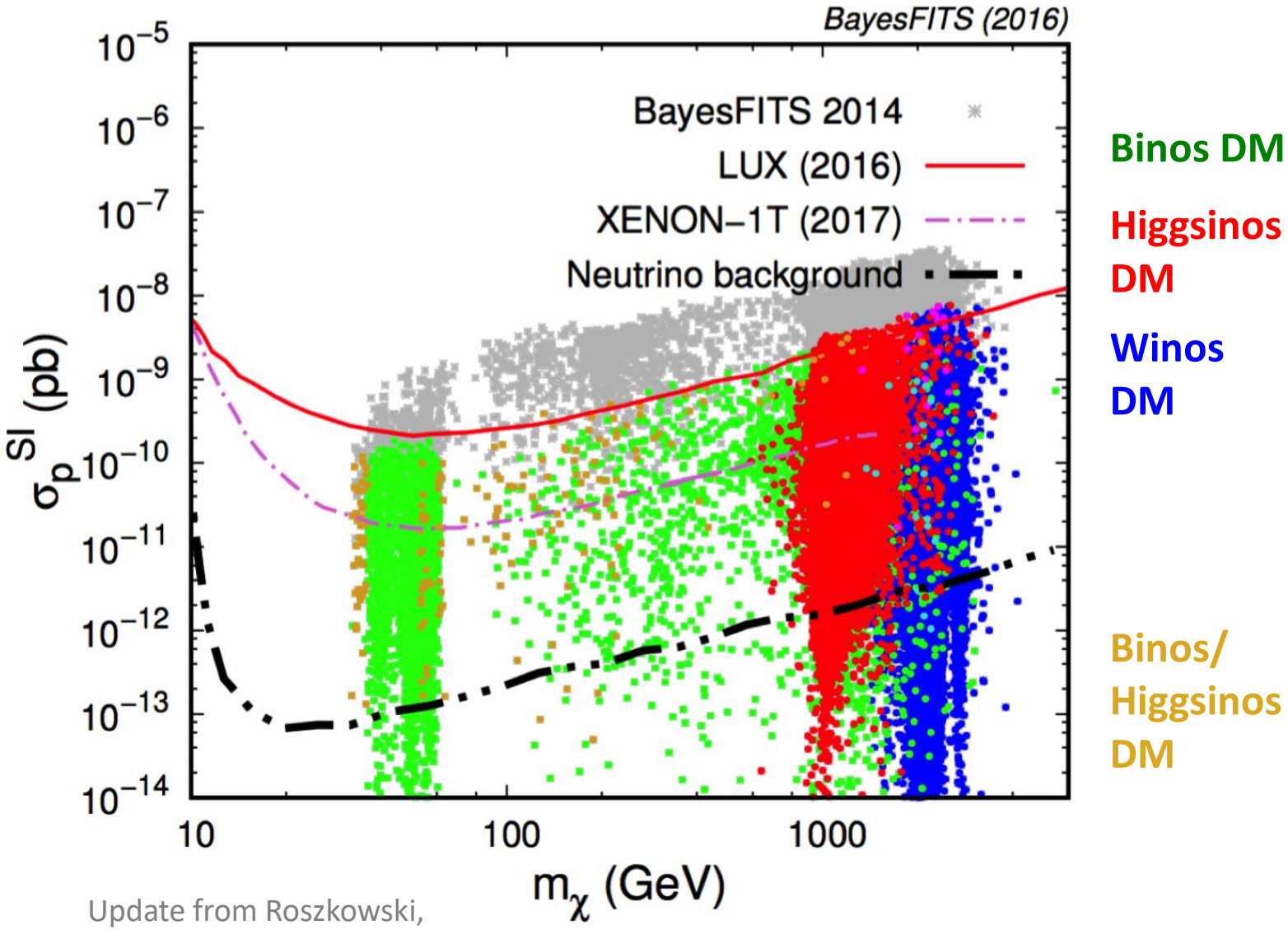
The neutralinos:

- Bino, Wino
- Higginos

Protected by a global symmetry
→ Stable

- Experimentally good target as they can also be searched for at LHC

Direct Detection constraints



Update from Roszkowski, Sessolo, Williams, 1411.5214

Binos DM

Higgsinos DM

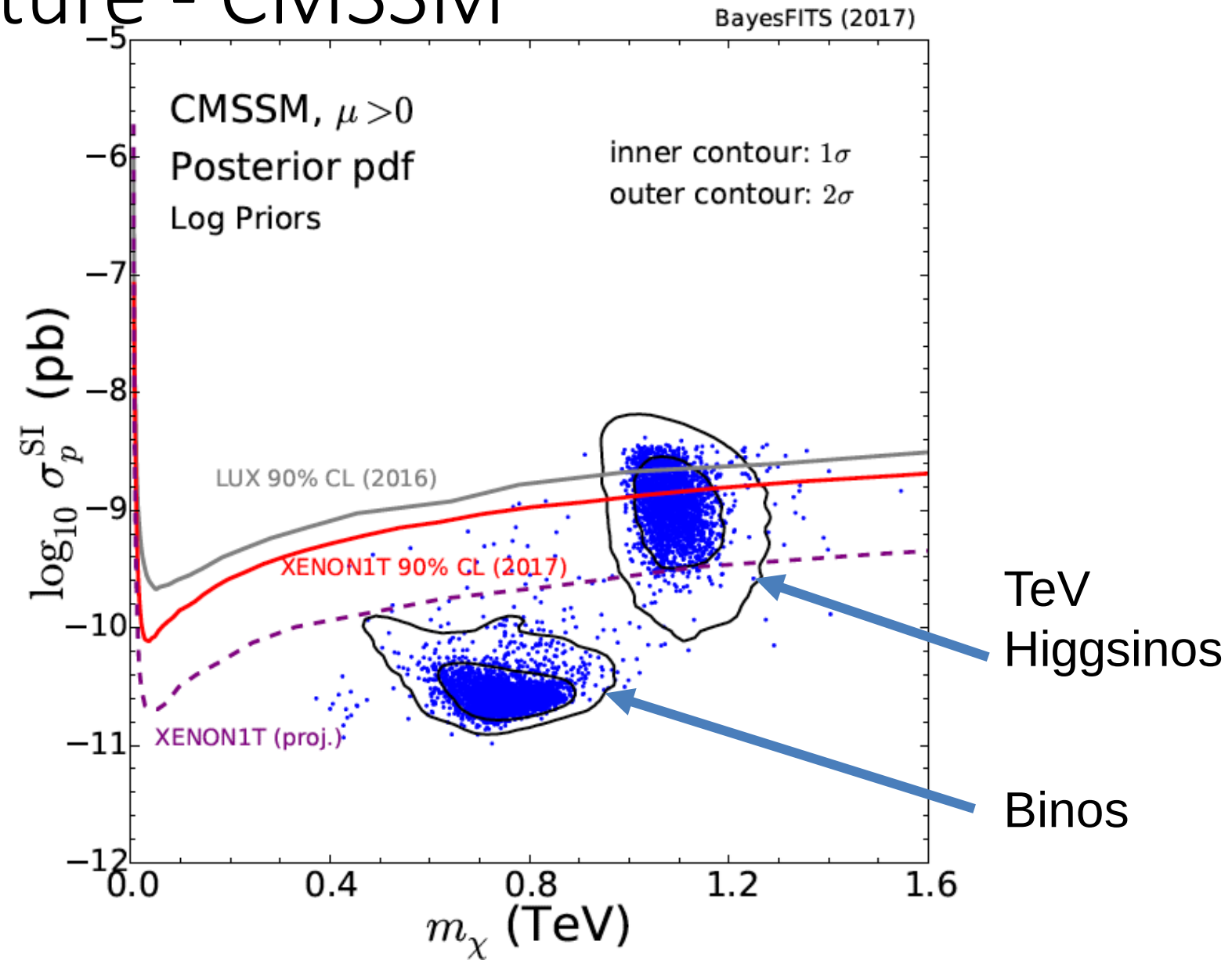
Winos DM

Binos/ Higgsinos DM

- Binos DM require additional mechanisms (e.g co-annihilation) to obtain correct relic density
- Higgsinos in the TeV range are very good thermal DM candidates
- Not directly constrained by collider searches → complementarity

Turning to the future - CMSSM

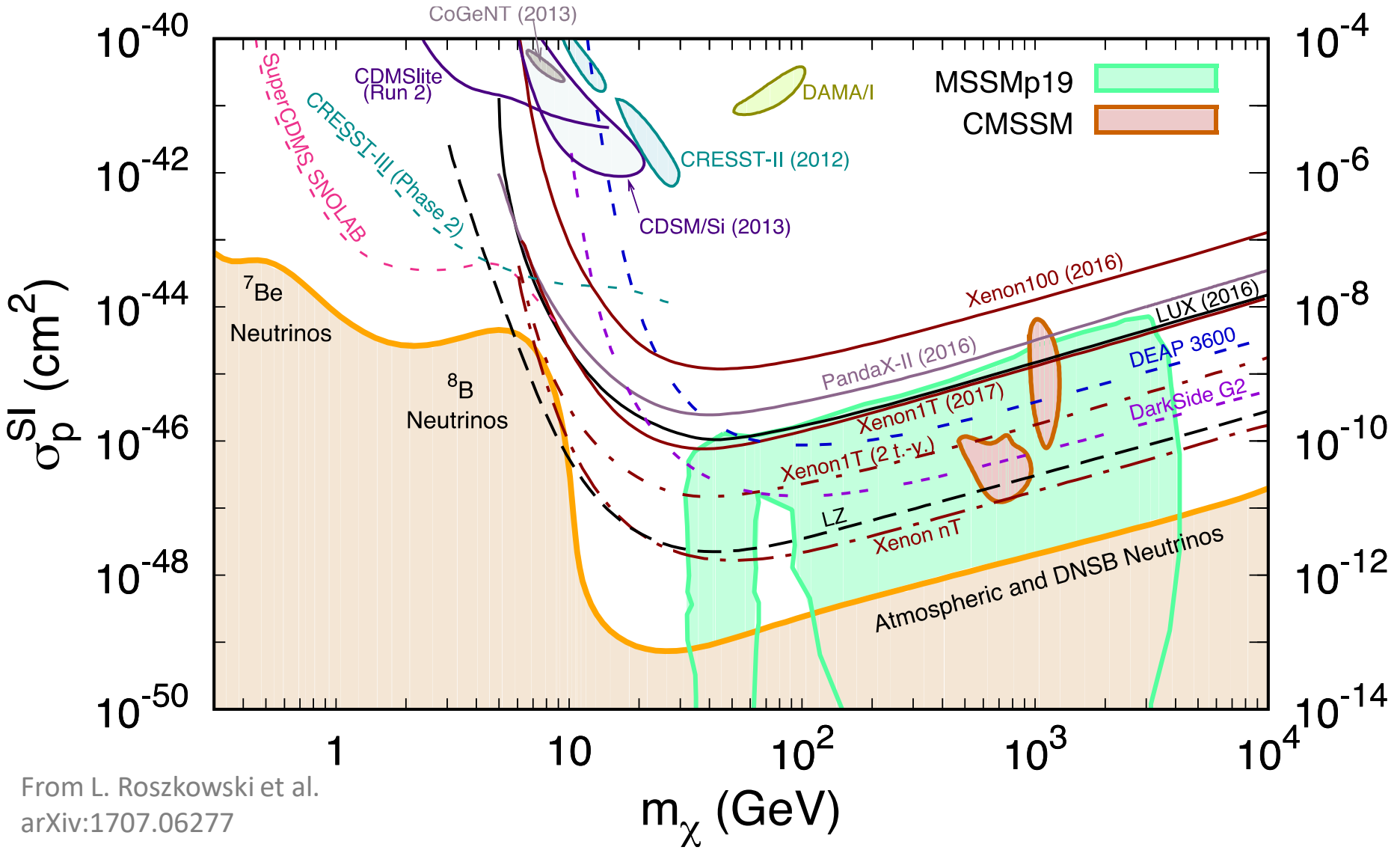
- The simplest SUSY realisations within reach



From L. Roszkowski et al. arXiv:1707.06277

Turning to the future – Direct Detection

- Bright prospect for WIMP searches
- Indirect searches also very constraining.

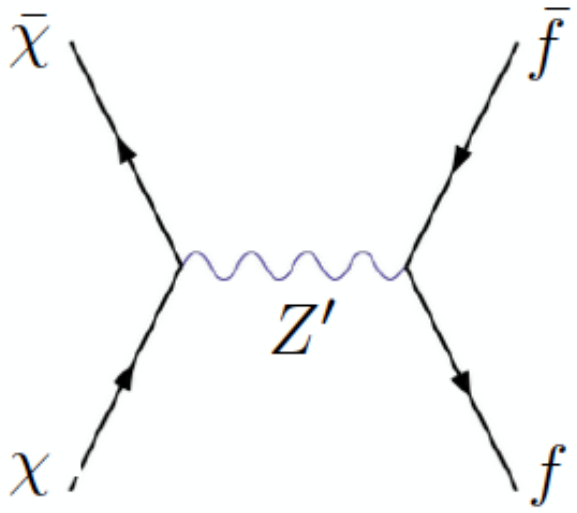


From L. Roszkowski et al.
arXiv:1707.06277

Sub-GeV Dark Matter
and
dark sector

What is required for such a DM?

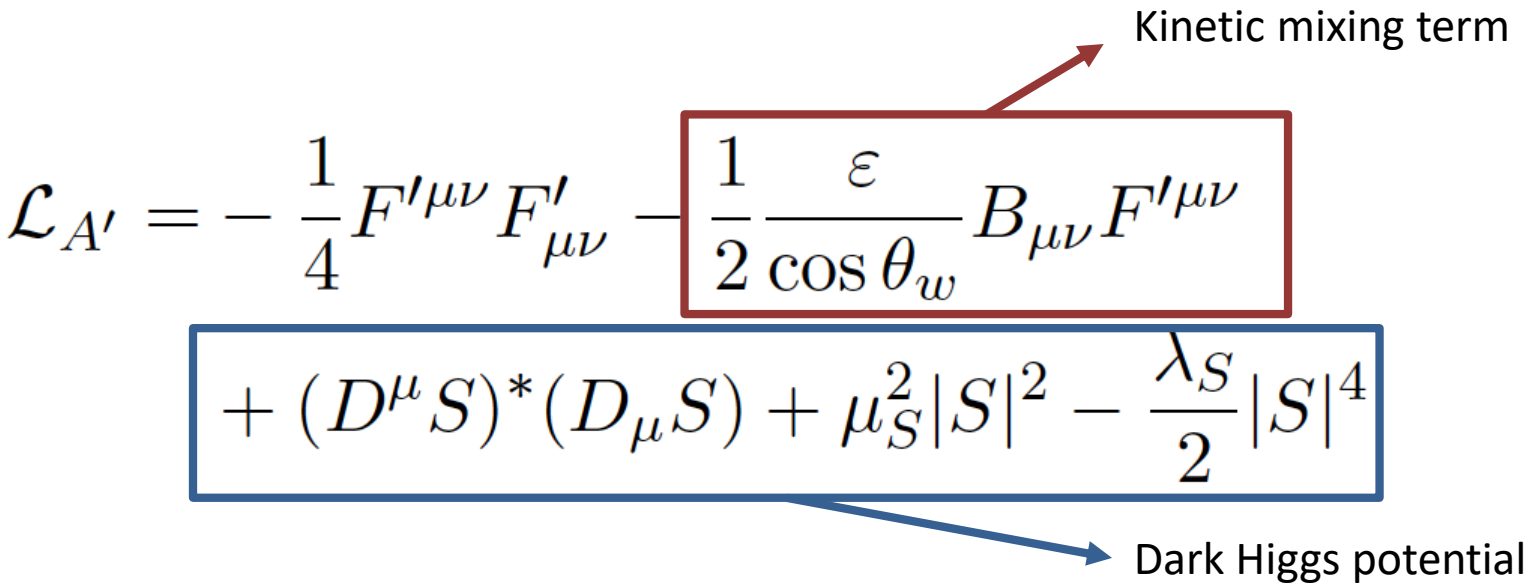
- Obtaining the thermal relic density (from freeze-out) → effective annihilation mechanism
  - Need a new, massive mediator, "dark photon"
  - Massive, around GeV
- Coupling to Standard Model → mixes with ordinary photon *kinetic mixing*



- Certain annihilation channels forbidden by indirect detection
- Self-interaction for Dark Matter, may be helpful in solving some difficulties of the CDM paradigm
  - *DM data at short scale* → Core-cusp problem
  - Caveat: baryonic feedback

A dark Higgs mechanism?

- Most logical way to give a mass to the Dark photon → Higgs mechanism.

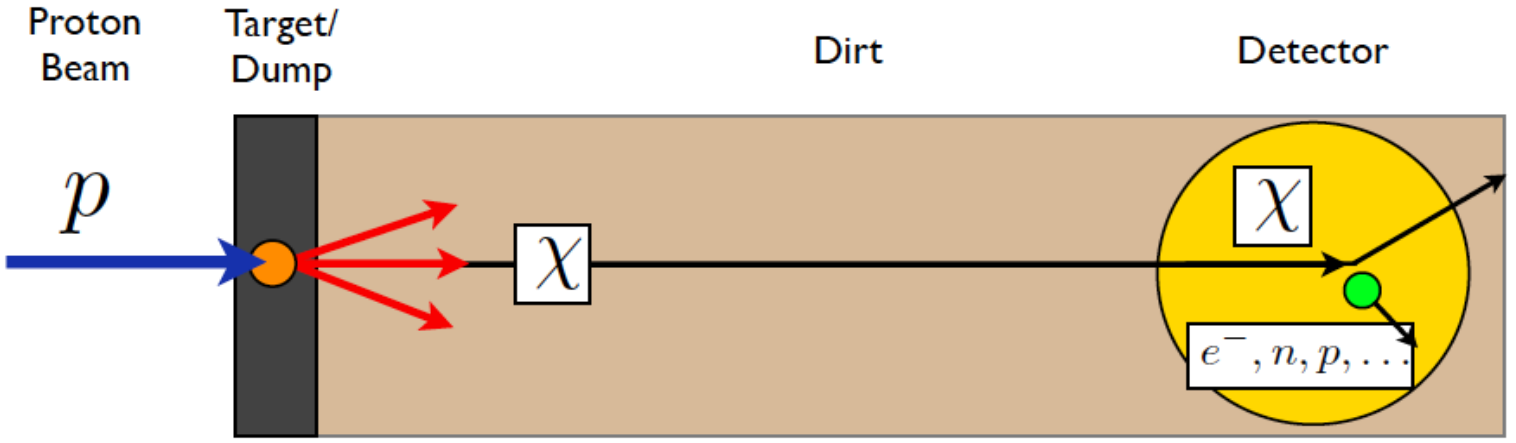


- The new "dark" U(1) symmetry is broken → the VEV of the dark Higgs gives a mass to the dark photon
- The dark Higgs is typically light and long-lived

Detection opportunities

- Main challenge: no significant energy deposit during scattering
  - Need dedicated experiments/searches -> many upcoming projects
- Also accessible at the *intensity frontier*
  - Low mass implies that one does not need huge collider, smaller scale installations but high intensity
  - Protons/electrons beam dump experiment (MiniBoonE, LSND, E137 ...)

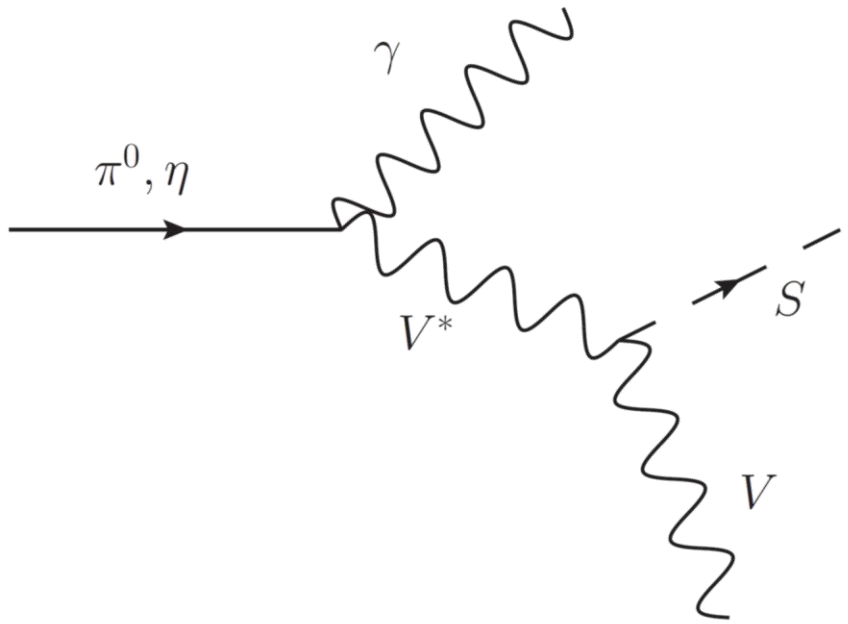
- Dark matter scattering
- Dark Higgs decay
- Dark photon searches (e.g. BaBar)



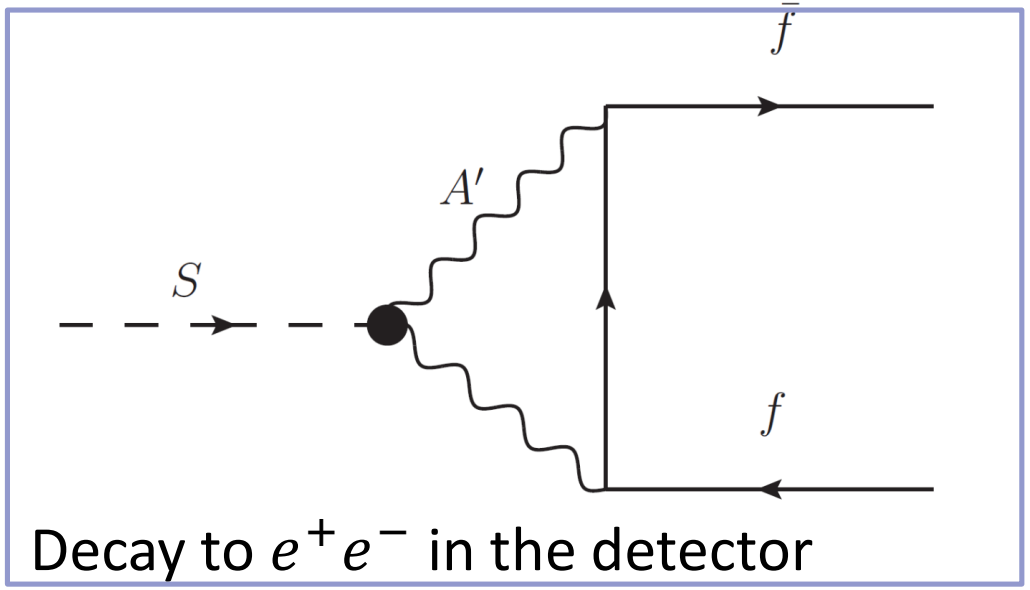
Suppressed processes – but huge statistics MiniBooNE: $2 \cdot 10^{20}$ proton on target, LSND: 10^{22} π^0mesons produced…

Dark Higgs signals

- Dark photon can mix with standard photon → kinetic mixing
- Dark Higgs be produced through dark Higgsstrahlung



Travel through shielding

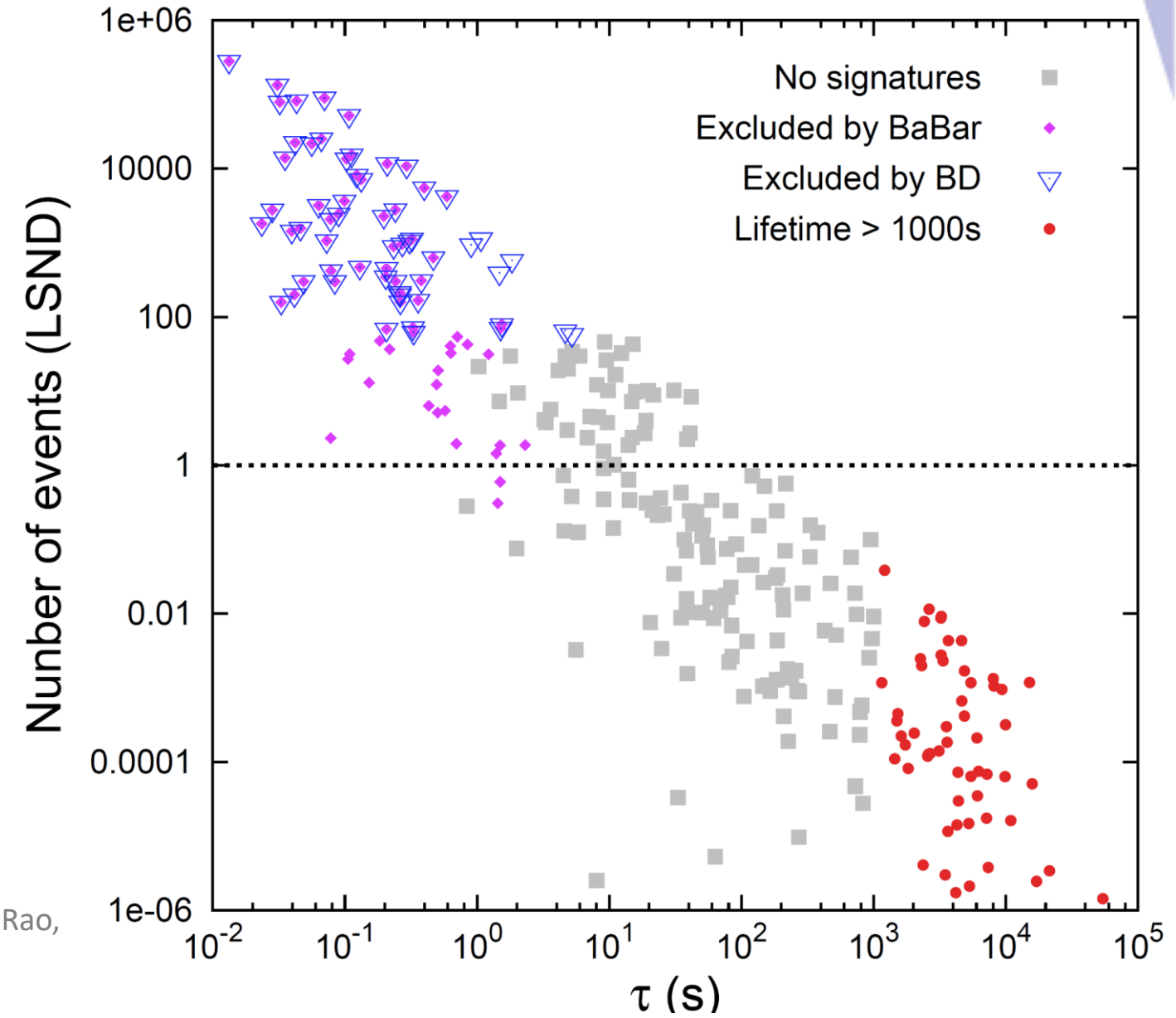


Decay to e^+e^- in the detector

- Phase space suppression compared to DM beam mode, but easier detection (decay to pair electron-positron)

Dark Higgs constraints

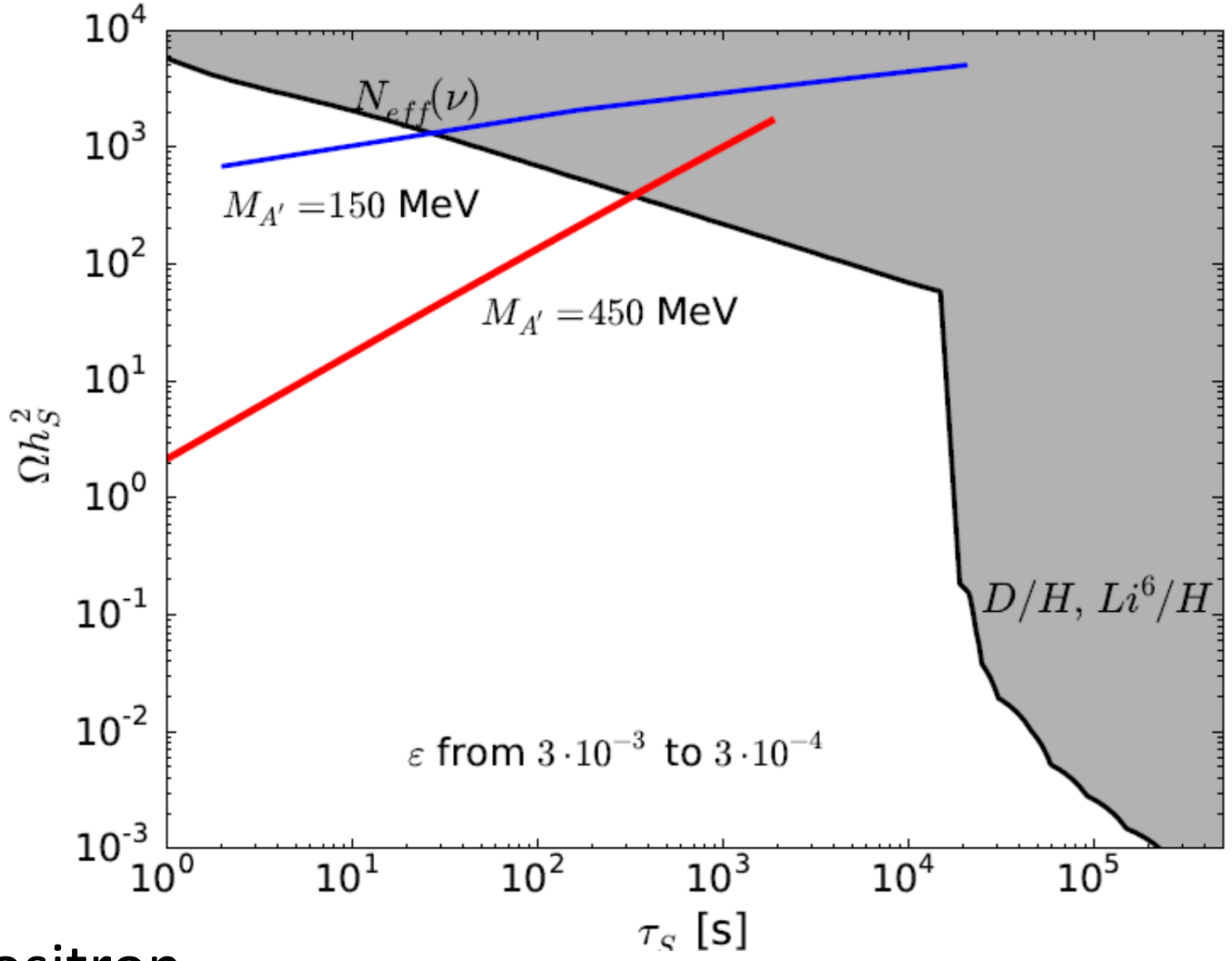
- Bounds from beam dump experiment (e.g. LSND, MiniBooNE …)
- Strong limit from BaBar, directly on the kinetic mixing ε
- BBN lower bounds →depends on $SS \to \chi\chi$ opened or not



Preliminary result: Darme, Rao, Roszkowski, 1710.xxxx

BBN and indirect detection

- Not many annihilation mechanisms available → Large metastable density after freeze-out
- Two relevant bounds
  - N_{eff} neutrino from late time energy injection ($\tau > 0.1$s)
  - Light element aboundances, e.g D/H ($\tau > 10^4$s)
- Light dark Higgs only decay electromagnetically (electron-positron pairs) → (relatively) weak bounds



Preliminary result: Darme, Rao, Roszkowski, 1710.xxxx

Conclusion

A lampposts story …

- Thriving experimental effort towards Dark Matter
- In the coming years the paradigmatic WIMP will be soon pushed down to the neutrino scattering limit

- Interesting developments on a sub-GeV DM candidate
  - New detection strategies
  - Rich dark sector phenomenology

Backup slides

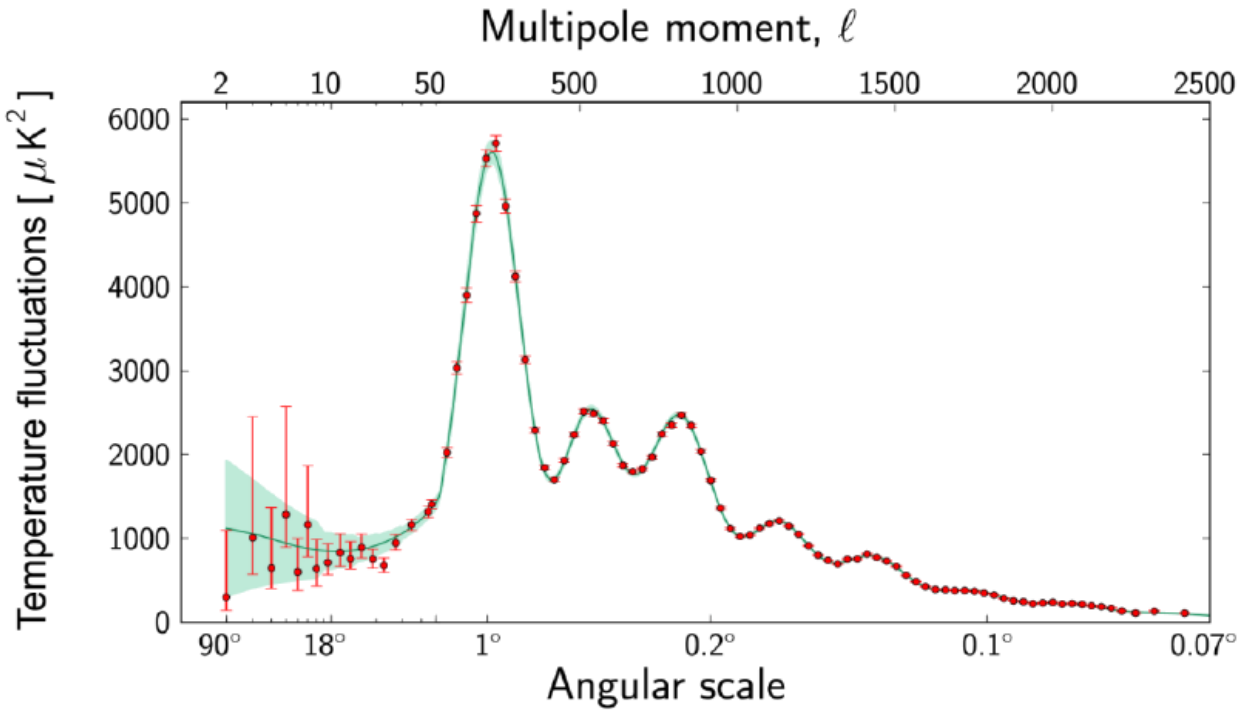
Other DM gravitational evidences

- Bullet cluster
  - Visible matter in red (gas in X-ray)
  - DM from gravitational lensing in blue

From Chandra X-ray laboratory

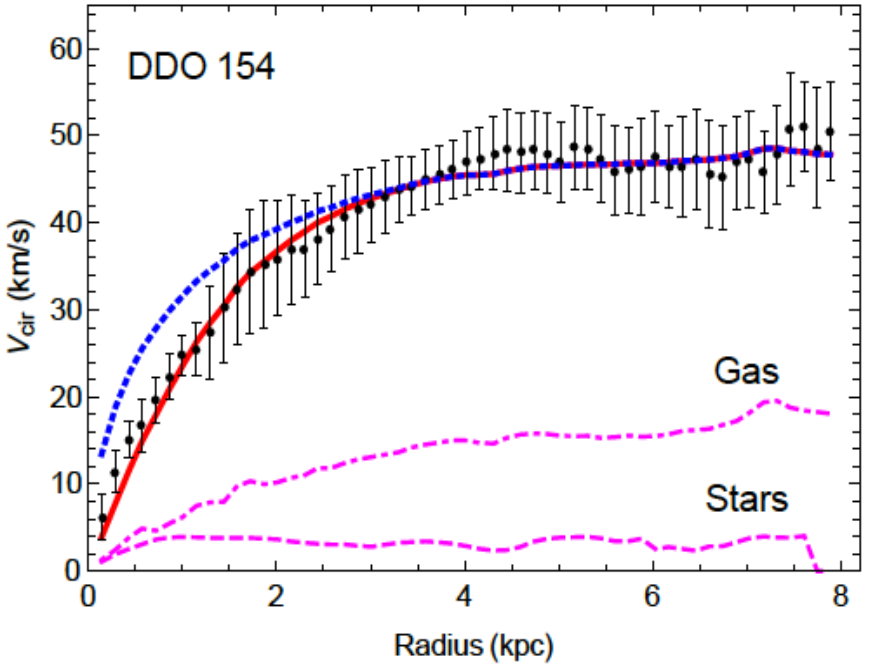
- Large Scale Structure formation
  - DM is needed from N-body simulation

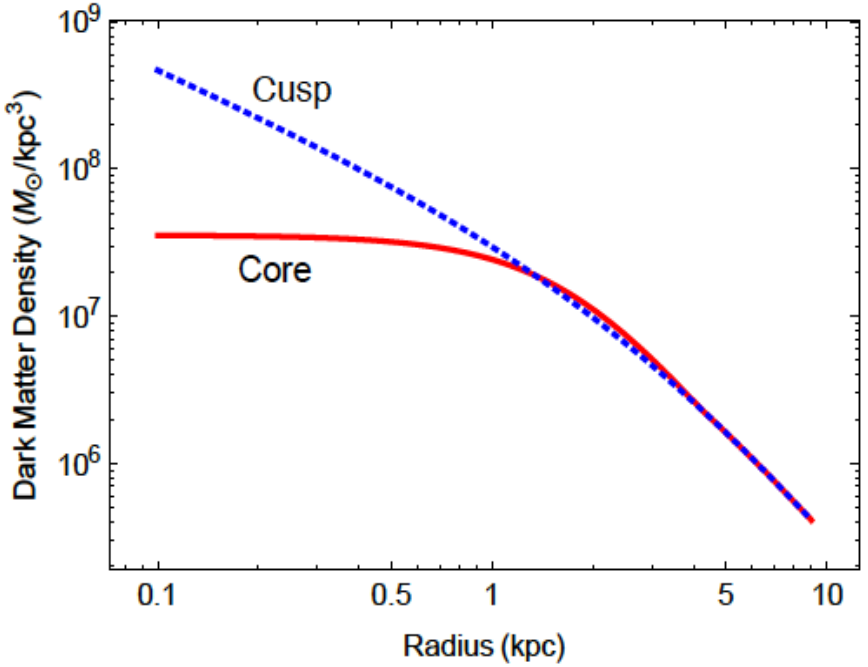
- Cosmic microwave background
  - The shape of the anisotropy power spectrum depends on the density of baryon and DM



Short scale anomalies

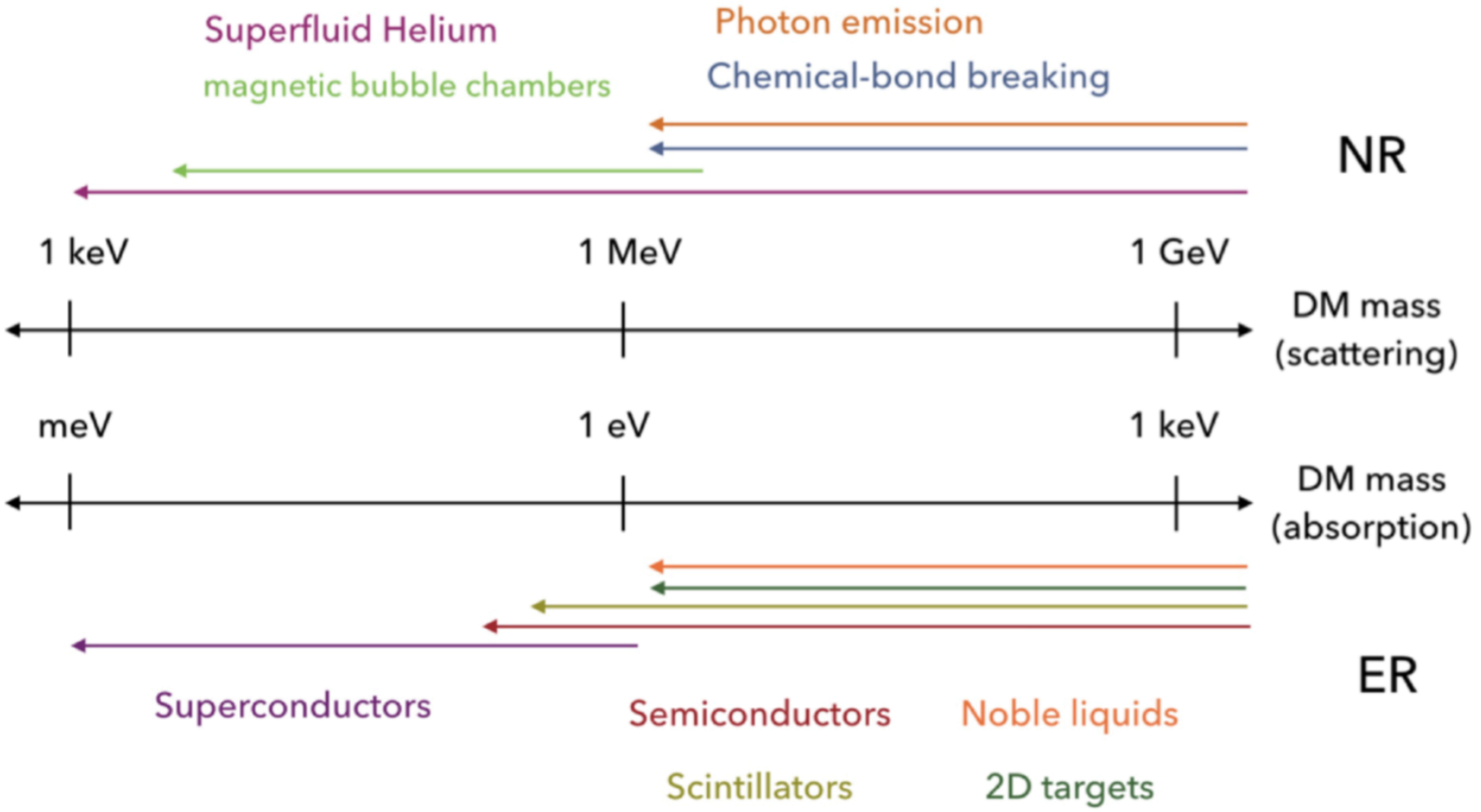
- May be helpful in solving some difficulties of the CDM paradigm, *N-body simulations have difficulties fitting the DM data at short scale*
  - Most famous: Core-cusp problem → Current simulations predict too-sharp of mass density profile in DM halo
- Dark photon → new, tuneable self-interaction for DM
- Caveat: debate over the influence of baryonic feedback





Detection strategies, sub-GeV DM

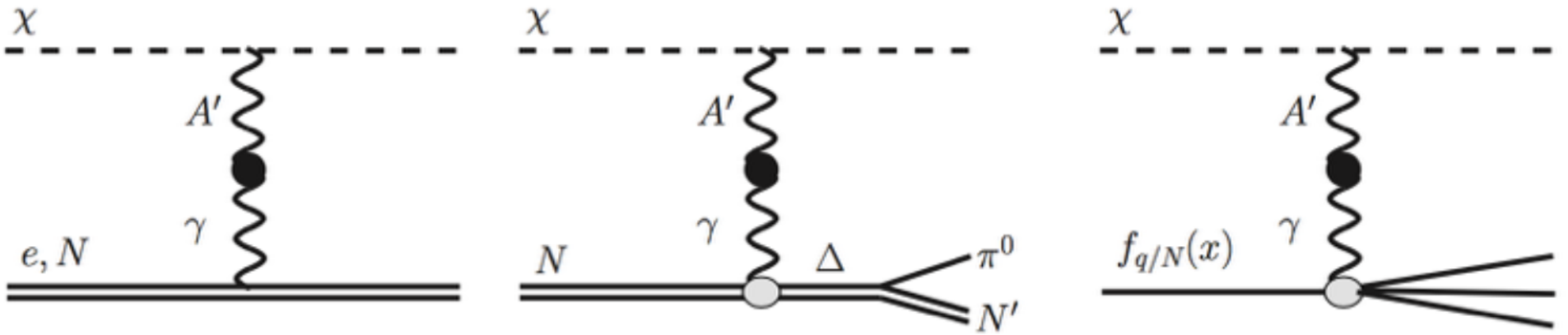
- Need for low-threshold experiments
  - DM-electron scattering
  - DM- low-Z elastic nucleus interactions
  - Bremsstrahlung in inelastic DM-nucleus scattering
- DAMIC, SENSEI, UA',NICE, SuperCDMS,NEWS



From arXiv:1707.04591

Beam dump and scattering -- detection

- Dark matter travel through the shielding
- Typically detector tens or hundreds of meter away



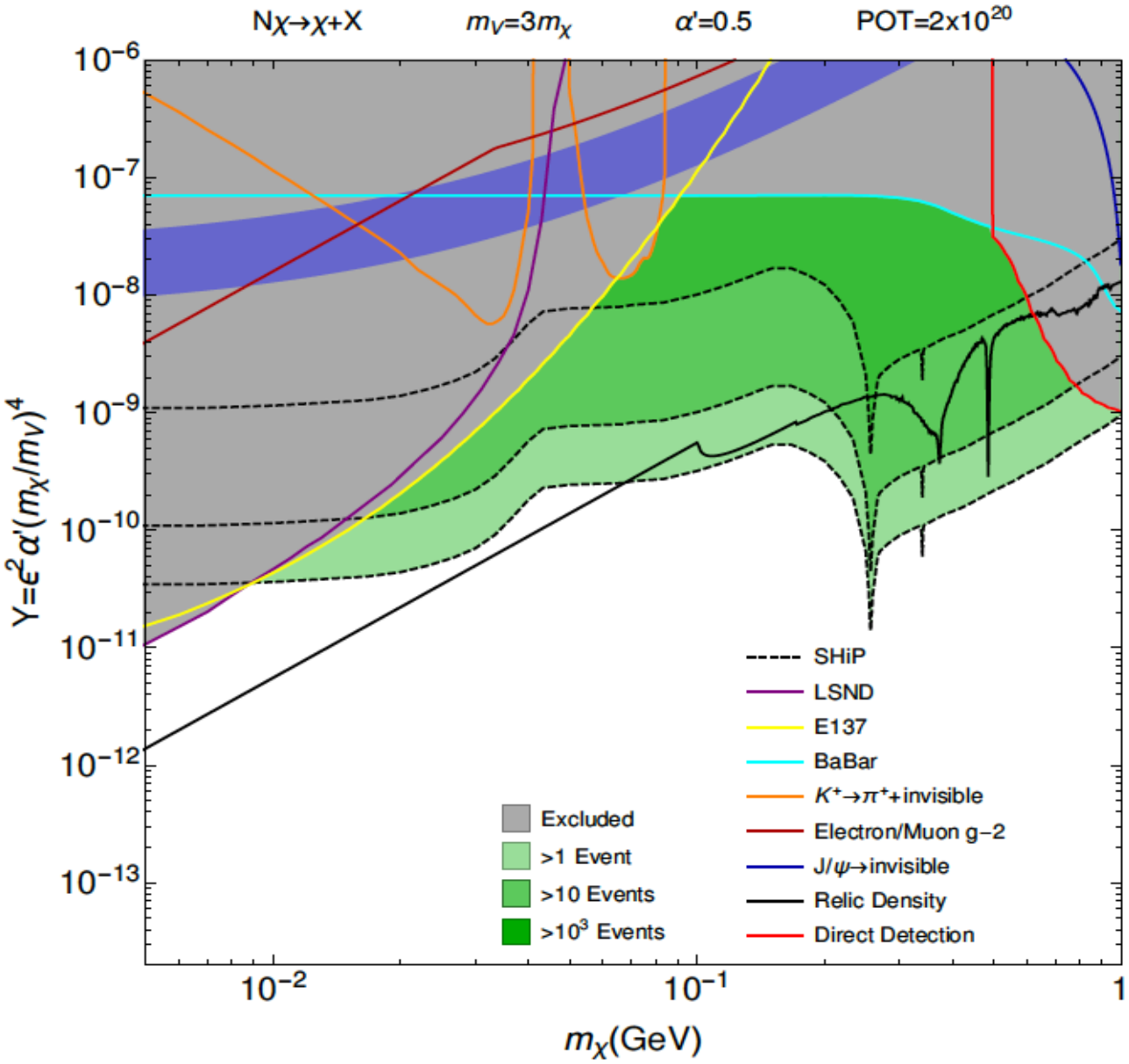
Elastic NC nucleon or electron scattering

Inelastic NC neutral pion - like scattering

Deep Inelastic scattering

- Signature similar to neutrino neutral current interaction → possible to use existing neutrino experiments

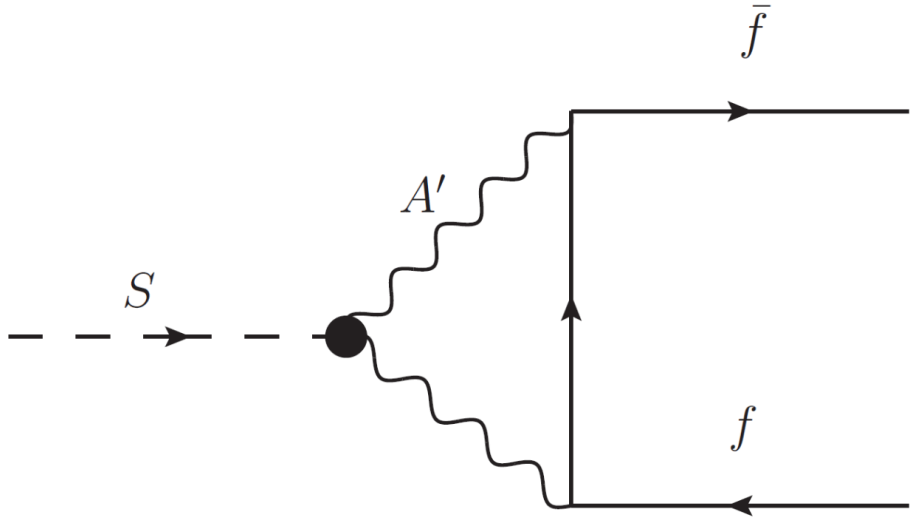
Example: reach of upcoming SHIP experiment



From deNiverville arXiv:1609.01770

Dark Higgs life-time

- Extremely long-lived
  - Two kinetic mixing insertion needed
  - Loop-factor
- Shorter life-time above di-muon threshold
- Hadronic uncertainties after di-pion threshold



$$\tau_S \propto 1\ \mathrm{s} \times \left(\frac{\alpha'}{\alpha}\right) \times \left(\frac{10^{-3}}{\varepsilon}\right)^4 \left(\frac{100\ \mathrm{MeV}}{M_S}\right) \left(\frac{M_{A'}}{100\ \mathrm{MeV}}\right)^2$$

- If kinematically available, it can decay instantaneously to DM or dark photon

Dark Higgs decay

- Long-lived, light particles
  → Signatures at beam dump experiments
- Dark Higgs produced through “dark higgstralhung”, in e.g. meson decay
- Decay to meson or lepton, depending on its mass