Dark matter signals at future high energy colliders

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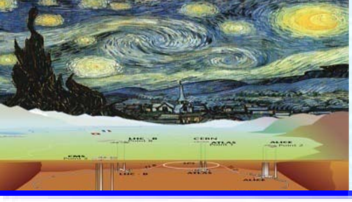
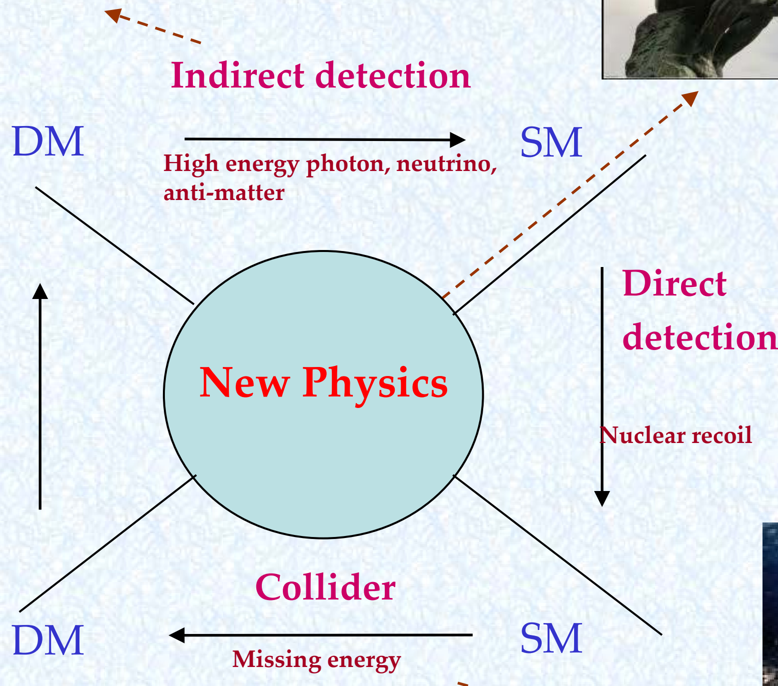
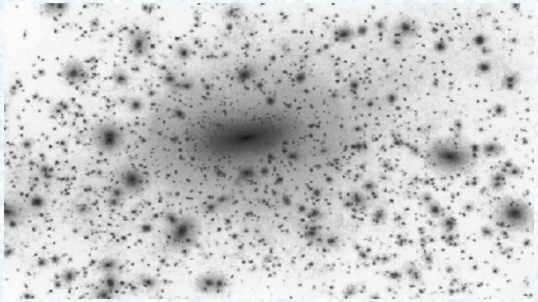
UCAS, Beijing, 2015.08.09

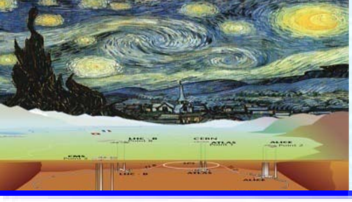


DM detections

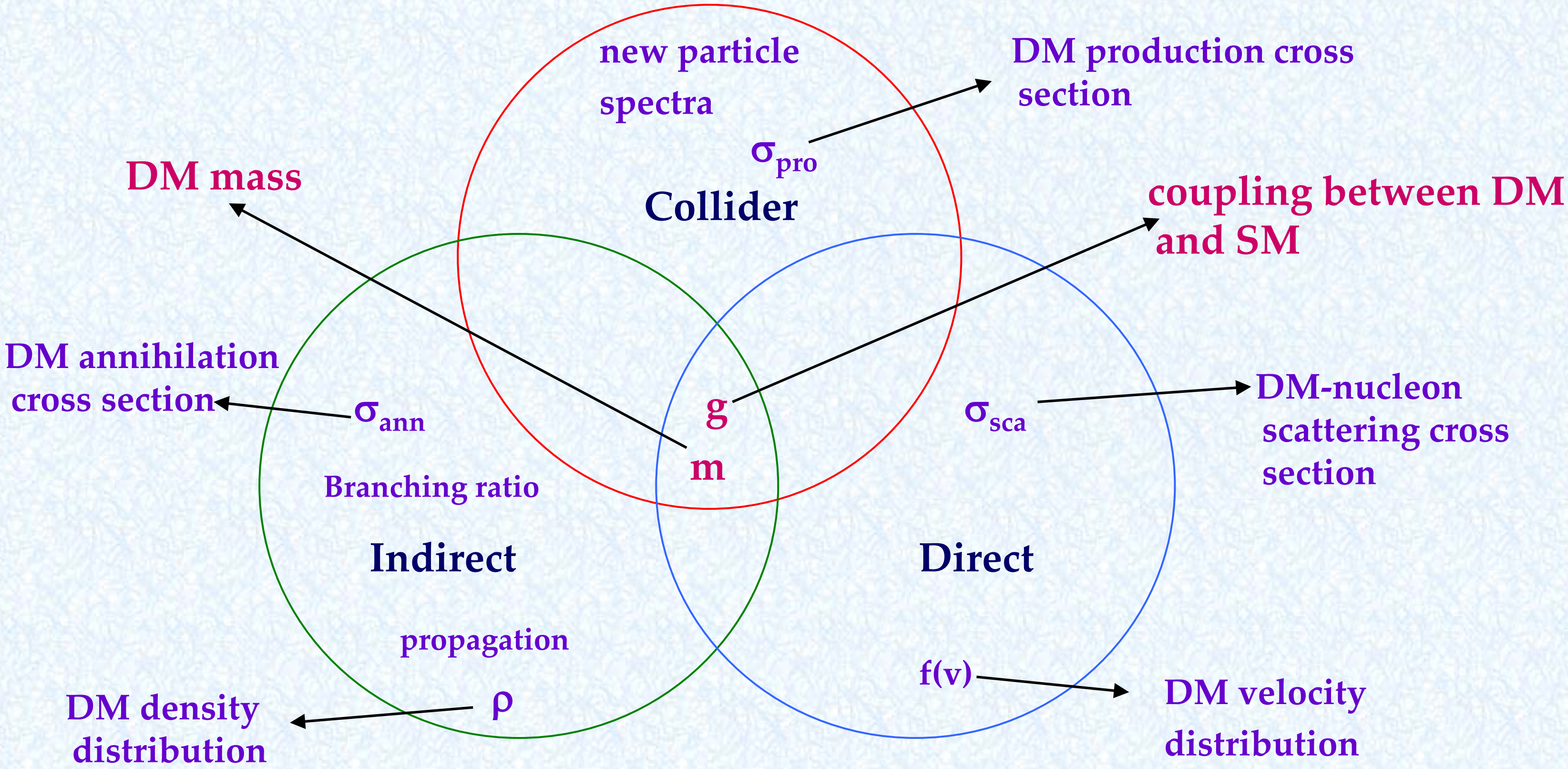




N-body simulation….

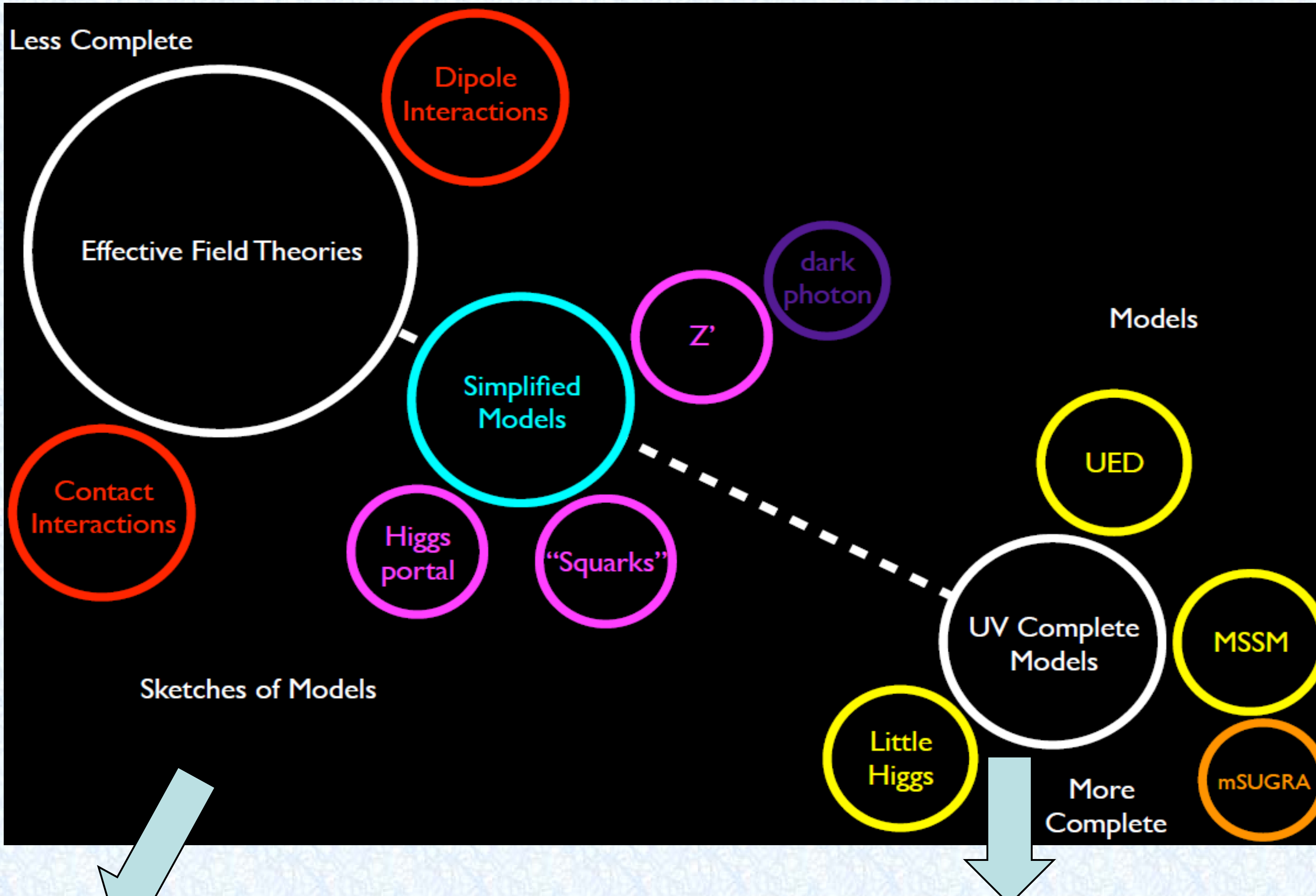


DM phenomenology



- Particle: DM-SM interaction, DM mass, spin, quantum numbers, symmetry…
- Cosmology: why observed relic density, cold or warm, distribution, relation to baryon, dark energy, structure formation…
- Ways:(1)Use available data to constrain known DM model
  (2)Build self-consistent model to explain the experiment results
  (3)Predict possible signals in the future DM detection experiments.

Models



From T. Tait' talk

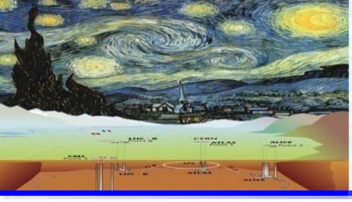
Mono-X

Direct production, "model-independent"

Multi final states +MET

Cascade decay, "model-dependent"

Other collider constraints

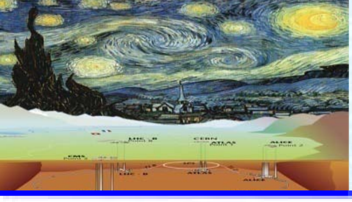


Search for DM at e^+e^- colliders

- Advantage: No large QCD background;
  precise beam energy; polarized beams;
  can precisely measure the mass, spin, and other quantum numbers of DM

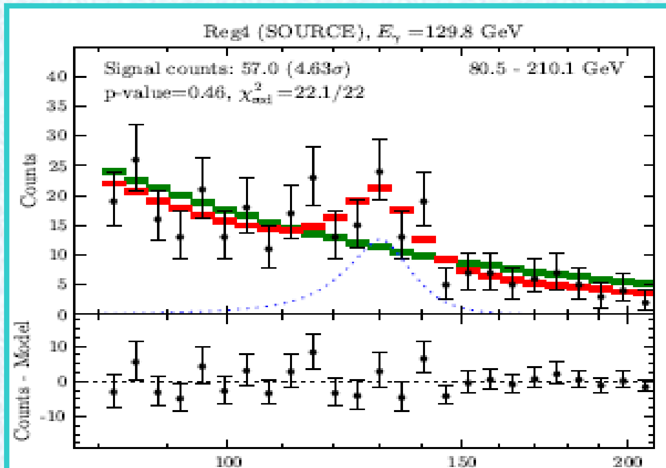
- Search for interactions between the DM and electrons/EW gauge bosons

- Disadvantage: Low CM energy;
  difficult to directly detect heavy DM

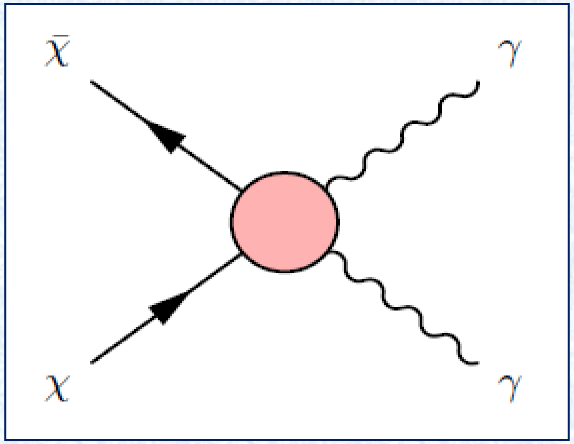


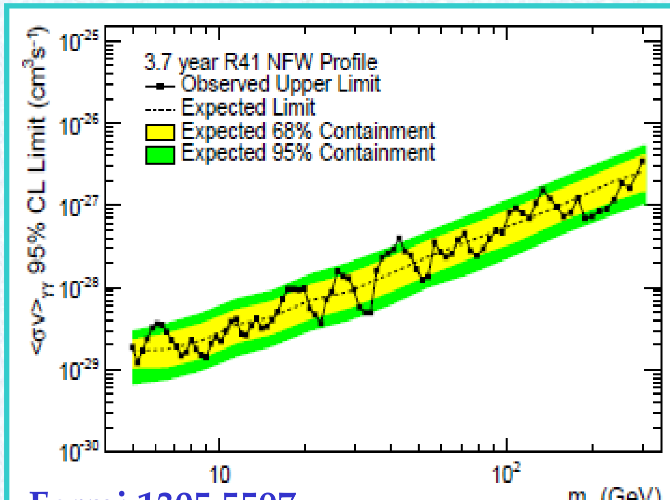
Gamma-ray line and mono-photon

- Gamma-ray line is a critical evidence of DM annihilation/decay
- ~3-4 σ signals reported by some groups
- Not confirmed by the Fermi-LAT collaboration; possible instrumental effect
- Search for corresponding mono-photon signals at future e^+e^- colliders

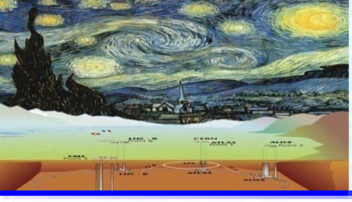


Weniger, 1204.2797





Fermi 1305.5597



Effective operators

- **Dirac Fermion DM**

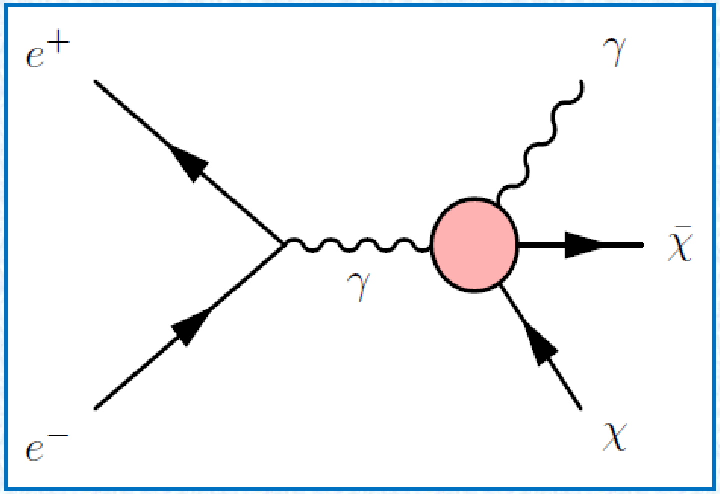
$$\mathcal{O}_F = \frac{1}{\Lambda^3}\bar{\chi} i\gamma_5 \chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\langle \sigma_{\rm ann} v\rangle_{\chi\bar{\chi}\to 2\gamma} \simeq \frac{4m_\chi^4}{\pi\Lambda^6} = 10^{-27}\ {\rm cm}^3\ {\rm s}^{-1}\left(\frac{m_\chi}{130\ {\rm GeV}}\right)^4\left(\frac{1272\ {\rm GeV}}{\Lambda}\right)^6$$

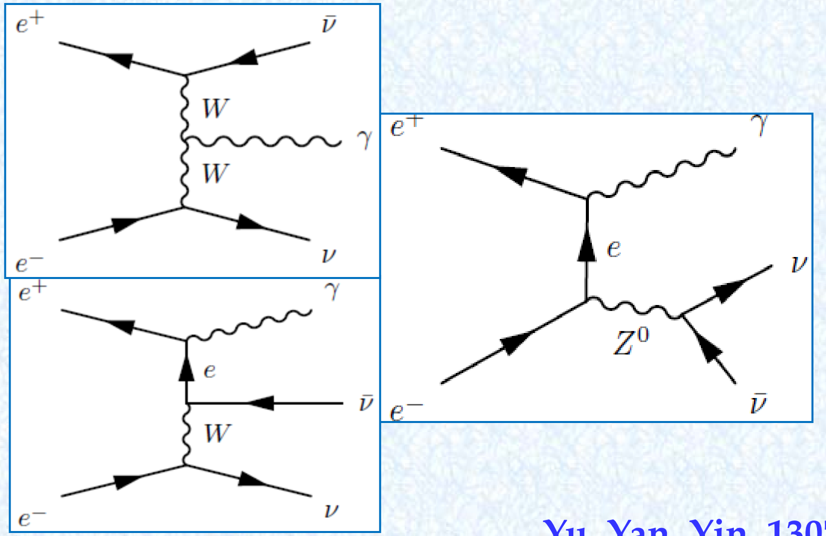
Mass scale for ~100 GeV and a detectable cross section is ~TeV

Similar for scalar DM

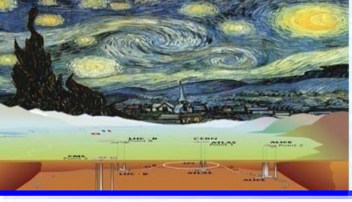
- **Signature: mono-photon**



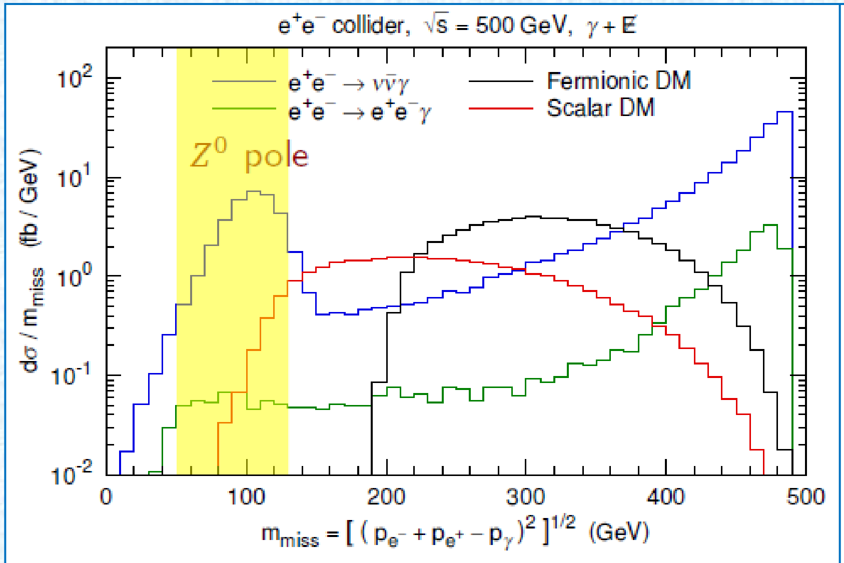
- **Backgrounds: mainly νν̄γ**

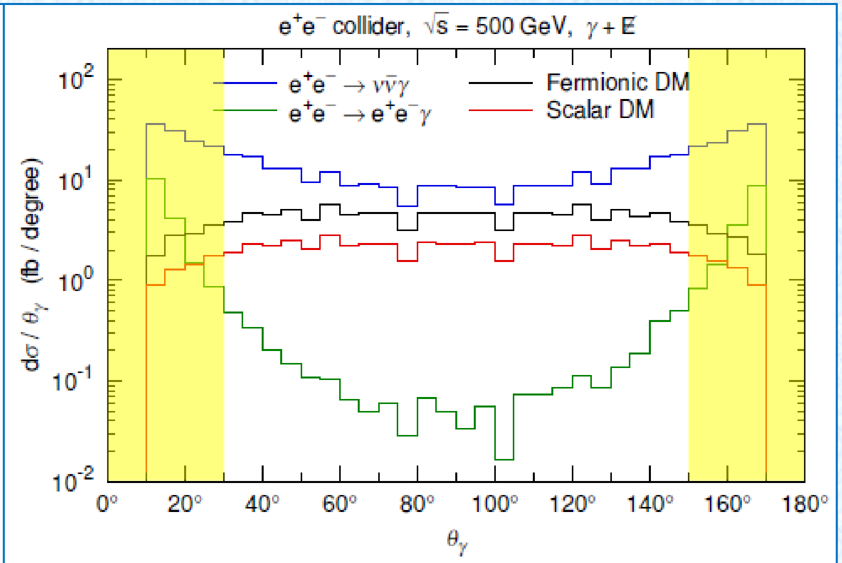


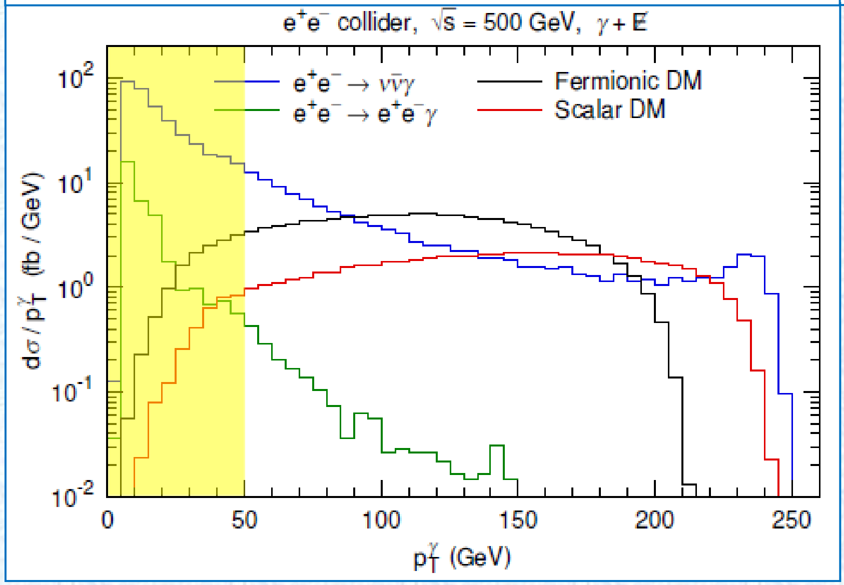
Yu, Yan, Yin, 1307.5740



Kinematical cuts



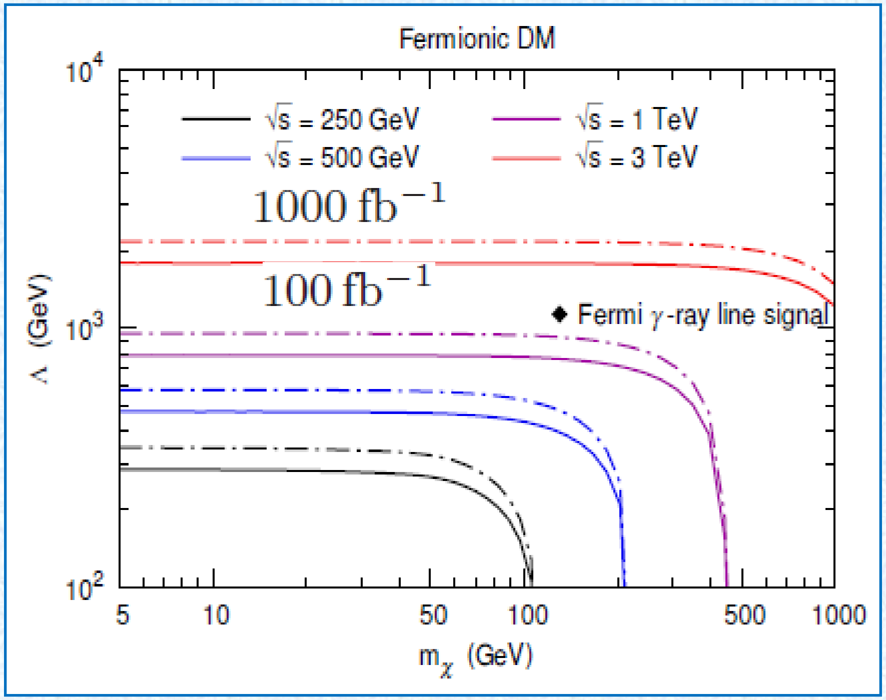


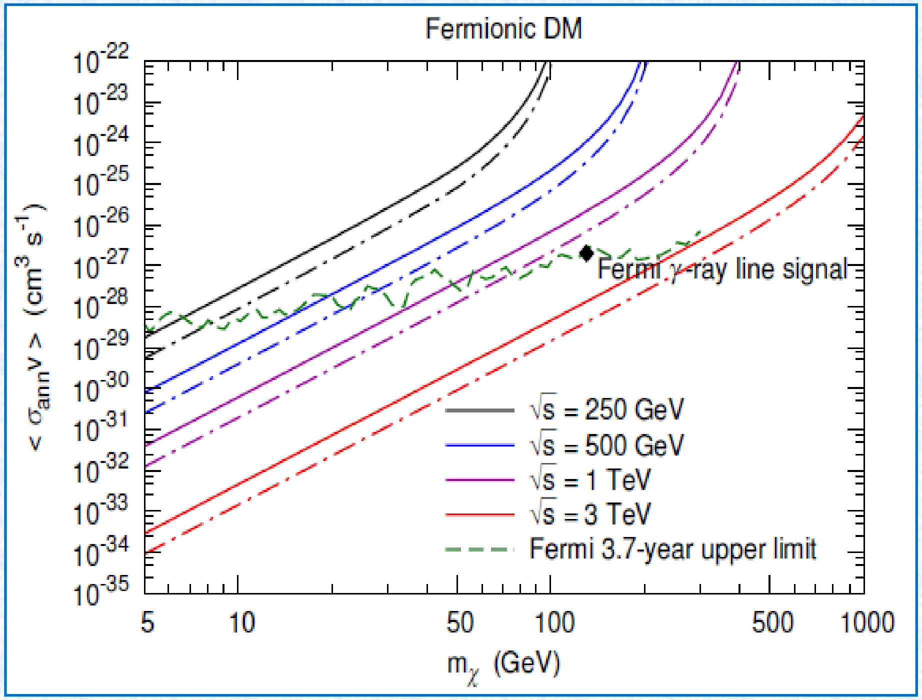


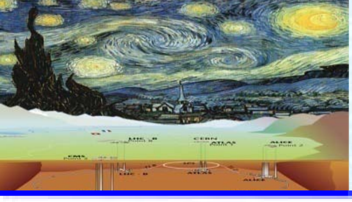
- **Photons in the signal are hard and not be close to beams**
- **Reject 50< m_{mis}<130 GeV**
- **Require 30^o< θ_γ <150^o**
- **Require p_γ > sqrt(s)/10**

Sensitivities

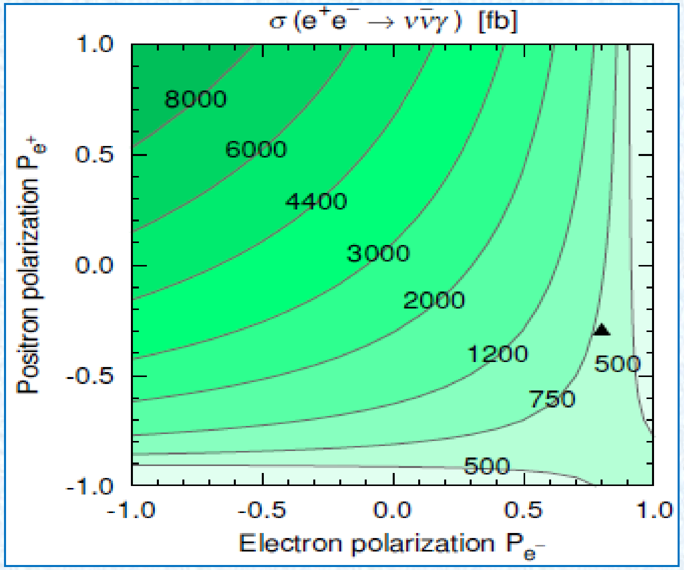
- Consider possible e^+e^- colliders with CM energies of 250, 500, 1000 and 3000 GeV
- 3 σ reaches for mass scale and annihilation cross section
- Require large luminosities

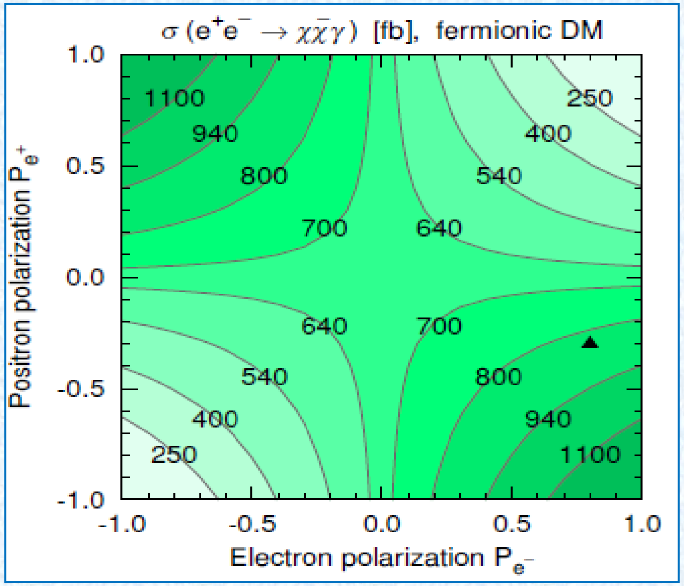




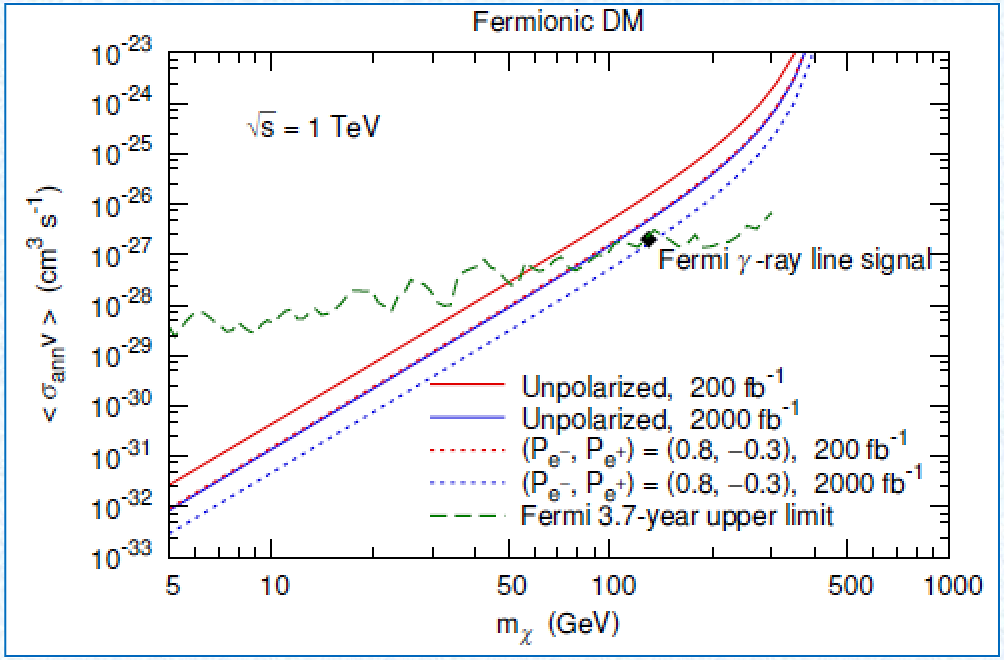


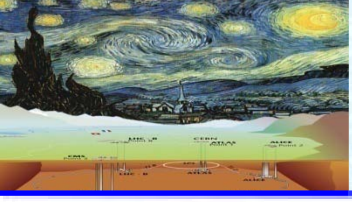
Beam polarization





- Polarized beams would be available at the future e^+e^- collider
- e.g at the ILC (P_{e-}, P_{e+})~(0.8,-0.3)
- Main EW backgrounds are induced by chiral interactions ; can be reduced by polarized beams
- Using polarized beams ~ increasing luminosity by a factor of one order



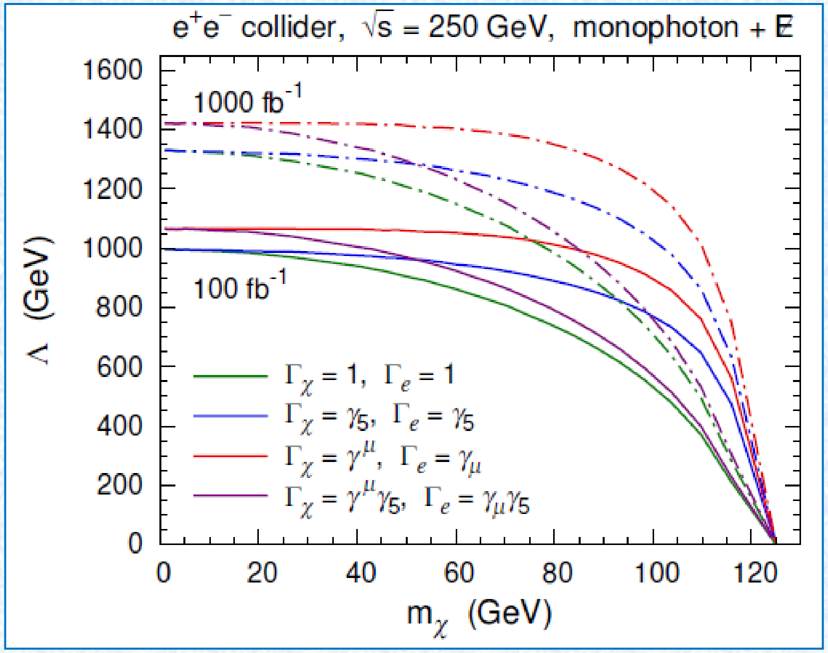


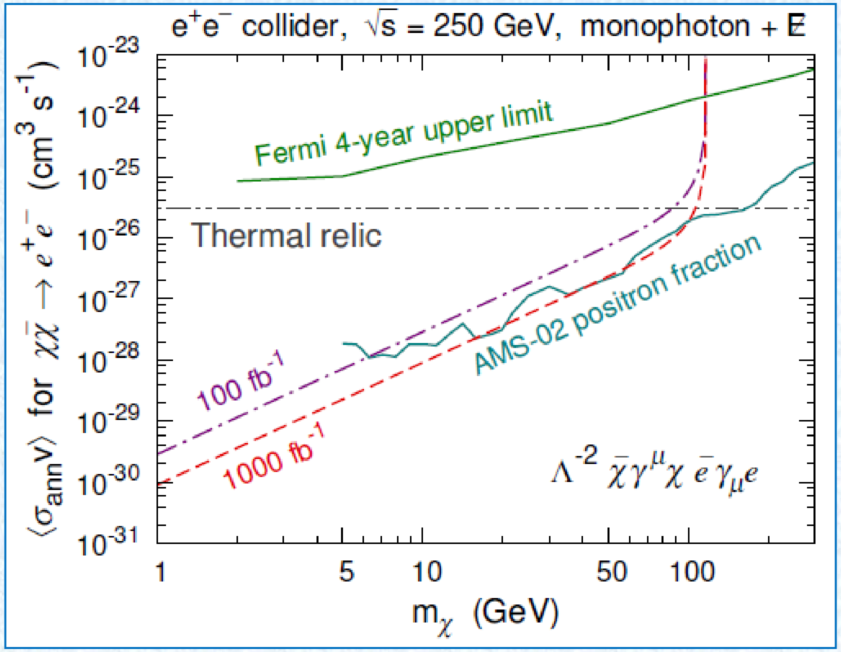
Results for DM interactions with electron/positron

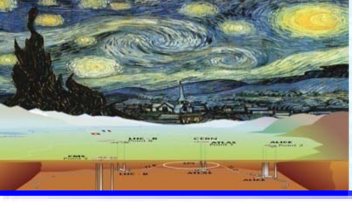
- Consider operators

$$\mathcal{O}_e = \frac{1}{\Lambda^2}\bar{\chi}\Gamma_\chi\chi\bar{e}\Gamma_e e \quad \Gamma_\chi, \Gamma_e \in \{1, \gamma_5, \gamma^\mu, \gamma^\mu\gamma_5, \sigma^{\mu\nu}\}$$

photon is emitted from initial state radiation



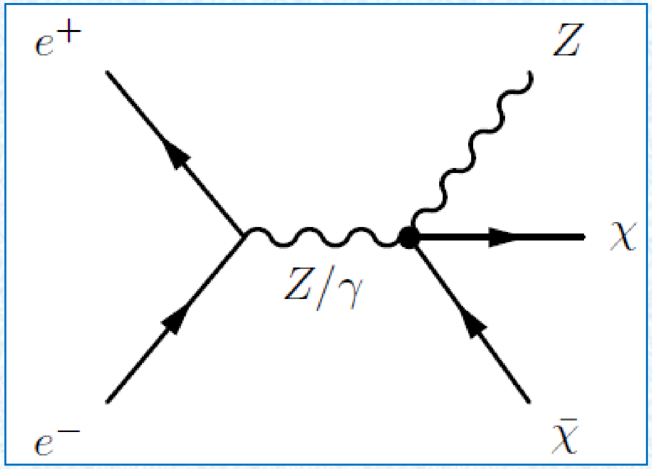




Mono-Z signals

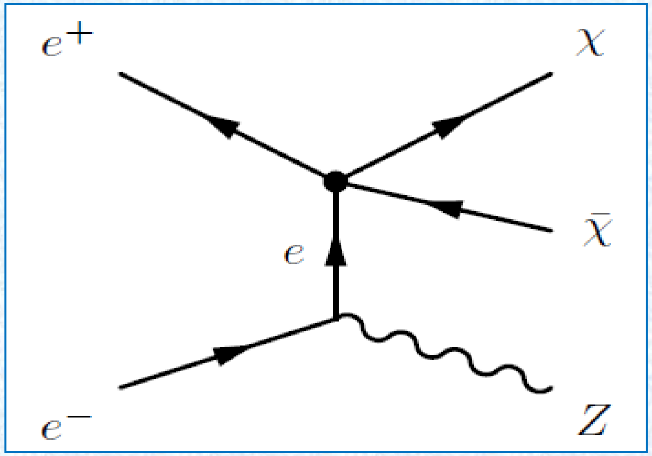
- DM can interact with both the photon and Z boson
- Consider effective operators

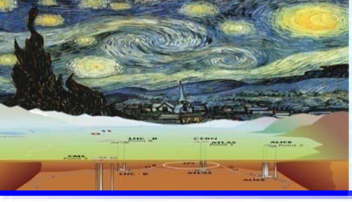
$$\mathcal{O}_{\mathrm{F1}} = \frac{1}{\Lambda_1^3}\bar{\chi}\chi B_{\mu\nu}B^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}\chi W^a_{\mu\nu}W^{a\mu\nu}$$
$$\supset \bar{\chi}\chi(G_{ZZ}Z_{\mu\nu}Z^{\mu\nu} + G_{AZ}A_{\mu\nu}Z^{\mu\nu})$$
$$\mathcal{O}_{\mathrm{F2}} = \frac{1}{\Lambda_1^3}\bar{\chi}i\gamma_5\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \frac{1}{\Lambda_2^3}\bar{\chi}i\gamma_5\chi W^a_{\mu\nu}\tilde{W}^{a\mu\nu}$$
$$\supset \bar{\chi}i\gamma_5\chi(G_{ZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu} + G_{AZ}A_{\mu\nu}\tilde{Z}^{\mu\nu})$$
$$\mathcal{O}_{\mathrm{FH}} = \frac{1}{\Lambda^3}\bar{\chi}\chi(D_\mu H)^\dagger D_\mu H \to \frac{m_Z^2}{2\Lambda^3}\bar{\chi}\chi Z_\mu Z^\mu$$



- Z boson can also com from initial state radiation

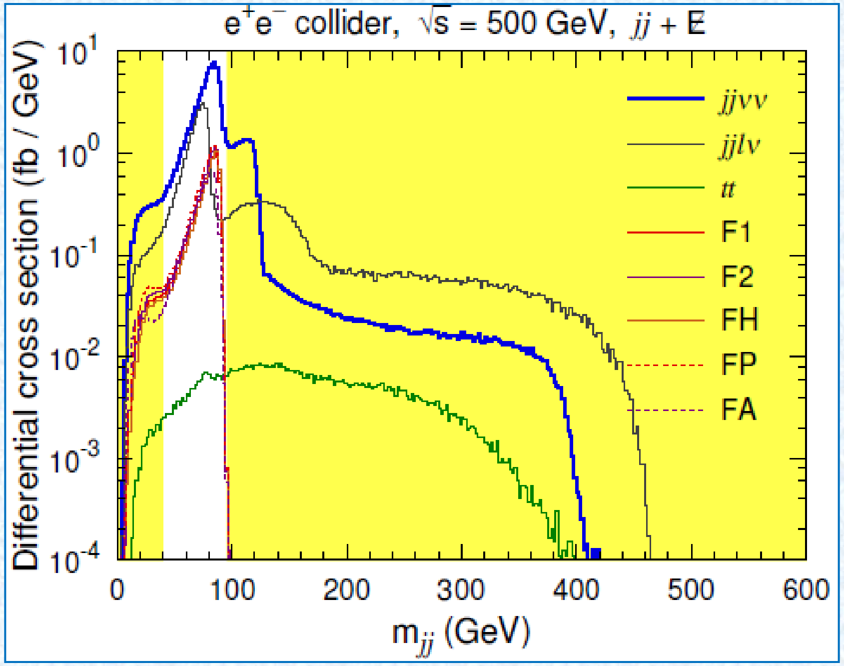
$$\mathcal{O}_{\mathrm{FP}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_5\chi\bar{e}\gamma_5 e,$$
$$\mathcal{O}_{\mathrm{FA}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma^\mu\gamma_5\chi\bar{e}\gamma_\mu\gamma_5 e$$

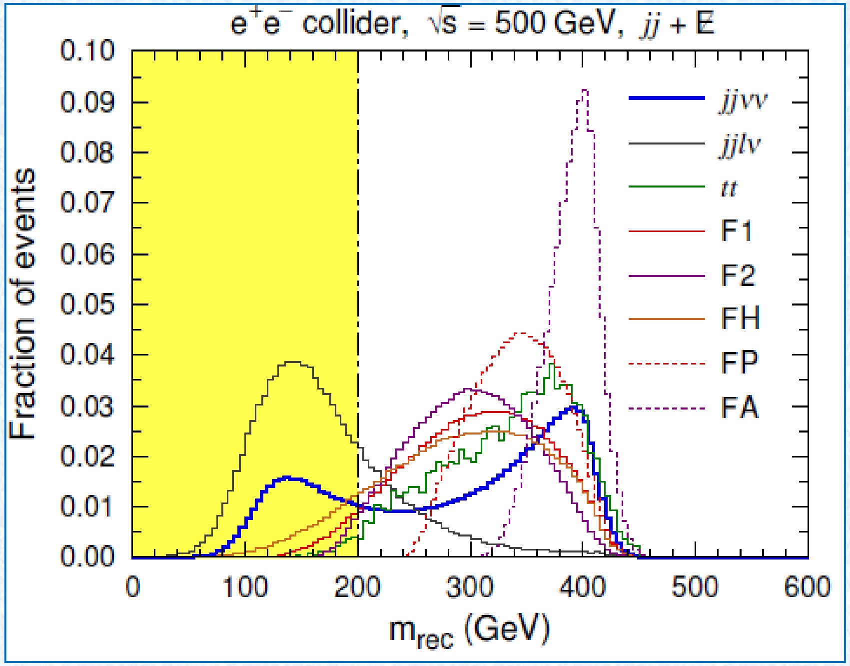


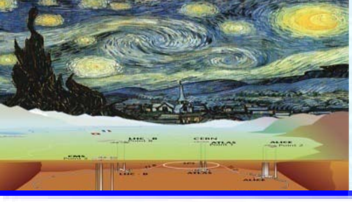


Reconstruct Z->jj

- Small QCD background at e^+e^- colliders ; reconstruct Z boson via hadronic channel
- Main background: jjνν, jjlν, tt
- Require two jets satisfying $40 < m_{jj} < 95$ GeV
- Reconstruct recoil mass $m_{\rm rec} = \sqrt{(p_{e^+} + p_{e^-} - p_{j_1} - p_{j_2})^2}$
- Similar for Z->ll

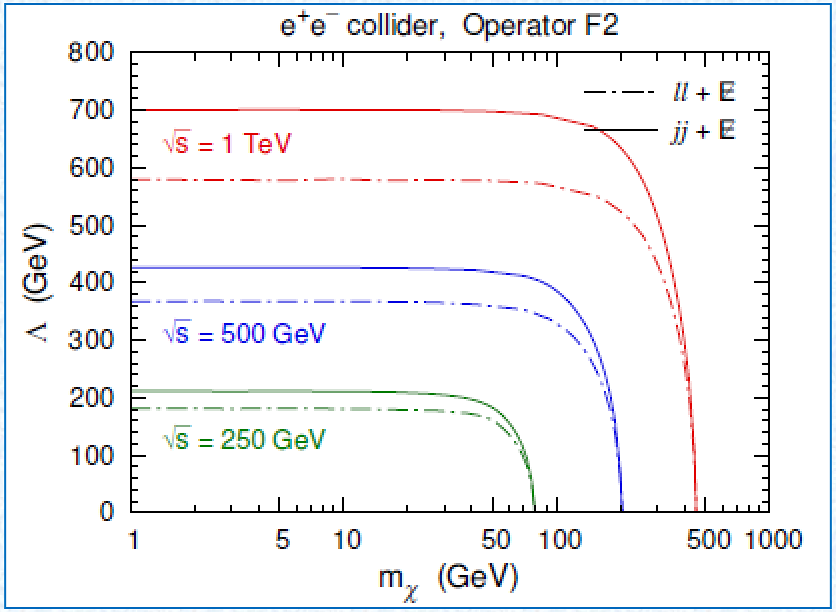


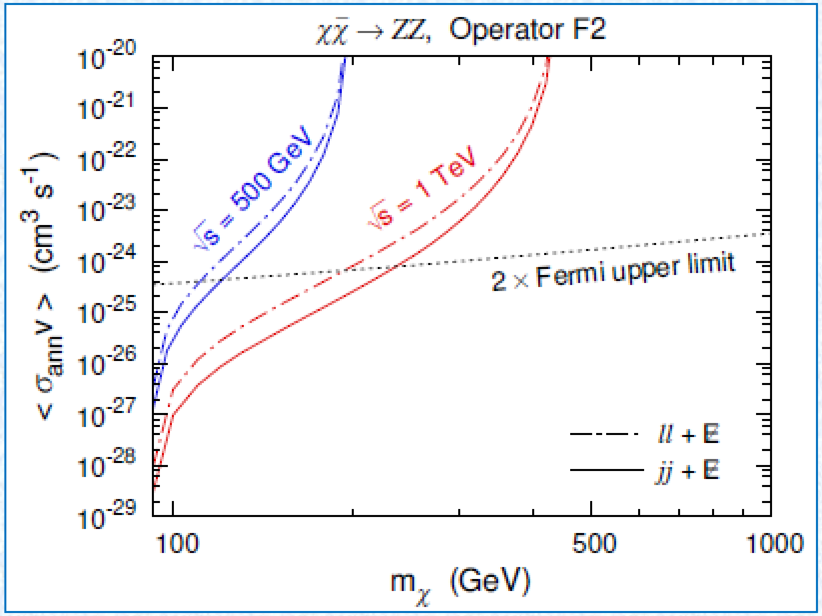




Reaches

- 3 σ reaches for interactions between the DM and gauge bosons
- Assume: 1000 fb^{-1} of data; $\Lambda=\Lambda_1=\Lambda_2$
- Compare with the limit from Fermi observations of dwarf galaxies





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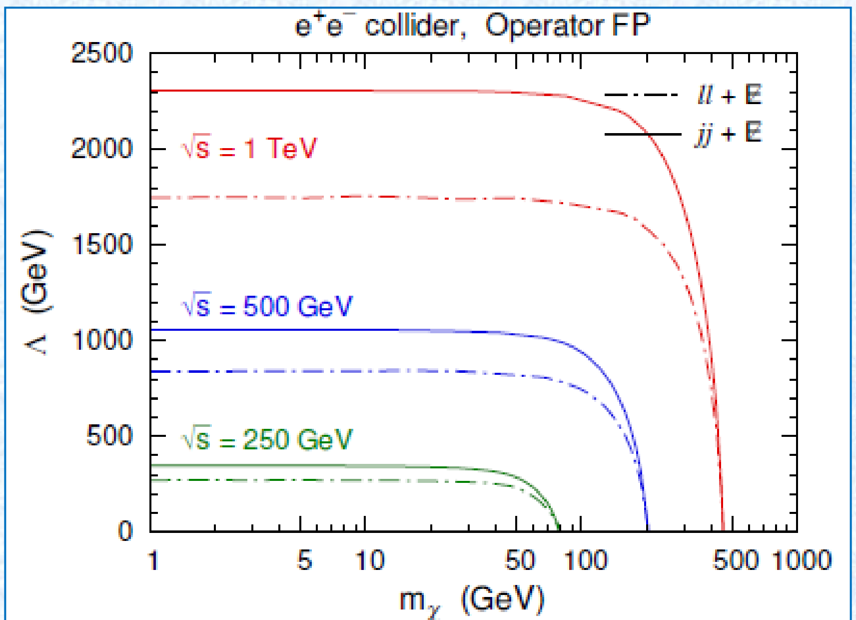
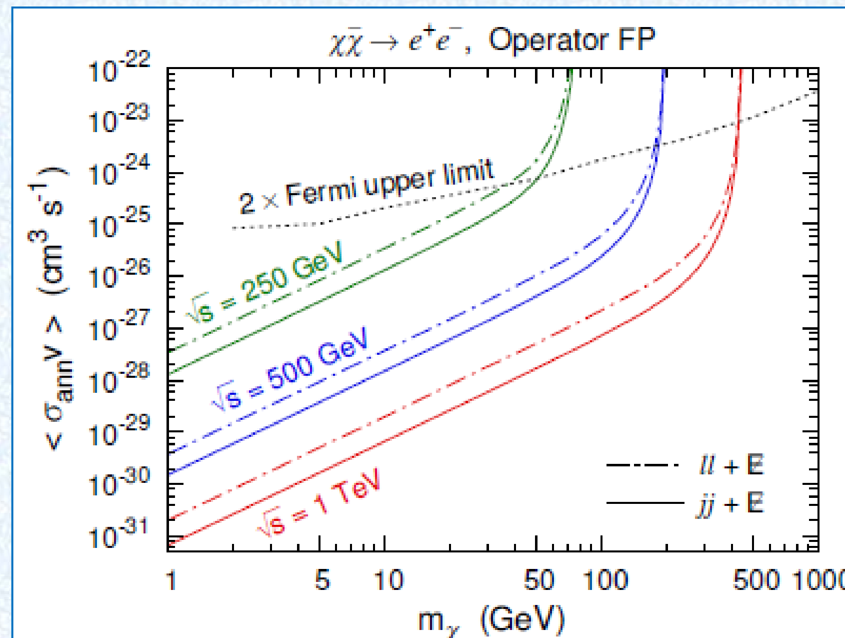
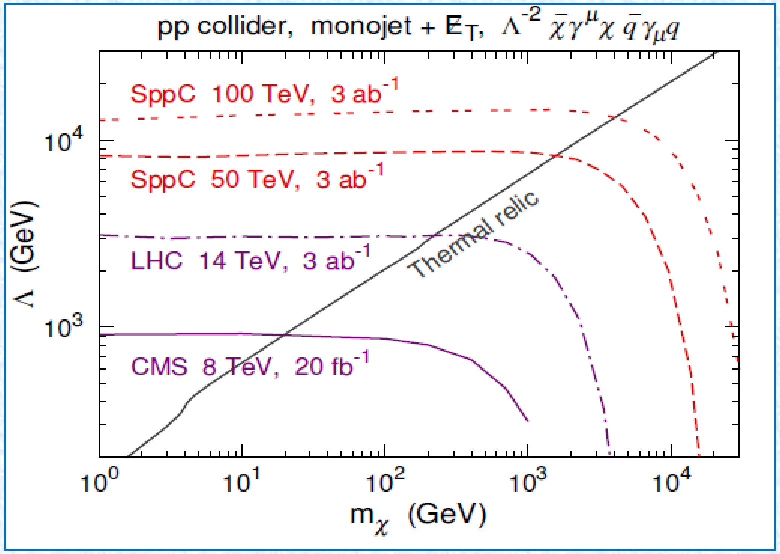
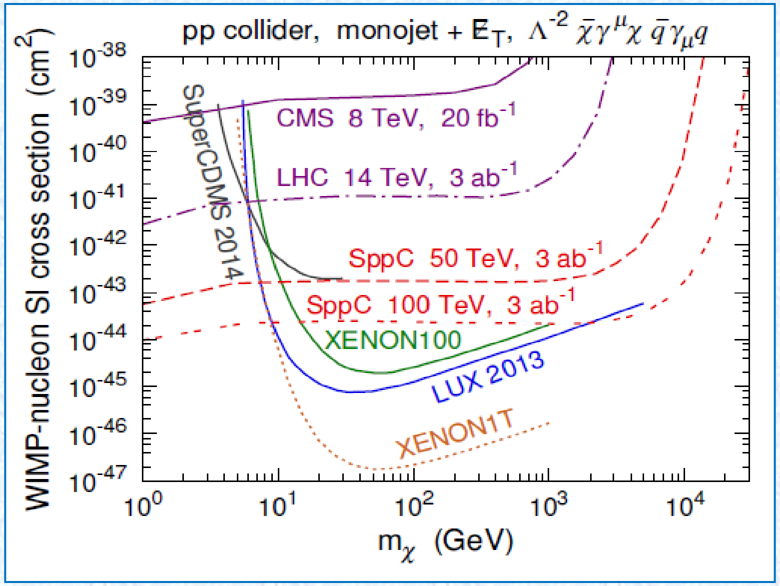


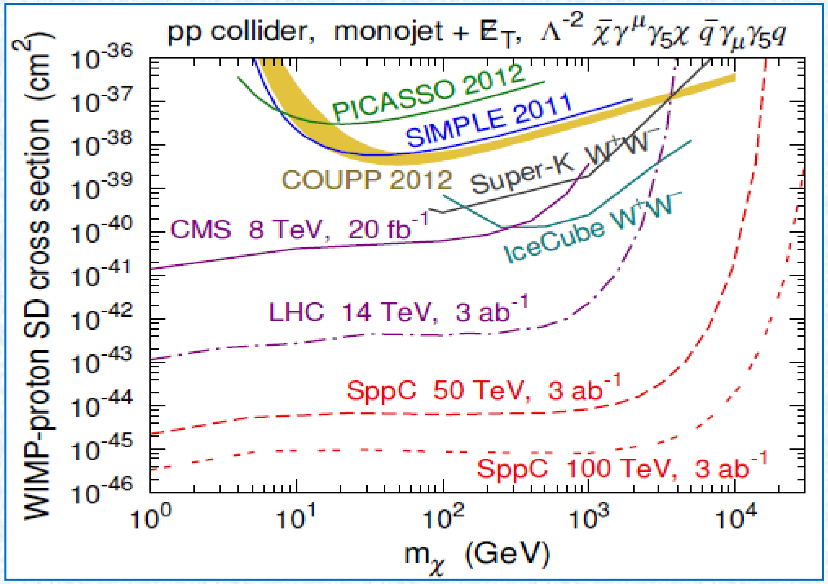


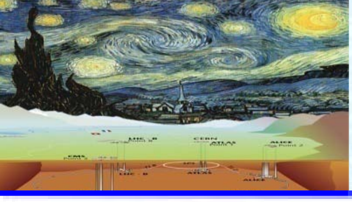
Search for DM at pp colliders



- Advantage: large energy and luminosity for DM production
- Disadvantage: large backgrounds
- Reaches for effective operator
- Better for light DM and spin-dependent interactions

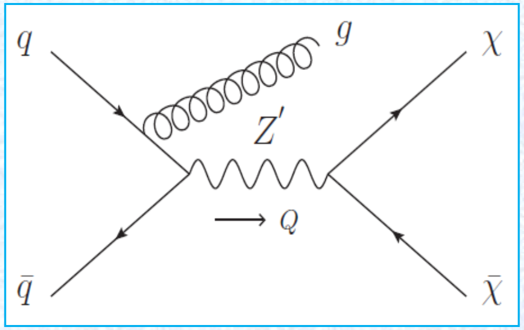






Breakdown of EFT

- Assume a Z' model



- EFT can not describe resonance effect
- Unitarily bound; small width limit; t-channel mediator….

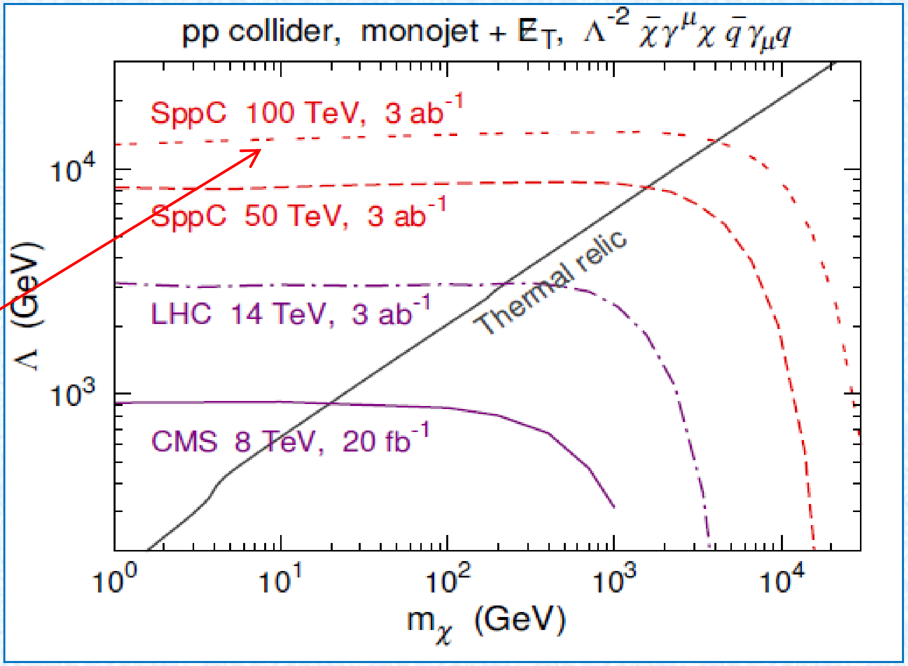
- EFT is valid for heavy mediator if $Q \ll m_{med}$

$$\frac{g_q\, g_\chi}{Q^2 - m^2_{\rm med}} \approx -\frac{g_q\, g_\chi}{m^2_{\rm med}} \left(1 + \frac{Q^2}{m^2_{\rm med}} + \mathcal{O}\left(\frac{Q^4}{m^4_{\rm med}}\right)\right)$$

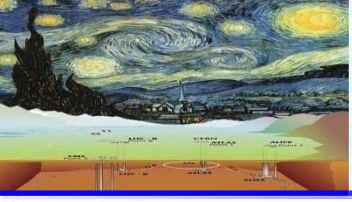
$$\Lambda \equiv \frac{m_{\rm med}}{\sqrt{g_q\, g_\chi}}$$

- If $Q \gg m_{med}$, EFT limit is too strong
  In this case, the mediator can be directly produced

$$\frac{g_q\, g_\chi}{Q^2 - m^2_{\rm med}} \approx \frac{g_q\, g_\chi}{Q^2} \left(1 + \frac{m^2_{\rm med}}{Q^2} + \mathcal{O}\left(\frac{m^4_{\rm med}}{Q^4}\right)\right)$$



e.g. Buchmueller at al, 1308.6799



From EFT to simplified model

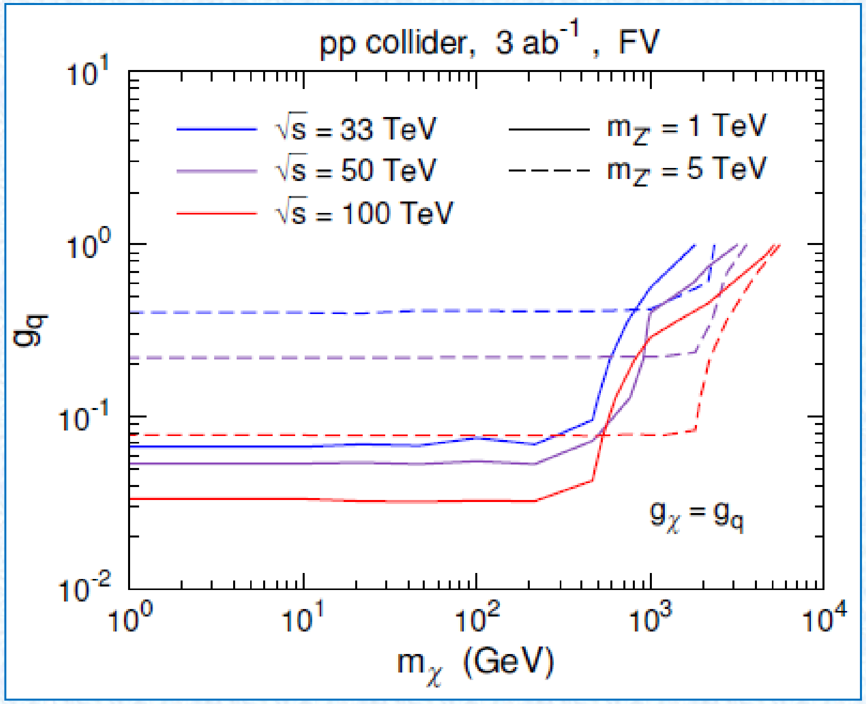
- (minimal) simplified models including Z′

$$\mathcal{L}_{\rm FV} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \chi$$

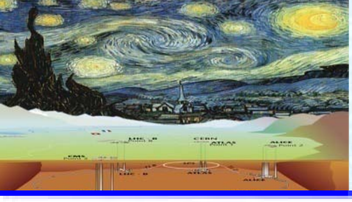
$$\mathcal{L}_{\rm FA} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu \gamma_5 q + g_\chi Z'_\mu \bar{\chi}\gamma^\mu \gamma_5 \chi$$

$$\mathcal{L}_{\rm SV} = \sum_q g_q Z'_\mu \bar{q}\gamma^\mu q + i g_\chi Z'_\mu [\chi^* \partial^\mu \chi - (\partial^\mu \chi^*)\chi]$$

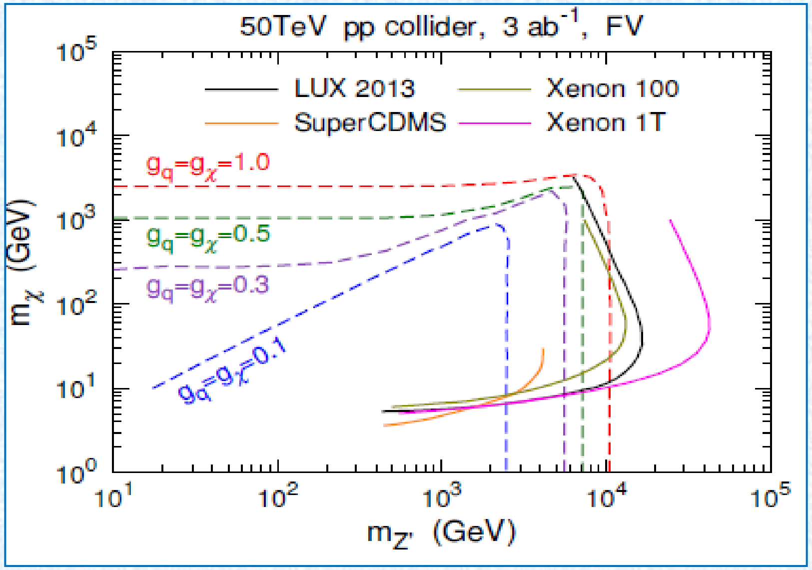
- Require $\Gamma_{Z'} < m_{Z'}$
- For simplicity, assume $g_q = g_\chi$
  Note that g_q can be limited by di-jet resonance searches.
  In the resonance region, Z′ width would affect the DM production rate

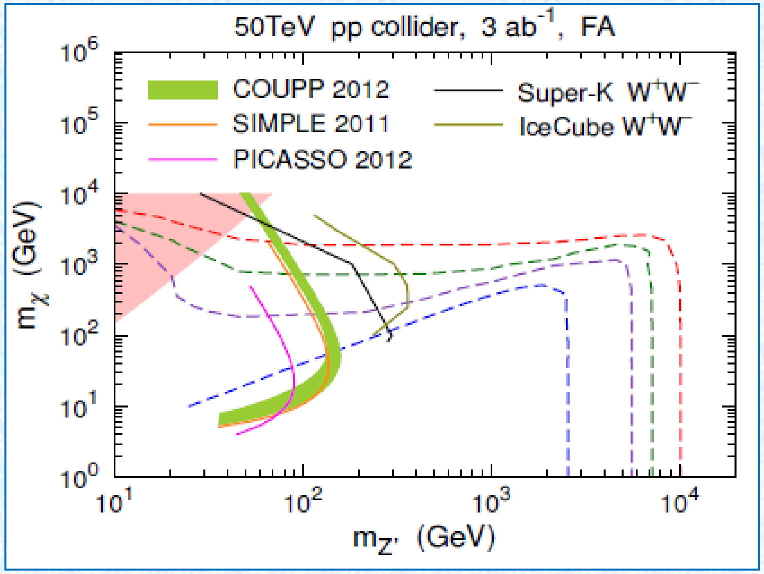


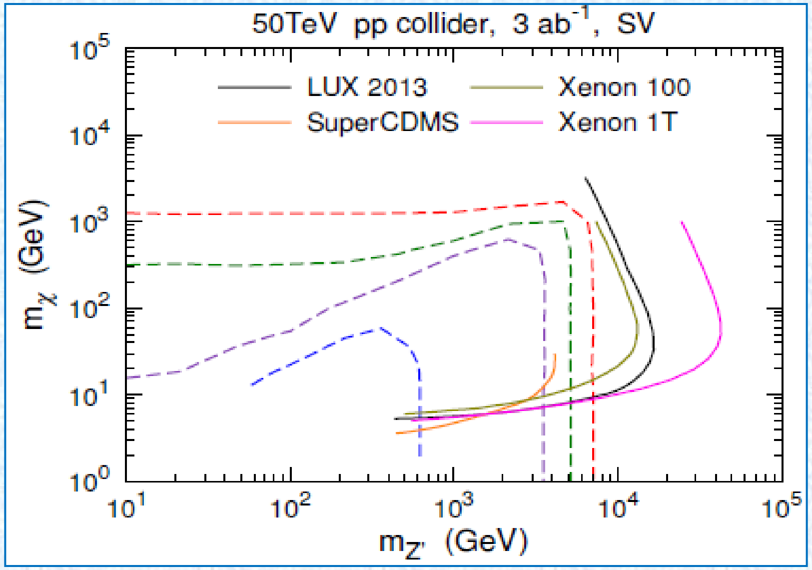
Xiang, Bi, Yin, Yu, 1503.02931



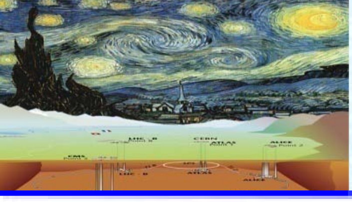
Sensitivities of SppC



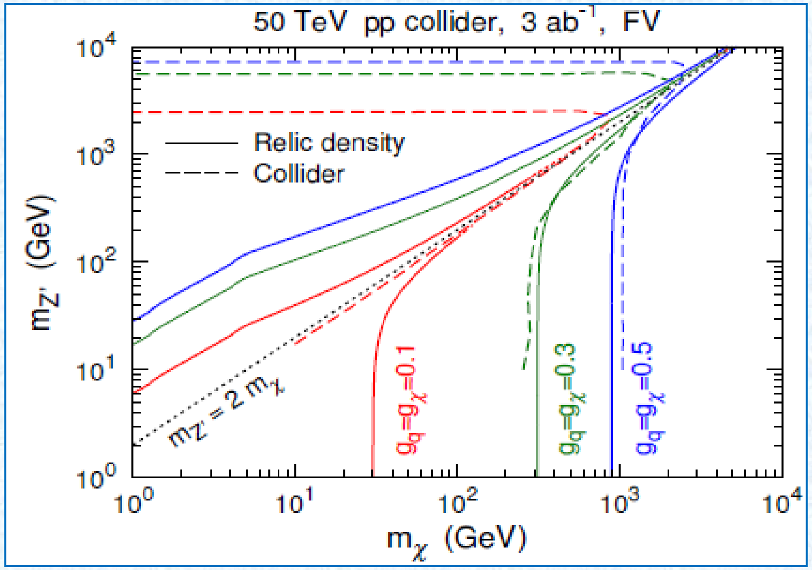


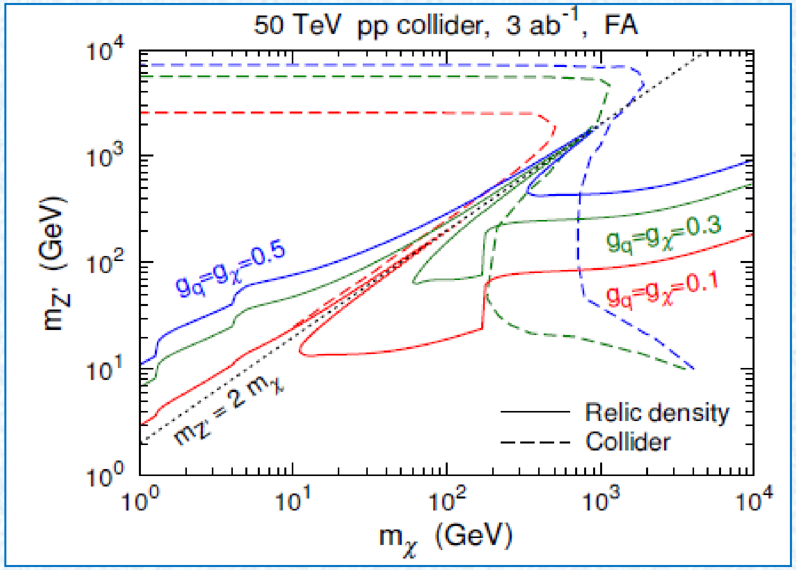


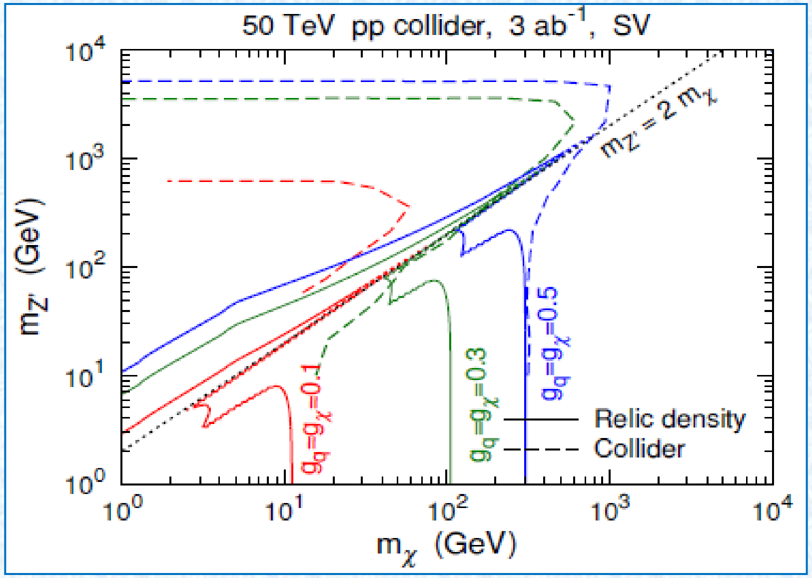
- Comparison with limits from direct detection
- Direct detection limits are derived for g=0.5



Collider reaches and relic density



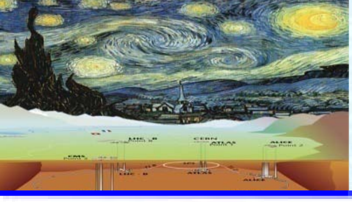




- Comparison with the parameter space given correct relict density
- Consider $\chi\chi$->ff and $\chi\chi$->Z′Z′

Summary

- Difficult to directly detect DM signals at e^+e^- colliders
- Collider has strong capability to search for the light DM
- EFT is not valid at future hadron colliders; simplified models should be taken into account
- Complementary to direct and indirect detections



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Thank you !