Muons:
Supersymmetry and Other Models and Links to Cosmology

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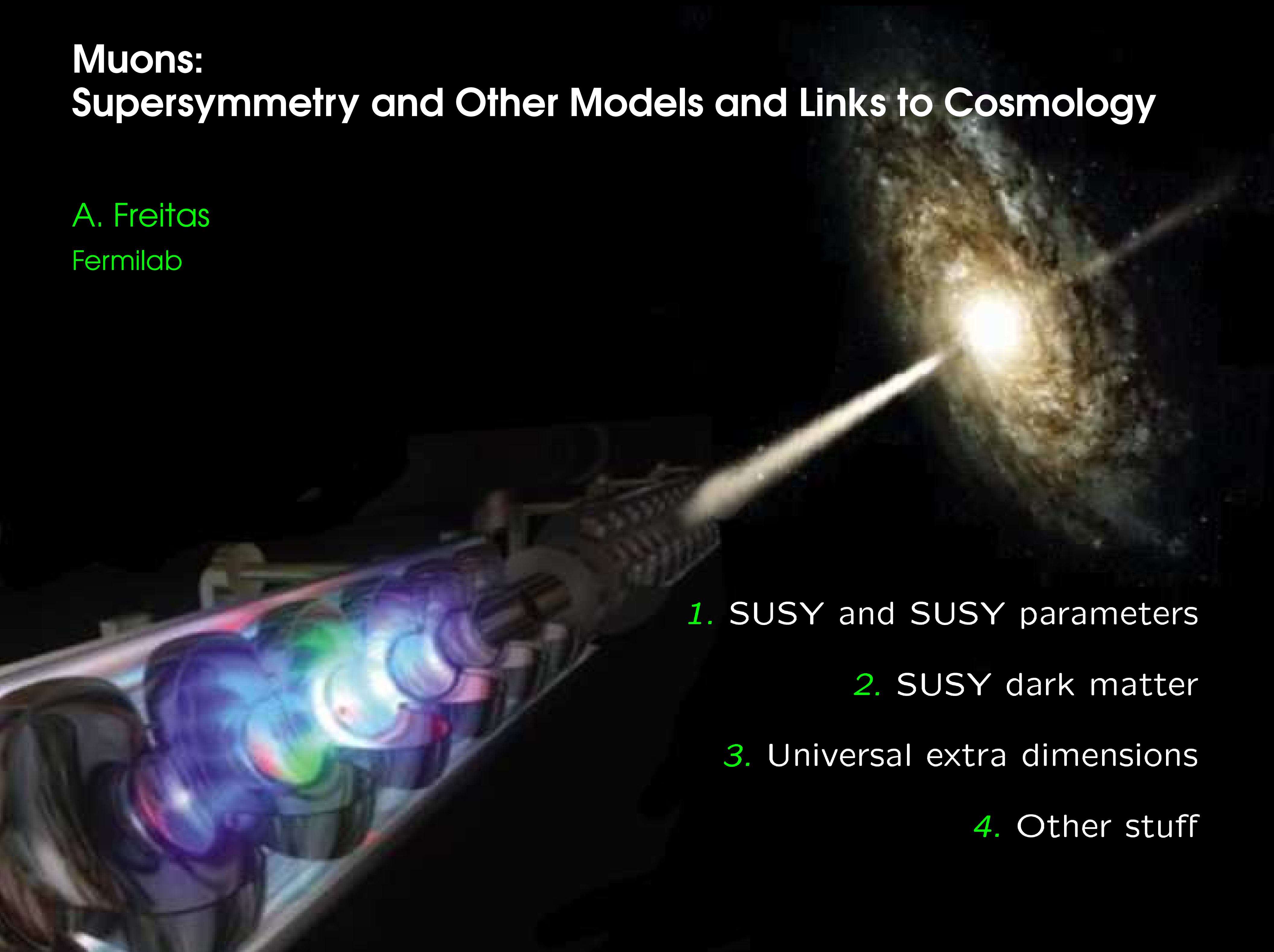
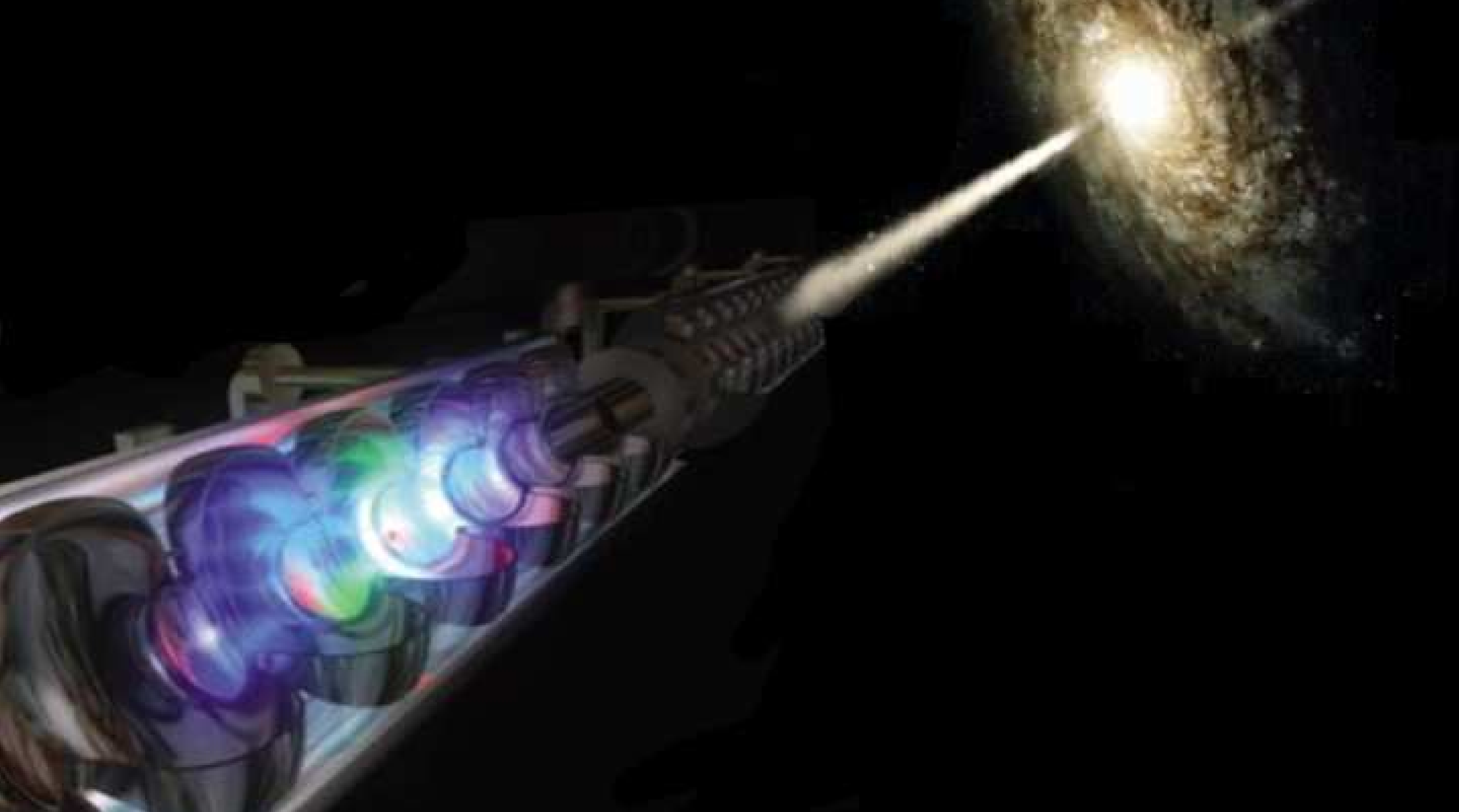
Fermilab



1. SUSY and SUSY parameters
2. SUSY dark matter
3. Universal extra dimensions
4. Other stuff

SUSY and SUSY Parameters

- Mass measurements
- Sparticle couplings



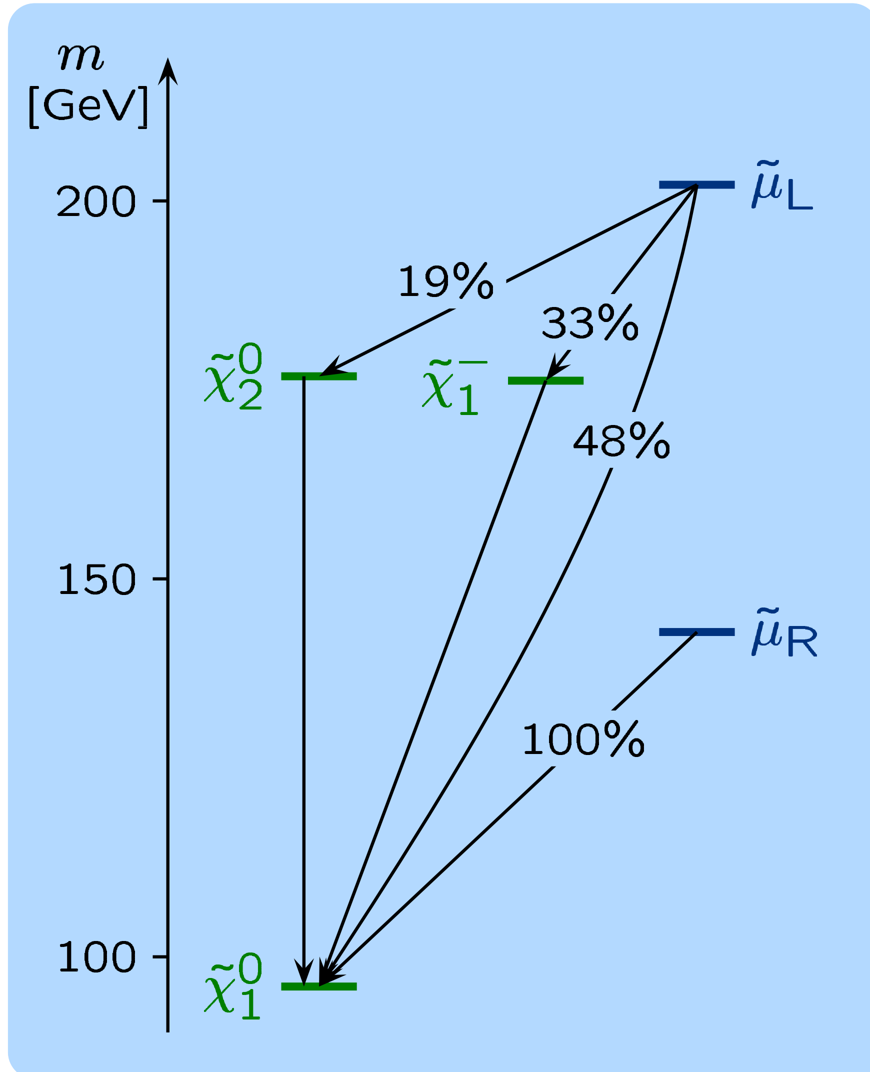
Mass measurements

Smuons mostly decay into muons and neutralinos (or gravitinos)
Use different decay modes to disentangle $\tilde{l}_R, \tilde{l}_L$

$$\tilde{\mu}_R \to \mu^- \, \tilde{\chi}_1^0$$

$$\tilde{\mu}_L \to \mu^- \, \tilde{\chi}_2^0$$
$$\hookrightarrow \tau^+ \tau^- \, \tilde{\chi}_1^0$$
$$\to \nu_\mu \, \tilde{\chi}_1^-$$
$$\hookrightarrow \tau^- \nu_\tau \, \tilde{\chi}_1^0$$

very clean signature:
few leptons $+ \not{E}$



SPS1a scenario

Neutralinos and **Charginos** can also decay via muons

$$\tilde{\chi}_2^0 \rightarrow \mu^+ \mu^- \tilde{\chi}_1^0$$

$$\tilde{\chi}_1^- \rightarrow \mu^- \nu_\mu \tilde{\chi}_1^0$$

BRs depend largly on SUSY scenario, but can be $\mathcal{O}(20\%)$.

Neutralinos and Charginos can be produced in various pairs,

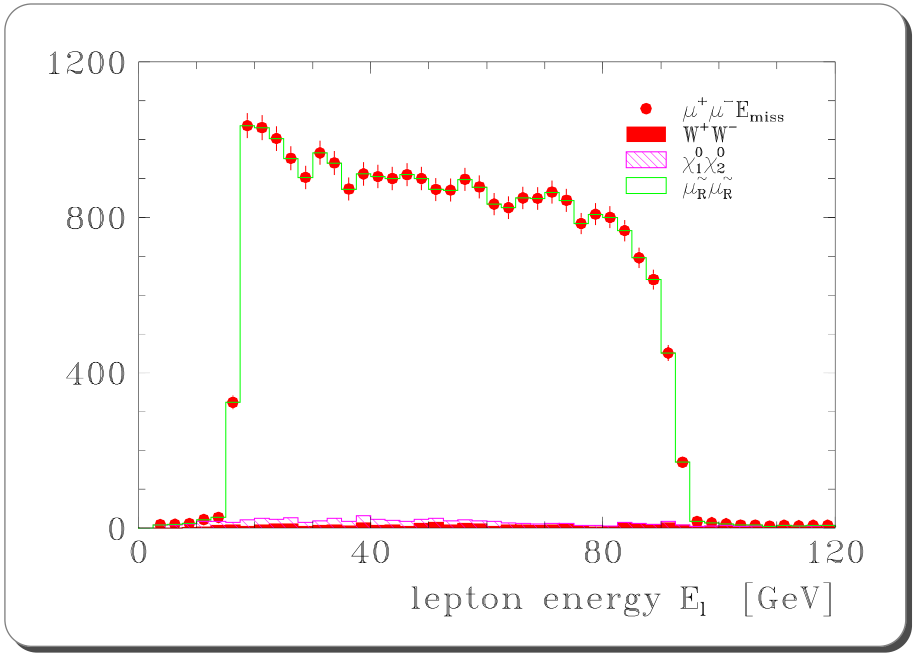
$$\begin{aligned} e^+e^- &\rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-, \; \tilde{\chi}_1^\pm \tilde{\chi}_2^\mp, \; \tilde{\chi}_2^+ \tilde{\chi}_2^- \\ &\rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0, \; \tilde{\chi}_1^0 \tilde{\chi}_3^0, \; \tilde{\chi}_2^0 \tilde{\chi}_2^0, \; \ldots \end{aligned}$$

$\rightarrow$ Often muons in conjunction with other leptons of jets in final state

Smuon mass measurement

- From edges in decay energy distributions

Example: $\tilde{\mu}_R \to \mu \tilde{\chi}_1^0$ Martyn '03



Typical resolution: 0.1–0.2%

Experimental challenges:

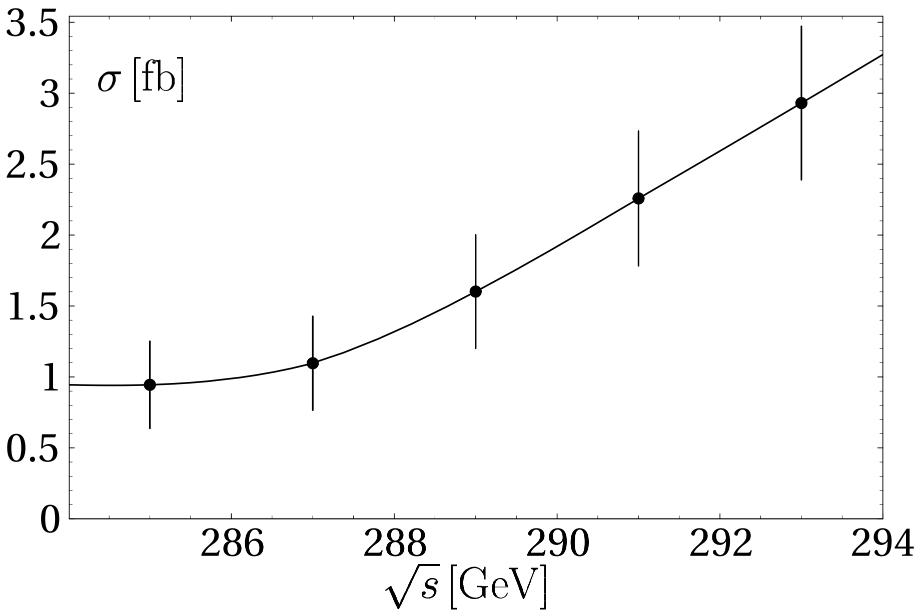
- Good momentum resolution → tracker
- Particle ID for rejection of backgrounds
- Good track–muon hit identification

■ Threshold scans — Freitas, v.Manteuffel, Martyn, Zerwas '00–04

in general P-wave $\propto \beta^3$

here assume 5×10 fb^{-1} in e^+e^-

$e^+e^- \to \tilde{\mu}_{\mathsf{R}}^+ \tilde{\mu}_{\mathsf{R}}^- \to \mu^+ \mu^- + \not{E}$



incl. beamstrahlung, ISR, etc.

Typical resolution: 0.1–0.2%

Experimental challenges:

- Measurement of beam energy
- Particle ID for rejection of backgrounds
- Determination of beamstrahlung spectrum

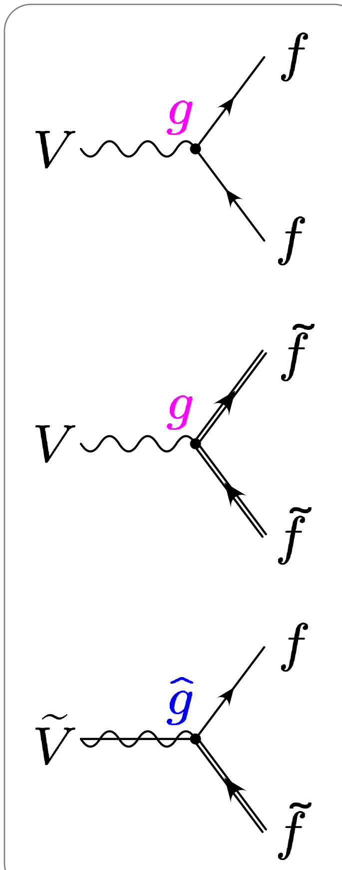
Slepton couplings

Fundamental supersymmetry relation

Gauge coupling g = Yukawa coupling $\hat{g}$

→ required to resolve hierarchy problem

→ compare precise cross-section measurements with theoretical predictions

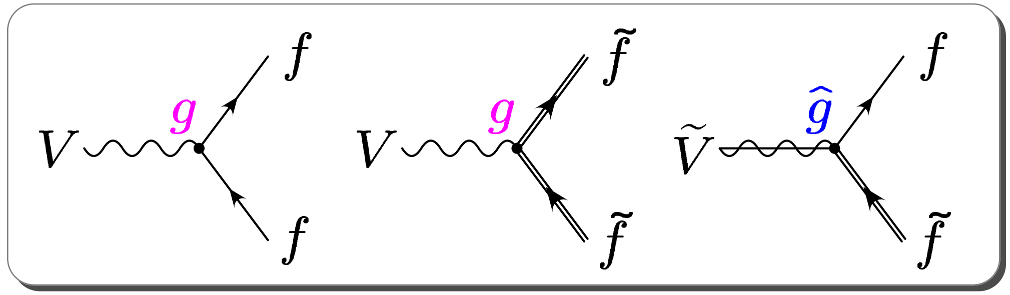


Experimental challenges:

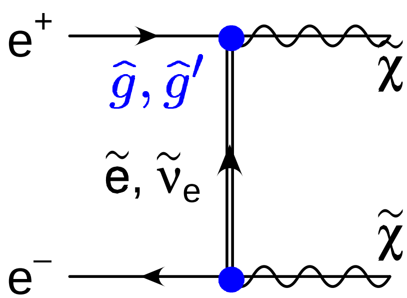
- Precise measurement of total cross-sections: better than 1%
- Accurate knowledge of particle ID efficiency for various μ energies
- Good rejection of fake muons

Slepton couplings

Electroweak gauge & Yukawa couplings can be probed in



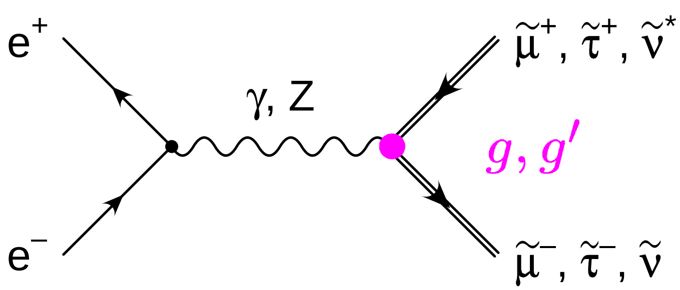
- Neutralino production

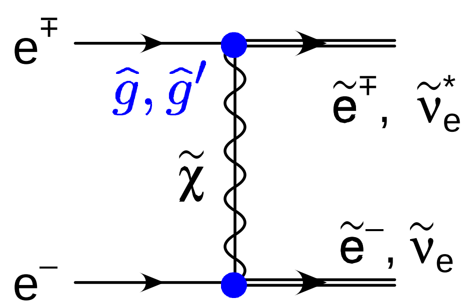


Choi, Kalinowski, Moortgat-Pick, Zerwas '01

- Slepton production

Freitas, v.Manteuffel '02





g' U(1) coupl.

g SU(2) coupl.

Tau backgrounds

Large tau backgrounds at ILC:

- from SM processes, such as $\gamma\gamma \to \tau^+\tau^-$

- from SUSY processes, in particular for large $\tan\beta \gtrsim 10$

$$\tilde{\chi}_2^0 \to \tau^+ \tau^- \tilde{\chi}_1^0$$

$$\tilde{\chi}_1^- \to \tau^- \nu_\tau \tilde{\chi}_1^0$$

- In 17.5% of the cases, tau decays into muons $\tau^- \to \mu^- \bar{\nu}_\mu \nu_\tau$

- Good understanding of muonic tau decay can help to evaluate tau background and thus obtain clean SUSY smsamples

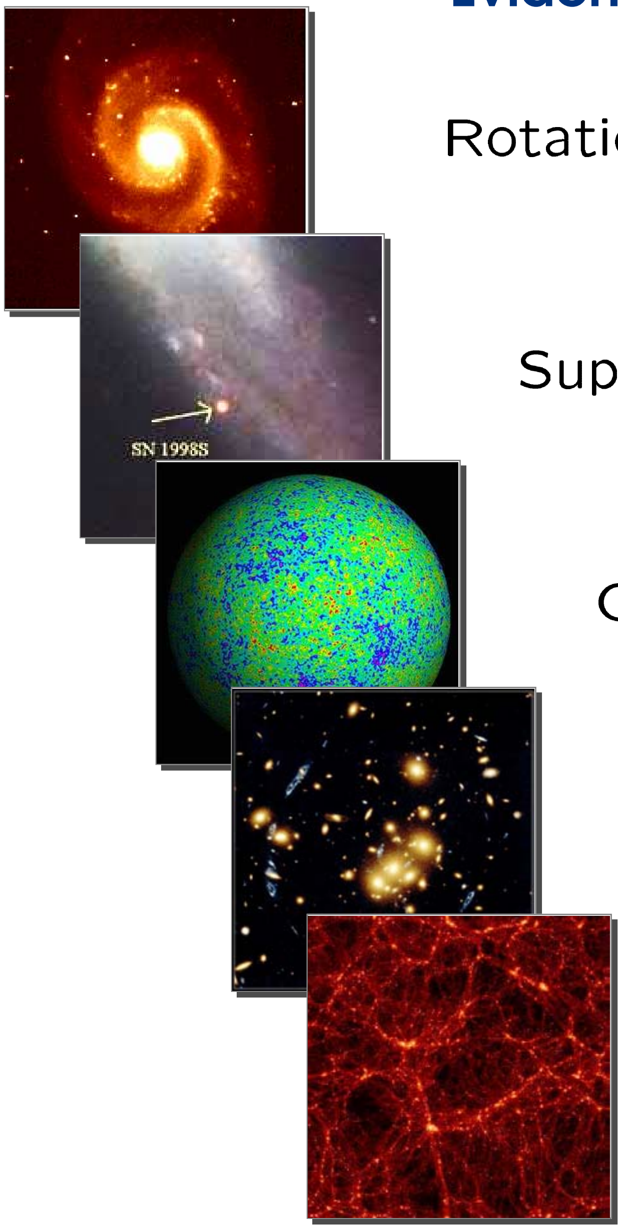
  $\to$ Precise knowledge of particle ID efficiency important

SUSY Dark Matter

- Smuon co-annihilation
- Focus point region

Dark matter

Evidence for dark matter from many sources:



Rotation curves of galaxies

Supernovae Ia redshift

CMB

Gravitational lensing

Large scale structure

~85% of matter in universe is **dark**

Dark matter and Supersymmetry

Dark matter has to be stable and weakly interacting

Supersymmetry has natural **dark matter** candidate:

lightest neutralino $\tilde{\chi}_1^0$ stable for R-parity conservation

- Dark matter particles freeze out when expanding universe cools
- After freeze-out dark matter particles annihilate
- Annihilation cross-section

$$\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to X$$

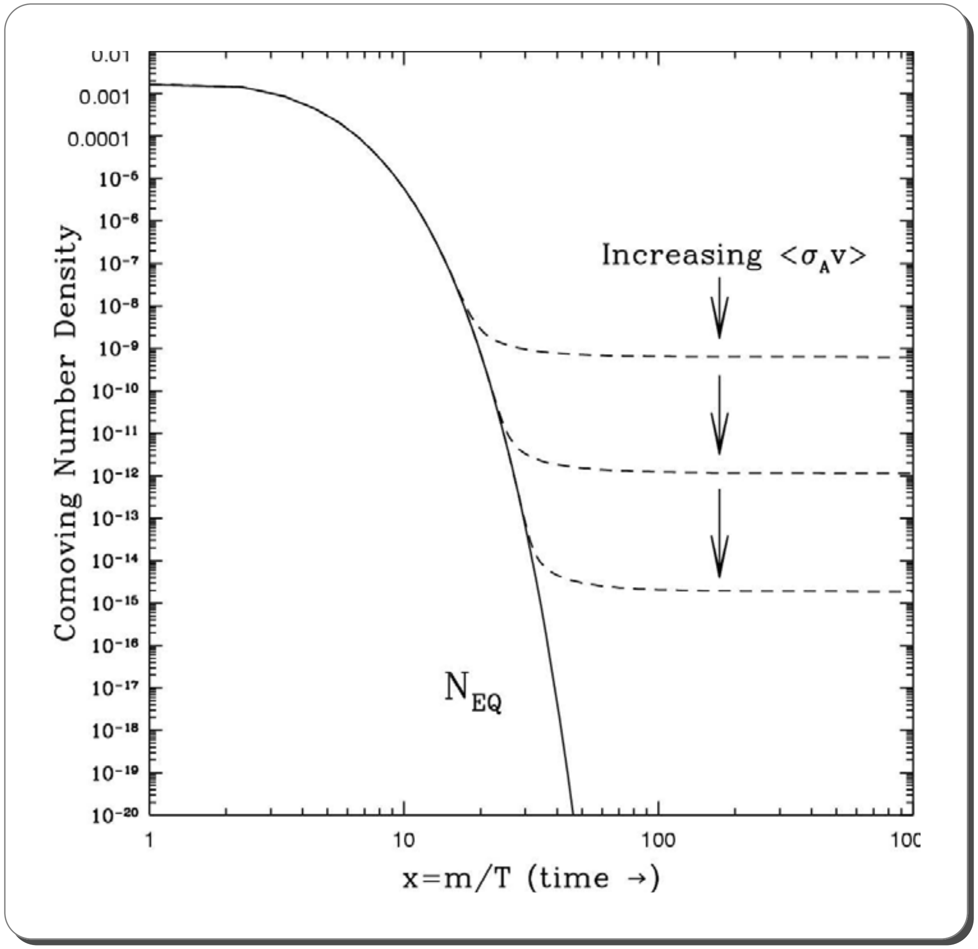
suppressed due to chirality conversation

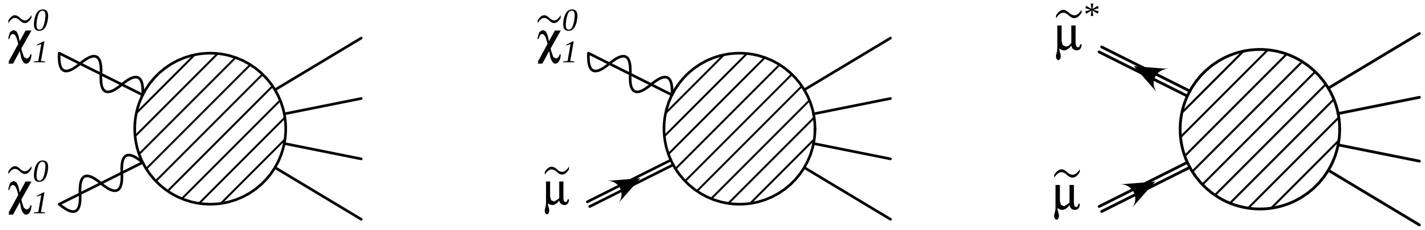
$\to$ Too large relic density in many SUSY scenarios

Co-annihilation

Mass of SUSY particle $\tilde{\mu}$ close to lightest neutralino $\tilde{\chi}_1^0$

- Freeze-out of $\tilde{\mu}$ and $\tilde{\chi}_1^0$ at roughly same temperature
- Annihilation in parallel (co-annihilation)
- Reduction of total dark matter density





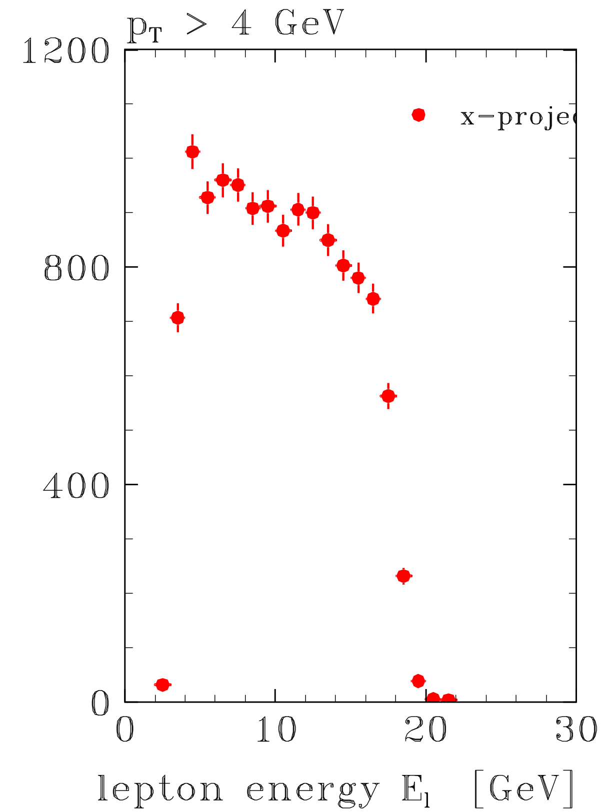
Typical parameter region

Typical mass difference for effective co-annihilation:

$\Delta m = m_{\tilde{\mu}} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(10\ \text{GeV})$

→ Muons in decay $\tilde{\mu}^{\pm} \to \mu^{\pm}\, \tilde{\chi}_1^0$ are soft

→ Require good and reliable muon ID for low-energy muons (few GeV)



$\sqrt{s} = 400$ GeV

$m_{\tilde{\mu}} = 143$ GeV

$\Delta m = 8$ GeV

Martyn '04

Focus point region

Sleptons and Squarks are heavy (few TeV)

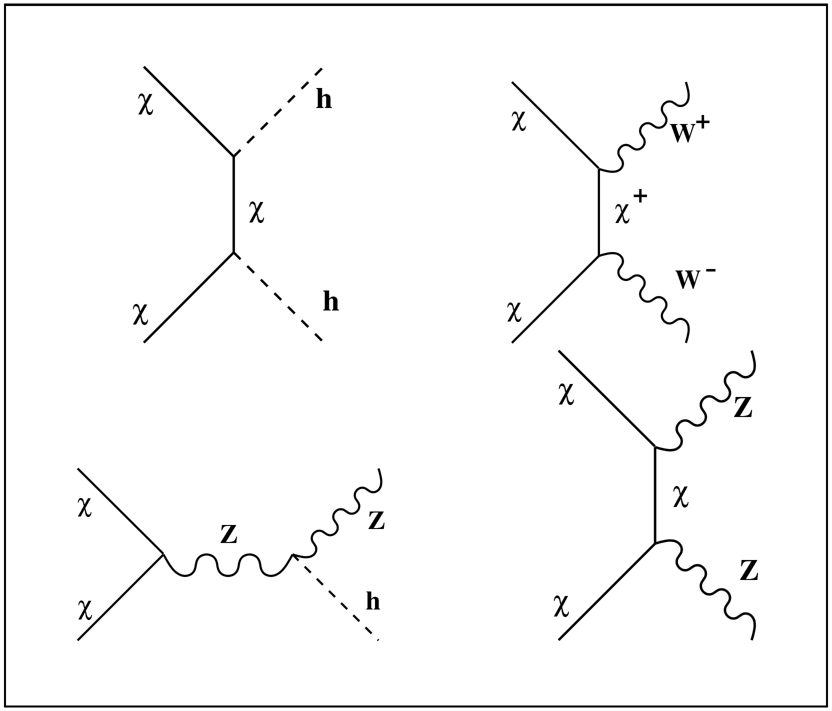
$\rightarrow$ Irrelevant for dark matter annihilation

$\rightarrow$ Beyond reach of colliders

Neutralinos and chargino can be light (few 100 GeV)

In mSUGRA: Electroweak symmetry breaking requires Higgs parameter μ to be relatively light

$\rightarrow$ Enhances annihilation into gauge-bosons



Focus point region

Analysis of focus point region at ILC:

- Determination of SUSY parameters M_1, M_2, μ and $\tan\beta$
- Most promising: production of $\tilde{\chi}_1^+\tilde{\chi}_1^-$, $\tilde{\chi}_1^\pm\tilde{\chi}_2^\mp$, $\tilde{\chi}_1^0\tilde{\chi}_2^0$, $\tilde{\chi}_1^0\tilde{\chi}_3^0$, $\tilde{\chi}_2^0\tilde{\chi}_2^0$
- Main decay mode via W and Z
  $\rightarrow$ 11% and 3% BR into muons

Typical channels in characteristic scenario (LCC2):

$\tilde{\chi}_1^+\tilde{\chi}_1^- \rightarrow jj\,l + \not{E}$

Birkedal et al. '05

$\tilde{\chi}_1^0\tilde{\chi}_k^0 \rightarrow jj + \not{E},\ ll + \not{E}$

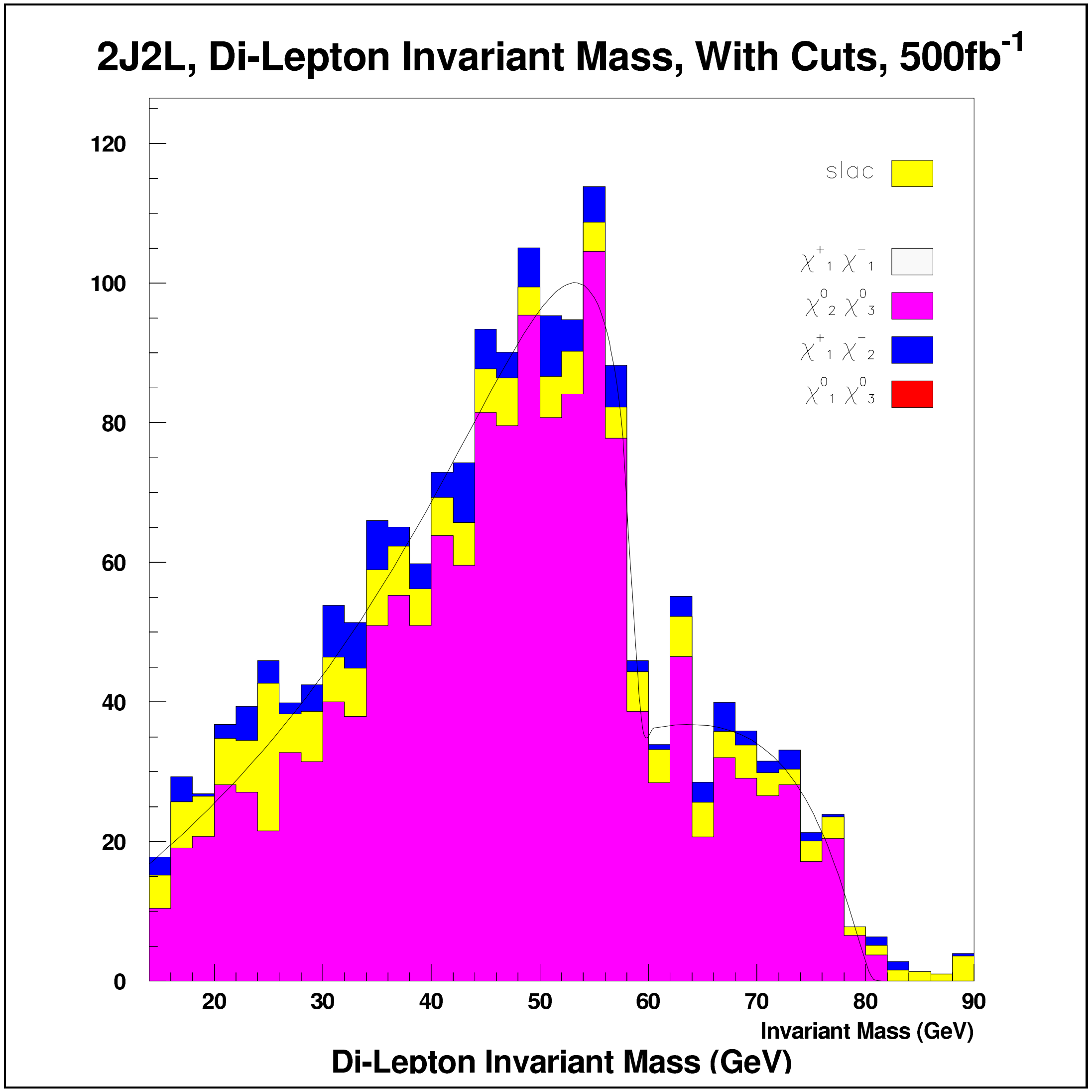
$\tilde{\chi}_2^0\tilde{\chi}_3^0 \rightarrow jj\,ll + \not{E}$

Signal signature with muons and jets:

- Good seperation of jets and muons
- Good momentum resolution
- Reliable muon ID over range of energies

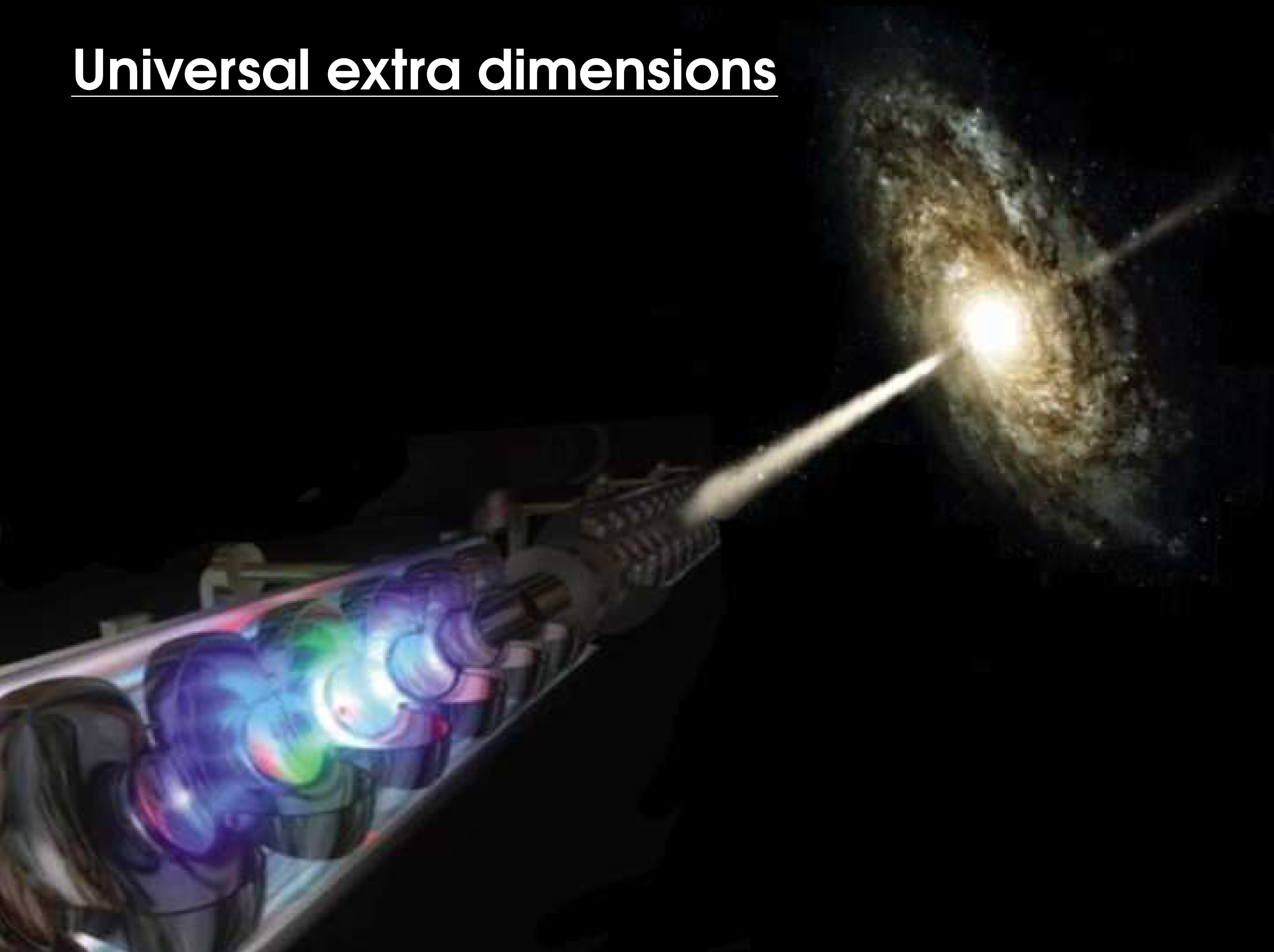
Distribution shapes

Distribution shapes contain important information:



Birkedal et al. '05

Universal extra dimensions



Extra dimensions

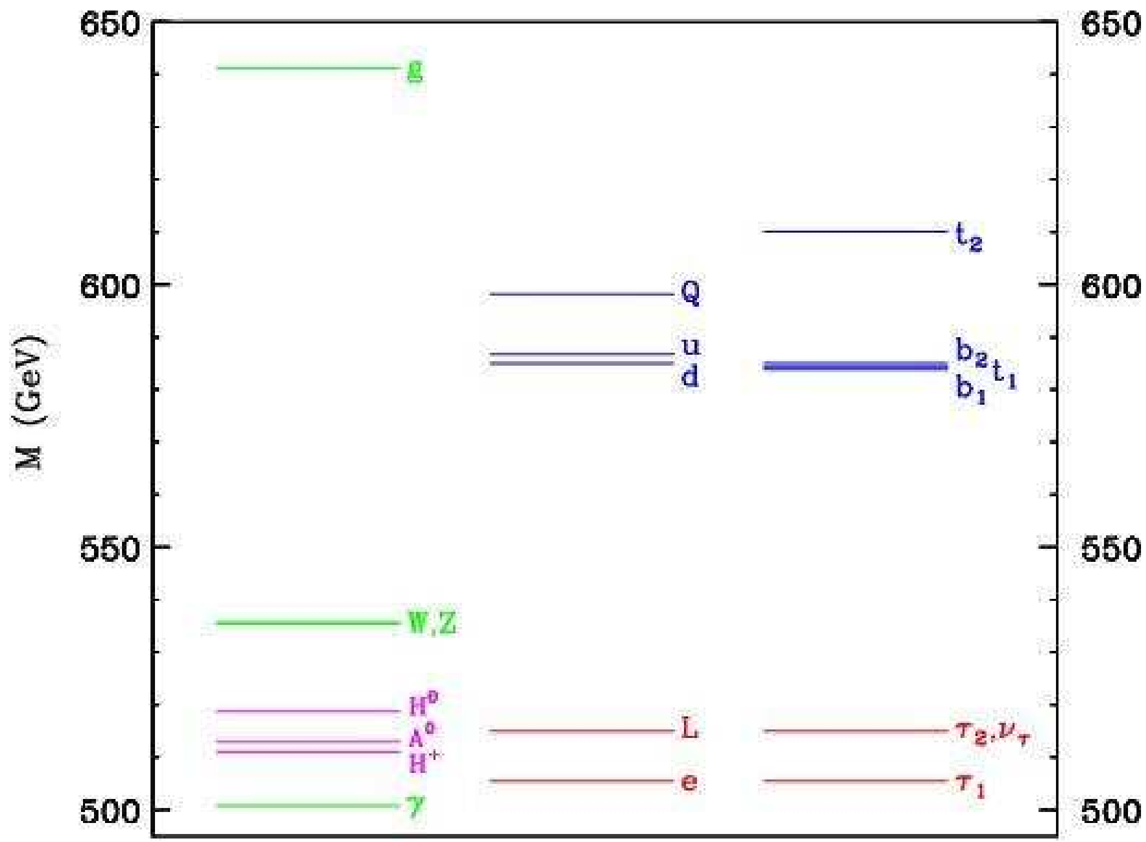
- Space-time can have more than 3+1 dimensions
- Extra dimensions have to be small, *e.g.* 5$^{\text{th}}$ dimension with cyclic geometry and radius $R \sim 1/\text{TeV} \sim 10^{-17}$ cm
- 5$^{\text{th}}$ of particle momentum is quantized in units of $1/R$:
  $p_0^2 - \vec{p}^2 = p_5^2 = m_{\text{eff}}^2 = (n/R)^2$
  $\rightarrow$ Conservation of p_5 becomes conservation of **KK number** $\boldsymbol{n}$
- KK number is broken my boundary terms to **KK parity** $P_{\text{KK}} = (-1)^n$
- **Universal Extra Dimensions**:

Appelquist, Cheng, Dobrescu ’01

all fields live in all dimensions
$\rightarrow$ Lightest KK particle (with $n = 1$ is stable
$\rightarrow$ All other $n = 1$ KK particles decay to LKP
$\rightarrow$ $n = 1$ KK particles must be pair produced

UED mass spectrum

- At 0$^{\text{th}}$ order all KK masses equal $m = 1/R$
- **Boundary terms** shift masses apart (similar to SUSY soft breaking terms)
- Since $\alpha_1 < \alpha_2 < \alpha_3$ we expect the LKP to be KK excitation of U(1) boson $B_\mu^{(1)}$
- The next-to-LKP is typically the right-handed lepton $l_{\mathrm{R}}^{(1)} = e_{\mathrm{R}}^{(1)}, \mu_{\mathrm{R}}^{(1)}$



Cheng, Matchev, Schmaltz '02

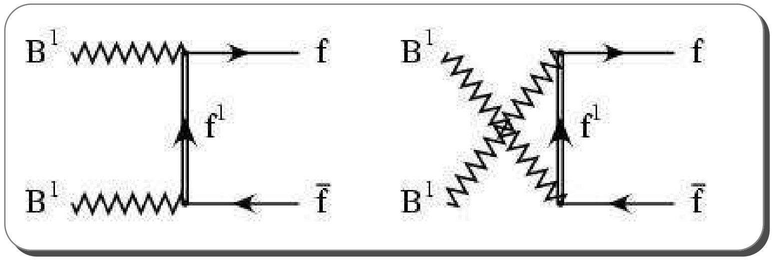
LKP dark matter

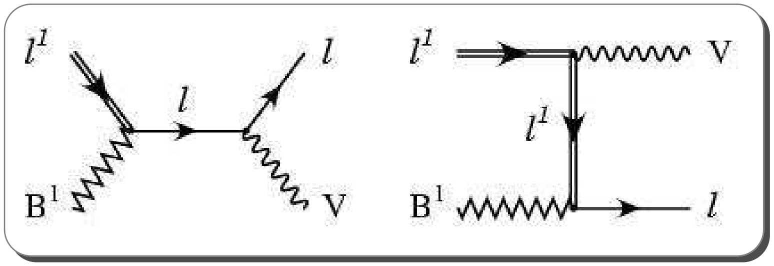
- Only free parameter:
  size of extra dimension R

- LKP annihilate as the universe evolves.
  Typical LKP masses in accordance with WMAP relic density: $m_{\mathrm{LKP}} \sim 500$ GeV

- If mass of $l_{\mathrm{R}}^{(1)}$ close to $B_{\mu}^{(1)}$
  co-annihilation is possible
  $\rightarrow$ m_{LKP} raised to 600–900 GeV

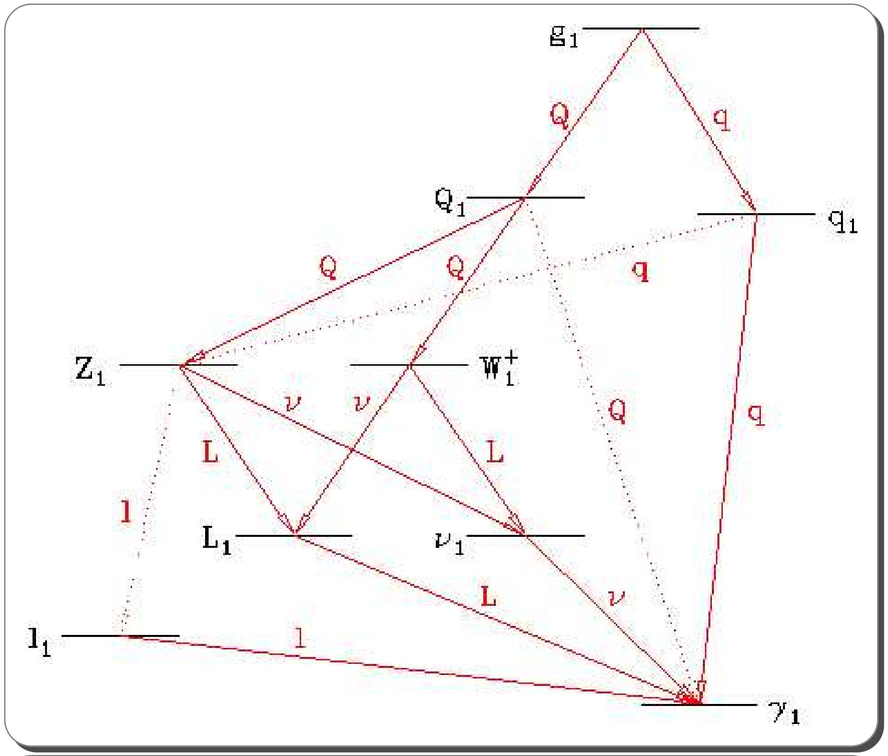
- More dimensions than 5 lower the preferred LKP mass

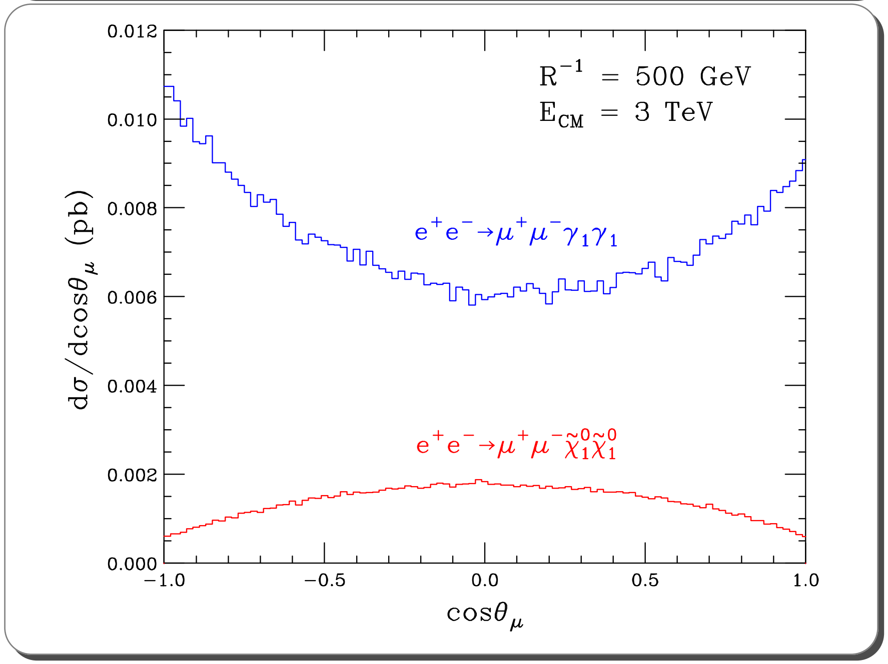




UED collider signatures

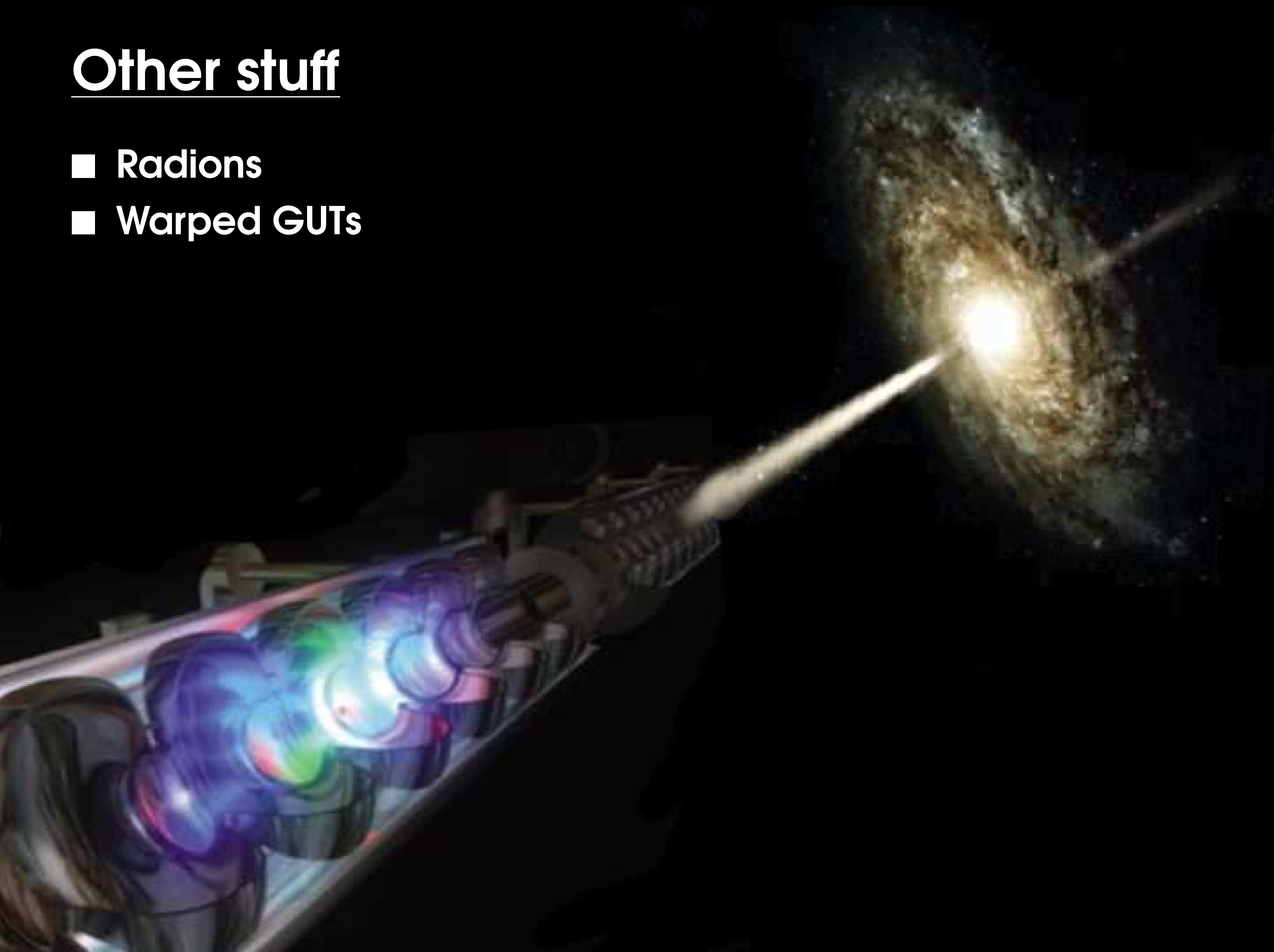
- At ILC: pair production of NLKP $e_R^{(1)}, \mu_R^{(1)}$
  $\rightarrow$ Decay into e, μ
- Cross-section rises steeply $\propto \beta$ at threshold
  $\rightarrow$ Distinction from SUSY
- Muons can be soft in case of co-annihilation
- Angular distribution
  $$\frac{d\sigma}{d\cos\theta} \sim 1 + \cos^2\theta$$
  as opposed to smuons
  $$\frac{d\sigma}{d\cos\theta} \sim 1 - \cos^2\theta$$
  $\rightarrow$ forward/backward muon coverage rq'd





Other stuff

- Radions
- Warped GUTs



Radions

- The **radion** corresponds to fluctuations of the size of the extra dimension

- Radions have various cosmological implications:
  - Dark matter
  - Inflation
  - Cosmoligcal perturbations

- Radions ϕ can mix with the Higgs boson, *i.e.* have an effect on $e^+e^- \to ZH, Z\phi$

  $\rightarrow$ Precise analysis of the $Z \to \mu^+\mu^-$ recoil spectrum essential for discovering radion effects

  $\rightarrow$ Good muon momentum resolution

  $\rightarrow$ Accurate knowledge of muon ID efficiency

Warped Grand Unified Theories (GUTs)

- Extra dimensions can be warped to explain hierarchy between **electroweak** and **GUT** scales

- Warped extra dimensions can be combined with **GUTs** and a stable KK fermion (right-handed neutrino $\boldsymbol{\nu_{\mathrm{R}}}$) can be **dark matter** candidate

- Depending on pattern of GUT breaking, the GUT partners of the ν_{R} decay very slowly

  $\rightarrow$ CHAMP (CHArged Massive Particle) signature

  $\rightarrow$ Can leave possible signature in muon detector
  $\rightarrow$ Distinction from muons?

Conclusions

No conclusions until ILC runs