

Light stops: connecting cosmology with (linear) colliders

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in collaboration with

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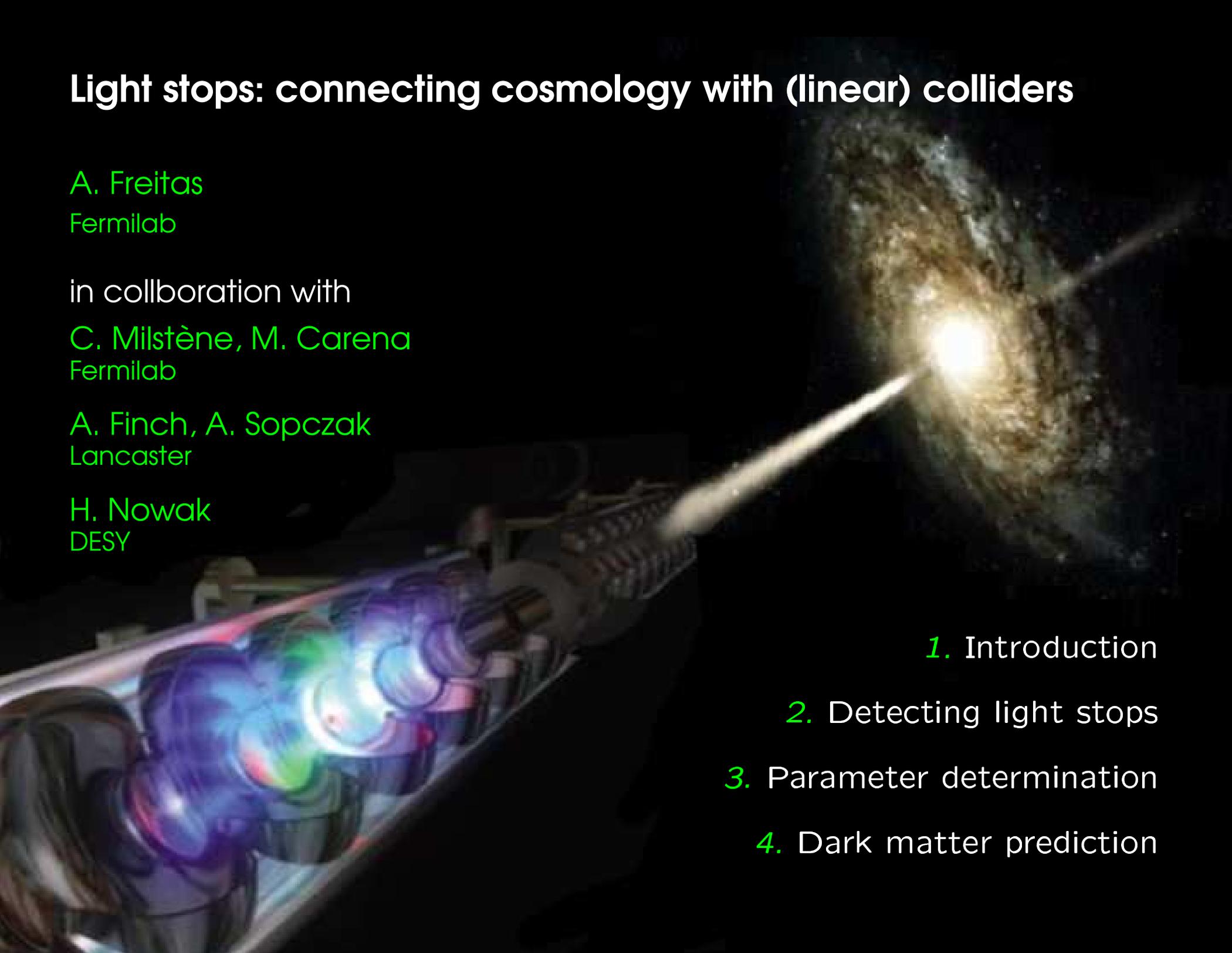
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DESY



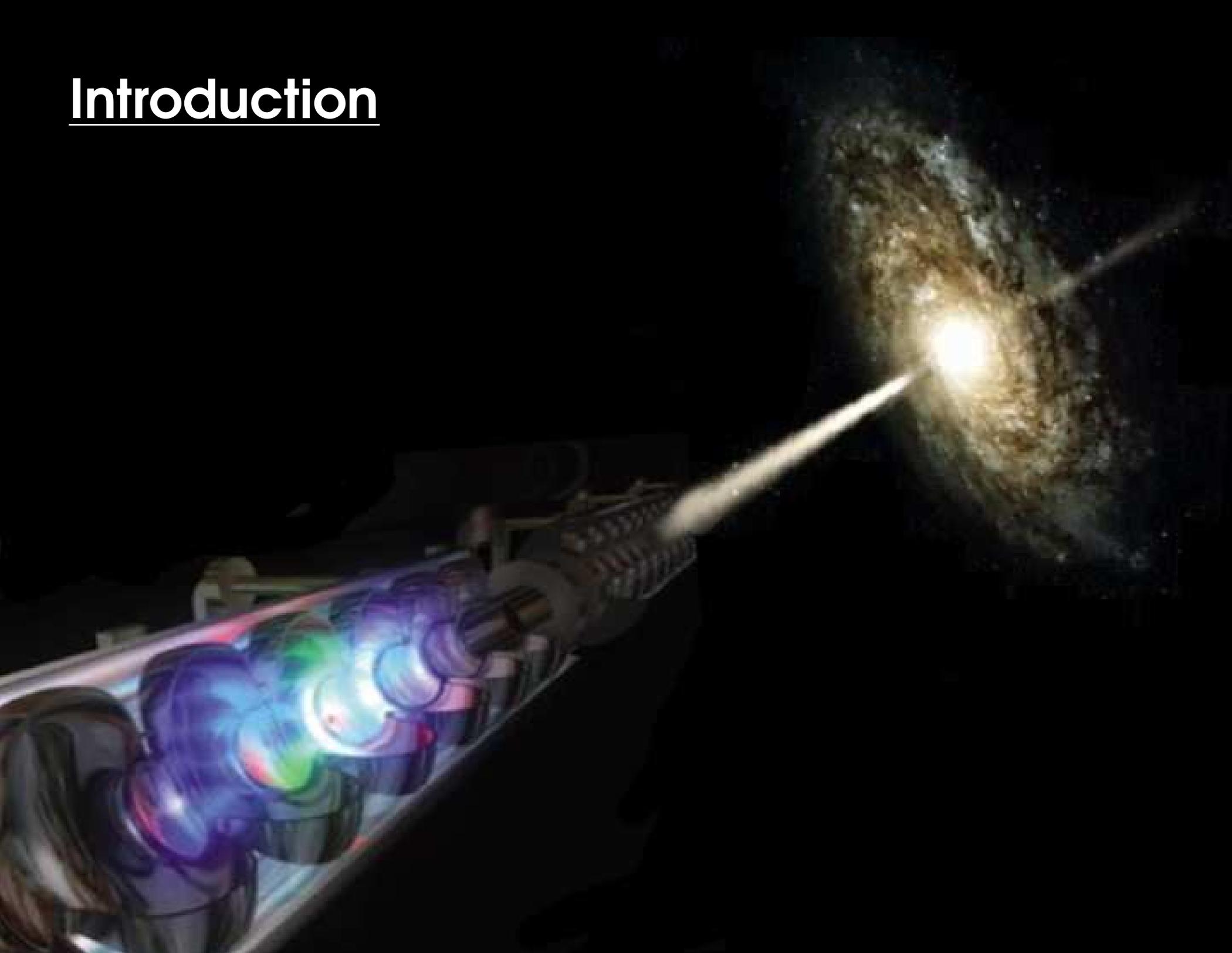
1. Introduction

2. Detecting light stops

3. Parameter determination

4. Dark matter prediction

Introduction



Electroweak Baryogenesis

Sakharov conditions:

■ Baryon number violation

In Standard Model and extensions through non-perturbative sphaleron processes

■ C and CP violation

CP violation in Standard Model through CKM phase
not sufficient to explain baryon asymmetry $\eta_{\text{BBN}} \sim 6 \times 10^{-10}$

■ Non-equilibrium

Strongly first order electroweak phase transition necessary

$$\frac{v(T_c)}{T_c} > 1$$

In Standard Model: $\frac{v(T_c)}{T_c} \approx \frac{g^2}{4\pi\lambda}$ with $\lambda \propto \frac{M_H^2}{v^2}$

→ not fulfilled for $M_H \gtrsim 40$ GeV

Electroweak Baryogenesis and Supersymmetry

EW baryogenesis:

- new boson degrees of freedom with strong Higgs coupling
- new sources for CP violation

Supersymmetry provides natural framework for EW baryogenesis

Carena, Quirós, Wagner '96

Higgs potential modified by scalar top (stop) \tilde{t}_1 :

Each stop has six degrees of freedom (3 color, 2 charge),
coupling $\mathcal{O}(1)$ to Higgs

$$\frac{v(T_C)}{T_C} \approx \frac{g^2 + 2y_t^2}{4\pi\lambda}$$

- Higgs masses up to 120 GeV
- Lightest stop must have mass below top quark

Electroweak Baryogenesis and CP violation

CP violating source needed to generate chiral charge asymmetry

→ particle currents coupling to the Higgs background

In Standard Model:

CP-violating CKM processes suppressed by Yukawa couplings m_q^2/M_W^2

Supersymmetry:

Carena, Quirós, Riotto, Vilja, Wagner '97

Additional contribution from stop and chargino currents

$$\begin{array}{cc} \uparrow & \uparrow \\ \propto \text{Im}(A_t \mu) & \propto \text{Im}(M_2 \mu) \end{array}$$

Higgs bound $M_{h^0} \gtrsim 114$ GeV: one stop eigen-state heavy

⇒ Charginos are dominant source if they are light

Phase can be rotated into μ parameter only

Dark matter

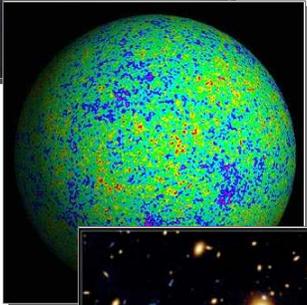
Evidence for dark matter from many sources:



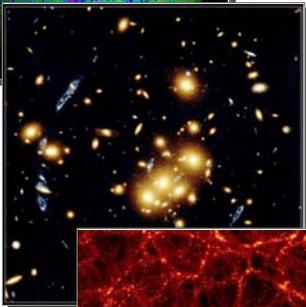
Rotation curves of galaxies



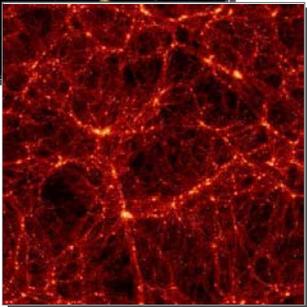
Supernovae Ia redshift



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

- In most of SUSY parameter space annihilation cross-section

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

suppressed due to chirality conversation

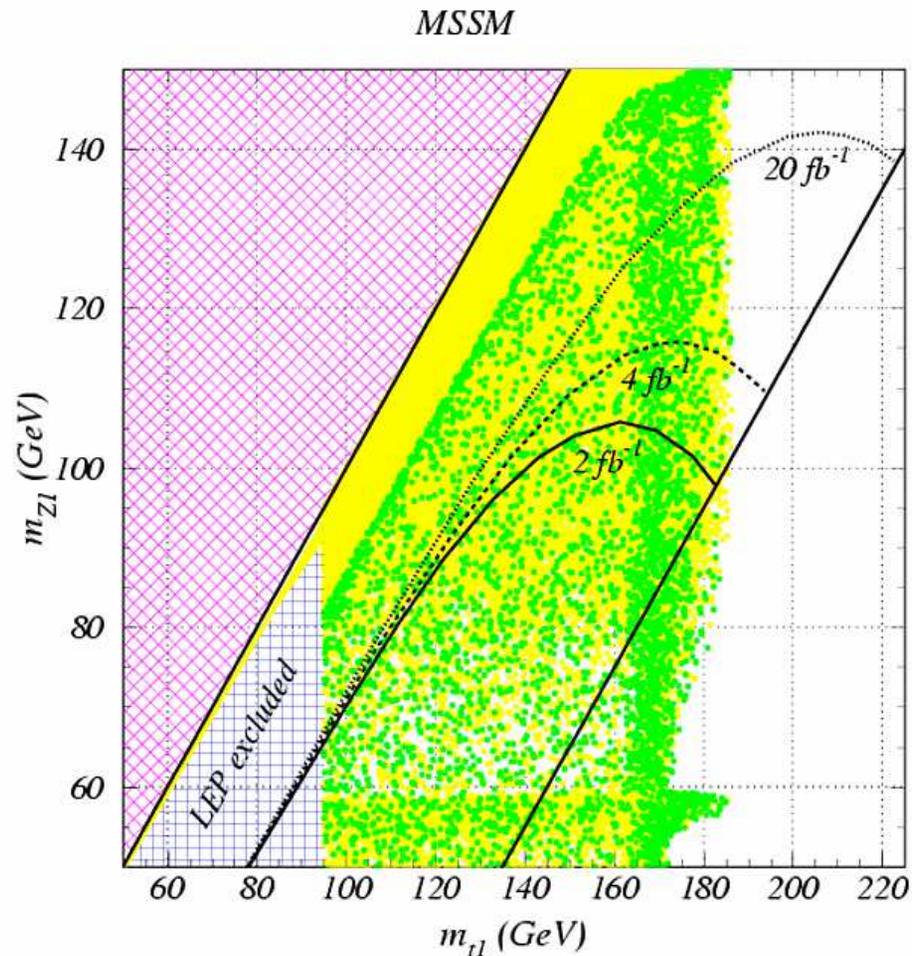
→ Too large relic density in many SUSY scenarios

- If mass of \tilde{t}_1 close to mass of $\tilde{\chi}_1^0$:

→ Stop-neutralino **co-annihilation** reduces dark matter density

Typical parameter regions

Carena, Balázs, Wagner '04



Green: Relic density consistent with WMAP

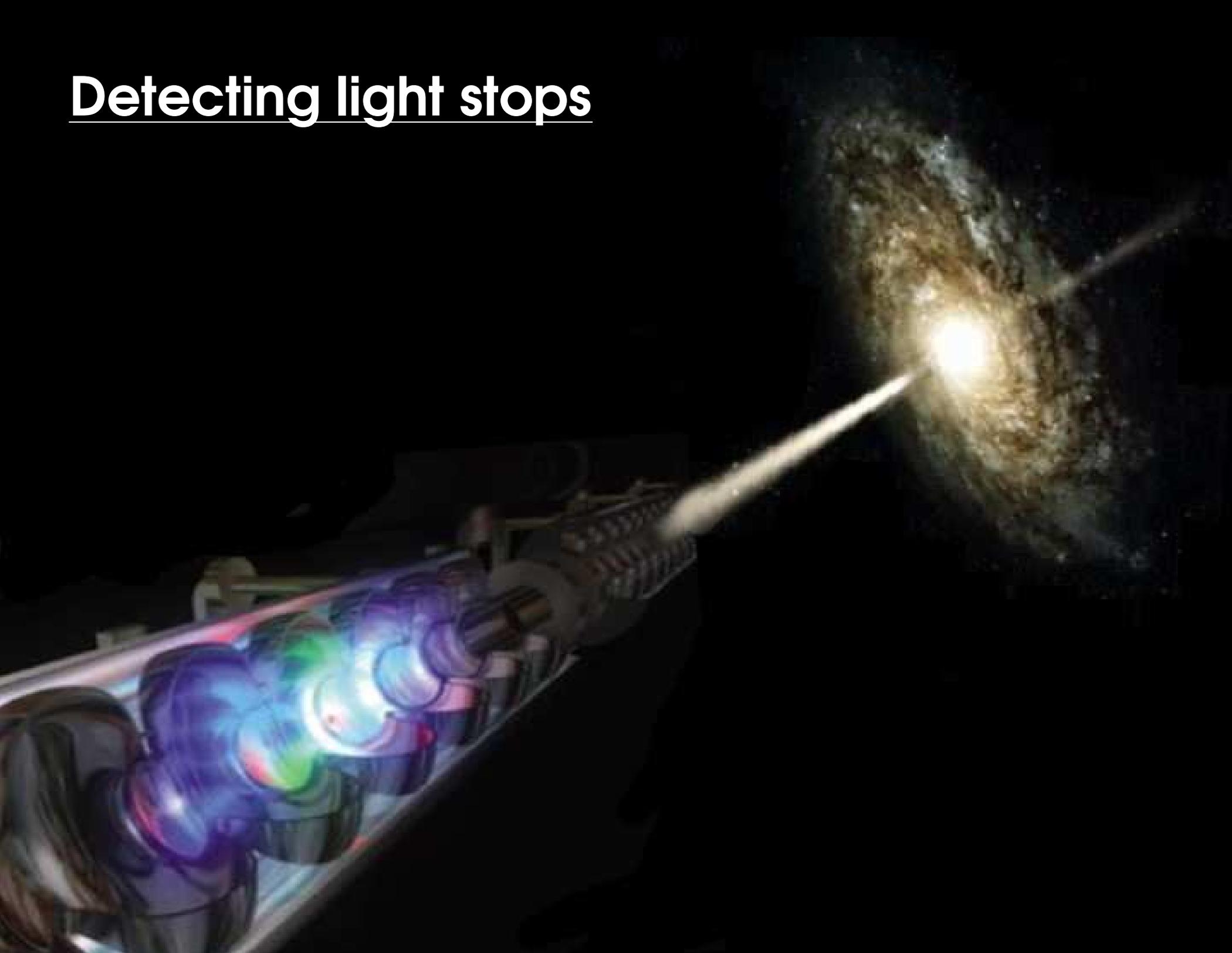
Co-annihilation for $\Delta m \lesssim 30 \text{ GeV}$

Difficult for searches at Tevatron

LHC will have similar difficulties

(possible additional channel:
 $pp \rightarrow \tilde{g}\tilde{g} \rightarrow \tilde{t}_1\tilde{t}_1 \bar{t}t$)

Detecting light stops



Light stop signature

Dominant decay for small mass differences $\Delta m = m_{\tilde{t}_1} - m_{\tilde{\chi}_1^0}$: $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$

Assume 100% branching ratio for $\tilde{t}_1 \rightarrow c \tilde{\chi}_1^0$

Signature at linear collider: $e^+e^- \rightarrow \tilde{t}_1 \tilde{t}_1^* \rightarrow c \bar{c} \tilde{\chi}_1^0 \tilde{\chi}_1^0$

Two (soft) charm jets plus missing energy

Discrimination from background requires detector simulation

- Event generation with **Pythia**
- Detector effects with fast simulation
- Include beamstrahlung with **Circe**

Generate SM background from various sources

Assume $\mathcal{L} = 500 \text{ fb}^{-1}$ at $\sqrt{s} = 500 \text{ GeV}$.

Signal and Background

process	cross-section [pb]			- = L + = R
	$P(e^-)/P(e^+) = 0/0$	-80%/+60%	+80%/-60%	
$\tilde{t}_1\tilde{t}_1, m_{\tilde{t}_1} = 120 \text{ GeV}$	0.115	0.153	0.187	$\sin \theta_{\tilde{t}} = 0.5$
$m_{\tilde{t}_1} = 140 \text{ GeV}$	0.093	0.124	0.151	
$m_{\tilde{t}_1} = 180 \text{ GeV}$	0.049	0.065	0.079	
$m_{\tilde{t}_1} = 220 \text{ GeV}$	0.015	0.021	0.026	
W^+W^-	8.55	24.54	0.77	
ZZ	0.49	1.02	0.44	
$W e \nu$	6.14	10.57	1.82	
eeZ	7.51	8.49	6.23	
$q\bar{q}, q \neq t$	13.14	25.35	14.85	
$t\bar{t}$	0.55	1.13	0.50	
$\gamma\gamma, p_t > 5 \text{ GeV}$	936			

Large Standard Model backgrounds!

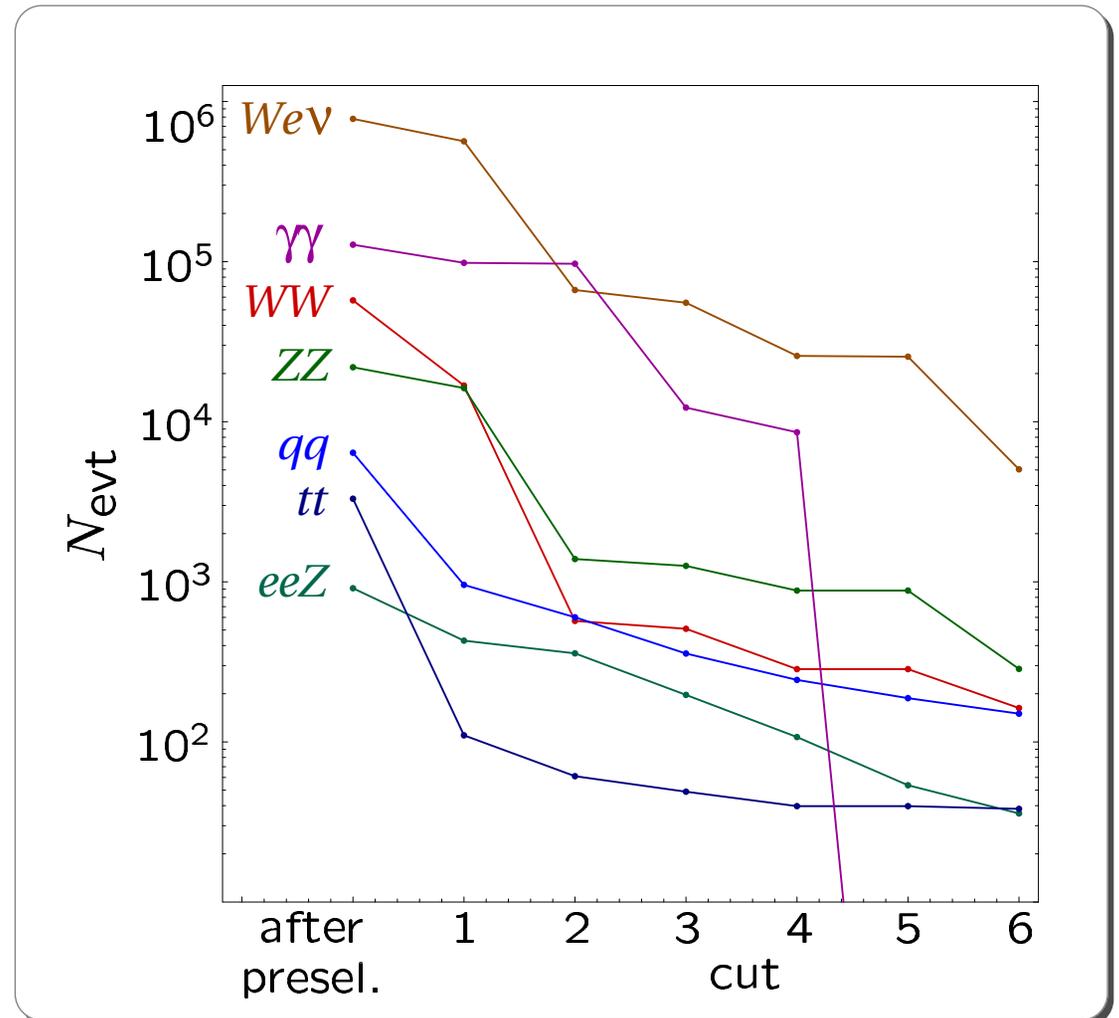
Reduction of background

Preselection:

1. $4 < N_{\text{chargedtracks}} < 50$
2. $p_t > 5 \text{ GeV}$
3. $|\cos \theta_{\text{Thrust}}| < 0.8$
4. $|p_{\text{long,tot}}/p_{\text{tot}}| < 0.9$
5. $E_{\text{vis}} < 0.75\sqrt{s}$
6. $m_{\text{inv}} < 200 \text{ GeV}$

Selection:

1. $N_{\text{jets}} = 2$
(Durham $y_{\text{cut}} = 0.003$)
2. $E_{\text{vis}} < 0.4\sqrt{s}$
3. $\cos \phi_{\text{aco}} > -0.9$
4. $|\cos \theta_{\text{Thrust}}| < 0.7$
5. $p_t > 12 \text{ GeV}$
6. $3500 \text{ GeV}^2 < m_{\text{inv}}^2 < 8000 \text{ GeV}^2$, c-tagging



Remaining background levels

Background	N_{evt} generated	N_{evt} after selection	scaled to 500 fb ⁻¹
W^+W^-	210,000	10	145
ZZ	30,000	30	257
$W e \nu$	210,000	624	5044
eeZ	210,000	3	36
$q\bar{q}, q \neq t$	350,000	10	200
$t\bar{t}$	180,000	25	38
$\gamma\gamma$	5,500,000	0	< 164

Largest remaining background from $e^+e^- \rightarrow W^\pm e^\mp \nu$

Signal efficiency

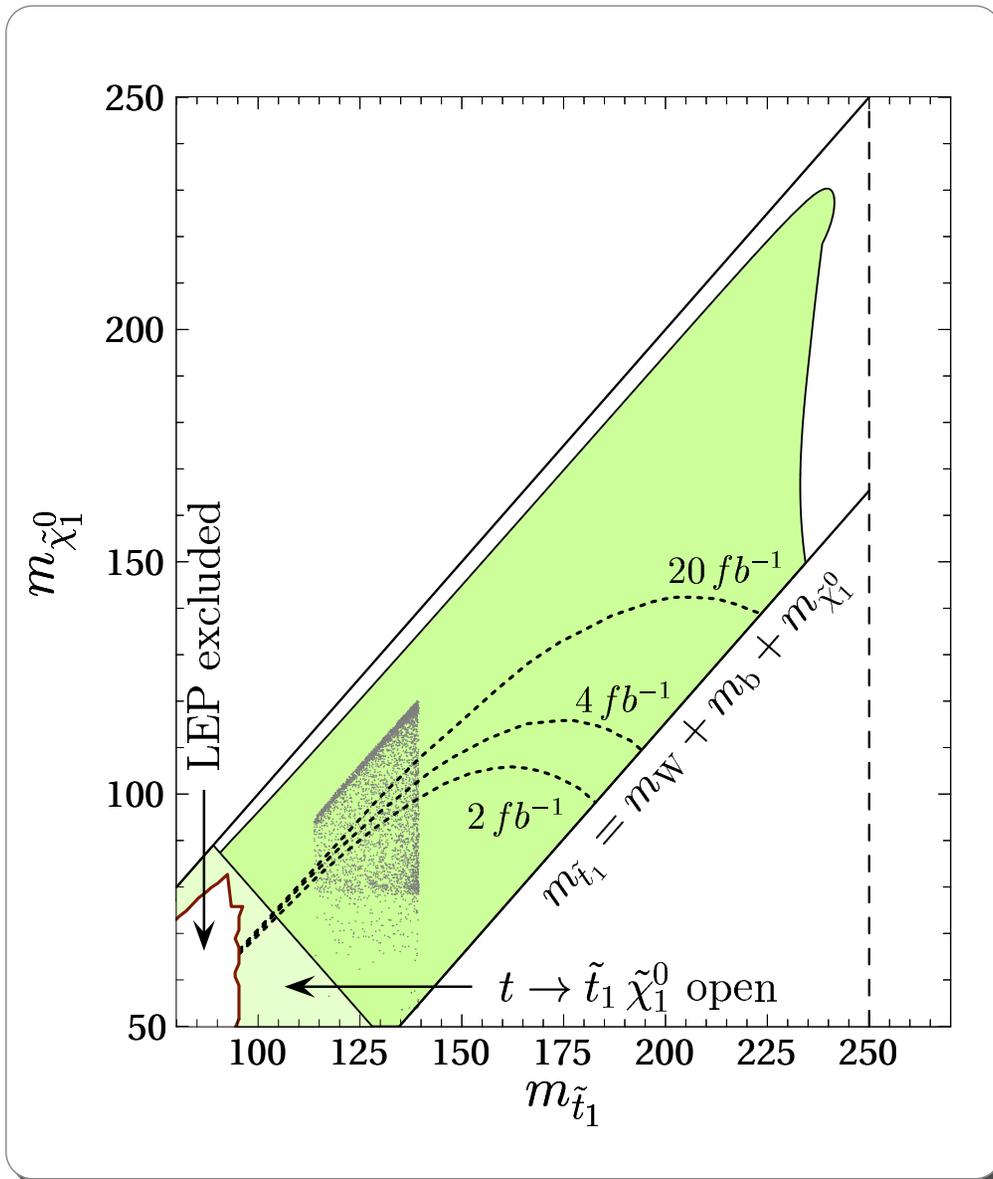
Δm	$m_{\tilde{\tau}_1} = 120$ GeV	140 GeV	180 GeV	220 GeV
80 GeV		10%	15%	19%
40 GeV		10%	20%	24%
20 GeV	17%	21%	28%	35%
10 GeV	19%	20%	19%	35%
5 GeV	2.5%	1.1%	0.3%	0.1%

Typical signal event number remaining after selection for 500 fb^{-1} , depending on $m_{\tilde{\tau}_1}$ and $\theta_{\tilde{\tau}}$: $N_{\text{sig}} \sim \mathcal{O}(10^3) - \mathcal{O}(10^4)$

→ same order as remaining background

Signal efficiency deteriorates for very small Δm

Stop discovery reach at linear collider



From simulations:

Background numbers B and signal efficiencies ϵ with theor. cross-section σ yields signal number $S = \epsilon\sigma$

Green region: $\frac{S}{\sqrt{S+B}} > 5$

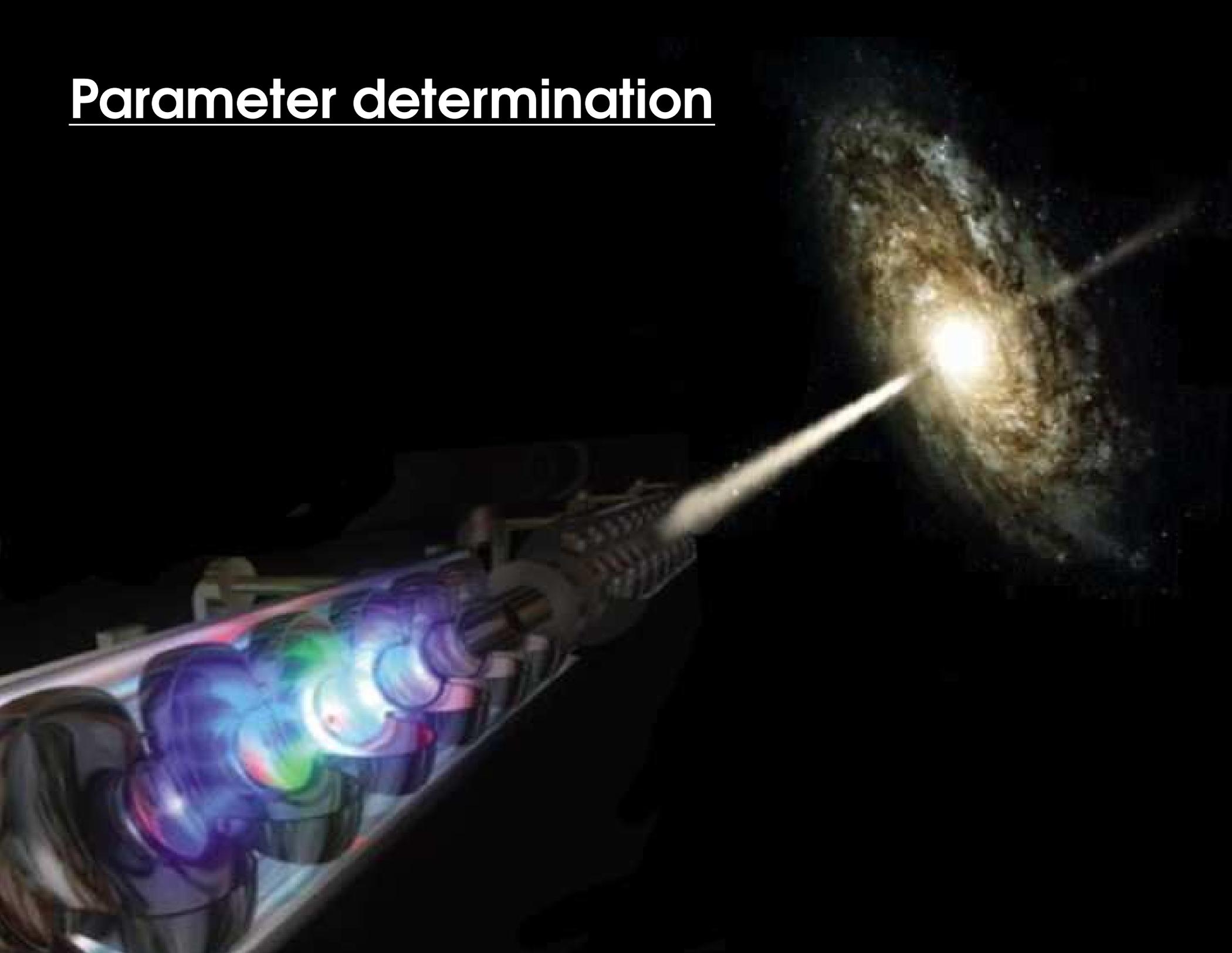
Light green:

decay $t \rightarrow \tilde{t}_1 \tilde{\chi}_1^0$ open
(not yet studied)

Detection of light stops possible for $\Delta m \sim \mathcal{O}(5\text{GeV})$

Cover complete co-annihilation region

Parameter determination



Sample parameter point

Point with light stop, gauginos, selectron and CP violation
→ Use existing studies where possible

$$\begin{array}{ll} M_1 = 112.6 \text{ GeV} & M_{u3}^2 = -99^2 \text{ GeV}^2 \\ M_2 = 225 \text{ GeV} & M_{q3} = 4200 \text{ GeV} \\ |\mu| = 320 \text{ GeV} & A_t = -1050 \text{ GeV} \\ \phi_\mu = 0.2 & \tan \beta = 5 \end{array}$$

→ Consistent with e and n EDM, m_{h^0} bound, baryogenesis

Sparticle masses:

$$m_{\tilde{\chi}_1^0} = 107.2 \text{ GeV} \quad m_{\tilde{t}_1} = 122.5 \text{ GeV} \quad \cos \theta_{\tilde{t}} = 0.0105$$

$$\Omega_{\text{CDM}} h^2 \approx 0.112$$

Stop parameters

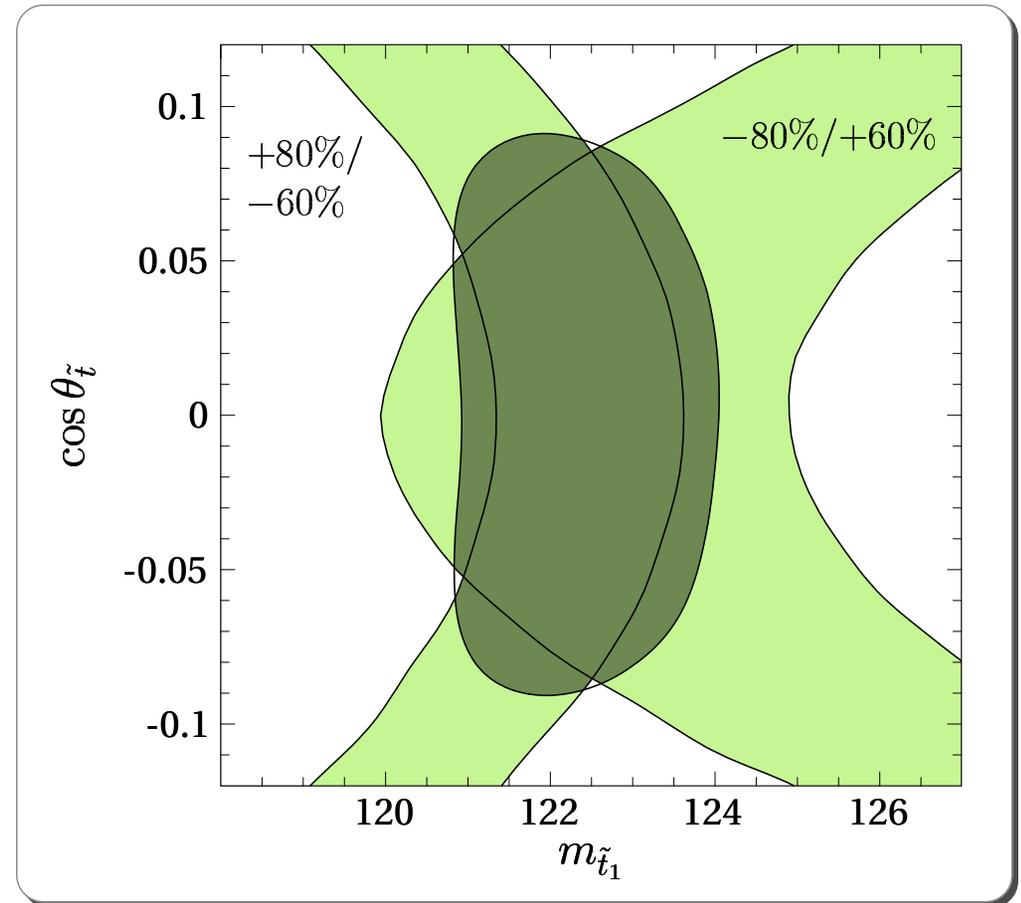
Use $e^+e^- \rightarrow \tilde{t}_1\tilde{t}_1^*$ cross-section measurements for two different beam polarizations:

$$P(e^-)/P(e^+) = -80\%/+60\% \\ +80\%/-60\%$$

$$\mathcal{L} = 250 \text{ fb}^{-1} \text{ each}$$

Systematic errors:

- $\delta m_{\tilde{\chi}_1^0} = 0.1 \text{ GeV}$
- $\delta P/P = 0.5\%$
- backgr. $\delta B/B = 0.3\%$
- $\delta \mathcal{L}/\mathcal{L} = 5 \times 10^{-4}$
- \tilde{t}_1 hadroniz./fragment.: $\sim 1\%$
- charm tagging/fragm.: 0.5%
- detector calibration: 0.5%
- beamstrahlung



$$\text{Result: } m_{\tilde{t}_1} = 122.5 \pm 1.0 \text{ GeV} \\ |\cos \theta_{\tilde{t}}| < 0.074 \\ \Rightarrow |\sin \theta_{\tilde{t}}| > 0.9972$$

Chargino/Neutralino parameters

Mass measurements:

- Heavy 1st/2nd generation squarks
→ Neutralino masses from squark cascades at LHC difficult
- Lightest neutralino $\tilde{\chi}_1^0$ mass from selectron and other decays at ILC → $\delta m_{\tilde{\chi}_1^0} = 0.11$ GeV
- Other neutralino/chargino masses from ILC threshold scans
LHC/ILC report '04

Most studies performed in SPS1a scenario

→ Scale errors with different cross-sections in our scenario

	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{\chi}_3^0$	$\tilde{\chi}_1^\pm$
δm	0.11	2.5	4	0.12 GeV

$$\begin{aligned}
 e^+e^- &\rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^- & P(e^-)/P(e^+) &= -80%/+60\% \text{ and } +80\%/-60\% \\
 e^+e^- &\rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0 & & \text{at } \sqrt{s} = 500 \text{ GeV} \\
 e^+e^- &\rightarrow \tilde{\chi}_2^0 \tilde{\chi}_2^0 & &
 \end{aligned}$$

Note: Light stop opens decay $\tilde{\chi}_1^+ \rightarrow \tilde{t}_1 \bar{b}$
with experimentally unknown BR

→ Use only **cross-section ratios** for $\sigma(e^+e^- \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-)$

Systematic errors in cross-sections:

- chargino/neutralino masses
- selectron/sneutrino masses in t-channel
- $\delta P/P = 0.5\%$

Experimental efficiency extrapolated from analysis for $e^+e^- \rightarrow \tilde{\chi}_1^0 \tilde{\chi}_2^0$

Chargino/Neutralino comprehensive analysis

Use χ^2 fit to extract fundamental SUSY parameters:

$$M_1 = 112.6 \pm 0.2 \text{ GeV}$$

$$M_2 = 225.0 \pm 0.7 \text{ GeV}$$

$$|\mu| = 320.0 \pm 3.3 \text{ GeV}$$

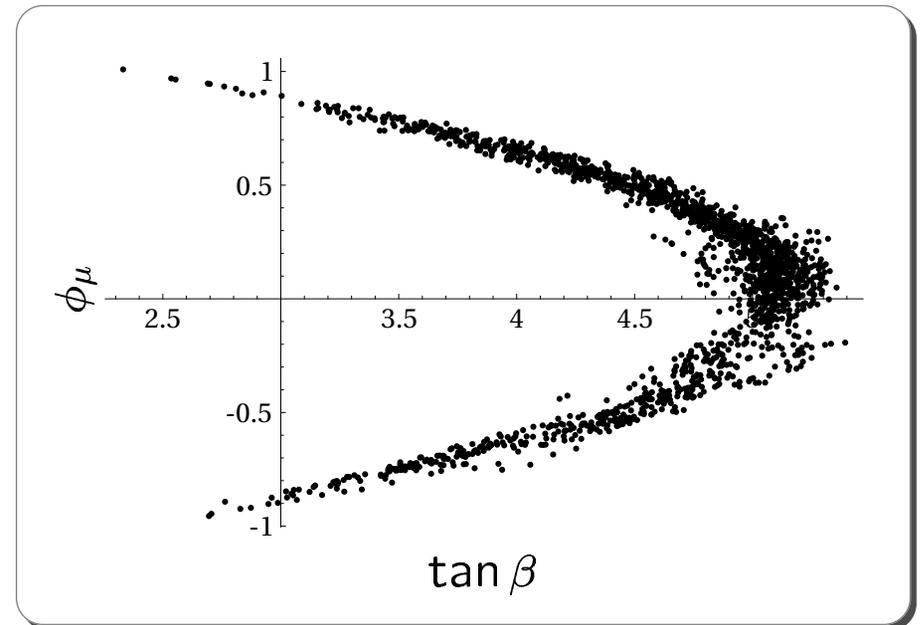
$$|\phi_\mu| < 1.0$$

$$\tan \beta = 5^{+0.5}_{-2.6}$$

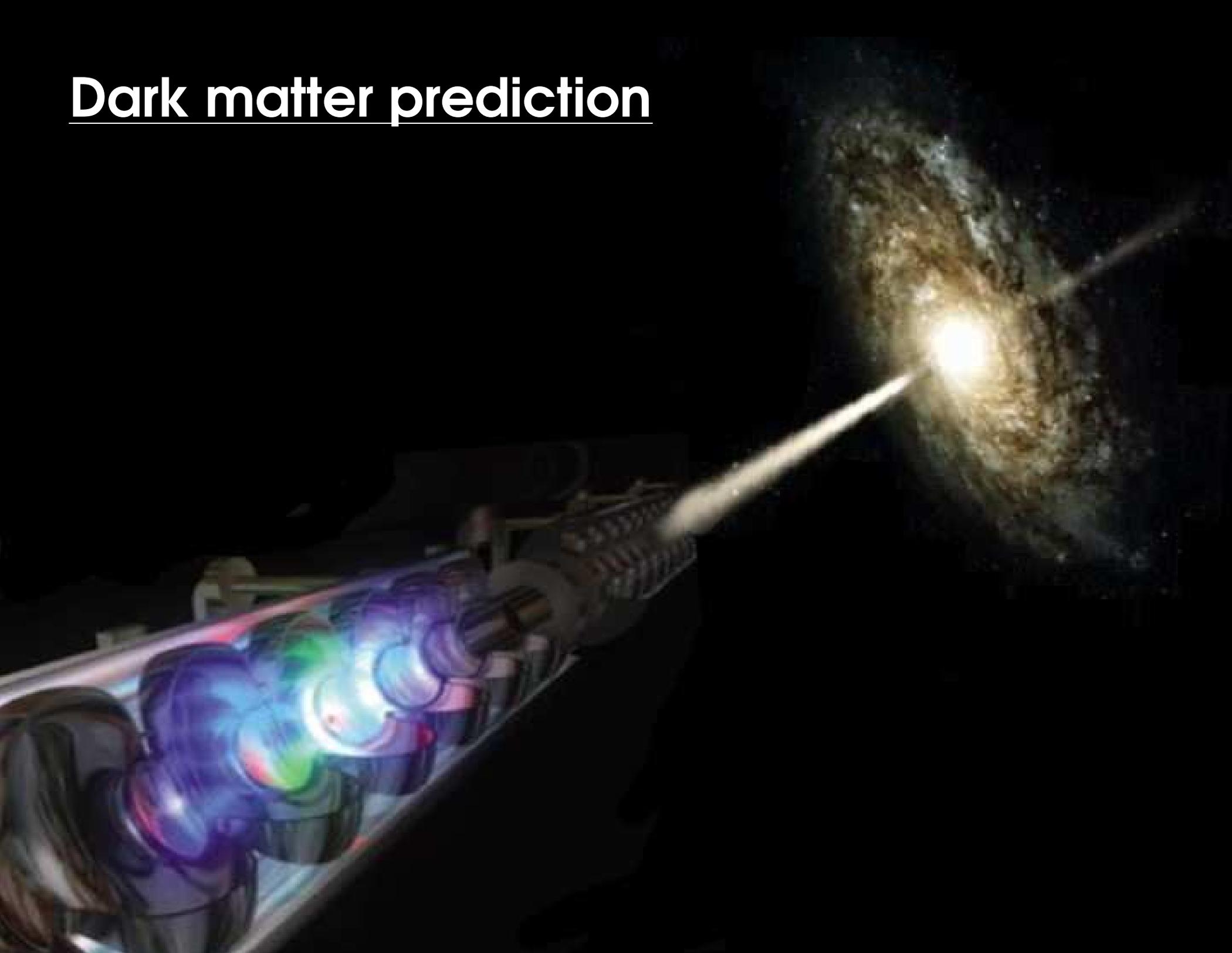
Large correlation between

$\tan \beta$ and ϕ_μ

→ Not problematic for
dark matter determination



Dark matter prediction



Computation of Ω_{CDM} from collider results

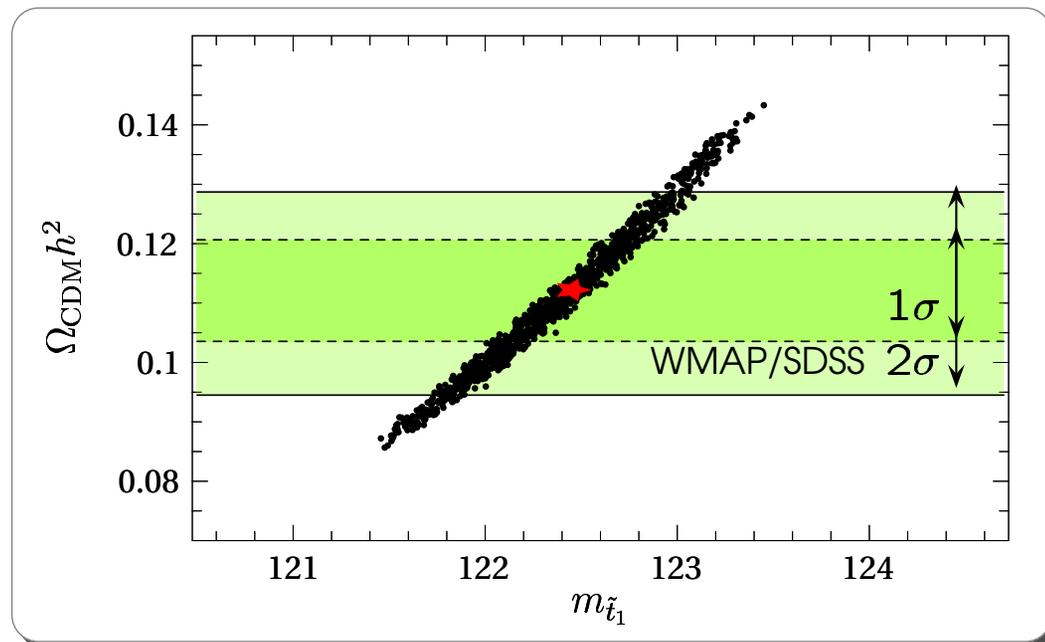
Use program by [D. Morrissey](#) for calculating Ω_{CDM}

Balázs, Carena, Menon, Morrissey, Wagner '04

Use inputs and propagate errors from

- Stop sector
- Chargino/neutralino sector
- Higgs sector

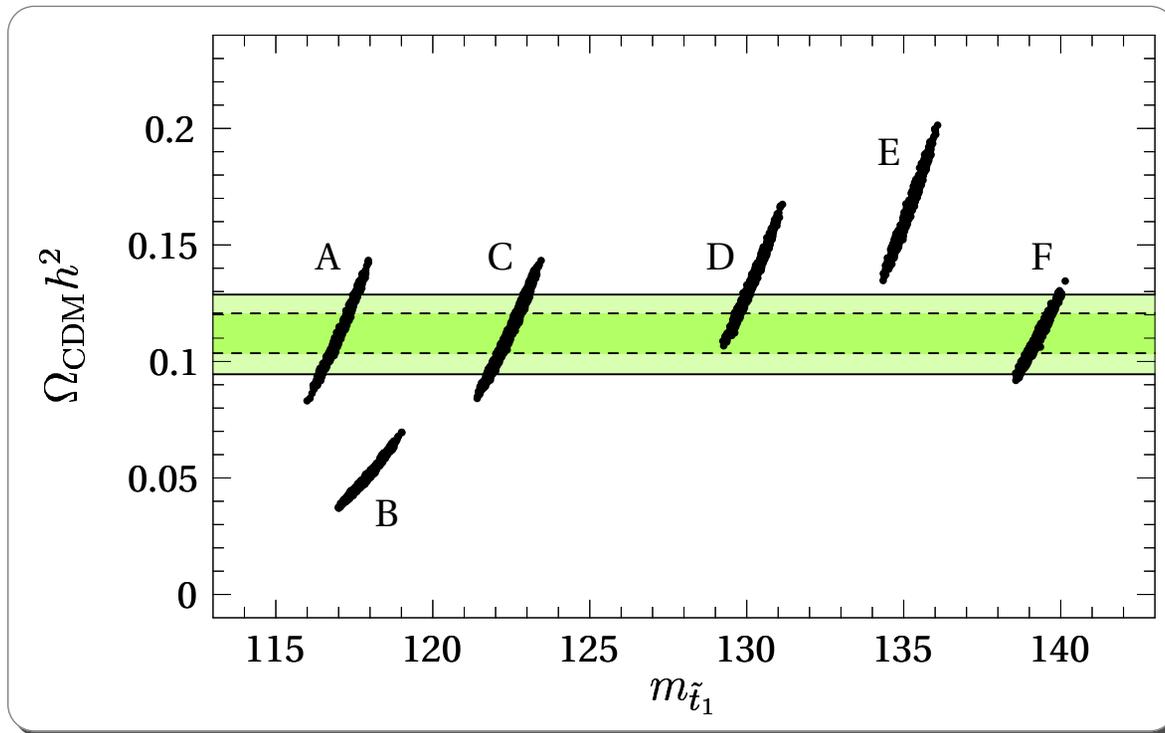
Account for correlations by using χ^2 fit



1σ constraints from
ILC/LHC measurements:
 $0.086 < \Omega_{\text{CDM}} h^2 < 0.143$
dominated by error on $m_{\tilde{t}_1}$

WMAP/SDSS (95% CL):
 $0.095 < \Omega_{\text{CDM}} h^2 < 0.129$

Different SUSY scenarios



ILC measurements could lead to different conclusions:

- Agreement with cosmological observations (A,C,E)
- SUSY predicts too little DM (B)
→ other sources?
- SUSY predicts too much DM (D,E)
→ constraints on parameters, revision of model of universe?

Conclusions

- ILC can cover complete stop-neutralino co-annihilation scenario
Can explore mass differences down to
$$\Delta m = m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0} \sim \mathcal{O}(5 \text{ GeV})$$
- Prediction of Ω_{CDM} in MSSM from collider measurements with precision comparable to cosmological measurements

Future avenues:

- Further refinements of the experimental analysis
- Analyze different dark matter scenarios
- Investigate effect of radiative corrections

Maybe at one point we will be able to figure out what this is