Making and Detecting Supersymmetric Dark Matter

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A typical spiral galaxy

Rotation curve

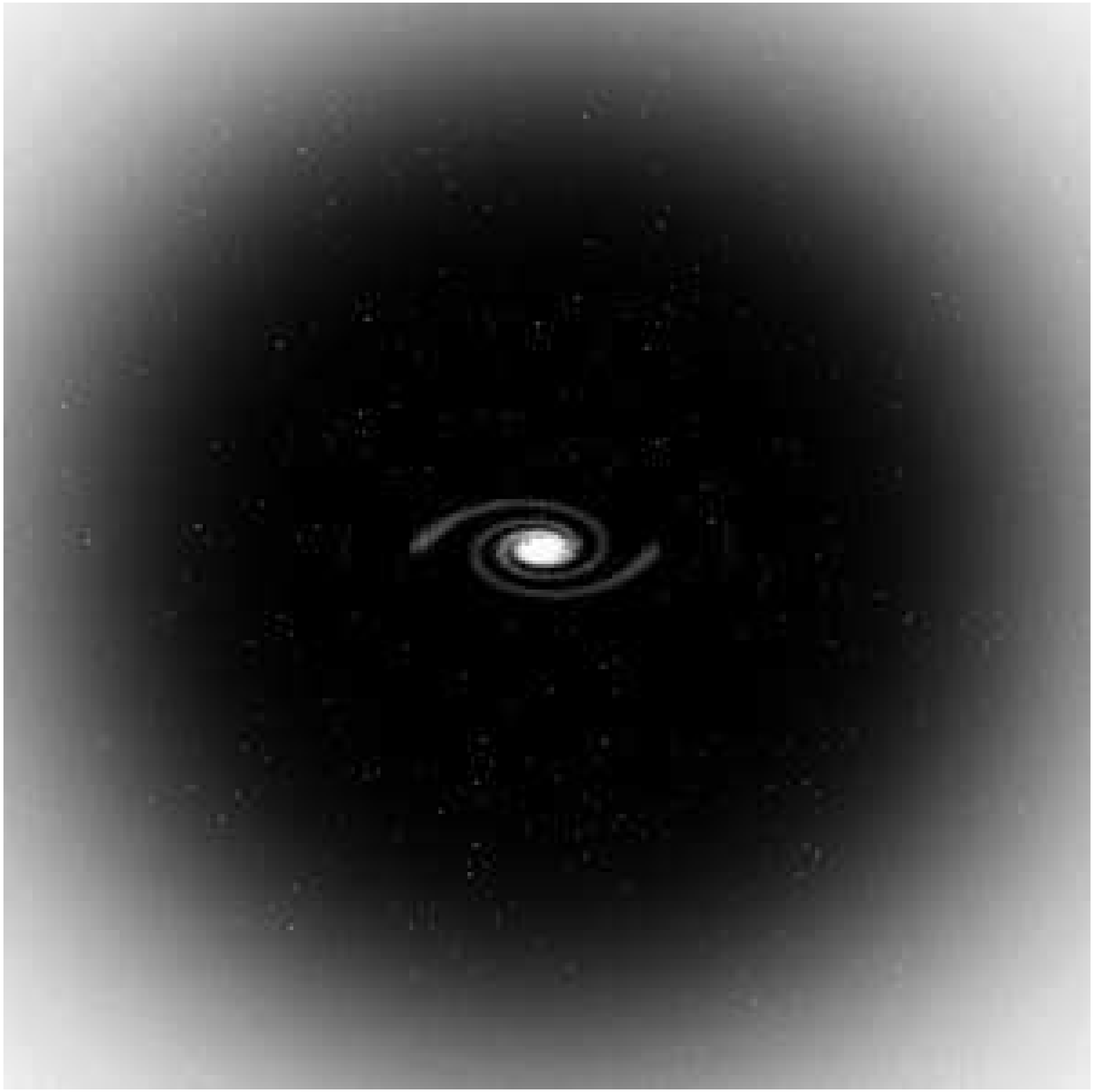
- Spiral galaxies rotate
- For object on stable circular orbit:

$$\begin{aligned} \text{centripetal force} &= \text{gravitational force} \\ \frac{v^2}{R} &= G_N \frac{M(R)}{R^2} \end{aligned}$$

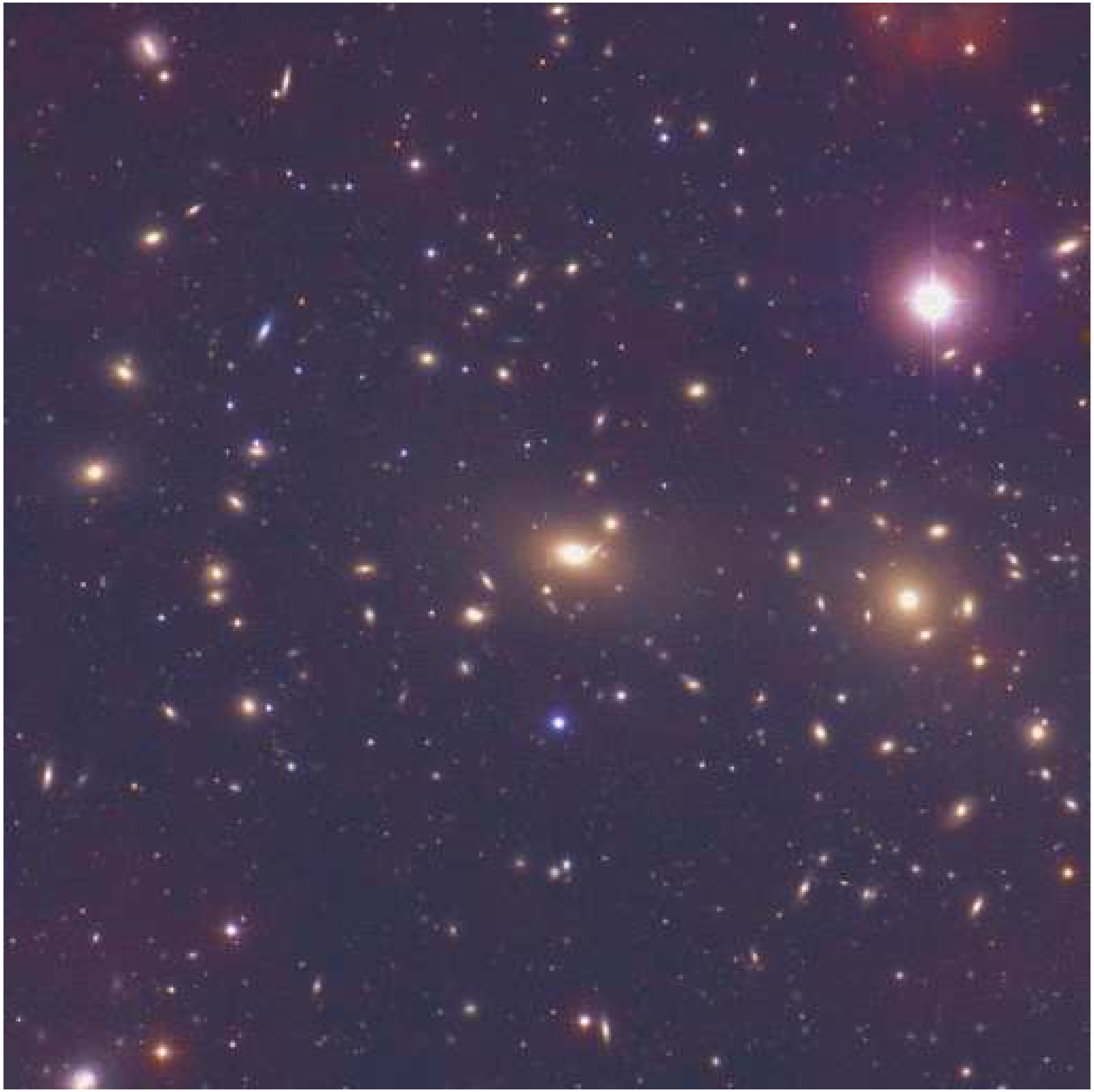
$M(R)$: Mass w/in orbit

- For large R: $M(R) \longrightarrow const.$, i.e. expect $v(R) \propto 1/\sqrt{R}$
- Observe: $v(R) \simeq const.$
- $\Longrightarrow M(R) \propto R$: Invisible, “Dark” Matter forms halo around visible galaxy

True picture of a galaxy



A typical galaxy cluster



Dark matter in clusters of galaxies

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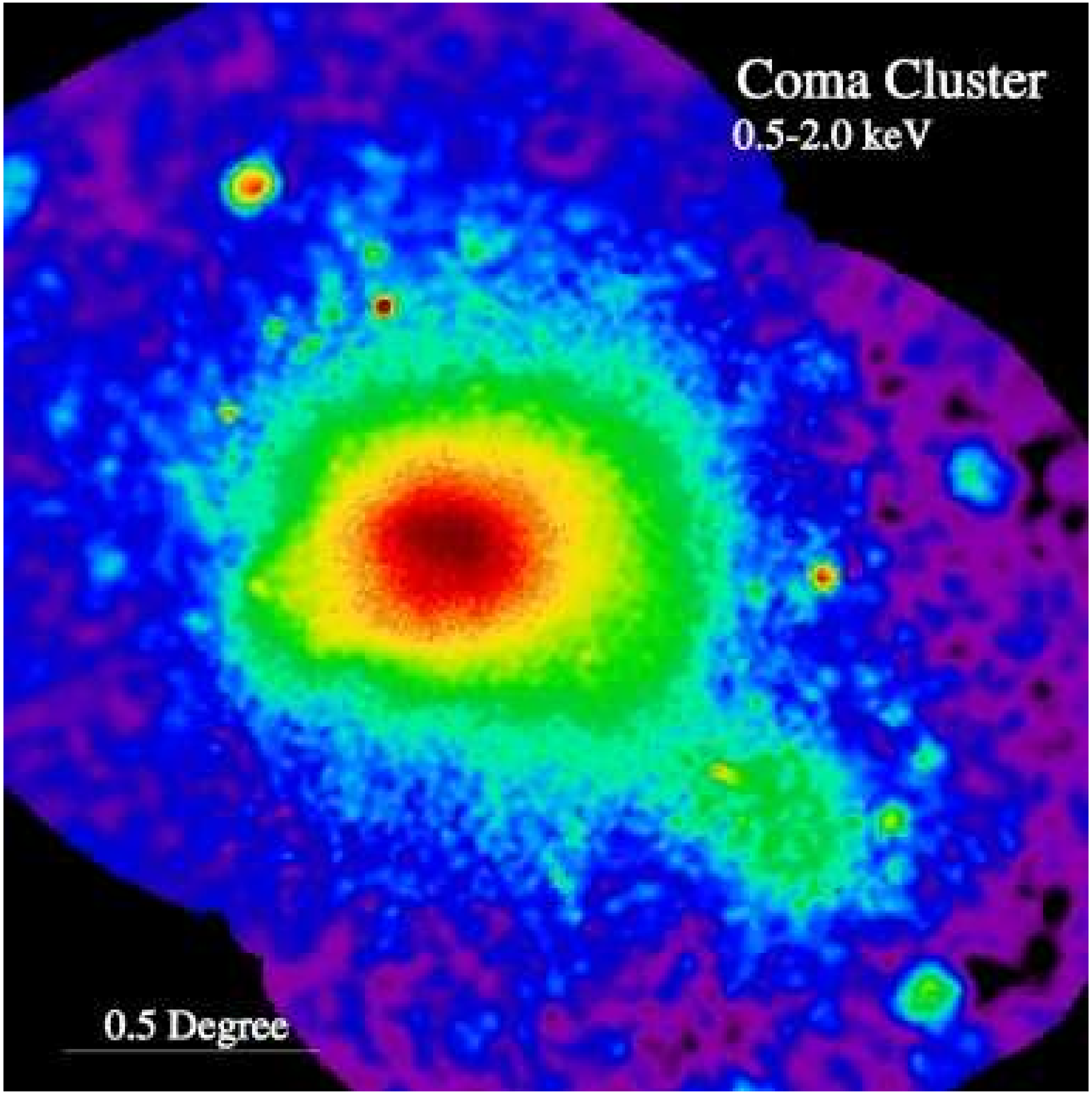
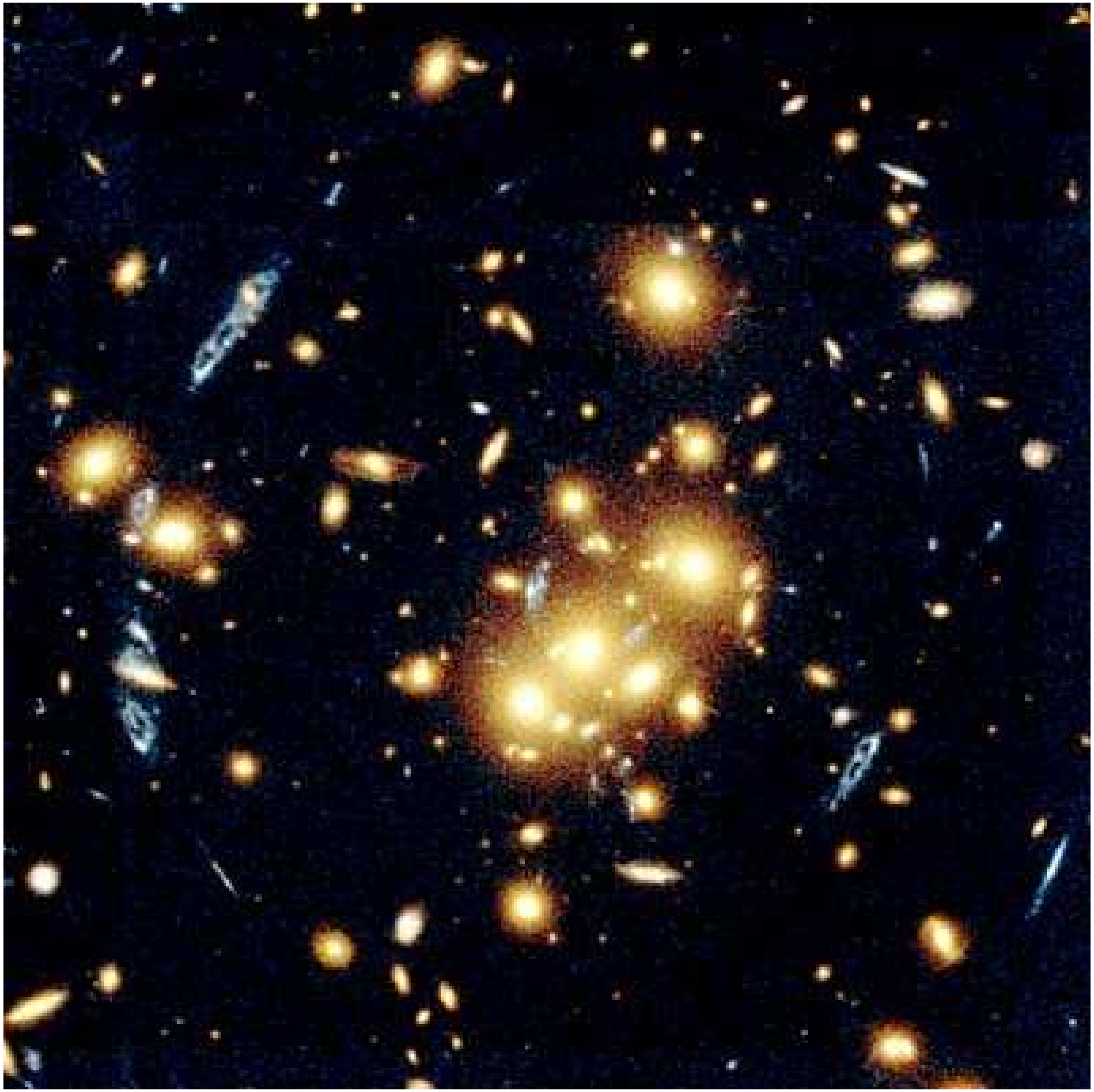
- “Gravitational lensing”: Mass deflects light, by angle $\propto$ mass: Most direct way to measure $M_{\rm cluster} \geq 10 \times M_{\rm visible}$!

Same cluster in X–ray light



Example of gravitational lensing

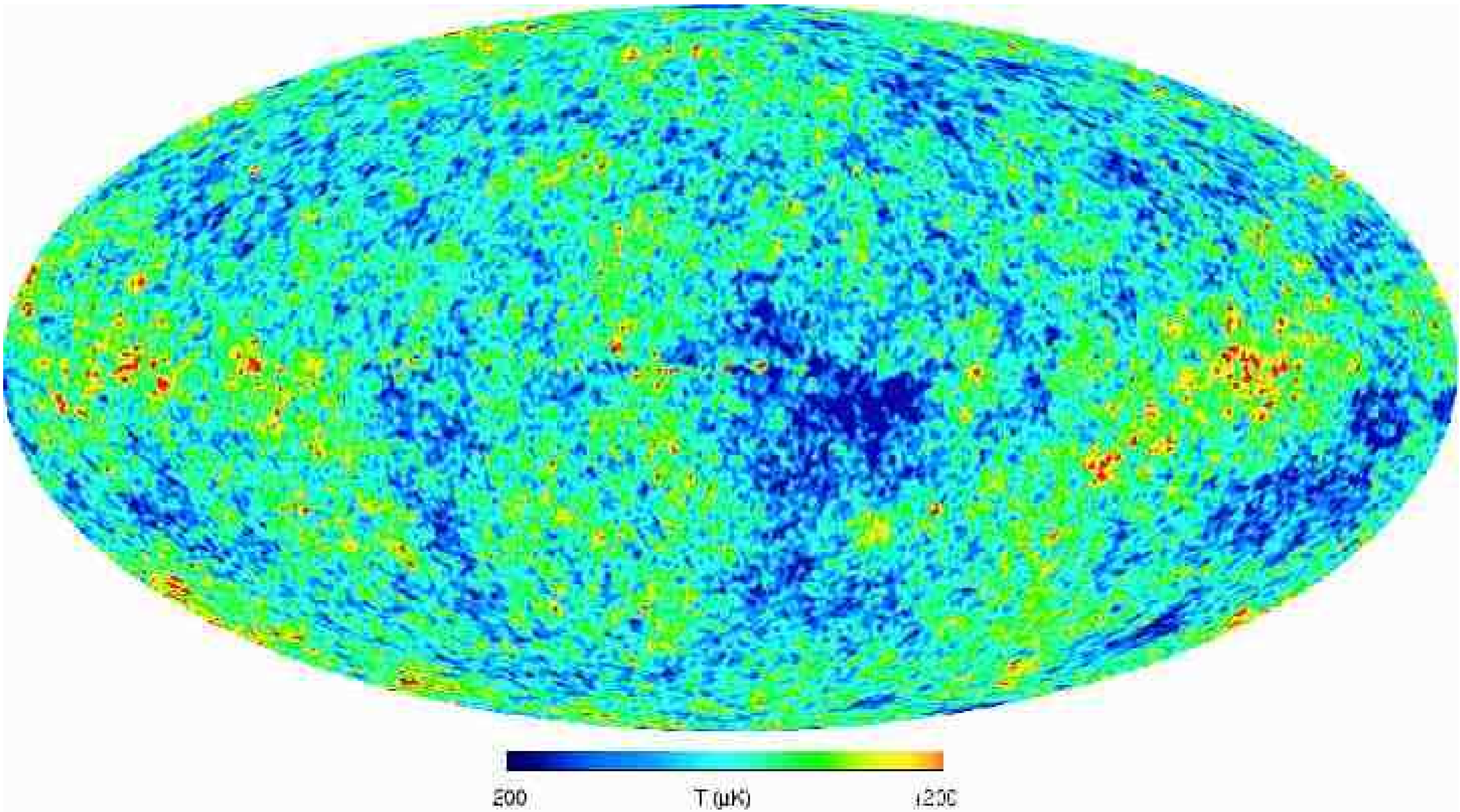


Cosmic Microwave Background (CMB)

(CMB)

- Prediction: Gamov 1950; Discovery: Penzias und Wilson 1964
- Mean temperature: 2.7 K ($= -270°$C)
- Temperature variation: $\delta T \simeq 10^{-4}$ K
- From angular distribution and size of these variations: can determine cosmological parameters!

The Microwave Sky



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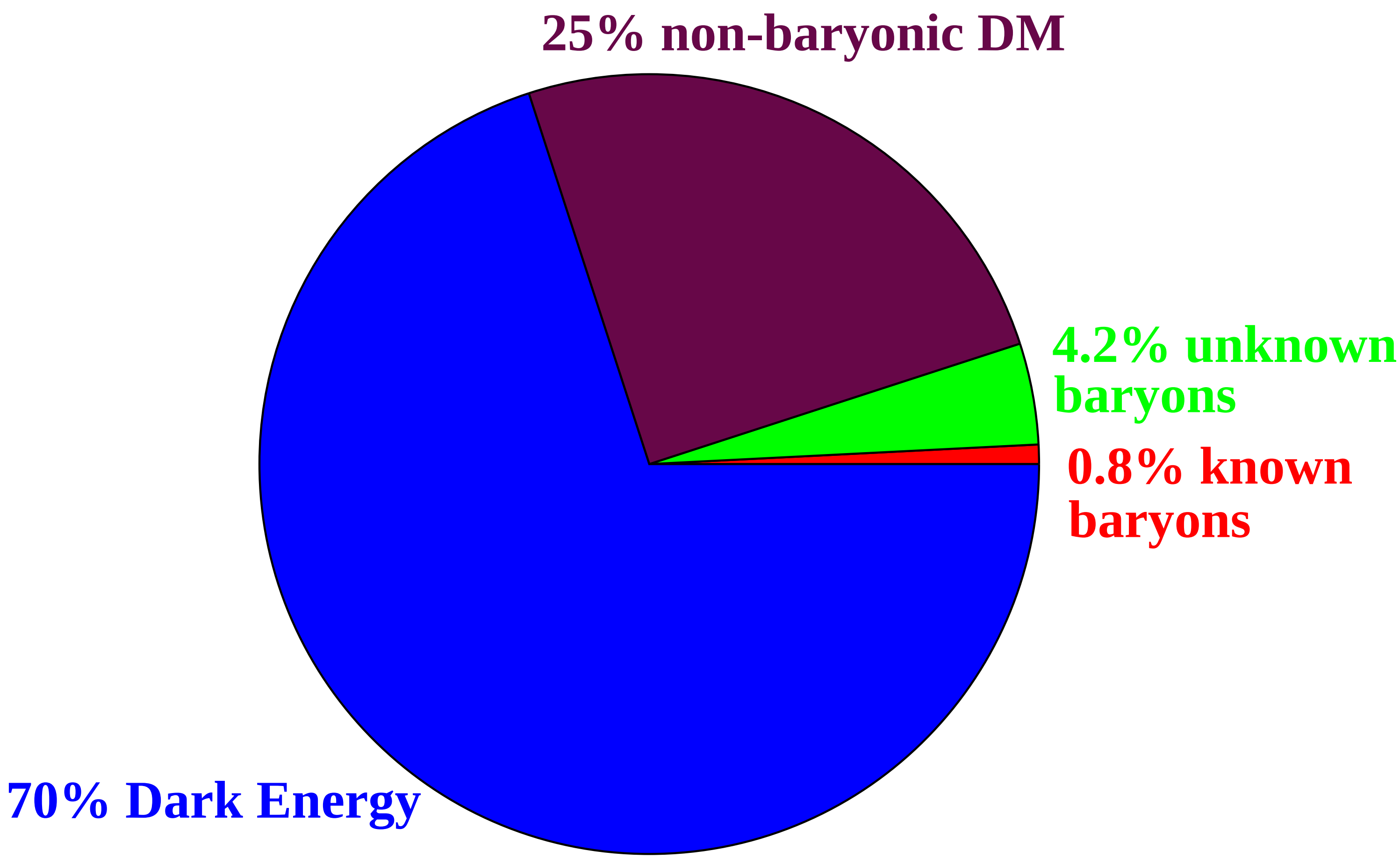
- Universal Dark Matter density: $\Omega_{\rm DM} h^2 = 0.105^{+0.007}_{-0.013}$

  Spergel et al., astro–ph/0603449

Composition of the Universe



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- Ca. 1 g baryonic matter (air)

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Possible loophole: primordial black holes; not easy to make in sufficient quantity sufficiently early.

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- and has (strongly) suppressed coupling to elm radiation

Remarks

- Precise “WMAP” determination of DM density hinges on assumption of “standard cosmology”, including assumption of nearly scale–invariant primordial spectrum of density perturbations: almost assumes inflation!

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- Evidence for $\Omega_{\rm DM} \gtrsim 0.2$ much more robust than that! (Does, however, assume standard law of gravitation.)

Possible problems with cold DM

Simulations of structure formation show some discrepancies with observations on (sub–)galactic length scales:

- Too many sub–halos are predicted: Might well be "dark dwarves" (w/o baryons; perhaps blown out by first supernovae)

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- Too many sub–halos are predicted: Might well be “dark dwarves” (w/o baryons; perhaps blown out by first supernovae)
- Simulations seem to over–predict DM density near centers of galaxies (“cusp problem”). Warning: many things going on in these regions!

DM is collisionless!

Observation of merging cluster 1E0657-56 (“bullet cluster”):

- Using X–rays (CHANDRA): observes hot (baryonic) gas

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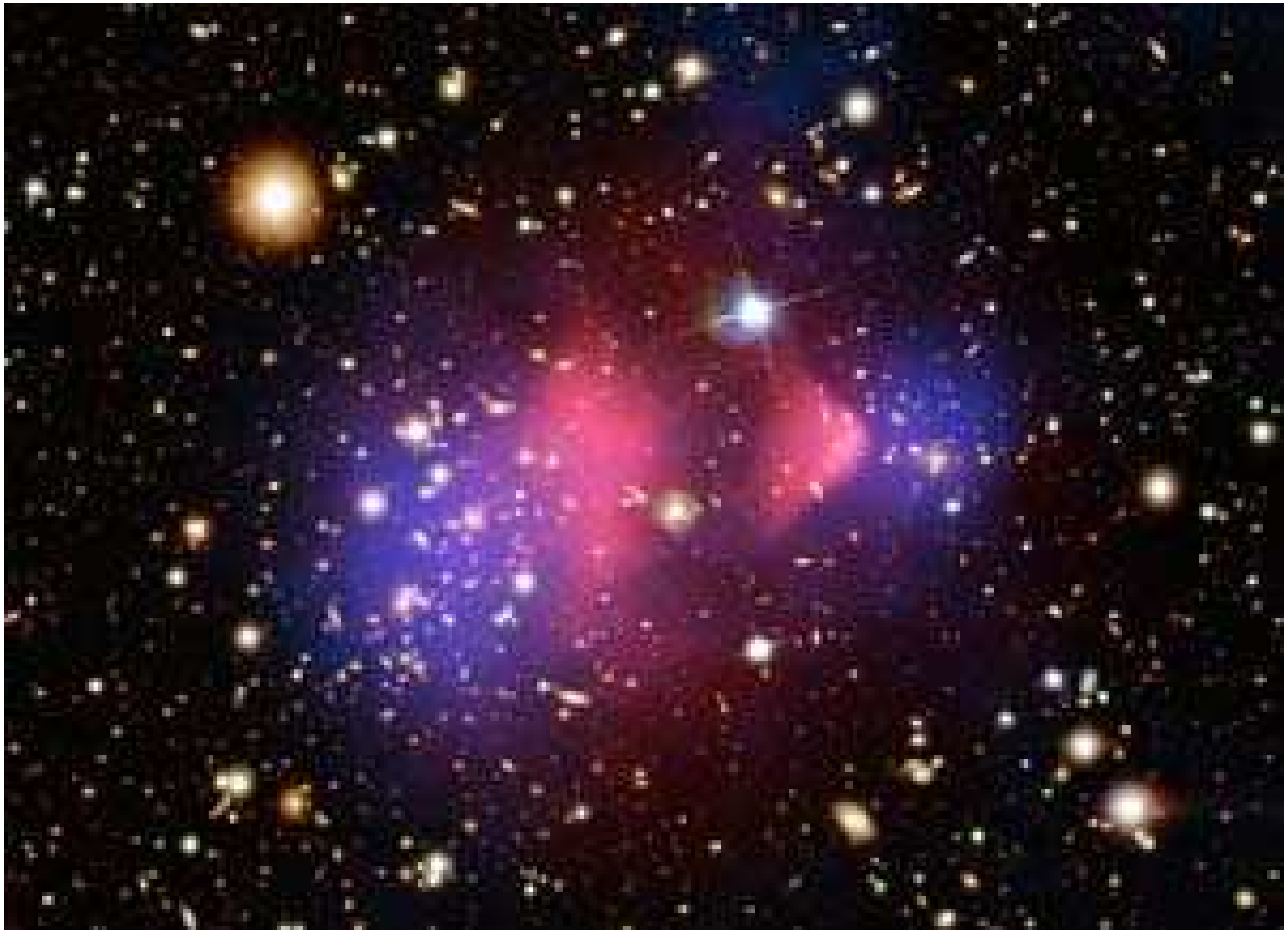
Resulting bound on DM–DM scattering cross section constrains models of interacting DM! Markevitch et al., astro–ph/0309303

Bullet cluster



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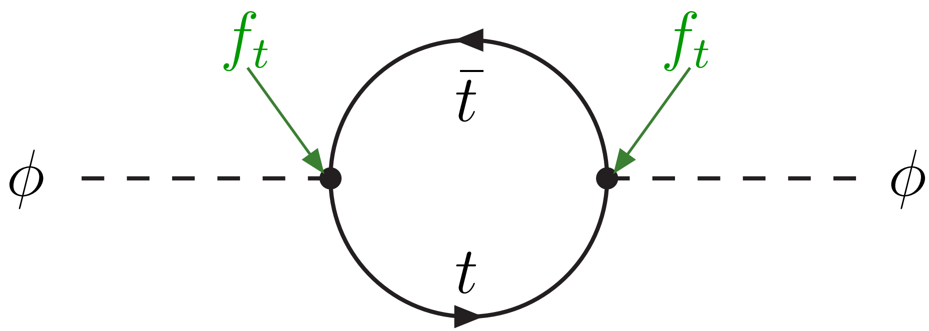
- $SU(2) \times U(1)$ invariance forbids all particle masses $\Longrightarrow$
- Need Higgs mechanism for spontaneous symmetry breaking; requires elementary spin–0 Higgs boson(s)

The naturalness/hierarchy problem

Standard Problem of Standard Model of particle physics: corrections to Higgs boson mass diverge quadratically!



$$\delta m^2_{\phi,t} = \frac{3 f_t^2}{8\pi^2}\Lambda^2 + \mathcal{O}(\Lambda/m_\phi)$$

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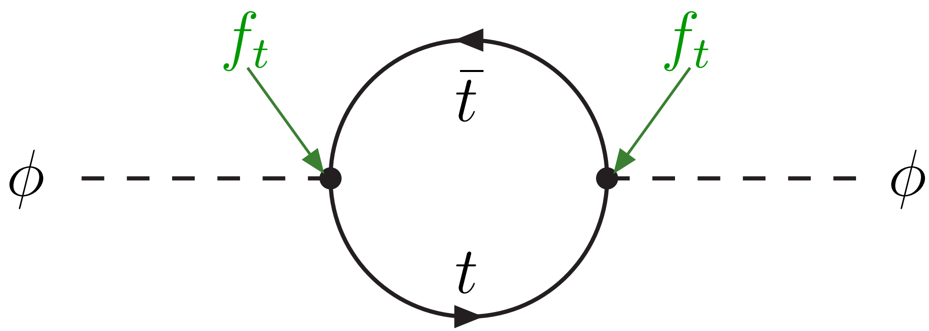

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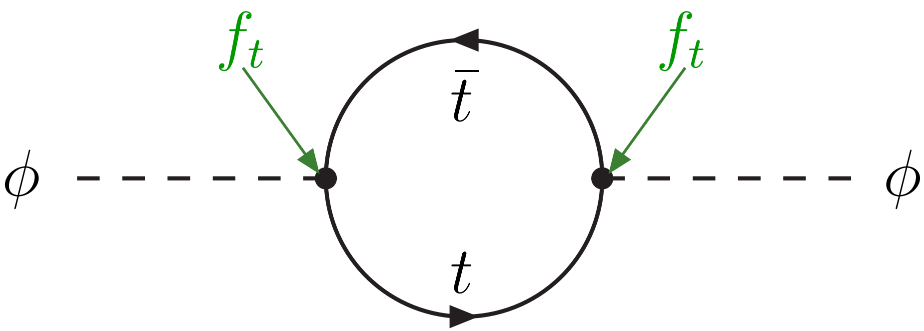

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If $m^2_{\phi,{\rm phys.}} = m^2_{\phi,0} + \delta m^2_\phi =\simeq (100 \text{ GeV})^2$: Need to finetune $m^2_{\phi,0}$ to 1 part in 10^{30}!

Nature abhors finetuning

- Quantum corrections to gauge or Yukawa couplings at worst diverge logarithmically: not so bad even for $\Lambda = M_{\mathrm{Planck}}$.

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- Standard cosmology has "flatness problem":
$$\Omega_{\rm BBN} - 1 \simeq 10^{-16} \left(\Omega_{\rm now} - 1 \right)$$
Here: $\Omega = \rho/\rho_{\rm crit}$; $\Omega = 1$ means flat Universe.
Is solved by inflation, which predicts:
  - $\Omega_{\rm now} \simeq 1$
  - Approximately scale invariant spectrum of density perturbations

Both predictions were confirmed by WMAP!

Supersymmetry solves finetuning problem

Postulate symmetry between bosons and fermions:

$$\text{boson} \to \text{fermion}, \quad \text{fermion} \to \text{boson}$$

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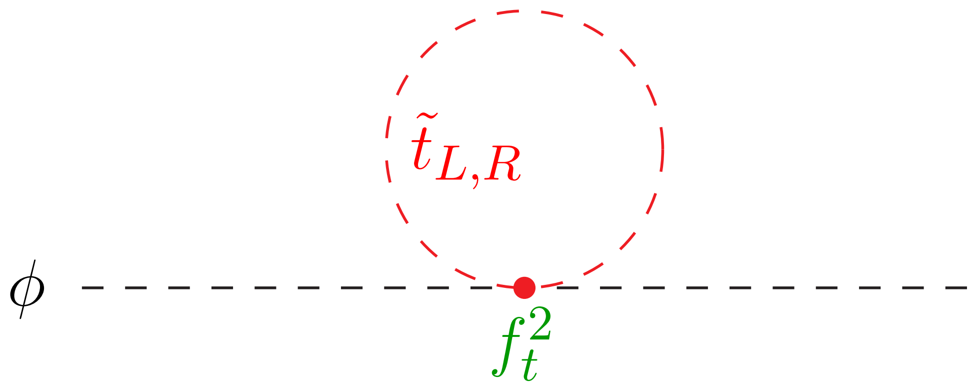
Quantum corrections:

$$\delta m_\phi \underset{\text{SUSY}}{=} \delta m_{\tilde{h}} \propto \ln \frac{\Lambda}{m_\phi}$$

No quadratic divergencies!

Diagrammatically: each chirality state of t quark has scalar superpartner $\tilde{t}_L,\ \tilde{t}_R$: get new corrections:



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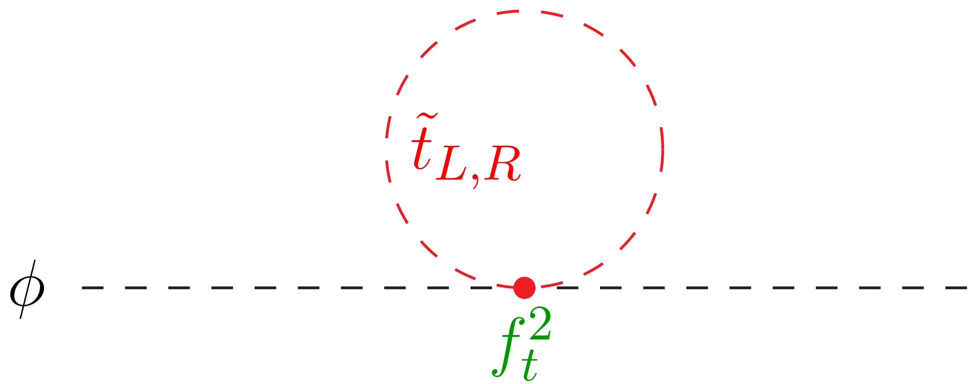

$$\delta m^2_{\phi,\tilde{t}} = -\frac{3f_t^2}{8\pi^2}\Lambda^2 + \cdots = -\delta m^2_{\phi,t} + \mathcal{O}\left([m_t^2 - m_{\tilde{t}}^2]\ln\frac{\Lambda}{m_t}\right)$$

Quadratic divergencies cancel exactly!

Other arguments for Supersymmetry

- Biggest possible symmetry of interacting QFT:
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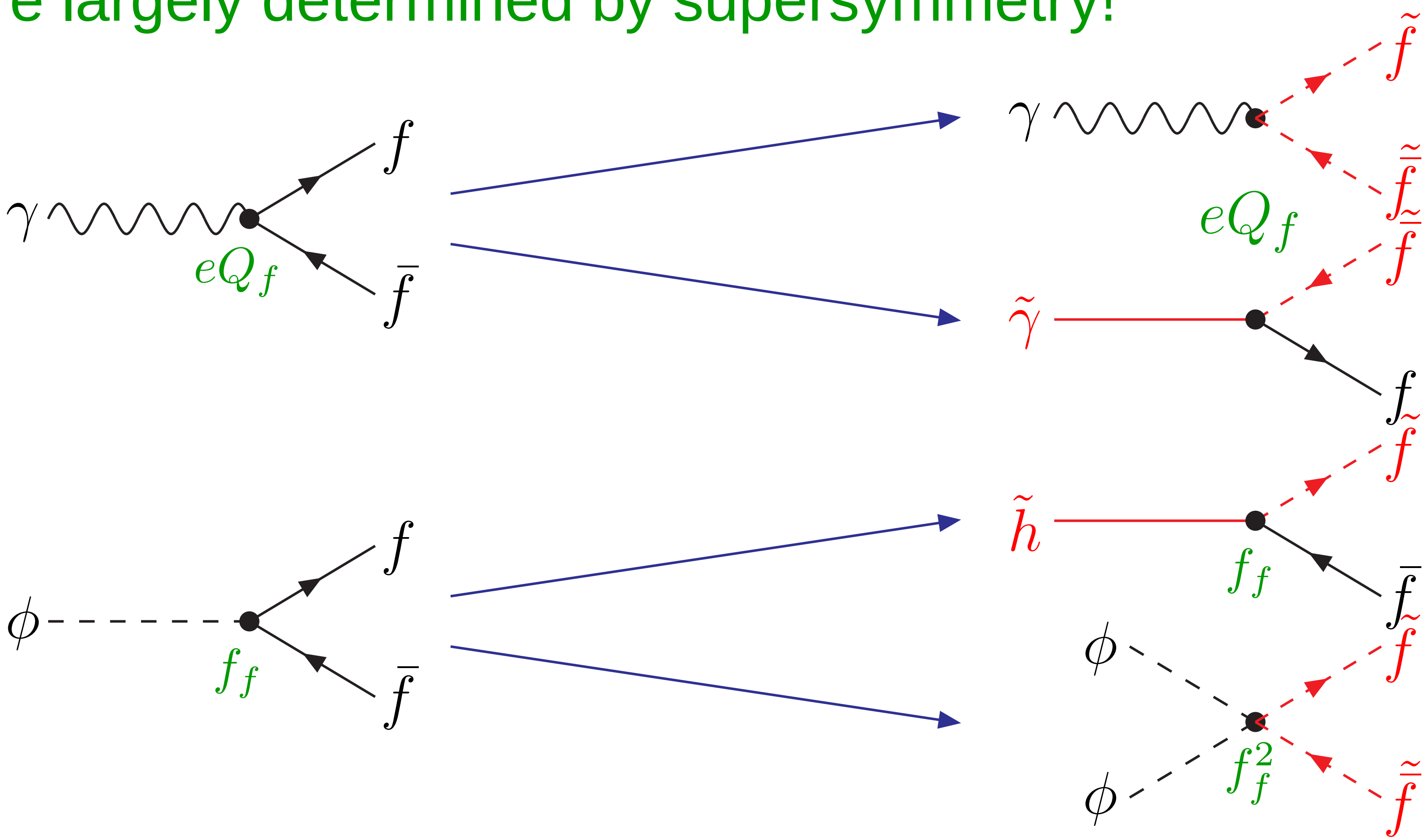
- *Automatically* contains good Dark Matter candidate (see below).

Interactions of superparticles

Are largely determined by supersymmetry!



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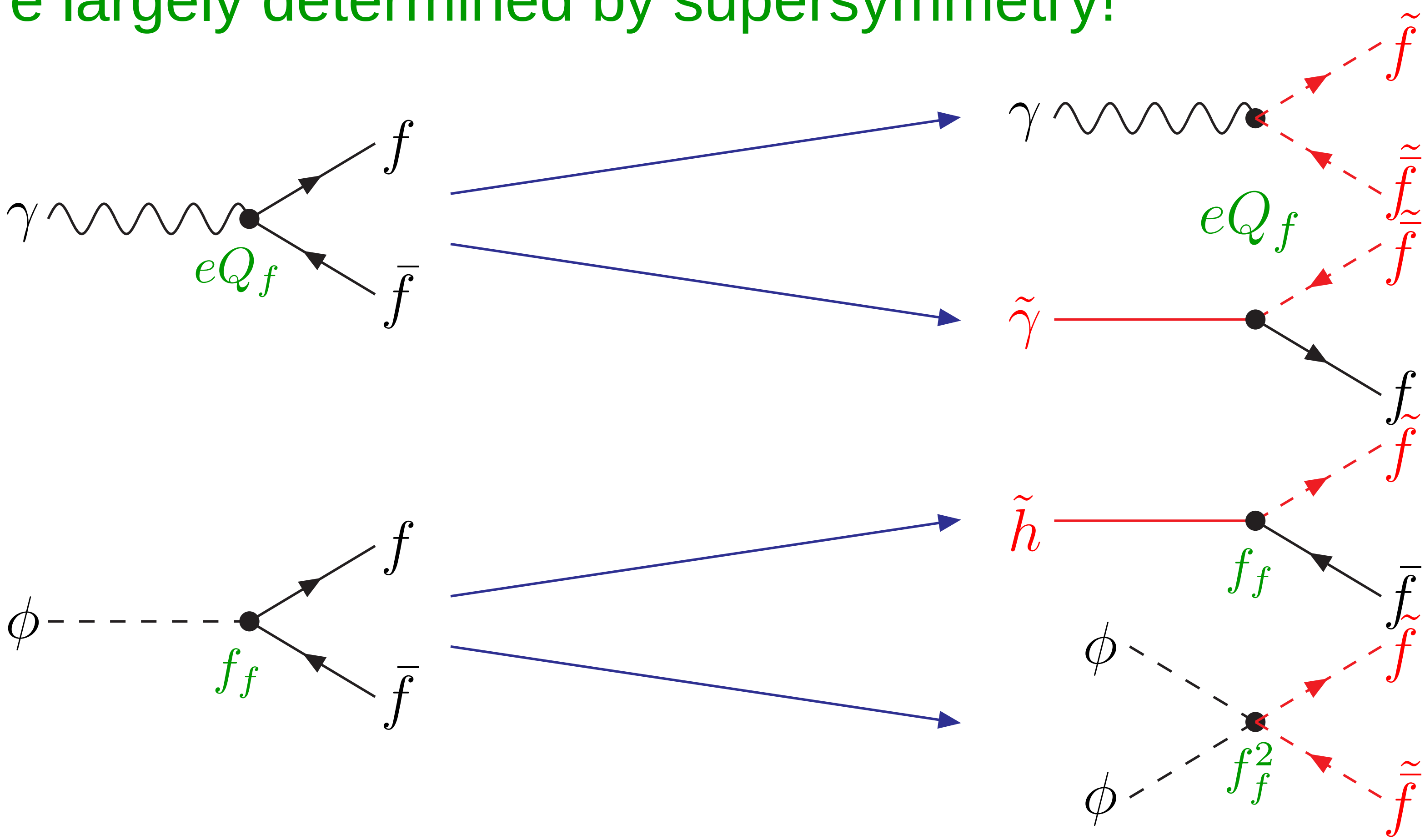

Note: Even number of superpartners at each vertex $\Rightarrow$ the lightest superparticle (LSP) is stable!

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- Postulate simple form of supersymmetry breaking at some high energy scale: Good for global analyses
- Allow general values for parameters relevant for specific process: Good for dedicated phenomenological analyses

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Note: DM is free bonus of Supersymmetry!

Dark Matter production

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Evolution of $n_{\tilde{\chi}}$ determined by Boltzmann equation:

$$\frac{dn_{\tilde{\chi}}}{dt} + 3Hn_{\tilde{\chi}} = -\langle \sigma_{\mathrm{ann}} v \rangle \left(n_{\tilde{\chi}}^2 - n_{\tilde{\chi},\,\mathrm{eq}}^2 \right)$$

$H = \dot{R}/R$: Hubble parameter
$\langle \ldots \rangle$: Thermal averaging
$\sigma_{\mathrm{ann}} = \sigma(\tilde{\chi}\tilde{\chi} \to \mathrm{SM\ particles})$
v : relative velocity between $\tilde{\chi}$'s in their cms
$n_{\tilde{\chi},\,\mathrm{eq}}$: $\tilde{\chi}$ density in full equilibrium

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Gives

$$\Omega_{\tilde{\chi}} h^2 \propto \frac{1}{\langle v \sigma_{\rm ann} \rangle} \sim 0.1 \text{ for } \sigma_{\rm ann} \sim \text{pb}$$

Application: Constraining SUSY Parameter Space

Here: for mSUGRA $\equiv$ CMSSM: define spectrum through:
m_0: Common scalar mass at GUT scale;
$m_{1/2}$: Common gaugino mass at GUT scale;
A_0: Common tri–linear scalar interaction at GUT scale;
$\tan\beta$: Ratio of Higgs vevs; signμ.

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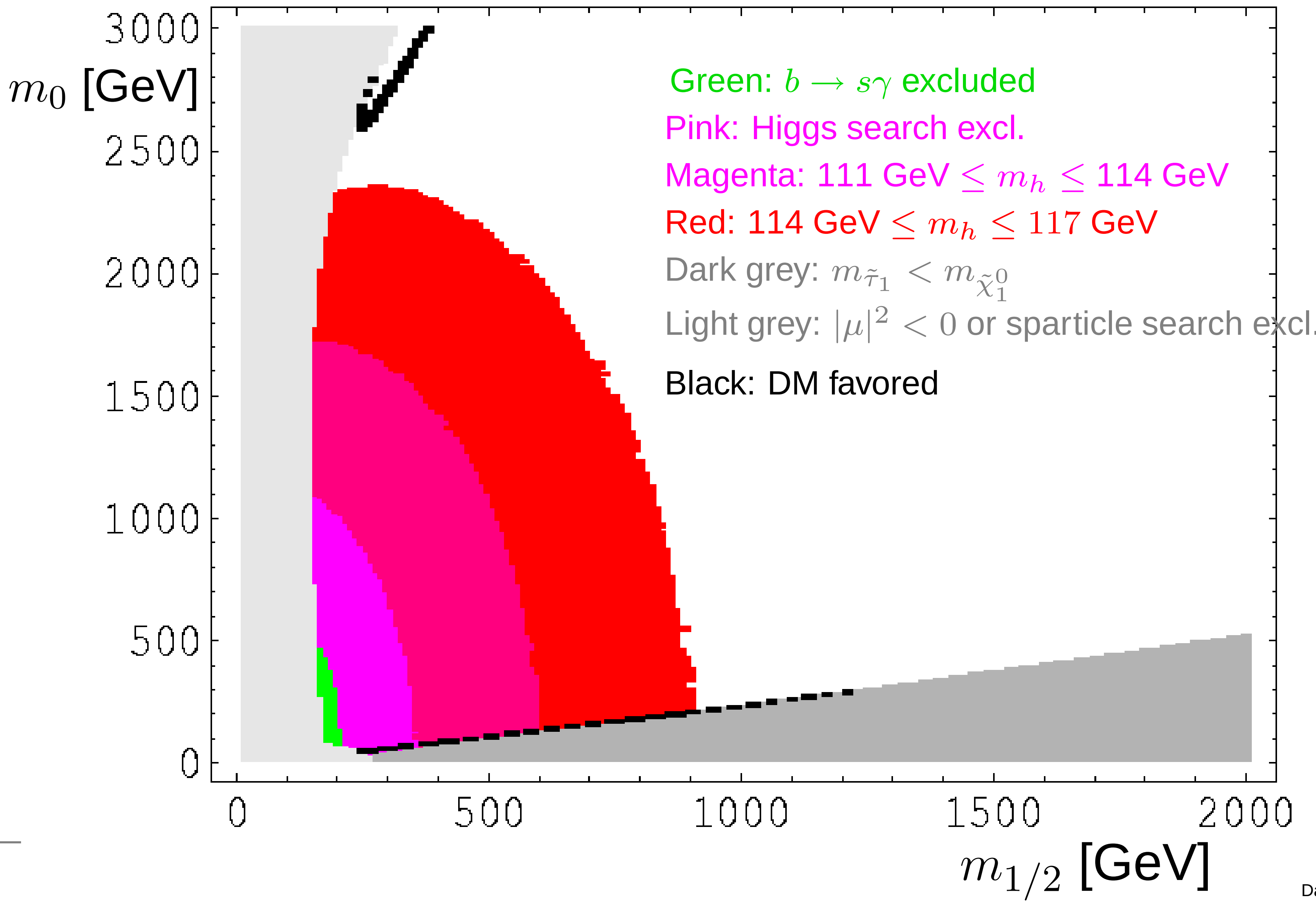
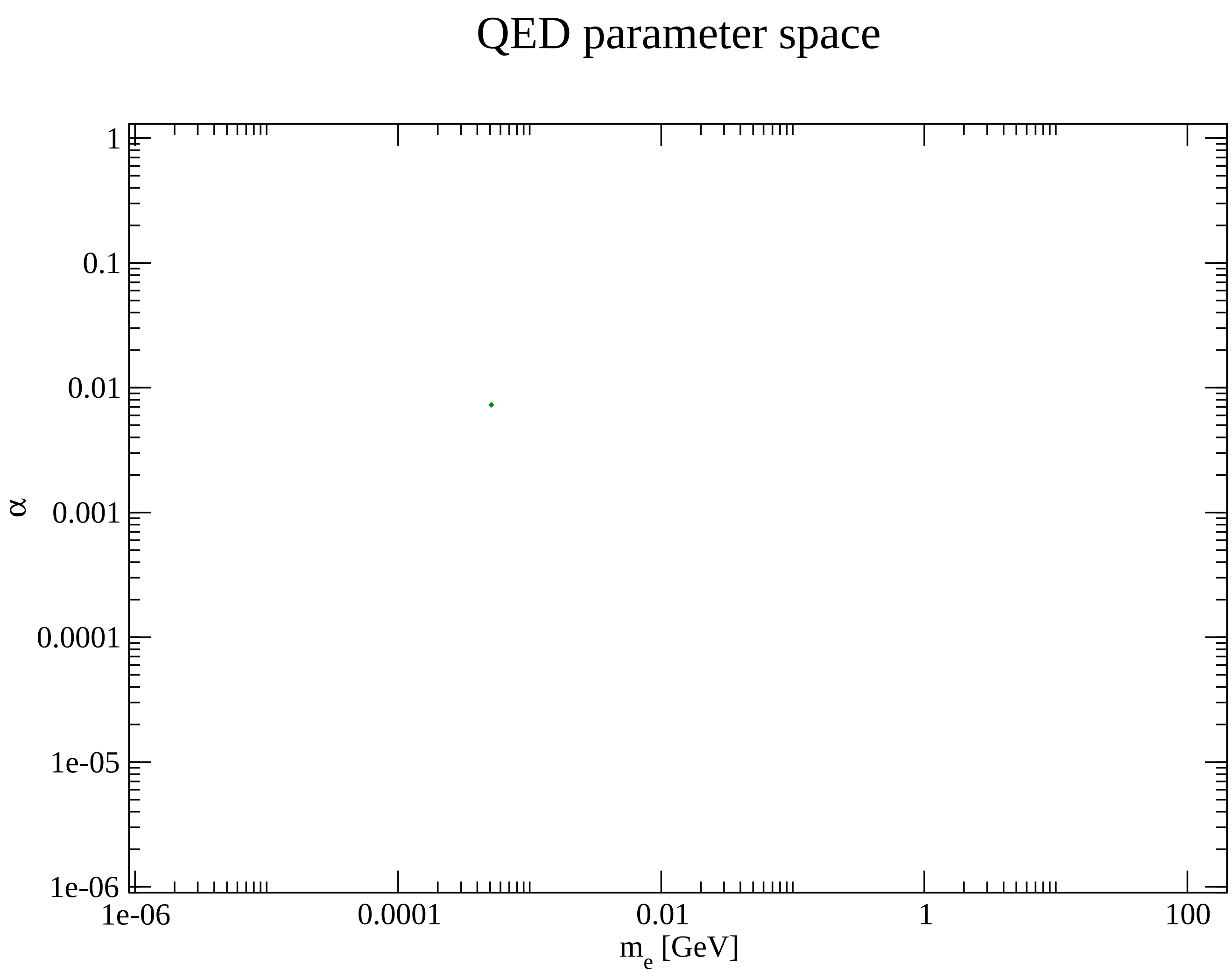
- Radiative symmetry breaking: loop corrections drive (combination of) squared Higgs masses negative, leaving squared sfermion masses positive
- Over much of parameter space, $\tilde{\chi}_1^0$ is stable LSP!

Example: $m_t = 172.7$ **GeV,** $\tan\beta = 10,\ A_0 = 0,\ \mu > 0$

(Djouadi, MD, Kneur, hep–ph/0602001)



Is the apparently small size of the allowed parameter parameter space a problem? Not necessarily . . .



Mass Bounds

More meaningful than "size of allowed parameter space"

mSUGRA, all parameters scanned over allowed region

particle	minimal mass [GeV]			min, max mass	
	basic	incl. $b \to s\gamma$	incl. DM	aggr. a_μ	incl. DM
$\tilde{\chi}_1^0$	52	52	53	53, 359	55, 357
$\tilde{\chi}_1^\pm$	105	105	105	105, 674	105, 667
$\tilde{\chi}_3^0$	135	135	135	135, 996	292, 991
$\tilde{\tau}_1$	99	99	99	99, 1020	99, 915
h	91	91	91	91, 124	91, 124
$H^\pm$	128	128	128	128, 979	128, 960
$\tilde{g}$	359	380	380	399, 1880	412, 1870
$\tilde{d}_R$	406	498	498	498, 1740	498, 1740
$\tilde{t}_1$	102	104	104	231, 1440	244, 1440

Low Temperature Scenarios

Found semi–analytic solution of Boltzmann eq. for low post–inflationary reheat temperature, $T_R \lesssim T_F$. MD, Imminniyaz, Kakizaki, hep-ph/0603165

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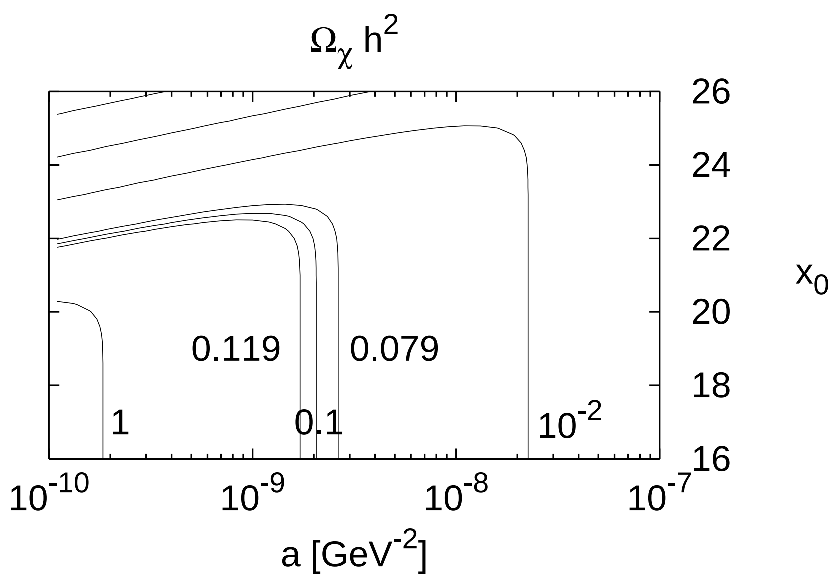

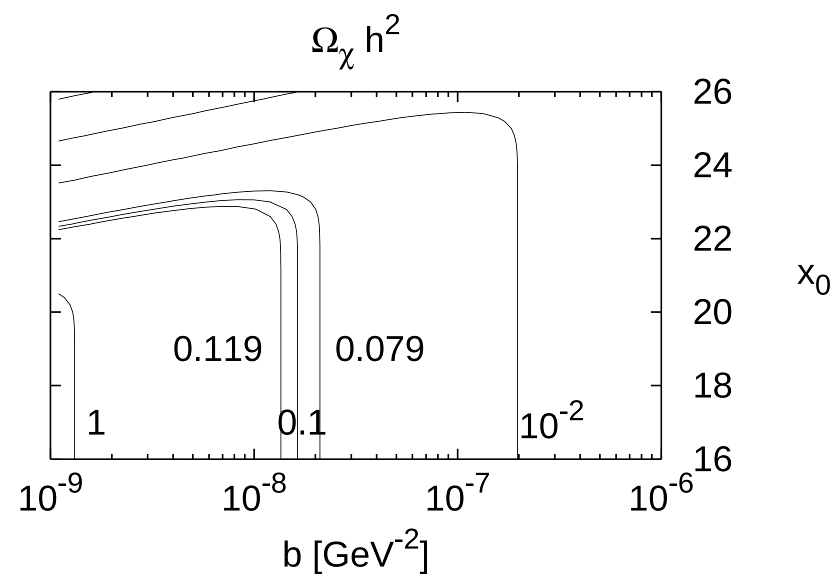

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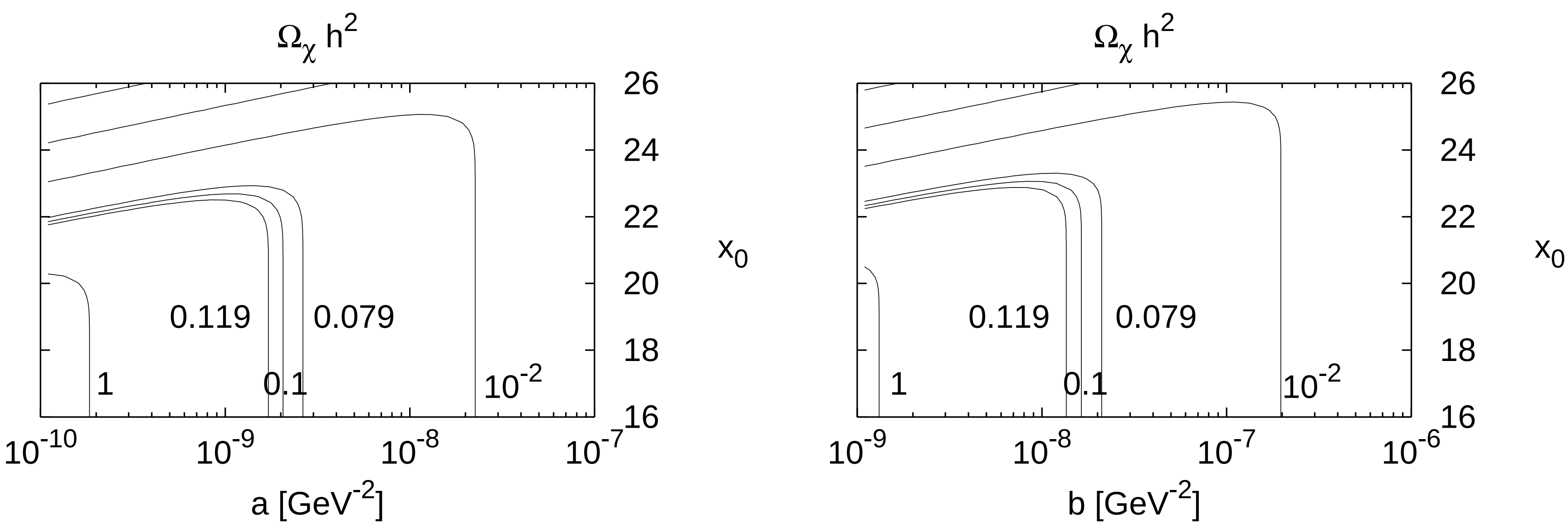

$$\Longrightarrow T_R \geq \frac{m_\chi}{23}$$

Holds independently of σ_{ann}!

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At any given time, several claimed signals, but none is very reliable.

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- Is being pursued vigorously around the world!

Direct WIMP detection: theory

Counting rate given by

$$\frac{dR}{dQ} = AF^2(Q) \int_{v_{\min}}^{v_{\rm esc}} \frac{f_1(v)}{v} dv$$

Q: recoil energy

$A = \rho\sigma_0/(2m_\chi m_r) =$ const.

$F(Q)$: nuclear form factor

v: WIMP velocity in lab frame

$v_{\min}^2 = m_N Q/(2m_r^2)$

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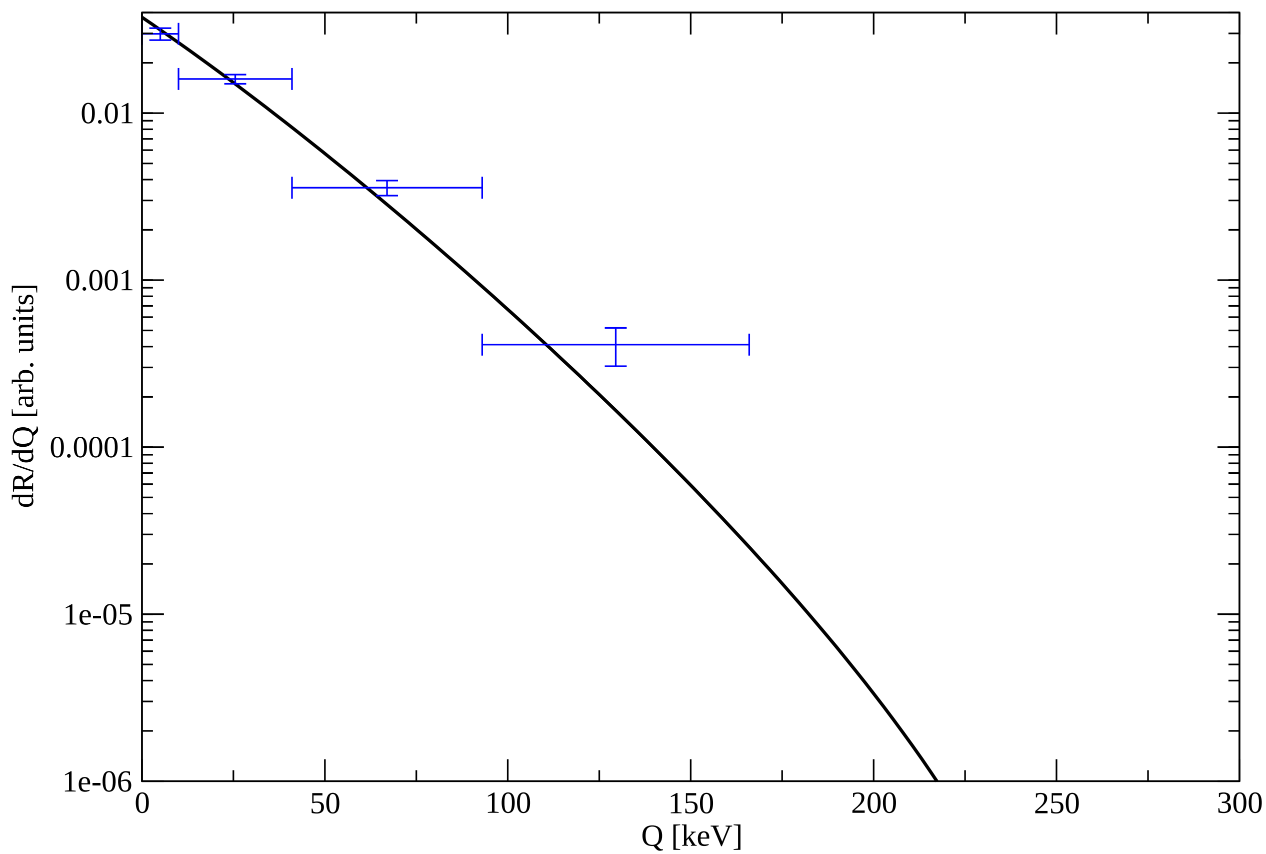
In principle, can invert this relation to measure $f_1(v)$!

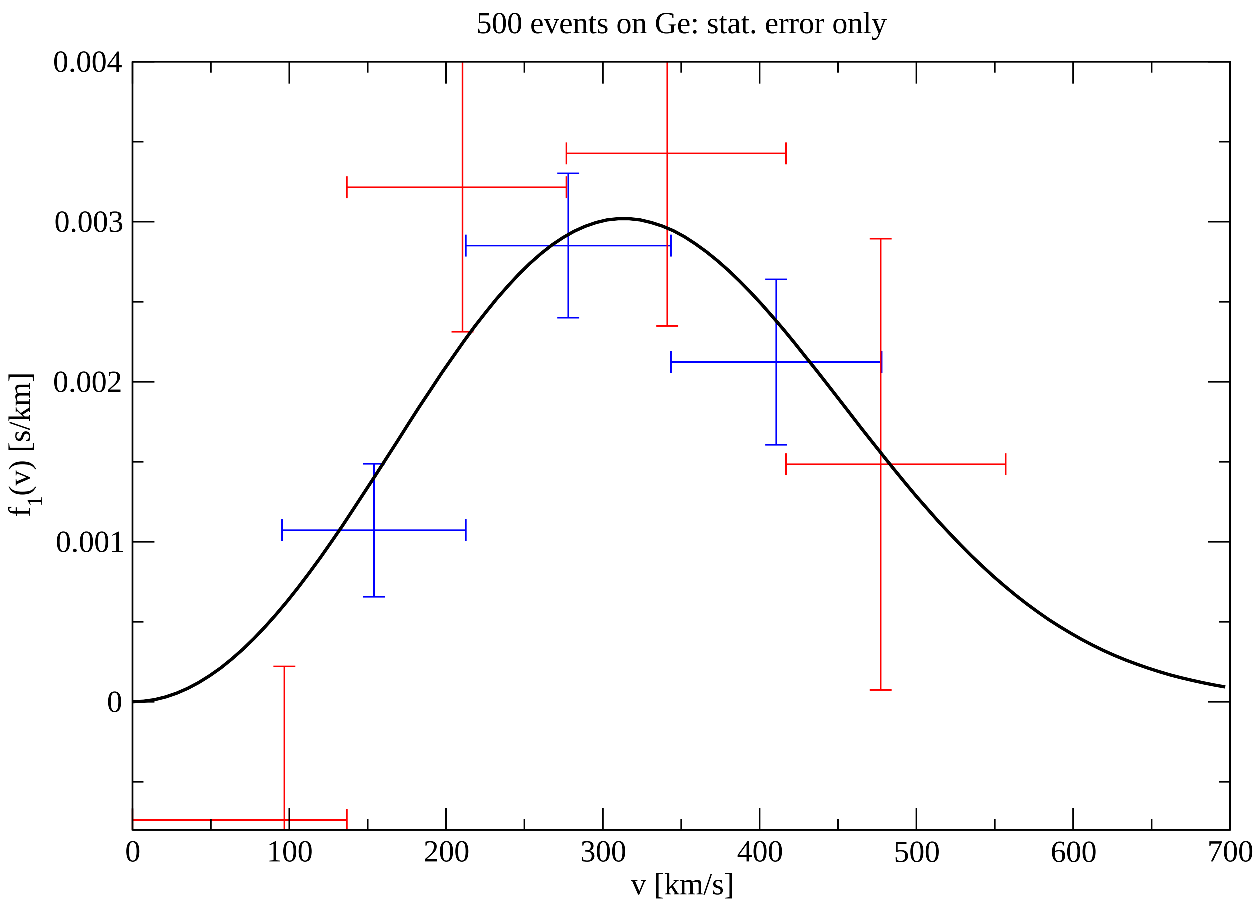
Recoil spectrum: prediction and simulated measurement

MD, Shan, in progress

500 events on Ge



$f_1(v)$: prediction and simulated measurement



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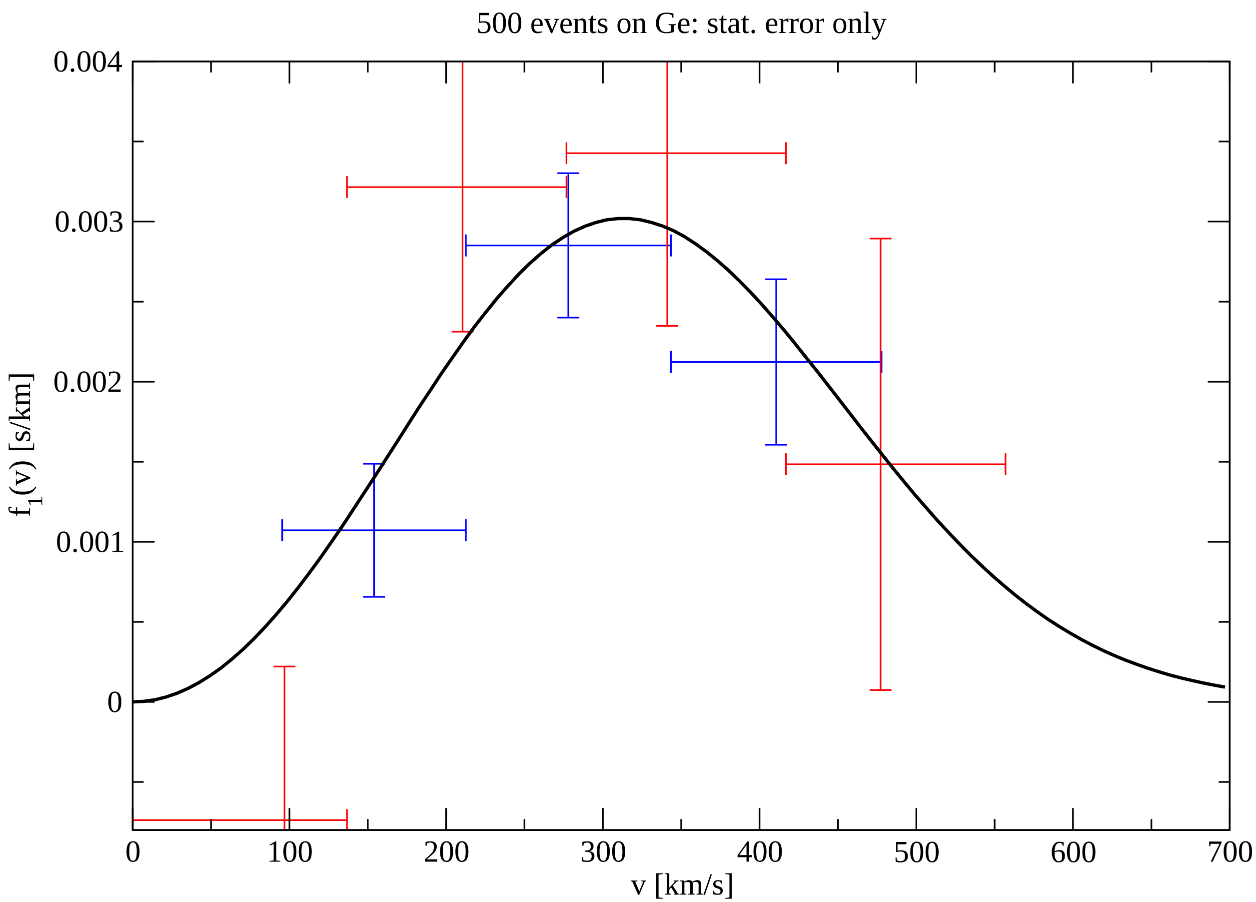

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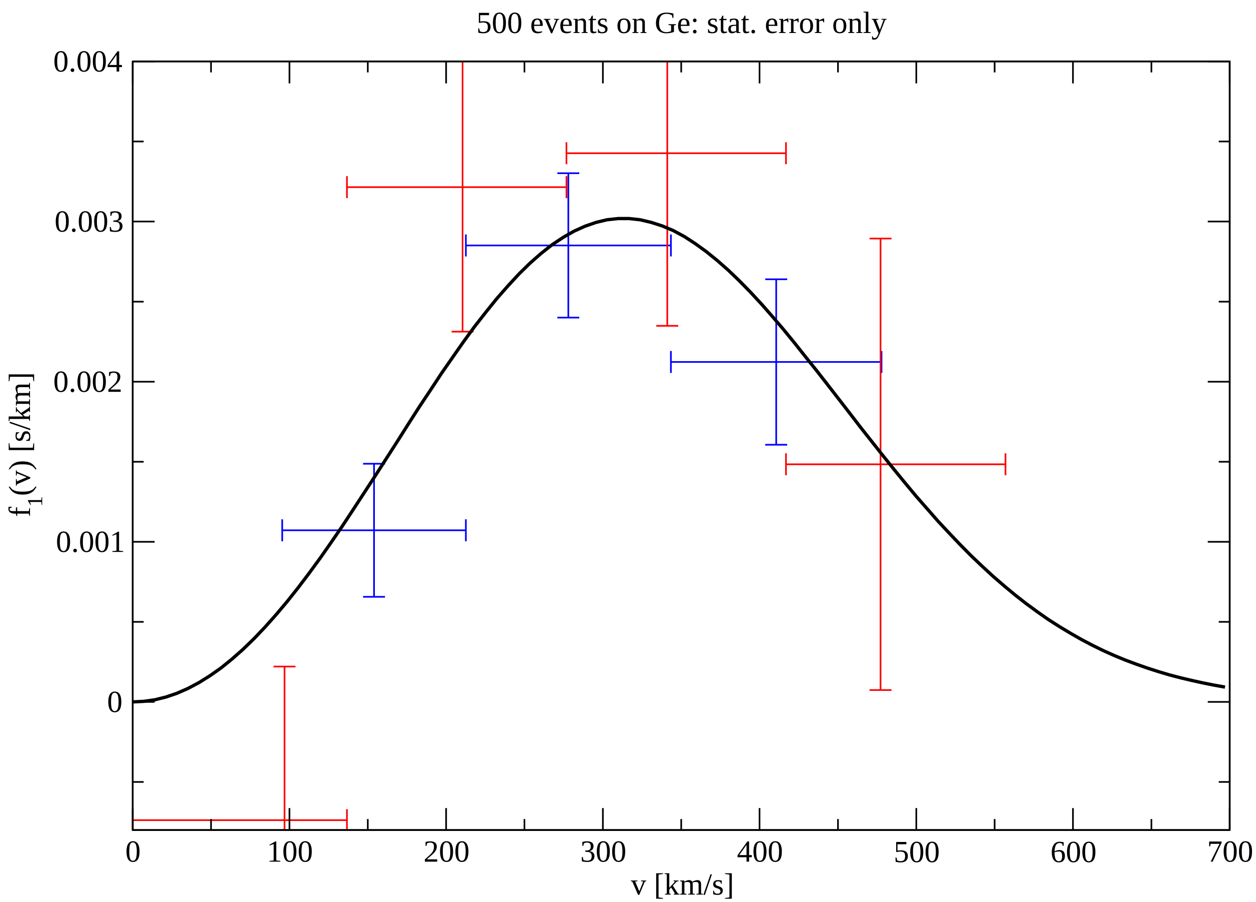

A few moments of $f_1(v)$ may be measurable with relatively few events

Once $f_1(v)$ and $\sigma(\tilde{\chi}N \to \tilde{\chi}N)$ are known: Can measure local $\rho_{\tilde{\chi}}$.

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- Neutralinos in mSUGRA remain well motivated, viable candidate
- Thermal production of DM particles remains most attractive mechanism: least dependent on details of cosmology
- If DM is made from thermal LSPs: lower bound on T_R increases by factor $\sim 10^4$
- LSP Dark Matter can be detected in a variety of ways; once detected, allows new probes of Universe