

COSMOLOGY AND THE LHC

Neal Weiner

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THE GREATEST EXPERIMENTS ON EARTH

With the Tevatron shutting down, the two
great experiments of our time will be

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The LHC

THE GREATEST EXPERIMENTS ON ~~EARTH~~

anywhere

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great experiments of our time will be



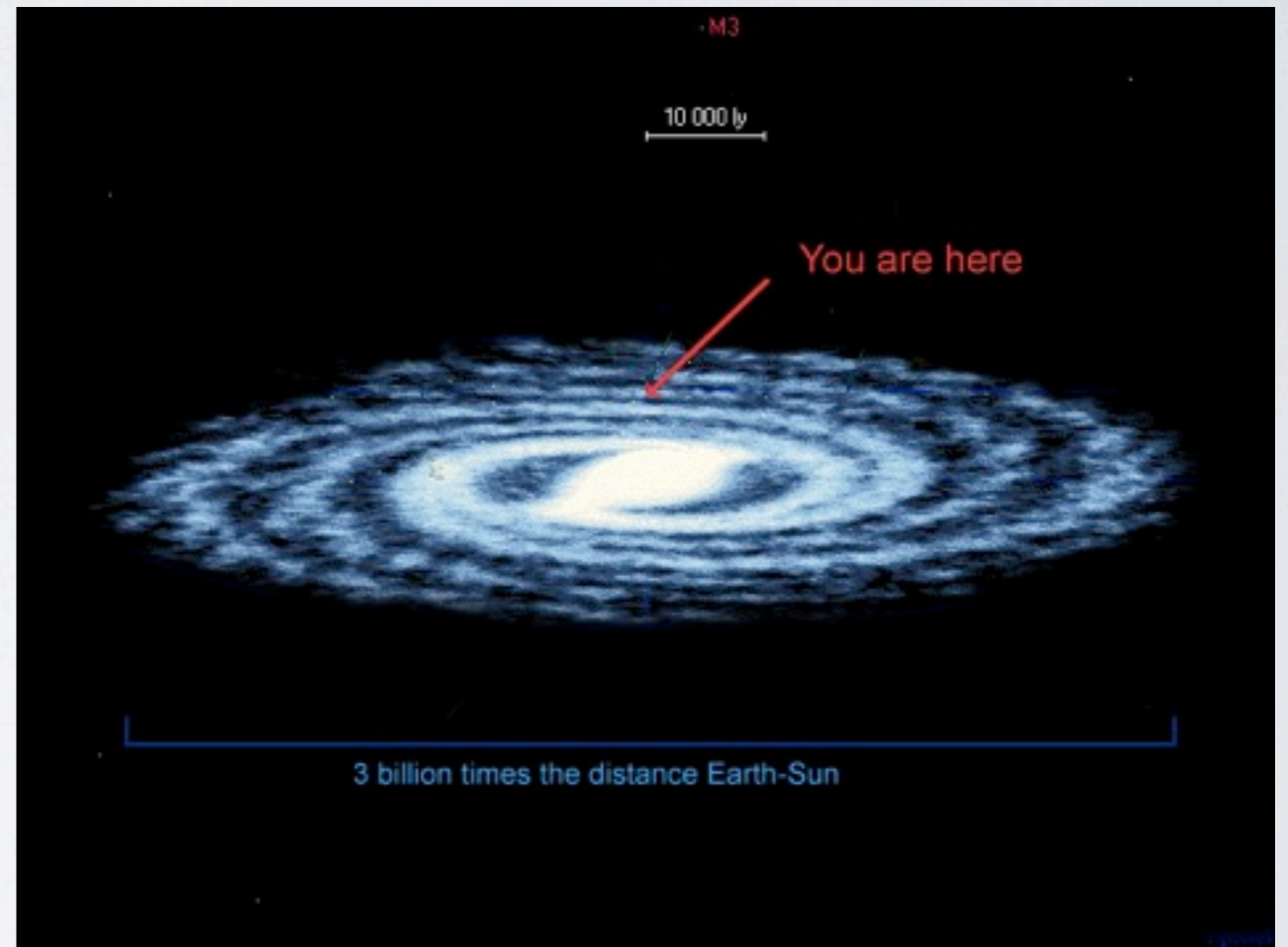
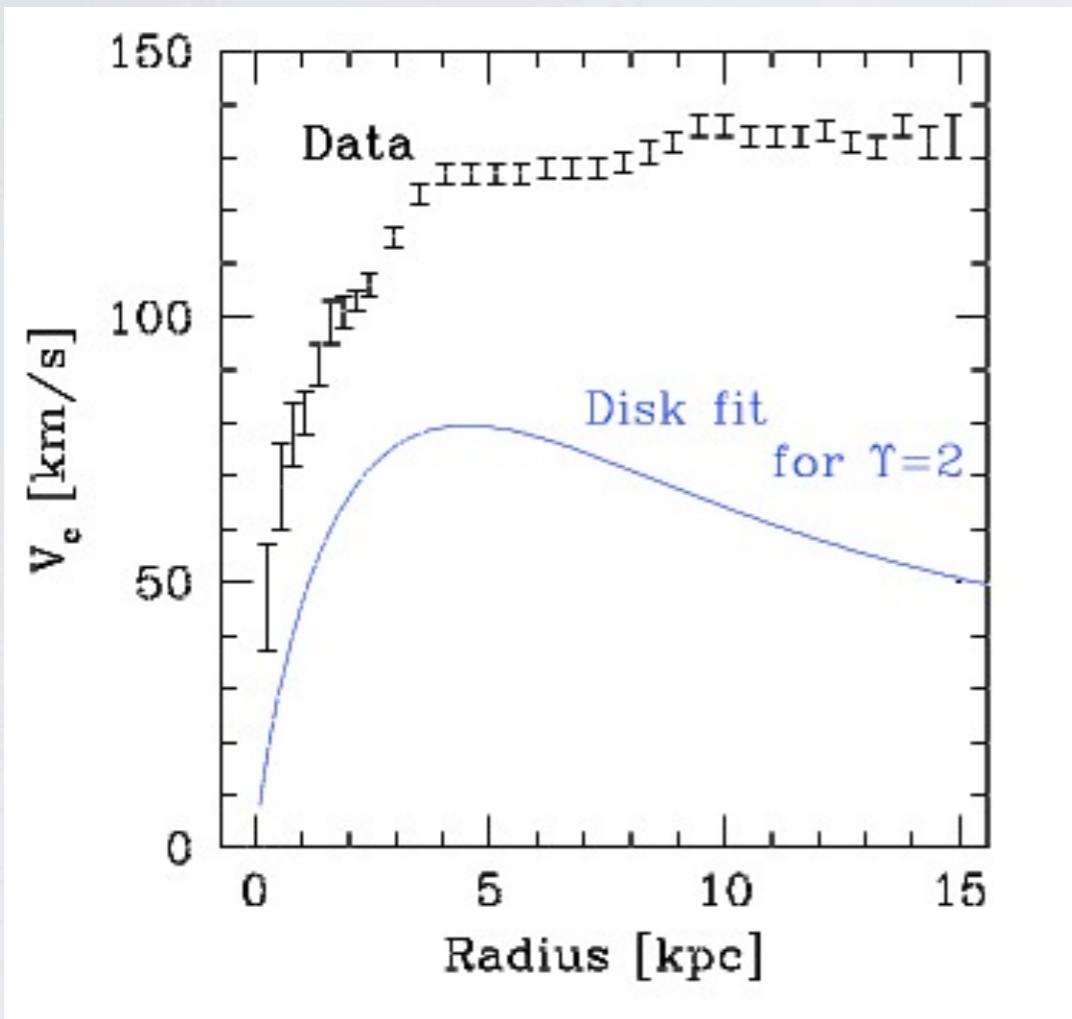
The LHC

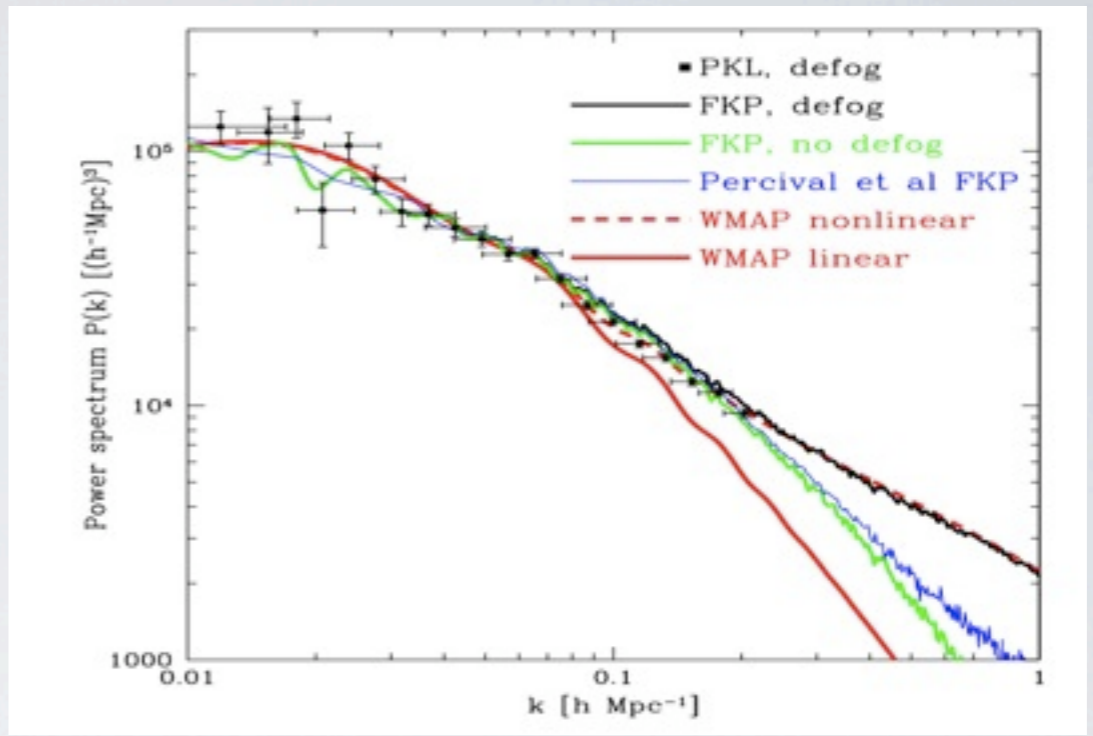
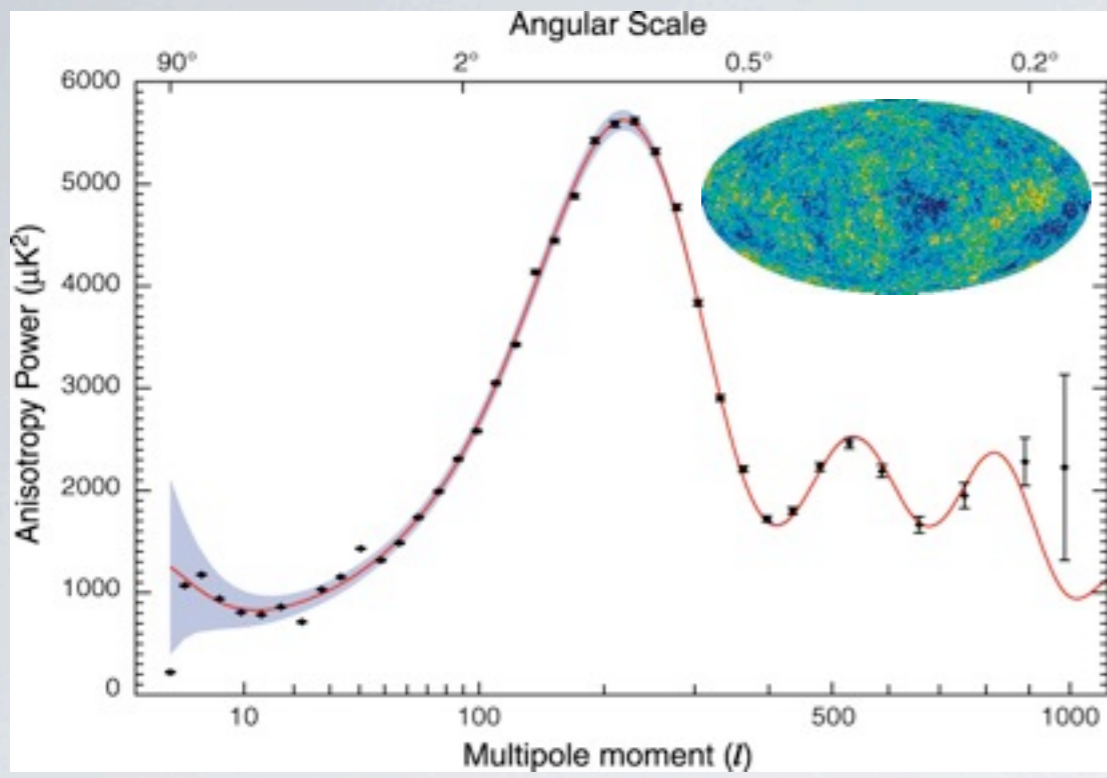


The Universe

can tell us about cosmology
can tell us about high energy physics

DARK MATTER





dark matter now robustly tested

so there ***is*** physics beyond the standard model...

but does it have anything to do with the TeV scale?

A classic tale...

$$\begin{aligned} & \text{SUSY} + B + L \\ & \subset \text{SUSY} + R\text{-parity} \end{aligned}$$

A classic tale...

$$\text{SUSY} + B + L \\ \simeq \text{SUSY} + R\text{-parity}$$

$$\text{SUSY} + R\text{-Parity} \\ = \text{Dark matter!!!} \\ (\text{often})$$

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$$\text{SUSY} + \text{R-Parity} \\ = \text{Dark matter!!!} \\ (\text{often})$$

is there more to the story?

- Precision and the standard model

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| Quantity | Value | Standard Model | Pull |
|--|---------------------------------------|----------------------------------|------|
| m_t [GeV] | $172.7 \pm 2.9 \pm 0.6$ | 172.7 ± 2.8 | 0.0 |
| M_W [GeV] | 80.450 ± 0.058 | 80.376 ± 0.017 | 1.3 |
| | 80.392 ± 0.039 | | 0.4 |
| M_Z [GeV] | 91.1876 ± 0.0021 | 91.1874 ± 0.0021 | 0.1 |
| Γ_Z [GeV] | 2.4952 ± 0.0023 | 2.4968 ± 0.0011 | -0.7 |
| $\Gamma(\text{had})$ [GeV] | 1.7444 ± 0.0020 | 1.7434 ± 0.0010 | — |
| $\Gamma(\text{inv})$ [MeV] | 499.0 ± 1.5 | 501.65 ± 0.11 | — |
| $\Gamma(\ell^+\ell^-)$ [MeV] | 83.984 ± 0.086 | 83.996 ± 0.021 | — |
| σ_{had} [nb] | 41.541 ± 0.037 | 41.467 ± 0.009 | 2.0 |
| R_e | 20.804 ± 0.050 | 20.756 ± 0.011 | 1.0 |
| R_μ | 20.785 ± 0.033 | 20.756 ± 0.011 | 0.9 |
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| R_c | 0.1721 ± 0.0030 | 0.17230 ± 0.00004 | -0.1 |
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| $A_{FB}^{(0,\mu)}$ | 0.0169 ± 0.0013 | | 0.5 |
| $A_{FB}^{(0,\tau)}$ | 0.0188 ± 0.0017 | | 1.5 |
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| A_e | 0.15138 ± 0.00216 | 0.1471 ± 0.0011 | 2.0 |
| | 0.1544 ± 0.0060 | | 1.2 |
| | 0.1498 ± 0.0049 | | 0.6 |
| A_μ | 0.142 ± 0.015 | | -0.3 |
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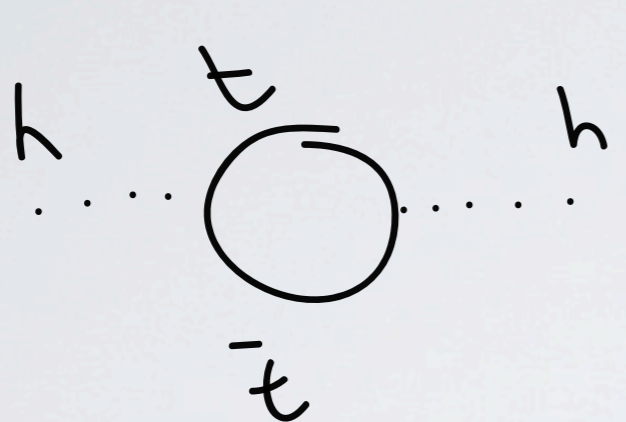


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The “LEP Paradox” (Barbieri+Strumia '00)
or “Little Hierarchy Problem”

The hierarchy problem

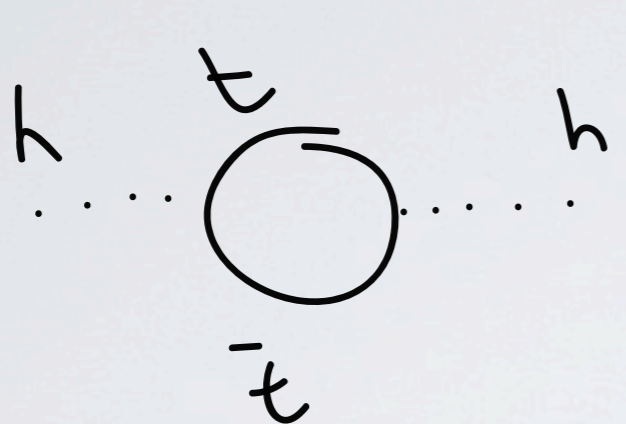
The hierarchy problem



A Feynman diagram showing a top quark loop. A circle represents the loop, with a top quark line (t) on top and an anti-top quark line (\bar{t}) on the bottom. Dotted lines on the left and right represent Higgs boson external lines (h).

$$\delta m_h^2 = \frac{3\lambda_t^2}{16\pi^2} \Lambda^2$$

The hierarchy problem



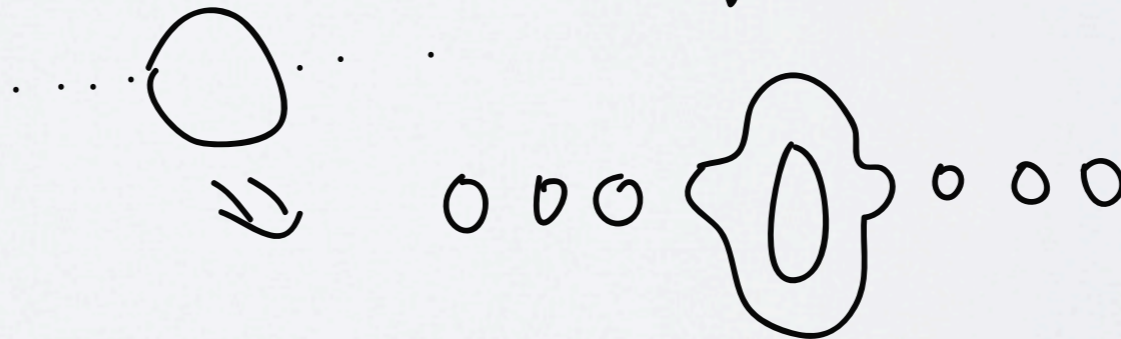
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$$\delta m_h^2 = \frac{3\lambda_t^2}{16\pi^2} \Lambda^2$$

t \tilde{t} SUSY

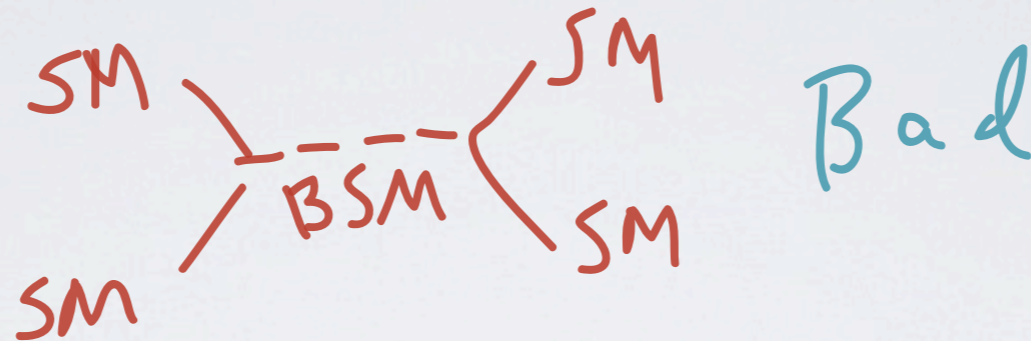
or

compositeness



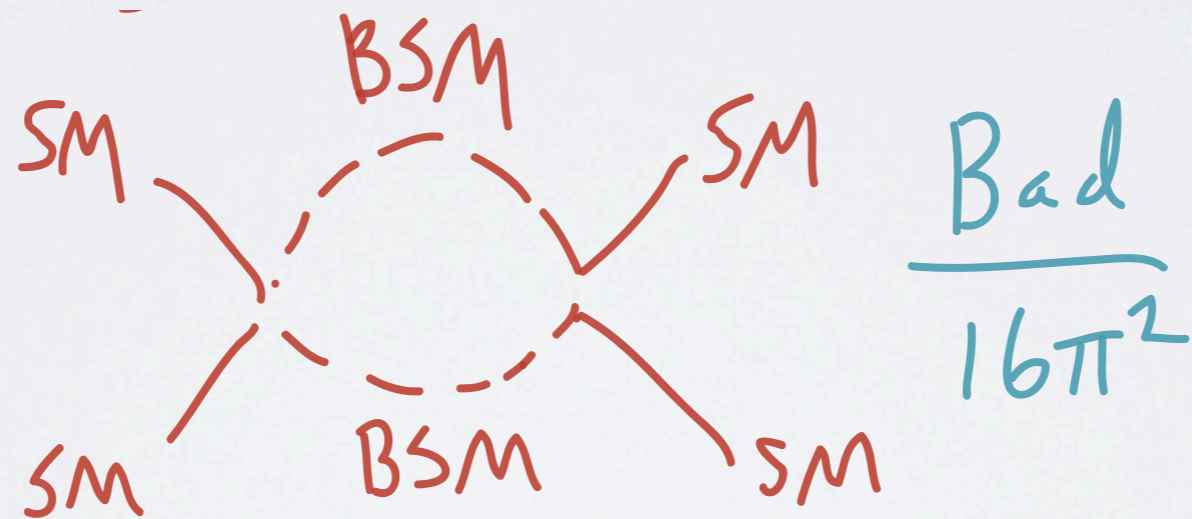
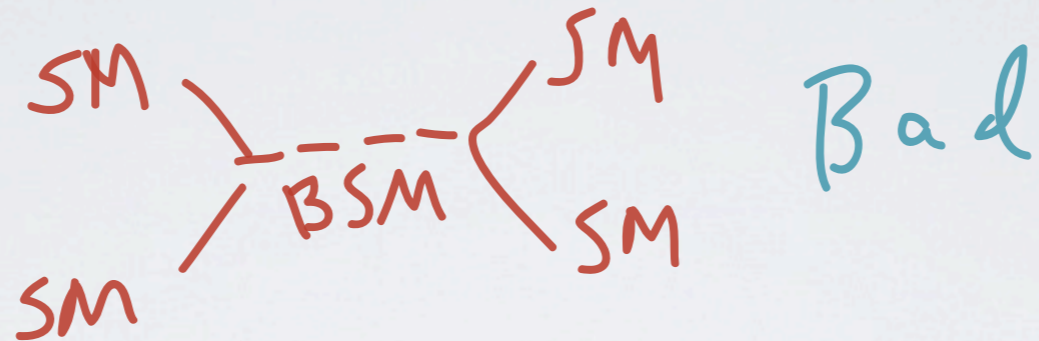
T-Parity (Cheng and Low)

- The problem arises from



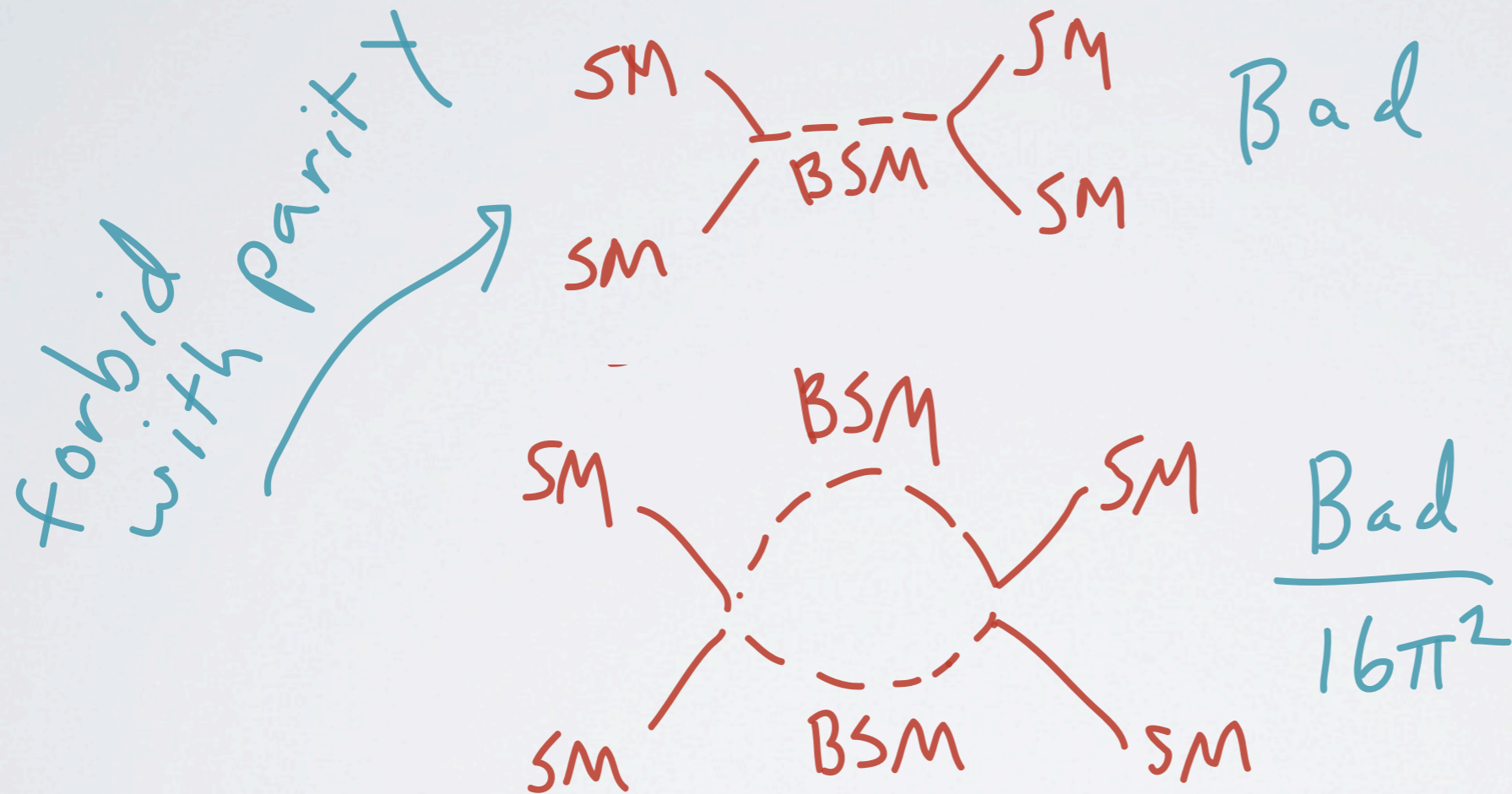
T-Parity (Cheng and Low)

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T-Parity (Cheng and Low)

- The problem arises from



I.e., problem is presence of single BSM field
If only even numbers of BSM fields were allowed, this
term is forbidden!

a parity is a natural/expected element of
weak scale physics

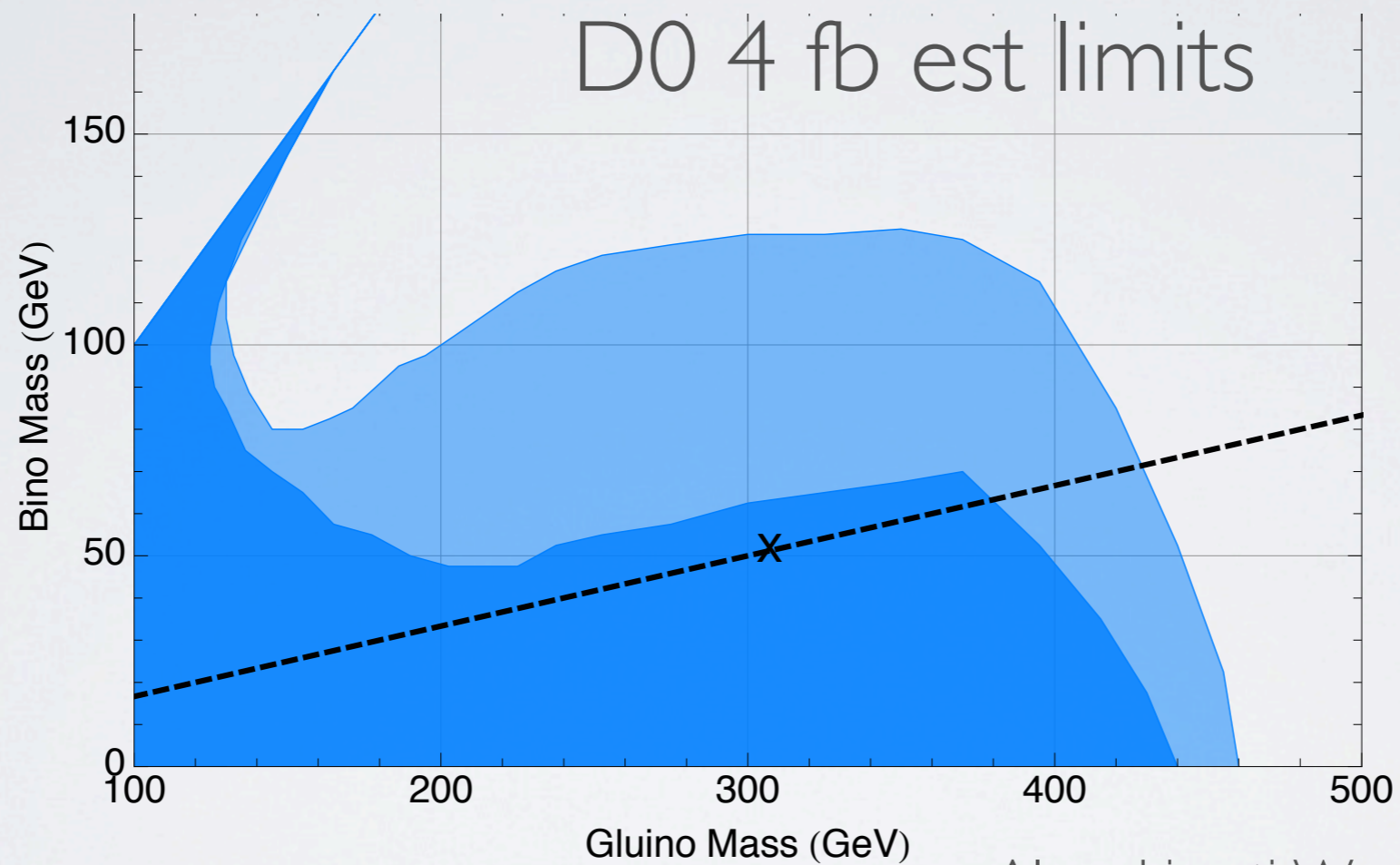
Lightest stable new particle should be
present! (LSNP)

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Lightest stable new particle should be
present! (LSNP)

so how much should we expect from MET?

HOW ROBUST IS MET?



Alves, Lisanti, Wacker, '08

Squeezed spectra a challenging - but not impossible

HOW ROBUST IS MET?

Is a squeezed spectrum even natural?

Maybe: accident in
extended anomaly mediation

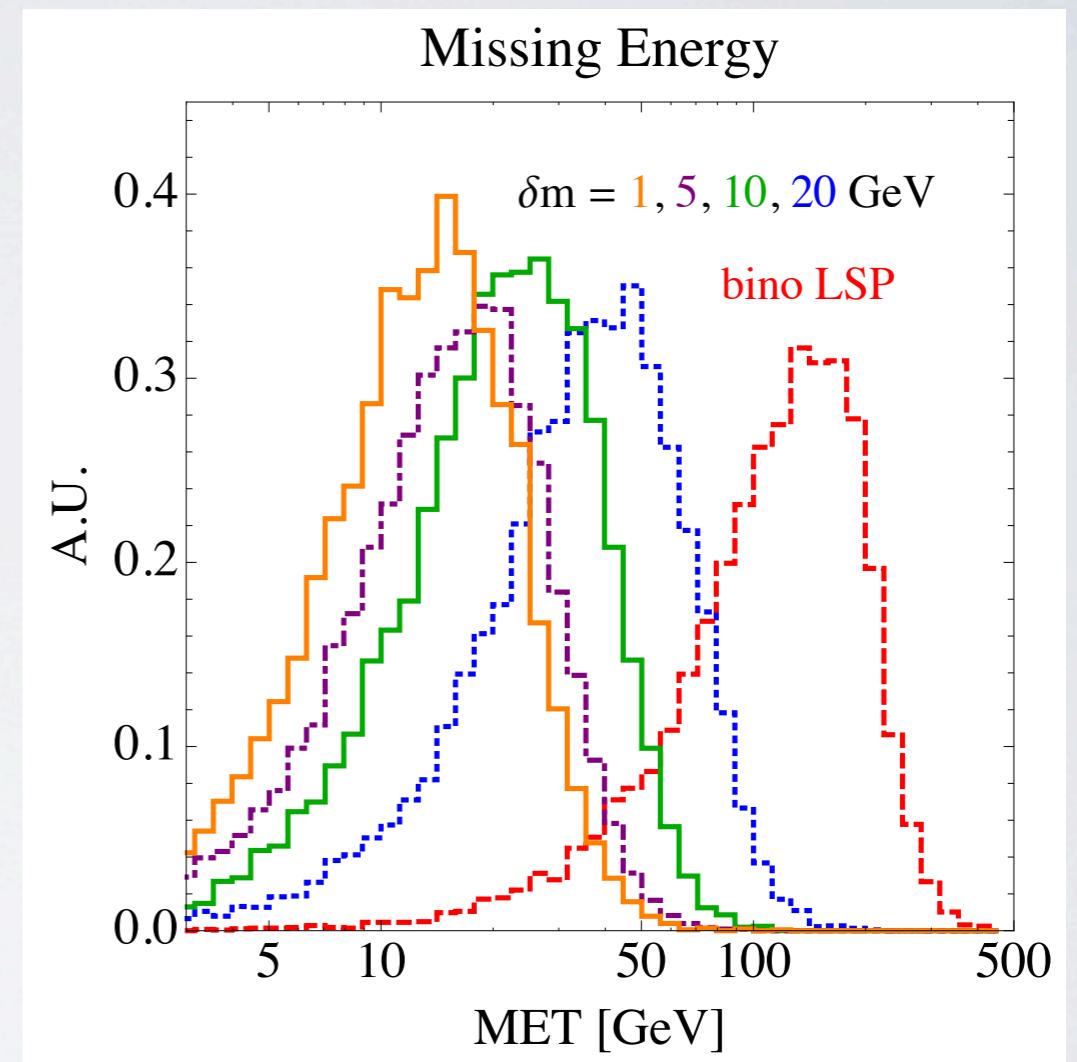
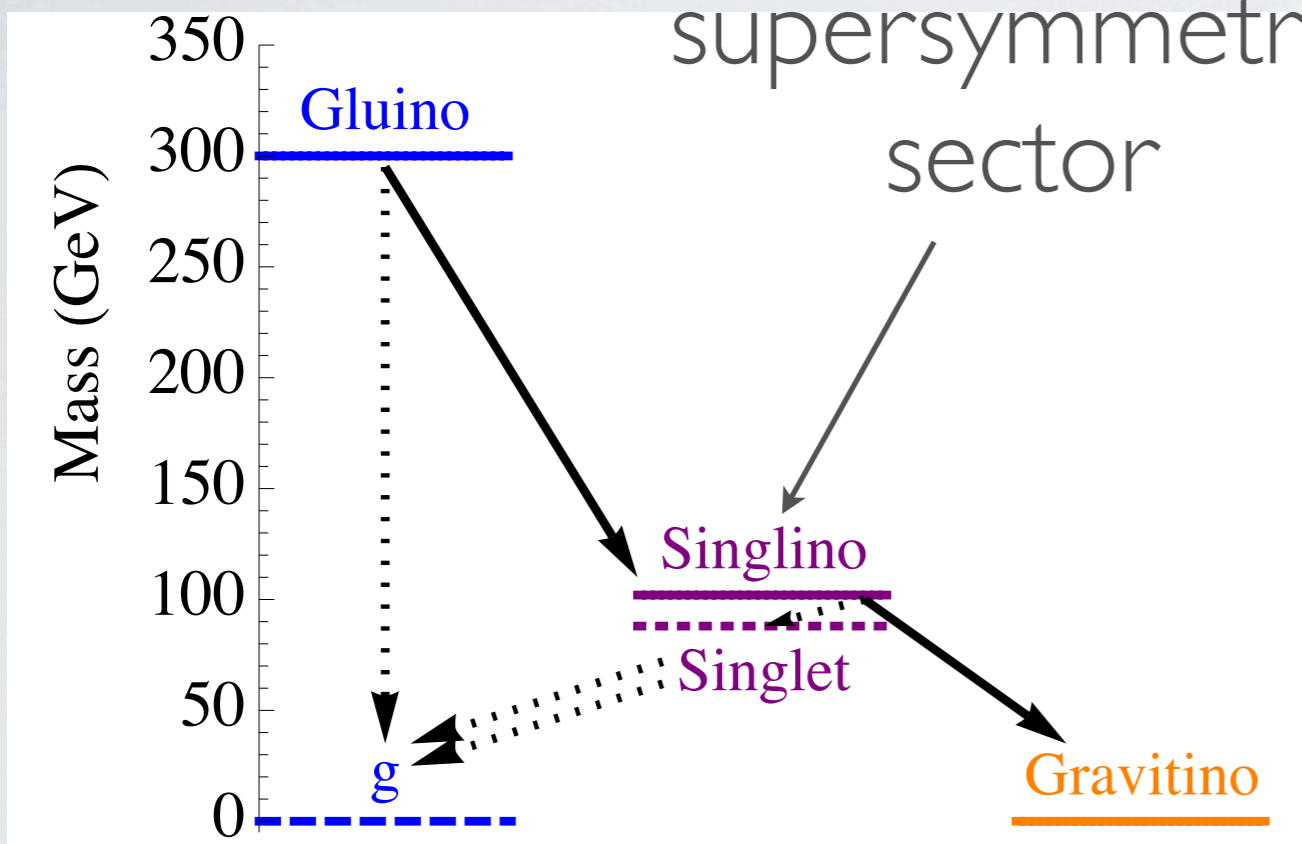
$$m_{1/2}^i \sim \alpha_i \beta_i$$
$$\alpha_i [\beta_i + 2N_{\text{mess}}] \quad (\text{Nelson, NW '02})$$

$$m_1 : m_2 : m_3 \sim 1 : 1 : 1.4$$

(Kaplan, NW in progress)

SUSY WITH (ALMOST) NO MET

approximately supersymmetric sector



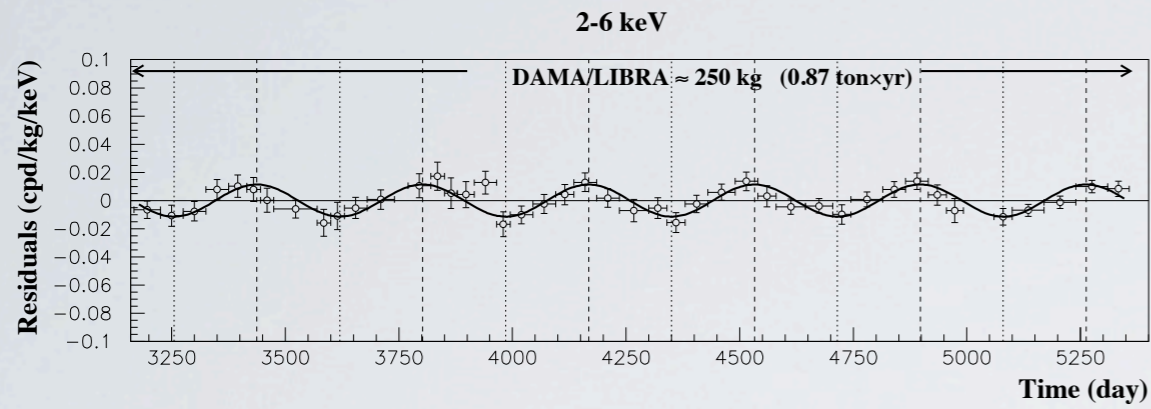
Fan, Reece, Ruderman '11

MET AND COSMOLOGY

- Parities are strongly motivated, and so MET is a likely scenario
- But MET can be lost, or suppressed!

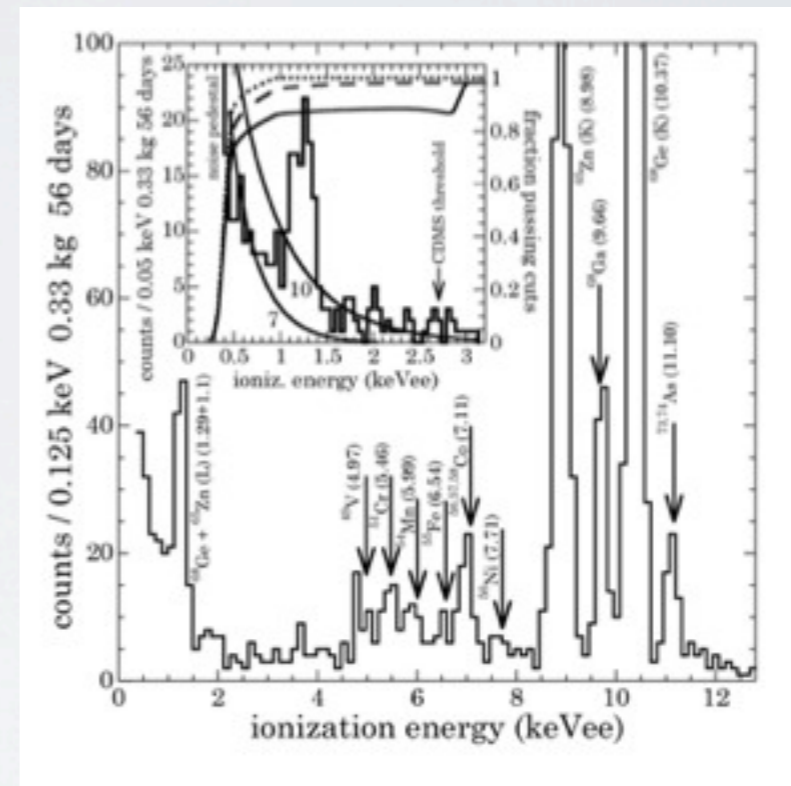
COSMOLOGY UNDERGROUND

LIGHT WIMP ANOMALIES

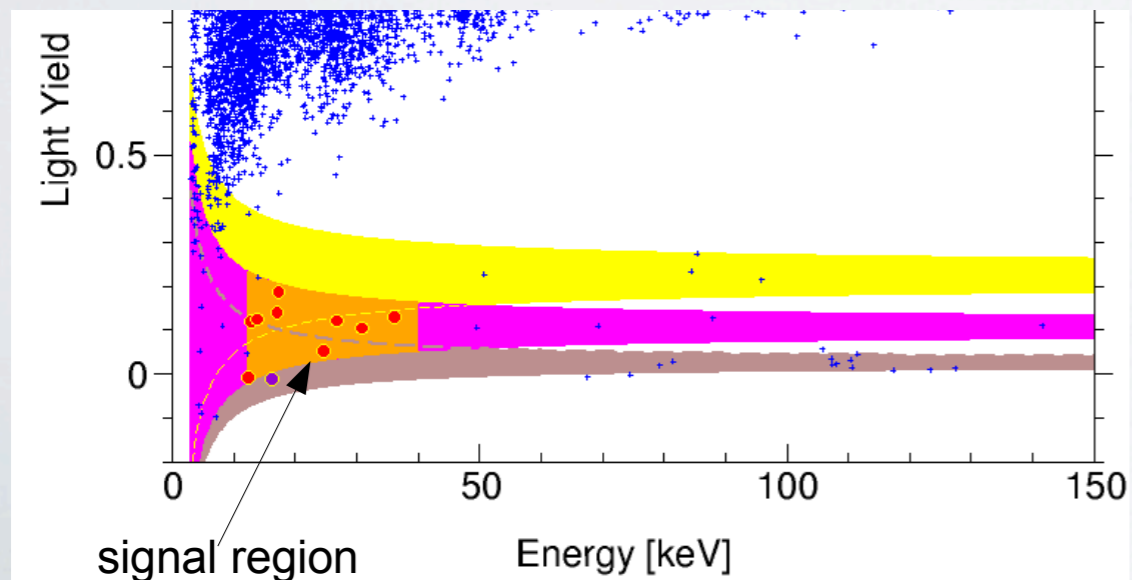


DAMA

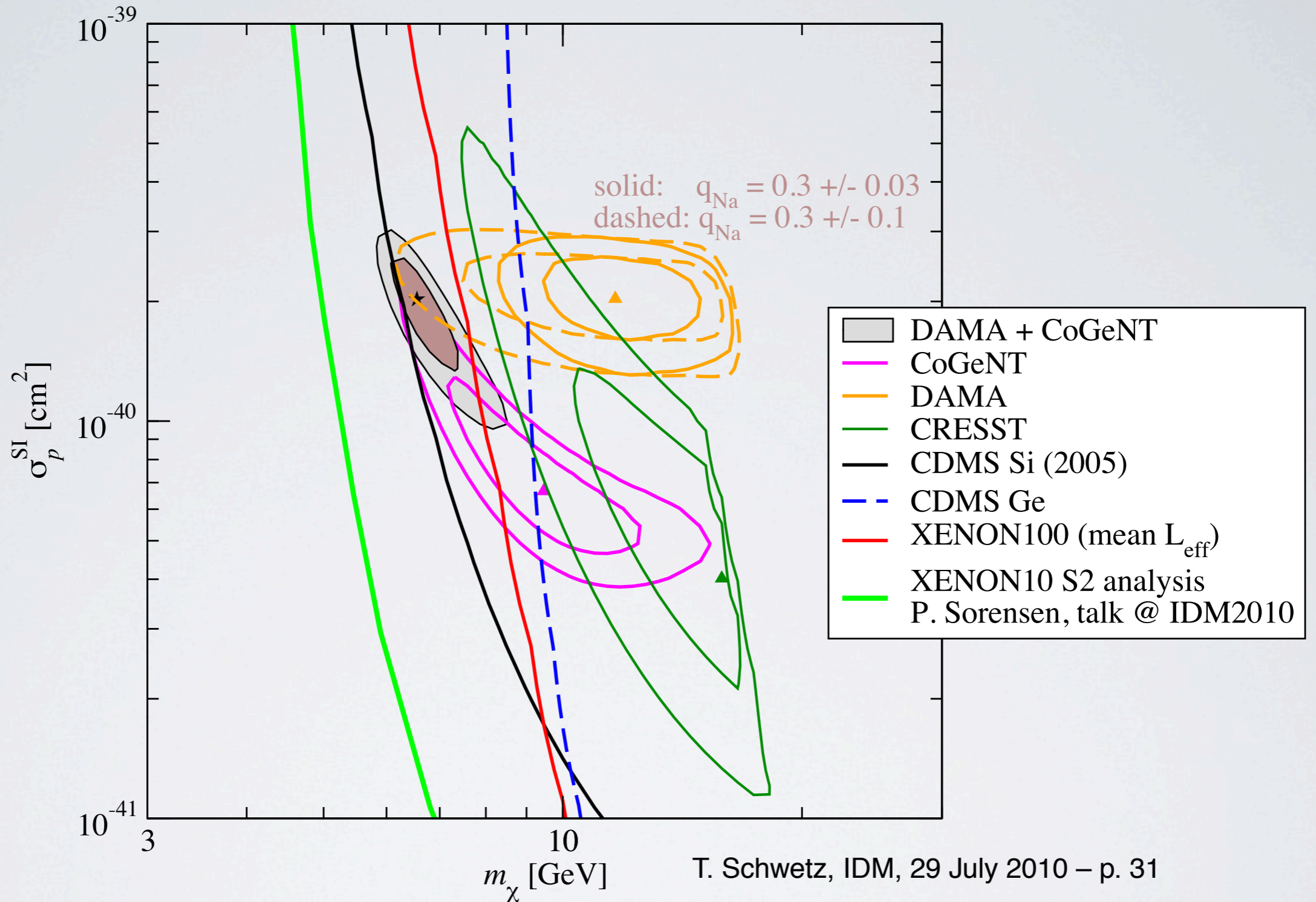
CoGeNT



CRESST

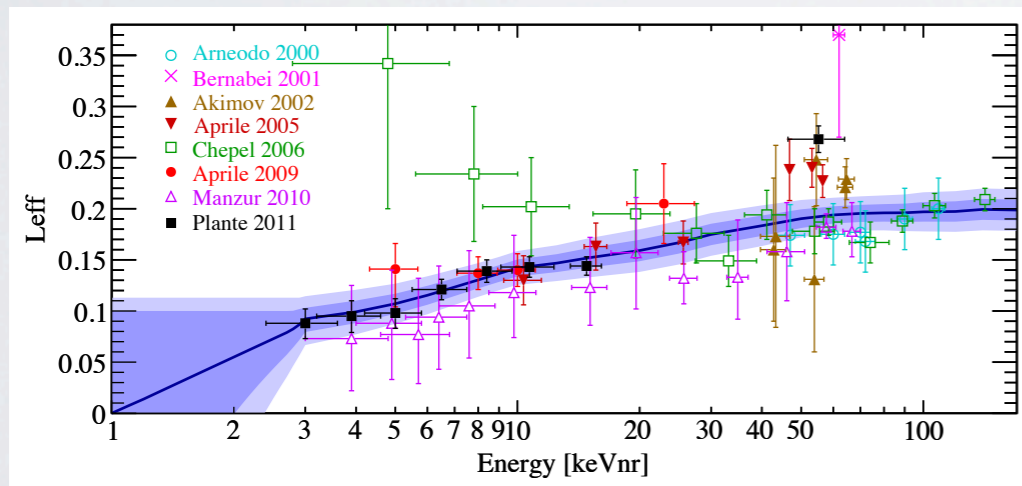
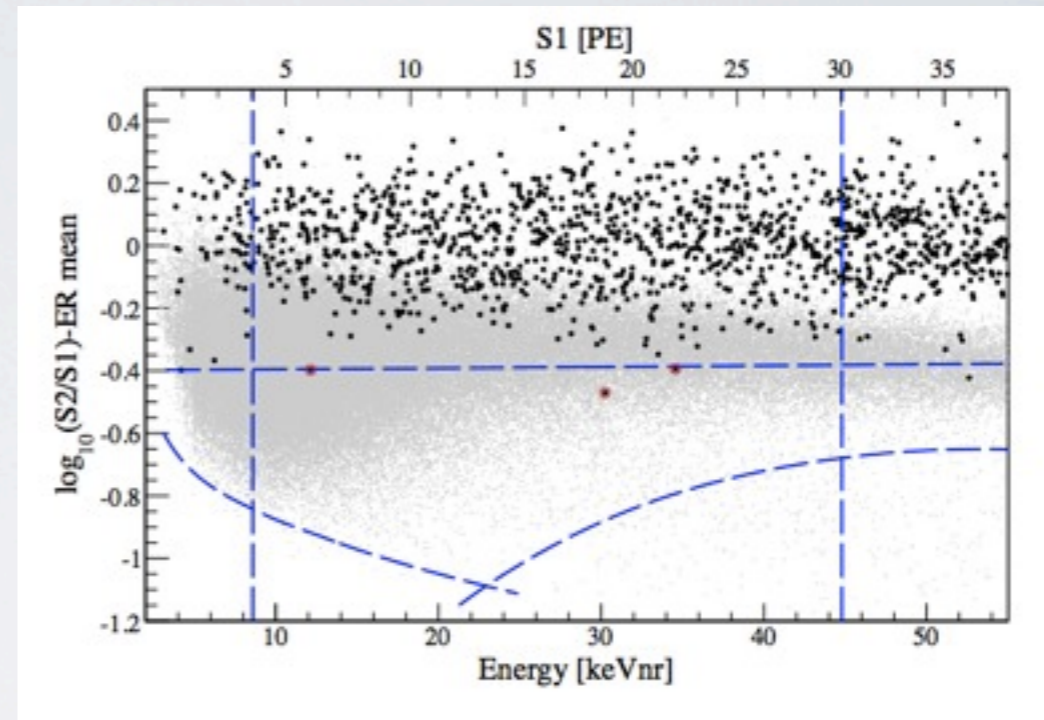
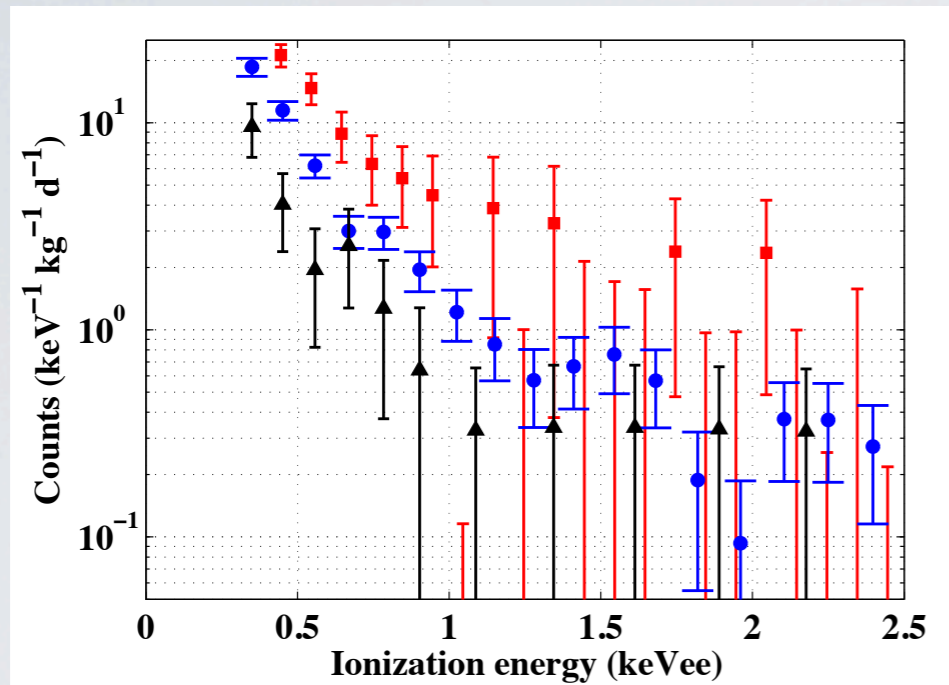


- The same beast?

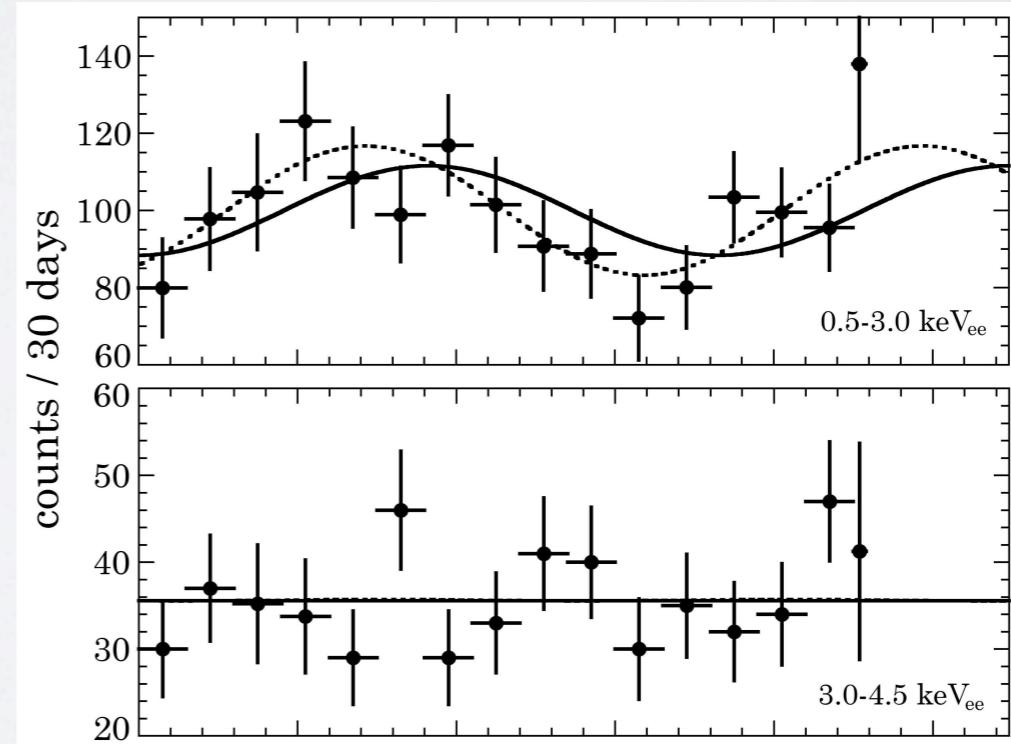
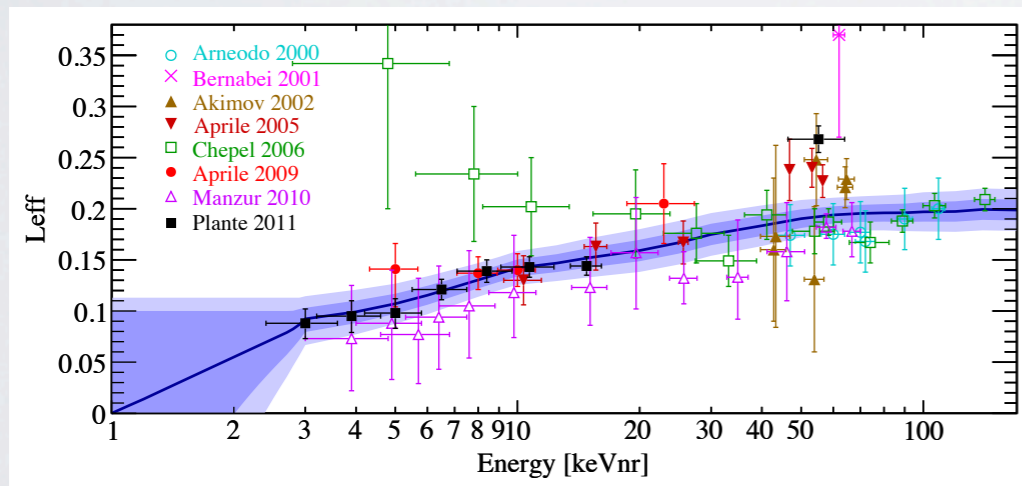
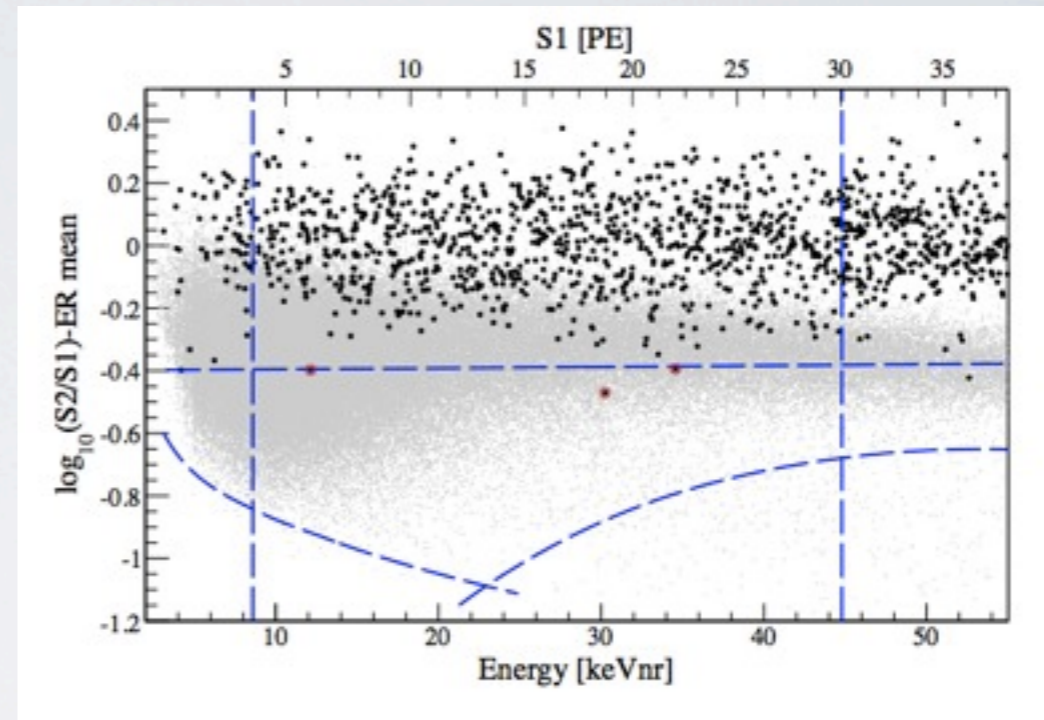
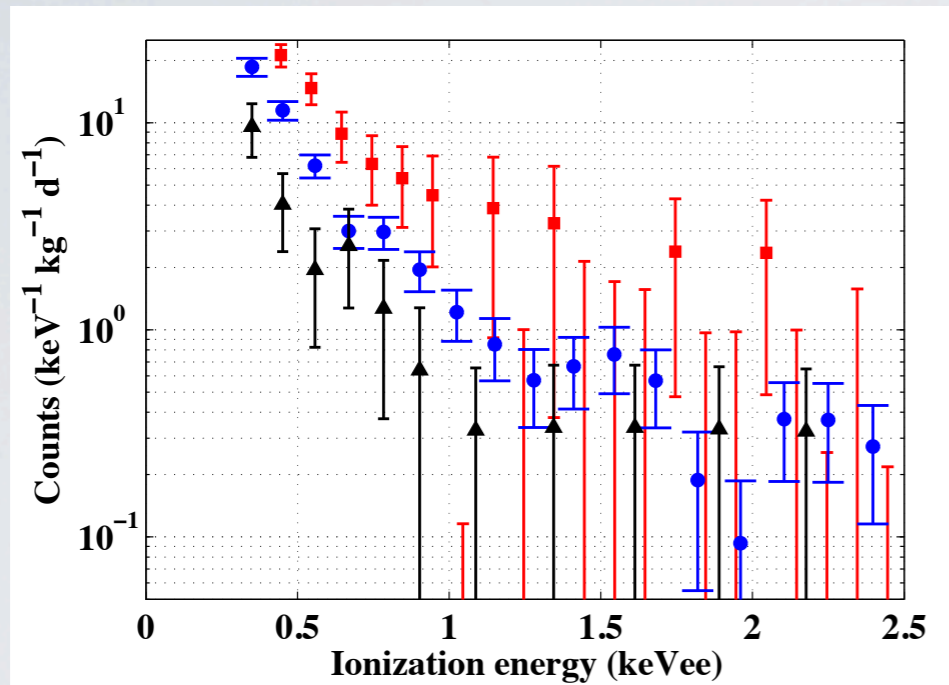


don't *really* line up, but within spitting distance

TENSIONS? EXCLUSIONS?



TENSIONS? EXCLUSIONS?



modulation?

WHAT WOULD IT BE?

Light neutralinos with large scattering cross sections in the minimal supersymmetric standard model

Eric Kuflik, Aaron Pierce, and Kathryn M. Zurek

Michigan Center for Theoretical Physics, University of Michigan, Ann Arbor, MI 48109

(Dated: July 20, 2010)

Motivated by recent data from CoGeNT and the DAMA annual modulation signal, we discuss collider constraints on minimal supersymmetric standard model neutralino dark matter with mass in the 5-15 GeV range. The lightest superpartner (LSP) would be a bino with a small Higgsino admixture. Maximization of the dark matter-nucleon scattering cross section for such a weakly interacting massive particle requires a light Higgs boson with $\tan \beta$ enhanced couplings. Limits on the invisible width of the Z boson, combined with the rare decays $B^\pm \rightarrow \tau\nu$, and the ratio $B \rightarrow D\tau\nu/B \rightarrow D\ell\nu$, constrain cross sections to be below $\sigma_n \lesssim 5 \times 10^{-42} \text{ cm}^2$. This indicates a higher local Dark Matter density than is usually assumed by a factor of roughly six would be necessary to explain the CoGeNT excess. This scenario also requires a light charged Higgs boson, which can give substantial contributions to rare decays such as $b \rightarrow s\gamma$ and $t \rightarrow bH^+$. We also discuss the impact of Tevatron searches for Higgs bosons at large $\tan \beta$.

WHAT WOULD IT BE?

Light neutralinos with large scattering cross sections in the minimal supersymmetric standard model

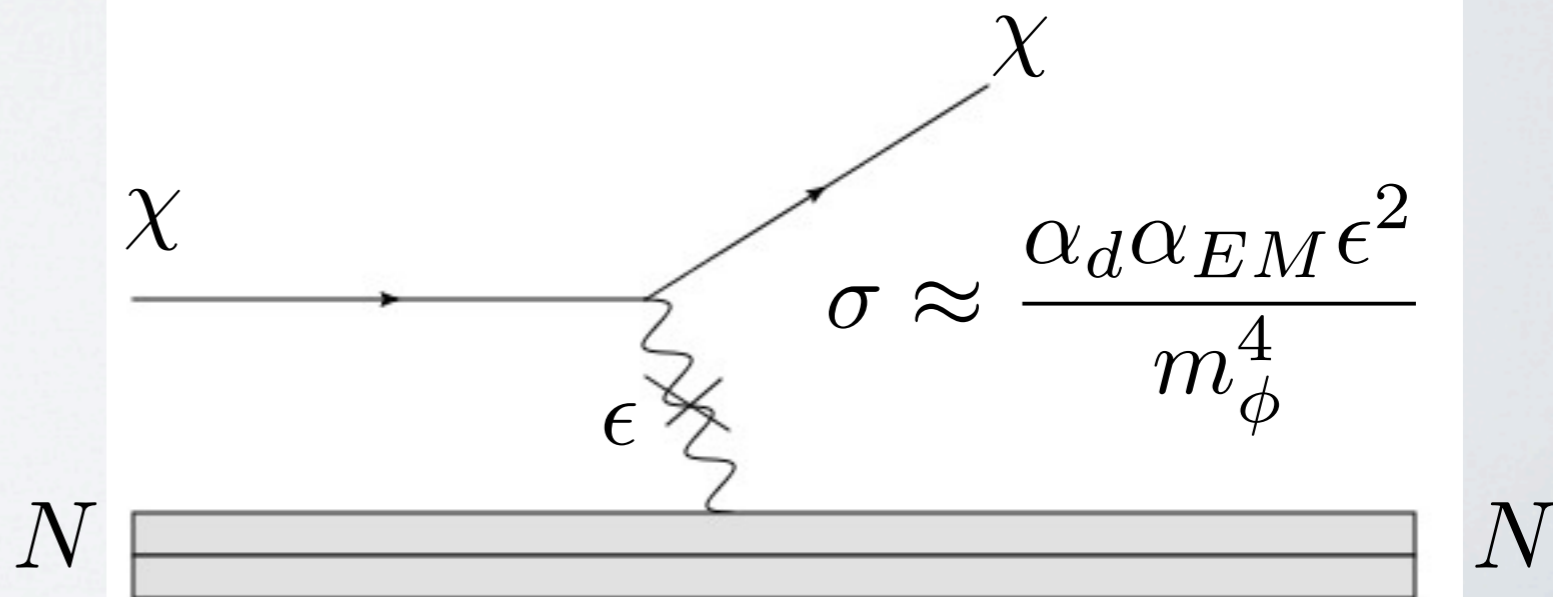
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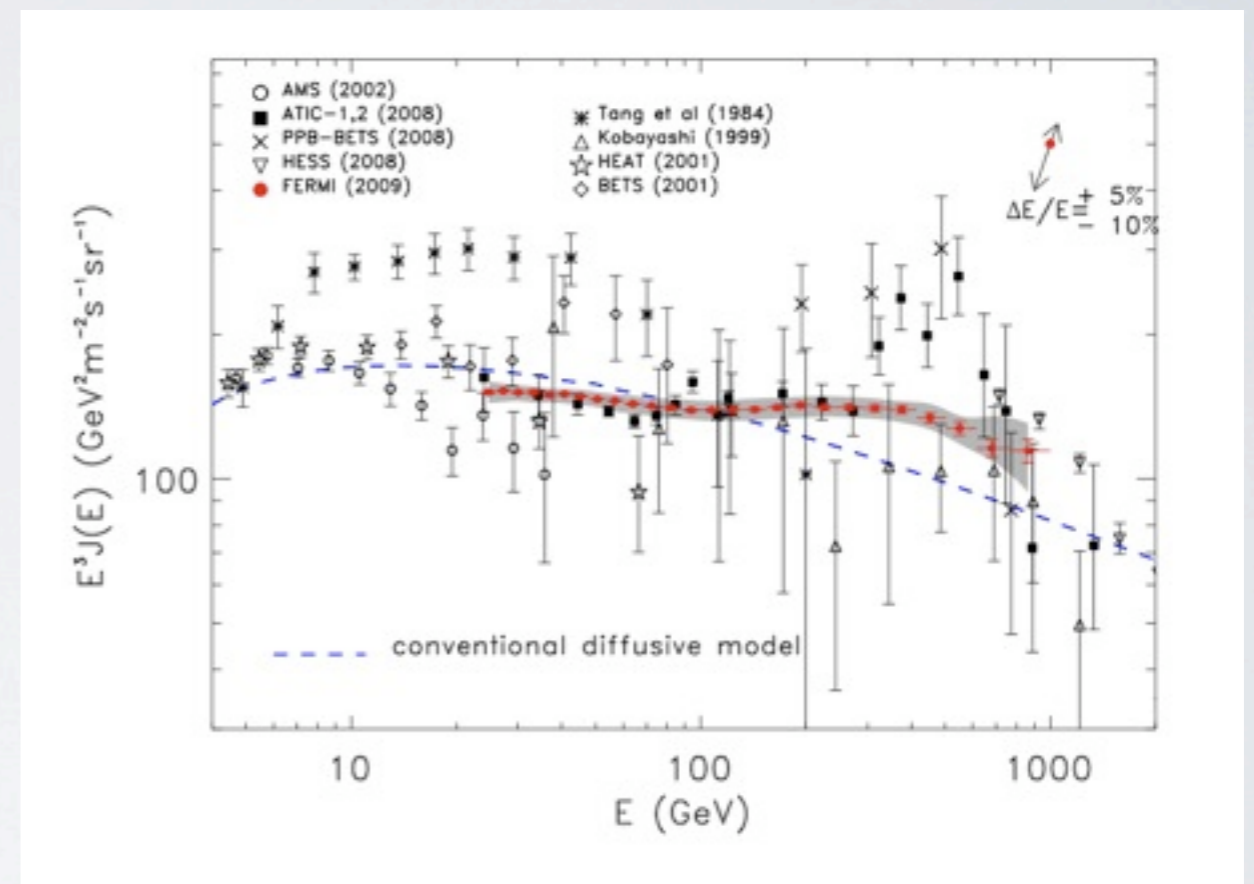
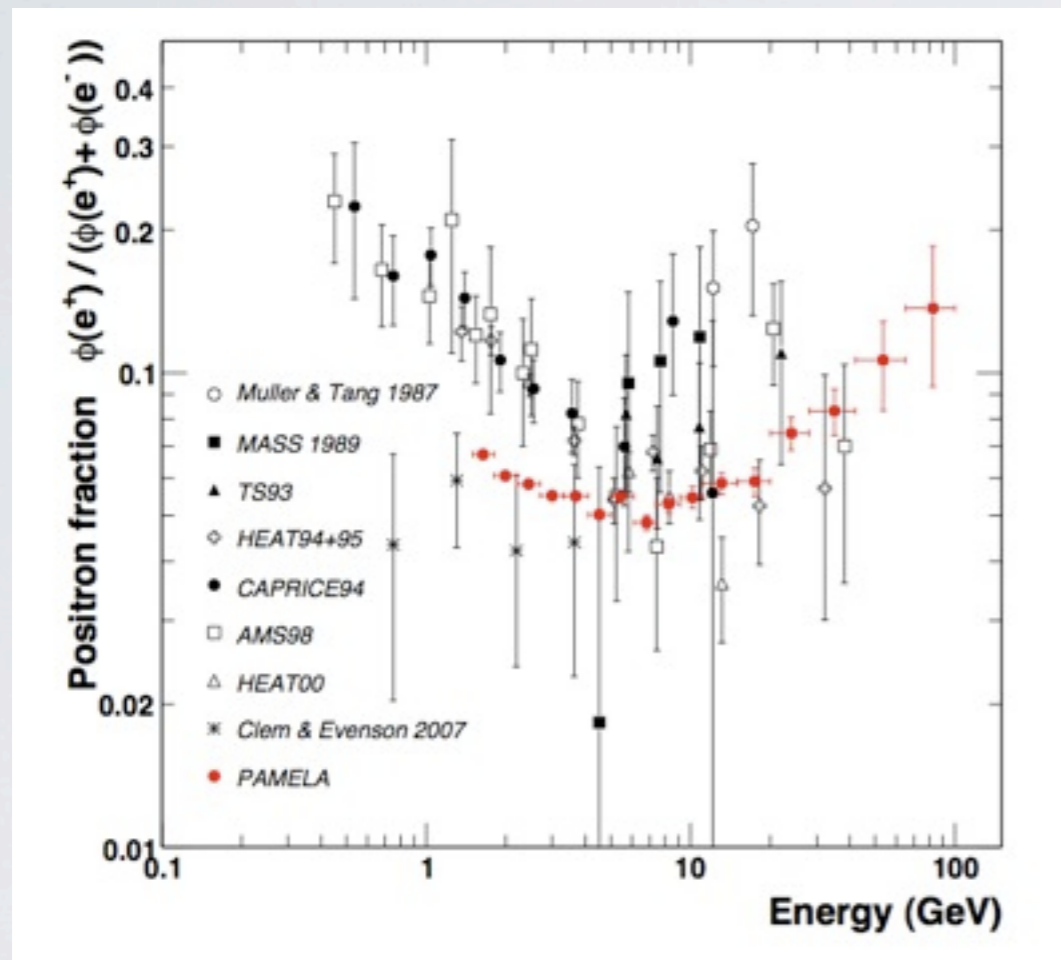
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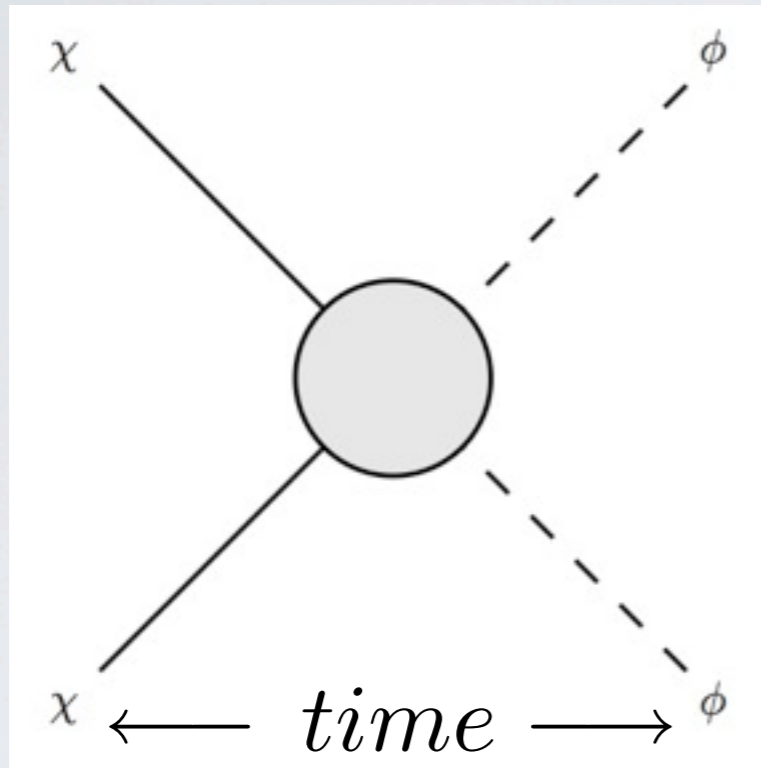
interaction through
a light sector?



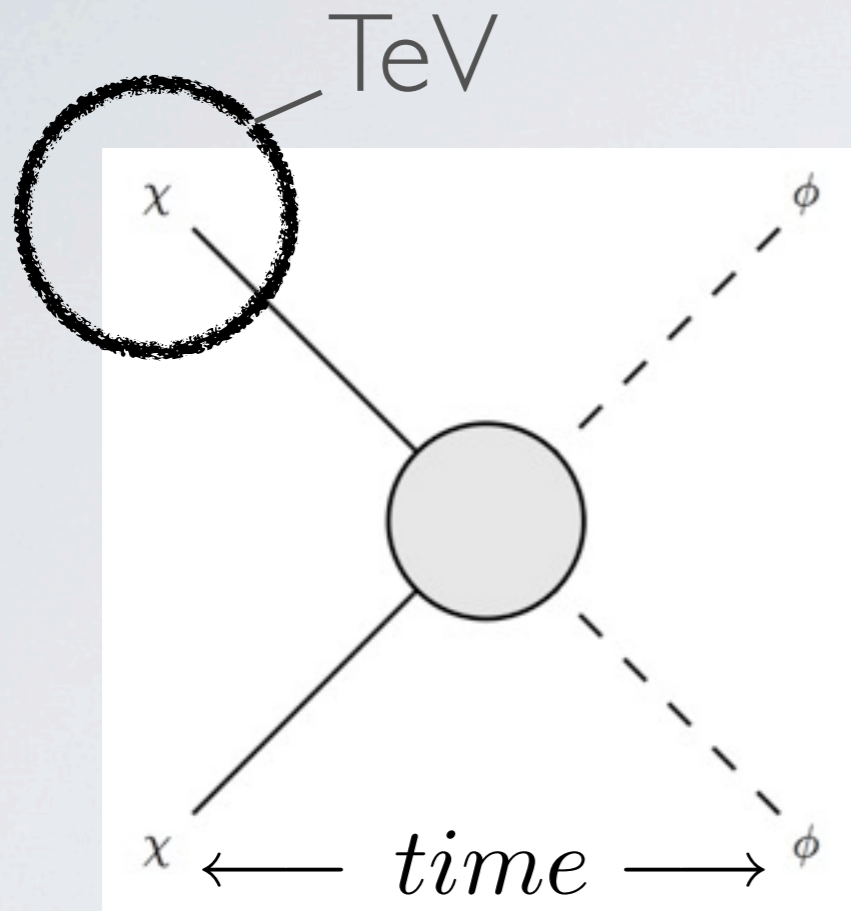
COSMOLOGY OUTSIDE THE BOX



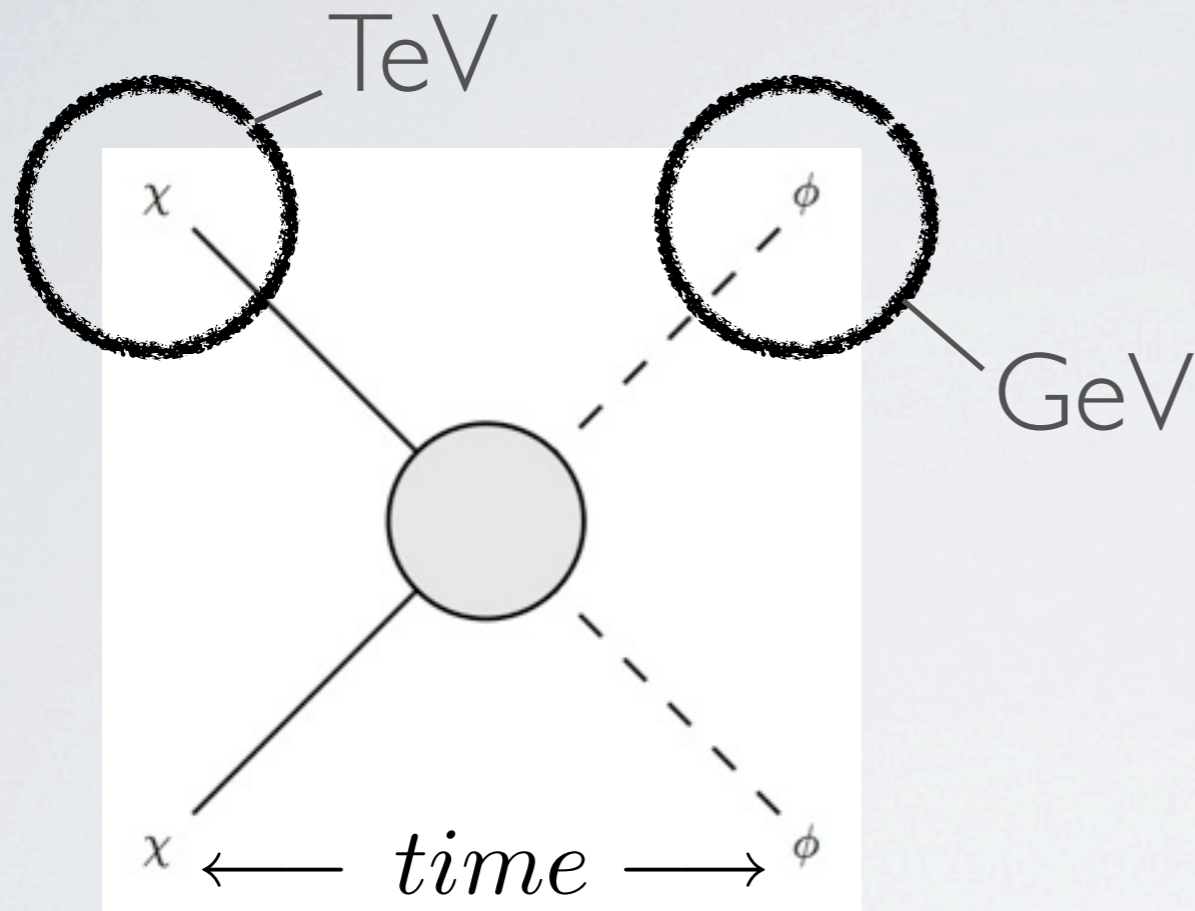
A LIGHT SECTOR TAKE 2



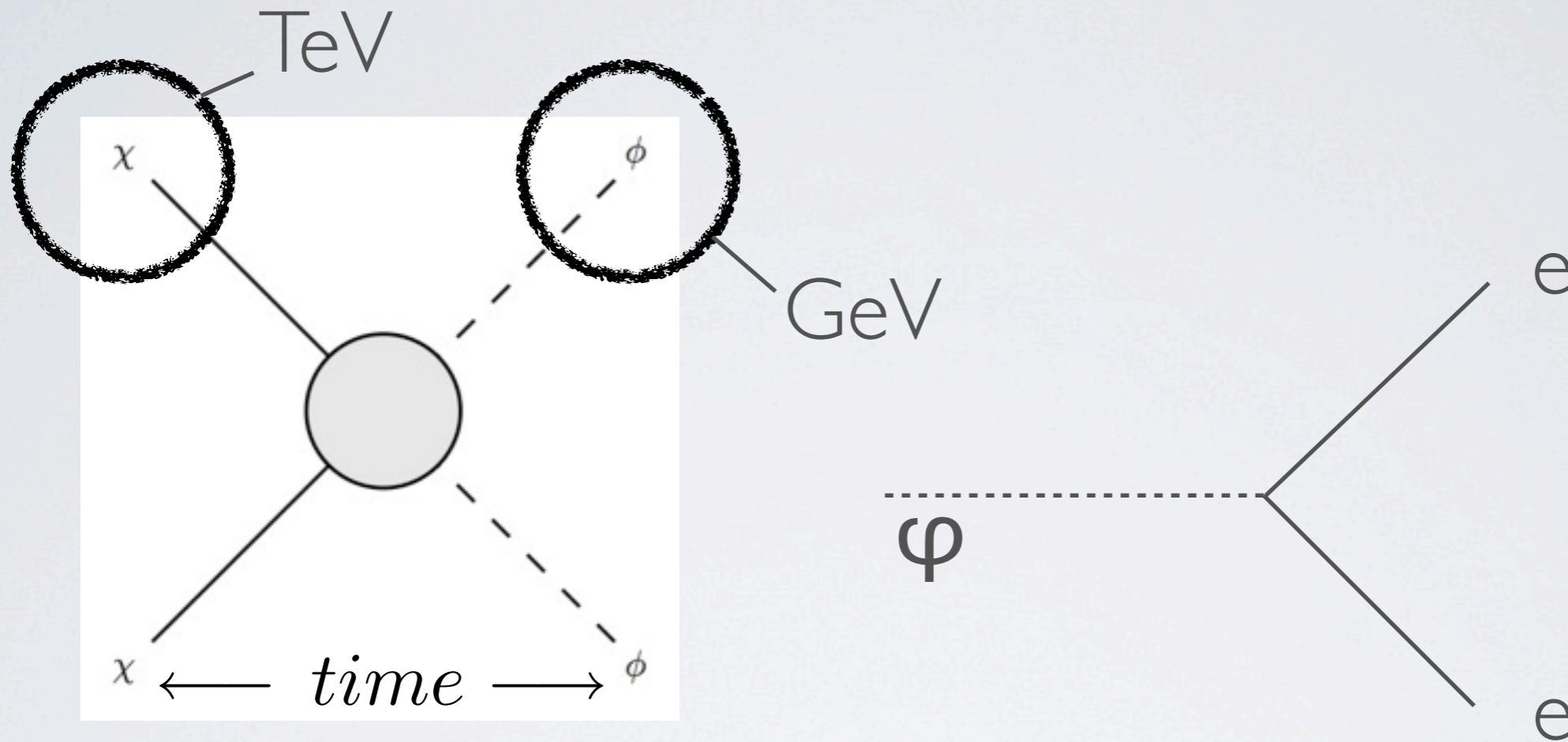
A LIGHT SECTOR TAKE 2



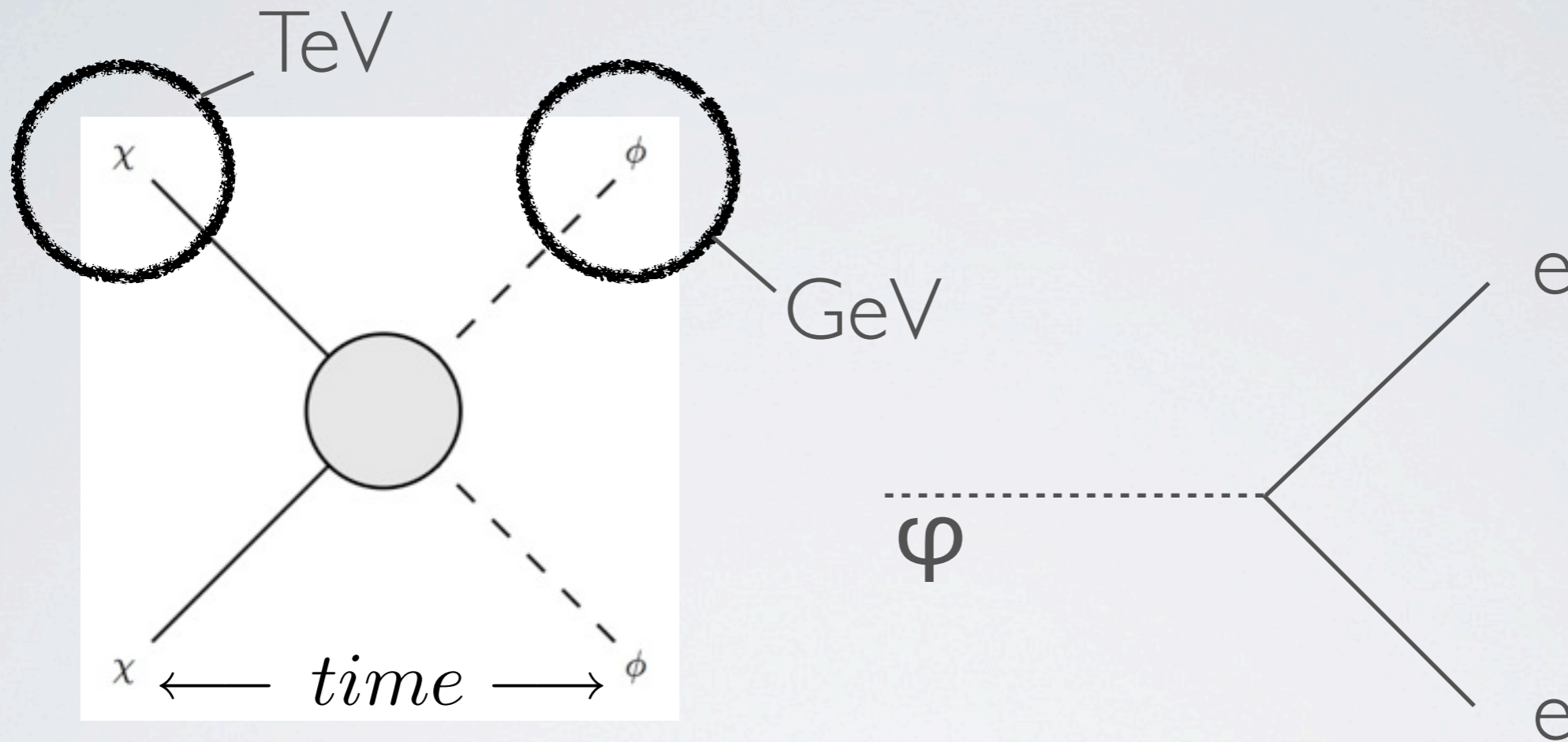
A LIGHT SECTOR TAKE 2



A LIGHT SECTOR TAKE 2

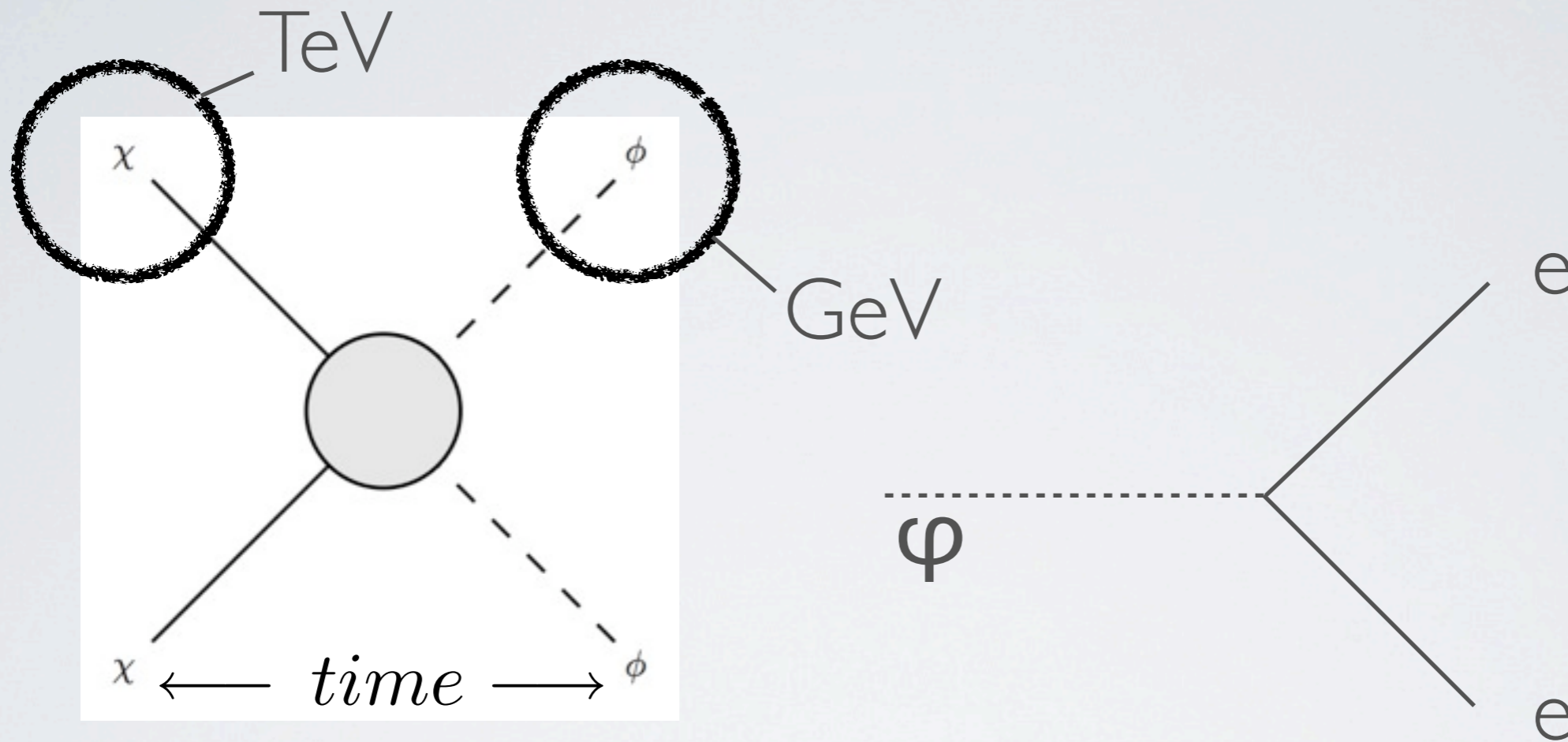


A LIGHT SECTOR TAKE 2



generates hard leptons by annihilations into a light mediator

A LIGHT SECTOR TAKE 2



generates hard leptons by annihilations into a light mediator

New GeV particles and GeV 'inos

NEW COLLIDER PHENO:

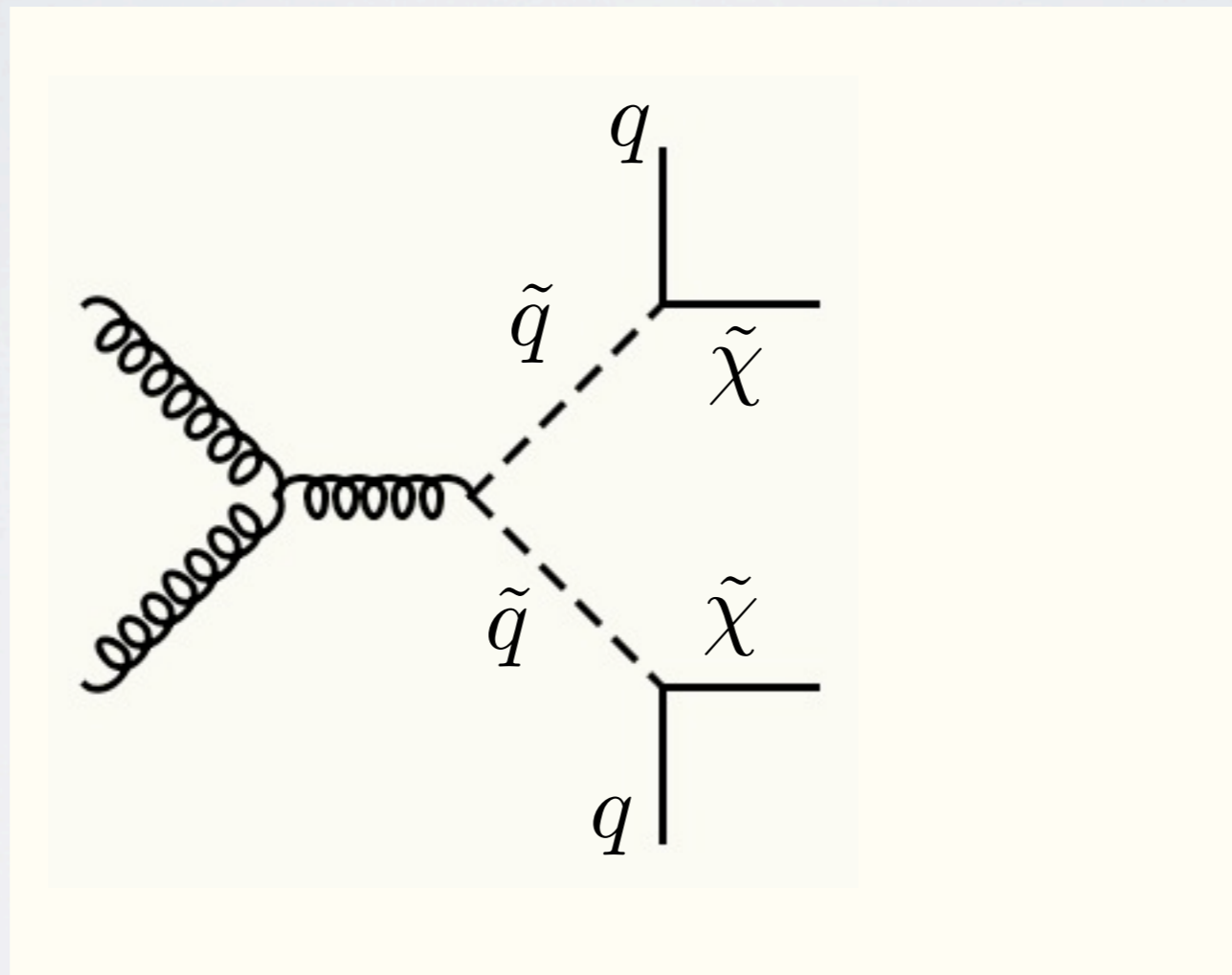
Production of light, dark states, yield boosted, highly collimated leptons (“lepton jets”)

Arkani-Hamed, NW, '08; Baumgart, Cheung, Ruderman, Wang, Yavin, ' 09; Bai, Han '09

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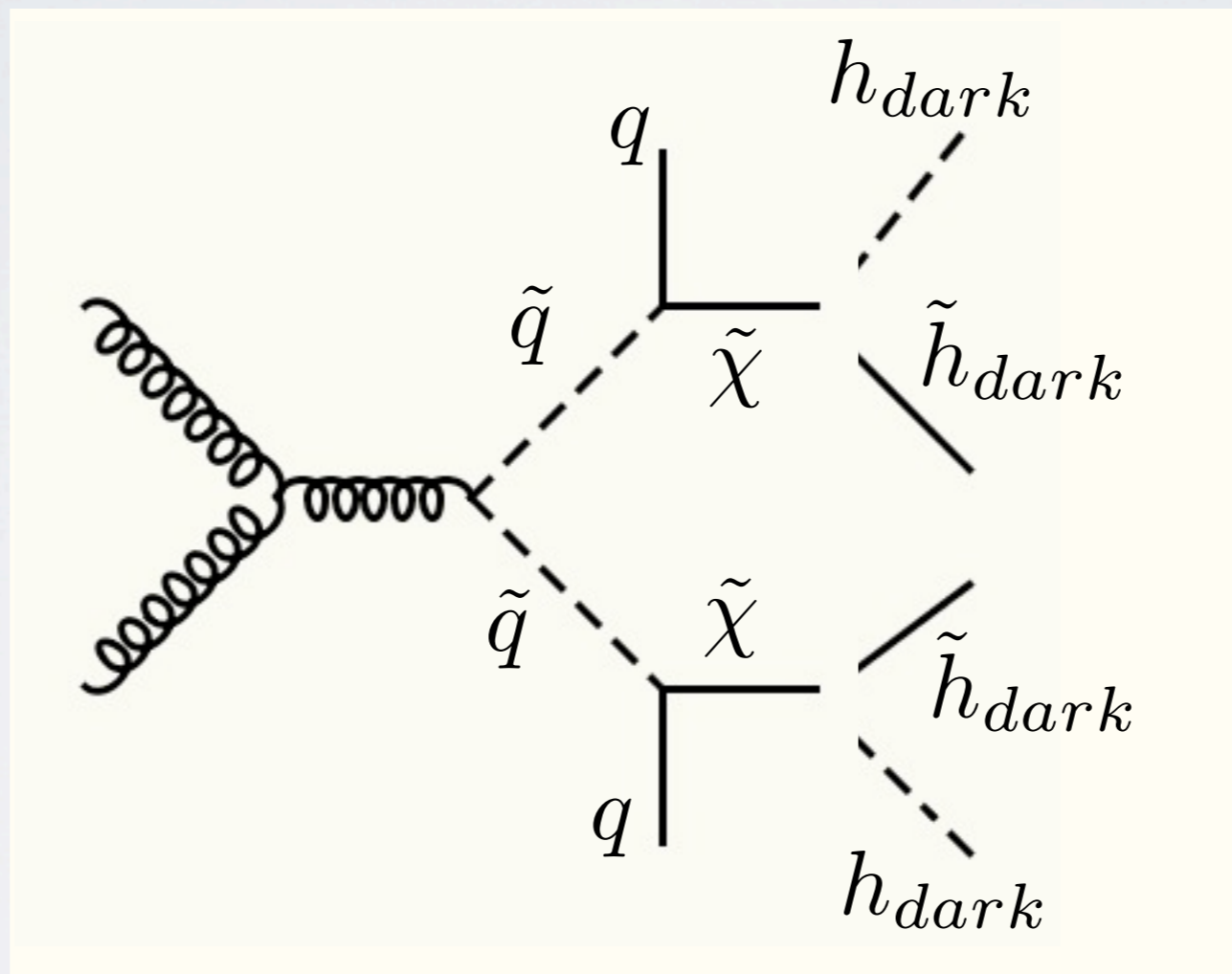
Arkani-Hamed, NW, '08; Baumgart, Cheung, Ruderman, Wang, Yavin, '09; Bai, Han '09



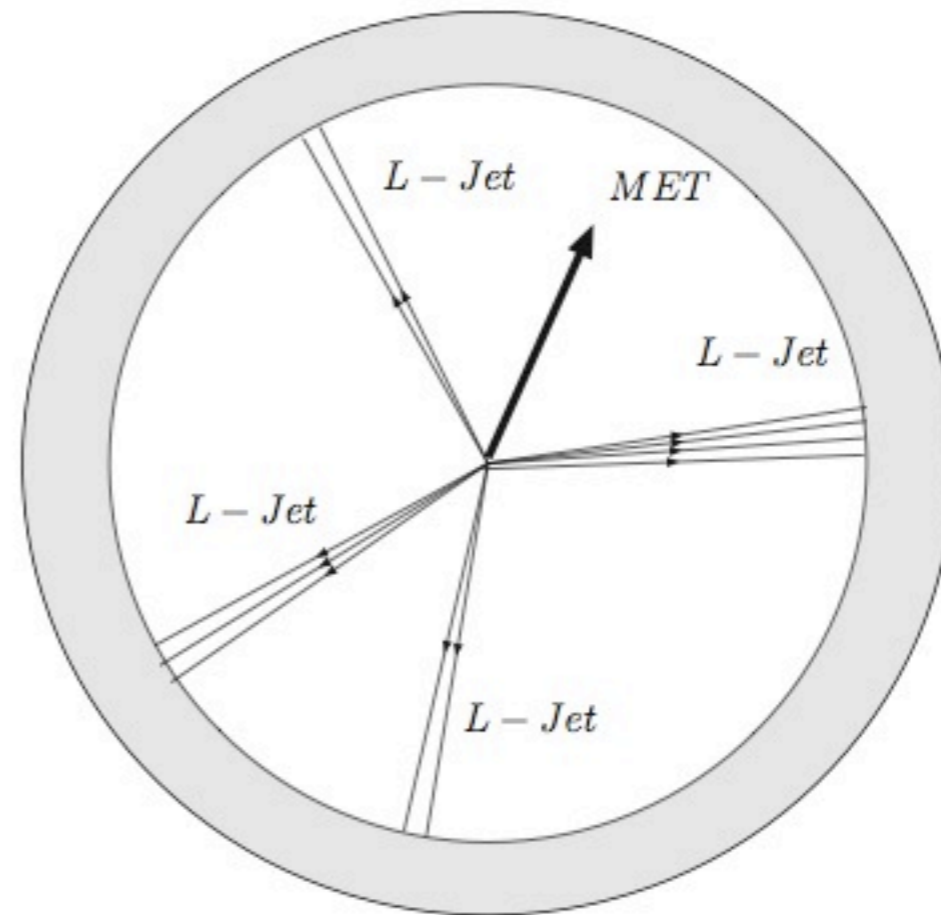
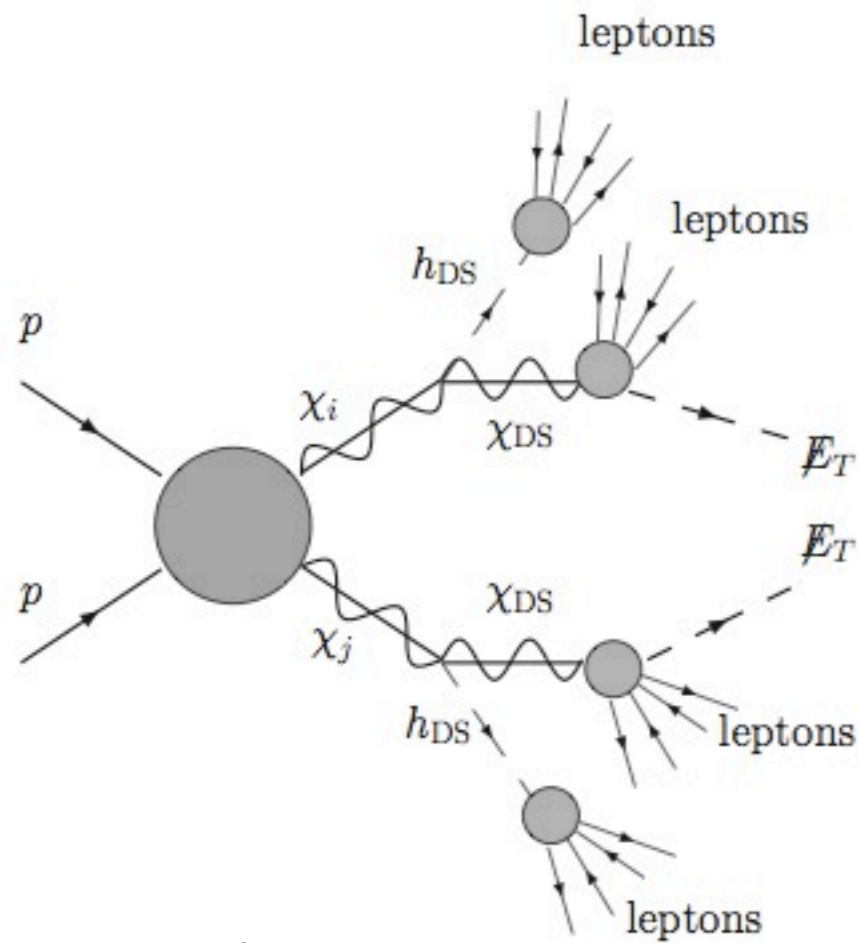
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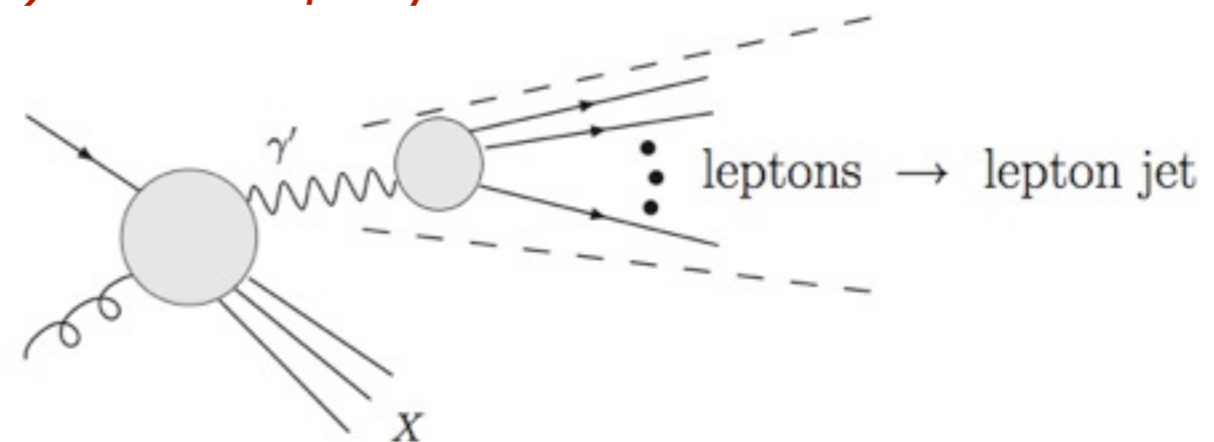
Arkani-Hamed, NW, '08; Baumgart, Cheung, Ruderman, Wang, Yavin, '09; Bai, Han '09



cf “Hidden Valley” models, Strassler and Zurek '06



A new phenomenology, motivated by (but not limited to) astrophysics



Baumgart, Cheung, Ruderman, Wang, Yavin, '09

THINKING ABOUT THE LATE EARLY UNIVERSE

Moduli in Supergravity

(in particular Acharya, Kane et al)

$$\int d^4\theta \frac{X^\dagger X}{M_{Pl}^2} \phi^\dagger \phi$$

$$\langle X \rangle = \theta^2 F \Rightarrow \tilde{m}^2 \phi^\dagger \phi$$

, 1?

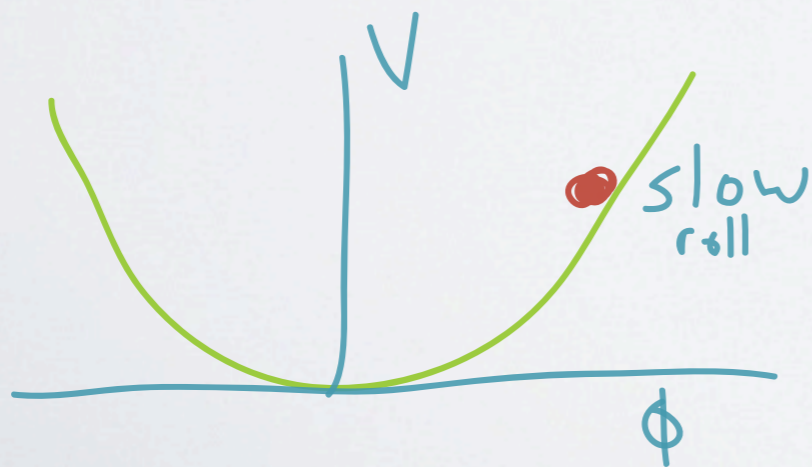
THINKING ABOUT THE LATE EARLY UNIVERSE

Moduli in Supergravity

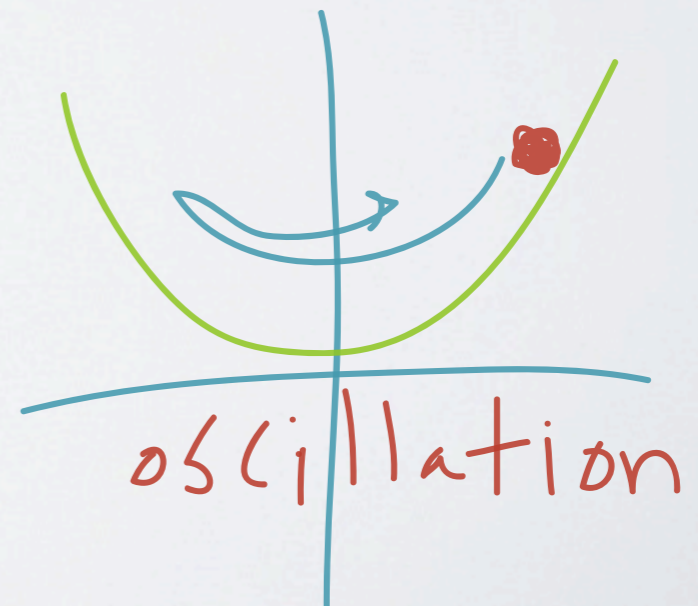
(in particular Acharya, Kane et al)

$$\int d^4\theta \frac{\chi^\dagger \chi \phi^\dagger \phi}{M_{pl}^2} \quad \langle \chi \rangle = \theta^2 F \Rightarrow \tilde{m}^2 \phi^\dagger \phi$$

What happens to ϕ ?



until $H \sim m \Rightarrow$



THINKING ABOUT THE LATE EARLY UNIVERSE

So ϕ evolves like matter
until it decays at time

$$t \sim \left(\frac{m_\phi^3}{M_{\text{pl}}^2} \right)^{-1}$$

at temperature

$$T \sim 10 \text{ MeV} \times \left(\frac{m_\phi}{\text{TeV}} \right)^{3/2} \quad \text{Yikes!}$$

$$\Rightarrow m_\phi \sim 30 \text{ TeV}$$

THINKING ABOUT THE LATE EARLY UNIVERSE

$$\frac{\chi^+ \chi \phi^+ \phi}{M_{\text{Pl}}^2} \leftrightarrow \frac{\chi^+ \chi Q^+ \bar{Q}}{M_{\text{Pl}}^2}$$

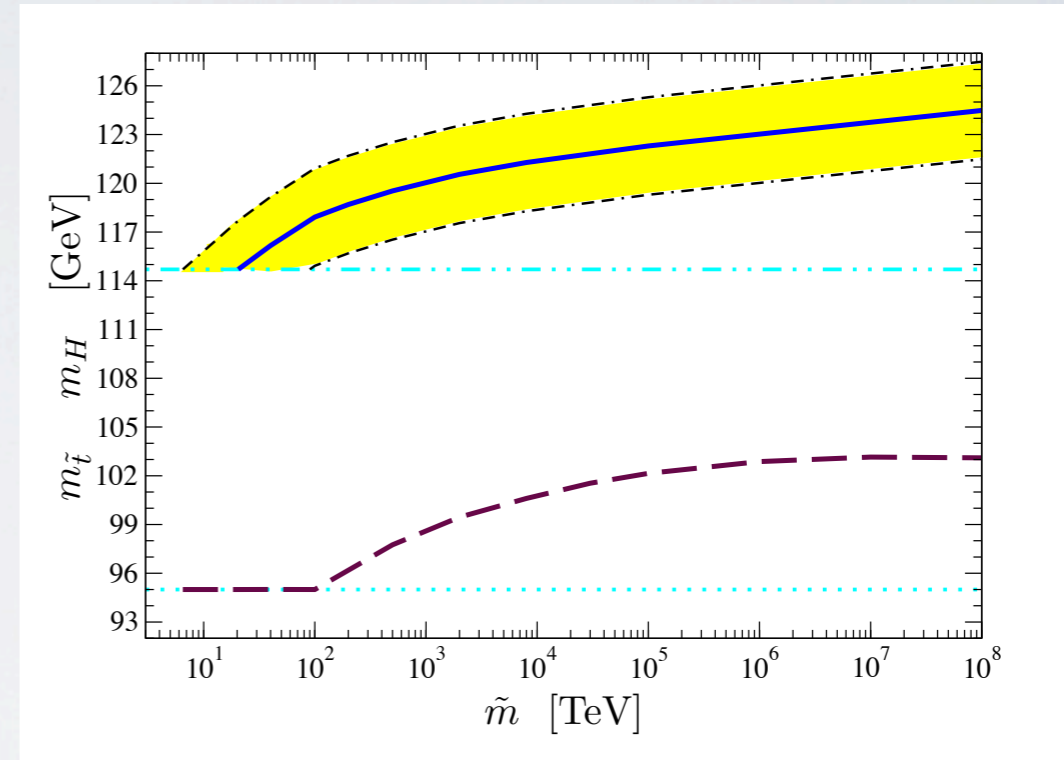
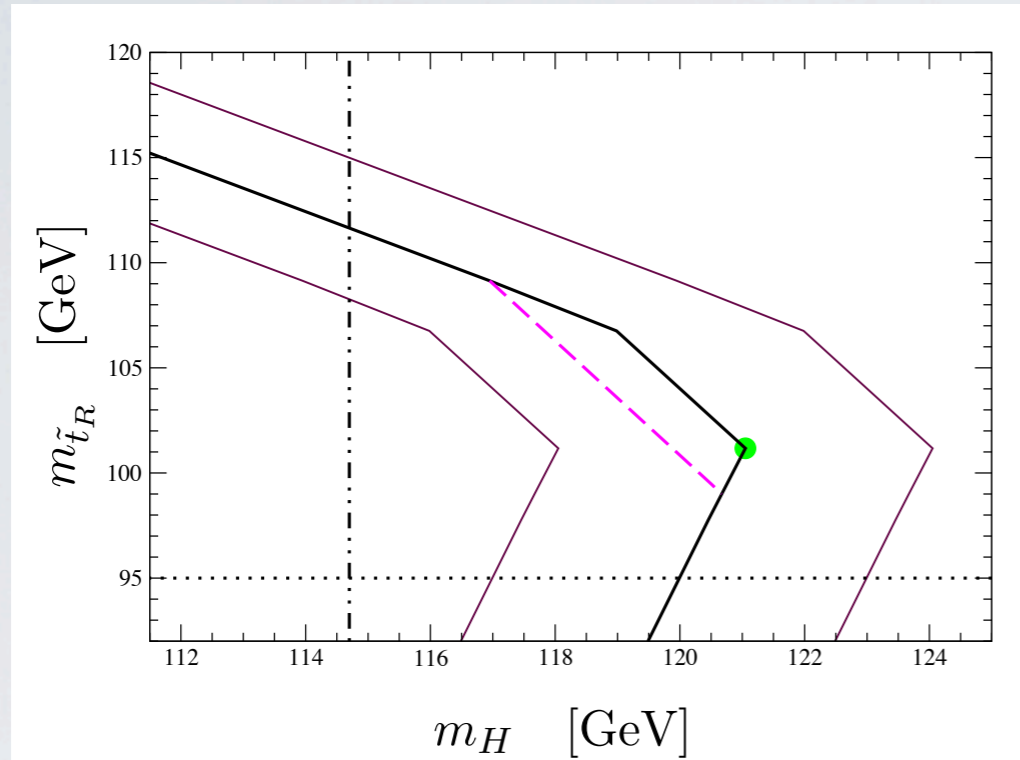
Squarks at 30 TeV?!?!
(except for "light" stops
at ~ 10 TeV)

Gauginos still light
(anomaly mediation)

WHY ARE WE HERE?

- Baryogenesis requires
 - C/CP Violation
 - Baryon number violation
 - First order phase transition
- Do these (esp FO EWPT) appear in our theories?

WHY ARE WE HERE?

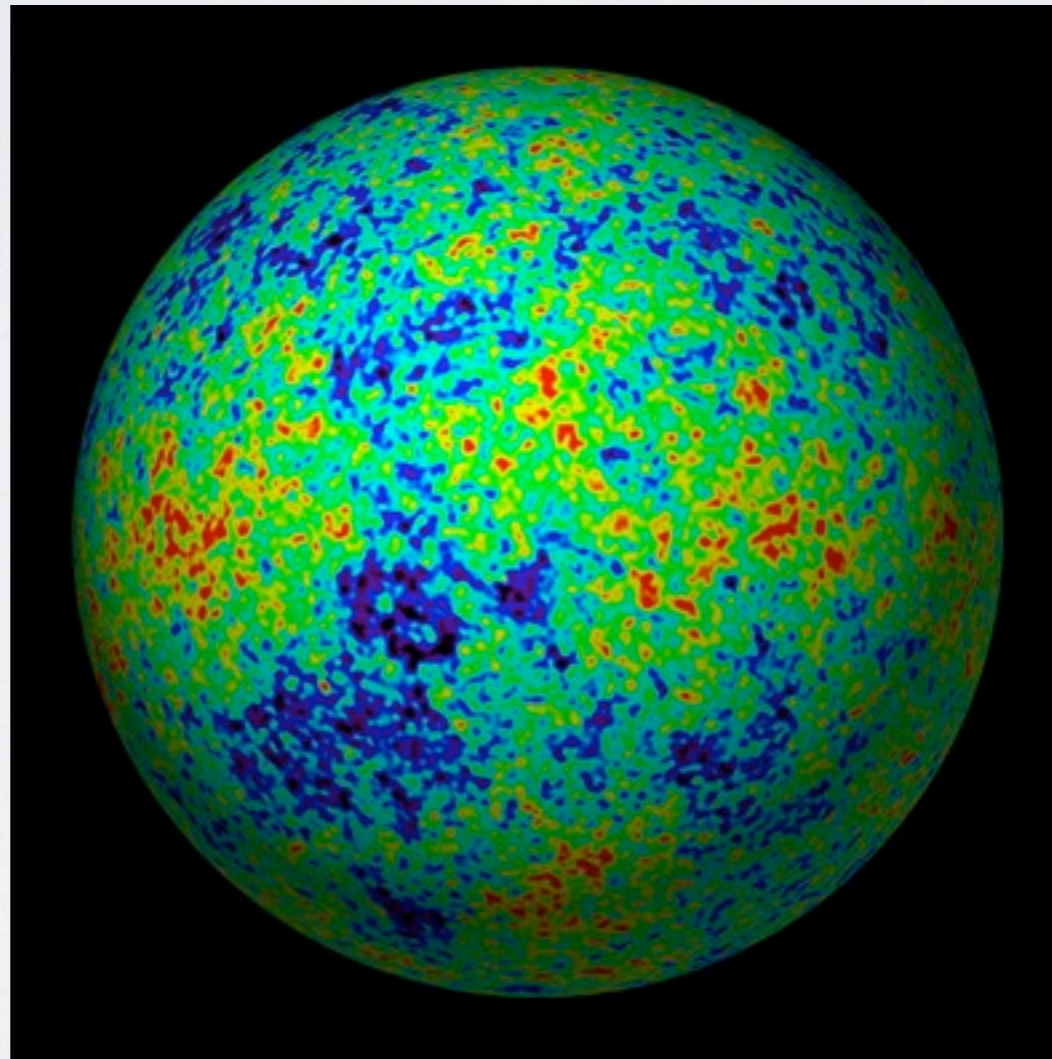


Carena, Nardini, Quiros, Wagner '08

Light stops \rightarrow First order phase transition
 \rightarrow the origin of matter?

PLANCK AND THE LHC

What if you see hints of new physics before the shutdown, and Planck sees tensor modes?



Tensor modes \Rightarrow inflation scale = MGUT!

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

TeV WIMPs

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

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TeV WIMPs

Light WIMPs

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TeV WIMPs

Light WIMPs

Prompt sparticle
decays

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

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(maybe not
much MET)

TeV WIMPs

Displaced
vertices

Light WIMPs

Prompt sparticle
decays

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

TeV WIMPs

Light WIMPs

Displaced
vertices

Very very
light stops

Prompt sparticle
decays

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

Displaced
vertices

Very very
light stops

Prompt sparticle
decays

TeV WIMPs

Light WIMPs

Very very
heavy stops!

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

lepton jets

Very very
light stops

Displaced
vertices

Prompt sparticle
decays

TeV WIMPs

Light WIMPs

Very very
heavy stops!

WHAT CAN THE LHC TELL US ABOUT COSMOLOGY?

Cosmology tells us

MET!

(maybe not
much MET)

lepton jets

Very very
light stops

SUSY +
Grand unification

(if we're lucky)

Displaced
vertices

Prompt sparticle
decays

TeV WIMPs

Light WIMPs

Very very
heavy stops!

- a lot of predictions, but it's a big universe

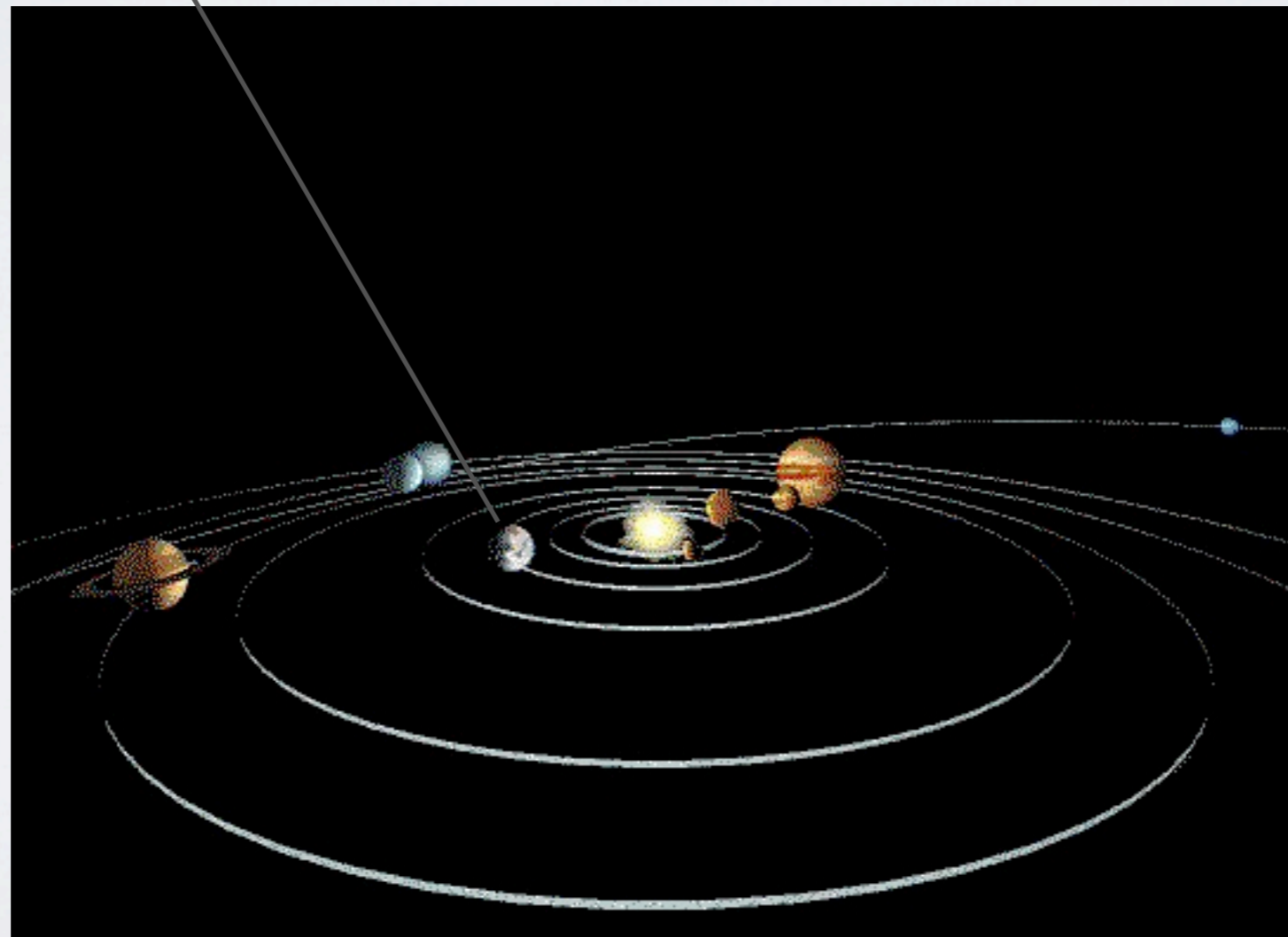
THE COPERNICAN EVOLUTION

You are here



THE COPERNICAN EVOLUTION

You are here



THE COPERNICAN EVOLUTION

You are here



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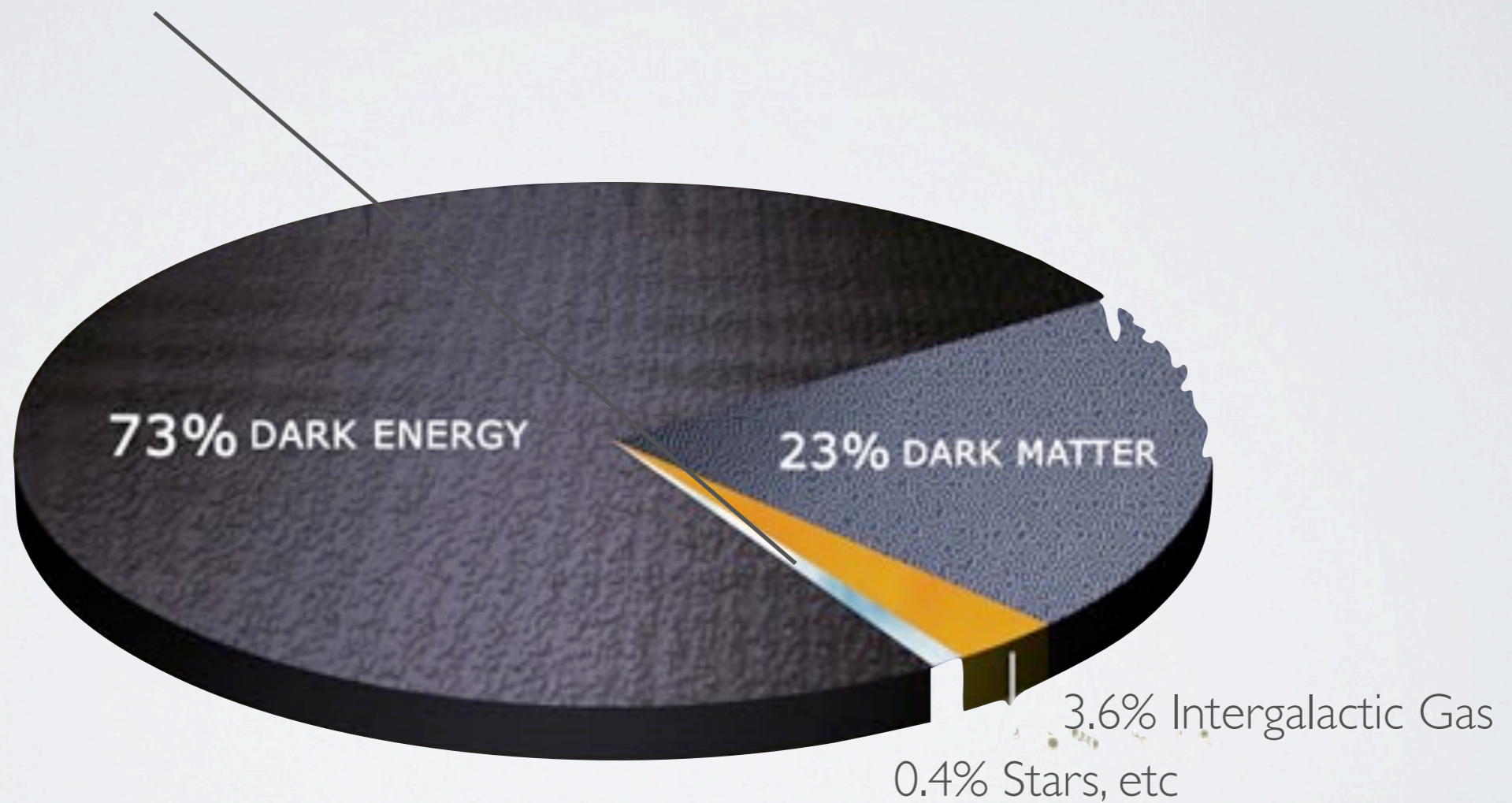
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Standard Model of FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

| Leptons spin = 1/2 | | | Quarks spin = 1/2 | | |
|---------------------------|-------------------------|-----------------|-------------------|---------------------------------|-----------------|
| Flavor | Mass GeV/c ² | Electric charge | Flavor | Approx. Mass GeV/c ² | Electric charge |
| ν_e electron neutrino | <1.5x10 ⁻⁸ | 0 | u up | 0.003 | 2/3 |
| e ⁻ electron | 0.000511 | -1 | d down | 0.006 | -1/3 |
| ν_μ muon neutrino | <0.0002 | 0 | c charm | 1.3 | 2/3 |
| μ^- muon | 0.106 | -1 | s strange | 0.1 | -1/3 |
| ν_τ tau neutrino | <0.02 | 0 | t top | 175 | 2/3 |
| τ^- tau | 1.7771 | -1 | b bottom | 4.3 | -1/3 |

Spin is the intrinsic angular momentum of particles. Spin is given in units of \hbar , which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58 \times 10^{-22}$ GeV s = 1.05×10^{-34} J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember $E = mc^2$), where 1 GeV = 10^9 eV = 1.60×10^{-10} joule. The mass of the proton is 0.938 GeV/c² = 1.67×10^{-27} kg.

Structure within the Atom

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS force carriers spin = 0, 1, 2, ...

| Unified Electroweak spin = 1 | | | Strong (color) spin = 1 | | |
|---|-------------------------|-----------------|--|-------------------------|-----------------|
| Name | Mass GeV/c ² | Electric charge | Name | Mass GeV/c ² | Electric charge |
| γ photon | 0 | 0 | g gluon | 0 | 0 |
| W ⁻ | 80.4 | -1 | Color Charge | | |
| W ⁺ | 80.4 | +1 | Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and W and Z bosons have no strong interactions and hence no color charge. | | |
| Z ⁰ | 91.187 | 0 | Quarks Confined in Mesons and Baryons | | |
| One cannot isolate quarks and gluons; they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: mesons qq and baryons qqq. | | | | | |
| Residual Strong Interaction | | | | | |
| The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons. | | | | | |

PROPERTIES OF THE INTERACTIONS

| Property | Gravitational | Weak (Electroweak) | Electromagnetic | Strong | |
|---|-----------------------------|--|----------------------|---------------------------|--------------------------------------|
| | | | | Fundamental | Residual |
| Acts on: | Mass - Energy | Flavor | Electric Charge | Color Charge | See Residual Strong Interaction Note |
| Particles experiencing: | All | Quarks, Leptons | Electrically charged | Quarks, Gluons | Hadrons |
| Particles mediating: | Graviton (not yet observed) | W ⁺ W ⁻ Z ⁰ | γ | Gluons | Mesons |
| Strength relative to electromag. for two u quarks at: | | | | | |
| 10 ⁻¹⁶ m | 10 ⁻⁴⁵ | 0.8 | 1 | 25 | Not applicable to quarks |
| 3x10 ⁻¹⁷ m | 10 ⁻⁴⁵ | 10 ⁻⁶ | 1 | 60 | Not applicable to hadrons |
| for two protons in nucleus | 10 ⁻³⁶ | 10 ⁻⁷ | 1 | Not applicable to hadrons | 20 |

Baryons qqq and Antibaryons qq̄q̄

Baryons are fermionic hadrons. There are about 120 types of baryons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c ² | Spin |
|------------|-------------|-------------------------|-----------------|-------------------------|------|
| p | proton | uud | 1 | 0.938 | 1/2 |
| \bar{p} | anti-proton | $\bar{u}\bar{u}\bar{d}$ | -1 | 0.938 | 1/2 |
| n | neutron | udd | 0 | 0.940 | 1/2 |
| Λ | lambda | uds | 0 | 1.116 | 1/2 |
| Ω^- | omega | sss | -1 | 1.672 | 3/2 |

Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ , and η , and η_c = c \bar{c}), but not K⁰ = d \bar{s}) are their own antiparticles.

Figures
These diagrams are an artist's conception of physical processes. They are not exact and have no meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.

A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.

An electron and positron (antiparticle) colliding at high energy can annihilate to produce B⁰ and \bar{B}^0 mesons via a virtual Z boson or a virtual photon.

Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

Mesons qq̄

Mesons are bosonic hadrons. There are about 140 types of mesons.

| Symbol | Name | Quark content | Electric charge | Mass GeV/c ² | Spin |
|----------------|--------|---------------|-----------------|-------------------------|------|
| π^+ | pion | u \bar{d} | +1 | 0.140 | 0 |
| K ⁻ | kaon | s \bar{u} | -1 | 0.494 | 0 |
| ρ^+ | rho | u \bar{d} | +1 | 0.770 | 1 |
| B ⁰ | B-zero | d \bar{b} | 0 | 5.279 | 0 |
| η_c | eta-c | c \bar{c} | 0 | 2.980 | 0 |

The Particle Adventure
Visit the award-winning web feature The Particle Adventure at <http://ParticleAdventure.org>

This chart has been made possible by the generous support of:
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Stanford Linear Accelerator Center
American Physical Society, Division of Particle and Field
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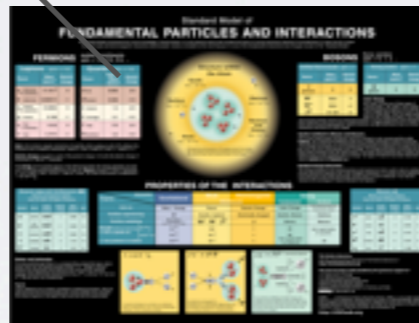
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SUSY?

Large extra dimensions?

Hidden sectors?



Conformal dynamics?

Dark forces?

Strong dynamics?