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Theory of Beyond the Standard Model Physics

Hitoshi Murayama (IPMU Tokyo & Berkeley)

Physics at the LHC 2010, DESY, Jun 8, 2010

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How stupid theorists are
and
Why LHC matters

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Standard Model

- A monument of the 20th century physics
- unifies quantum mechanics and relativity (but not GR)
- minimal particle content, renormalizable
- explains 1340 pages of Particle Data Group with only 19 parameters
- tested down to 10^{-12} for electron g_e-2
- the only missing particle is Higgs boson

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T-shirt ready

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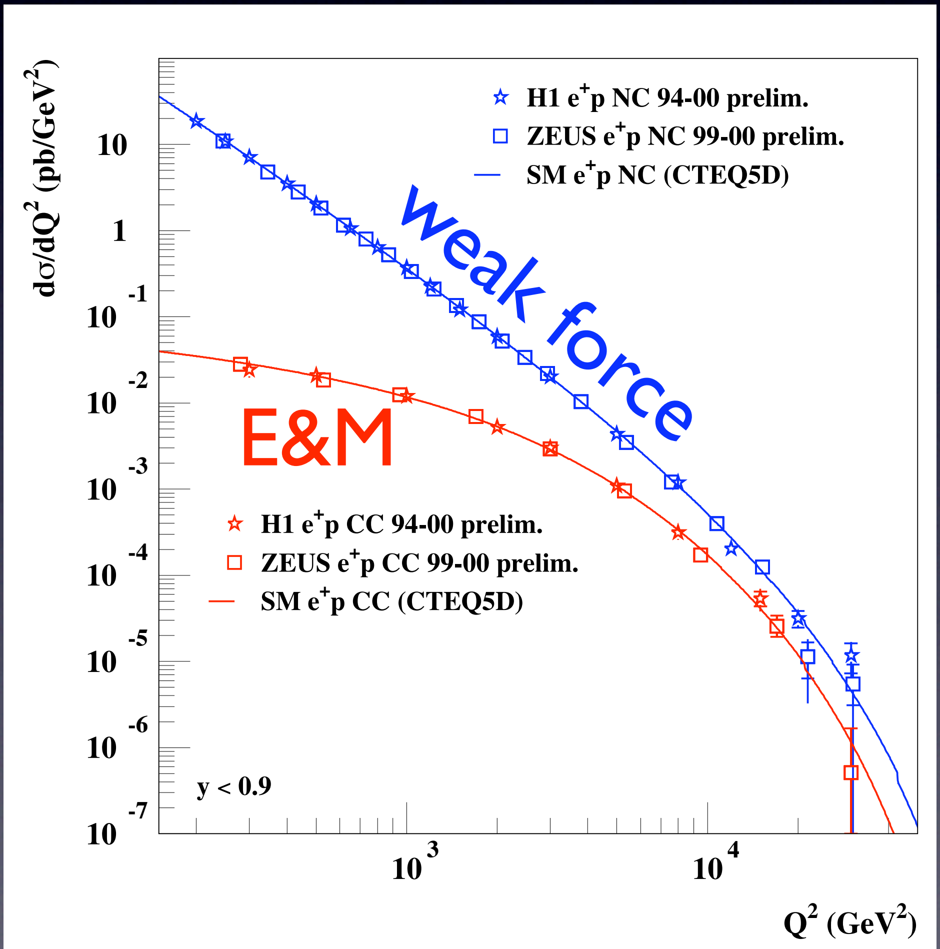
$$
\begin{aligned}
\mathcal{L} = \\
& -\frac{1}{4g'^4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4g^2} W^a_{\mu\nu} W^{\mu\nu a} - \frac{1}{4g_s^2} G^a_{\mu\nu} G^{\mu\nu a} \\
& + \bar{Q}_i i \not{D} Q_i + \bar{u}_i i \not{D} u_i + \bar{d}_i i \not{D} d_i + \bar{L}_i i \not{D} L_i + \bar{e}_i i \not{D} e_i \\
& + (Y_u^{ij} \bar{Q}_i u_j \tilde{H} + Y_d^{ij} \bar{Q}_i d_j H + Y_l^{ij} \bar{L}_i e_j H + c.c.) \\
& - \lambda (H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}
\end{aligned}
$$

an imminent unification

HERA ep collider



- Unification of electromagnetic and weak forces

$\Rightarrow$ electroweak theory

- Long-term goal since '60s
- We are getting there!
- The main missing link: Higgs boson
- Then aren't we done??

Why BSM?

Once upon a time, there was a hierarchy problem...

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \mathrm{GeV}\frac{10^{-17}\mathrm{cm}}{r_e}$$

- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}$cm
- Breakdown of theory of electromagnetism

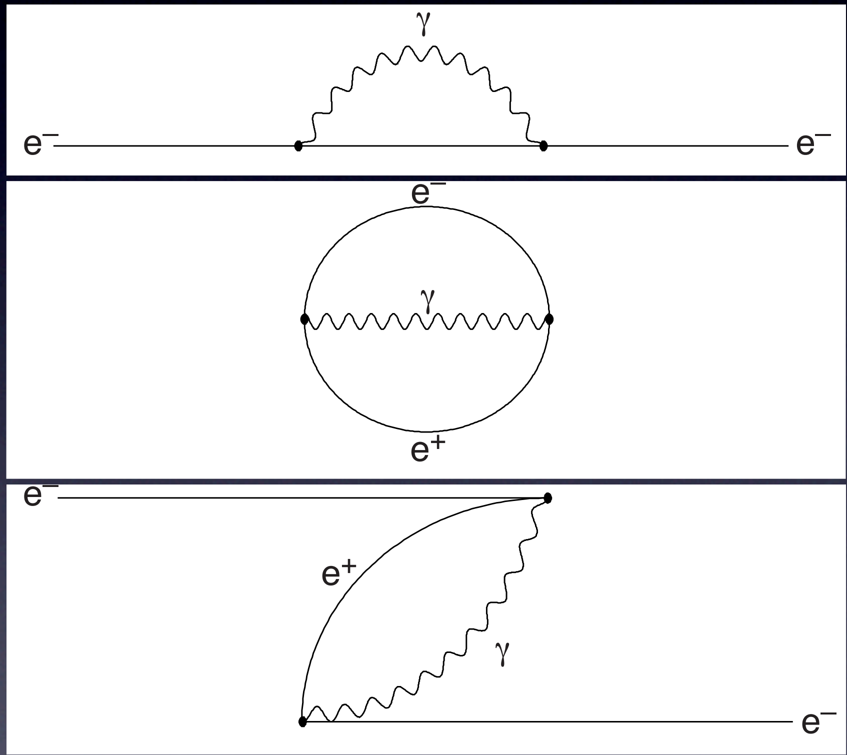
  ⇒ Can't discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

⇒ only 10% of mass even

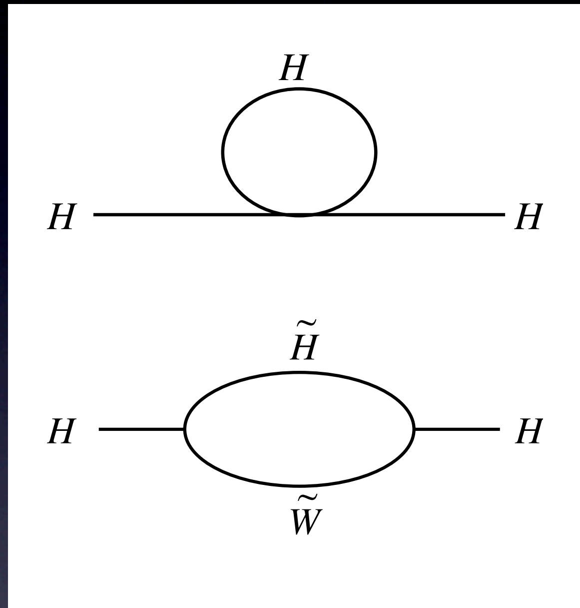
for Planck-size r_e~10^{-33}cm



$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

History repeats itself?

- Higgs also repels itself
- Double #particles again
  ⇒ superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Three Directions

History repeats itself

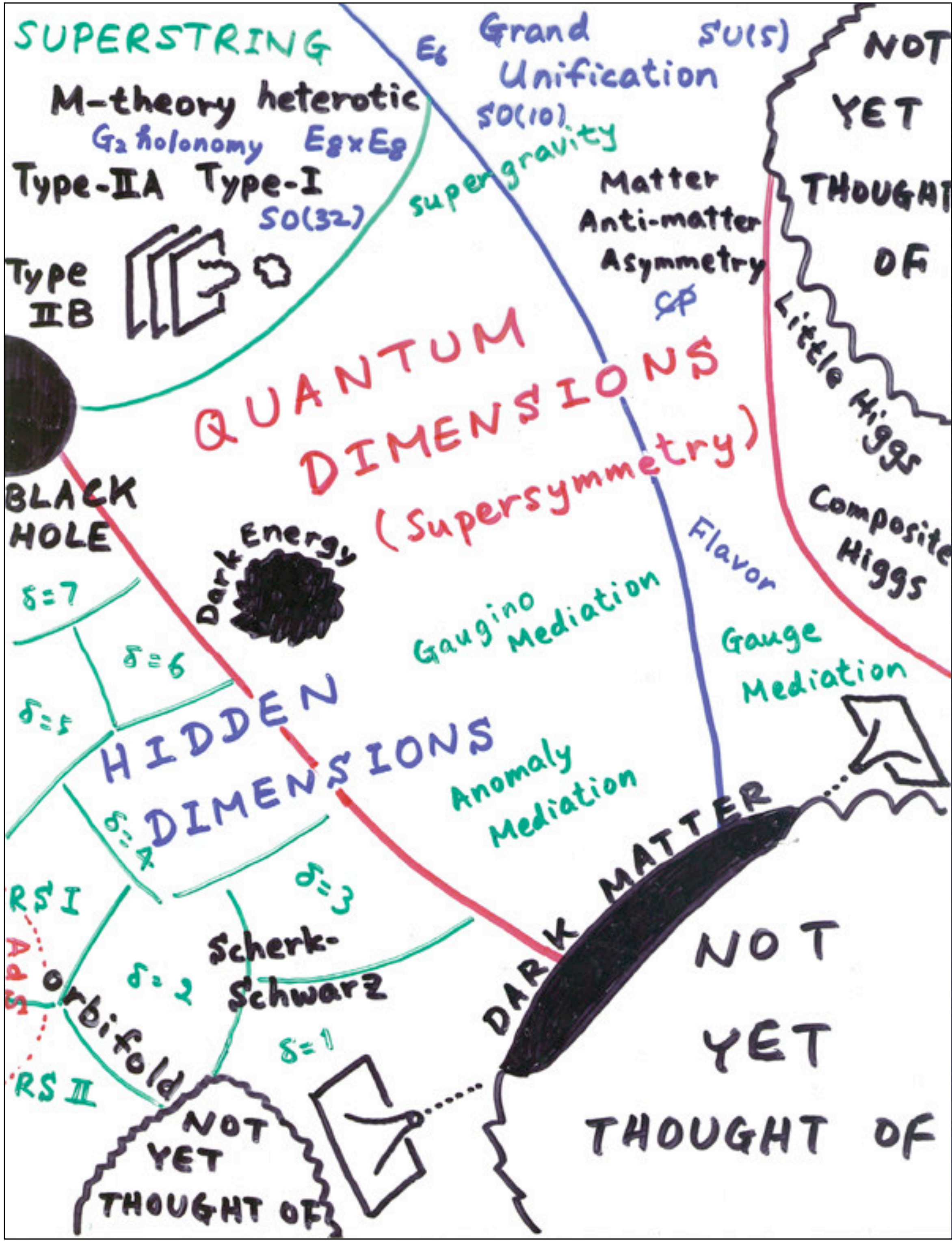
- Crisis with electron solved by anti-matter
- Double #particles again ⇒ supersymmetry

Learn from Cooper pairs

- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite
  ⇒ technicolor

Physics as we know it ends at TeV

- Ultimate scale of physics: quantum gravity
- May have quantum gravity at TeV
  ⇒ hidden dimensions (0.1 mm to 10^{-17} cm)



- We really don't know what is going on at TeV
- Can we zoom in onto a point on this map?

Growing Concern among theorists

- No established deviations in
  - precision electroweak
  - flavor physics
  - LEP/Tevatron searches
- Is nature fine-tuned?
- after all, cosmological constant tuned 10^{-120}
- maybe there isn't anything beyond the Standard Model? ⇒ *There definitely is!*

Five empirical evidences

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - accelerated expansion of the Universe
  - apparently acausal density fluctuations
  - baryon asymmetry

The New Minimal SM

Davoudiasl, Kitano, Li, HM

$$L_\Lambda = (2.3 \times 10^{-3}\ eV)^4$$ dark energy, dof=0

$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$ dark matter, dof=1

$$L_\varphi = \frac{1}{2}\partial_\mu \varphi \partial^\mu \varphi - \frac{1}{2} m^2 \varphi^2 - \frac{\mu}{3!}\varphi^3 - \frac{\kappa}{4!}\varphi^4.$$ inflation, dof=1

$$L_N = \bar{N}_\alpha i \partial\!\!\!/ N_\alpha - \left(\frac{M_\alpha}{2} N_\alpha N_\alpha + h_\nu^{\alpha i} N_\alpha L_i \tilde{H} + c.c. \right).$$ neutrino mass, dof=4

$$L_{RH} = -\mu_1 \varphi |H|^2 - \mu_2 \varphi S^2 - \kappa_H \varphi^2 |H|^2 - \kappa_S \varphi^2 S^2 - (y_N^{\alpha\beta} \varphi N_\alpha N_\beta + c.c.).$$

$$L_{NMSM} = L_{MSM} + L_S + L_\Lambda + L_N + L_\varphi + L_{RH}$$

can incorporate all known established data

even small modification affects LHC data

invisible Higgs, direct detection of DM

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New Era

- ~1900 reached atomic scale 10^{-8}cm $\approx \alpha/m_e$
- ~1970 reached strong scale 10^{-13}cm $\approx M e^{-2\pi/\alpha_s b_0}$
- ~2010 will reach weak scale 10^{-17}cm=TeV^{-1}
- known since Fermi (1933), finally there!
- presumably it is also a derived scale
  - from SUSY breaking? extra dimensions? string theory?
- If so, we expect rich spectrum of new particles!
- We'll start with Higgs boson(s)

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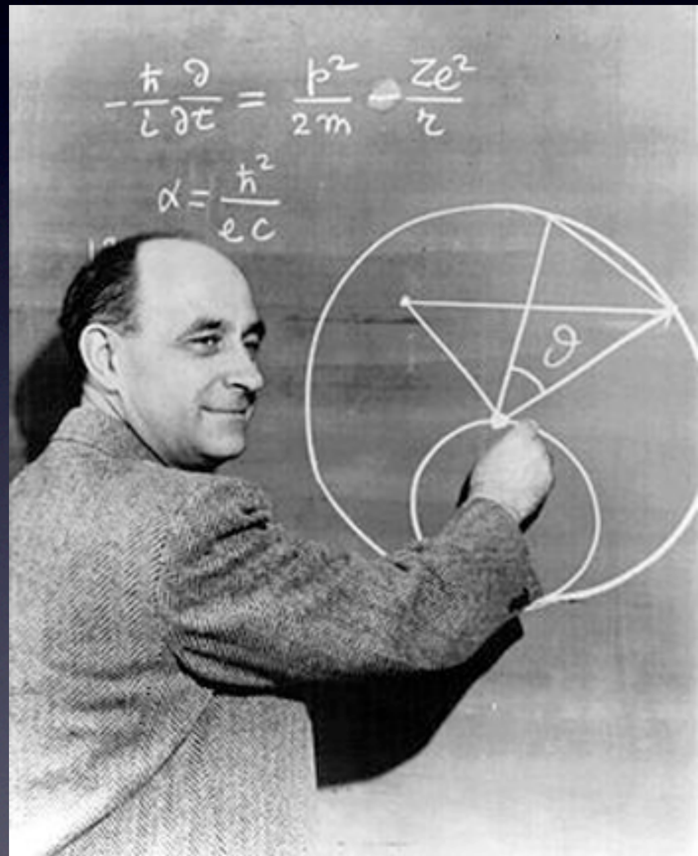
Fermi's dream era

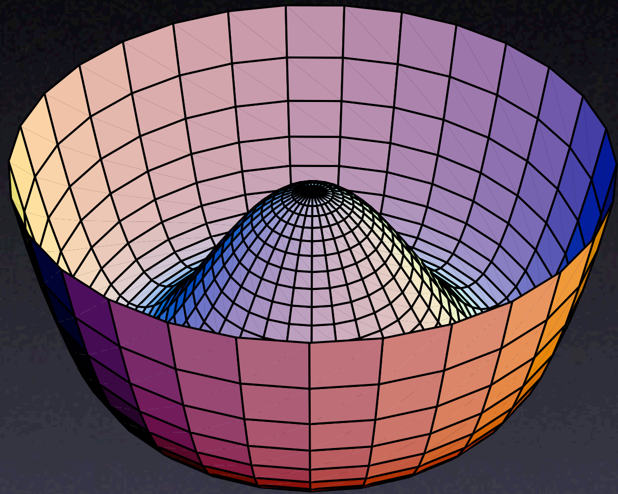
- Fermi formulated the first theory of the weak force (1932)
- *The required energy scale to study the problem known since then:* ~TeV
- We are finally getting there!



Higgs
=Cosmic Superconductor

Post-Higgs Problem

- robust discovery by ATLAS/CMS
- We see “what” is condensed
- But we still don’t know “why”
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of condensation ~TeV<<M_{Pl}=10^{15}TeV
- Explanation most likely to be at ~TeV scale because this is the relevant energy scale



Three Directions

Supersymmetry

- Higgs just one of *many* scalar bosons
- SUSY loops make m_h^2 negative

Higgsless/composite

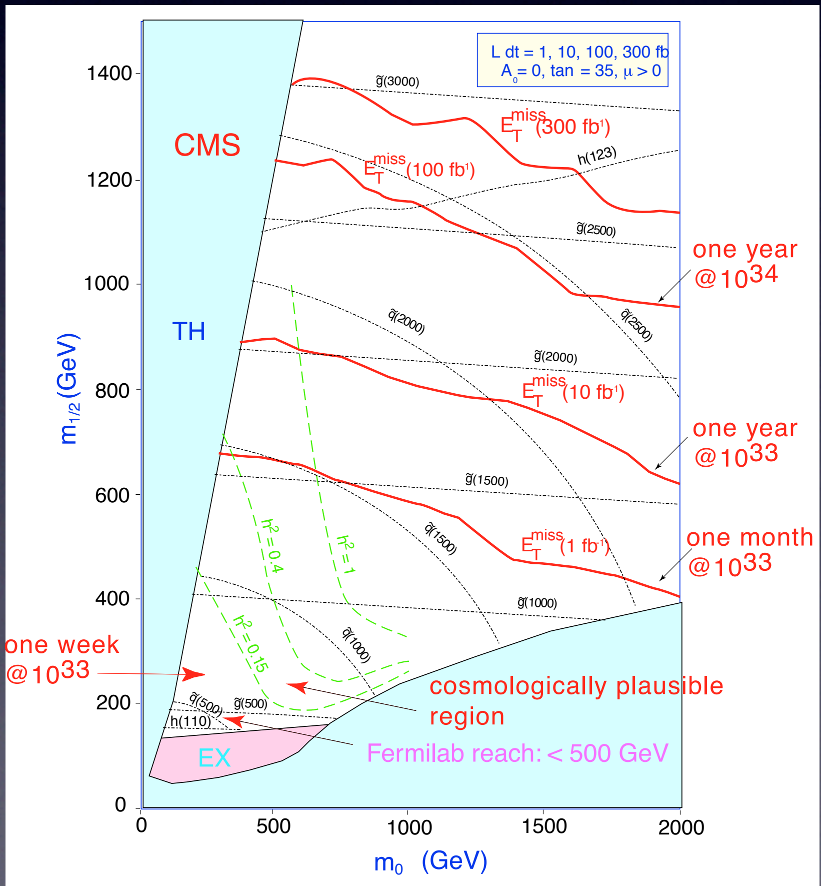
- Higgs bound state of elementary fermions
- condenses because of strong attractive force

Extra dimension

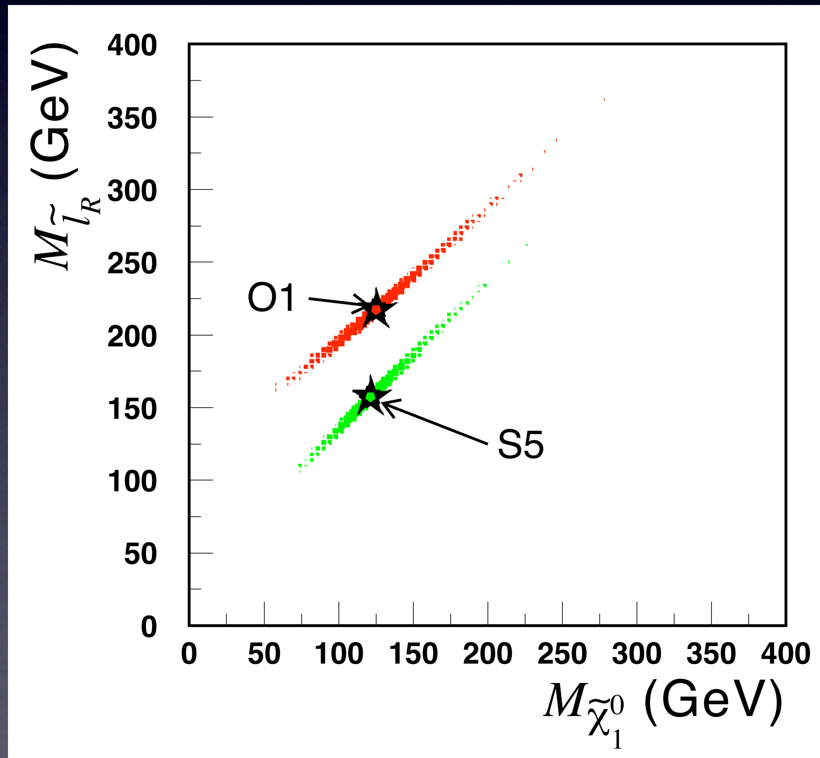
- Higgs spinning in extra dimensions
- new forces from particles running in extra D

Supersymmetry

discover supersymmetry



Can do many measurements at LHC



The New York Times

July 23, 2015

The Other Half of the World Discovered

Geneva, Switzerland

As an example, supersymmetry

"New-York Times level" confidence

still a long way to

"Halliday-Resnick" level confidence

"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

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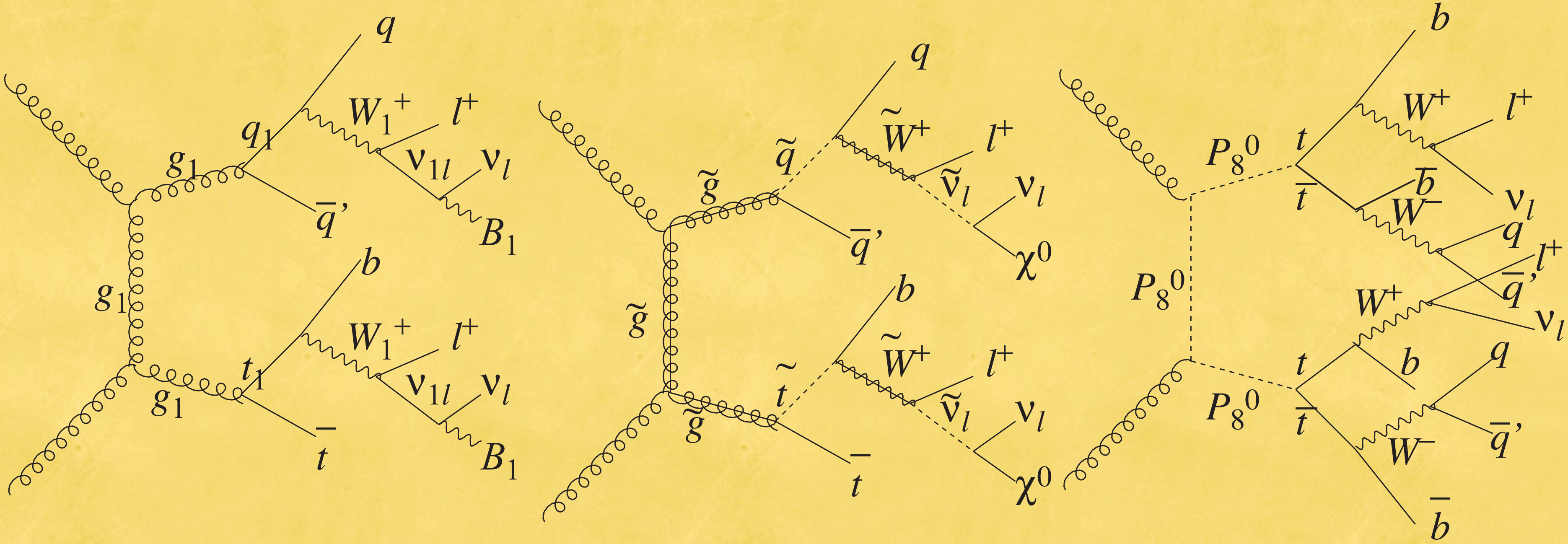
New physics looks alike

missing E_T, multiple jets, b-jets, (like-sign) leptons



UED
spin 1

SUSY
spin 1/2

technicolor
spin 0

+4th generation, little Higgs with T-parity

need precision mea

- spectroscopy
- precision mass, BR measurements
- need to do this *without* assuming the underlying model!

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Squarks $J=0$?

PDG 2016

The following data are averaged over all light flavors, presumably u, d, s, c with both chiralities. For flavor-tagged data, see listings for Stop and Sbottom. Most results assume minimal supergravity, an untested hypothesis with only five parameters. Alternative interpretation as extra dimensional particles is possible. See KK particle listing.

SQUARK MASS

VALUE (GeV)	DOCUMENT ID	TECN	COMMENT
538±10	**OUR FIT**		**mSUGRA assumptions**
532±11	[1]ABBIENDI 11D	CMS	Missing ET with mSUGRA assumptions
541±14	[2]ADLER 11O	ATLAS	Missing ET with mSUGRA assumptions
• • • We do not use the following data for averages, fits, limits, etc • • •			
652±105	[3]ABBIENDI 11K	CMS	extended mSUGRA with 5 more parameters

[1]ABBIENDI 11D assumes minimal supergravity in the fits to the data of jets and missing energies and set $A_0=0$ and $\tan\beta = 3$. See Fig. 5 of the paper for other choices of A_0 and $\tan\beta$. The result is correlated with the gluino mass M_3. See listing for gluino.

[2]ADLER 11O uses the same set of assumptions as ABBIENDI 11D, but with $\tan\beta = 5$.

[3]ABBIENDI 11K extends minimal supergravity by allowing for different scalar masses-squared for Hu, Hd, 5* and 10 scalars at the GUT scale.

SQUARK DECAY MODES

MODE	BR(%)	DOCUMENT ID	TECN	COMMENT
j+miss	32±5	ABE 10U	ATLAS	
j l+miss	73±10	ABE 10U	ATLAS	lepton universality
j e+miss	22±8	ABE 10U	ATLAS	
j μ +miss	25±7	ABE 10U	ATLAS	
q χ^+	seen	ABE 10U	ATLAS	

Helicity and phase

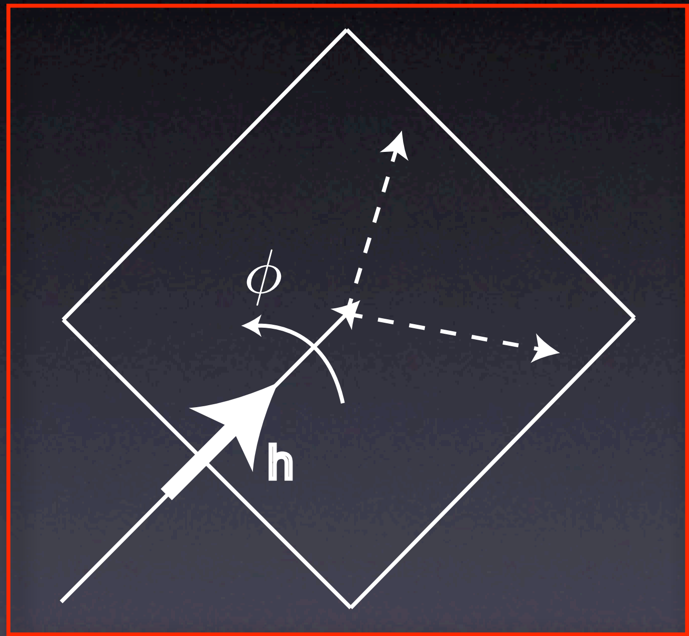
- Decay of particle with spin h along the momentum axis
- Rotations about z-axis of decay plane given by

$$\mathcal{M} \propto e^{iJ_z\phi}$$

$$J_z = \frac{(\vec{s} + \vec{x} \times \vec{p}) \cdot \vec{p}}{|\vec{p}|} = \frac{\vec{s} \cdot \vec{p}}{|\vec{p}|} = h$$

- rotational invariance: a single helicity state has flat distribution in ϕ:

$$\left|e^{ih\phi}\right|^2 = 1$$



Quantum Interference among helicities

(with M. Buckley, W. Klemm, and V. Rentala)

- If particles produced in multiple helicities:

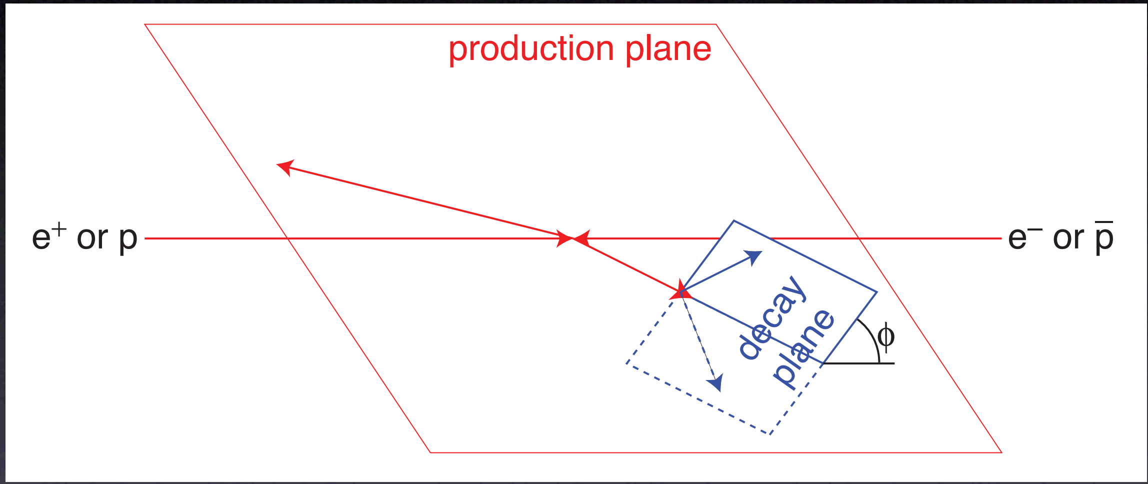
$$\sigma \propto \left| \sum \mathcal{M}_{prod.} \mathcal{M}_{decay} \right|^2$$

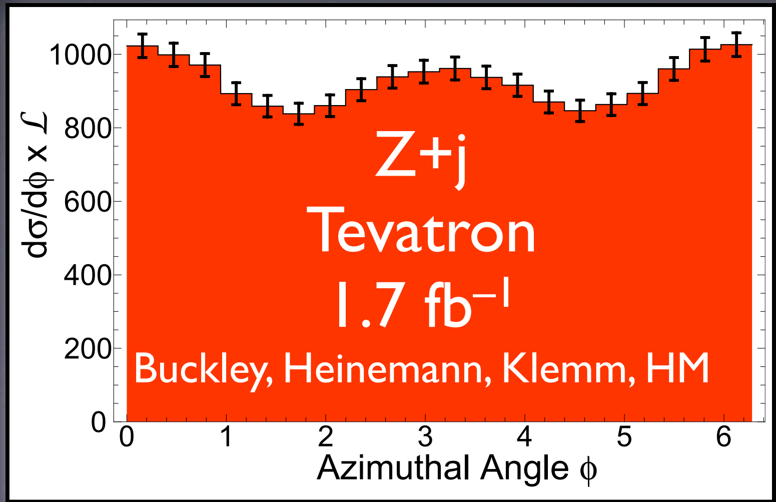
$$\mathcal{M}_{decay} = e^{ih\phi} \mathcal{M}_{decay}(h, \phi = 0)$$

- Different helicities interfere once they decay!
- ϕ dependence of cross section tells us what helicities contributed to the interference.
- Can measure only helicity differences (akin to neutrino oscillation)

Definition of the azimuthal angle

- Beam and produced particles span the production plane
- Parent particle and its decay products span the decay plane
- azimuth is the relative angle between two planes





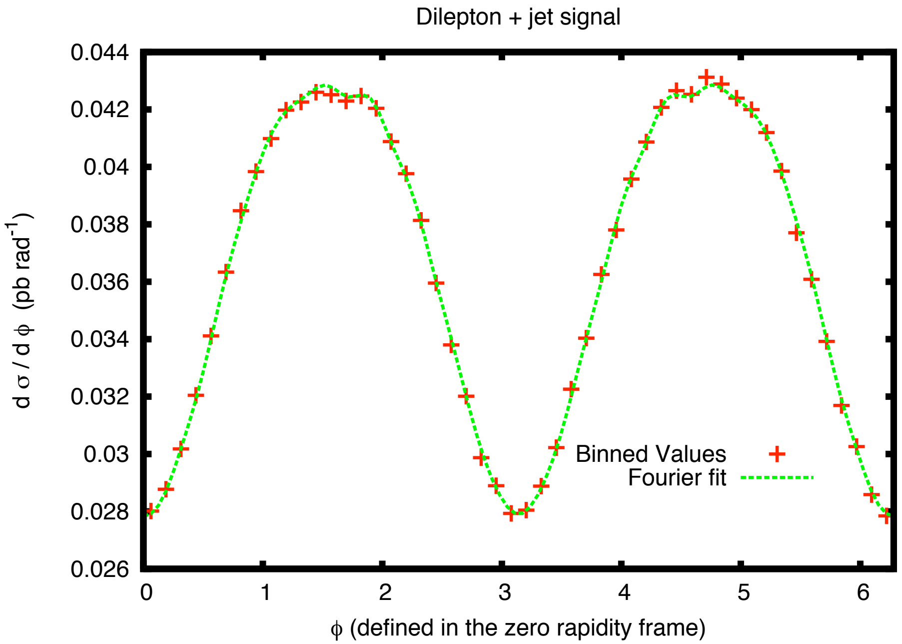
should be easy at LHC2011!

KK graviton

(with Vikram Rentala)

- LHC: pp→G+j show cos(4ϕ)! Doable for TeV KK graviton with > 100 fb^{-1}

σ_{signal}=230fb vs σ_{BG}=0.15fb



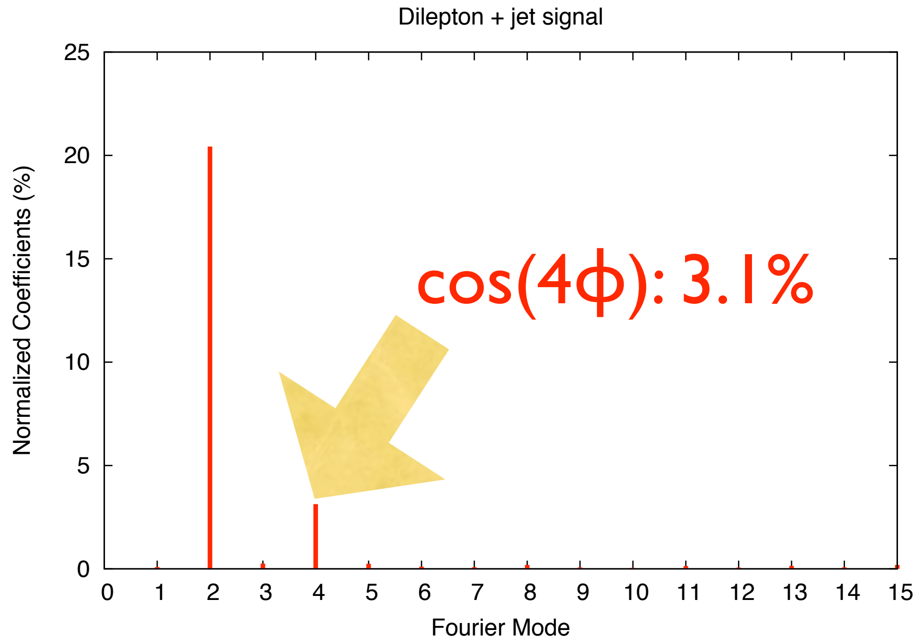
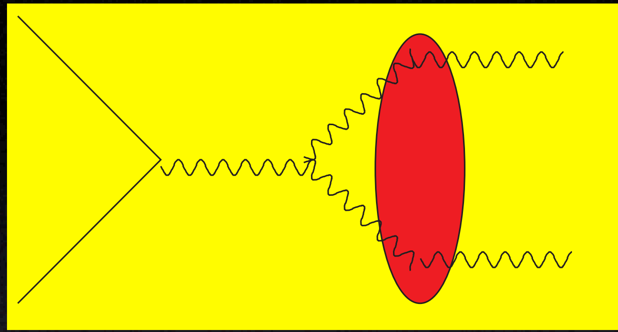


FIG. 5: Differential distribution ($\frac{d\sigma}{d\phi}$) for m_1 = 1 TeV and c = 0.1. A strong $\cos(2\phi)$ mode can be seen but there is also a $\cos(4\phi)$ component. The Fourier fit is shown in green.

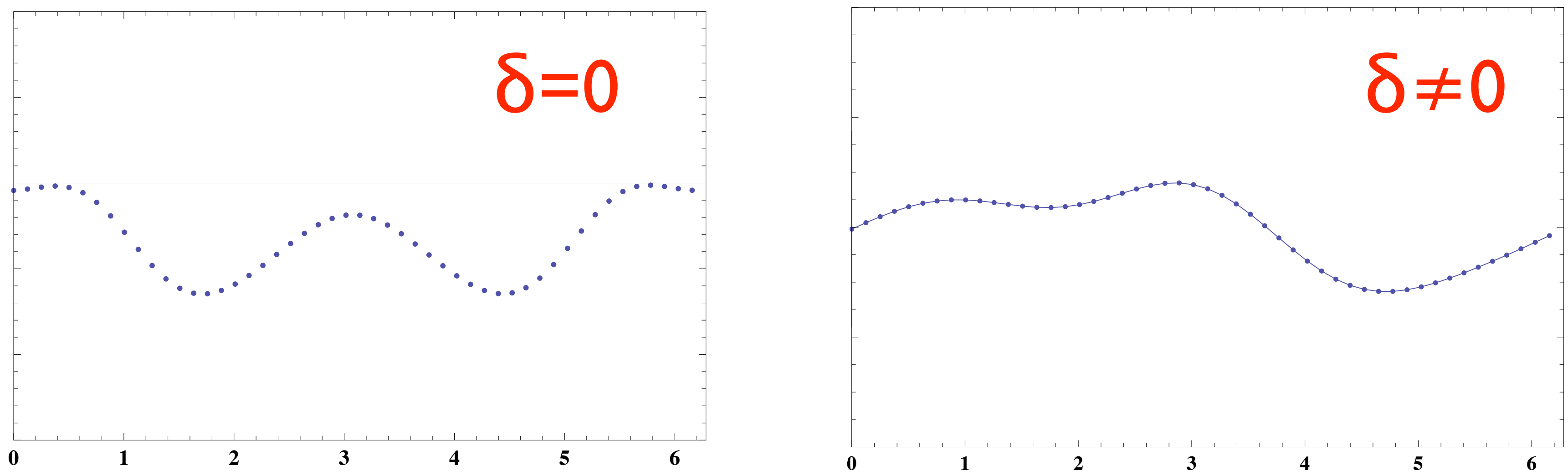
FIG. 6: Discrete Fourier Transform of the binned differential cross-section shown in Figure 5 corresponding to $N = 50$ bins. The errors are negligible and disappear in the limit of large statistics.

strong WZ scattering

$$\mathcal{A}(u\bar{d} \to W_L^+ Z_L) = |\mathcal{A}_{LL}| e^{i\delta}$$



- "rescattering phase" (cf. $K \to \pi\pi$)
- interference with $W_T Z_T$ after decay



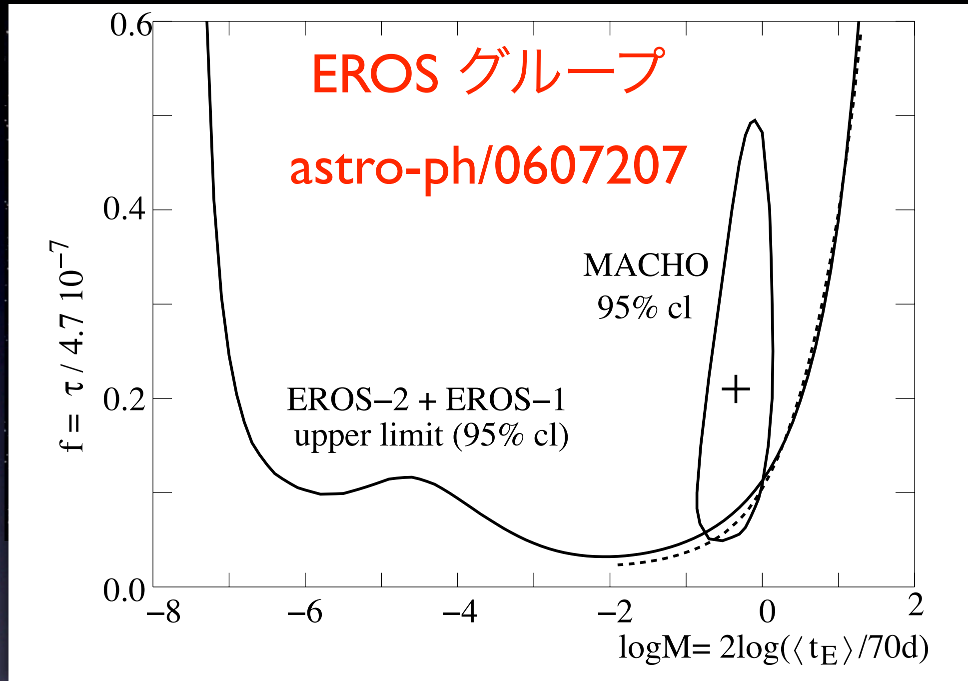
with Vikram Rentala, Jing Shu

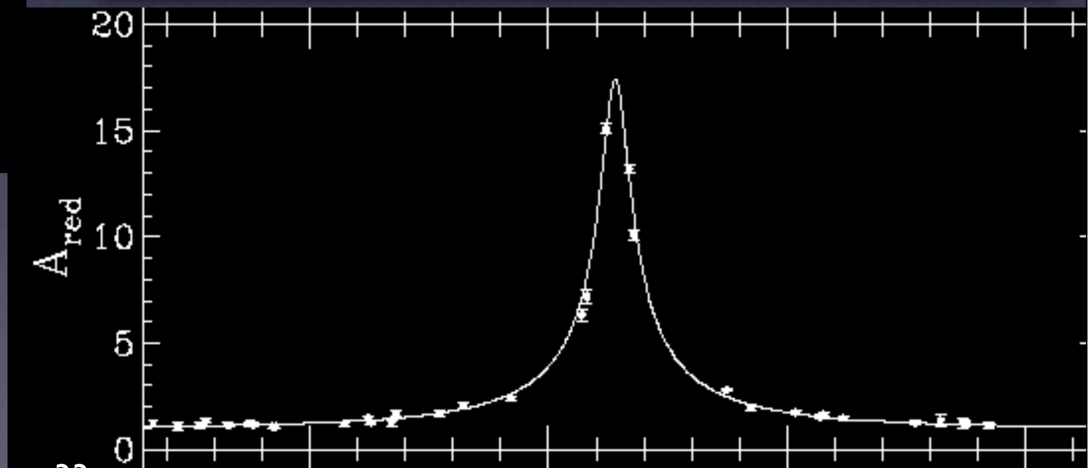
Dark Matter

You don’t want to be there

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)

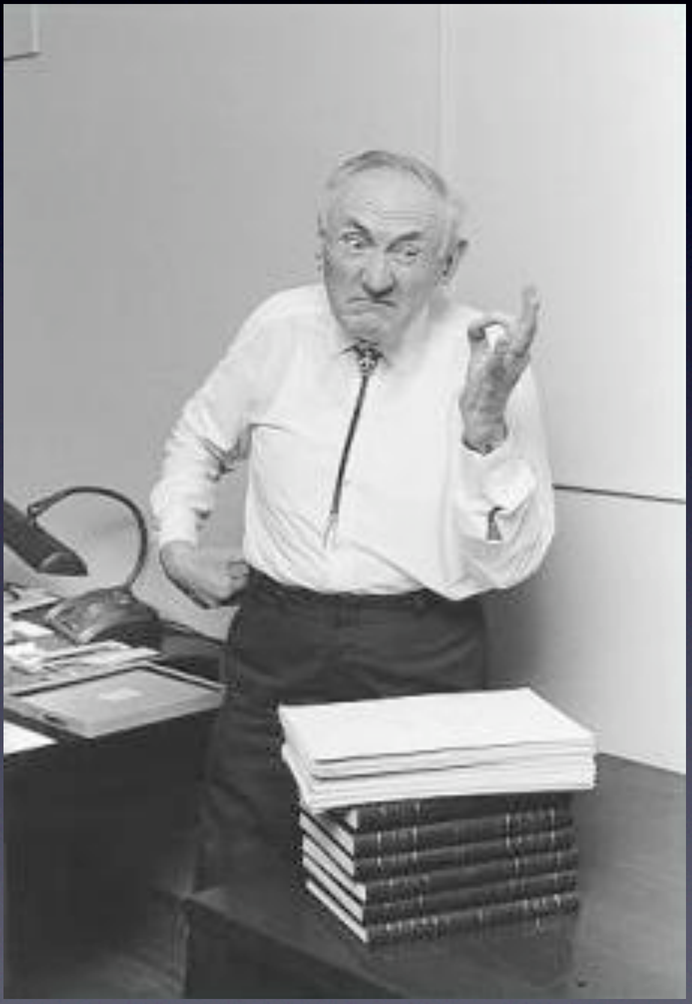




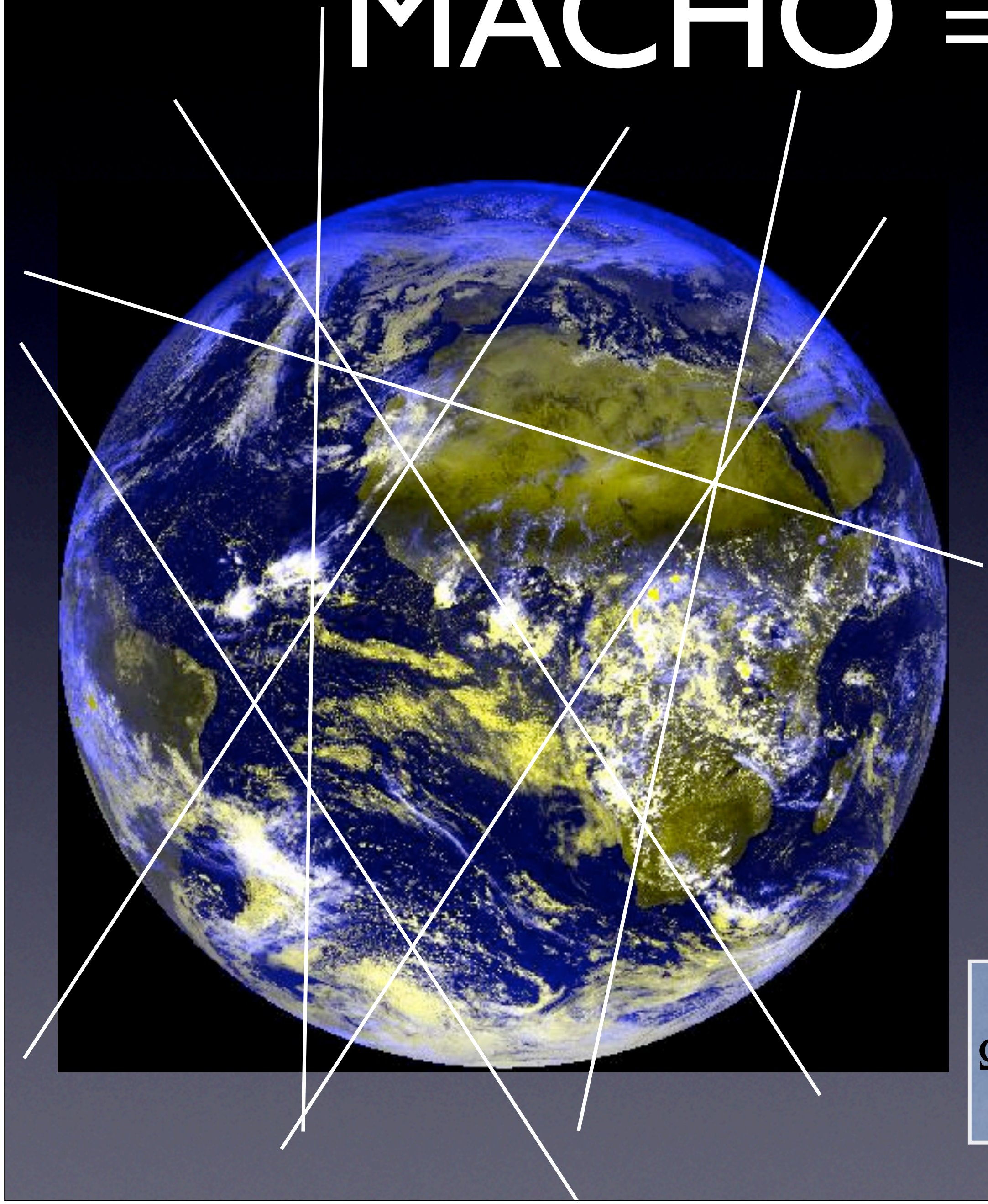
Not enough of them!

Mass Limits

- moves in $V = G_N \frac{Mm}{r}$
- "Bohr radius" $r_B = \frac{\hbar^2}{G_N M m^2}$
- if too light, won't fit inside the galaxy!
- 10^{-31} GeV to 10^{50} GeV
- narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



MACHO ⇒ WIMP



- *Probably WIMP (Weakly Interacting Massive Particle)*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

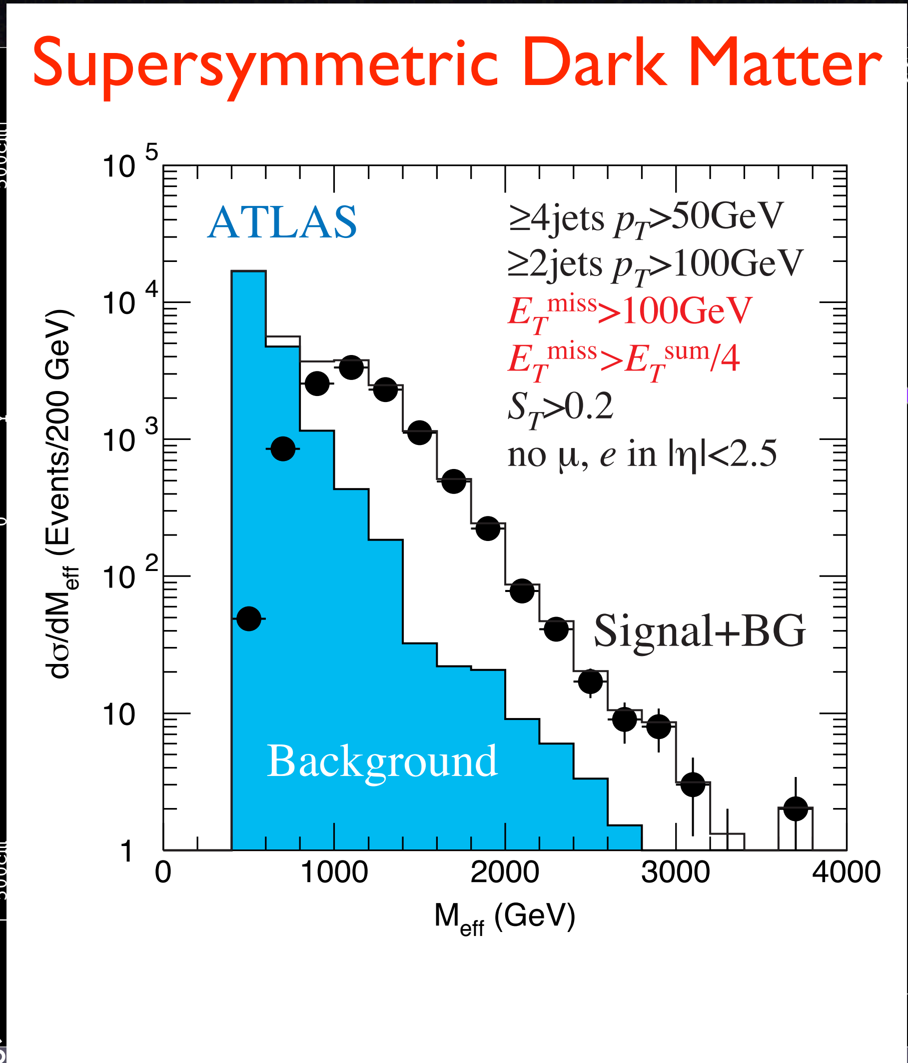
How do we "see" invisible dark matter?

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector

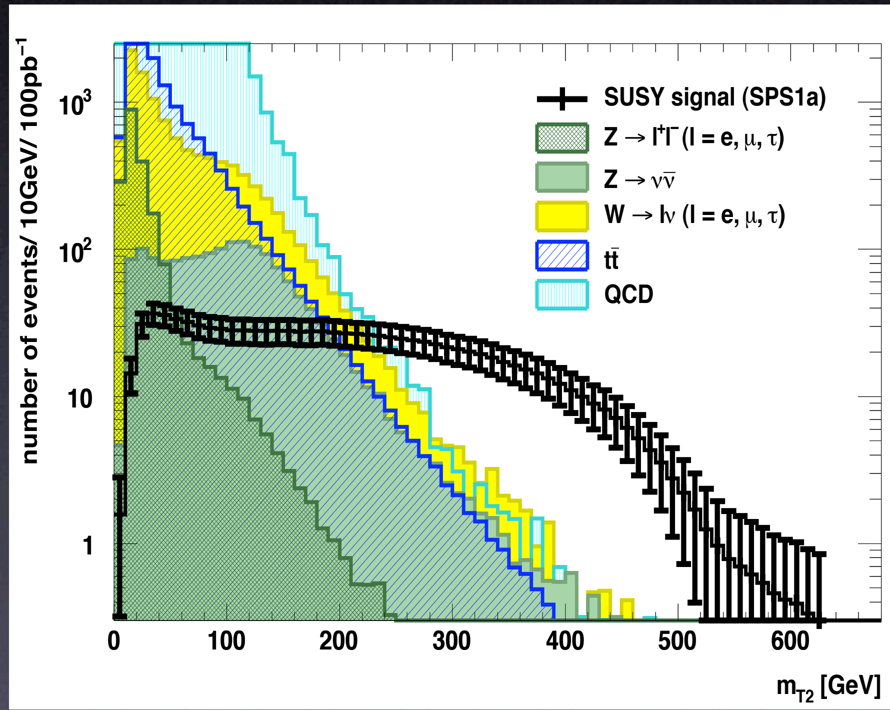
⇒Dark Matter!?



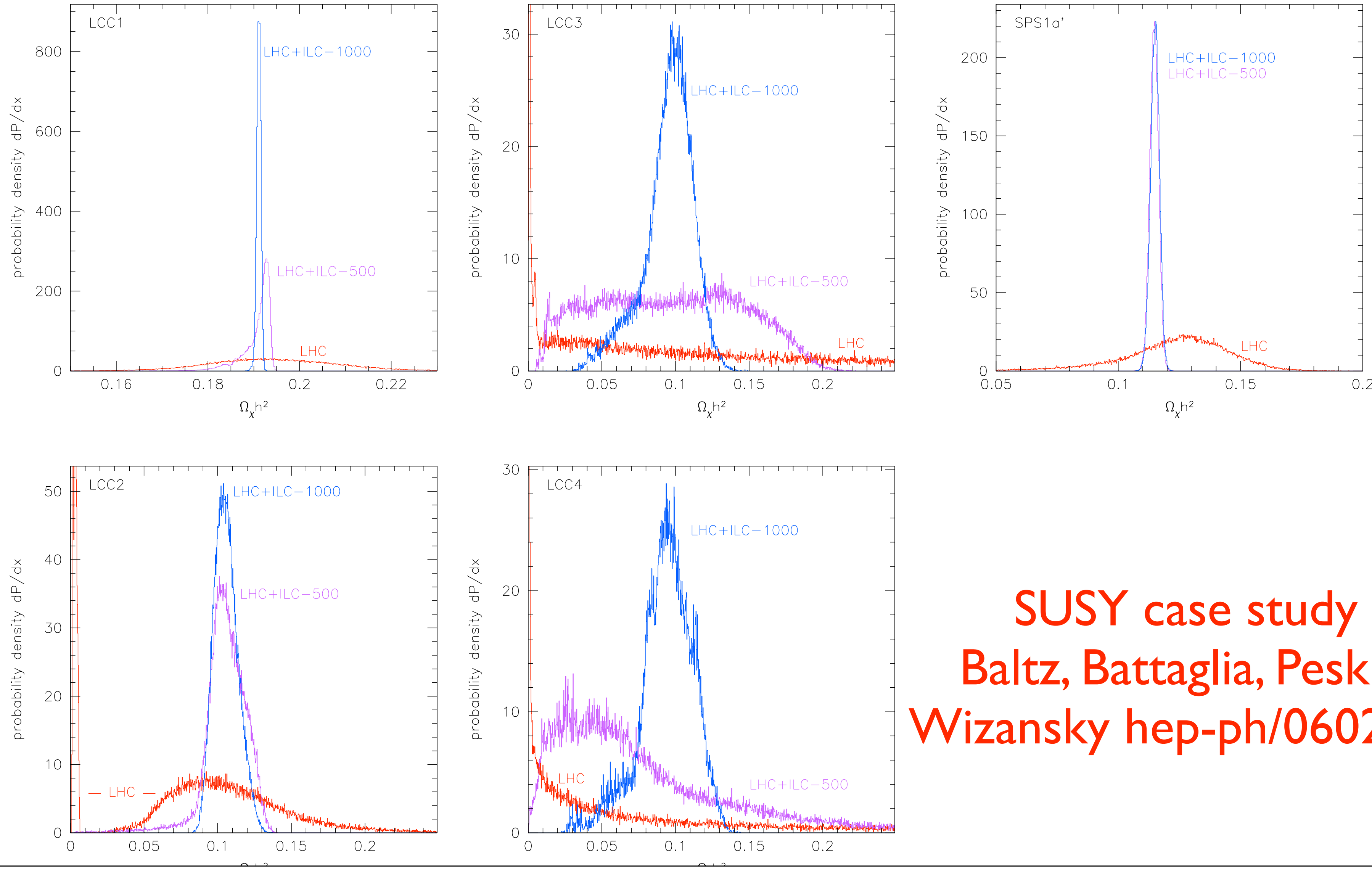
m_{T2} for discovery

- still room for improving the search strategy
- a quicker discovery with m_{T2} than ΣE_T

(A. Barr, C. Gwenlan)



Omega from colliders



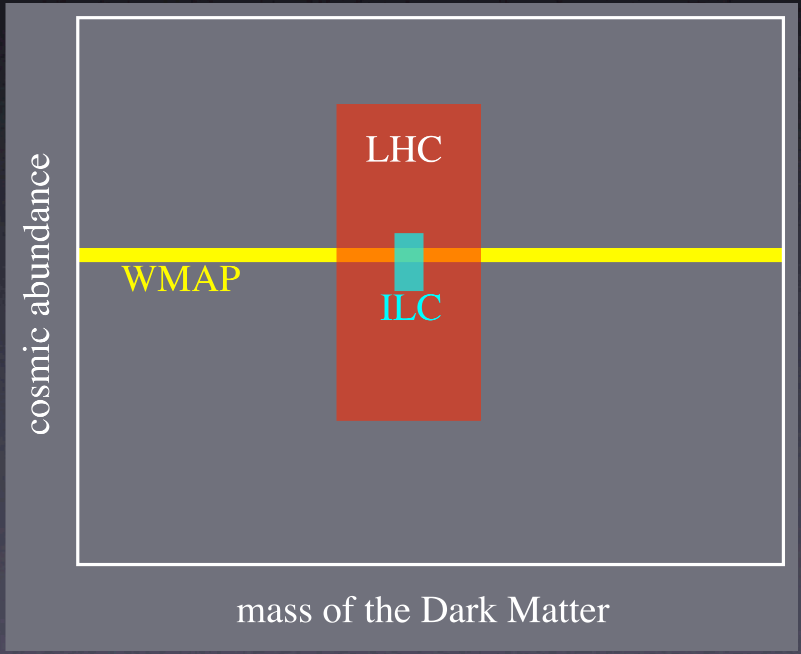
SUSY case study
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187

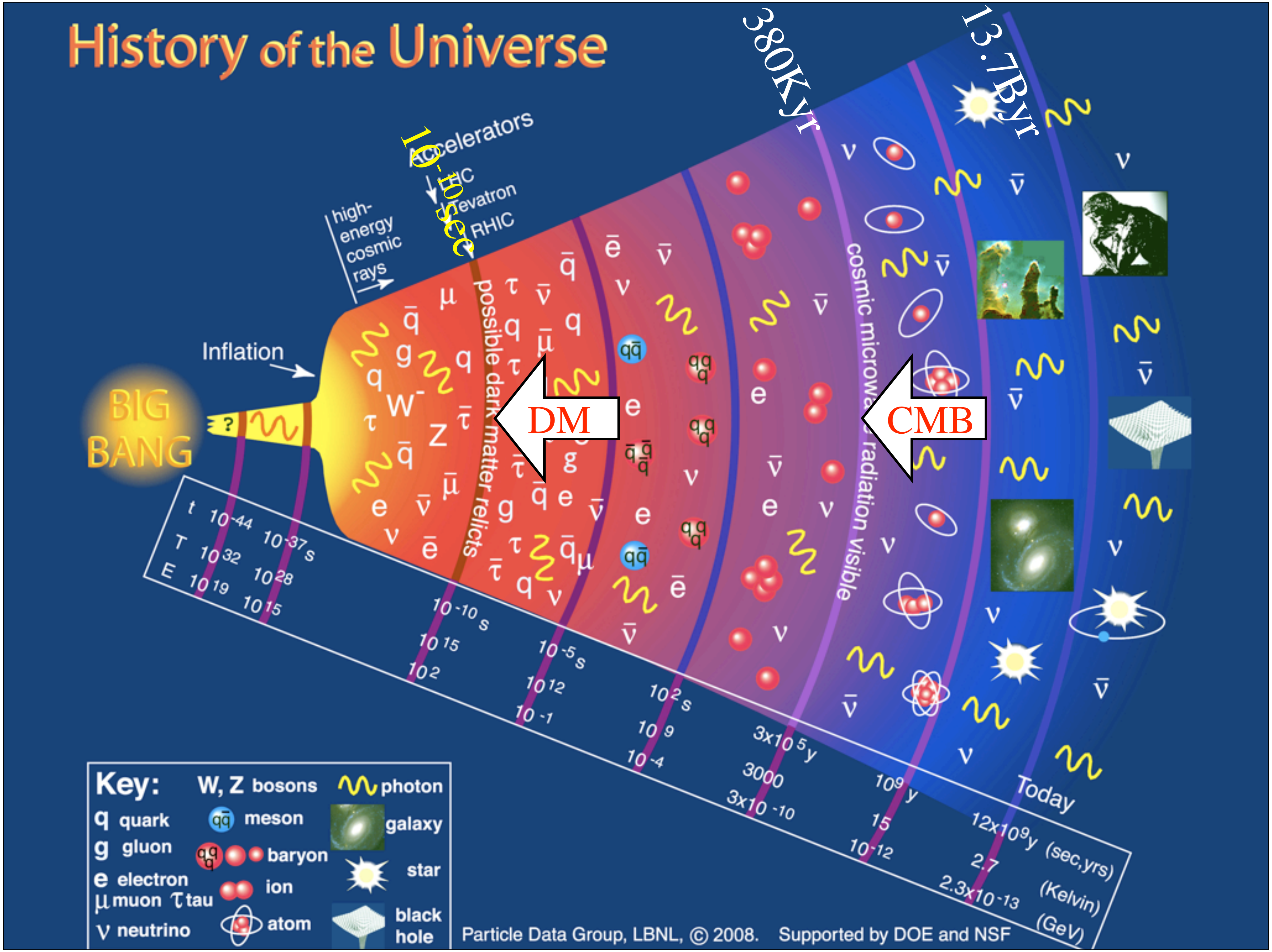
How do we know what Dark Matter *is*?

- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:

$\Rightarrow$ Will know *what Dark Matter is*

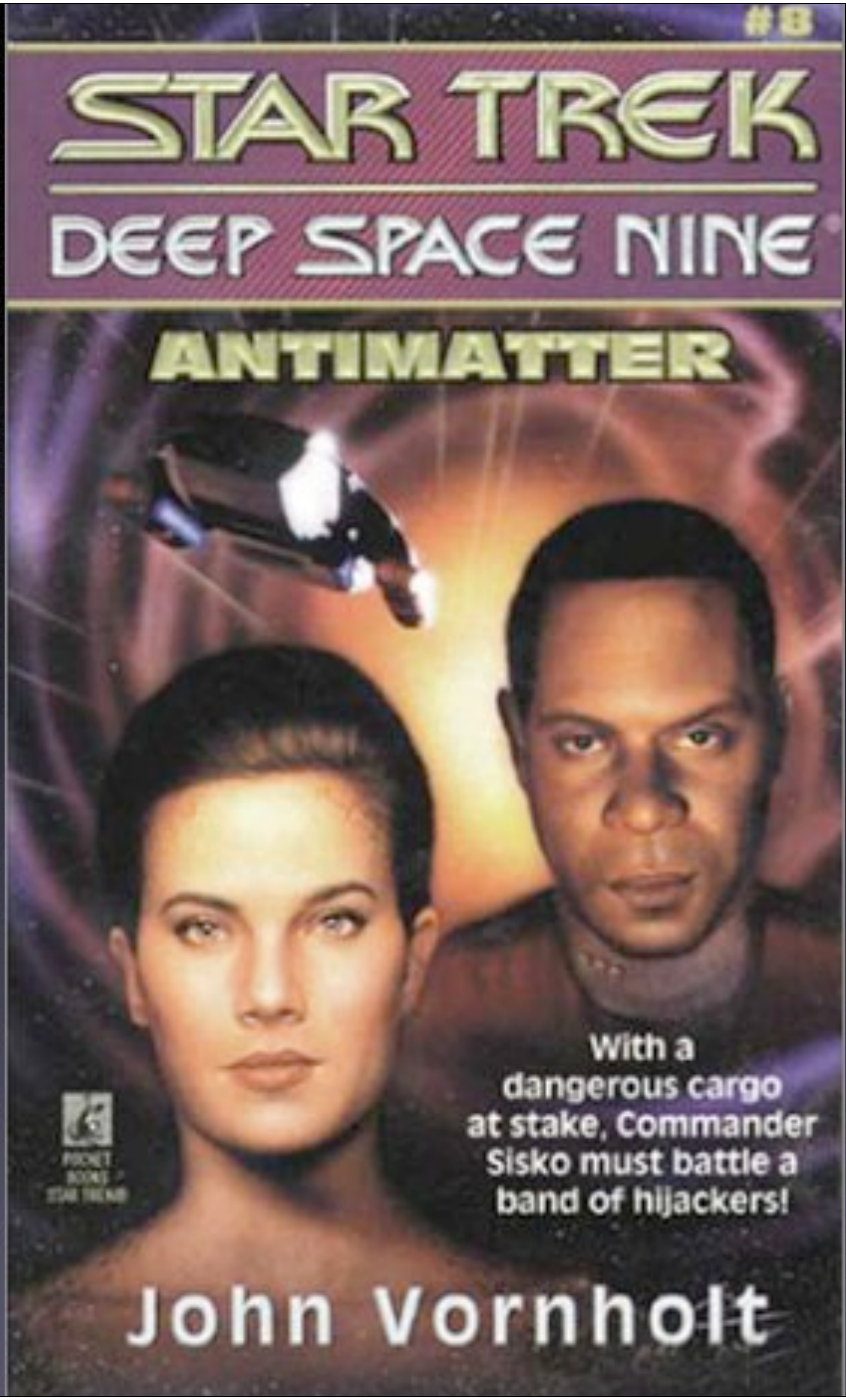
$\Rightarrow$ Will understand universe back to $t \sim 10^{-10}$ sec

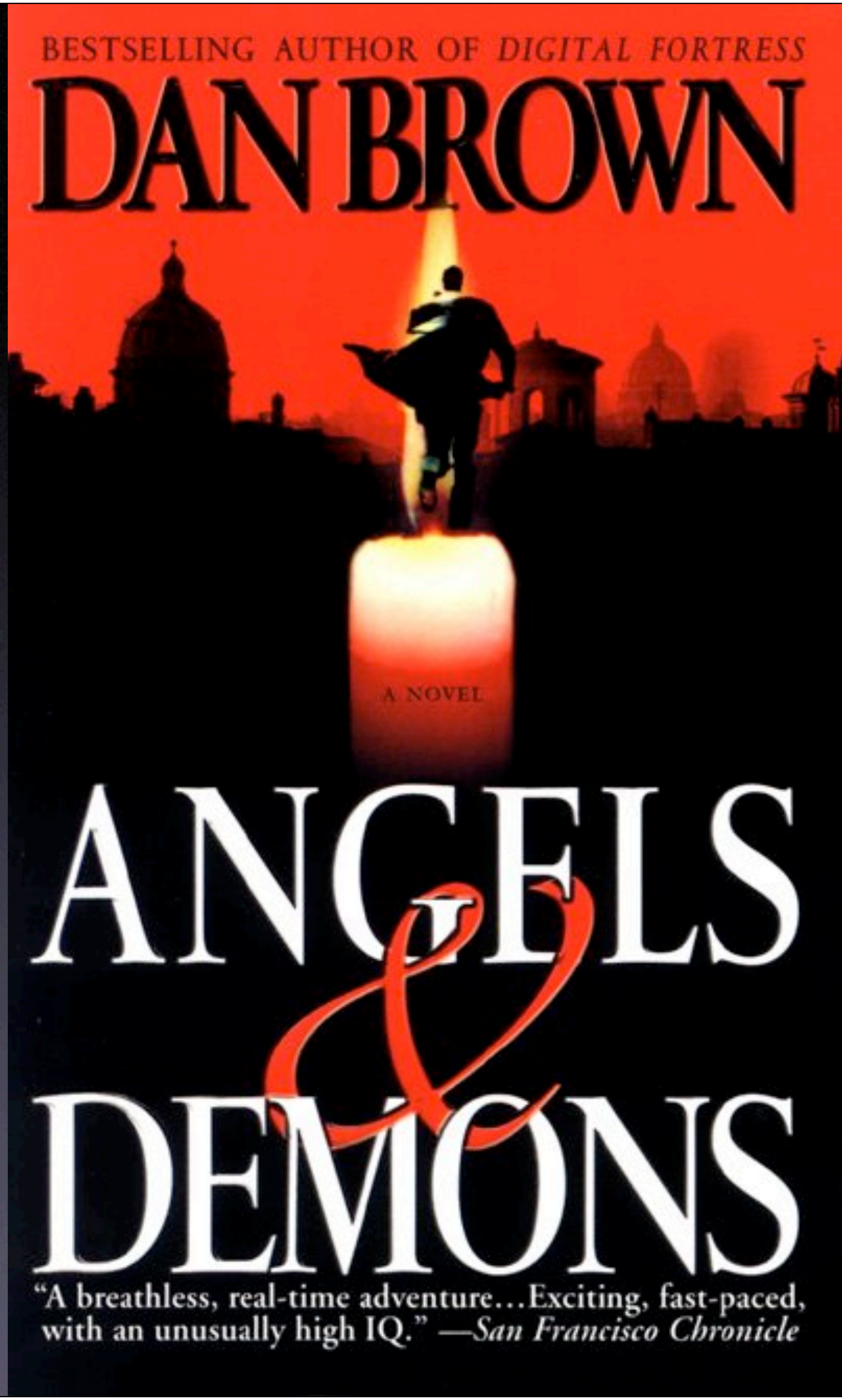




History of the Universe
380Kyr
13.7Byr
10^-10 sec
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
DM
CMB
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Anti-Matter


#8
STAR TREK
DEEP SPACE NINE
ANTIMATTER
With a dangerous cargo at stake, Commander Sisko must battle a band of hijackers!
John Vornholt


BESTSELLING AUTHOR OF DIGITAL FORTRESS
DAN BROWN
A NOVEL
ANGELS & DEMONS
"A breathless, real-time adventure…Exciting, fast-paced, with an unusually high IQ." —San Francisco Chronicle

Beginning of Universe

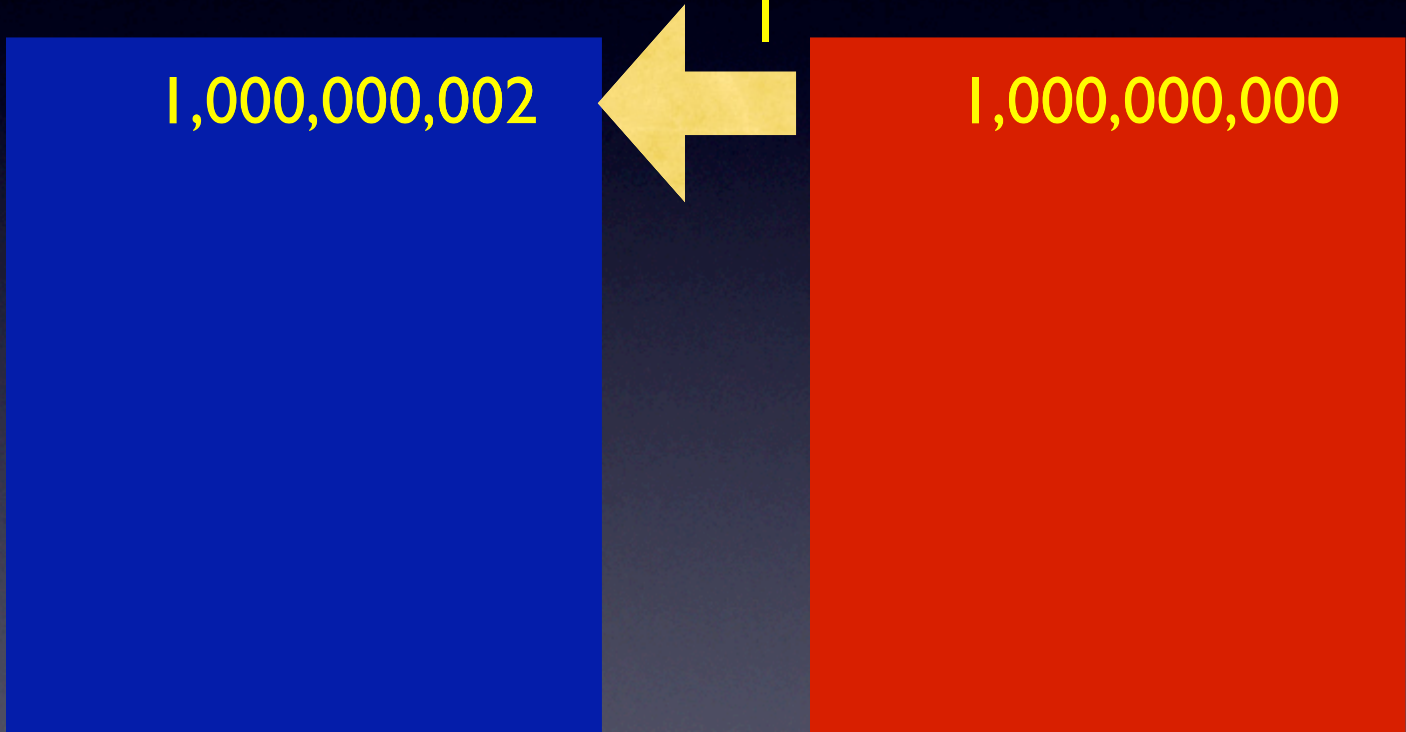
1,000,000,001

matter

1,000,000,001

anti-matter

fraction of second later



matter *anti-matter*

turned a billionth of anti-matter to matter

Universe Now

2

•

us

matter *anti-matter*

This must be how we survived the Big Bang!

CP Violation

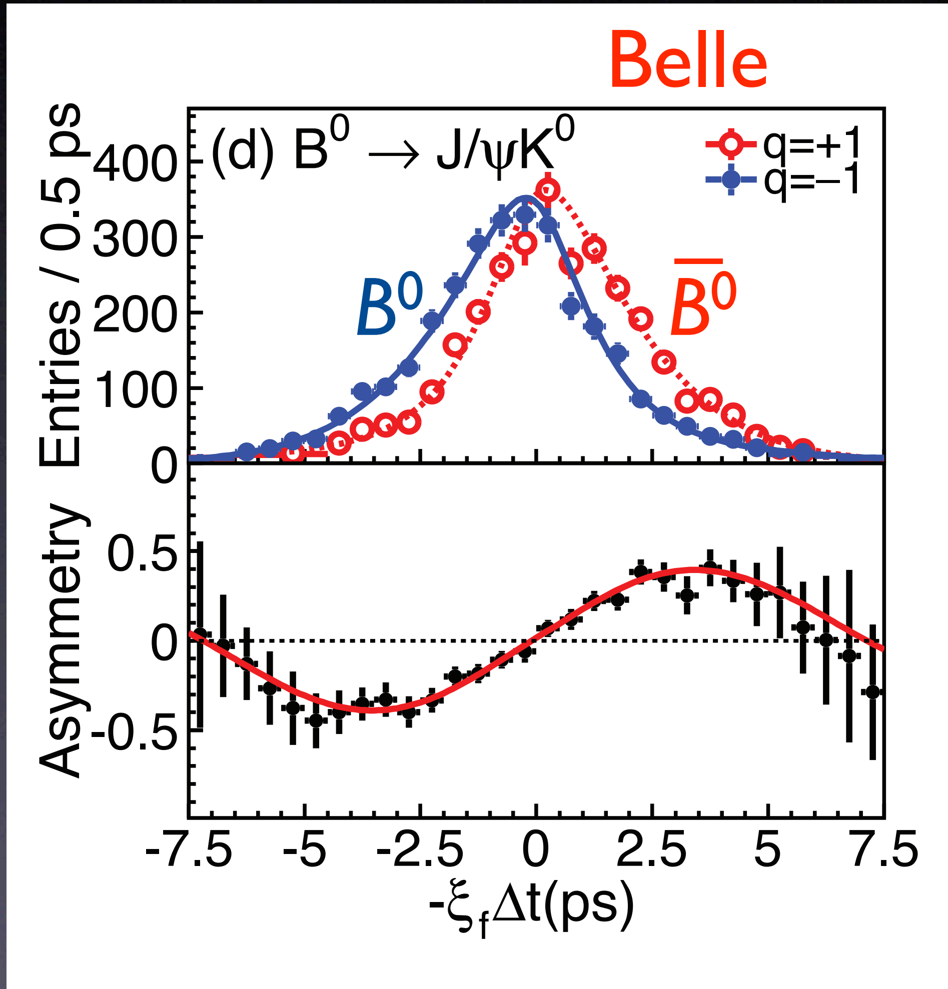
- Is anti-matter the exact mirror of matter?

1964 discovery of CP violation

- But only one system, hard to tell what is going on.

2001, 2002 Two new CP-violating phenomena

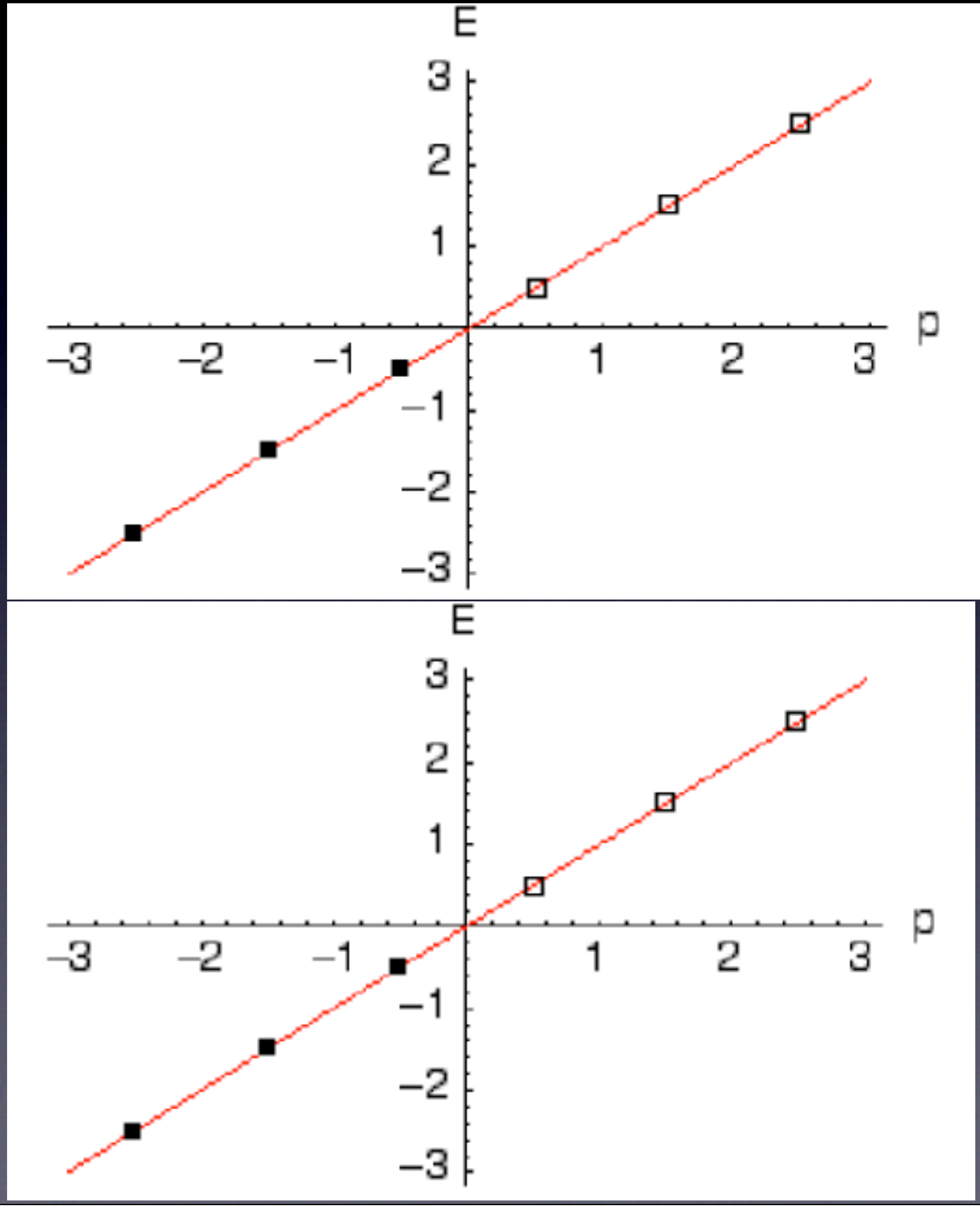
- But CP violation observed so far is too small by a factor of 10^{-16} to explain the absence of anti-matter
- Need new particles, new CP phases
- we don't know the energy scale



SM violates *B*

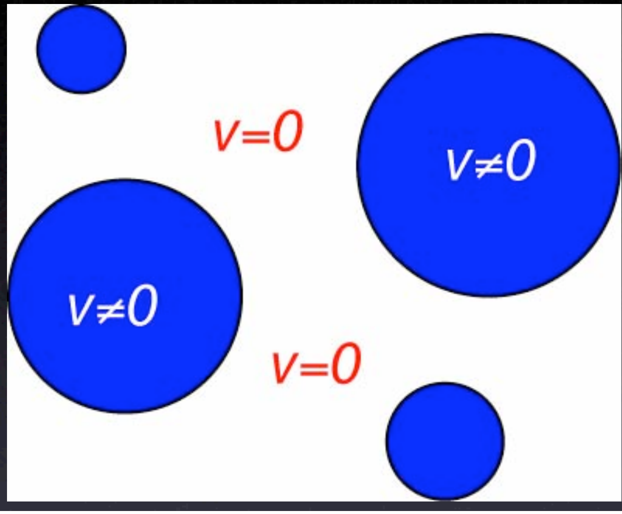
- *W* and *Z* bosons massless at high temperature
- *W* field fluctuates just like in thermal plasma
- solve Dirac equation in the presence of the fluctuating *W* field

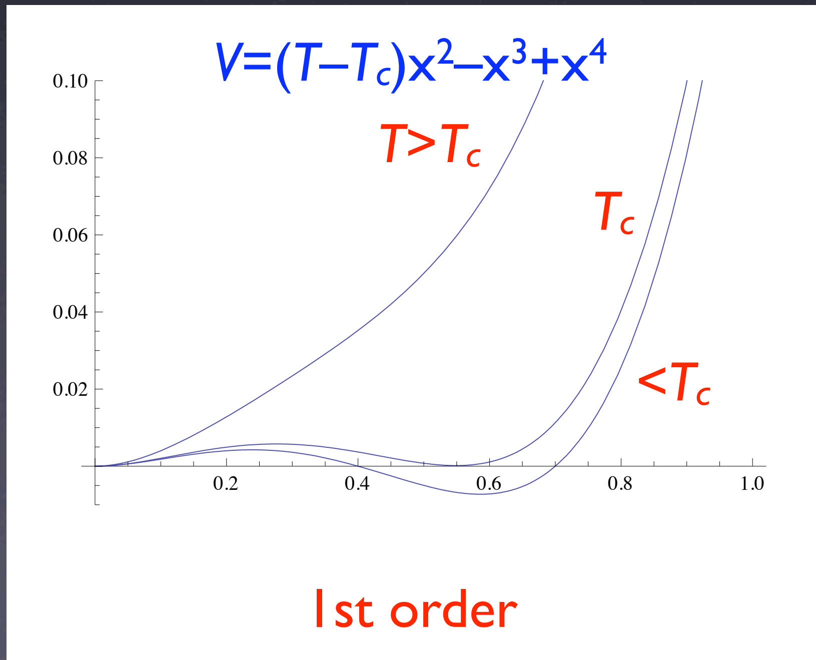
change #q, #l



Sakharov's conditions

- ✓ Need *B* violation
- Need CP violation
  - new particles
- Need out-of-equilibrium
  - *bubbles* in first-order phase transition
  - need extra "light" bosons in loops
  - e.g. stop~160 GeV, extra Higgs bosons
  - should be in the LHC range
  - or H^6 potential?





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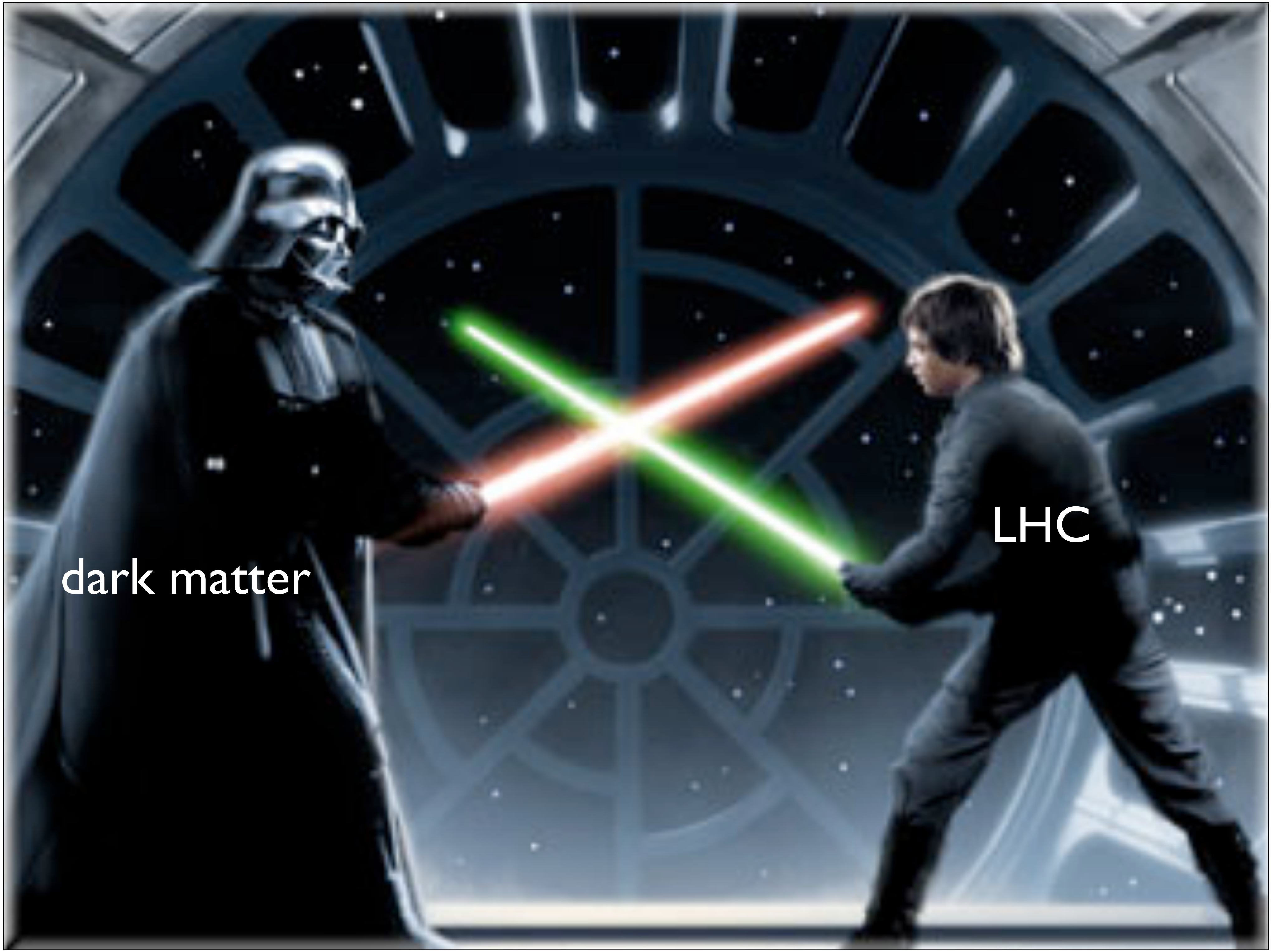
Conclusions

- We are entering the new era
  - twice in century opportunity!
- Standard Model is definitely not the whole story: five evidences
- LHC well prepared to address some of the five, physics behind Higgs BEC
- no guarantee, and that's why we need data

Can't wait to see the data from LHC!


LHC
dark matter