Lecture I

Hitoshi Murayama (Berkeley)

Cargèse, 31/07/2007

- Title given by Geraldine:

  Supersymmetry: motivations, phenomenology, dark matter candidates, neutrinos

  many big subjects!

Plan

1: Non-technical Overview of Supersymmetry
what SUSY is supposed to give us
2: From formalism to the MSSM
Global SUSY formalism, Feynman rules,
soft SUSY breaking, MSSM
how to break SUSY, mediation mechanisms
3: SUSY in the universe
dark matter, dark energy, problems
4: Neutrino physics
oscillation data, implications

Standard Model

A Long History

- Since Fermi and Yukawa to the "Standard Model," it took almost 40 years to build
- Since deep inelastic scattering and J/ψ to precision measurements, it took almost 30 years to test
- Now many beautiful experimental tests: LEP, Tevatron, Møller scattering, neutrino DIS, atomic parity violation, etc etc
- Yet not completely established

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	*e*	*B*	*W*	*g*	*H*	*G*
$SU(3)_C$	3	3	3	1	1	1	1	8	1	1
$SU(2)_L$	2	1	1	2	1	1	3	1	2	1
$U(1)_Y$	+1/6	−1/3	+2/3	−1/2	+1	0	0	0	−1/2	0
spin	−1/2	+1/2	+1/2	−1/2	+1/2	1	1	1	0	2
flavor	3	3	3	3	3	1	1	1	1	1
seen?	Y	Y	Y	Y	Y	Y	Y	Y	N	N

Anomaly Cancellation

$U(1)^3$ $\quad 3\times 2\left(\frac{1}{6}\right)^3+3\times\left(-\frac{2}{3}\right)^3+3\times\left(\frac{1}{3}\right)^3+2\left(-\frac{1}{2}\right)^3+(+1)^3=0$

$U(1)(\text{gravity})^2$ $\quad 3\times 2\left(\frac{1}{6}\right)+3\times\left(-\frac{2}{3}\right)+3\times\left(\frac{1}{3}\right)+2\left(-\frac{1}{2}\right)+(+1)=0$

$U(1)(SU(2))^2$ $\quad 3\times 2\left(\frac{1}{6}\right)+2\left(-\frac{1}{2}\right)=0$

$U(1)(SU(3))^2$ $\quad 3\times 2\left(\frac{1}{6}\right)+3\times\left(-\frac{2}{3}\right)+3\times\left(\frac{1}{3}\right)=0$

$(SU(3))^3$ $\quad \#3-\#3^*=2-1-1=0$

$(SU(2))^3$, $(SU(3))^2SU(2)$, $SU(3)(SU(2))^2$ $\quad 0$

$SU(2)$ $\quad \#2=3+1=4=\text{even}$

Non-trivial connection between q & l

General

- The most general renormalizable Lagrangian with the given particle content

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

Parameters

- 3 gauge coupling constants + θ_{QCD}
- 2 parameters in the Higgs potential (G_F, m_H)

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

$g' \sim 0.36$, $g \sim 0.65$, $g_s \sim 1.2$

$G_F \sim (300\ \text{GeV})^{-2}$, m_H unknown, $\theta_{QCD} < 10^{-10}$

Parameters

- 3x3 complex Y_u^{ij}, Y_d^{ij}, Y_l^{ij}: 54 real params
- reparameterization $U(3)_{Q,d,u,L,e}{}^5/U(1)_{B,e,\mu,\tau}{}^4=41$

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

$54-41=13=3_u+3_d+3_l+(3+1)_{CKM}$

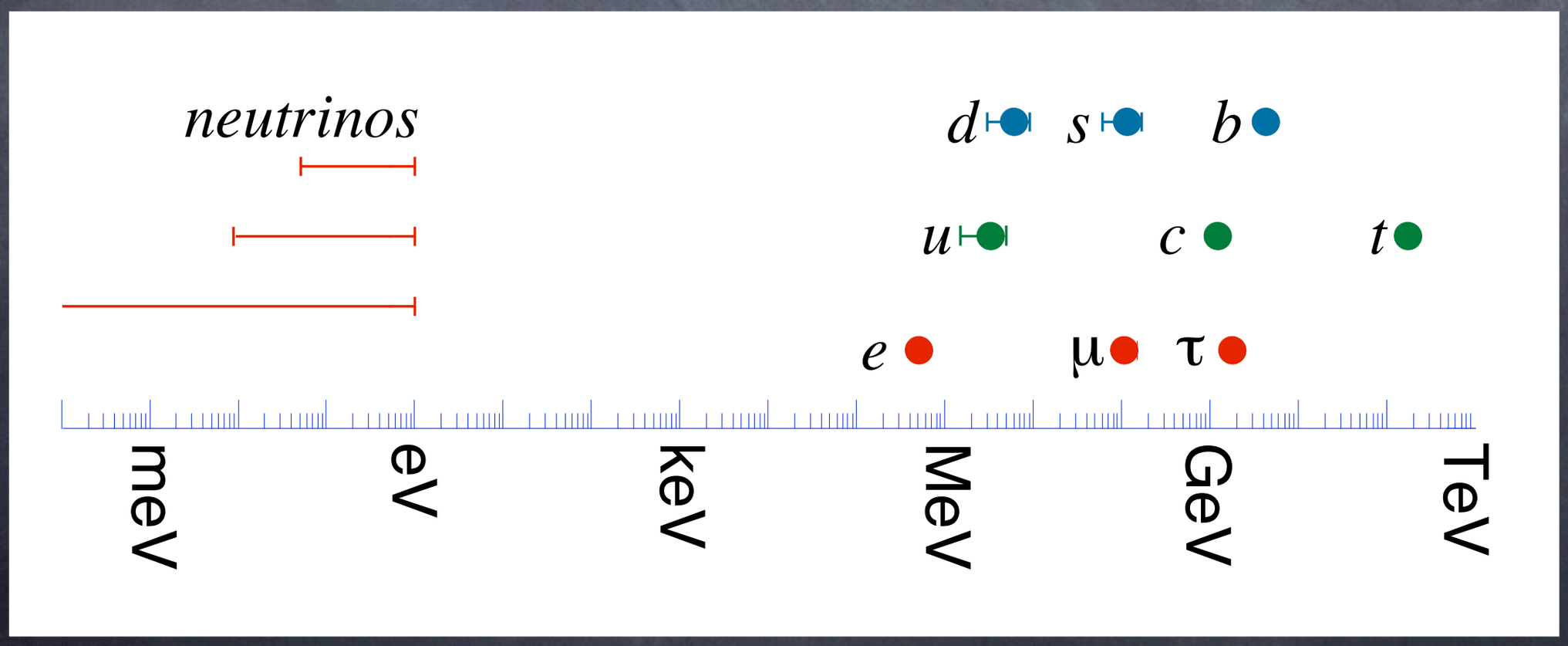
Masses and Mixings

- Choose masses and mixings as observed

$$V_{CKM} \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ -\lambda^3(1+\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

λ≈0.22

A, ρ, η≈O(1)



Standard Model is extreeeemely successful

- Take Particle Data Group "Reviews of Particle Physics" with 400+ pages
- With only a few exceptions, all numbers in the book are consistent with the Standard Model with suitably chosen 19 parameters
- Some of them tested at 10^{-9} –10^{-12} level
- Many at 10^{-3} level

Standard Model is extreeeemely successful

- baryon and lepton number conserved (apart from anomaly $\propto e^{-8\pi^2/g^2}$) $\tau(t \to e^+ \bar{\nu}_\mu \bar{\nu}_\tau) \sim 10^{150}$years
- flavor approximately conserved (apart from small mixing in V_{CKM})
- especially flavor-changing neutral current small (e.g. $s \to d$ vanishes at tree-level, suppressed by m_c^2/m_W^2 at one-loop)

So,
what's the problem?

empirically incomplete

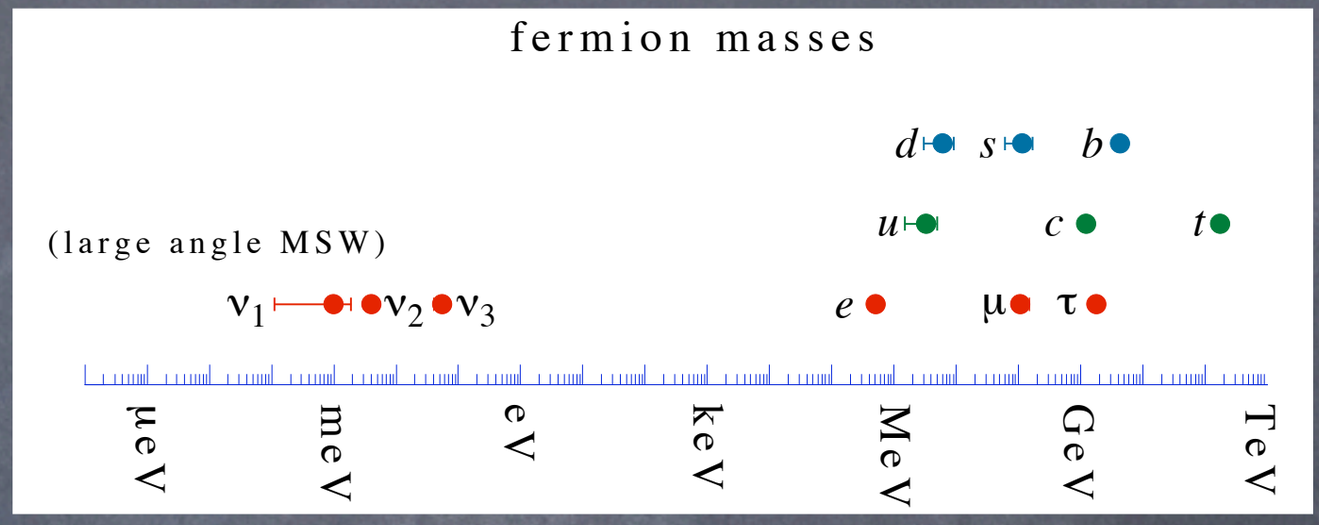
- neutrino mass
- dark matter
- dark energy
- nearly scale-invariant apparently acausal density fluctuation
- baryon asymmetry

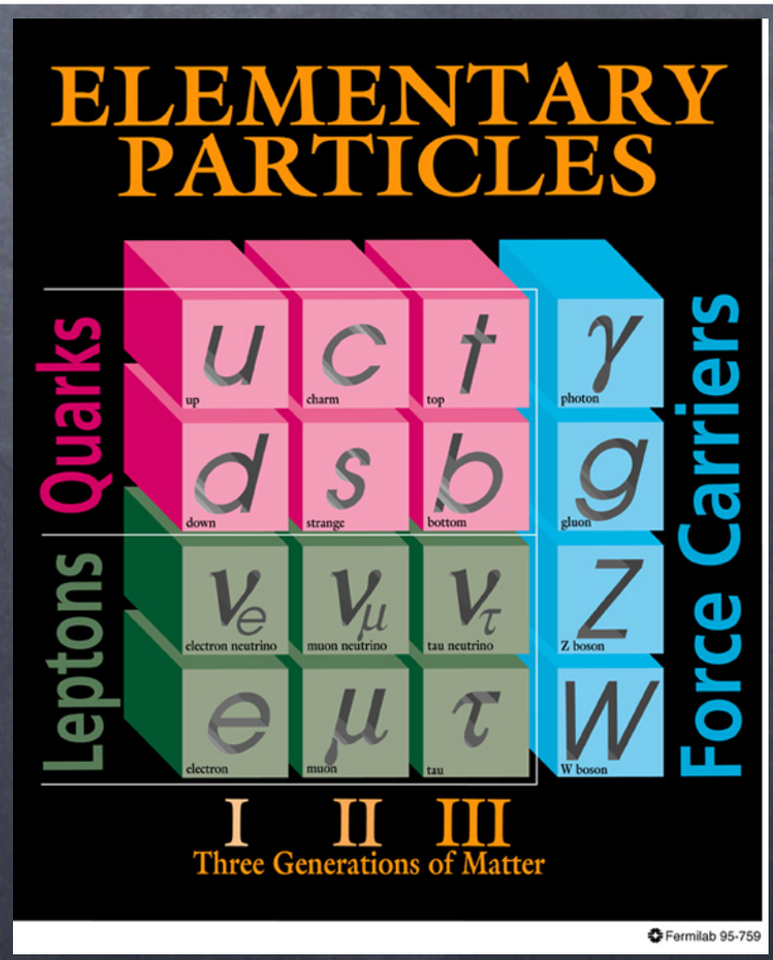
aesthetically unacceptable

- structure is quite complicated
- many naturalness problems
- no quantum gravity
- questions in four categories

Big Questions -Horizontal-

- Why are there three generations?
- What physics determines the pattern of masses and mixings?
- Why do neutrinos have mass yet so light?
- What is the origin of CP violation?
- Why $\theta_{QCD} \ll 10^{-10}$?
- What is the origin of matter anti-matter asymmetry in Universe?





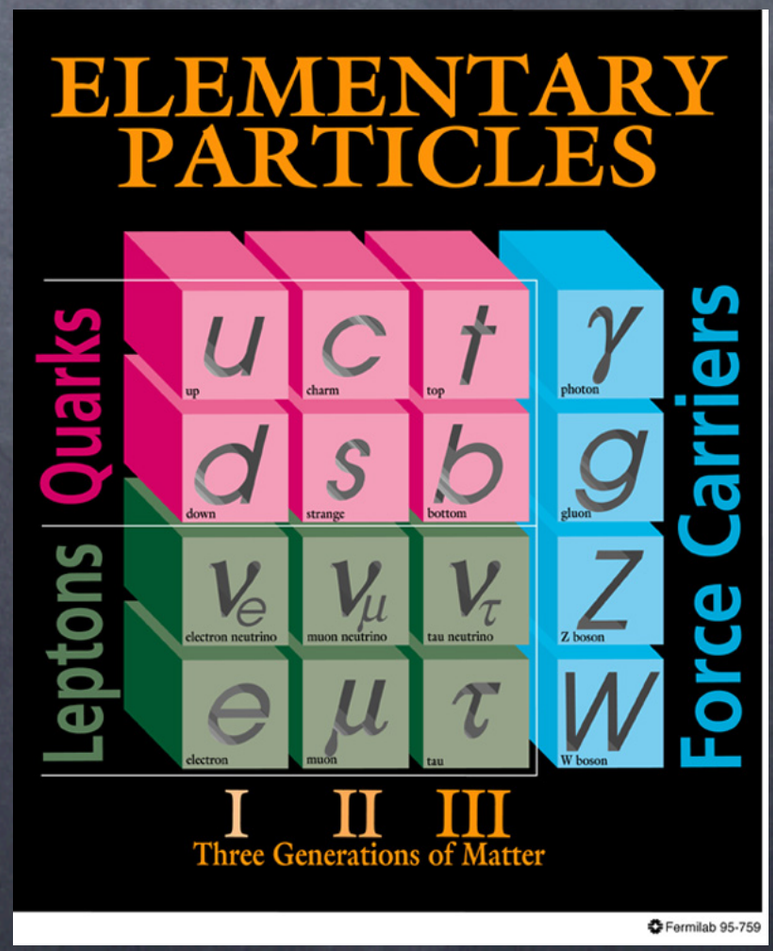
Big Questions -Vertical-

- Why are there three unrelated gauge forces?
- Why is strong interaction strong?

$$Q(\mathbf{3},\mathbf{2},+\frac{1}{6}),\quad u(\mathbf{3},\mathbf{1},+\frac{2}{3}),\quad d(\mathbf{3},\mathbf{1},-\frac{1}{3}),$$
$$L(\mathbf{1},\mathbf{2},-\frac{1}{2}),\quad e(\mathbf{1},\mathbf{1},-1)$$

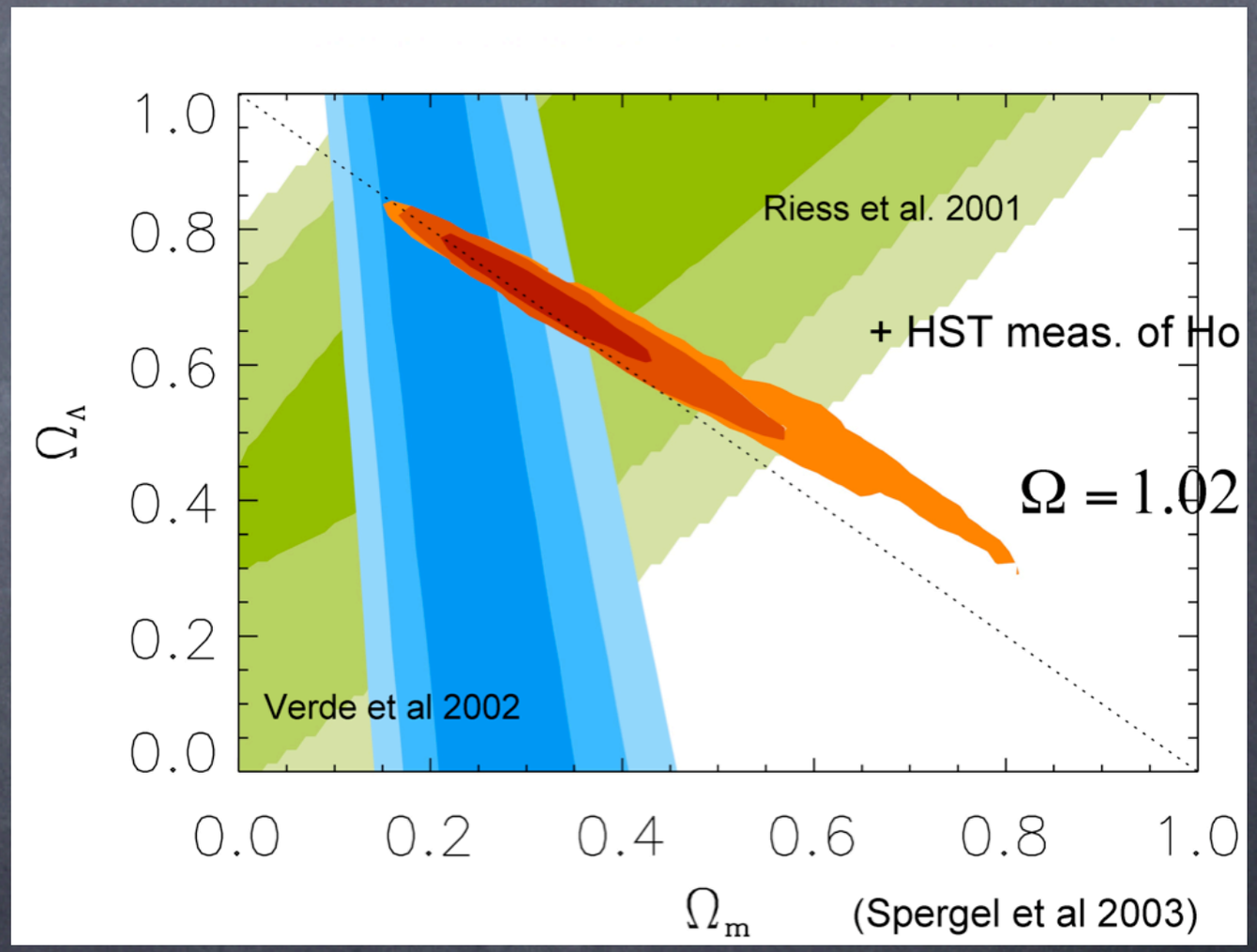
- Charge quantization
- anomaly cancellation
- quantum numbers
- Is there a unified description of all forces?
- Why is $m_W \ll M_{Pl}$?

(Hierarchy Problem)



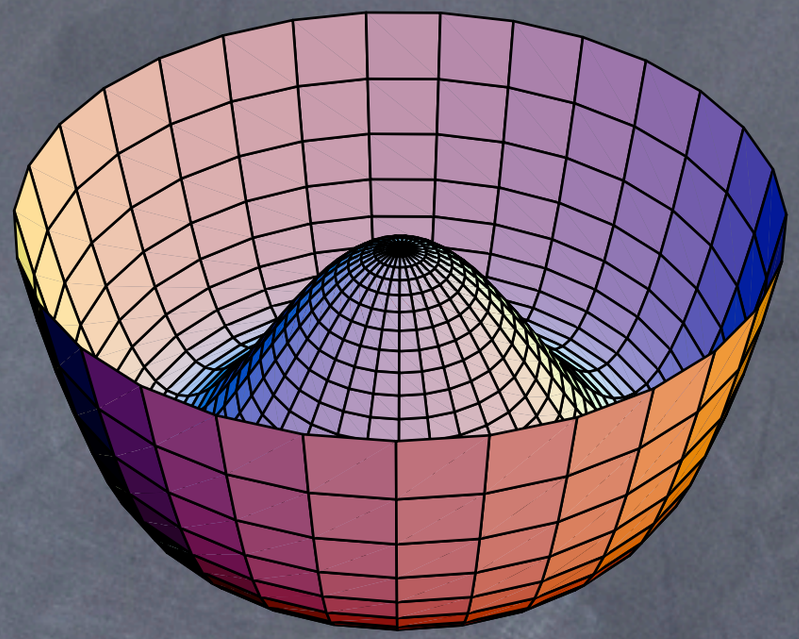
Big Questions
-From the Heaven-

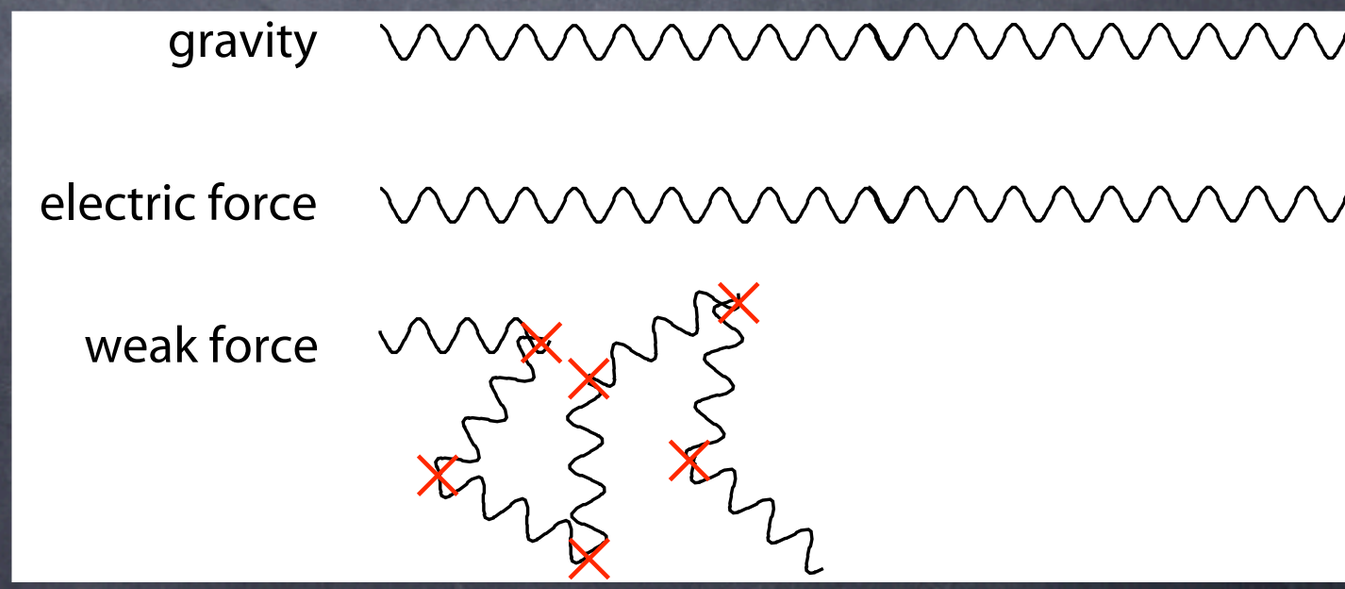
- What is Dark Matter?
- What is Dark Energy?
- Why now? (Cosmic coincidence problem)
- What was Big Bang?
- Why is Universe so big? (flatness problem, horizon problem)
- How were galaxies and stars created?



Big Questions
-From the Hell-

- What is the Higgs boson?
- Why does it have negative mass-squared?
- Why is there only one scalar particle in the Standard Model?
- Is it elementary or composite?
- Is it really condensed in our Universe?





Standard Model is fragile

The minute you allow for additional fields and/or gauge groups, much of the success is destroyed

- suppressed flavor-changing neutral currents
- no proton decay
- no neutrino mass either (good&bad)
- consistency with precise electroweak data
- no excessive CP violation (e/n EDM)
- no charge/color breaking

Standard Model is fragile

- The minute you allow for parameters to vary, it exhibits very different physics
- take $m_d<m_u$, all protons decay to neutrons and there are no atoms
- take $m_e>4m_p-m_\alpha$, Sun doesn't burn, no us
- if v>>TeV, $|m_n-m_p|$ too big and neutron decays even inside nuclei; no chemistry, no life
- If $m_c\sim m_t$, no J/ψ before the end of cold war

and no high-energy physics funding by now

Dark Field =

cosmic superconductor

Big Questions
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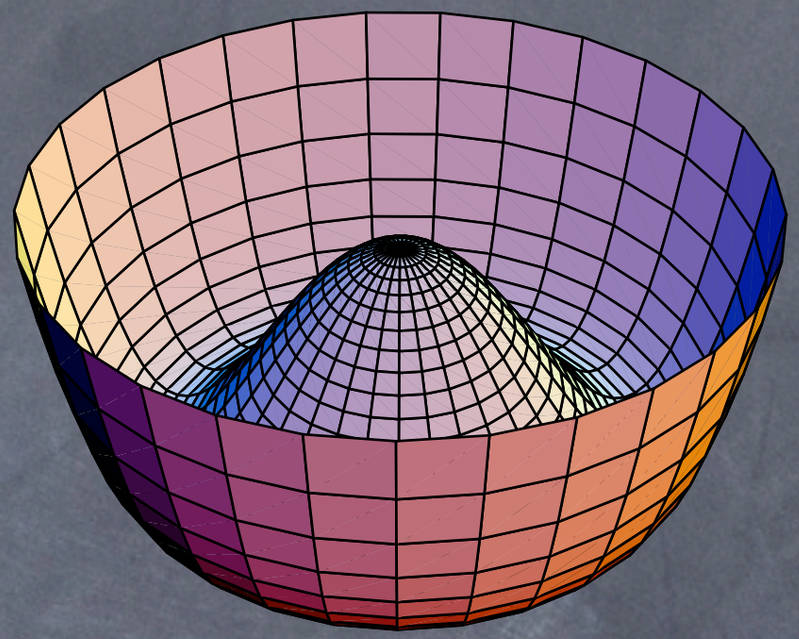
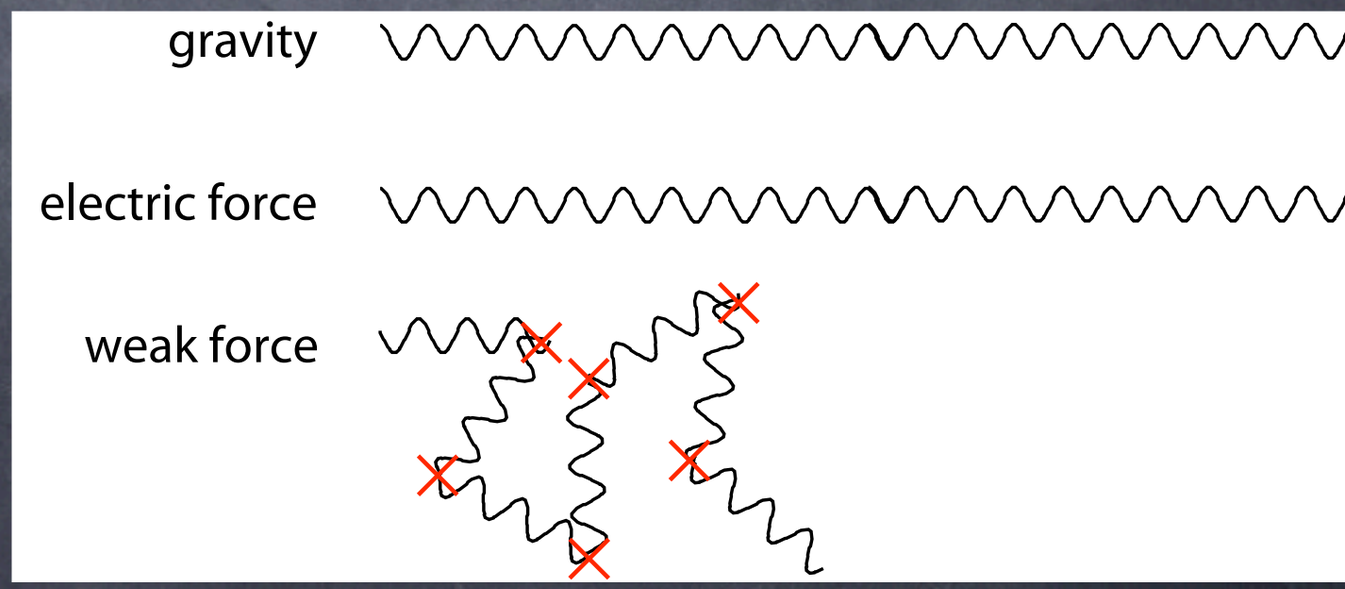


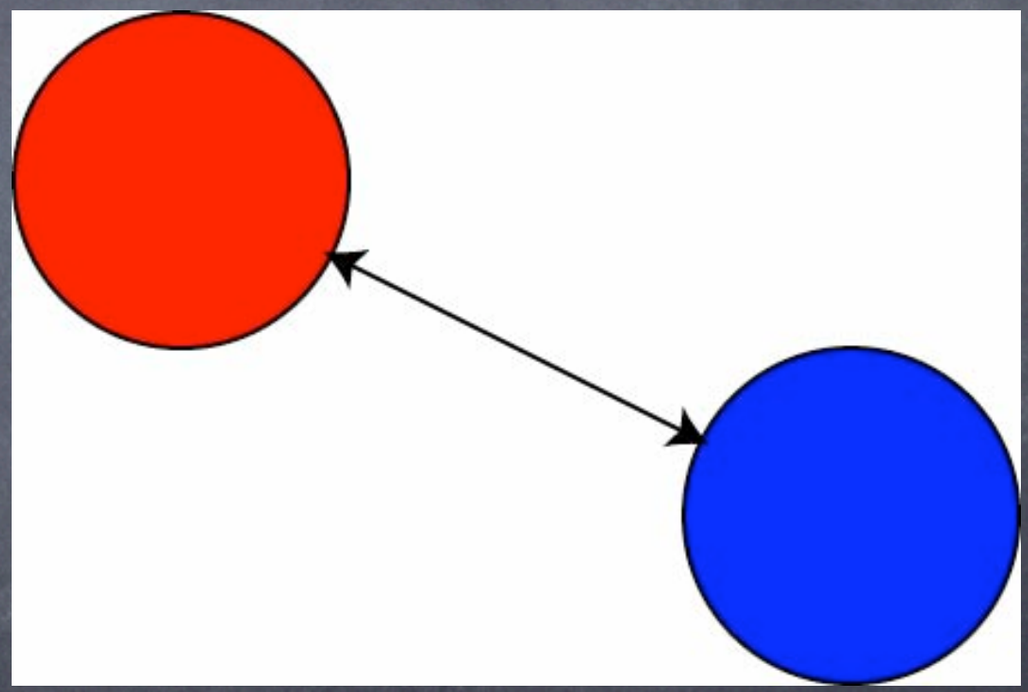


Mystery of the weak force

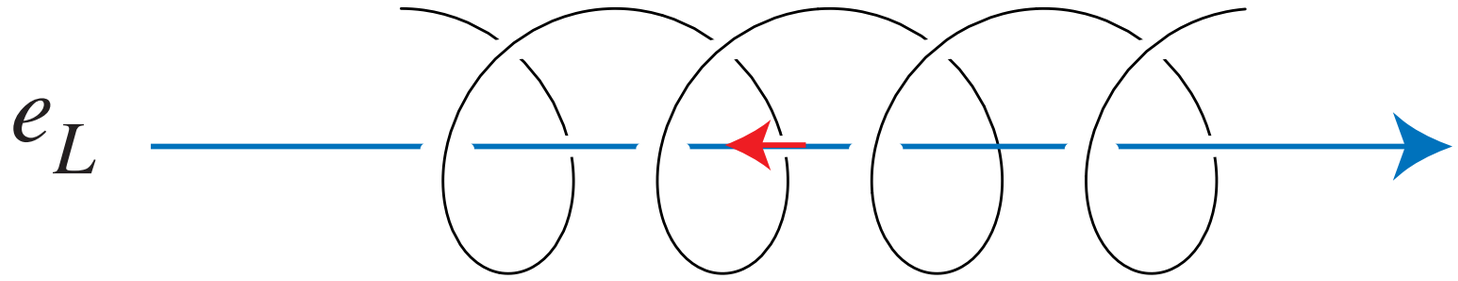
- Gravity pulls two massive bodies (long-ranged)
- Electric force repels two like charges (long-ranged)
- Weak force pulls protons and electrons (short-ranged) acts only over 0.000000001 nanometer

[need it for the Sun to burn!]

- We know the energy scale: 0.3 TeV



Mystery deepens

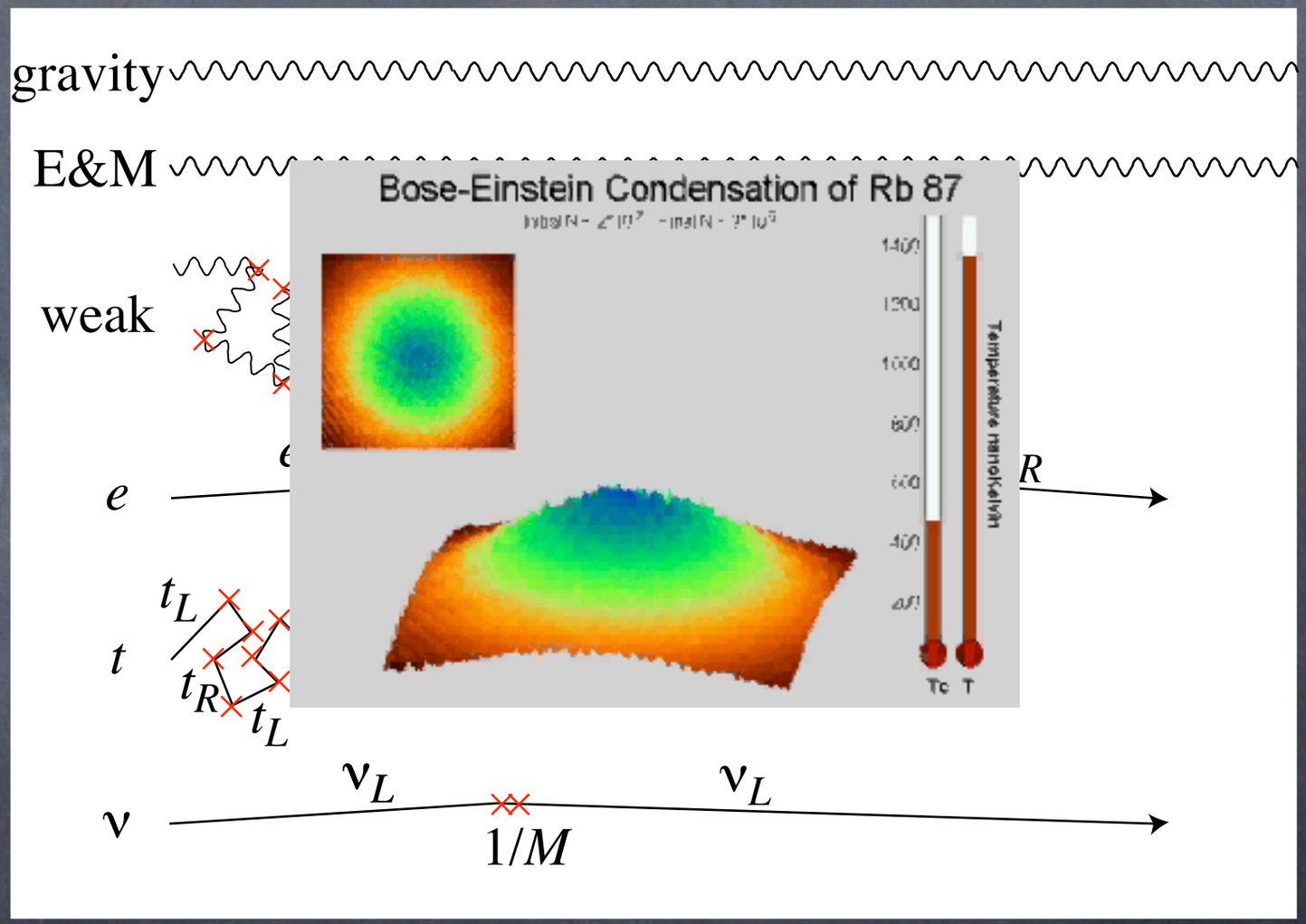


- Nuclear beta decay is due to a yet another force, the weak force
- Strangely, only left-handed particles participate in the weak force
- That sounds OK as long as they are moving
- but when they stop???

We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- What is it??

Extremely bizarre theory!



Cosmic Superconductor

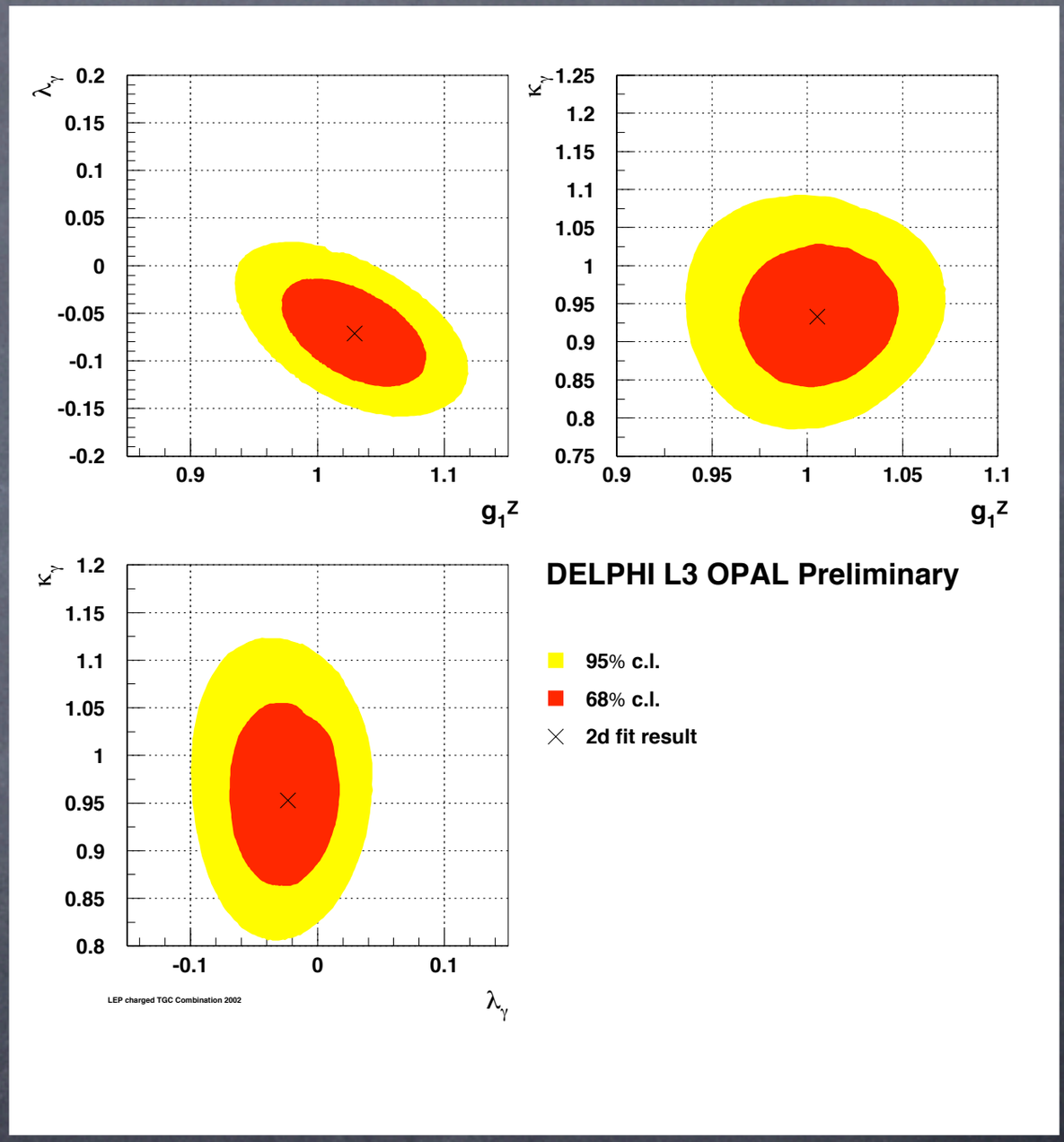
- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"
  - ⇒ Magnetic field is short-ranged!

Imagine a physicist living in a superconductor

- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two "Dark Field" in her "Universe"
  - But doesn't know what the Dark Field is, nor why it is there
  - Doesn't have enough energy (gap) to break up Cooper pairs

Textbook

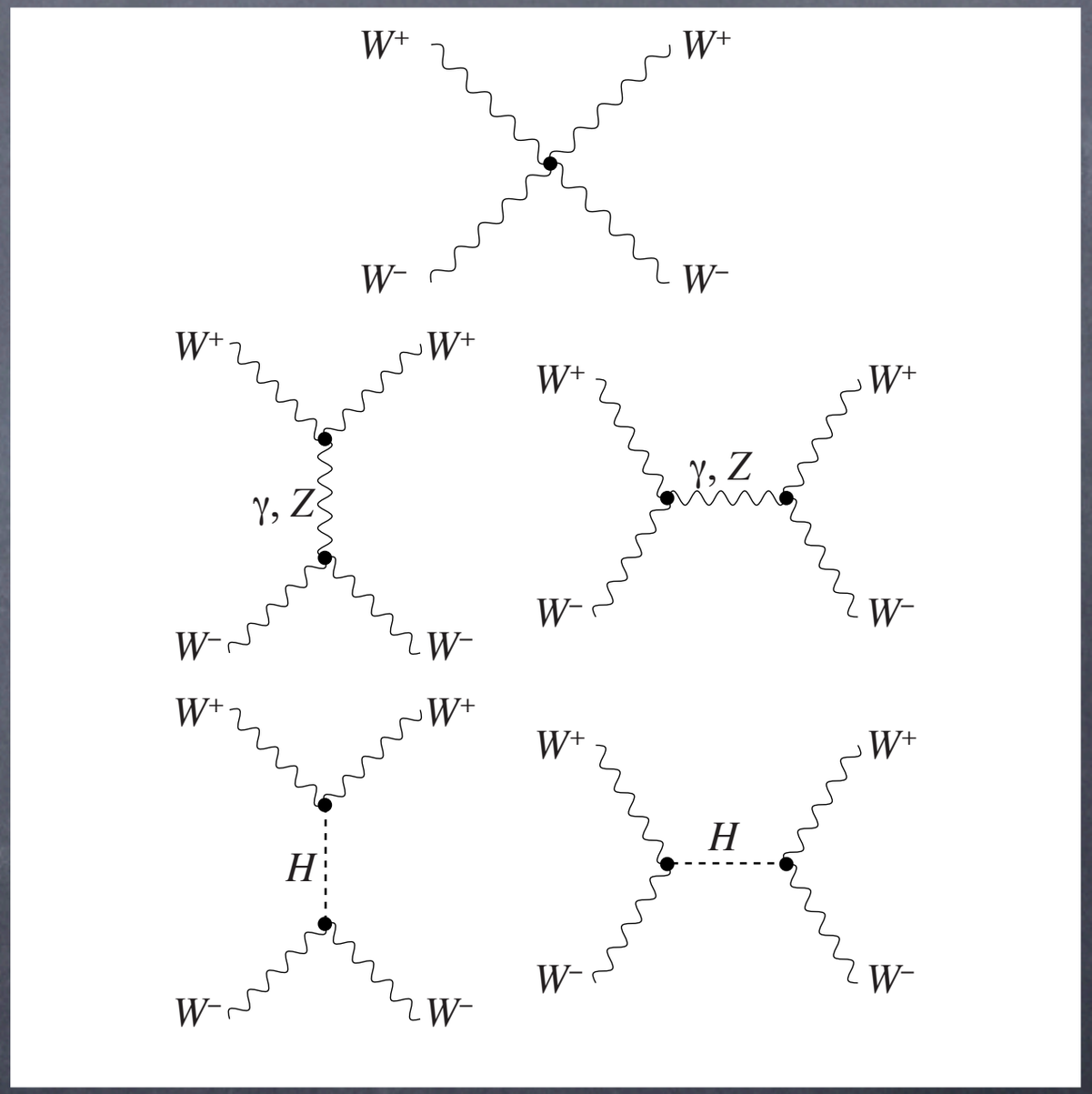
- W and Z are massive vector bosons
- Only known consistent (renormalizable) quantum field theory of massive vectors is gauge theory with Higgs mechanism
- Therefore, W and Z bosons must be gauge bosons, broken by a Higgs



Now added evidence of vector boson self-couplings

unitarity

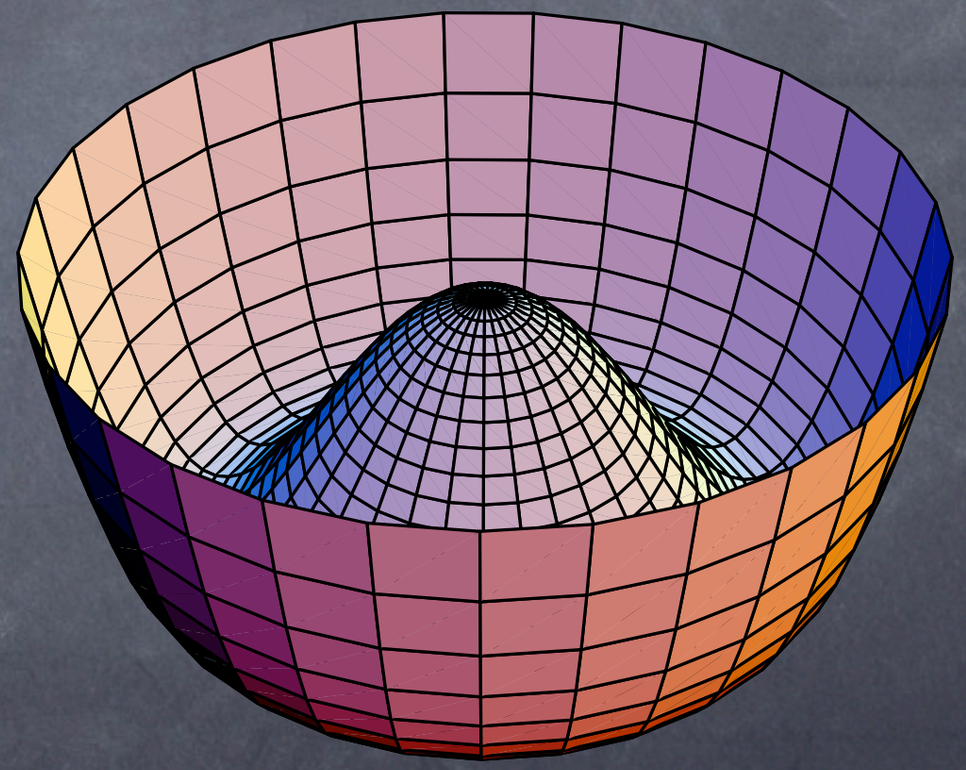
- W-boson scattering grows with energy $A \sim G_F E^2$ and violates unitarity at 1.8TeV
- If you allow only one extra particle beyond what we know to restore unitarity, the only possibility is to add a spin zero particle whose couplings are precisely those of the SM Higgs



C. H. Llewellyn Smith; D. A. Dicus and V. S. Mathur;
J. M. Cornwall, D. N. Levin and G. Tiktopoulos

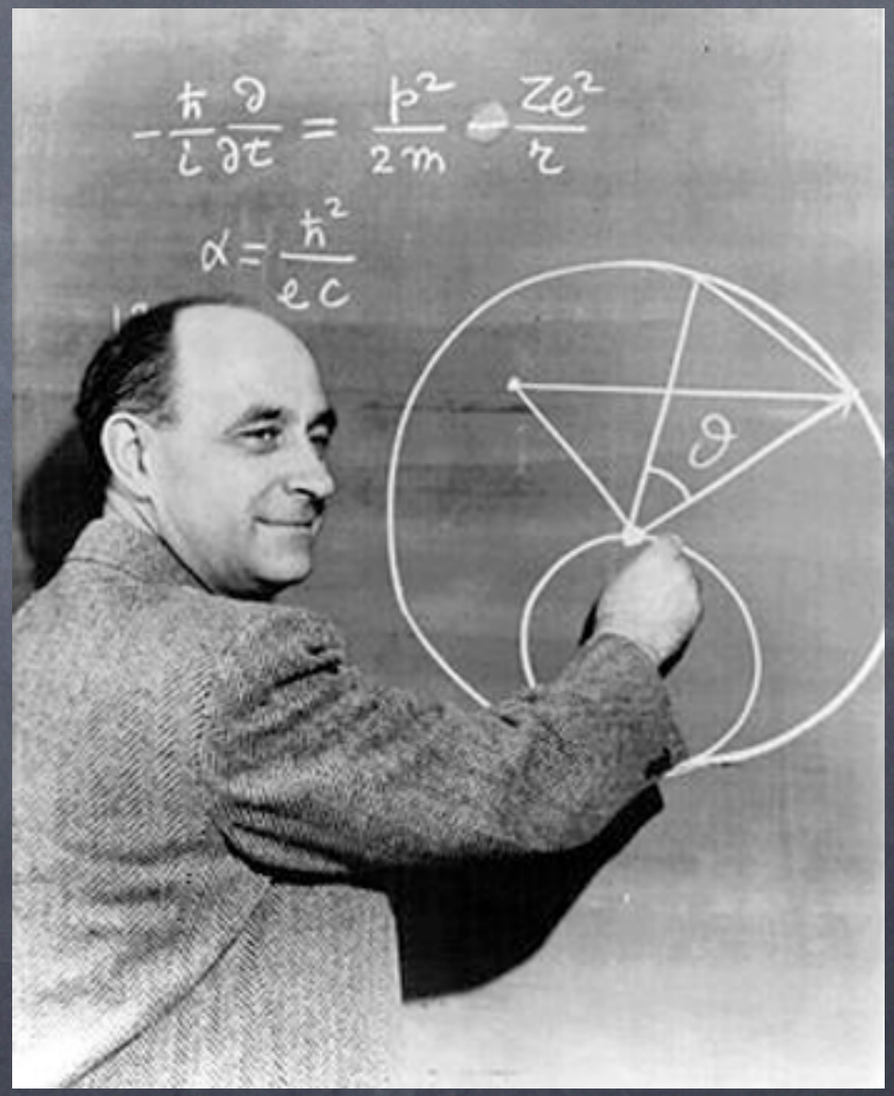
ugly

- $V=\lambda|H|^4-\mu^2|H|^2$
- Why negative mass-squred?
- Why only one scalar in the SM?
- Hierarchy problem because of its quadratic divergence
- does not appear fundamental, i.e. Ginzburg-Landau vs BCS



Fermi's dream era

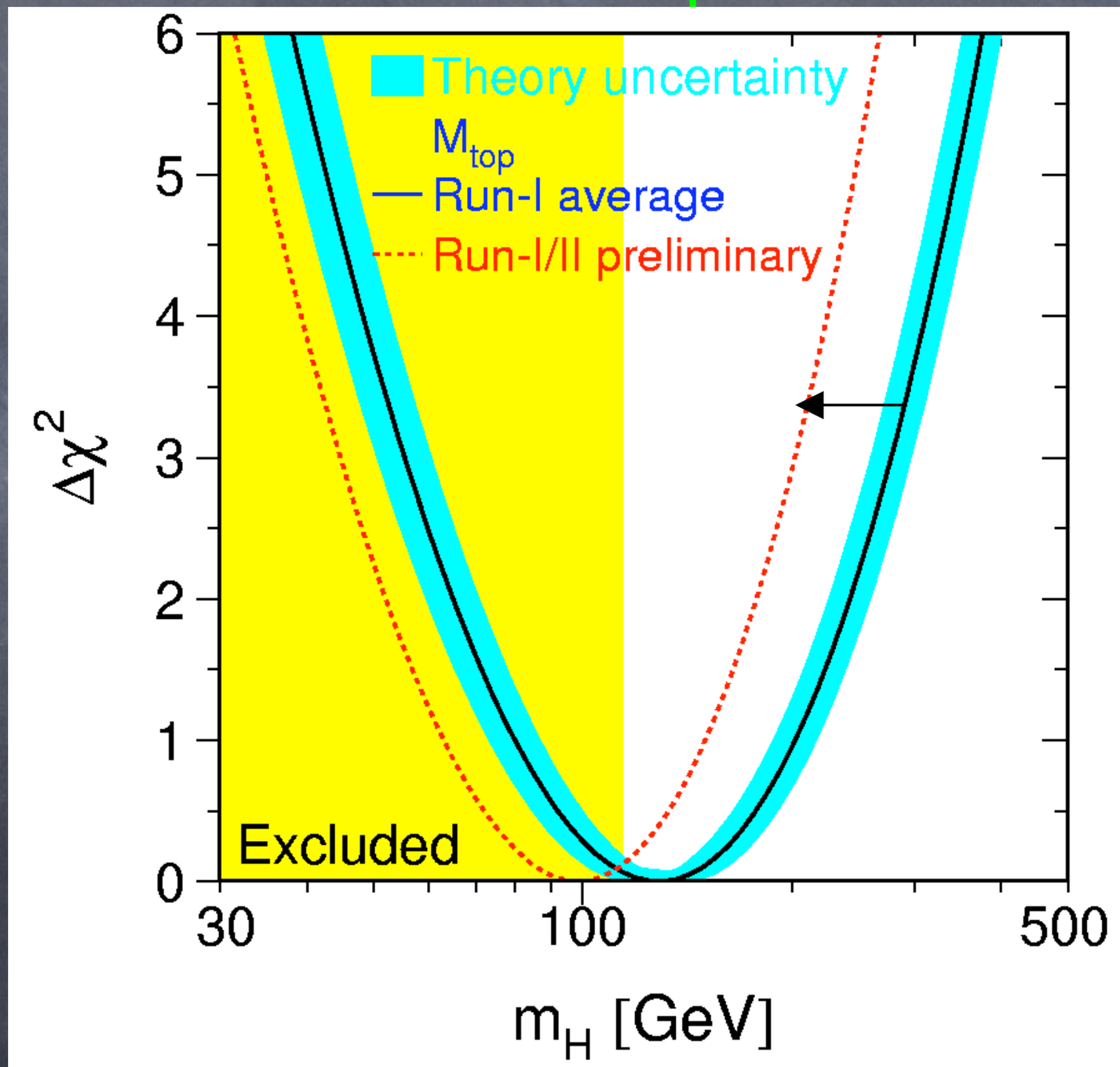
- Fermi formulated the first theory of the weak force (1933)
- The required energy scale to study the problem known since then: ~TeV
- We are finally getting there!



Gap Excitation

the top mass is
a crucial input data

- We know the energy scale of the problem:
  $G_F \approx (300\ \mathrm{GeV})^{-2}$
- the gap excitation is called "Higgs boson"
- Current data combined with the Standard Model theory predict
  $m_H < 208\ \mathrm{GeV}$ (95%CL)



Kick out Dark Field from the vacuum

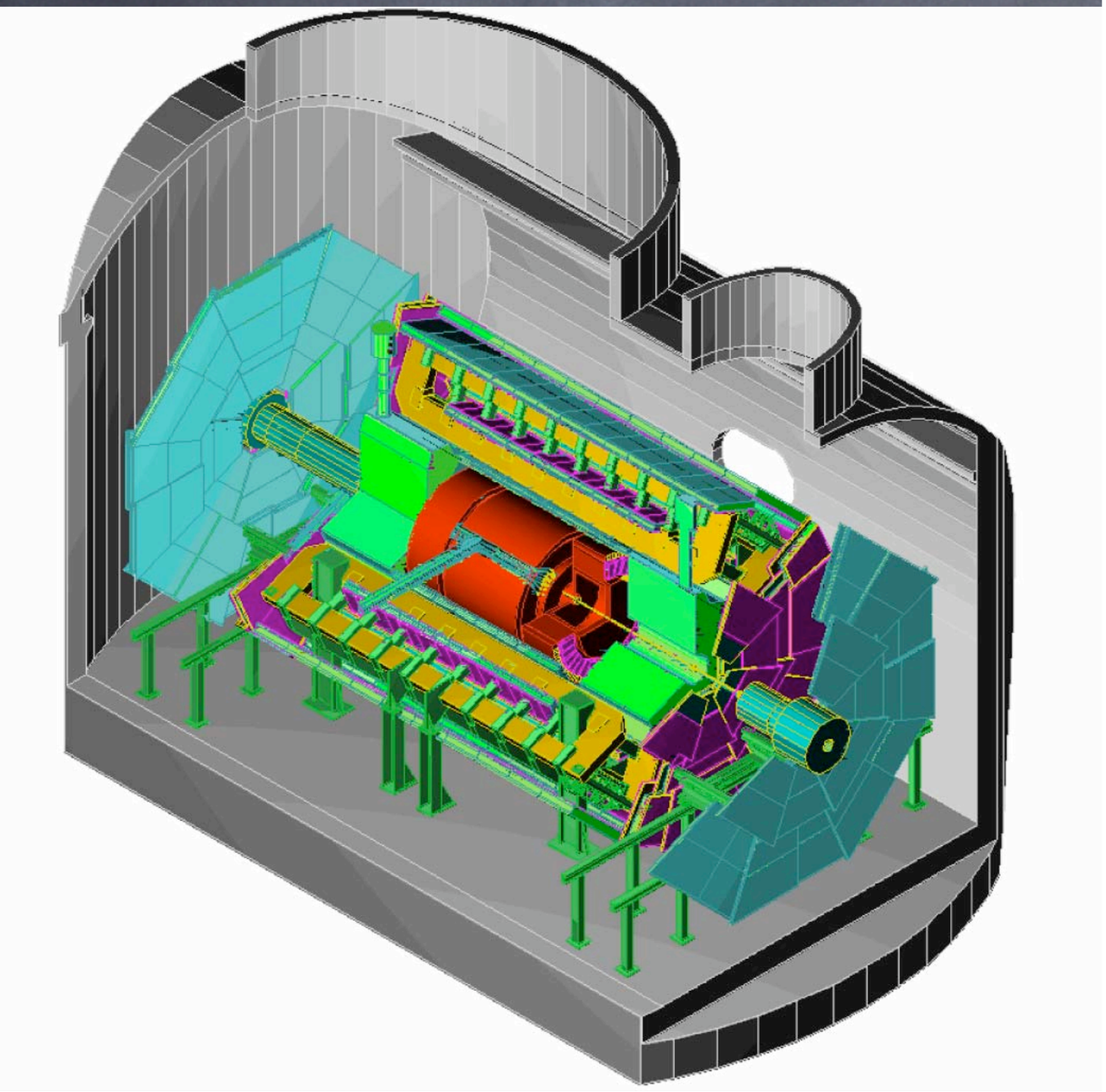
- We know the energy scale of the problem:

  0.3 TeV

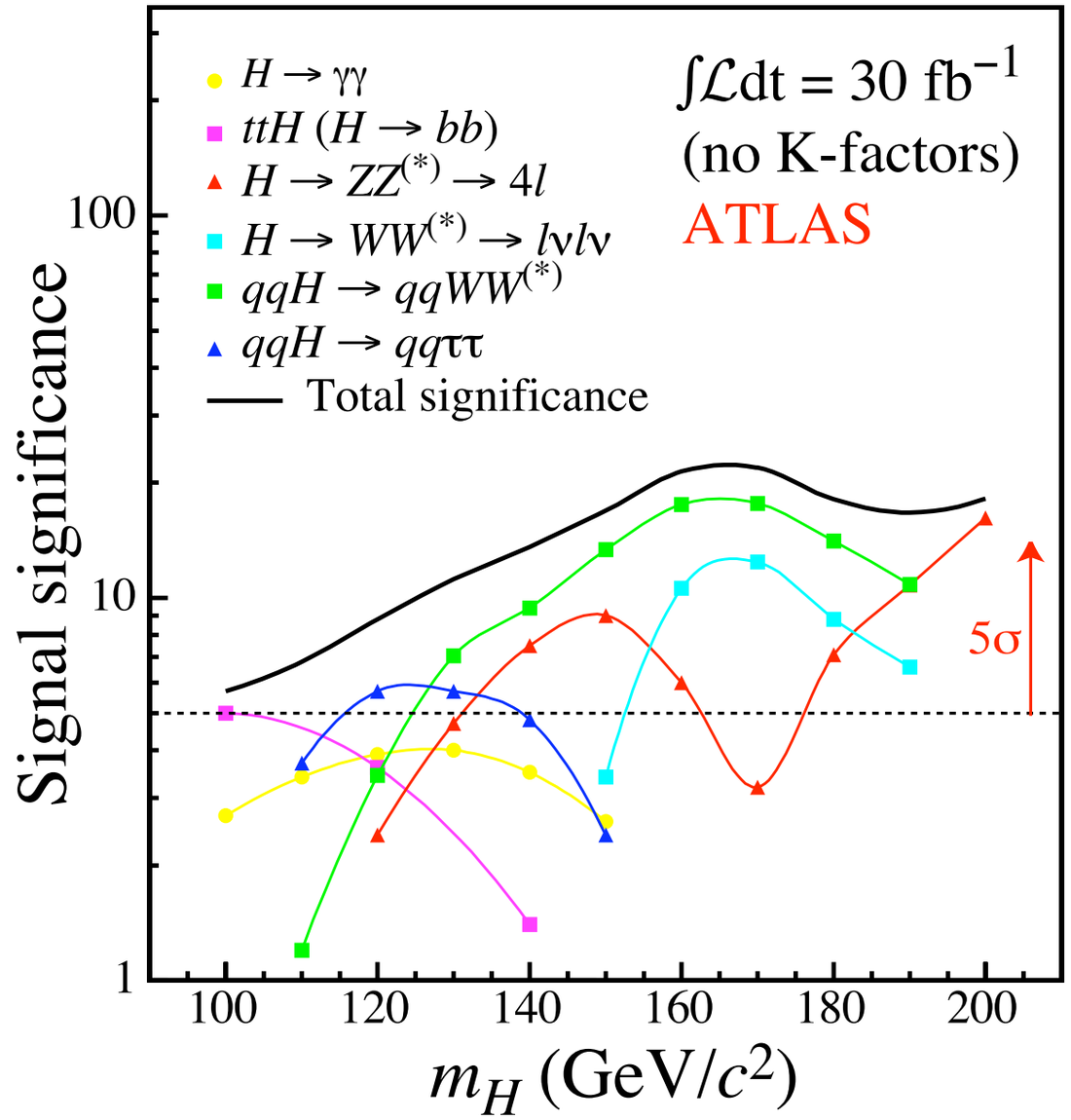
- pump energy into empty space to kick out whatever makes Dark Field: "Higgs boson"

- LHC will find it!!!!!

Higgs at ATLAS



Robust discovery



Better be sure

- For something this bizarre, we'd better make sure
- Is the particle discovered *really* the Higgs boson?
  - Is it really responsible for particle masses?
  - Does this have the right properties?
  - Is it really stuck in our Universe?

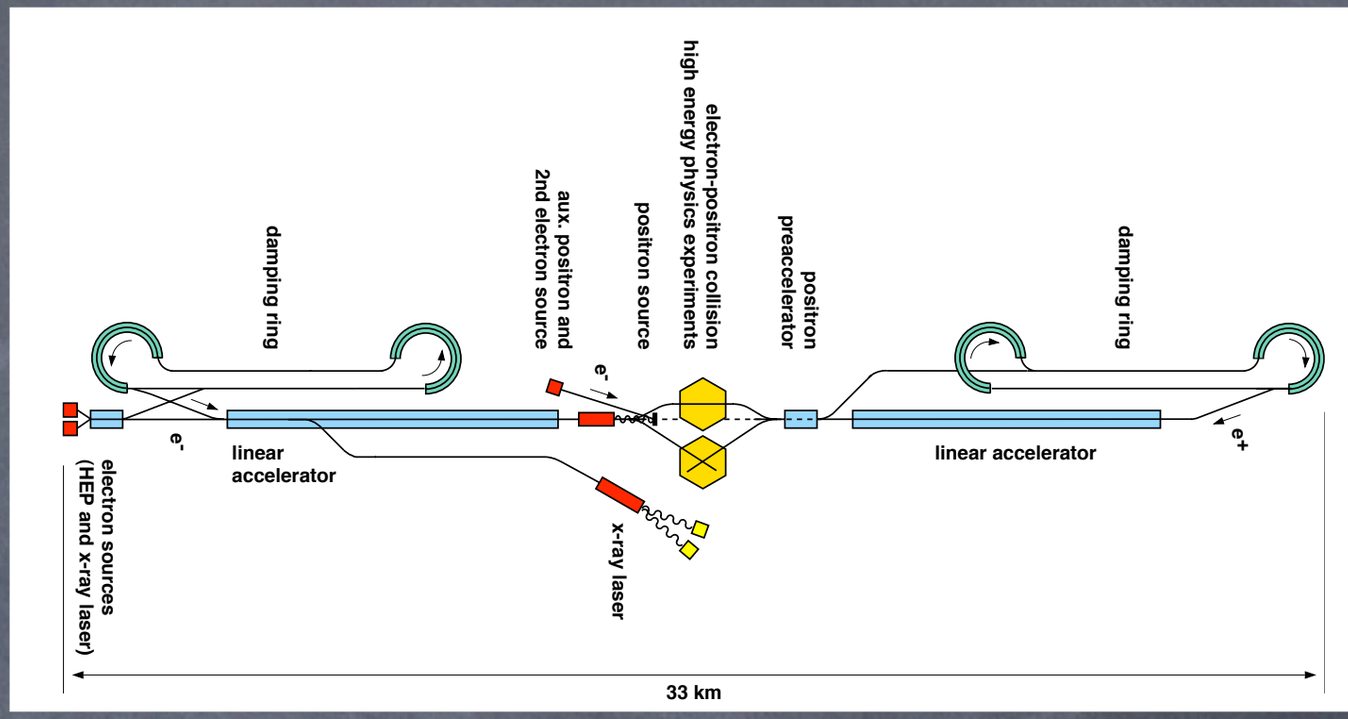
Need detailed measurements for the proof

Questions to be answered

- Is the particle discovered really the Higgs boson?
  - Is it really responsible for particle masses?
  - Does this have the right quantum number $J^P=0^+$?
  - Is it condensed in the Universe, namely here?
- Prove it is the "Mother of Mass"
  - Coupling ∝ mass?
  - Size of the condensate

Linear Collider

- Electron-positron collider
- e^-, e^+ point-like with no structure
- Well-understood environment
- Linear instead of ring to avoid synchrotron loss
- Super-high-tech machine
- Accelerate the beam over >15km
- Focus beam down to a few nanometers and make them collide



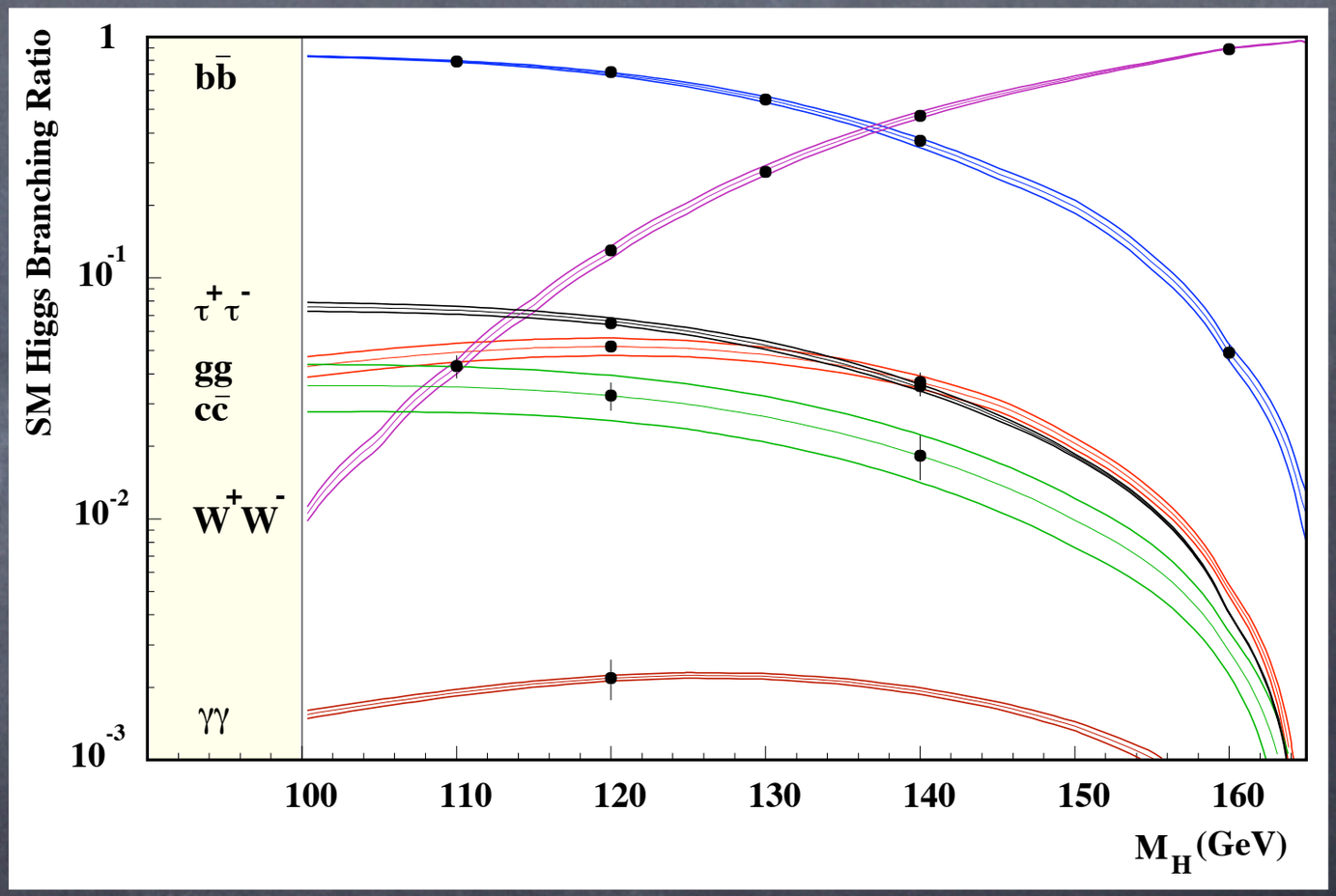
International Linear Collider (ILC)

Prove its coupling ∝

- Branching Fractions test the relation

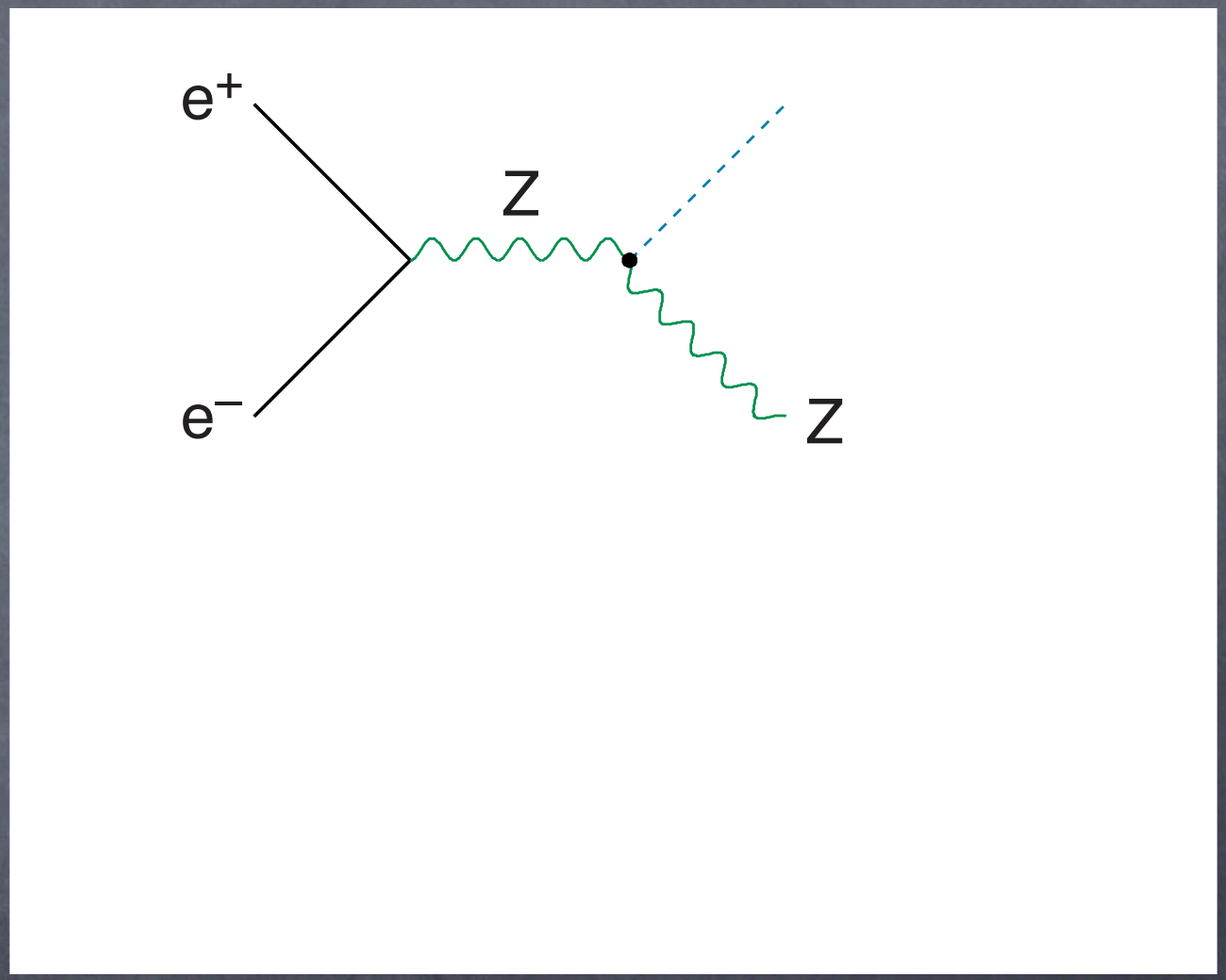
  coupling ∝ mass

⇒ proves that Higgs Boson is the Mother of Mass



Prove it is condensed

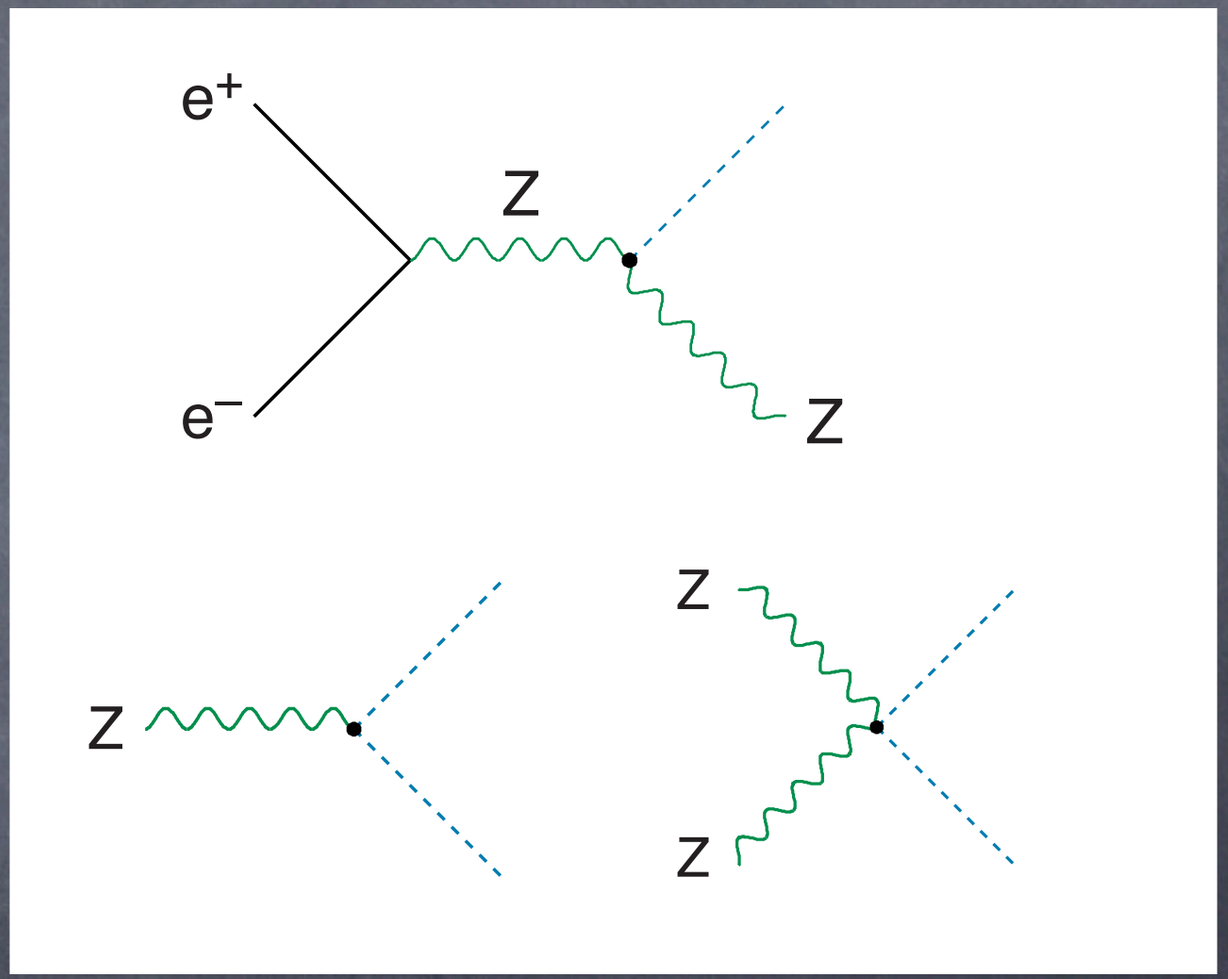
- ZH final state
- Prove the ZZH vertex



Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z:gauge boson, H: scalar boson

⇒ *only two types of vertices*



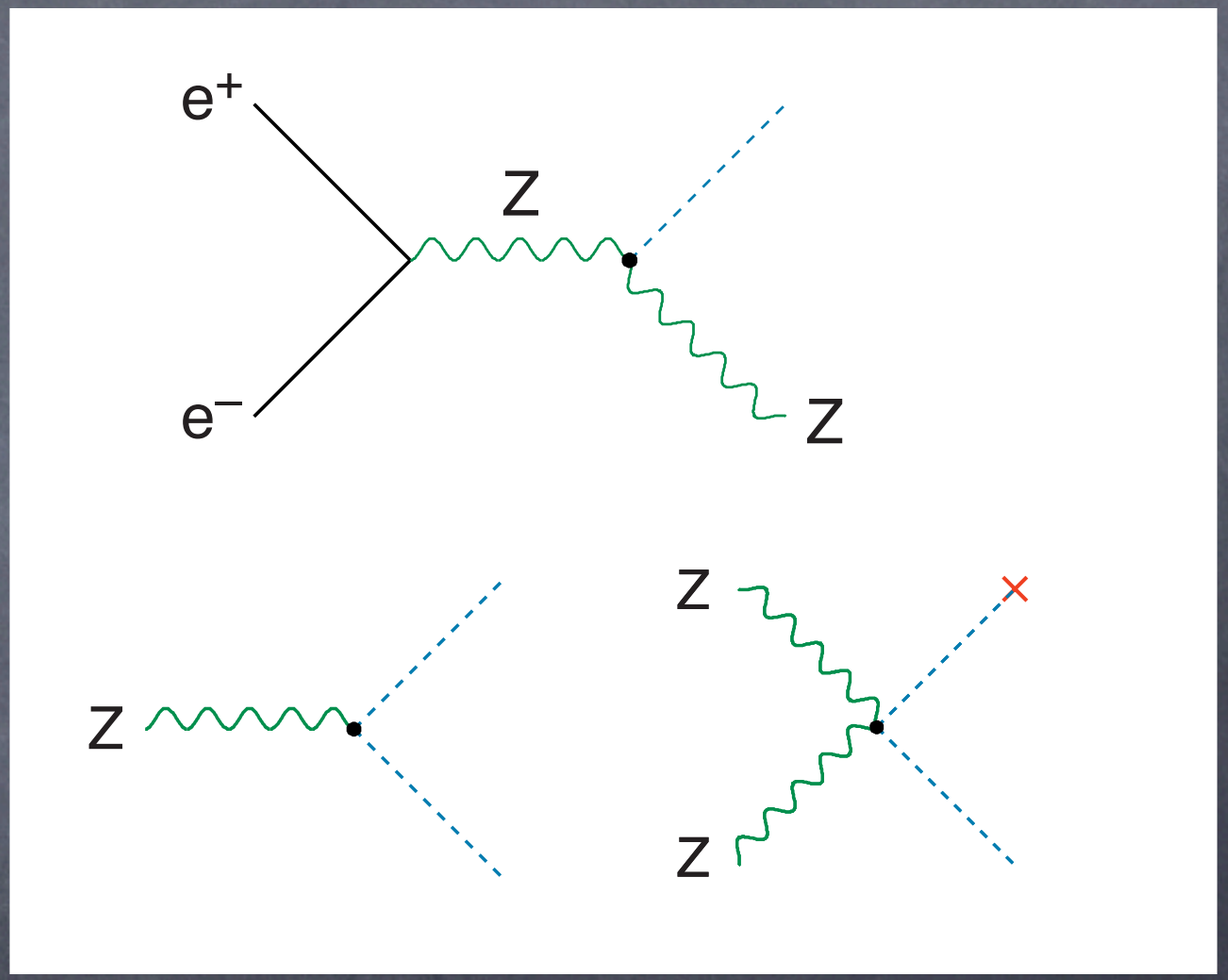
Prove it is condensed

- ZH final state
- Prove the ZZH vertex
- We know Z:gauge boson, H: scalar boson

⇒ *only two types of vertices*

- Need a condensate to get ZZH vertex

⇒ *proves it is condensed in Universe*



Prove it is condensed

- ZH final state
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- We know Z:gauge boson, H: scalar boson

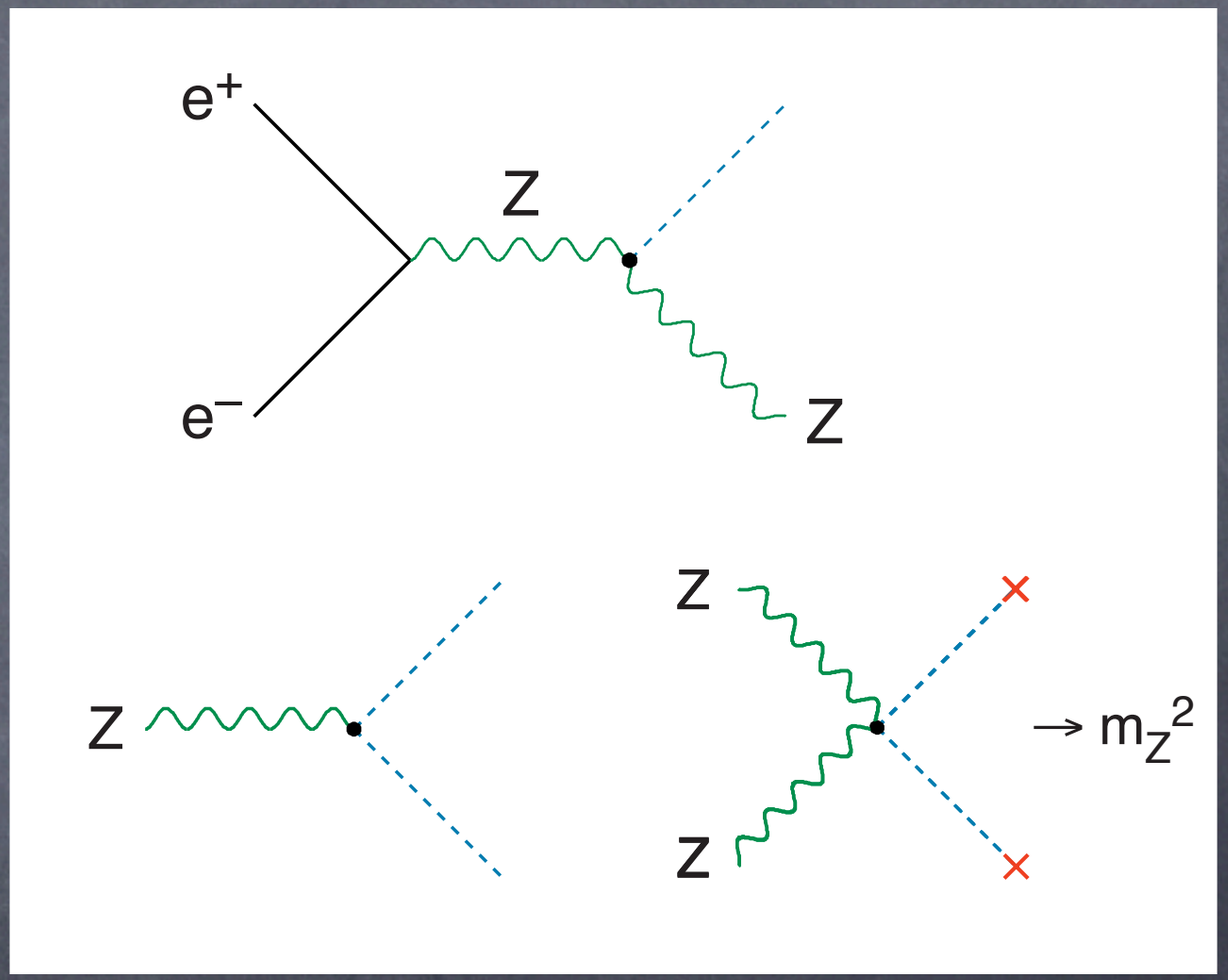
⇒ *only two types of vertices*

- Need a condensate to get ZZH vertex

⇒ *proves it is condensed in Universe*

⇒ *proves it is the origin of* m_Z

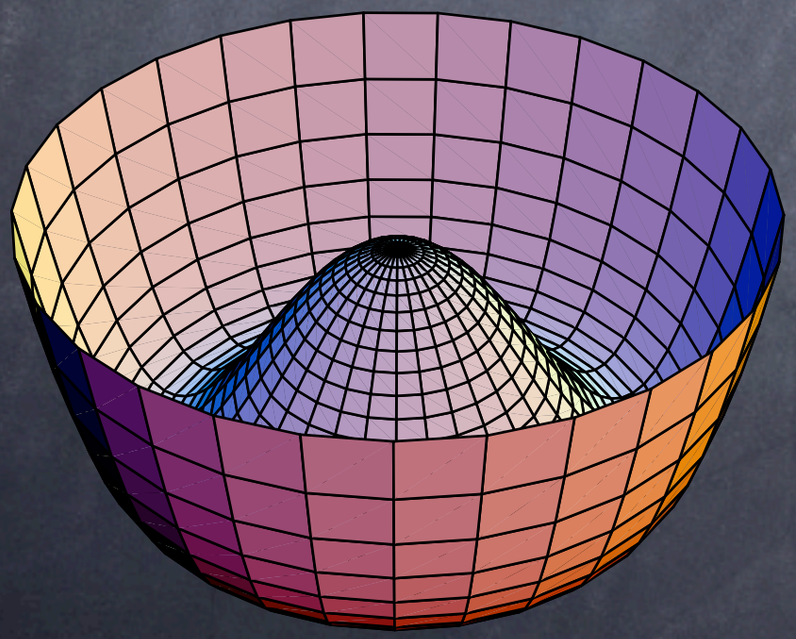
HM, hep-ex/9606001

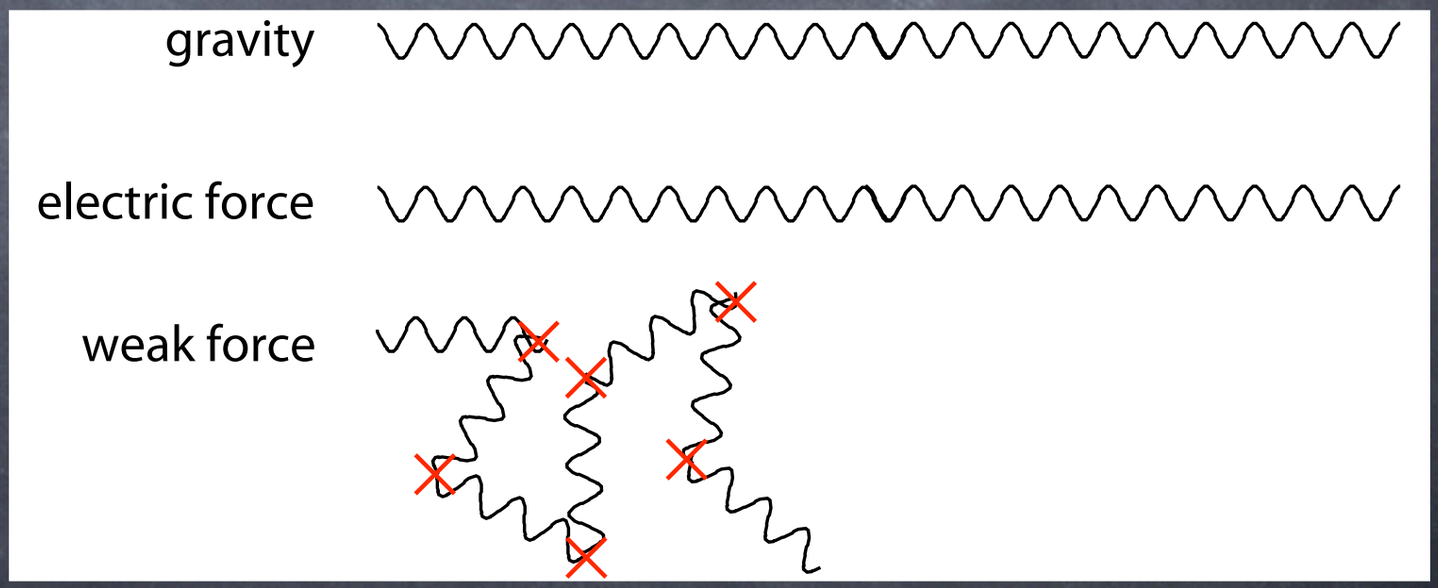


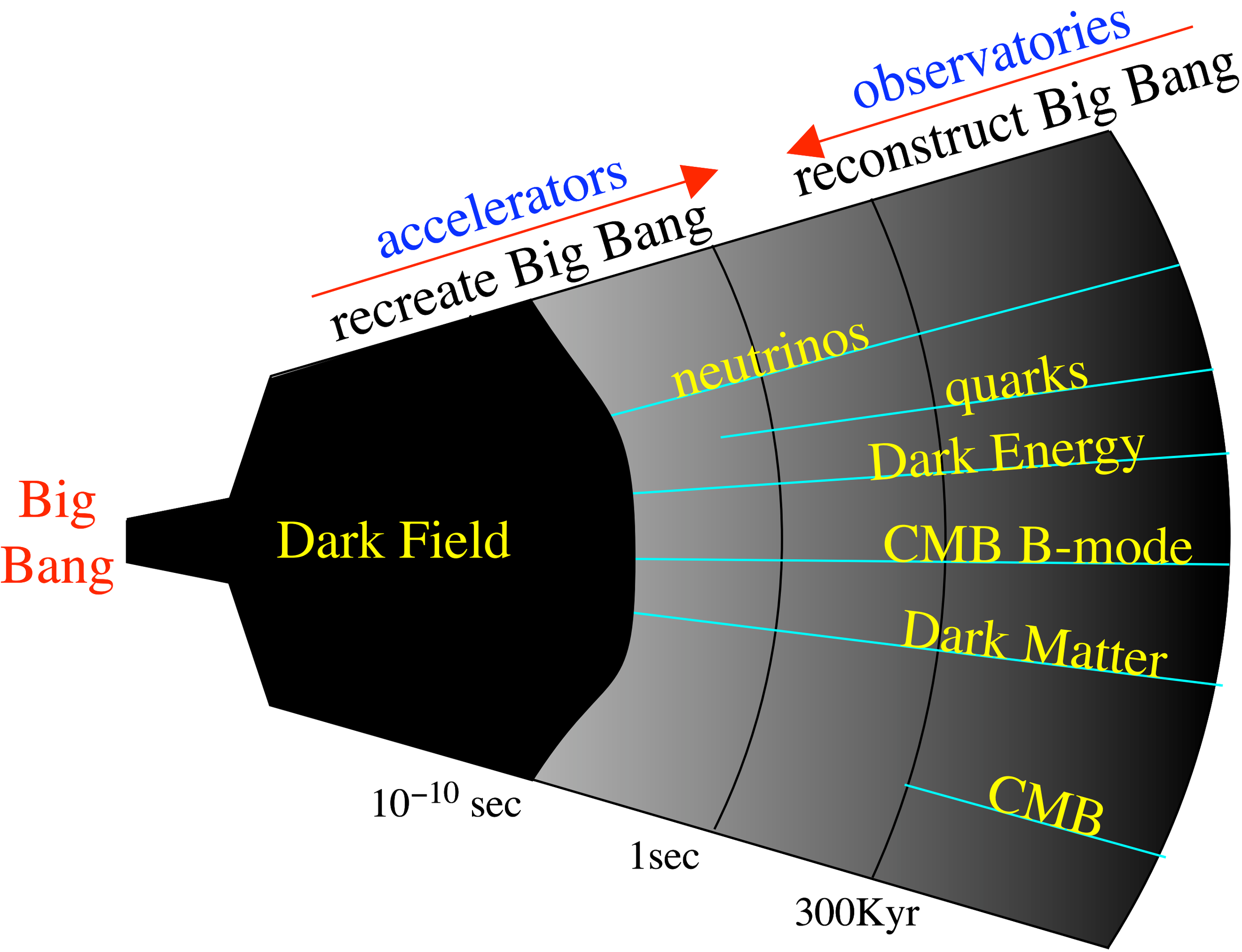
Post-Higgs Problem

- We see "what" is stuck in our universe
- But we still don't know "why"
- Two problems:
  - Why anything is condensed at all
  - Why is the scale of Dark Field 0.3TeV much much smaller than the scale of gravity ~10^{15} TeV
- Explanation most likely to be at ≤TeV scale because this is the relevant energy scale

Hierarchy Problem



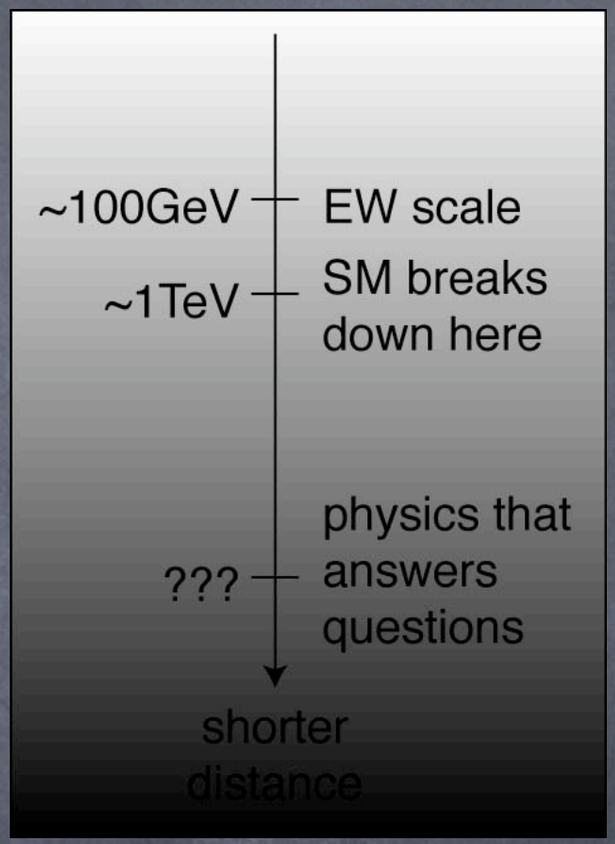



accelerators
recreate Big Bang
observatories
reconstruct Big Bang
Big Bang
Dark Field
neutrinos
quarks
Dark Energy
CMB B-mode
Dark Matter
CMB
10^{-10} sec
1sec
300Kyr

The Main Obstacle

- We look for physics beyond the Standard Model that answers big questions about early universe
- By definition, that is physics at shorter distances
- Then the Standard Model must survive down to whatever shorter distance scale
- Hierarchy problem is the main obstacle to do so

⇒ We can't even get started!



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 $10^{-17}\mathrm{cm}$
- Need a lot of energy to keep it small!

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

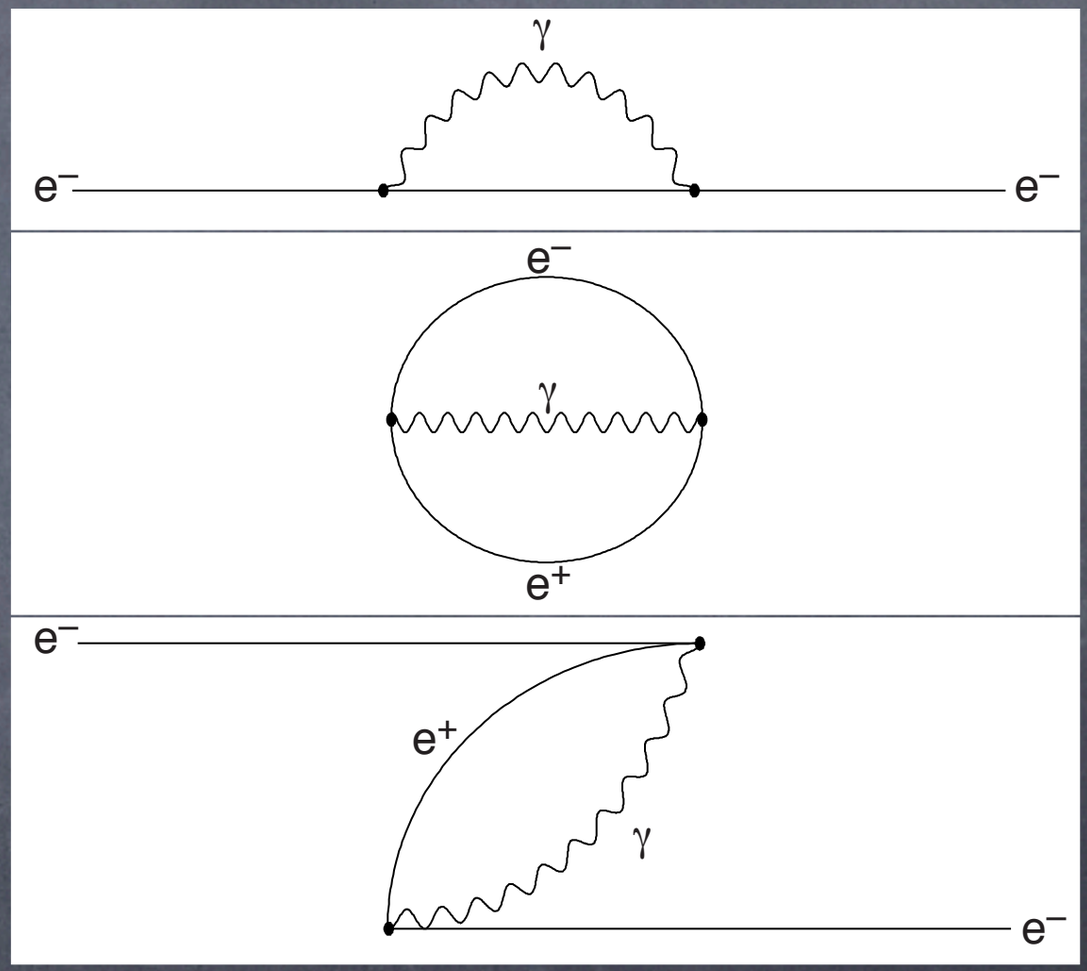
- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}\mathrm{cm}$
- Breakdown of theory of electromagnetism

  $\Rightarrow$ Can't discuss physics below $10^{-13}\mathrm{cm}$

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

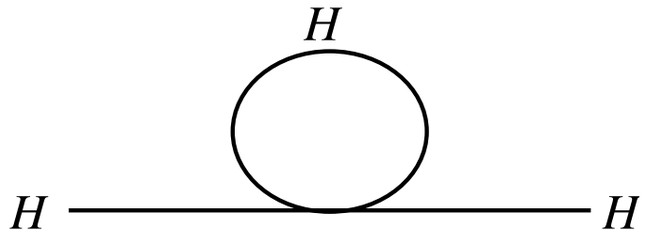
⇒ only 10% of mass even for Planck-size $r_e \sim 10^{-33}$cm



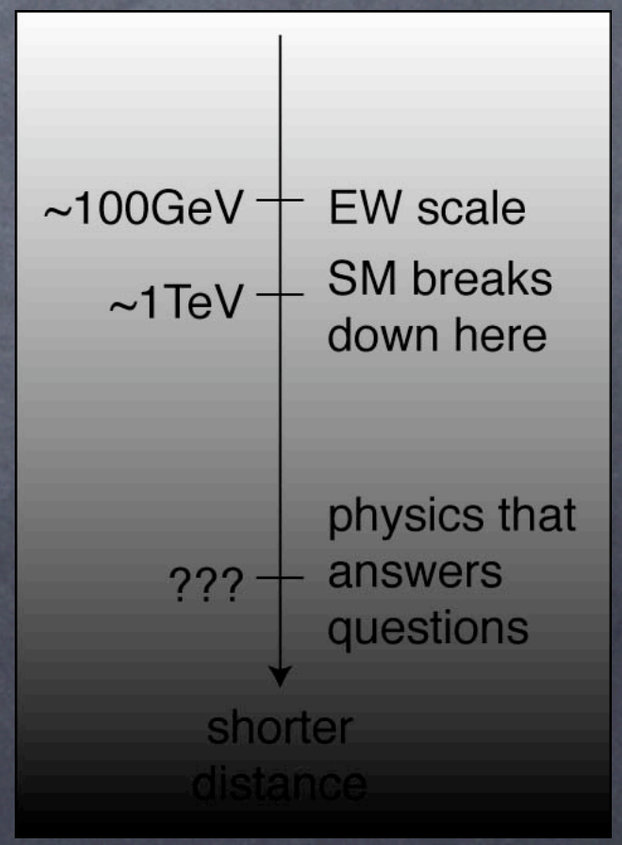
$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too

- Just like electron repelling itself because of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force
- Can't get started!

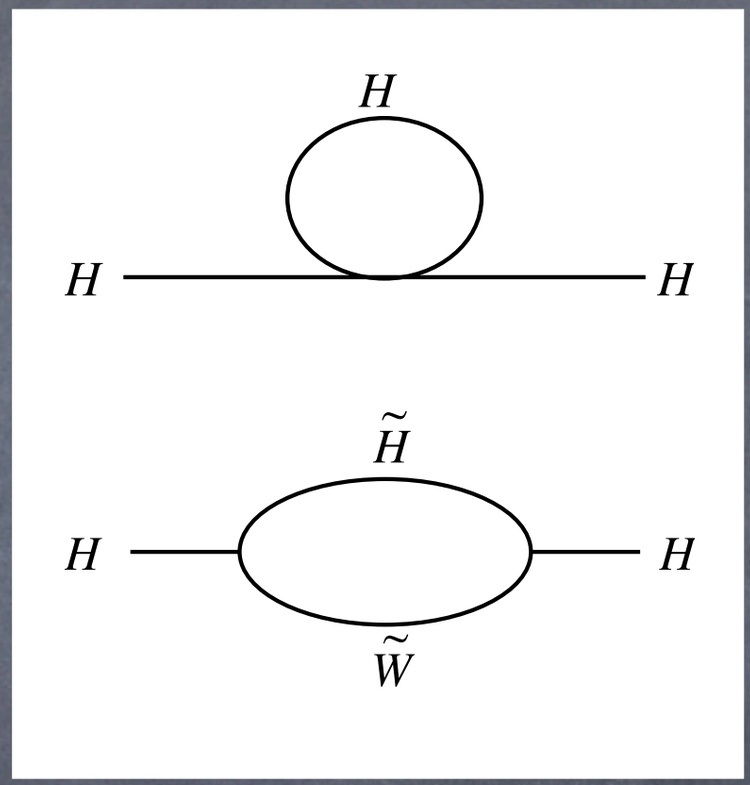


$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$



History repeats 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

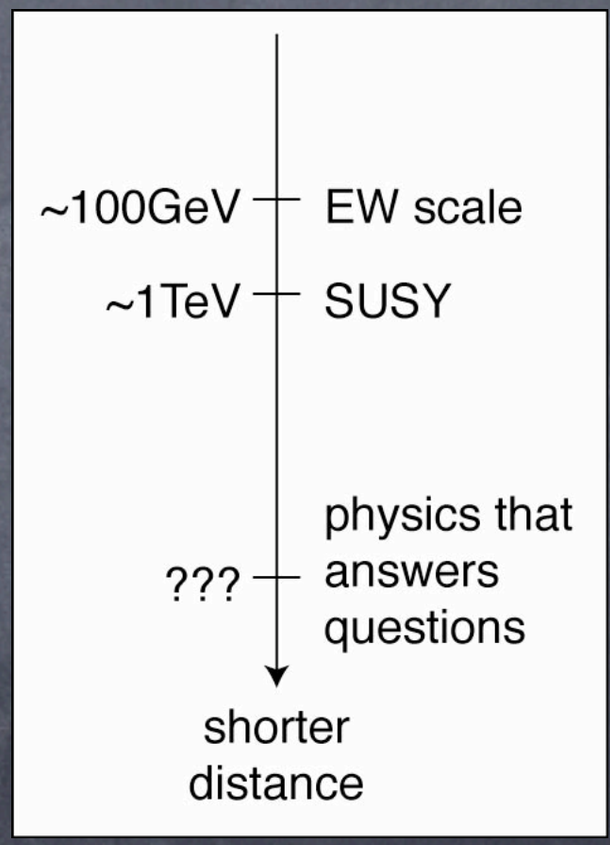


$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Opening the door

- Once the hierarchy problem solved, we can get started to discuss physics at shorter distances and earlier universe.
- It opens the door to the next level:

  Hope to answer big questions
- The solution to the hierarchy problem itself, e.g., SUSY, provides additional probe to physics at short distances



Three Directions

History repeats itself

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

Learn from Cooper pairs

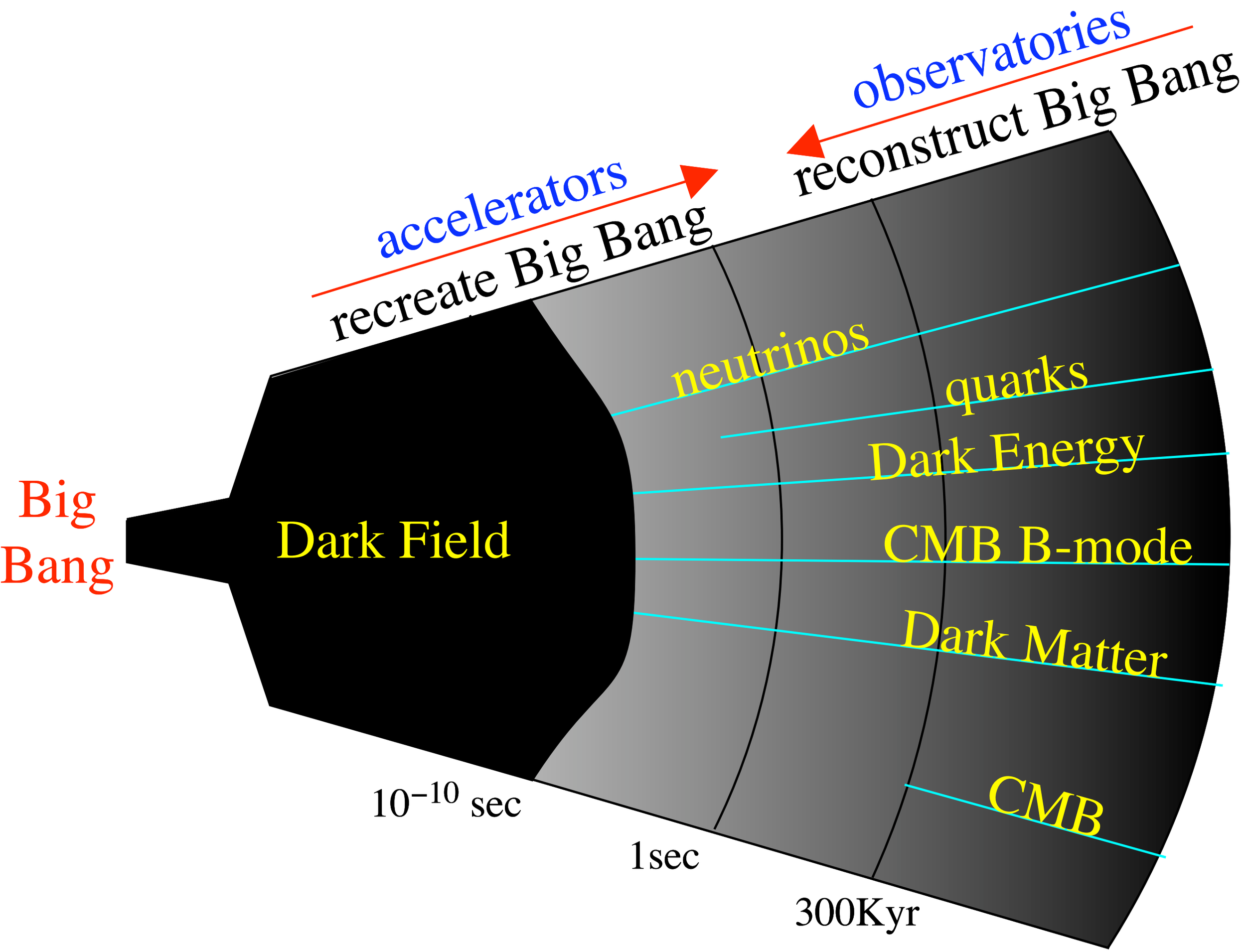
- Cooper pairs composite made of two electrons
- Higgs boson may be fermion-pair composite ⇒ technicolor

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)

More Directions

- Higgs boson as a Pseudo-Nambu-Goldstone boson (Little Higgs)
- Higgs boson as an extra-dimensional gauge boson (Gauge-Higgs Unification)
- Fat Higgs (Composite)
- Higgsless and $W^{\pm}$ as Kaluza-Klein boson
- technicolorful supersymmetry


accelerators
recreate Big Bang
observatories
reconstruct Big Bang
Big Bang
Dark Field
neutrinos
quarks
Dark Energy
CMB B-mode
Dark Matter
CMB
10^{-10} sec
1sec
300Kyr

Anthropic reason?

- Maybe electroweak scale is what it is simply because that is the only kind of universe we can observe
- if v>>TeV, $|m_n - m_p|$ too big and neutron decays even inside nuclei; no chemistry, no life
- after all, cosmological constant is "clearly" not natural
- if this were the case, there may be nothing else to be seen at the LHC other than the "elementary" Higgs boson
- See, however, "A Universe Without Weak Interactions" (Harnik, Kribs, Perez)

Growing Uneasiness

- If there are indeed new physics ≤TeV that makes EW scale "natural"
- They why didn't it show any imprints in
  - EW precision observables?
  - FCNC (K^0-K^0, $B_d \to \phi K_S$, B_S-B_S)?
  - CP violation (EDMs)?
- Maybe no new physics ≤TeV?

uneasiness in cosmology

- Before COBE, upper limit on CMB anisotropy kept getting better and better
- Before 1998, the universe appeared younger than oldest stars
- cosmologists got antsy
- "crisis in standard cosmology"

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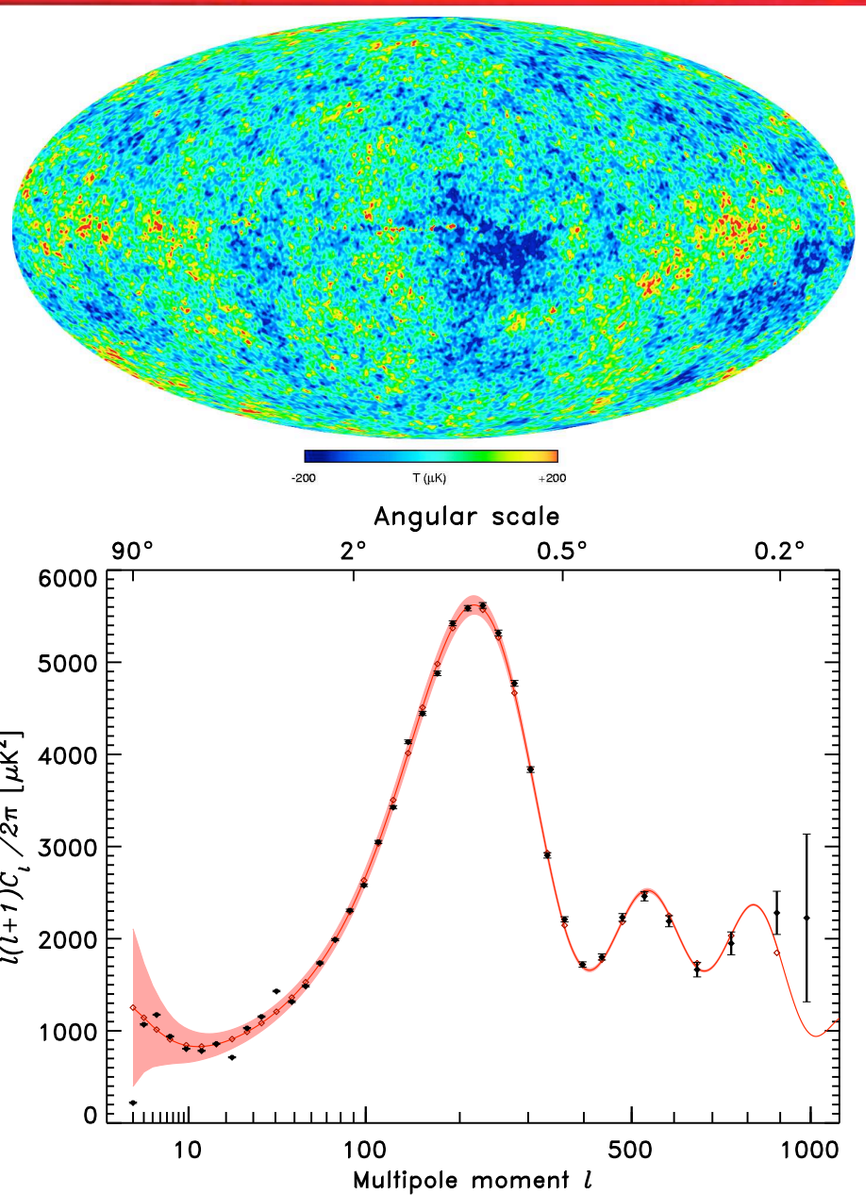


EWSB models

- We know the energy scale of electroweak symmetry breaking; we are getting there!
- We need to understand
  - what kind of "quantum liquid" we are dipped in
  - why it is there
  - what causes it condense
- Otherwise we can't study physics at shorter distances, universe before the BEC

Supersymmetry

Supersymmetry

- SUSY
  - Higgs only one of many scalars that happen to acquire negative mass-squared
  - SUSY stabilizes the hierarchy
- easily consistent with the EW precision observables because it is "decoupling" physics
- fully consistent, renormalizable, calculable theory
- can be connected to GUT, string, etc

A Broken Symmetry

- Supersymmetry predicts boson and fermion to have the same mass
- Clearly not true in nature

- It has to be broken, partners heavier than the SM particles
- Once broken, it is natural for partners to be heavier as their masses allowed by SU(2)×U(1), while quark, lepton, W, Z masses forbidden

Soft supersymmetry breaking

- Purpose of supersymmetry is to protect hierarchy
- Arbitrary terms in Lagrangian that break supersymmetry reintroduce power divergences
- "Soft supersymmetry breaking" classified:

$m\lambda\lambda$, $m^2{}_{ij}\phi^{i*}\phi^j$, $A_{ijk}\phi^j\phi^j\phi^k$, $B_{ij}\phi^j\phi^j$, $C_i\phi^j$

gaugino mass, squark/slepton mass-squared, etc

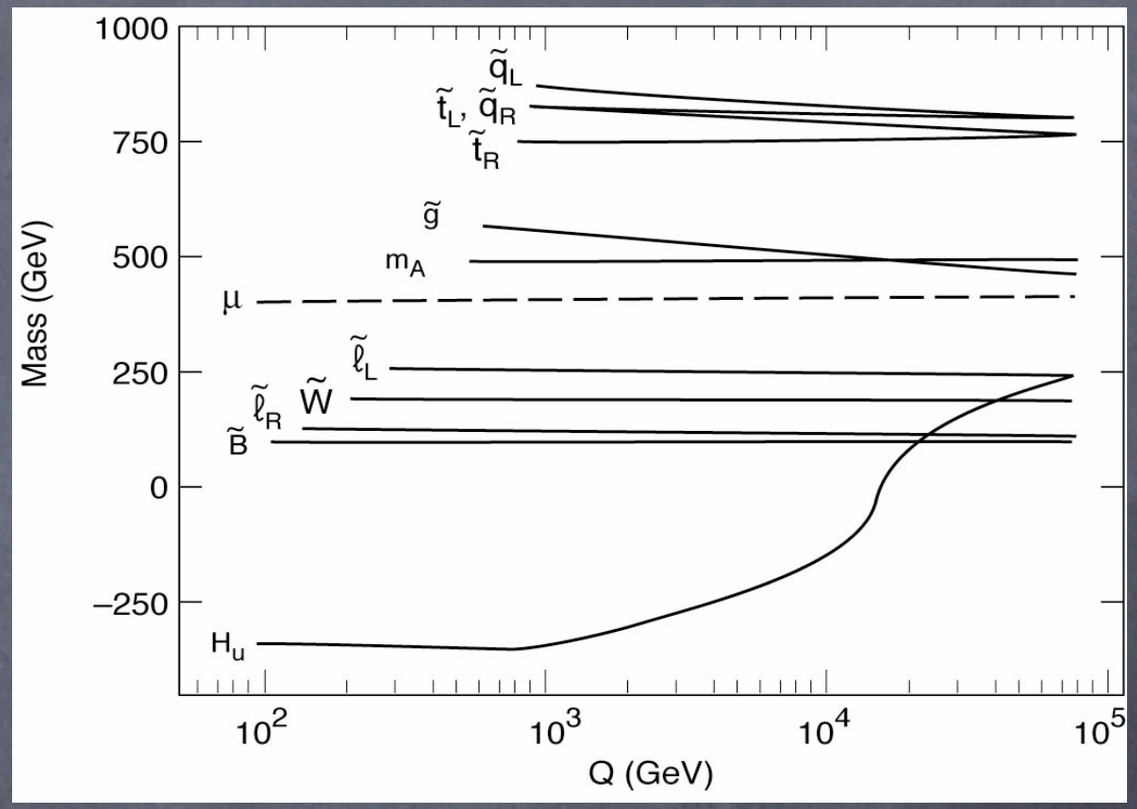
- Dark horse terms (not always allowed):

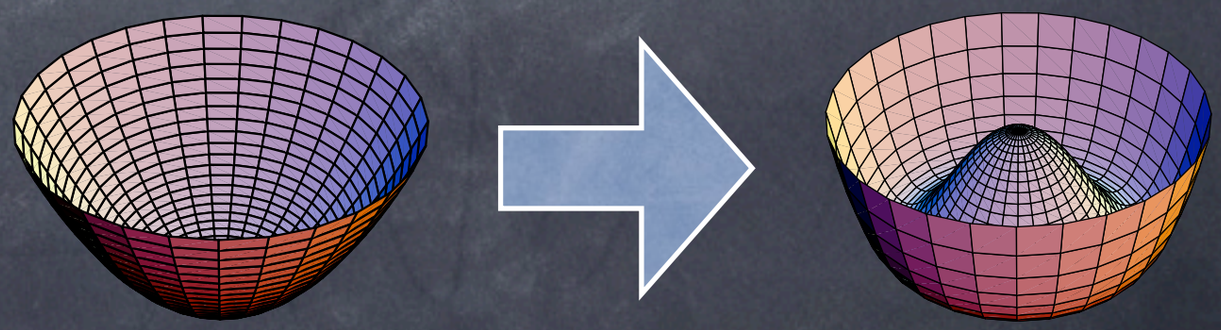
$\phi^{j*}\phi^j\phi^k$, $\lambda\psi^j$, $\psi^i\psi^j$

Radiative Symmetry Breaking

(Inoue et al; Alvarez-Gaumé et al; Ibañez-Ross)

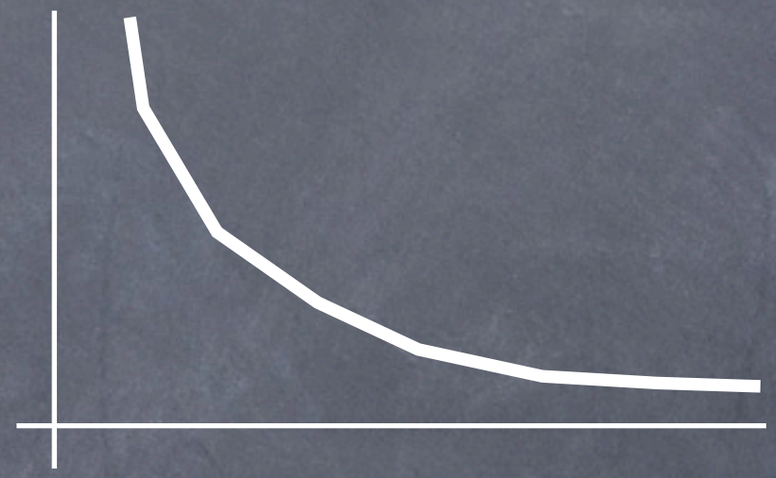
- In the MSSM, electroweak symmetry does not get broken
- Only after supersymmetry is broken, Higgs can obtain a VEV $v \sim m_{\text{SUSY}}$
- EWSB is as a consequence of supersymmetry breaking
- EW symmetry and hierarchy "protected" by supersymmetry





Origin of Hierarchy

(Witten)



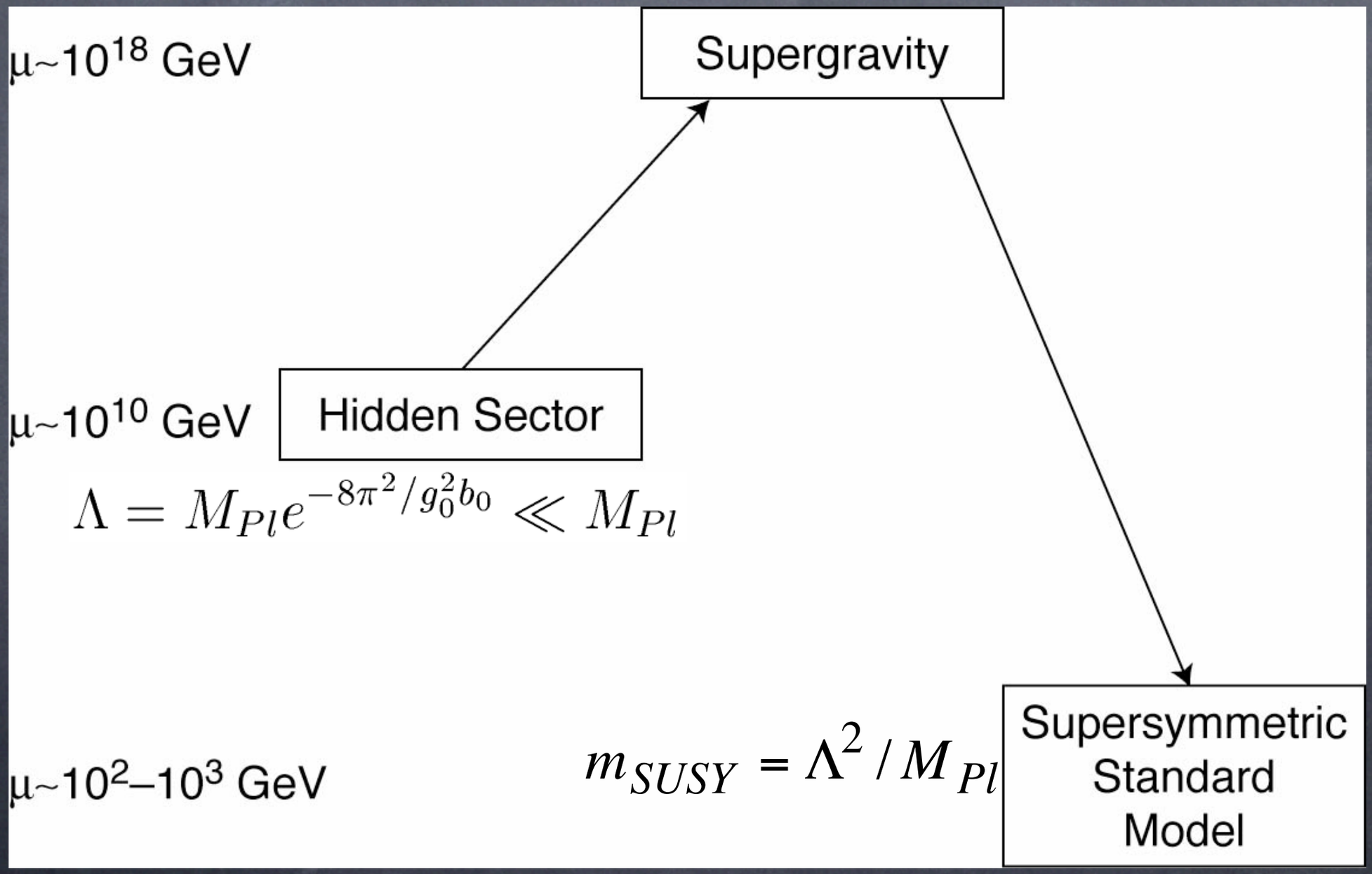
- $v \ll M_{Pl}$ because $v \sim m_{SUSY} \ll M_{Pl}$
- Why $m_{SUSY} \ll M_{Pl}$?
- Idea: running coupling constant
- SUSY broken by strong gauge dynamics with
- "Dynamical supersymmetry breaking"

$$\Lambda = M_{Pl} e^{-8\pi^2/g_0^2 b_0} \ll M_{Pl}$$

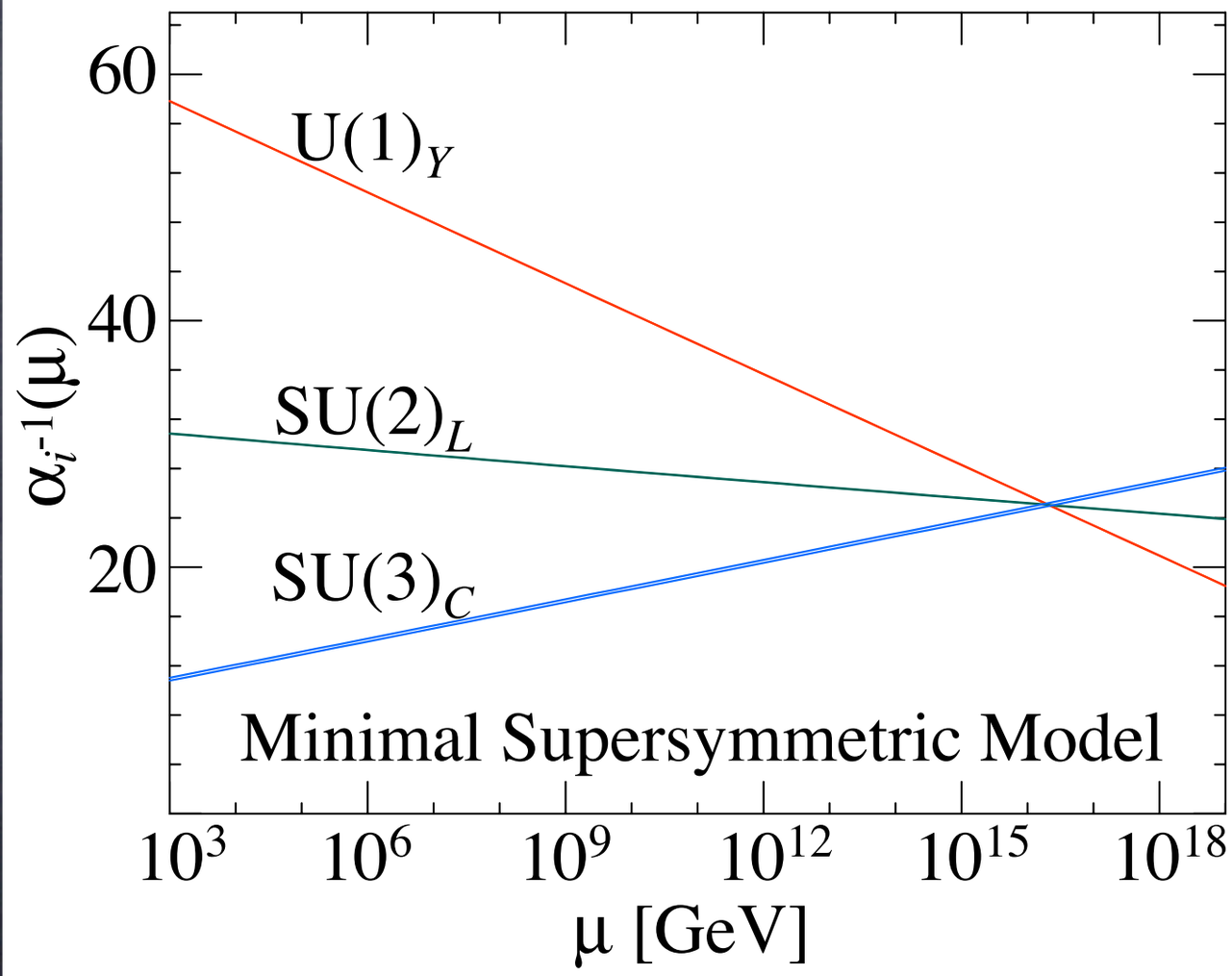
- e.g., SO(10) with one 16

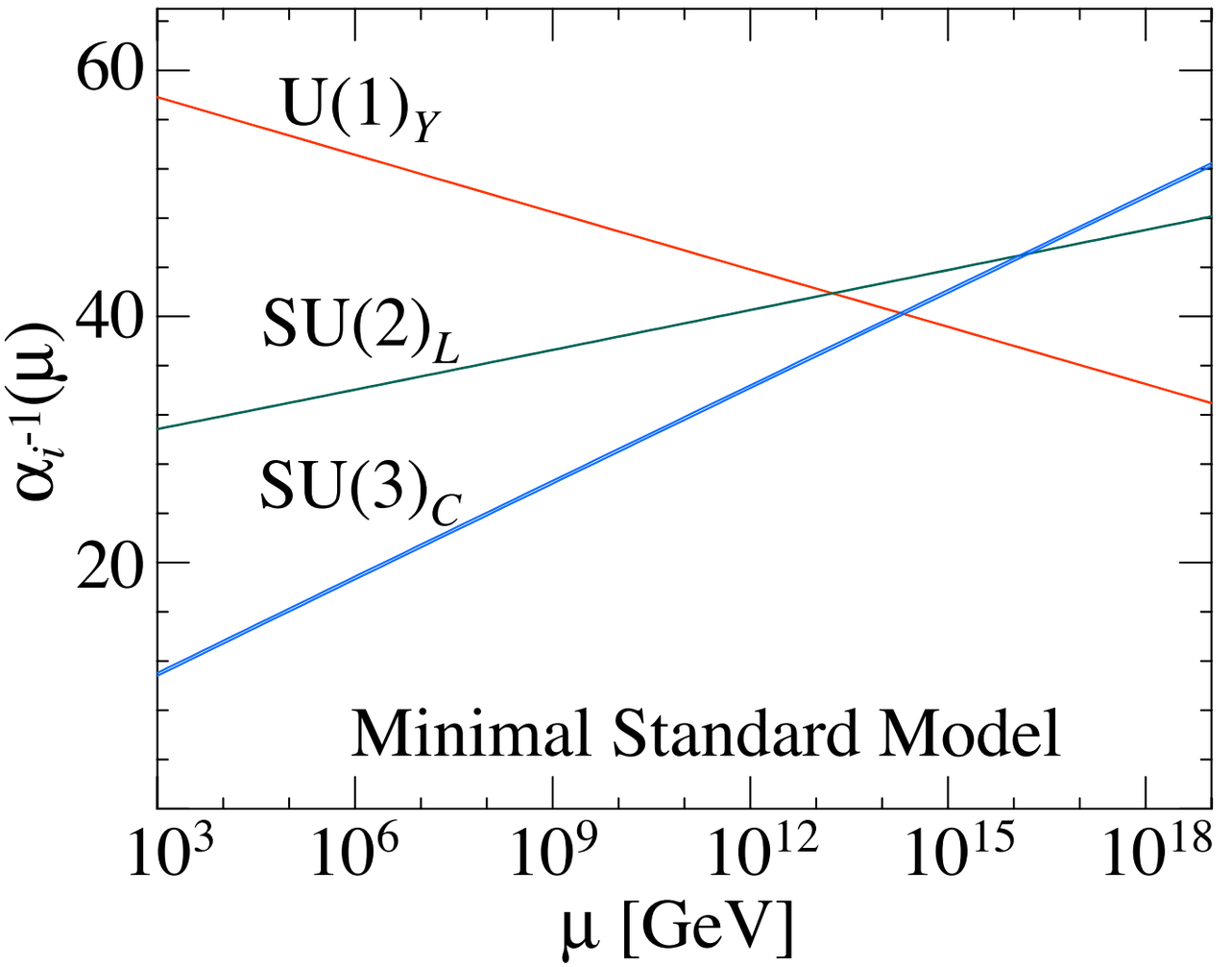
(Affleck, Dine, Seiberg; HM)

The paradigm

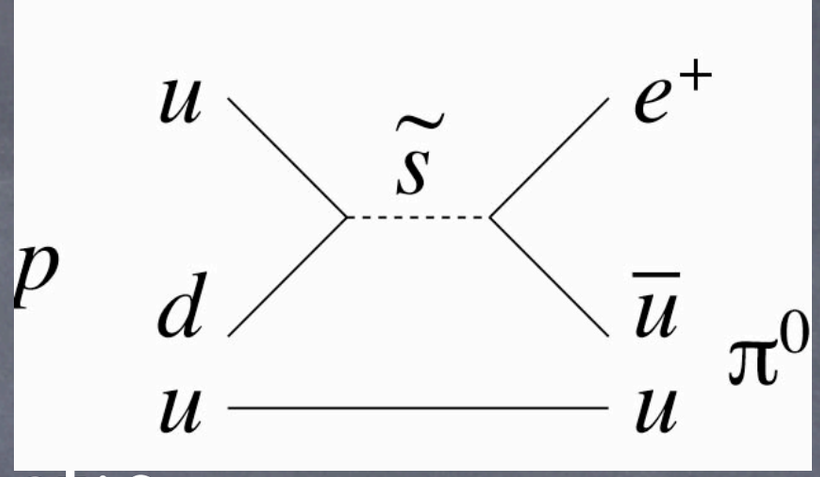


gauge coupling unification





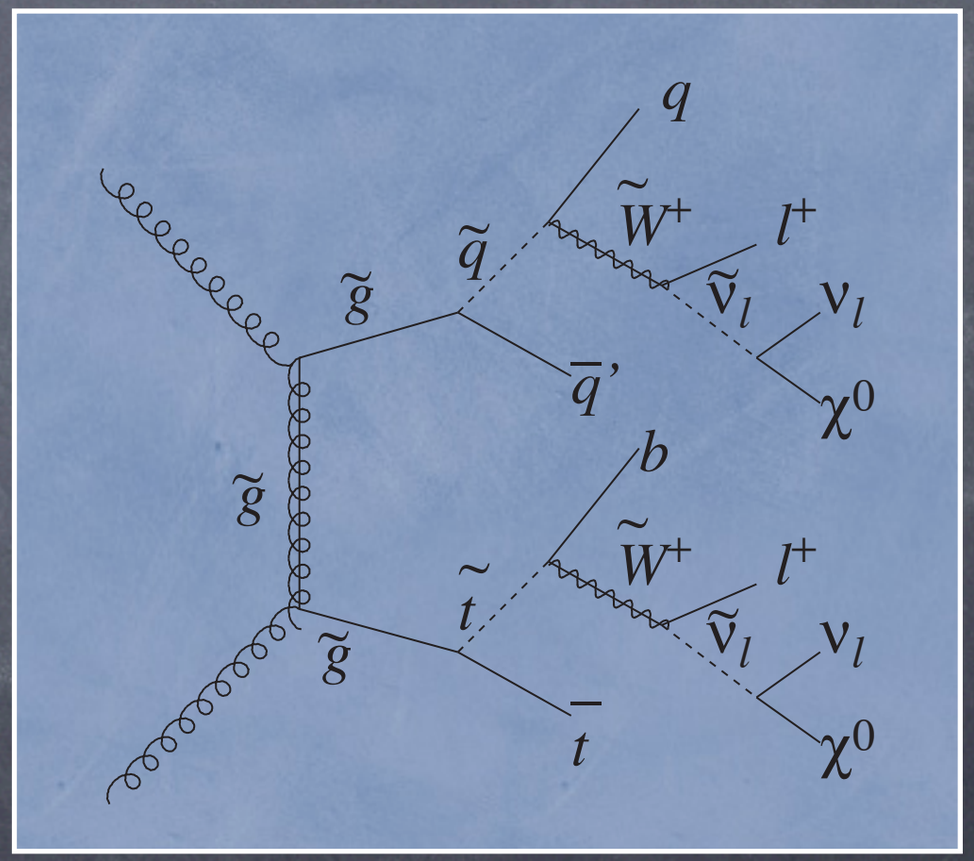
R-parity



- B, L-conservation not automatic
- W=udd+QdL+LLe+LHu
- If they exist with $O(1)$ couplings:
- $\tau_p \sim m_{sq}^4/m_p^5 \sim 10^{-12}$ sec!
- Product of two couplings < 10^{-26}
- Impose R-parity = $(-1)^{3B+L+2S}$
- Forbids B and L number violation
- R-parity is non-anomalous; may be gauged
- Stable Lightest Supersymmetric Particle
  $\Rightarrow$ Cold Dark Matter
- SUSY particles always pair-produced and decay into the LSP: missing energy signal

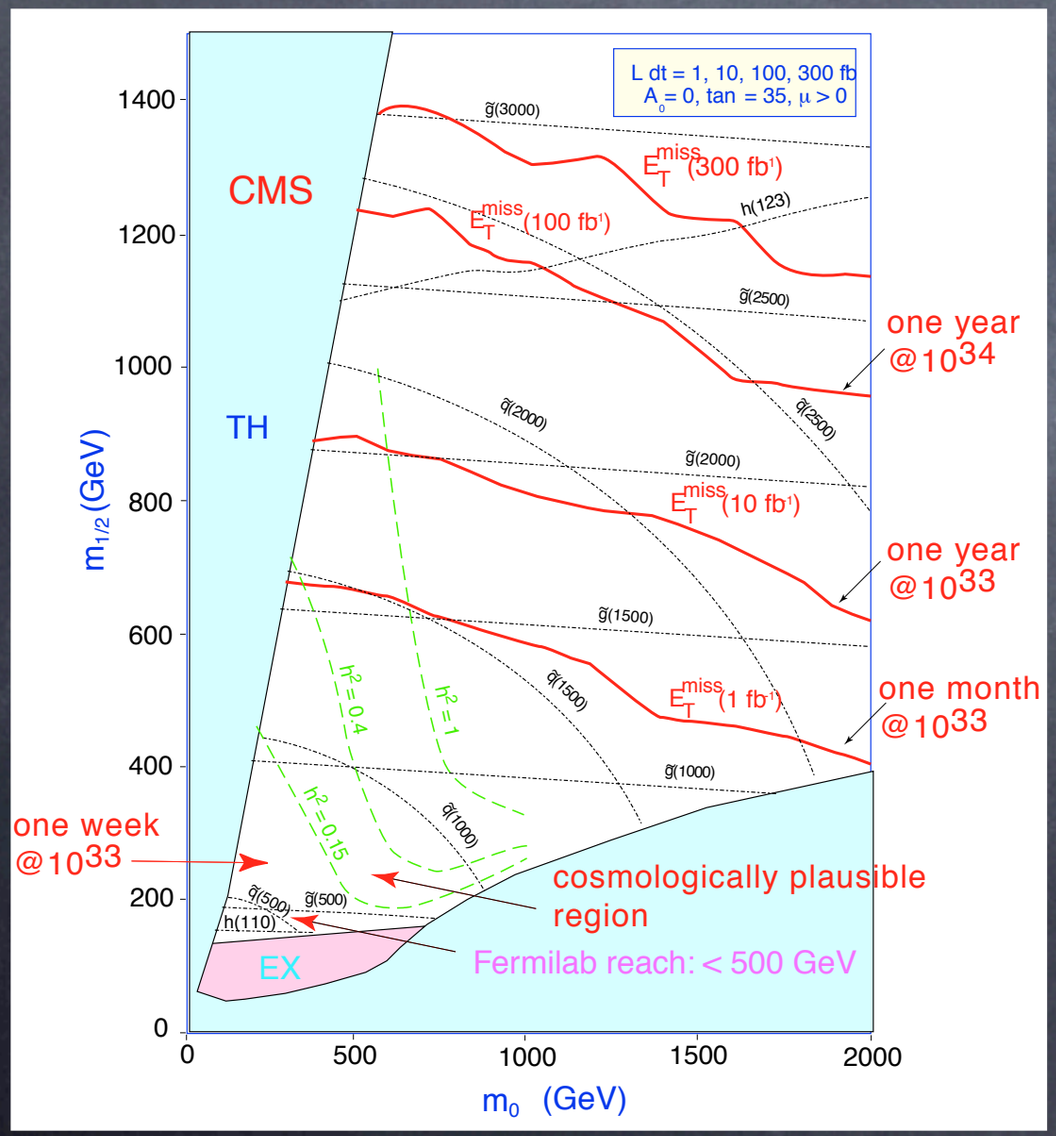
Supersymmetry at hadron colliders

- colored particles produced dominantly
- R-parity:
  - production in pairs
  - decay to LSP
- LSP escapes detection: "missing E_T"

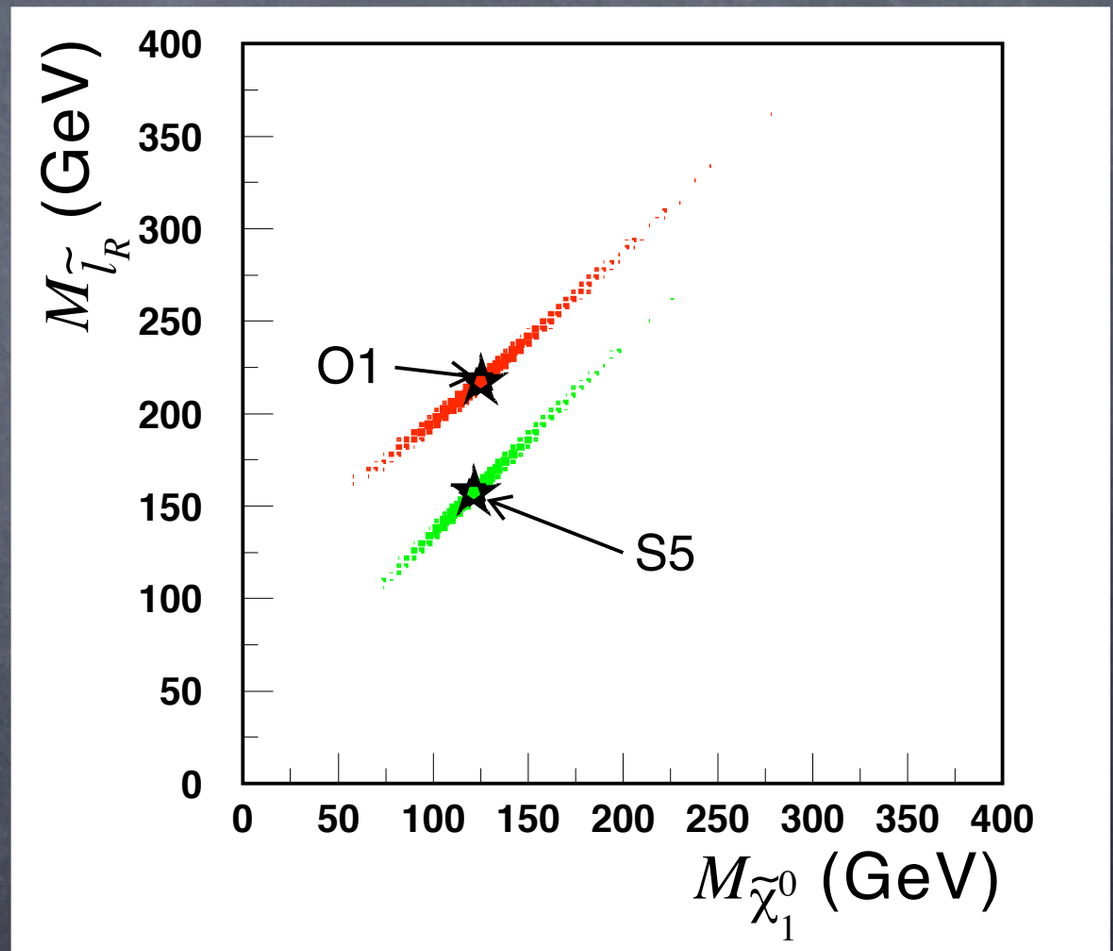


Supersymmetry

Tevatron/LHC will discover



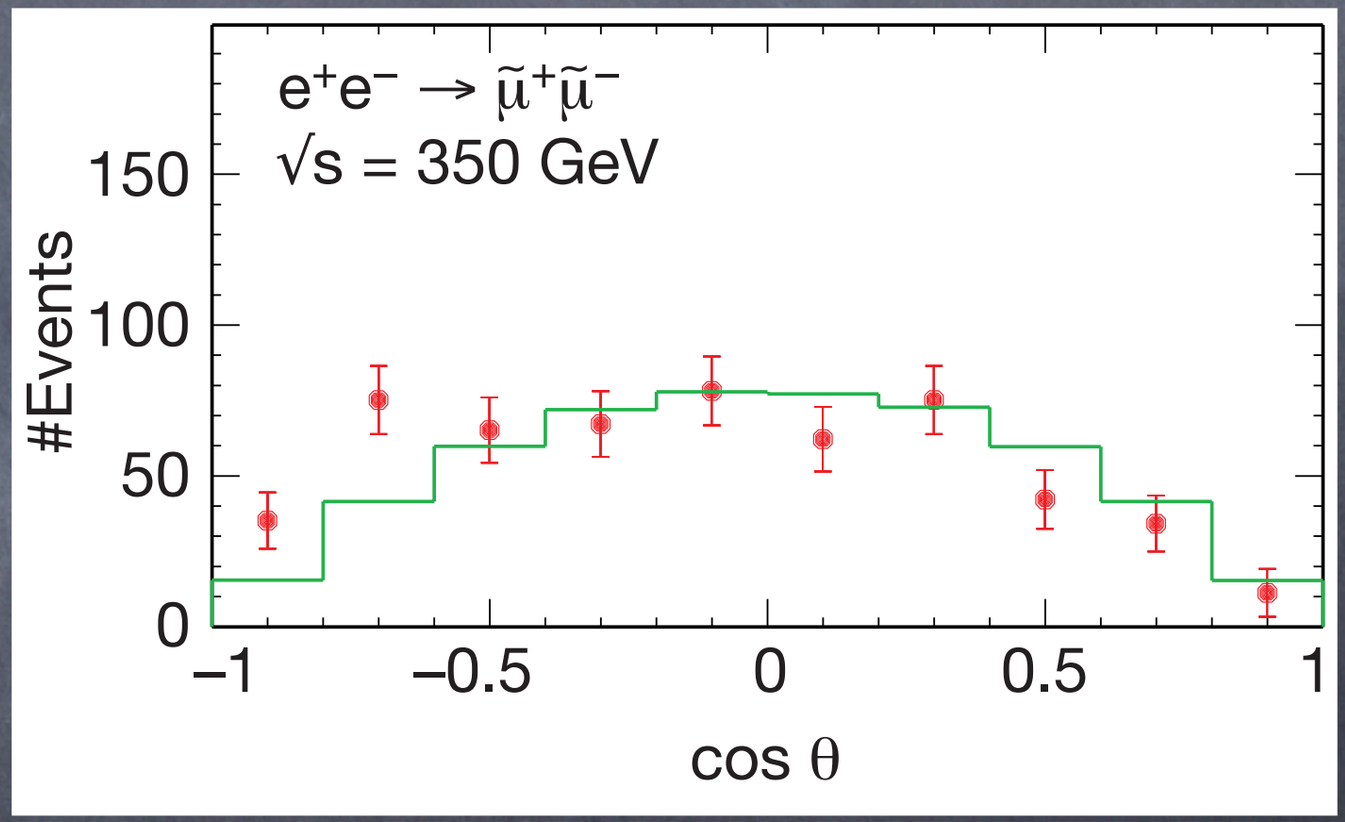
Can do many measurements at LHC



Prove Supersymmetry

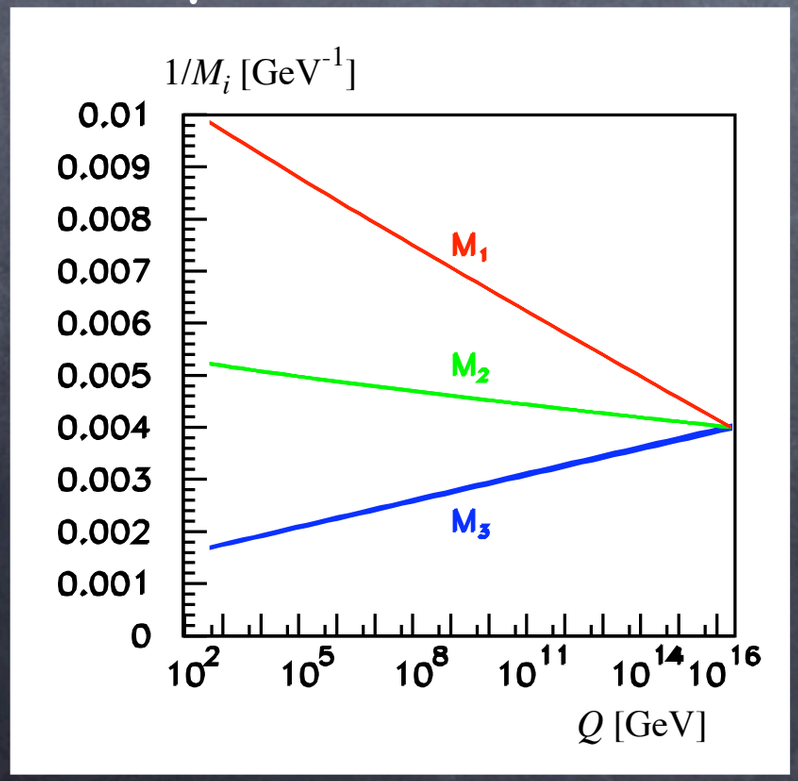
- Discovery at Tevatron Run II and/or LHC
- Test they are really superpartners
  - Spins differ by 1/2
  - Same $SU(3)\times SU(2)\times U(1)$ quantum numbers
  - Supersymmetric couplings

Spin 0?

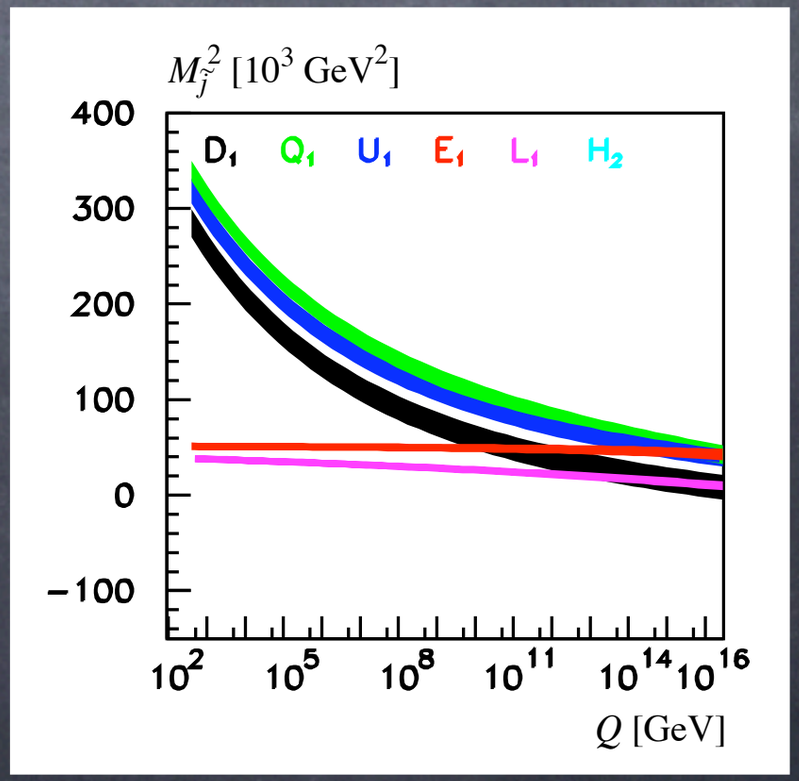


Gaugino and scalars

- Gaugino masses test unification indep. of intermediate scales and/or extra multiplets



- Scalar masses test beta functions at all scales, depend on the particle content (Kawamura, HM, Yamaguchi)



Particle Dark Matter

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

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

- TeV the correct energy scale
- We hope to produce DM directly at colliders

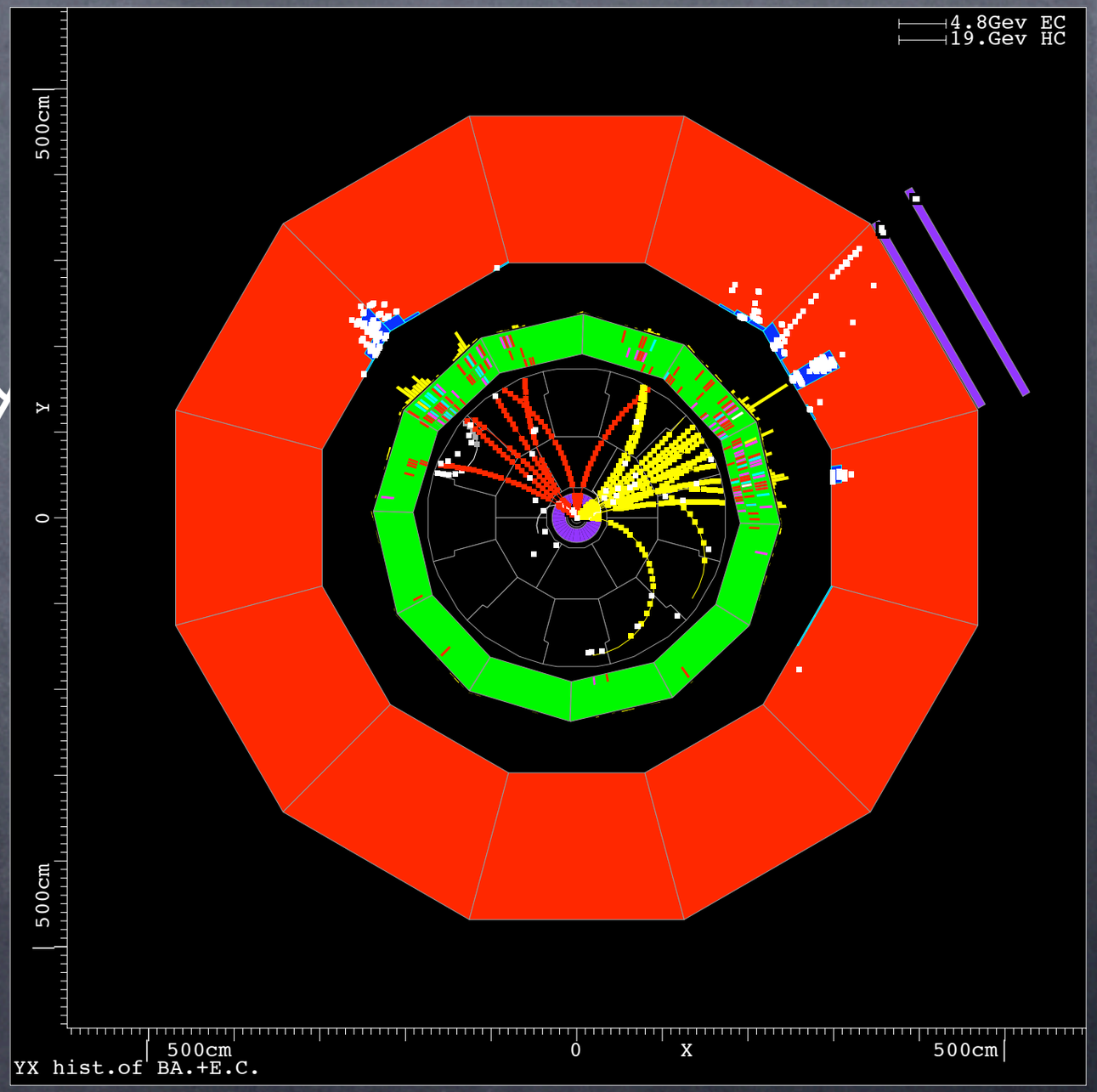
Producing Dark Matter in the laboratory

- Collision of high-energy particles mimic Big Bang
- We hope to create Dark Matter particles in the laboratory
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

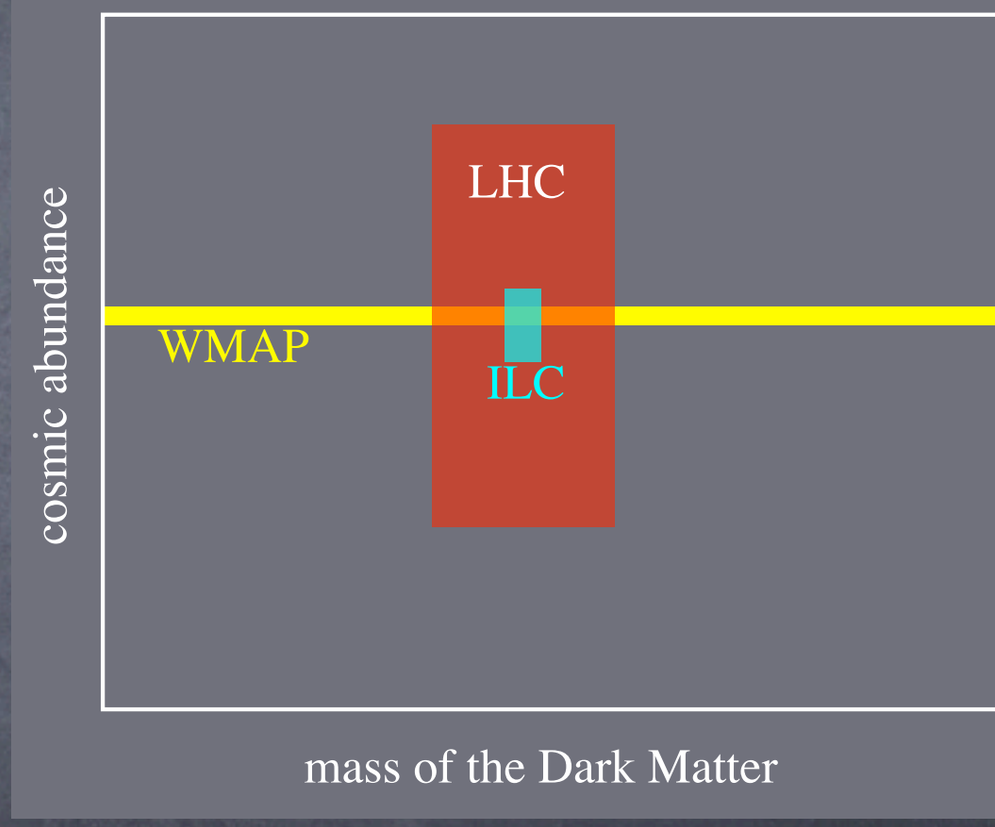
- Something is escaping the detector
- electrically neutral, weakly interacting

⇒Dark Matter!?



How do we know what Dark Matter *is*?

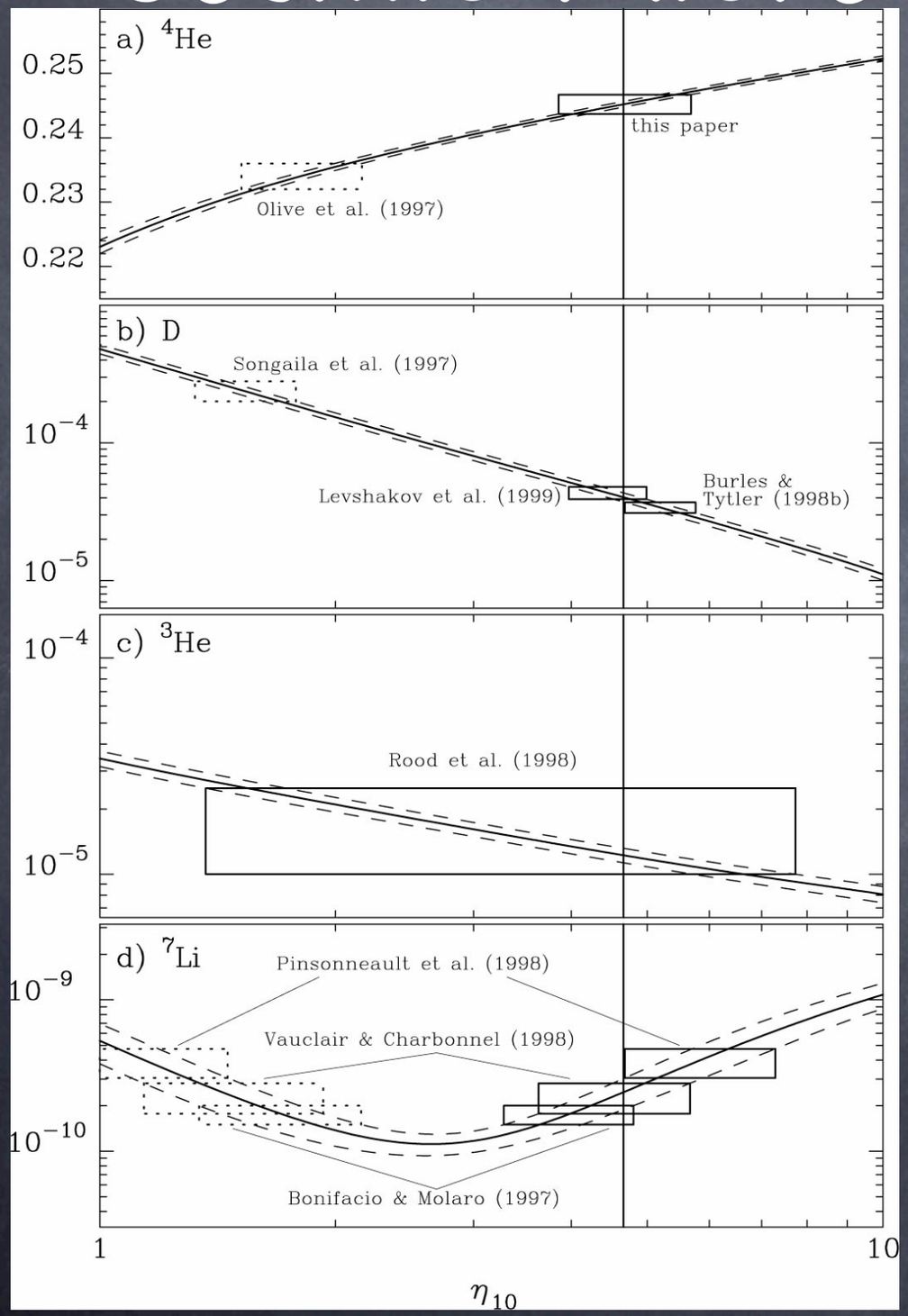
- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:



$\Rightarrow$ Will know what Dark Matter is

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

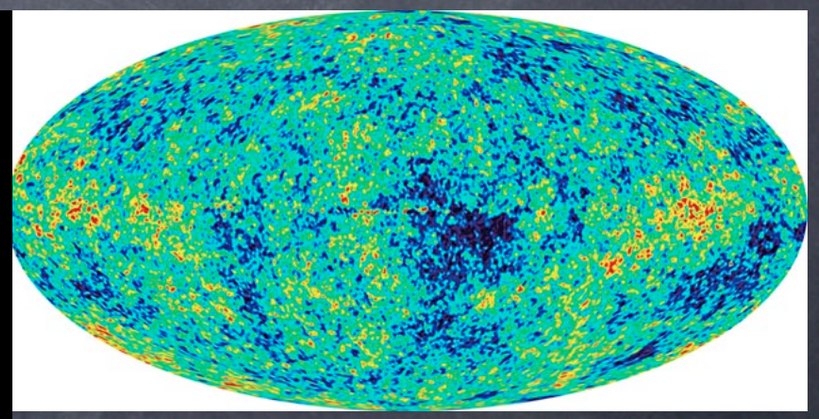
Big-Bang Nucleosynthesis
Cosmic Microwave Background

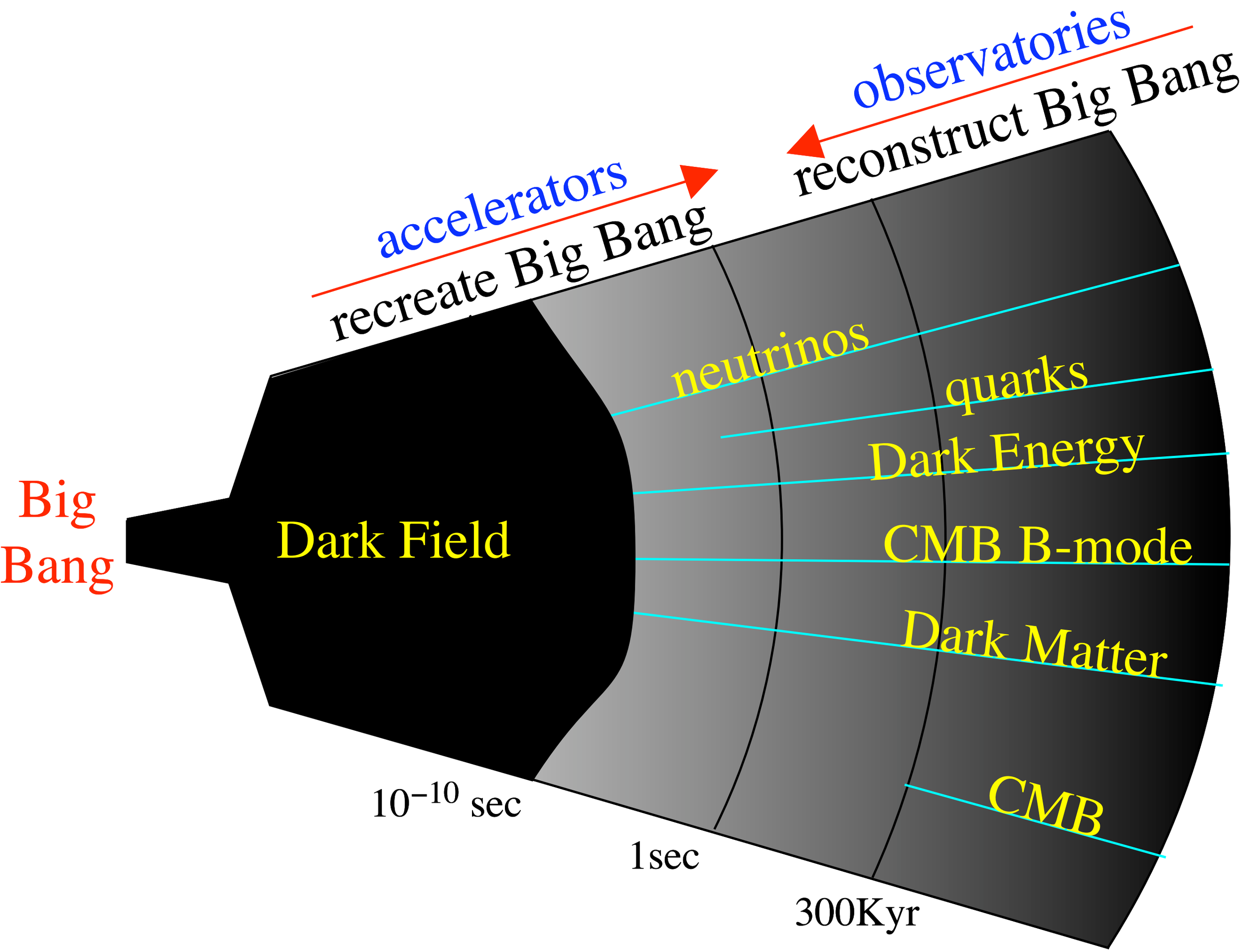


$$\eta = \frac{n_B}{n_\gamma} = \left(4.7^{+1.0}_{-0.8}\right) \times 10^{-10}$$ (Thuan, Izatov)

$$(5.0 \pm 0.5) \times 10^{-10}$$ (Burles, Nollett, Turner)

WMAP $(6.5^{+0.4}_{-0.3}) \times 10^{-10}$




accelerators
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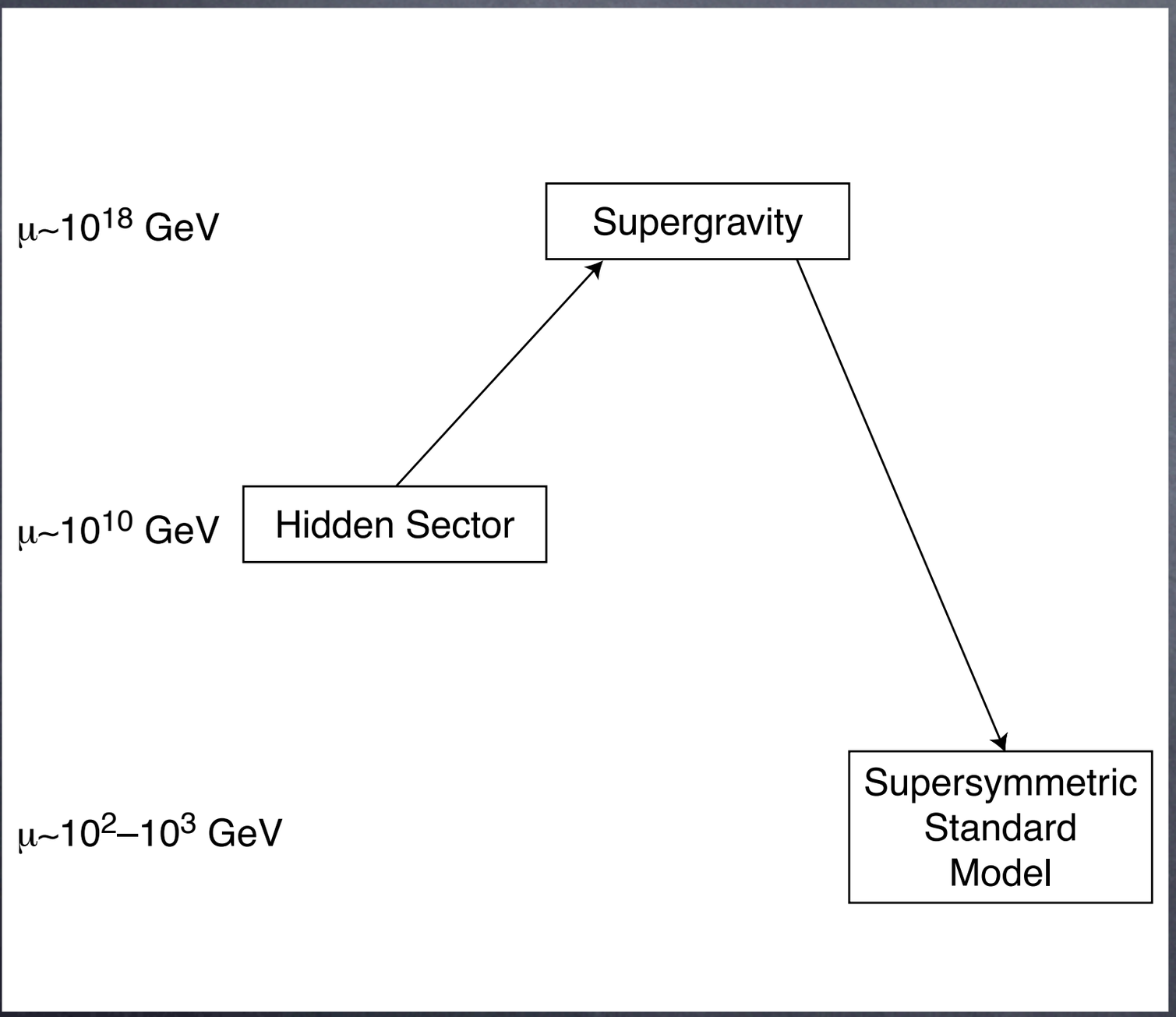
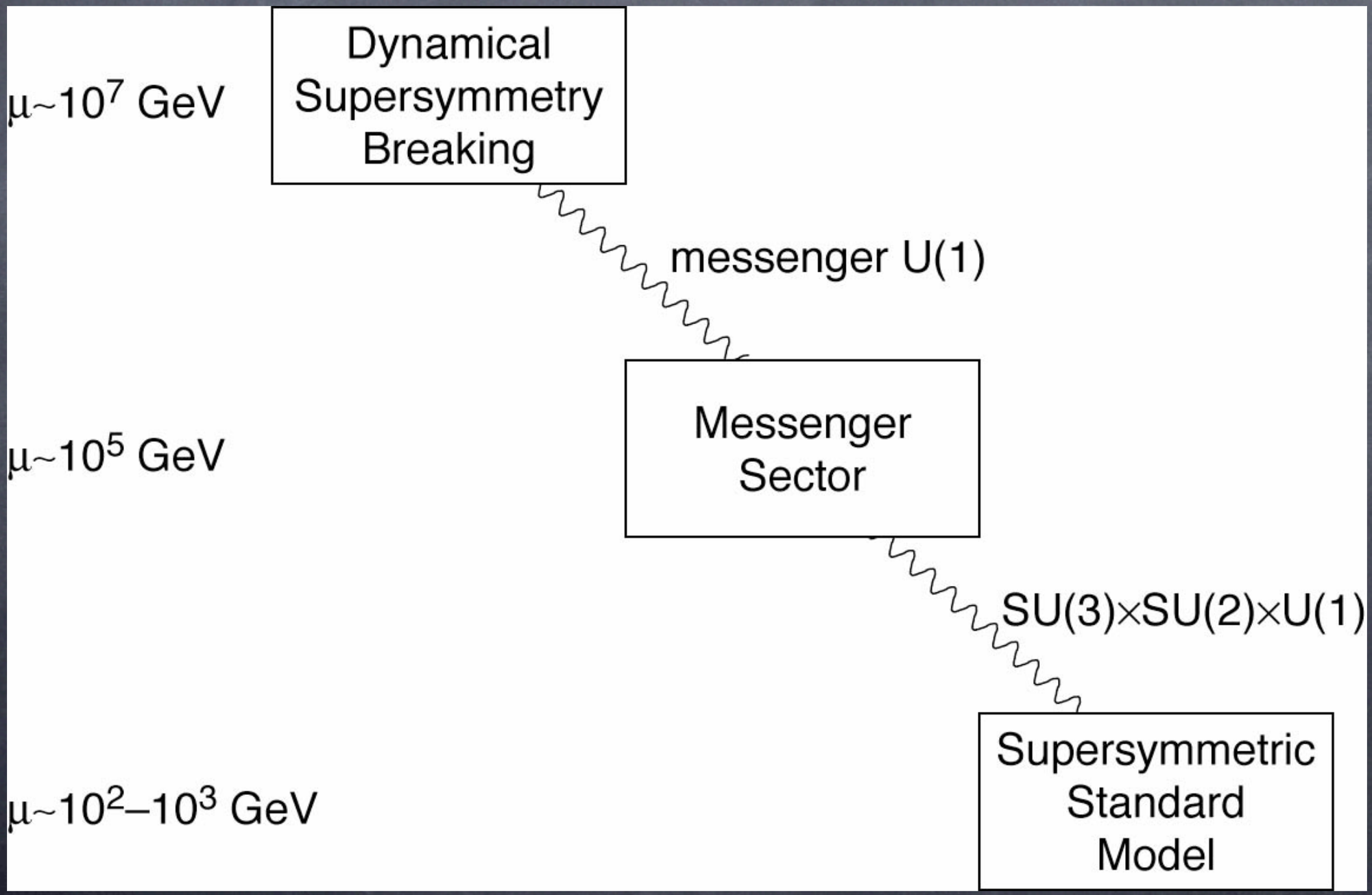
Some Information

Gravity Mediation

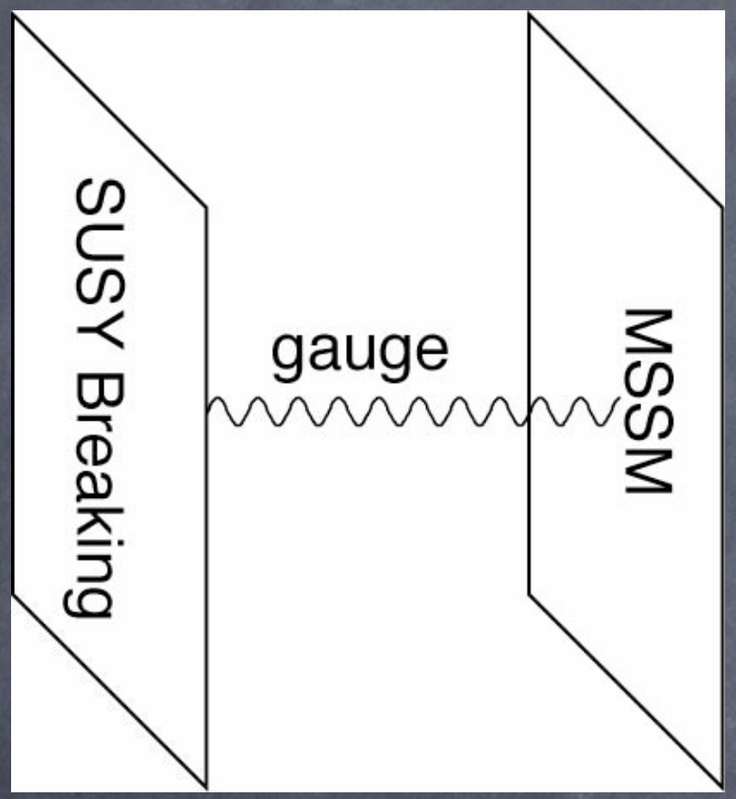


- Not really gravity, but rather gravity-scale mediation

Gauge Mediation (GMSB)



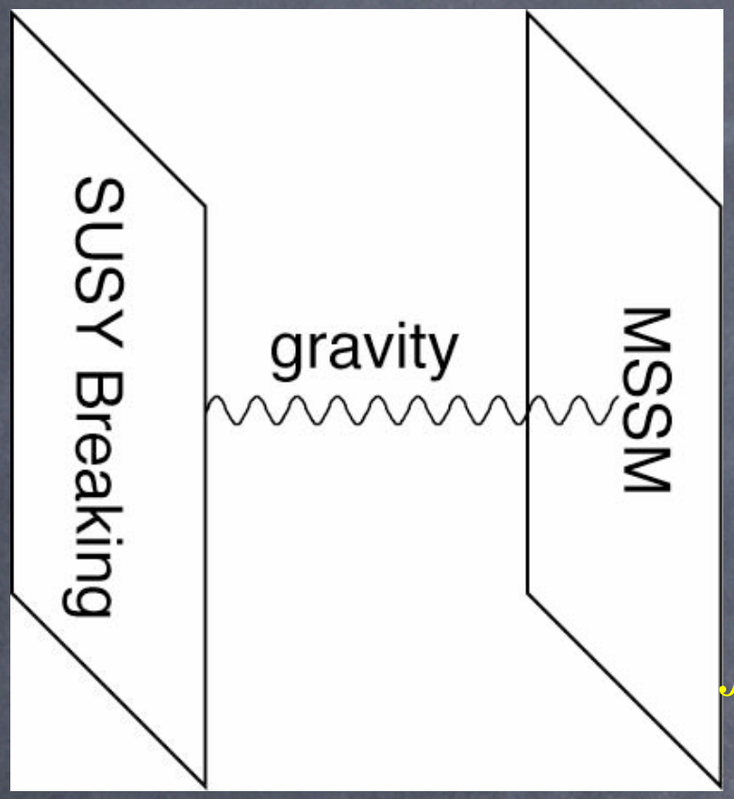
Gaugino Mediation (χMSB)



- DSB in another brane
- Gauge multiplet in the bulk
- Gauge multiplet learns SUSY breaking first, obtains gaugino mass
- MSSM at the compactification scale with gaugino mass only
- Scalar masses generated by RGE

Kaplan, Kribs, Schmaltz
Chacko, Luty, Nelson, Ponton

Anomaly Mediation (AMSB)



Randall, Sundrum
Giudice, Luty, HM, Rattazzi

- no direct coupling between two sectors
- Supersymmetry breaking in the chiral compensator $\langle S\rangle = 1 + \theta^2 m_{3/2}$

$$\int d^4\theta S\bar{S}\phi^*\phi + \int d^2\left(S^3\lambda_{ijk}\phi_i\phi_j\phi_k + \frac{1}{g^2}W_\alpha W^\alpha\right)$$

- can be scaled away $\phi \to \phi/S$
- but the UV cutoff acquires S: $\Lambda_{UV} \to \Lambda_{UV} S$
- SUSY breaking through cutoff dependence: superconformal anomaly

SUSY spectra