IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Present and Future of High Energy Physics

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BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Accelerators and Particle Physics

- *accelerators have been the enabling technology for particle physics*
- *non-accelerator experiments are becoming more important partly because of price tags*
- *However, I expect & hope that accelerator-based HEP remains main drivers in the foreseeable future*

non-accelerator physics

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- *dark matter: LHC & ILC?*

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- K2K/MINOS *confirmation of neutrino oscillation*

Outline

- *Introduction*
- *Energy Frontier*
  - *Firm and established needs for TeV*
  - *less firm but exciting needs for beyond*
- *Intensity Frontier*
  - *needs for intense neutrinos*
  - *high precision flavor physics*

Energy Frontier

New Era

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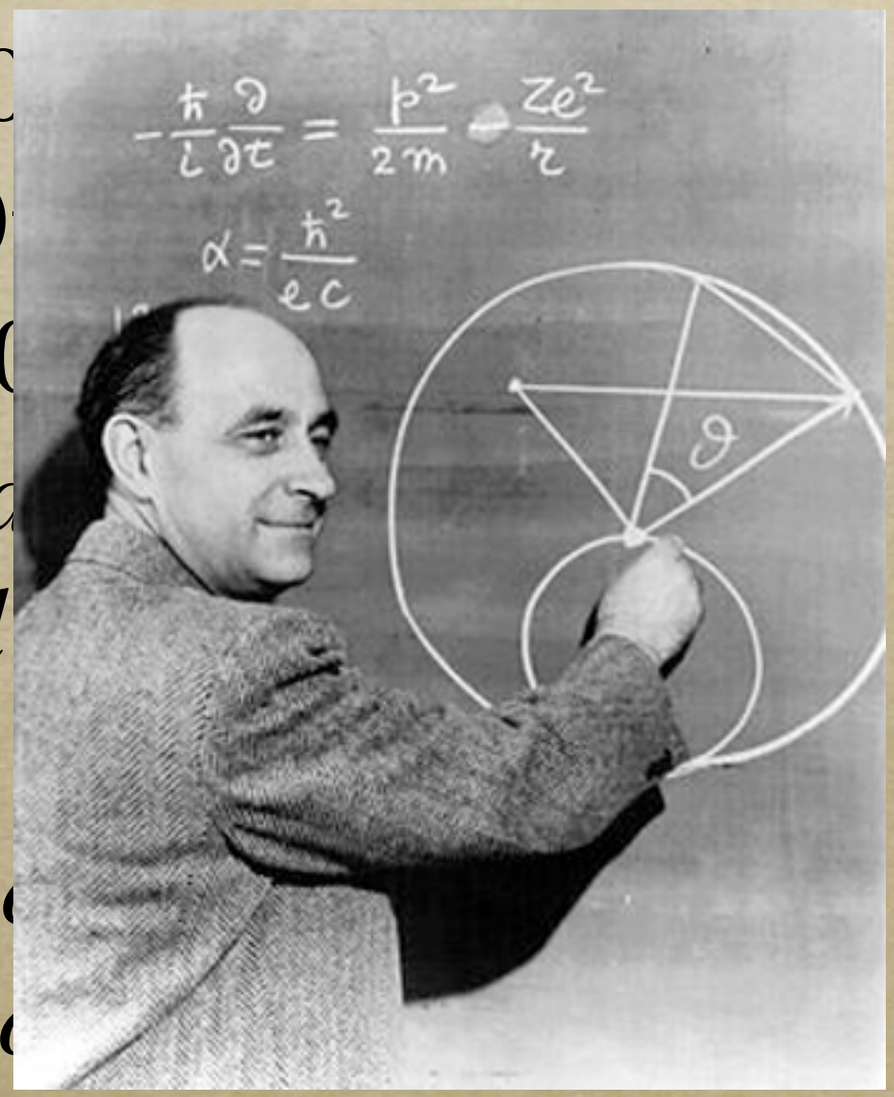
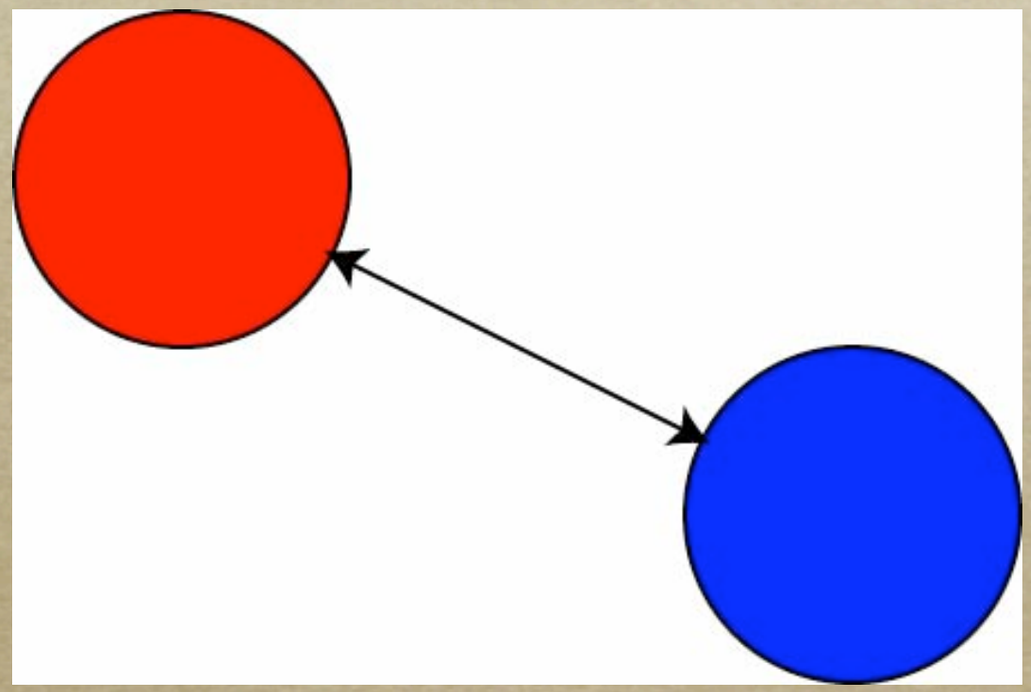


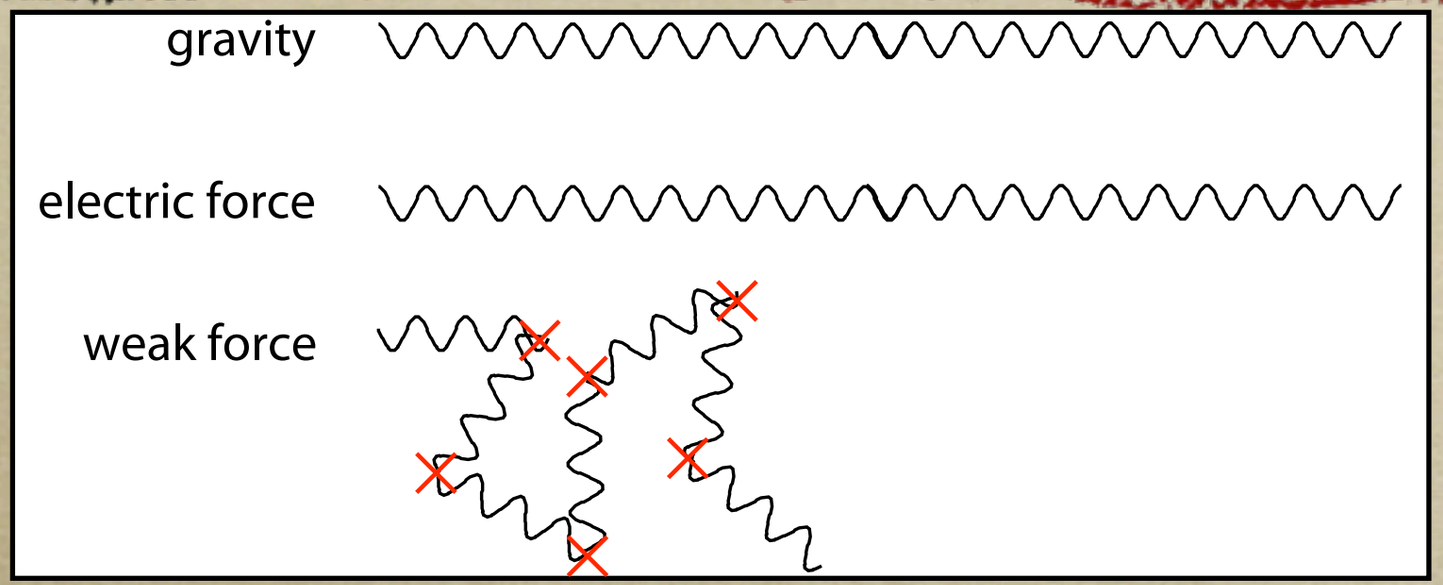
TeV

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* 10^{-16} cm [need it for the Sun to burn!]



Something is in the Universe



- *There is something filling our Universe*
- *It doesn't disturb gravity or electric force*
- *It does disturb weak force and make it short-ranged*
- *In fact, it is the "mother of mass" for all elementary particles*
- *What is it??*

Like a superconductor

- *In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"*

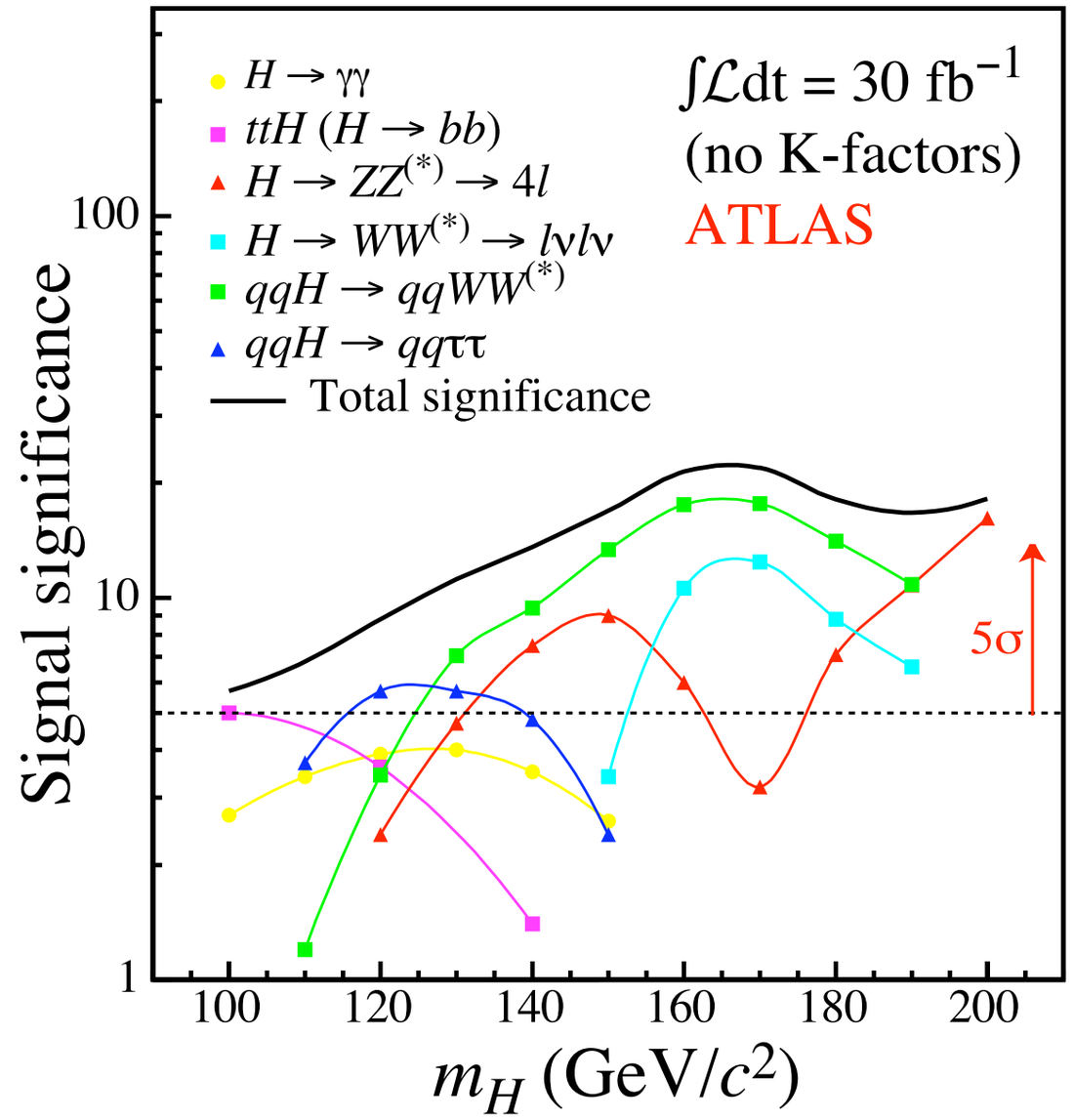
  ⇒ *Magnetic field is short-ranged!*

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

That's the stage where we are!

Large Hadron Collider (LHC): Exploring the TeV-scale

Robust discovery



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- *Is the particle discovered really the Higgs boson?*
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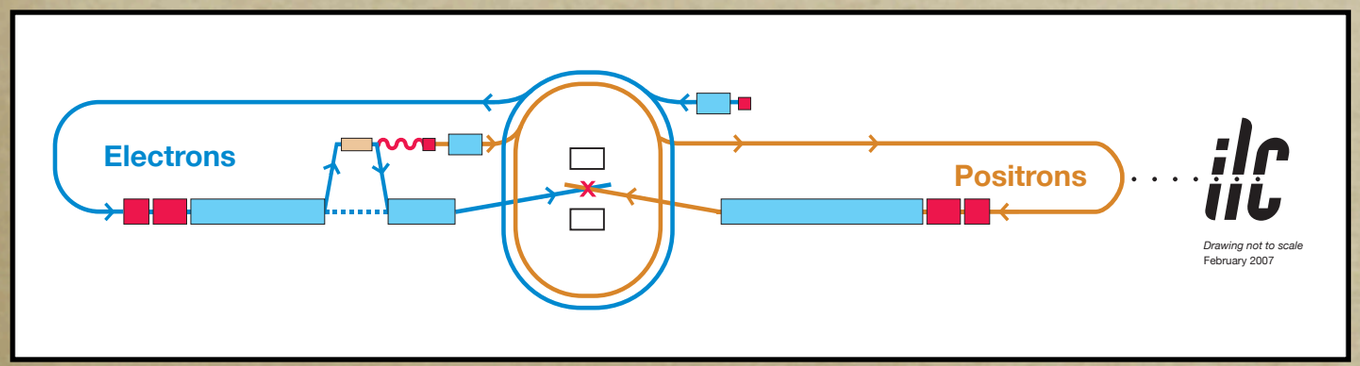
  - *Is it condensed in the Universe?*
- *Prove it is the "Mother of Mass"*
  - *Spin/Parity*
  - *Couplings*
  - *Branching Ratios*
  - *Size of the condensate*

Linear Collider



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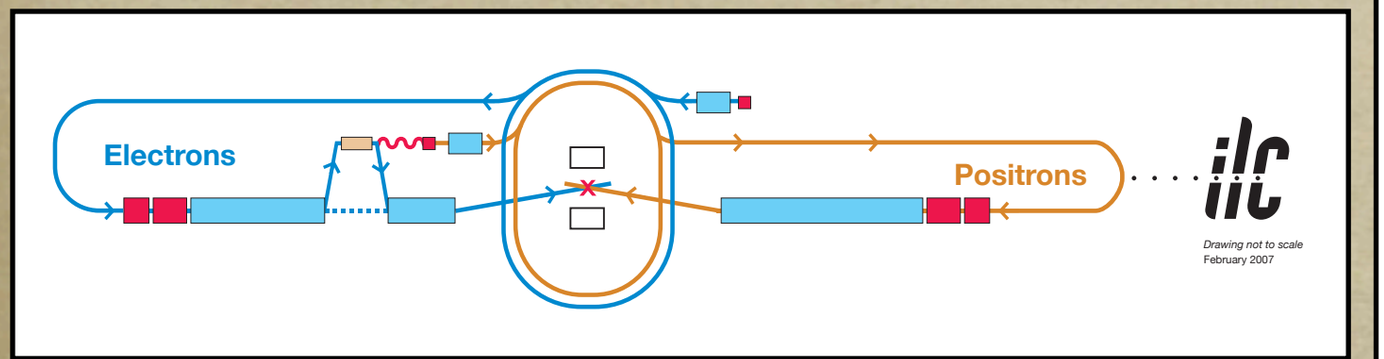

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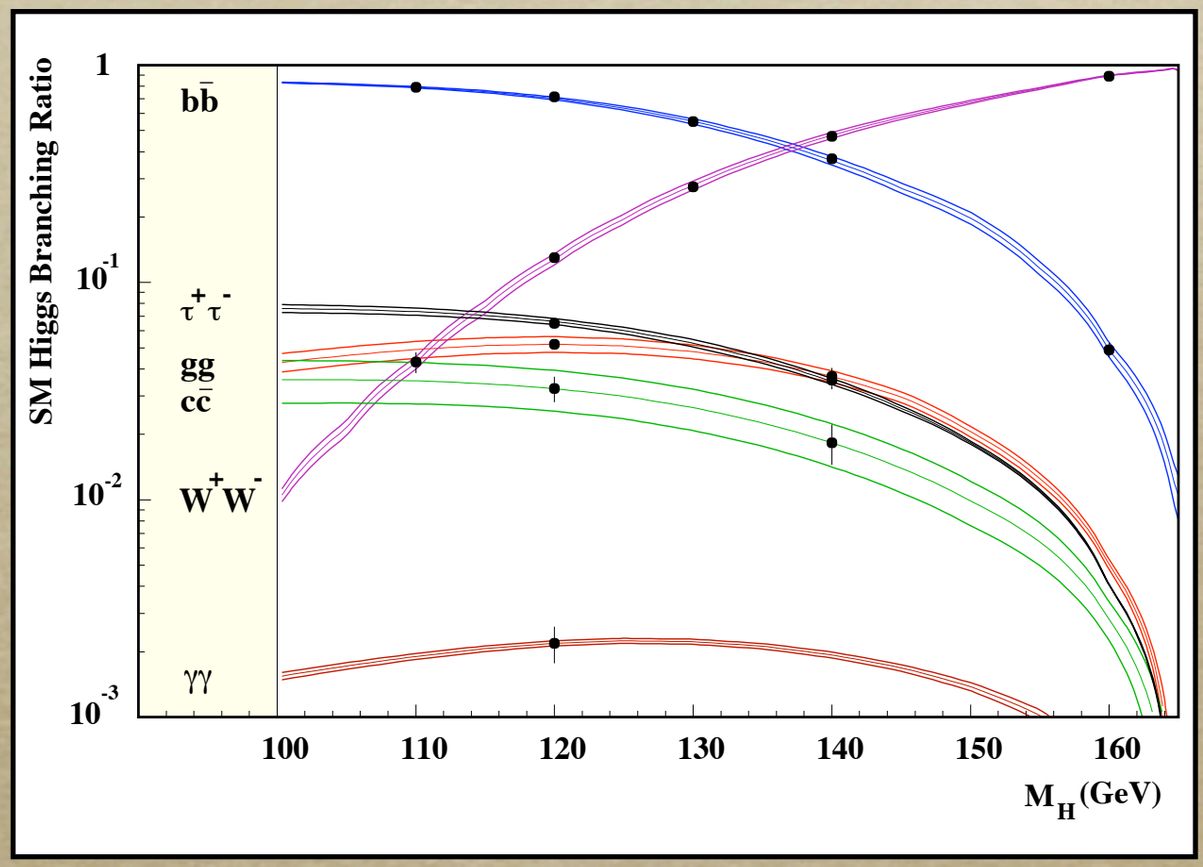


- *Branching Fractions test the relation: coupling ∝ mass*

⇒ *proves that Higgs Boson is the Mother of Mass*

TeV to multi-TeV

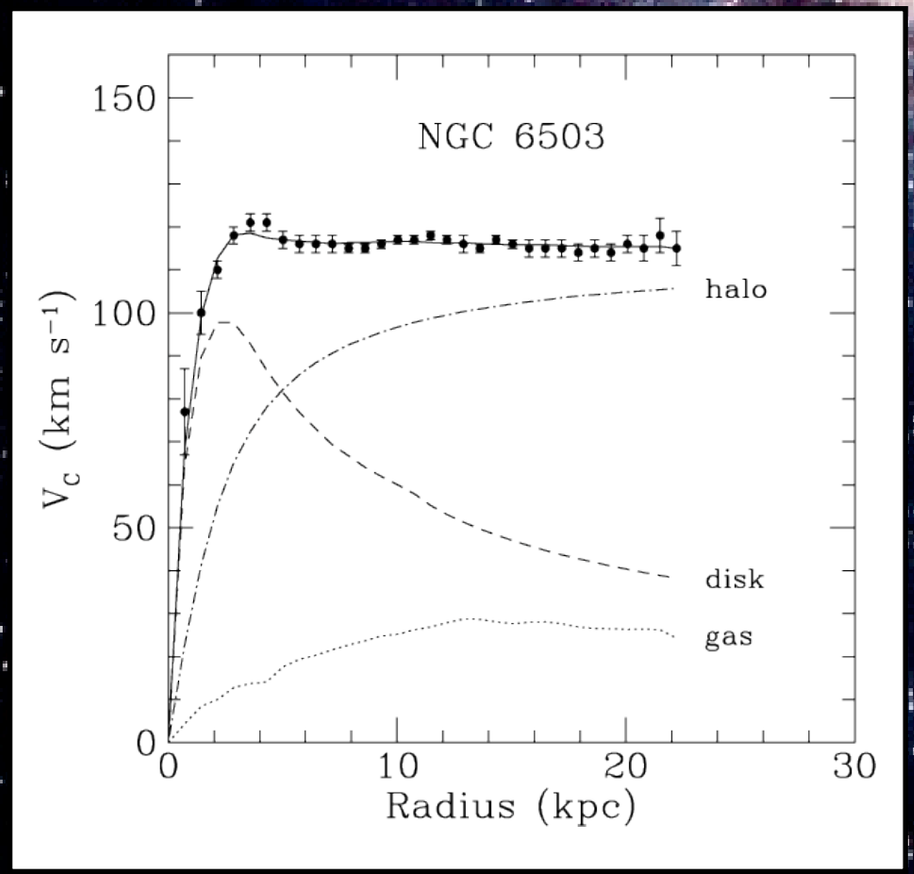
Three reasons beyond Higgs

- *Hierarchy Problem*
- *Dark Matter of the Universe*
- *Physics behind Higgs*

all suggest rich physics at

sub-TeV to multi-TeV

Evidence for Dark Matter



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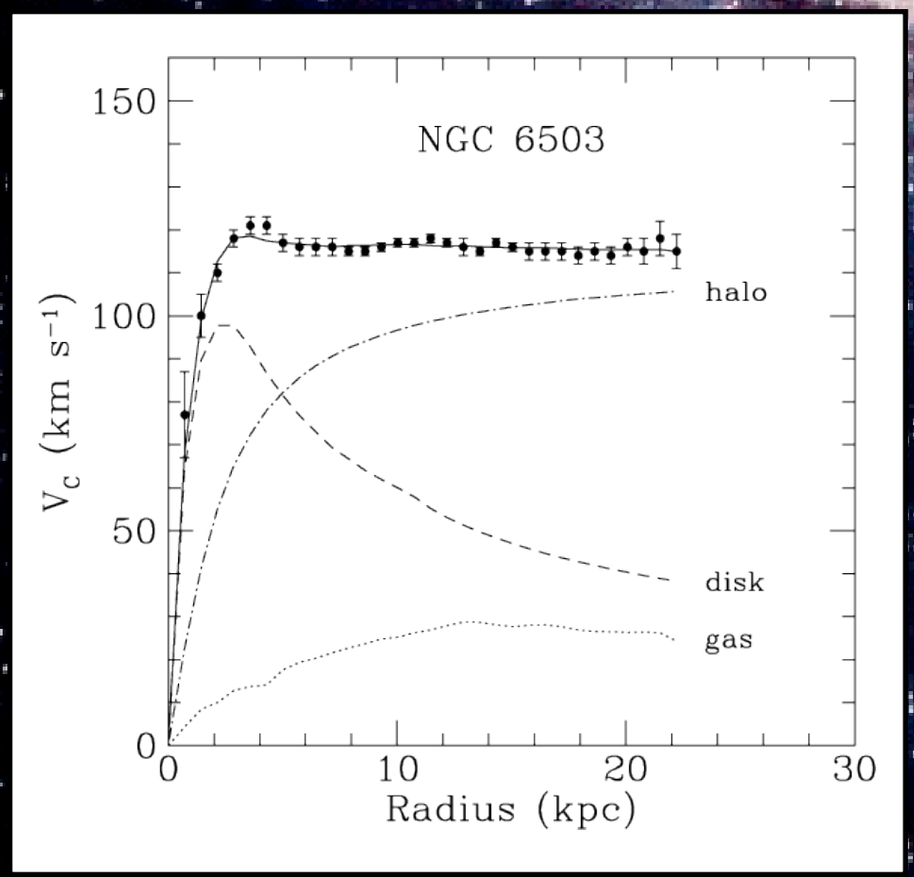


Galaxy is held together by mass far bigger than all stars

Cosmic Microwave Background

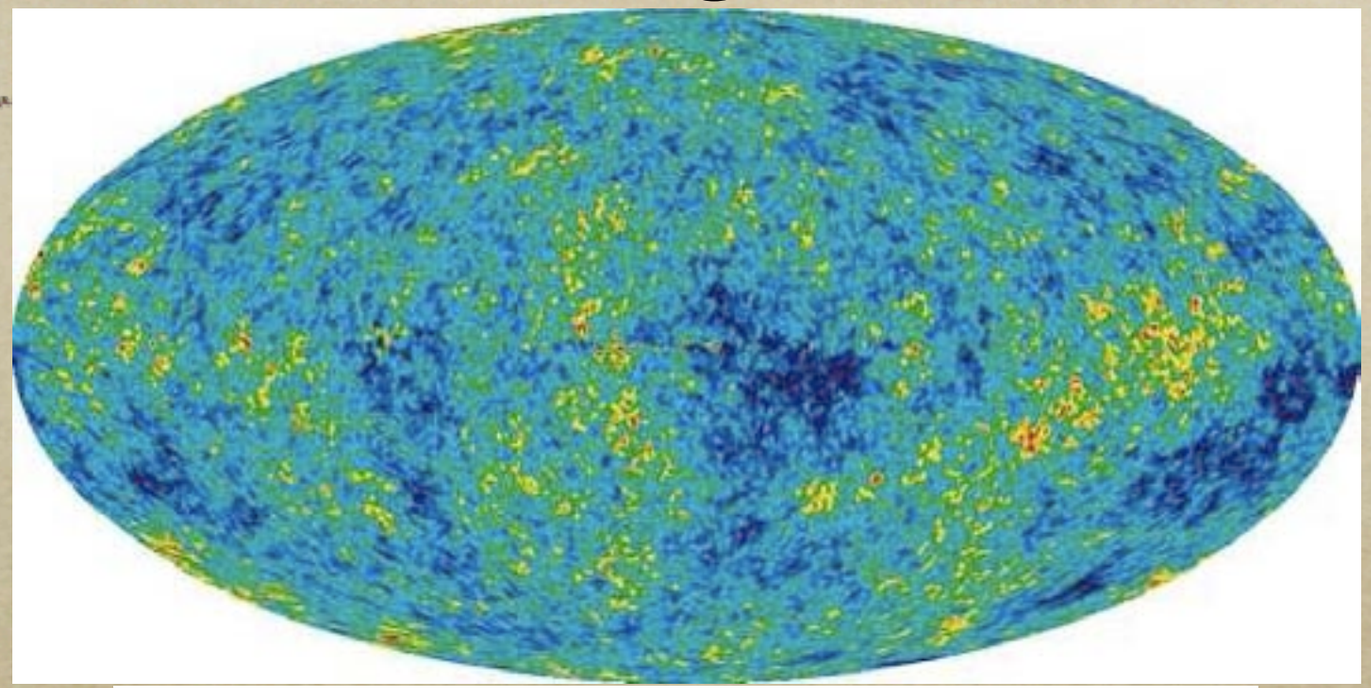
- *WMAP satellite result*

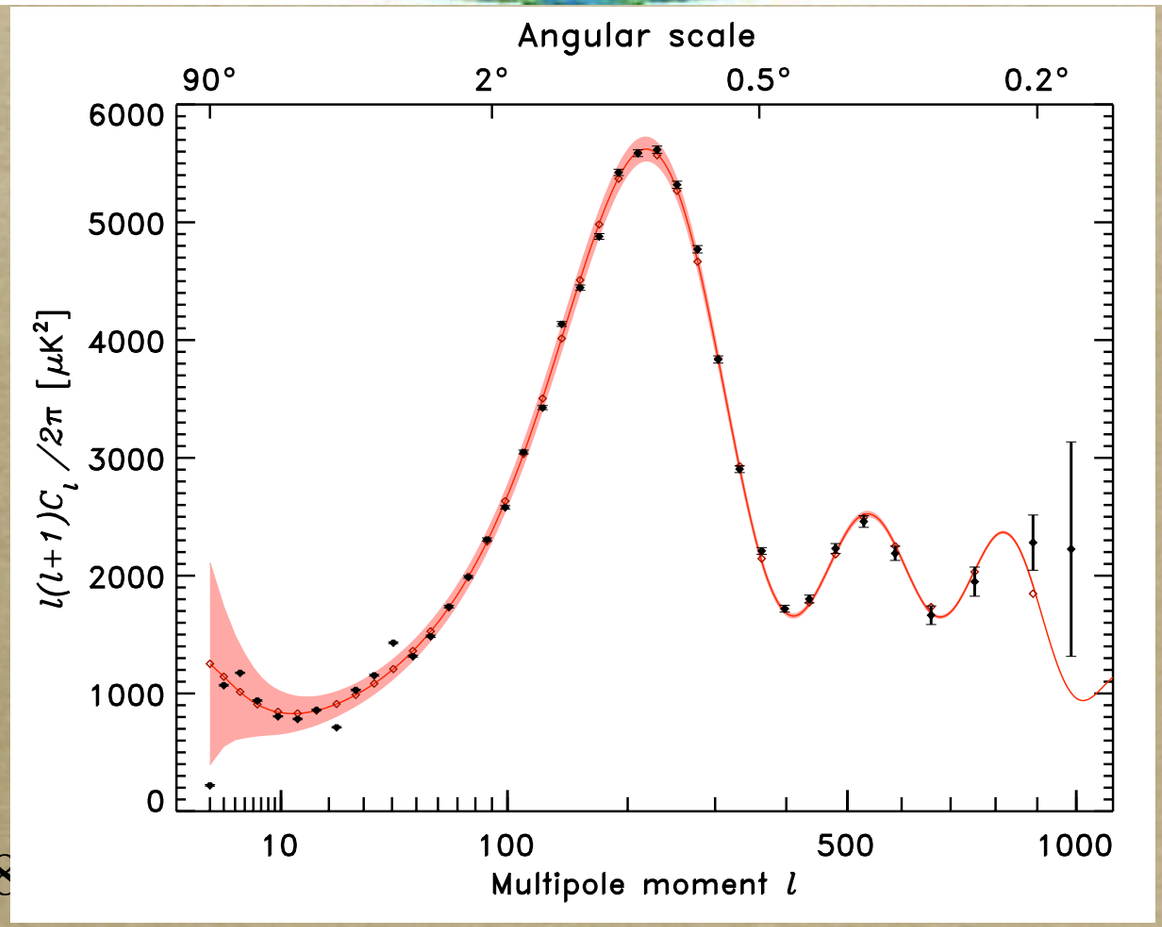
$\Omega_M h^2 = 0.135 \pm 0.009$

$\Omega_b h^2 = 0.0224 \pm 0.0009$

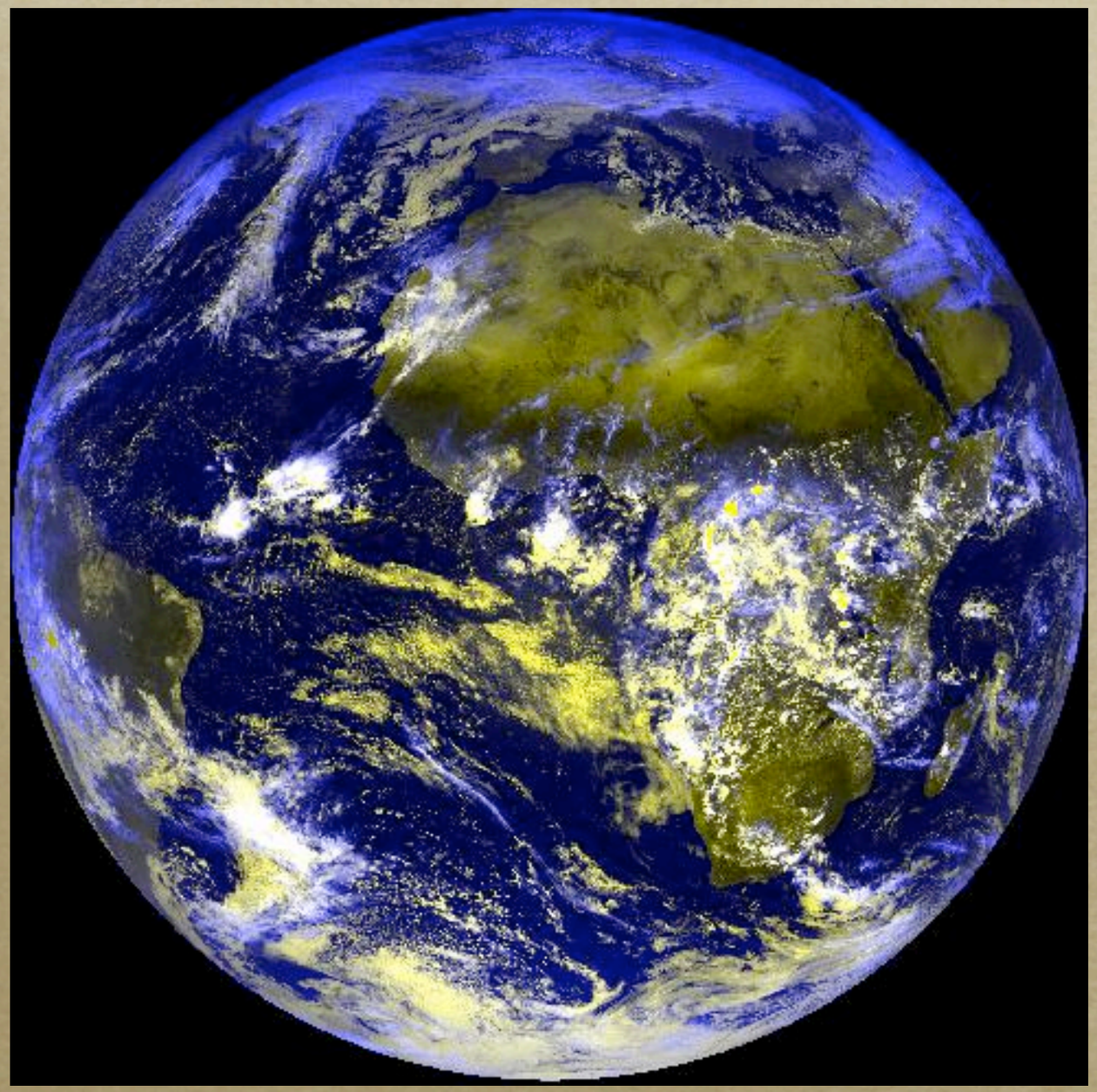
$\Omega_M / \Omega_b = 5.70 + 0.39 - 0.61$

- *dark matter is not atoms!*





WIMP



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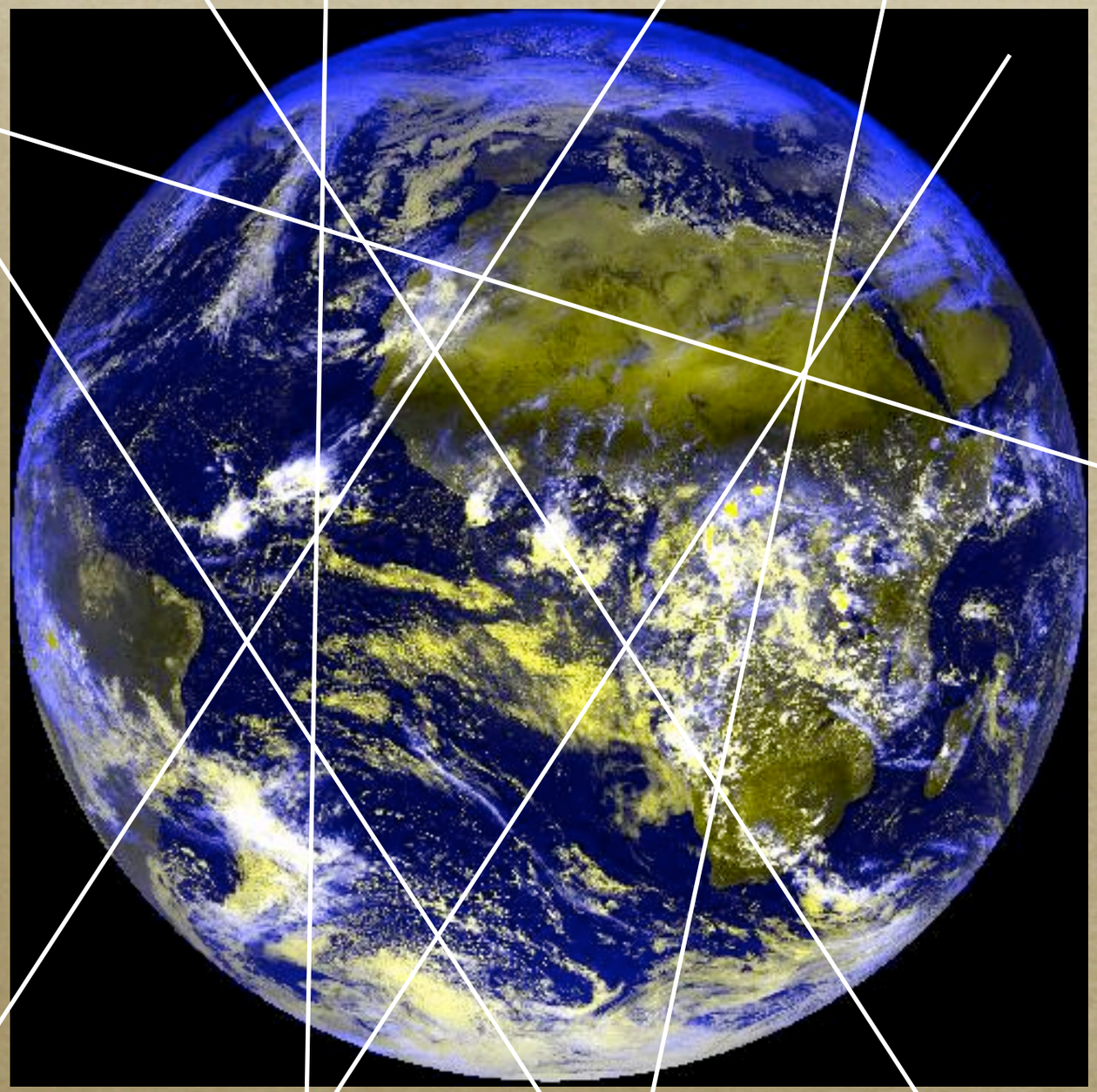

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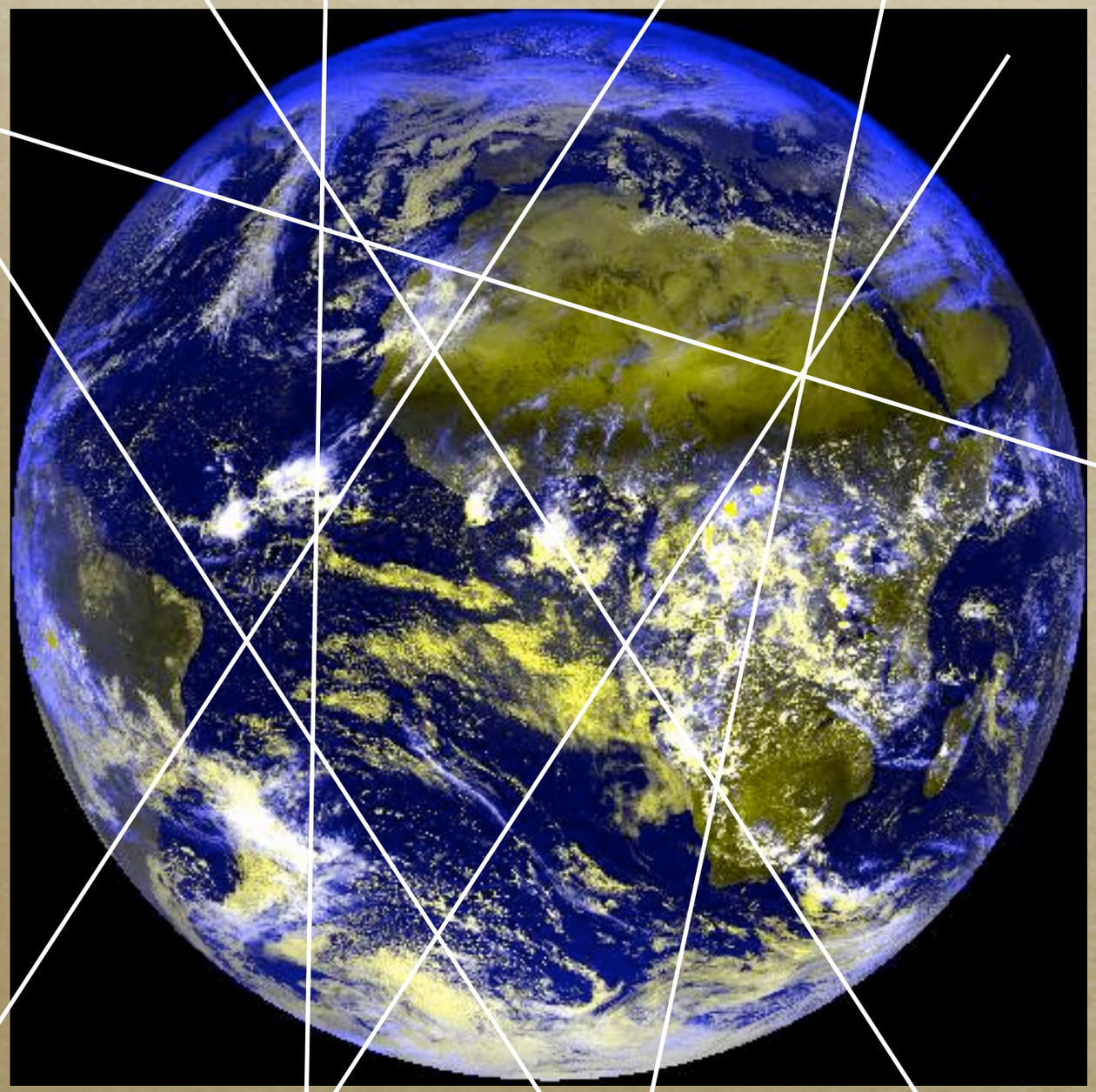

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- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

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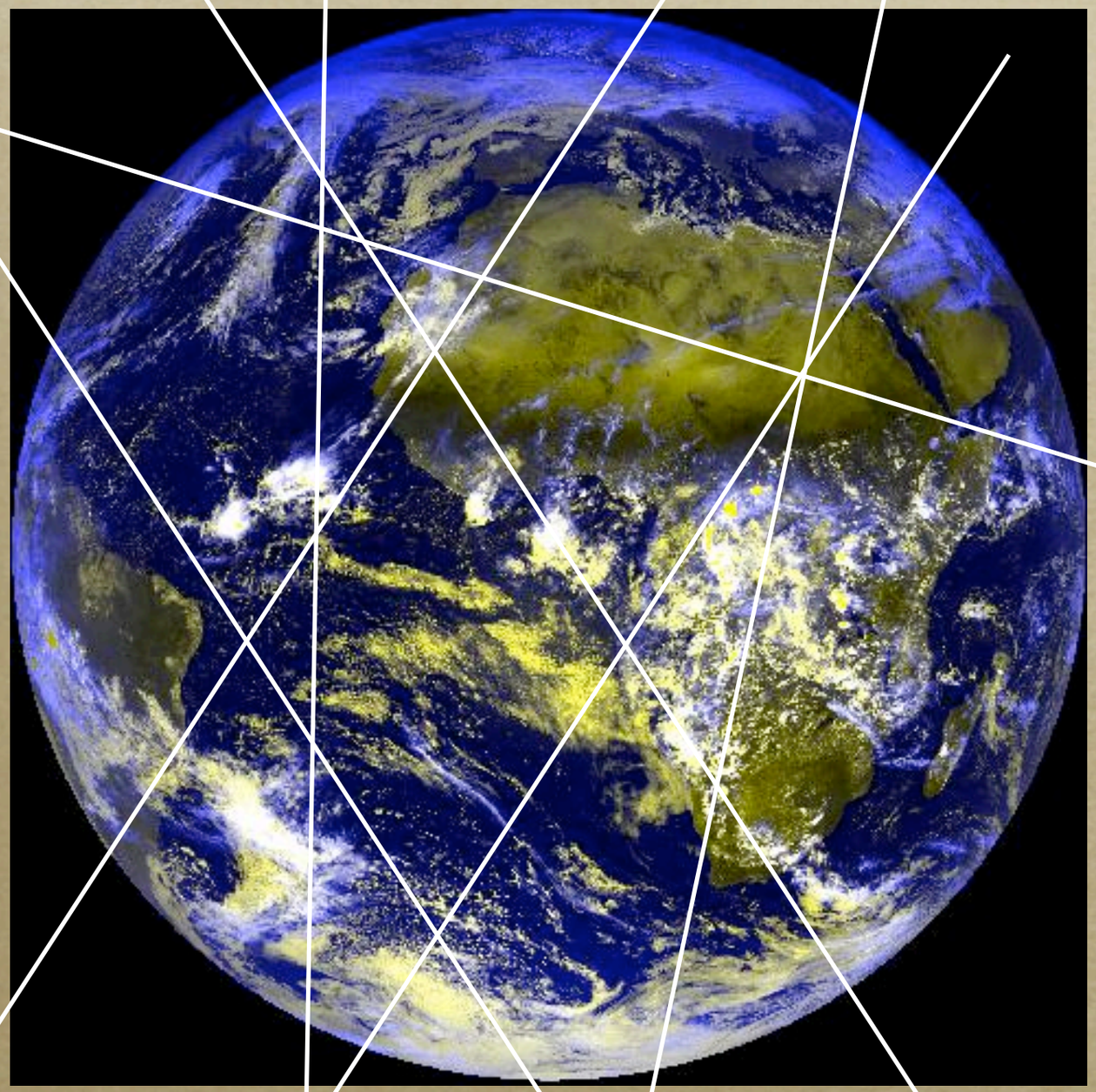

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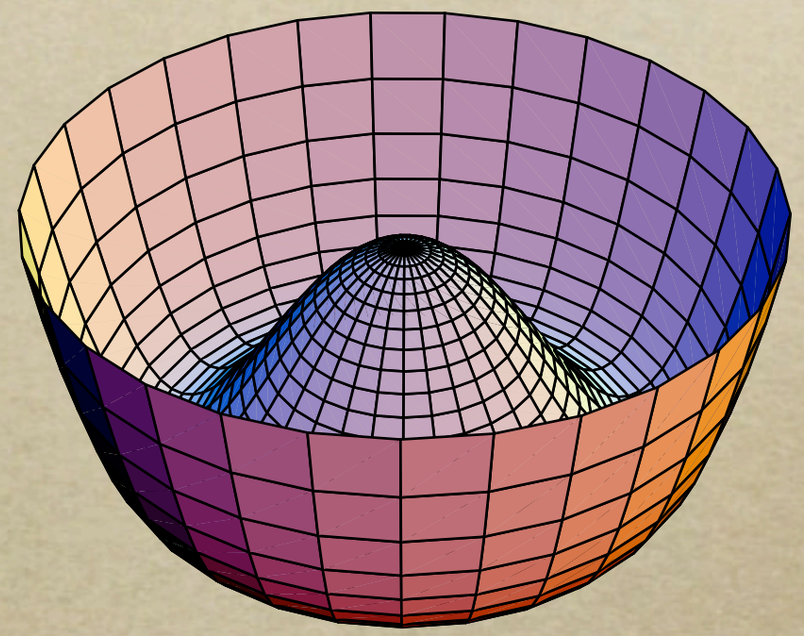
$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

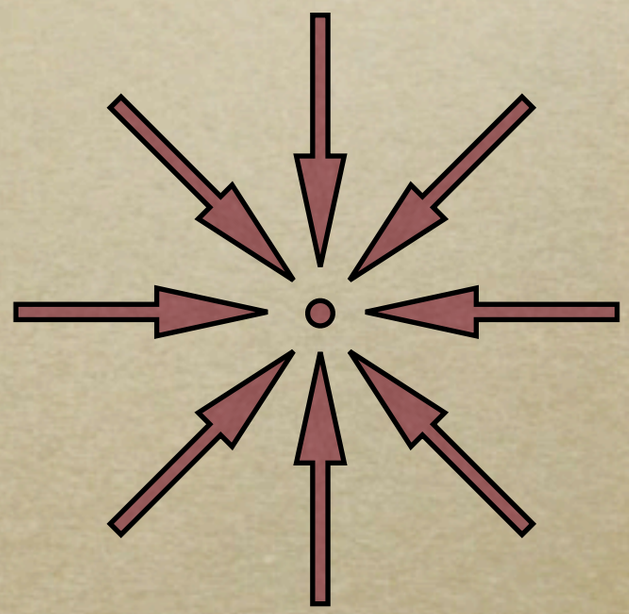
Post-Higgs Problem



- *We see "what" is condensed*
- *But we still don't know "why"*
- From Ginzburg-Landau to BCS theory
- *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*
- *study Higgs properties and interaction in detail!*

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!*



$$\Delta m_e c^2 \sim \frac{\alpha}{r_e} \sim \text{GeV}\,\frac{10^{-17}\,\text{cm}}{r_e}$$

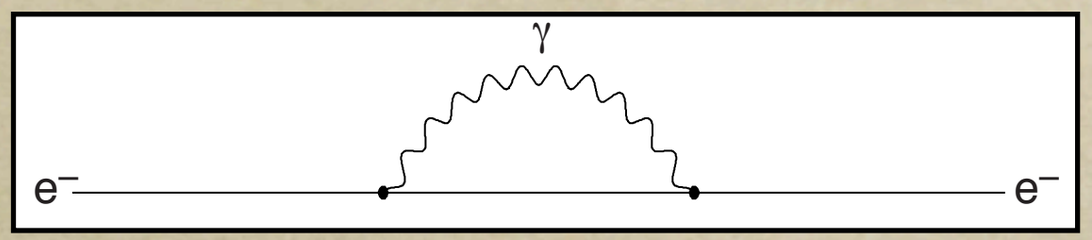
- *Correction* $\Delta m_e c^2 > m_e c^2$ *for* $r_e < 10^{-13}$cm
- *Breakdown of theory of electromagnetism*

$\Rightarrow$ *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*



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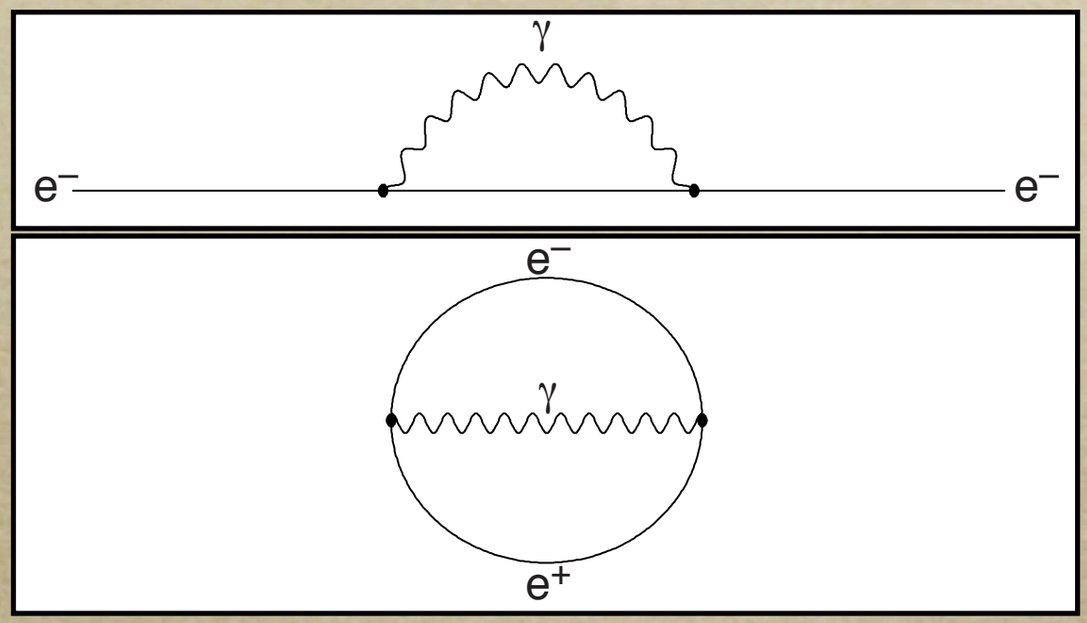

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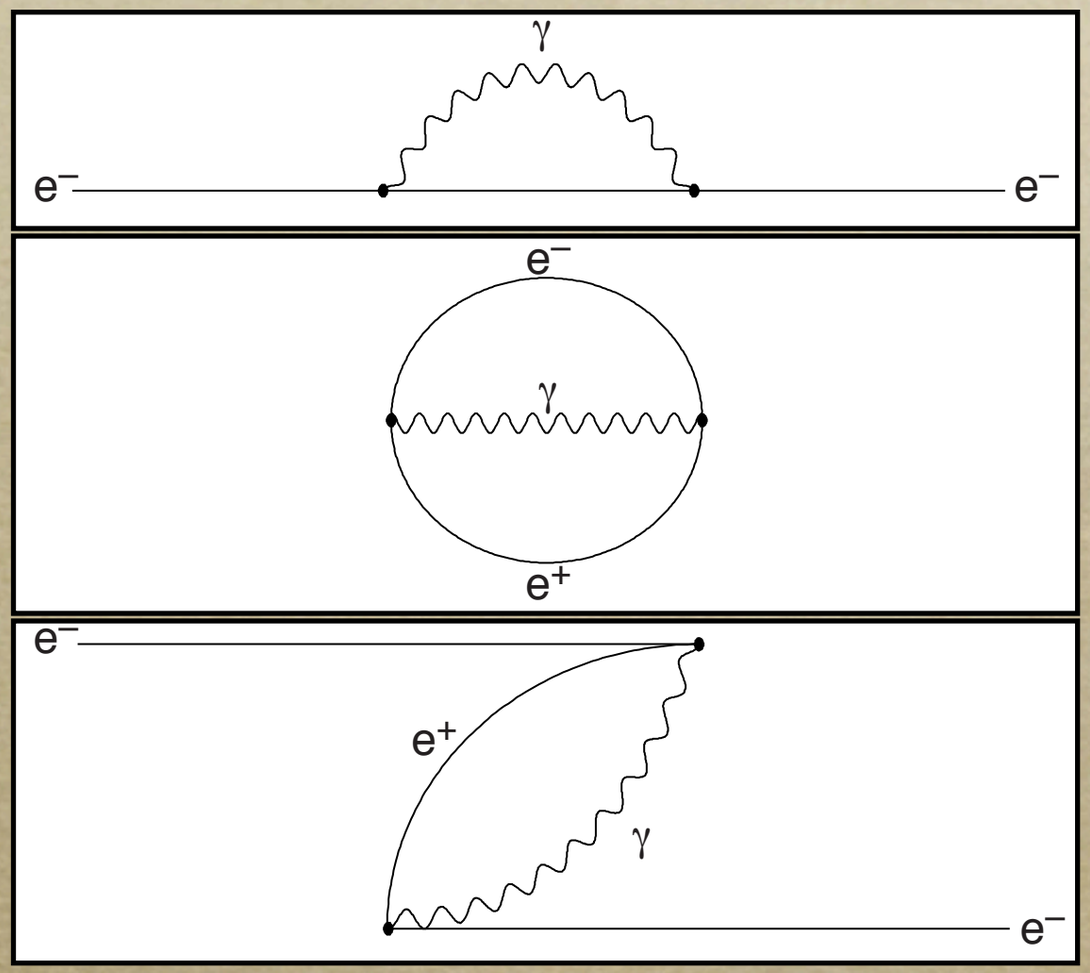

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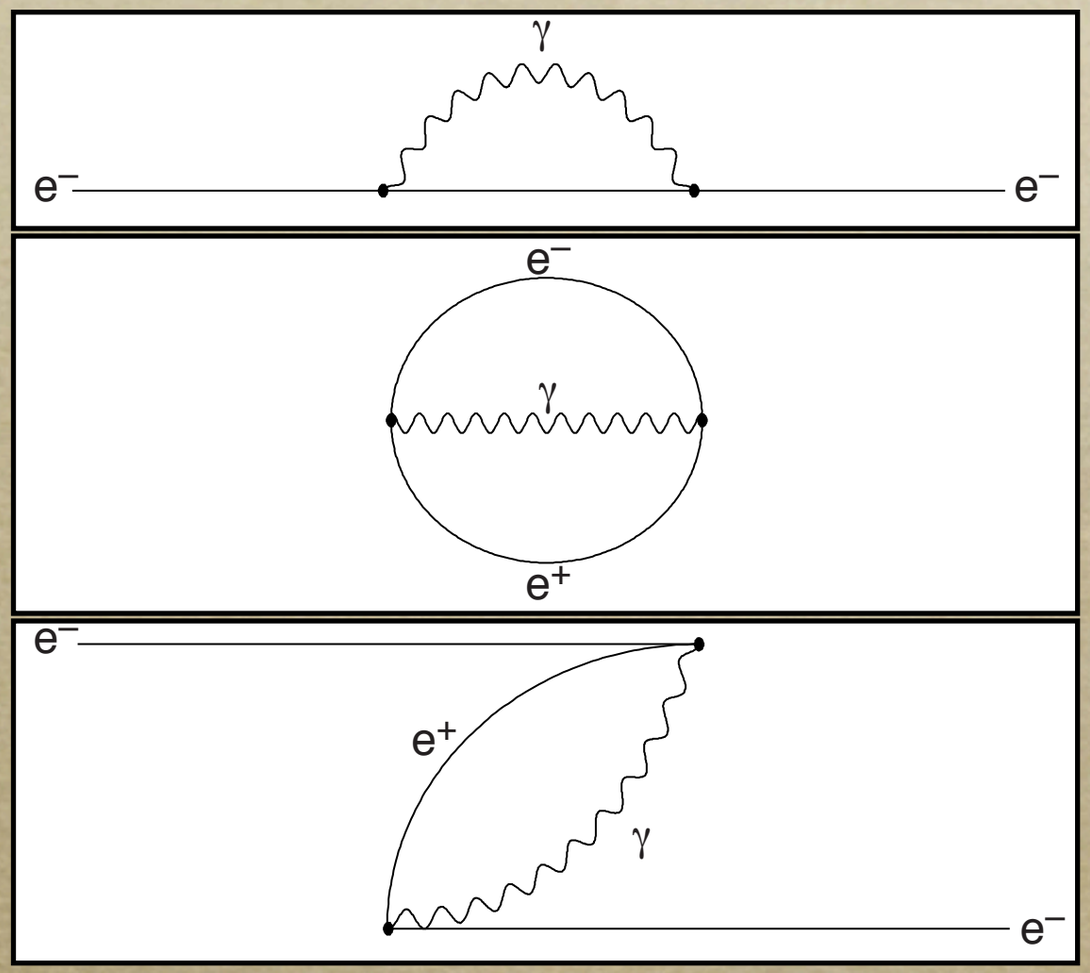
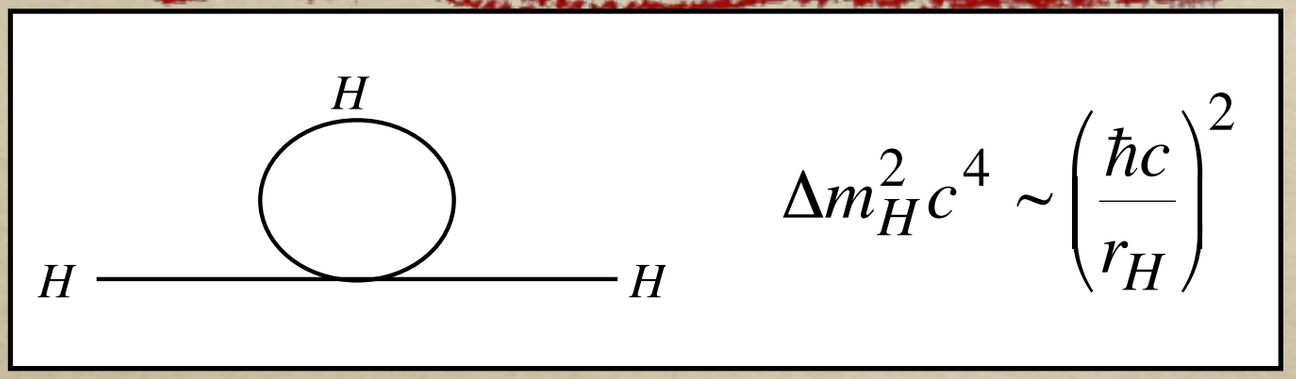
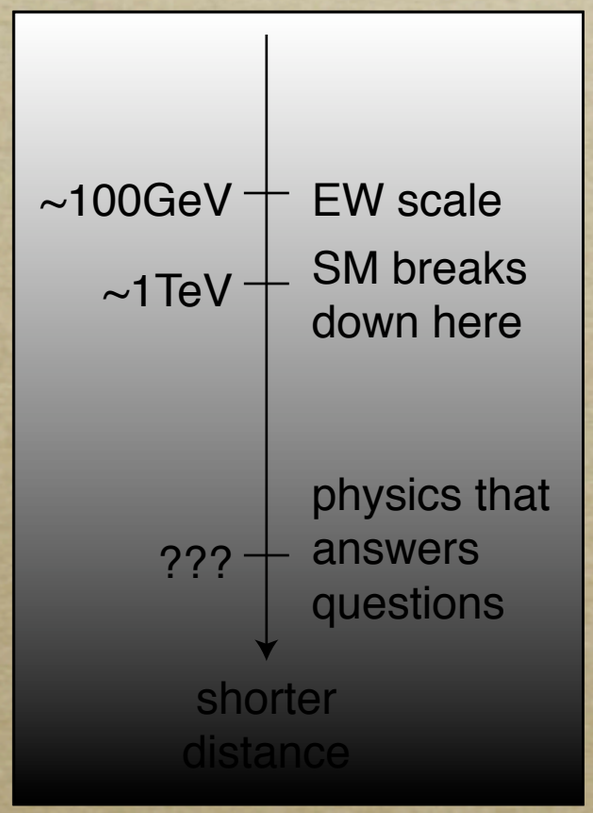


$$\frac{\Delta m_e}{m_e} \sim \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too

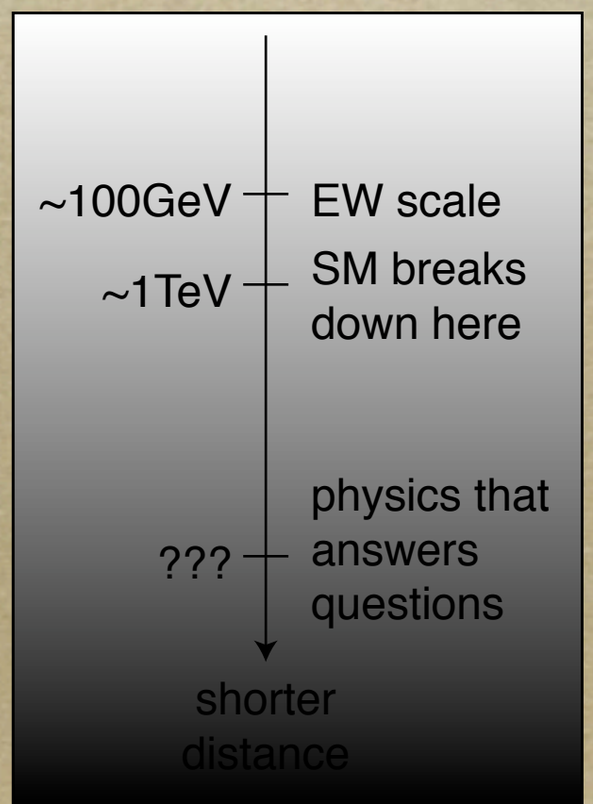
- *Just like electron repelling itself because of its charge, Higgs boson also repels itself*
- *Requires a lot of energy to contain itself in its point-like size!*
- *Breakdown of theory of weak force*
- *Can't even think about short distance physics!*





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*



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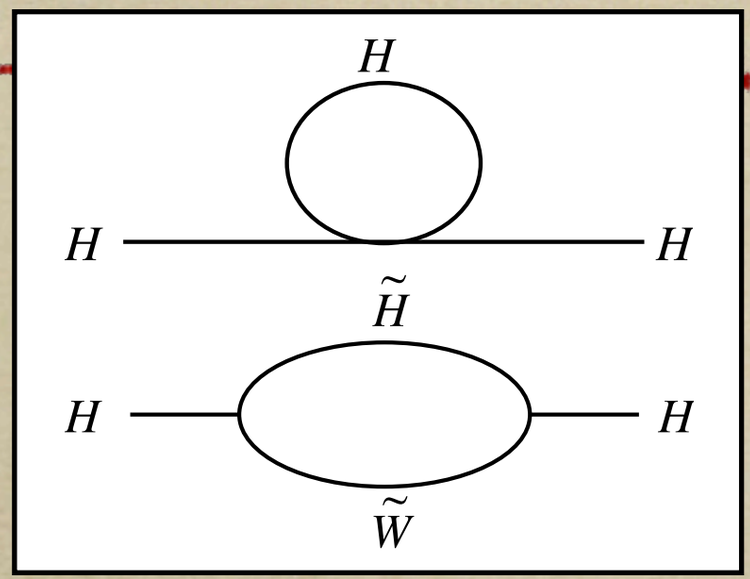

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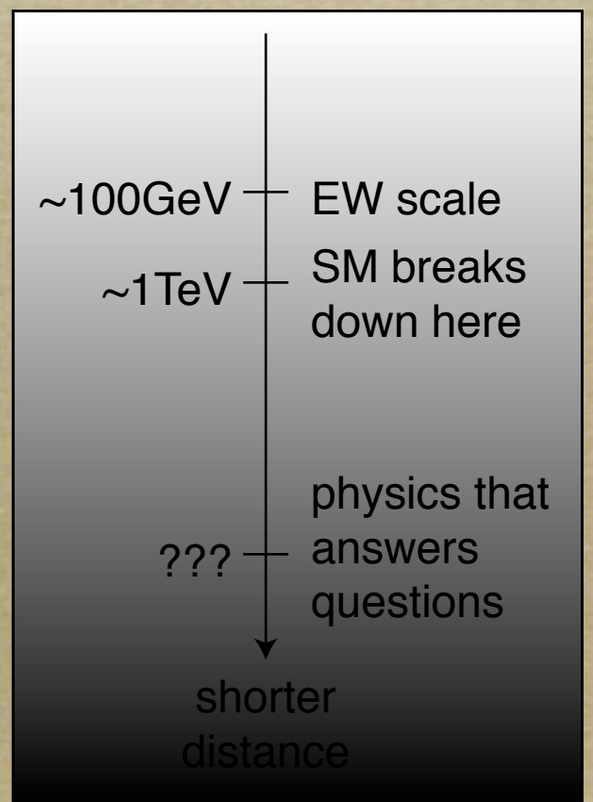

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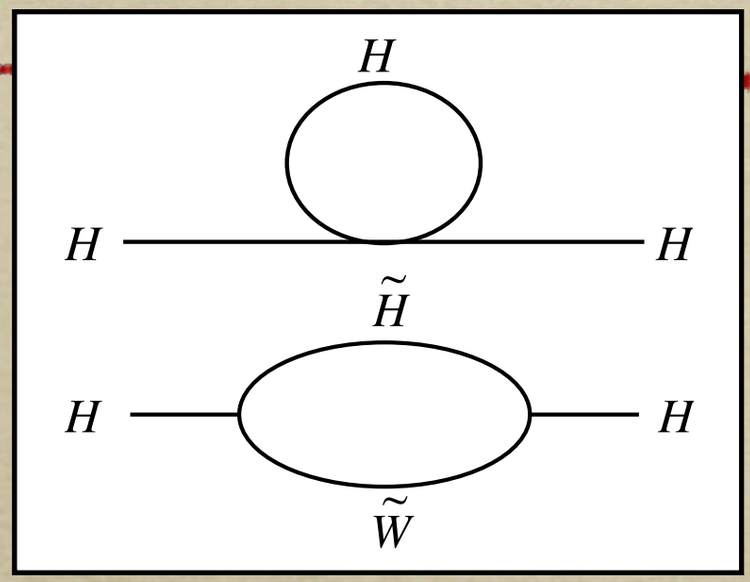

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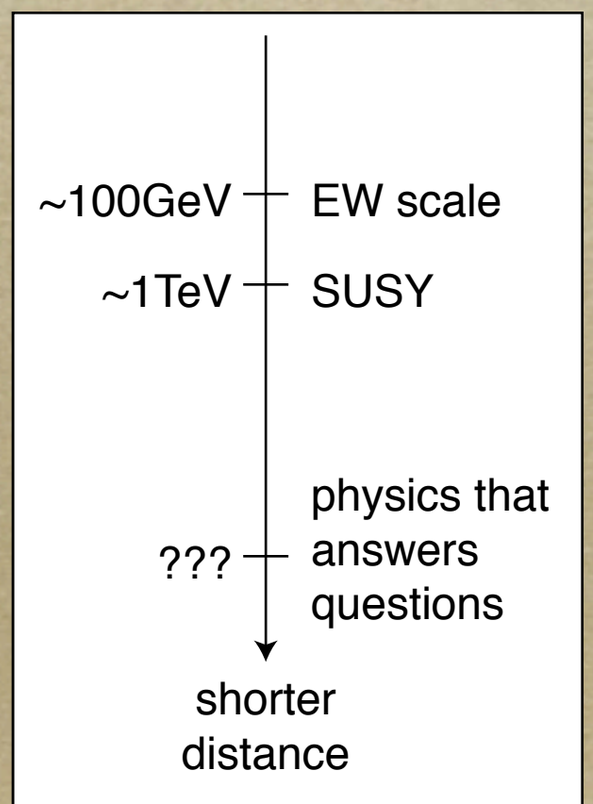

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    ⇒ *technicolor*
- *Physics as we know it ends at* TeV
  - *Ultimate scale of physics: quantum gravity*
  - *May have quantum gravity at* TeV
    ⇒ *hidden dimensions* (0.01 cm *to* 10^{-17} cm)

bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
6th gen
5th gen
4th gen
S,T,U
vector-like family
lepto quark
sterile ν
heavy Majorons
fractionally charged
effective SUSY
SUSY
NMSSM
MSSM +νR
unnified SM
axigluon
W_R
X Y
milli-charged
mono-pole
shadow matter
mirror symmetry
triplet Higgs
doubly charged Higgs
Type I
Type II
general 2HDSM
spontaneous CP
superweak
Majoron
axion
saxion
axino
familon
NGB
Weinberg's 3HD
milli-weak
contact int.
string
hetero tic
matrix
M
IIB
IIA
F
I
N=2
N=4
N=8
quintessence
k-ssence
composite W,Z
worm-hole
Extra dim

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"New-York Times level" confidence

The New York Times

July 23, 2009

The Other Half of the World Discovered

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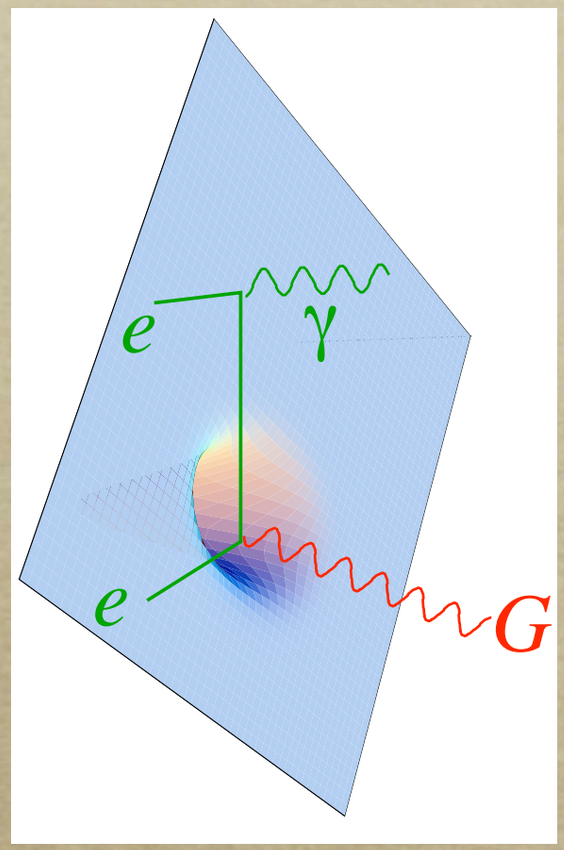
"We have learned that all particles we observe have unique partners of different spin and statistics, called superpartners, that make our theory of elementary particles valid to small distances."

Hidden Dimensions

- *Hidden dimensions*
- *Can emit graviton into the bulk*
- *Events with apparent energy imbalance*



⇒ How many extra dimensions are there?

Hidden Dimensions

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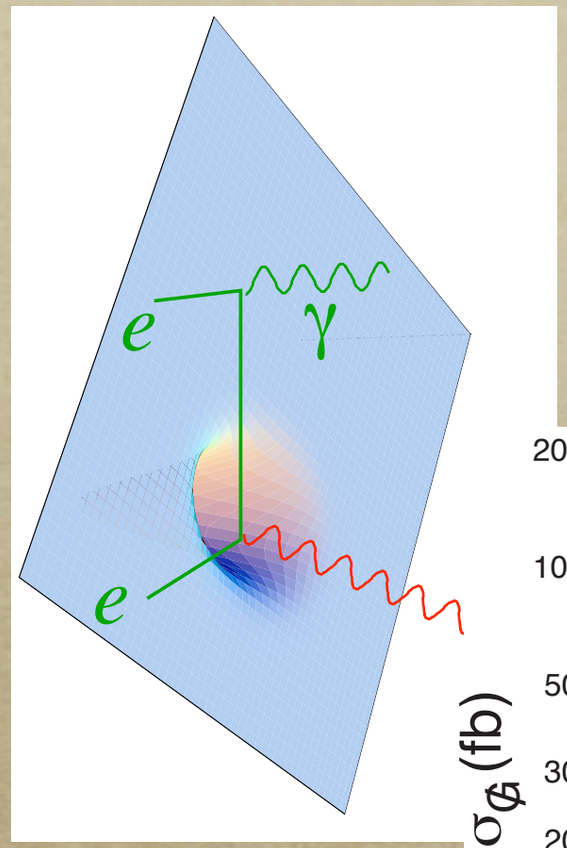
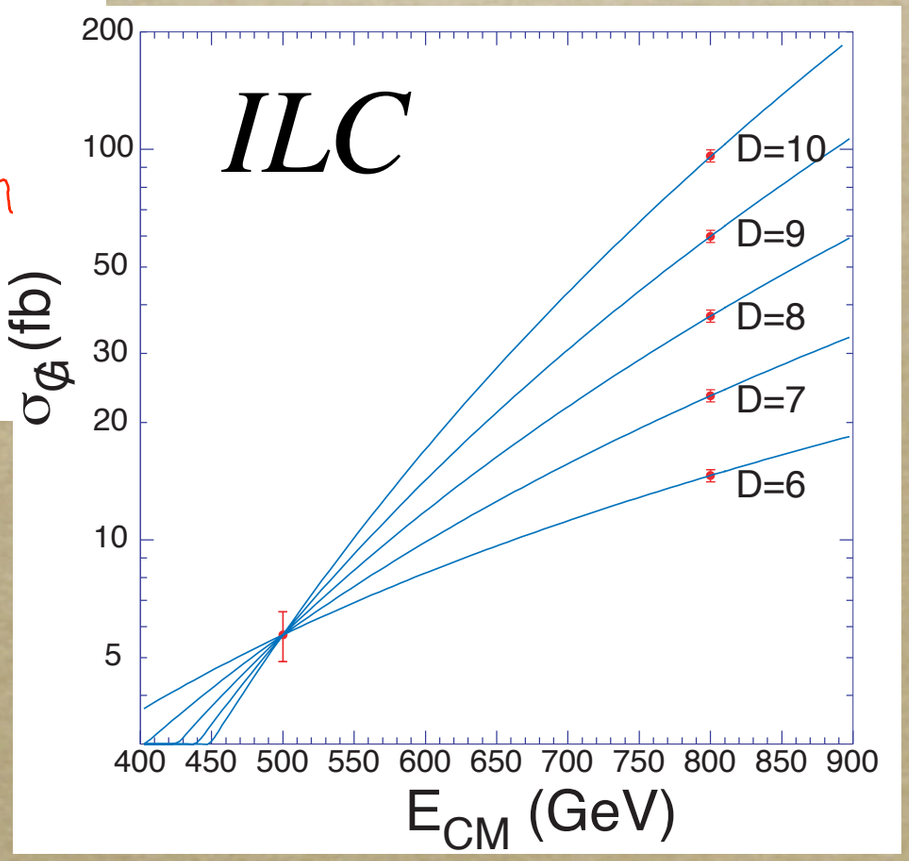
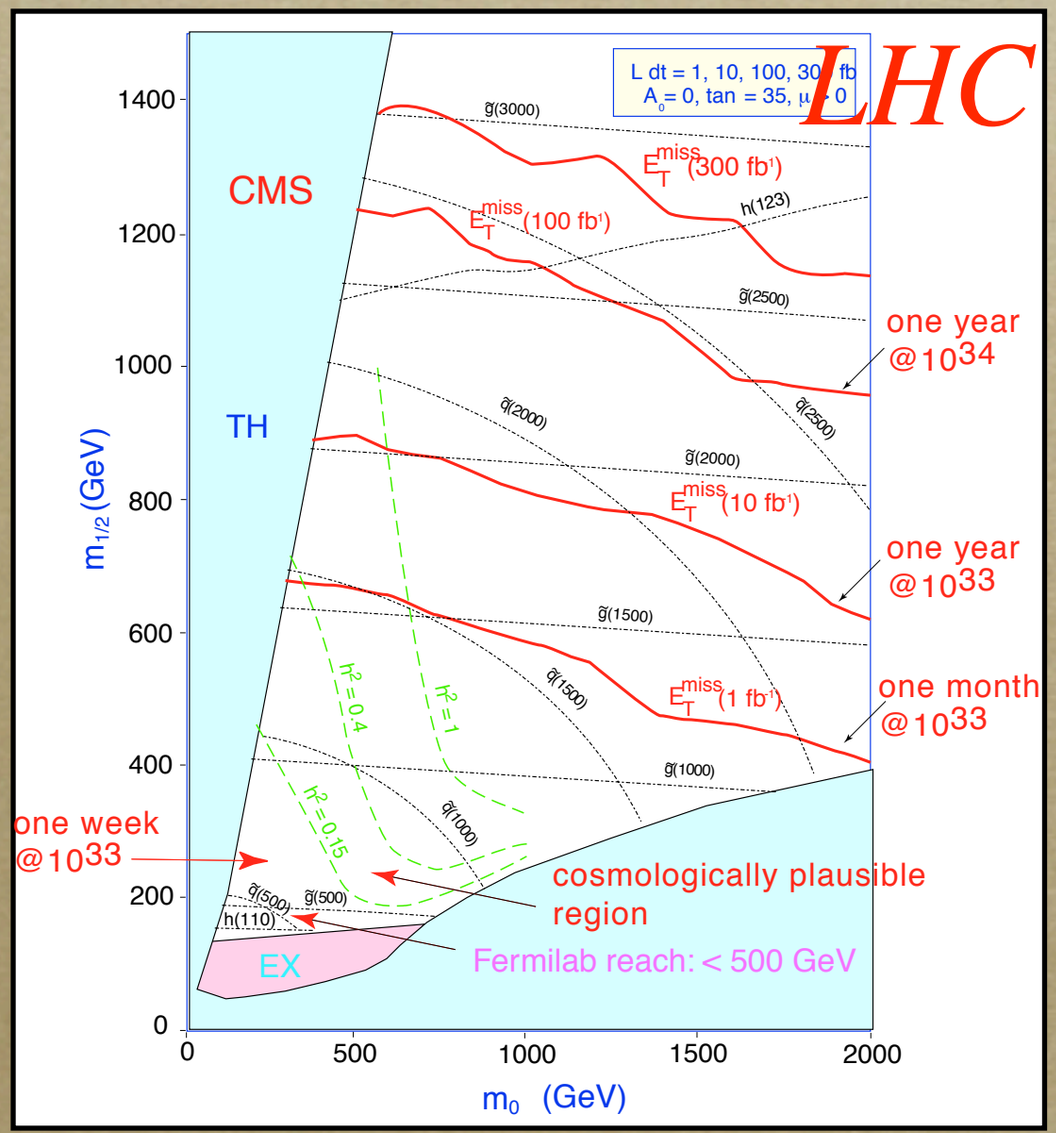


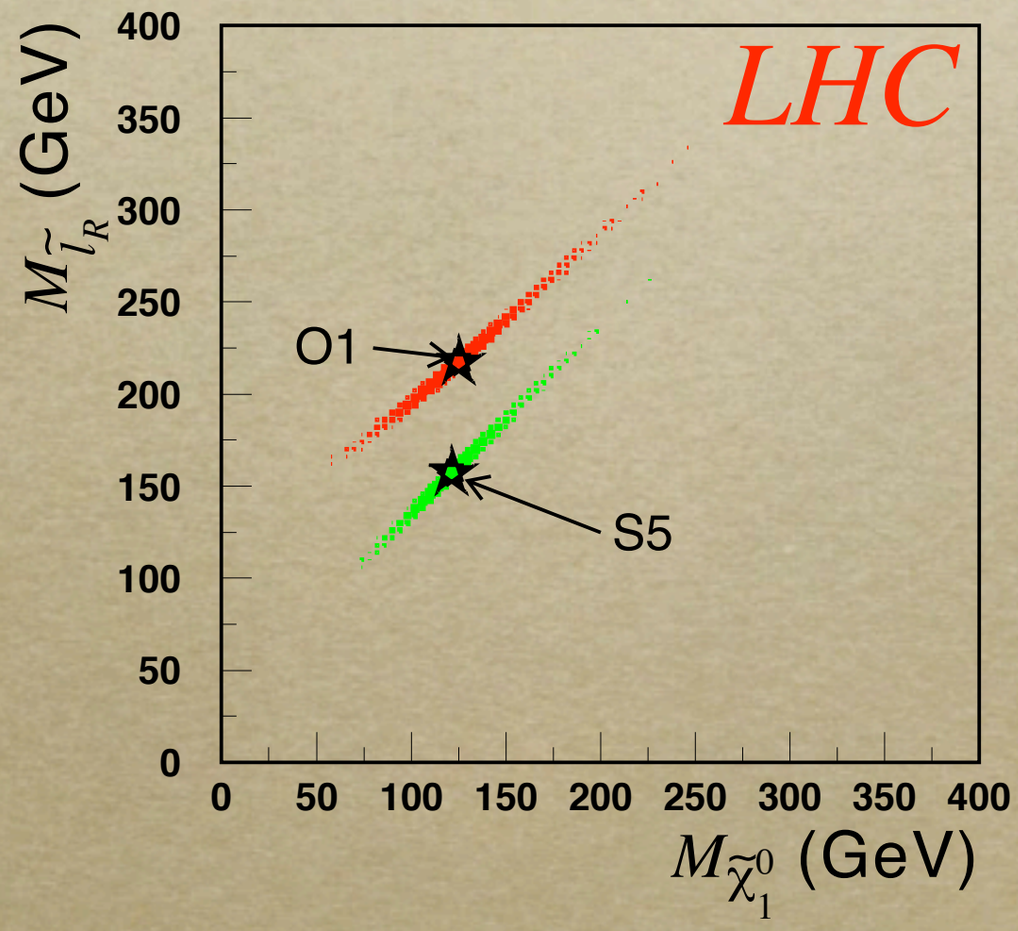


Supersymmetry

Tevatron/LHC will discover supersymmetry



Can do many measurements at LHC



Prove Superpartners have different spin

- *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*
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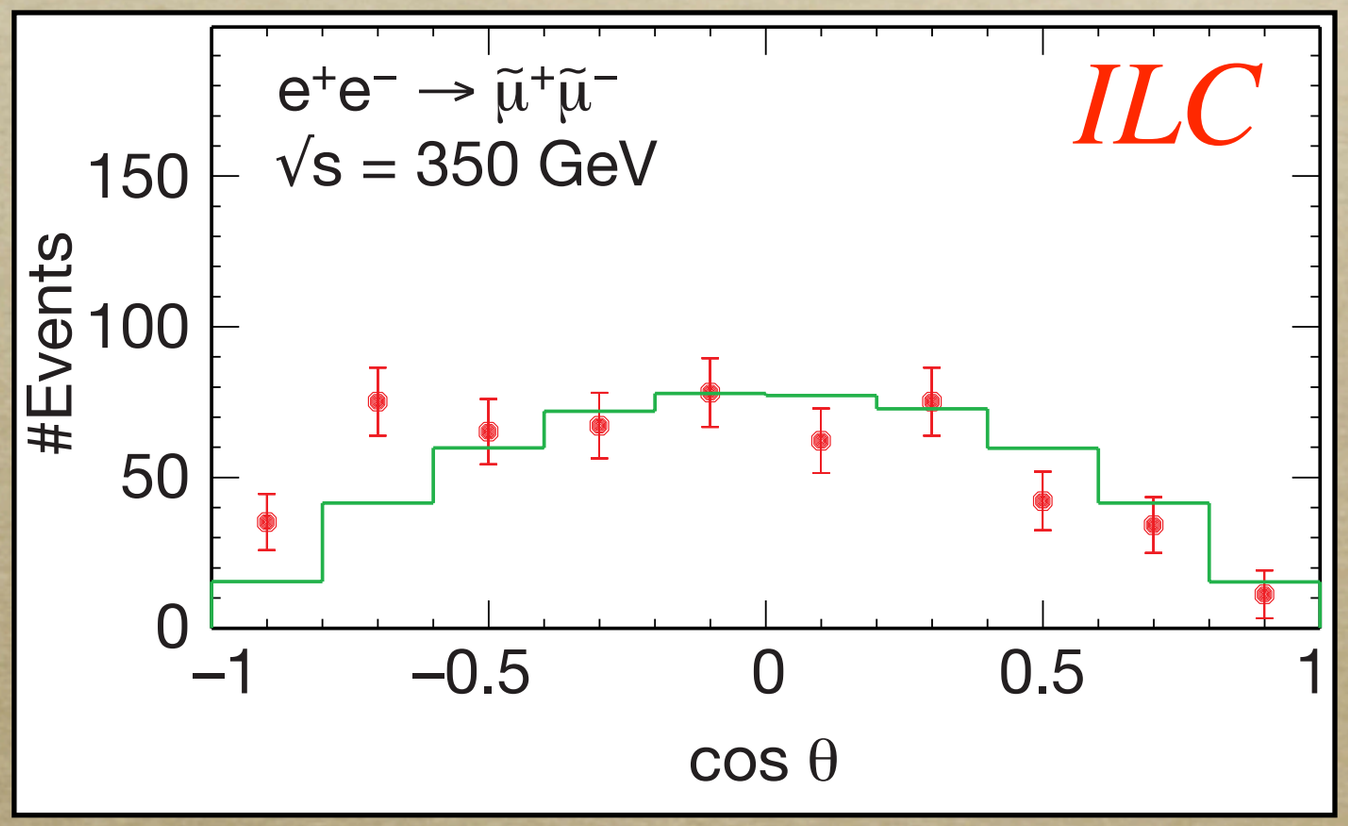


Tsukamoto, Fujii, HM, Yamaguchi, Okada

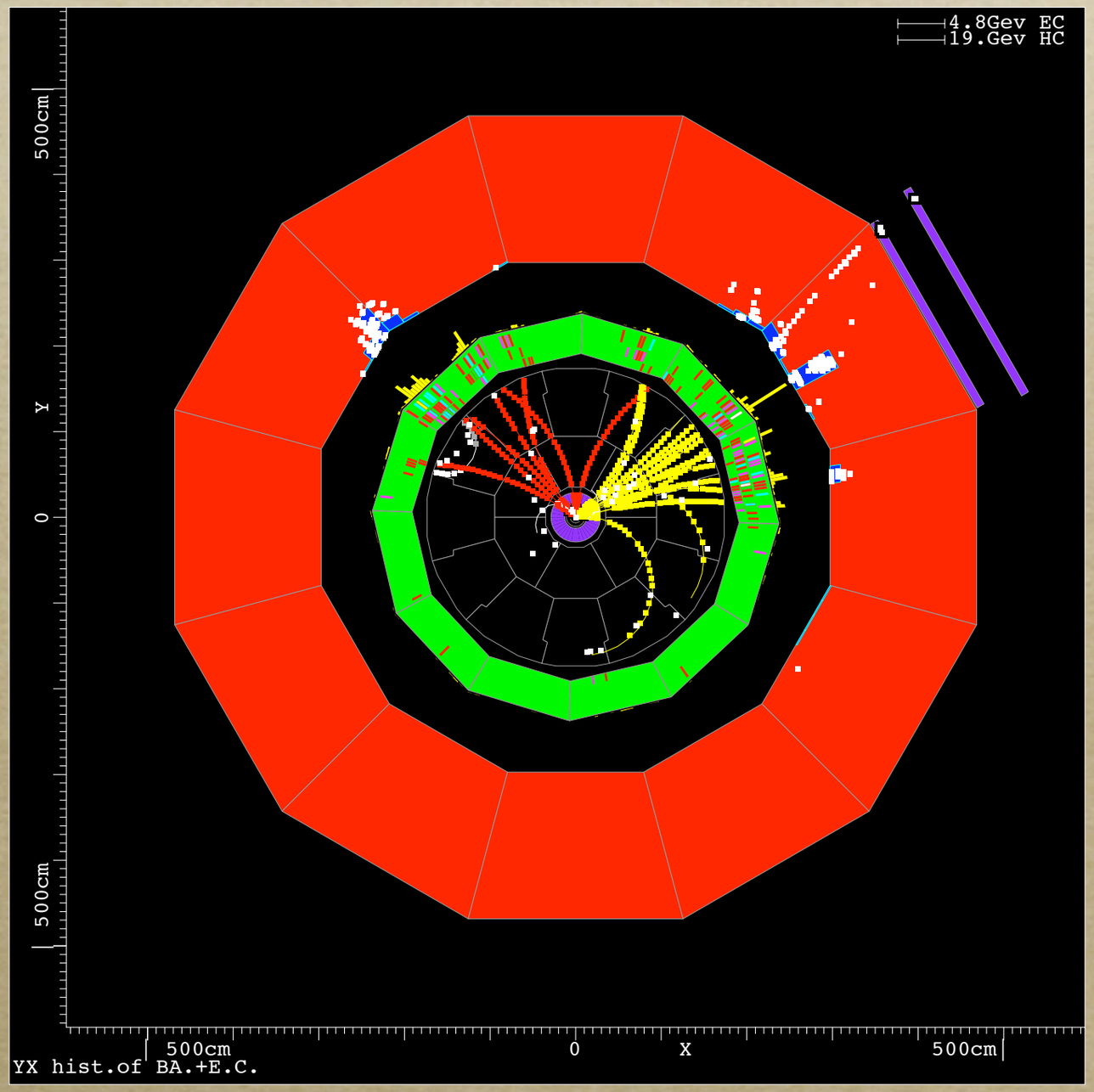
Creating Dark Matter

- *Look for reactions where energy and momenta are unbalanced*

  "missing energy" E_{miss}

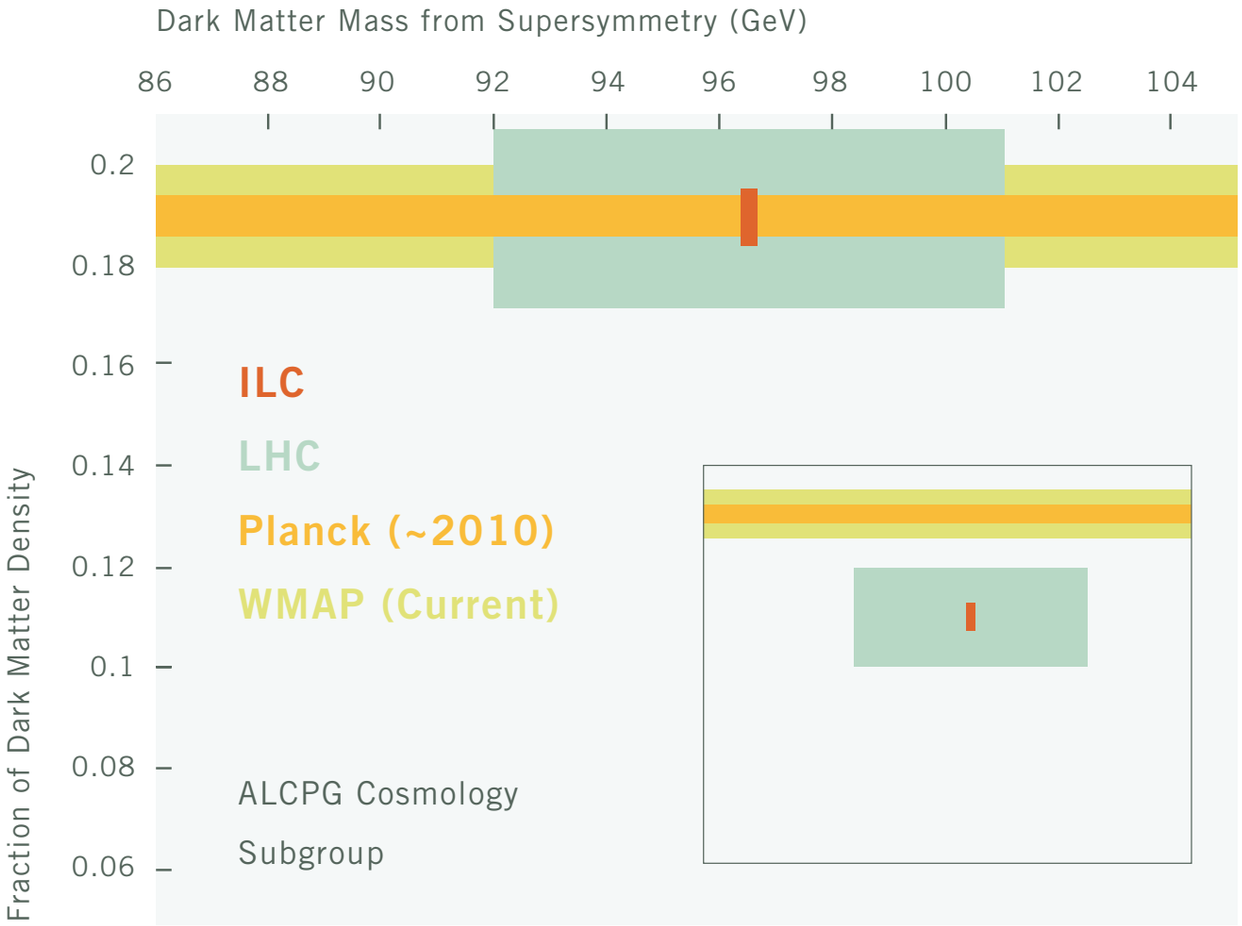
- *Something is escaping the detector*
- *electrically neutral, weakly interacting*

  ⇒Dark Matter!?



Dark Matter Concordance

abundance



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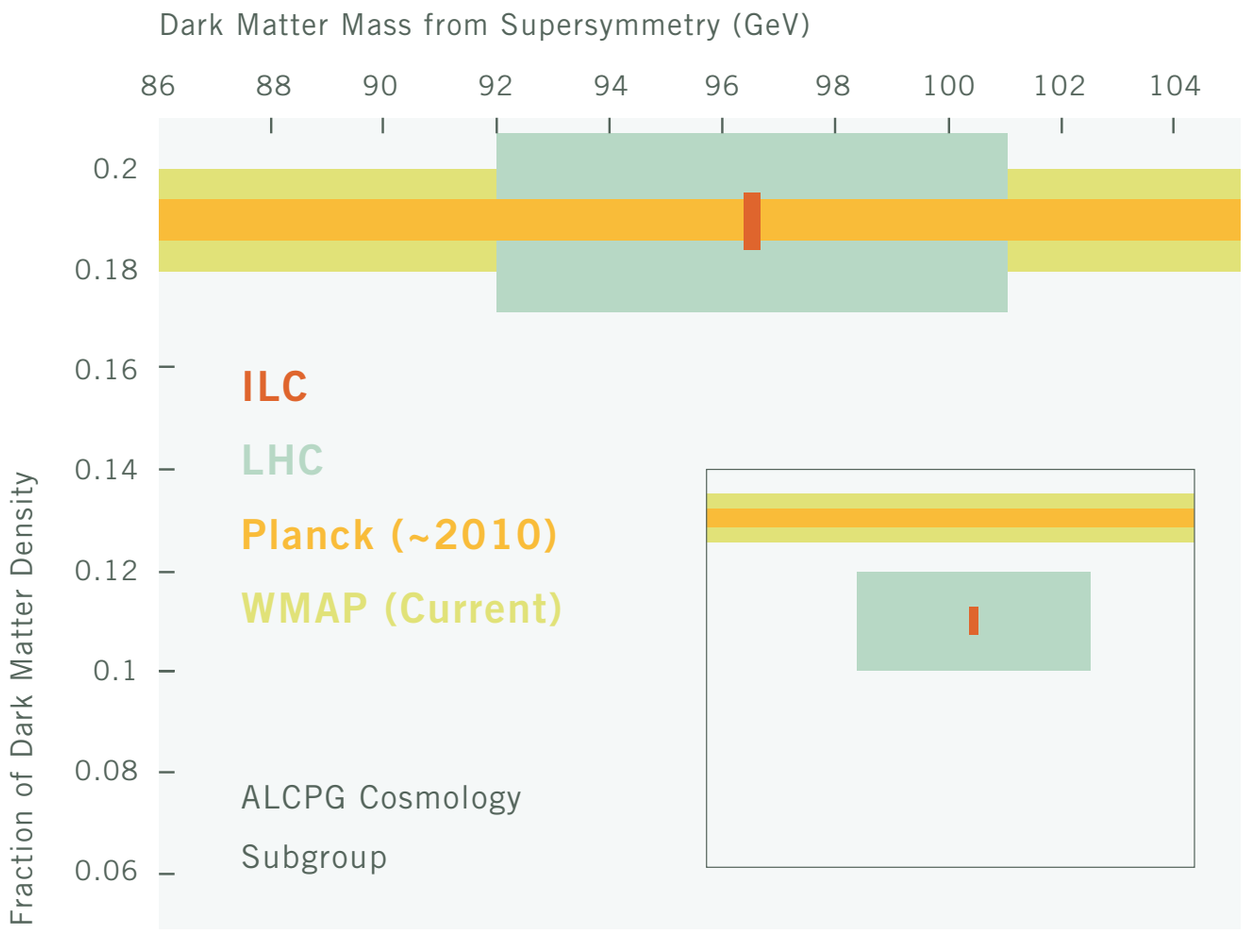
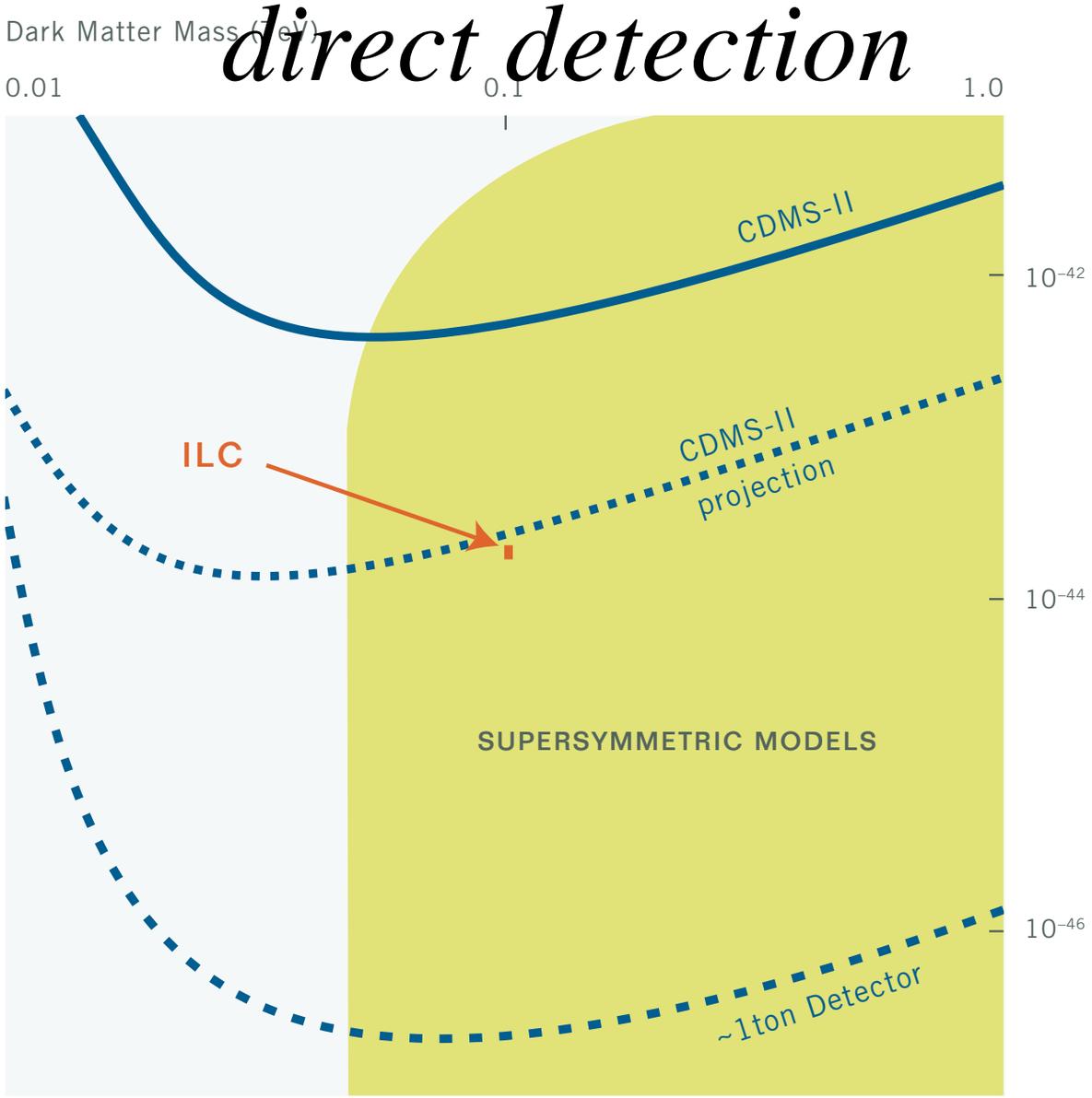


direct detection

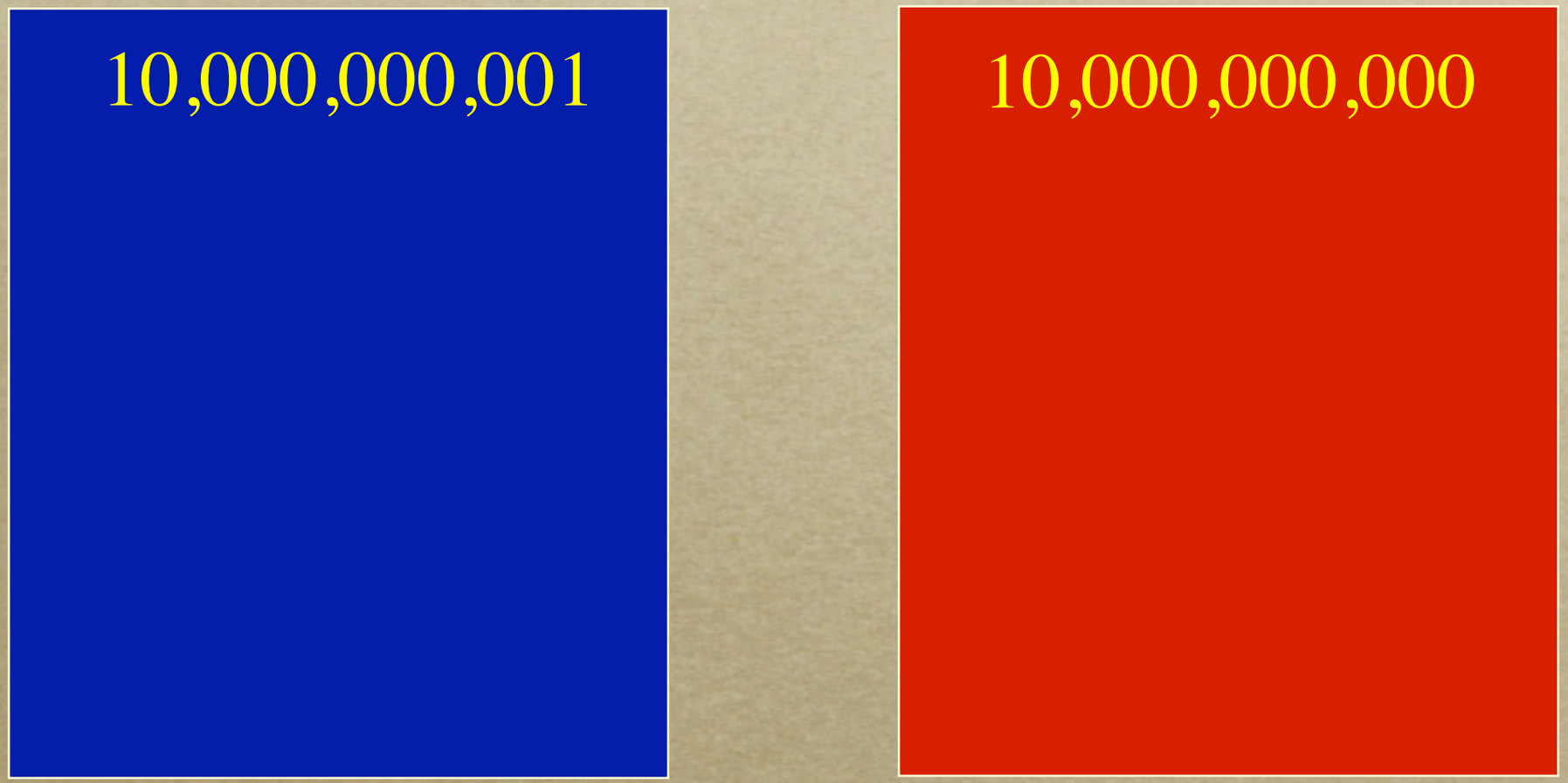


Required New Facilities

- *LHC & ILC may do it if new particles are light enough*
- *Possibly, we need to go beyond them*
- *need a tandem of proton & lepton*
- *need to keep eyes on* a few to 10 TeV
- *higher gradient cavities, CLIC, high-field magnets, muon collider, plasma*

Intensity Frontier

Baryon Asymmetry
Early Universe



q $\overline{q}$

Baryon Asymmetry
Current Universe

1

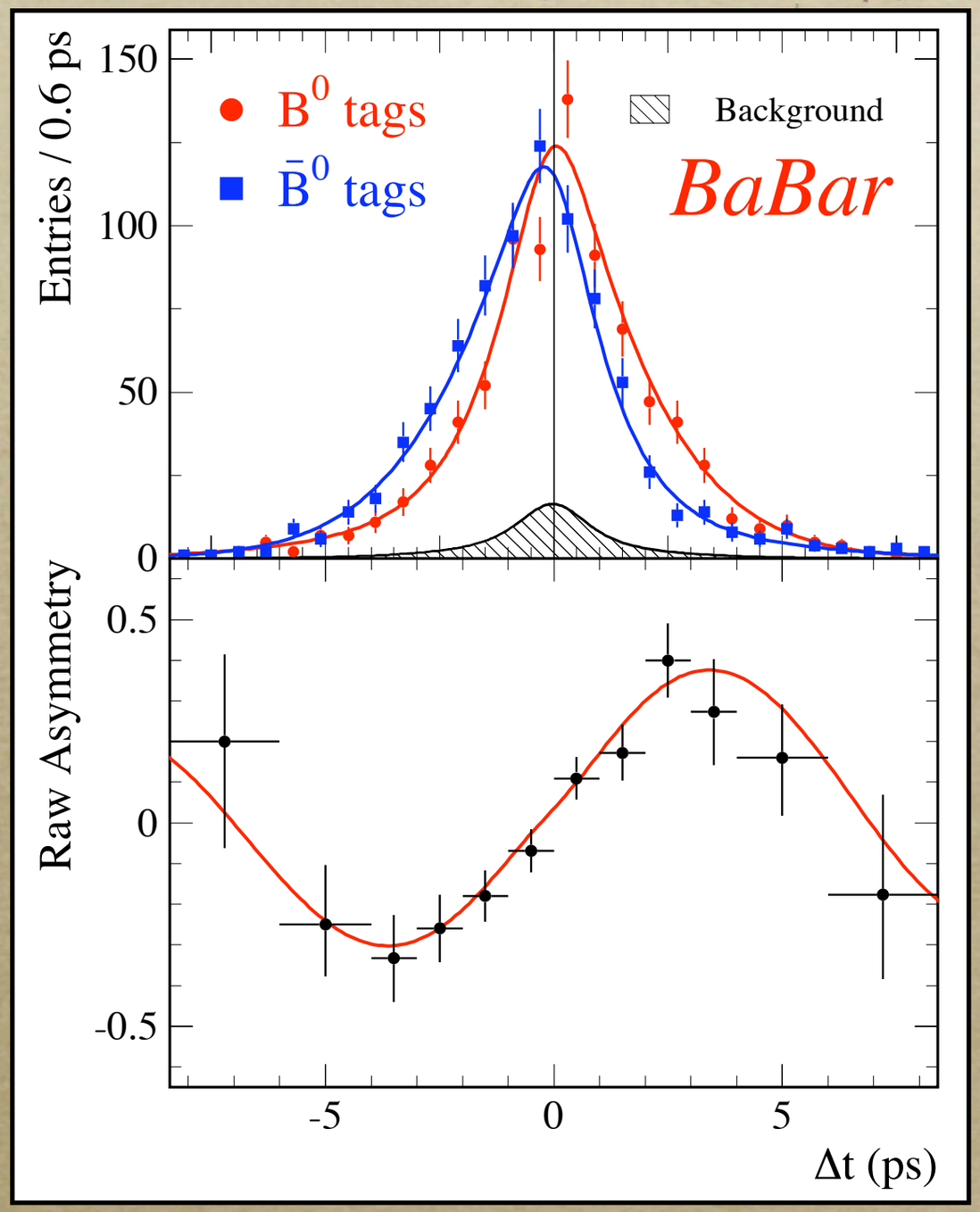
us

q $\overline{q}$

The Great Annihilation

CP Violation

- *Is anti-matter the exact mirror of matter?*
- *1964 discovery of CP violation in neutral kaon system*
- *But only one system, hard to tell what is going on.*
- *2001 Found kaon and anti-kaon decay differently at 10^{-6} level*
- *2002 Found CP violation also in B-meson system*
- *But no CP violation observed so far is large enough to explain the absence of anti-matter*



Leptogenesis

- *Neutrinos may be their own anti-particles*

- *They can transform matter to anti-matter and vice versa*

- *Maybe they are responsible for our existence!*

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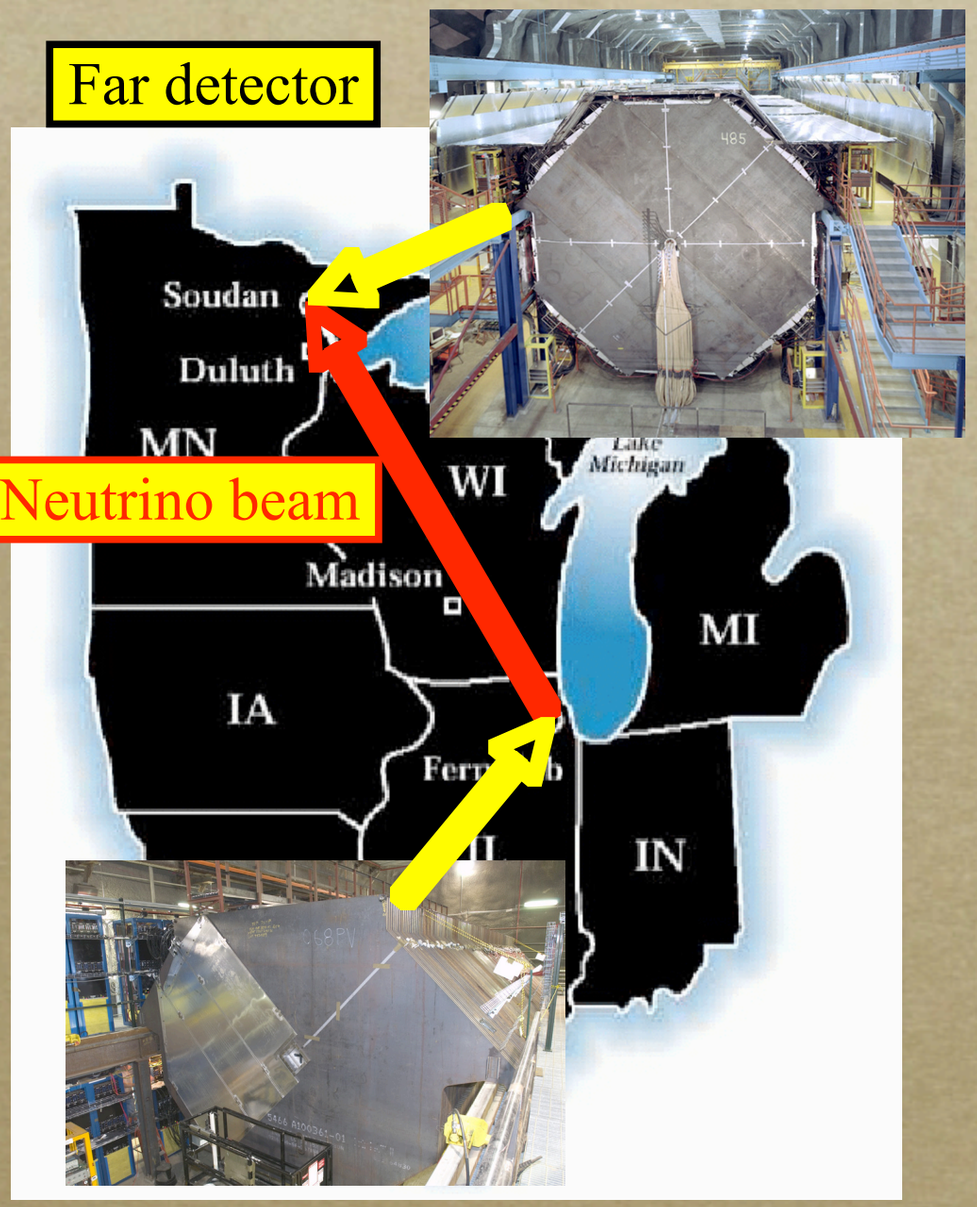
- *CP-violation may be observed in neutrino oscillation*

$$P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e) = -16 s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

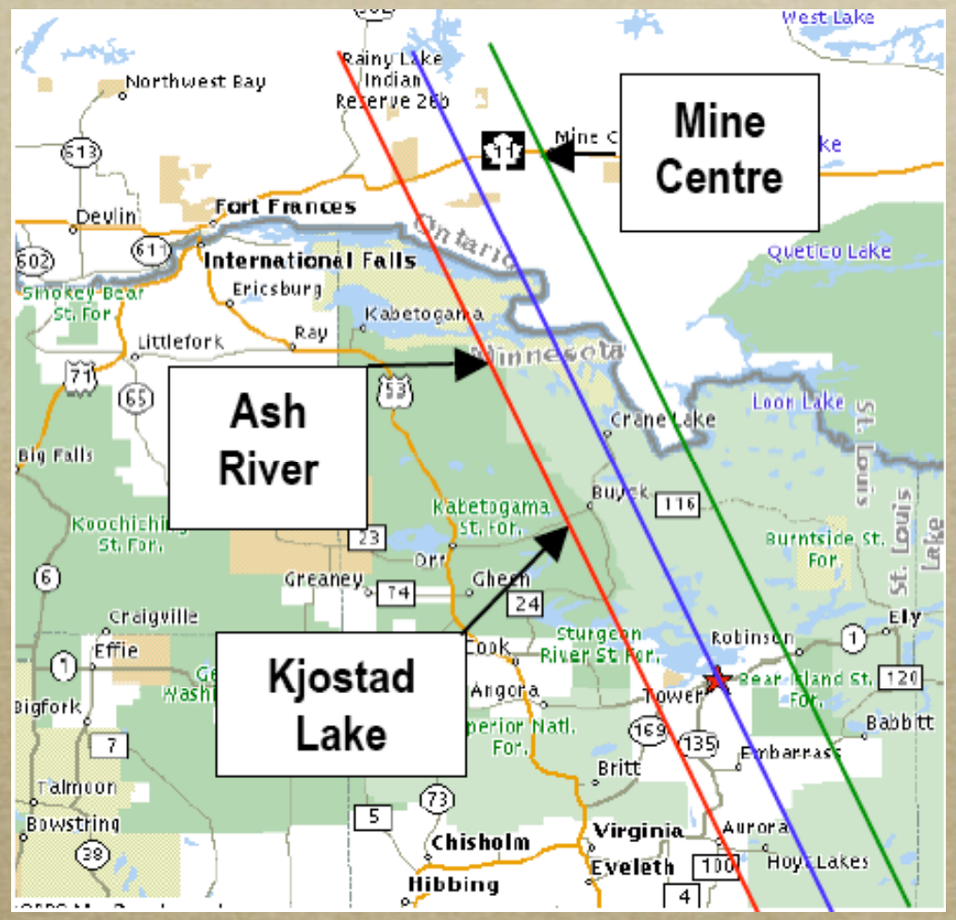
- *Plans to shoot neutrino beams over thousands of kilometers to see this*

First Steps

MINOS



NOvA



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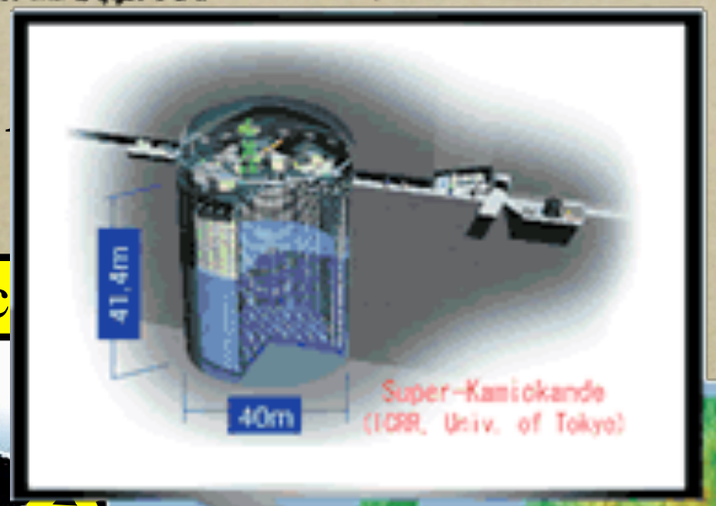
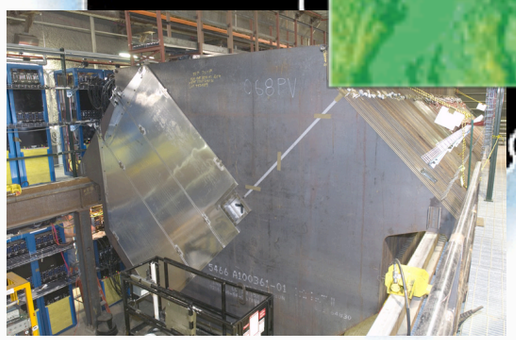
NOvA

Far detec



Neutrino beam

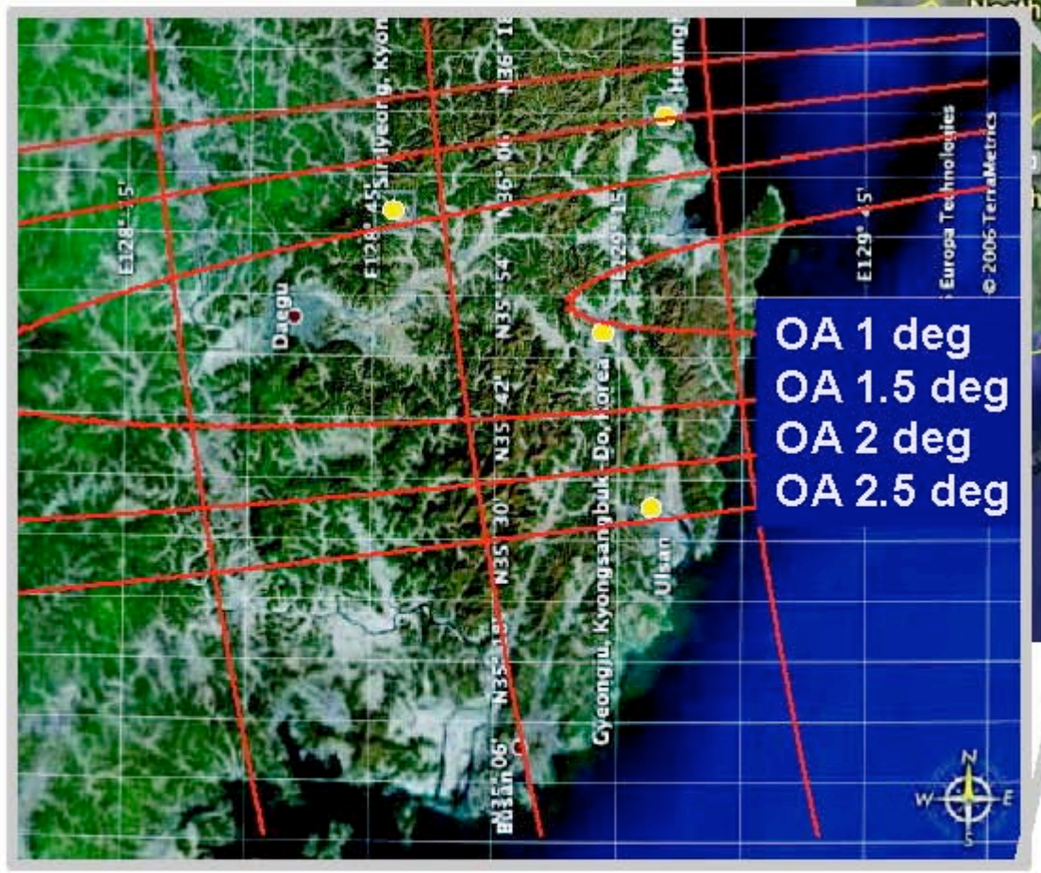
T2K starts next year

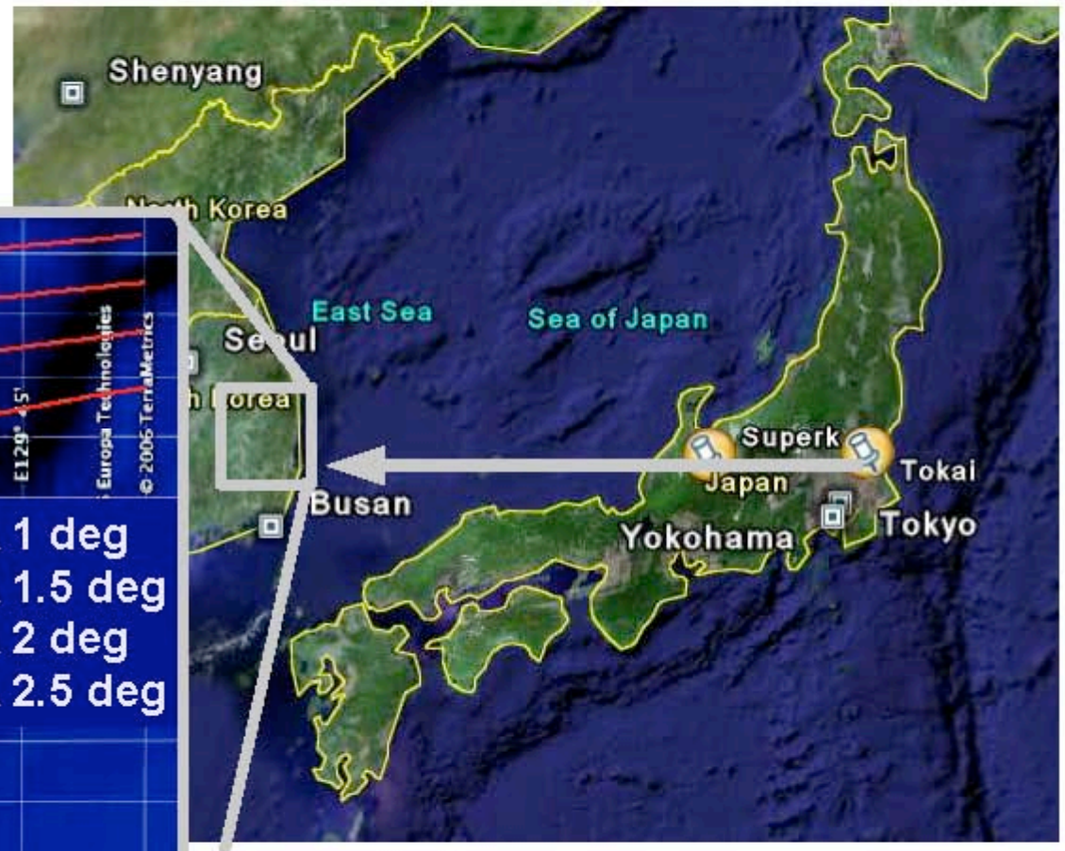


Very Long Baseline Experiment

T2KK (T2K to Korea)

Detecting neutrinos from T2K in Korea → T2KK





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(Kamioka fixed at 2.5º)

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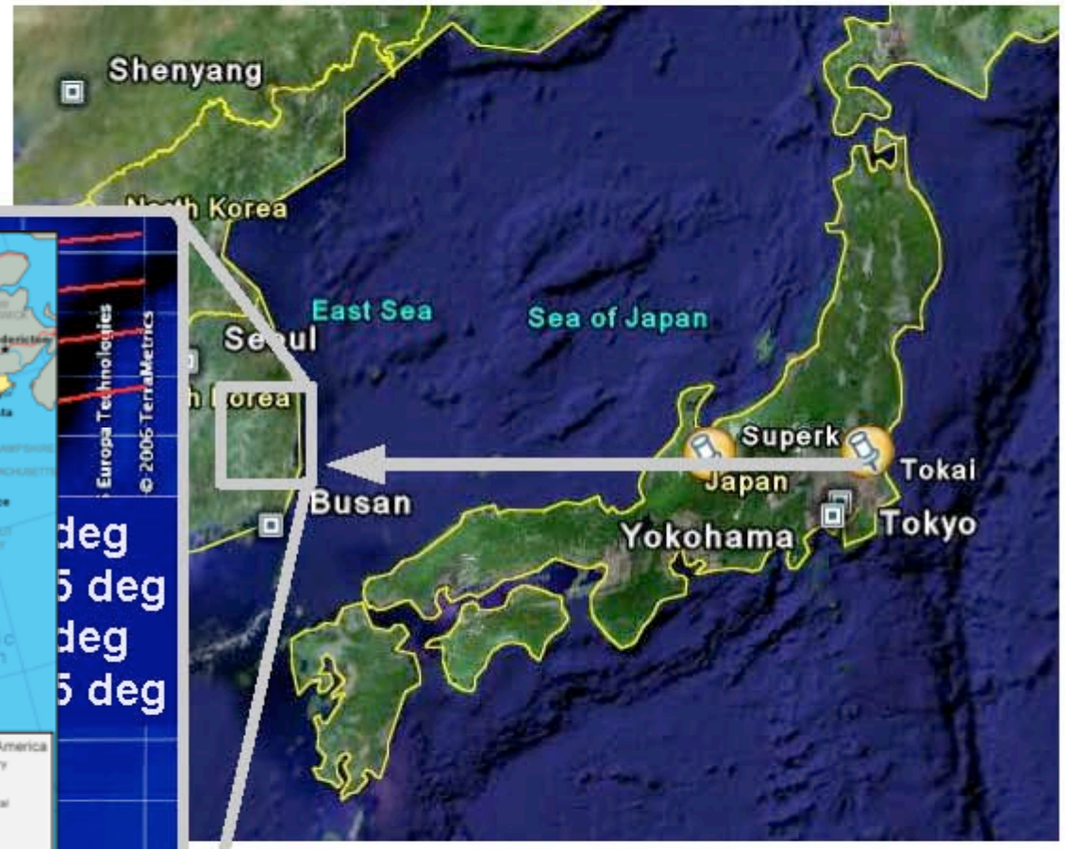
Shoot the beams over thousands of kilometers to see CP violation in neutrinos



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Once new particles at TeV

- *What do they do with flavor?*
  - *Do they come in three generations?*
  - *If so, do they mix the same way as quarks and leptons?*
  - *If not, do their interactions preserve or violate flavor?*
- *Ultimately, what is the origin of flavor?*
- *need a large sample of kaons, muons, B's*

Required New Facilities

- *high-intensity proton machine* (4MW?)
  - *to produce intense neutrino beams*
  - *to create kaons for precision studies*
- *high-intensity electron machine* (10^{36}?)
  - *to create B mesons for precision studies*
- *high-intensity muon source* (10^{20}?)
  - *neutrino factory*
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much stronger case with LHC discoveries

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  - *dark matter, beyond Higgs, hierarchy*
- *Need high intensity neutrinos*
- *need to study consequences of new particles on flavor physics*

Our Future Rests On You!

Disney PRESENTS A PIXAR FILM

THE INCREDIBLES

NOW PLAYING