ILC, Future Particle Physics and Cosmology

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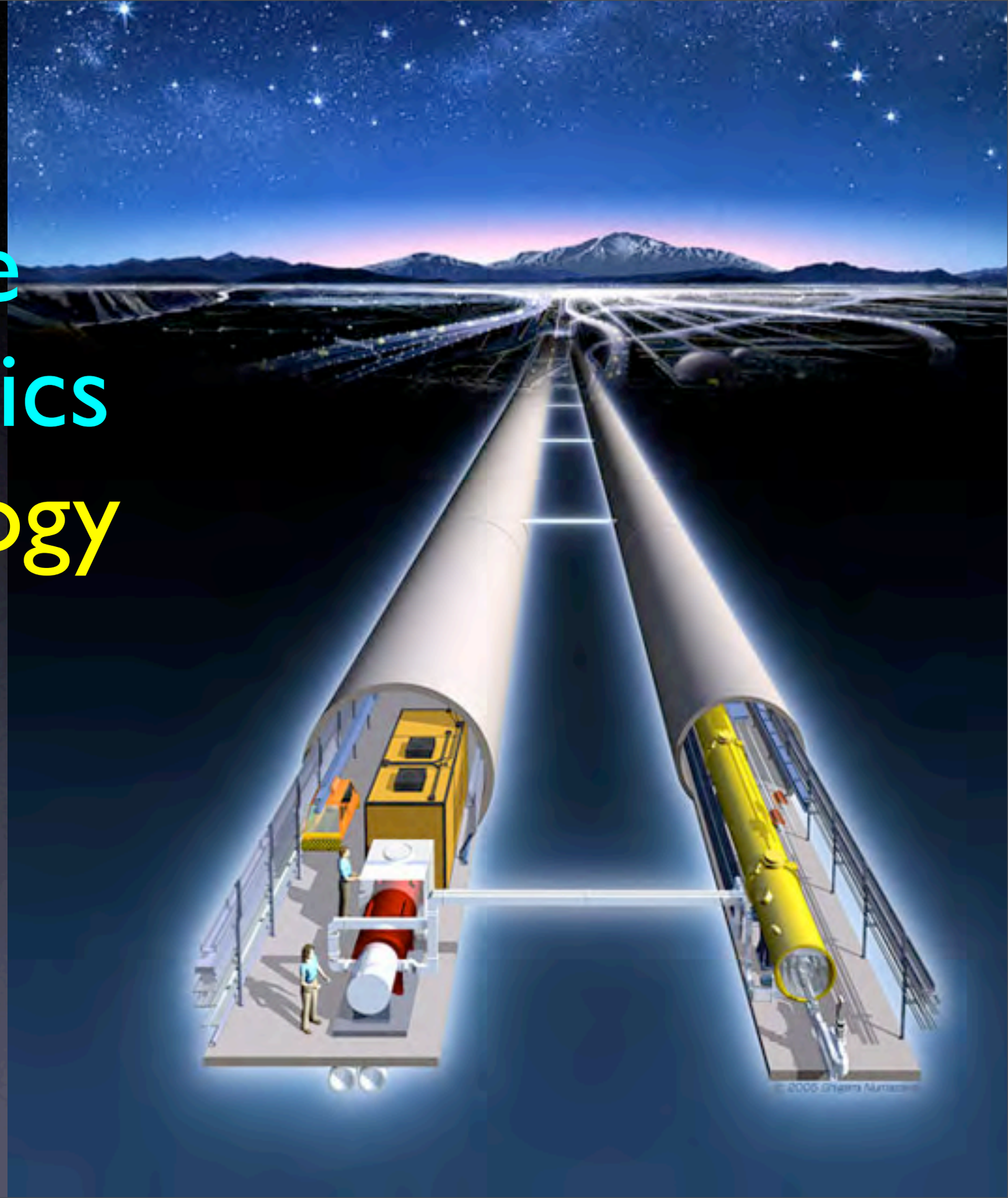
TILC08, March 3, 2008



Particle Physics and Cosmology

To understand physics at the largest scale:
Universe
we need to understand the smallest scale:
elementary particles

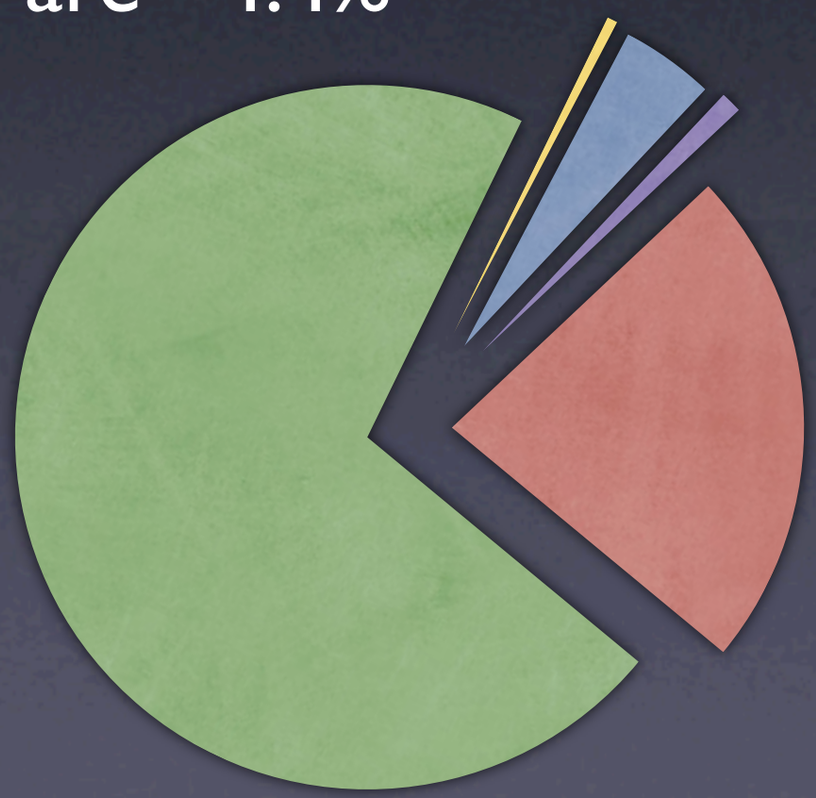
Questions of the New Millennium

- What is the Universe made of?
- How did it come to be?
- Why do we exist?

Moving from philosophy to physics

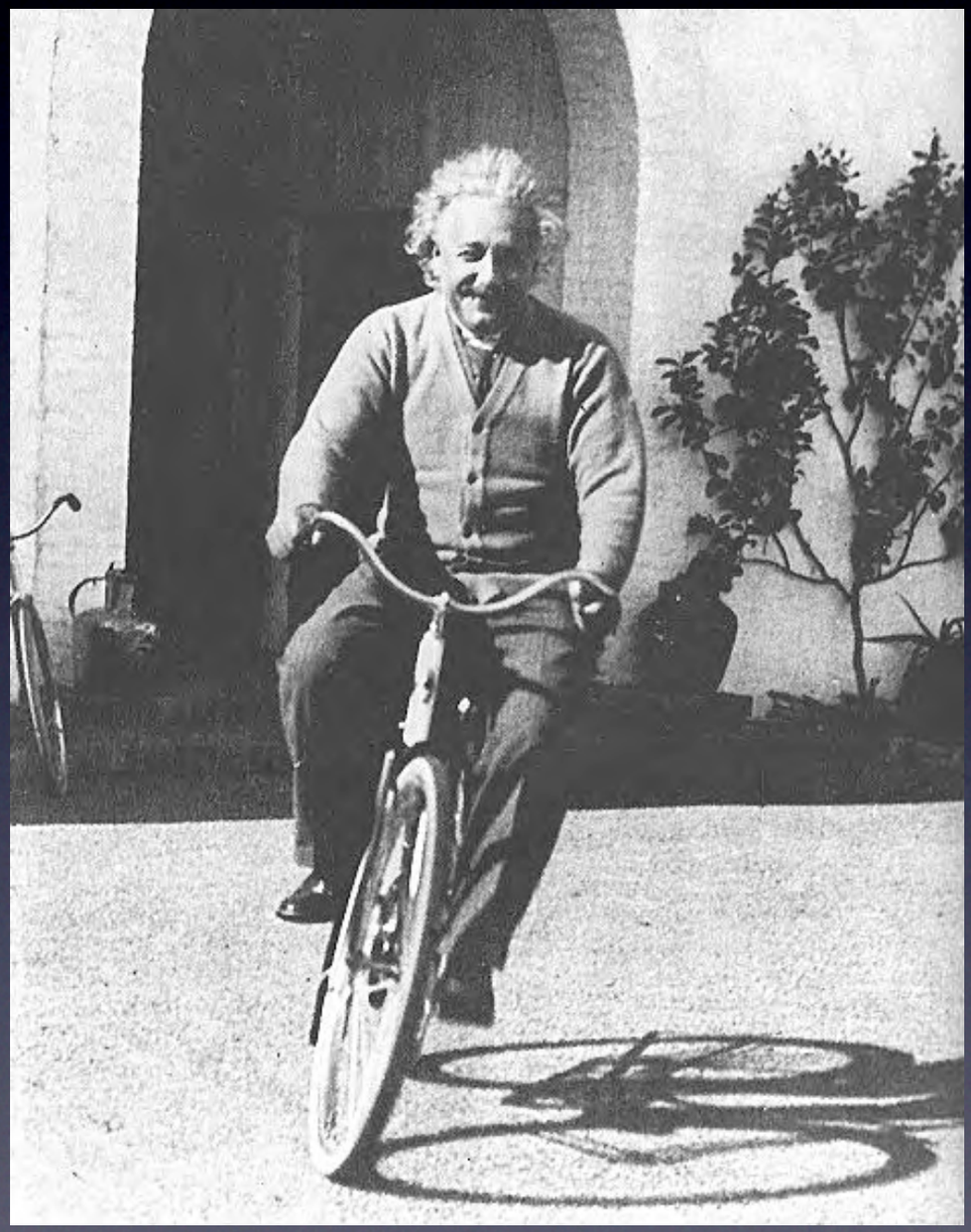
Energy Budget of the Universe

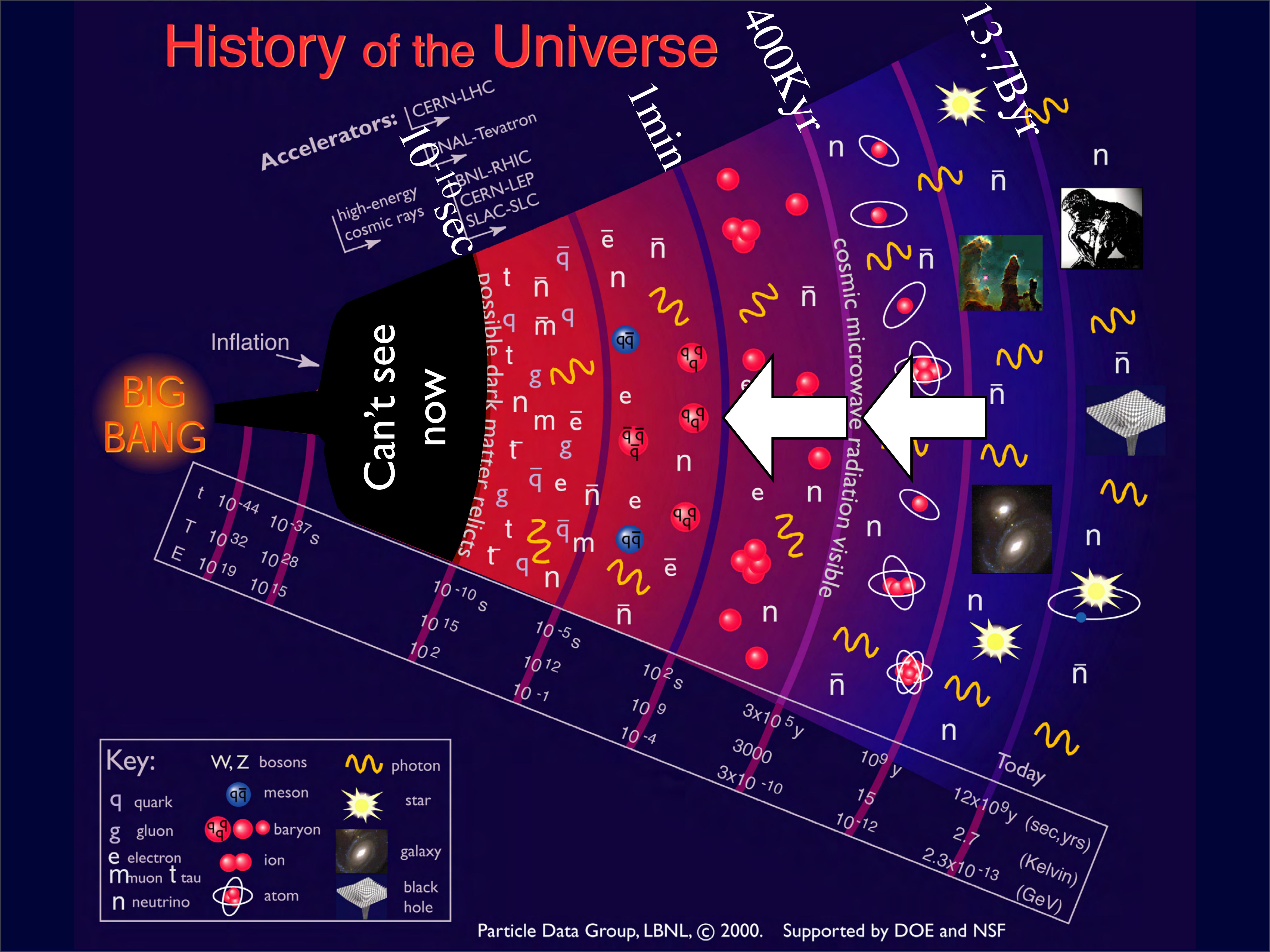
- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–1.5%
- Rest of ordinary matter
  (electrons, protons & neutrons) are ~4.4%
- Dark Matter ~20%
- Dark Energy ~75%
- Anti-Matter 0%
- Dark Field ~10^{62}%??



Einstein's Dream

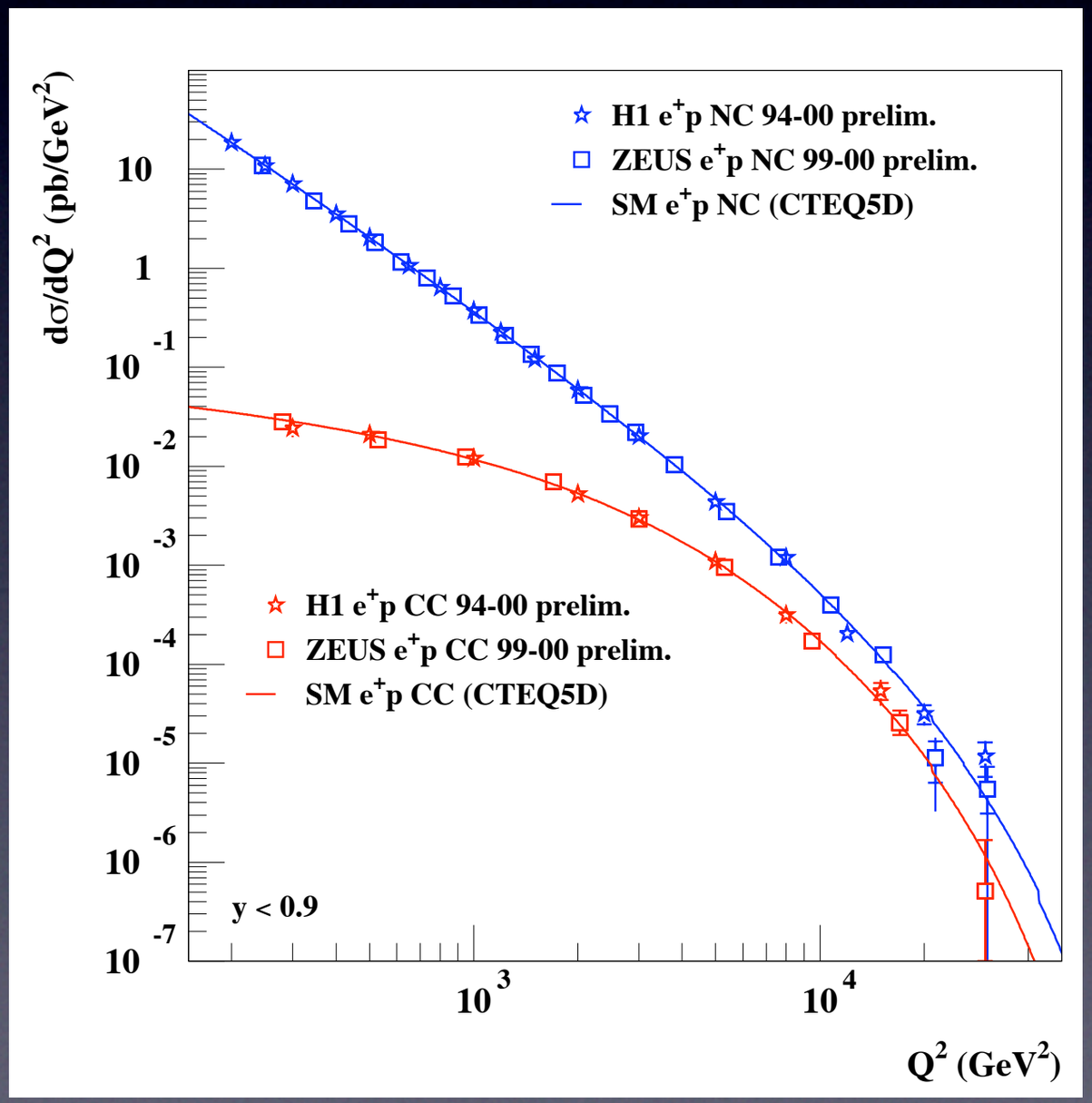
- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)
- We need a unified theory to approach the Beginning of the uinverse




History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
10-10sec
1min
400Kyr
13.7Byr
Inflation
BIG BANG
Can't see now
possible dark matter relicts
cosmic microwave radiation visible
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:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Just about to achieve a new layer of unification

HERA ep collider



- Unification of electromagnetic and weak forces

⇒ electroweak theory

- Long-term goal since '60s
- We are getting there!
- The main missing link: Dark Field

Terascale: rich physics?

- *Dark Matter*

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

- *Fermi (Dark Field) scale*

  $G_F^{-1/2}$=0.3TeV

- *Dark Energy*

  $\rho_\Lambda \sim (2\mathrm{meV})^4$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

- *Neutrino*

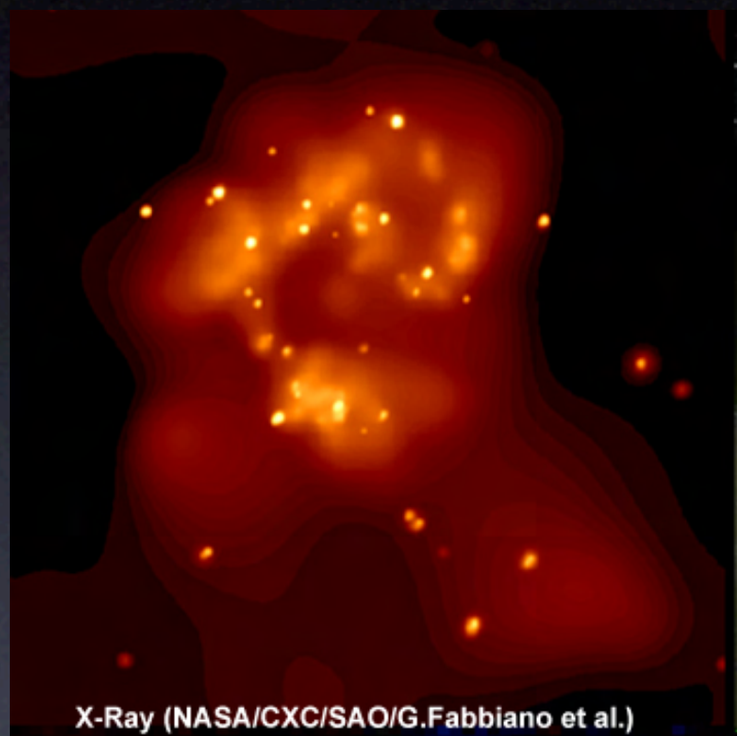
  $(\Delta m^2_{LMA})^{1/2} \sim 7\mathrm{meV}$ *vs* $(\mathrm{TeV})^2/M_{Pl} \sim 0.5\mathrm{meV}$

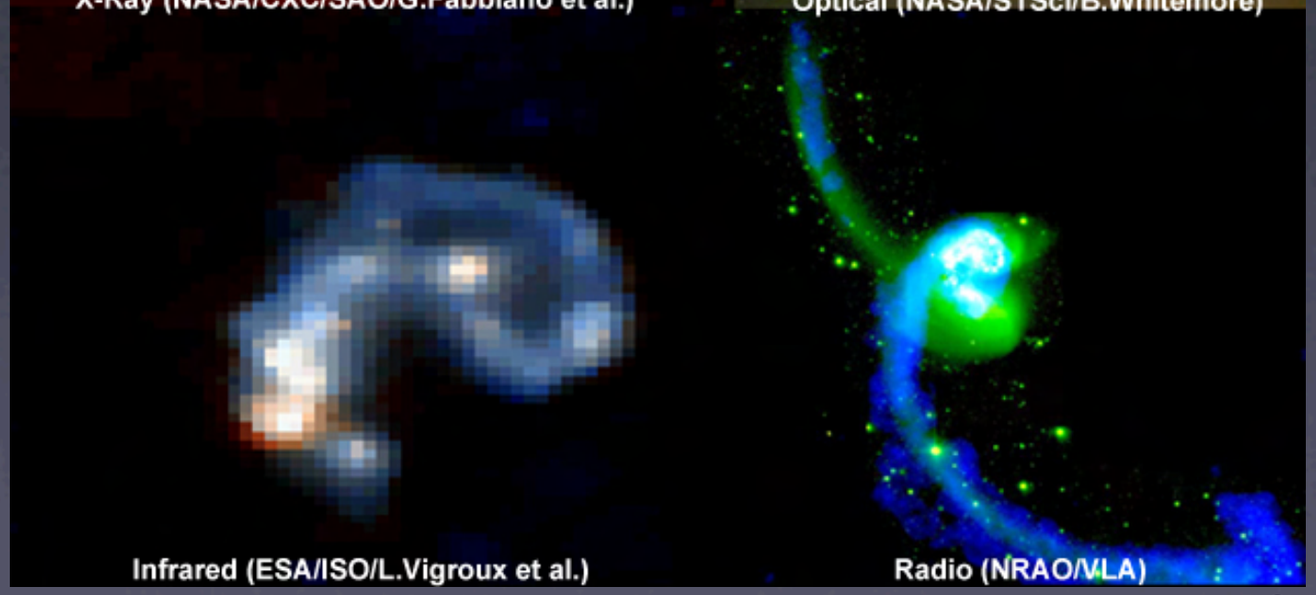
Terascale physics likely to be rich

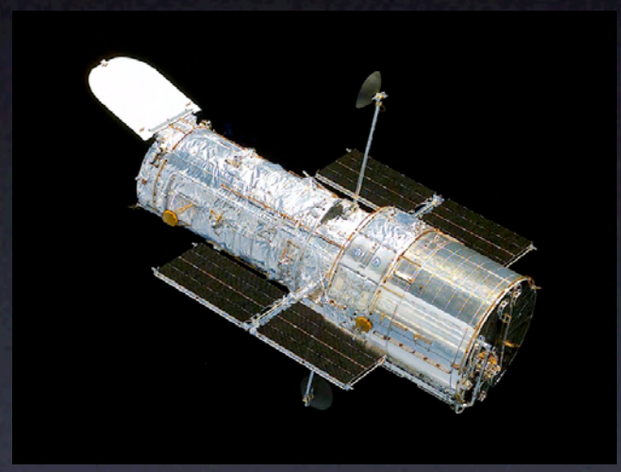
We are now getting there!

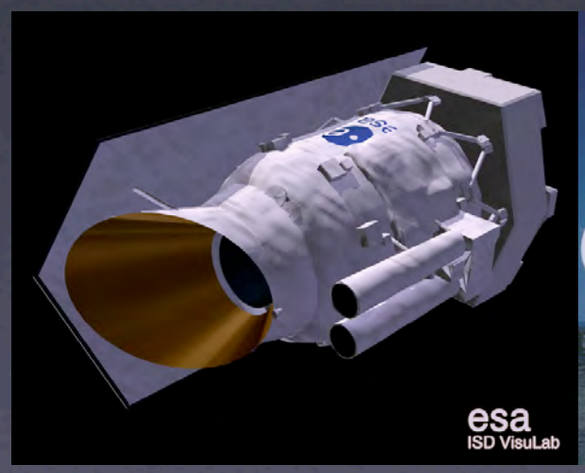
Need for Multiple Tools

Multiple Wavebands in Astronomy









Colliding galaxies!

Telescopes vs Accelerators

purpose	need	telescopes	accelerators
probe deeper	better resolution	better mirrors, CCD	higher energy
better image	better exposure	larger telescopes, more time	more powerful beams (luminosity)
full understanding	multiple probes	visible, radio, X-ray, infrared, UV, gamma	protons, electrons, neutrinos

Large Hadron Collider (LHC)

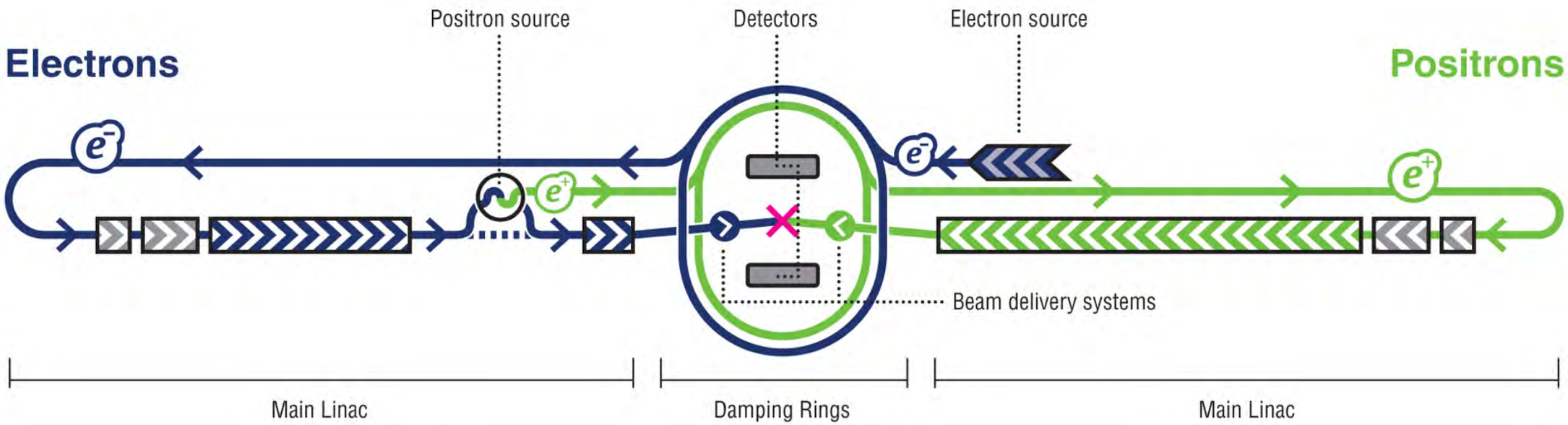
Recreating Big Bang

Large Hadron Collider (LHC)

Recreating Big Bang

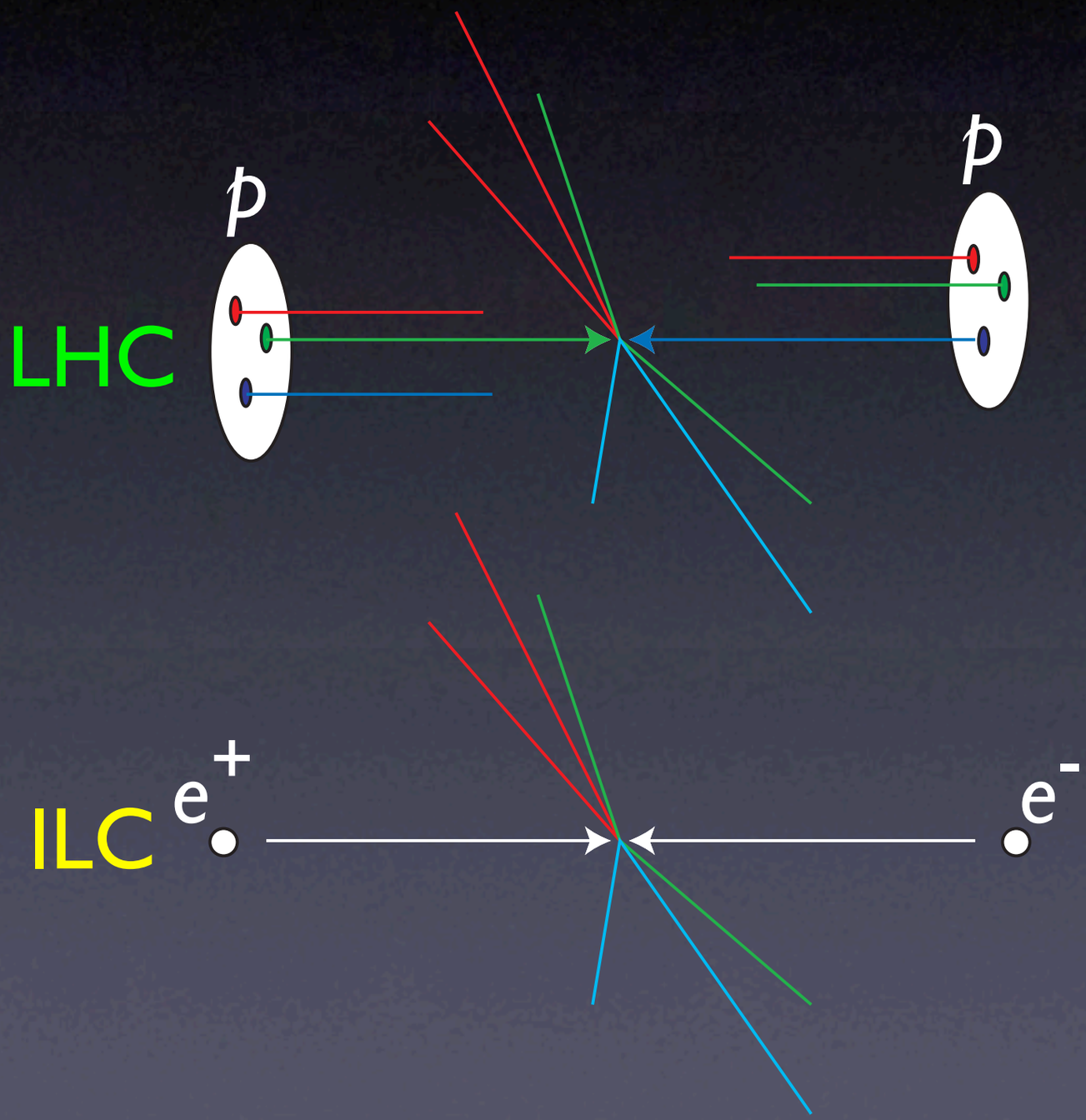
ILC

- electron position collider at 0.5-1 TeV
- about 20 miles long
- super-high-tech: nanometer beams



ILC

- elementary particles
- well-defined energy, angular momentum
- uses its full energy
- can produce particles democratically
- can capture nearly full information



LHC vs ILC

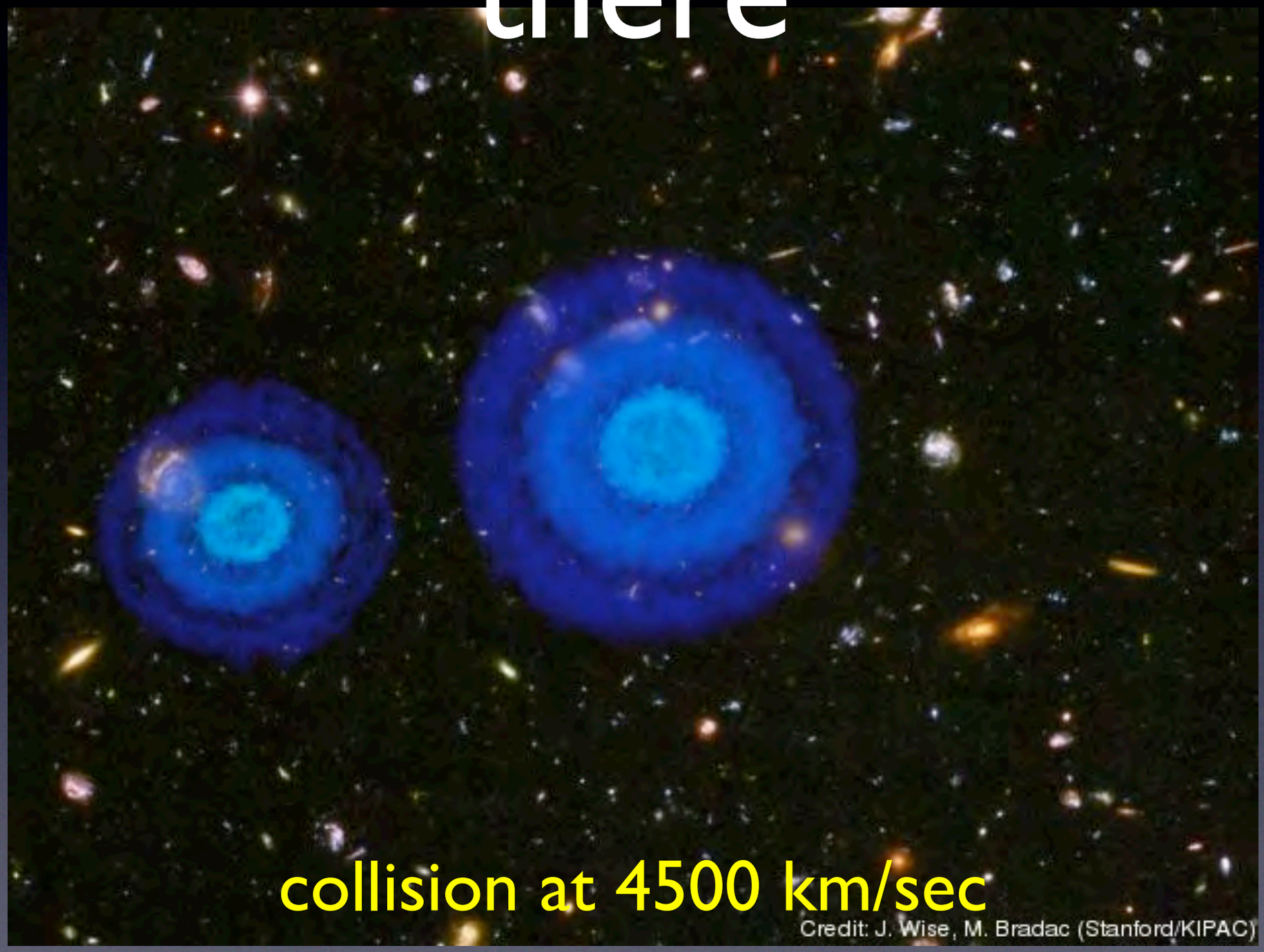
(oversimplified)

total energy	14TeV	0.5-1 TeV
usable energy	a fraction	full
beam	proton (composite)	electron (point-like)
signal rate	high	low
noise rate	very high	low
analysis	specific modes	nearly all modes
events	lose info along the beams	capture the whole
status	under construction	needs to finish design

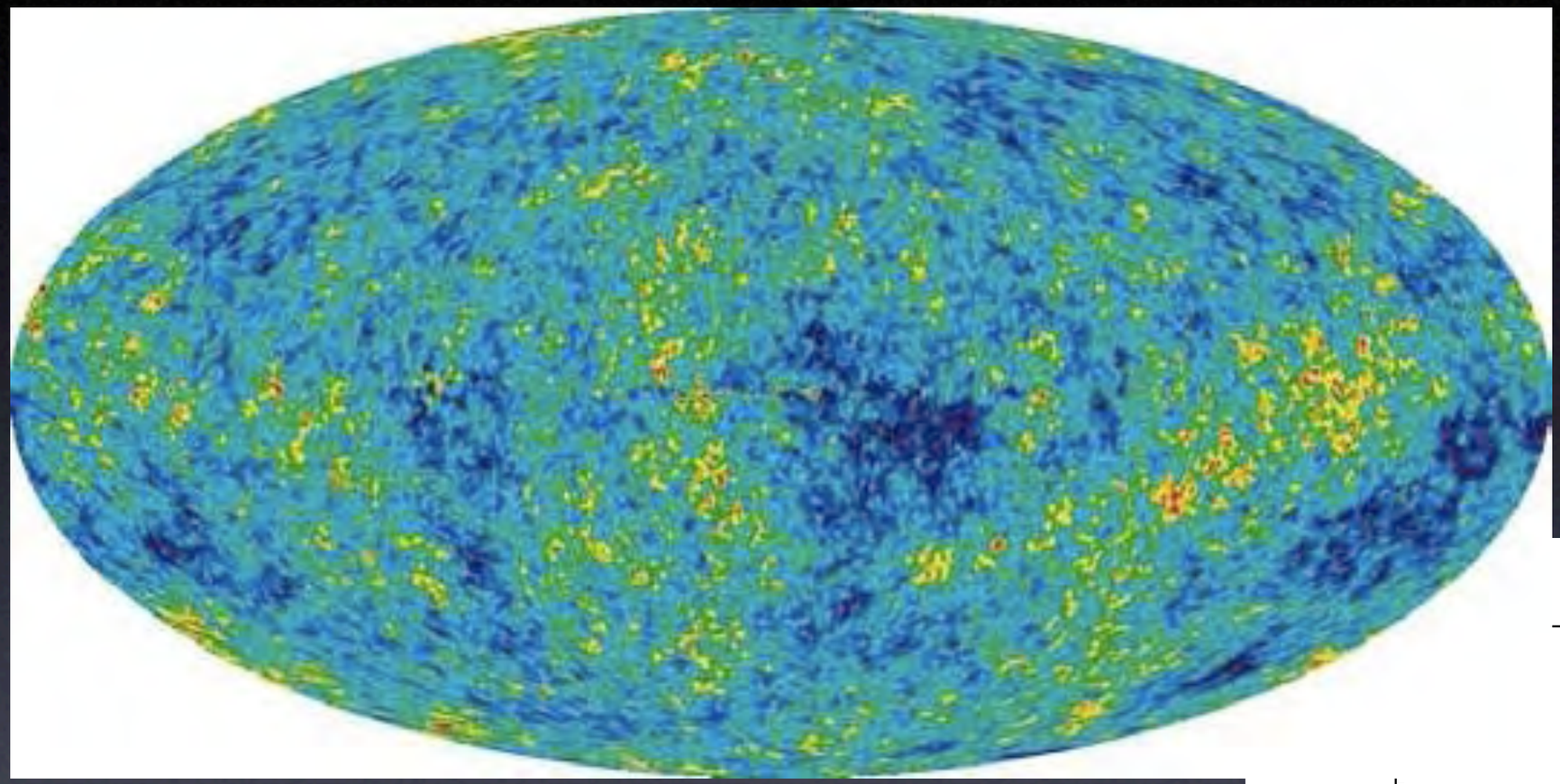
Dark Matter

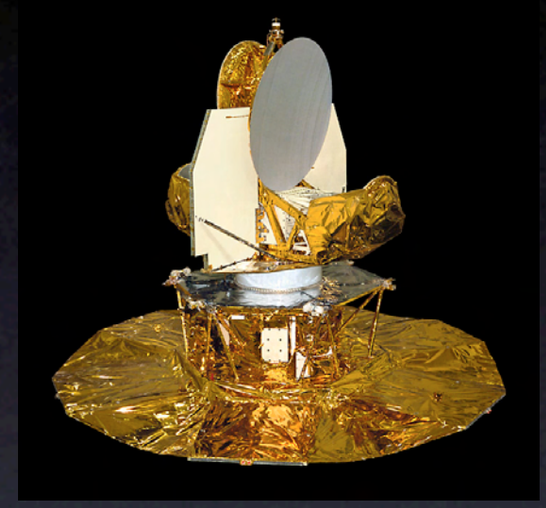
You don't want to be there

You don't want to be there

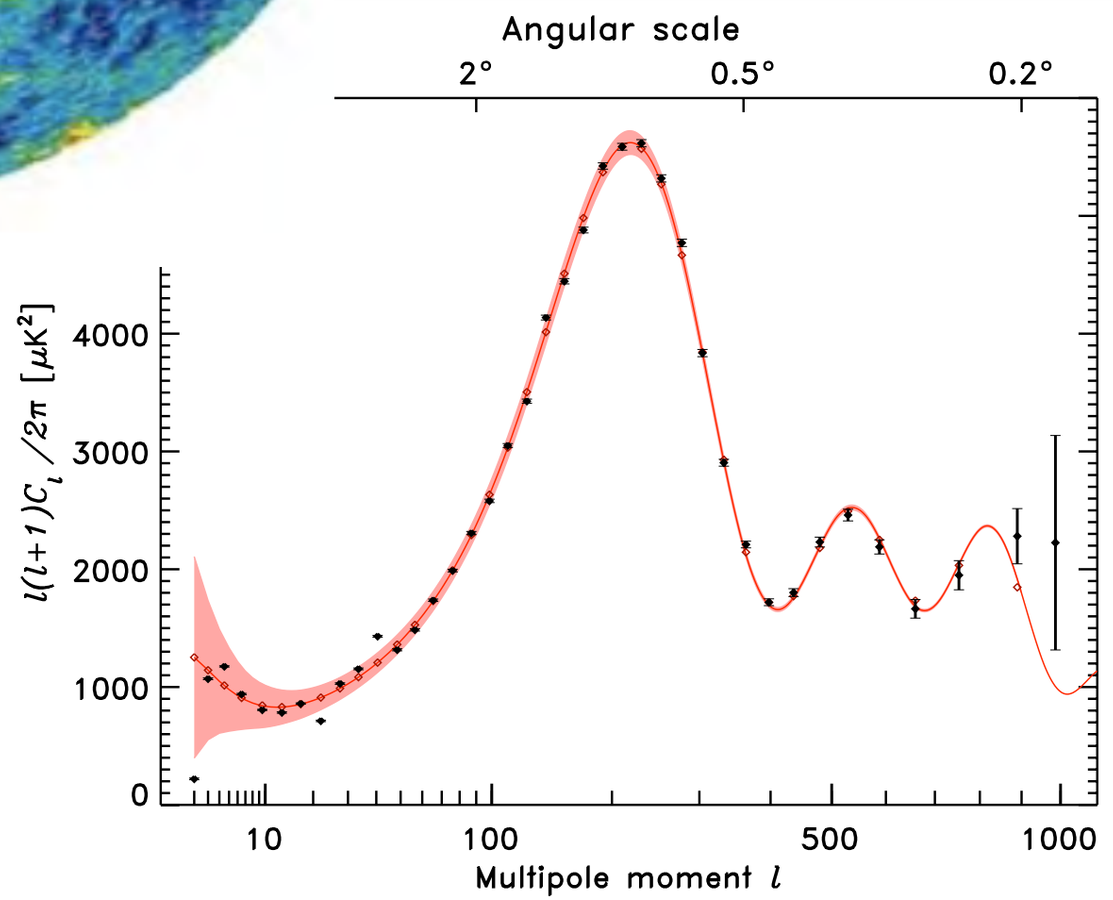


Cosmological scales



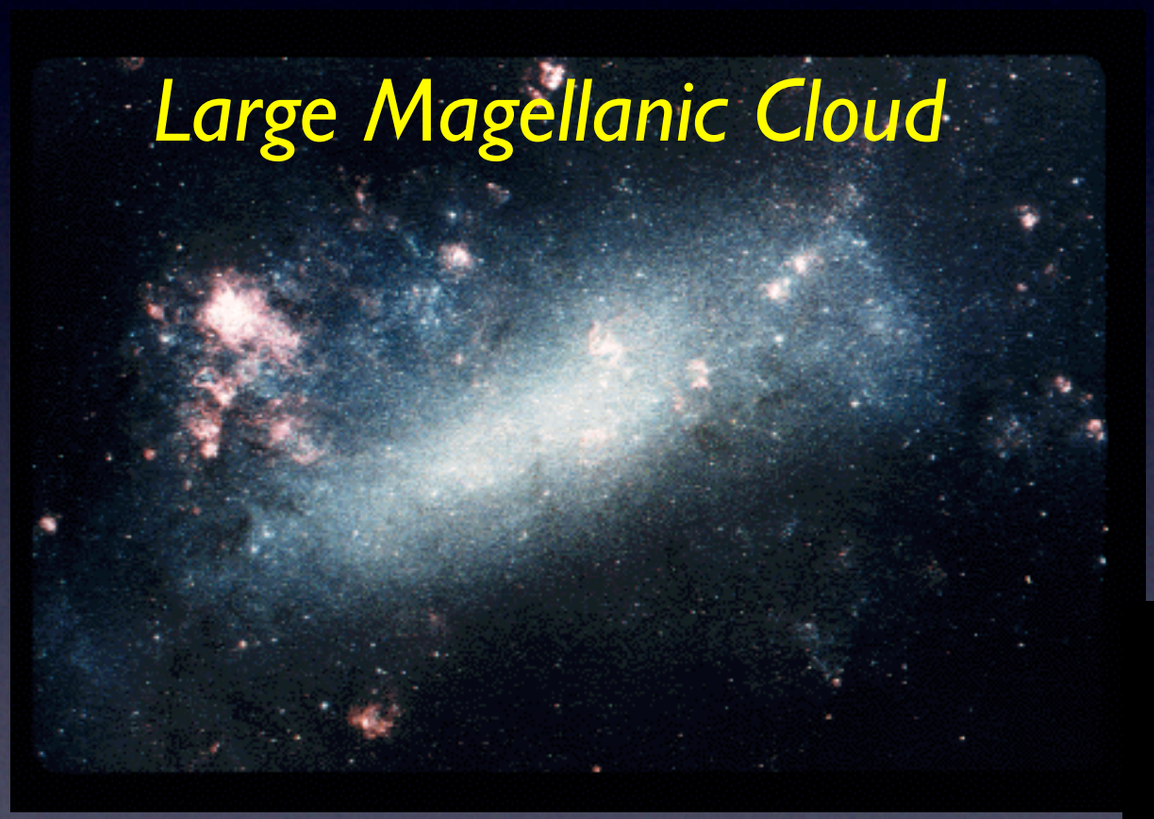


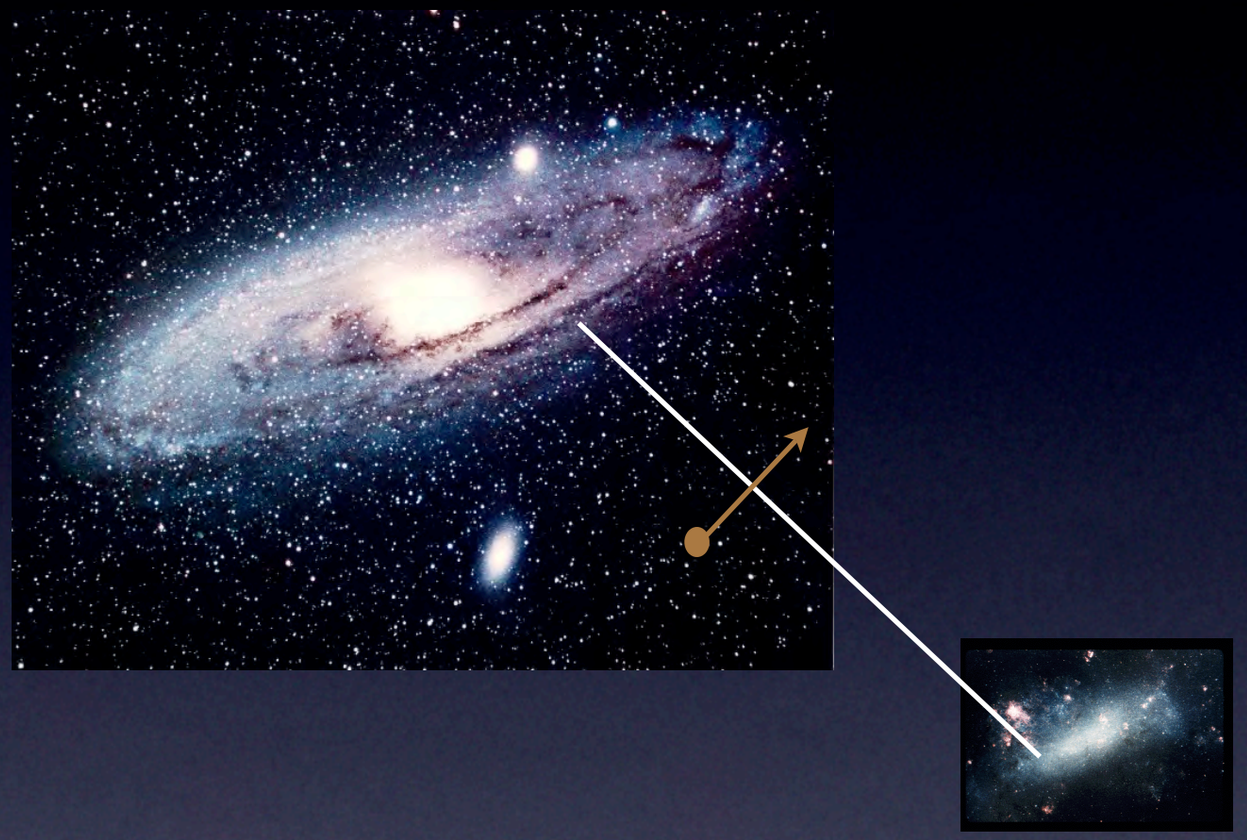
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

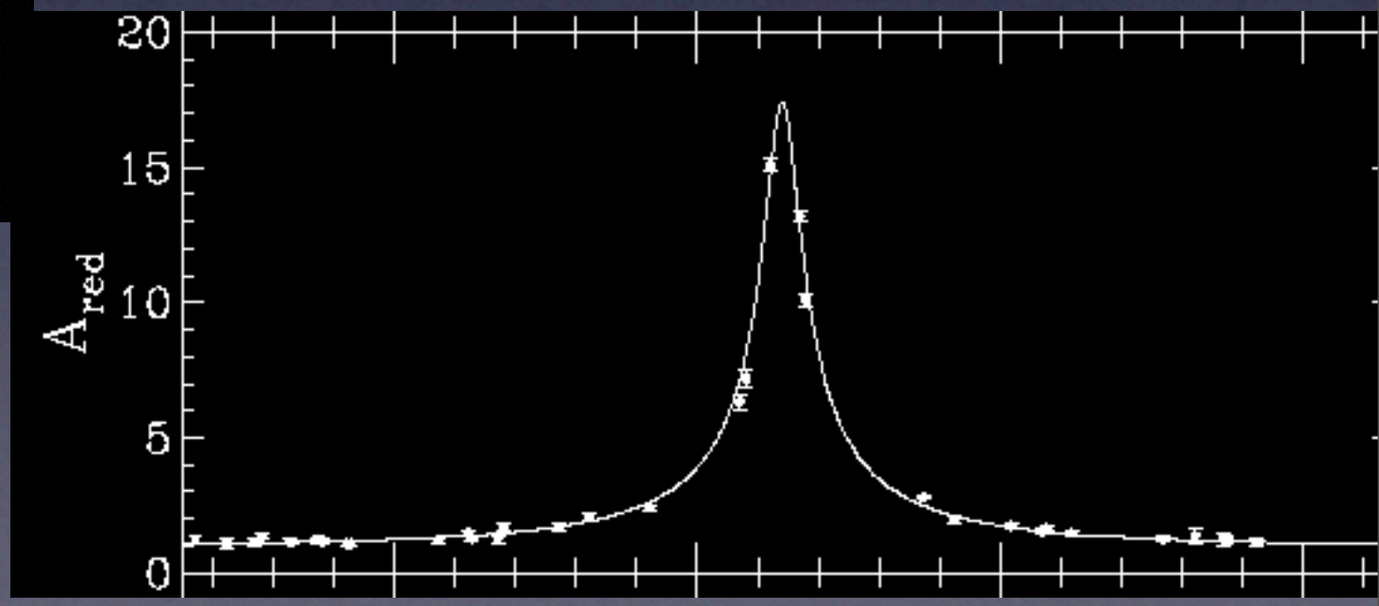


Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)



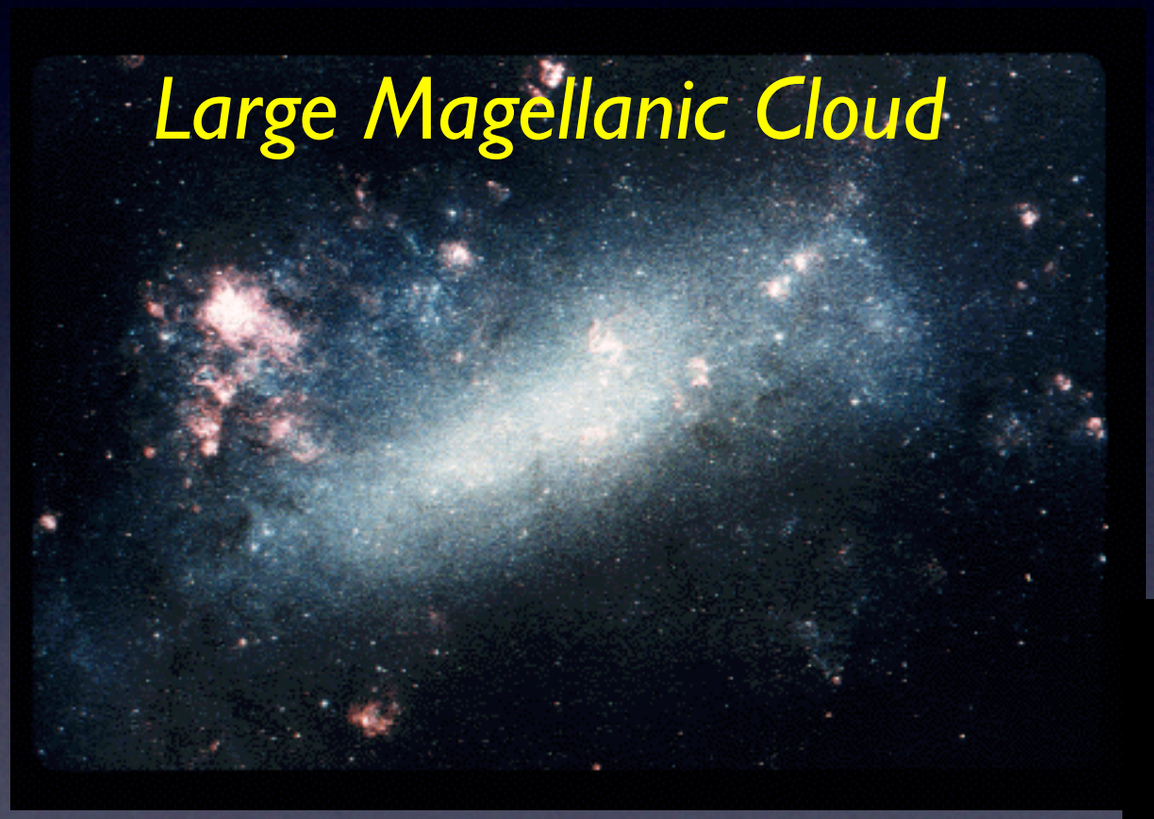


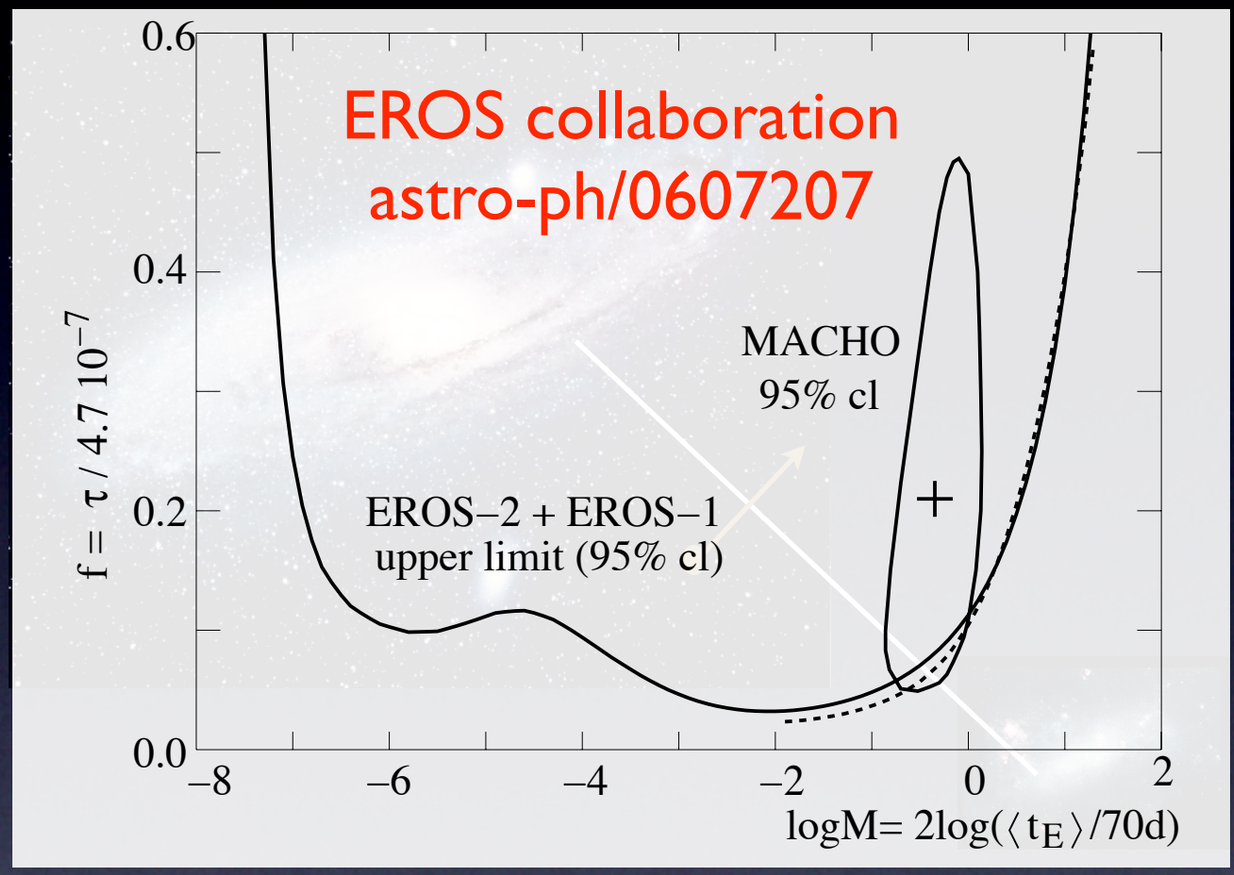


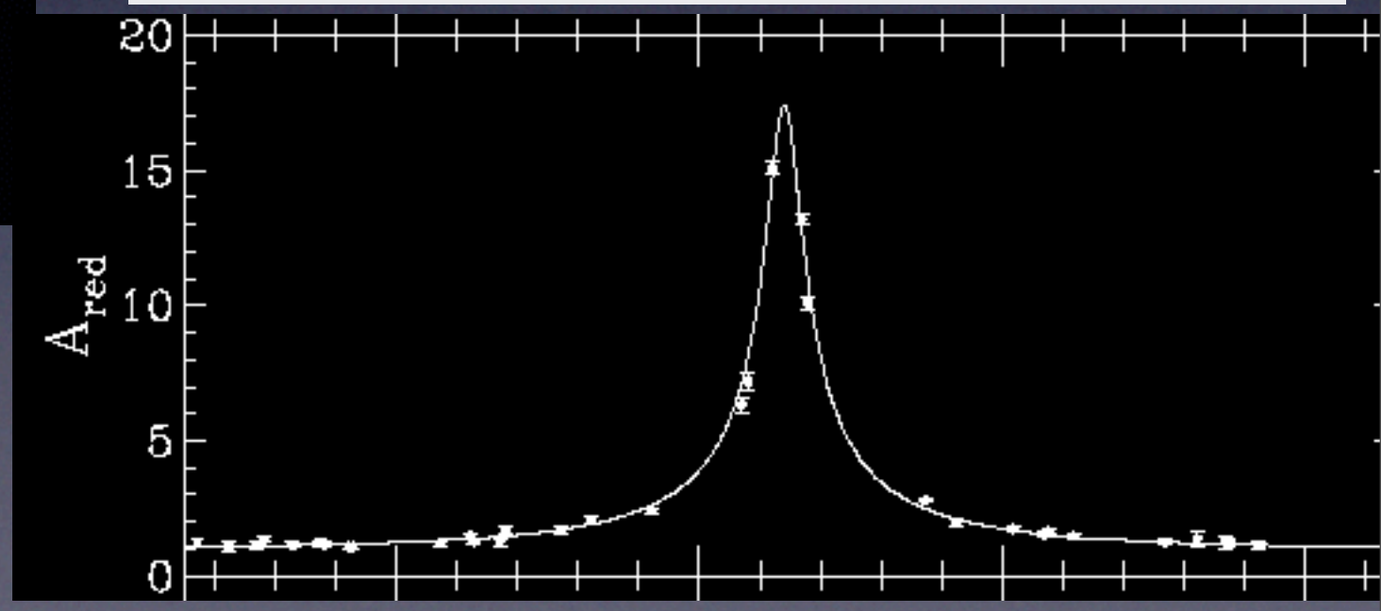
Not enough of them!

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)

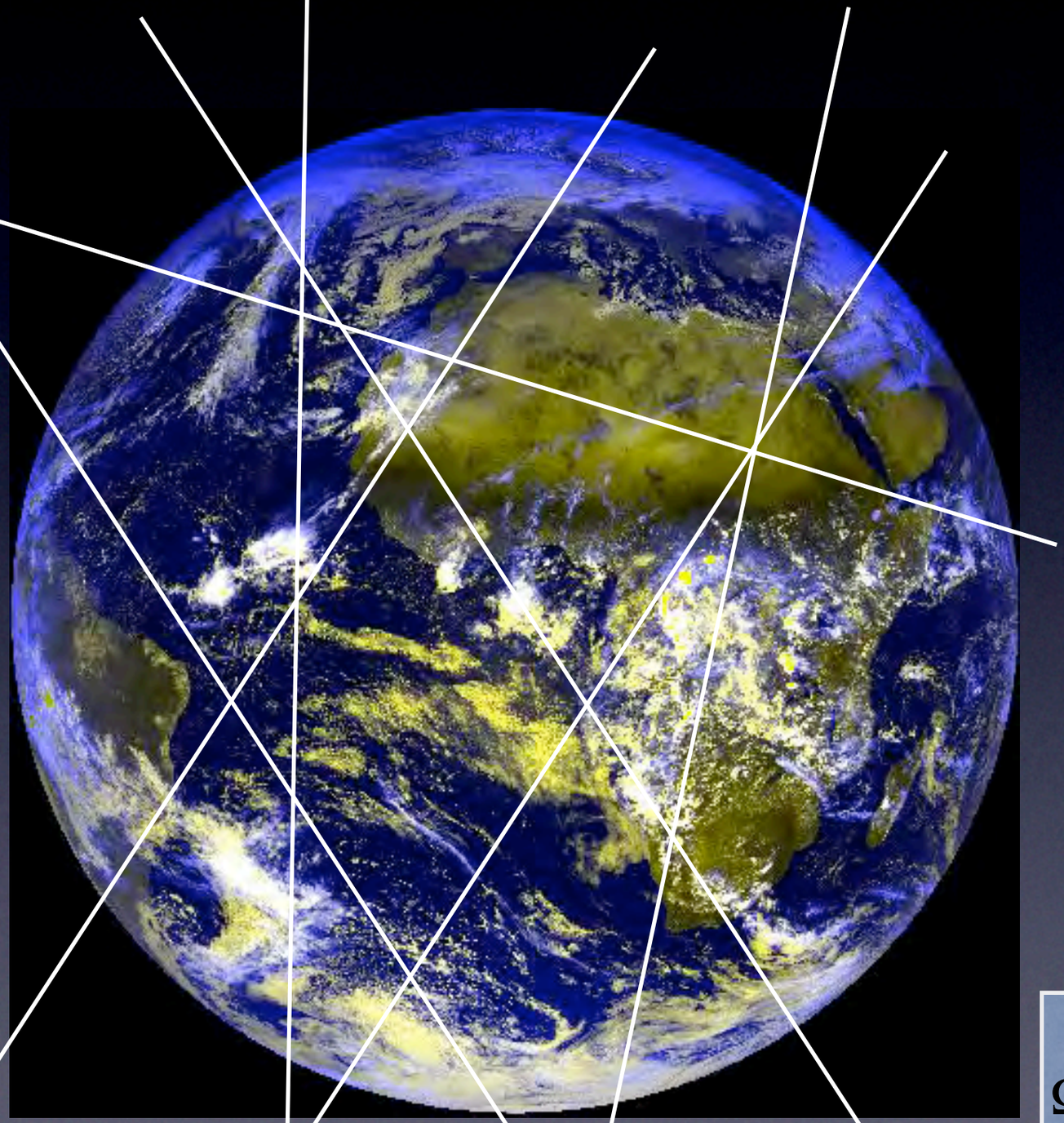






Not enough of them!

MACHO ⇒ WIMP



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

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

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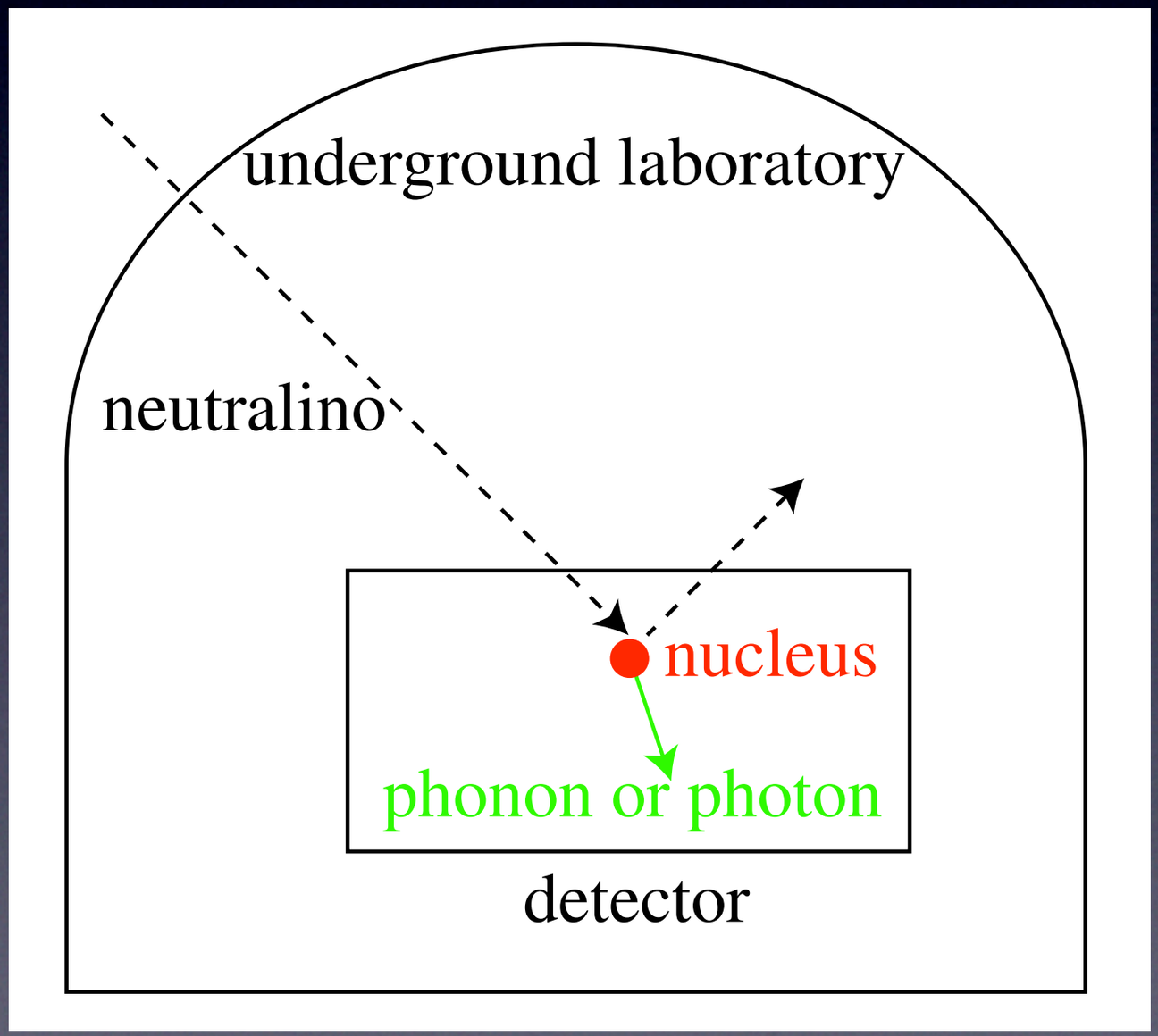
Finding Dark Matter

Direct method



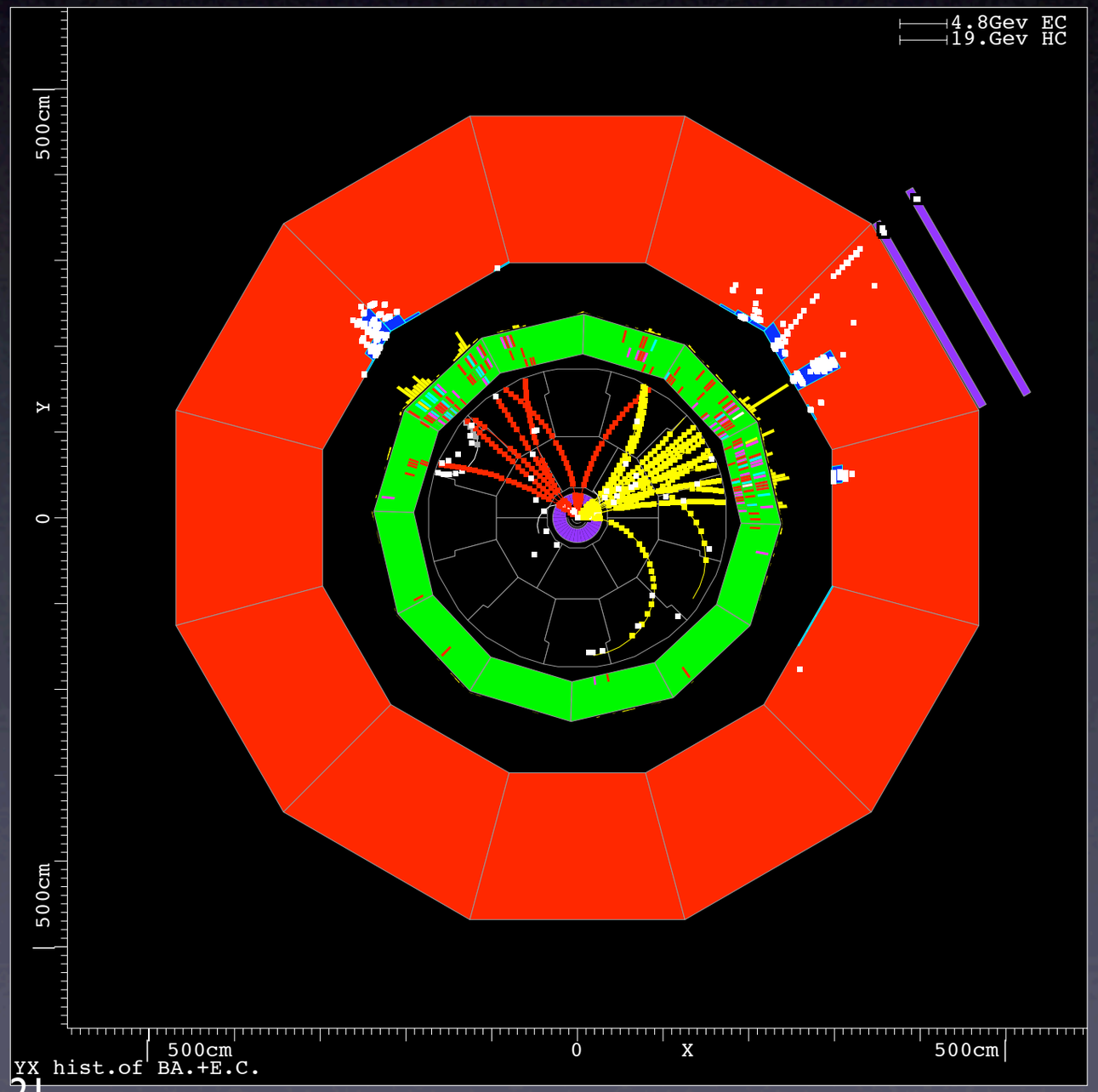
Producing Dark Matter in the laboratory

- 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!?



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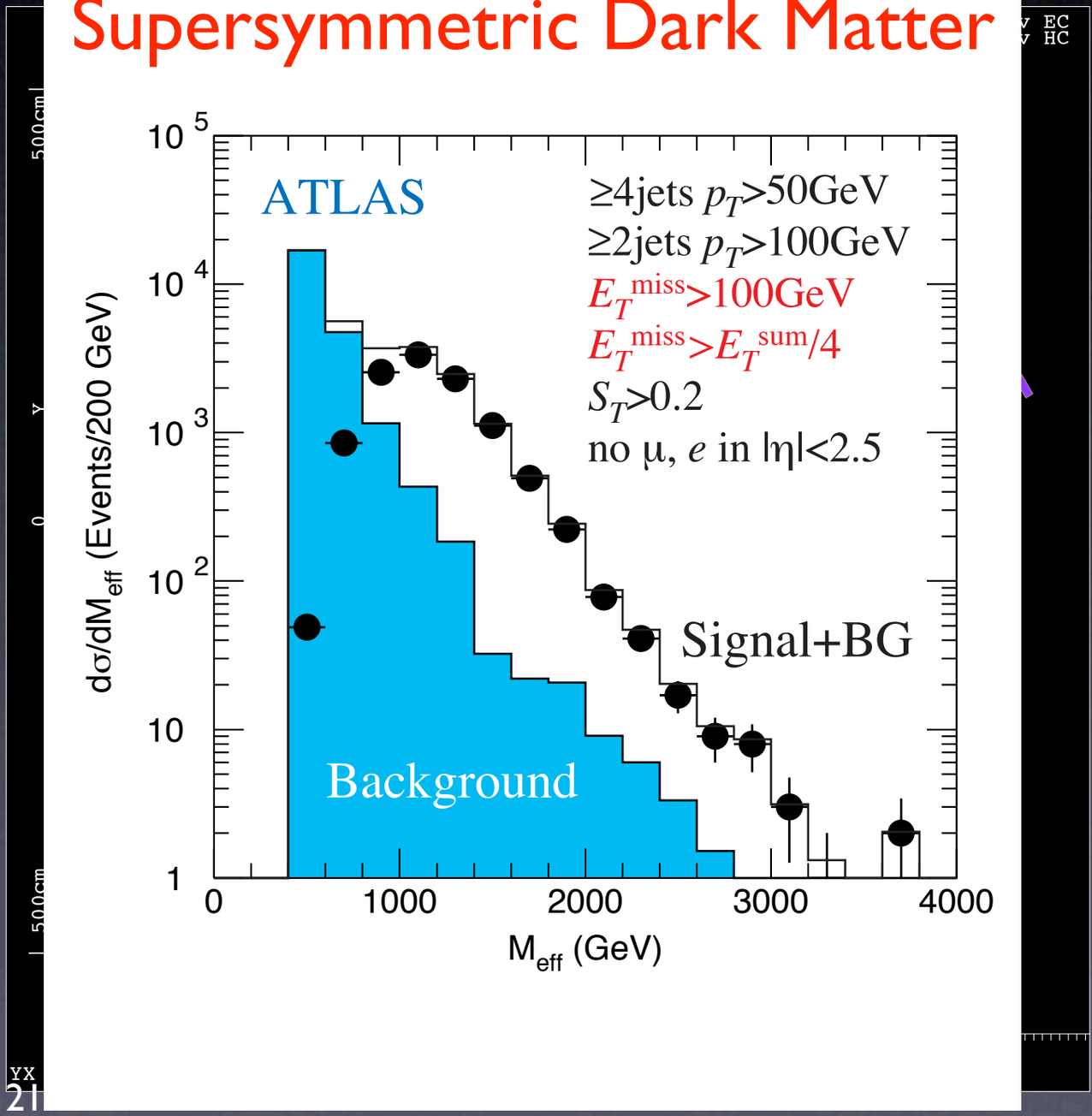
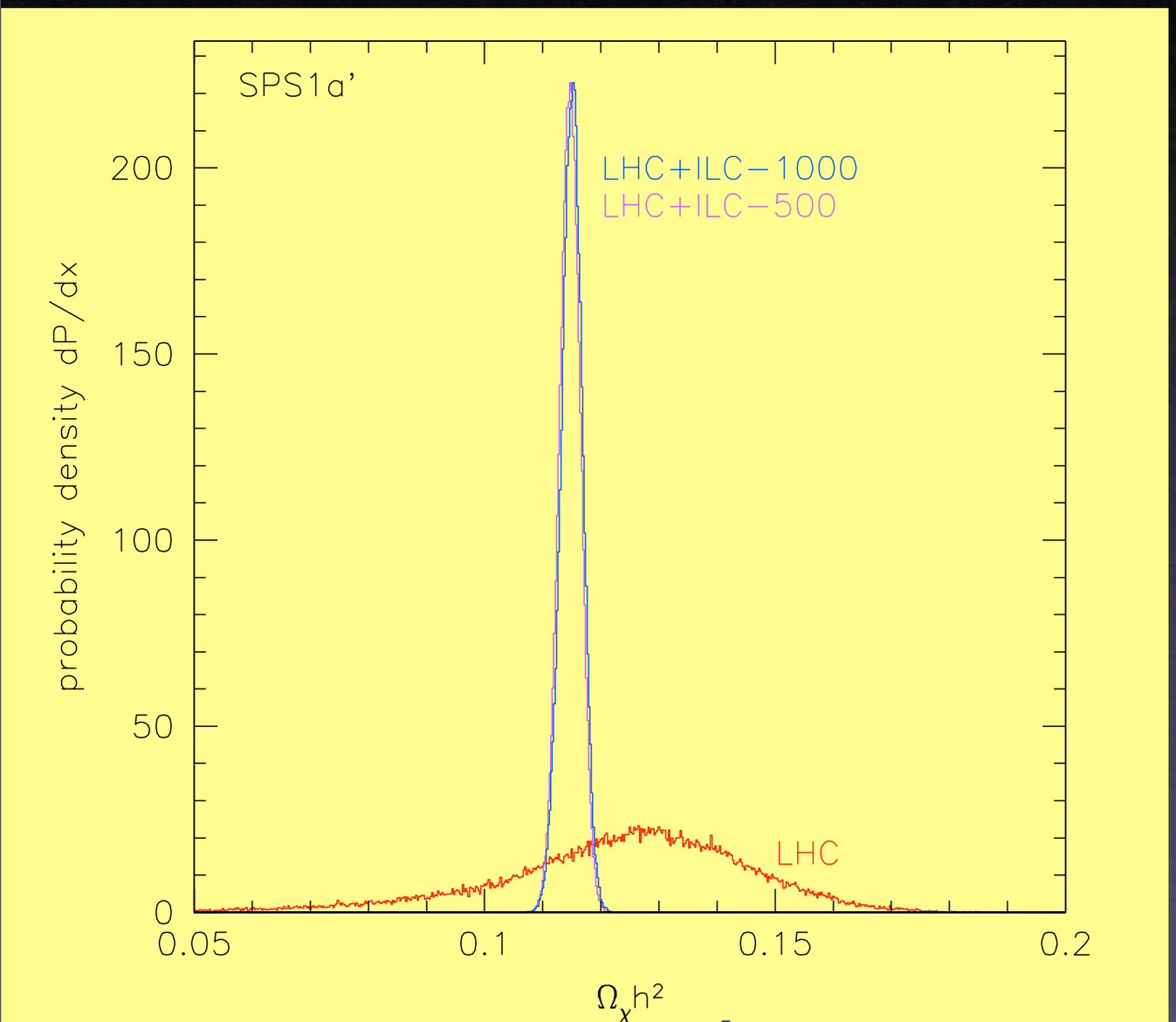
⇒Dark Matter!?

Supersymmetric Dark Matter



Measure the Universe with colliders



case study

Baltz, et al, hep-ph/0602187

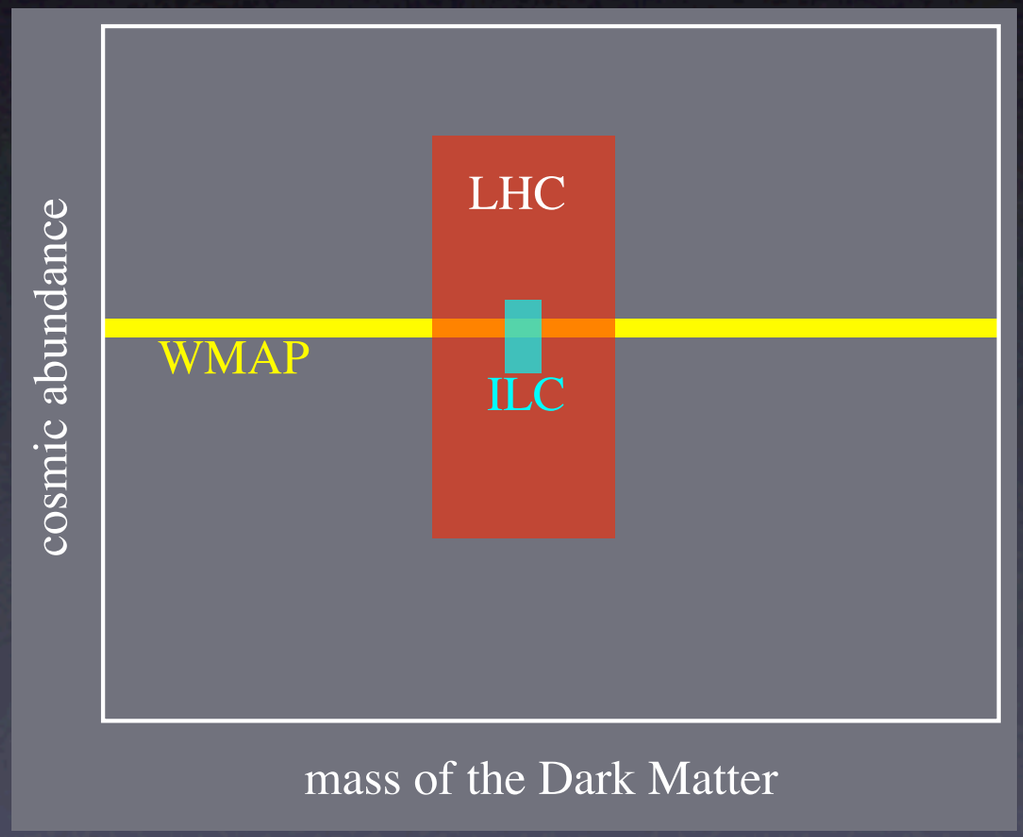
- With LHC & ILC data, we can calculate how much dark matter there *should* be
- Does that agree with the way the Universe *is*?

Dark Matter Concordance

- 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

Accelerators: CERN-LHC, FNAL-Tevatron, BNL-RHIC, CERN-LEP, SLAC-SLC

high-energy cosmic rays

10⁻¹⁰ sec

1 min

400 Kyr

13.7 Byr

BIG BANG

Inflation

Can't see now

possible dark matter relicts

cosmic microwave radiation visible

	10⁻⁴⁴ s	10⁻³⁷ s	10⁻¹⁰ s	10⁻⁵ s	10² s	3x10⁵ y	10⁹ y	Today
t								
T	10³²	10²⁸	10¹⁵	10¹²	10⁹	3000	15	2.7
E	10¹⁹	10¹⁵	10²	10⁻¹	10⁻⁴	3x10⁻¹⁰	10⁻¹²	2.3x10⁻¹³

12x10⁹ y (sec,yrs)
(Kelvin)
(GeV)

Key:

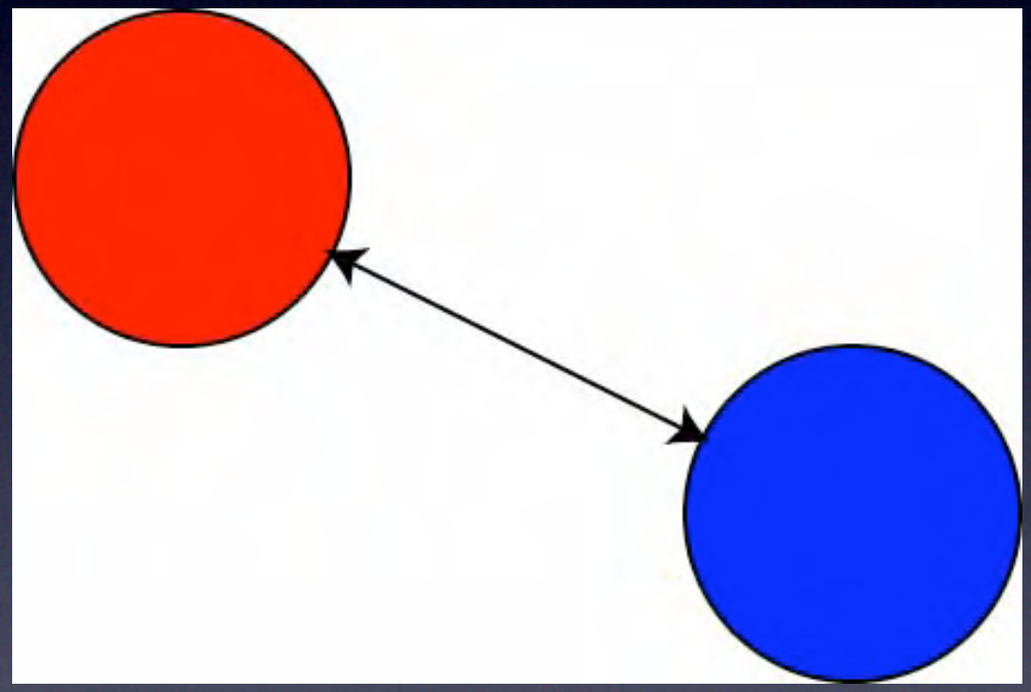
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
qq̄ meson
qqq baryon
ion
atom
photon
star
galaxy
black hole

Dark Field

=Cosmic Superconductor

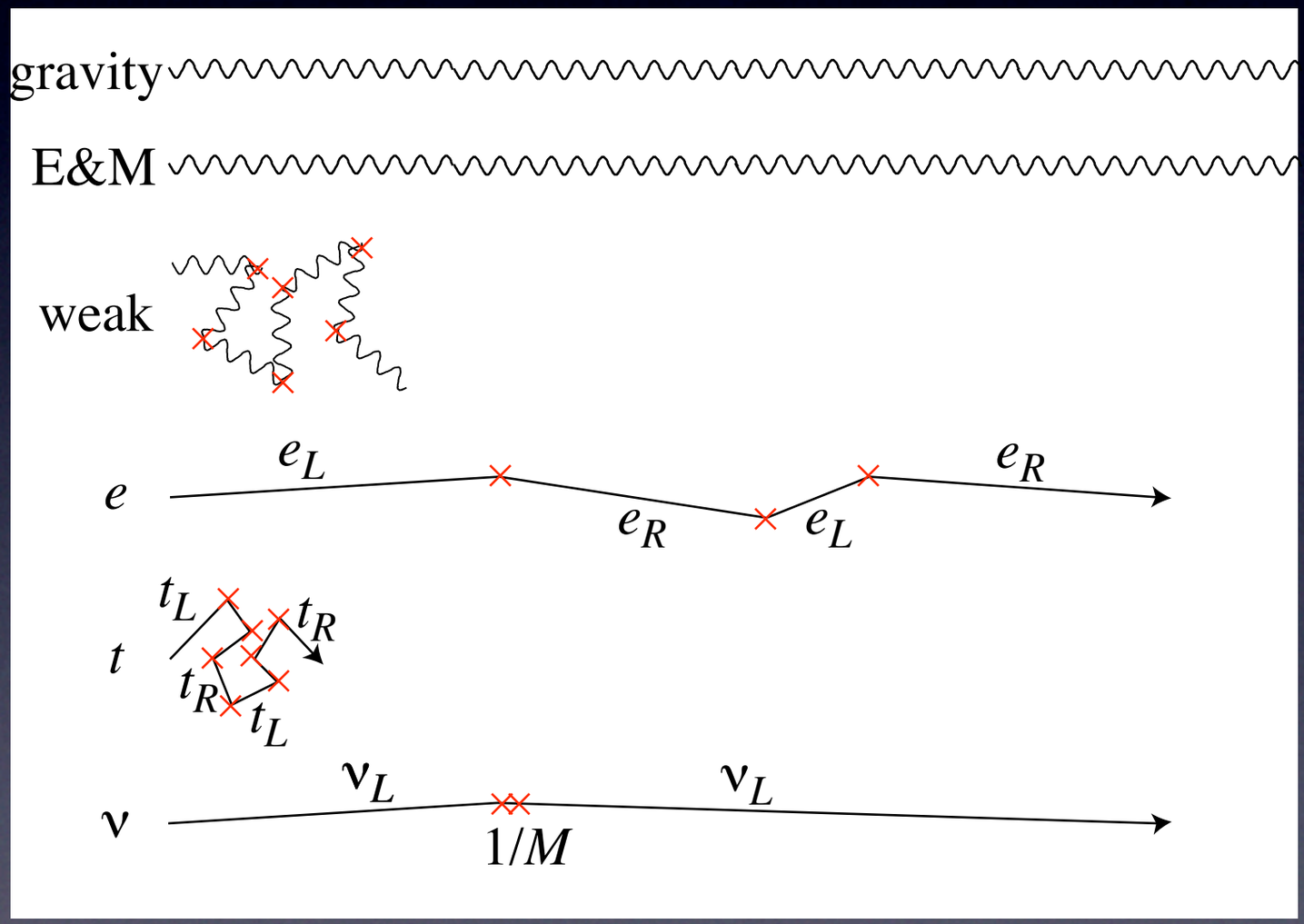
Mystery of the weak force

- 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
- We know the energy scale: ~0.3 TeV



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
- otherwise no atoms!
- What is it??



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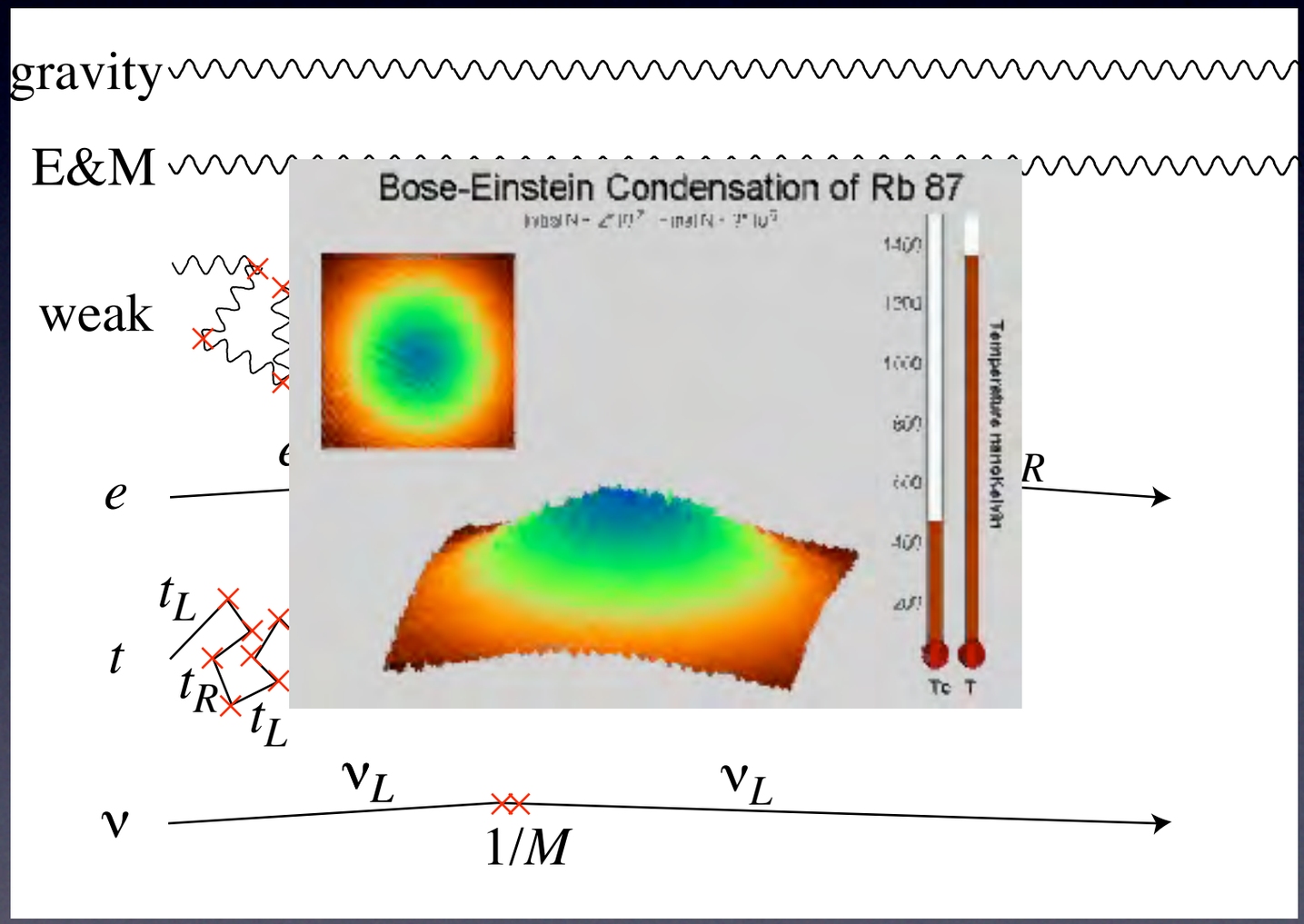


Cosmic Superconductor

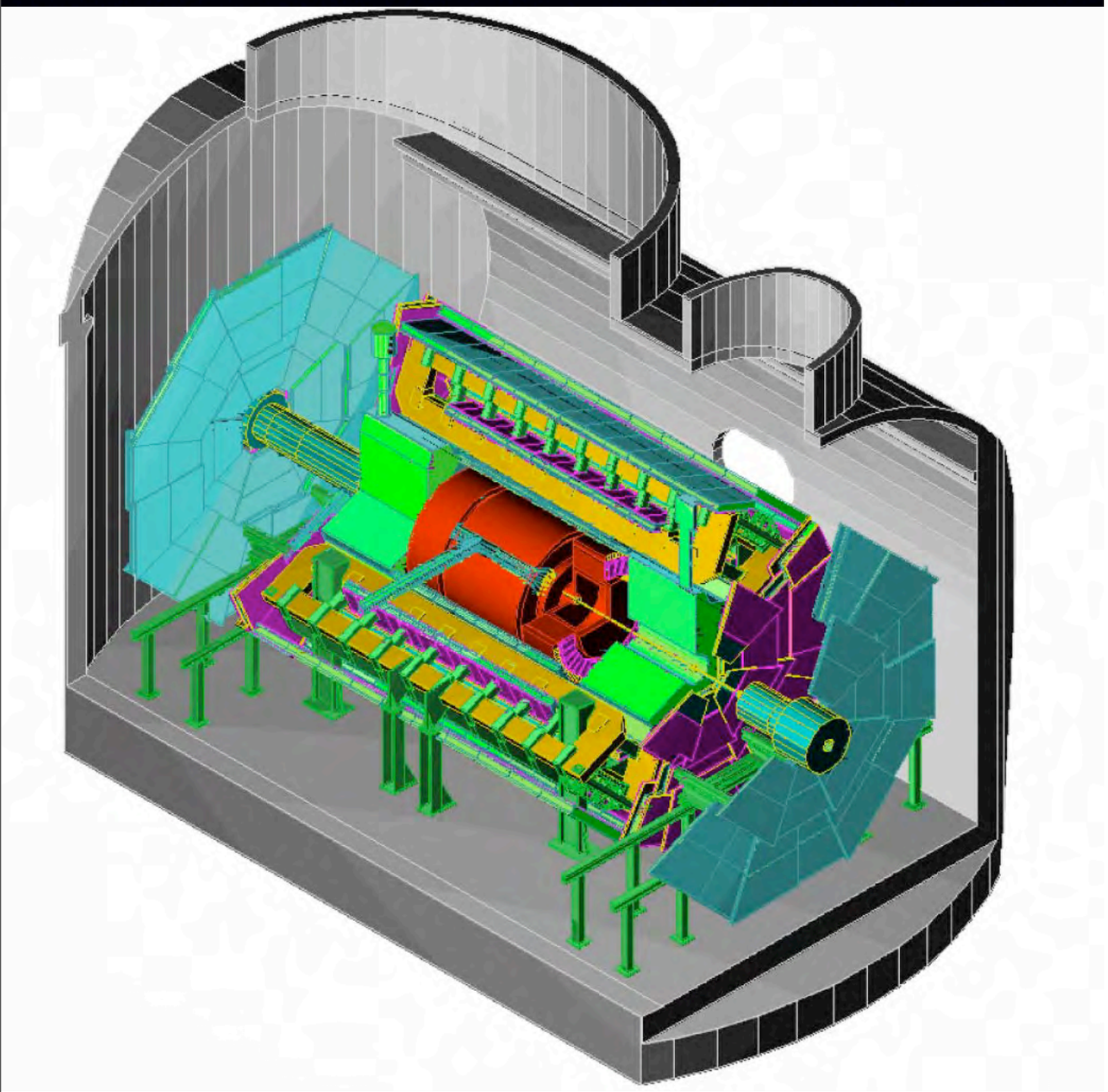
- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the "penetration length"

  ⇒ Magnetic field is short-ranged!

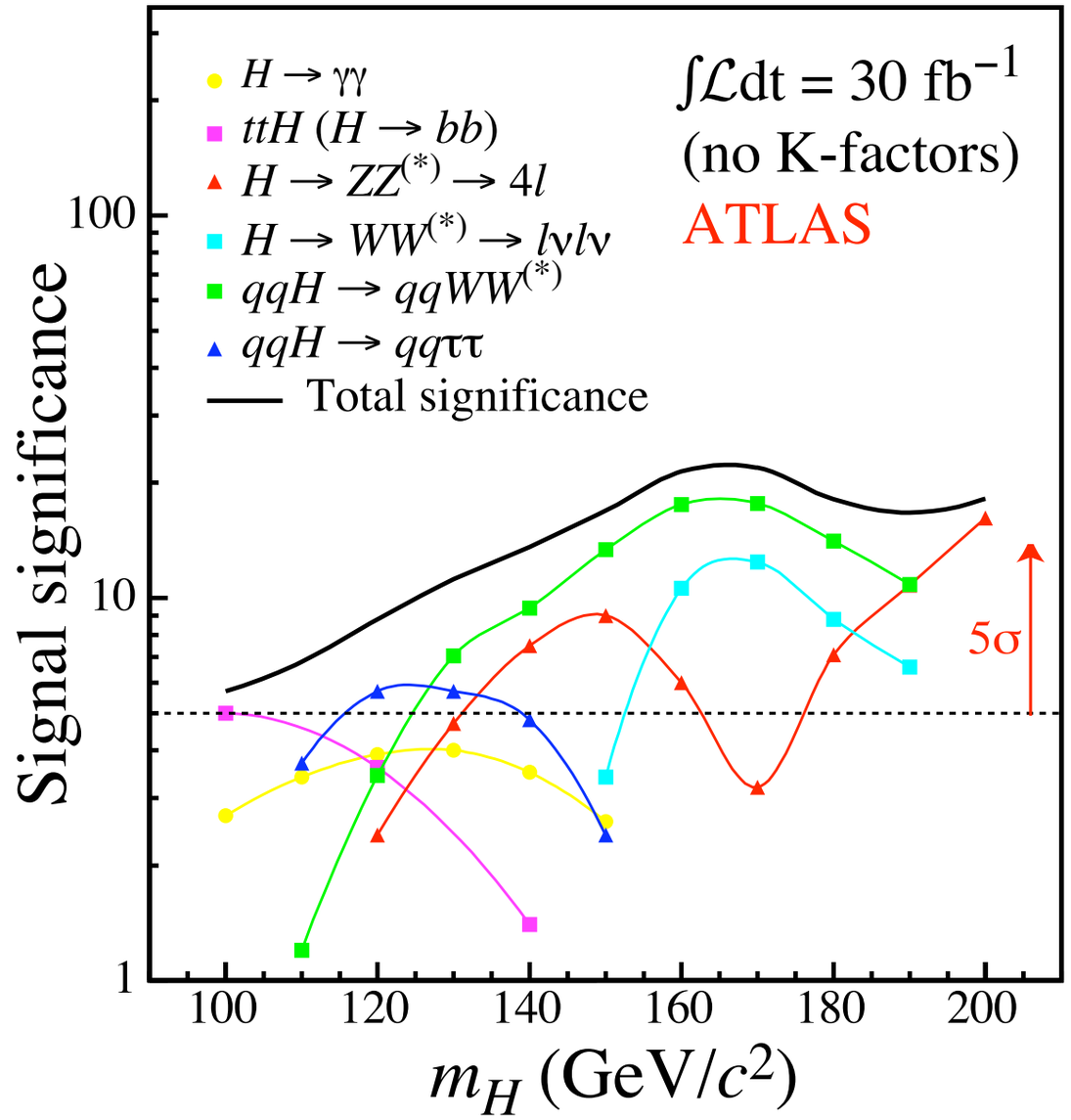
- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her "Universe"
  - But doesn't know what the condensate is, nor why it condenses
  - Doesn't have enough energy (gap) to break up Cooper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

That's the stage where we are!

Higgs at LHC



Robust discovery



Post-Higgs Problem

- 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

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)

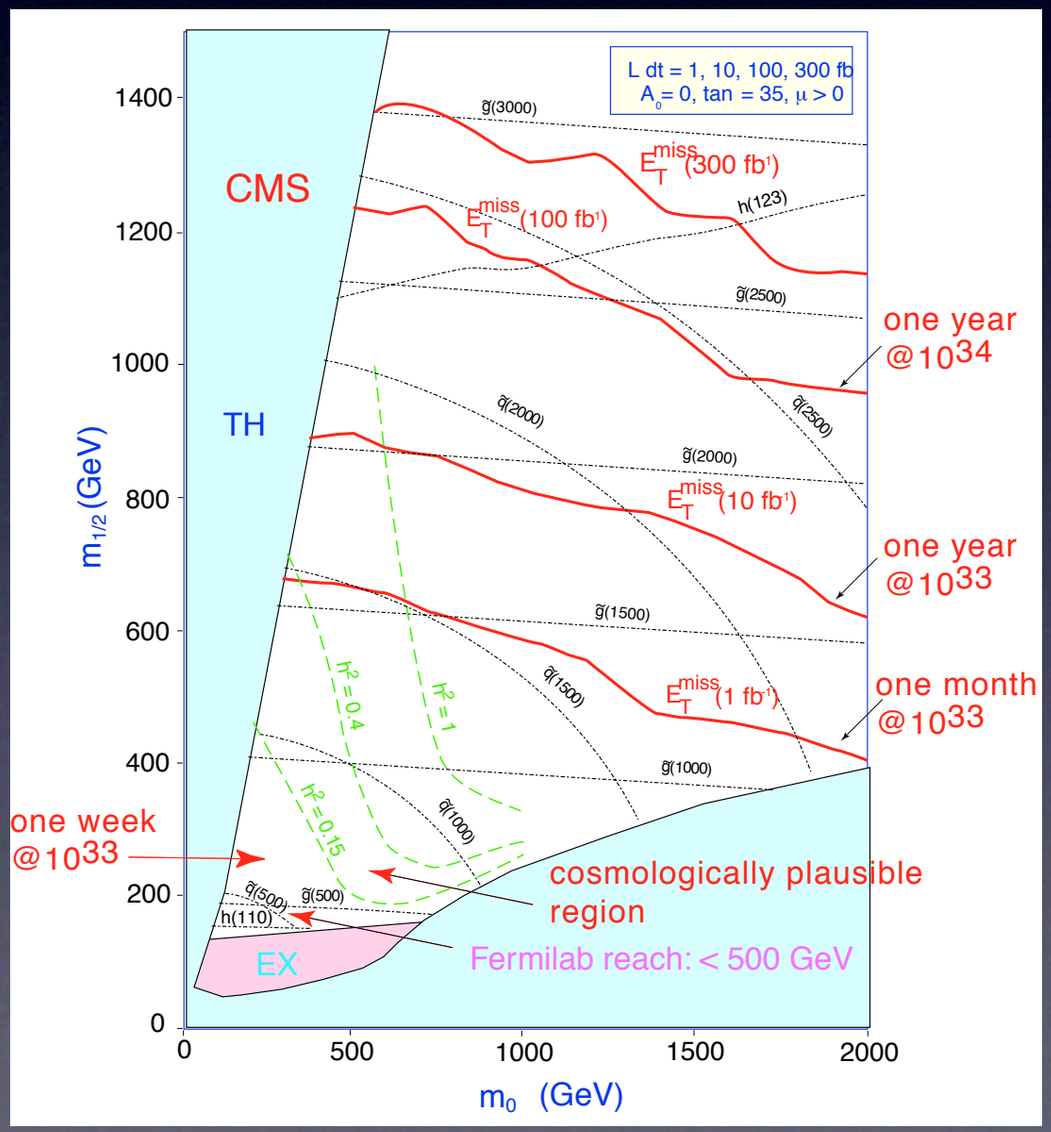
More Directions

- 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

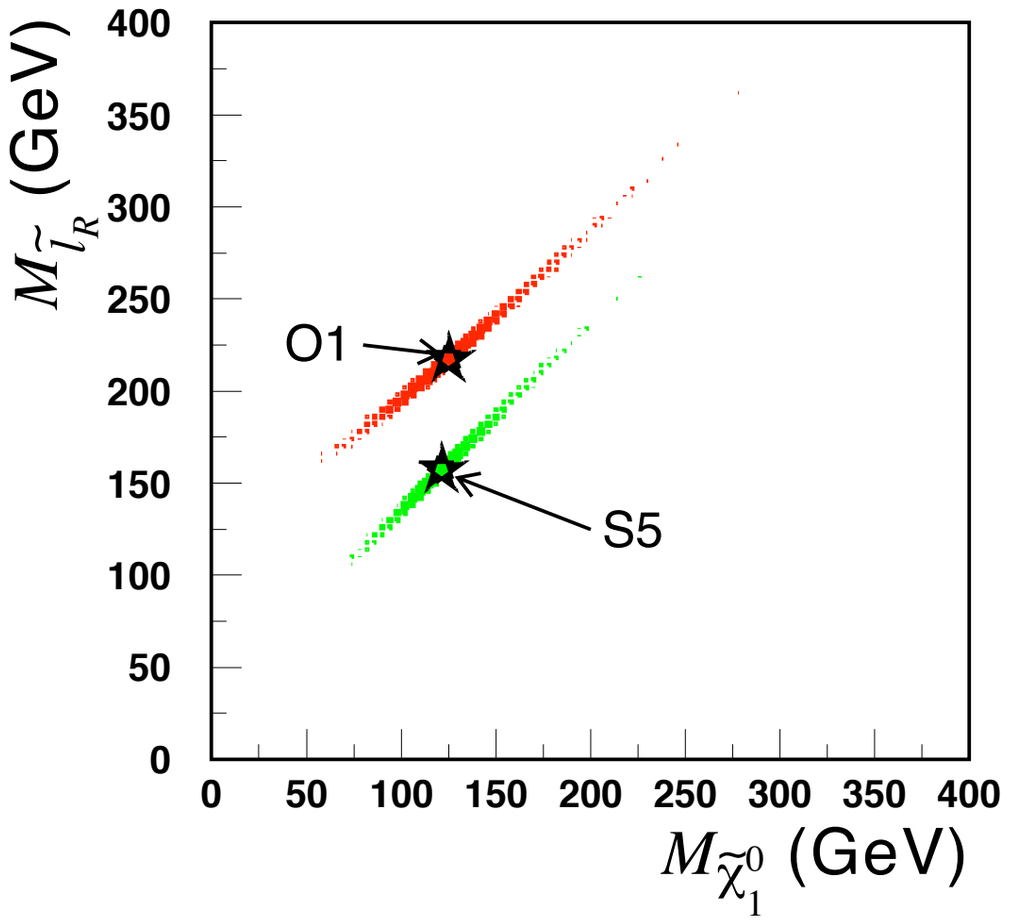
TC
bosonic TC
composite Higgs
TC-TC
hypercolor
supercolor
techni-GIM
extended TC
pseudo NGB
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
NOT YET THOUGHT OF
effective SUSY
SUSY
NNMSSM
NMSSM
MSSM +νR
ununified SM
axigluon
sterile ν
heavy Majorana ν
6th gen
5th gen
4th gen
lepto quark
vector-like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

Supersymmetry

Tevatron/LHC will discover supersymmetry

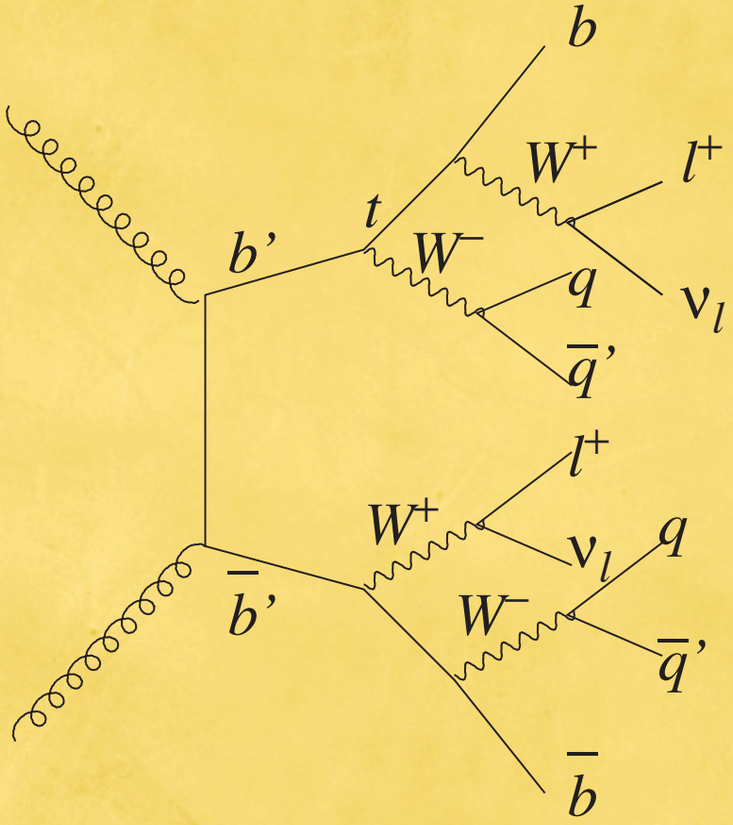


Can do many measurements at LHC

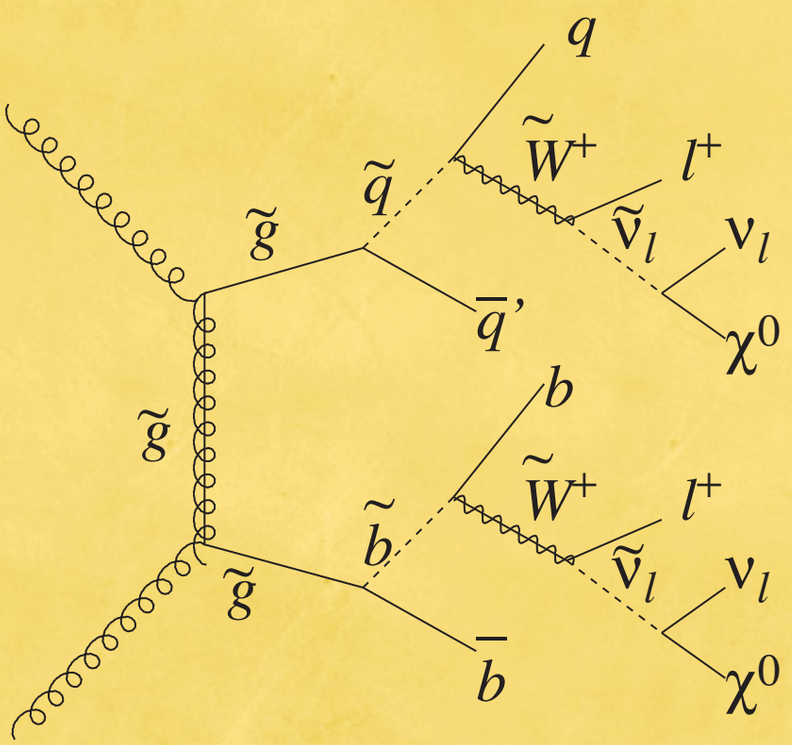


New physics looks alike

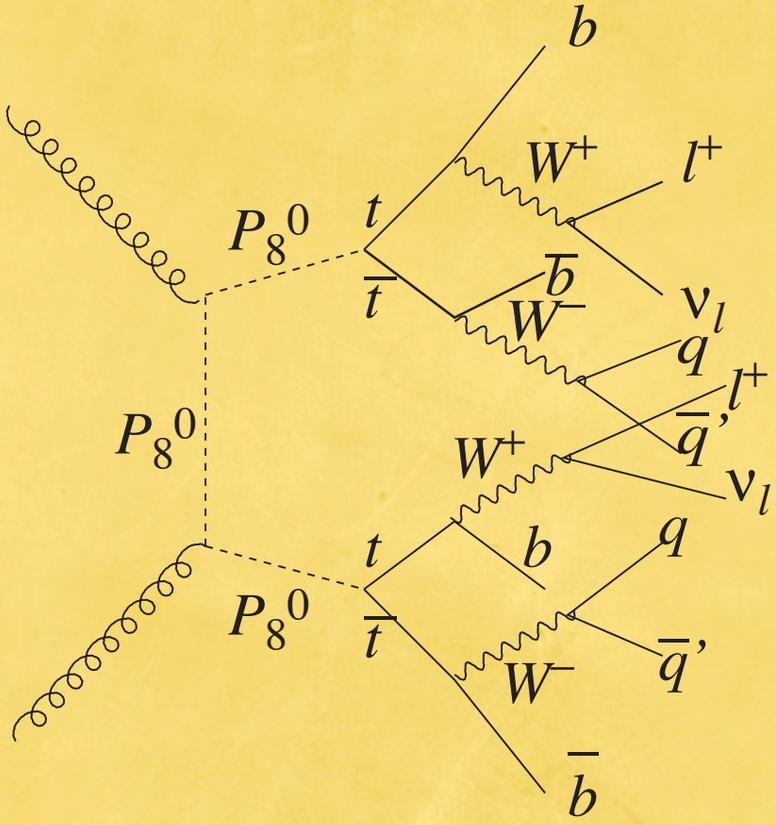
missing E_T, multiple jets, b-jets, (like-sign) di-leptons



4th generation



SUSY



technicolor

+Universal extra dimension, little Higgs with T-parity

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Need absolute confidence

As an example, supersymmetry

"New-York Times level" confidence

The New York Times

July 23, 2008

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."

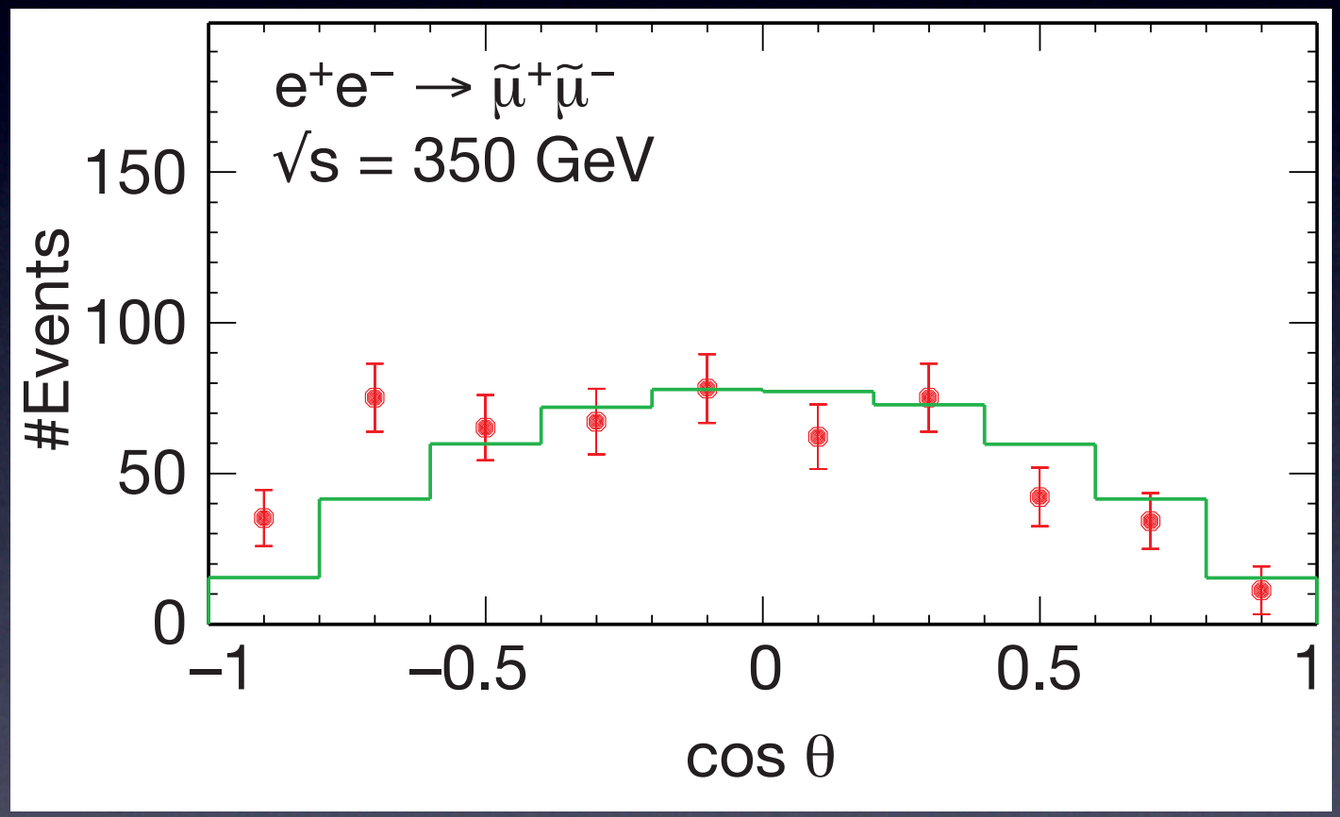
Reconstruct Lagrangian from data

- Specify the fields
  - mass
  - spin:Klein-Gordon, Dirac, Majorana, gauge
  - SU(3)xSU(2)xU(1) quantum numbers
  - mixing of states
- Specify their interactions
  - gauge interactions
  - Yukawa couplings
  - trilinear and quartic scalar couplings

Prove Superpartners

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

Spin 0?

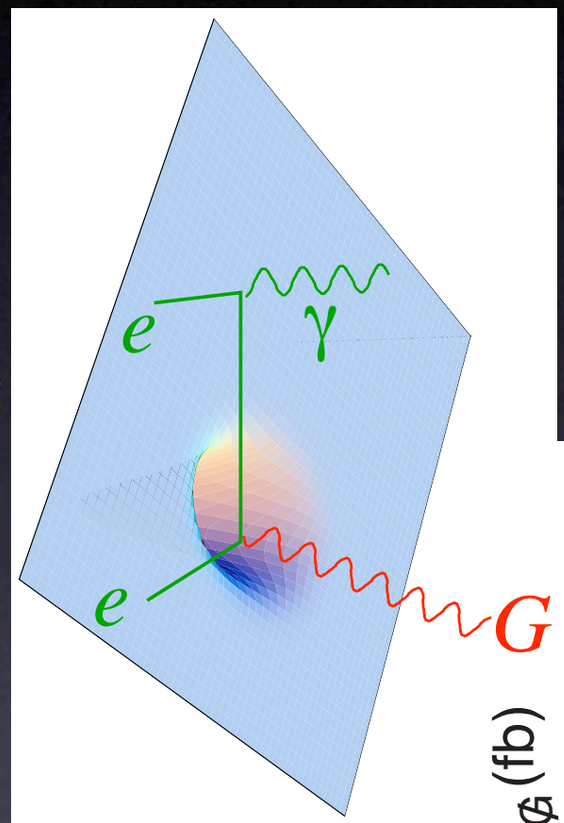


Tsukamoto, Fujii, HM, Yamaguchi, Okada

Hidden Dimensions

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

⇒ How many extra dimensions are there?



History of the Universe

Accelerators: CERN-LHC, FNAL-Tevatron, BNL-RHIC, CERN-LEP, SLAC-SLC

high-energy cosmic rays

10⁻¹⁰ sec

1 min

400 Kyr

13.7 Byr

BIG BANG

Inflation

Can't see now

possible dark matter relicts

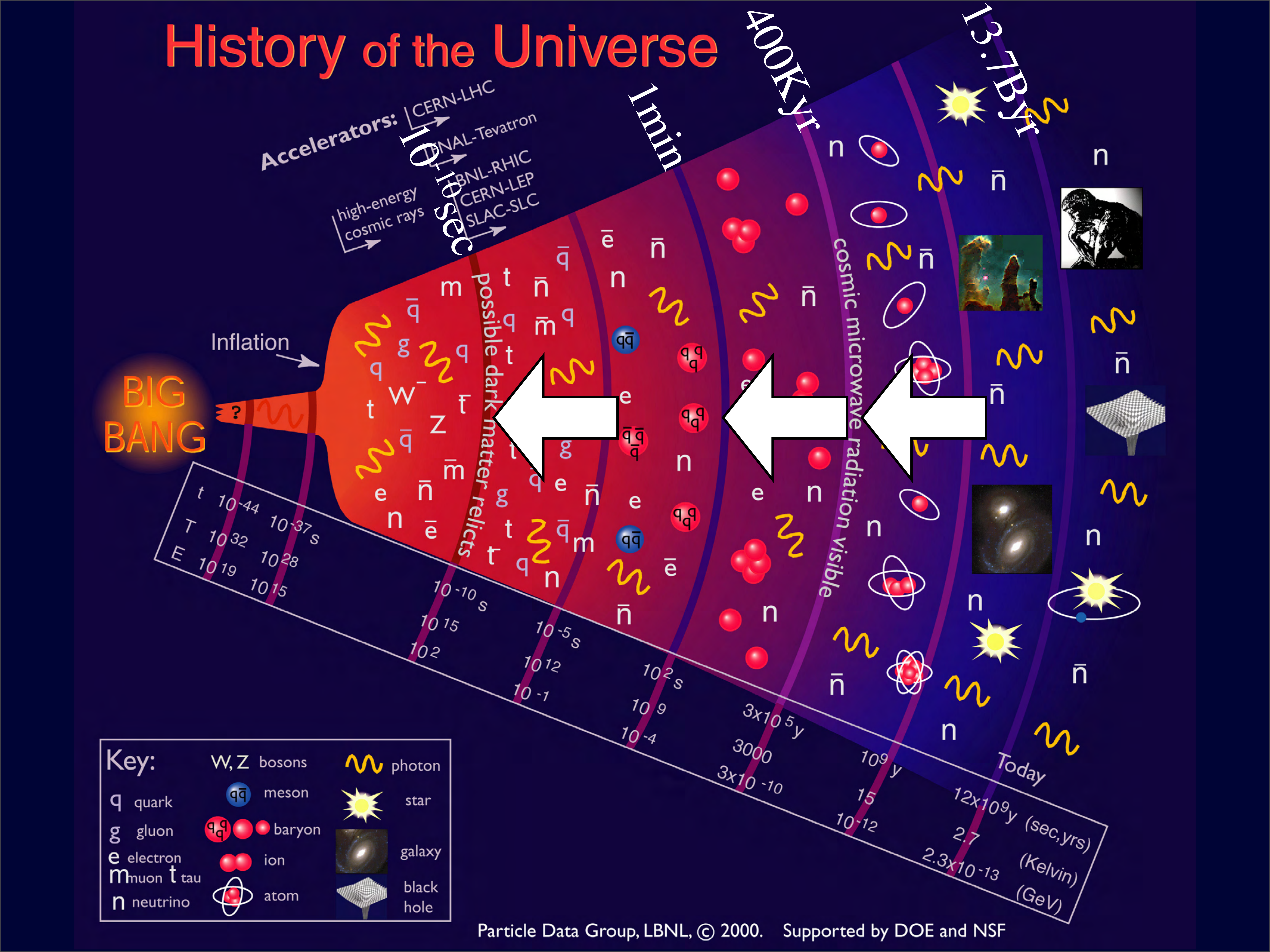
cosmic microwave radiation visible

	10⁻⁴⁴ s	10⁻³⁷ s	10⁻¹⁰ s	10⁻⁵ s	10² s	3x10⁵ y	10⁹ y	Today
t								
T	10³²	10²⁸	10¹⁵	10¹²	10⁹	3000	15	2.7
E	10¹⁹	10¹⁵	10²	10⁻¹	10⁻⁴	3x10⁻¹⁰	10⁻¹²	2.3x10⁻¹³

12x10⁹ y (sec,yrs)
(Kelvin)
(GeV)

Key:

q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
qq̄ meson
qqq baryon
ion
atom
photon
star
galaxy
black hole



History of the Universe
Accelerators:
CERN-LHC
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high-energy cosmic rays
10-10sec
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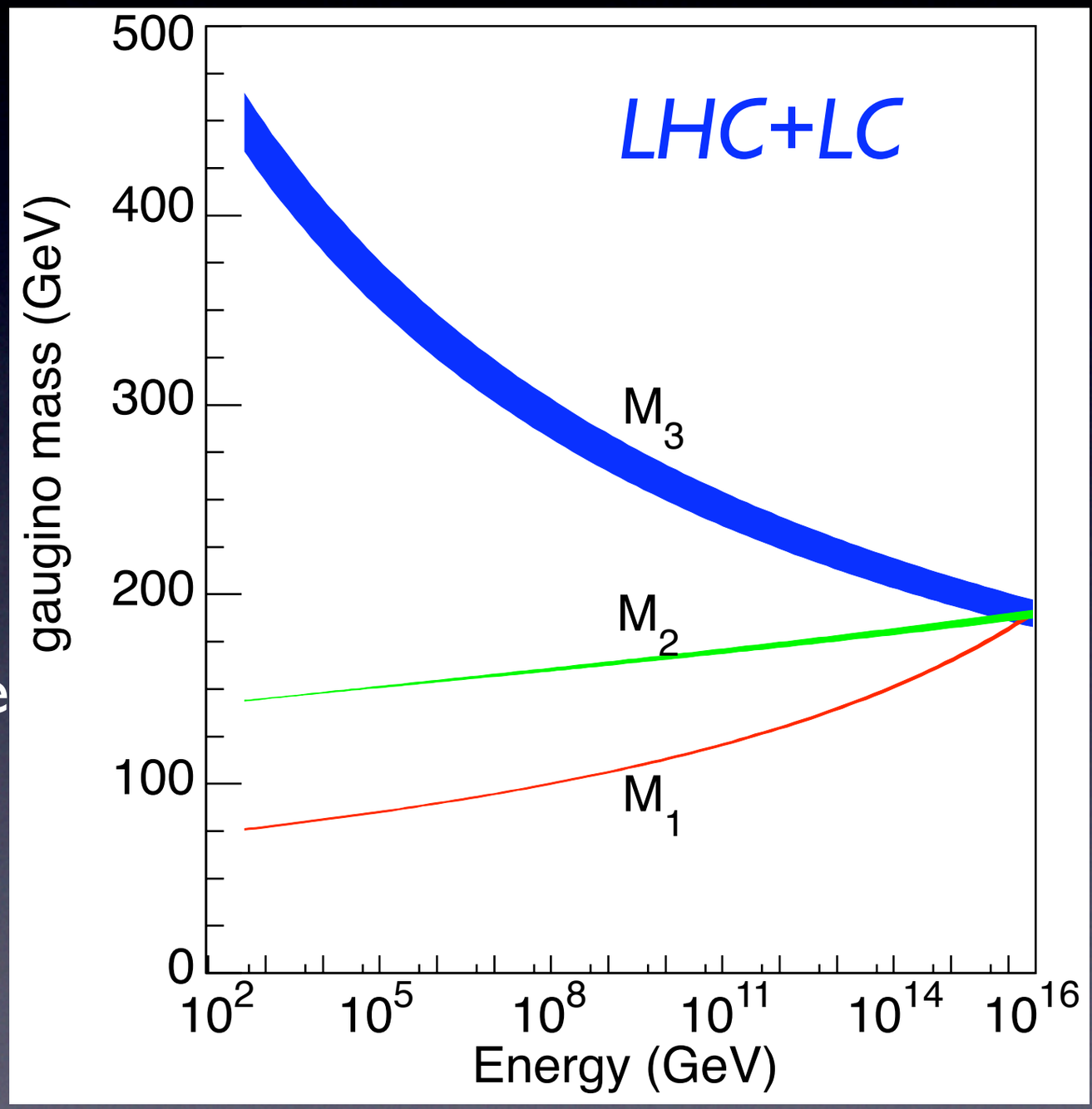
cosmic microwave radiation visible
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Superpartners as probe

- Most exciting thing about superpartners beyond existence:

They carry information of small-distance physics to something we can measure

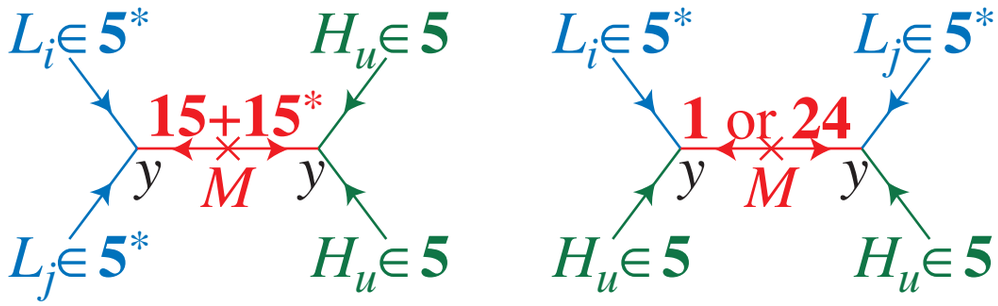
"Are forces unified?"

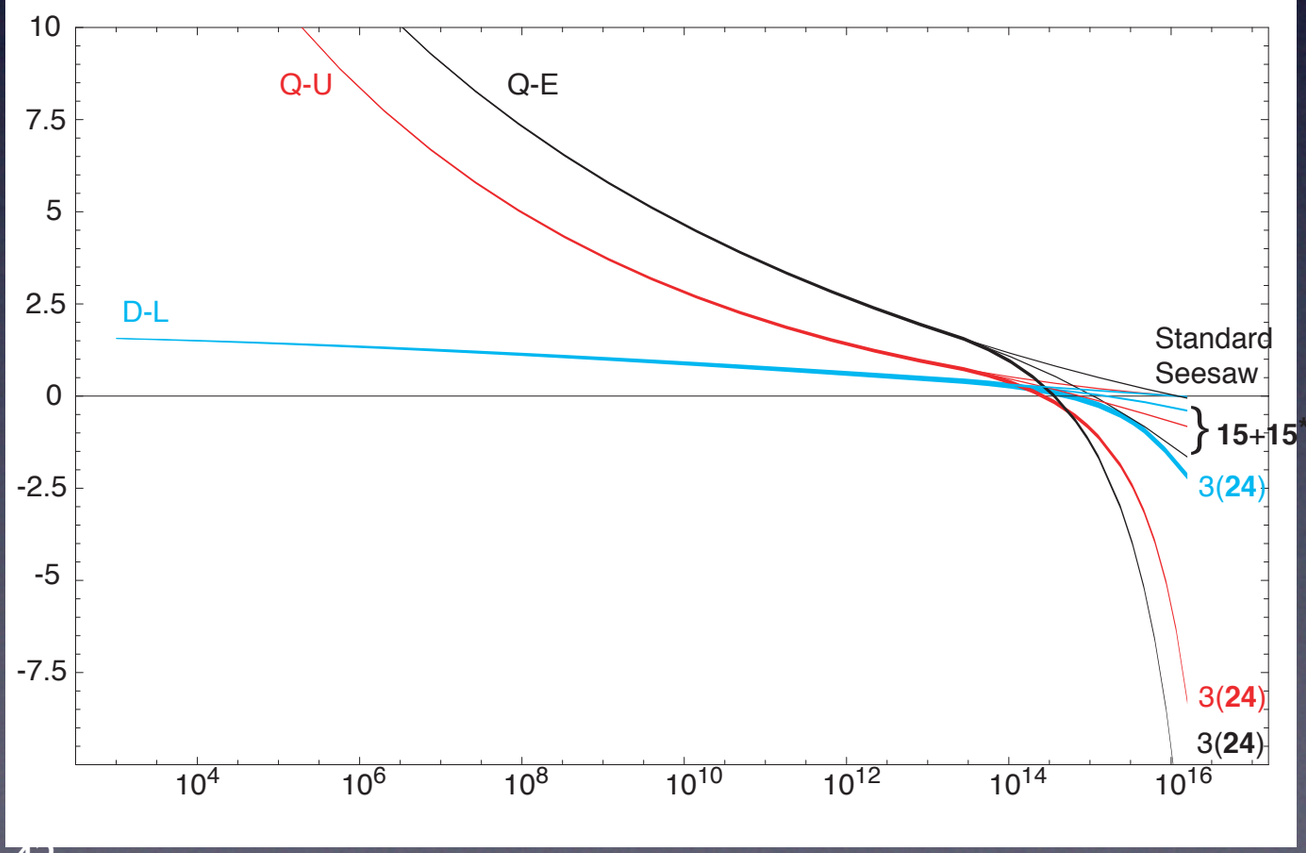


Why neutrino mass?

- Neutrino mass likely comes from physics at $>10^{10}$ GeV
- How will we ever know?
- Precision measurements at LHC/ILC determine boundary conditions at 10^{16} GeV
- With both ends fixed, we can constrain physics in between

Buckley, HM





Einstein's Telescope

With both LHC and ILC, we hope to see

- way beyond the energy scale we can probe directly, i.e. unification and string scales
- Back to the Beginning of the Universe

Conclusions

- Particle Physics and Cosmology are intimately connected
- Questions of the New Millennium facing us
- Many reasons to believe Terascale is rich
- But Terascale physics totally unknown
- to figure out what it is, we need ILC
- Hope to understand what dark matter is
- Looking back at the Beginning