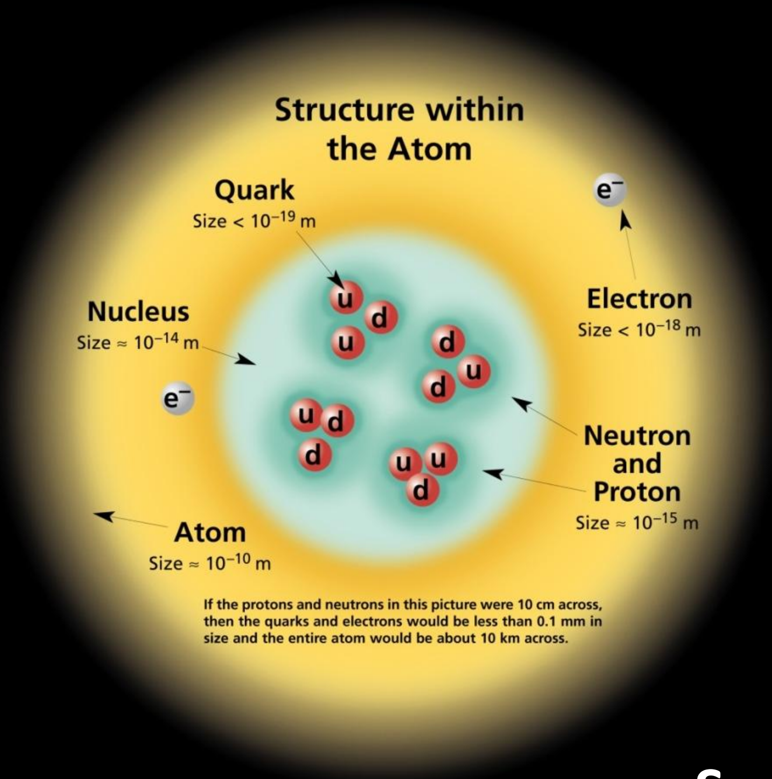
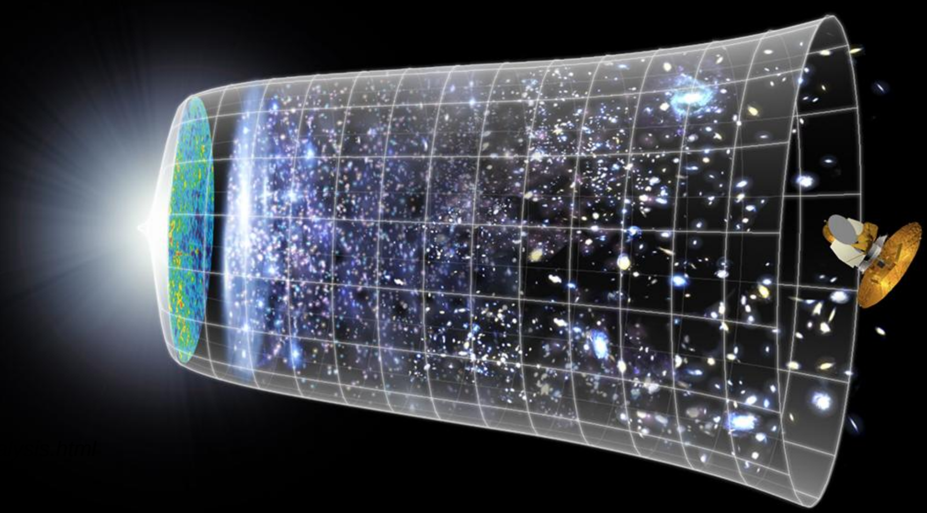
Hunting For Dark Matter with Pixel Detectors

University of Hawaii Colloquium





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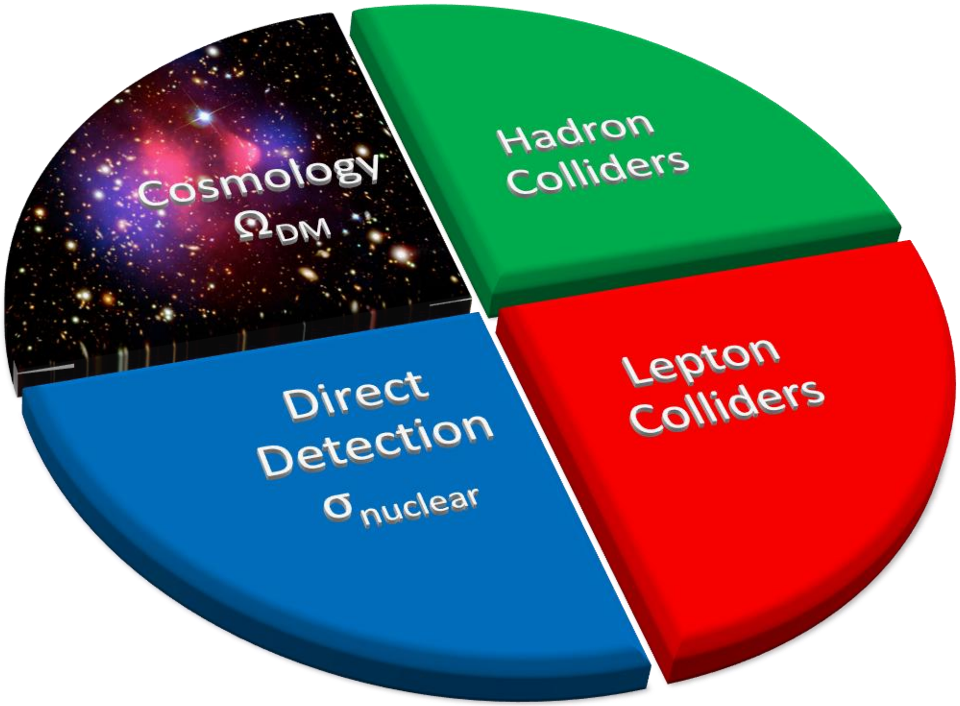
Lawrence Berkeley Lab

Solving the Dark Matter Problem

- Clear evidence for Dark Matter from Experimental Cosmology
  - Undiscovered elementary particle ?



- Multiple experiments needed to clarify
  - Produce DM particle
  - Measure it precisely
  - (In)Directly Detect DM

Compare results→ do we understand
- DM Production in early universe?
- DM in our galaxy today?

Exciting: Next Discoveries possible soon at Large Hadron Collider!

Outline

- Introduction
  - The Standard Model of Particle Physics
  - Why the Standard Model is not enough
  - The Dark Matter: Supersymmetric Particle?
- Hadron Colliders
- Lepton Colliders
- Direct Dark Matter Detection

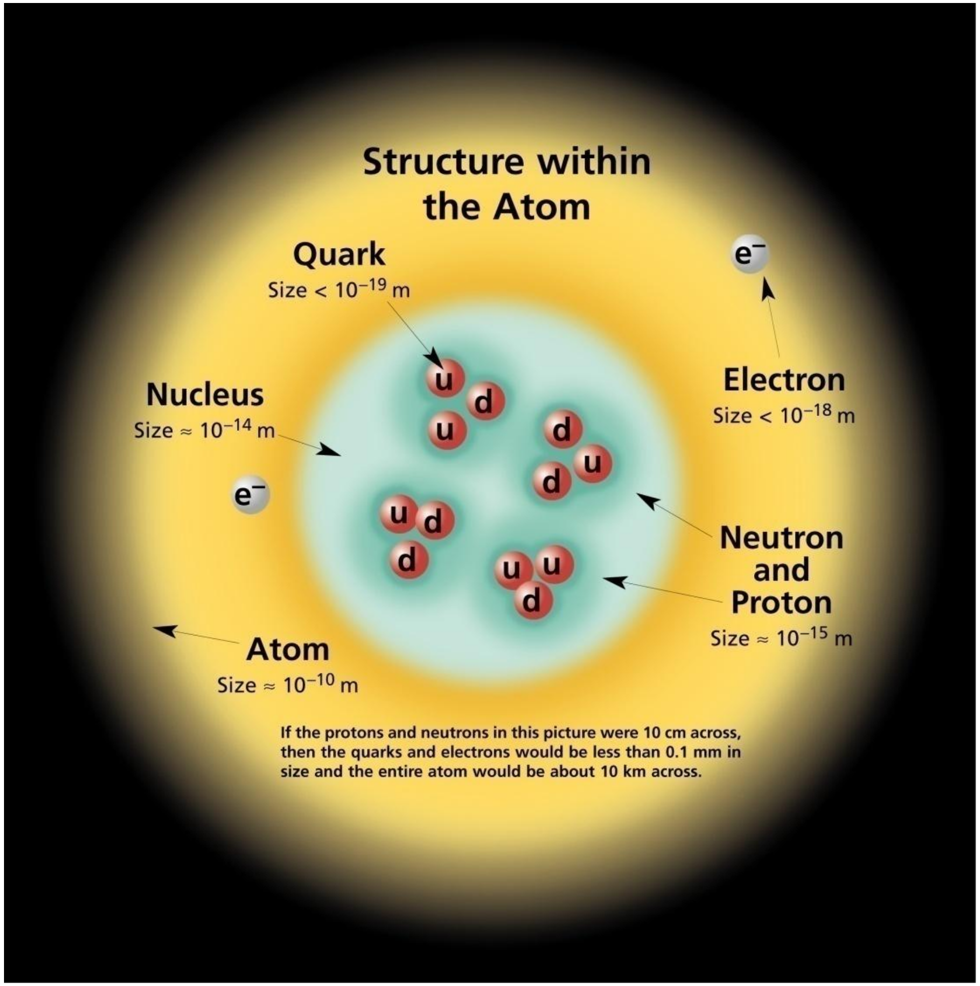
- Probing the Dark Matter Problem
- How Silicon Pixel Detectors help

“Ordinary Matter”

- All ordinary matter consists of Atoms
  - human beings
  - everything in this room
  - the earth
- Three types of elementary particles
  - up
  - down
  - electron

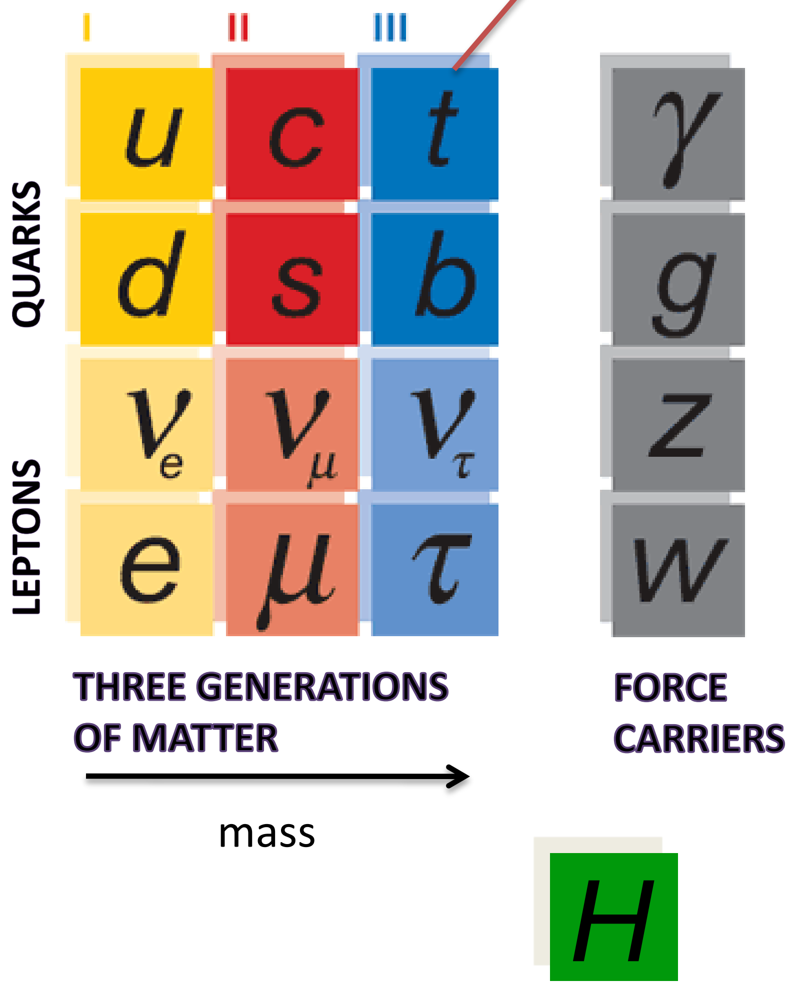
quarks (up, down)

lepton (electron)



The Standard Model of Particle Physics

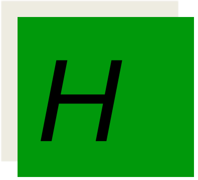
175 GeV (=proton masses). Discovered 1995.



- Physicist have produced additional particles in the laboratory
  - Heavier and unstable
  - Present in earlier universe
- Theoretically described by “Standard Model” since early 1970s
  - A success story, survived numerous experimental tests
- Only Higgs Boson has not been found experimentally
  - Gives mass to particles
  - Required for mathematical consistency at high energies

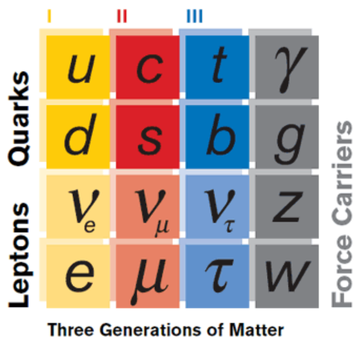
Are we there yet?

"So we just need to find the Higgs now…
…and then we're done with particle physics?"

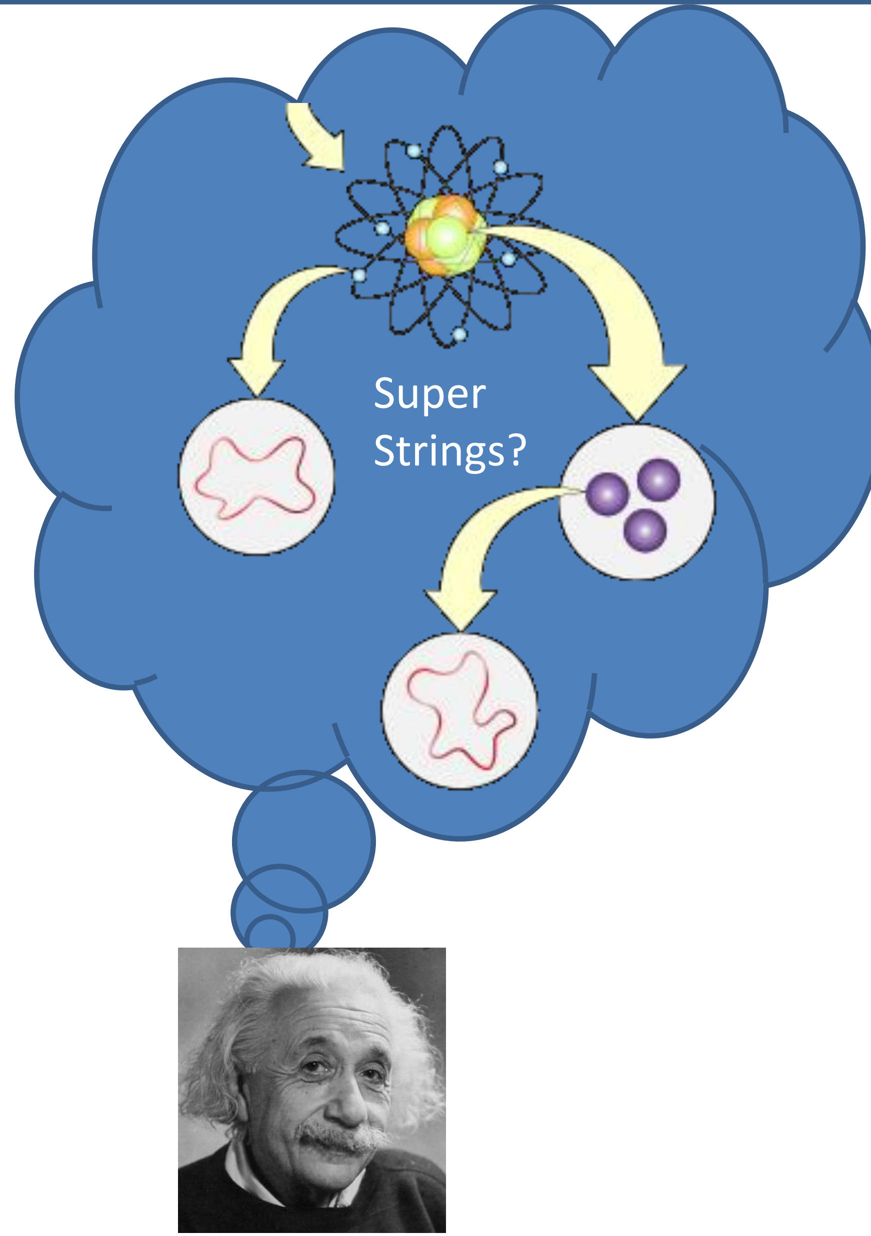


Why we are not finished

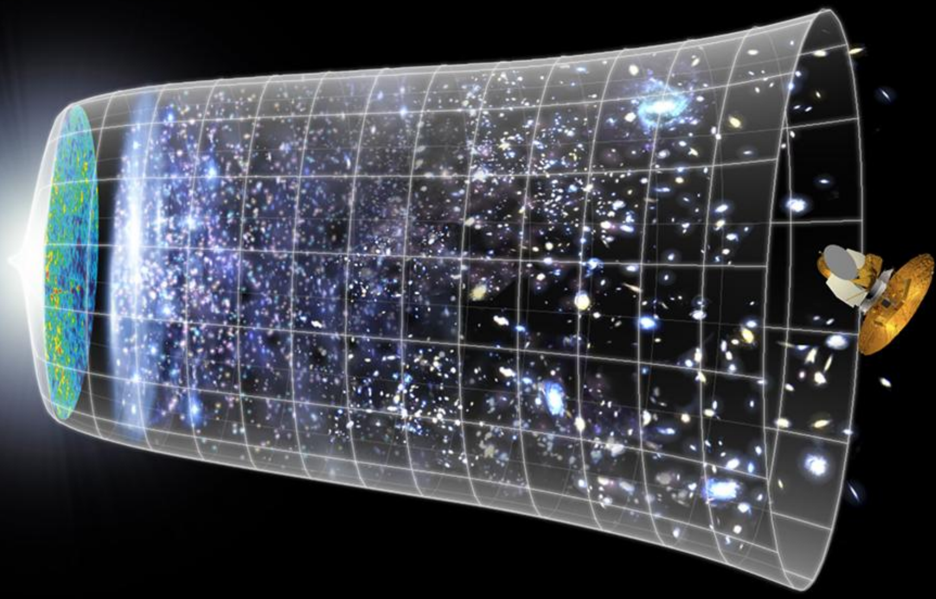
- We dream of a deeper, all encompassing theory, that
  - unifies all forces in nature
  - explains flavor structure
  - solves hierarchy problem



- Observations not explained by the standard model
  - neutrino masses (1998)
  - dark energy (1998)
  - dark matter (1933, 2003)



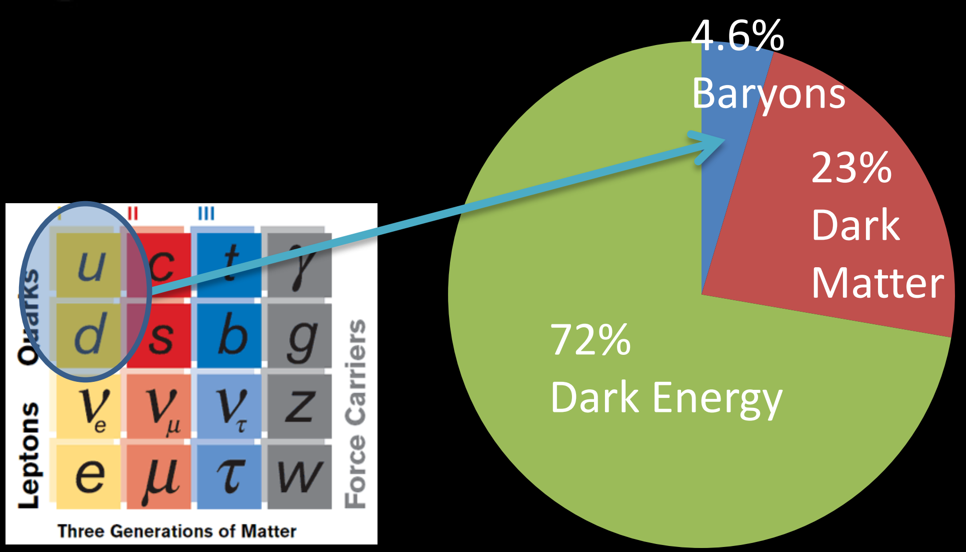
Surprise from Experimental Cosmology



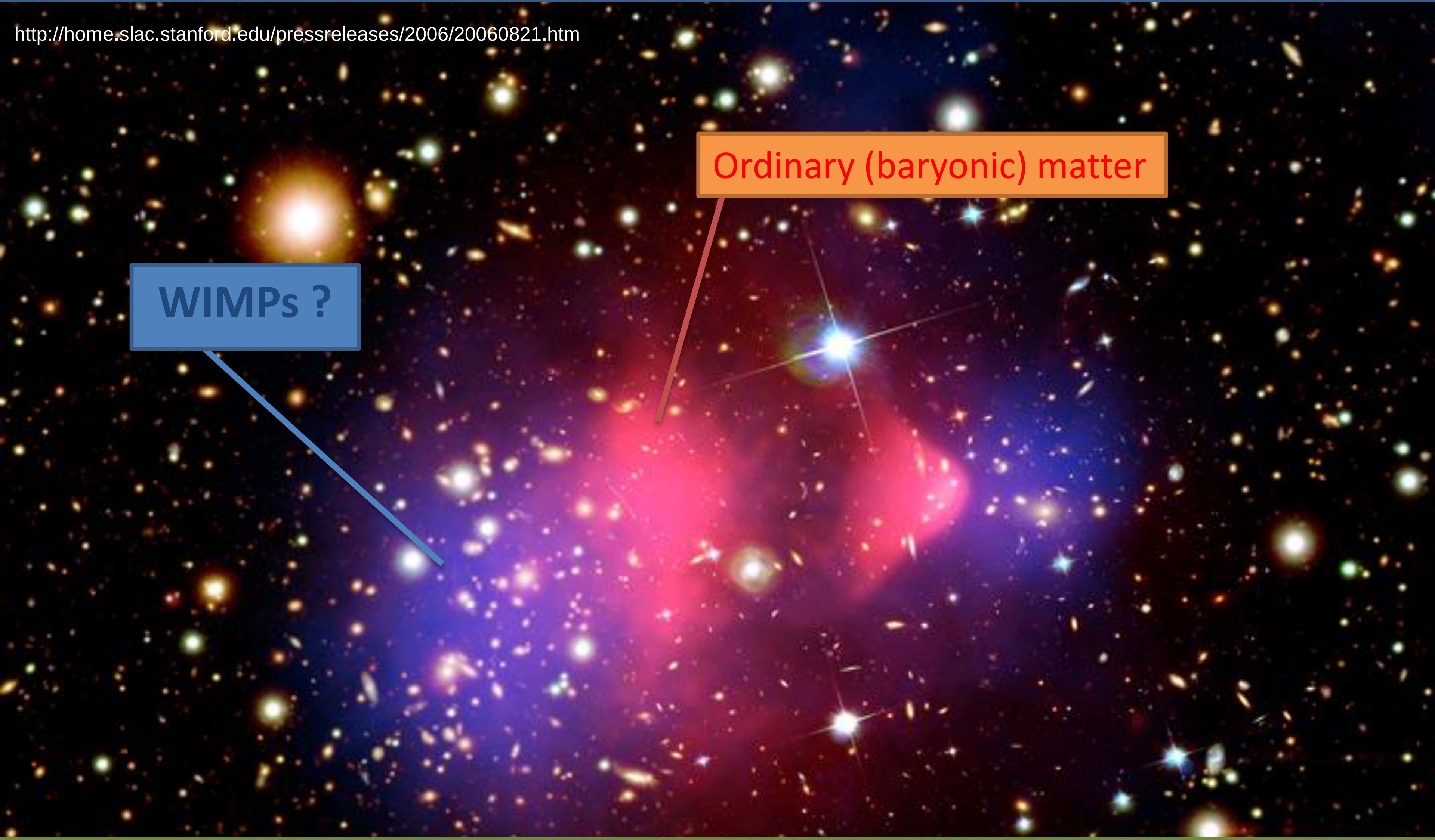
- Last decade: Significant advances in experimental cosmology

→ Precise *Cosmological* Standard Model

- Standard Model particles accounts for only 5% of energy in the universe
- The big question: What is the rest?



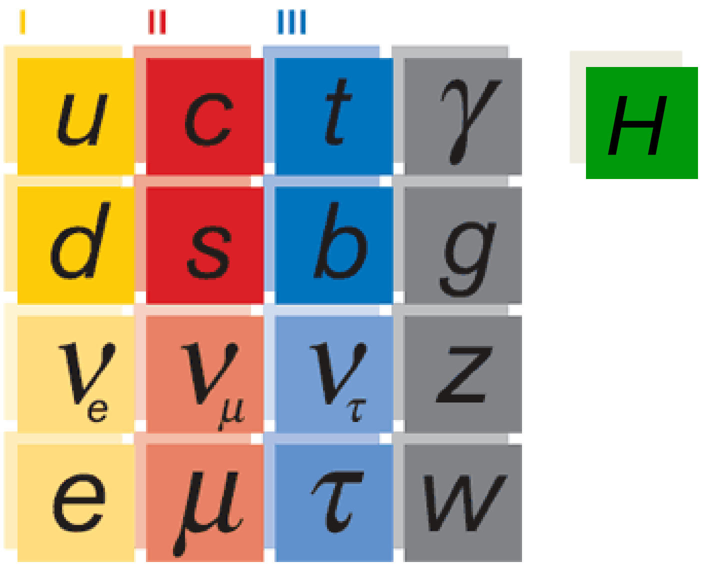
What does the Dark Matter consist of?

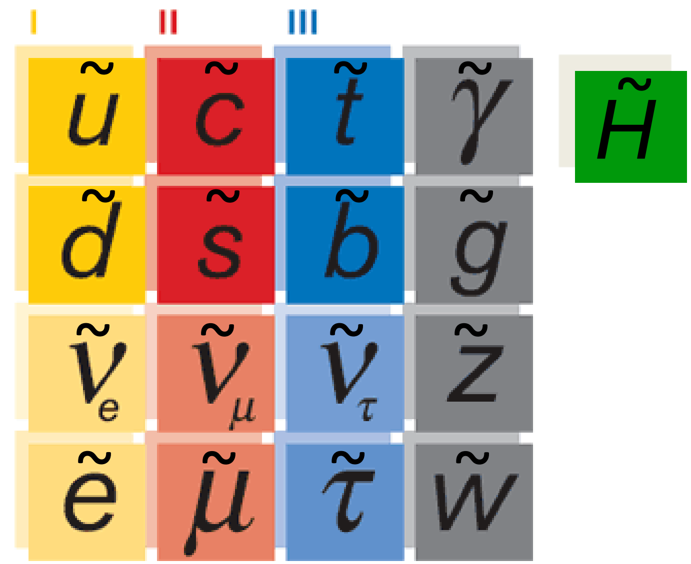


The Dark Matter may consist of undiscovered elementary particles - WIMPS.
A favorite WIMP candidate is the *Lightest Supersymmetric Particle*

Supersymmetry (SUSY)

- Possible Extension of Standard Model
  - Symmetry: Bosons ↔ Fermions
  - Each presently known particle has a partner with Δs=1/2

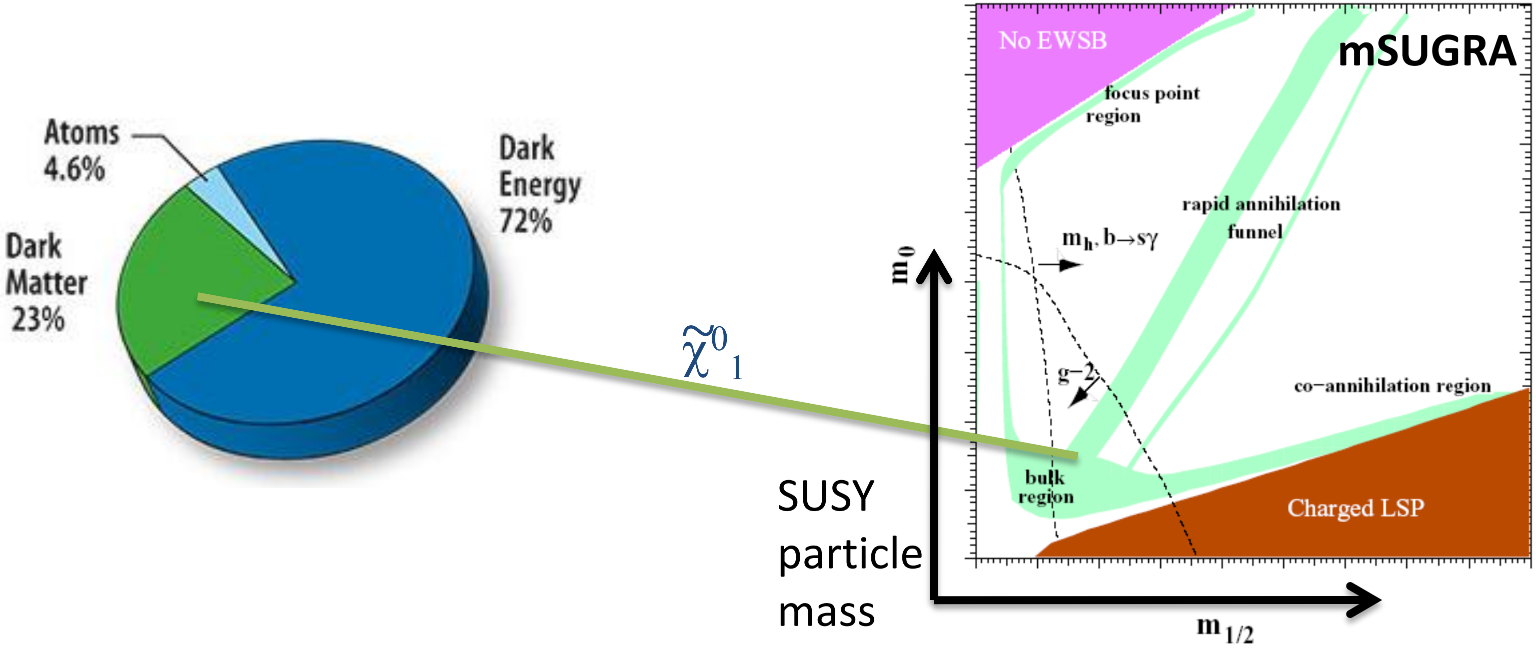




- Partners with same quantum numbers mix
  - EW gauginos + Higgsinos → 2 charginos $\tilde{\chi}^{+/-}_{1,2}$
    4 neutralinos $\tilde{\chi}^{0}_{1,2,3,4}$

Models in this talk: mSUGRA, Lightest Neutralino $\tilde{\chi}^{0}_{1}$ is Dark Matter candidate

SUSY May Explain Dark Matter



- Amazingly, SUSY can get the dark matter density exactly right
- Tends to happen when new particles are light

→ Should see SUSY particles at Large Hadron Collider!

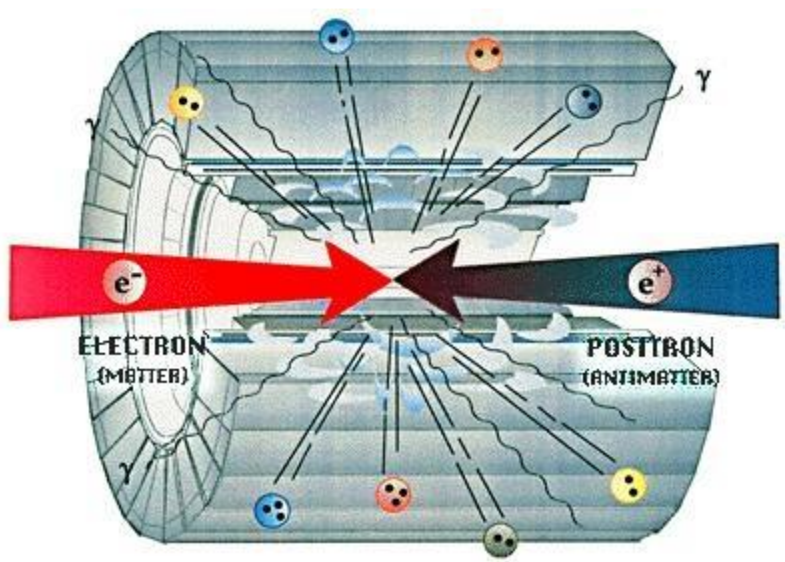
Particle Accelerators

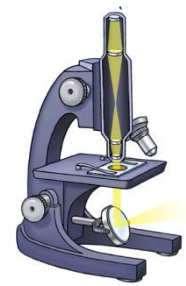
how we arrived at the standard model
& how we hope to go beyond

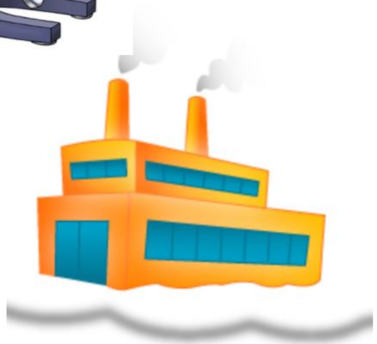
Particle Physics: Tools of the Trade

Proven recipe over last 100 years - since days of Rutherford

- **Accelerators: Collide *known particles (e or p)* together hard**
- **Detectors: See what comes out of collisions**







Resolving Sub-structure

- Standard Model:
  Relativistic **Quantum** Field Theory

- Particles propagate like waves
  $\lambda = h/p \sim h/E$ (De Broglie)

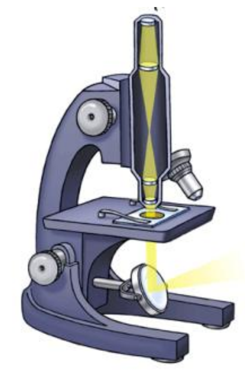
- Large particle energy → small λ
  → resolve smaller structures

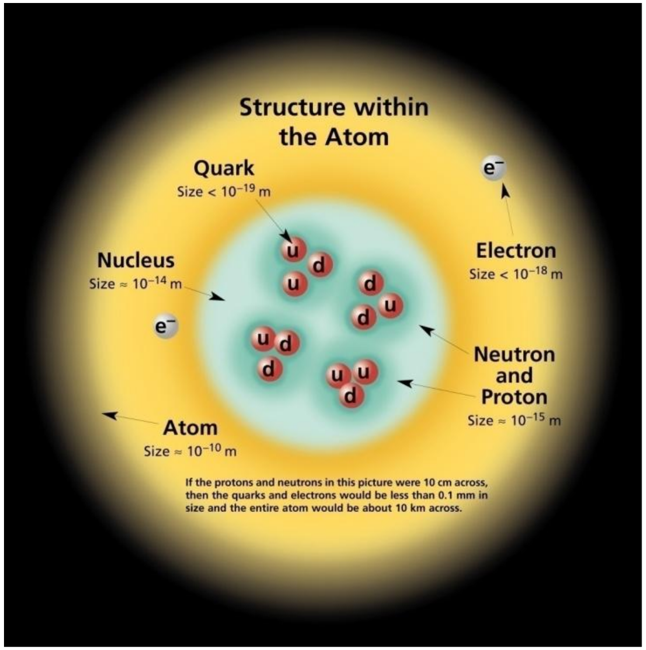
  - 1950s (*Hofstadter*) E=0.4 GeV electrons
    - $\lambda = 3x10^{-15}m$

    → saw protons inside nucleus

  - 1969 (SLAC): E=20 GeV electrons
    - $\lambda = 6x10^{-17}m$

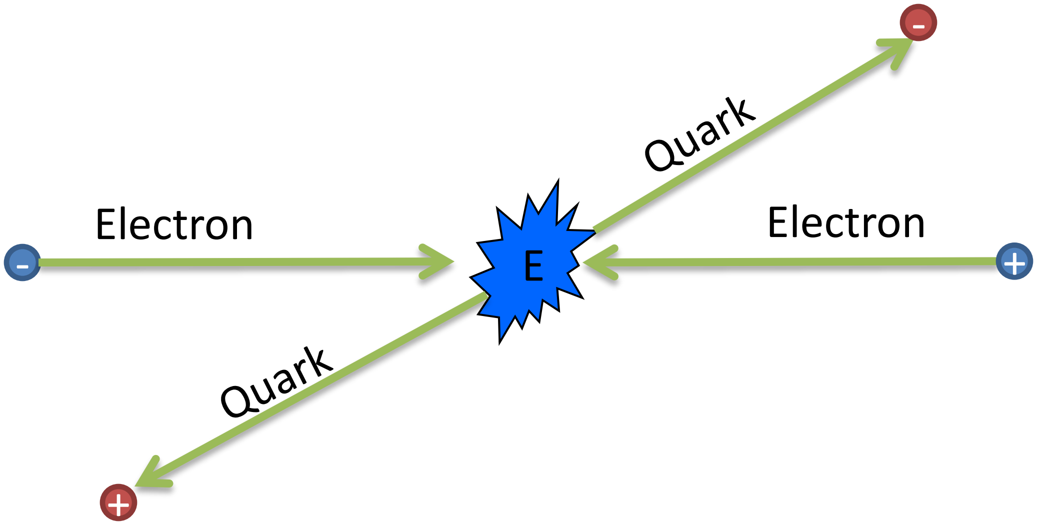
    → saw quarks inside protons





Creating New Particles

- Standard Model:
  Relativistic Quantum Field Theory

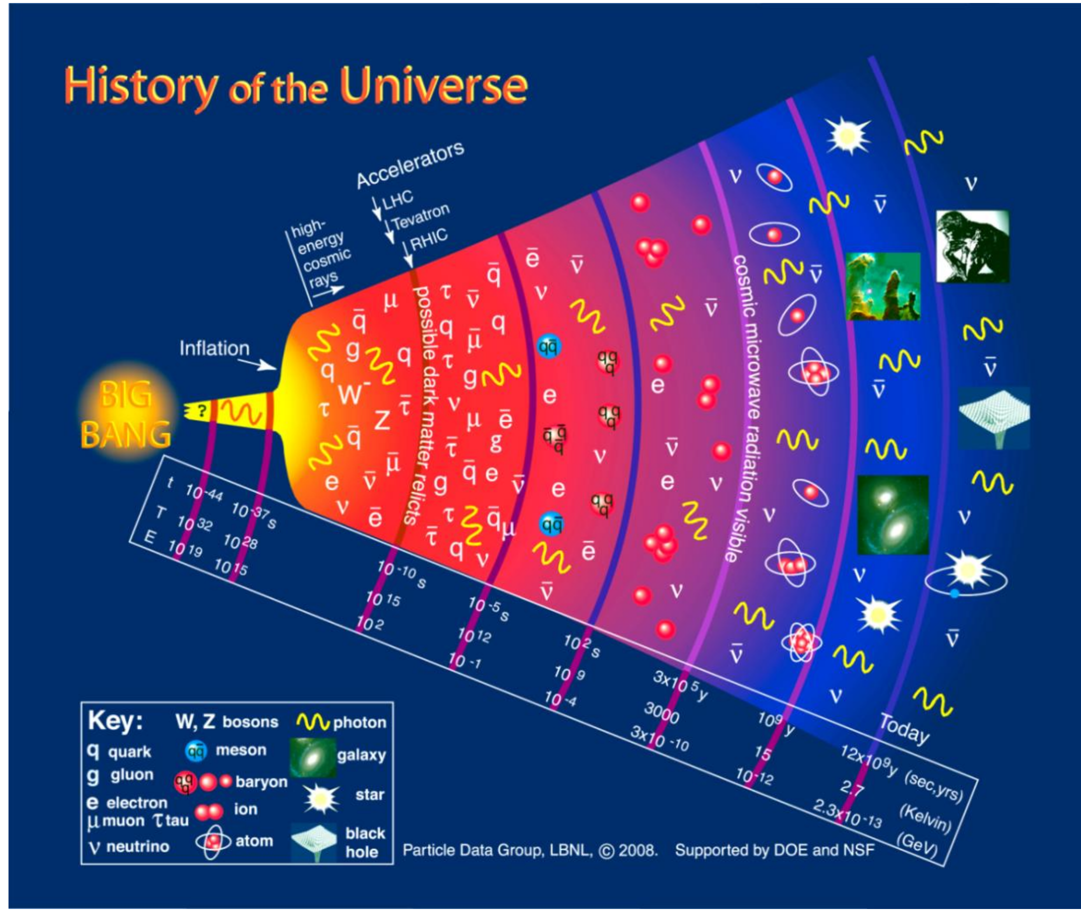


- Not necessarily same particle in initial / final state!
- Kinetic Energy → mass via $E=mc^2$
- If E>350 GeV → can create any known particle in standard model

Collide known elementary particles with large Energy
→ discover the particles you don't know!

Accelerators "look back in time"…

by re-creating processes that occurred in early universe



<u>Universe today</u>

- T = 2.7K
- E=kT = 2.3 x 10^{-4} eV
- Insufficient thermal energy to create elementary particles

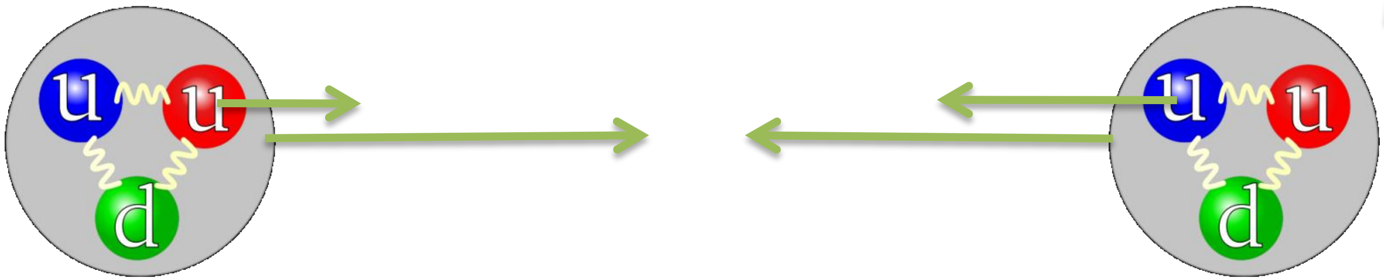
<u>Universe at t < 10^{-10}s</u>

- E=kT > 100 GeV
- Thermal production of SM
- SUSY, Dark Matter particles ?
- Most decayed / annihilated as universe cooled

- **Dark matter Particle: Stable & Weakly Interacting → still around today**
- **Need to understand physics at <u>10^{-10}s</u> to understand DM density today.**

Two Types of Colliders

- **Hadron Collider: Best for discovering unknown particles**
  - Easier to achieve high beam energy in circular accelerators
  - Different COM energy for each collision, unknown COM frame
  - Large rate of collisions, but small fraction of “interesting” ones



- **Lepton Collider: Best for precision studies of known particles**
  - Point particles → Same COM energy each collissions, known frame
  - Can tune COM energy to enhance production of specific particles
  - Smaller rate of collisions, but large fraction of “interesting” ones

Two complementary approaches with different detector challenges

Hadron Colliders

The Discovery Frontier

Hadron Collider History

Since 1931, circular accelerators with increasing energy

1931

Lawrence's
First Cyclotron
0.0008 GeV

1954

antiproton

Bevatron
6 GeV

1983

top quark

Fermilab Tevatron
1 TeV on
1 TeV

Historically: Large step in Energy → new discoveries

The Large Hadron Collider (LHC)

- Highest Energy Accelerator to date: Two beams of 7 TeV protons → E=14 TeV
- 4 large detectors where protons collide
- CMS and ATLAS: Search for the Higgs Boson & Physics beyond Standard Model
- > 10,000 scientists and engineers from over 100 countries

LHC Construction

- 7-TeV protons kept in orbit by superconducting magnets
- 8.33T, cooled by superfluid Helium at 1.9K
- Magnet Production, Installation & Commissioning → major driver of LHC schedule

Lowering one of 1232 dipoles...

... after installation 100 m under ground

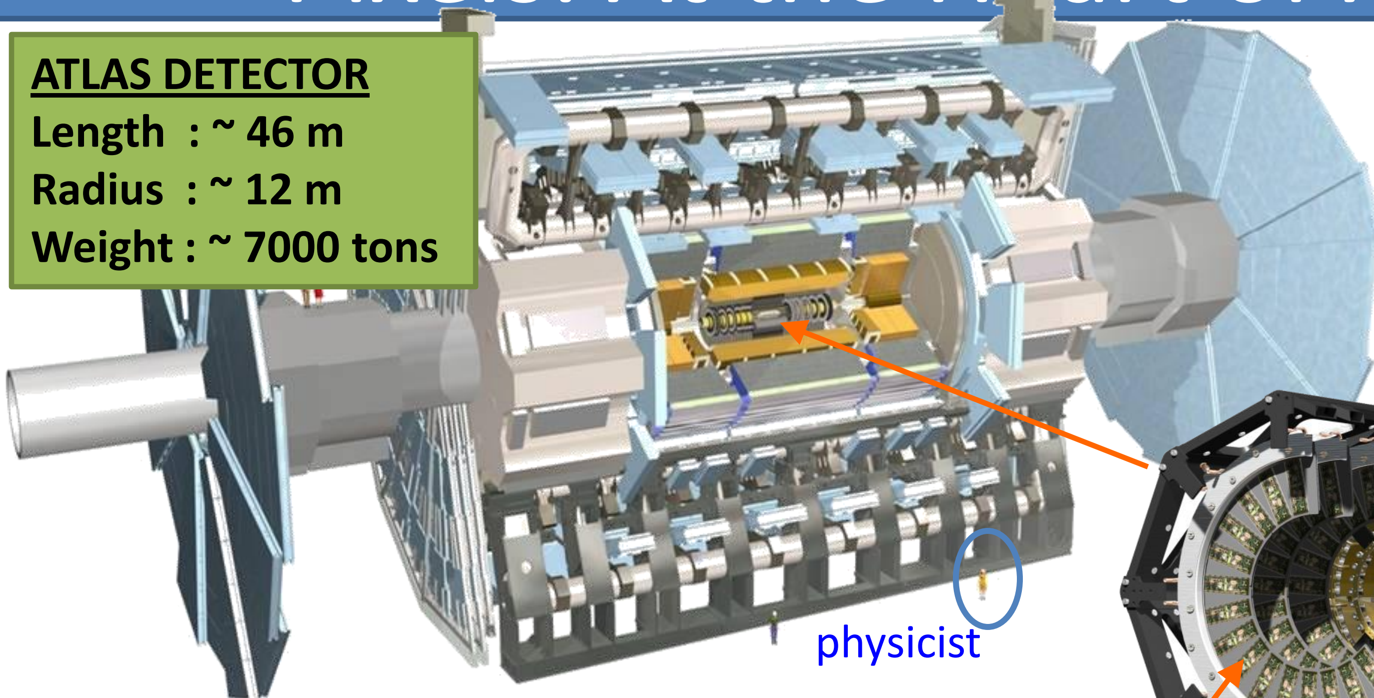
First Beams Circulated September 9th 2008

Magnet Accident September 19th 2008

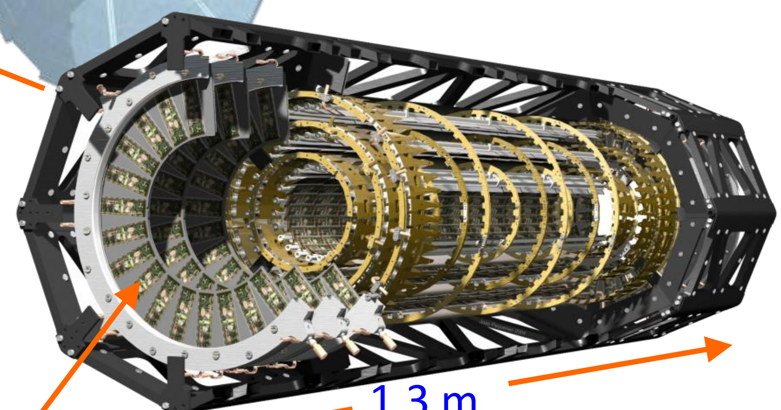
Extensive repairs and retrofits during last 12 months.
LHC scheduled to re-start November 2009 - Exciting!

Pixels: At the Heart of ATLAS

ATLAS DETECTOR
Length : ~ 46 m
Radius : ~ 12 m
Weight : ~ 7000 tons

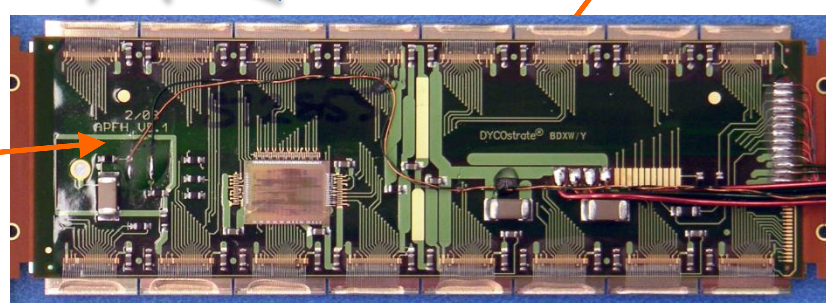


ATLAS Pixel Detector
– Innermost tracking detector, surrounding beam pipe



16 FE Chips

6 cm



Pixel

x46080

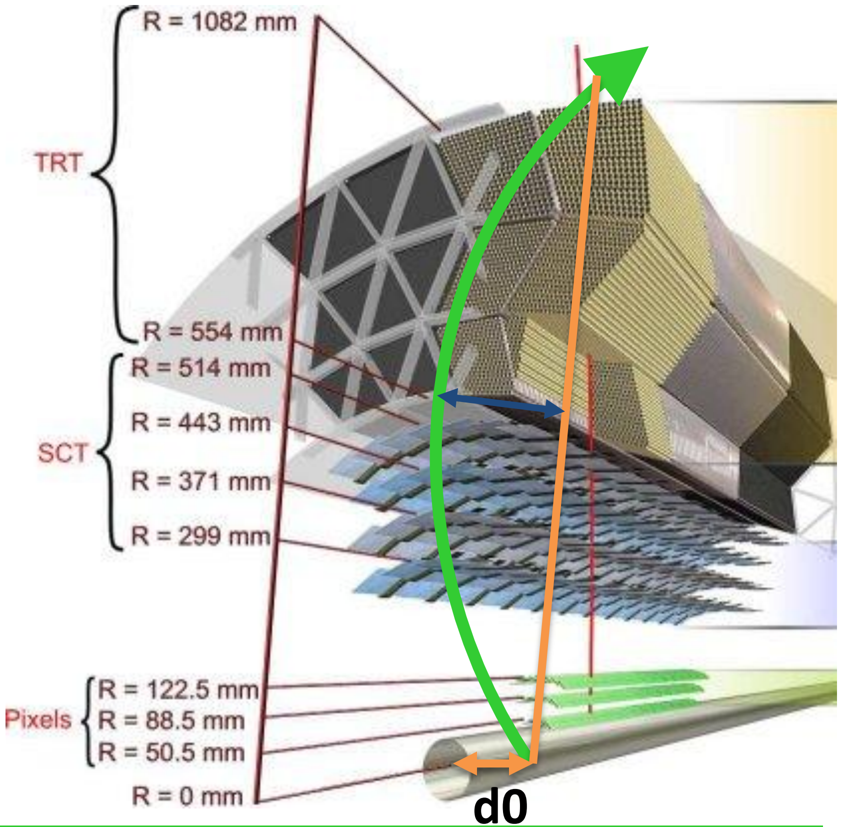
50 x 400 µm

Detection of charged particles takes place in 1744 identical *ATLAS Pixel Modules*

1744 modules x 46080 pixels = 80 million channels!

Tracking Charged Particles in ATLAS

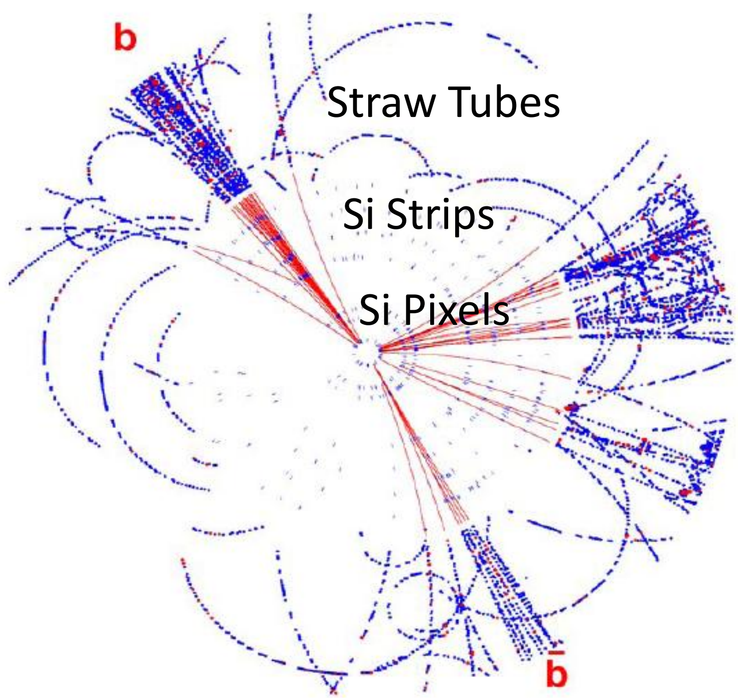
- Three subdetectors inside 2T magnetic field
- Pixels crucial for track finding, b-tagging, primary vertex finding
  - σ_{d0} ~ 11 µm
- Tracking important for understanding of SUSY
  - measure masses with di-lepton final states

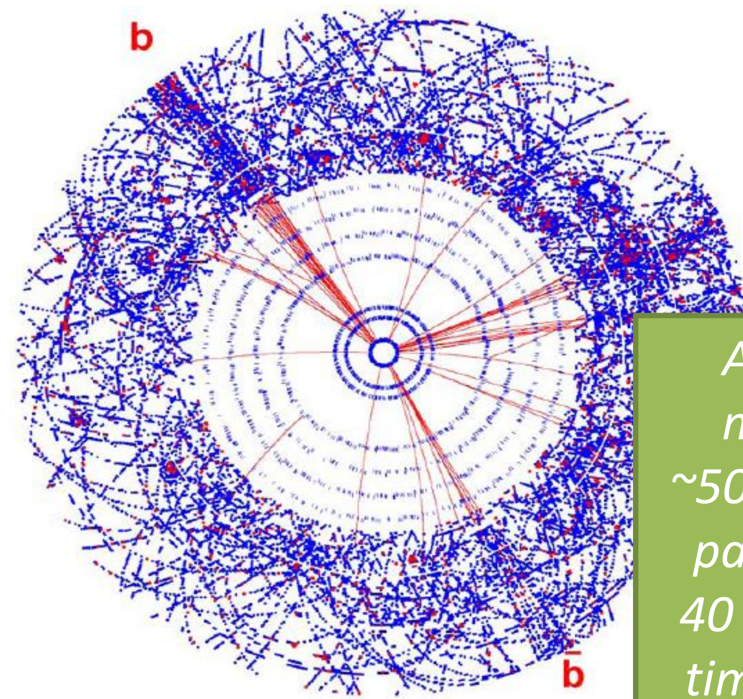


	spacepoints	$\sigma_{r\text{-}\Phi}$	σ_z	channels	other info
TRT	36 (1D)	130 µm	-	420K	Particle ID
SCT	4 (2D)	17 µm	580 µm	6.2M	61 m^2 silicon
Pixels	3 (2D)	10 µm	115 µm	80M	1.8 m^2 silicon

Why we need Pixels at the LHC

H→bb interaction



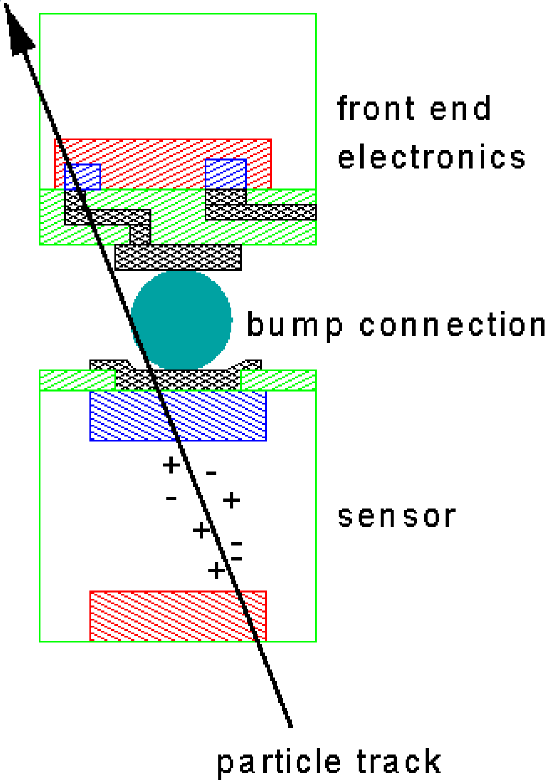


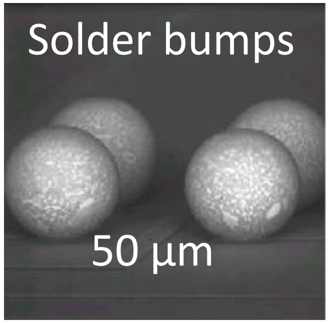
A real mess! ~500-1000 particles 40 million times per second!

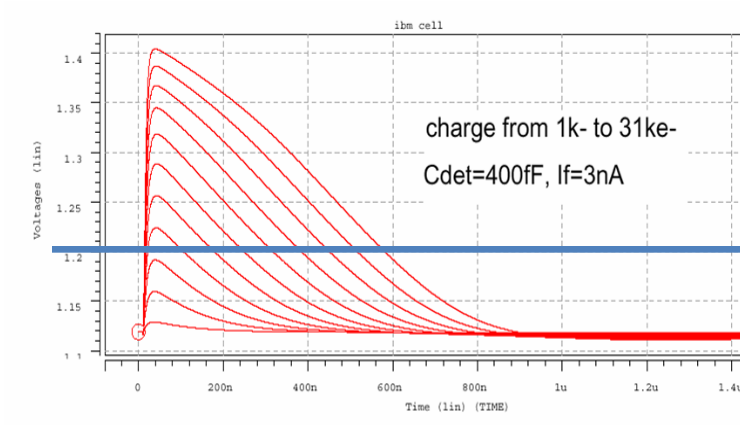
__Pixels just outside beampipe, must meet unprecedented performance requirements__

- Perform pattern recognition in high track density environment
- Distinguishing hits 25ns apart
- Store hits on detector for up to 3.2 μs (LVL1 trigger latency)
- Withstand huge radiation dose ~10^{15}n/cm^2

Single Pixel: Detection of a Charged Particle







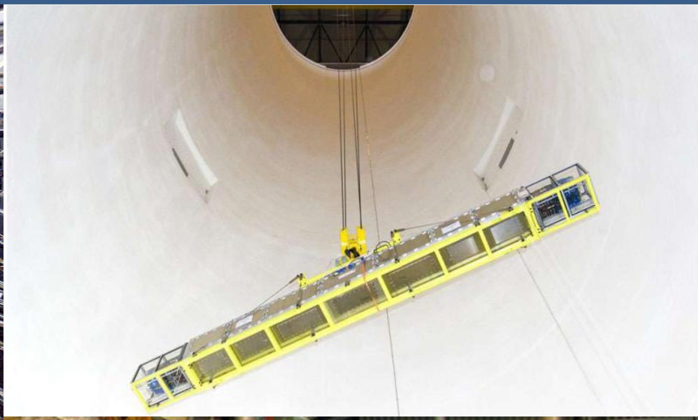
- ***Each 50 µm –size pixel is a little detector with it's own amplifier!***
- How it works
  - Particle at normal incidence liberates ~20k electron-hole pairs
  - Charge swept towards bumps and into preamp by electric field, converted to voltage pulse
  - If above threshold, discriminator produces HIT
    - Location
    - Bunch crossing ID
    - TOT
  - Typical
    - threshold ~ 4000 e^-
    - noise ~ 170 e^-

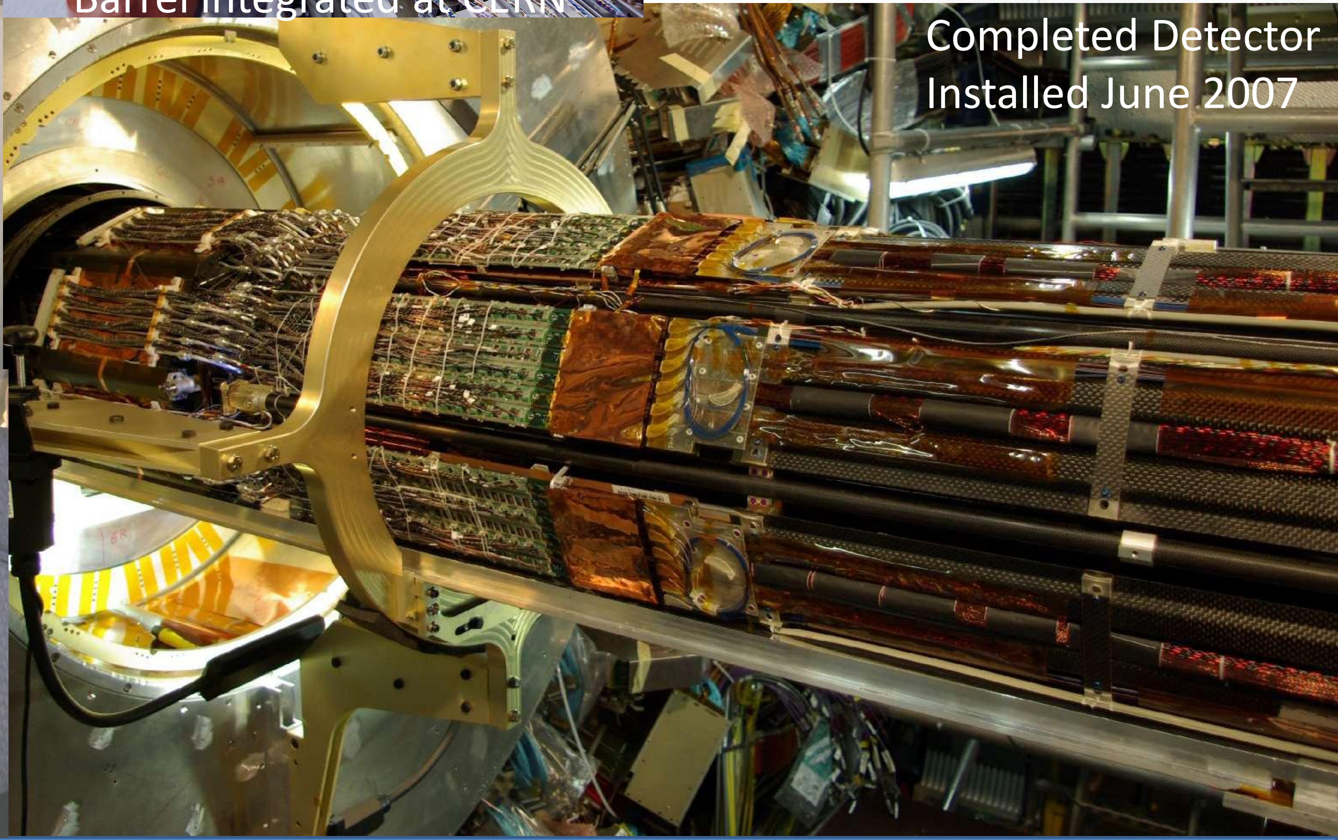
→High efficiency, low noise occupancy

Integration & Installation


Endcaps integrated at Berkeley LAB


Barrel integrated at CERN

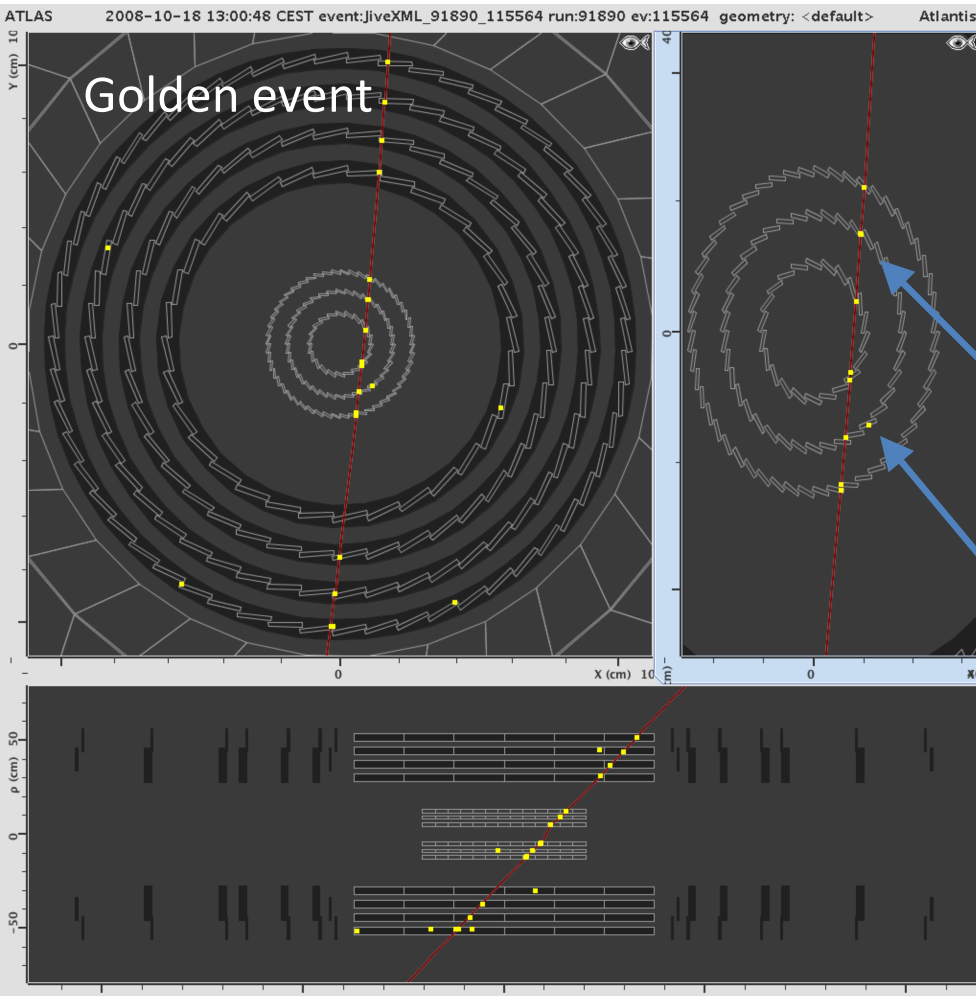



Completed Detector Installed June 2007


On the way to CERN!

Commissioning with Cosmic Rays

- First Cosmics in Sep 2008. 200M events, 400k with track through Pixels
- Very useful for calibration and alignment



Excellent Pixel Detector Performance

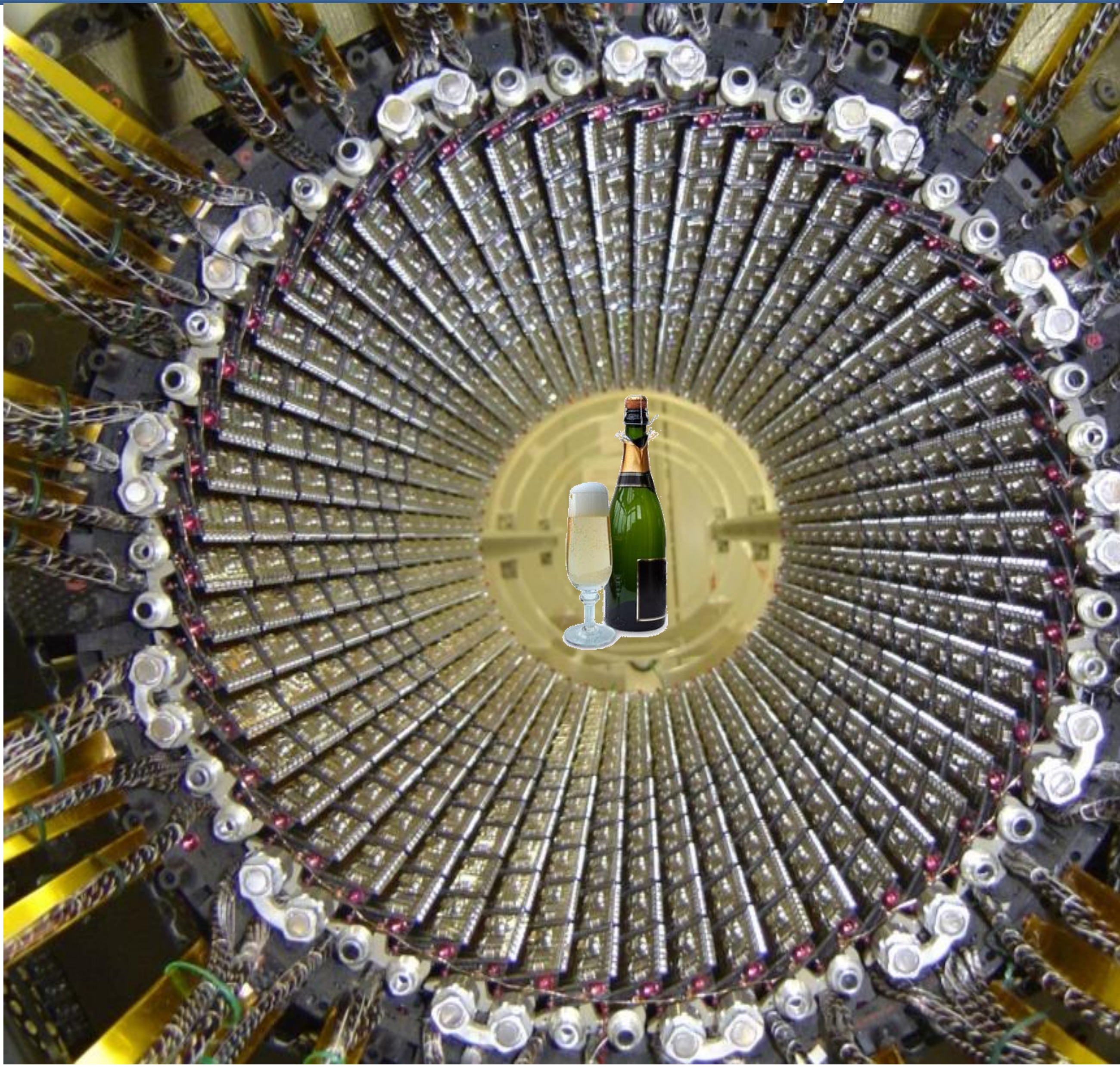
- Hit efficiency: ~99.8% (excludes inactive detector regions)
- Noise occupancy ~10^{-10} per BC (After masking ~0.01% noisy pixels)

at least one hit in each pixel layer

a single noise hit (out of 75M active pixels)

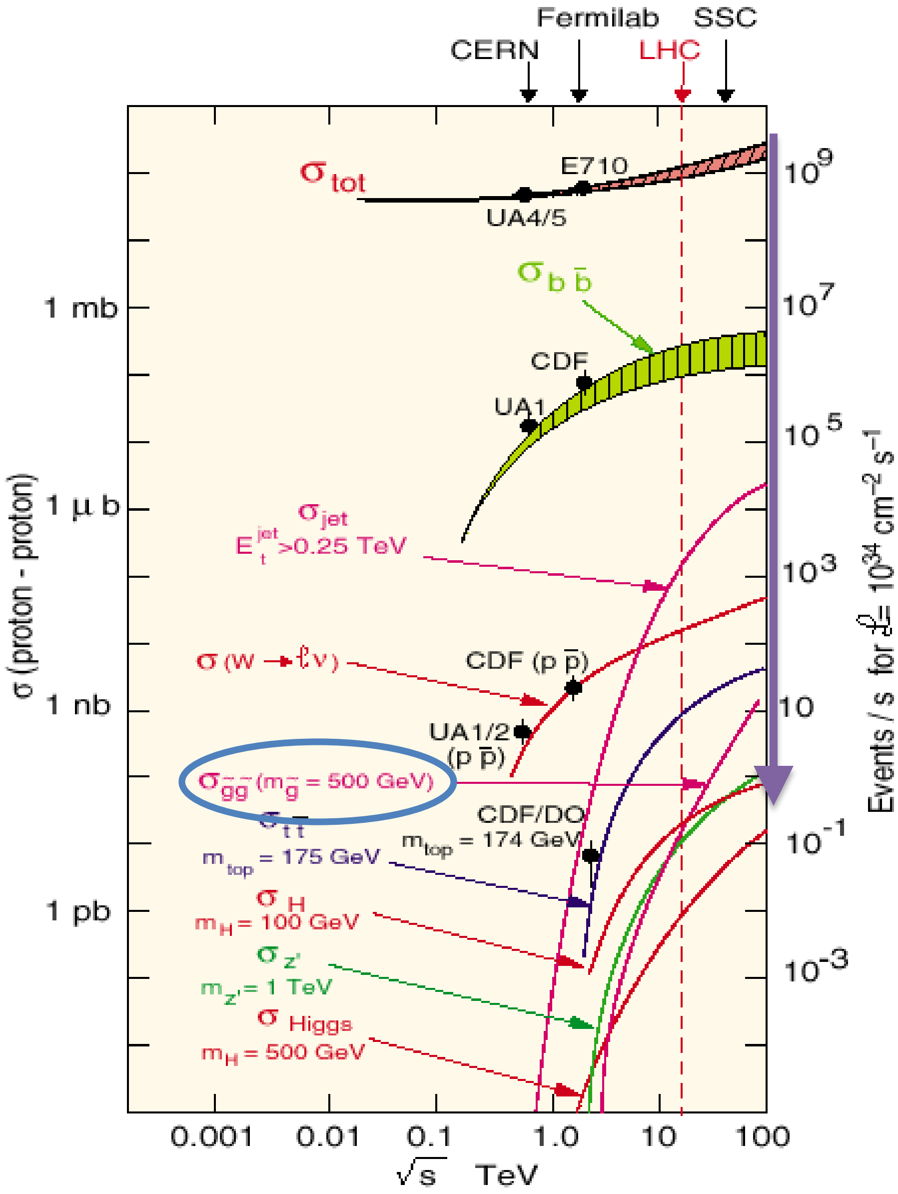
Conclusion on ATLAS Pixel Project

- After more than a decade of work
- Pixel Detector installed & operational in ATLAS
- On track to meet design goals
- Ready for first LHC collisions!

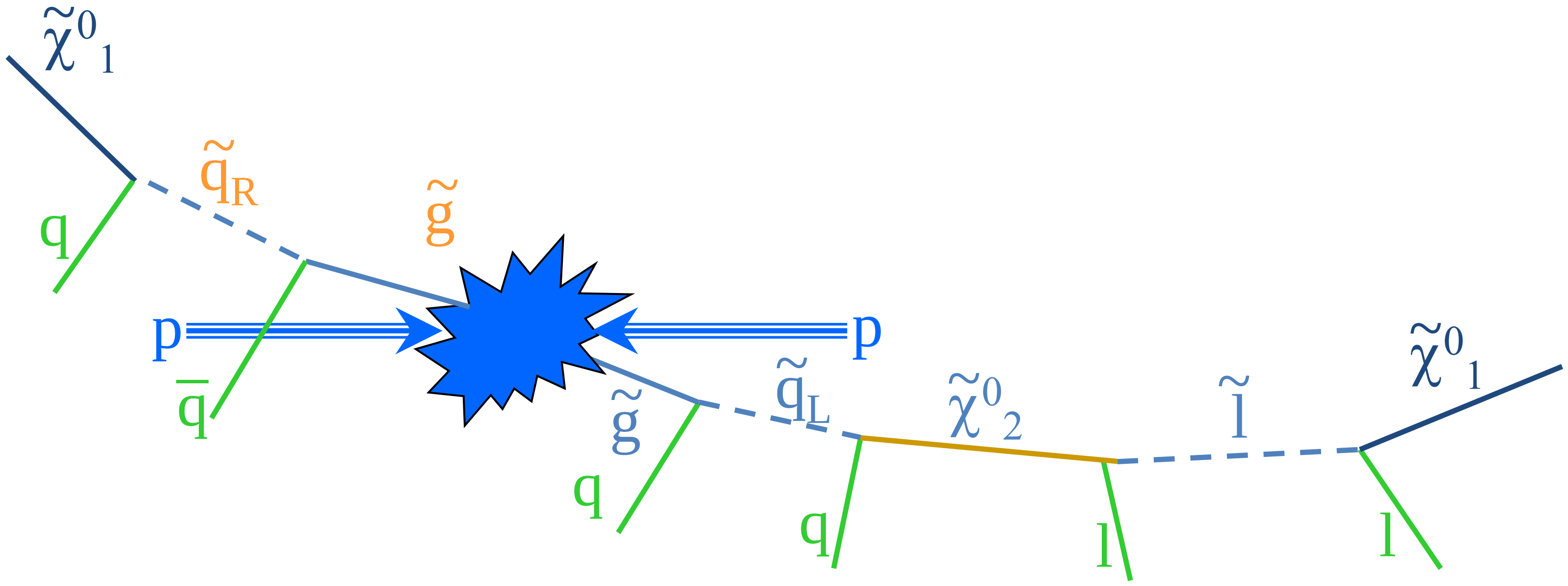


Will ATLAS Discovery SUSY?

- If SUSY particles are light, the LHC will almost certainly produce them
  - SUSY Production at Hadron Colliders calculated to NLO
  - largely independent of model
- Actually discovering SUSY is challenging
  - reject SM by factor of ~10^{11}
  - decays model dependent



How to Discover SUSY?



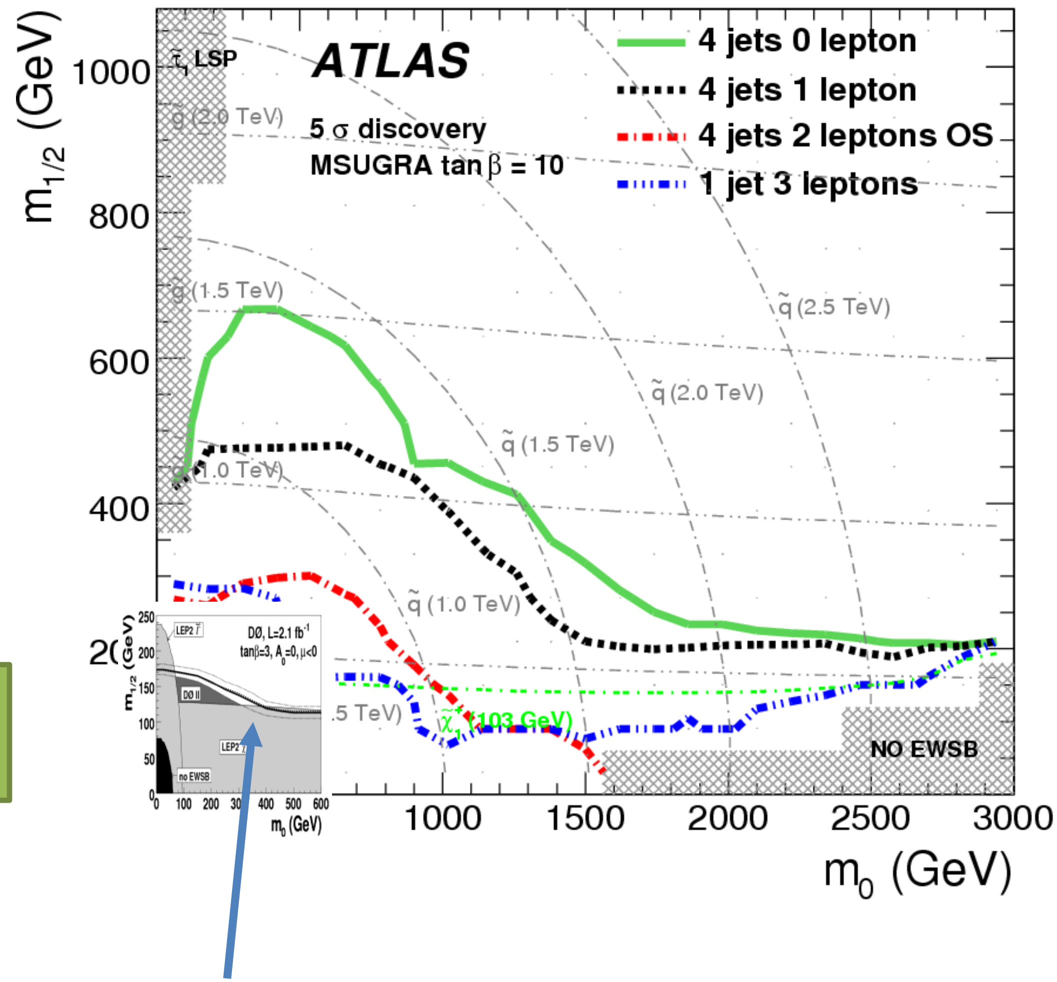
- Dominated by QCD production: squarks and gluinos
- Two sparticles initially
- Decays down to Light SUSY Particle: *jets, leptons*
- $\tilde{\chi}^0{}_1$ is stable, escapes undetected: *large* E_T^{miss}

→ **Inclusive signatures are most promising for discovery**: E_T^{miss}, high-p_T jets, leptons

L ~ 1 fb^{-1}: ATLAS SUSY Discovery Potential

- Good chance of finding TeV scale SUSY with 1fb^{-1} – by 2011!?
- Dream scenario!
- SUSY at higher mass scales could still show up later, but would make detailed studies difficult
- Ultimate LHC reach ~ 3 TeV

Moment of Truth for TeV Scale SUSY
LHC should find it or rule it out

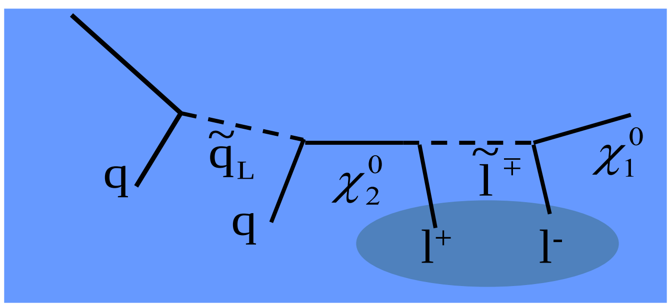


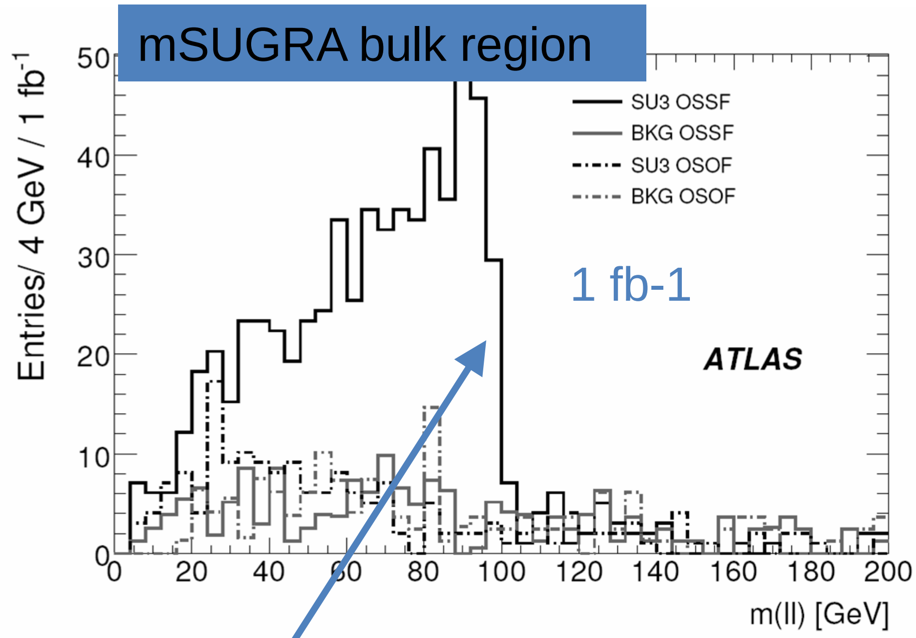
Tevatron Exclusion, 2.1 fb^{-1}!

LHC after discovery: Mass reconstruction

How do we learn more?

- Leptonic decays important
- *Example: Opposite sign, same flavor* di-leptons from single neutralino decay





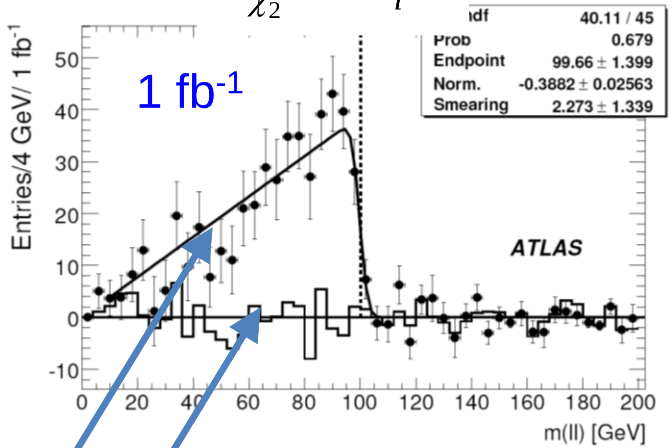
- Position of mass-edge sensitive to combination of sparticle masses

$$m_{\ell\ell}^{\text{edge}} = m_{\tilde{\chi}_2^0}\sqrt{1-\left(\frac{m_{\tilde{\ell}}}{m_{\tilde{\chi}_2^0}}\right)^2}\sqrt{1-\left(\frac{m_{\tilde{\chi}_1^0}}{m_{\tilde{\ell}}}\right)^2}$$

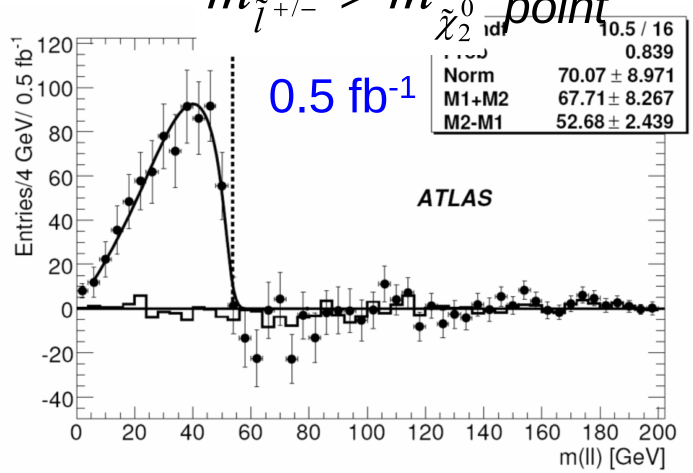
LHC after discovery: Mass reconstruction

- Method sensitive to any sleptons lighter than 2nd neutralino

$m_{\tilde{\chi}_2^0} > m_{\tilde{l}^{+/-}}$ *Bulk region*



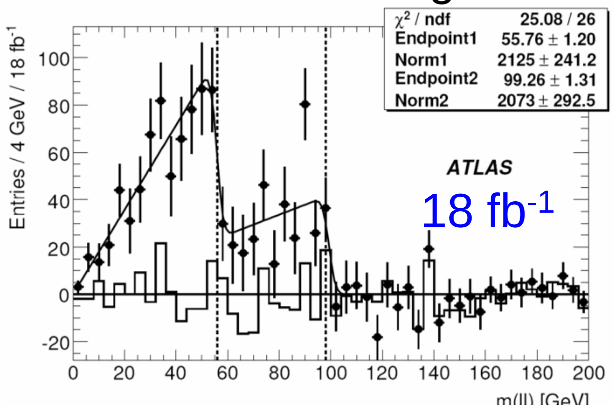
$m_{\tilde{l}^{+/-}} > m_{\tilde{\chi}_2^0}$ *Low mass point*

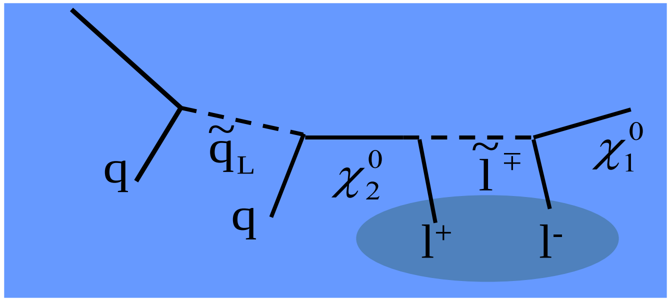


SUSY

Standard Model

Two light sleptons,
Coannihilation region



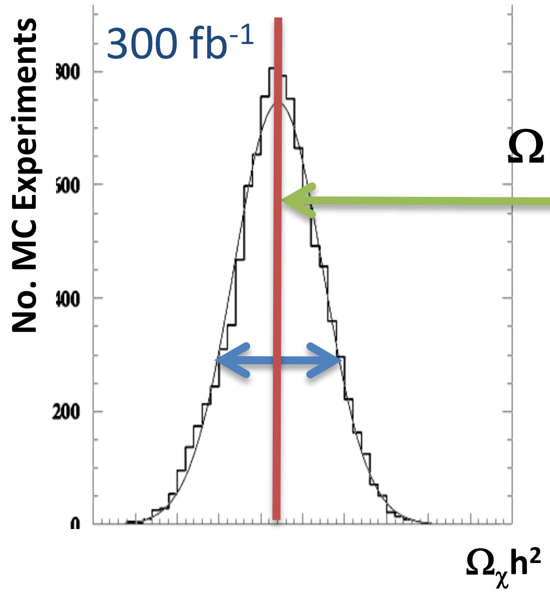


Already with 1 year of low luminosity running, could learn at lot at LHC!

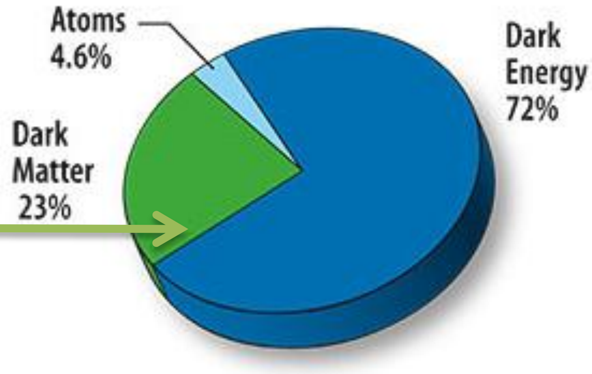
Comparing with Experimental Cosmology

- If SUSY particles light, many similar measurements possible at LHC
- At end of LHC program (10 years from now?), combine all information
  → predict dark matter density resulting from thermal production in early universe

Polesello, Tovey JHEP 0405 (2004) 071



$\Omega_\chi = \Omega_{DM}$?



- Is neutralino seen at LHC compatible with dark matter created in early universe?
- What fraction of the dark matter is neutralinos?

Assumes LHC friendly scenario, constrained SUSY model
May be confused after LHC → require input from lepton colliders

Comparing with Direct Detection

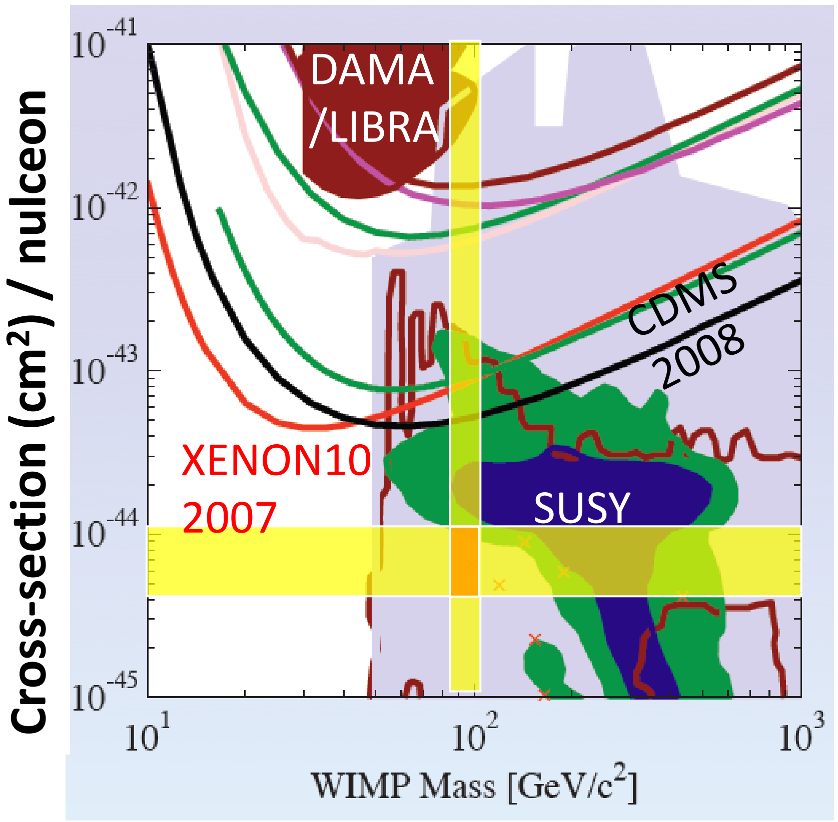
- Based on LHC measurements, also predict direct detection

$$m_{\tilde{\chi}_1^0} = 96.05 \pm 4.7 \text{ GeV}$$

$$\log_{10}(\sigma_{\chi p}/1\text{pb}) = -8.17 \pm 0.039$$

(300 fb^{-1})

- WIMP seen at LHC compatible with DM in our galaxy today?



- To cover all SUSY scenarios → need ton-scale or larger direct detection experiments
- But such large detectors may be limited by irreducible backgrounds → challenges

Lepton Colliders

The Precision Frontier

Lepton Colliders

Precision studies of known particles,
highly complementary to Hadron Colliders

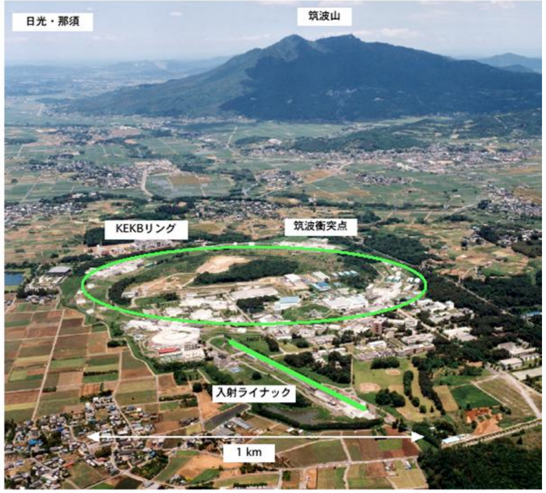
1989

18 million Z bosons

LEP, Switzerland
91 - 209 GeV

1999

800 million b-quark pairs

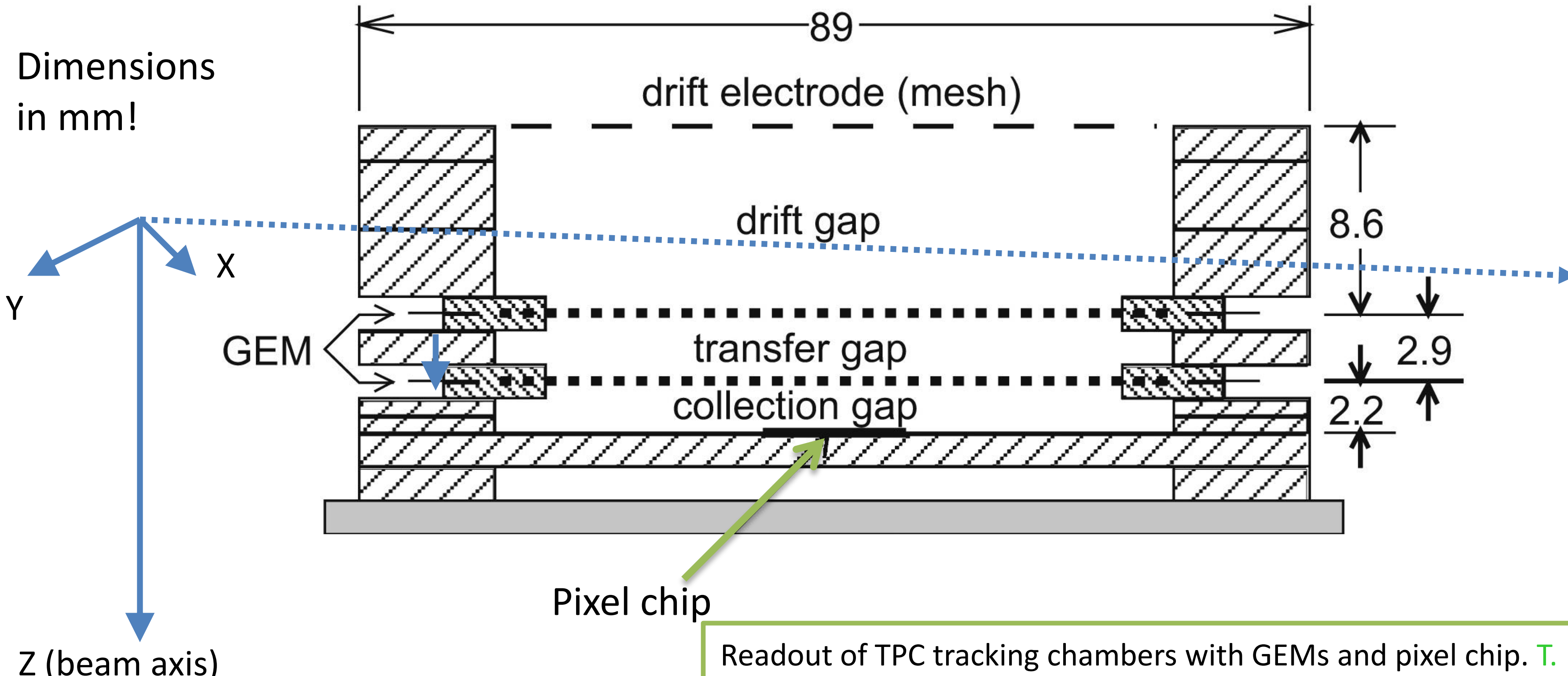


KEK-B, Japan
10.58 GeV

Detector challenge at future lepton colliders will be precision.
E.g. Will need 10x better momentum resolution than LHC detectors!

Time Projection Chamber with Pixel Readout

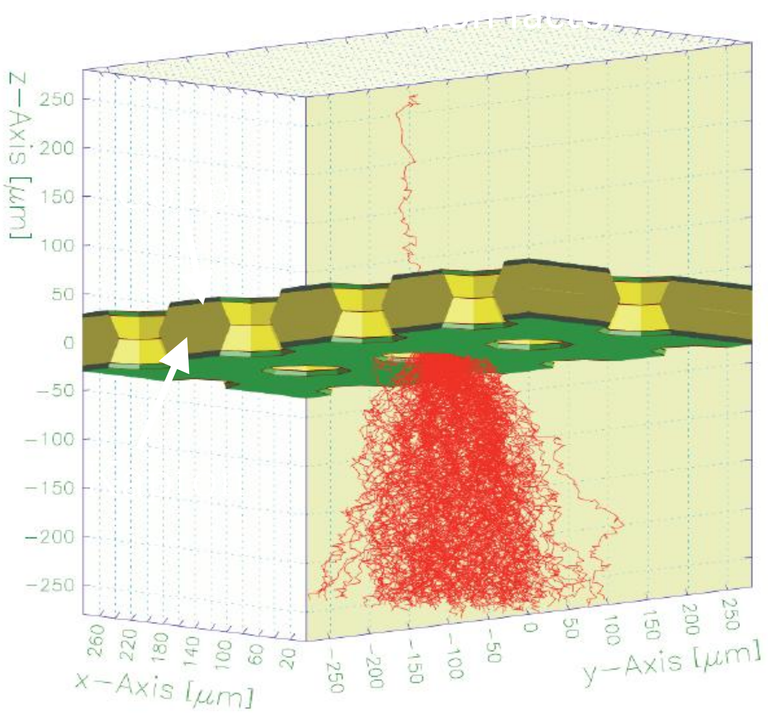
- Desired momentum resolution achievable with 200 measurements of each track
  - each with resolution σ_X, σ_Y ~100 µm → TPC with Pixel Readout?
- Also seems promising for detection of *neutral* particles (e.g. neutralinos)

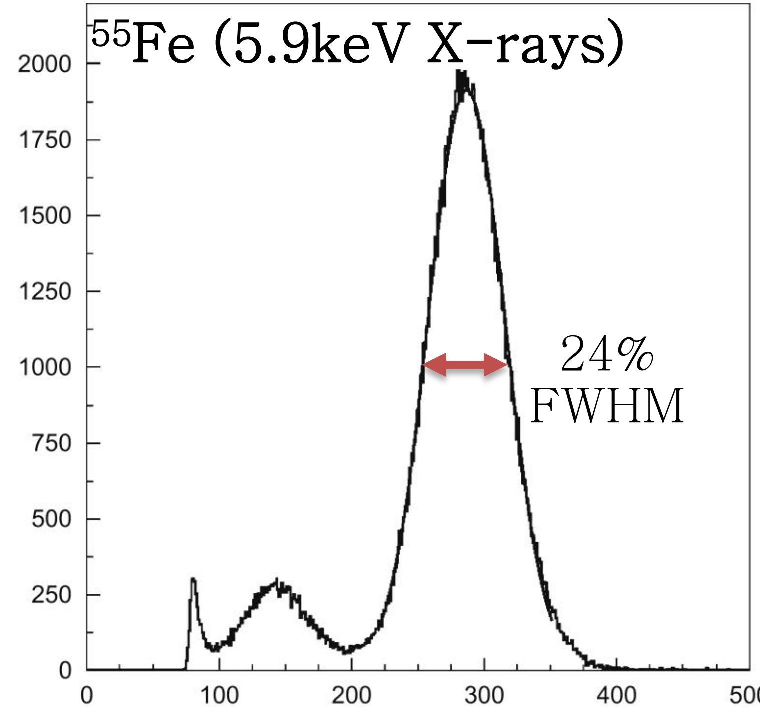


Readout of TPC tracking chambers with GEMs and pixel chip. T. Kim, M. Freytsis, J. Button-Shafer, J. Kadyk, S.E. Vahsen, W.A. Wenzel (LBL, Berkeley) . 2008. 12pp. NIM (2008)

Amplification: Gas Electron Multipliers (GEMs)

- Electrons multiplied by avalanching in GEMs
- Off-the shelf GEMs from CERN
  - 5cm x 5cm x 60 µm
  - Hole spacing: 140 µm
- Reliable without sparking with single-GEM gain up to 300 (Ar/CO_2)
- Two GEMS in series: higher gain with less risk of sparking:
  500V + 400V → gain = 40000



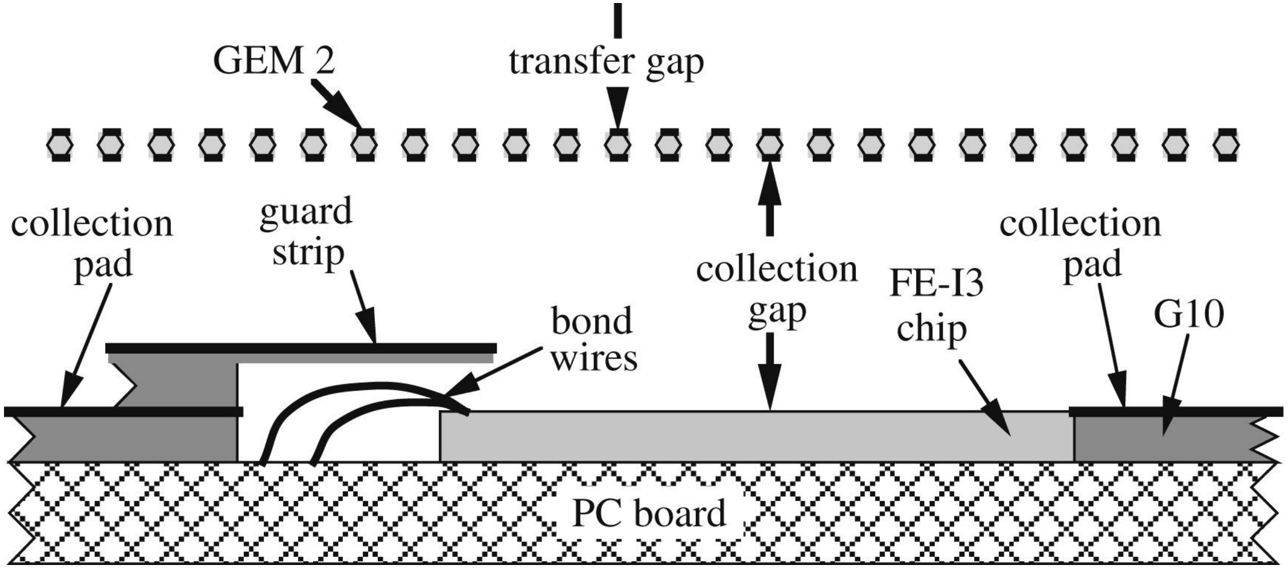


Simulated and measured gain consistent

Charge Collection: FE-I3 Pixel Chip

- x/y from pixel coordinate (50x400µm)
- relative z from drift-time (25ns)

- Noise level ~120 electrons
- 2-3 pixels out of 2880 masked
  → no noise hits



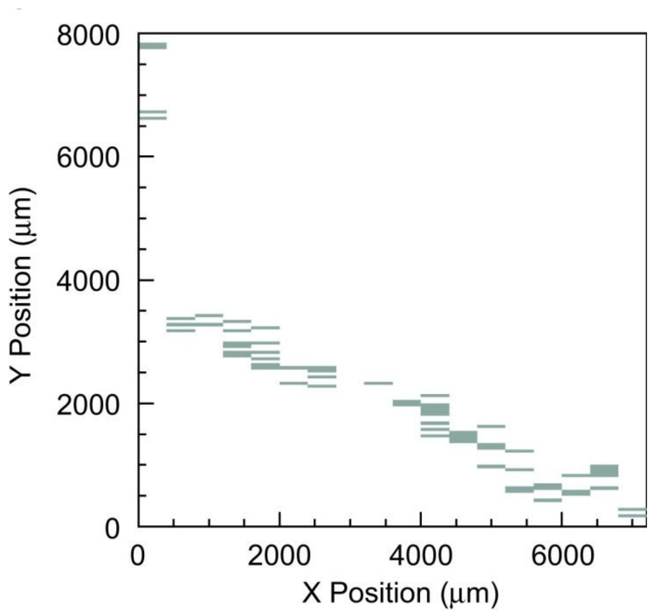
Expect good x,y resolution: gem hole spacing, pixel size
Expect good z resolution: fast electron signal & pixel FEs

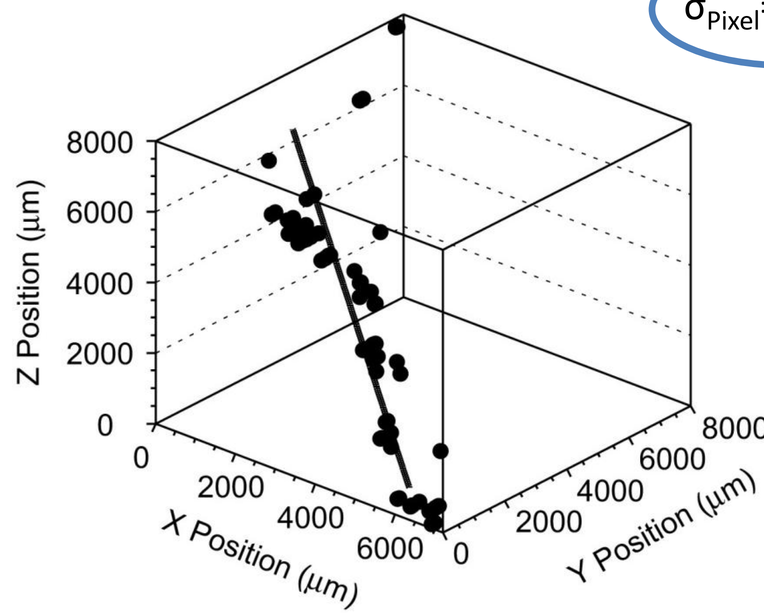
Position Resolution with Cosmics

- Large sample of cosmic rays
- Require >10 pixel hits
- 3D track at least 4.5mm long
- Gain=9000, threshold=1800e-
- LC: diffusion < 100 μm w/ magnet

	track fit residual	Diffusion	$\sigma_{GEM+Pixel}$
σ_X (μm)	170	110	130
σ_Y (μm)	130	110	70
σ_Z (μm)	240	190	150

σ_{Pixel}=14 μm

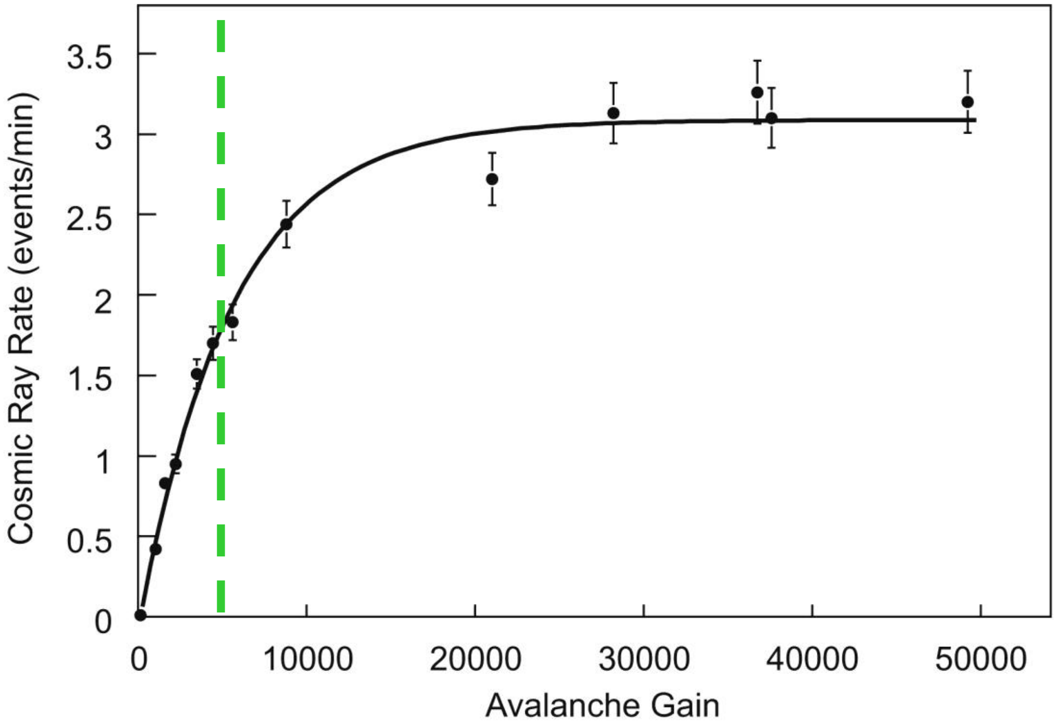




Sufficiently precise for detectors at future lepton colliders!

Bonus: High Efficiency

- Pixel threshold at 5k electrons
- Rate plateaus at gain ~20k
- 20k electrons per primary ionization electron (vs. 20k electrons per MIP/layer in ATLAS)
- *Suggest system is capable of collecting all the ionization from primary track - even single electrons!*



Can observe *tiny* signals!

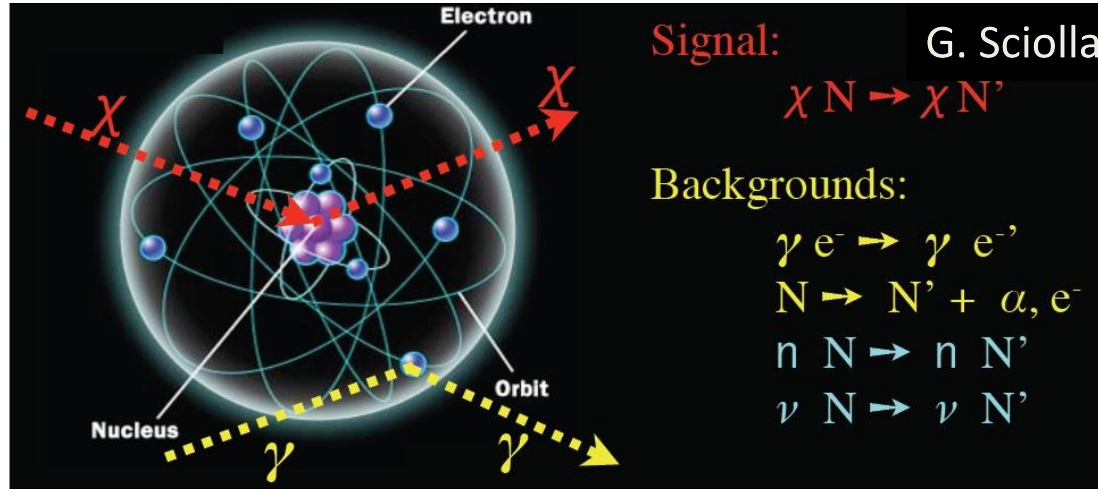
Direct Dark Matter Detection

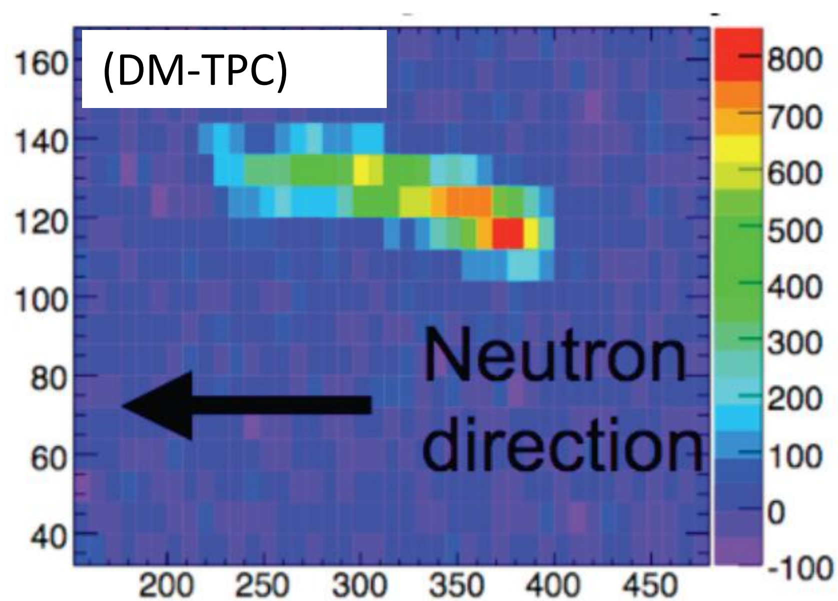
The Cosmic Frontier

Detecting DM with Tracking Detectors

- The ability to read out tiny ionization signals with low/zero background is exactly what is needed in to detect Dark Matter directly
- Nuclear recoil signal
  - low energy (10-100keV)
  - low rate
  - many backgrounds
- In a TPC with low pressure gas, typical nuclear recoil gives 1-2 mm tracks
- TPC with pixels can image such recoils!

→ ***Directional* Dark Matter Detection!**

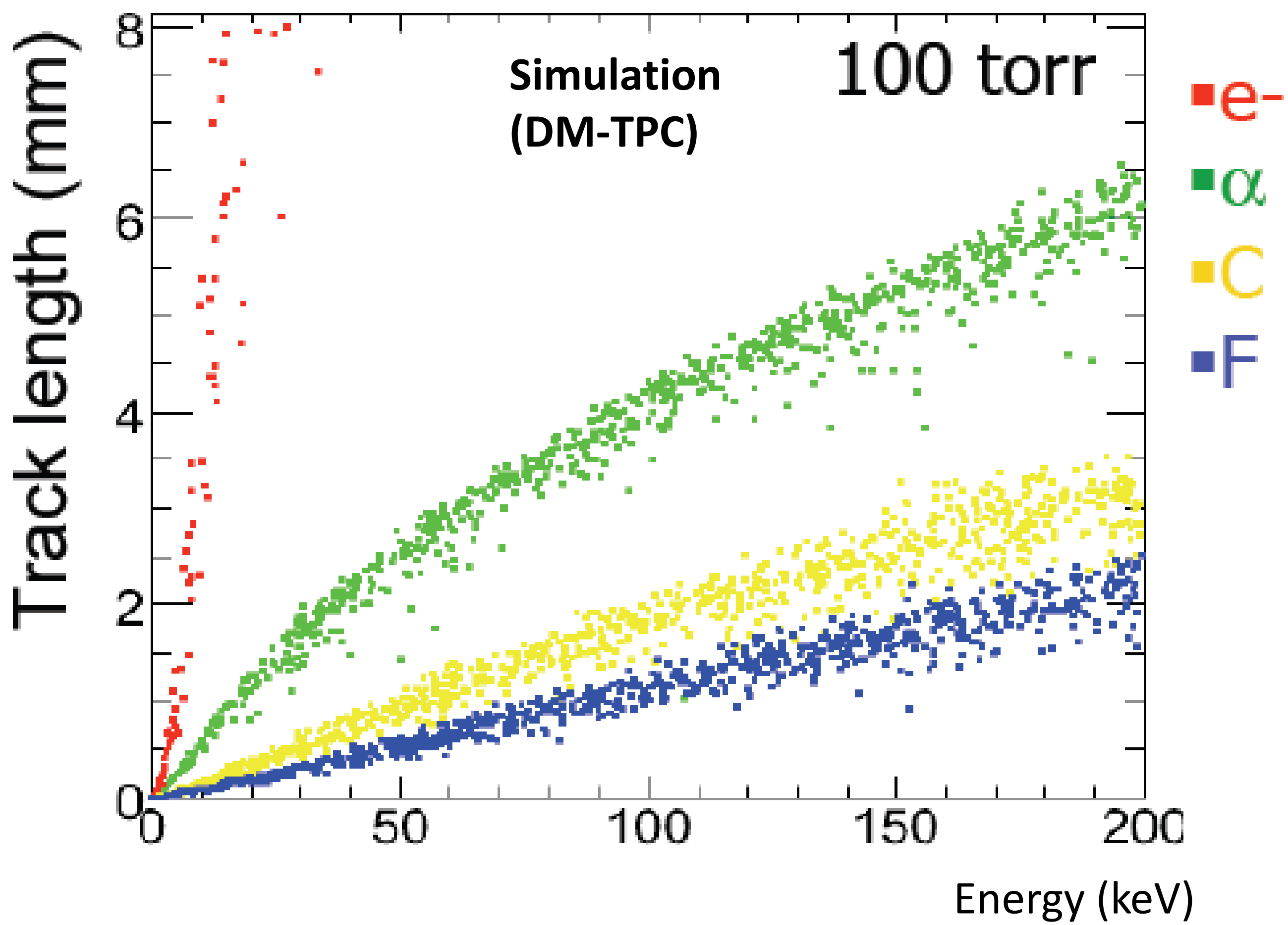




Powerful technique, highly complementary to existing direct detection approaches!

Background Suppression

- Measuring both recoil length and energy improves signal / background separation



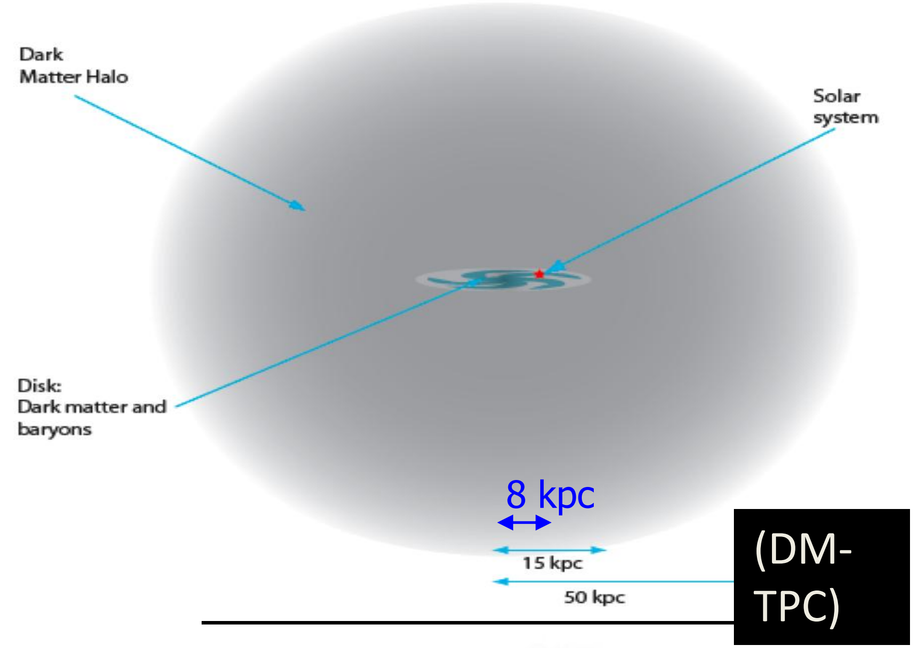
Smoking Gun: Directional Signal

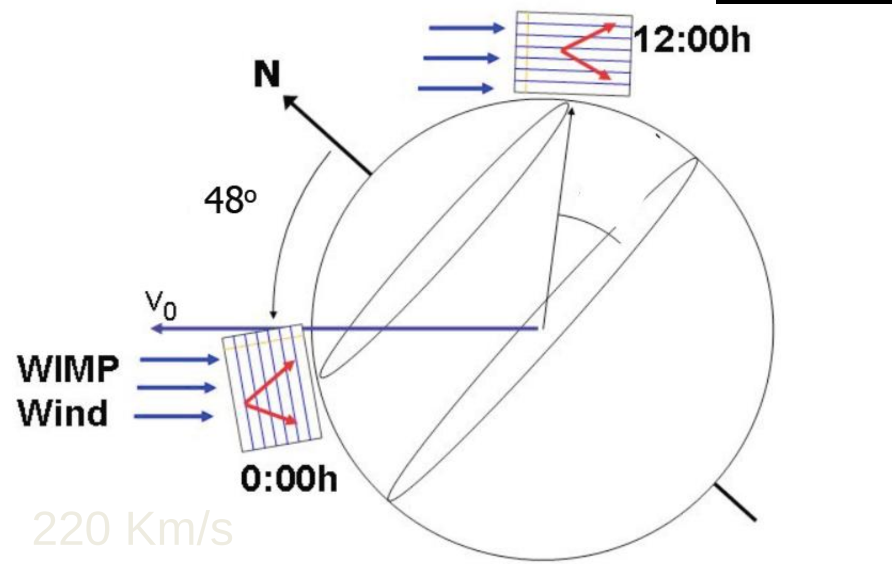
- Galaxy rotation → earth/solar system sees DM wind of ~220 Km/s
- **Average WIMP direction changes by 90 degrees every 12h!**

  → smoking gun signal

  Spergel PRD 37,1353 (1988)

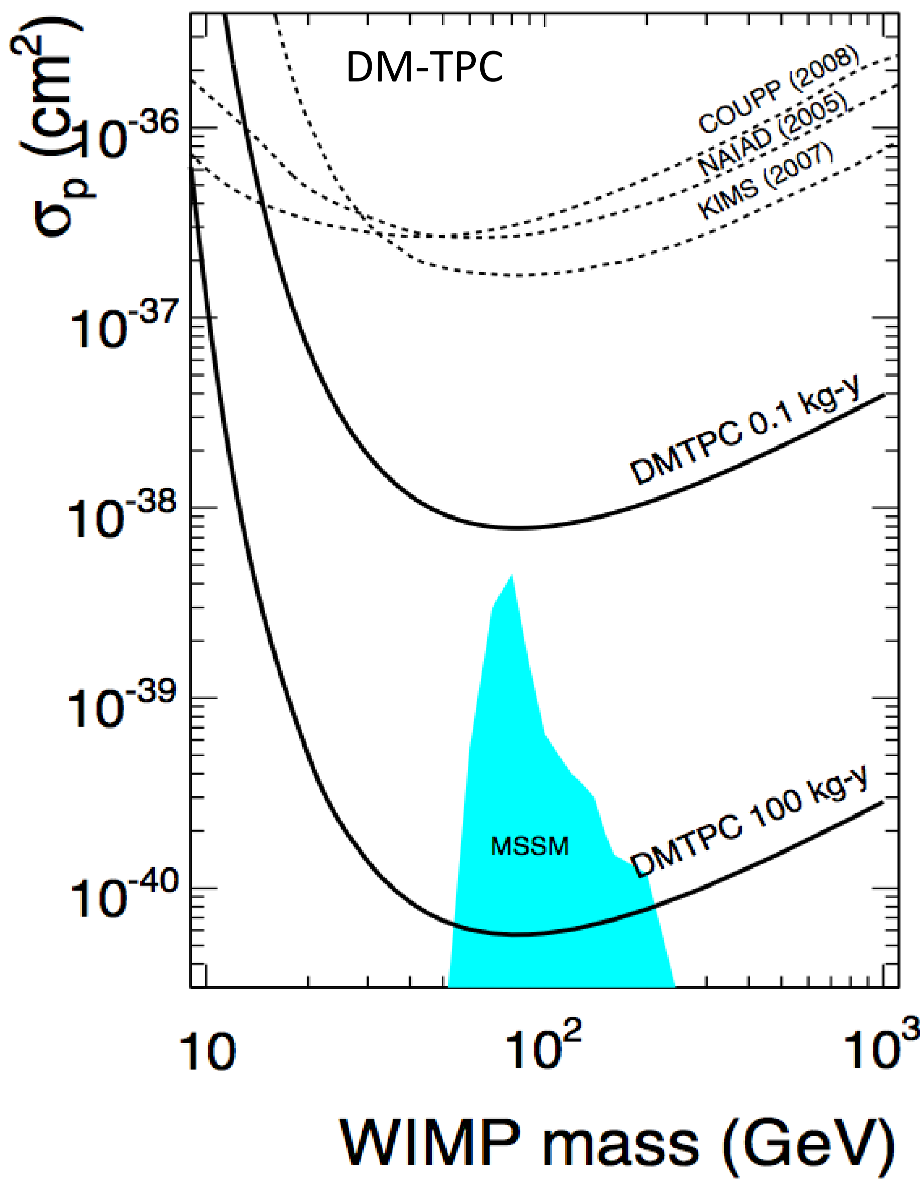
- Allows suppressing directional backgrounds (i.e. solar neutrinos)
- Large facility: WIMP Astronomy!





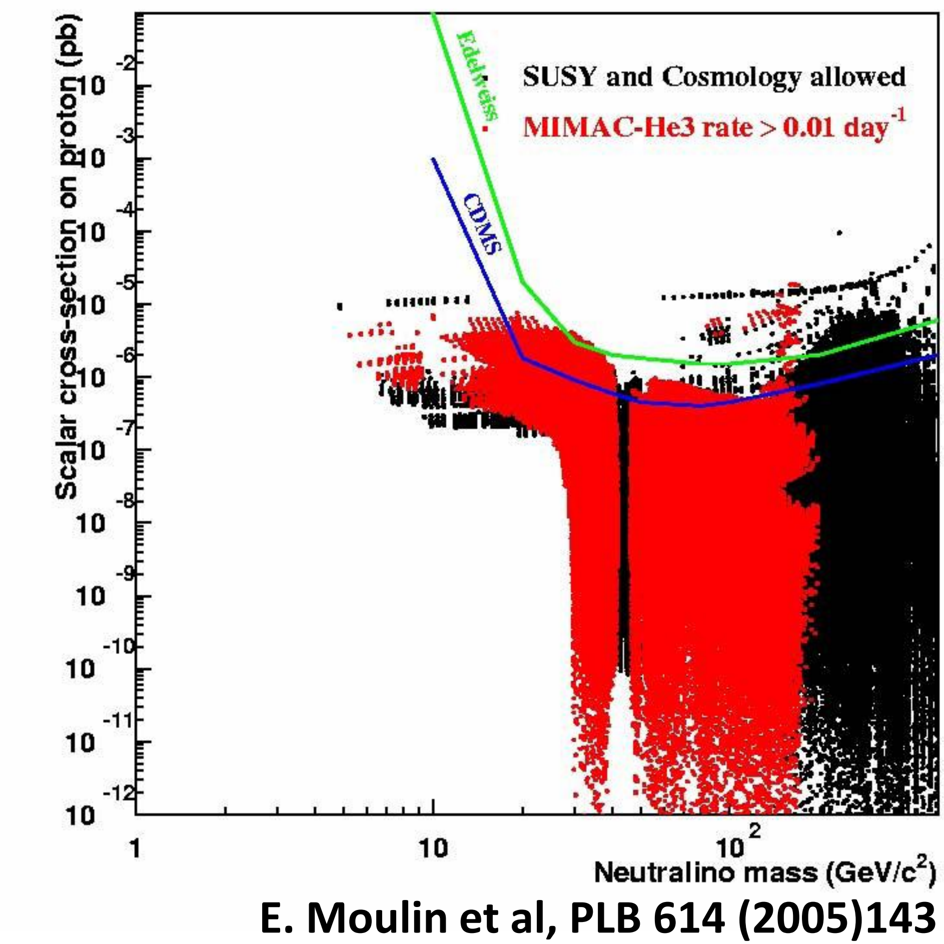
Various Size Detectors are Interesting

- Gas TPC: choose target
  - e.g. CF_4 to probe spin-dependent WIMP interaction
- 0.1 kg-y
  - $1m^3$ CF_4 , 75 torr, 3 month
  - improves spin-dependent limits by order ~50
- 2.7 kg-y
  - sensitive to in-elastic Dark Matter Scenario compatible with DAMA arXiv:0906.0002v1
- 100 kg-y CF_4
  - probes far into MSSM (SUSY) (see next page!)



Spin Dependent Sensitivity

- Spin-dependent scattering dominates in some SUSY models
  - Possible that SUSY WIMP discovered first in spin dependent search!
  - If it happens in SUSY, what about physics we haven't thought of?



E. Moulin et al, PLB 614 (2005)143

All points: MSSM without gaugino mass unification at GUT scale

Red points: models discoverable by ~10 kg-y ^{3}He spin-dependent search

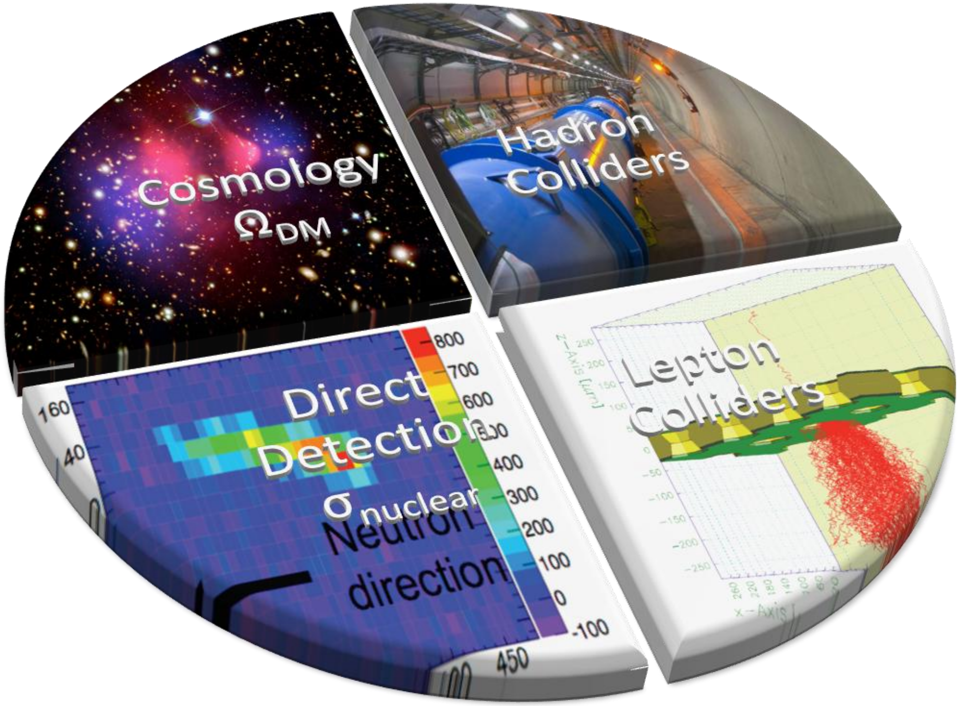
Increasing Interest in Directional Detection

Cygnus 2009: 2nd Workshop on Directional Dark Matter Detection

- 3-4 groups working on similar detectors
- Picture above is good fraction of world community
- Eventually merge into collaboration?
  - "Manifesto" paper in preparation
  - Proposal for large underground facility?

Conclusion

- Dark Matter is one of the most exciting mysteries in physics today
- LHC may produce it
- Full understanding of DM will require progress on multiple frontiers
- Pixels will play a crucial role, can help with multiple difficult detectors challenges
  - Radiation at Hadron Colliders
  - Precision at Lepton Machines
  - Directionality and background rejection in direct detection



The future looks bright for pixel detectors!