3rd International Summer School on Astroparticle Physics "NIJMEGEN09"

Hadron Collider Results Impact on Particle Astrophysics

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Some Context Before We Begin

Experimental Particle Physicist by Training

- CDF (Tevatron) and CMS (LHC) experiments
- SUSY phenomenology at the interface of particle physics and cosmology
  - Particles of the Early Universe
  - Dark Matter in the Universe today
  - Convener of the CDF Supersymmetry (SUSY) group

Cosmo-Particle Searches at Collider Experiments

Alternative Talk Titles

"Looking for the Particles of the Early Universe in Collider Experiments"

"Cosmo-Particle Searches at Collider Experiments

Outline

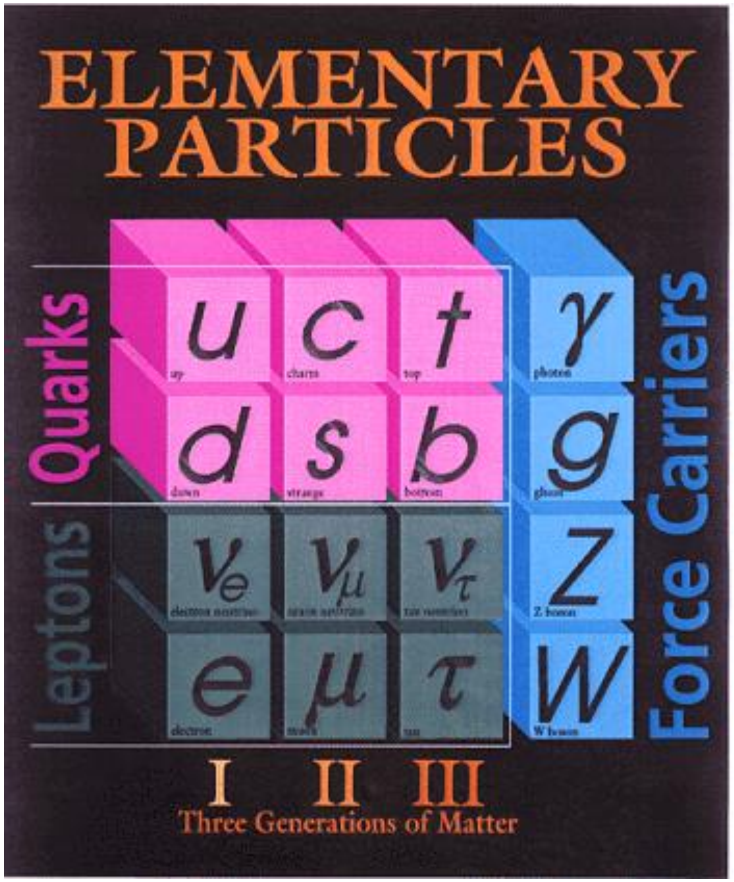
- What we know and what questions we're trying to answer
- Supersymmetry and other Ideas
- Searching for New Physics in Collider Physics Experiments
- Tevatron Results
- Some stuff about the LHC in advance of its turn-on

Where to Start…

- *What do we know and what do we not know?*
- *What Questions are we trying to answer?*
- *Is there a single solution to some very different physics/astronomy problems?*

The Known Particles*

The Standard Model of particle physics has been enormously successful. **But:**

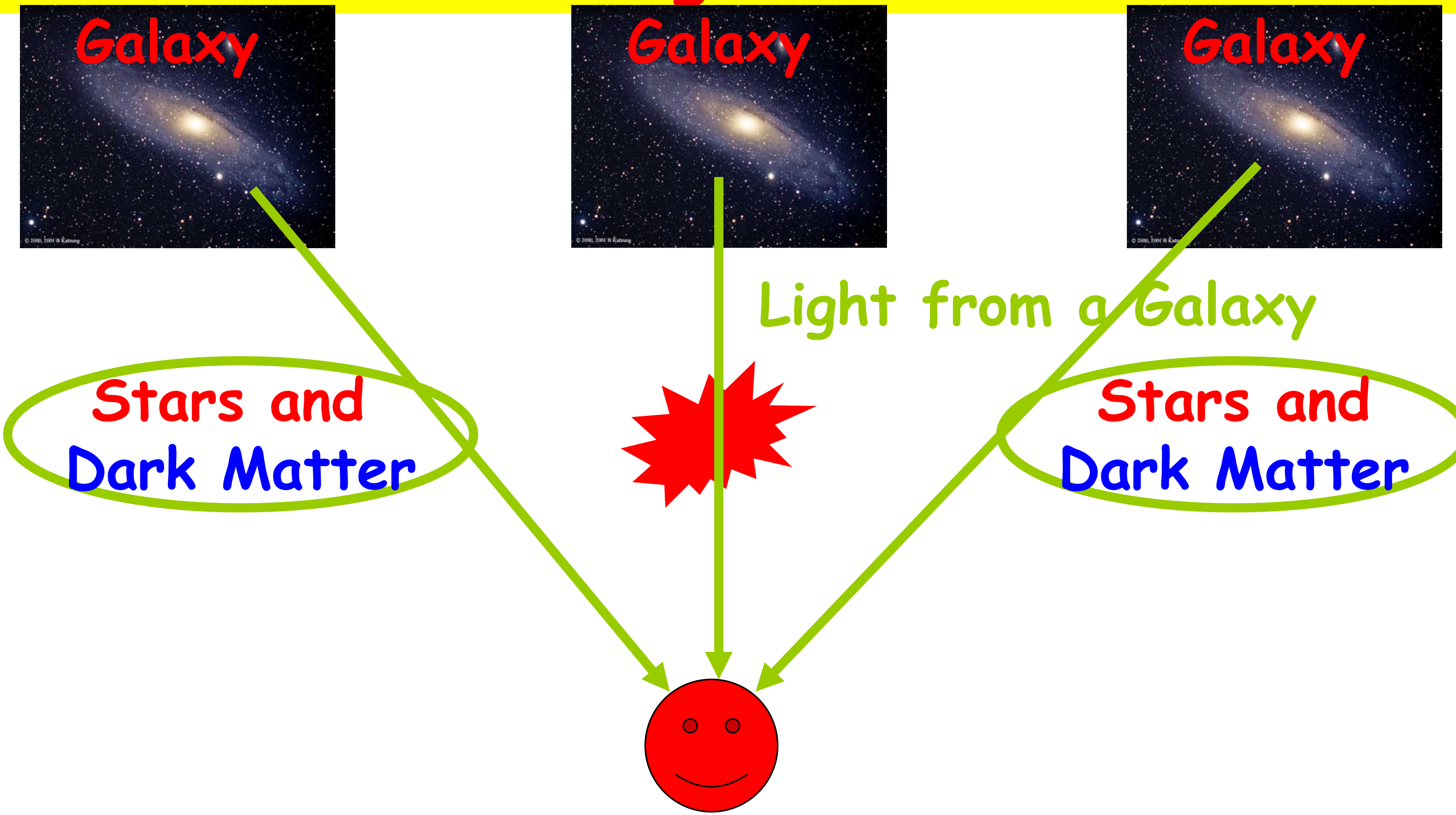


- *Why do we need so many different particles?*
- *How do we know we aren't missing any?*
- Lots of other unanswered questions…

*Not a review of particle physics

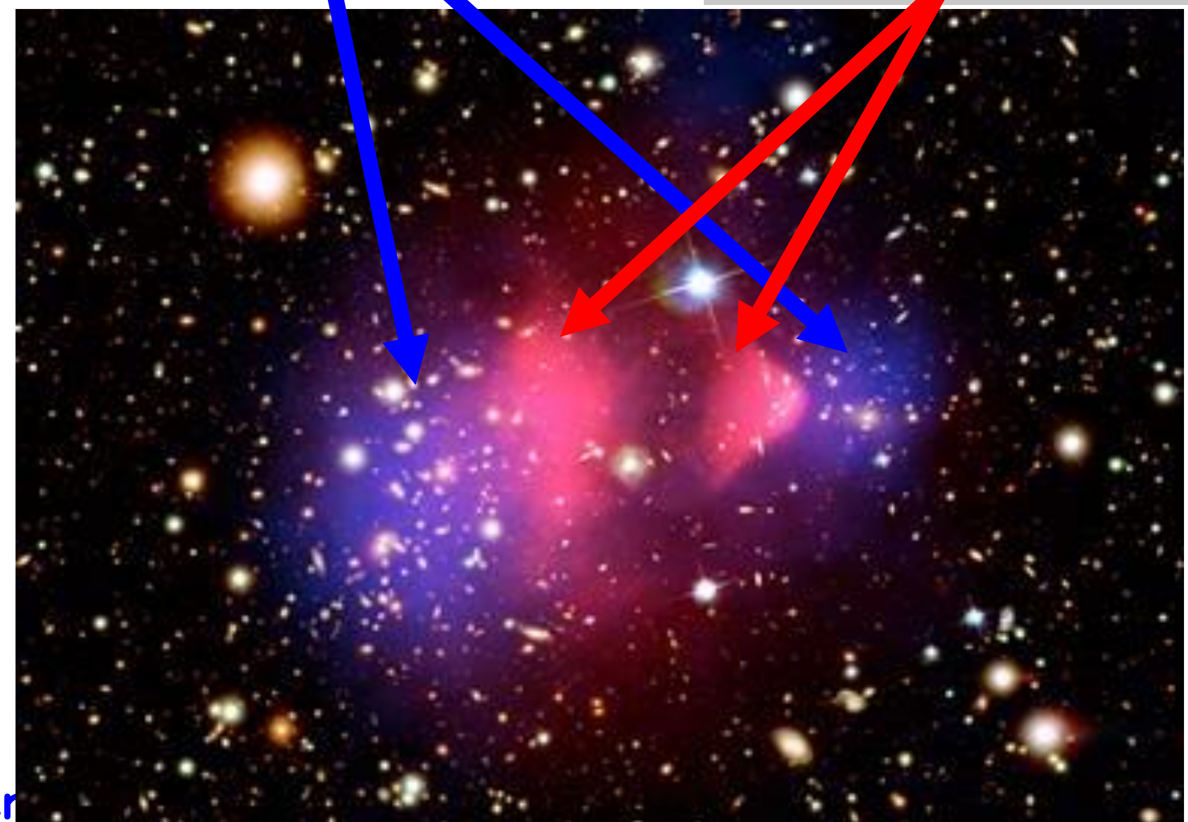
Evidence for Dark Matter as Particles

Colliding Galaxies

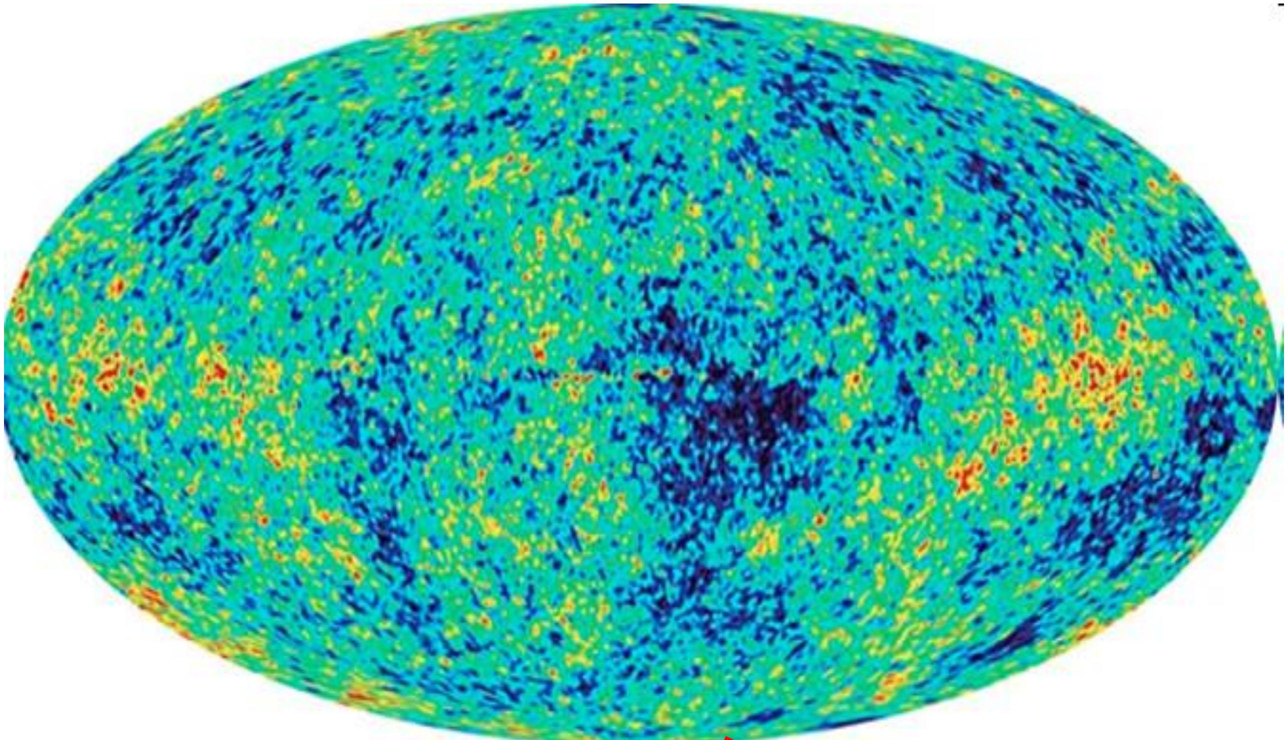


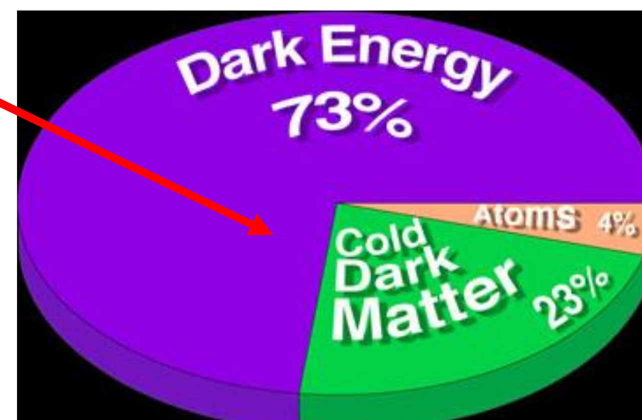
Blue (Dark Matter) is the part from lensing only:
Fast → Weakly Interacting Particles

Red part from x-ray observations
Slow→Particles with Standard Model Interactions



Entering the Era of Precision Cosmology





WMAP data currently measures the Dark Matter density to be $0.94 < \Omega_{DM} h^2 < 1.29$

Particle Physics solution to an Astronomy problem?

- Good: Predict massive stable particles that explain Dark Matter effects
- Better: Provide both a model of particle physics and cosmology that gets the Early Universe Physics correct and correctly predicts the Dark Matter Relic Density

What IS the Dark Matter and How did it Get there?

<u>Guess:</u> The Dark Matter in the ... se is made up of LOTS of ... e haven't di...

Got creat... like ev... here today!

Big Bang!

Then Universe gets bigger

<u>Today:</u> 5 times more Dark Matter than Atoms in the Universe

The Known Particles

Many theories/models attempt to address these issues, but none have been experimentally verified

As best as we can tell Dark Matter isn't a known particle of nature that we've already discovered here on Earth

Many other credible reasons to believe there are new fundamental particles out there to be discovered

Models of New Physics to Try and Help Answer the Questions: Each Predicts New Particles

- Higgs
- SUSY
  - Lots of different versions
- Heavy versions of the vector bosons
  - W' and Z'
- Leptoquarks, Composite leptons
- Extra Dimensions
- Axions

Why Focus on Supersymmetry?

There are some theories that are so compelling that it's worth doing a comprehensive and systematically deep set of searches to see if they are realized in nature

→Supersymmetry is such a theory

First things First: *What is Supersymmetry and why do we care?*

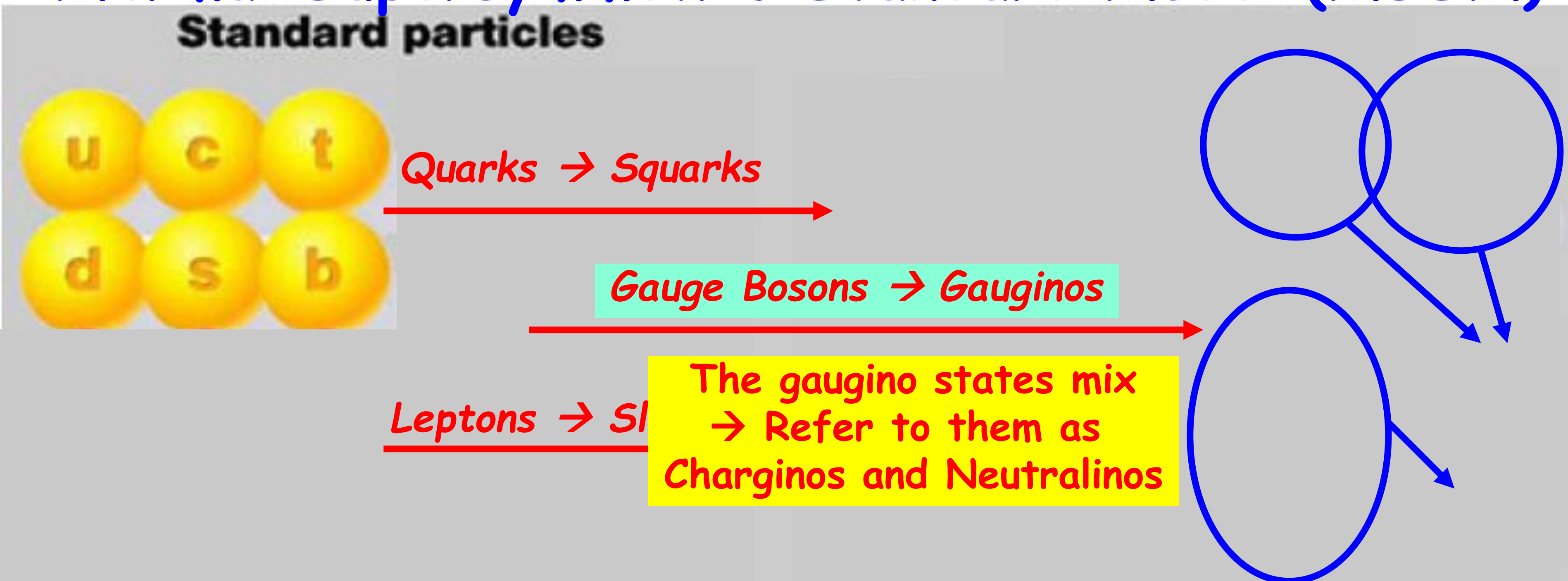
What is Supersymmetry?

Supersymmetry (SUSY) is a theory that postulates a symmetry between fermions and bosons

$$Q|Boson\rangle = |Fermion\rangle$$

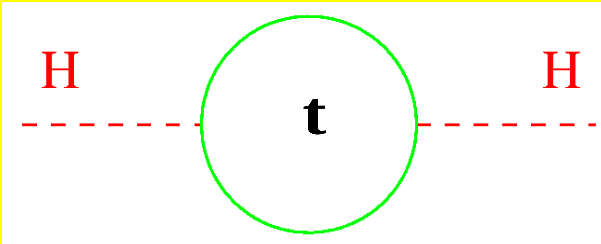
$$Q|Fermion\rangle = |Boson\rangle$$

Minimal Supersymmetric Standard Model (MSSM)



The hierarchy problem and how SUSY helps

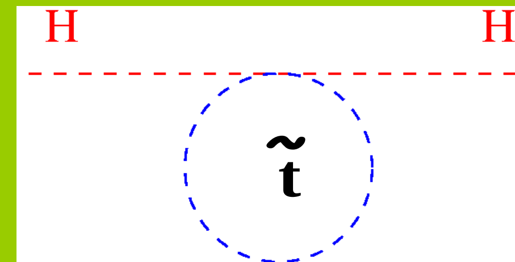
The Standard Model



Corrections to Higgs boson mass not only finite, but in fact divergent

$$\delta m_H^{\,2} \approx \Lambda^2 >> m_H^{\,2}$$

Supesymmetry



Fermion and Boson contributions to the Higgs cancel nearly exactly in supersymmetry (finite)

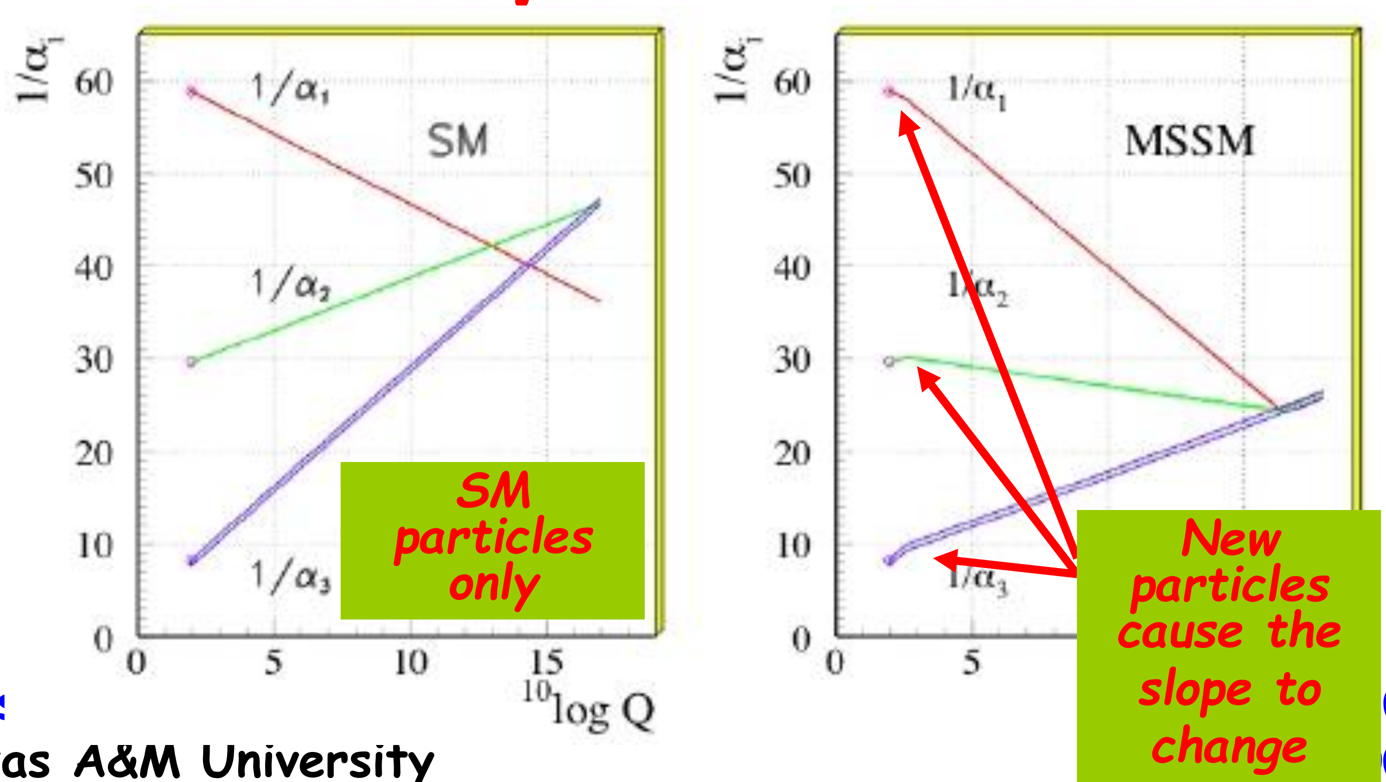
$$\delta m_H^{\,2} \approx O\left(\frac{\alpha}{\pi}\right) \times \left(m_B^{\,2} - m_F^{\,2}\right)$$

$< TeV^2$

The one loop divergences will cancel, provided that the SUSY particles have masses below the Fermi scale

SUSY and the Coupling Constants

Another issue is that adding extra particles provides a "natural" way for the running of the coupling constants to unify at the GUT Scale



Advantages and Disadvantages of SUSY

- There is no unique explanation of the origin of the sparticle masses or couplings
- With all these new couplings and particles it's possible we could have our known SM particles decaying through loops
  - Any version that predicts/allows a quick proton decay is clearly wrong
  - Any version that has the same mass for the particles and the sparticles must be wrong
    - Haven't observed any bosonic electrons in nature

    → $m_{positron} = m_{electron} \neq m_{selectron}$

→SUSY is broken somehow

Different Ways to Proceed

- There is no unique explanation of the symmetry breaking → need to make some assumptions
- Can put in masses and couplings by hand
  - General SUSY has over 100 new parameters
- Use experimental constraints and theoretical prejudices to further restrict the parameter space
  - To protect the proton lifetime can define R-parity = $(-1)^{3(B-L)+2s}$ and assert that it's conserved

  →R = 1 for SM particles

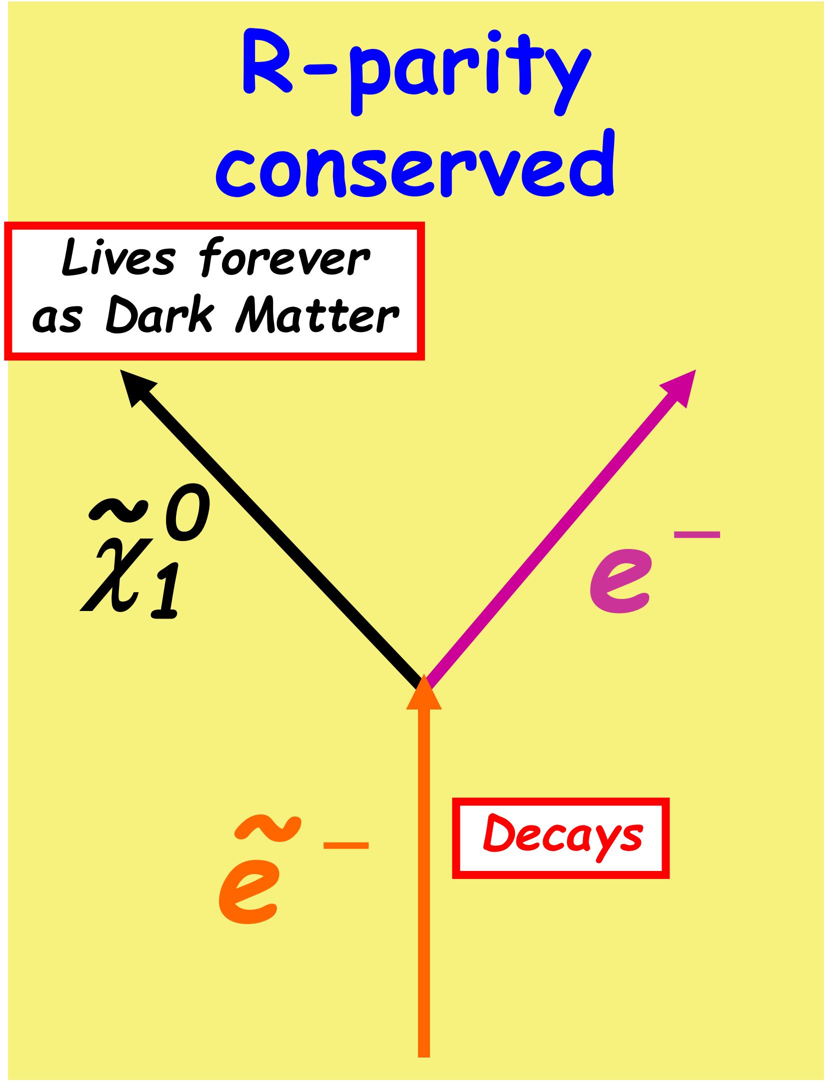
  →R = -1 for MSSM partners
- R-Parity violating terms would also have to be small for lepton number violation and still allow neutrino mixing

SUSY can provide a Dark Matter Candidate

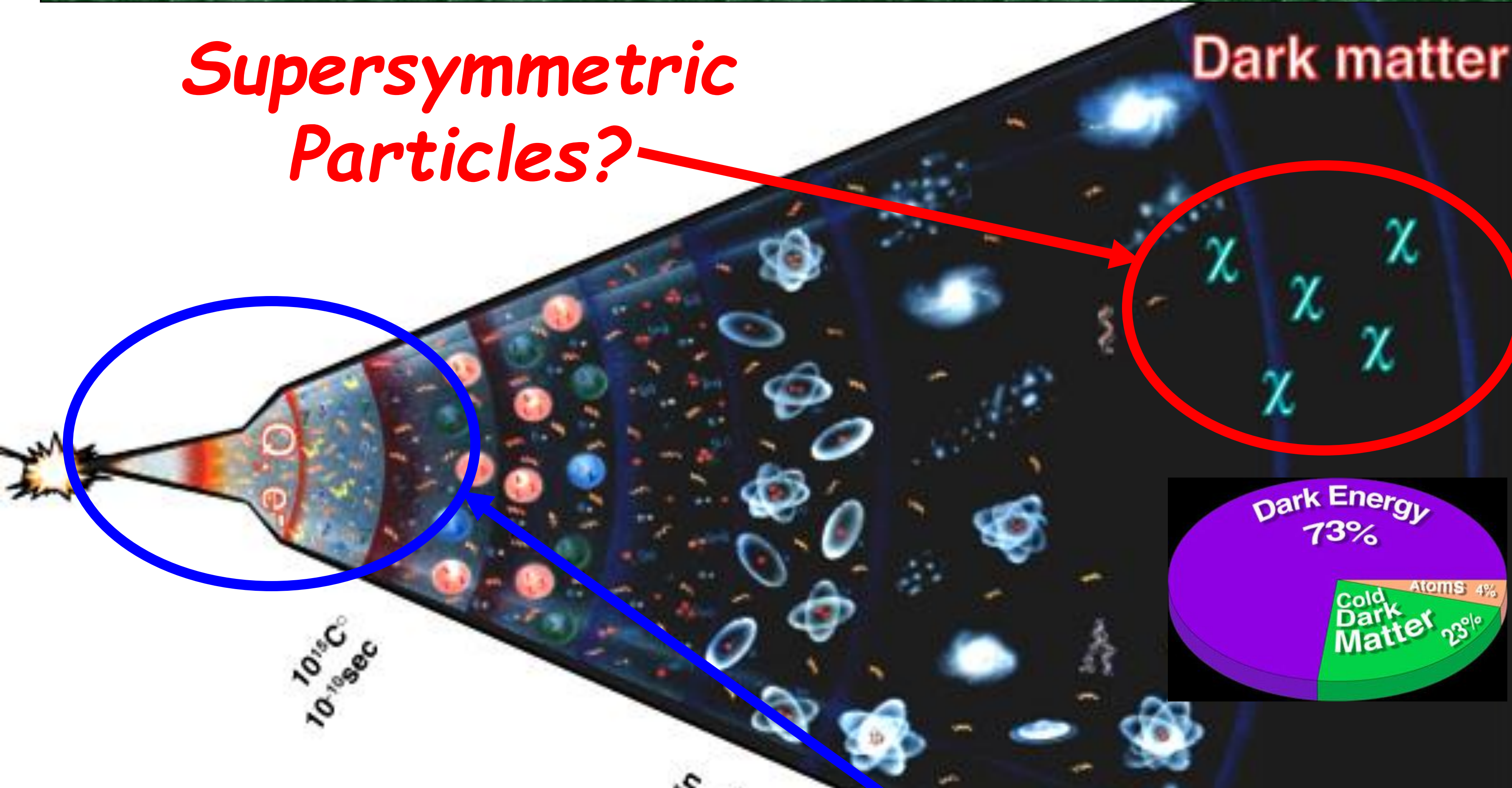
If R-Parity is conserved then the lightest SUSY Particle can't decay and, if neutral

→Provides an excellent dark matter candidate

Provides a tie between Dark Matter, Cosmology and Particle Physics?



Dark Matter = Supersymmetric Particles?



SUSY provides a full calculation of $\Omega_{SUSY\ DM}$

Not good enough to simply provide a candidate, need to describe early Universe physics and correctly predict the Dark Matter relic density

Different Types of SUSY Solutions

Cold Dark matter Produced in the Early Universe

Sparticle Masses and Lifetimes matter

Warm Dark matter Produced later in time

Cold Dark matter Produced after a month or so

Cosmology and Particle Physics?

Minimal Solution with Cold Dark Matter

- Minimal Solution → A particle produced in the early Universe is stable and weakly interacting → still here today
- CDM favored by most Cosmological models
- Lots of Supersymmetry models have a lightest particle that fits this description
- The minimal SUSY model that incorporates supergravity grand unification is known as mSUGRA → our baseline Cold Dark Matter search model

Non-Minimal Solution with Cold Dark Matter

- Many non-Minimal solutions to the Dark Matter we observe today
- Example: Long-lived Charged particles (CHAMPS) that decay to the Dark Matter

Example: CHAMP

$\tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$

Stable on the timescale of inflation	Stable on the timescale of the age of the Universe

Non-Minimal Solution with Warm Dark Matter

Warm Dark Matter also consistent with Astronomical data and inflation models

Example: Gauge Mediated SUSY with

$\tilde{\chi}_1^0 \rightarrow \gamma \tilde{G}$

Dark Matter is more complicated or has nothing to do with SUSY

- *Axions?*

Look for the most general models including R-Parity violating scenarios

Collider Physics

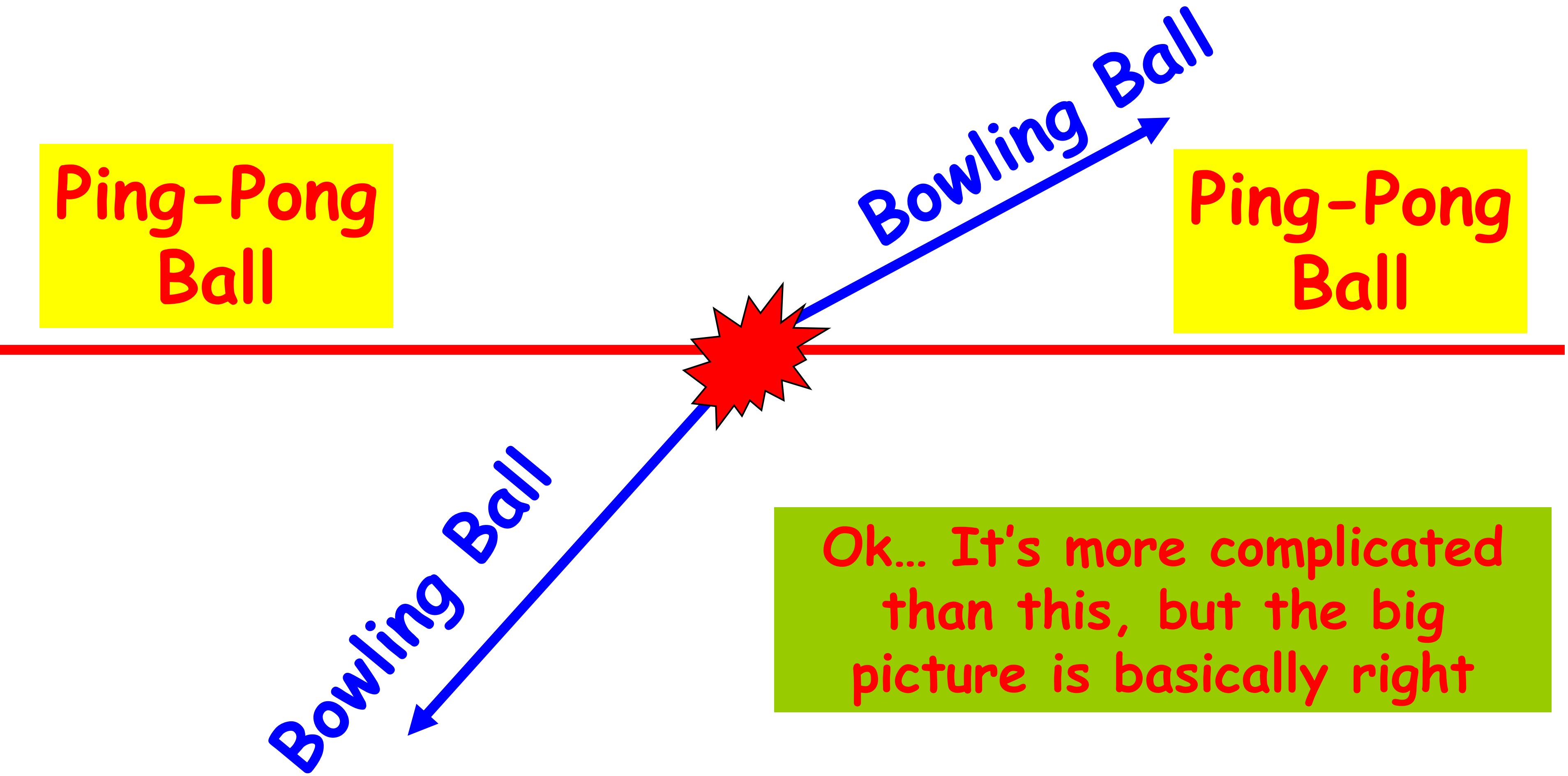
How does Collider Physics Help us answer these questions?

The Hope

- Our theories about what the particle IS are basically correct
- SUSY or Dark Matter particles have a mass that is small enough that we can PRODUCE them in a collision

$$E=mc^2$$

How everything looks to a collider experimentalist



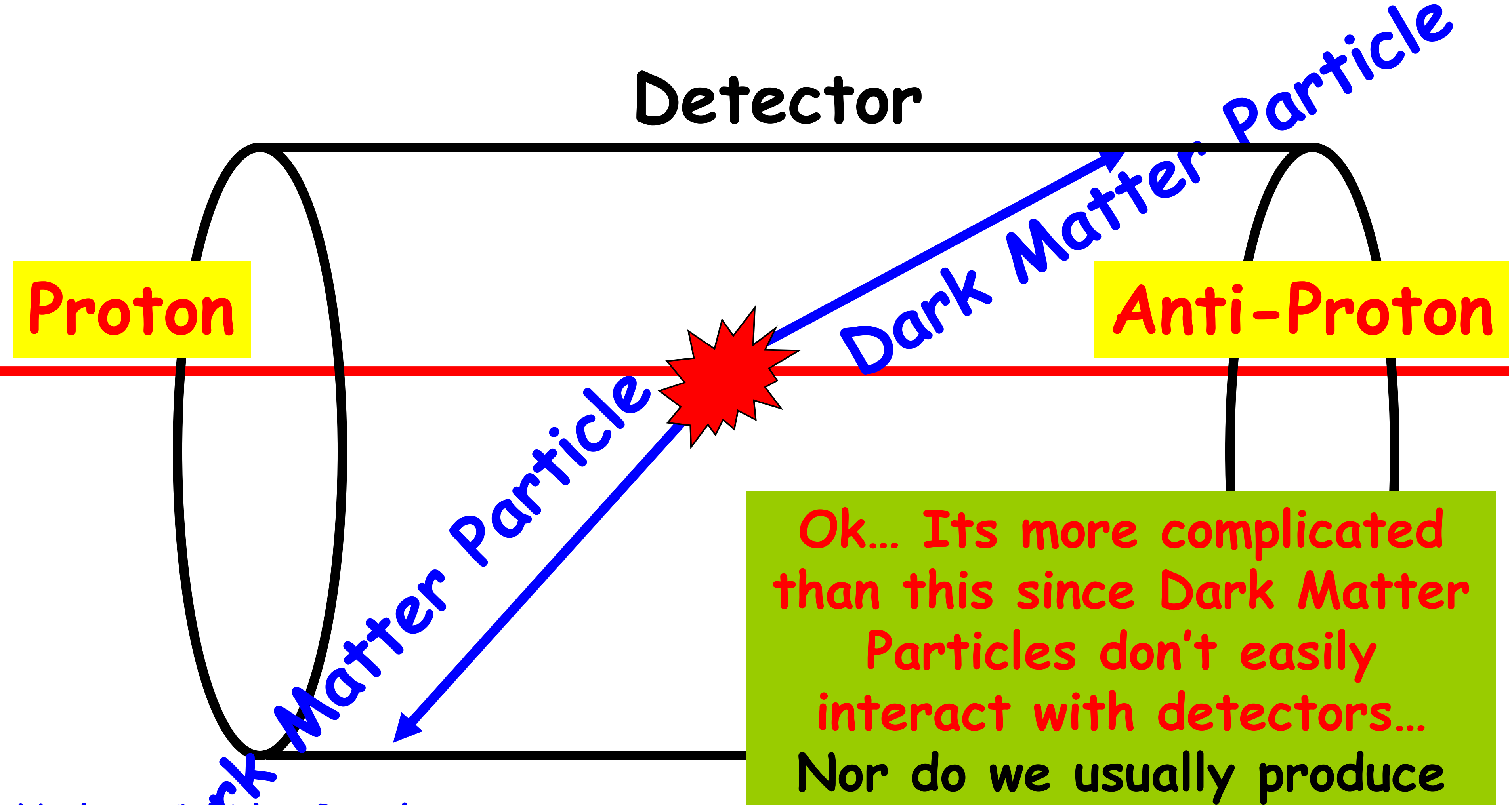
Can we Make and Discover Dark Matter?

- Lots of high energy collisions between particles in the Early Universe
- Recreate the conditions like they were RIGHT AFTER the Big Bang
- If we can produce Dark Matter in a collision then we can STUDY it

More hopes

- If we can PRODUCE it in a collision, then we can surround the collision point with a detector and STUDY it
- Lots of IFs so far, but if our understanding of Cosmology and Particle Physics (Supersymmetry) are correct than we know what we are looking for and what it should look like in our detectors!

Particle Physics = High Energy Collisions



Ok… Its more complicated than this since Dark Matter Particles don't easily interact with detectors…

Nor do we usually produce them directly

Collider Physics Experiments

Next:

A better look at the Accelerators and Detectors

Today: Fermilab

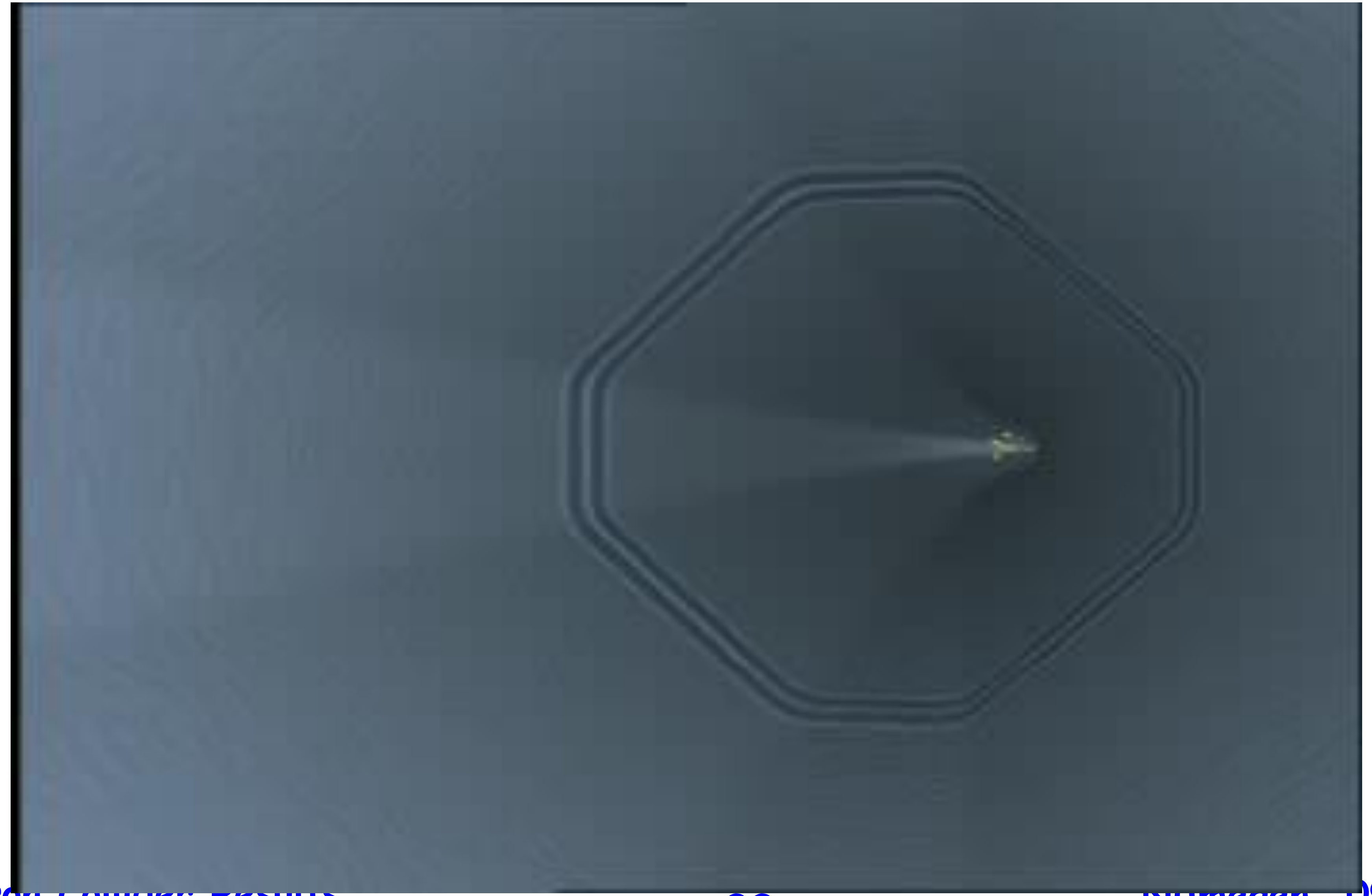
Today: Fermilab Tevatron

The worlds highest energy accelerator

- Proton anti-proton collisions
- Center of Mass energy of ~2 TeV
- 1 collision every 396 nsec

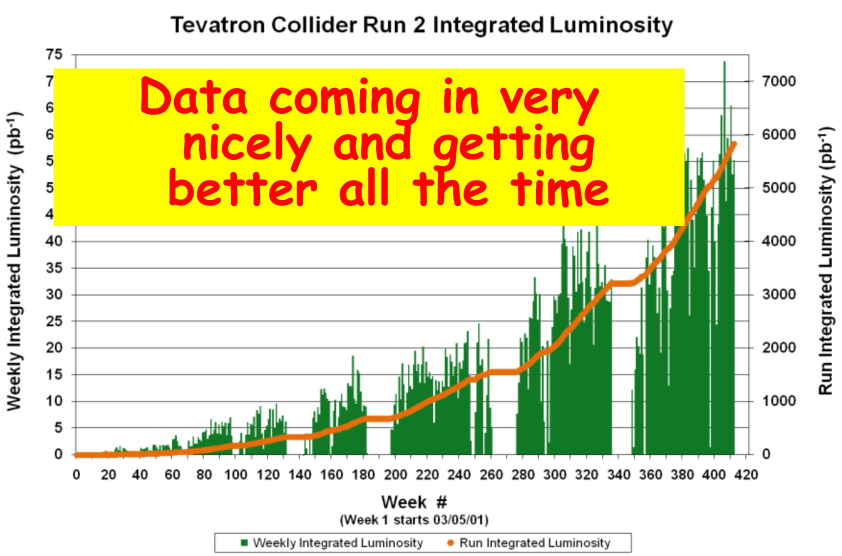
→(2.5 Million/sec)

Inside the Accelerator

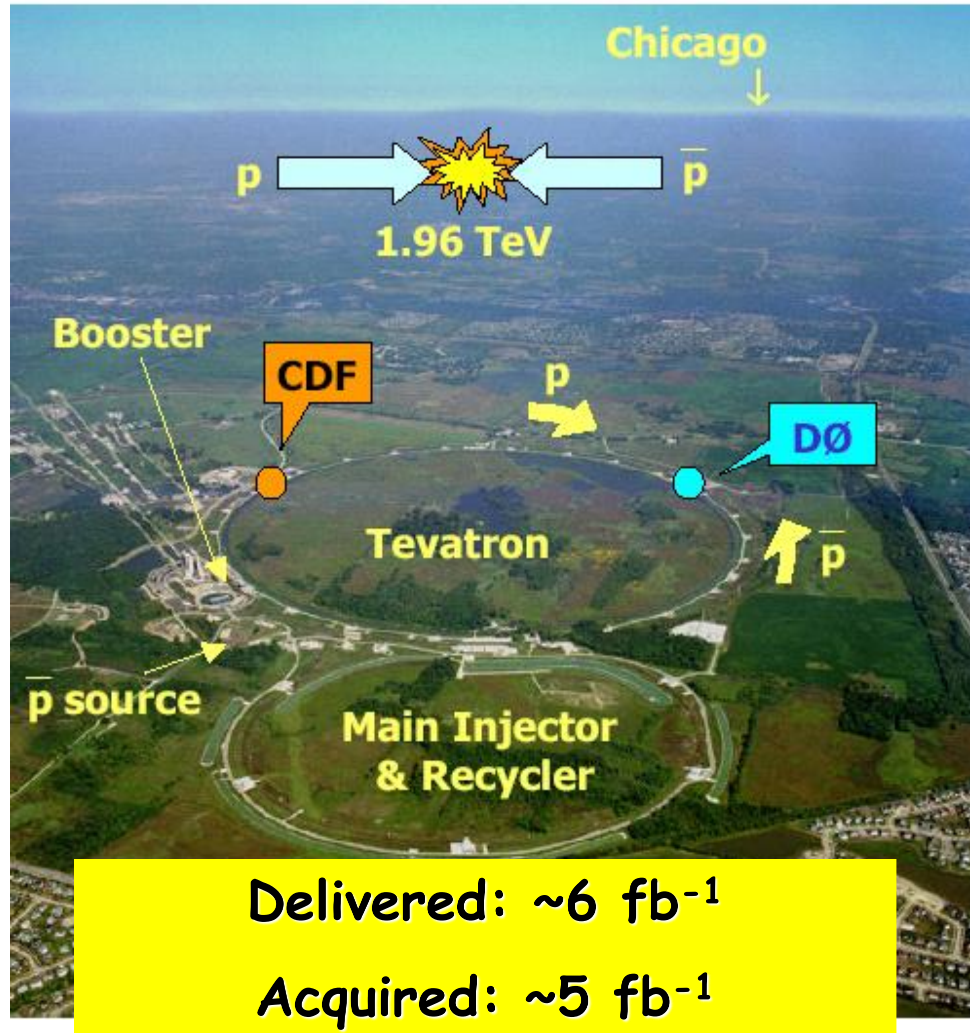


The Fermilab Tevatron

- The Tevatron is the high Energy Frontier until LHC turn-on
- Rumours of running until 2012 to be complementary to LHC



Data coming in very nicely and getting better all the time



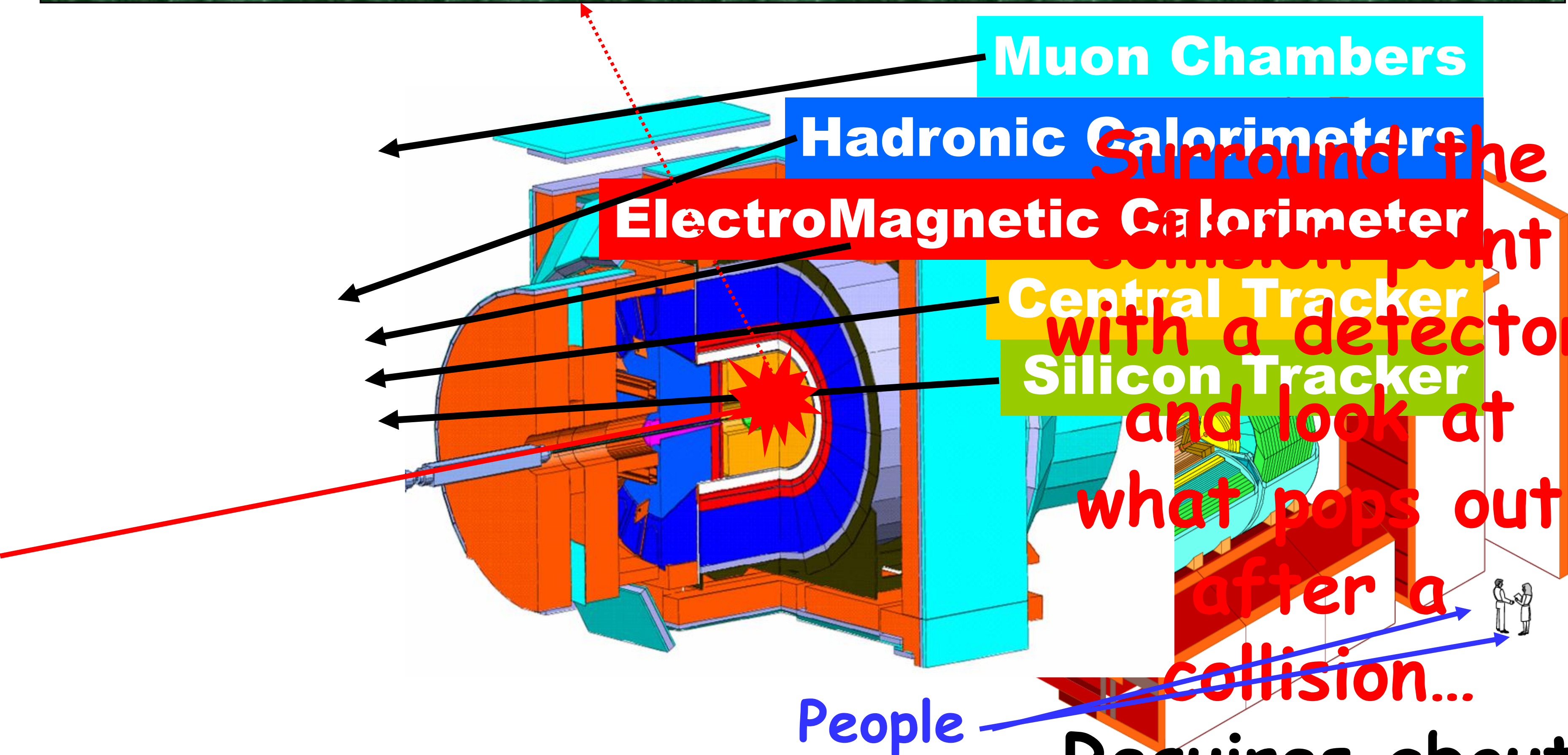
Delivered: ~6 fb^{-1}

Acquired: ~5 fb^{-1}

Analyzed: ~2-3 fb^{-1}

(depending on the analysis)

The CDF and DØ Detectors

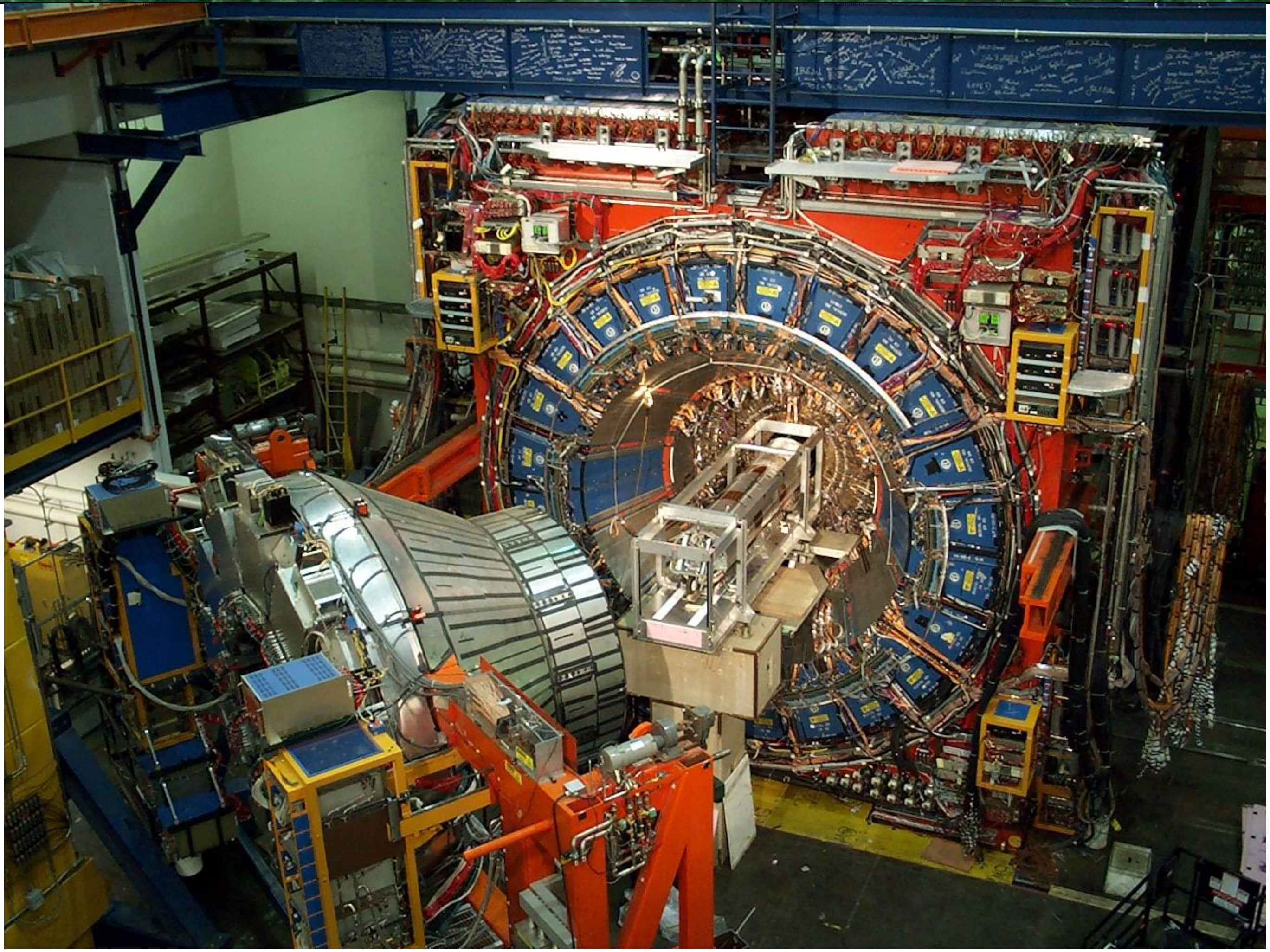


Surround the collision point with a detector and look at what pops out after a collision…

Requires about 600 friends

DØ looks different, but is designed in much the same way

The CDF Detector

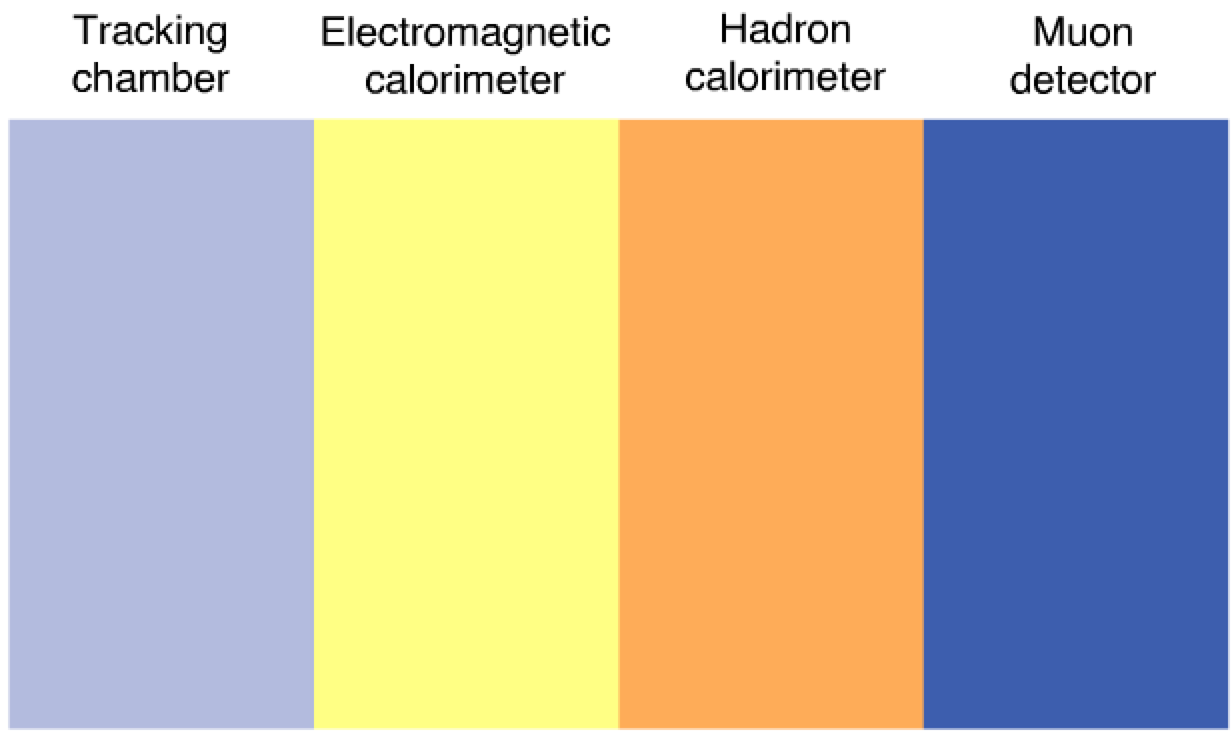


Powerful multi-purpose detector

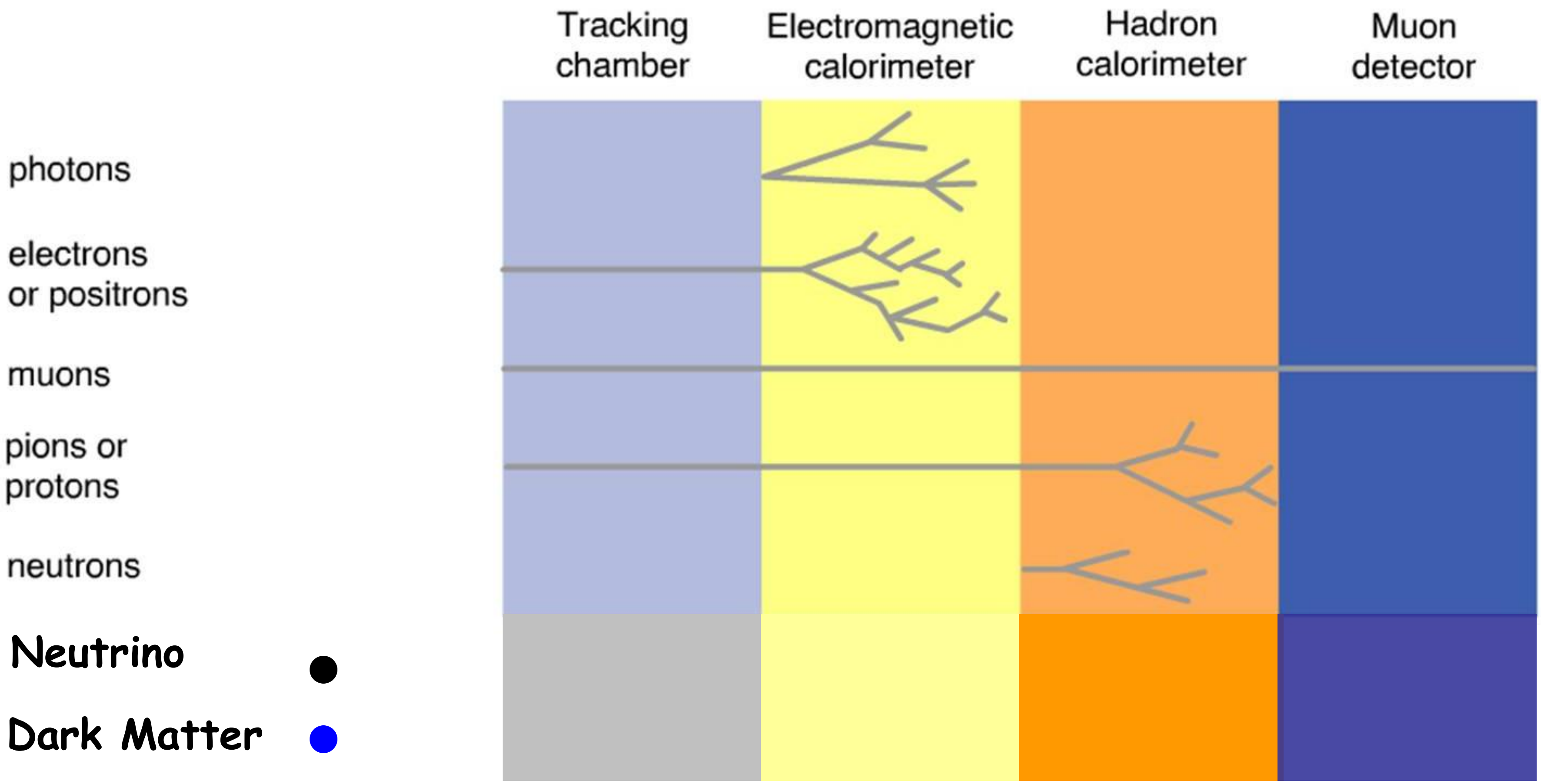
High quality identification for electrons, muons, taus, jets, Missing Energy, photons, b's etc.

Identifying the Final State Particles

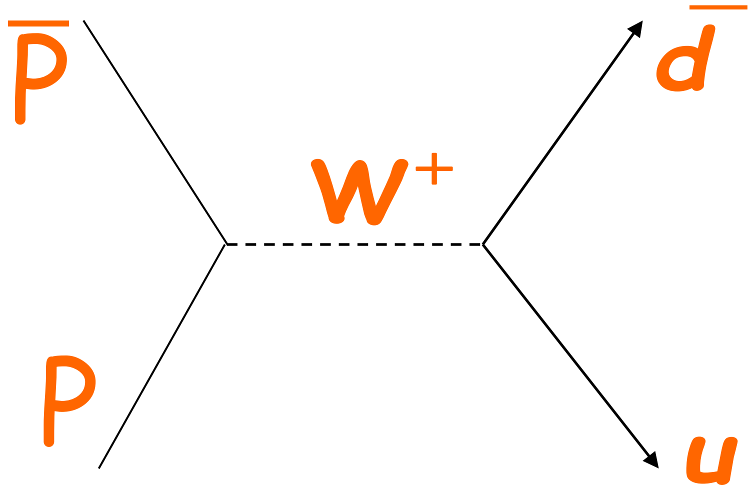
- Many particles in the final state
  - Want to identify as many as possible
  - Determine the 4-momentum
- Two types: short lived and long lived
  - Long lived: electrons, muons, photons…
  - Short lived: quarks, W, Z…"decay" into long lived particles
- Observe how long lived particles interact with matter
  - Detection

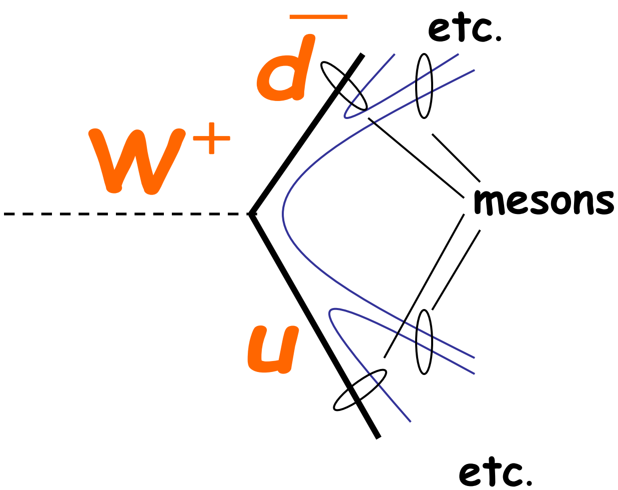

Tracking chamber
Electromagnetic calorimeter
Hadron calorimeter
Muon detector

Neutrinos and Dark Matter Don't Interact with the Detectors

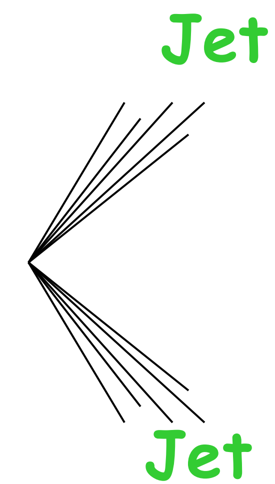


Short Lived Particles in the Detector





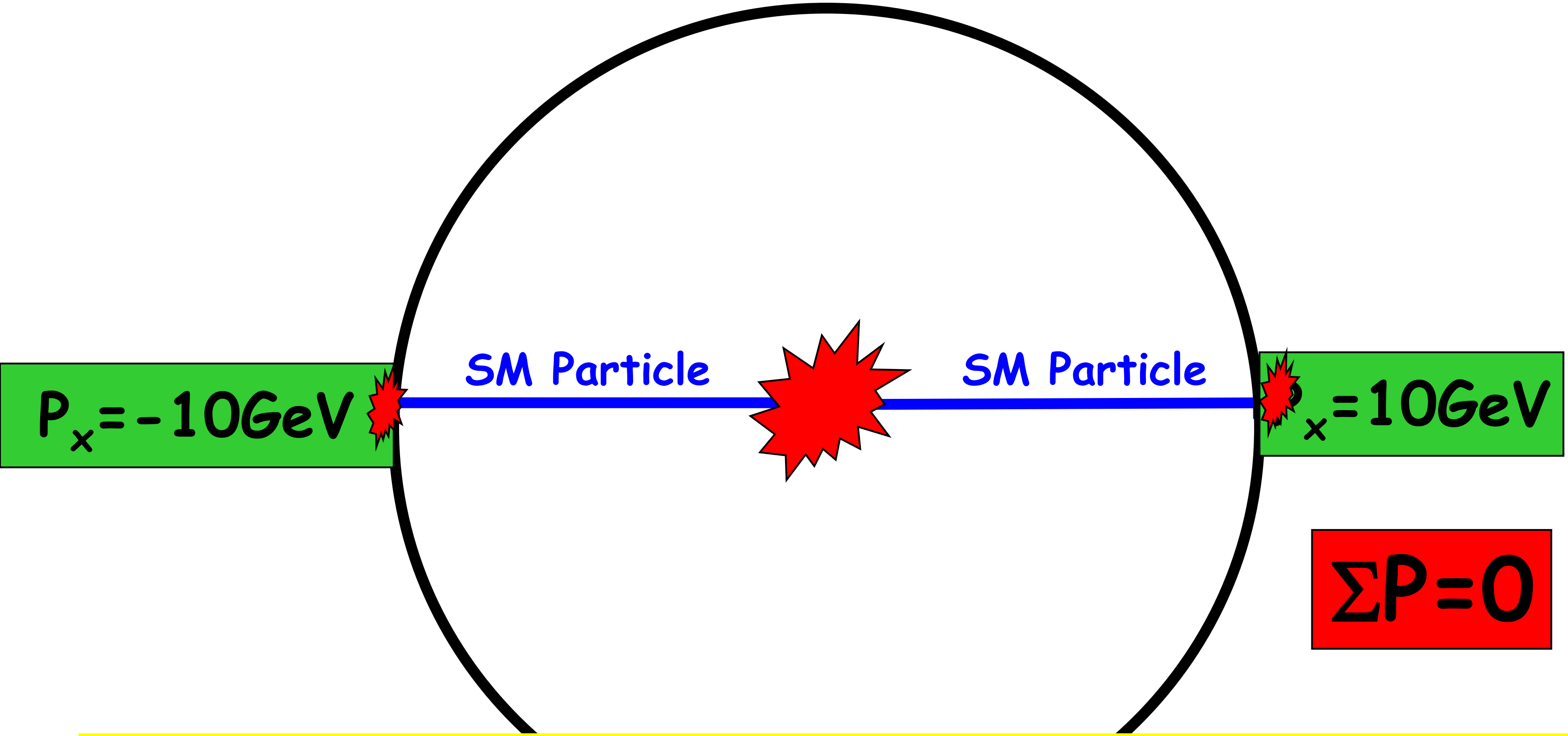
The $q\bar{q}$ pairs pop from the vacuum creating a spray of particles



In the Detector

Now look at the head-on view of particles coming out

Detector End-View



Proton and Anti-Proton Collide in the middle and produce SM particles

Particle momenta measured by detector

A Dark Matter and a SM particle at the same time?

ΣP=-10 GeV

in the x-direction

→Missing Energy!

Smoking Gun for Dark Matter

SM Particle Deposits energy, but Dark Matter particle doesn't interact with the detector and leaves

High Energy Collisions

So… The accelerators makes really high energy collisions that can be studied

- Recreating the conditions like they were RIGHT AFTER the Big Bang
- Look for Missing Energy as a signature of Dark Matter/SUSY

"Quarks. Neutrinos. Mesons. All those damn particles you can't see. That's what drove me to drink. But now I can see them!"

Review

How does one search for new particles at the Tevatron?

- **Bang a proton and an anti-proton together and look at what comes out (an event)**
- **Compare Missing Energy from Standard Model events to the expectations for SUSY/Dark Matter**