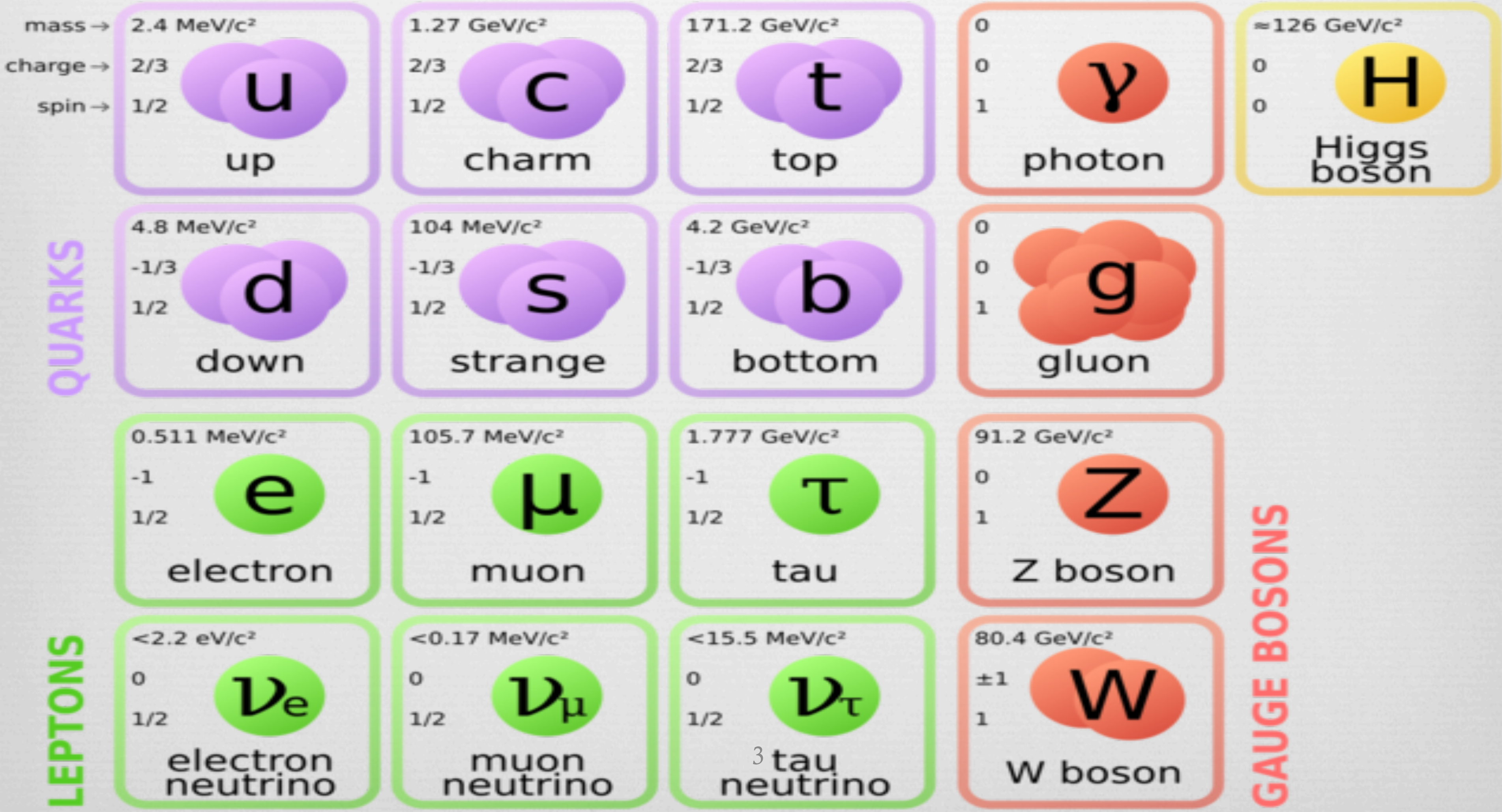
# Contents / Overview

- What do we already know about the universe?
- How do we know something is missing?
- If there is something missing, what are its properties?
- What could it be??
- How do we look for it?
- Have we found anything promising yet?

# The Standard Model

- Empirical Theory
- Decades of experimental testing
- Best model we have for explaining our known universe
- Not perfect…
- Not complete…

# The Standard Model



# Is this really all there is?…

- Hierarchy Problem?
- Sterile Neutrinos?
- Gravity?
- Dark Energy?
- Dark Matter

# Let's start from the beginning…

- Virial Theorem
  - Kinetic energy should be half the gravitational potential binding energy of the system

$$2 < T >= -\sum_{k=1}^{N} < F_k \cdot r_k >= n < V_T >$$

$$T \approx \frac{1}{2} v^2 \approx \frac{3}{2} \sigma^2 \qquad \frac{GM}{R} = \frac{GM_{vir}}{R_{vir}} \approx \sigma^2$$

$$\frac{M_{vir}}{R_{vir}} \propto v^2$$

# So first, a bit of history

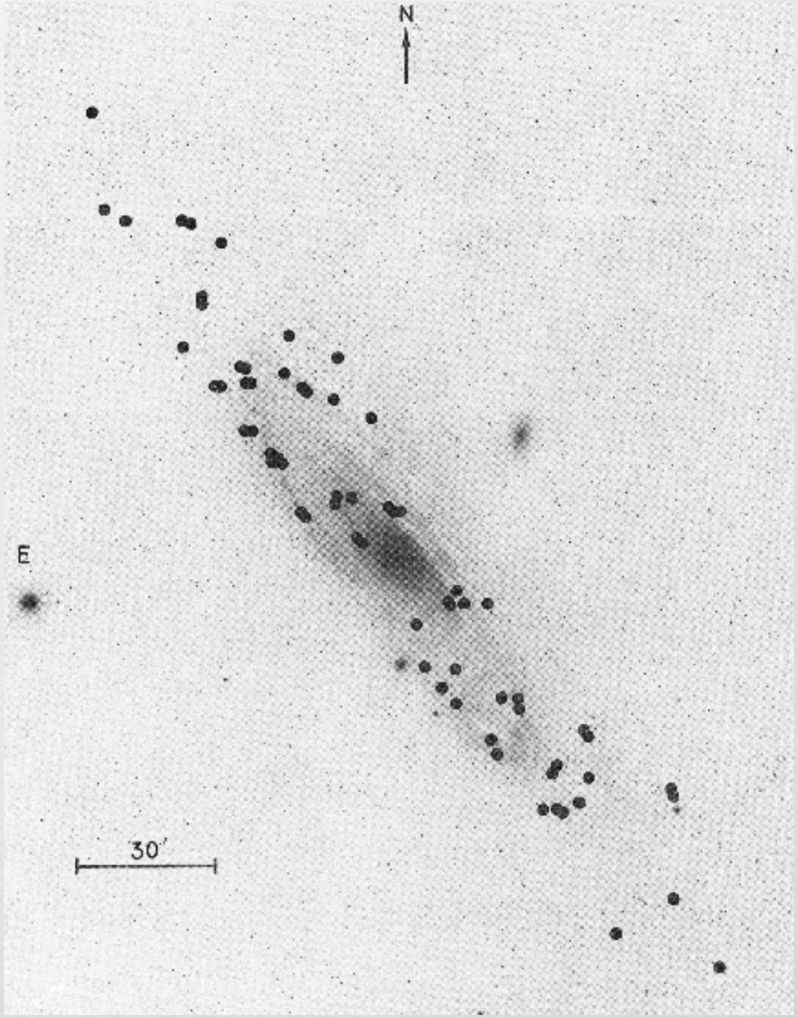
- Jan Oort
  - Galactic Halo of Milky Way Galaxy (1924)
  - Calculated the distance between Milky Way center and Earth (1927)
  - First evidence for Dark Matter – measured mass of galactic disc (1932)
    - Data/Calculations Proven Erroneous!
- Fritz Zwicky
  - Applied Virial Theorem to Coma Cluster to reveal evidence of unseen mass (1933)
  - Came to conclusion that there was ~ 400 times more mass than observed in cluster
  - "Missing Mass Problem"

# First Concrete Evidence

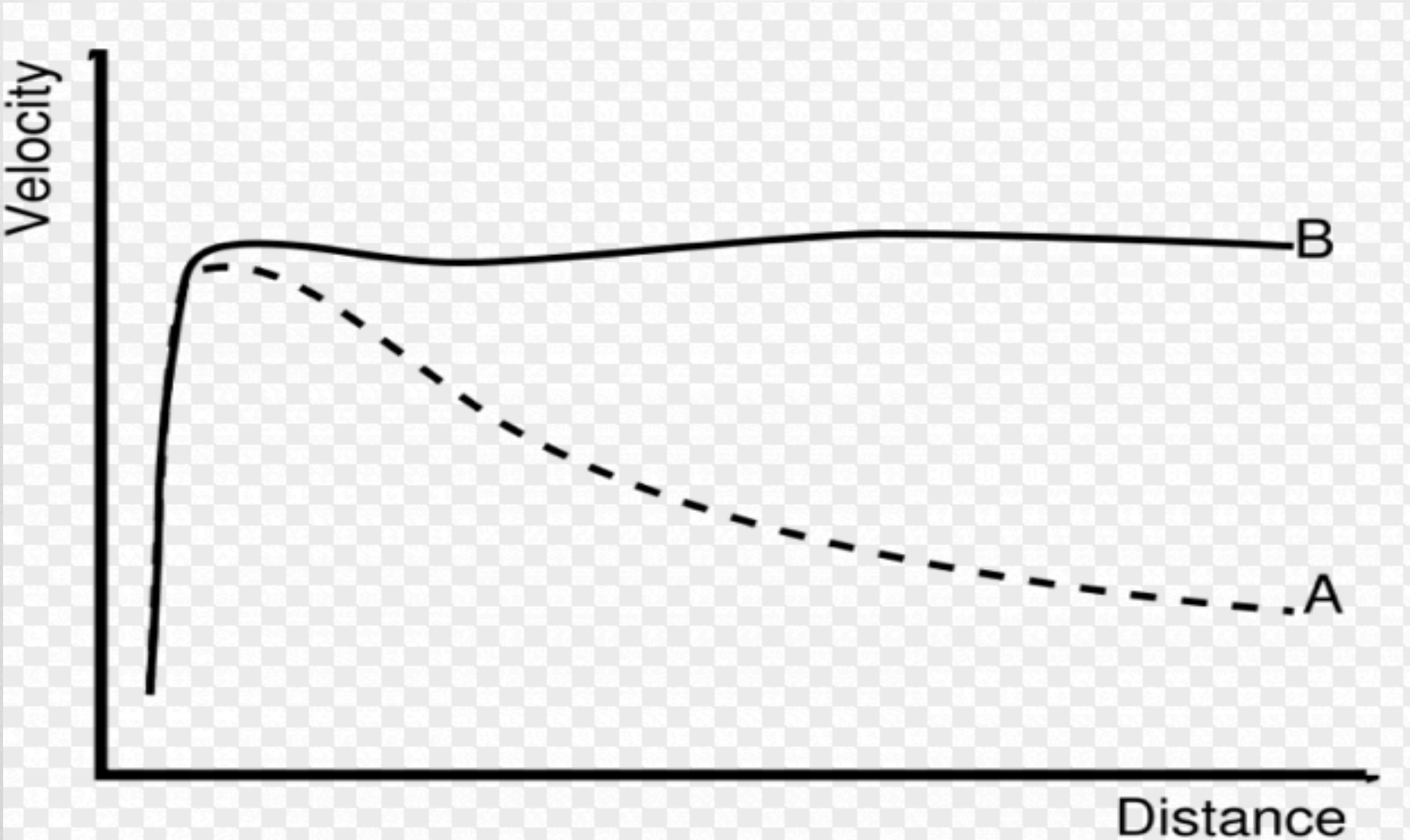
- 1969 – Vera Rubin and Kent Ford
- Utilized spectral emission lines from 67 points on Andromeda Galaxy to calculate velocities
- One goal was to observe velocity field and determine mass
- Interesting results…

# First Concrete Evidence

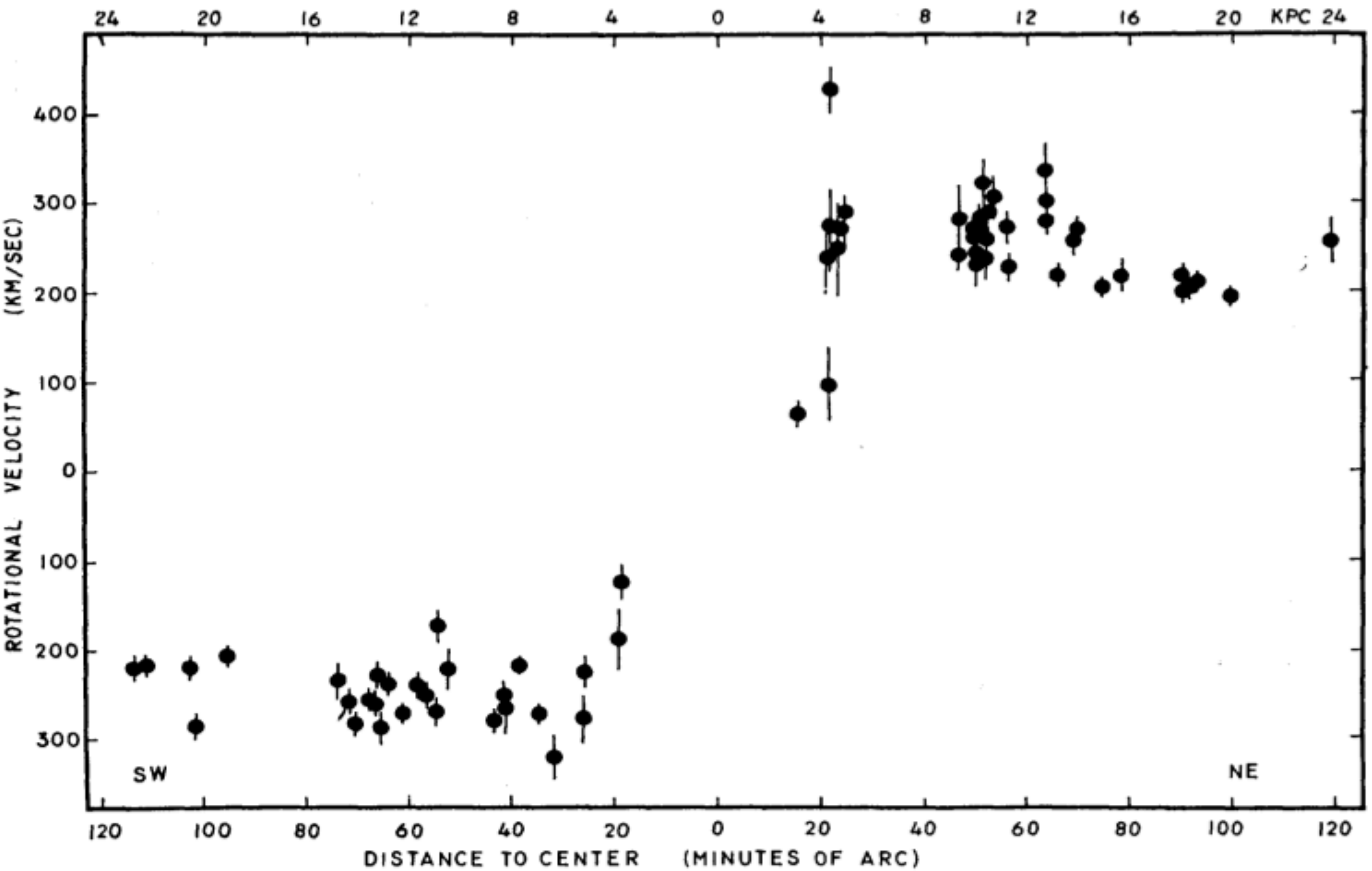
- Image of M-31
- Emission regions for which velocities have been measured
- Varying distances from 'galactic bulge'



# Just to clarify…

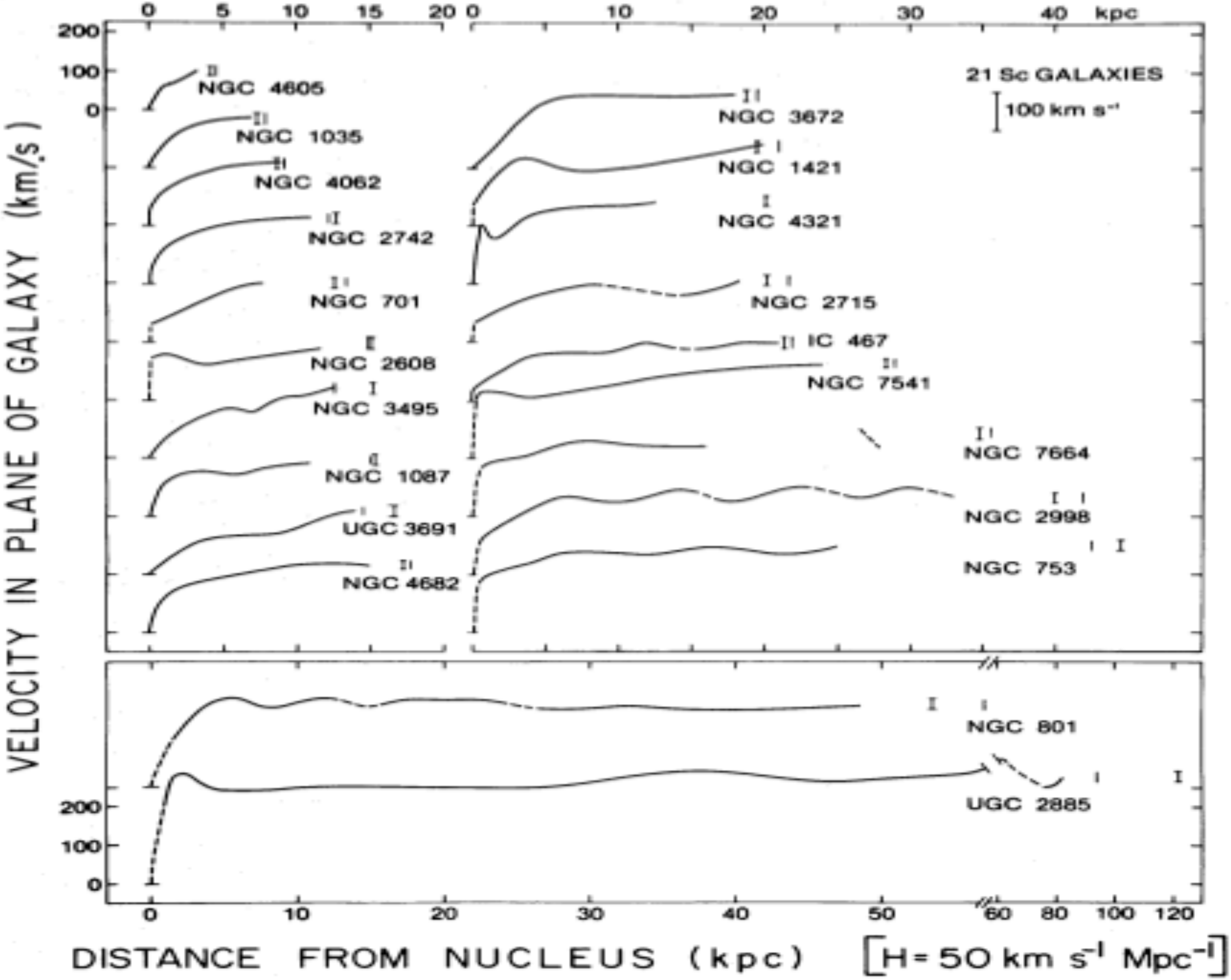


# First Concrete Evidence



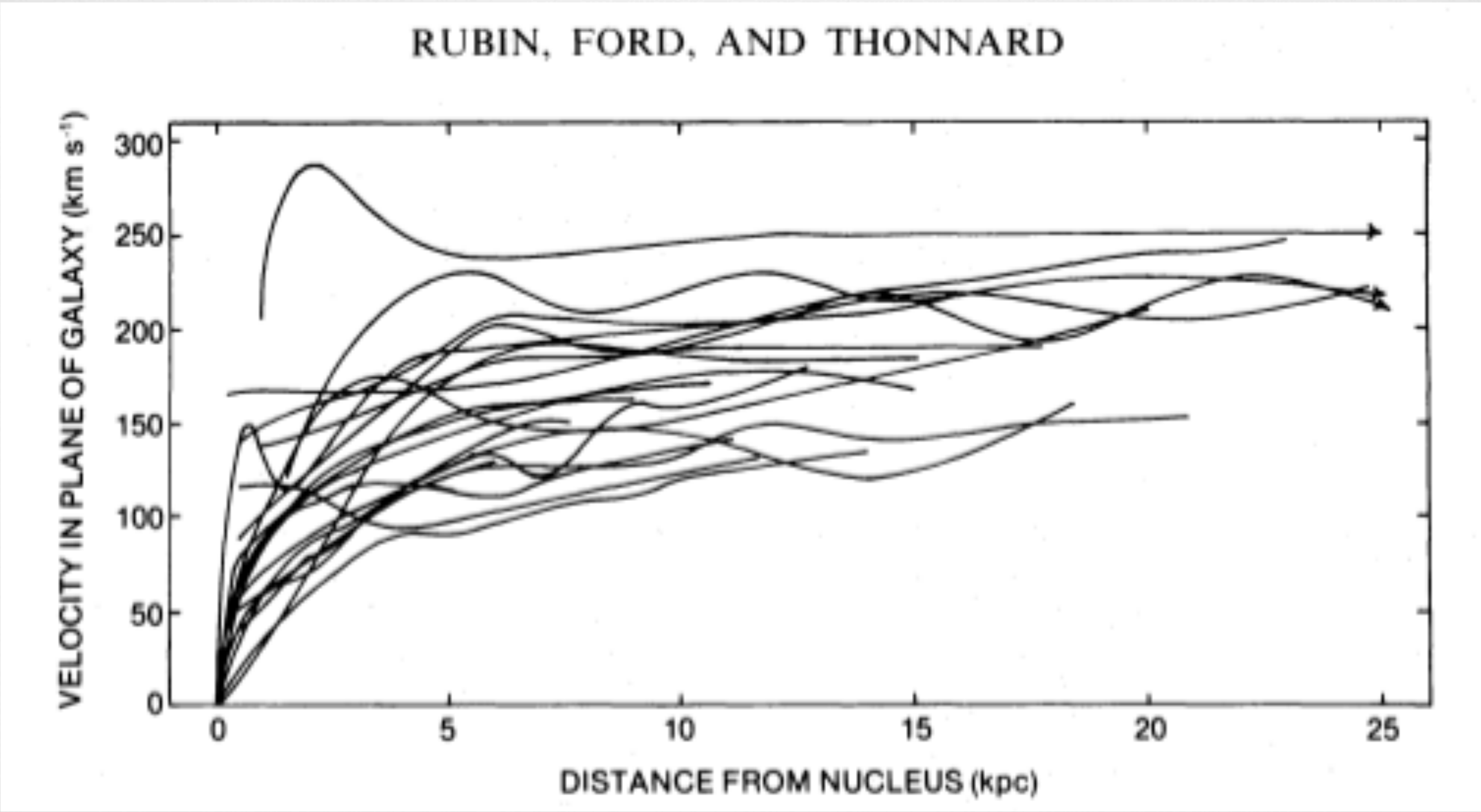
# Proof At Last!

- Rubin, Ford, Thonnard 1979
- Performed precise galactic velocity mapping for numerous galaxies ranging in luminosity and radius
- Results were conclusive: velocity did not diminish with distance from rotation point
- *There must be a spherically-symmetric "hidden" mass distribution about every galaxy!*



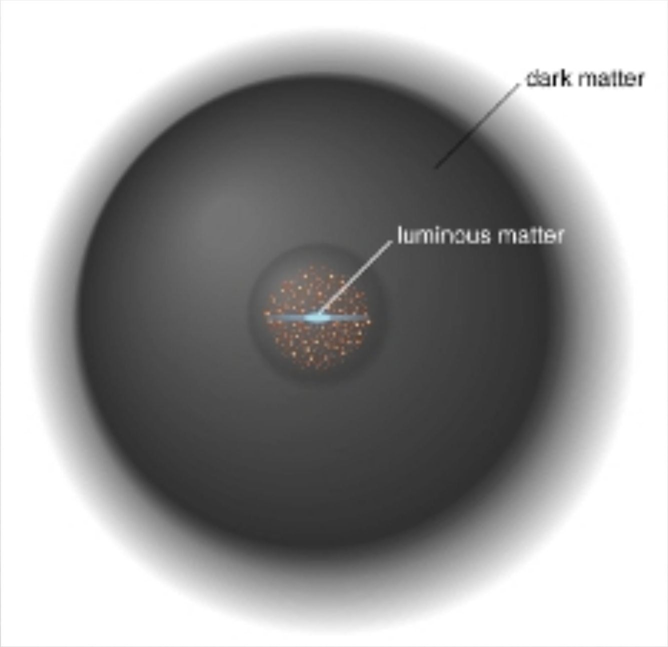
VELOCITY IN PLANE OF GALAXY (km/s)
DISTANCE FROM NUCLEUS (kpc)
[H = 50 km s⁻¹ Mpc⁻¹]
21 Sc GALAXIES
100 km s⁻¹
kpc
NGC 4605
NGC 1035
NGC 4062
NGC 2742
NGC 701
NGC 2608
NGC 3495
NGC 1087
UGC 3691
NGC 4682
NGC 3672
NGC 1421
NGC 4321
NGC 2715
IC 467
NGC 7541
NGC 7664
NGC 2998
NGC 753
NGC 801
UGC 2885

# Clearly a trend…



# So, something's up…

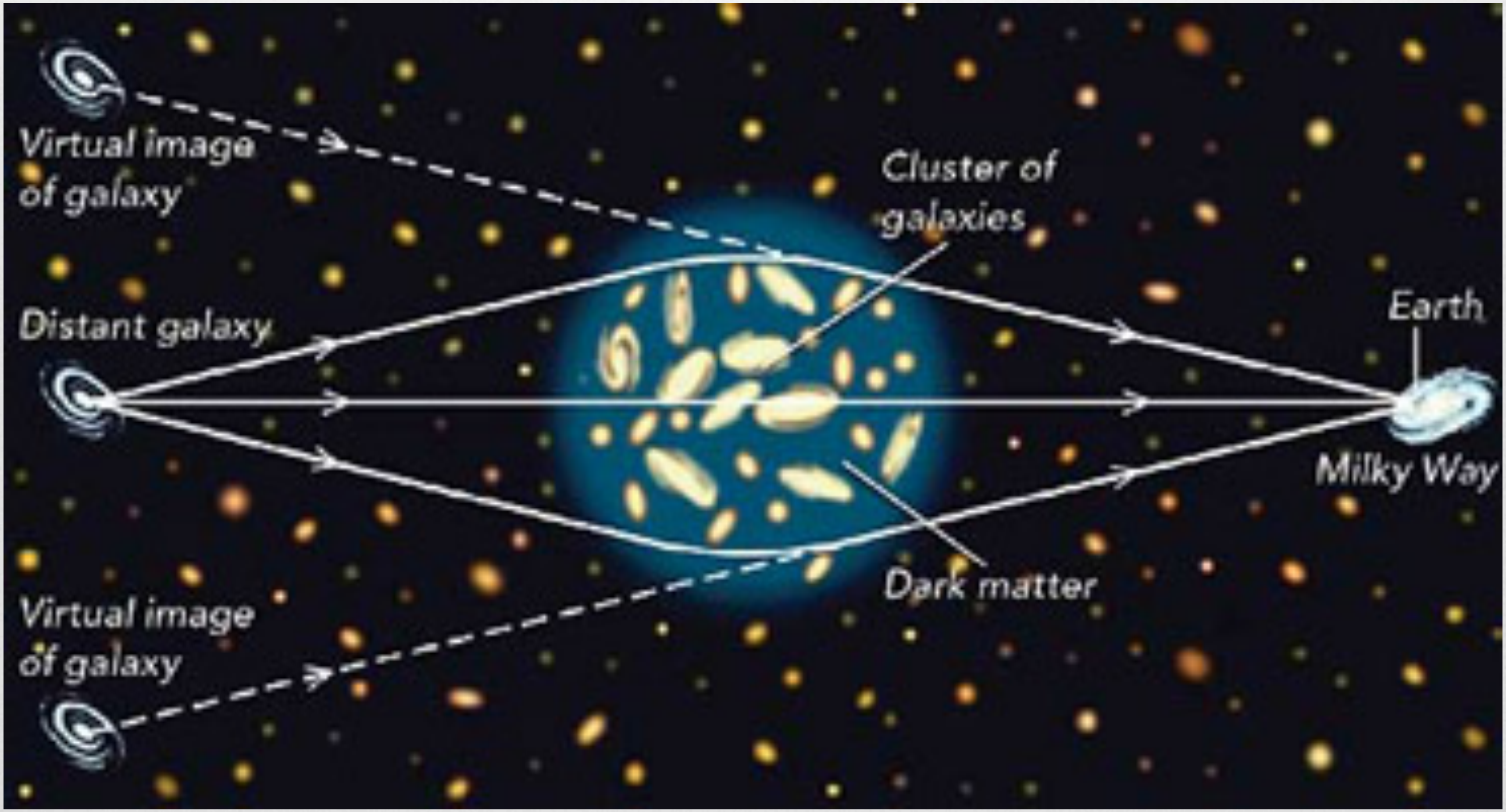
- Virial Theorem states that for the velocity curves given, there must be a spherically-symmetric "hidden mass" distribution about each galaxy (most galaxies contain about 6 times as much DM as LM)



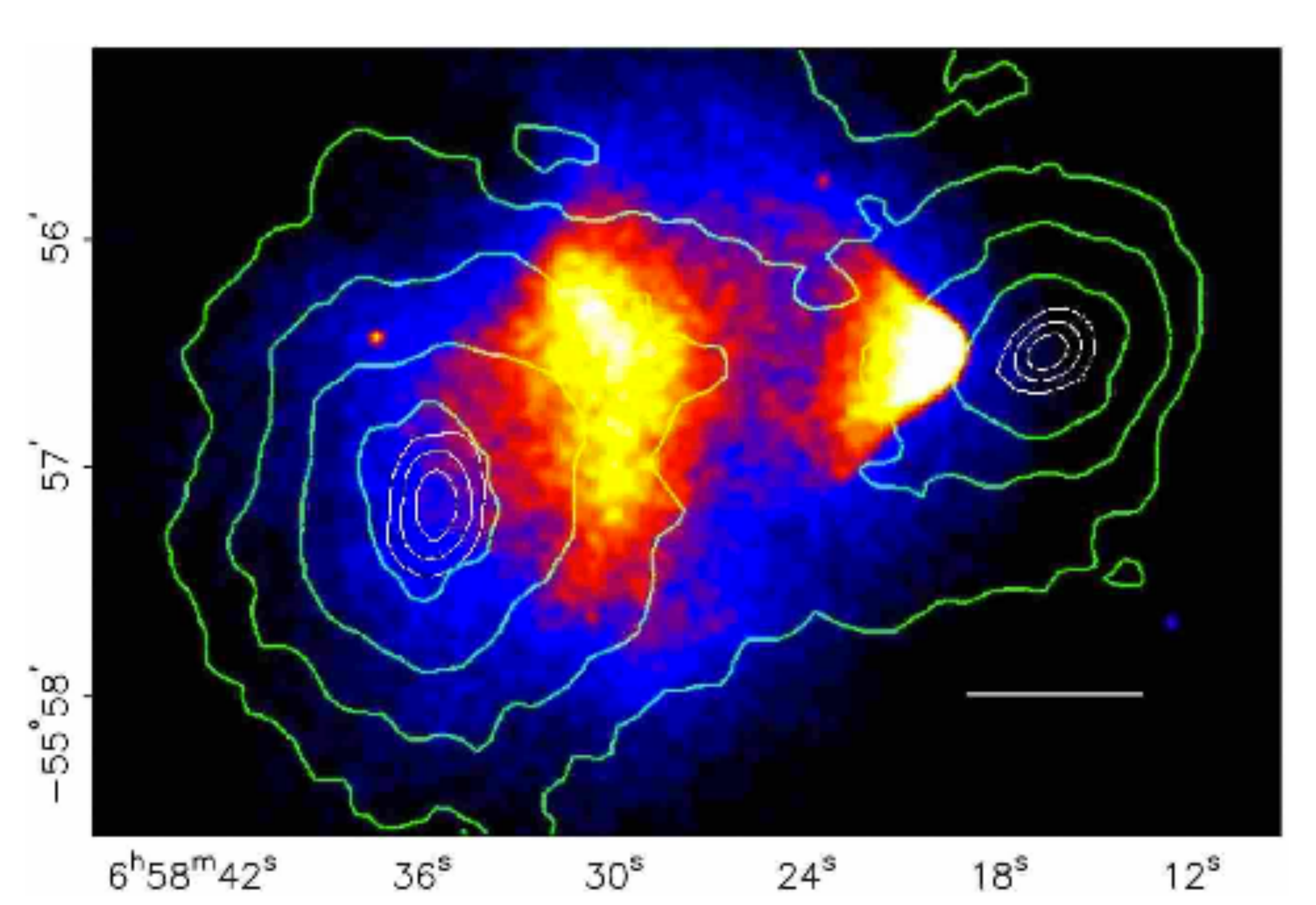
# But how *else* do we know?

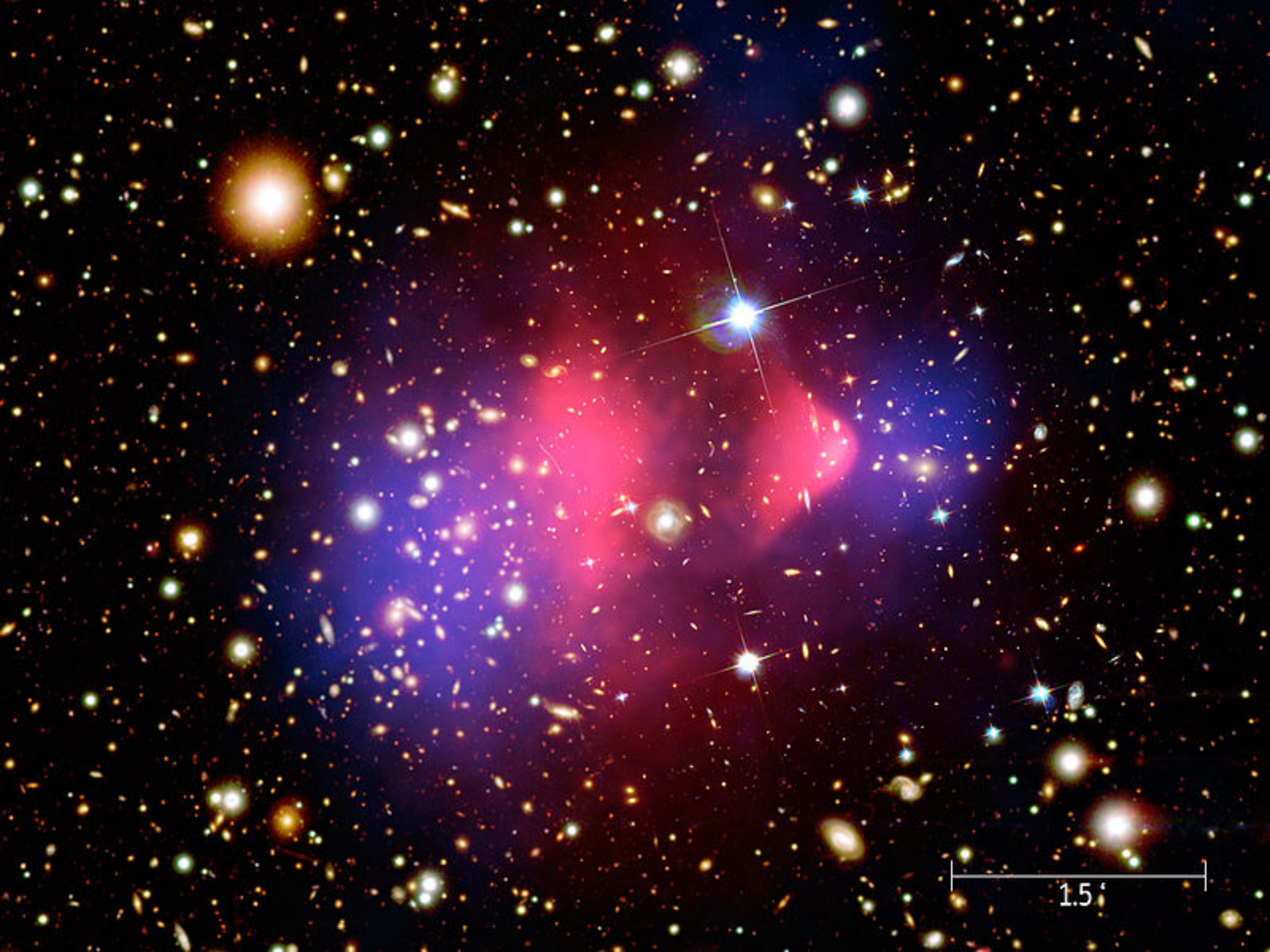
- Galaxy *Clusters* are important!
  - Radial velocity distributions of galaxies inside them provide clues (we know that now)
  - X-Ray emission from galaxies – provide insight on temperature and pressure of gasses allowing us to build a mass profile comparing temperature and gravity
  - **Gravitational Lensing**

# Gravitational Lensing



# "A Direct Empirical Proof of the Existence of Dark Matter" (2006)




1.5 '

# In conclusion…

- So, we know from the dynamics of galactic rotations, and from looking at the space-time distortion of galactic clusters that there is extra 'hidden' mass in galaxies everywhere – and A LOT of it!

- So…what could it be??

# So what *is* Dark Matter??

- We can't see it
- It does not interact via Electromagnetic Force
- It *may* interact weakly…
- It DOES interact gravitationally!

# Viable Theories Proposed

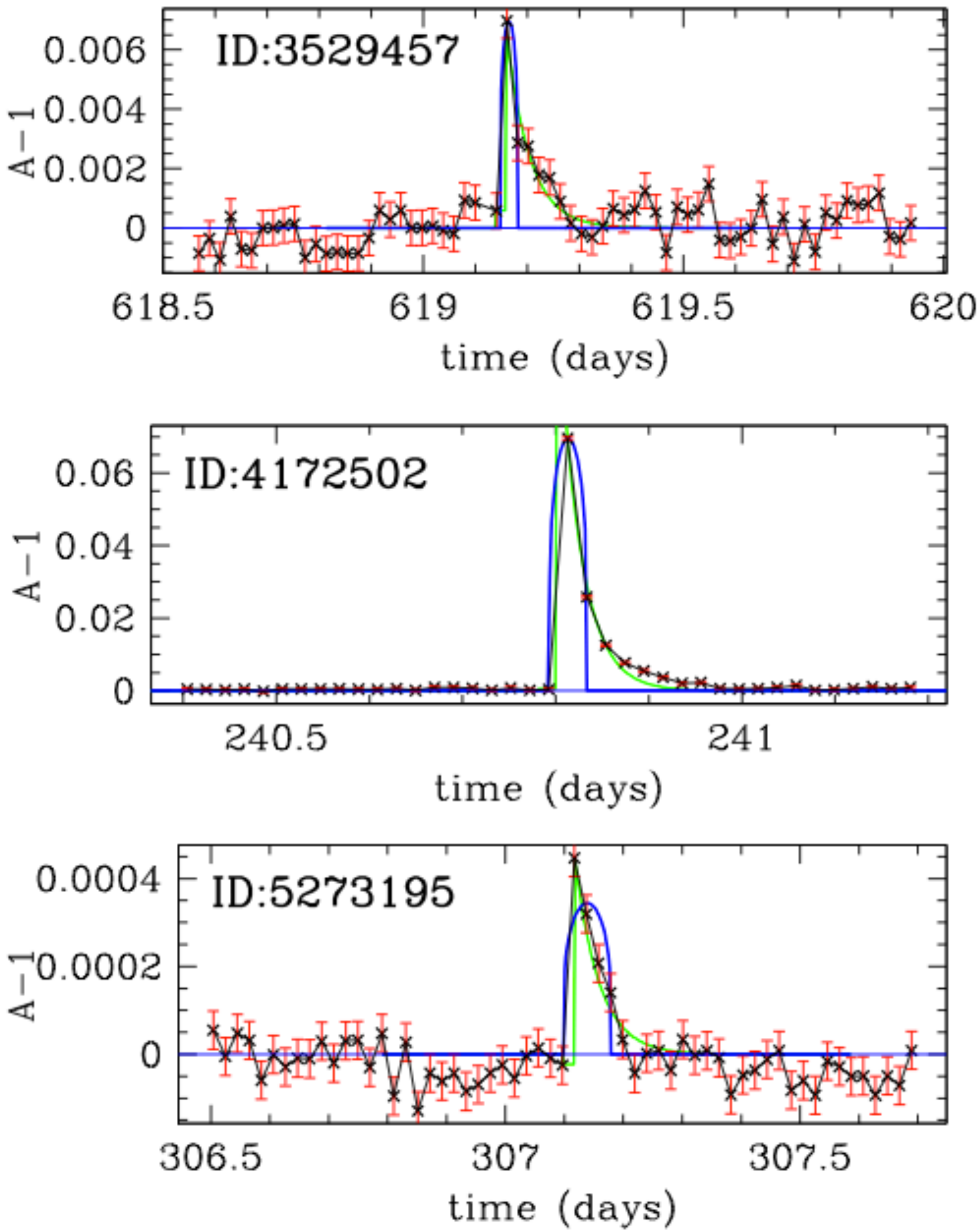
- Massive Compact Halo Objects (MACHOs)
- Neutrinos (Sterile Neutrinos)
- Weakly Interacting Massive Particles (WIMPs)
  - Supersymmetry (SUSY Neutralinos)
- Axions
- MOND
- Etc…etc…etc…

# MACHOs

- Black holes, Neutron Stars, Brown Dwarfs, rouge planets, etc…
- Attractive because no BSM model necessary!
- Any massive, rouge body amidst the galactic halo
  - Composed of baryonic matter
  - Produces little to no radiation
  - Unassociated with any planetary system
- Very hard to detect…

# MACHO Searches…

- Search for PBHs/MACHOs using Kepler Mission Data (Griest et. al. 2013)
- Utilized gravitational microlensing
  - PBH's ~ size of large asteroid
  - $2x10^{-10} M_{\odot}$ - $2x10^{-6} M_{\odot}$
- Obtain light curves for different stars and look for microlensing events
  - Compare to background data
    - Variable stars, flares, comets, asteroids, etc…


ID:3529457
0.006
0.004
0.002
0
A−1
618.5
619
619.5
620
time (days)
ID:4172502
0.06
0.04
0.02
0
A−1
240.5
241
time (days)
ID:5273195
0.0004
0.0002
0
A−1
306.5
307
307.5
time (days)

# MACHOs

- Found no microlensing candidates after removing background
- Constrained masses of MACHO candidates to $2x10^{-9}\ M_{\odot}$ - $2x10^{-7}\ M_{\odot}$
- Turns out, this isn't a huge problem…
- After looking for evidence of MACHOs, we see there are simply not enough of them to explain the "Missing Mass Problem"

# WIMPs

- "Weakly Interacting Massive Particles"
- Many theories involving WIMPs!
  - Literally. Hundreds.
- What we DO know:
  - Electrically neutral
  - Massive
  - Weakly Interacting
  - Gravitationally Interacting

# But, what *are* they?

- "Relic Dark Matter Particles"
  - Relationship to thermal equilibrium of early universe
- Very low interactions cross sections
  - For the current DM mass abundance, self-annihilation cross section can be no larger than the weak scale
- Very low self-annihilation rates
  - Low probability for detection!

# ‘Direct’ vs ‘Indirect’ DM Searches

- Direct Searches
  - The goal is to *cause* a particle reaction in which SUSY particles (DM candidates) are *produced* and recorded/ inferred
    - Particle colliders
- Indirect Searches
  - DM particles interact with SM particles and cause a reaction which we subsequently record/infer.
    - Self-annihilation

# Direct Searches

- We are pretty familiar with SUSY by now…
- SUSY Partners have same parameters as SM particles with exception of spin
  - Well…okay, mass
- Lightest SUSY Particle (LSP) could be stable, and *weakly* interacting
  - Good WIMP Candidate…
- Can we produce it?!?
  - Particle Colliders
    - LHC

# MSSM Recap

- Simplified parameter space of SUSY and the SM
  - Conceived in 1981 to stabilize weak scale
  - 120 parameters
- All super-partners fall into one of five categories
  - Sleptons
  - Charginos
  - Neutralinos
  - Squarks
  - Gluinos
- Expect SUSY particles to be 100-1000 times the proton mass ($\approx 100 - 1000\ ^{\mathrm{GeV}}/c^2$)

$$R = (-1)^{2s+3B+L}$$

- R-Parity is a symmetry associated with the MSSM
  - R = +1 for SM particles, R = -1 for SUSY particles
- SUSY does not require B and L be conserved
  - Experimentally, this is a problem for Proton decay
- R-Parity is a quantum number which may or may not be conserved
- If R-Parity is conserved:
  - The lightest supersymmetric particle (LSP) must be stable
  - Non-LSP SUSY particles must decay to an odd number of LSPs (and SM particles)
  - In collider experiments, SUSY particles can only be produced in even numbers (pairs)

# SUSY Particles as WIMPs

- If R-Parity conserved, sparticle production eventually results in LSP (lightest supersymmetric particle)
- Neutral LSP (Neutralino) is ideal Dark Matter candidate!
  - Neutral
  - Massive
  - Electroweak-strength interactions
  - Neutralino does not *have* to be LSP…

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

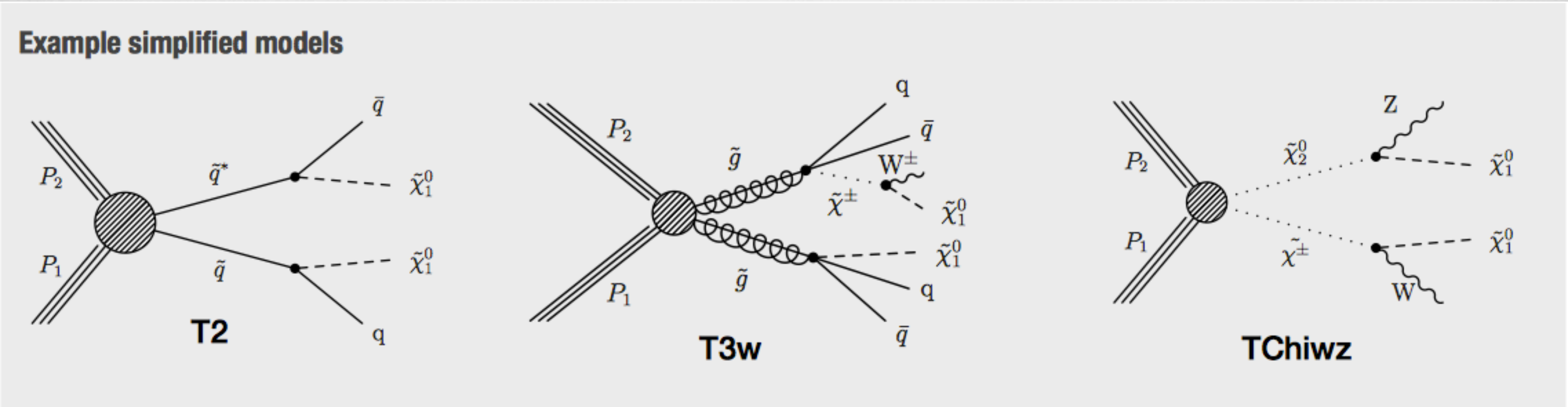
# SUSY Neutralinos

- The neutralino is a mix of SUSY partners of SM fields
  - 2 Higgs Doublet Model
- It is the lightest mass eigenstate of the mixture of the following superfields:
  - Bino
  - Wino
  - Up-type Higgsino
  - Down-type Higgsino

$$\tilde{\chi}_1^0 = Z_1 \tilde{B} + Z_2 \tilde{W} + Z_3 \tilde{H}_u + Z_4 \tilde{H}_d$$

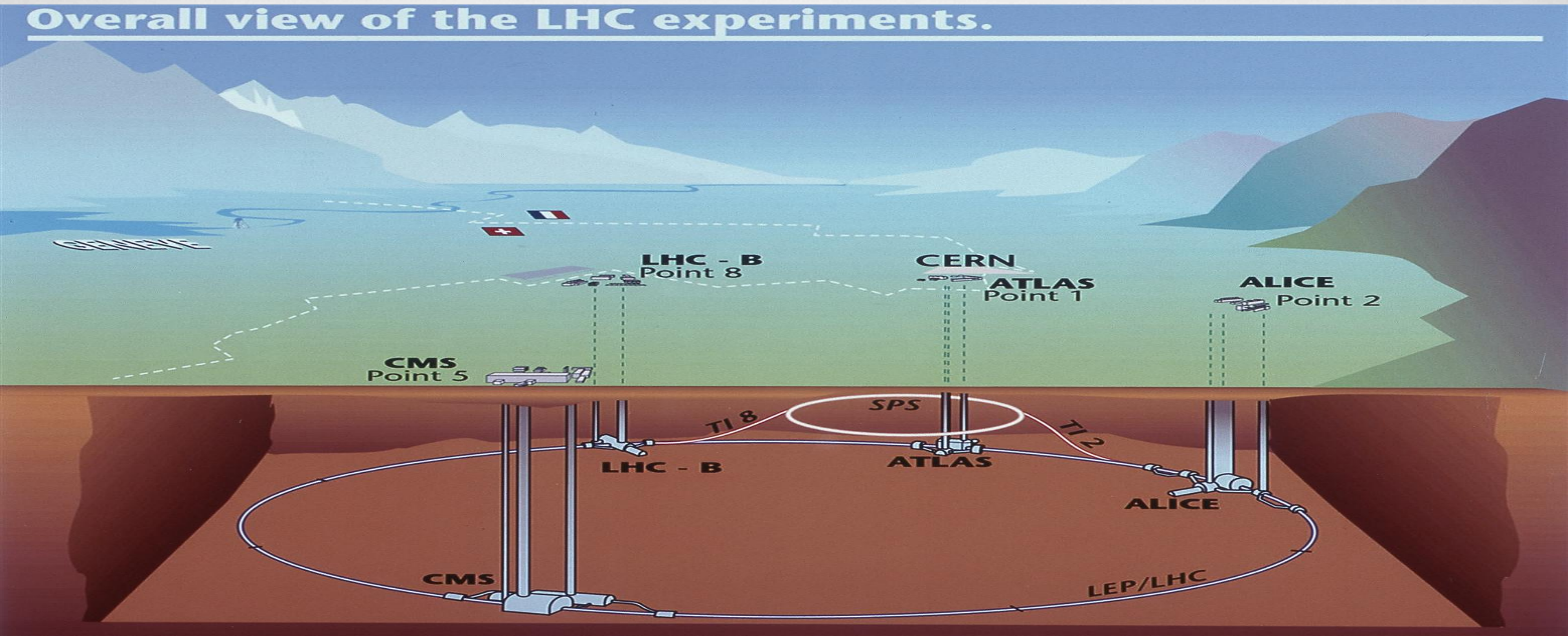
# Parameter space is big…

- Depending on mass parameters and interactions of decay products, many different types of sparticle decay are possible…
- Many final state signatures



# Large Hadron Collider

- Leading the way in direct production searches of DM
- Largest, most powerful collider in the world to date
- Comprised of 4 major experiments



# "Search for Supersymmetry in Events with Photons and Low Missing Transverse Energy in pp Collisions at $\sqrt{s}$ = 7TeV" (2012)

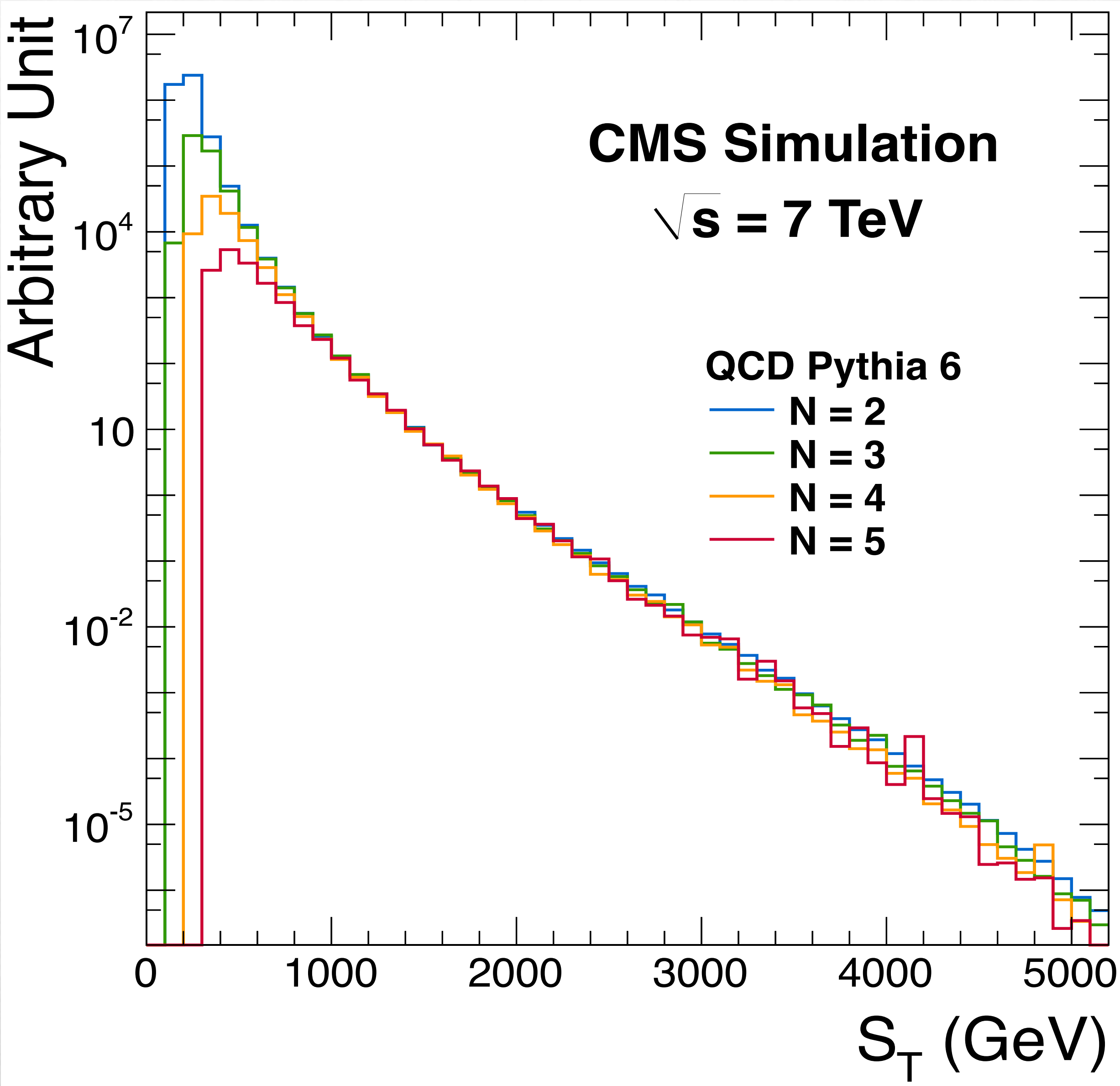
- Assume that the Neutralino is *not* the LSP!
  - First paper of its kind
- Allow for a hidden sector where the Neutralino decays to SM particles and an LSP
  - Gravitino – Still a good DM candidate!

# Methodology of Search

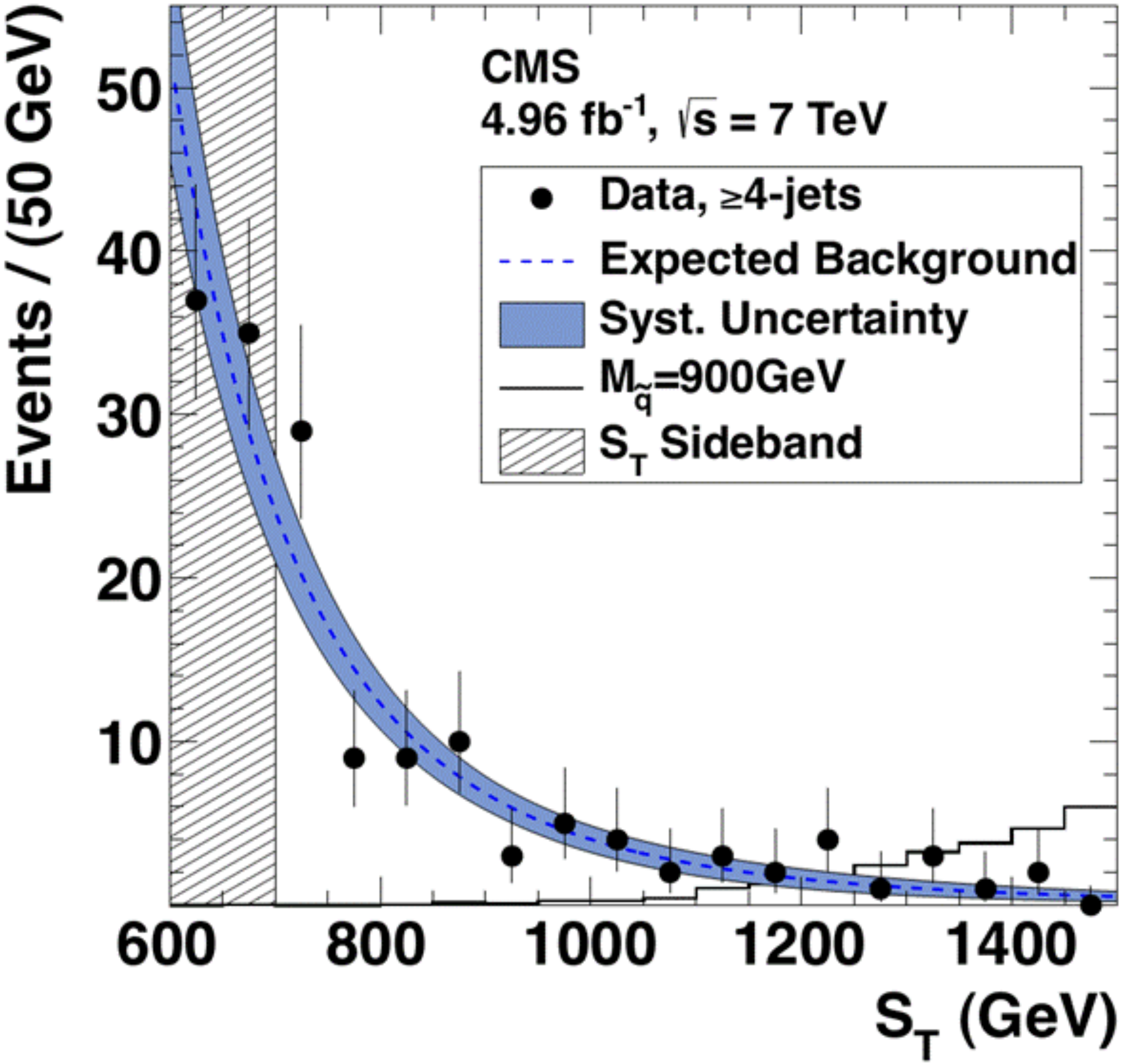
- Construct variable called “$S_T$”
  - First employed by Black Hole searches at LHC
- Scalar Sum of all $P_T$ of final state particles
  - Resonances will show a ‘bump’ in the distribution!
- Data-driven analysis!

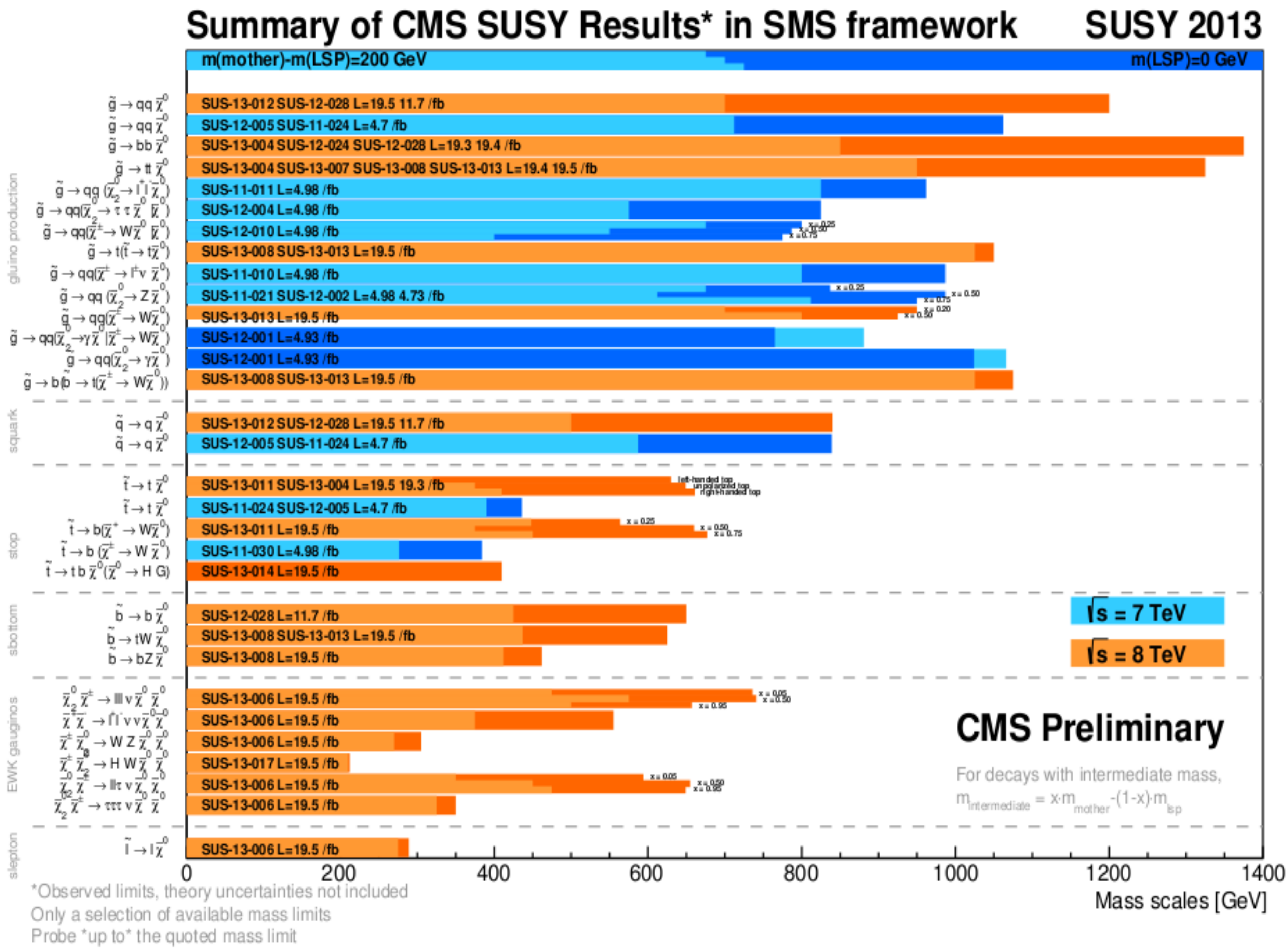
$$S_T = \Sigma P_{T(Jets)} + \Sigma E_{T(Photons)} + \Sigma(MET)$$

# $S_T$ Scaling



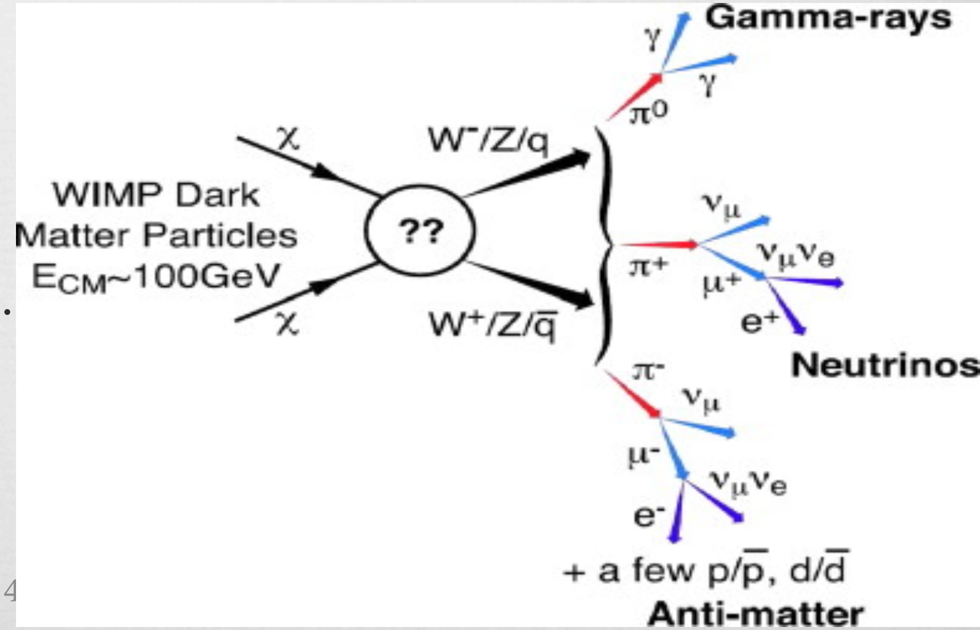
CMS Simulation
$\sqrt{s}$ = 7 TeV
QCD Pythia 6
N = 2
N = 3
N = 4
N = 5
Arbitrary Unit
$10^7$
$10^4$
10
$10^{-2}$
$10^{-5}$
0
1000
2000
3000
4000
5000
$S_T$ (GeV)


CMS
4.96 fb-1, √s = 7 TeV
Data, ≥4-jets
Expected Background
Syst. Uncertainty
M q̃ =900GeV
ST Sideband
Events / (50 GeV)
10
20
30
40
50
600
800
1000
1200
1400
ST (GeV)

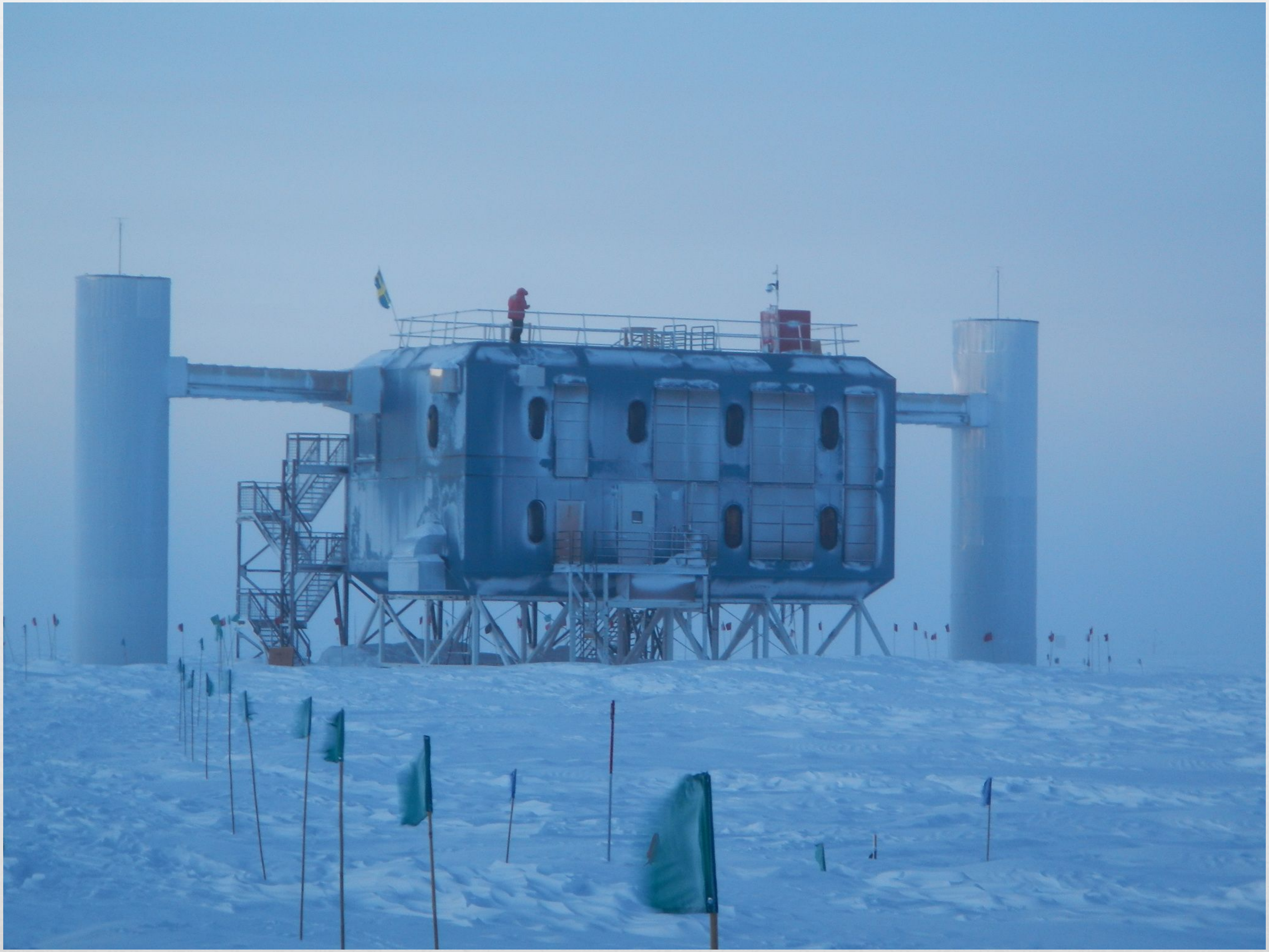

Summary of CMS SUSY Results* in SMS framework
SUSY 2013
m(mother)-m(LSP)=200 GeV
m(LSP)=0 GeV
gluino production
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
SUS-13-004 SUS-12-024 SUS-12-028 L=19.3 19.4 /fb
SUS-13-004 SUS-13-007 SUS-13-008 SUS-13-013 L=19.4 19.5 /fb
SUS-11-011 L=4.98 /fb
SUS-12-004 L=4.98 /fb
SUS-12-010 L=4.98 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-11-010 L=4.98 /fb
SUS-11-021 SUS-12-002 L=4.98 4.73 /fb
SUS-13-013 L=19.5 /fb
SUS-12-001 L=4.93 /fb
SUS-12-001 L=4.93 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
squark
SUS-13-012 SUS-12-028 L=19.5 11.7 /fb
SUS-12-005 SUS-11-024 L=4.7 /fb
stop
SUS-13-011 SUS-13-004 L=19.5 19.3 /fb
left-handed top
unpolarized top
right-handed top
SUS-11-024 SUS-12-005 L=4.7 /fb
SUS-13-011 L=19.5 /fb
SUS-11-030 L=4.98 /fb
SUS-13-014 L=19.5 /fb
sbottom
SUS-12-028 L=11.7 /fb
SUS-13-008 SUS-13-013 L=19.5 /fb
SUS-13-008 L=19.5 /fb
EWK gauginos
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-017 L=19.5 /fb
SUS-13-006 L=19.5 /fb
SUS-13-006 L=19.5 /fb
slepton
SUS-13-006 L=19.5 /fb
√s = 7 TeV
√s = 8 TeV
CMS Preliminary
For decays with intermediate mass,
m_intermediate = x·m_mother + (1-x)·m_lsp
0
200
400
600
800
1000
1200
1400
Mass scales [GeV]
*Observed limits, theory uncertainties not included
Only a selection of available mass limits
Probe *up to* the quoted mass limit

# Indirect Searches

- DM WIMPs interact gravitationally
  - Could be getting ‘sucked’ into Sun and building up!
- Increased number density = greater self-annihilation rate!!
  - Weakly Interacting
  - Produce Neutrinos!
    - Among other things…



# IceCube Neutrino Observatory

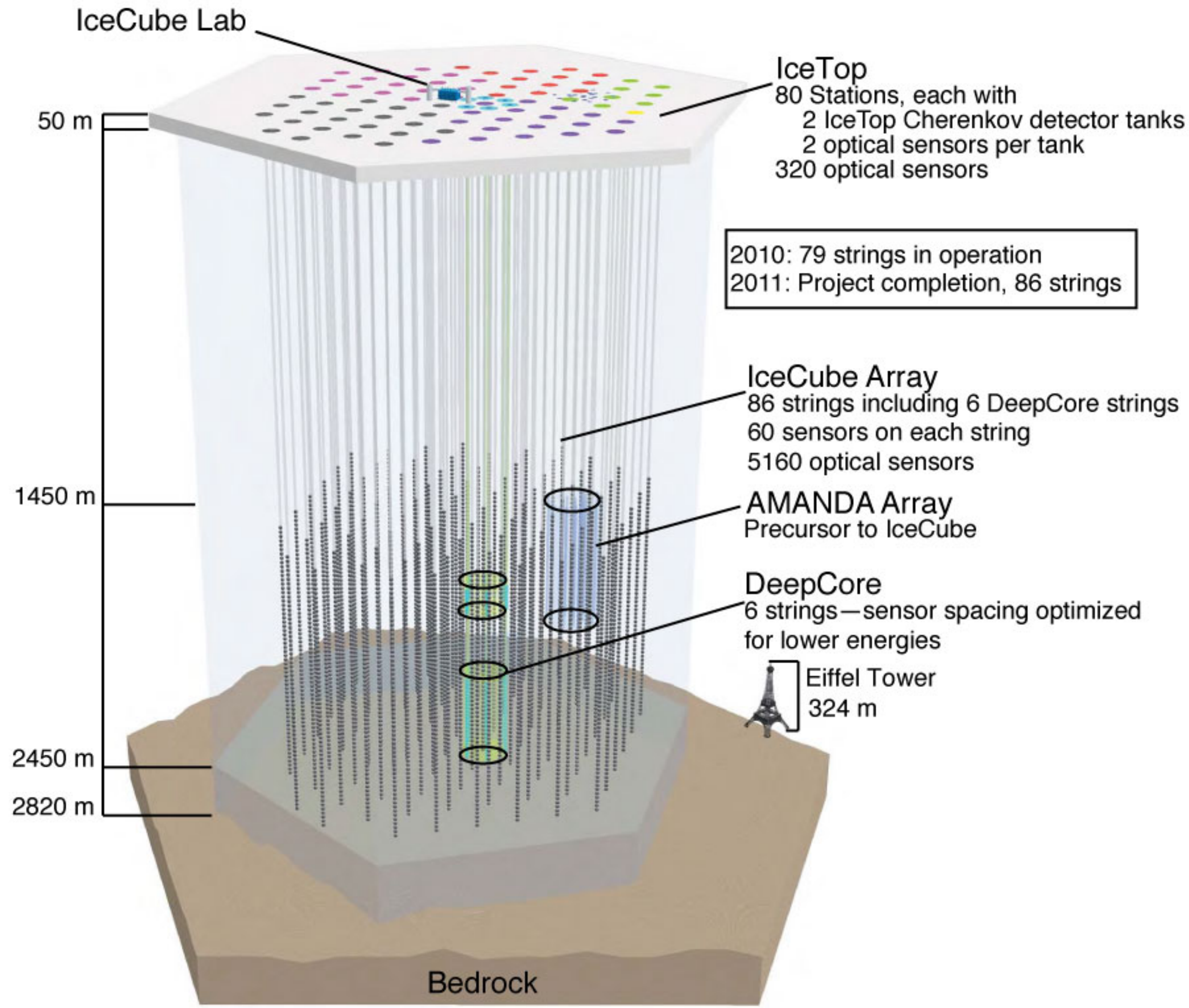


# IceCube Neutrino Observatory

- "Neutrino telescope", located at South Pole
- Comprised of 5,160 (Digital Optical Module) DOM detectors
- Built over the existing, decommissioned AMANDA project
- Relies on neutrino interactions with existing ice/water molecules

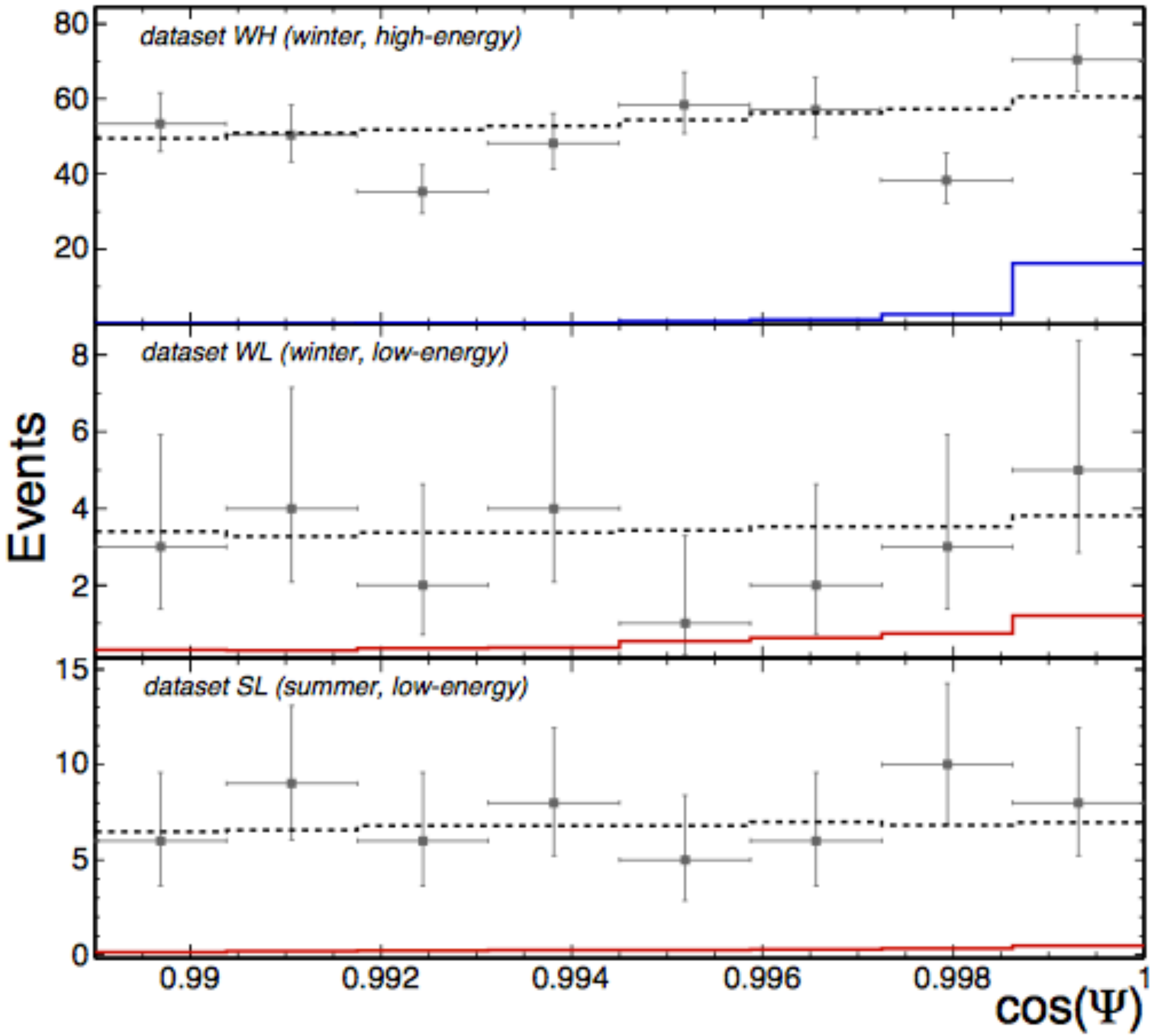
# Ice Cube's process…

- Main goal is to look for very high energy neutrinos
- We know where and how many neutrinos are produced (pretty well)
- Look for sources of extraterrestrial, abnormally high energetic neutrino production
- Directional searches show us where they are coming from!


IceCube Lab
IceTop
80 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
320 optical sensors
2010: 79 strings in operation
2011: Project completion, 86 strings
IceCube Array
86 strings including 6 DeepCore strings
60 sensors on each string
5160 optical sensors
AMANDA Array
Precursor to IceCube
DeepCore
6 strings—sensor spacing optimized
for lower energies
Eiffel Tower
324 m
50 m
1450 m
2450 m
2820 m
Bedrock

# "Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector"

- Looked at Muon neutrinos from the Sun's core
  - June 2010 – May 2011
- Muons react with ice molecules and produce muons
  - Cherenkov light from muons!
  - DOMs capture blue Cherenkov light and produce a "track" of the muon
    - Measures direction and energy
- Must compare with background events!



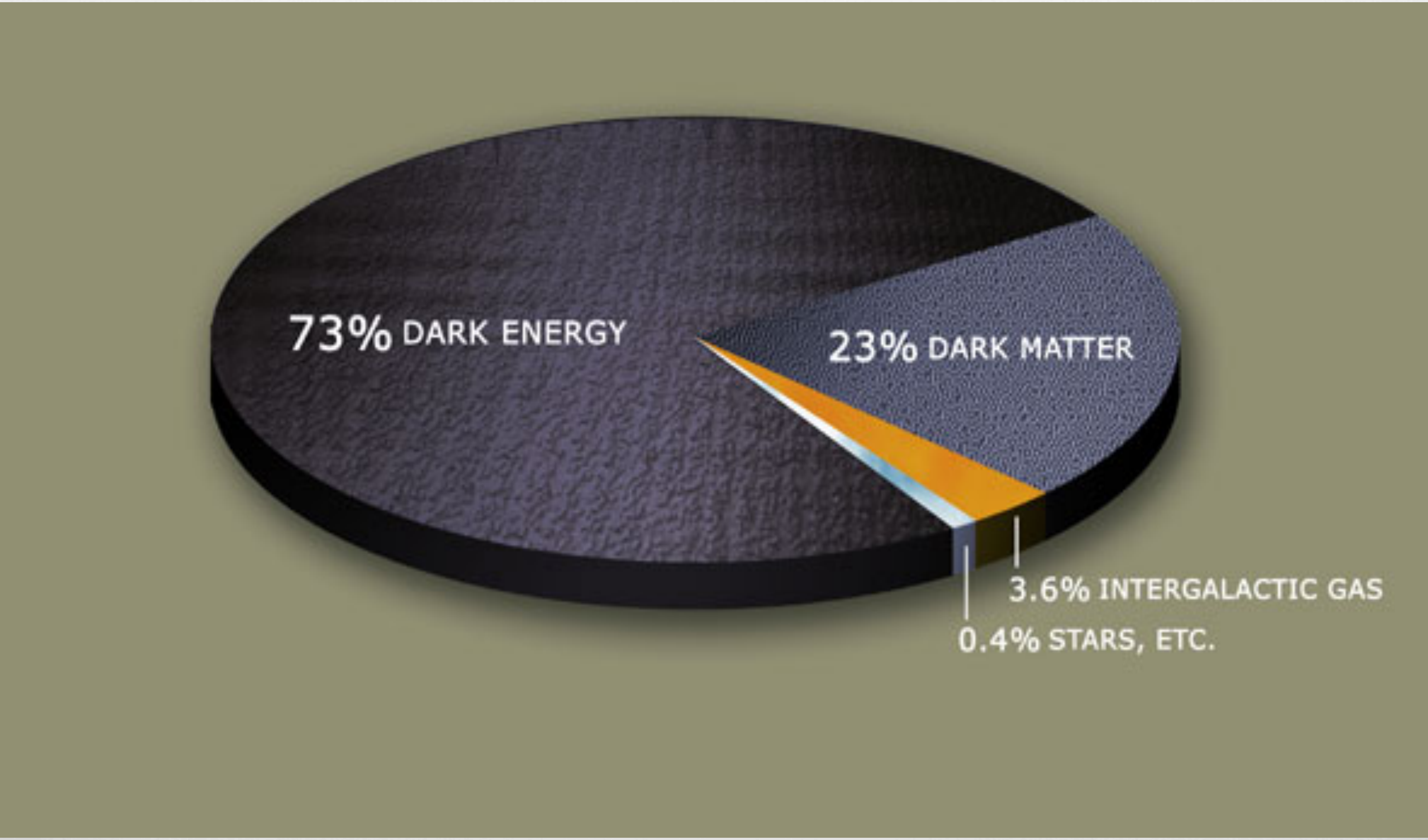
dataset WH (winter, high-energy)
dataset WL (winter, low-energy)
dataset SL (summer, low-energy)
Events
cos(Ψ)
0.99
0.992
0.994
0.996
0.998
1
80
60
40
20
8
6
4
2
15
10
5
0

# “Search for Dark Matter Annihilations in the Sun with the 79-String IceCube Detector”

- Findings were consistent with atmospheric backgrounds (muons and neutrinos)
- Set upper limits on:
  - WIMP-Proton cross sections for WIMP masses 20 – 5000 $^{GeV}/c^2$
  - Dark Matter annihilation rate
- No evidence of Dark Matter yet…

# Summary

- So, we pretty much know DM is real, what its general properties are, and where it is.
- We have theories that explain DM's presence and properties, and have implemented searches.
- We have set limits on MACHO masses, SUSY Neutralino/LSP masses, and self-annihilation rates of WIMP candidates.
  - But have not observed anything…yet.


73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

# Conclusion

- Are there SUSY LSPs in our universe?
- Are there WIMPs in general in our universe?
- Are there more MACHOs that we haven't observed?
- Do we have this all wrong??
  - MOND
- We need to continue solving the mysteries of our Universe!!

# Thank You!!