Astroparticle physics began at the University of Chicago

DAVID SCHRAMM

- Creator of the Chicago Mafia
and Michael Turner
ENORMOUS PROGRESS OVER THE LAST CENTURY

Our creation myth is right (hot Big Bang)
At the turn of the Millenium, recent experiments answered BIG QUESTIONS:

• We know the geometry of the universe
• We know the energy density of the universe
• We understand the physics all the way to the edge of the observable universe (the horizon)
• BUT many questions remain: what is the universe made of (dark matter and dark energy)? How did it begin? How will it end?
Astroparticle Physics
Big Questions Now

- How did the Universe Begin: Inflation?
- What is the Universe Made of?
  - What is the Dark Matter?
  - Will we find Dark Stars?
- What is the Dark Energy?
From Theory to Observation: Predictions of Inflation are right

1) flat universe: \( \Omega = 1 \)

2) Spectrum of density perturbations:
   \[ |\delta_k|^2 \propto k^n, \ n \sim 1 \]

3) superhorizon correlations
4) Adiabatic Density perturbations
5) gravitational wave modes

Individual models make specific predictions.
Can test inflation as a concept and can differentiate between models.
Very powerful bounds on nonGaussianities
Planck had major impact on inflation models

- No NonGaussianities implies
- MOST MODELS ARE DEAD. THAT IS PROGRESS.
- MOST REMAINING MODELS ARE SIMPLE: SINGLE FIELD ROLLING DOWN A HILL
Inflation after Planck: only the simplest well-motivated models survive

Freese, Frieman, Olinto 1990
Use axions for natural inflation:
Could be cosine (purple) or axion monodromy
Natural inflation models (cosine in tension at 2sigma level, axion monodromy)
Predictions about Inflation

- B-modes are found
  - Natural Inflation is right of course
    - Either $r=0.3$
    - Or linear potential is right
- OR
- Tunneling models: evidence of bubble collisions in Advanced LIGO
- AND
- Multiverse is dead: no longer needed in theories
- Spectral distortions teach us about higher up in inflationary potentials
Minimal inflation:

- 1) a single weakly-coupled neutral scalar field, the inflaton, drives the inflation and generates the curvature perturbation
- 2) with canonical kinetic term
- 3) slowly rolling down featureless potential
- 4) initially lying in a Bunch-Davies vacuum state

If any one of these conditions is violated, detectable amplitudes of nonGaussianity should have been seen.

\[
\langle \Phi(k_1)\Phi(k_2)\Phi(k_3) \rangle = (2\pi)^3 \delta^{(3)}(k_1 + k_2 + k_3) B_\Phi(k_1, k_2, k_3).
\]

\[
B_\Phi(k_1, k_2, k_3) = f_{NL} F(k_1, k_2, k_3).
\]
No primordial nonGaussianities in Planck

- Single field models: so small as to be undetectable
- Other models: three shapes (configurations of triangles formed by the three wavevectors)
- Any detection of nonGaussianity would have thrown out all single field models
- Data show no evidence of nonGaussianity, implying single field models work!

- Data bound the speed of sound $c_s > 0.02$
Philosophy and Progress

- Planck killed almost all models
- What is left? Simplest models
- Very few inflationary models are theoretically well motivated. Particle physics does NOT allow you to write down arbitrary garbage.
- Wonderful thing: the best motivated models in this sense are the ones that survive!
- Natural (axion) inflation
- Starobinsky inflation eg. As motivated by supergravity
- Higgs inflation
- MY PREDICTION: WE WILL FIND GRAVITY WAVES. PEOPLE WILL BE CONVINCED!
PIE CHART OF THE UNIVERSE

WHAT ARE THE PIECES OF THE PIE???
What is the Dark Matter?

Candidates:

- WIMPs (SUSY or extra dimensions)
- Axions
- Neutrinos (too light, ruin galaxy formation)
- Sterile Neutrinos: no Standard Model interaction
- Asymmetric Dark Matter
- Self Interacting Dark Matter
- Primordial black holes
- WIMPzillas
- Axinos and gravitinos
- MeV dark matter

TODAY’s DATA ANOMALIES WILL THEY HOLD UP?
WIMPs I: ATLAS bounds on CMSSM. Will LHC find anything?
WIMPs II: is DAMA right?  
Bounds on Spin Independent WIMPs

BUT:
--- it’s hard to compare results from different detector materials
--- can we trust results near threshold?
WIMPs III: Is Fermi/LAT gamma-ray excess due to DM?

Goodenough & Hooper (2009)

Daylan, Finkbeiner, Hooper, Linden, Portillo, Rodd, Slatyer (2014)

Towards galactic center:
- Model and subtract astrophysical sources
- Excess remains
- Spectrum consistent with DM DM annihilation
3.5 keV line. From sterile neutrino?
Final Intriguing Signal: 511 keV line in INTEGRAL data

Seen in Galactic bulge, out to 6 degrees (3 kpc). No clear astrophysical explanation. Low mass xray binaries were most compelling option but not looking good.

Is it DM annihilation to e+e- pairs?

Would be MeV dark matter.

(Boehm, Hooper, Silk, Casse, Paul 2003)
WHAT’S HOT IN DARK MATTER?
Unexplained signals.

WIMPS:
- DAMA annual modulation (but XENON, LUX)
- Indirect Detection from DM annihilation:
  The HEAT/PAMELA/FERMI/AMS positron excess
  FERMI gamma ray excess near galactic center
- Theorists are working to reconcile data sets.

7 keV Sterile neutrinos
- 3.5 keV x-ray line in Perseus, M31, and GC

MeV dark matter 511 keV line in INTEGRAL DATA
My prediction: We will find dark matter by 2042

- We will have completed searches for WIMPs
- Ditto for axions
- Ditto for light dark matter (MeV)
- Ditto for sterile neutrinos
- Something new?

- Directional detection allows up to map DM distribution in MW including streams etc
DNA/RNA Tracker: directional detection with nanometer resolution

1 kg Gold, 1 kg ssDNA, identical sequences of bases with an order that is well known

BEADED CURTAIN OF ssDNA

WIMP from galaxy knocks out Au nucleus, which traverses DNA strings, severing the strand whenever it hits.

Drukier, KF, Lopez, Spergel, Cantor, Church, Sano
Dark Stars will be found

The first stars to form in the history of the universe may be powered by Dark Matter annihilation rather than by Fusion. Dark stars are made almost entirely of hydrogen and helium, with dark matter constituting less than 1% of the mass of the star).

- This new phase of stellar evolution may last millions to billions of years
- Dark Stars can grow to be very large: up to ten million times the mass of the Sun. Supermassive DS are very bright, up to a billion times as bright as the Sun. These can be seen in James Webb Space Telescope.
- Once the Dark Matter runs out, the DS has a fusion phase before collapsing to a big black hole: Is this the origin of supermassive black holes?
Figure 7. Spectra for supermassive DSs formed at $z_{\text{form}} = 15$ (formation redshift)
DS detectable in JWST, the upcoming sequel to HST
Million solar mass SMDS as H-band dropout

(see in 2.0 micron but not 1.5 micron filter, implying it’s a z=12 object)
How to different dark stars from early galaxies: DS pulsations (p-modes)
What is the Dark Energy?

- Really Hard! Both observationally and theoretically.
- Is it time dependent? Dark Energy Task Force.
- What about new theories: time dependent vacua quintessence, modified Einstein’s equations e.g. Cardassian, disformal, self-accelerating solutions due to massive gravity, chameleonic, Chaplygin gas, etc etc

I agree with Wendy: Might be epicycles?
The three women representing Dark Matter are, from the right, Katherine Freese, Elena Aprile, and Glennys Farrar. Continuing to the left are three men representing Dark Energy: Michael Turner, Saul Perlmutter and Brian Greene (co-host of the Festival).
“Dark matter is attractive, while dark energy is repulsive!”
Astroparticle Physics in 2042: My predictions

- Beginnings of the Universe?
- Inflation is right. Gravity Waves are found.
- What is the Universe Made of?
  - We will find the Dark Matter
  - If dark matter is WIMPs, we will find Dark Stars
  - We will know more about Dark Energy, e.g. its time dependence, but we still won’t know its theory. Maybe it is epicycles? Still the cc problem remains unsolved.
THE REAL PREDICTION

- How can we possibly know?
- WE WANT NEW PHYSICS!!

- TO boldly go where no one has gone before

- Star Trek