... some personal conclusions

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A few numbers …

- 90 talks
- 9 posters
- 45 hours of meeting + 50 min.
- 27 hours of: ski-gondolas-chairlift-skilift-skilessonssunbaths-sauna-swimming

... or simply email reading, or ...
... a bit of statistics

**Moriond Talk Distribution**

<table>
<thead>
<tr>
<th>Number</th>
<th>CMB</th>
<th>Clusters</th>
<th>DM</th>
<th>Mod-G</th>
<th>DE</th>
<th>Cosmo sce.</th>
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</table>

**Participants**

- Blanchard
- Santos
- Koshelev
- Dunlop
- Tartari
- Kirilova
- Beelen
- Iliev
- Tigrak
- Penin
- Finke
- Regos
- Delsart
- DiPorto
- Battye
- Dufaux
- Serra
- Badziak
- Gawiser
- Clesse
- Zaroubi
- Vikman
- Brentjens
- Caprini
- Peterson
- Popa
- Mesinger
- Godlowski
- Leahy
- Raeth
- Dickinson
- Bonvin
- Errard
- Shaw
- Kusaka
- Lewis
- Charlassier
- Hinshaw
- Hernandez-M
- Shanks
- Salatino
- Piat
- Gubitosi
- Pajot
- Bunn
- Tristram
- Amblard
- Fauvet
- Delabrouille
- Rossi
- Dafni
- Lanz
- Girardi
- Rozo
- Foex
- Pratt
- Ferrari
- Finoguenov
- Lanoux
- Sartoris
- Mazzotta
- Bazin
- Bourdin
- Colafrancesco
- Mohr
- Democles
- Borgani
- Fromentau
- Pointecouteau
- Lopez-Cruz
- Serfass
- Bird
- Gerbier
- Nuss
- Chodorowski
- Cline
- Polesello
- Clerbaux
- Camera
- Strahler
- Viel
- Kainulainen
- Vieregg
- Thomas
- Desjacques
- Zakharov
- Serra
- Regnault
- Mortonson
- Palanque-Del.
- Sawicki
- Kronborg
- Thomas
- Gangler
- Taylor
- Marra
- Crighton
- Copeland
- Abate
- Garcia-Bellido
- Busca
- Pearson
- Abdalla
- Quartin
- Ziaepour
- Fourmanoit
- Baldi
- Dokuchaev
... a bit of statistics

- CMB
- CMB Pol
- SZE cl
- X/O cl
- NT cl
- DM Direct
- DM Indirect
- Mod-G
- DE
- Cosmo IR
- Cosmo sce.
- Cosmo high-z

Bar chart showing the number of entries for each category.
... a bit of statistics

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Number of observations:

- **CMB**
- **CMB Pol**
- **SZE cl**
- **X/O cl**
- **NT cl**
- **DM Direct**
- **DM Indirect**
- **Mod-G**
- **DE**
- **Cosmo IR**
- **Cosmo sce.**
- **Cosmo high-z**

Multi-messenger

New vision

New approach
... a bit of statistics

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$z \rightarrow \infty$

$z \sim 0$

$z \sim 0$

$z \gg 1$

Multi-messenger

New vision

New approach

Multi-messenger

Multi-messenger
CMB

- Established framework
  - COBE
  - Boomerang
  - WMAP
  - PLANCK (... some surprise at the horizon?)

- Look for more details
  - Polarization
  - Anomalies
  - Non Gaussianity
First detection of temperature fluctuations (anisotropy): sets the scale of the signal – brighter than the Galactic foreground!
1990’s: A Decade of Progress!

to name a few...

QMASK  DASI  Boomerang  Maxima
CMB: intensity

WMAP-7yr

23 GHz

33 GHz

41 GHz

61 GHz

94 GHz
The imprint of sound waves is visible in the co-added degree-scale hot & cold spots.

The expected radial/tangential polarization pattern around these extrema is clearly seen in the 7-year WMAP data.

This pattern is also imprinted on the baryon gas (baryon acoustic oscillations or BAO) that evolves to form large scale structure.
ΛCDM Parameters*

Blue curves/contours – 5-year data
Grey curves/contours – 3-year data

Biggest improvements in:
- Optical depth, \( \tau \)
- Amplitude of fluctuations @ 8 Mpc, \( \sigma_8 \)
- Matter densities, \( \Omega_b h^2, \Omega_c h^2 \)

Age: \( t_0 = 13.69 \pm 0.13 \) Gyr

*based on WMAP data only
The next step

Planck First Light!
Fig 2.11.— The solid lines in the upper panels of these figures show the power spectrum of the concordance $\Lambda$CDM model with an exactly scale invariant power spectrum, $n_S = 1$. The points, on the other hand, have been generated from a model with $n_S = 0.95$ but otherwise identical parameters. The lower panels show the residuals between the points and the $n_S = 1$ model, and the solid lines show the theoretical expectation for these residuals. The left and right plots show simulations for WMAP and Planck, respectively.
Fig 2.22.—The left panel (from Huterer & Turner 2001) shows forecasts of constraints on the dark energy equation of state parameter $w$ and $\Omega_m$ for various experiments including Planck. The right panel (from Seo & Eisenstein 2003) shows forecasts of constraints on the time evolution of $w$, parameterised through $w = w_0 + w_1 z$, for Planck combined with various redshift surveys and SNe observations from SNAP (see text for details).
... but in the meantime

**SPT**

With ACT, we are entering a new regime in CMB physics.
SPT Survey Field

150 GHz
CMB anisotropy @ small scales

No evidence for SZ in power spectrum, nor for a **clustered** component of point sources!
Need to analyses maps @ multi-ν to break degeneracies

**Astrophysics**
- point-like
- extended sources

\[ A_{SZ} < 1.63 (95\%) \]

\[ A_p = 11.2 \pm 6.6 (2\sigma) \mu K^2 \]

mm spectroscopy
SAGACE
MILLIMETRON
[ O 12 Blazars in WMAP (3 in Boomerang) ]
Multi-frequency analysis \[ \{ \text{O 54 Blazars with } \Delta T > 50 \mu K^2 \} \]
CMB: dig into the noise

Astrophysical sources from sub-mm to IR
CMB: anisotropies of anisotropies

Sources:
- CMB lensing
- Power asymmetries
- Anisotropic primordial power
- Spatially-modulated primordial power
- Primordial B-field (causal)
- Non-Gaussianity

- Point-like and extended sources
- Source clustering effect

Other sources:
- Systematics
- Anisotropic noise
- Beam-effects

... Powerful method to test for a wide class of anisotropic theoretical models & instrumental systematics

Interesting physical effects on very large cosmological scales
CMB: anomalies

Large-angle CMB anomalies don’t “prove” that anything nonstandard is going on, but may provide hints of places to look for interesting phenomena on large scales.

- Large-scale power deficit
- North-south asymmetry

Important to make predictions and choose statistics in advance for new data sets, to avoid a posteriori statistics.

Need a data set that probes other perturbation modes on ultralarge scales:

- Alignment of multipoles (“axis of evil”)
- CMB polarization
- Large-scale structure / 21 cm tomography?
- Kamionkowski-Loeb remote quadrupole measurements?
CMB polarization

WMAP-5yr

K band

Ka band

V band

Q band

W band
CMB polarization

Scalar quadrupole moment

Produced by adiabatic fluctuations at last scattering
Large polarization: photons travel significant distance between scatterings (!)
Only on causally-connected angular scales (< 1°)
A bit smaller-scale than structure in total intensity
Polarized brightness up to 10% of total intensity fluctuations
Driven by very-large scale gravitational waves, generated at inflation.

Tensor-to-scalar power ratio depends on inflationary energy scale:
$r \approx \left( V^{1/4} / 3.3 \times 10^{17} \text{ GeV} \right)^4$
Nearly negligible on ‘causal’ scales, strongest @ ~2°
CMB polarization

- **E-modes:**
  - Direct probe of last scattering surface
  - Best constraint on early re-ionization ($z \sim 10$)
  - Independent check on cosmological model fitted to Temperature data
  - (Nearly) independent of temperature pattern: eventually reduces cosmic variance (needs better SNR)

- **Gravitational lensing B-modes:**
  - Sensitive probe of mass distribution: $\sigma_8$, mass vs light, tests of GR consistency.

- **Primordial B-modes:**
  - “Holy Grail of Cosmology”
  - Relic from inflationary epoch: $t = 10^{-37}$ s,
  - Fixes inflation energy scale: big clue to relevant physics
  - Non-gaussian B-modes sensitive test of defects

- **Quantum effects in CMB:**
  - Planck-scale induced birefringence
Dominated by BICEP at $\ell < 300$, QUaD at higher $\ell$

Best limit:

$r < 0.72$ (95%) (BICEP)

1 more year of BICEP, full year of QUIET data already taken.
Expect modest improvement.

Several experimental and technological advances needed $\rightarrow r < 0.1$

Space: 3  
Ballon: 4  
Ground-based: 12
Projects ongoing and planned

**Space**
- Planck
- CMBPOL/EPIC
- BPOL

**Ground-based**
- QUIET1 (40/90 GHz)
- C-BASS (5 GHz)
- QUIJOTE1 (10-18, 30 GHz)
- BICEP2 (150 GHz)
- GEM-P (5 GHz)
- ABS (145 GHz)
- POLARBear (150 GHz)
- QUIET2 (30/40/90)
- QUIJOTE2 (30)
- Keck Array (100/150/220)
- QUBIC

**Balloon**
- EBEX
- PILOT (Dust)
- SPIDER
- Boomerang II
CMB polarization: challenges

- **Sensitivity:** 100 nK (E); 10 nK (B)
- **Receivers:** bolometers, TES, KIDs, Q-dots
- **Detectors:**
  - bolometer arrays
  - Polarimeter on chip
  - Wave-plate polarimeters, FTS-SP
- **Systematics**
- **Field description (matrix structure)**
- **Experimental artifacts**

- **Signal extraction**
  - Polarization signal reconstruction
  - Data analysis techniques
CMB polarization: challenges

🔮 Polarization calibrators
(bright, non-variable)

*m Astronomical “calibrators”
known to $\sim 2^\circ$

✉ Use physical polarization reference

Wire-grid Calibrator
CMB polarization: challenges

- Few, sparse samples
- Need larger, deeper catalogues
- Large Π variability

\[ \frac{C_{1,\text{Blazar-pol}}(\nu)}{C_{1,\text{Blazar-pol}}(1.4\text{GHz})} \propto \left( \frac{\nu \text{ GHz}}{1.4} \right)^{2\zeta} \]

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Galaxy clusters

Planck SZ all sky survey
Clusters

Clusters are excellent Cosmological probes
- X-rays
- Optical
- SZ

Not completely understood physics (excellent Astro-Particle Physics Labs.)
- Evolution
- Potential wells: DM vs. Mod G
- Atmosphere complexity
  - X-ray view and systematics
  - O view and systematics
  - SZ view and systematics
  - GL view and systematics

New data:
- SZ (mm) needed, especially spectra & polarization
- X-ray: assessment (hopefully also polarization)
- O: refinement needed (galaxy population, AGN fraction, ...)
- Radio: new data and not data re-analysis (B-field FR, ...
Clusters are excellent Cosmo-evolu-meters

\[ N(M) = \frac{\rho}{M} f(\nu) \frac{d\nu}{dM} \]

\[ f(\nu) = \frac{\sqrt{2}}{\sqrt{\pi}} \exp\left(-\frac{\nu^2}{2}\right) \]

\[ \nu = \frac{\delta(z) D(z, \Omega)}{\sigma(M) D(0, \Omega)} \]

• Understand their physics (DM, baryons, Galaxy feedback, CRs, B)

• Derive their total gravitational mass \( M \sim \rho_b R^3_f \)

• Collect large, unbiased catalogues at various \( z \) \( N(M,z) \)
Clusters @ X-ray

X-ray observations currently the most efficient and well-tested way to find clusters

\[ L_X \sim n^2 T^{1/2} f(E, Z, T) \]
Clusters @ X-rays

Non Cool-core

Cool-core

Evidence for the presence of non-gravitational phenomena
Clusters: non-thermal phenomena

- AGN feedback
- CRs
- B field
- DM feedback
Clusters: non-thermal phenomena

**AGN feedback**

**Perseus cluster** ($X, \gamma$)
- Multi-T
- Cool Core
- AGN-dominated core
- Mini Radio halo
- Non-thermal plasma
  (DM, CRs, WRs, BH,...)

**RXJ1347-1145 cluster** ($\mu$wave-mm)
- Multi-T
- AGN-dominated core
- Non-thermal plasma
  (DM, CRs, WRs, BH,...)
Clusters: non-thermal phenomena

Possibility to detect γ-rays from Perseus
• in low-states of the central AGN
• in the outer parts of the cluster
Clusters: non-thermal phenomena

❖ Cosmic Rays
  ❖ Radio halos: LOFAR, SKA
  ❖ X-ray: cavities (Chandra)
  ❖ SZE th+non-th: PLANCK, Millimetron, SAGACE
  ❖ HXRs ICS + Brem.: NuStar,
  ❖ Gamma-rays Brem+ICS+p0 decay: Fermi, CTA, ...

❖ Origin
  • Acceleration: shocks, merging
  • In situ: hadrons + secondary e+-
  • Injection

❖ Impact on cluster evolution
  ❖ to be determined
Clusters: non-thermal phenomena

- Cosmic Rays
- Cavities: hadronic CR support

Radio emission
\( \nu = 37 \text{MHz} \quad E_{\text{Gev}}^2 B_\mu \)

Merging shocks

- MS0735.6+7421
- RXJ1314.4-2515
- A3667
Clusters: non-thermal phenomena

- Acceleration vs. merging

Shock acceleration: relativistic covariant formulation

Turbulent acceleration

Power-law

Maxwellian

$\tau_{eq} \ll \tau_{acc}$
Clusters: non-thermal phenomena

**B field**
- More and more evidence & constraints
- Simulations help to check ideas/models

- Non-linear evolution in bound structures
- Origin: open question (primordial or post recombination?)
  - Approach 1: galaxy/AGN outflows + cavities + ...
  - Approach 2: evolving from primordial B-field ($10^{-100} \text{ G}$)
B-field in clusters: evidence

**Synchrotron radiation**

Radio Halos

\[ B \approx 0.1 - 5 \mu G \]

Radio Relics

\[ B \approx 0.2 - 8 \mu G \]

**Faraday Rotation**

\[ B \approx 1 - 50 \mu G \]
B-field from early ages

Non-linear evolution coupling with DM & baryons
Observable effects

- **X-rays:**
  - scaling-law problem

- **SZE:**
  - modifies signal power spectrum

- **Radio halo population evolution**

\[ 2K + 2U + U_B + W = 0 \]

\[
\frac{\partial p_g(r,B)}{\partial r} + \frac{\partial p_B(r,B)}{\partial r} = -\frac{GM(\leq r)}{r^2} \rho_g(r,B),
\]
Clusters: M determination

Mass proxy

\[ T, L_X, Y_X, Y_{SZ}, R_O, f_{\text{gas}}: \] which is the best

**Scatter:** under control (!?); extremes due to cool cores & mergers

**Evolution:** less known
Cluster mass determination: Lensing

- From shear to surface density (Kaiser-Squires, 1993):

\[ \kappa + i\beta = \partial^{-2} \partial^* \partial^* (\gamma_1 + i\gamma_2) \]

- \( \kappa/\beta \) (E/B) decomposition:
3-D Dark Matter Mass ($\phi$) Maps

3-D density maps of HST-STAGES A901/2

\[ \ddot{\phi} = \Psi + \Phi \rightarrow \rho_m \]
Clusters: redshifts

- **z** determination: Optical surveys

- **z** proxy

  The location of the red-sequence allows for robust redshift estimates.
Clusters: simulations

**Pearce et al. ‘06**

L = 500 $h^{-1}$ Mpc

$N_{gas} + N_{DM} = 10^9$

$\varepsilon_{Pl} = 50 \, h^{-1} \text{kpc}$

Non-radiative

**Tornatore et al. ‘10**

L = 75 $h^{-1}$ Mpc

$N_{gas} = N_{DM} = 512^3$

$\varepsilon_{Pl} = 2.5 \, h^{-1} \text{kpc}$

SF + SN + enrichment

**Dolag et al. ‘06**

$M \sim 2 \times 10^{15} \, h^{-1} \, M_\odot$

$N_{gas} = N_{DM} \sim 10^7$

$\varepsilon_{Pl} = 2.5 \, h^{-1} \text{kpc}$

SF + SN + enrichment
Clusters: simulations

From single objects to representative parts of the Universe

- Useful to calibrate clusters for cosmology

- N-body simulations fail to reproduce inner cluster structure + other detailed features
Cluster and cosmology: surveys

RASS
XMM-COSMOS
XMM-LSS
SXDF
E-ROSITA
WFXT
...

PLANCK
SPT
ACT
SAGACE
MILLIMETRON
...

DES
...

+ Optimal Selection Function
Galaxy clusters probe the physics behind our accelerating universe in a way that is fundamentally different from geometrical probes (e.g. BAO or SN).
Clusters and DM

_clusters are useful labs for indirect DM search_
Dark Matter

- All evidence is astronomical
- Anomaly in 1933 up to 1970’s
- Accepted (needed) Anomaly up to today
  - CMB
  - Cosmology + LSS (3D-DM distributions from GL)
  - Cluster + GL + galactic physics

- Experimental frustration:
  - anomalies: DAMA, Pamela, ATIC
  - Data-theory tension: go for hidden DM

- Big experimental effort:
  - Underground: direct search
  - Ground: Indirect search: telescopes
  - Above the ground: indirect search: satellites

- A multi\(^3\) approach: m-freq. + m-mess. + m-exp.
- Huge data analysis and theoretical effort
- New directions to go !?
The Dark Matter Scenario: timeline

- 1930
- 1940
- 1950
- 1960
- 1970
- 1980
- 1990
- 2000
- 2010

**Missing mass Dynamics**

- Rotation curves

- N-body simulations

- Lensing

- CMB

**Astro Particle Physics & cosmology**

- 1977
  - Thermal relics (Lee & Weinberg)

- 1984
  - Indirect DM search idea (Silk & Srednicki)

- 1985
  - Direct DM experiments (Goodman & Witten)

- Today

- **ν mass theoretical & experimental**

- **SUSY**

- **AXION**

- **Sterile ν**

Supersymmetric "shadow" particle $\Delta m^2_\nu$
Hunt for the DM particle

DM exists:
we feel its (gravitational) presence

DM is mostly non-baryonic:
we must think of a specific search strategy

DM is very elusive:
we must consider un-ambiguous evidence

Crucial Probes are required!
Dark Matter probes

- Under-ground
- On-the-ground
- Above-the-ground
The latest results: CDMS II

2 events in the observed signal region. Based on background estimate, the probability of observing two or more background events is ~23%.

Many direct detection experiment in the (next) future

Ahmed et al. arXiv:0912.3592v1
DM - Astrophysical probes

**INFERENC**

- Virial Theorem
- Hydro Equilibrium
- Gravitational lensing

**PHYSICAL**

- Annihilation
- Decay
DM - Astrophysical search

**INFERENCE**

**NOT CRUCIAL**

Vulnerable against:

**MOND**: Modified Newtonian Dynamics

**TeVeS**: Tensor-Vector-Scalar

Ordinary matter feels a transformed metric

\[
\tilde{g}_{\mu\nu} = e^{-2\phi} g_{\mu\nu} + 2 \sinh(2\phi) U_\mu U_\nu
\]

**PHYSICAL**

**CRUCIAL**

Testable against:

**Electromagnetic signals**

DM illuminates thru its interaction
DM - Astrophysical search

Clean and unbiased location in the sky
- Best Astrophysical Laboratories

Clear and specific SED in the e.m. spectrum
- Most specific e.m. signals

NO

YES
Multi-wavelength

Multi-messenger

Multi-experiments
The Galactic Center

Galactic center region across the spectrum:
red: radio 90 cm (VLA); green: mid-infrared; blue: X-ray (1-8 keV; Chandra ACIS-I)
A multiwavelength close-up of the recent massive star-forming region near the Galactic center. The color image, plotted also in standard Galactic coordinates, is a composite of 20-cm radio continuum (red); 25-µm mid-infrared (green); and 6.4-keV line emission (blue).
Galactic Center demography

Crowded, active environment

Fermi (1GeV)

HESS

EGRET source

Central Black Hole

X-ray source

SNR

Sgr A East non-thermal filaments (radio)
The DM challenge: Fermi

No evidence of DM signals in Fermi (11 months) data
The GC region DM challenge: limits

Stronger constraints from radio + γ-rays

- Radio: constrain to ~ GeV-TeV mass
- γ-rays: constrain to ≤ GeV mass
- ν’s: constrain to > 10 TeV mass

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<th>ν (GHz)</th>
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<th>Flux density</th>
<th>Error</th>
<th>Ref.</th>
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<tr>
<td>0.074</td>
<td>VLA</td>
<td>2'</td>
<td>16,200 Jy</td>
<td>1,000 Jy</td>
<td>[71]</td>
</tr>
<tr>
<td>0.330</td>
<td>Green Bank</td>
<td>39</td>
<td>18,000 Jy</td>
<td>6%</td>
<td>[71]</td>
</tr>
<tr>
<td>1.408</td>
<td>Effelsberg</td>
<td>0.4'</td>
<td>7,300 Jy</td>
<td>10%</td>
<td>[72]</td>
</tr>
<tr>
<td>2.417</td>
<td>Parkes</td>
<td>10.4'</td>
<td>4,900 Jy</td>
<td>6%</td>
<td>[74]</td>
</tr>
<tr>
<td>2.056</td>
<td>Effelsberg</td>
<td>4.3'</td>
<td>4,400 Jy</td>
<td>10%</td>
<td>[76]</td>
</tr>
<tr>
<td>10.26</td>
<td>Nobeyama</td>
<td>2.9'</td>
<td>1,400 Jy</td>
<td>7%</td>
<td>[76]</td>
</tr>
</tbody>
</table>

Radio + EGRET

[Regis & Ullio 2008]

Radio + HESS

[Borriello et al. 2008]
Charge-dependent solar modulation important below 5-10 GeV

Rapid climb above 10 GeV indicates the presence of a primary source of cosmic ray positrons!

Astrophysical expectation (secondary production)
Are these signal from DM?

- Shape consistent with some generic Dark Matter candidates but with:
  - Very hard spectrum
  - Large fraction of annihilation to $e^+e^-, \mu^+\mu^-$ or $\tau^+\tau^-$

- Flux is a factor of 100-1000 too big for a thermal relic;
  → requires dramatic enhancement

- Astrophysics
  - More small-scale structure than expected ("boost factor" of ~1000)
  - A narrow diffusion region
  - A large nearby clump of dark matter

**KK dark matter with $m \sim 600$ GeV**

Cheng, Feng, Matchev (2002)
Are these signal from DM?

- Shape consistent with some generic Dark Matter candidates but with:
  - Very hard spectrum
  - Large fraction of annihilation to \(e^+e^-, \mu^+\mu^-\) or \(\tau^+\tau^-\)
- Flux is a factor of 100-1000 too big for a thermal relic;
  \(\rightarrow\) requires dramatic enhancement
  - Astrophysics
  - Particle physics
    - Non-perturbative effects as the “Sommerfeld Enhancement”
      important for \(m_\phi < m_X\) and \(v_X \ll c\)
      (such as in the halo, where \(v_X/c \sim 10^{-3}\))
- No enhancement seen in anti-protons
- Constraints from antiprotons, gamma rays, synchrotron, IC emission, radio...

\[\text{KK dark matter with } m \sim 600 \text{ GeV}\]

HESS and Fermi

Fermi and HESS do not confirm ATIC: 
→ consistent with bkgd. expectations

Astrophysics can explain PAMELA:
- Pulsars
- SN remnants
- Diffusion effects

[Zhang, Cheng (2001); Hooper et al. (2008)
Yuksel et al. (2008); Profumo (2008)
Fermi LAT Collaboration (2009)]
Neutralino DM: Hidden DM !?! 

Experimental Frustration

• No direct evidence (DAMA vs. other underground experiments)
• No photonic signals (only upper limits from Multi-ν (M³) analysis)
• No particle signal (Pamela → ATIC: embarassing results)

What do we really know about dark matter?

All solid evidence is gravitational
Also solid evidence against strong and EM interactions

The anomalies (DAMA, PAMELA, ATIC, ...) are not easily explained by canonical WIMPs → go beyond MSSM WIMP model

A reasonable 1st order guess:
Dark Matter has no SM gauge interactions, i.e., it is hidden

[Kobsarev, Okun, Pomeranchuk (1966); many others]
[Feng et al. 2009]

What one seemingly loses:
Connection to central problems of particle physics
Non-gravitational signals
The WIMP miracle
Dark Matter exists!

… or not!? 

A team of researchers has found the first direct proof for the existence of dark matter, the mysterious and almost invisible substance thought to make up almost a quarter of the universe. In this composite image, two clusters of galaxies are seen after a collision. Hot gas, seen in red, was dragged away from the galaxies during the collision. That gas makes up more than 90 percent of the mass of normal, or visible, matter. But most of the mass—and thus matter—is located in the galaxy portions of the clusters, shown in blue, scientists say. In other words, the bulk of visible matter in the clusters has been separated from the majority of mass—which therefore must be dark matter.

J. Moffat suggests that his Modified Gravity (MOG) theory can explain the Bullet Cluster observation. MOG predicts that the force of gravity changes with distance. Moffat thinks that the present day expectation by many that dark matter must exist is similar to the expectation by many leading scientists in the beginning of the 20th century that a "luminiferous ether" should exist. This was a hypothetical substance, in which the waves of light were supposed to propagate.

[Image of galaxies with a red hot gas trail]

[F. Zwicky 1933]

J. Moffat and colleagues suggest that there is a good reason dark matter why has never been directly detected: It doesn't exist. 

Dark matter does not exist! Einstein wins again!
J. Moffat says, "If the multi-billion dollar laboratory experiments now underway succeed in directly detecting dark matter, then I will be happy to see Einstein and Newtonian gravity retained. However, if dark matter is not detected and we have to conclude that it does not exist, then Einstein and Newtonian gravity must be modified to fit the extensive amount of astronomical and cosmological data, such as the bullet cluster, that cannot otherwise be explained.

Could MOG explain also the dynamics of the bullet cluster?
DM: the most palpable proof
Dark Energy: the 3-fold way out

- Usual 2 ways of explaining dark energy:
  \[ G_{\mu\nu} = 8\pi G T_{\mu\nu} \]  
  
  **Modified Gravity**

- **New fundamental fields**
  - Quintessence, Quartessence, K-essence, Chaplygin gas, interacting fields, vector fields, n-Forms, Braiding fields...

- Actually, there is a **third** way out!
  - Keep Einstein theory and "normal" (cold + baryonic) matter
  - Change the **metric**
Different approaches to Dark Energy include amongst many:

- A true cosmological constant -- but why this value?
- Solid –dark energy such as arising from frustrated network of domain walls. [see Pearson talk]
- Time dependent solutions arising out of evolving scalar fields -- Quintessence/K-essence.
- Modifications of Einstein gravity leading to acceleration today.
- Anthropic arguments.
- Perhaps GR but Universe is inhomogeneous.

Over 2200 papers on archives since 1998 with dark energy in title.
Dark Energy: probes

Cosmo-evolu-meters:
- X+SZ+O clusters
- GL

Global Geometry
- BAO
- LSS
- SNe
- Cosmic parallax
DE: generic predictions

**SN:** Union compilation (Kowalski et al. 2008)
- distances to 307 Type Ia SNe at $z \lesssim 1$

**CMB:** WMAP5 (Komatsu et al. 2009)
- distance to $z = 1100$, matter density $\Omega_m h^2$

**BAO:** SDSS (Eisenstein et al. 2005)
- 4% distance at $z = 0.35$

**$H_0$:** SHOES measurement with HST (Riess et al. 2009)
- 5% Hubble constant from SNe at $z < 0.1$

Data:
- SN
- CMB
- BAO
- $H_0$

Best fit dark energy model $H(z)$

$$D(z) = \frac{1}{\sqrt{|\Omega_K| H_0^2}} \sinh \left[ \sqrt{|\Omega_K| H_0^2} \int \frac{dz}{H(z)} \right]$$

Upcoming CMB, SN, and BAO data sets will make more precise growth predictions and enable even sharper tests of dark energy models.
Dark Energy Equation of State: $\rho_{de} \sim (1+z)^3(1+w)$

Kowalski et al (2009)
Union set: 307 SN

Flat (k=0) models

All data:
$w = -0.96 \pm 0.05$

Anisotropic DE scenarios $\Delta w < 2.1 \times 10^{-4}$
Dark Energy Constraints

Evolution of $w$: $w(z) = w_0 + w_a \frac{z}{1+z}$
DE: experimental efforts

DES
BOSS
AAOmega QSO survey
HETDEX
EUCLID
COSMOS
Union SN data
SNLS
SN factory
WFXRT
SPT
E-ELT and CODEX
GAIA
...

Euclid
The 6 Parameters of $\Lambda$CDM*

- Plasma epoch – matter, radiation content, $\Omega_b$, $\Omega_c$
- Inflation – initial conditions, $A$, $n_s$
- Dark ages → first stars – polarization, $\tau$
- Large scale structure – dark energy, $\Omega_\Lambda$, $\sigma_8$
- *The amplitude parameters $A$ and $\sigma_8$ are not independent; flatness of the universe is assumed in $\Lambda$CDM.*
Parameters in $\Lambda$CDM

...pretty well estimated
SNIIa, CMB, P(k)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vanilla</th>
<th>Vanilla + $\Omega_k$</th>
<th>Vanilla + $w$</th>
<th>Vanilla + $\Omega_k + w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_\gamma h^2$</td>
<td>0.0227 ± 0.0005</td>
<td>0.0227 ± 0.0006</td>
<td>0.0228 ± 0.0006</td>
<td>0.0227 ± 0.0005</td>
</tr>
<tr>
<td>$\Omega_c h^2$</td>
<td>0.112 ± 0.003</td>
<td>0.109 ± 0.005</td>
<td>0.109 ± 0.005</td>
<td>0.109 ± 0.005</td>
</tr>
<tr>
<td>$\theta$</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.085 ± 0.017</td>
<td>0.088 ± 0.017</td>
<td>0.087 ± 0.017</td>
<td>0.088 ± 0.017</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.963 ± 0.012</td>
<td>0.964 ± 0.013</td>
<td>0.967 ± 0.014</td>
<td>0.964 ± 0.014</td>
</tr>
<tr>
<td>$\log(10^{10} A_s)$</td>
<td>3.07 ± 0.04</td>
<td>3.06 ± 0.04</td>
<td>3.06 ± 0.04</td>
<td>3.06 ± 0.04</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-0.005 ± 0.007</td>
</tr>
<tr>
<td>$w$</td>
<td>-1</td>
<td>0</td>
<td>0</td>
<td>-0.005 ± 0.012</td>
</tr>
</tbody>
</table>

Very stable
Probing detailed evolution: SNe

What if SNIa evolved?

$$\Delta m(z) = K \left( \frac{t_0 - t(z)}{t_0 - t_1} \right)$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Vanilla</th>
<th>Vanilla + $\Omega_k$</th>
<th>Vanilla + $w$</th>
<th>Vanilla + $\Omega_k + w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_0 h^2$</td>
<td>0.0228 ± 0.0006</td>
<td>0.0227 ± 0.0005</td>
<td>0.0227 ± 0.0006</td>
<td>0.0226 ± 0.0006</td>
</tr>
<tr>
<td>$\Omega_k h^2$</td>
<td>0.110 ± 0.004</td>
<td>0.109 ± 0.005</td>
<td>0.113 ± 0.005</td>
<td>0.111 ± 0.005</td>
</tr>
<tr>
<td>$\theta$</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
<td>1.042 ± 0.003</td>
</tr>
<tr>
<td>$\tau$</td>
<td>0.088 ± 0.017</td>
<td>0.087 ± 0.017</td>
<td>0.085 ± 0.017</td>
<td>0.085 ± 0.016</td>
</tr>
<tr>
<td>$n_s$</td>
<td>0.968 ± 0.013</td>
<td>0.965 ± 0.013</td>
<td>0.963 ± 0.014</td>
<td>0.960 ± 0.014</td>
</tr>
<tr>
<td>$\log(10^{10} A_s)$</td>
<td>3.07 ± 0.04</td>
<td>3.06 ± 0.04</td>
<td>3.07 ± 0.04</td>
<td>3.06 ± 0.04</td>
</tr>
<tr>
<td>$\Omega_k$</td>
<td>0</td>
<td>-0.002 ± 0.007</td>
<td>0</td>
<td>-0.017 ± 0.013</td>
</tr>
<tr>
<td>$w$</td>
<td>-1</td>
<td>-1</td>
<td>-1.112 ± 0.148</td>
<td>-1.33 ± 0.242</td>
</tr>
<tr>
<td>$K$</td>
<td>-0.042 ± 0.042</td>
<td>-0.035 ± 0.042</td>
<td>-0.105 ± 0.091</td>
<td>-0.133 ± 0.077</td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>0.747 ± 0.017</td>
<td>0.745 ± 0.020</td>
<td>0.756 ± 0.022</td>
<td>0.744 ± 0.022</td>
</tr>
<tr>
<td>Age</td>
<td>13.6 ± 0.1</td>
<td>13.7 ± 0.4</td>
<td>13.6 ± 0.1</td>
<td>14.5 ± 0.7</td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>0.253 ± 0.017</td>
<td>0.257 ± 0.025</td>
<td>0.244 ± 0.022</td>
<td>0.272 ± 0.029</td>
</tr>
<tr>
<td>$\sigma_8$</td>
<td>0.801 ± 0.026</td>
<td>0.794 ± 0.029</td>
<td>0.846 ± 0.068</td>
<td>0.867 ± 0.060</td>
</tr>
<tr>
<td>$z_{re}$</td>
<td>11.1 ± 1.5</td>
<td>11.0 ± 1.4</td>
<td>10.9 ± 1.5</td>
<td>10.8 ± 1.4</td>
</tr>
<tr>
<td>$h$</td>
<td>0.725 ± 0.017</td>
<td>0.720 ± 0.036</td>
<td>0.748 ± 0.038</td>
<td>0.703 ± 0.042</td>
</tr>
</tbody>
</table>
Probing detailed evolution: Dark Ages
Reionization

~9% of CMB photons are Thompson-scattered by free electrons at $z > 6$.

Scattered radiation is polarized if incident radiation has a quadrupolar brightness distribution.

Polarization strength probes optical depth of reionized gas.
Key Questions in Reionization

- What are the first sources?
  - Stars: How did they form?
    - The role of $H_2$ & HI cooling.
  - Pop.II vs Pop III
  - BH + mini-QSOs
  - DM decay or annihilation.
- How did reionization proceed?
  - Topology of the IGM during the EoR.
- When reionization became complete?
- Typical size of ionized regions
- Thermal history of the IGM
- Influence of the EoR on subsequent structure and evolution
- Do we know that reionization is photon starved? Is this a strong constraint of reionization?
- What could the EoR teach us about Cosmology?
Large-Scale Simulations of Reionization
[Iliev et al. 2006a, 2007a; Mellema, Iliev, et al. 2006; and in prep.]

N-body: CubeP³M
1728³-3072³ part.
(5.2 to 29 billion) or more -
4000³-5488³ (64-165 billion)
density slices
velocity slices
halo catalogues-sources
Scales well at least up to
21,952 cores

C²-Ray code
(Mellema, Iliev, et al. 2006)
radiative transfer
noneq. chemistry
precise
highly efficient
coupled to gasdynamics
massively parallel
(scales well up to
10,240 cores).

35-114/h Mpc (CubeP³M)
resolving $10^8 \, M_{\odot}$ halos
up to $21 \times 10^6$ sources
50-100 dens. snapshots
simple source models
sub-grid clumping
no hydro – large scales.

Coupled to hydro
Observing the Reionization Epoch

- Redshifted 21-cm
- Kinetic Sunyaev-Zeldovich effect (kSZ)
- Ly-α sources
- CMB polarization
- NIR fluctuations

The 21-cm probe

Results from approximate methods

~12mK

Thomas & Zaroubi 2008
Towards Inflation... & other Exotics

- Inflaton $\phi$
- Higgs-type auxiliary field $\psi$
- Hybrid potential (Linde, astro-ph/9307002)

$$V(\phi, \psi) = \frac{1}{2} m^2 \phi^2 + \frac{\lambda}{4} (M^2 - \psi^2)^2 + \frac{\lambda'}{2} \phi^2 \psi^2$$

$\ln [V(\phi, \psi)]/m_{pl}^4$

$\lambda = \lambda' = 1, M = 0.1 m_{pl}, m = 10^{-6} m_{pl}$

**Figure:** The angular power spectrum of rotation for a network of strings with
$G_\mu = 1 \times 10^{-7}$. The blue and yellow boxes show the forecasted error for two
surveys with $f_{\text{sky}} = 0.1$ and $f_{\text{sky}} = 0.5$ respectively.
A visionary’s vision: experiments

Breakthru

Pathfinders

Asset
A visionary’s vision: experiments

**Survey instruments:**
- Fermi, e-ROSITA, XMM, EUCLID, DES, HETDEX, BOSS, LSST, HERSCHEL, PLANCK, B-Pol, SPT, ACT, MILIMETRON, SAGACE, LOFAR, SKA, ...

**Pathfinder instruments:**
- ground based
- ballon borne

**Observatories:** Chandra, XMM, HST, Optical Telescopes, HERSCHEL, LMT, Radio telescopes, ...

**Questions**
- Timeline and timescale for big projects
- Rate of knowledge increase by smallest, timely experiments
- Evolution of science focus from multi-frequency & multi-messenger studies.
A visionary’s vision: ideas

Breakthru

Pathfinders

Asset
Still … a bit of statistics

Moriond Talk Distribution

Number

CMB | Clusters | DM | Mod-G | DE | Cosmo sce.
--- | --- | --- | --- | --- | ---
2010
2008
Acknowledgements

Good

- Meeting
- Program
- Accommodation
- Food & Drinks
- **Weather arrangement**
  - Snow (1.-2.5 m.)
  - Sunshine (7/7)
  - Clear sky (7/7)

Slightly less good

- Proceedings
- (Good & safe) trip back home

Thanks to:

Jacques D.
Yannick G-H
Christophe M.
Reza A.

Jean & Kim TTV

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for your attention!