# Elementary particles: The key to the origin of the universe


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# Outline

1. Elementary particles and fundamental interactions
2. Connections between particle physics and astrophysics
3. Recent progress in cosmology
4. Closer to home: Energetic particles and space weather prediction
5. Proposed collaboration with CERN

# 1. Elementary particles and fundamental interactions

- Elementary / fundamental / sub-atomic particles
- Ordinary matter: protons, neutrons, electrons
- Cosmic rays and high energy collisions can produce many other particles
- “High Energy Physics” (HEP)
- experiment, phenomenology, theory

# The four fundamental interactions

| Force | Range | Timescale |
|---|---|---|
| 1. Strong nuclear force | $10^{-13}$ | $10^{-23}$ s |
| force between quarks | | |
| 2. Electromagnetic force | Infinite | $10^{-16}$ s |
| force between charged particles | | |
| 3. Weak nuclear force | $10^{-13}$ | $10^{-8}$ s |
| only way to *change* particle type | | |
| 4. Gravitational force | Infinite | - |
| force between all matter & energy | | |

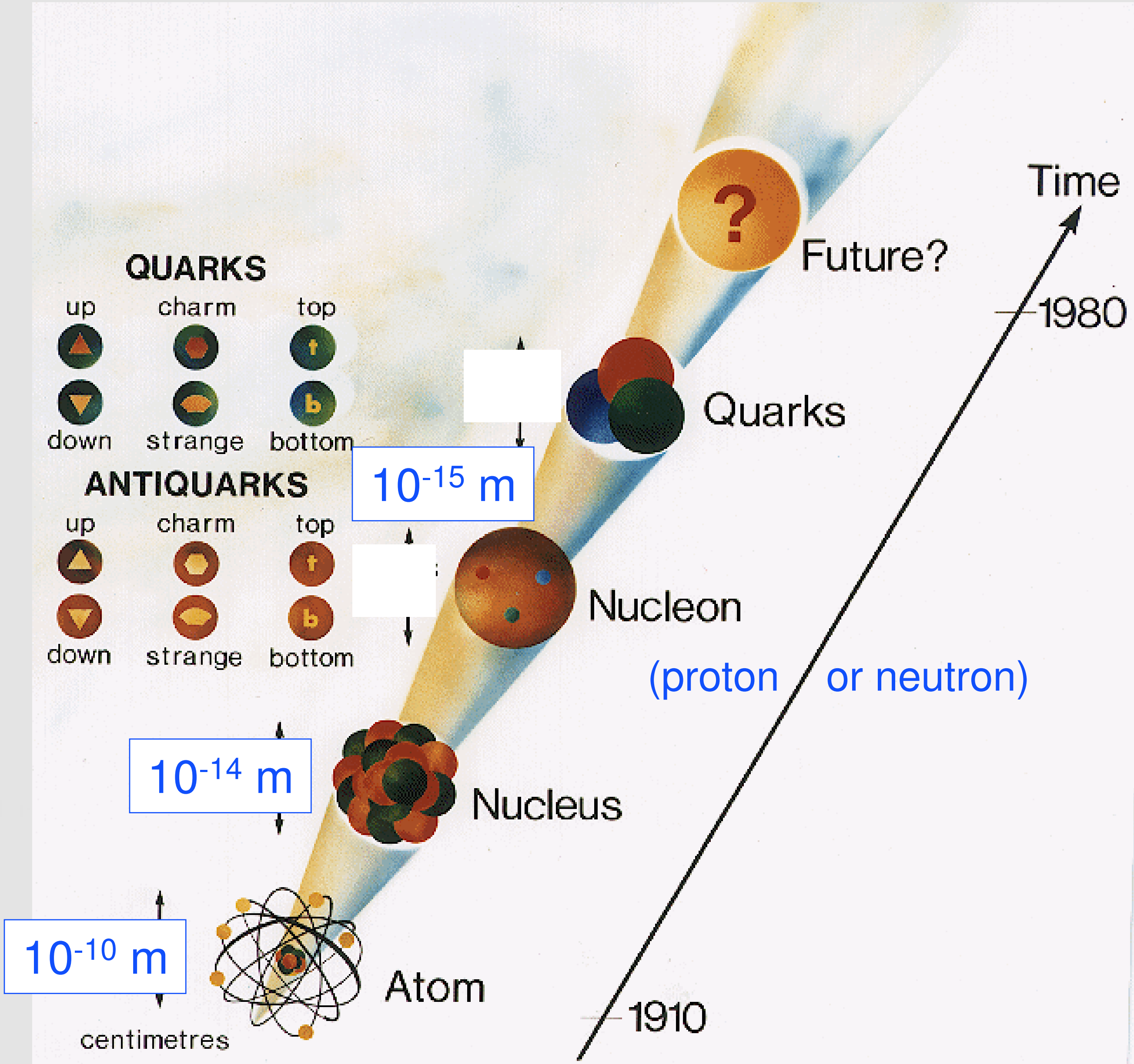



Image credit: www.triumf.ca/atoms_to_quarks.gif

# The most elementary particles: gauge bosons, leptons, and quarks

- Gauge bosons “mediate” interactions: photons, $W^+$, $W^-$, $Z^0$, gluons, gravitons?

- Leptons – size not resolved:
  electron, muon, tauon + neutrinos
  $e^-$ $\mu^-$ $\tau^-$ $\nu_e$ $\nu_\mu$ $\nu_\tau$
  + antiparticles

# Quarks

- 6 “flavors” in 3 “families”

  (up, down) (charm, strange) (top, bottom)

- Most particles are

| | | |
|---|---|---|
| baryons | q q q | (e.g., proton = uud |
| mesons | q $\bar{q}$ | neutron = udd) |
| antibaryons | $\bar{q}$ $\bar{q}$ $\bar{q}$ | |
| pentaquark | q q q q $\bar{q}$ | NEW (2003) |

# Beyond the "standard model"

- <u>neutrino oscillations</u> (Nobel Prize 2002)
  cosmic rays, solar physics
- origin of mass – the "Higgs particle" ?
  new accelerators will search for this
- why so many free parameters, scales that are very different (up to 13 orders of magnitude) for no apparent reason ?

# Collider experiments

- Collider facility → collider → detector

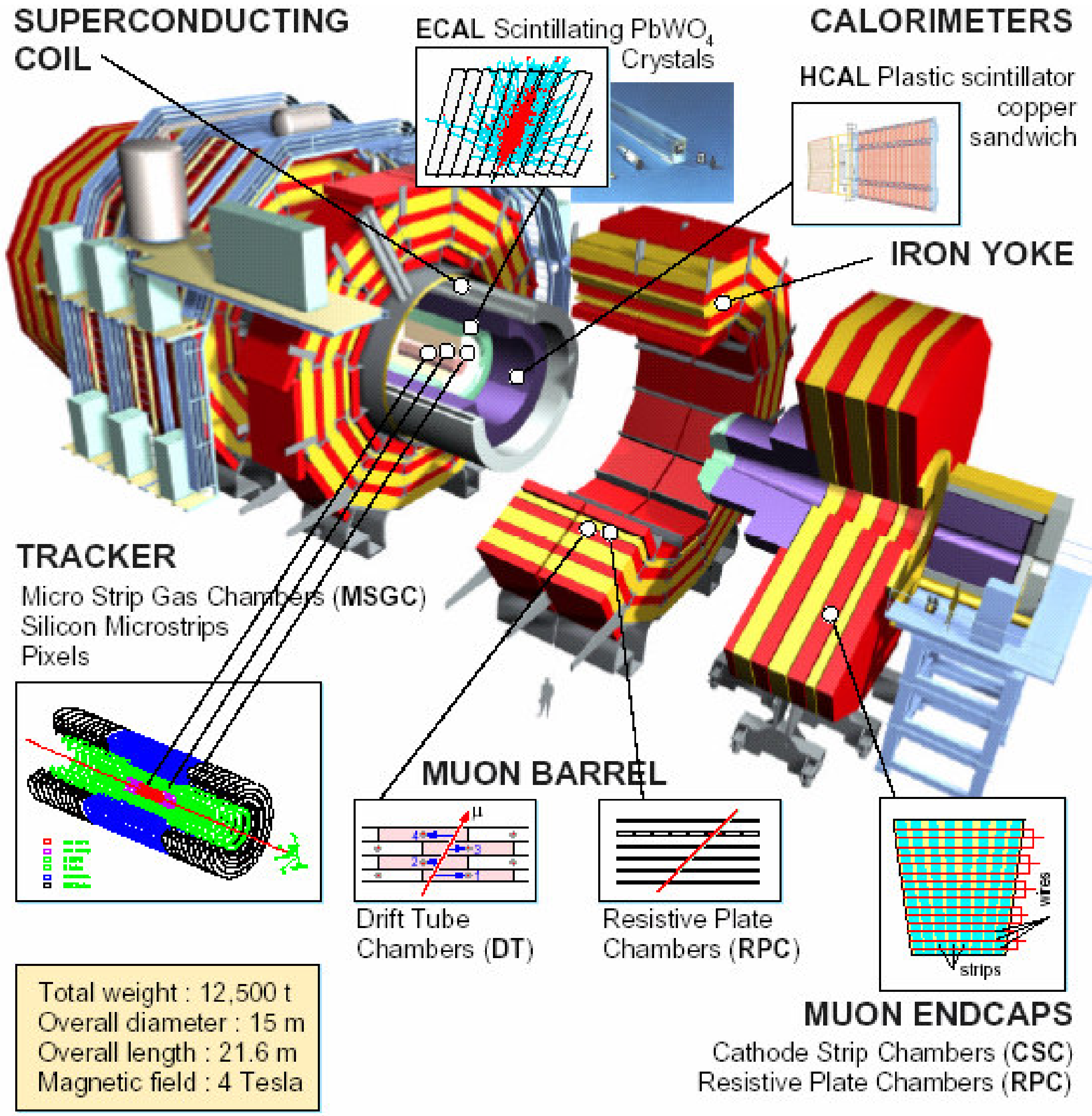
e.g., Fermilab (US) → Tevatron → CDF, D0

(p + p at 1 + 1 TeV, discovered top quark)

- New: CERN (Europe) → LHC → CMS, etc.

(p + p at 17 + 17 TeV, hoping to find Higgs)

(CERN = European Organization for Nuclear Research, LHC = Large Hadron Collider, CMS = Compact Muon Solenoid)



SUPERCONDUCTING COIL
ECAL Scintillating $PbWO_4$ Crystals
CALORIMETERS
HCAL Plastic scintillator copper sandwich
IRON YOKE
TRACKER
Micro Strip Gas Chambers (MSGC)
Silicon Microstrips
Pixels
MUON BARREL
μ
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
wires
strips
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers (RPC)
Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

# CMS Institutions

Shown here:
144 institutions
with about
1700 scientists
(more now)

**ARMENIA**
- Yerevan Physics Inst., Yerevan

**AUSTRIA**
- HEPHY, Wien

**BELARUS**
- Institute of Nuclear Problems, Minsk
- National Centre of Part. and HEP, Minsk
- Res. Inst. of Applied Physical Probl., Minsk
- Byelorussian State Univ., Minsk

**BELGIUM**
- Univ. Instelling Antwerpen, Wilrijk
- Univ. Libre de Bruxelles, Brussels
- Vrije Universiteit Brussel, Brussels
- Univ. Catholique de Louvain, Louvain-la-Neuve
- Univ. de Mons-Hainaut, Mons

**BULGARIA**
- Inst. for Nucl. Res. and Nucl. Energy, Sofia
- Univ. of Sofia, Sofia

**CHINA, PR**
- Inst. of High Energy Physics, Beijing
- Peking Univ., Beijing
- Univ. for Science & Tech. of China, Hefei, Anhui

**CROATIA**
- Tech. Univ. of Split, Split
- Univ. of Split, Split

**CYPRUS**
- Univ. of Cyprus, Nicosia

**ESTONIA**
- Inst. of Chemical Phys. and Biophys., Tallinn

**FINLAND**
- Helsinki Institute of Physics, Helsinki
- Dpt. of Phys., Univ. of Helsinki, Helsinki
- Univ. of Jyväskylä, Jyväskylä
- Helsinki University of Technology, Helsinki
- Univ. of Oulu, Oulu
- Tampere Univ. of Tech., Tampere

**FRANCE**
- LAPP, IN2P3-CNRS, Annecy-le-Vieux
- IPN, IN2P3-CNRS, Univ. Lyon I, Villeurbanne
- LPNHE, Ecole Polytech., IN2P3-CNRS, Palaiseau
- DSM/DAPNIA, CEA/Saclay, Gif-sur-Yvette
- IRES, IN2P3-CNRS - ULP, UHA, LEPSI, Strasbourg

**GEORGIA**
- High Energy Phys. Inst., Tbilisi State Univ., Tbilisi
- Inst. of Physics Academy of Science, Tbilisi

**GERMANY**
- RWTH, I. Physik. Inst., Aachen
- RWTH, III. Physik. Inst. A, Aachen
- RWTH, III. Physik. Inst. B, Aachen
- Humboldt-Univ. zu Berlin, Berlin
- Inst. für Exp. Kernphysik, Karlsruhe

**GREECE**
- Univ. of Athens, Athens
- Inst. of Nucl. Phys. "Demokritos", Attiki
- Univ. of Ioánnina, Ioánnina

**HUNGARY**
- KFKI Res. Inst. for Part. & Nucl. Phys., Budapest
- Kossuth Lajos Univ., Debrecen
- Institute of Nuclear Research ATOMKI, Debrecen

**INDIA**
- Panjab Univ., Chandigarh
- Bhabha Atomic Res. Centre, Mumbai
- Univ. of Delhi South Campus, New Delhi
- TIFR - EHEP, Mumbai
- TIFR - HECR, Mumbai

**ITALY**
- Univ. di Bari e Sez. dell'INFN, Bari
- Univ. di Bologna e Sez. dell'INFN, Bologna
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- Univ. di Firenze e Sez. dell'INFN, Firenze
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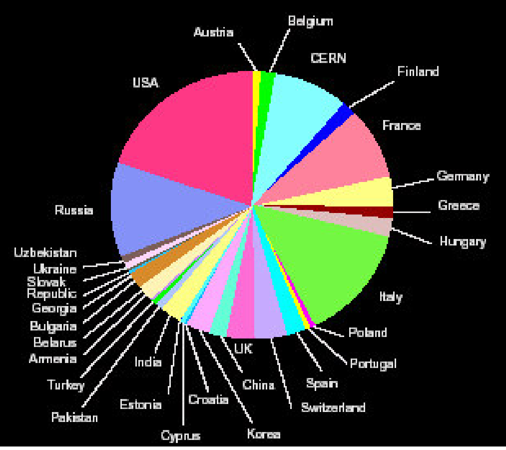
- Dongshin University, Naju
- Kangnung National University, Kangnung
- Kangwon National University, Chunchon
- Kon-Kuk University, Seoul
- Korea University, Seoul
- Kyungpook National University, Taegu
- Pohang University of Science and Technology, Pohang
- Seonam University, Namwon
- Seoul National Univ. of Education, Seoul
- Wonkwang University, Iri
- Gyeongsang National University, Jinju

**PAKISTAN**
- Quaid-I-Azam Univ., Islamabad
- Ghulam Ishaq Khan Institute, Swabi

**POLAND**
- Inst. of Exp. Phys., Warsaw
- Soltan Inst. for Nucl. Studies, Warsaw

**PORTUGAL**
- LIP, Lisboa

**RUSSIA**
- JINR, Dubna
- Inst. for Nucl. Res., Moscow
- Inst. for Theoretical and Exp. Phys., Moscow
- P.N. Lebedev Phys. Inst., Moscow
- Moscow State Univ., Moscow
- Budker Inst. for Nucl. Phys., Novosibirsk
- Inst. for High Energy Phys., Protvino
- Petersburg Nucl. Phys. Inst., Gatchina (St Petersburg)

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- Slovak University of Technology, Bratislava

**SPAIN**
- CIEMAT, Madrid
- Univ. Autónoma de Madrid, Madrid
- Univ. de Oviedo, Oviedo
- IFCA, CSIC-Univ. de Cantabria, Santander

**SWITZERLAND**
- Univ. Basel, Basel
- CERN, Geneva
- Paul Scherrer Inst., Villigen
- Inst. für Teilchenphysik, ETH, Zurich
- Univ. Zürich, Zurich

**TURKEY**
- Cukurova Univ., Adana
- Middle East Technical Univ., Ankara

**UKRAINE**
- Inst. of Single Crystals of Nat. Ac. of Science, Kharkov
- Kharkov Inst. of Phys. and Tech., Kharkov
- Kharkov State Univ., Kharkov

**UNITED KINGDOM**
- Univ. of Bristol, Bristol
- Brunel Univ., Uxbridge
- Imperial College, Univ. of London, London
- RAL, Didcot

**USA**
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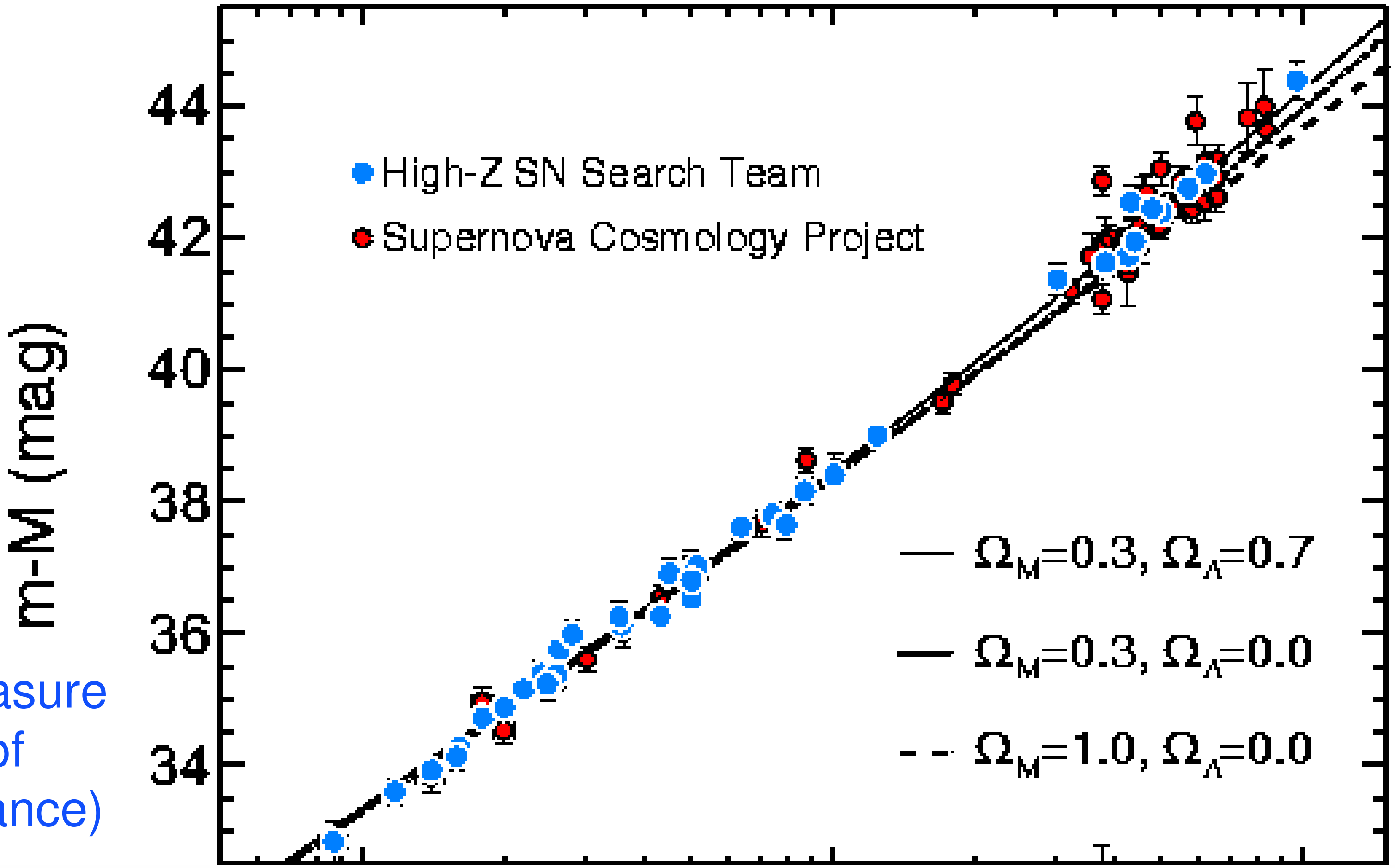
- Iowa State Univ., Ames
- Boston Univ., Boston
- California Inst. of Tech., Pasadena
- Carnegie Mellon Univ., Pittsburgh
- Univ. of Illinois at Chicago, Chicago
- Fairfield Univ., Fairfield
- Fermi National Accelerator Lab., Batavia
- Florida State Univ. - HEPG, Tallahassee
- Florida State Univ. - SCRI, Tallahassee
- Univ. of Florida, Gainesville
- The Univ. of Iowa, Iowa City
- Johns Hopkins Univ., Baltimore
- LLNL, Livermore
- Los Alamos Nat. Lab., Los Alamos
- Univ. of Maryland, College Park
- Univ. of Minnesota, Minneapolis
- Univ. of Mississippi, Oxford
- Massachusetts Inst. of Tech., Cambridge
- Univ. of Nebraska-Lincoln, Lincoln
- Northeastern Univ., Boston
- Northwestern Univ., Evanston
- Univ. of Notre Dame, Notre Dame
- The Ohio State Univ., Columbus
- Princeton Univ., Princeton
- Purdue Univ., West Lafayette
- Rice Univ., Houston
- Univ. of California, Riverside
- Univ. of Rochester, Rochester
- Rutgers, the State Univ. of New Jersey, Piscataway
- Texas Tech Univ., Lubbock
- Univ. of Texas at Dallas, Richardson
- Univ. of California at Davis, Davis
- UCLA, Los Angeles
- Univ. of California San Diego, La Jolla
- Virginia Polytech. Inst. and State Univ., Blacksburg
- Univ. of Wisconsin, Madison

**UZBEKISTAN**
- Inst. of Nucl. Phys. of the Uzbekistan Acad. of Sciences, Tashkent

# 2. Connections between particle physics and astrophysics

- In the past, almost all HEP research used cosmic rays; now use accelerators/colliders
- HEP ← astro: cosmic rays, including solar neutrinos, highest energy collisions; detection techniques
- HEP → astro: energetic particle collisions (solar flares, active galactic nuclei, early universe); detection techniques

# 3. “Classical Cosmology” – Hubble diagram

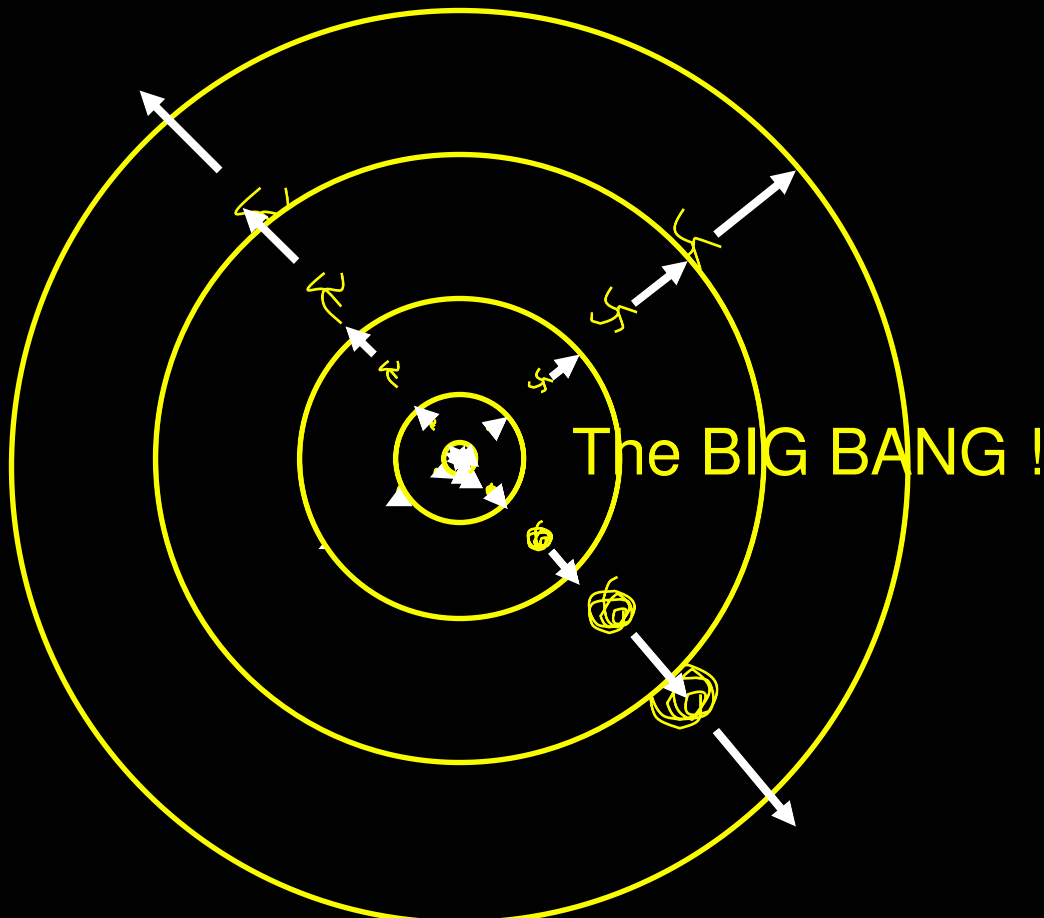



(measure of distance)

0.01 0.1 1

z (measure of radial velocity)

# Expansion of the universe

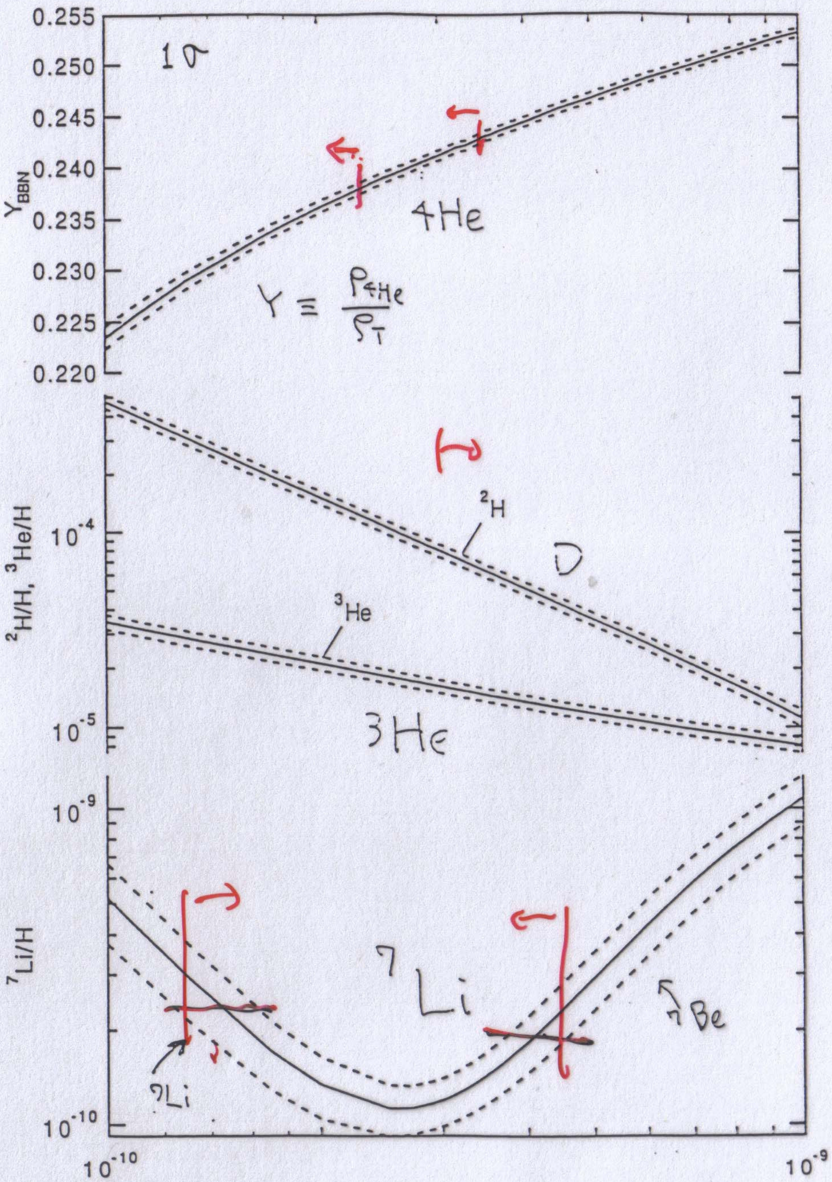


# Other physical evidence for the Big Bang

- Cosmic microwave background (1967): radiation left over from the early universe (now at 3 K)
- Primordial abundances of $^{1}H$, $^{2}H$, $^{3}He$, $^{4}He$, and $^{7}Li$ (see next slide)

Big Bang Nucleosynthesis

# More evidence for the Big Bang …




$\eta = \frac{\text{baryons}}{\text{photons}}$

—95—

IV. Comparison with BBN calculation.

$N_\nu = 3$ .

- $Y_p \le 0.238\ (0.243)$

  $\Rightarrow \quad \eta_{10} \equiv \frac{\eta_B}{10^{-10}} \le 2.5\ (3.8)$

- $\left(\frac{D + {}^3He}{H}\right)_p \le 10^{-4}$

  $\Rightarrow \quad \eta_{10} \ge 2.7$

- $\left(\frac{{}^7Li}{H}\right)_p \le 2.3 \times 10^{-10}$

  $\Rightarrow \quad \eta_{10} \le 5.3$

- $\left(\frac{D}{H}\right)_p \ge 1.8 \times 10^{-5}$

  $\Rightarrow \quad \eta_{10} \le 7.2$

from M. Kawasaki, in JSPS-ICRR Intl Spring School '9

# Modern cosmology: cosmic microwave background fluctuations

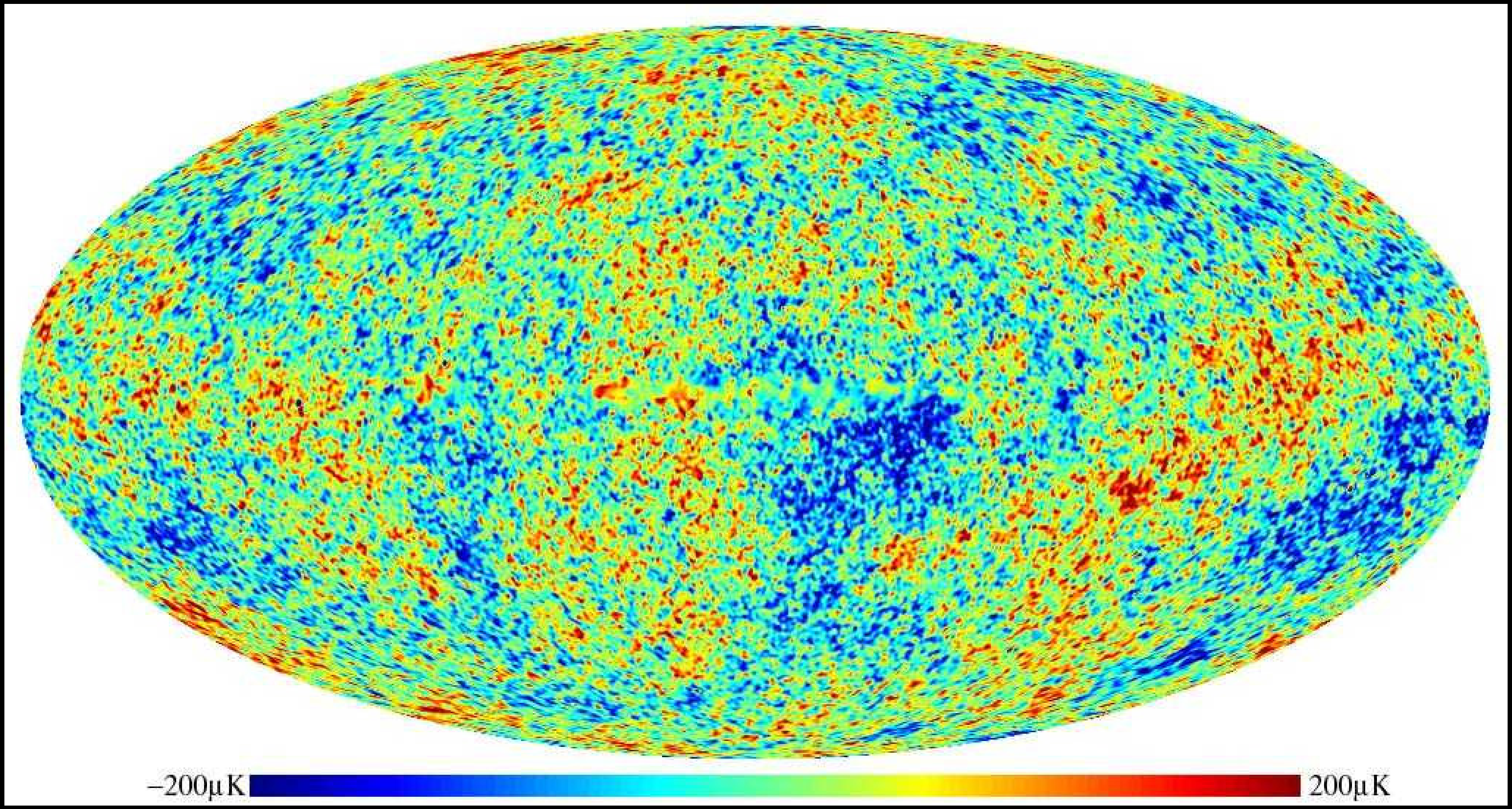
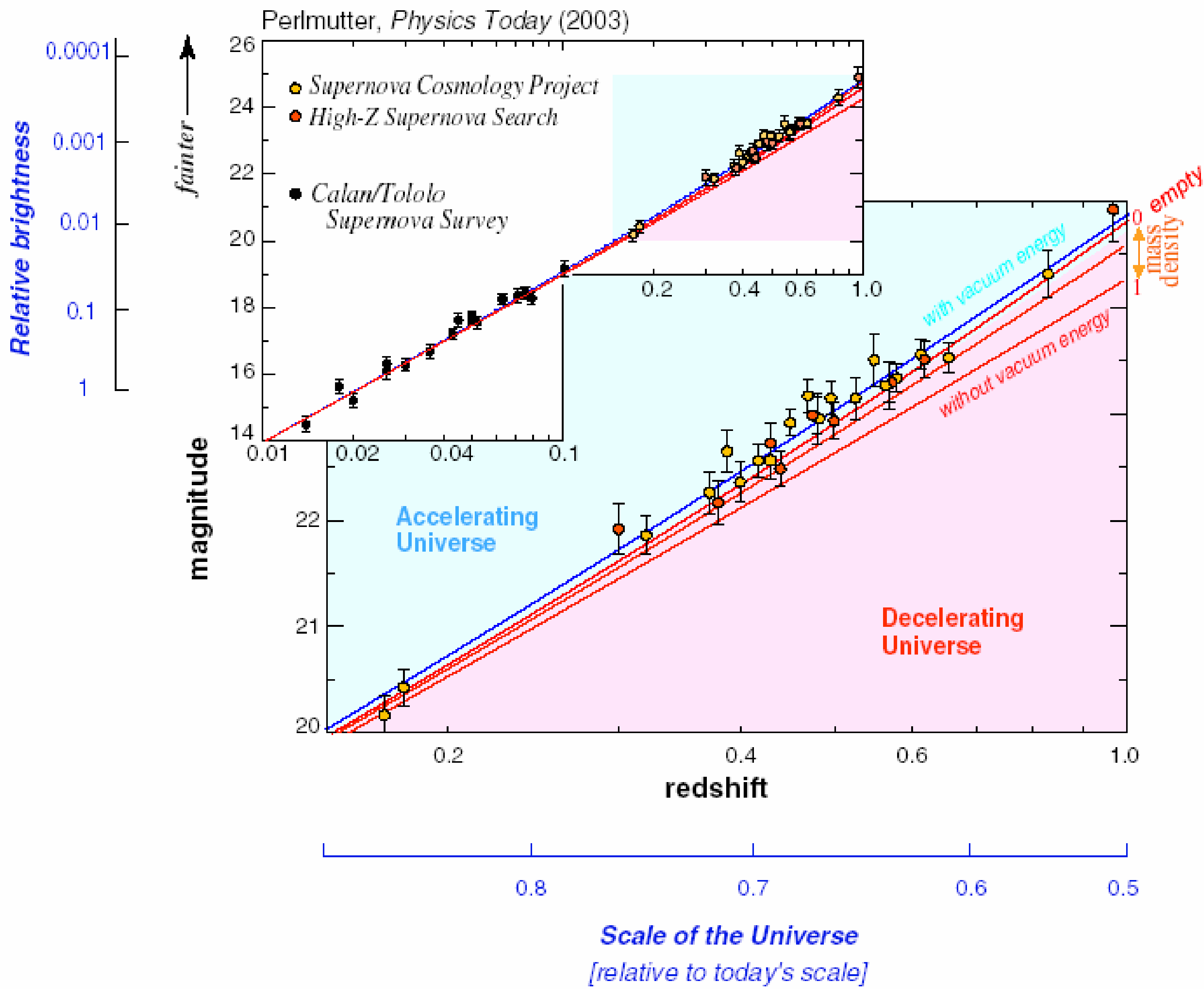



Image credit: http://www.hep.upenn.edu/~max/wmap3.html

# Evidence for an accelerating universe



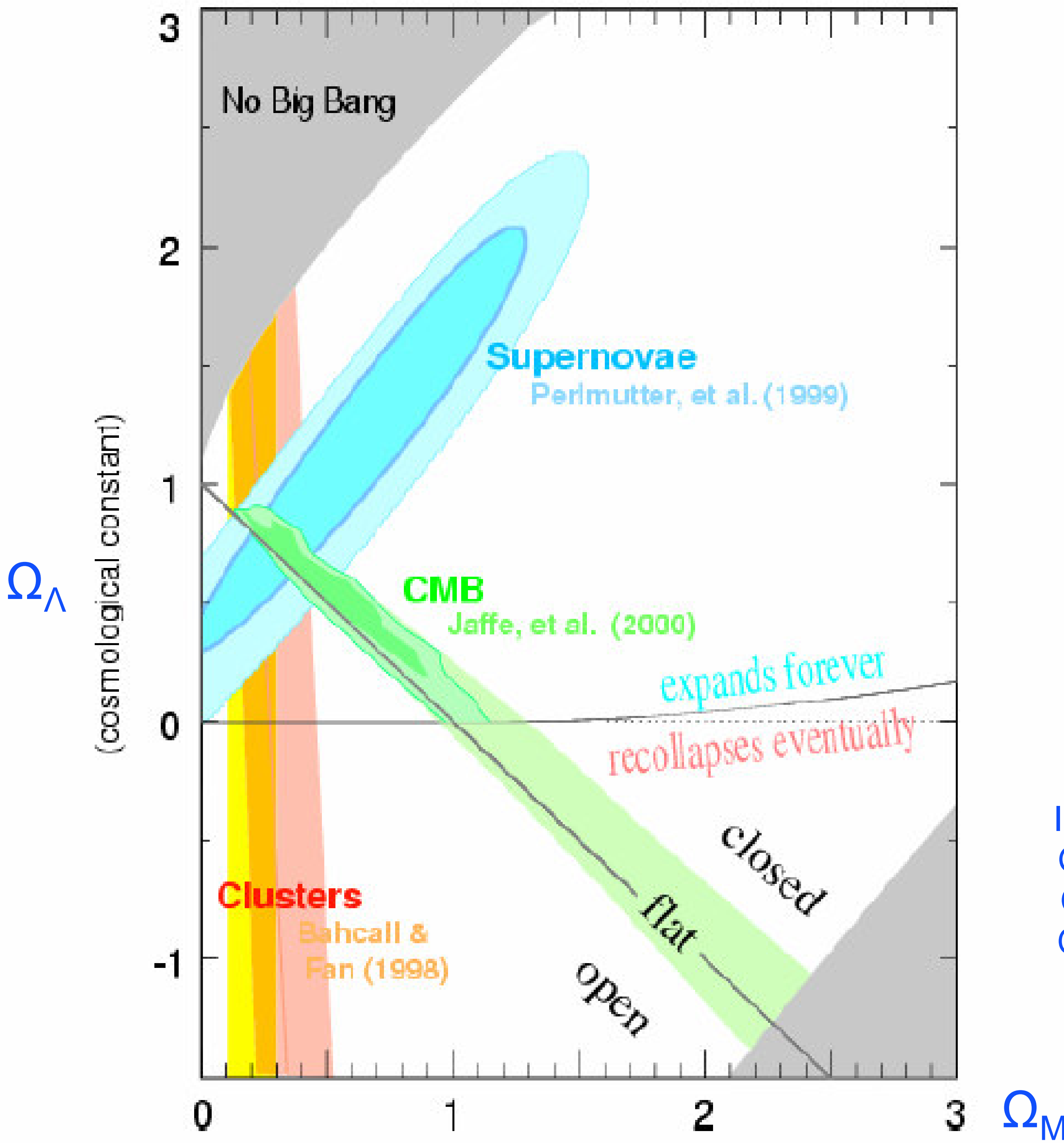
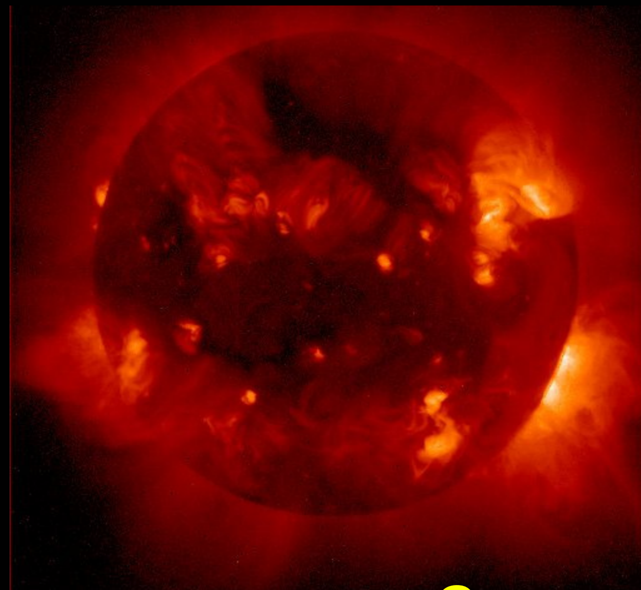



Image credit: Goobar, Intl. Cosmic Ray Conf. (2001)

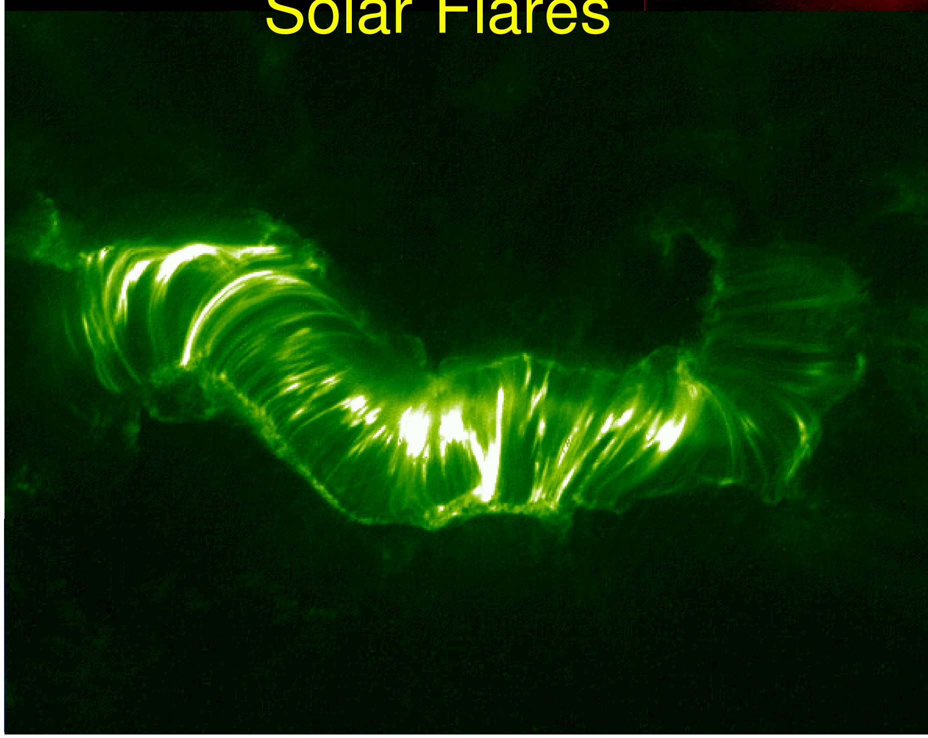
4. Closer to home …

Solar Magnetic Fields

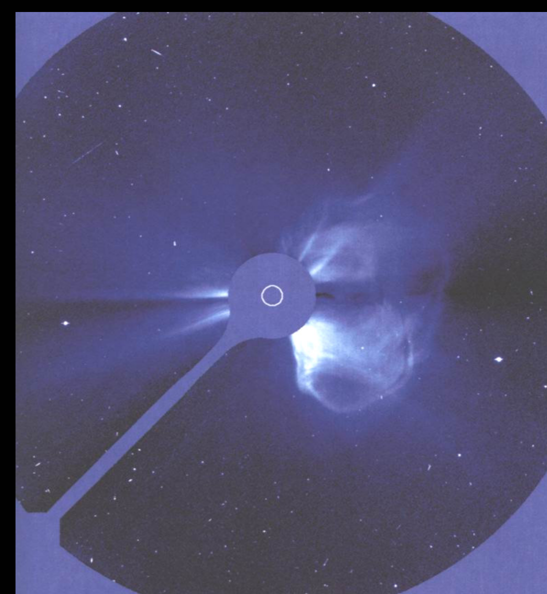


Solar storms!

Solar Flares

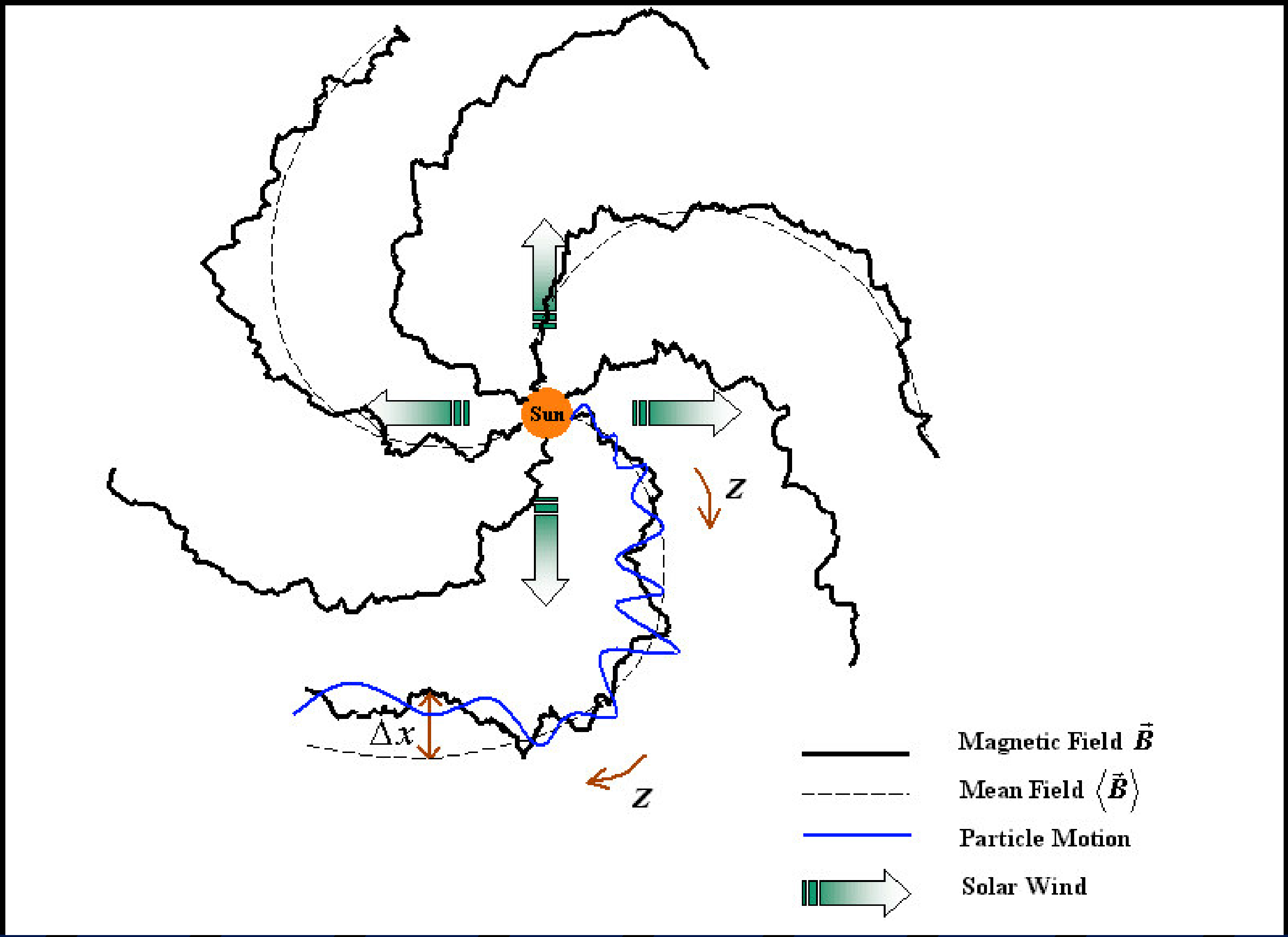


Coronal mass ejection(CME)



# Plasmas and magnetic fields in the inner solar system

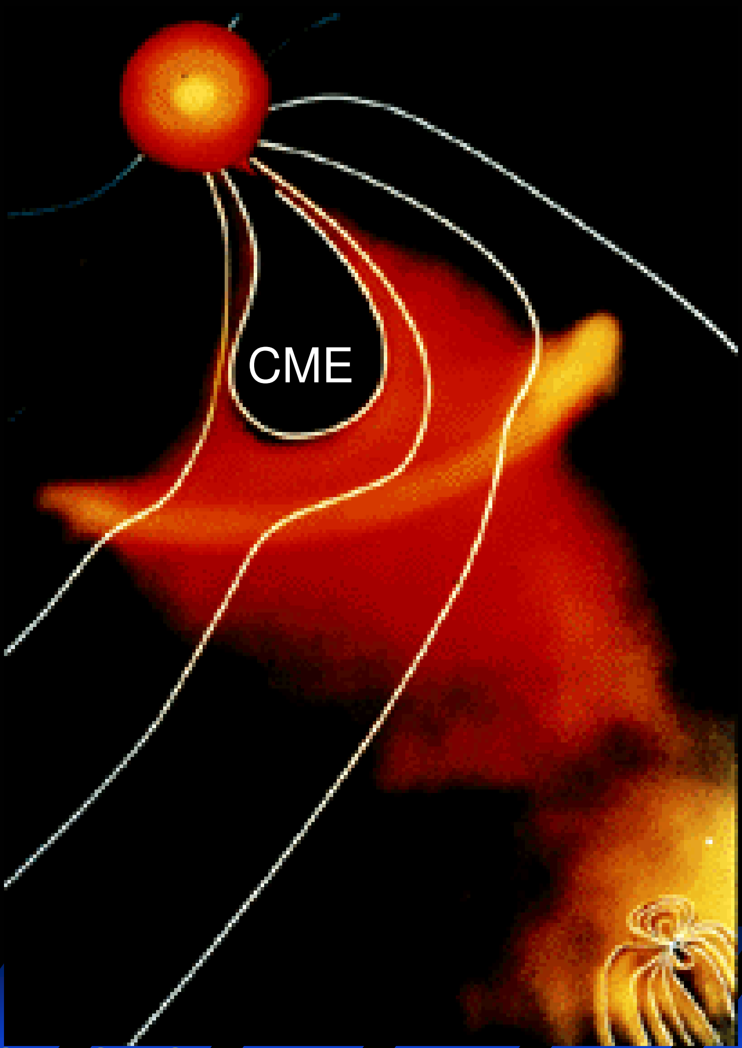




# CME (Coronal Mass Ejections)

- Distort magnetic fields and generate shocks
- <u>Accelerate particles at the shock</u>

  [DR, *Astrophys. J. Lett.*, **481,** L119 (1997)]
- Compress the Earth's magnetosphere



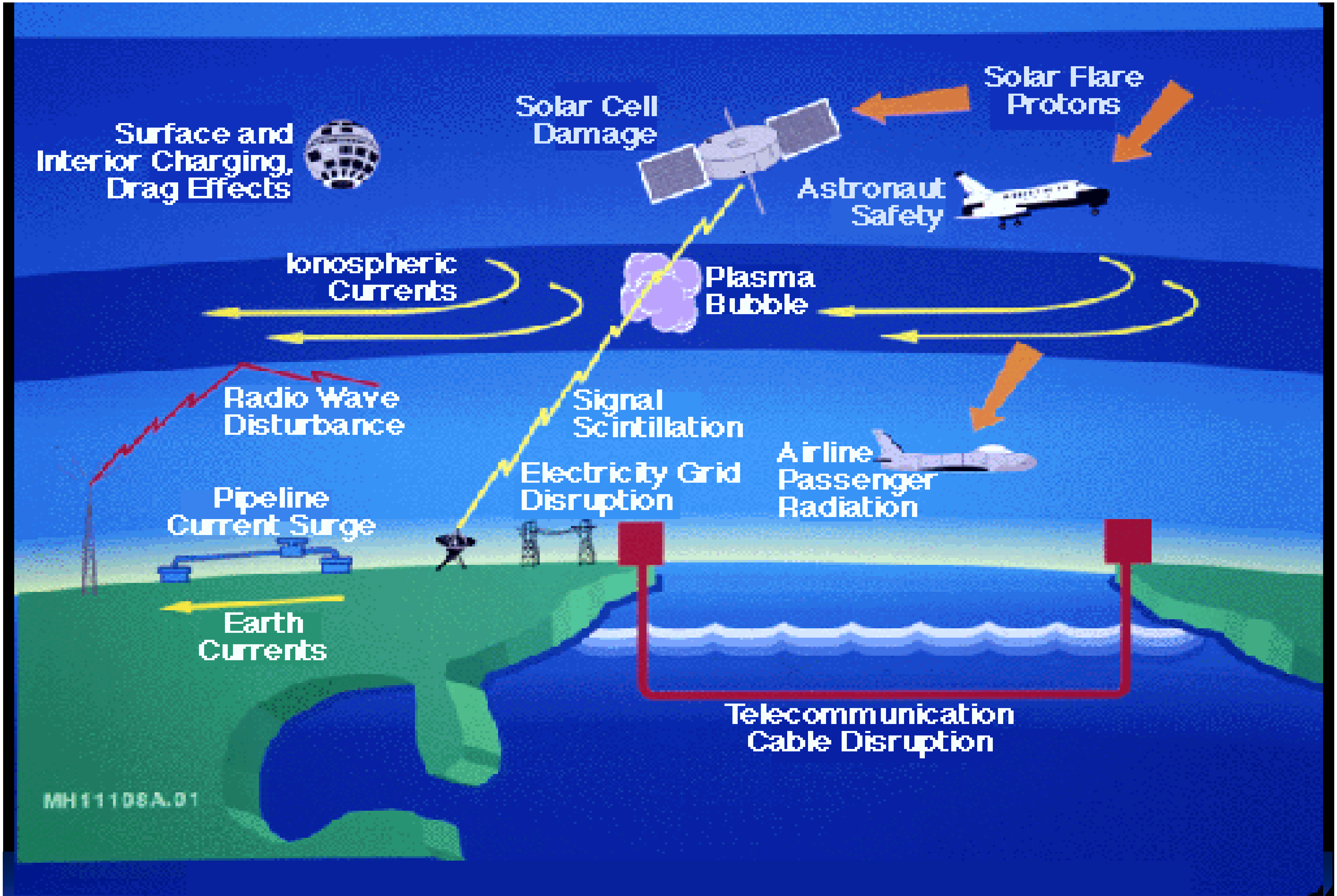
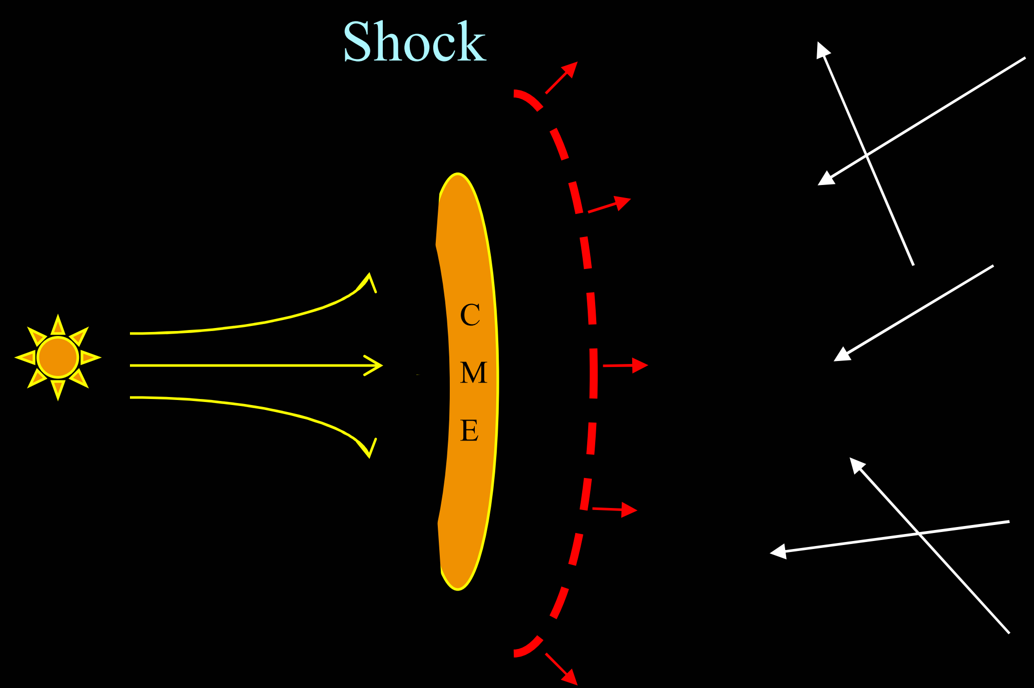



Image Credit: L. J. Lanzerotti, Bell Laboratories, Lucent Technologies, Inc.

# Shock Acceleration Theory $\longrightarrow$ Space Weather Forecasting !




GCR =
Galactic
Cosmic
Rays
(from outside
the solar
system)

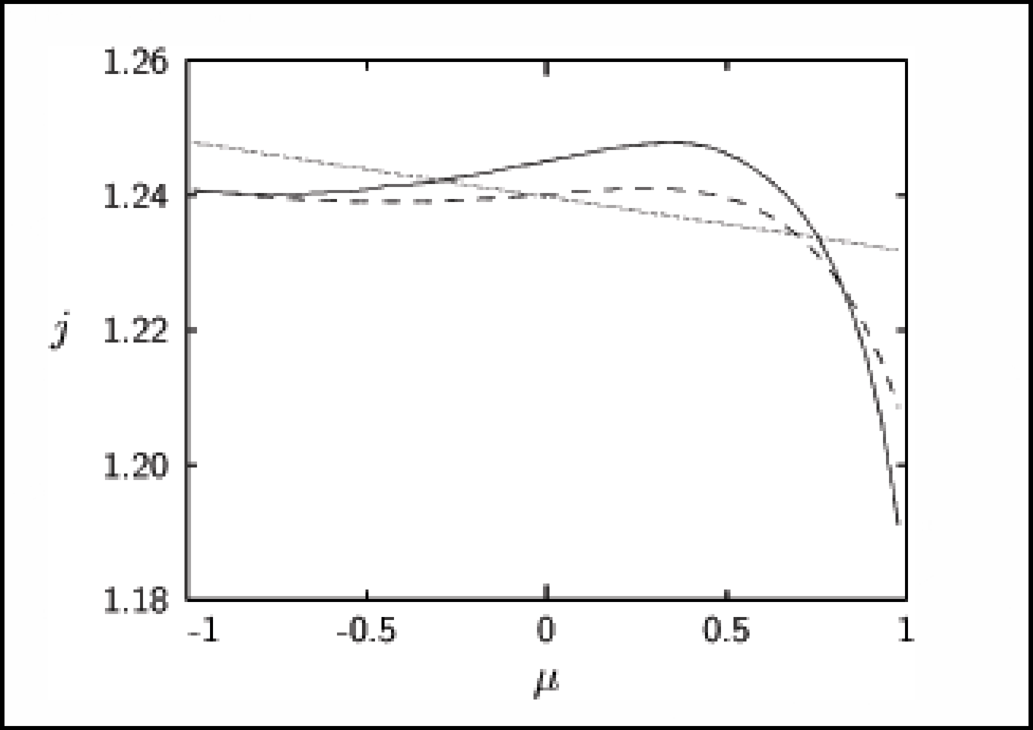
Inside (after the shock has passed)

fewer GCR

(most are reflected by the shock)

Outside (before the shock comes)

GCR in large numbers




motion toward Sun ⟵ μ=cos(θ) ⟶ motion away from Sun

Before the shock arrives at Earth,

observe that GCR decrease in outward directions.

We can provide advance warning of an approaching shock!

[Leerungnavarat, DR, and Bieber, *Astrophys. J.*, **593,** 587 (2003)]

# 5. Proposed collaboration with CERN

- Experimental High Energy Physics
- Very High Performance Computing (GRID)
- Engineering (e.g., quality control, management of large projects, sensor & magnet technology
- Nurturing Career Researchers in Experimental HEP