Astroparticle Physics

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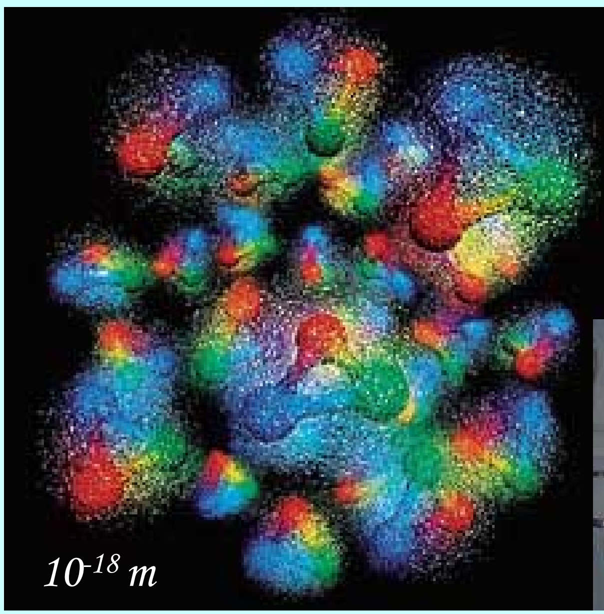
Astroparticle Physics

- The physics governing elementary particles is deeply connected to that governing the evolution of stars/galaxies/the universe

- Interface between Astrophysics and Particle Physics: one of the most exciting areas with many new discoveries in recent years



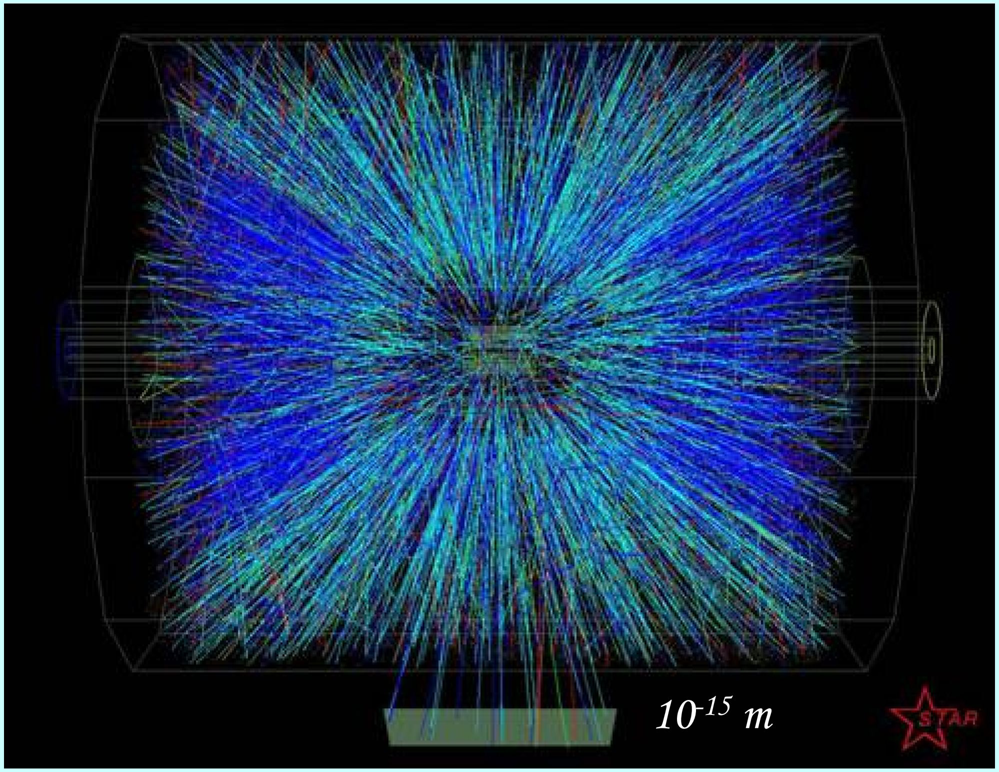
Cartoon showing the quarks inside nucleons *courtesy BNL*

Deep space showing galaxies

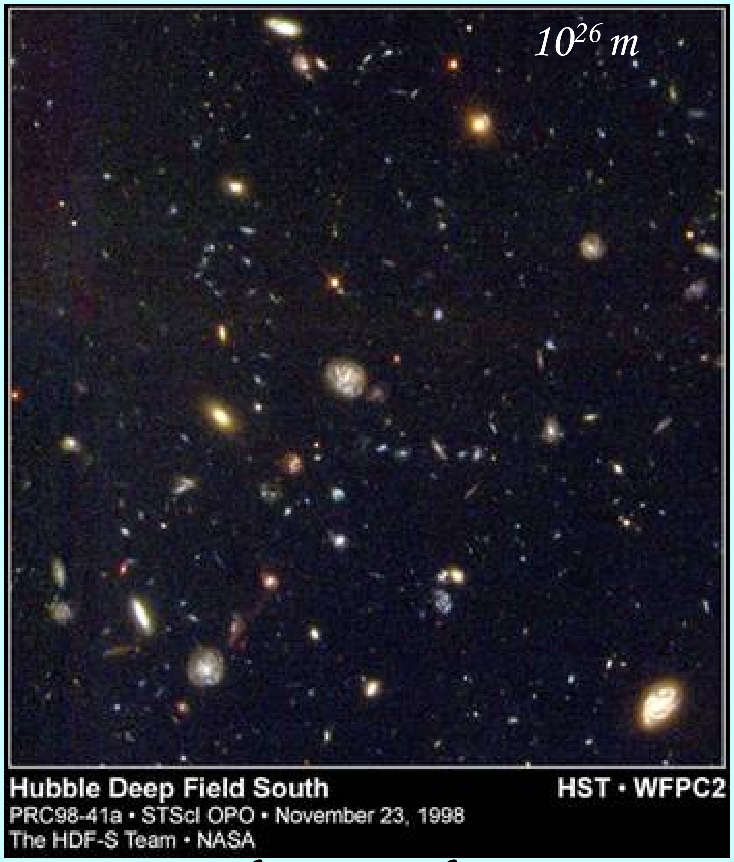
Photo courtesy NASA/STScI

Astroparticle Physics

- *Unification of forces → conditions at early universe, inflation, …*
- *Dark energy and dark matter → new particle experiments/theories*



Production of particles in accelerator *courtesy STAR/BNL*



Deep space showing galaxies

Photo courtesy NASA/STScI

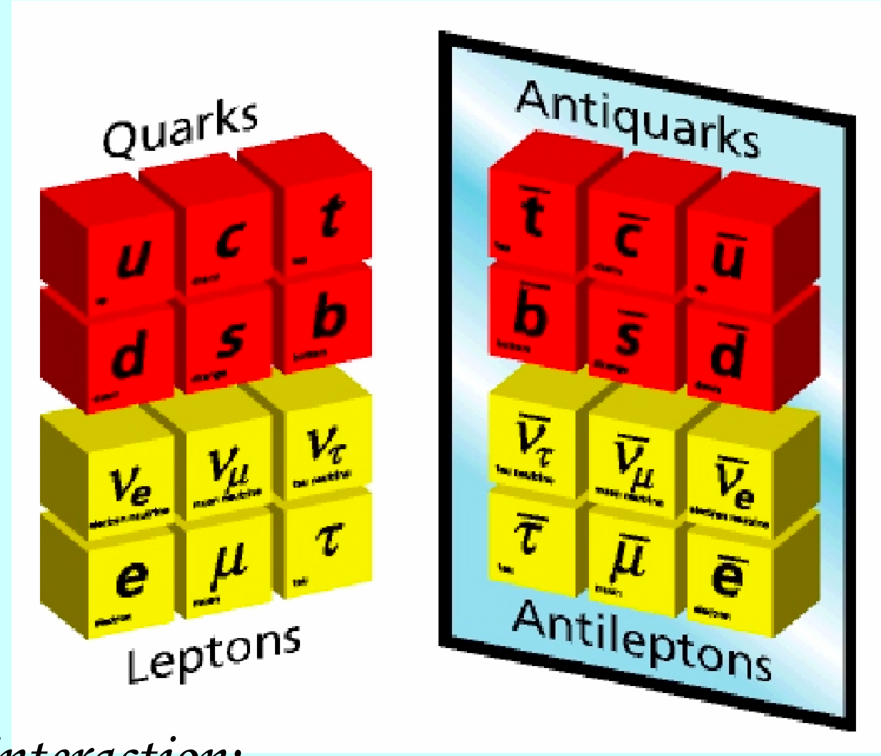
Astroparticle Physics

Two examples:

1. 3 ways to set quarks free – Big Bang, supernova, LHC
2. Dark matter – cosmological probes, direct detection, LHC, hybrid stars

Standard Model of Particle Physics

- *All matter are made up of quarks and leptons, which are elementary (point-like, structureless)*



- *Interactions (strong, weak, EM, gravity) are characterized by a set of fundamental constants*

- *strong, electroweak are unified as gauge interaction; gravity is still described by General Relativity*

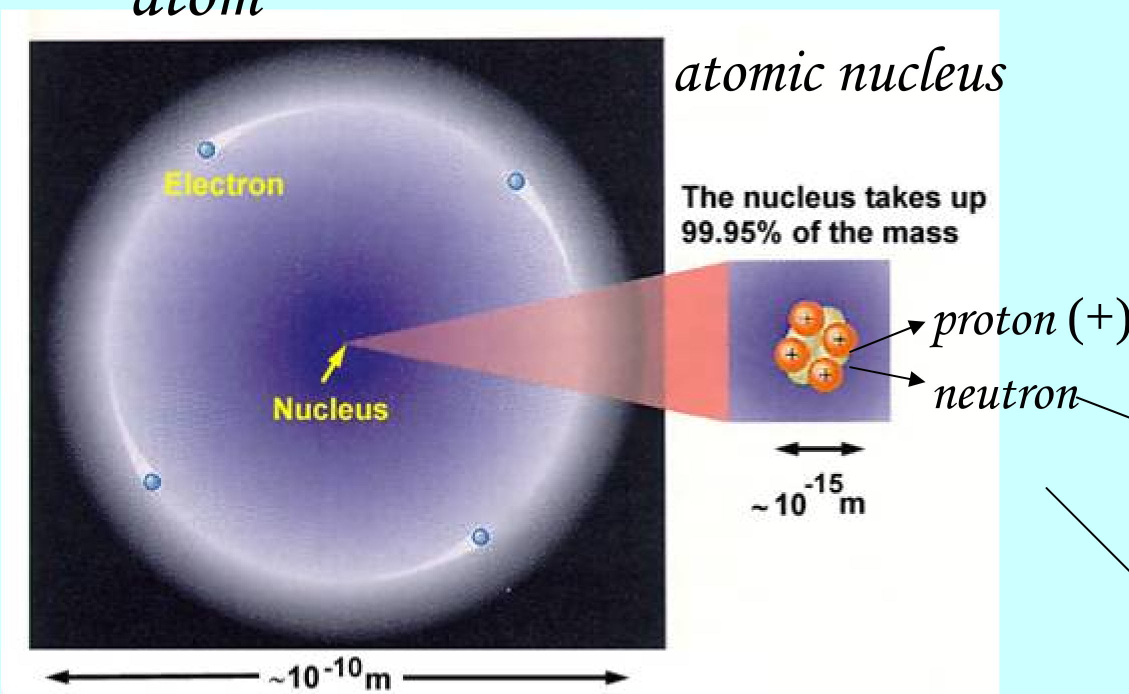
- *There are 3+1 space-time dimensions*

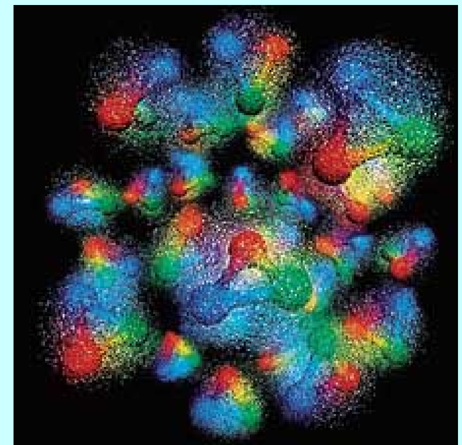
Quark Confinement

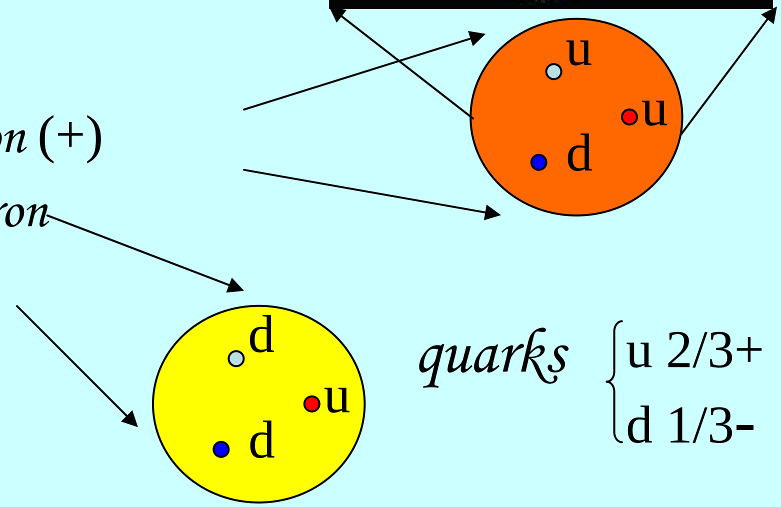
Strong interaction among quarks/gluons → tightly bound to form hadrons (eg. protons, neutrons)

*No free quarks → **permanent confinement?***

atom

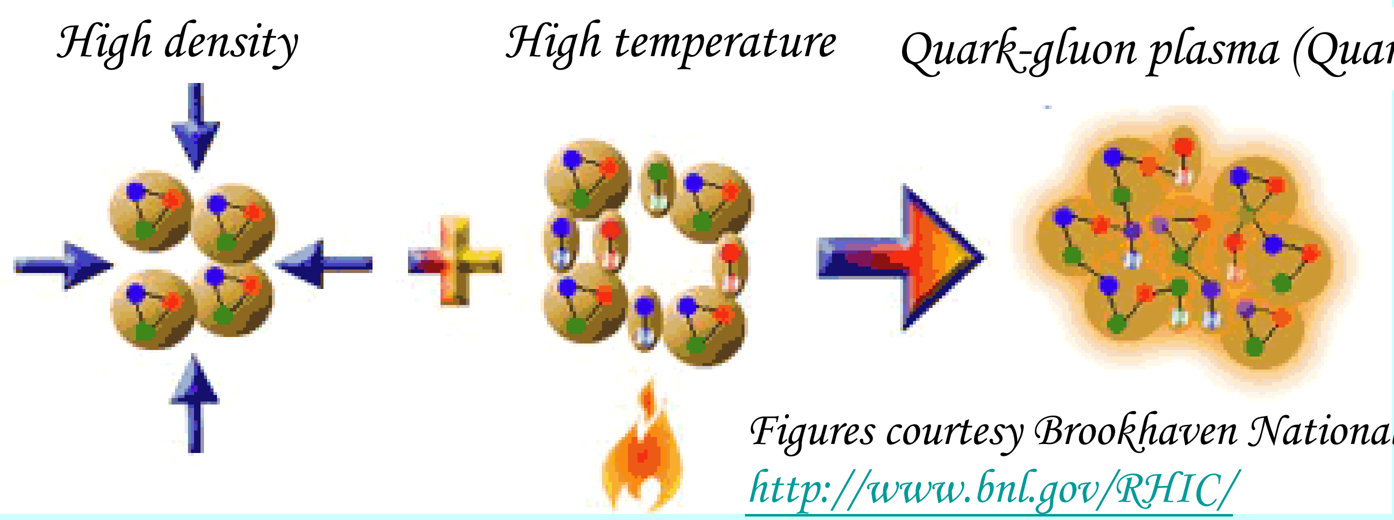






quarks {u 2/3+ ; d 1/3-

Quark Matter



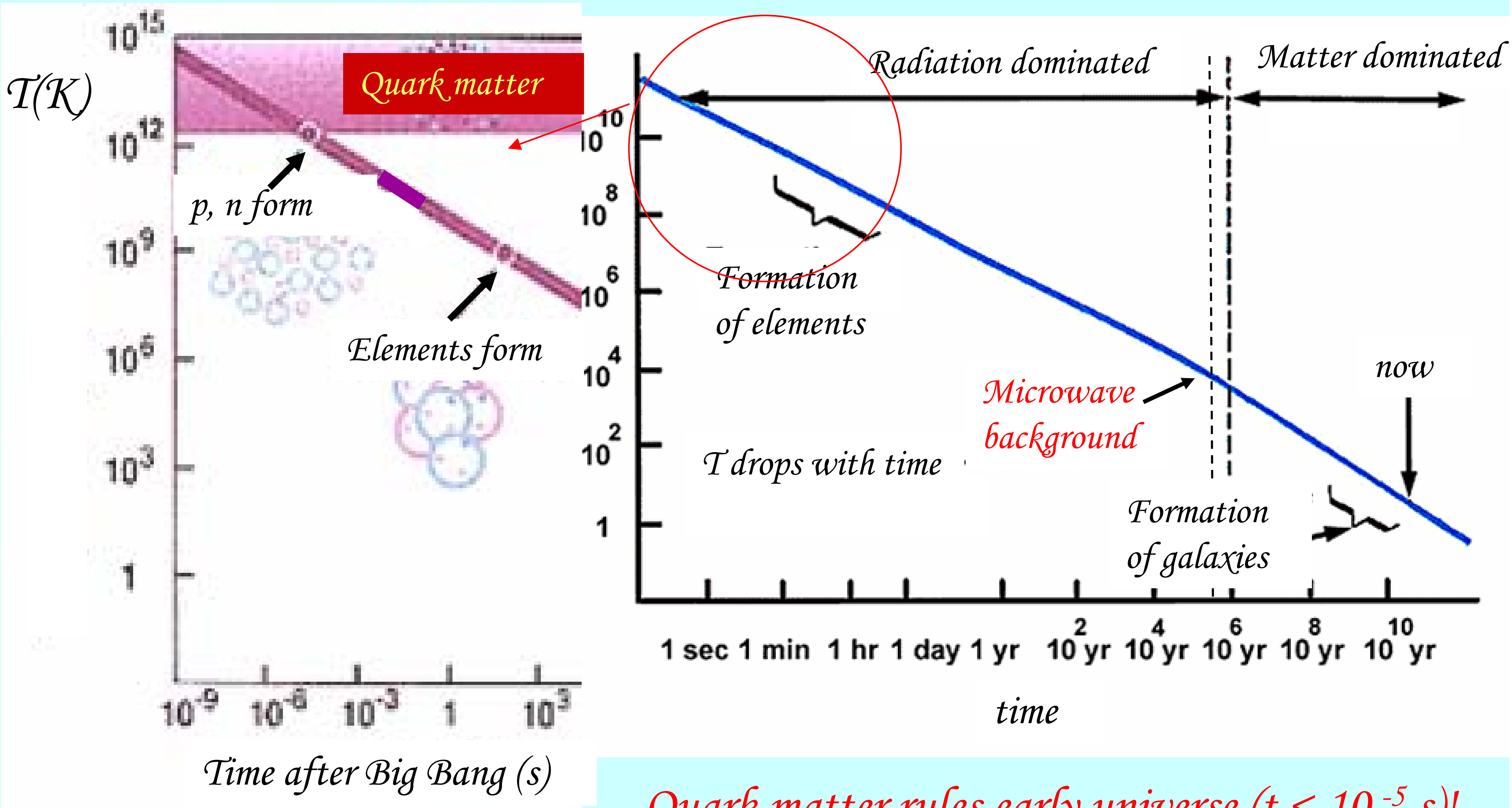
Figures courtesy Brookhaven National Lab
http://www.bnl.gov/RHIC/

- Quantum Chromodynamics (QCD): asymptotic freedom – quarks interact weakly when they are very close together!
- → high T/density: free quarks/gluons in a phase transition
- Analogy: water → steam $T_c \sim 10^{12}$ K!
- How to get that?

Prof. Frank Wilczek's Nobel Lecture:
http://nobelprize.org/nobel_prizes/physics/laureates/2004/wilczek-lecture.html

3 possible ways to release quarks:
Big Bang, Supernova, LHC

Hot Big Bang



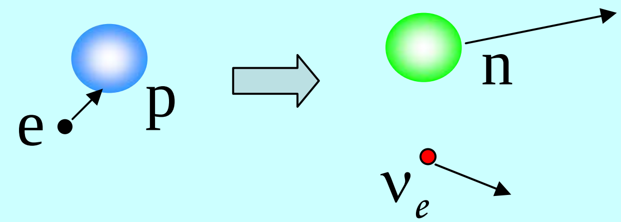
Quark matter rules early universe ($t < 10^{-5}$ s)!

Supernova (超新星)

- *Massive stars ($M > 3M_o$) die as supernovae*
- *As bright as 10^9 - 10^{10} x Sun. Releases 10^{46} J ~ 10^{12} yr of solar energy in days; T~ 10^{11} K!*

Animation courtesy Bryan Preston (STScI/AVL)

A dense core remains (~ 1.5 M_o, R ~ 10-100 km; $\rho \sim 10^{14}$ g/cc, nucleus density): neutron star?



- *~10% rest mass → neutrinos, carrying most energy → neutrino physics critical importance!*

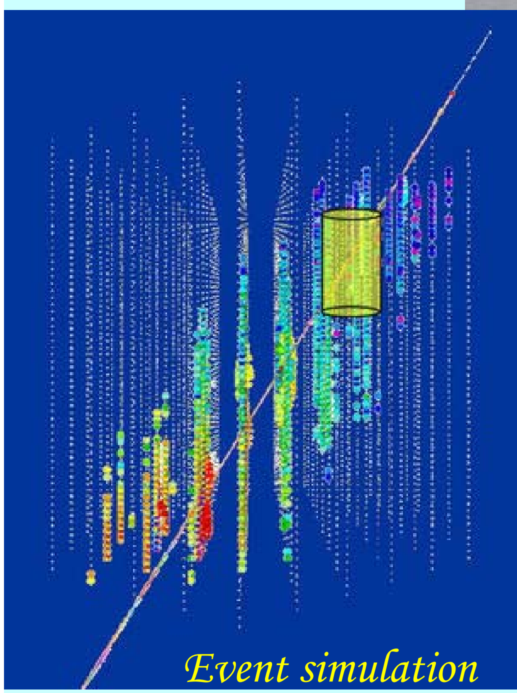
- *Supernova neutrinos: observed, new observational tool*

Neutrino Observatory

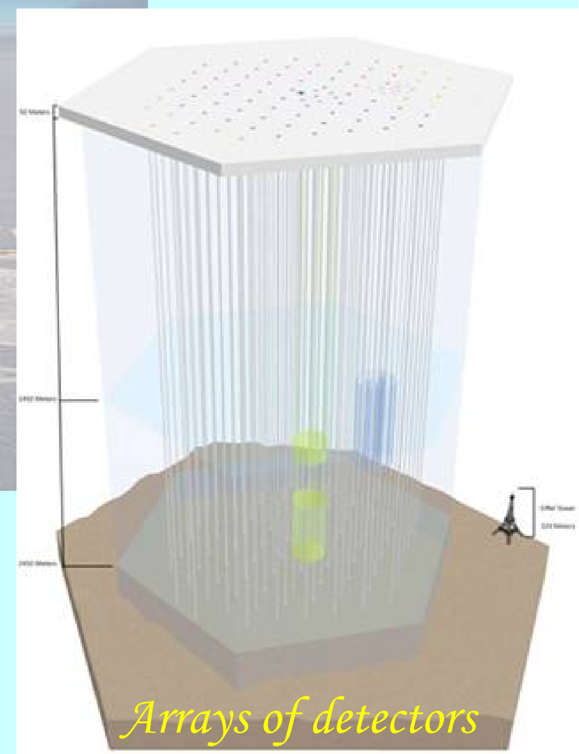
Eg. IceCube
http://icecube.wisc.edu/

A giant neutrino telescope in S. Pole


S. Pole

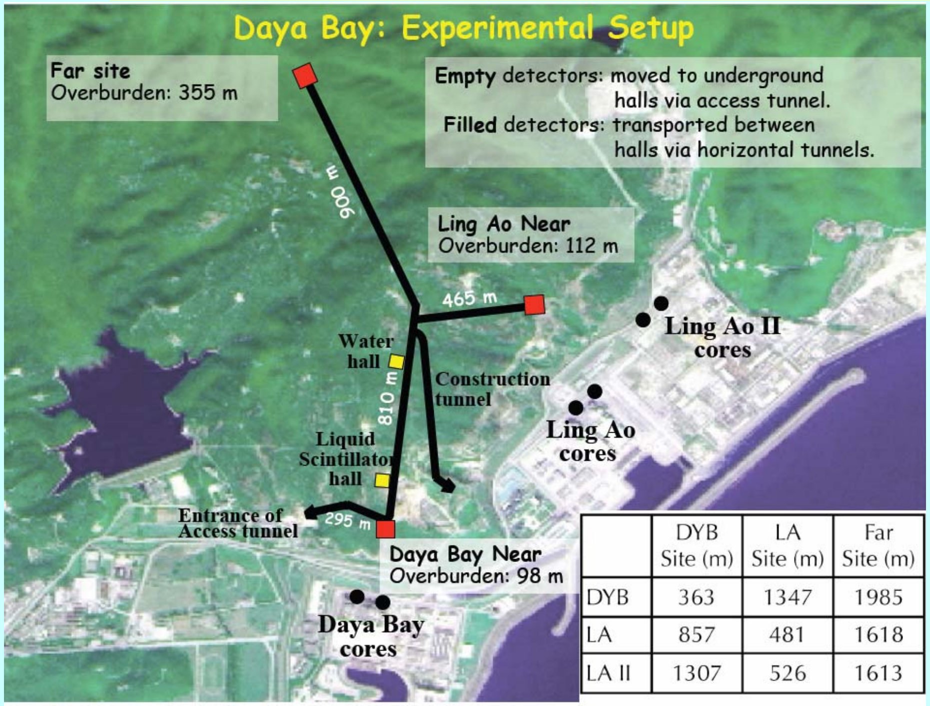

Event simulation


Detectors in drill hole


Arrays of detectors

Photos and illustrations from: http://gallery.icecube.wisc.edu/external/main.php

Neutrino (中微子) Physics



	DYB Site (m)	LA Site (m)	Far Site (m)
DYB	363	1347	1985
LA	857	481	1618
LA II	1307	526	1613

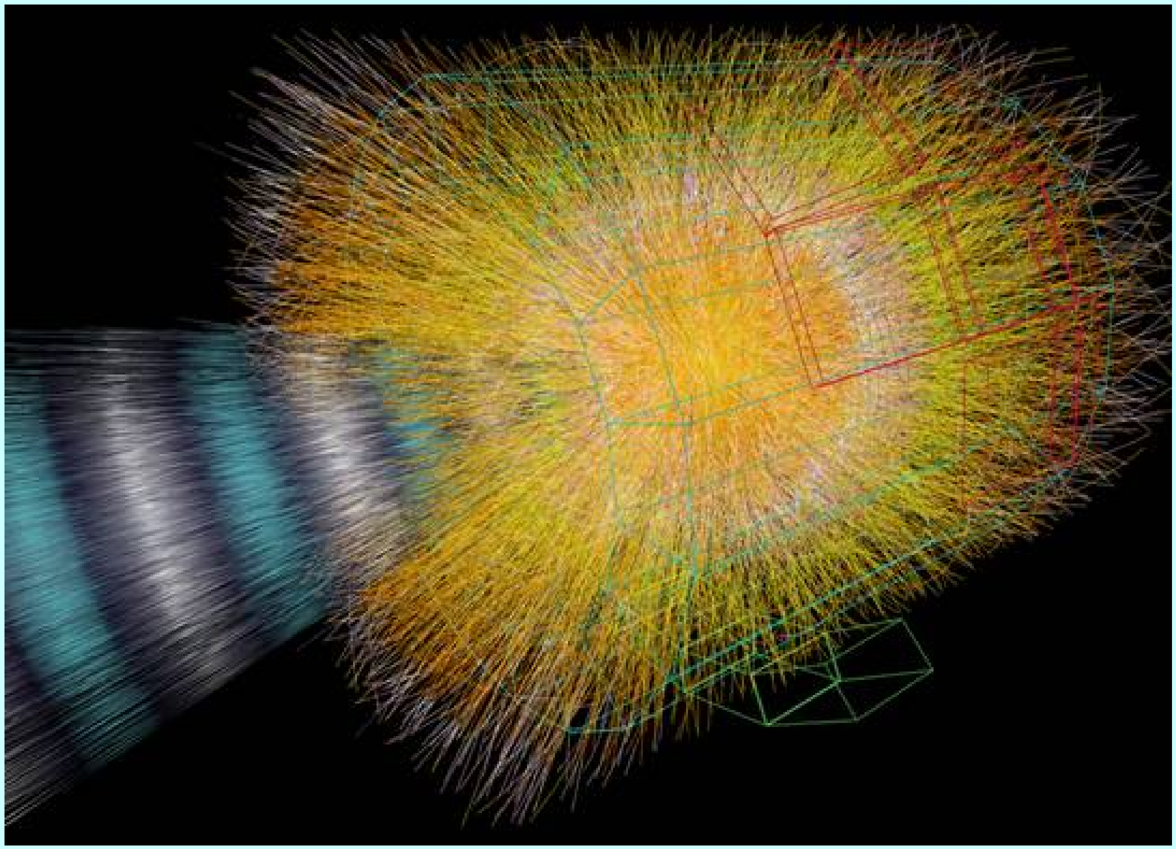
Daya Bay: 6 nuclear reactors = one of the most powerful neutrino sources in the world

CUHK team:

-Actively involved in the Daya Bay neutrino oscillation experiment

- study cosmic rays surface and underground

Lab recreation of quark matter



Simulation of detectors' view

Eg. ALICE in LHC: collisions of heavy ions to reach ~10^{12}K for 10^{-22}s

Mini-Bang

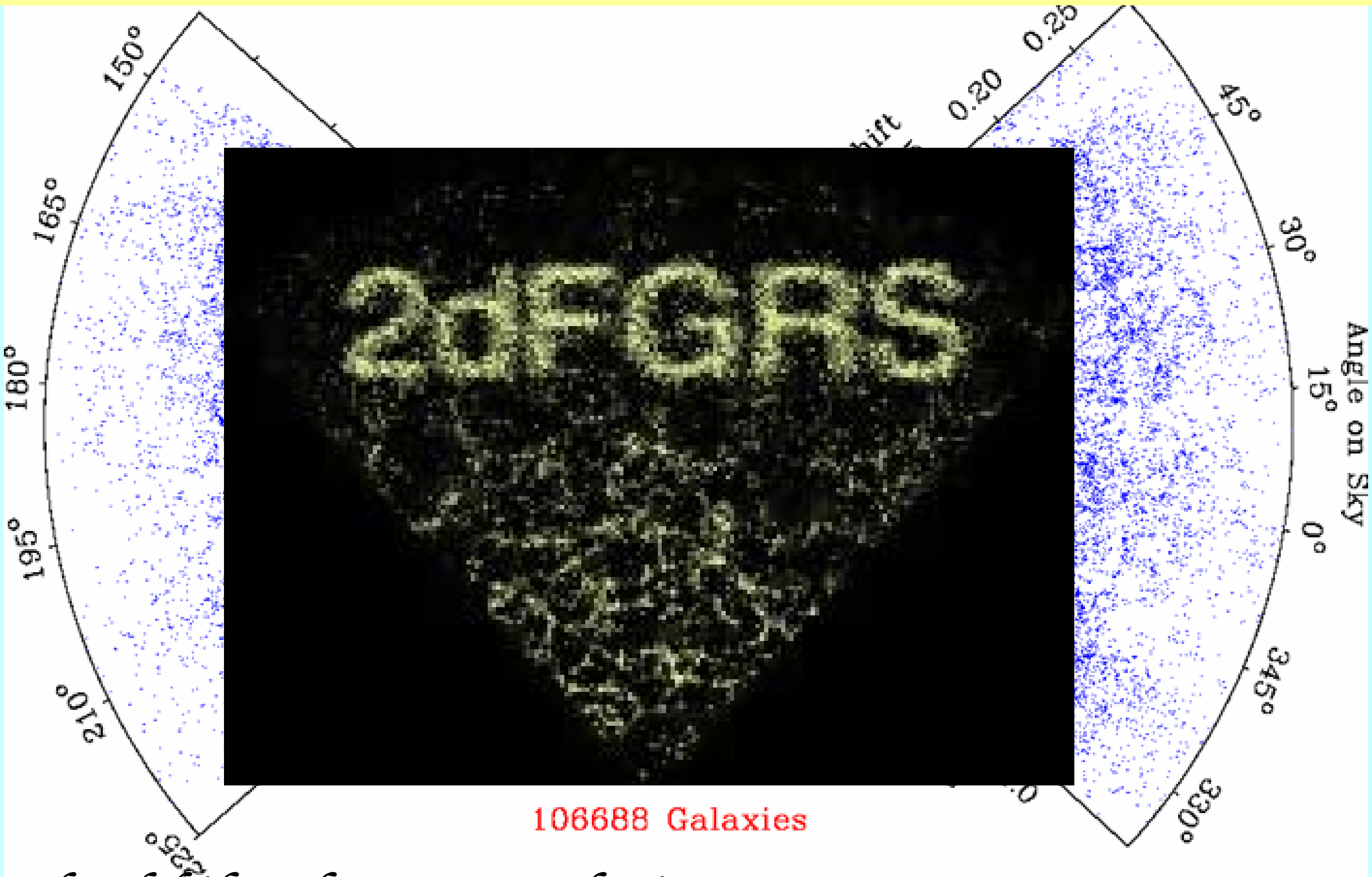
Downloaded from http://aliceinfo.cern.ch/Public/en/Chapter4/Chapter4_ForPress.html

2. Dark matter –cosmological probes, direct detection, LHC, hybrid stars

Dark Matter (暗物質)

- *Must have much more dark matter than normal matter (~ 5 times more)*
- *Enormous implications on evolution of the universe → look for their signatures in cosmological signals*
- *They should be all around us → direct detection*
- *Most candidates are massive undiscovered particles → need high energy to create them → LHC*
- *Our crazy idea: use stars as our detectors*

Large Scale Structure Survey



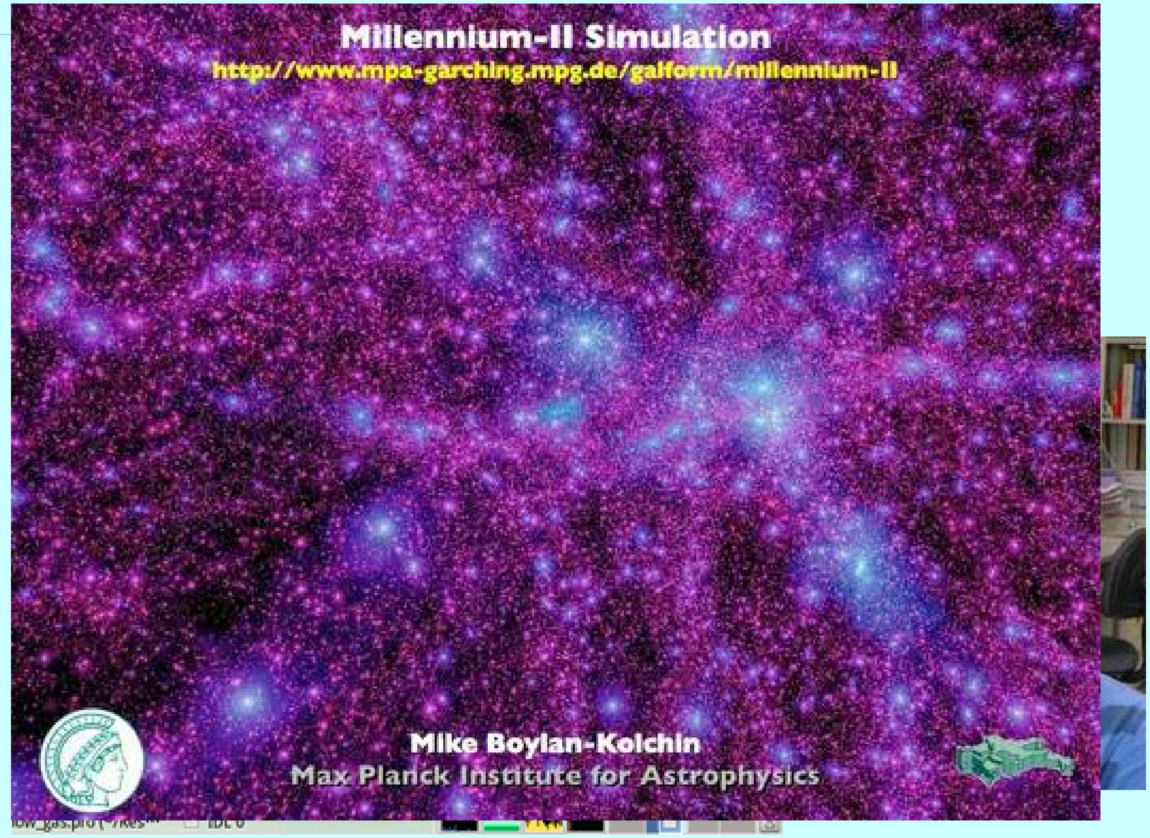
Obtained redshifts of 220,000 galaxies, 23,000 quasars → 3D map of how galaxies are distributed

Clustering of matter gives information on cosmological parameters, especially matter content [*http://www.aao.gov.au/2df/*](http://www.aao.gov.au/2df/)

Simulation of structure formation in the universe

Large scale simulation of how structures (galaxies, clusters, etc.) form → must have lots of dark matter! Eg. Millenium II Simulation: 10^{10} particles, > $2x10^7$ galaxies, $2x10^9$ l.y.s, standard cosmology (83% of matter is dark).

Dark matter properties are important for the evolution of the universe!



Structure formation animation by Cheng Dalong

Movie from Millenium simulation project
http://www.mpa-garching.mpg.de/galform/virgo/millennium/

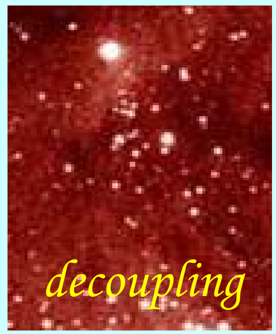
http://www.youtube.com/watch?v=W35SYkfdGtw&feature=related

CMB = Cosmic thermal radiation from 13.7 billion years ago

-At t ~ 400,000 years (decoupling), T ~ 3,000 K → mostly red light

-the universe has expanded by ~ 1,000 since then

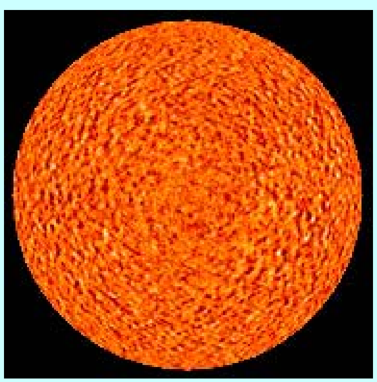
- red light (λ ~ 10^{-6} m) → microwave (λ ~ 10^{-3} m)



t

t ~ 0 | t ~ 400,000 yrs | today

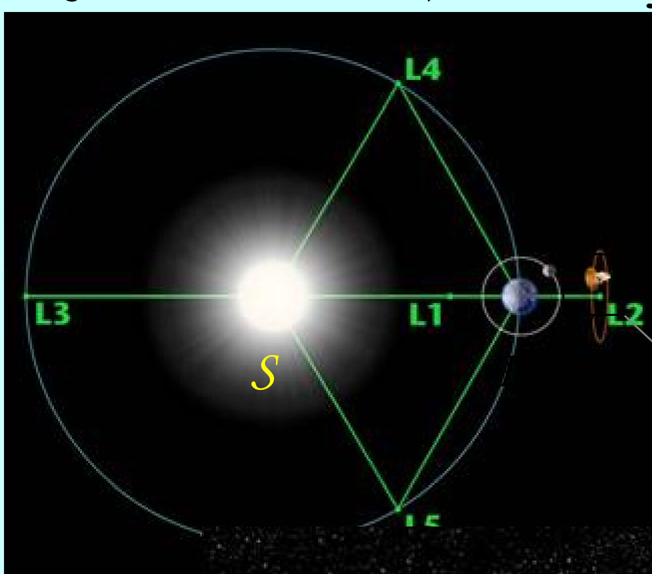
- fluctuations → physics of early universe!

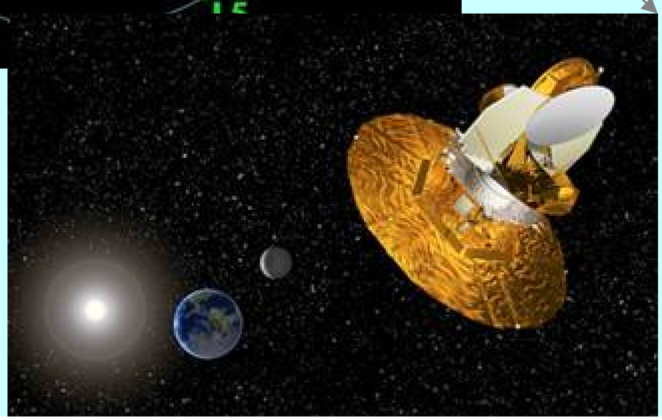


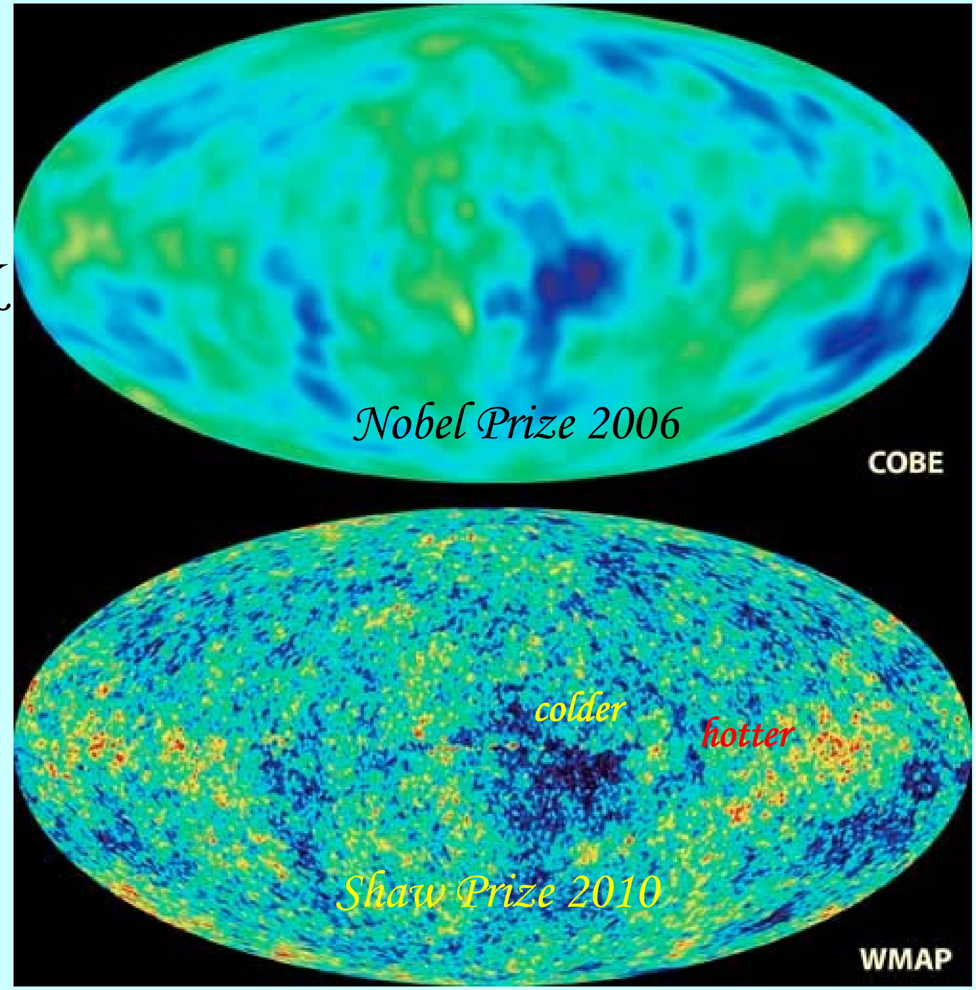
Study dark energy and dark matter properties via CMB fluctuation pattern

Wilkinson Microwave Anisotropy Probe

- *Launched 1/4/02, at L2 (~ 1.5×10^6 km from Earth)*
- *Collecting data since 12/02*
- *Resolution < 0.3^o ;sensitivity ~ 20 μK*







7-year data set released!

http://map.gsfc.nasa.gov/

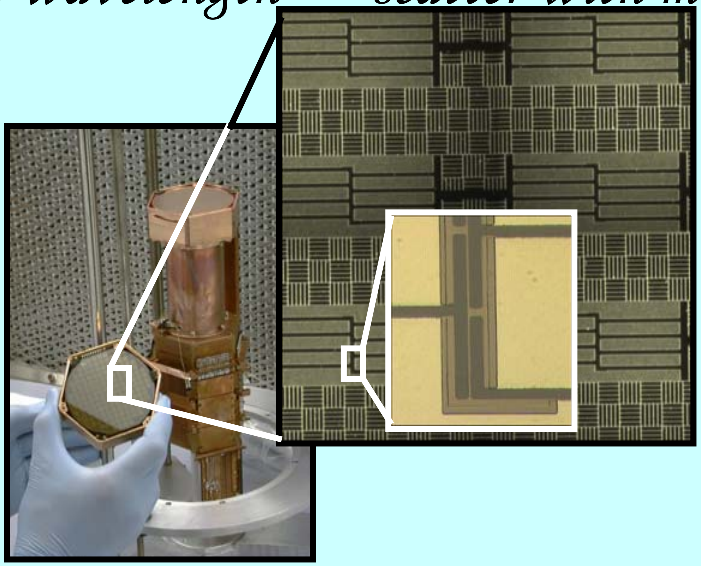
http://www.sciencemag.org/sciext/btoy2003/

Photos are from NASA/WMAP

Direct Search for Weakly Interacting Massive ParticleS

WIMPS: weak interaction → elastic scattering off nuclei in matter

- long de Broglie wavelength → scatter with many nucleons at once



→ Put a large and sensitive detector underground and monitor rare signals vs. time for years

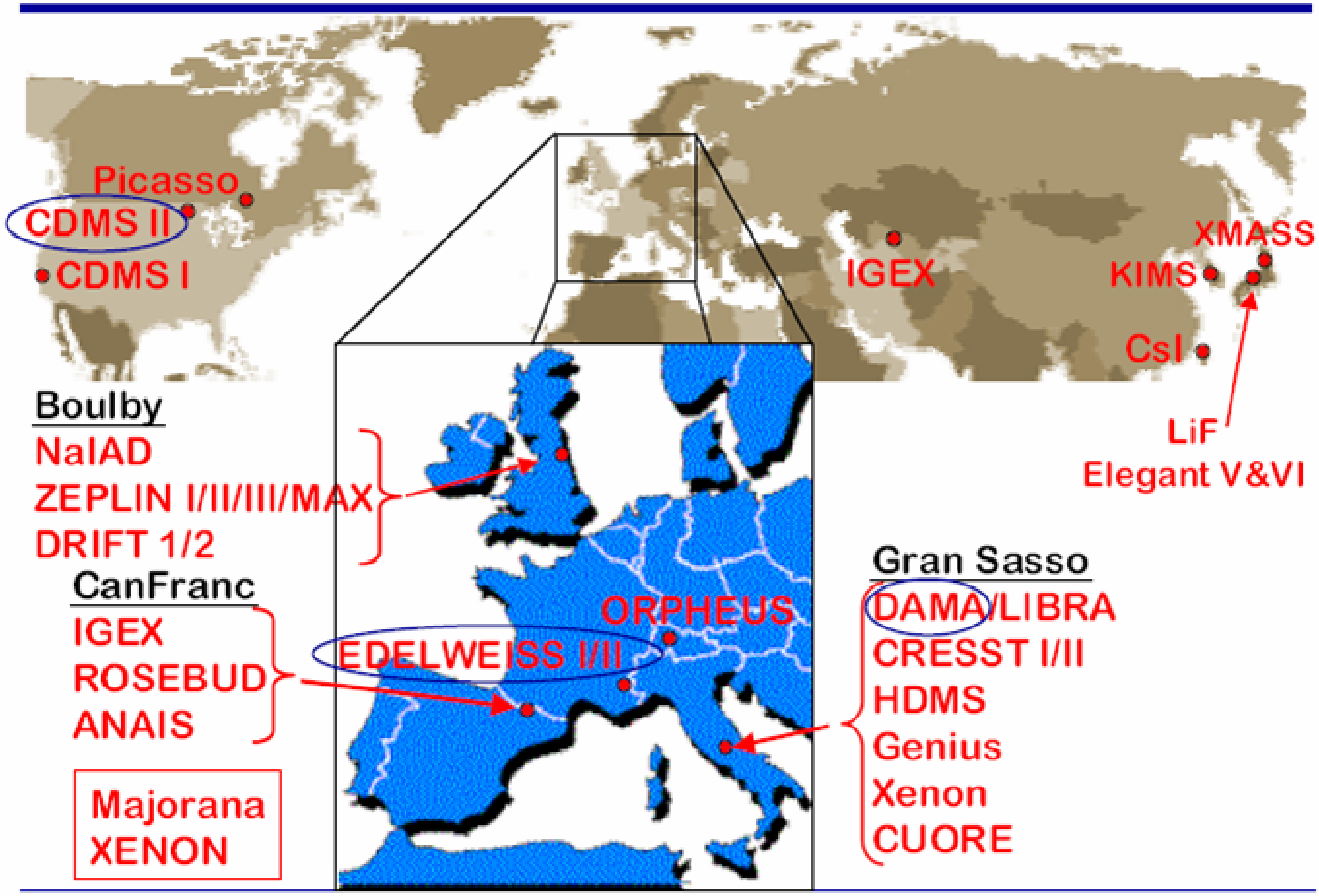
shield against cosmic rays

Our cosmic ray study in Aberdeen Tunnel will be useful!

There will be an underground lab in Sichuan. One in Hong Kong?

photo from CDMS: http://cdms.berkeley.edu/experiment.html

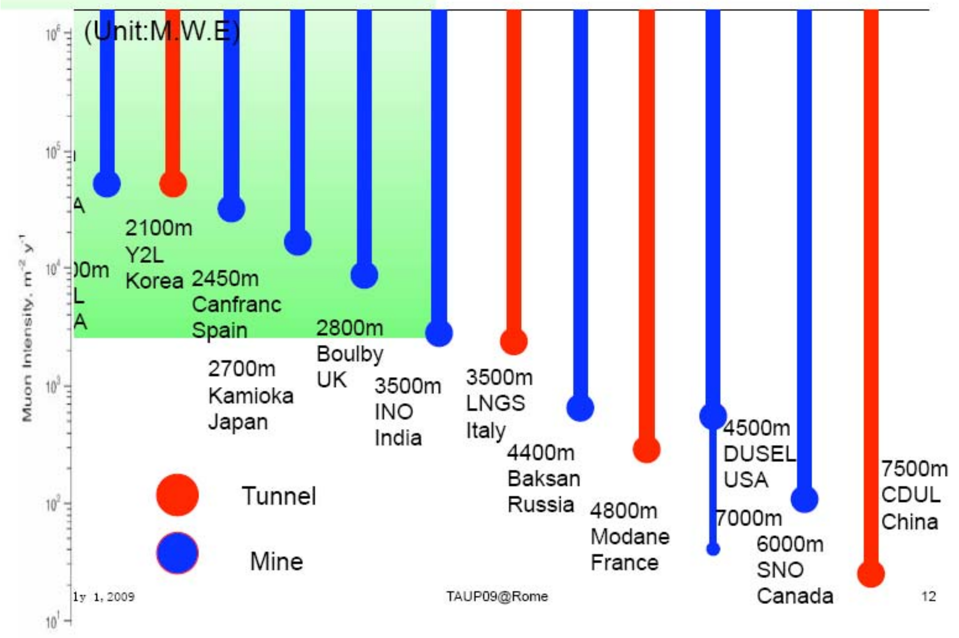
WIMP-detection Experiments Worldwide



From [*http://cdms.berkeley.edu/experiment.html*](http://cdms.berkeley.edu/experiment.html)

China Deep Underground Lab

Comparison of main ULs in the world



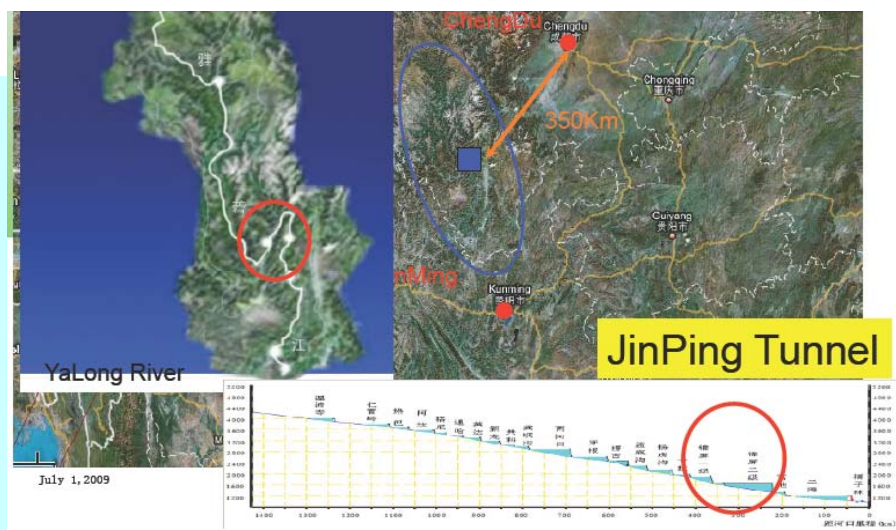
China Darkmatter EXperiment (CDEX)

J. P. Cheng, Z. Deng, D. Han, K.J. Kang, Y.J. Li, Y.L. Li, Y. Wang, Q.F. Wu, Q. Yue, Y.G. Yang, Z. Zhang
(Tsinghua University, THU)
K.X. Jing, C.J. Tang, Z.Y. Tang, H.Y. Xing, C. W. Yang, J.J. Zhu
(Sichuan University, SCU)
X.Q. Li, Y. Xu, C.X. Yu
(Nankai Univeristy,NKU)
K.J. Dong, X.C. Ruan, Z.Y. Zhou
(China Institute of Atomic Energy, CIAE)
J. Li
(Institute of Hign Energy Physics, IHEP)
Y.H. Chen, B.M. Shen, J.M. Wang, S.Y. Wu, X.H. Zeng
(Ertan Hydropower Development Company, EHDC)
K.M. Cheung, S.C. Lee
(National Tsinghua University, NTHU)

H.T. Wang (TEXONO Collaboration)

S.K. Kim (KIMS Collaboration) PI

July 1, 2009 TAUP09@Rome 19



Taken from Qian Yue's talk:
http://taup2009.lngs.infn.it/slides/jul1/yue.pdf

LHC production of supersymmetric (SUSY) partners

A popular theory: supersymmetric partners (超對稱粒子)
eg: fermionic partner of photons/gluons = neutralino, m ~ 100 GeV – 1 TeV, weakly interacting, stable

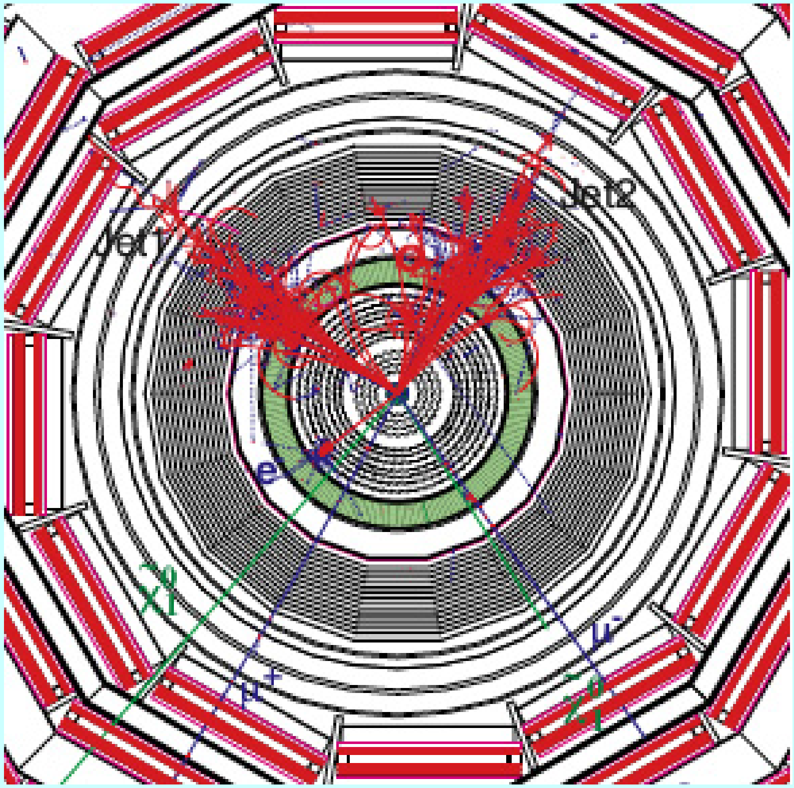
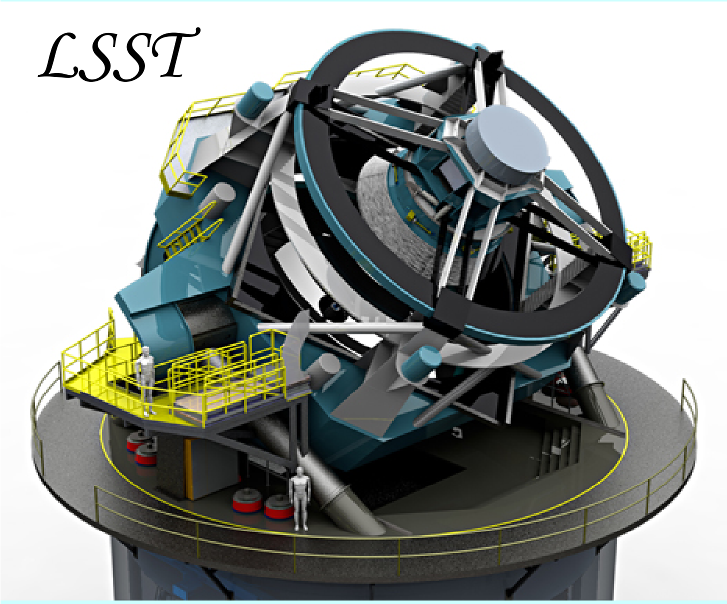


Illustration downloaded from CMS website
http://cms.web.cern.ch/cms/Physics/Supersymmetry/CMS.html

Search for missing energy/momentum

Eg.: 2 stable SUSY particles (X) leaving the detector

Dark Matter (暗物質)



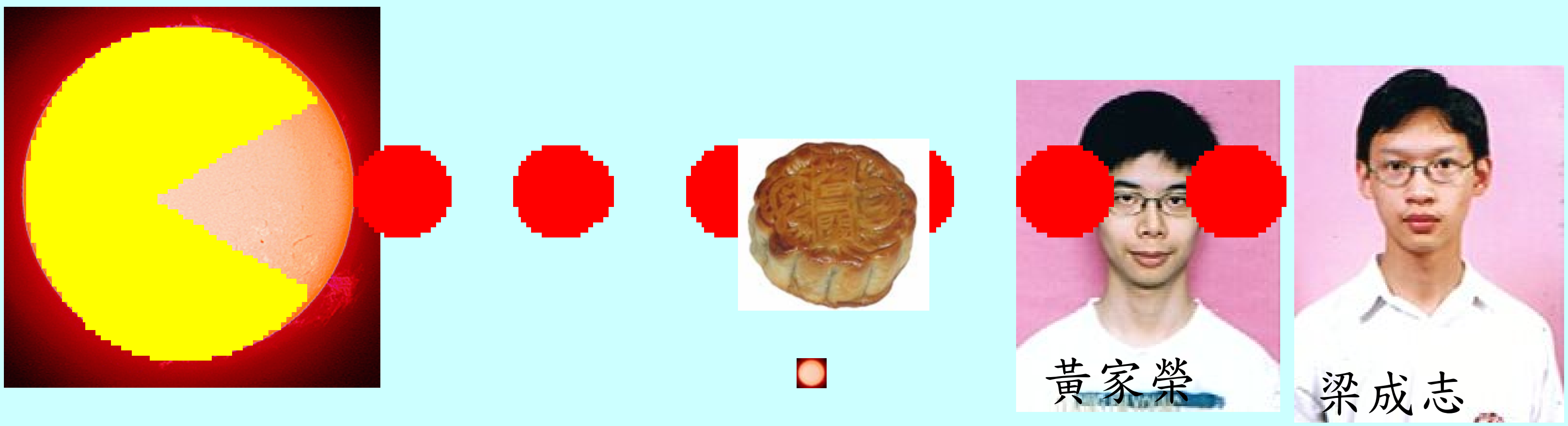
Drawing from LSST: http://www.lsst.org/lsst

Photo from ATLAS: http://est-div-lea-at.web.cern.ch/est-div-lea-at/atlas_lhcpicturesAERIAL.htm

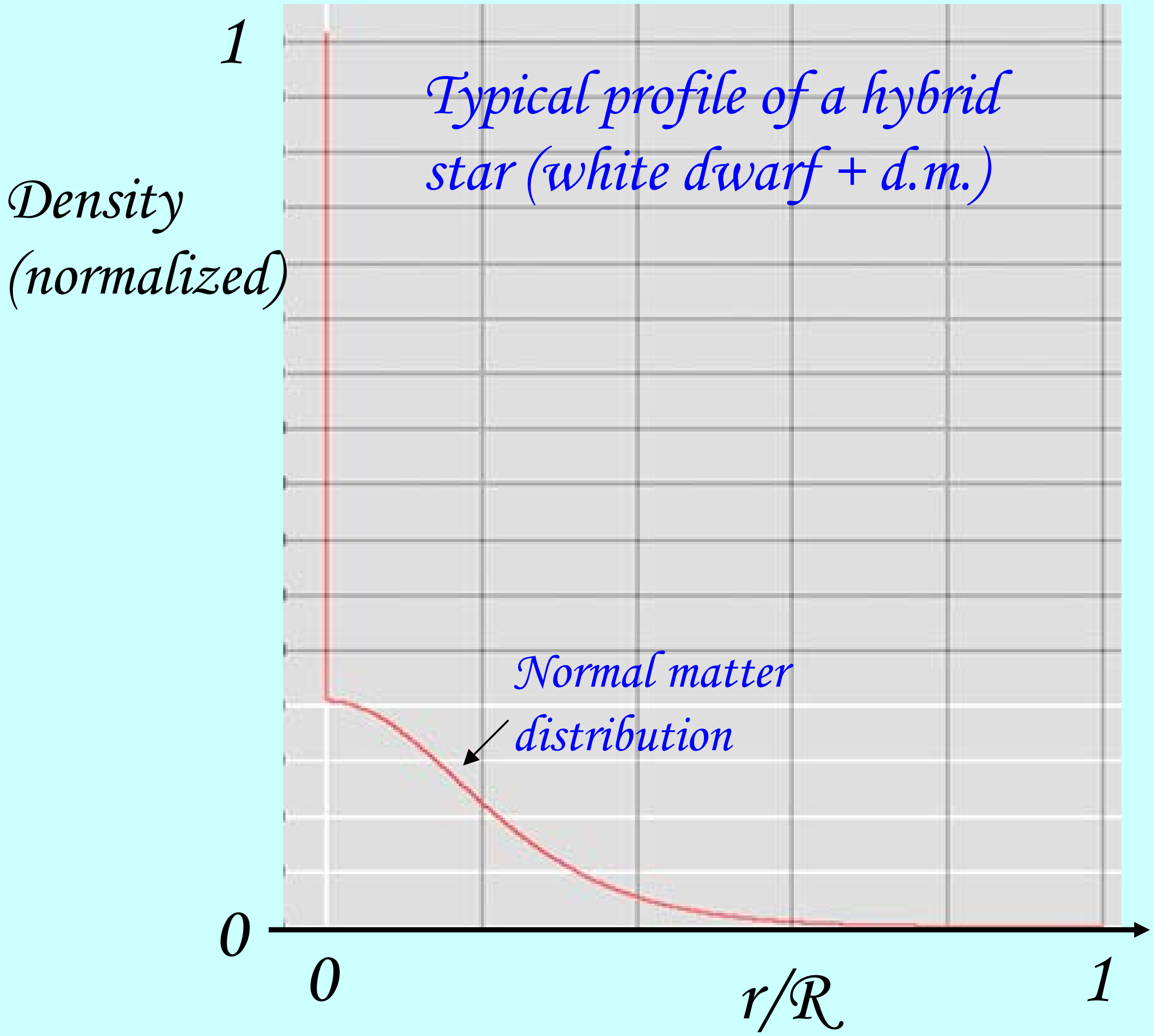
From CDMS: http://cdms.berkeley.edu

CUHK Hybrid stars

What happens if a white dwarf /neutron star 'eats' up some dark matter (d.m.)?



Hybrid stars

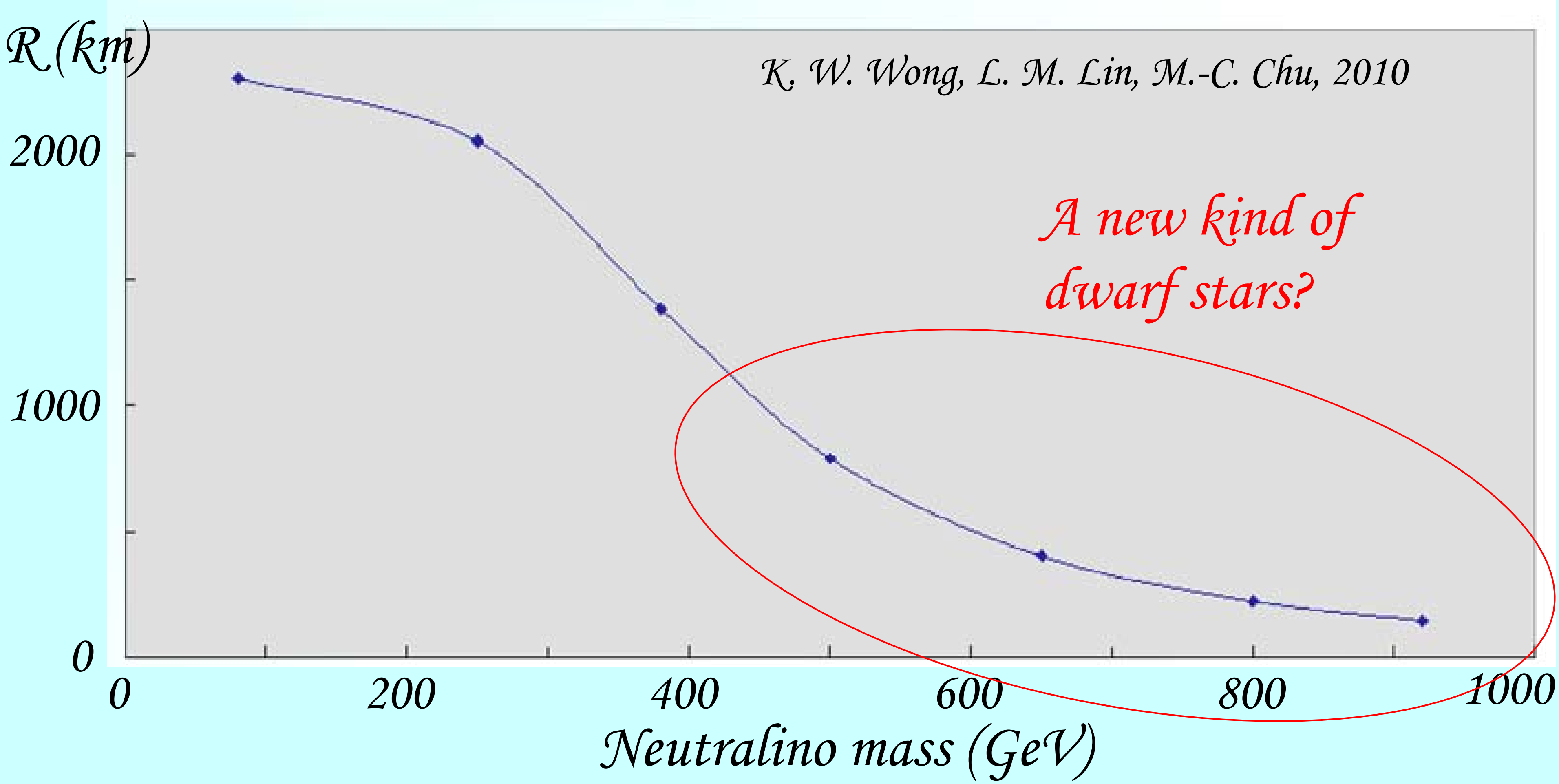


- Take neutralinos as dark matter (m ~ 10-1000 GeV)
- d.m. dominates core density: $10^{15} – 10^{24}$ g/cc
- d.m. concentrates within 1cm – 10m
- d.m. distorts the normal matter if total mass exceeds a critical value: the entire white dwarf becomes much smaller (100's km)!

K. W. Wong, L. M. Lin, M.-C. Chu, 2010

Hybrid stars

Radius of hybrid star vs. d.m. particle mass for total mass = 1.23 M_o, dark matter mass $2x10^{-7}$ M_o



Summary

Astroparticle Physics = Extreme science!

- astro/cosmological objects: natural labs with extreme conditions

Eg. white dwarfs: average density ~ 10^6 g/cc; neutron stars: 10^{14} g/cc;

Early universe: > 10^{10}K at t <1s. Universe today: density ~ 10^{-30} g/cc

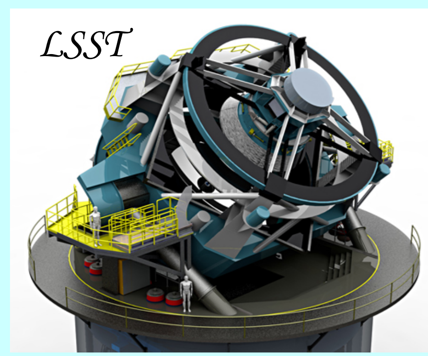
- Stretching to the extremes → stringent tests of, new insights in particle physics theories

- many particle physics experiments: astrophysics/cosmology in the lab

Still ahead: Many exciting discoveries and mysteries! Tons of new data!

From CDMS:

From underground to outer space!



Drawing from LSST:

PLANCK

Astroparticle Physics

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