Osservatorio Astronomico di Trieste , INAF, ITALY

A Generalized Equation of State for Dark Energy

Zhu, Zong-Hong

朱，宗　宏

(zhuzh@bnu.edu.cn)

Beijing Normal University, Beijing 100875, China

北京　师范　大学，　北京　100875，
中国

&

J.S. Alcaniz, E.M. Barboza, R. Silva

Introductio
n

The universe acceleration and DE：

The most important discovery in recent 10 years

北京師範大學 BEIJING NORMAL UNIVERSITY

- 1998：Two USA groups discovered the universe acceleration via SNeIa.
- 2003：WMAP、SDSS and more SNeIa verified the discovery.
- **2006：Leading scientists of the two SNe group won Shaw Prize.**
- **2007: Leading scientists of the two SNe group won Gruber Prize.**

The universe acceleration and DE：

Leading to public interests

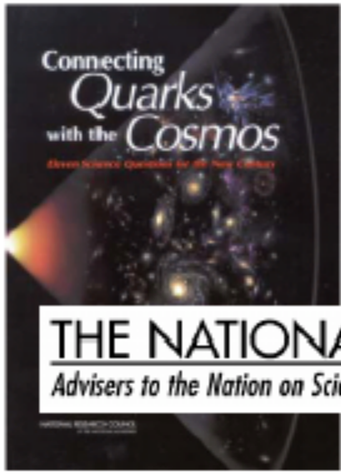
The universe acceleration and DE：

Ranked as a top issue in physics and astronomy

北京师范大学 BEIJING NORMAL UNIVERSITY

BOARD ON PHYSICS AND ASTRONOMY

The advances made by physicists in understanding the deepest inner workings of matter, space and time and by astronomers in understanding the universe as a whole as well as the objects within it have brought these fields together in new ways. The questions now being asked about the universe at its two extremes-the very large and the very small-are inextricably intertwined. The Committee on the Physics of the Universe (CPU) was convened in recognition of the deep connections that exist between quarks and the cosmos.



THE NATIONAL ACADEMIES
Advisers to the Nation on Science, Engineering, and Medicine

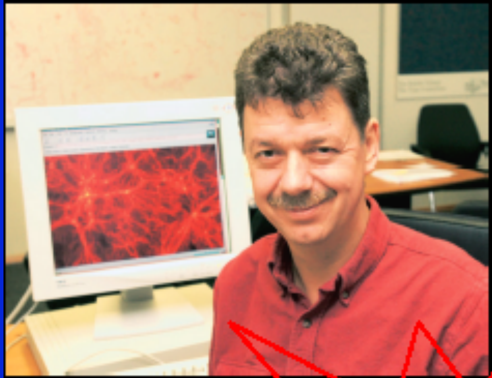
In framing this report, we have seized on eleven particularly direct questions that encapsulate most of the physics and astrophysics we discuss. They do not cover all of these fields, but rather focus on the interface between them. They are also questions that we have a good chance of answering in the next decade, or should be thinking about answering in following decades. The eleven questions are these:

- *What is the dark matter?* 暗物质
- *What is the nature of the dark energy?* 暗能量
- *How did the universe begin?* 宇宙初始条件
- *Did Einstein have the last word on gravity?* 引力性质
- *What are the masses of the neutrinos, and how have they shaped the evolution of the universe?* 中微子质量
- *How do cosmic accelerators work and what are they accelerating?*
- *Are protons unstable?*
- *Are there new states of matter at exceedingly high density and temperature?*
- *Are there additional spacetime dimensions?*
- *How were the elements from iron to uranium made?*
- *Is a new theory of matter and light needed at the highest energies?*

The universe acceleration and DE:

Leading to debates among academia

北京師範大學 BEIJING NORMAL UNIVERSITY

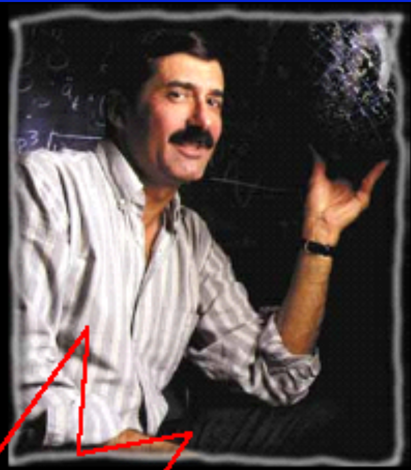


Dark energy is **bad** for astronomy

Fundamentalist physics: why Dark Energy is bad for Astronomy

Simon D.M. White

ArXiv:0704.2291



Dark energy can be **good** **for astronomy**

A Thousand Invisible Cords Binding Astronomy and High-Energy Physics

Rocky Kolb

ArXiv:0708.1199

The universe acceleration and DE:

One of the 3 biggest puzzles in modern astrophysics

BEIJING NORMAL UNIVERSITY

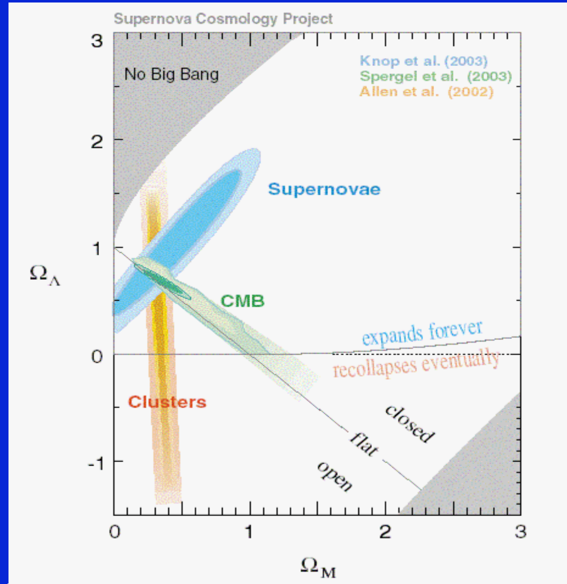
General Relativity: $\frac{\ddot{R}}{R} = -\frac{4}{3}\pi G(\rho + \underline{3P})$

$$\frac{\ddot{R}}{R} = -\frac{4}{3}\pi G(\rho_m + \rho_{DE} + 3P_m + 3P_{DE})$$

($3P_m \to 0$)

$$\ddot{R} > 0 \Leftrightarrow P_{DE} < -\frac{1}{3}(\rho_m + \rho_{DE})$$

$$P_{DE} < 0\ !$$



What powered the Big Bang?

What happens at the edge of a black hole?

What is dark energy

The universe acceleration and DE:

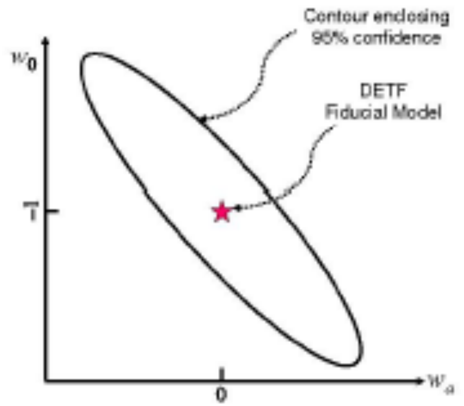
The central problem is to determine EoS, $w \equiv p/\rho$

北京师范大学 BEIJING NORMAL UNIVERSITY

Dark Energy Task Force (DETF report: astro-ph/0609591)

The Dark Energy Task Force (DETF) was established by the Astronomy and Astrophysics Advisory Committee (AAAC) and the High Energy Physics Advisory Panel (HEPAP) as a joint sub-committee to advise the Department of Energy, the National Aeronautics and Space Administration, and the National Science Foundation on future dark energy research.

- **Investigating into two major tasks**
- **Does w deviate from -1?**
- **Is w evolving?**



The DETF figure of merit is defined as the reciprocal of the area of the error ellipse in the w_0–w_a plane that encloses the 95% C.L. contour. (We show in the Technical Appendix that the area enclosed in the w_0–w_a plane is the same as the area enclosed in the w_p–w_a plane.)

$w \equiv p/\rho$

The DETF figure of merit is the reciprocal of the area of the error ellipse enclosing the 95% confidence limit in the w_0–w_a plane. Larger figure of merit indicates greater accuracy.

Three approaches to find w(z) from observations

- To solve the scalar field equation
- To build w(z) in terms of w_0 & $w' \equiv dw/d\ln a$
  - $w(z)=w_0+w_{p1}z$; $w_0+w_{p2}\ln(1+z)$; $w_0+w_{p3}z/(1+z)$
- Parameter-free approach
  - Binned EoS; Decomposition into orthognal basis; ......

To determine EoS：previous results

- **Assuming a constant w and withdraw the constraint ω>-1.**
- **Data：angular diameter of compact radio source and X-ray gas mass fraction of galaxy clusters.**
- **Conclusion：ω<-1！**

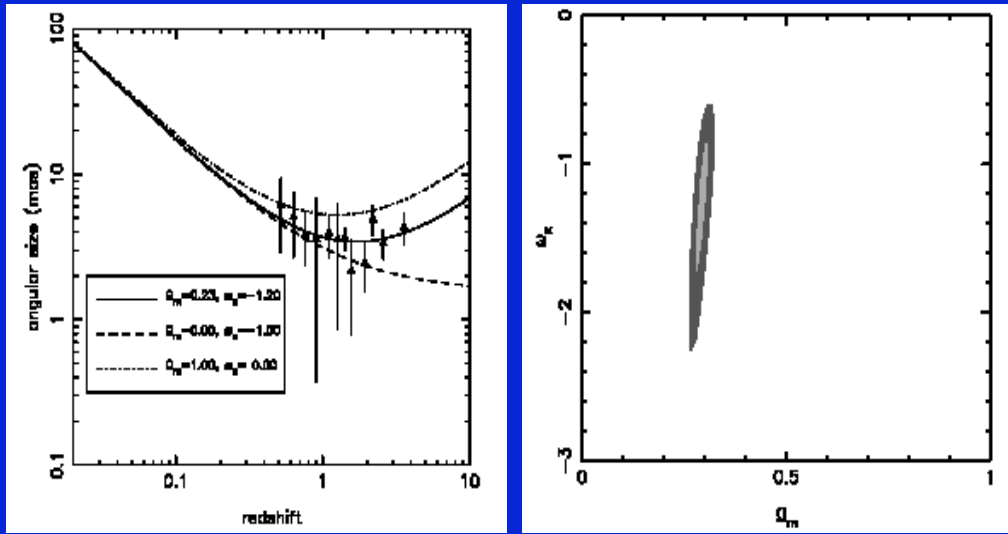
DE model with w cross -1

◆**ICG model**

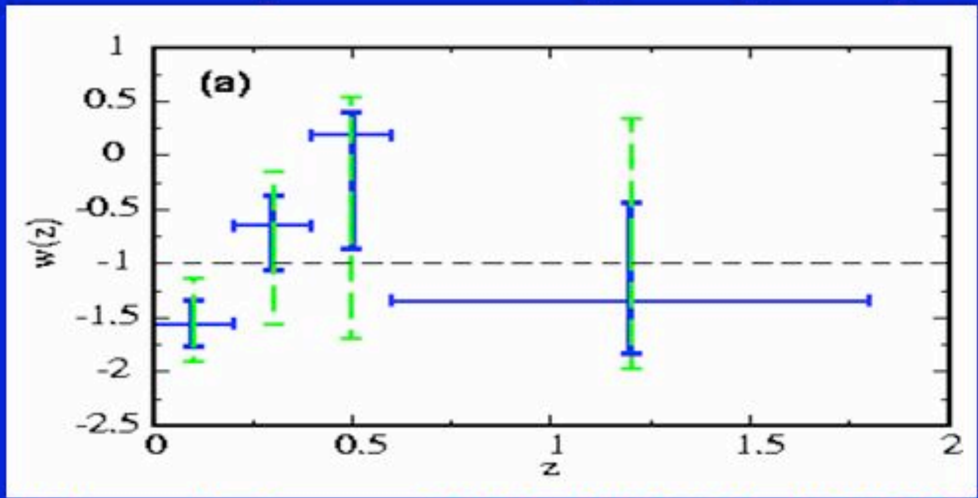
Zhang& ZHZ PRD73(2006)043518

◆**DGP+scalar field。**

Zhang& ZHZ PRD75(2007)023510

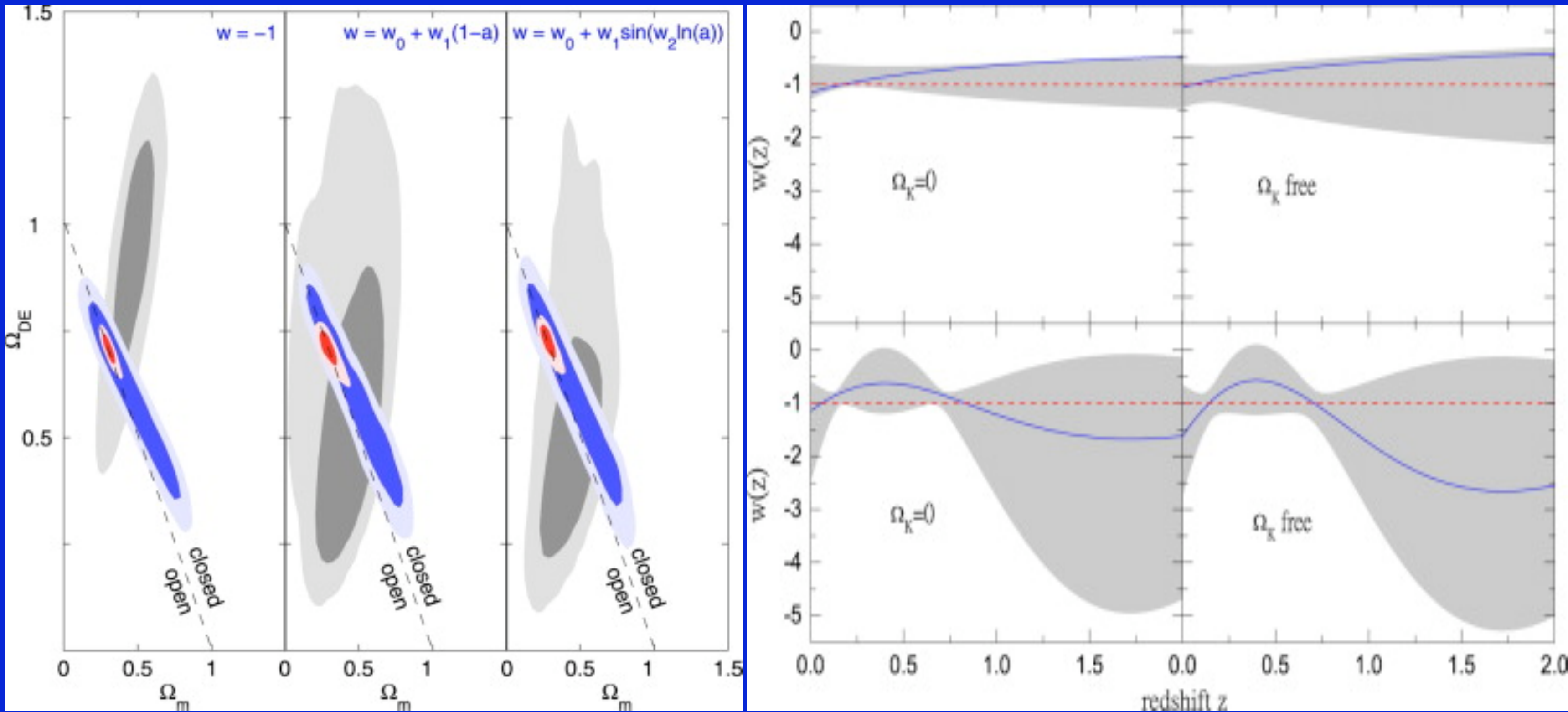


ZHZ & Fujimoto 2004, A&A, 417,833



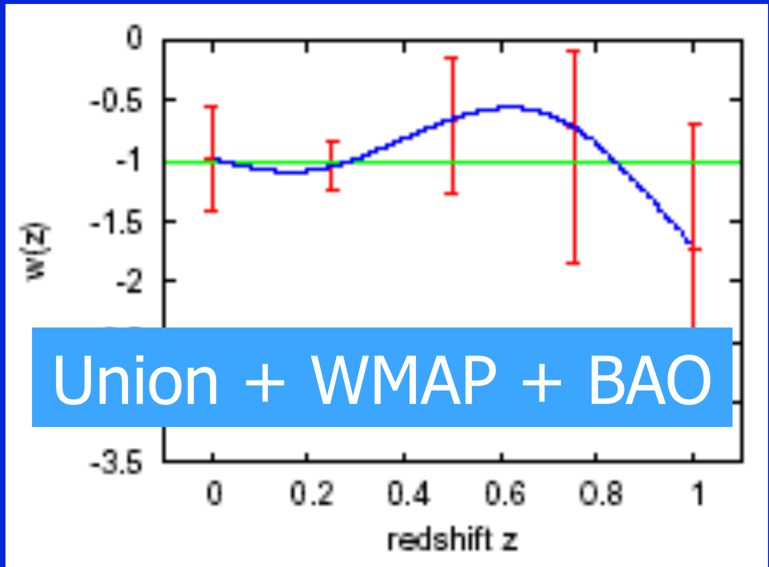
Huterer & Cooray 2005, PRD, 71, 023506

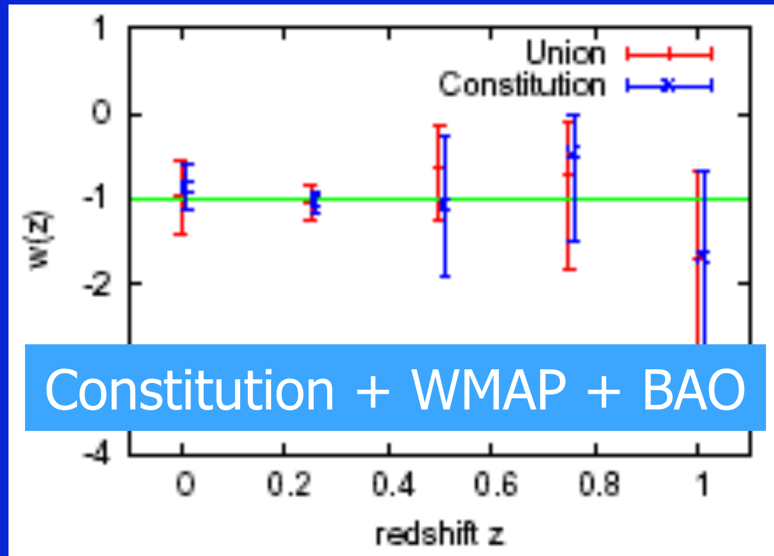
To determine EoS: previous results

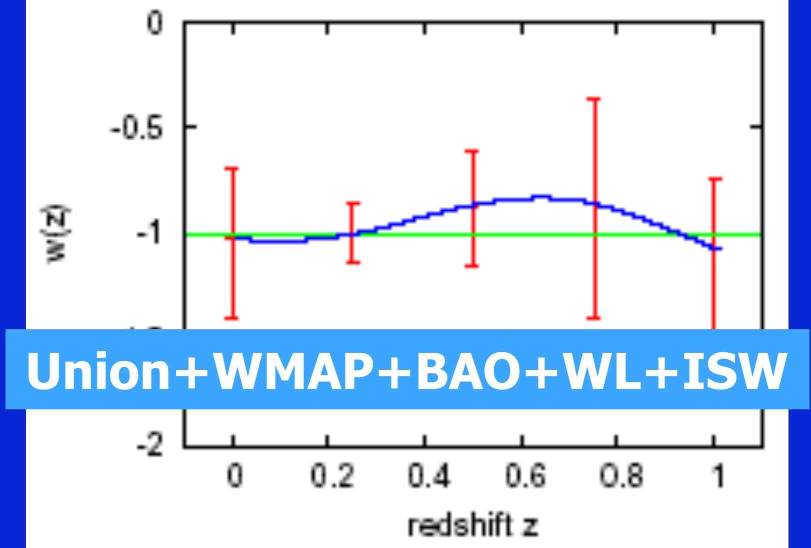


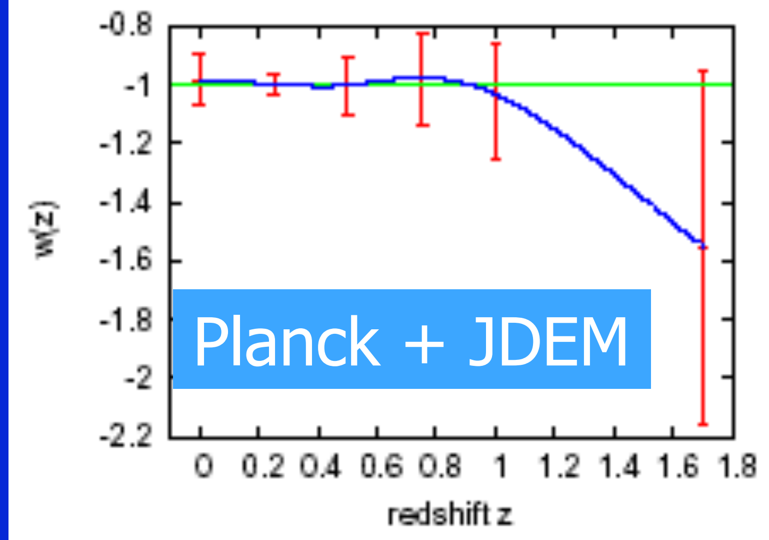
Zhao, Xia, Li, Tao, Virey, ZHZ & Zhang 2007 PLB, 648, 8

Binned EoS: recent results (Serra et al. 2009)

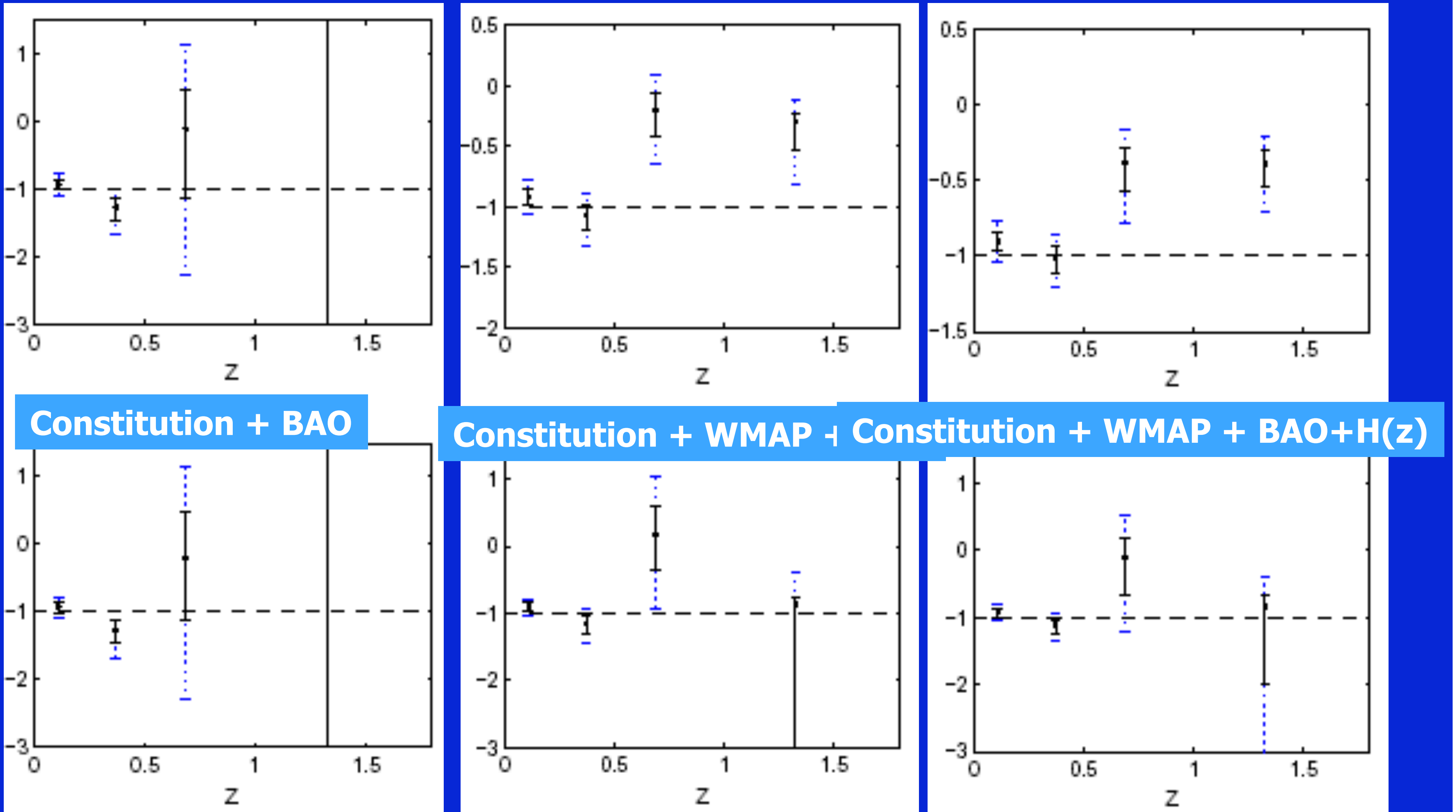








Binned EoS: our results (Gong,Cai,Chen & ZHZ 2009)



The most investigated EoS parametrizations

$$
w(z) = \begin{cases} w_0 + w_{P1} z & \text{(P1)} \\ w_0 + w_{P2} \ln(1+z) & \text{(P2)} \\ w_0 + w_{P3} z/(1+z) & \text{(P3)} \end{cases}
$$

- P1: linear variation (Cooray & Huterer 1999)
  - Quintessence, constant or slow changing EoS. Blows up for z>1
- P2: Empirical fit (Efstathiou 2000)
  - Dynamical scalar field (z<4)
- P3: asymptoting to a constant at high z (Chavallier & Polarski 2001; Linder 2003)
  - Many scalar field potetials

A generalized EoS for DE

A generalized EoS for dark energy, P_β

$$w(a) = w_0 - w_\beta \frac{a^\beta - 1}{\beta} \qquad (P_\beta)$$
$$= w_0 - w_\beta \frac{(1+z)^{-\beta} - 1}{\beta},$$

$$\beta \to -1 \quad \Rightarrow \quad P_\beta \to P1,$$
$$\beta \to 0 \quad \Rightarrow \quad P_\beta \to P2,$$
$$\beta \to +1 \quad \Rightarrow \quad P_\beta \to P3,$$

Introducing β admits new cosmological solutions beyond P1, P2, P3.

Evolution of $f_\beta \equiv \rho_\beta/\rho_\beta^0$ (From energy conservation law)

$$f_\beta = a^{-3(1+w_0+w_\beta/\beta)} \exp\left[\frac{3w_\beta}{\beta}\left(\frac{a^\beta - 1}{\beta}\right)\right] .$$

$$f_{P1} = a^{-3(1+w_0-w_1)} \exp\left[3w_1\left(\frac{1}{a} - 1\right)\right], \text{ if } \beta = -1,$$

$$f_{P2} = a^{-3[1+w_0-(w_2/2)\ln a]}, \text{ if } \beta = 0,$$

$$f_{P3} = a^{-3(1+w_0+w_3)} \exp\left[3w_3\left(a - 1\right)\right], \text{ if } \beta = 1.$$

1. $\beta > 0$ ($w_\beta \gtreqless 0$): At early times the dark energy is a subdominant component if $w_0 + w_\beta/\beta \leq 0$.
2. $\beta < 0$ and $w_\beta > 0$: At early times the dark energy always dominates over the other material components.
3. $\beta < 0$ and $w_\beta < 0$: At early times the dark energy density vanishes.

Evolution of ρ_β/ρ_m (w_0=-1, $\rho_\beta{}^0/\rho_m{}^0$~2.33)

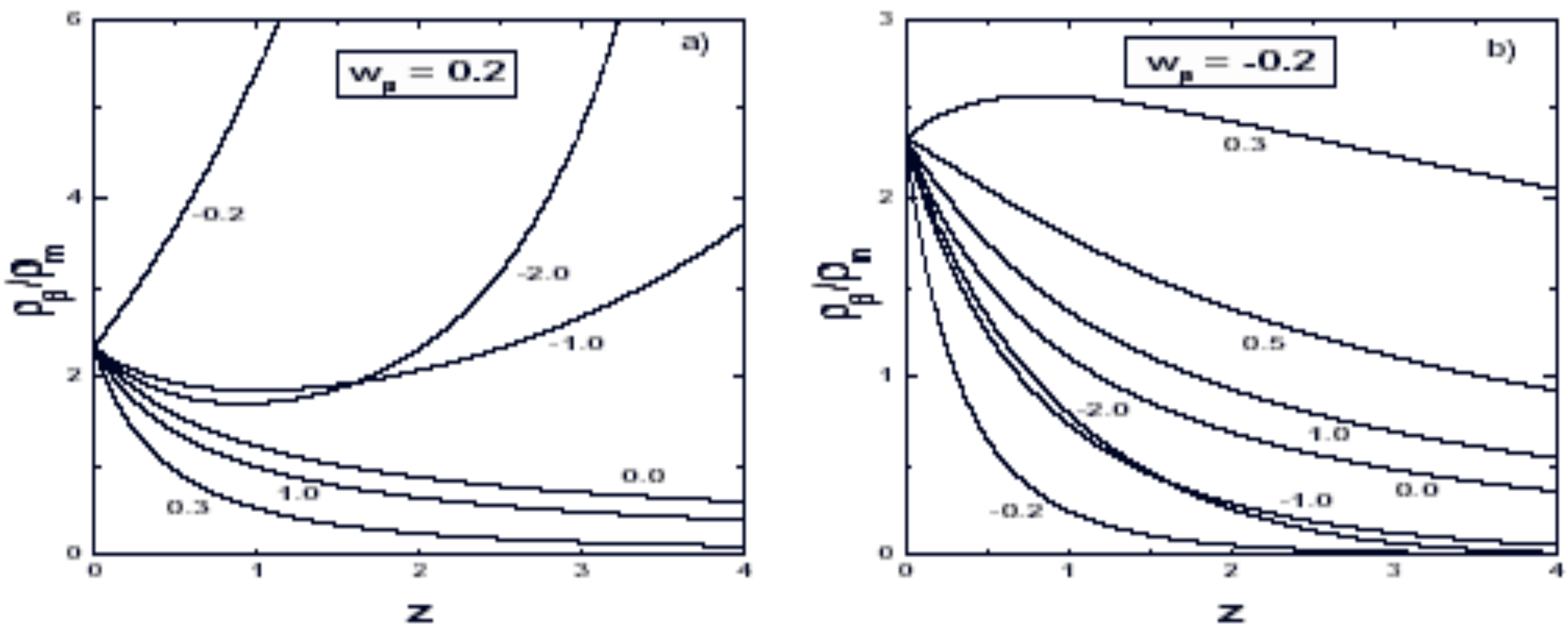


FIG. 1: a) The ratio ρ_β/ρ_m as a function of the redshift parameter z for $w_0 = -1.0$, $w_\beta = 0.2$ and $\rho^0_\beta/\rho^0_m \simeq 2.33$. The value of β is displayed below the corresponding curve. Note that the class of $P_{\beta<0}$ models presents an undesirable behaviour at high-z in agreement with Eq. (3). b) The same as in Panel (a) for $w_\beta = -0.2$. In this case, the dark energy contribution for negative values of β becomes negligible at $z \gtrsim 4$.

P_β can incorporate many DE scenarios

- Models approximated by P3 are particular examples of P_β
- Thawing scalar field models (PNGB)
- A generalization of P3, $w(z)=w_0+w_{p3}(1-a^b)$ (Linder & Huterer 2005)

Friedmann Eq. & Deceleration parameter

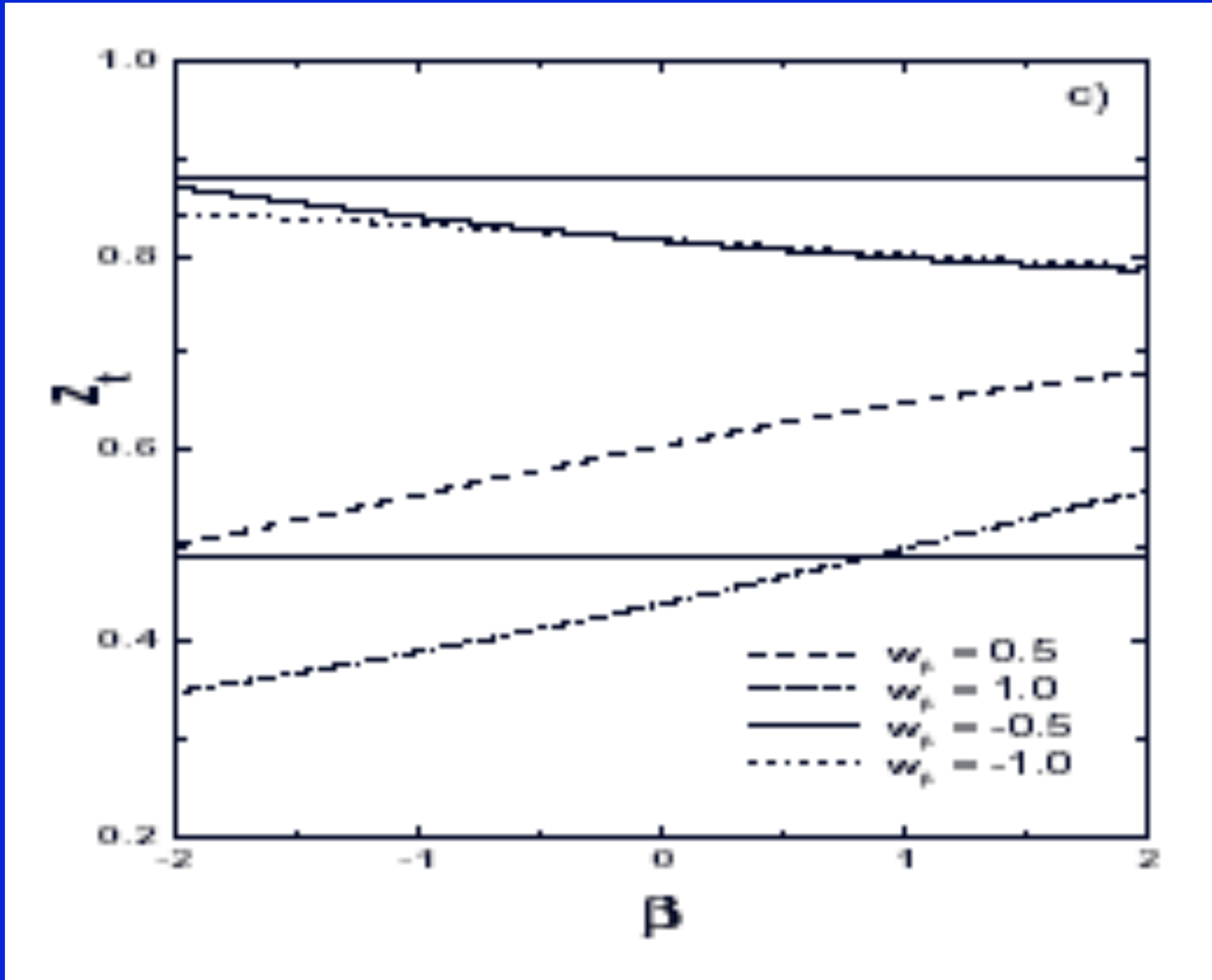
BEIJING NORMAL UNIVERSITY

$$\mathcal{H}(z;\mathbf{s}) = \sqrt{\Omega_m^0 a^{-3} + (1-\Omega_m^0 - \Omega_k) f_\beta + \Omega_k^0 a^{-2}}\,,$$

$$q(a) = \frac{1}{2}\frac{\Omega_m^0 a^{-3} + (1-\Omega_m^0 - \Omega_k)(f_\beta'/a - 2 f_\beta)}{\Omega_m^0 a^{-3} + (1-\Omega_m^0 - \Omega_k) f_\beta + \Omega_k^0 a^{-2}}\,,$$

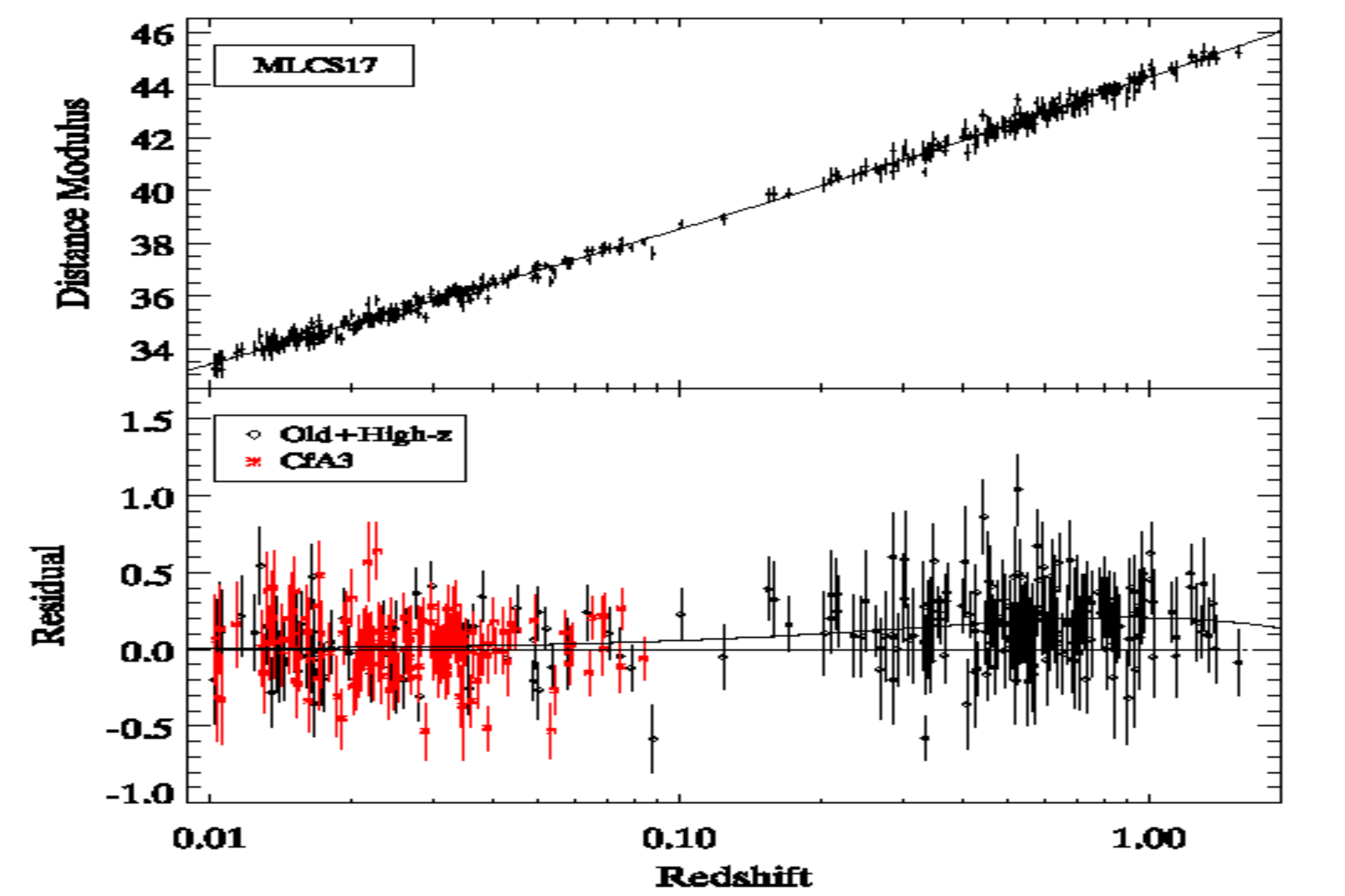
where $f_\beta'/a = 3(1+\omega_0+\frac{\omega_\beta}{\beta}) f_\beta - \frac{3\omega_\beta a^\beta}{\beta} f_\beta$.

Transition redshift z_t as a function of β ($w_0=-1, \Omega_m^0=0.3$)

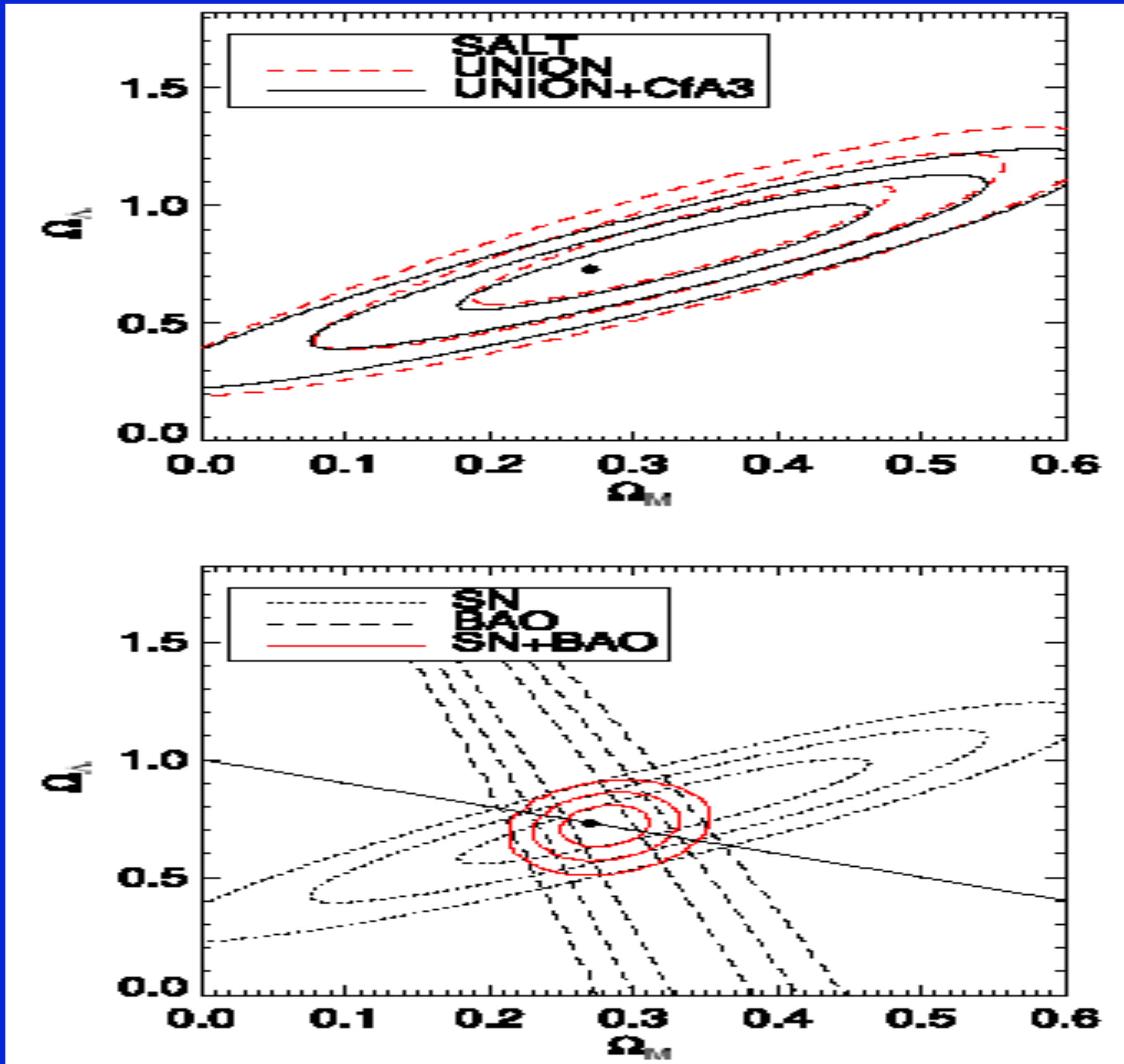


Observation
al
constraints

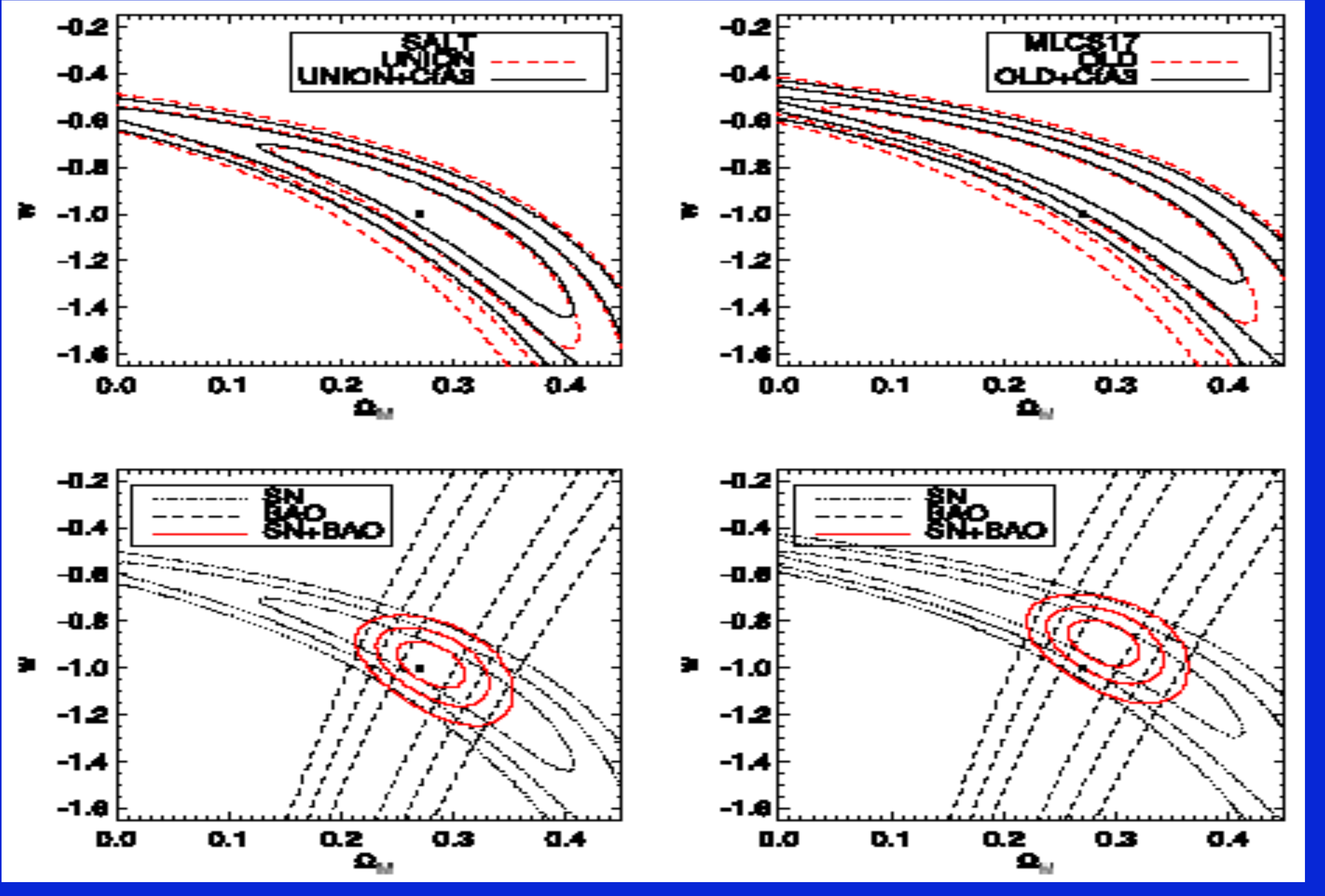
Constitution Set: Hubble diagram (Hicken et al.2009)



Constitution Set: Contours of Ω_Λ vs. Ω_m (Hicken et al. 2009)



Constitution Set: Contours of w vs. Ω_m (Hicken et al.2009)



CMB shift parameter & BAO parameter

$$\mathcal{R} \equiv \sqrt{\Omega_m^0} \int_0^{z_{ls}} \frac{dz'}{\mathcal{H}(z'; \mathbf{s})} = 1.70 \pm 0.03,$$

Wang & Mukherjee 2006

$$A = D_V \frac{\sqrt{\Omega_{m0} H_0^2}}{z_*},$$

Eisenstein et al. 2005

H(z) data (Simon et al. 2005)

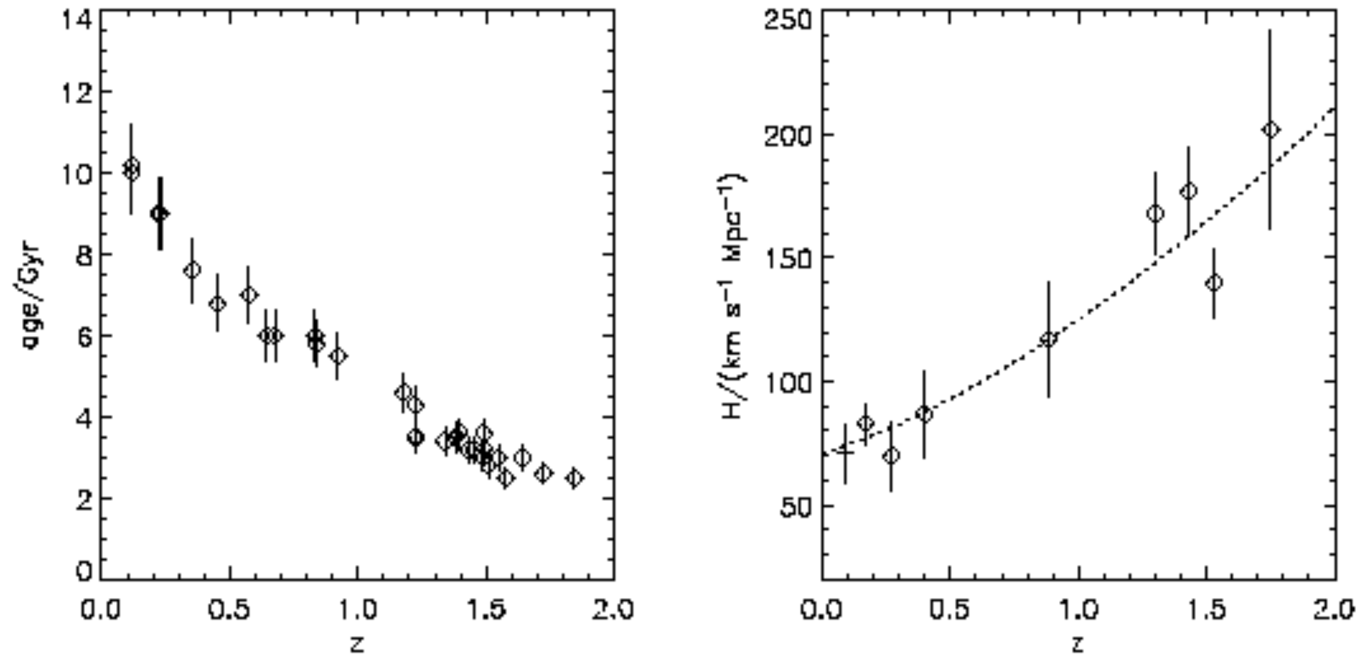
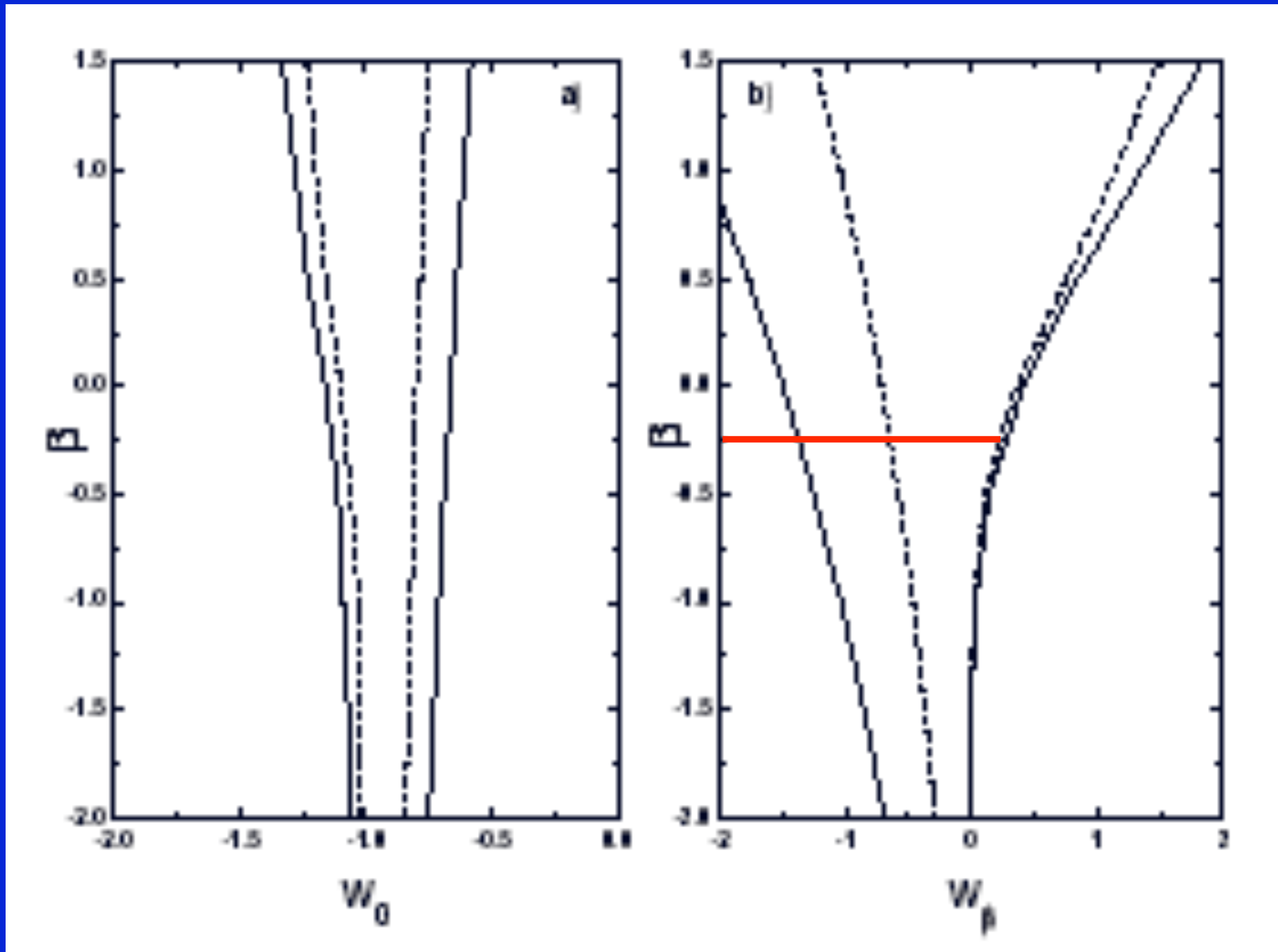


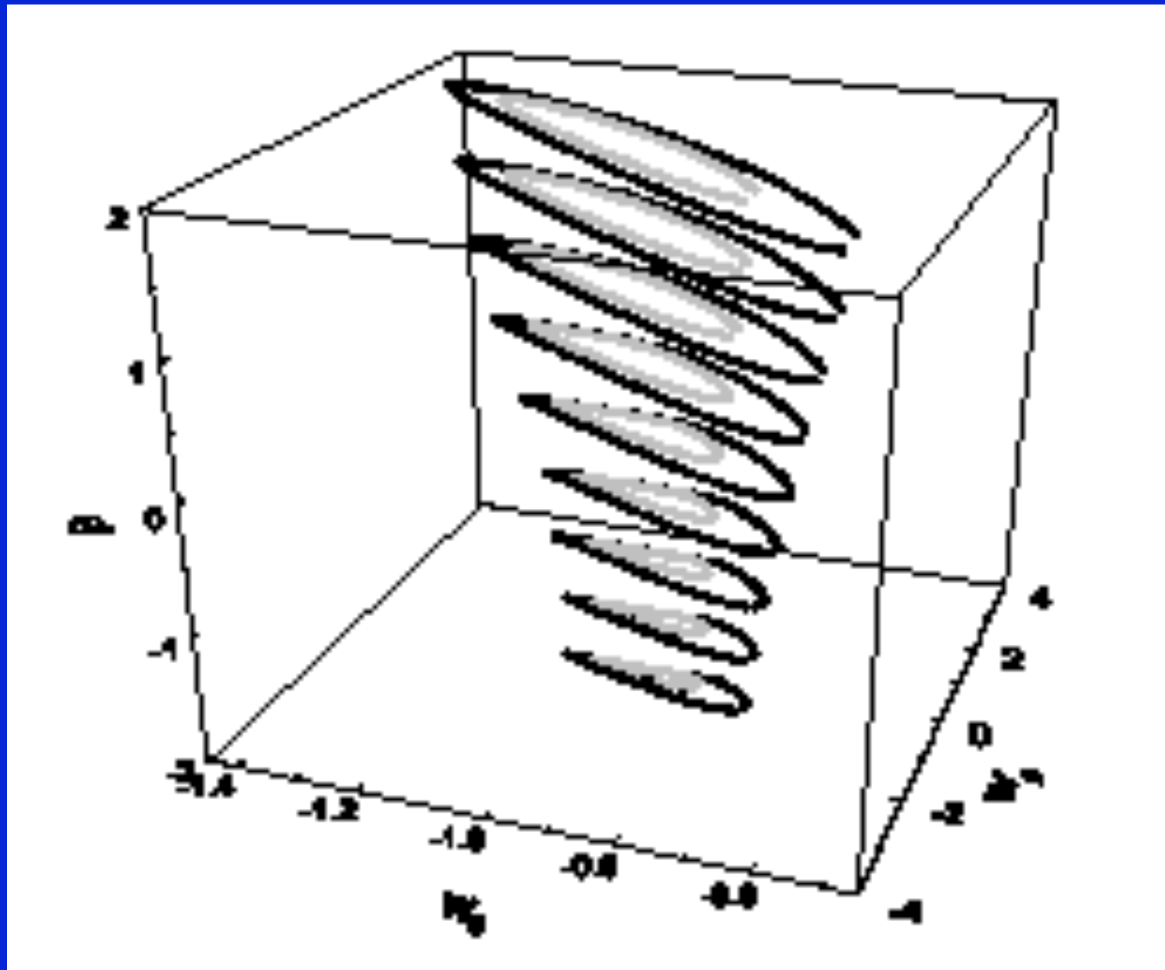
FIG. 1: Left panel: the absolute age for the 32 passively evolving galaxies in our catalogue (see text for more detals) determined from fitting stellar population models is plotted as a function of redshift. Note that there is a clear age-redshift relation: the lower the redshift the older the galaxies. Right panel: the value of the Hubble parameter as a function of redshift as derived from the *differential* ages of galaxies in the left panel. The determination at $z \sim 0.1$ indicated by the '+' symbol is the hubble constant determination of H from [27]. The dotted line is the value of $H(z)$ for the LCDM model.

Contours of (w_0,β) & (w_β,β)

北京师范大学 BEIJING NORMAL UNIVERSITY



Contours of (w_0, w_β, β) with best fit (-1,0.28,0.1)



Summary

- A generalized EoS for DE, P_β, is proposed.
- P_β can recover the most investigated EoS para-metrizations, P1, P2, P3.
- P_β can incorporate many DE scenarios. There is a family of $P_{\beta>0}$ solutions compatible with current data.
- The next generation of DE experiments can determine (if any) interval of (w_β, β) .

Thanks for all your patience!

&

Welcome to visit BNU!

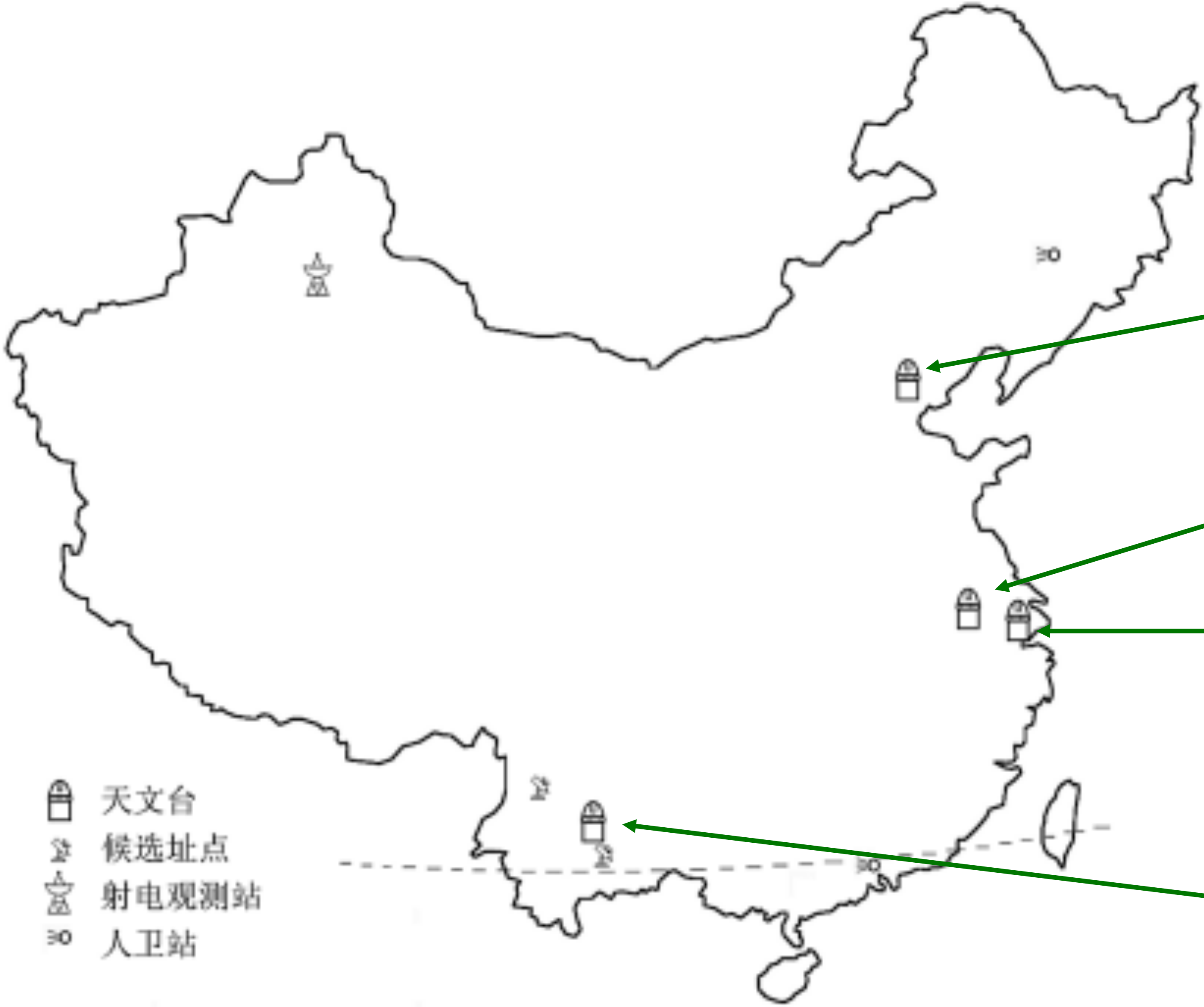
北京師範大學
BEIJING NORMAL UNIVERSITY

Astronomy in China

Outline

- Astronomical Observatories in China
- Astronomy in Chinese Universities
- Beijing Normal University (BNU)
- Department of Astronomy of BNU
- Research in my group
- Summary and Prospects

1. Astronomical Observatories in China



Beijing (NAOC)

Nanjing (PMO)

Shanghai (SHAO)

Kunming (YNAO)

1.1 NAOC

- National Astronomical Observatories of China
- Headquarter: in Beijing

Observation Stations

- Xinglong station (in Hebei province):
  Optical telescopes: ～10 (Max. 4-m)
- Miyun station (Suburb of Beijing):
  Radio telescope: 50-m; array of 28 9-m
- Huairou station (Suburb of Beijing):
  Solar telescope: 3-dimension magnetic field
- Urumqi station (in Xinjiang province):
  Radio telescopes: 25-m

Xinglong station before LAMOST

- 2.16-m telescope
- Made in 1989
  by Nanjing factory
- Instruments:

—Coudé spectrograph

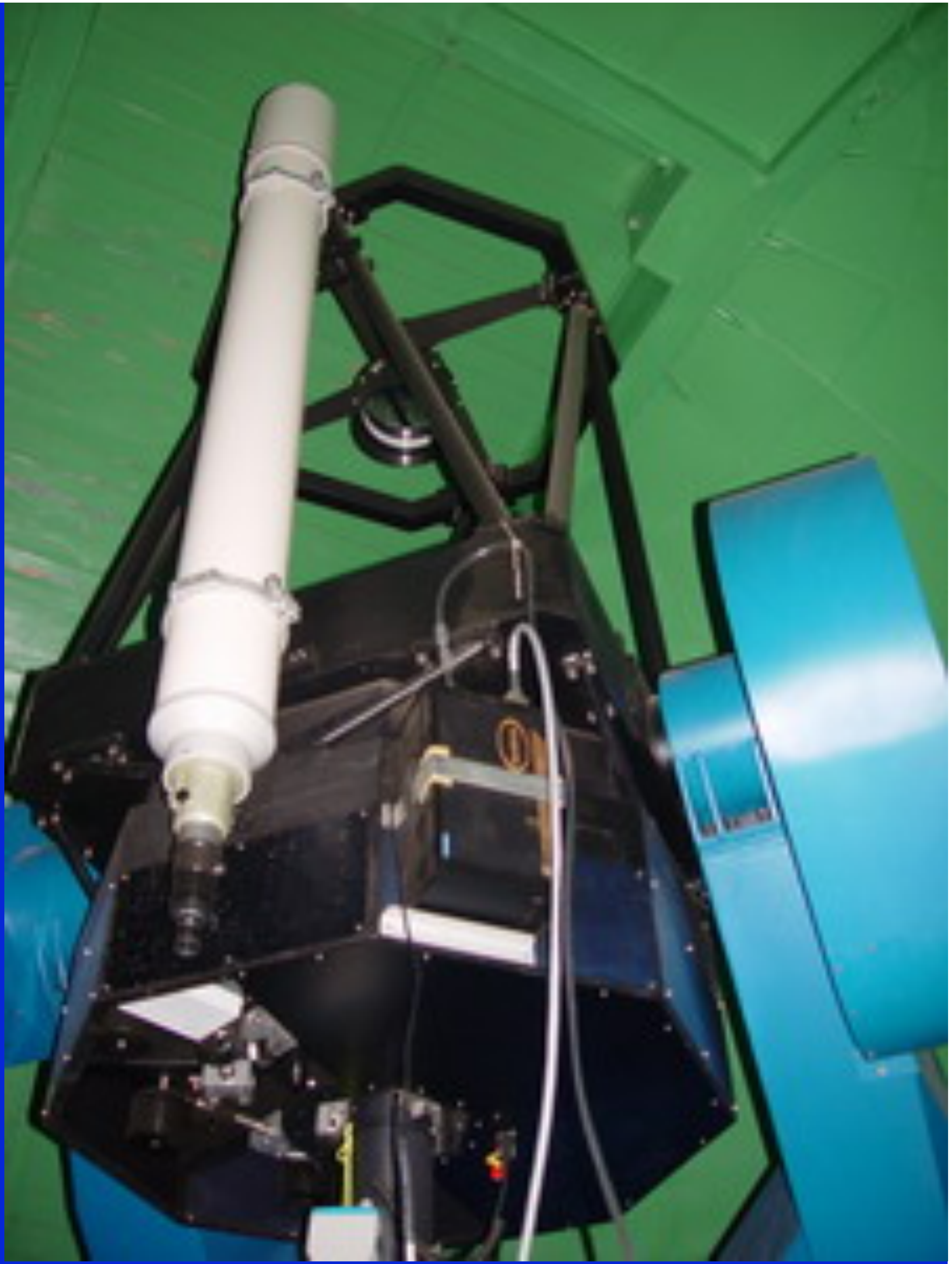
—OMR: spectrograph
  Cassegrain focus

—BFOSC:
  Photometry +
  spectrograph

- 1.26-m infrared telescope
- Made in 1980's in China
- Single-channel detector

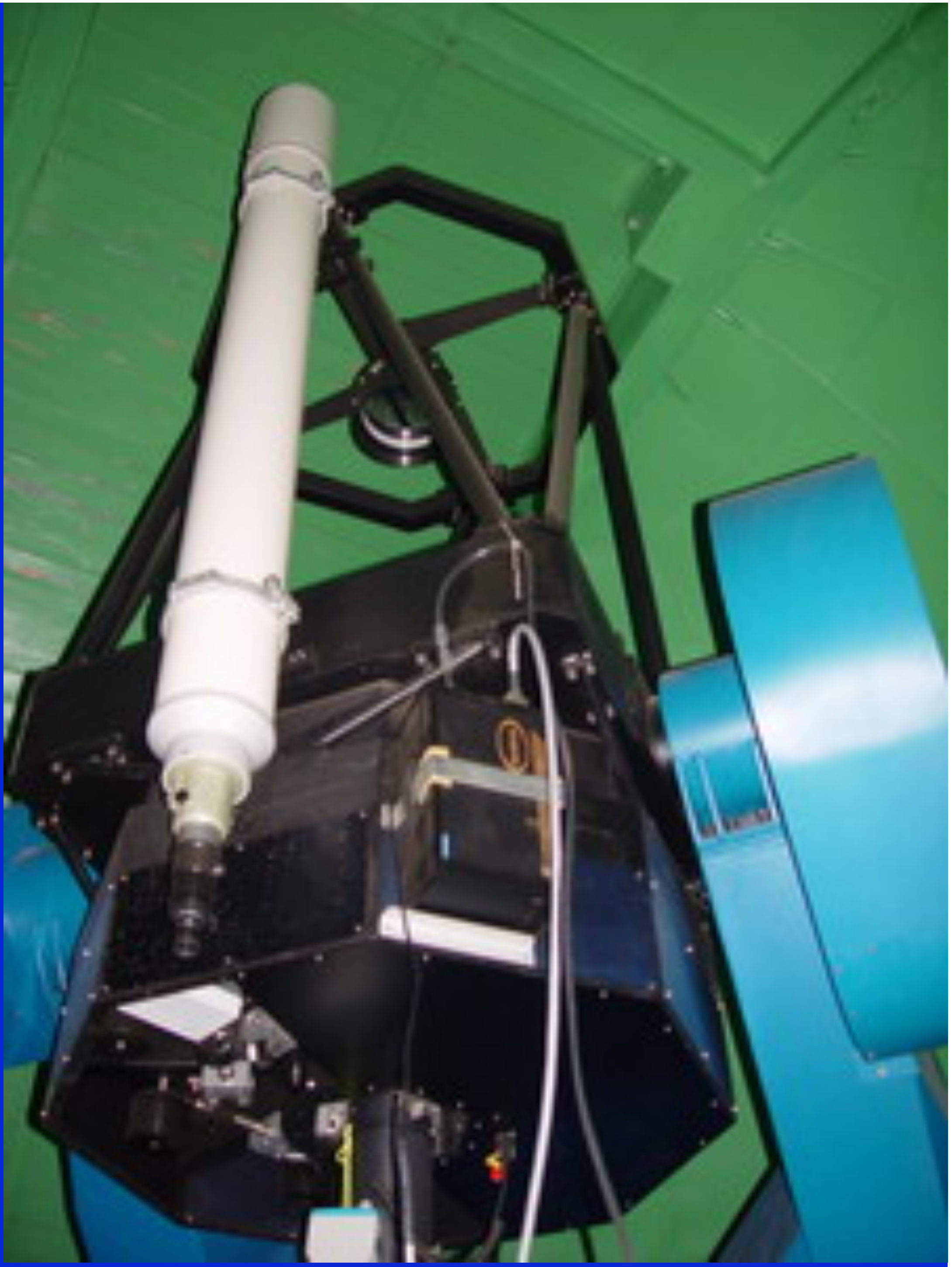
- 85-cm reflector
- CCD camera at the focus of the primary mirror
- High-precision photometry

- 80-cm telescope
- Made by AstroOptik company of Germany
- CCD camera
- Collaborate with Tsinghua University of China



- 60/90 Schmidt telescope
- 4k×4k CCD, 90′ ×90′ FOV

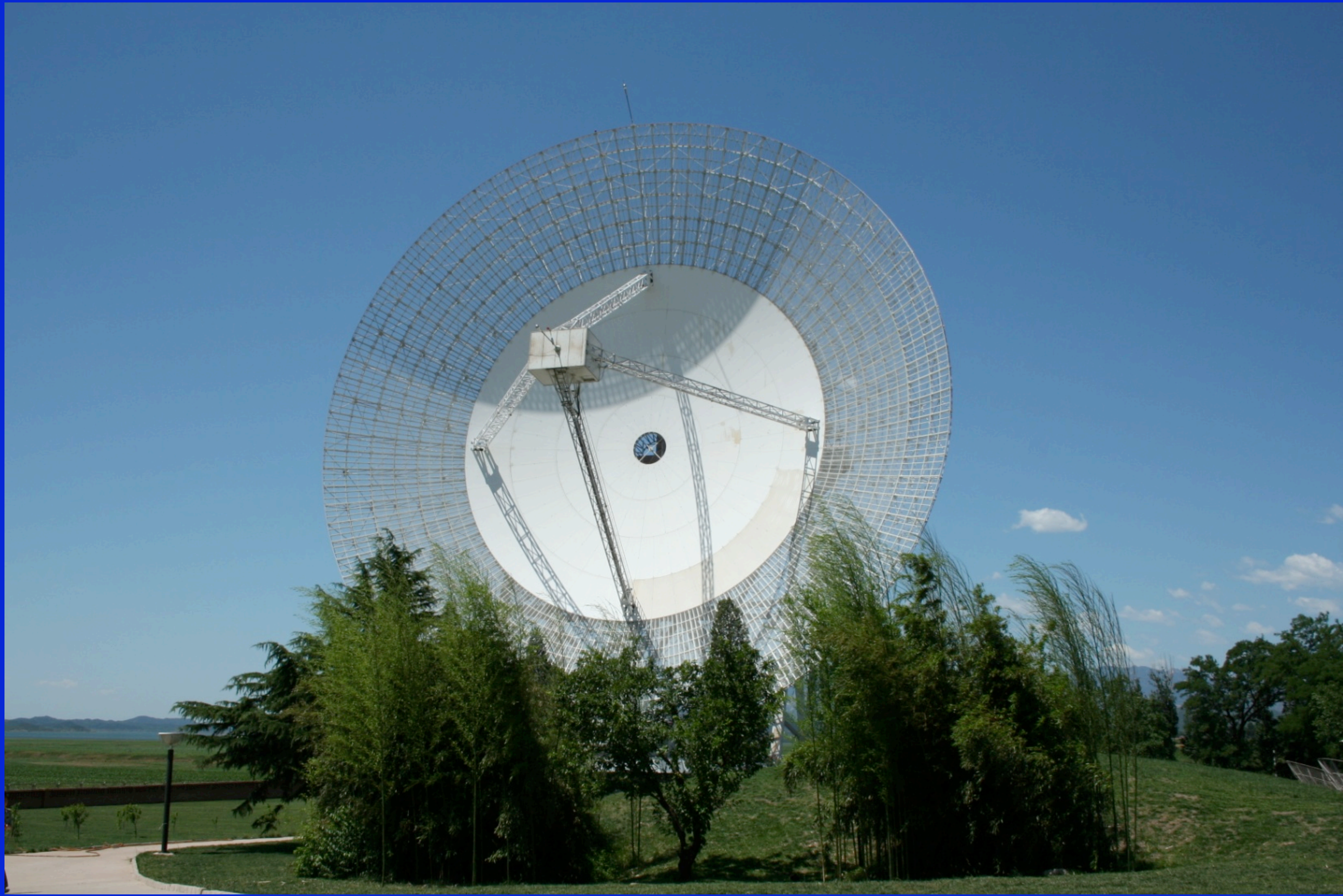
- 80-cm telescope
- Made by AstroOptik company of Germany
- CCD camera
- Collaborate with Tsinghua University of China



Miyun array of radio telescopes

A 50-m radio telescope at Miyun station

北京師範大學
BEIJING NORMAL UNIVERSITY



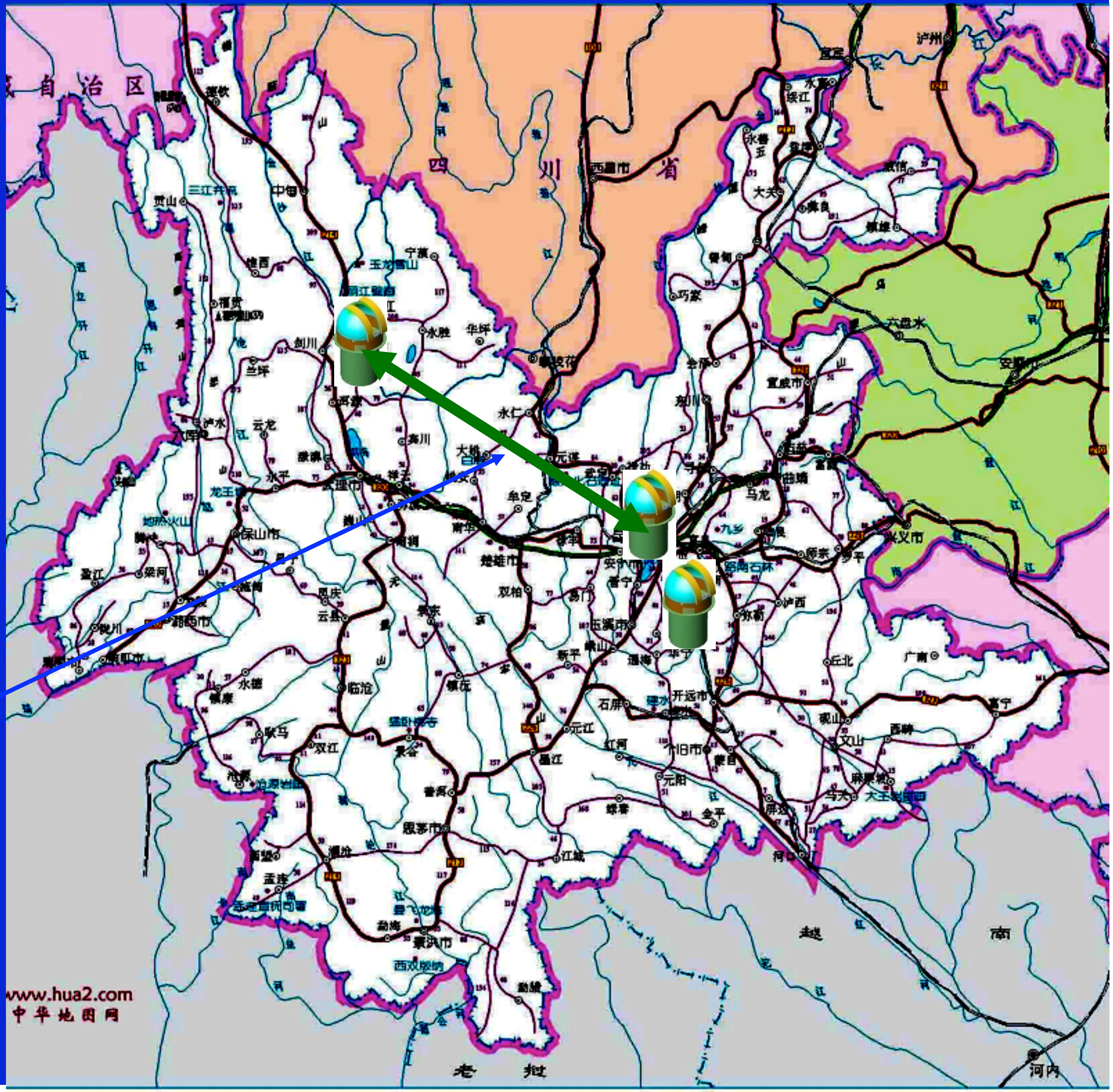
Huairou solar telescope

1.2 YNAO

- YunNan Astronomical Observatory
- Headquarter: Kunming (Yunnan province)

Observation Stations

- Kunming HQ:
  - 40-m radio telescope
  - 1-m optical telescope;
  - 0.6-m optical telescope
- Lijiang station:
  - 2.4-m optical telescope
- Chenjiang station:
  - 1-m infrared solar telescope



四 川 省
西昌市
泸州
六盘水
兴义市
大理市
保山市
临沧
玉溪市
开远市
个旧市
文山
广南
富宁
思茅市
景洪市
西双版纳
河内
www.hua2.com
中华地图网

560 km

40-m radio telescope

- 2.4-m telescope at Lijiang station

Personnel (NAOC+YNAO, in 2002)

- Employee: 648
  - Professor: 79
  - Associate professor: 163
  - Technical support staff: 192
  - Post-doc: 14
  - Ph.D. students: 83
  - M.Sc. Students: 116
  - Visiting staff: 56

1.3 PMO

- Purple Mountain Observatory
- Headquarter: in Nanjing (Jiangsu prov

Observation Stations

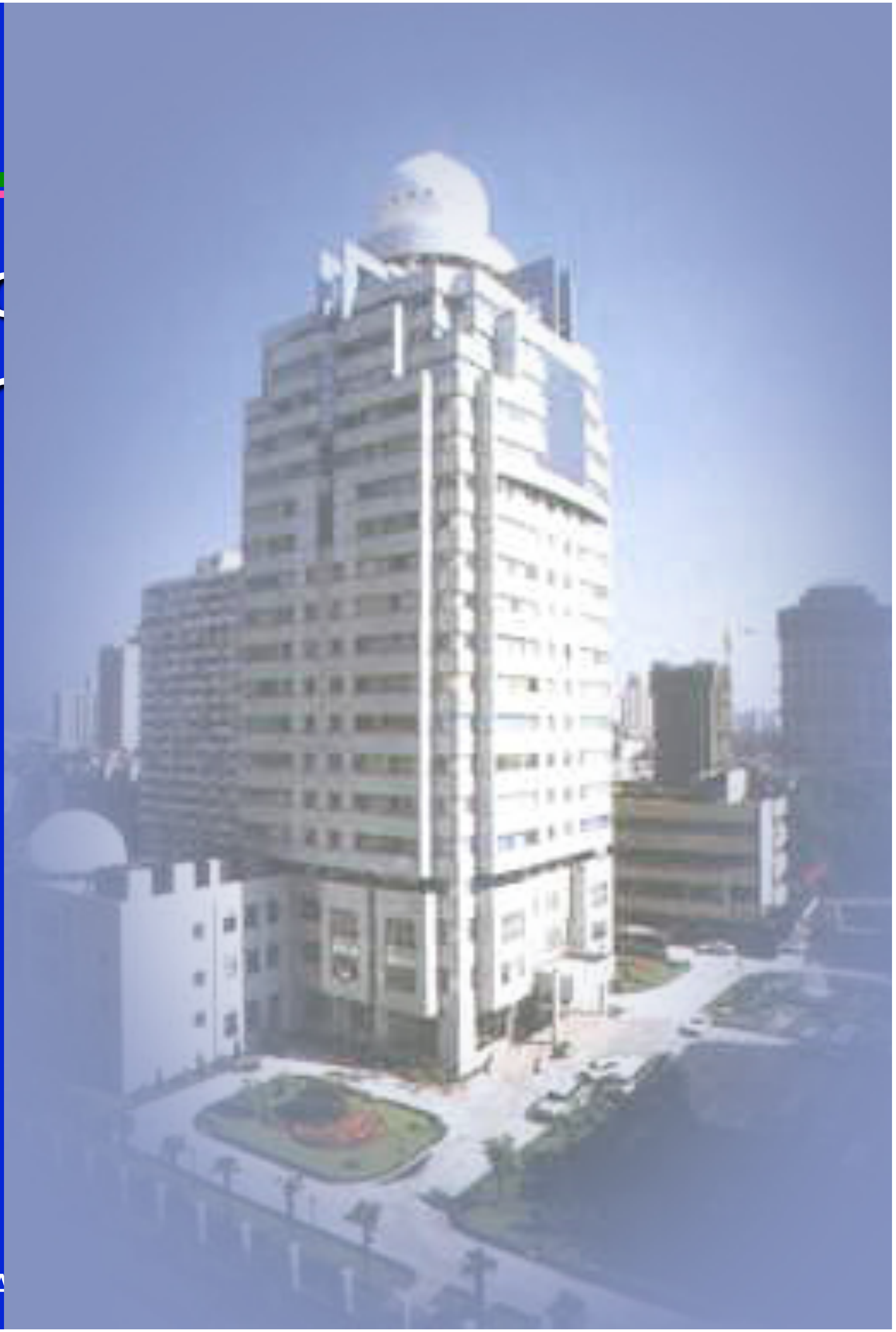
- Delingha station: (in Qinhai province)
  - 13.7-m radio telescope (mm-band)
- Xuyu station: (in Jiangsu province)
  - 1.05/1.20-m Schmidt telescope:
    - near-earth objects
  - 0.65-m optical telescope:
    - space pieces

Delingha station

Xuyu station

1.4 SHAO

- ShangHai Astronomic
- Headquarter: in Shan



Observation Stations

- Sheshan station: (in suburb of ShangHai)
  —25-m radio telescope
  a VLBI station
  —1.56-m telescope:
  photometry
  spectroscopy
  —60-cm Satellite Laser Ranging (SLR)

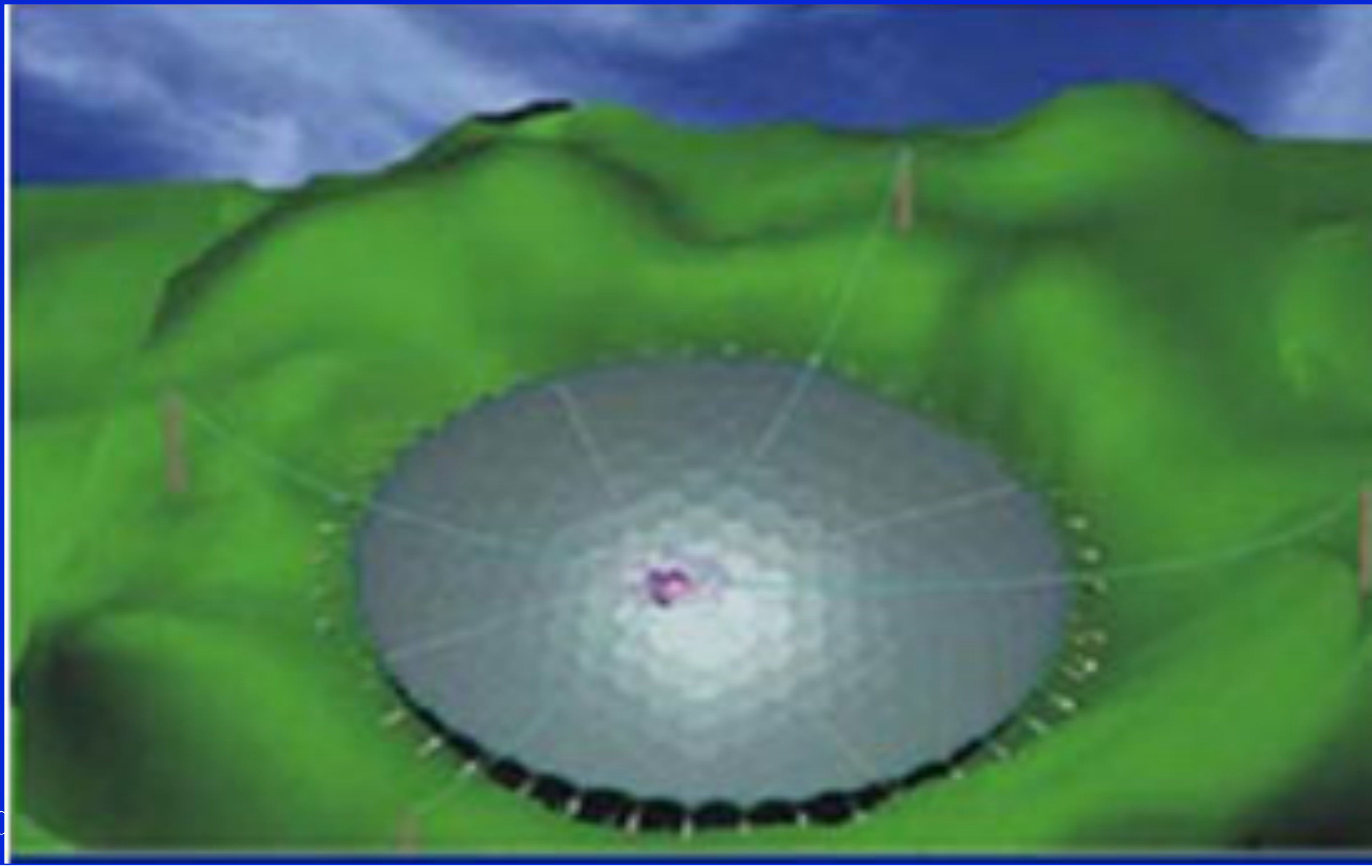
25-m radio telescope (VLBI)

1.56-m telescope

60-cm SLR

1.5 Large projects

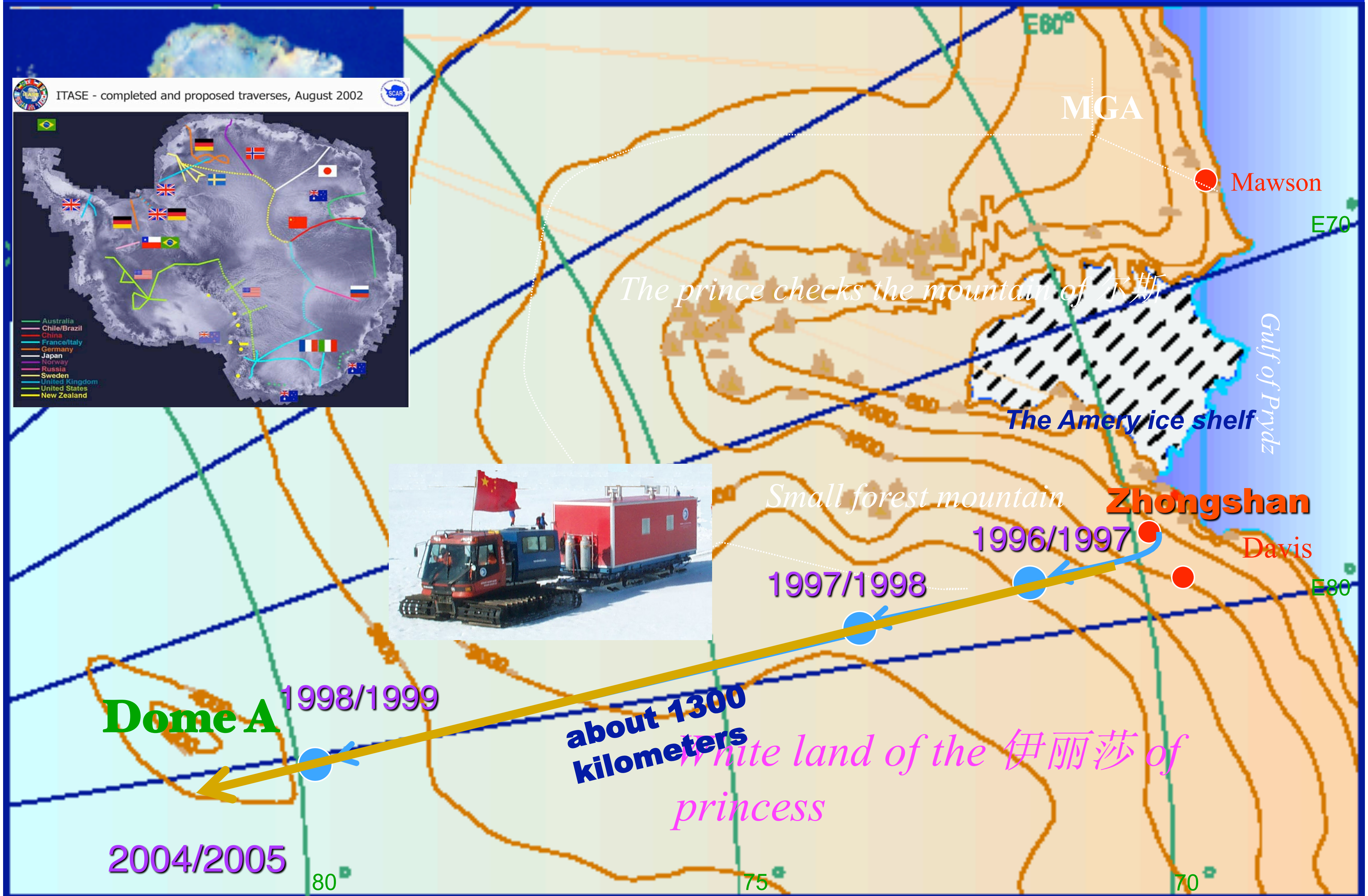
- FAST: 500-m radio telescope
  the largest in the world



- LAMOST: 4-m schmidt telescope
  the largest schmidt telescope in the world

- CSTAR: Chinese Small Telescope Array
  4 small optical telescopes mounted at one construction installed in Dome A of Antarctica
  —altitude: 4093-m
  —Diameter: 14.5-cm
  —CCD: 1k×1k Frame Transfer CCD
  —Filter: White light, g,r,i
  —Field of view: 4.5°×4.5°/telescope
  —Observation: continuous photometry of all objects in the field, site monitor
  —Date: Jan. 12, 2008

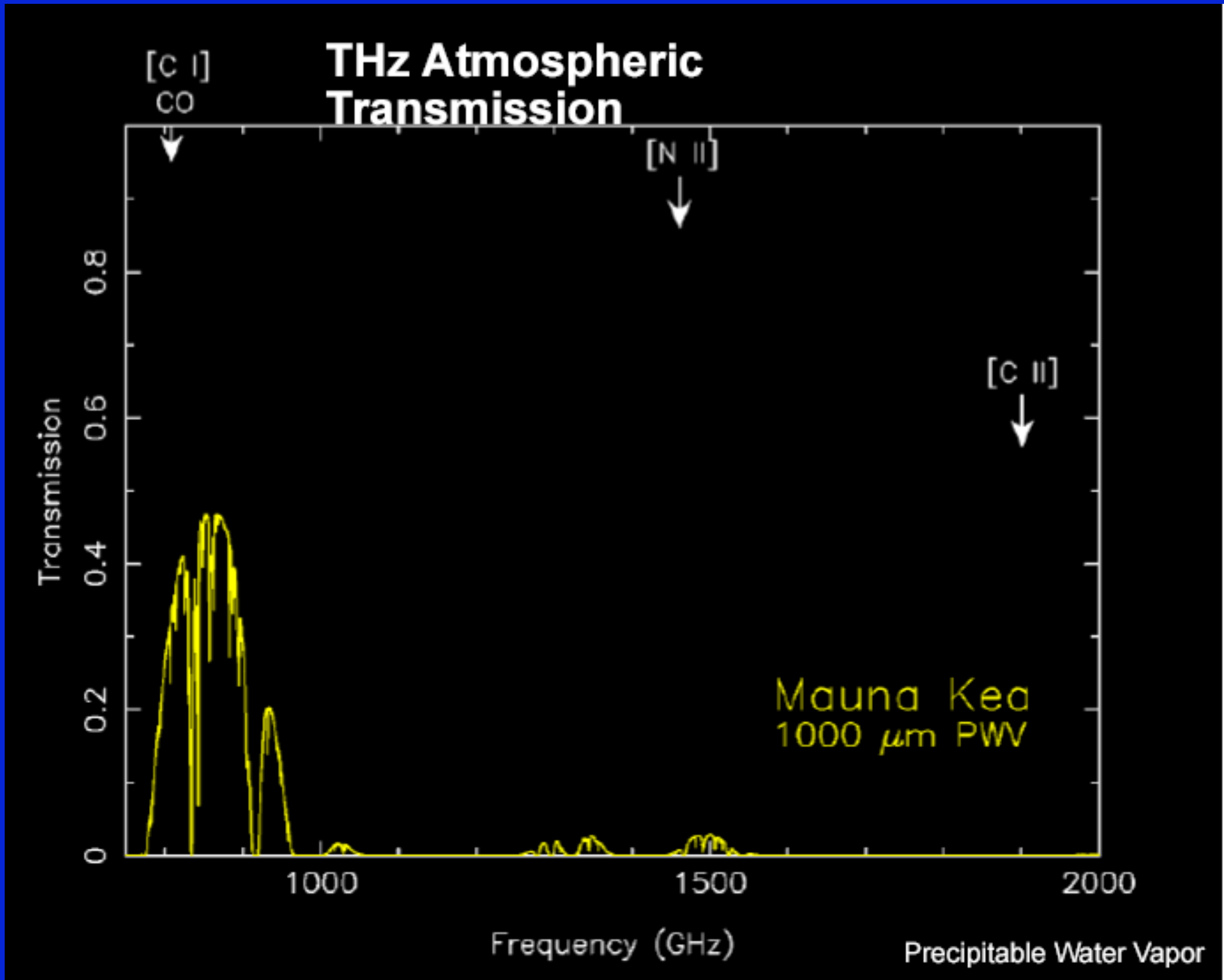
In Nanjing of China

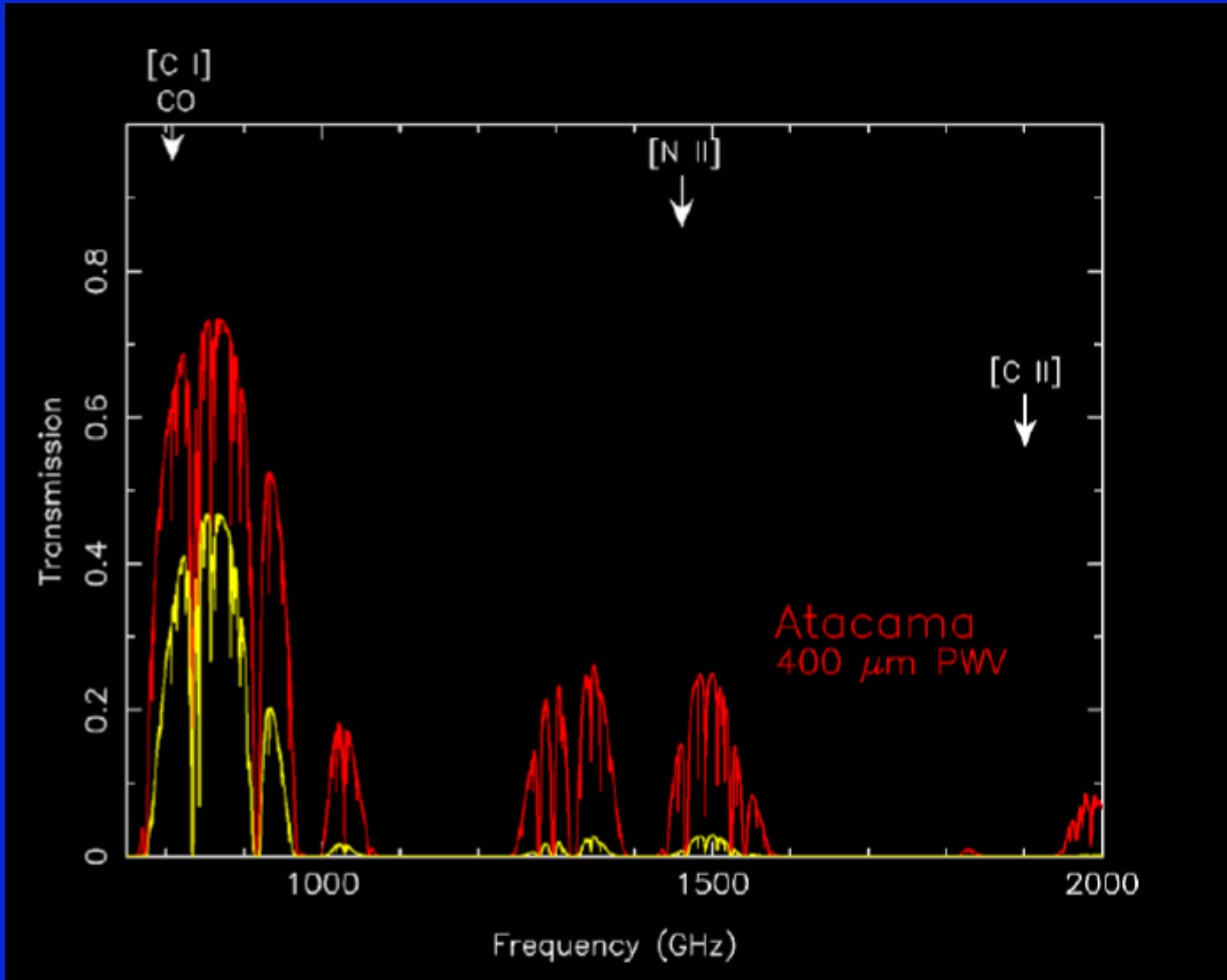


ITASE - completed and proposed traverses, August 2002
Australia
Chile/Brazil
China
France/Italy
Germany
Japan
Norway
Russia
Sweden
United Kingdom
United States
New Zealand
MGA
Mawson
E70
The prince checks the mountain of 尔斯
The Amery ice shelf
Gulf of Prydz
Small forest mountain
Zhongshan
1996/1997
Davis
1997/1998
E80
1998/1999
Dome A
about 1300 kilometers
White land of the 伊丽莎 of princess
2004/2005
80
75
70

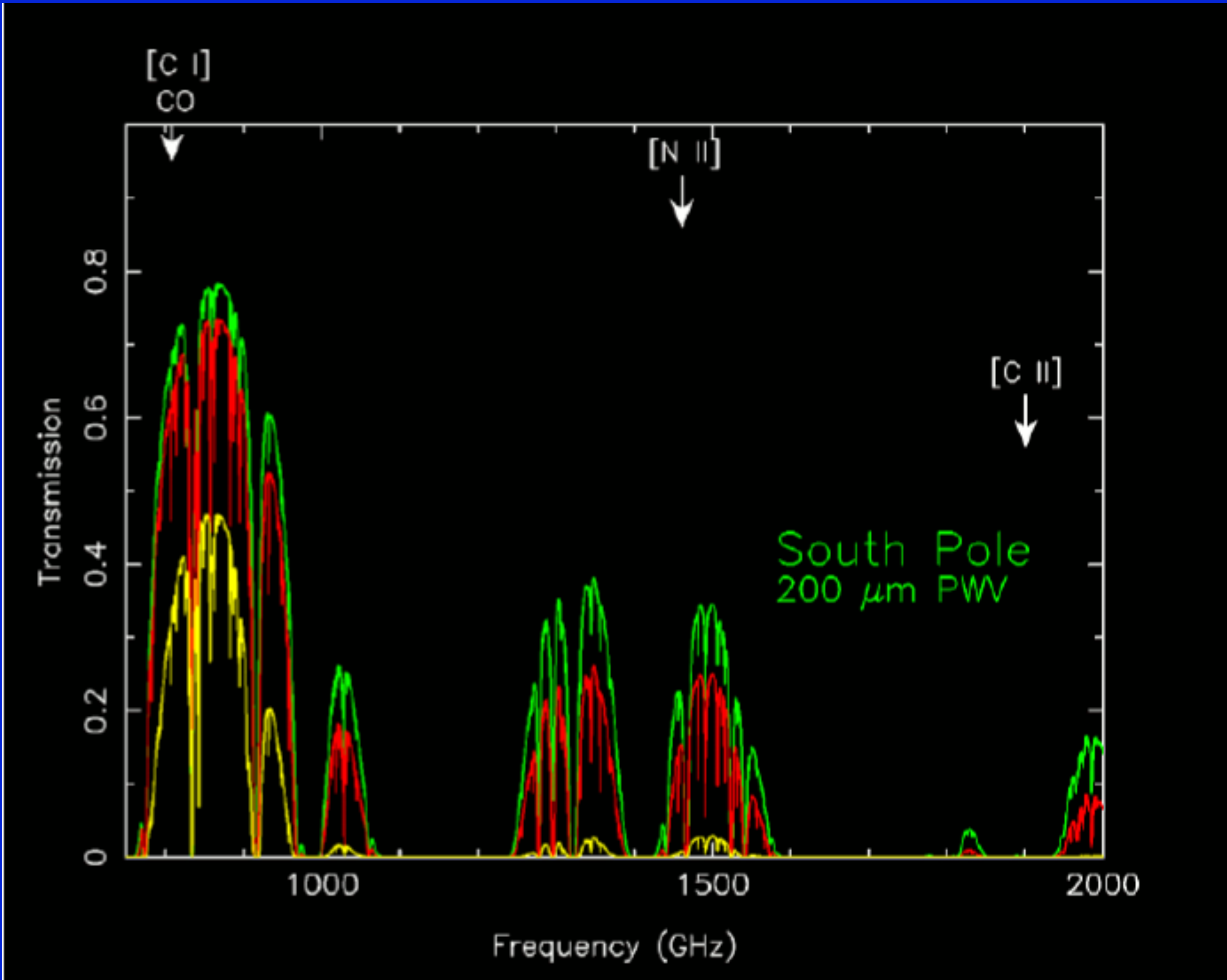
- First astronomers at Dome A: Xu Zhou (Left), and Zhenxi Zhu (Right)

Jan 10, 2008

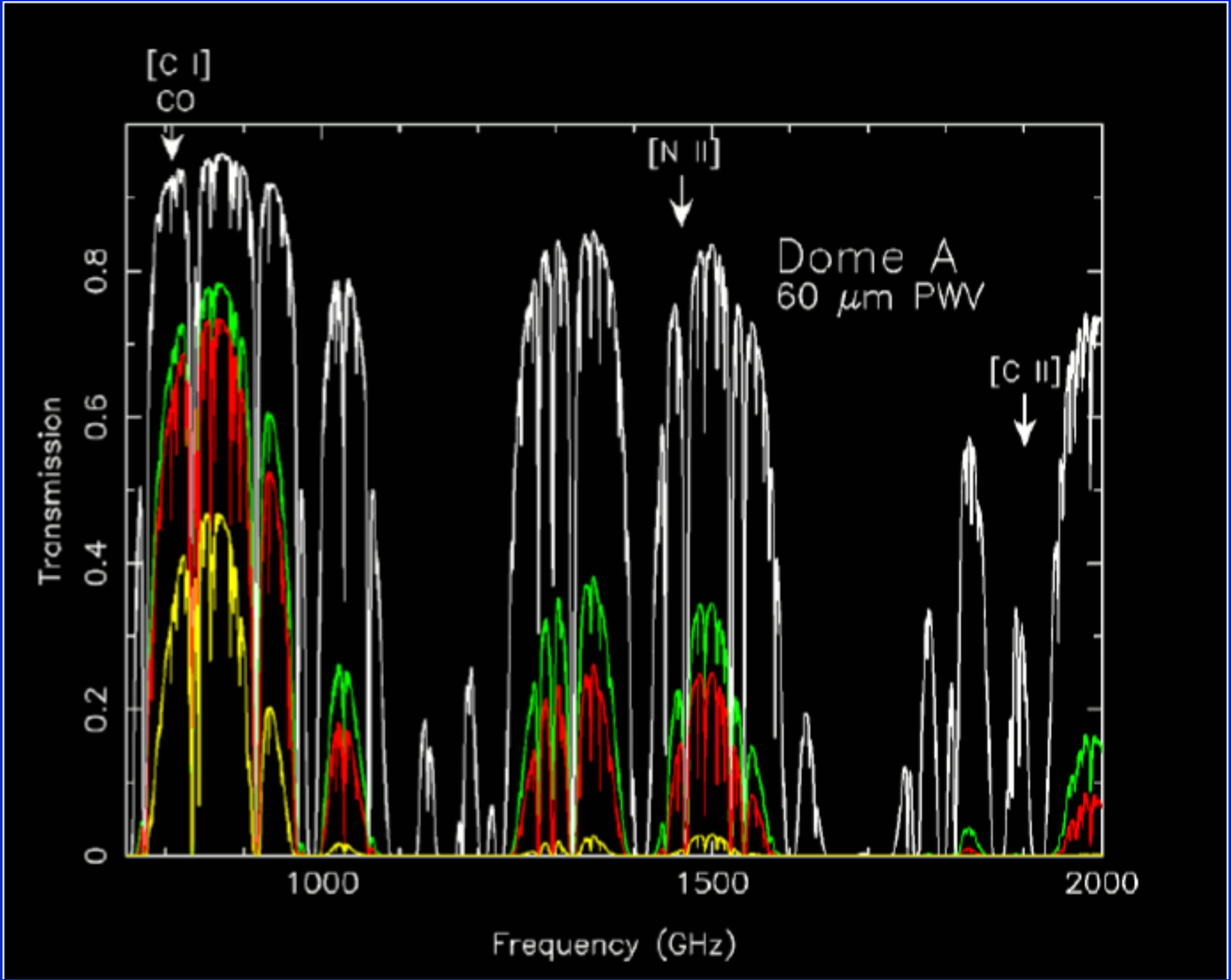

THz Atmospheric Transmission
[C I]
CO
[N II]
[C II]
Transmission
0
0.2
0.4
0.6
0.8
1000
1500
2000
Frequency (GHz)
Mauna Kea
1000 μm PWV
Precipitable Water Vapor



[C I]
CO
[N II]
[C II]
Atacama
400 μm PWV
Transmission
0
0.2
0.4
0.6
0.8
1000
1500
2000
Frequency (GHz)

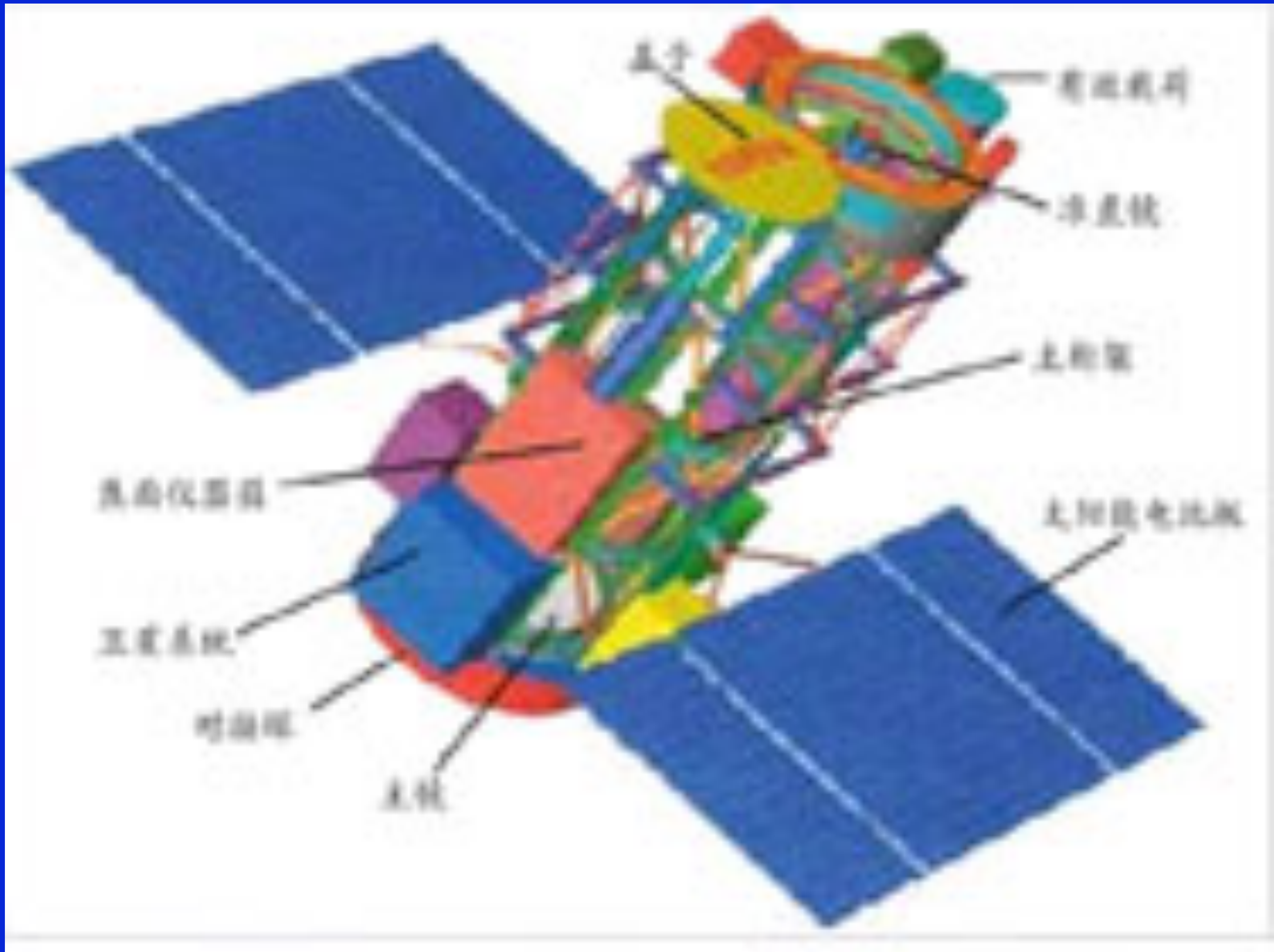


[C I]
CO
[N II]
[C II]
South Pole
200 μm PWV
Transmission
0
0.2
0.4
0.6
0.8
1000
1500
2000
Frequency (GHz)

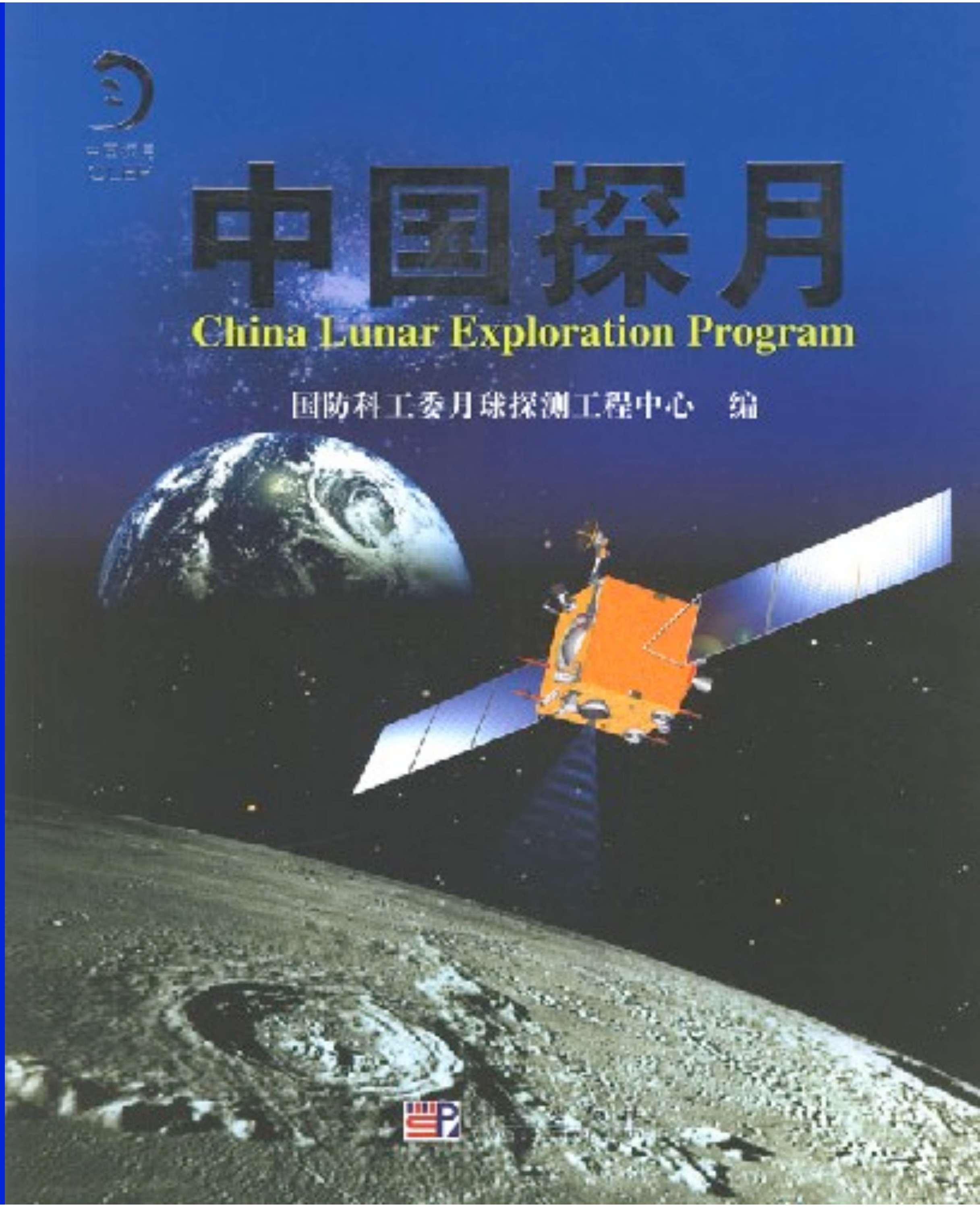


[C I]
CO
[N II]
Dome A
60 μm PWV
[C II]
Transmission
0
0.2
0.4
0.6
0.8
1000
1500
2000
Frequency (GHz)

SST: Space Solar Telescope 1-m



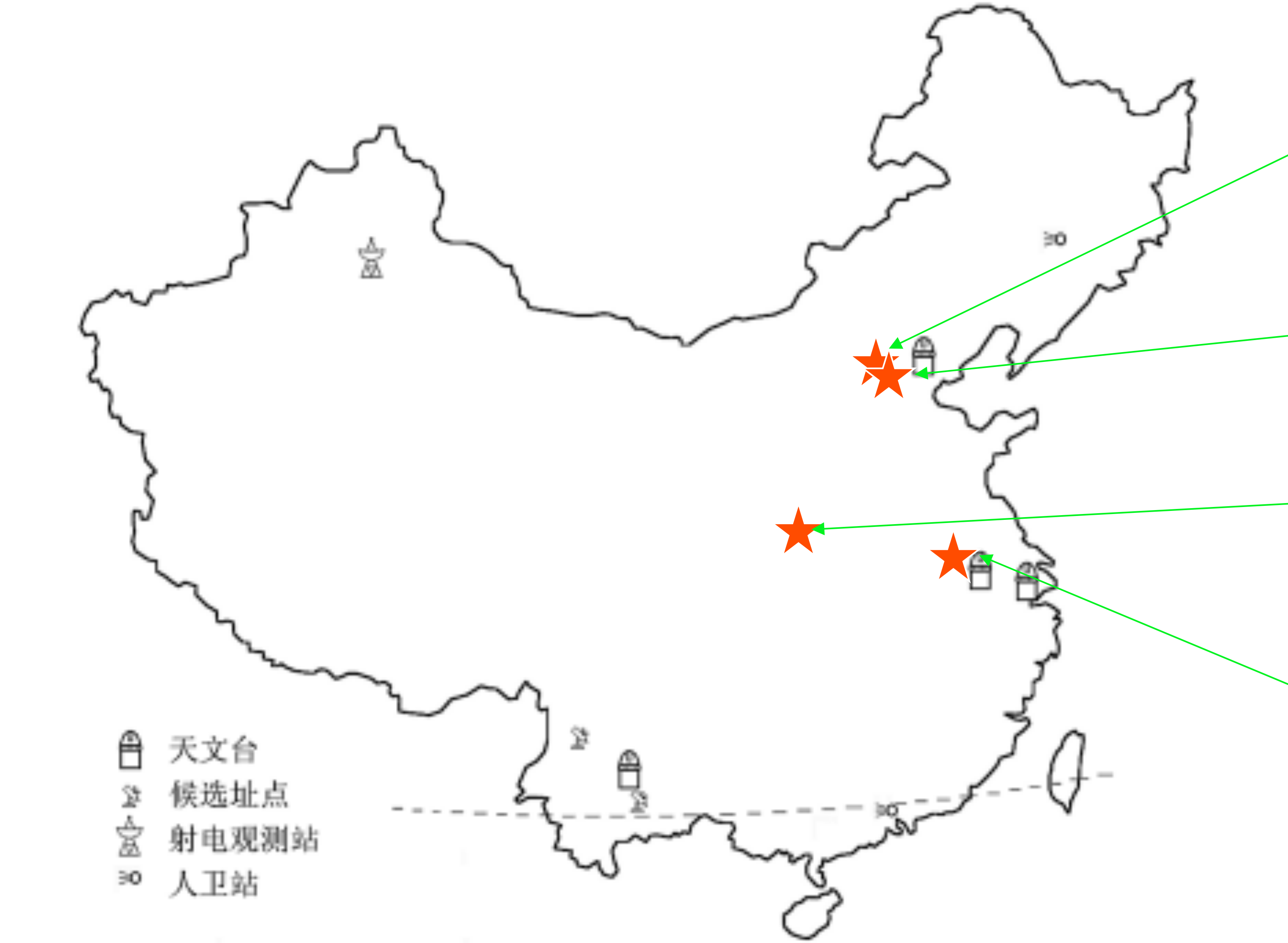
- Moon mission: launched on Oct. 24, 2007


中国探月
China Lunar Exploration Program
国防科工委月球探测工程中心 编

- HXMT:
  a Hard-X ray Modulation Telescope satellite
- Other satellites for astronomy

- New site survey in the west of China:
  —in Xinjiang province
  —in Tibet province

2. Astronomy in Chinese Universities


天文台
候选址点
射电观测站
人卫站
PKU
BNU
UST
NJU

Universities holding Department of Astronomy (DA)

- NJU: Nanjing University
  in Nanjing of Jiangsu province
  DA Staff: 30
  undergraduate student: ～30 /year
- UST: University of Science and Technology
  in Hefei of Anhui province
  DA Staff: 21
  undergraduate student: ～20 /year

Universities holding Department of Astronomy (DA)

- PKU: Peking University

  in Beijing

  DA Staff: 9

  undergraduate student: ～10 /year
- BNU: Beijing Normal University

  in Beijing
- Some universities with astrophysical center

Beijing Normal University and its Astronomy Dept.

Beijing Normal University: main building

Beijing Normal University: introduction

- BNU: Born in 1902
- BNU students:
  - Undergraduate student: ~9,000
  - Graduate student: ~9,000
  - Foreign student: ~1,500
  - Adult student: ~10,000
- BNU staff: ~3,000
  - Faculty member: ~1600
  - Ph.D. holder: ~75%
- BNU Faculties: 23
  - Departments: 3
  - Institutes: 10

Beijing Normal University: astronomy department

- Founded in 1960

  — the second Department of Astronomy (DA) at Universities in China
- Staff: 20

  — a modern Astrophysics Lab

  — an Astronomy Detection Technology Lab — an Accurate Satellite Orbit Determination Lab

  — an Astronomical Observations Lab

Beijing Normal University: astronomy department

— Undergraduate student: ~20 /year;
  MSc. graduate student: ~10 /year;
  Ph.D. student: ~5-8 /year;
  In total: ~130 students in astronomy.

— Master's degree in 3 areas:
  - Astrophysics,
  - Astrometry and Celestial Mechanics,
  - Optics.

— Ph.D. degree:
  - Astrophysics.

— Equipments:

two 40-cm telescopes on the campus;

one radio telescope on the campus;

¼ time of a 85-cm telescope at XL;

A computer room for students.

Beijing Normal University: astronomy department

北京師範大學
BEIJING NORMAL UNIVERSITY

Two 40-cm telescopes in Beijing

Beijing Normal University: astronomy department

Beijing Normal University: astronomy department

A radio telescope: 2.1-m

¼ time of 85-cm at Xinglong station

- Research fields:
  - —Cosmology: 3 staff members
  - —Stellar physics: 6 staff members
    variable stars, massive stars,
    star formation.
  - —Quasar: 2 staff members
  - —Galaxy: 2 staff members etc.
  - —Laboratory assistant: 2

Beijing Normal University: astronomy department

- Research funds:

  ～15,000 ＄/person/year
- Sources:

  Ministry of Education

  Ministry of Science and Technology

  National Natural Science Foundation

  Beijing Local Government

  Chinese Academy of Sciences

  Beijing Normal University

  etc.

My group

- Postdoc:

  Nan Liang: cosmology, gamma ray bursts

  Yi Zhang: cosmology

- Students:
  - Ph.D. student: 6
  - Graduate student: 5
  - Undergraduate student: 2

- Research fields
  - Cosmology: DE, X-ray clusters, Lensing
  - Gravitational waves

Thanks for all your patience!

&

Welcome to visit BNU!

北京師範大學
BEIJING NORMAL UNIVERSITY