Particle Physics in China

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Tsinghua University
June 30, 2016

BEPC & BES

The Starting Point of Particle Physics in China

张文裕同志并朱光亚同志：

文裕同志来并二机四〇一所一十八位同志一信，已由我看过，也要同志看转到。看了很高兴，这是用初步的设想，已要我们那些科学家来对此意见。

现在请文裕同志陪同全面的科学院二机部有关科学院那些同志给我们一看。由光亚同志请朱先生率领有关方面一谈吧，请不要再推，先谈出个方案来，再讨论采用。

这件事不能再延迟了。科学院必须把基础科学和理论研究抓起来，同时又要把理论研究与科学实验结合起来。高能物理研究和高能加速器的预制研究，应该成为科学院要抓的主要项目之一。所望多多有所进步的收获。

周恩来

一九七二年九月十一日

方毅同志听取李政道教授对
中国第一台高能加速器建设方案的意见

1984年10月7日，北京正负电子对撞机工程破土动工，邓小平等党和国家领导人亲自为工程奠基

A bit of history

1984 Construction start
1989 Physics with BESI
1993 CAS approved the 1st upgrade plan: higher luminosity for BEPC, BESI to BESII.

1998 Physics with BESII
2003 State council approved 2nd upgrade plan: BEPC to BEPCII, BESII to BESIII.
2004 BEPC shutdown & dismounting for BEPCII.

2008 Physics with BESIII

BEPC and BESI

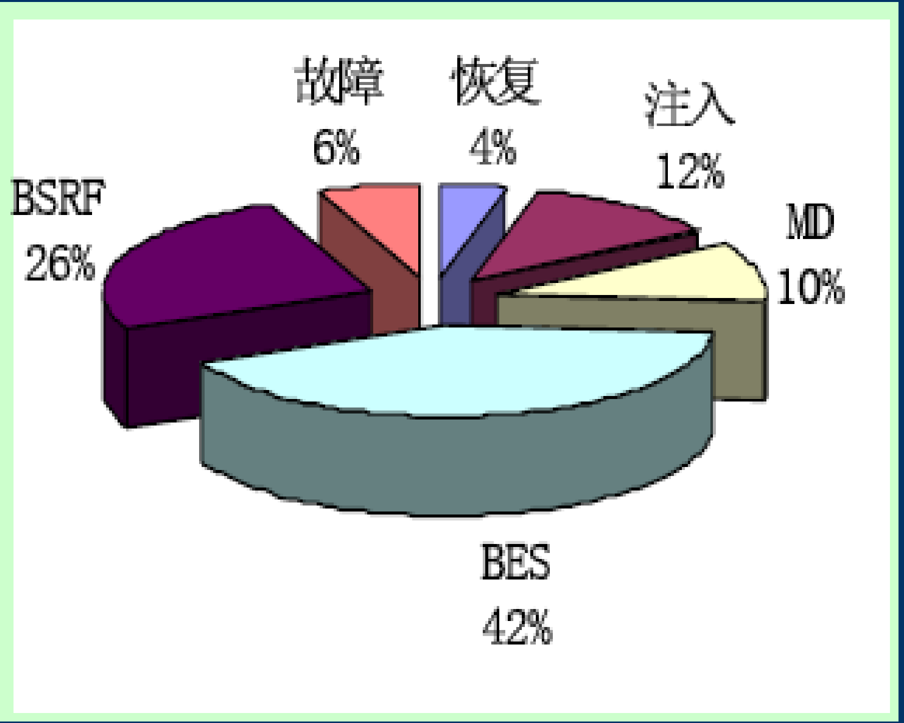
- Beijing Electron-Positron Collider (BEPC) and Beijing Spectrometer (BES) is the 1st large facility for high energy physics ever built in China.

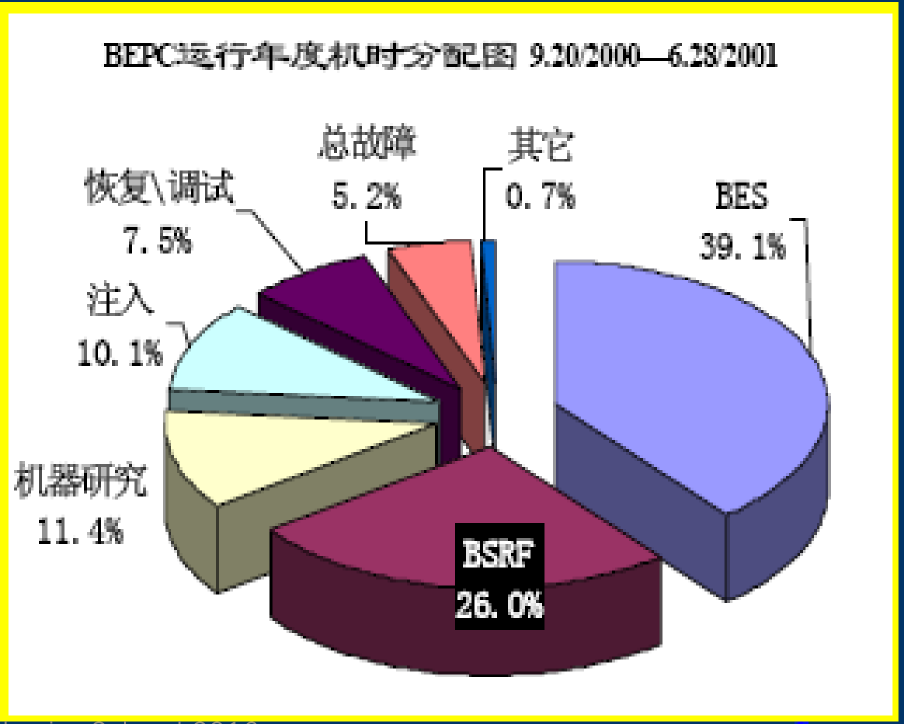
E_{cm} : 2-5 GeV

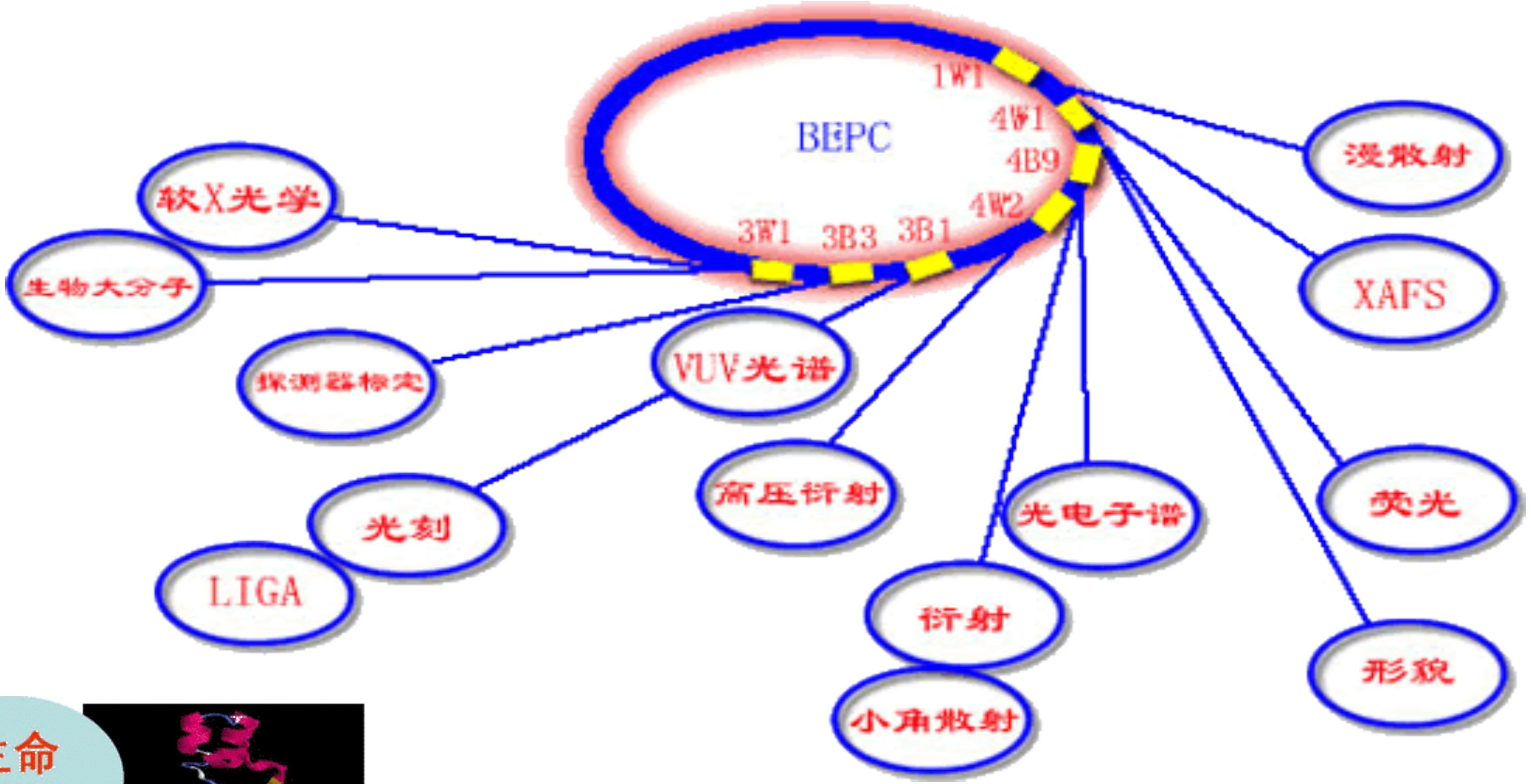
Luminosity: ~10^{30}-10^{31} $cm^{-2}s^{-1}$

年度机时分配

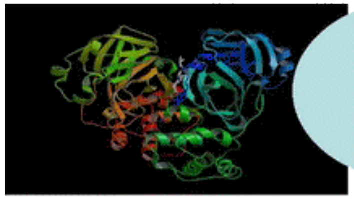
年度		运行	恢复	注入	调试	MD	BES	BSRF	其它	故障
00–01	计划	6648	266	798	-	694	2791	1700	0	399
	实际	6581	490.4	664.7	-	750.2	2574	1708	47.8	345.2



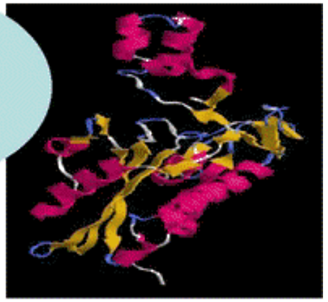




生命科学

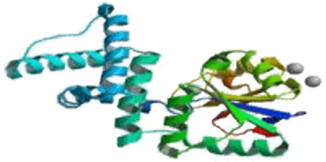


SARS主蛋白酶CoV Mpro



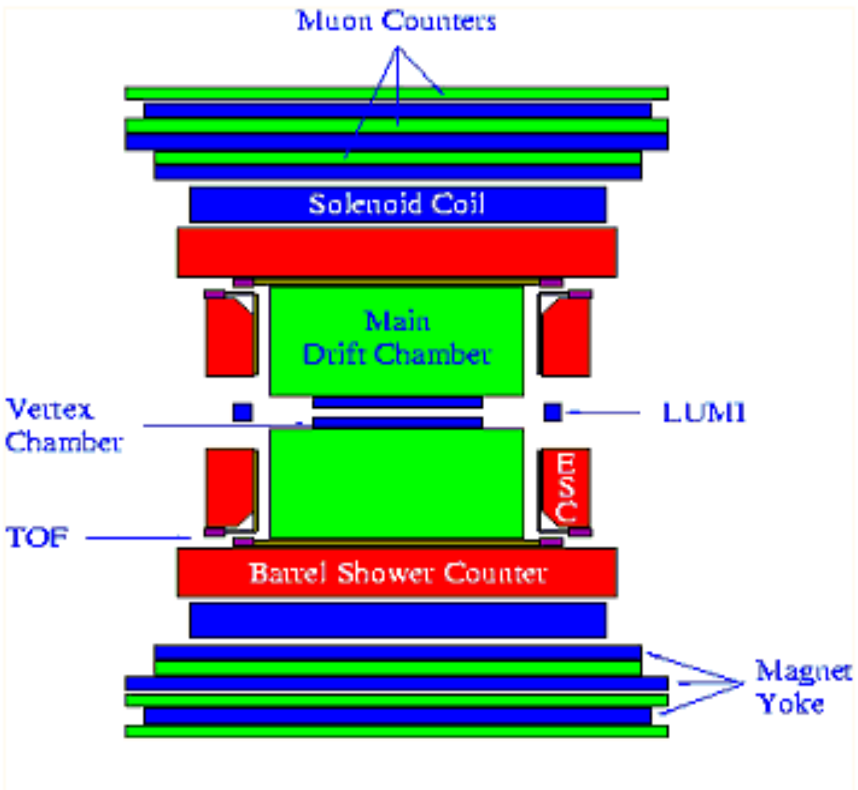
一种CRISP蛋白F3323的结构

（利用单对同晶置换+反常衍射得到结构）

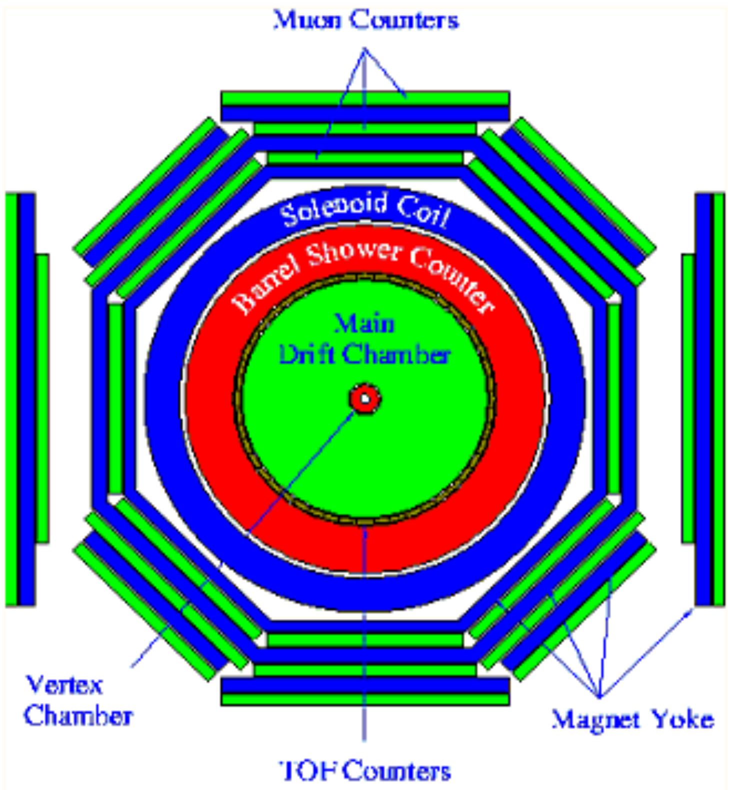


利用MAD方法解析的
甲基转移酶（MASA）的结构

BESII Detector (1995-1997 upgraded)



Side view of the BES detector



End view of the BES detector

VC: σ_{xy} = 100 μm

MDC: σ_{xy} = 250 μm

$\sigma_{dE/dx}$ = 8.4 %

$\Delta p/p = 1.8\sqrt{(1+p^2)}$

TOF: σ_T = 180 ps

BSC: $\Delta E/\sqrt{E}$ = 22 %

σ_ϕ = 7.9 mr

σ_z = 2.3 cm

μ counter: $\sigma_{r\phi}$ = 3 cm

σ_z = 5.5 cm

B field: 0.4 T

Dead time/event: 〈10 ms

Institutions (ever) in BES Collaboration

Institute of High Energy Physics
California Institute of Technology
CCAST
Chonhuk University
Colorado State University
Gyeongsang National University
Henan Normal University
Huazhong Normal University
Hunan University
KEK
Korea University
Liaoning University
Miyazaki University
Nankai University
Nihon University
Queen Mary University of London

Peking University
Shandong University
Shanghai Jiaotong University
Sichuan University
SLAC
Seoul National University
University of Hawaii
University of California at Irvine
University of Science and Technology of China
University of Texas at Dallas
Tokyo Institute of Technology
University of Tokyo
Tsinghua University
Wuhan University
Zhejiang University

Highlights of BESI/BESII Physics Results

- Precise measurement of the mass of tau lepton
- Precise measurement of R value in 2-5 GeV
- $\psi(2S)$ decays: Study many decay modes, the 12% rule
- J/ψ decays: Light hadron spectroscopy, search for
- multi-quark candidates, glueballs
- $\psi(3770)$ decays and D physics

Selected results from BESI/BESII

- τ mass measurement (1991)

Lepton universality was re-confirmed!

PDG2007

τ MASS

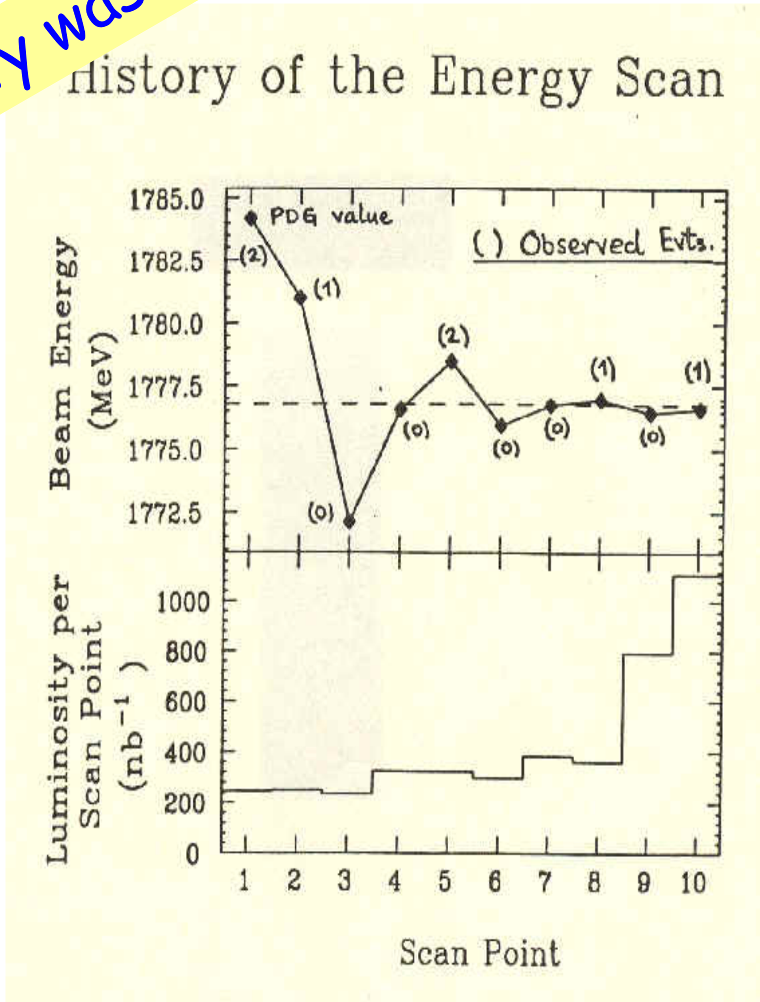
VALUE (MeV)	EVTS	DOCUMENT ID		TECN	COMMENT
1776.90±0.20 OUR AVERAGE					
$1776.81^{+0.25}_{-0.23} \pm 0.15$	81	ANASHIN	07	KEDR	6.7 [illegible] .54–3.78GeV
$1775.1 \pm 1.6 \pm 1.0$	13.3k	[1] ABBIENDI	00A	O[illegible]	[illegible] 1995 LEP runs
$1778.2 \pm 0.8 \pm 1.2$		ANASTASSOV	97	CLE[illegible]	E^{ee}_{cm}= 10.6 GeV
$1776.96^{+0.18}_{-0.21}{}^{+0.25}_{-0.17}$	65	[2] BAI	96	BES	E^{ee}_{cm}= 3.54–3.57 GeV
$1776.3 \pm 2.4 \pm 1.4$	11k	[3] ALBRECHT	92M	ARG	E^{ee}_{cm}= 9.4–10.6 GeV
$1783 \ {}^{+3}_{-4}$	692	[4] BACINO	78B	DLCO	E^{ee}_{cm}= 3.1–7.4 GeV
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$1777.8 \pm 0.7 \pm 1.7$	35k	[5] BALEST	93	CLEO	Repl. by ANASTASSOV 97
$1776.9 \ {}^{+0.4}_{-0.5} \pm 0.2$	14	[6] BAI	92	BES	Repl. by BAI 96

[1] ABBIENDI 00A fit τ pseudomass spectrum in $\tau \rightarrow \pi^{\pm} \leq 2\pi^0 \nu_\tau$ and $\tau \rightarrow \pi^{\pm}\pi^{+}\pi^{-} \leq 1\pi^0 \nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[2] BAI 96 fit $\sigma(e^+e^- \rightarrow \tau^+\tau^-)$ at different energies near threshold.

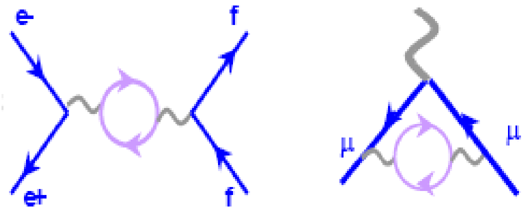
[3] ALBRECHT 92M fit τ pseudomass spectrum in $\tau^- \rightarrow 2\pi^-\pi^+\nu_\tau$ decays. Result assumes m_{ν_τ}=0.

[4] BACINO 78B value comes from $e^{\pm}X^{\mp}$ threshold. Published mass 1782 MeV increased by 1 MeV using the high precision $\psi(2S)$ mass measurement of ZHOLENTZ 80 to eliminate the absolute SPEAR energy calibration uncertainty.



Selected results from BESI/BESII

- R measurement (1998-1999)

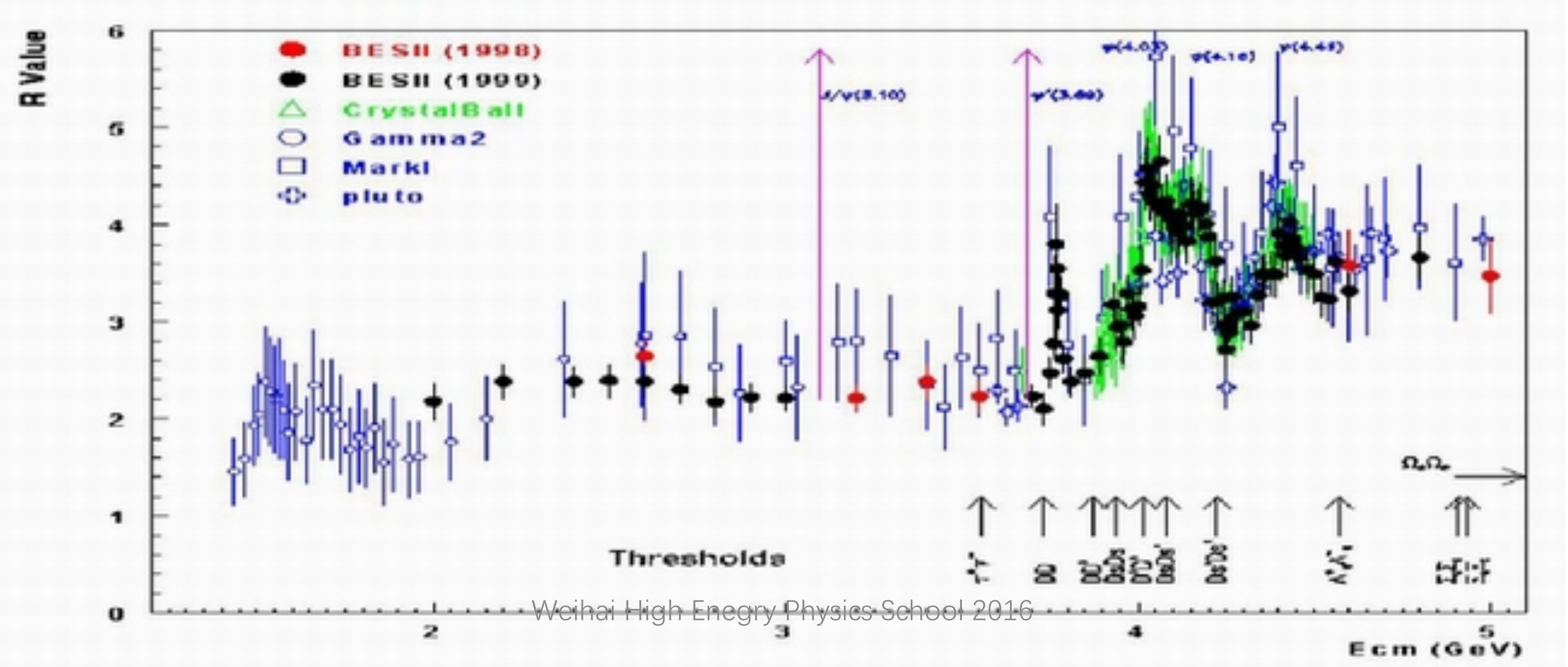


$\alpha(m^2_Z) = \alpha/(1-\Delta\alpha)$ $a_\mu \sim \alpha(Q^2)/2\pi$

$$\Delta\alpha_{lepton} = \sum_{l=e,\mu,\tau} \frac{\alpha}{3\pi}\left(\log\frac{m_Z^2}{m_l^2} - \frac{5}{3}\right) + \ldots$$

Optical Theorem

$$\Delta\alpha_{hadron} = -\frac{\alpha}{3\pi}\int_{4m_\pi^2}^{\infty} \frac{m_Z^2 ds'}{s'\left[s'-m_Z^2\right]} \frac{\sigma(e^+e^- \to \gamma^* \to q\bar{q})}{\sigma(e^+e^- \to \gamma^* \to \mu^+\mu^-)}$$



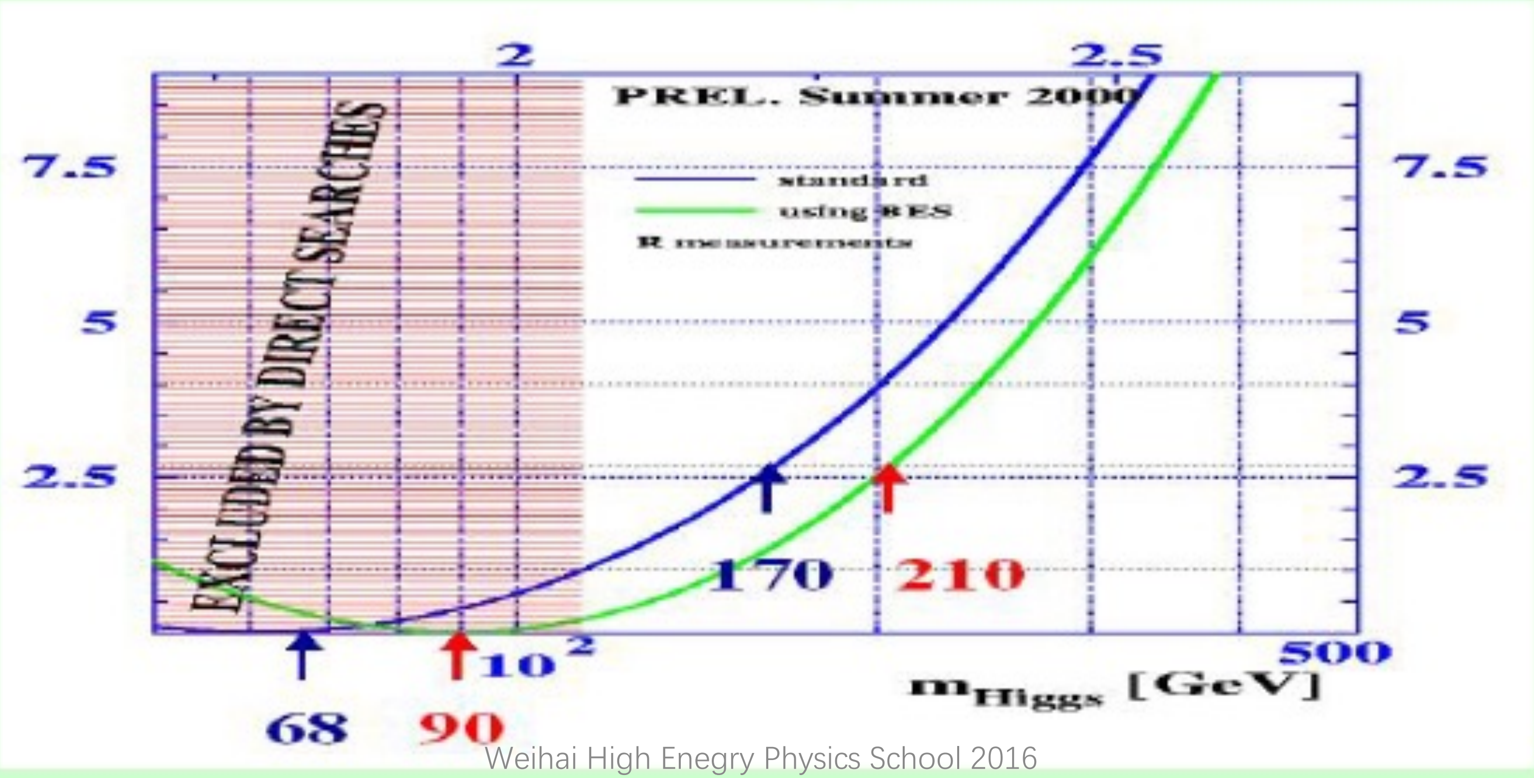
Impact of BES's New R Values on the SM Fit for α(M_z^2) and Higgs mass

1995 before BES R data

$$\alpha(M_Z^2)^{-1} = 128.890 \pm 0.090$$

2001 after BES R data

$$\alpha(M_Z^2)^{-1} = 128.936 \pm 0.046$$



18

Selected results from BESI/BESII

- Test the 12% rule

$$Q_h = \frac{B_{\psi'} \quad \times}{B_{J/\psi} \quad \times} = \frac{B_{\psi'} \quad e^+e}{B_{J/\psi} \quad e^+e} = 12\%$$

M. Appelquist and H. D. Politzer, PRL34, 43 (1975)

$$\Gamma_h = |M_h|^2 |\Psi(0)|^2$$

$$= (2/9\pi)(\pi^2 - 9)\tfrac{5}{18}\alpha_s{}^3(\tfrac{4}{3}\alpha_s)^3 m_{\varphi'}. \quad (3)$$

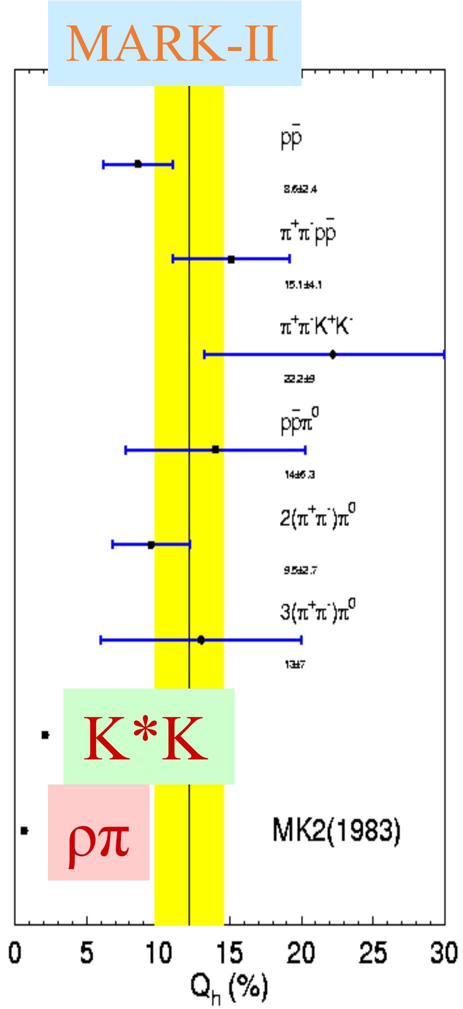
The leptonic width via one photon into $\bar{l}l$ is

$$\Gamma_l = |M_l|^2 |\Psi(0)|^2 = \tfrac{1}{2}(\tfrac{2}{3}\alpha)^2(\tfrac{4}{3}\alpha_s)^3 m_{\varphi'}, \quad (4)$$

where $\alpha \approx \frac{1}{137}$. Although separately these calculations are not trustworthy, the ratio

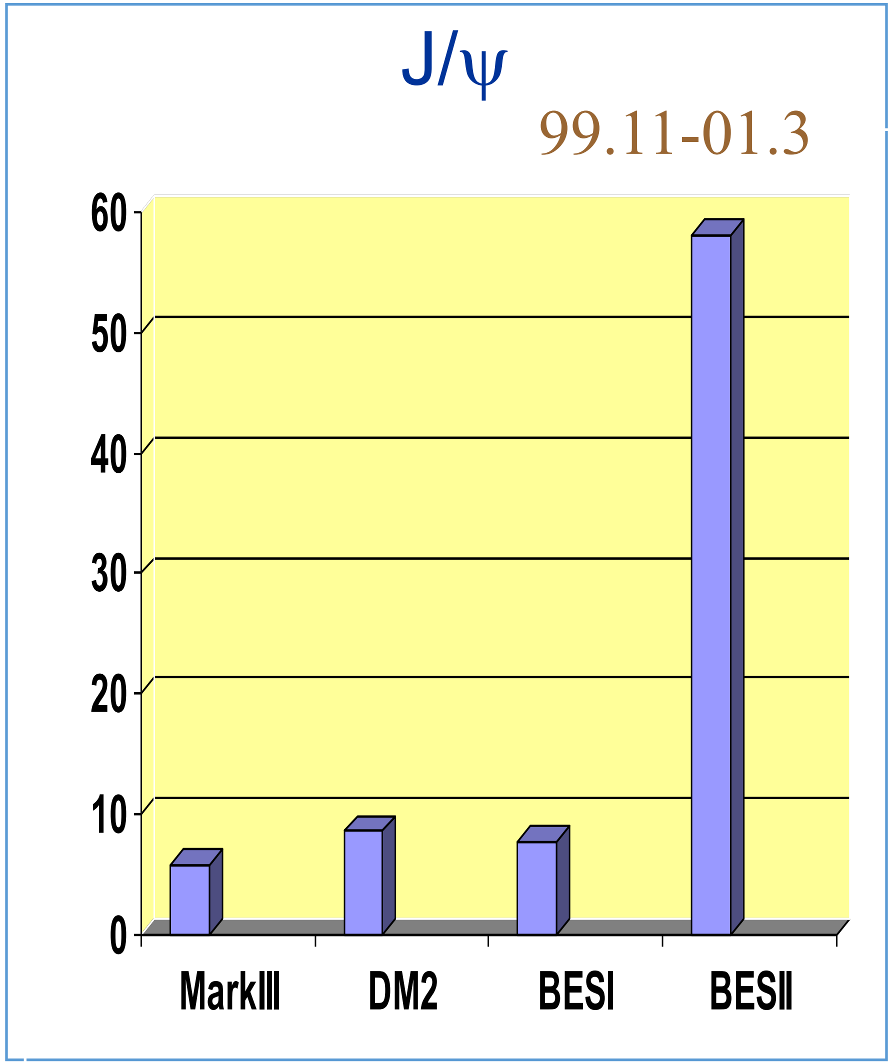
$$\frac{\Gamma_l}{\Gamma_h} = \frac{\frac{2}{9}\alpha^2}{(2/9\pi)(\pi^2 - 9)5/\alpha_s{}^3} \quad (5)$$

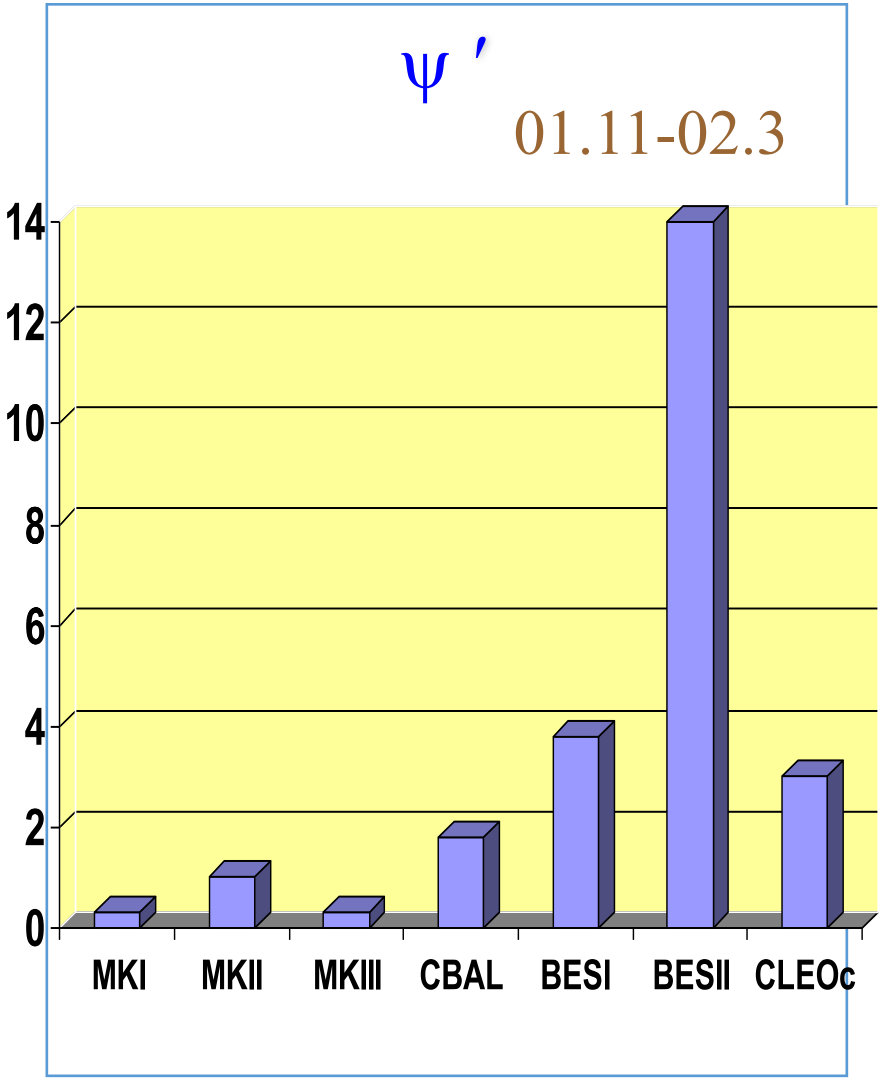
is independent of wave-function effects.



"ρπ puzzle"

World largest J/ψ and ψ′ data samples (10^6)





Extensively studied by BESII

- VP mode: $\rho\,\pi$, $K^{*+}K^{-}$+c.c., $K^{*0}K^{0}$+c.c., $\omega\pi^0$,…
- PP mode: $K_S K_L$, K^+K^-, $\pi^+\pi^-$
- VT mode: $K{*}K{*}_2$, $\phi f_2'$, $\rho a2$, ωf_2
- 3-body: $p\bar{p}\pi^0$, $p\bar{p}\eta$, $p\bar{n}\pi^-$, $\bar{p}n\pi^+$, …
- Multi-body: $\pi^+\pi^-\pi^0$ K^+K^- , $3(\pi^+\pi^-)$, …
- Radiative mode: $\gamma K\bar{K}\pi$, $\gamma\eta\pi\pi$

ψ' → VP : suppressed

ψ' → PP : enhanced/suppressed

ψ' → VT : suppressed

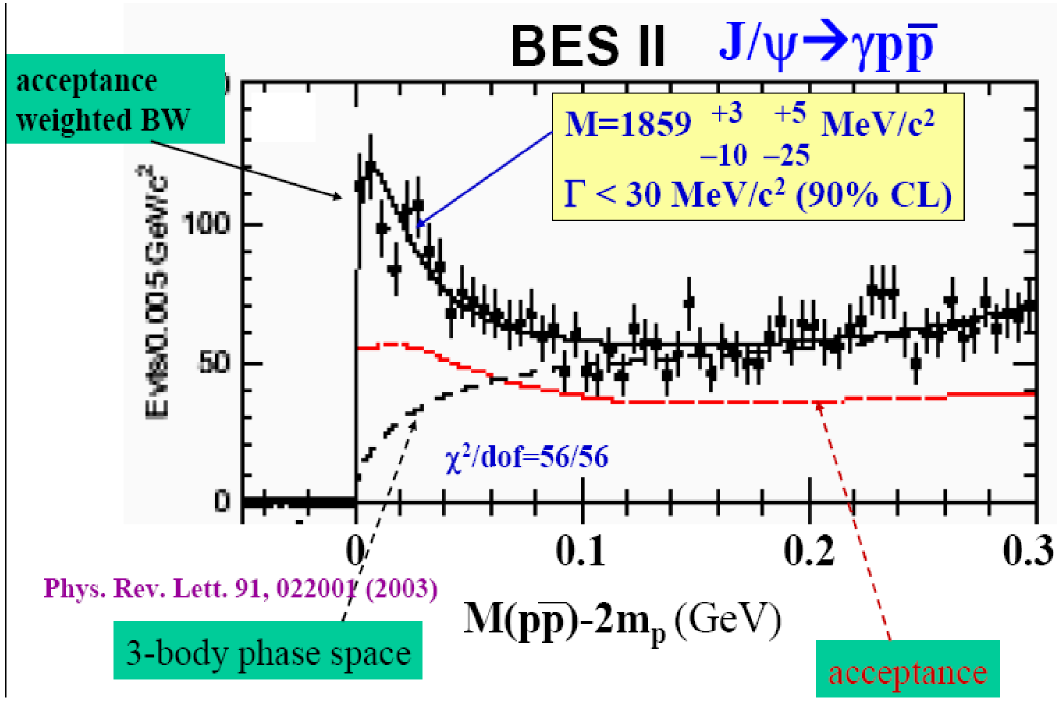
Multi-body : obey/sup

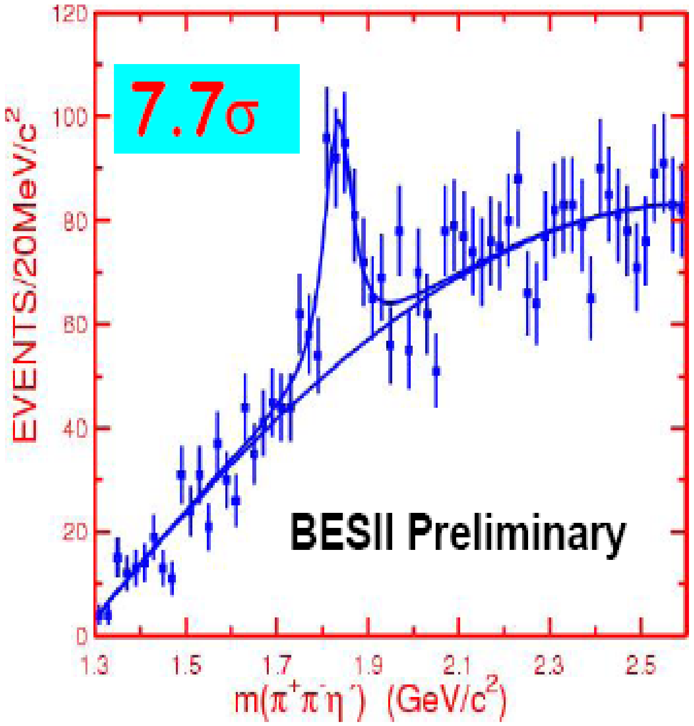
Radiative : enhanced/suppressed

Is there a rule here?

Selected results from BESI/BESII

- X(1835)





The $\pi^+\pi^-\eta'$ mass spectrum for η' decaying into $\eta' \to \pi^+\pi^-\eta$ and $\eta' \to \gamma\rho$

$N_{obs} = 264 \pm 54$

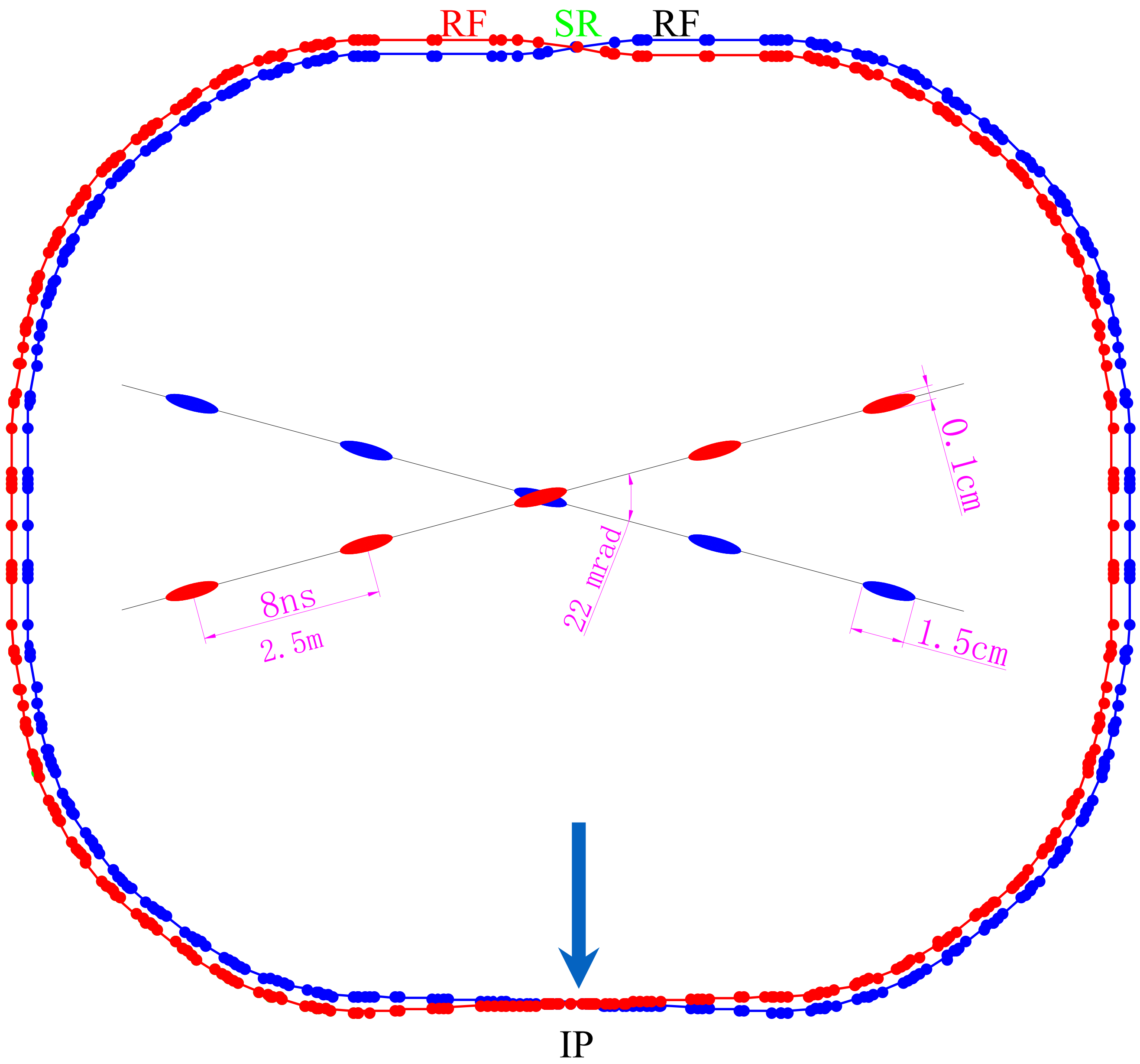
$m = 1833.7 \pm 6.1 \pm 2.7 MeV$

$\Gamma = 67.7 \pm 20.3 \pm 7.7 MeV$

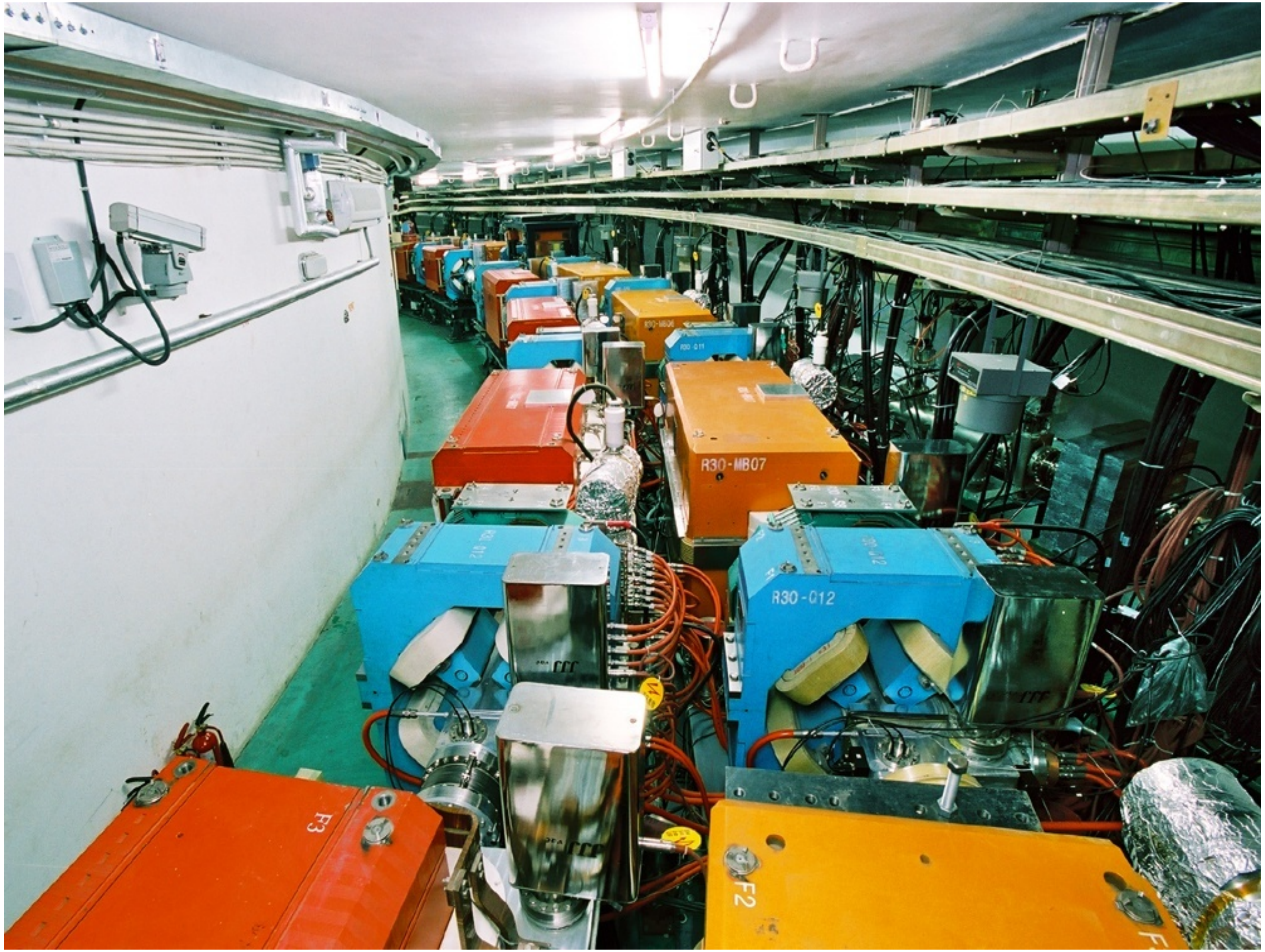
BEPCII and BESIII upgrade

- The state council approved the upgrade plan in 2003, total budget 650M RMB
- Upgrade BEPC to a tau-charm factory: BEPCII
- Build a state of the art detector: BESIII
- First physics run in 2008

BEPC II Storage ring: Large angle, double-ring

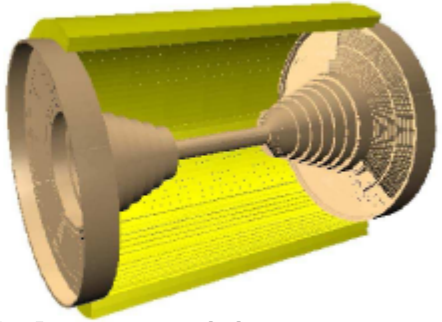


Beam energy:
1.0-2.3 GeV
Luminosity:
1×10^{33} $cm^{-2}s^{-1}$
Optimum energy:
1.89 GeV
Energy spread:
5.16×10^{-4}
No. of bunches:
93
Bunch length:
1.5 cm
Total current:
0.91 A
SR mode:
0.25A @ 2.5 GeV

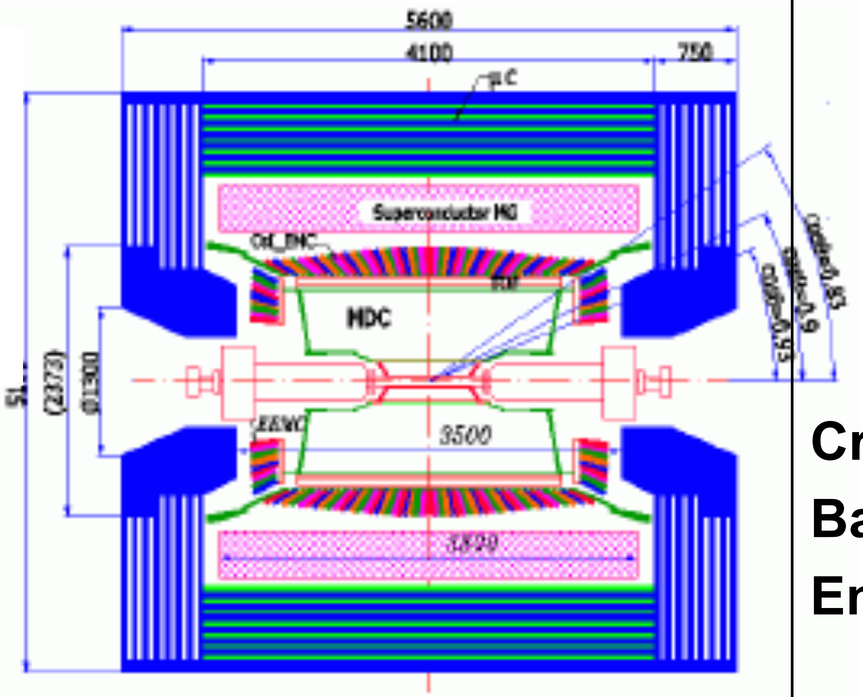

R30-MB07
R30-Q12
F3
F2

BESIII Detector

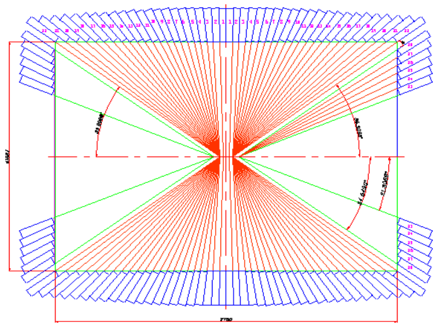
MDC



R inner: 63mm ;
R outer: 810mm
Length:2582 mm
Layers: 43

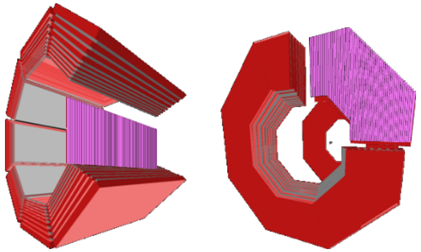


CsI(Tl) EMC



Crystals: 28 cm(15 X_0)
Barrel: $|\cos\theta|<0.83$
Endcap:
$0.85 < |\cos\theta| < 0.93$

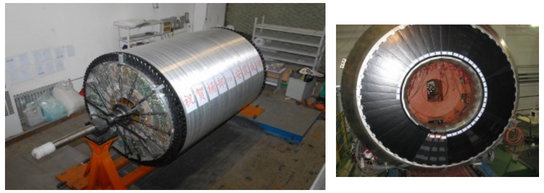
RPC MUC



BMUC: 9 layers – 72 modules
EMUC: 8 layers – 64 modules

TOF

BTOF: two layers
ETOF: 48 crys. for each



- Drift chamber and its electronics (IHEP, Sichuan, Tsinghua)
- CsI(Tl) calorimeter and its electronics (IHEP, Tsinghua)
- TOF（IHEP, USTC，Tokyo，Hawaii）
- TOF electronics （USTC）
- RPC（IHEP, Uni. of Washington）
- RPC electronics（USTC）
- Trigger（IHEP, USTC）
- DAQ & online software (IHEP, Tsinghua)
- Offline software （IHEP, Peking，Shangdong，Nanjing）
- Superconducting magnet （IHEP，Wang NMR）
- Mechanics (IHEP)
- Technical support (IHEP, Tsinghua）

BESIII International Collaboration

Political Map of the World, June 1999

US (6)

Univ. of Hawaii
Univ. of Washington
Carnegie Mellon Univ.
Univ. of Minnesota
Univ. of Rochester
Univ. of Indiana

Europe (13)

Germany: Univ. of Bochum, Univ. of Giessen, GSI
Univ. of Johannes Gutenberg
Helmholtz Ins. In Mainz
Russia: JINR Dubna; BINP Novosibirsk
Italy: Univ. of Torino, Frascati Lab, Ferrara Univ.
Netherland: KVI/Univ. of Groningen
Sweden: Uppsala Univ.
Turkey: Turkey Accelerator Center

Korea (1)

Seoul Nat. Univ.

Japan (1)

Tokyo Univ.

~400 members from
12 countries
54 institutions

Pakistan (2)

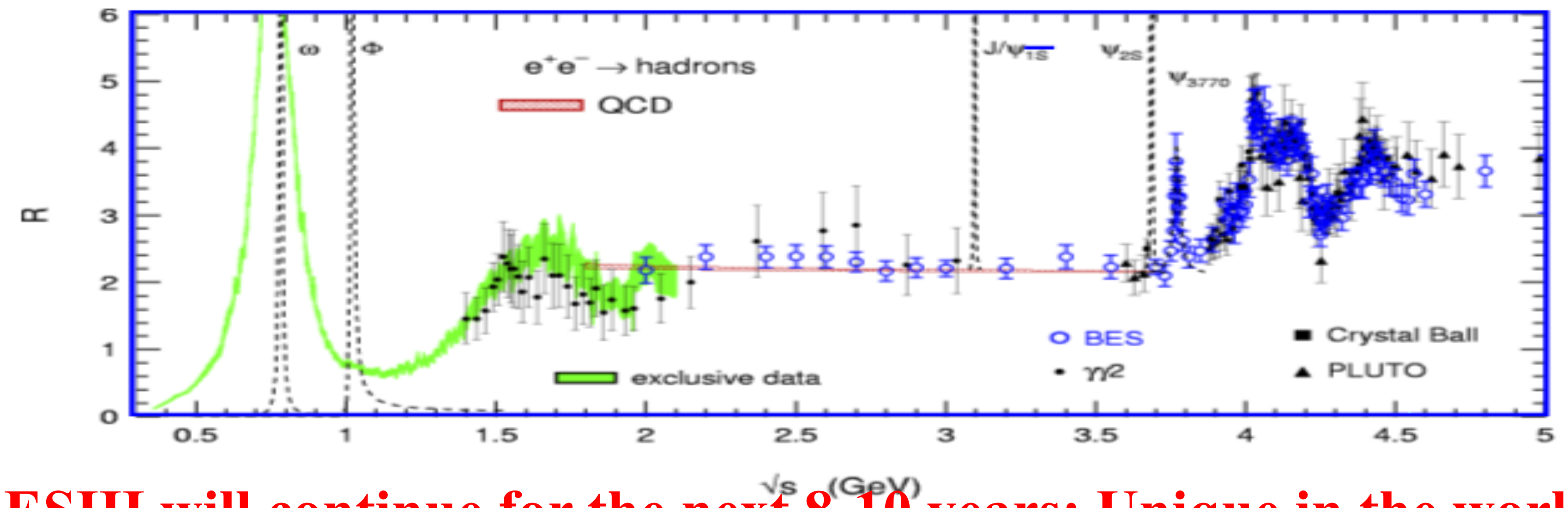
Univ. of Punjab
COMSAT CIIT

China(29)

IHEP, CCAST, GUCAS, Shandong Univ.,
Univ. of Sci. and Tech. of China
Zhejiang Univ., Huangshan Coll.
Huazhong Normal Univ., Wuhan Univ.
Zhengzhou Univ., Henan Normal Univ.
Peking Univ., Tsinghua Univ. ,
Zhongshan Univ.,Nankai Univ., Beihang Univ.
Shanxi Univ., Sichuan Univ., Univ. of South China
Hunan Univ., Liaoning Univ.
Nanjing Univ., Nanjing Normal Univ.
Guangxi Normal Univ., Guangxi Univ.
Suzhou Univ., Hangzhou Normal Univ.
Lanzhou Univ., Henan Sci. and Tech. Univ.

BESIII Data Taking Status & Plan

	Previous Data set	BESIII now	Goal
J/psi	BESII: 58M	1.2 B	10B
Psi'	CLEO: 28 M	0.5 B	3B
Psi"	CLEO: 0.8 /fb	3.0/fb	20 /fb
ψ(4040)/ψ(4160) /X(4260) etc.	CLEO: 0.6/fb @ ψ(4160)	0.5/fb ψ(4040); 2.3/fb @~4260, 0.5/fb@ ~4360; 1/fb@~4420; 0.5/fb@~4600	~ 10 /fb
R scan & Tau	BESII @10K/pnts	105 pnts@3.8-4.6 GeV	100K/pnts



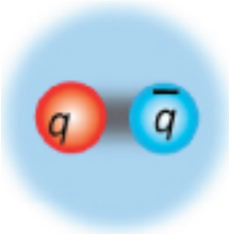
BESIII will continue for the next 8-10 years: Unique in the world

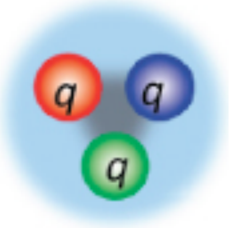
New Type of Hadrons

- Normal hadrons are made of 2 or 3 quarks：

Quark Model：

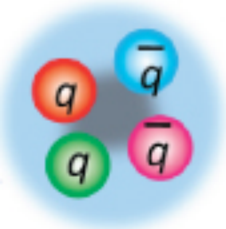
mesons



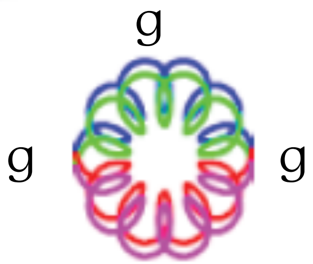


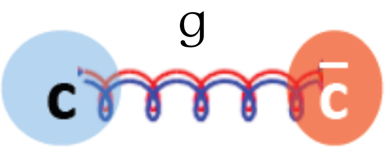
Baryons

- QCD predict new type of hadrons:
  - Multi-quark states： No. of quarks >= 4



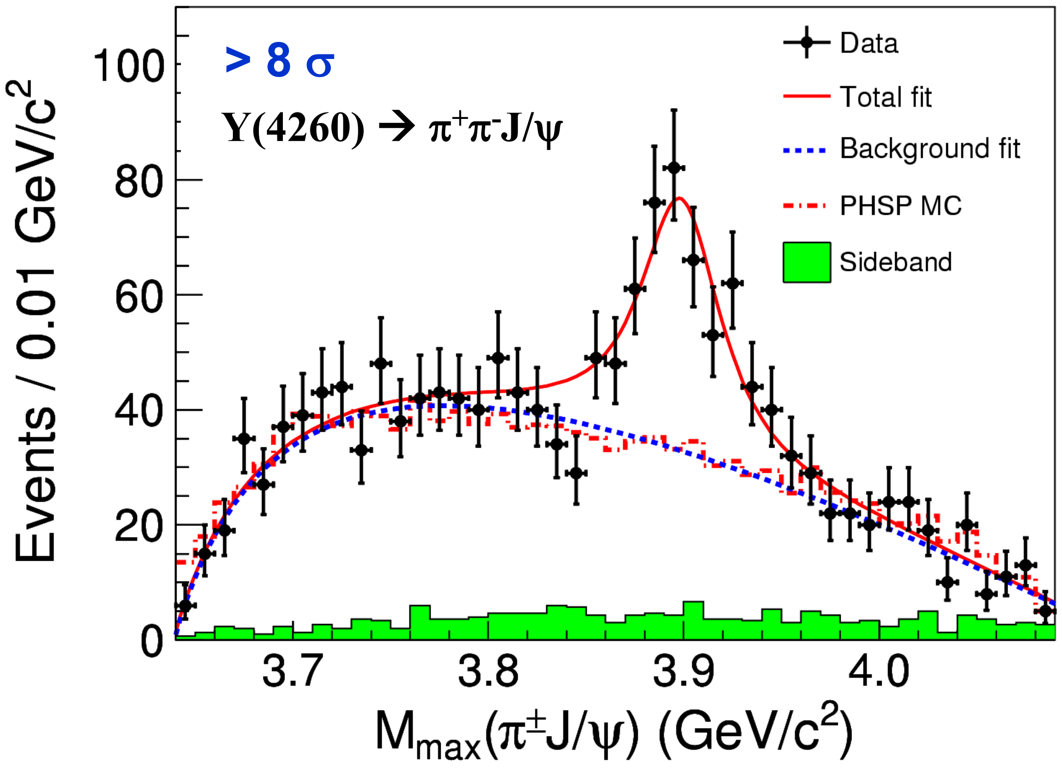
  - Hybrids： qqg
  - Glue balls： gg， ggg …





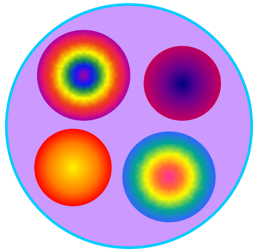
No experimental proof of new types of hadrons

BESIII: Observation of Zc(3900)



PRL110, 252001 (2013)

- Close to $M(D\bar{D}^*)$
- Couples to $c\bar{c}$
- Has electric charge
- At least 4-quarks
- What is its nature?



- S-wave Breit-Wigner with efficiency correction
- Mass = (3899.0±3.6±4.9) MeV
- Width = (46±10±20) MeV
- Fraction = (21.5±3.3±7.5)%

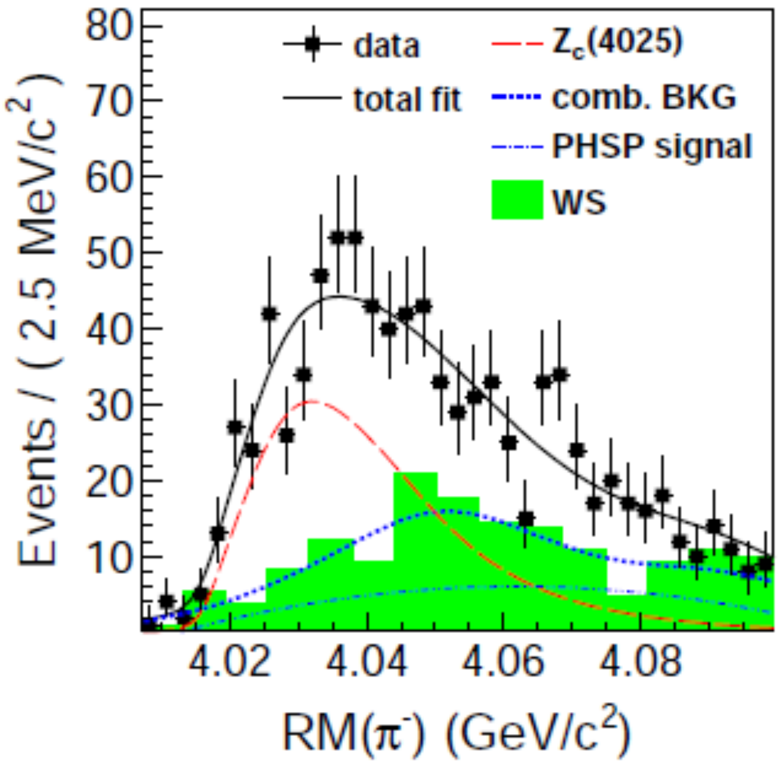
By collecting a lot of data, we may understand the nature of Y(4260), Zc and probably, many XYZ particles with the help of LQCD

$Z_c(4025)/Z_c(4020)$: Excited State of $Z_c(3900)$?

PRL 112, 132001 (2014)

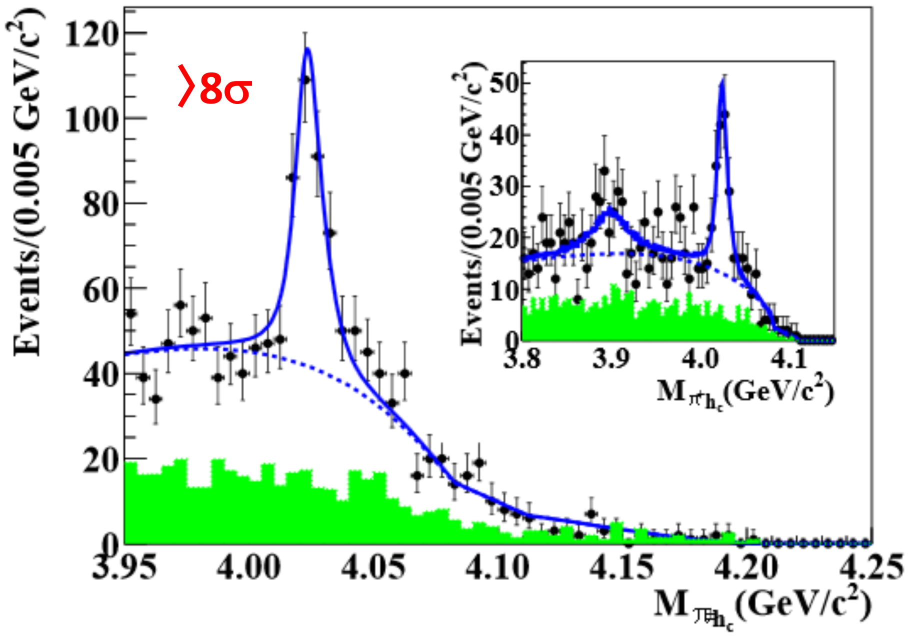
PRL 111, 242001 (2013)

$e^+e^- \rightarrow \pi^- (D^*\underline{D}^*)^+ + c.c.$

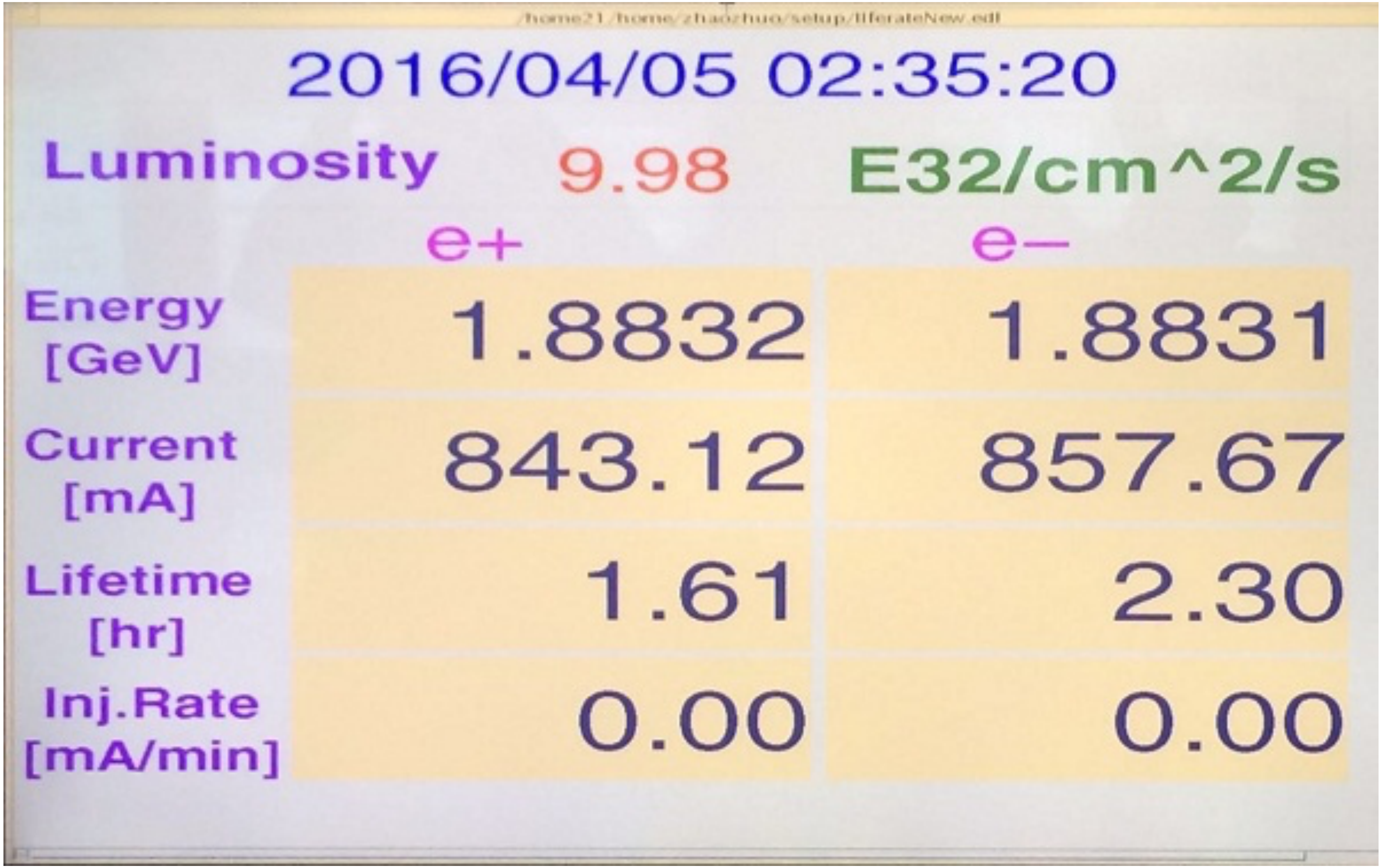


$M(Z_c(4025)) = 4026.3 \pm 2.6 \pm 3.7$ MeV;
$\Gamma(Z_c(4025)) = 24.8 \pm 5.7 \pm 7.7$ MeV

$e^+e^- \rightarrow \pi^+\pi^- h_c(1P)$

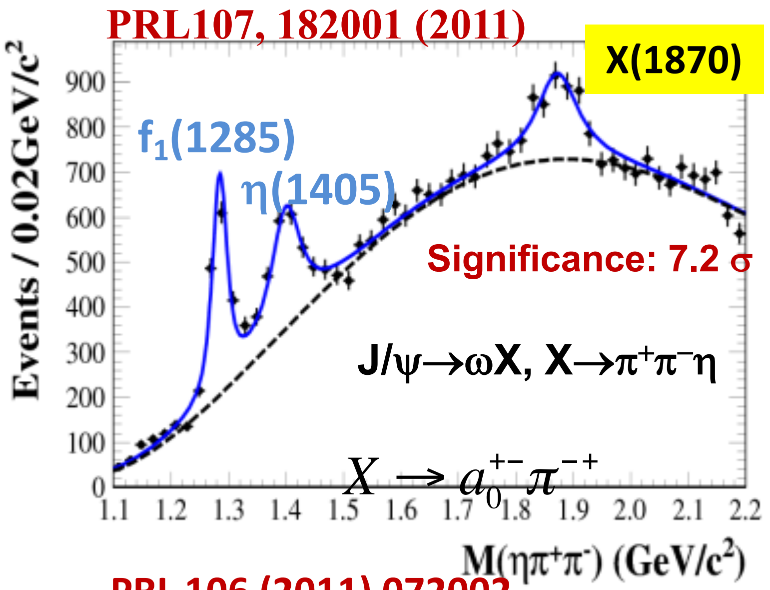


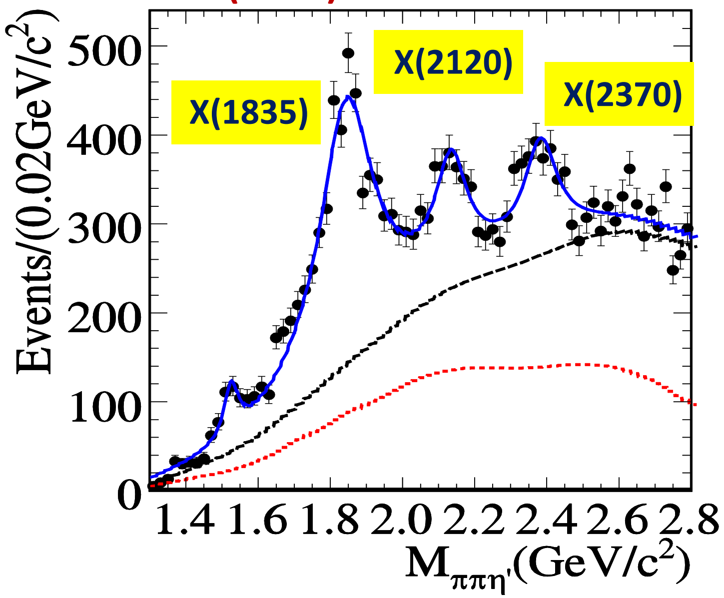
$M(Z_c(4020)) = 4022.9 \pm 0.8 \pm 2.7$ MeV
$\Gamma(Z_c(4020)) = 7.9 \pm 2.7 \pm 2.6$ MeV


/home21/home/zhaozhuo/setup/lliferateNew.edl
2016/04/05 02:35:20
Luminosity 9.98 E32/cm^2/s
e+
e−
Energy [GeV] 1.8832 1.8831
Current [mA] 843.12 857.67
Lifetime [hr] 1.61 2.30
Inj.Rate [mA/min] 0.00 0.00

Summary of physics at BEPCII/BESIII

- BEPCII/BESIII is the best facility for light hadrons spectroscopy and Charmonium physics: glueballs, m_τ, f_D, f_{Ds}, R, etc.
- ~ 20 papers/year, ~100 papers in total so far.
- BESIII will continue to operate for another ~8 years.
- After 2020, a possible scenario:
  - a circular e+e- collider at 90GeV and 250 GeV (Z & Higgs factory)
  - a pp collider in the same tunnel afterwards





#13   25-AUG-1986 04:11:24   NEWMAIL
From: VXCRNA::SHUQIN
To: STEINBERGER
Subj: link

dear jack,i am very glad to send this letter to you via computing link which
i think is first succssful link test between cern and china.i would like
to thank you again for your visit which leads this valuable test to be success.
now i think each collaborators amoung aleph callaboration have computing link wh
ich
is very important.ofcause we still have problems to use this link effectively
for analizing dst of aleph in being. and need to find budget in addition,but mos
t
important thing is to get start.at the moment,we use the ibm-pc in 710 institute
to connect to you,later we will try to use the microwave communicated equipment
which we have used for linking m160h before,to link to you dirrectly
from our institute.
lease send my best regards to all of our colleagues and best wishes to you.cynt
hia
and your family.
by the way,how about the carpet you bought in shanghai?
weimin

吴为民向瑞士的斯坦伯格教授发出的中国第一封电子邮件原件

现代物理知识 2009 Vol. 21 (3): 57-61

Particle Physics & Internet in China

1986 1st email to CERN

1991 Network link IHEP-SLAC

1993 64K BPS internet connection to the world. Email service for institutions and universities.

1994 Connected to WWW

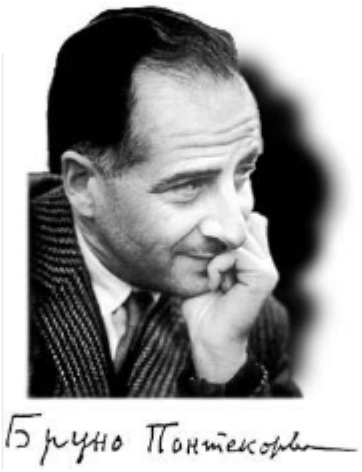
2008 LCG

DayaBay & JUNO

Neutrino Oscillation

- If the neutrino mass eigenstate is different from that of the weak interaction, neutrinos can oscillate: from one type to another during the flight:

$\nu_e \rightarrow$ $\nu_\mu \rightarrow$ $\nu_e \rightarrow$ $\nu_\mu \rightarrow$



Bruno Pontecorvo

Oscillation probability: $P(\nu_e \rightarrow \nu_\mu) = \sin^2(2\theta)\, \sin^2(1.27\Delta m^2 L/E)$

Oscillation amplitude (↑ $\sin^2(2\theta)$)

Oscillation frequency (↑ Δm^2)

Oscillation matrix for 3 generations:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

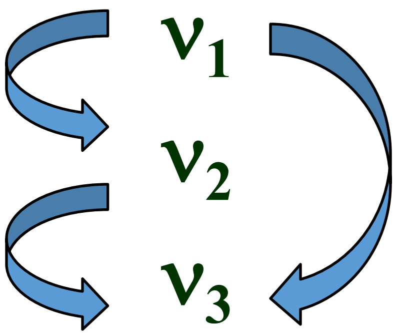
- **Known parameters:** θ_{23}, θ_{12}, $|\Delta M^2_{23}|$, ΔM^2_{12},
- **Recent progress:** θ_{13}
- **Unknown parameters:** mass hierarchy(ΔM^2_{23}), CP phase δ

Next Question in 2003: θ_{13} ?

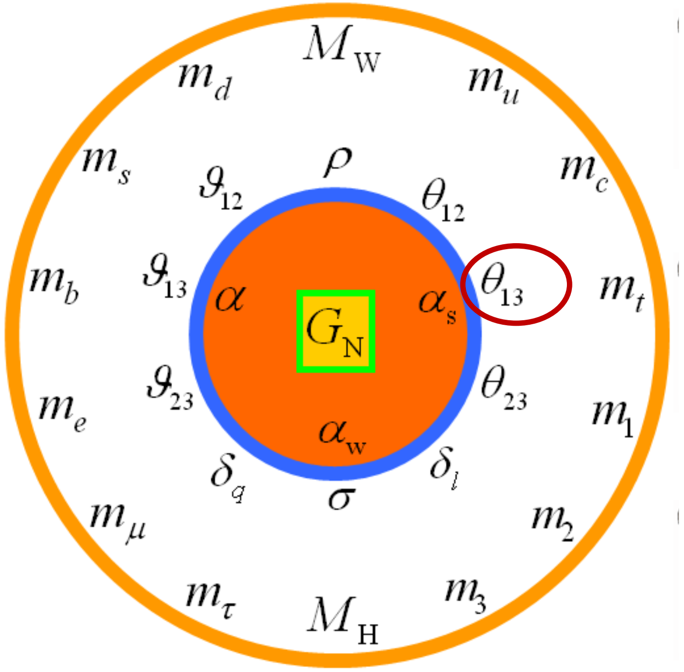
- **Fundamental principles**
- **Fundamental parameter**
- **Direction of future neutrino physics:**
  - **If θ_{13} is too small, CPV cannot be figured out in the near future**

Solar ν Oscillation
$\sin^2 2\theta_{12} \sim 0.9$

Atm. ν Oscillation
$\sin^2 2\theta_{23} \sim 1$



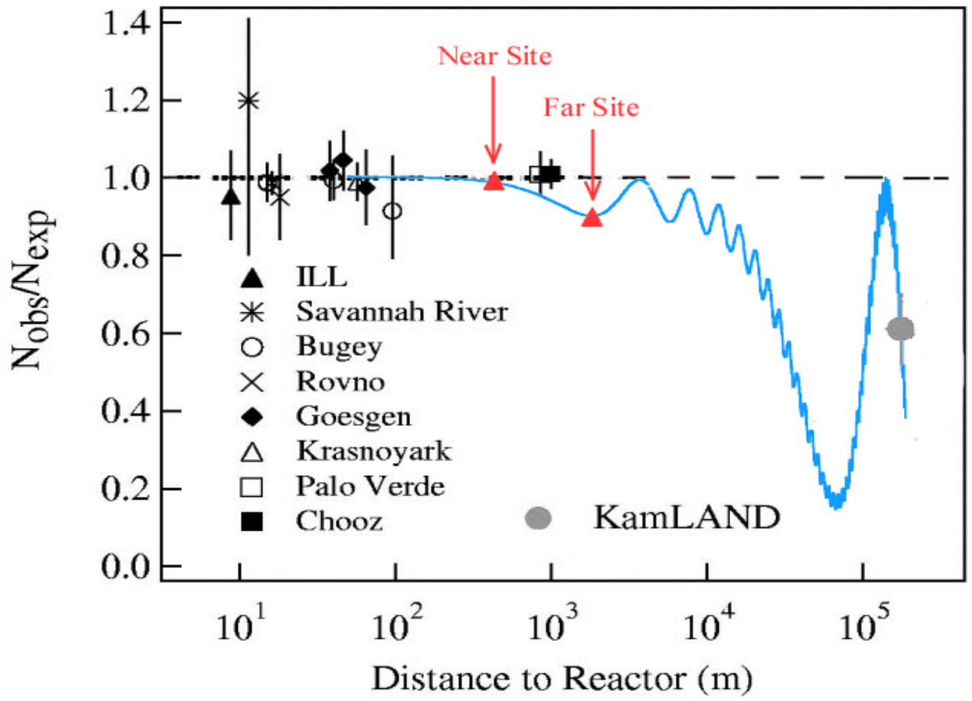
θ_{13} ?



Two ways to measure θ_{13} :
At reactor
At accelerators

How to Measure θ_{13} at Reactors ?

$$P_{e \to e} \approx 1 - \sin^2 2\theta_{13} \sin^2 (1.27 \Delta m^2_{13} L/E) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 (1.27 \Delta m^2_{12} L/E)$$



Precision of past experiments (typically 3-6%):

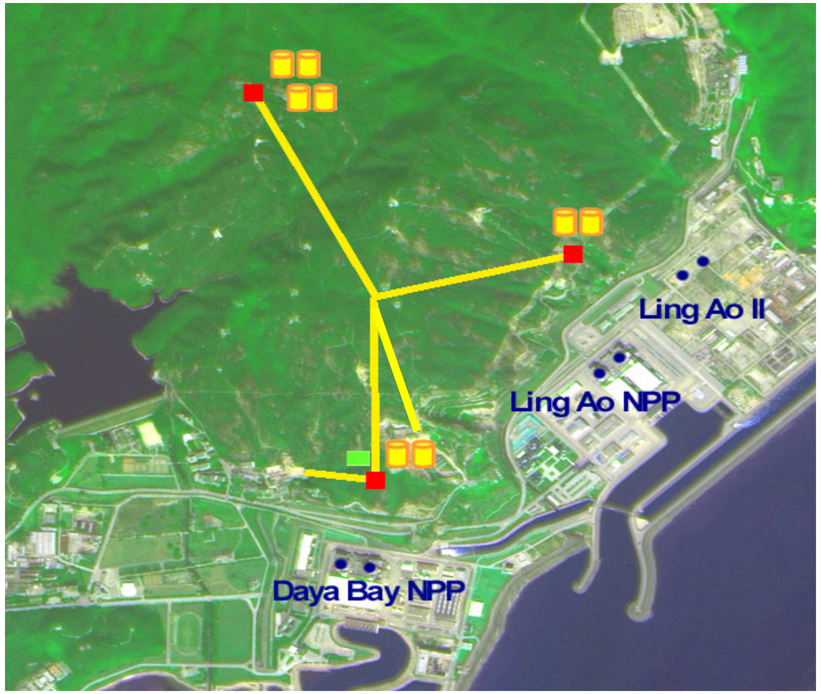
- Reactor power: ~ 1%
- Spectrum: ~ 0.3%
- Fission rate: 2%
- Backgrounds: ~1-3%
- Target mass: ~1-2%
- Efficiency: ~ 2-3%

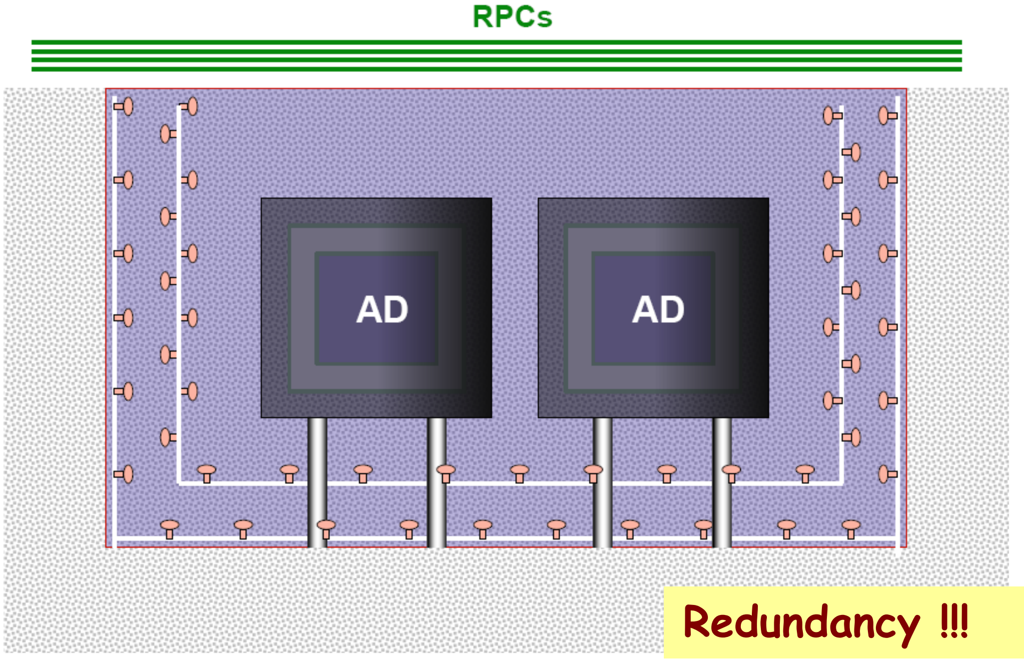
Past searches: $\sin^2 2\theta_{13} < 0.15$ @ 90%C.L.

Model prediction: $\sin^2 2\theta_{13} \sim$ 0-0.20, but mostly around 0.01

Our design goal: $\Delta(N_{obs}/N_{exp}) \sim 0.4\%$ ➔ ÷10 improvement !

Daya Bay Experiment: Layout





- Relative measurement to cancel Corr. Syst. Err.
  - **2 near sites, 1 far site**
- Multiple AD modules at each site to reduce Uncorr. Syst. Err.
  - **Far: 4 modules，near: 2 modules** Cross check; Reduce errors by $1/\sqrt{N}$
- Multiple muon detectors to reduce veto eff. uncertainties
  - **Water Cherenkov： 2 layers**
  - **RPC： 4 layers at the top + telescopes**

The Daya Bay Collaboration

Europe (2)

JINR, Dubna, Russia
Charles University, Czech Republic

North America (16)

BNL, Caltech, LBNL, Iowa State Univ., Illinois Inst. Tech., Princeton, RPI, UC-Berkeley, UCLA, Univ. of Cincinnati, Univ. of Houston, Univ. of Wisconsin, William & Mary, Virginia Tech., Univ. of Illinois-Urbana-Champaign, Siena

~250 Collaborators

Asia (20)

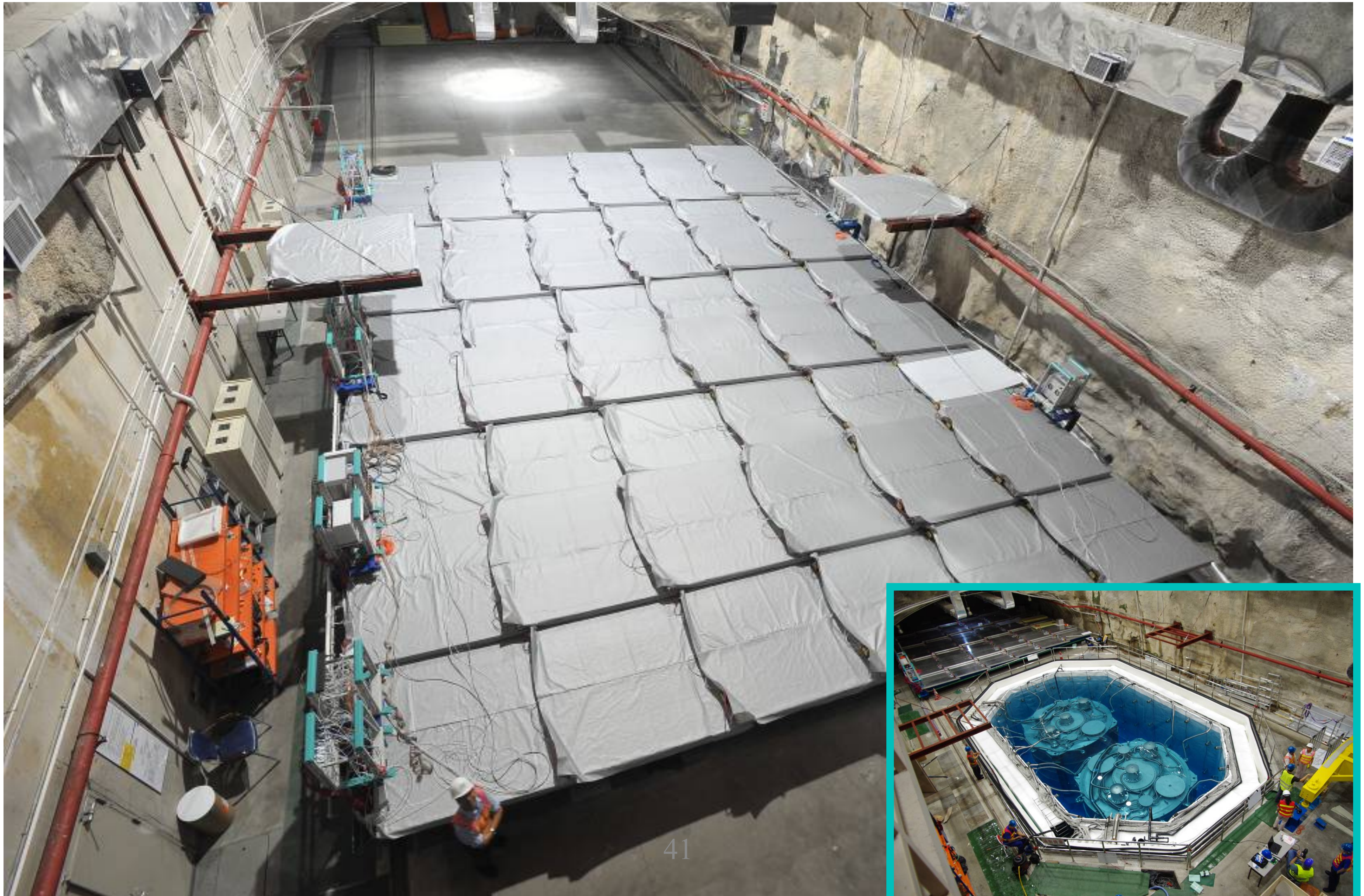
IHEP, Beijing Normal Univ., Chengdu Univ. of Sci. and Tech., CGNPG, CIAE, Dongguan Polytech. Univ., Nanjing Univ., Nankai Univ., NCEPU, Shandong Univ., Shanghai Jiao tong Univ., Shenzhen Univ., Tsinghua Univ., USTC, Zhongshan Univ., Univ. of Hong Kong, Chinese Univ. of Hong Kong, National Taiwan Univ., National Chiao Tung Univ., National United Univ.

Tunnel and Underground Lab

- Tunnel: ~ 3100m
- 3 Exp. hall
- 1 hall for LS
- 1 hall for water

A total of ~ 3000 blasting right next reactors. No one exceeds safety limit set by National Nuclear Safety Agency（0.007g）

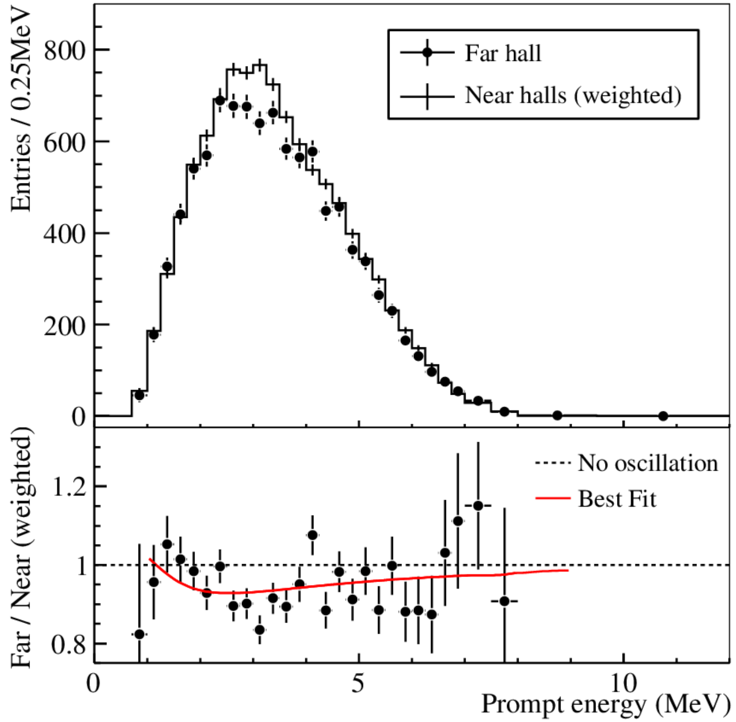
Experimental Hall in Operation

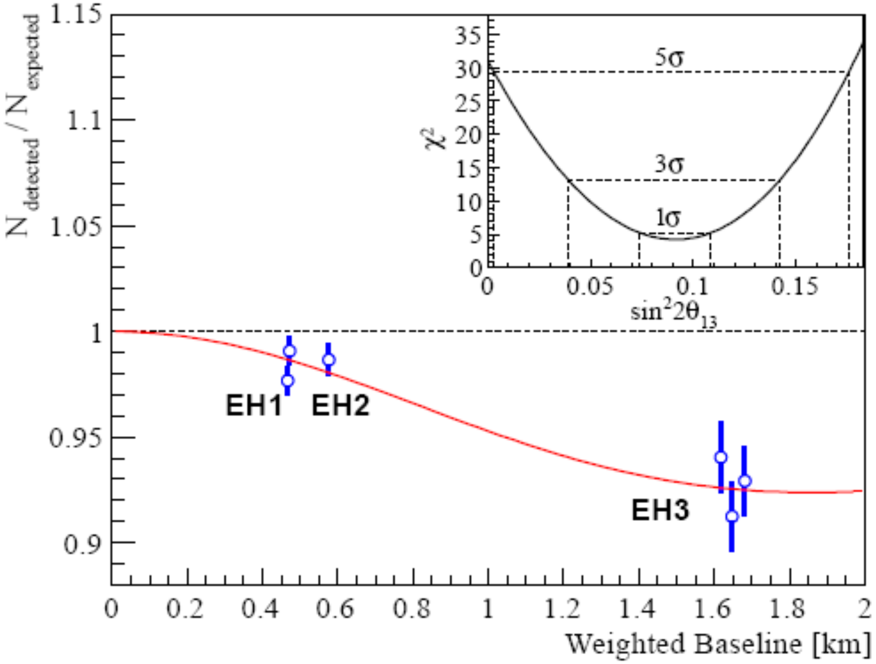


- Observation of electron anti-neutrino disappearance:

R = 0.940 ±0.011 (stat) ±0.004 (syst)

announced on Mar. 8, 2012





$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

$\chi^2/NDF = 4.26/4$, 5.2 σ for non-zero θ_{13}

F.P. An et al., NIM. A 685(2012)78

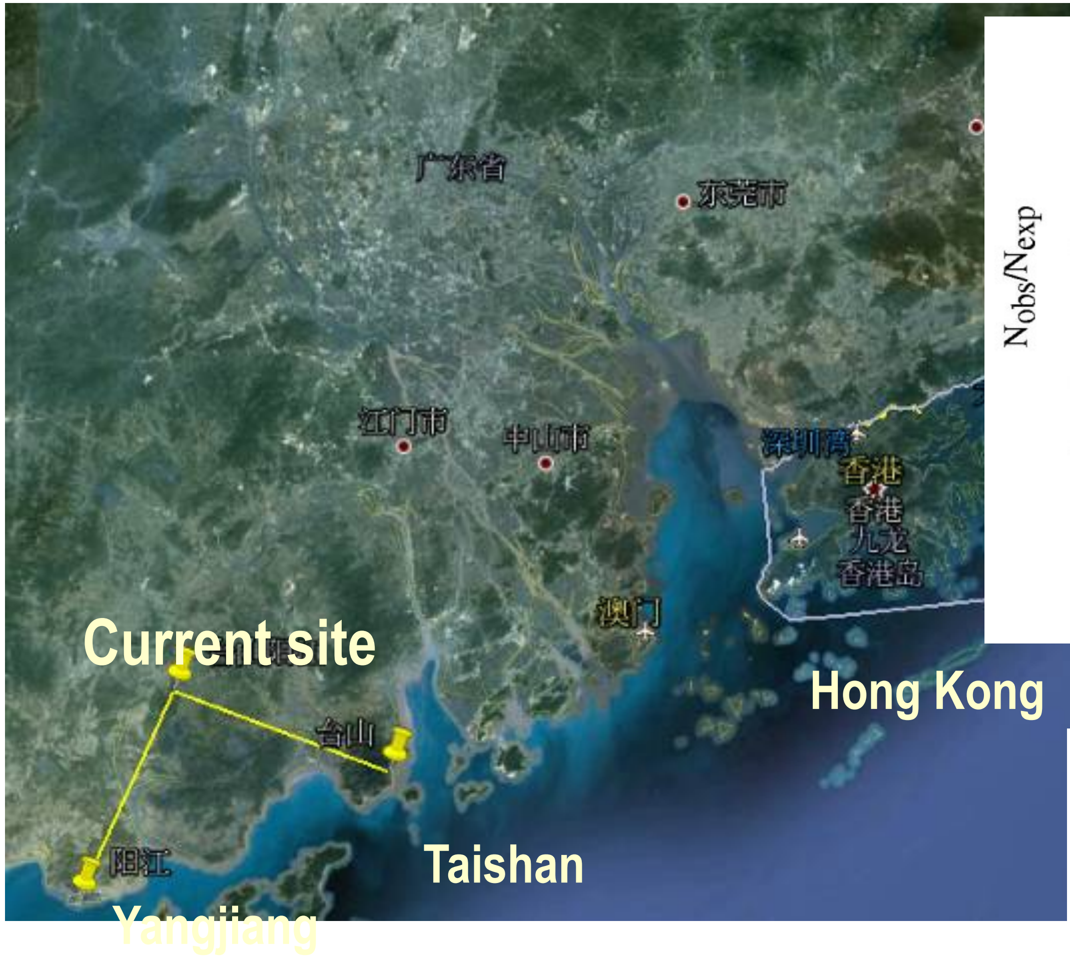
F.P. An et al., Phys. Rev. Lett. 108, (2012) 171803

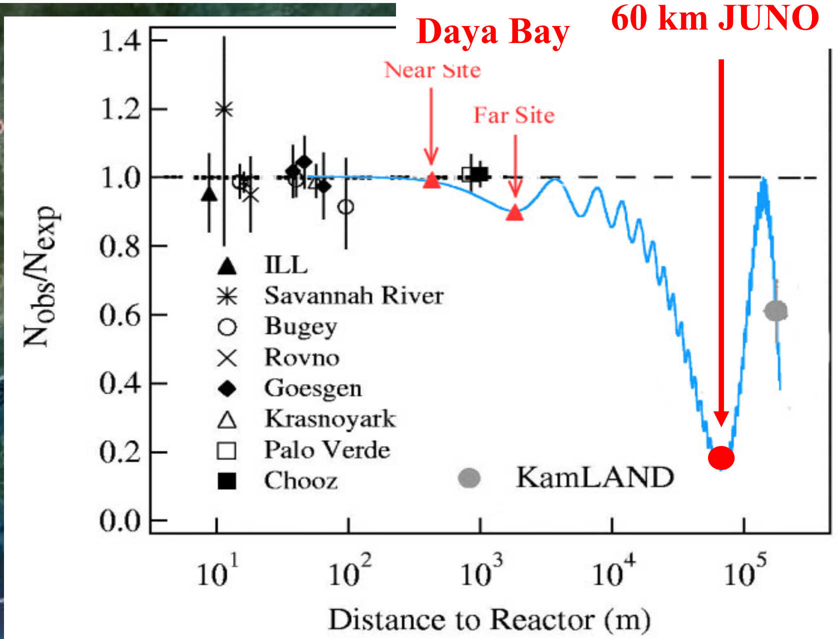
Still a Lot of Unknowns

- Neutrino oscillation:
  - **Neutrino mass hierarchy ?**
  - **Unitarity of neutrino mixing matrix ?**
  - **Θ_{23} is maximized ?**
  - **CP violation in the neutrino mixing matrix as in the case of quarks ? Large enough for the matter-antimatter asymmetry in the Universe ?**
- What is the absolute neutrino mass ?
- Neutrinos are Dirac or Majorana ?
- Are there sterile neutrinos?
- Do neutrinos have magnetic moments ?
- Can we detect relic neutrinos ?
- ……

Next Step: Mass Hierarchy

	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	running	planned	approved	Construction	construction
power/GW	17.4	17.4	17.4	17.4	18.4

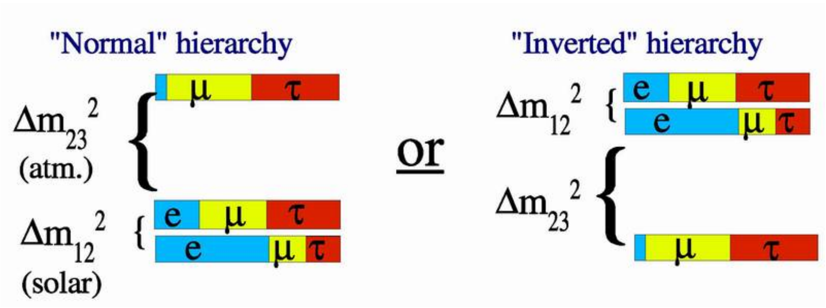




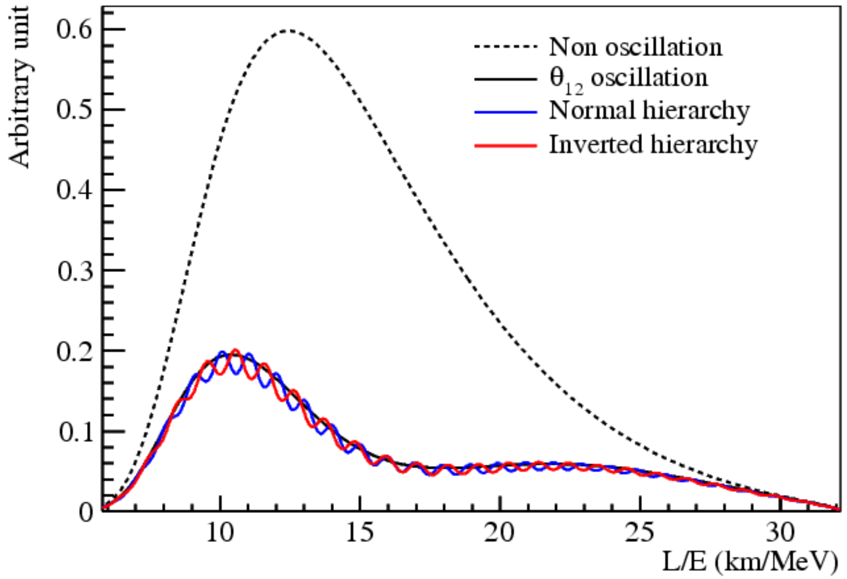
Talk by YFW at ICFA seminar 2008, Neutel 2011; by J. Cao at NuTurn 2012 ;

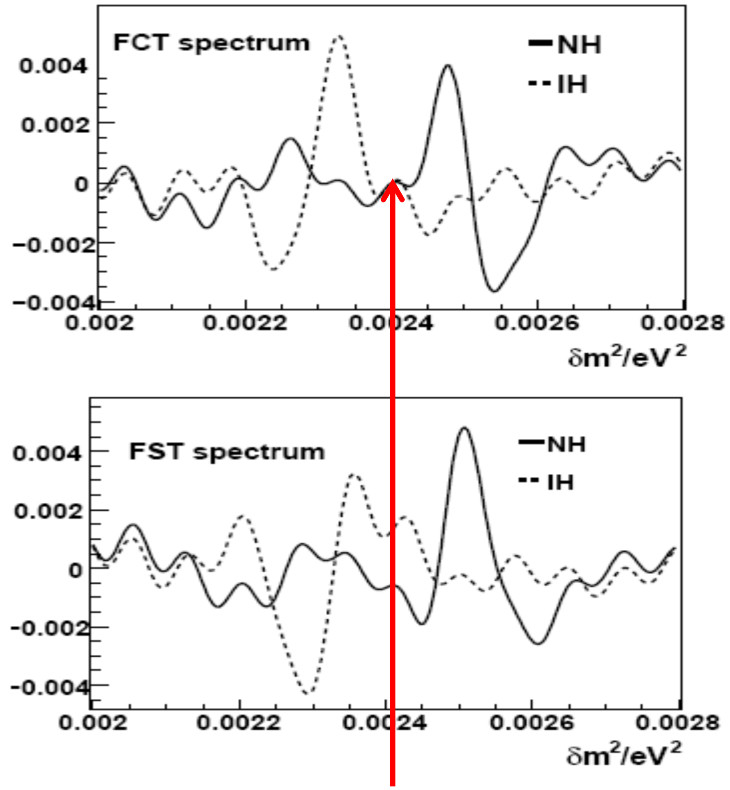
Paper by L. Zhan, YFW, J. Cao, L.J. Wen, PRD78:111103,2008; PRD79:073007,2009

Mass Hierarchy at Reactors



$$\Delta m^2_{31} = \Delta m^2_{32} + \Delta m^2_{21}$$
$$\mathrm{NH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| + |\Delta m^2_{21}|$$
$$\mathrm{IH}: \ |\Delta m^2_{31}| = |\Delta m^2_{32}| - |\Delta m^2_{21}|$$





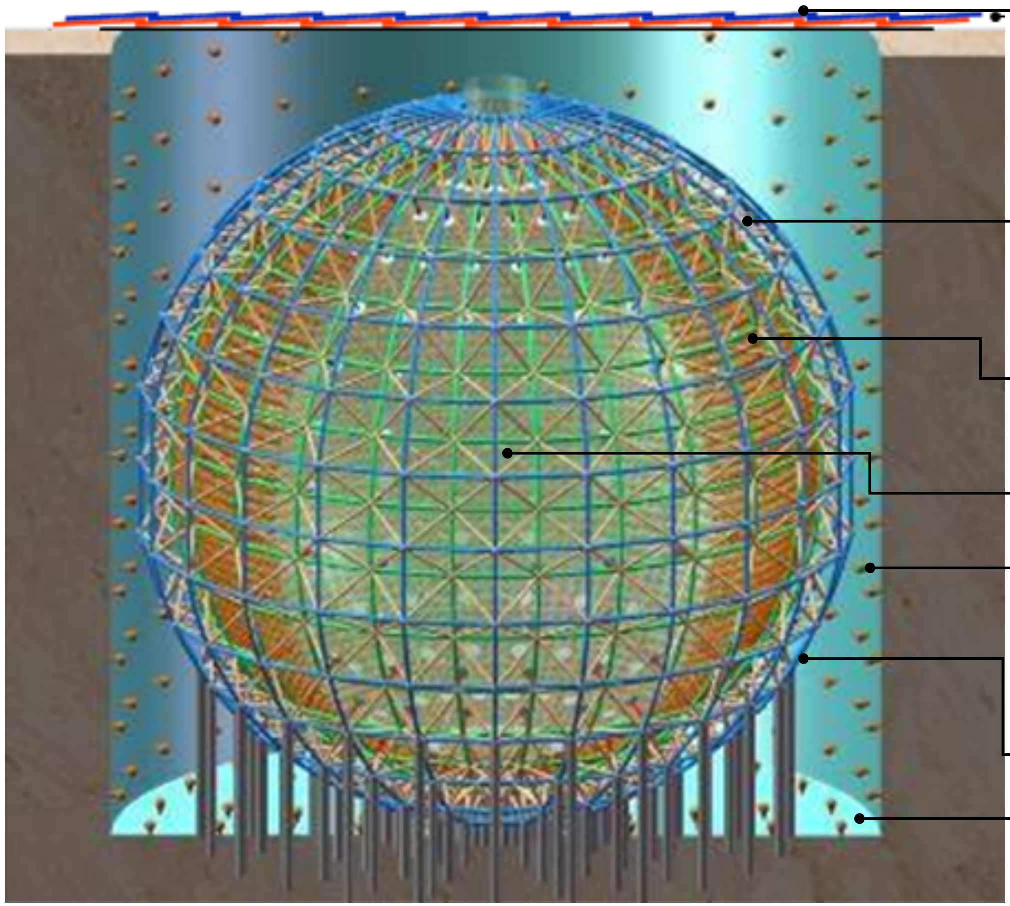
ΔM^2_{23}

$$P_{ee}(L/E) = 1 - P_{21} - P_{31} - P_{32}$$
$$P_{21} = \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21})$$
$$P_{31} = \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31})$$
$$P_{32} = \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32})$$

L. Zhan et al., PRD78:111103,2008; PRD79:073007,2009

The Plan: a Large LS Detector

- **LS volume: × 20 ➔ for more statistics (40 events/day)**
- **light(PE) × 5 ➔ for better resolution (ΔM^2_{12}/ ΔM^2_{23} ~ 3%)**



Physics Reach

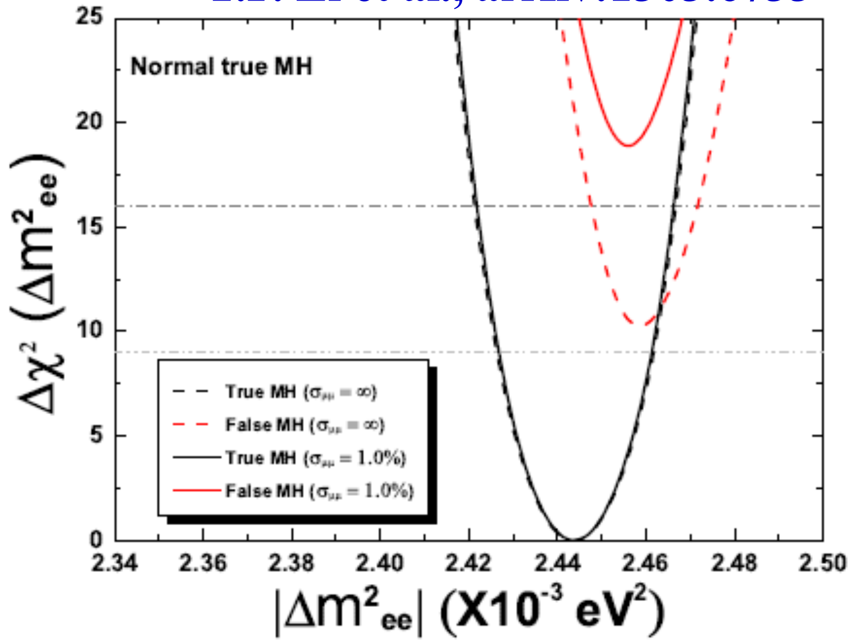
Thanks to a large θ_{13}

- **Mass hierarchy**
- Precision measurement of mixing parameters
- Supernova neutrinos
- Geoneutrinos
- Sterile neutrinos
- ……

	Current	Daya Bay II
Δm^2_{12}	4%	0.6%
Δm^2_{23}	4%	0.6%
$\sin^2\theta_{12}$	6%	0.7%
$\sin^2\theta_{23}$	10%	N/A
$\sin^2\theta_{13}$	6% → 4%	~ 15%

Detector size: 20kt
Energy resolution: 3%/√E
Thermal power: 36 GW

Y.F. Li et al., arXiv:1303.6733



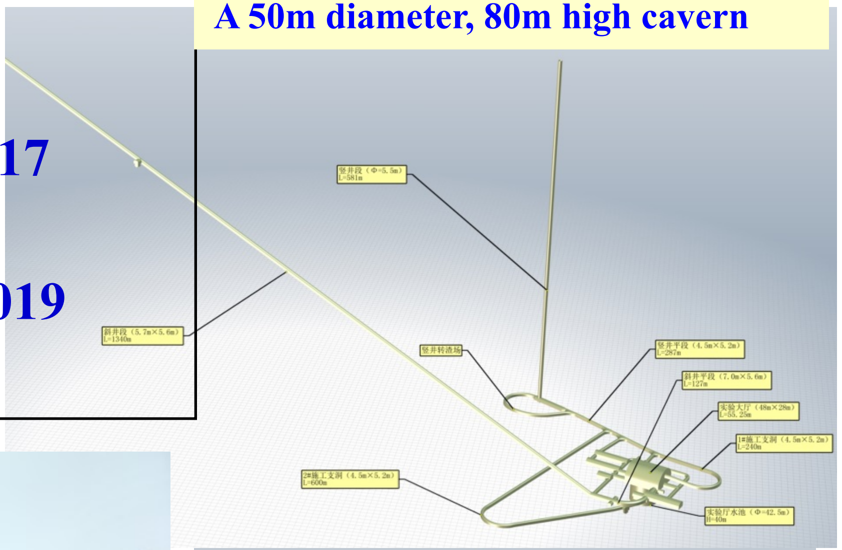
For 6 years, mass hierarchy cab be determined at 4σ level, if $\Delta m^2_{\mu\mu}$ can be determined at 1% level

Schedule & Current Status

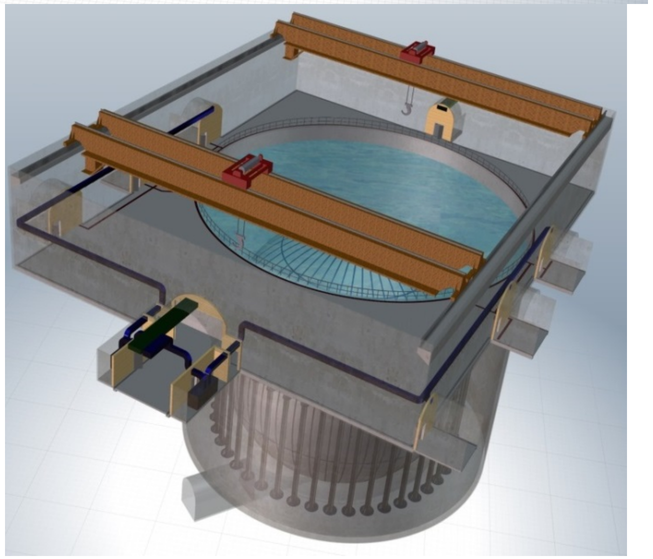
Schedule:

- Civil preparation：2013-2014
- Civil construction：2014-2017
- Detector component production：2016-2017
- PMT production：2016-2019
- Detector assembly & installation：2018-2019
- Filling & data taking：2020

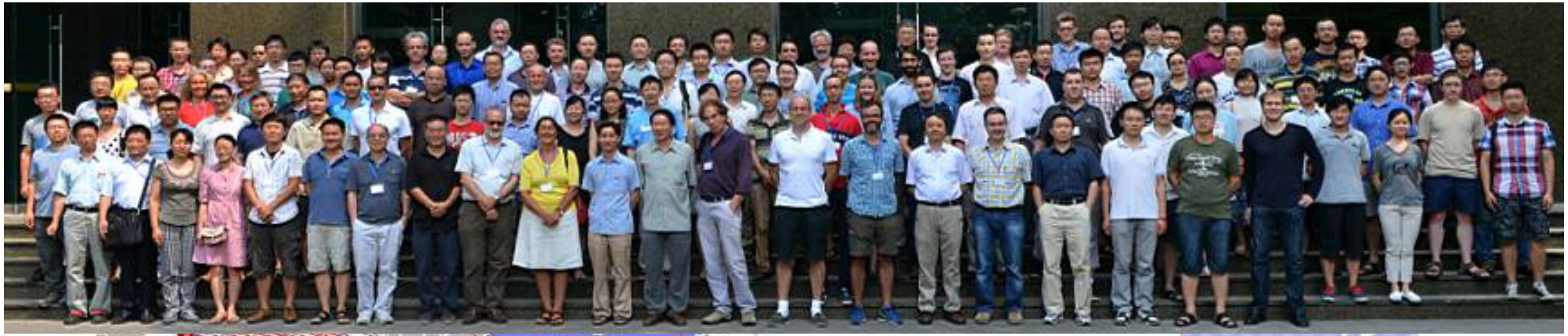
A 600m vertical shaft
A 1300m long tunnel(40% slope)
A 50m diameter, 80m high cavern



Grounding breaking on Jan. 10, 2015



JUNO collaboration



Europe (24)

France(5)
APC Paris
CPPM Marseille
IPHC Strasbourg
LLR Paris
Subatech Nantes

Czech(1)
Charles U

Finland(1)
U.Oulu

Russia(2)
INR Moscow
JINR

Italy(7)
INFN-Frascati
INFN-Ferrara
INFN-Milano
INFN-Mi-Bicocca
INFN-Padova
INFN-Perugia
INFN-Roma 3

Armenia(1)
Yerevan Phys. Inst.

Belgium(1)
ULB

Germany(6)
FZ Julich
RWTH Aachen
TUM
U.Hamburg
U.Mainz
U.Tuebingen

America(3)

US(2)
UMD
UMD-Geo

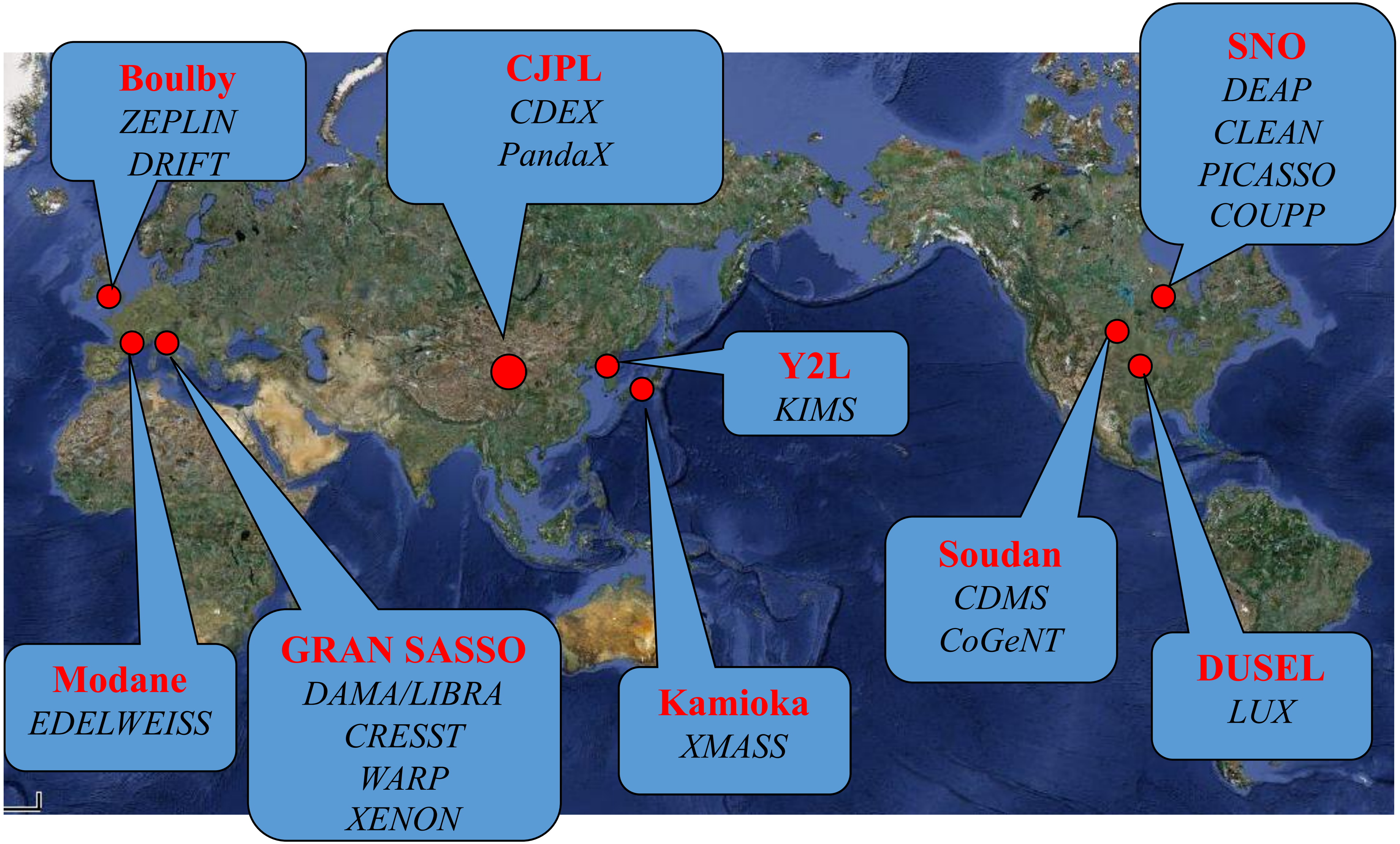
Chile(1)
Catholic Univ. of Chile

Asia (28)

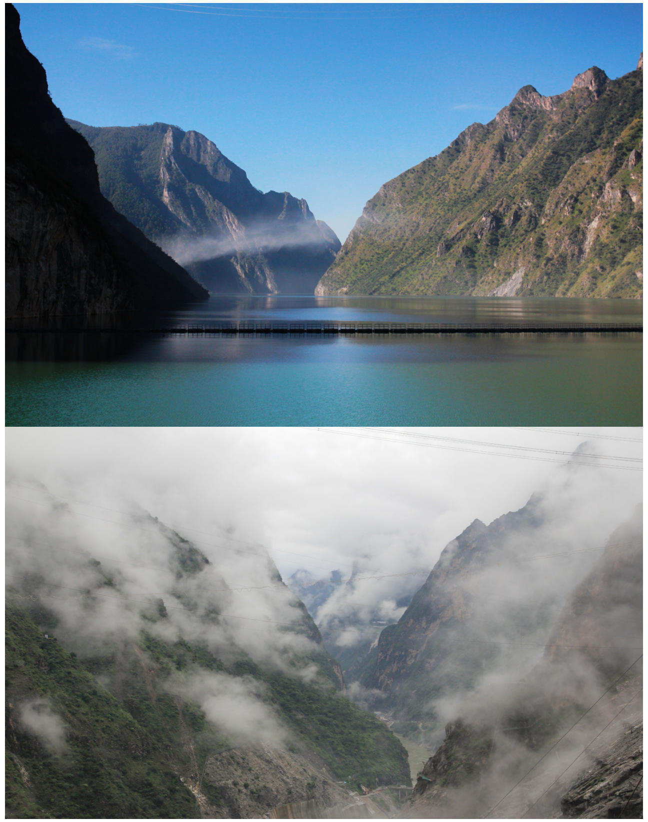
BJ Nor. U.
CAGS
Chongqing U.
CIAE
DGUT
ECUST
Guangxi U.
HIT
IHEP
Jilin U.
Nanjing U.
Nankai U.
Natl. Chiao-Tung U.
Natl. Taiwan U.
Natl. United U.
NCEPU
Pekin U.
Shandong U.
Shanghai JT U.
Sichuan U.
SYSU
Tsinghua U.
UCAS
USTC
Wuhan U.
Wuyi U.
Xi'an JT U.
Xiamen U.

JinPing Underground Lab

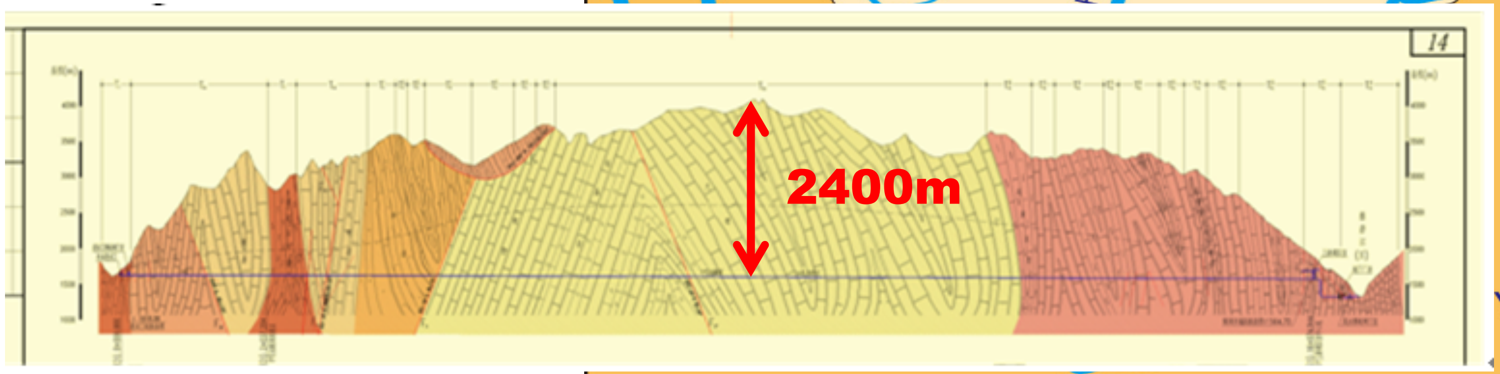
Underground abs in the world



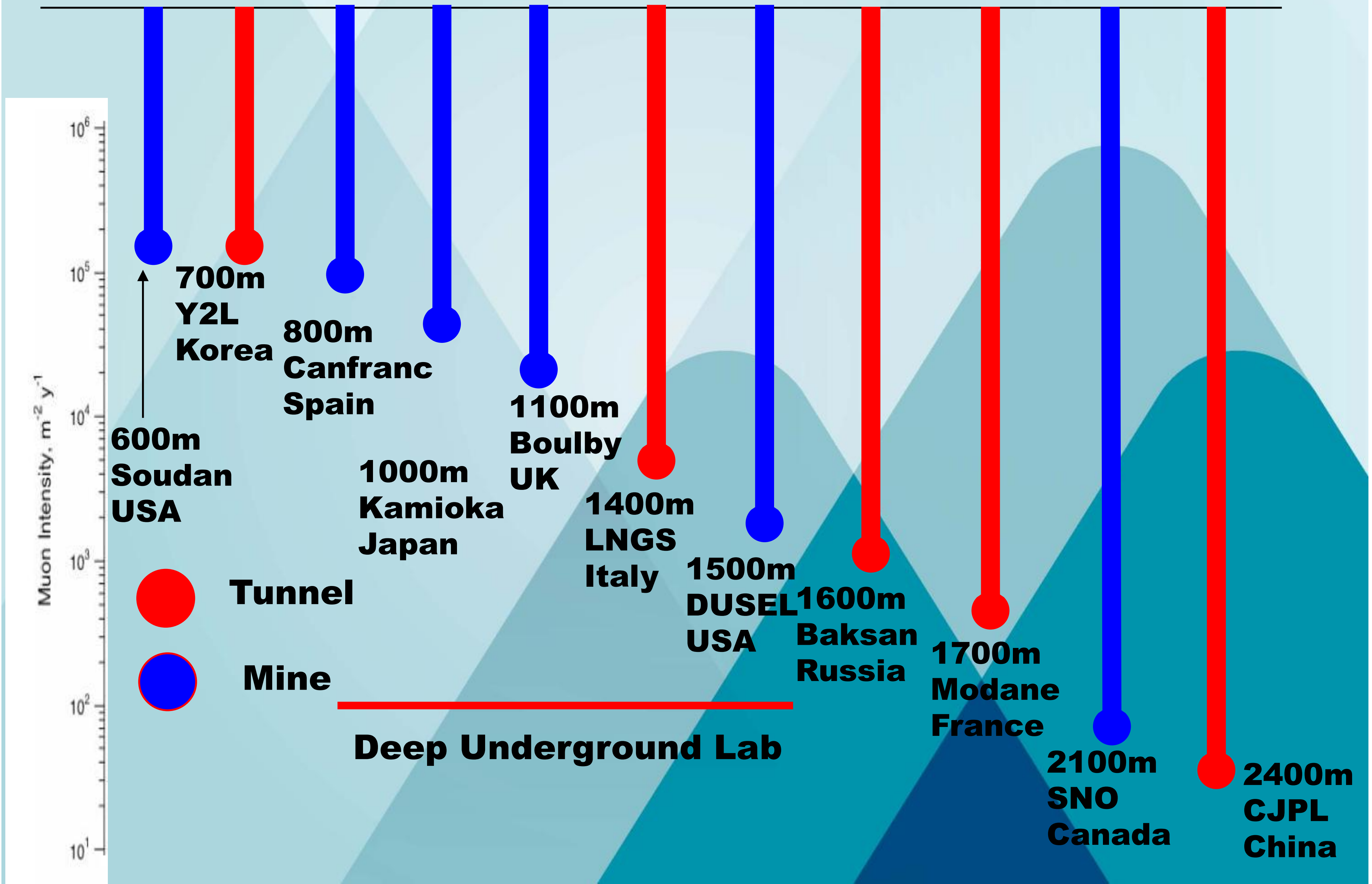
CJPL site



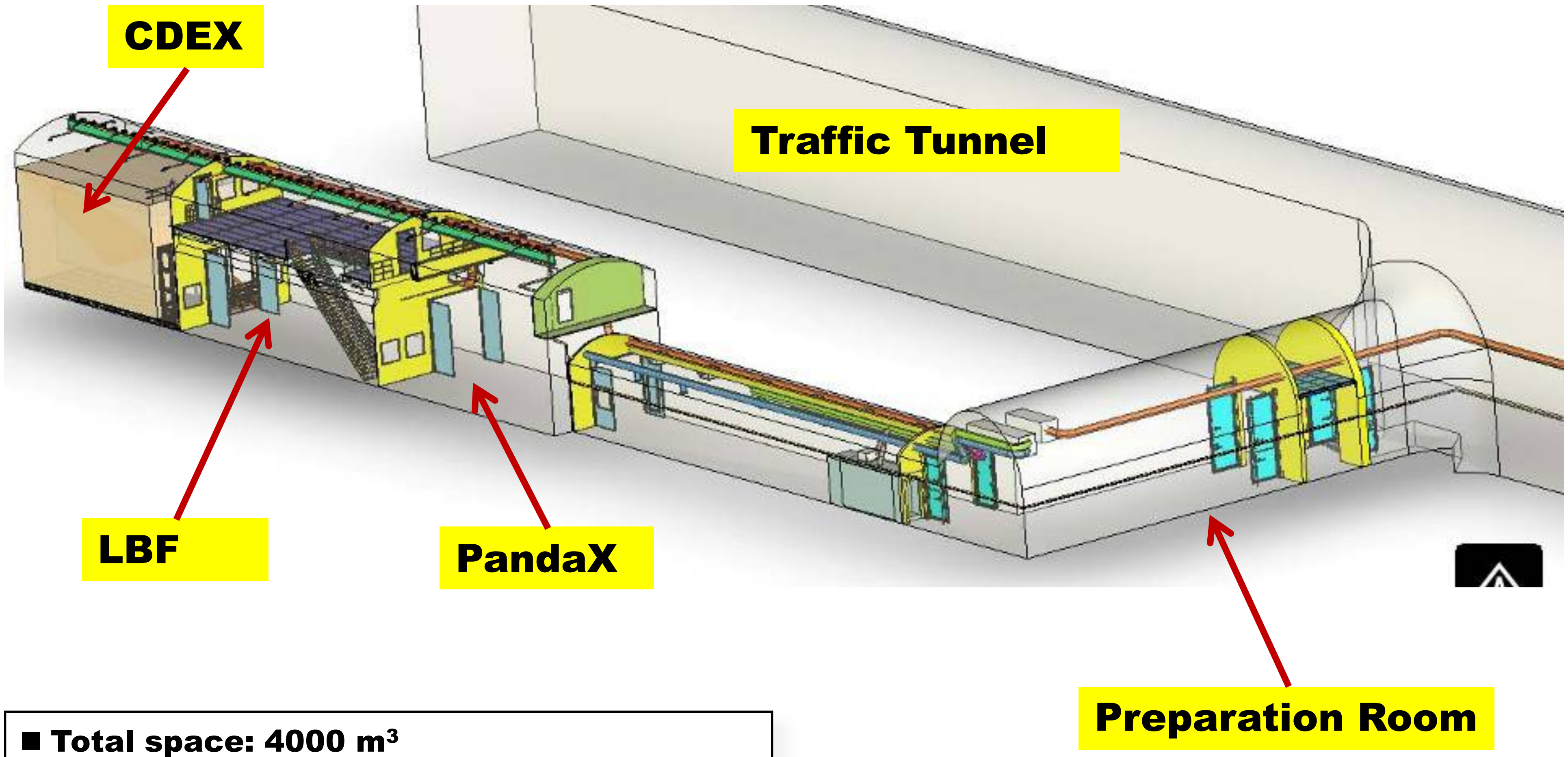

CHINA
YaLongRiver
Sichuan Province
Jinsha River
Jinping tunnels
River
N
Yunnan Province


14
2400m

UL in the world(rock overburden)

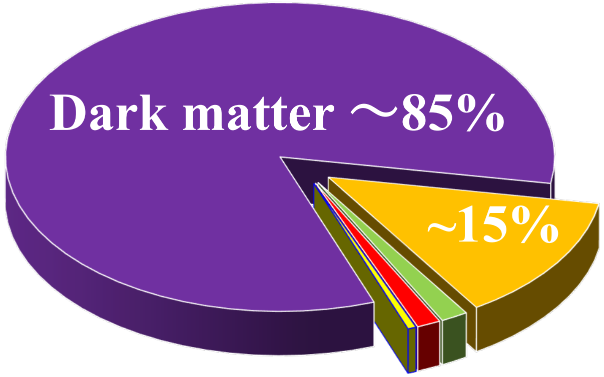


Layout of CJPL-I

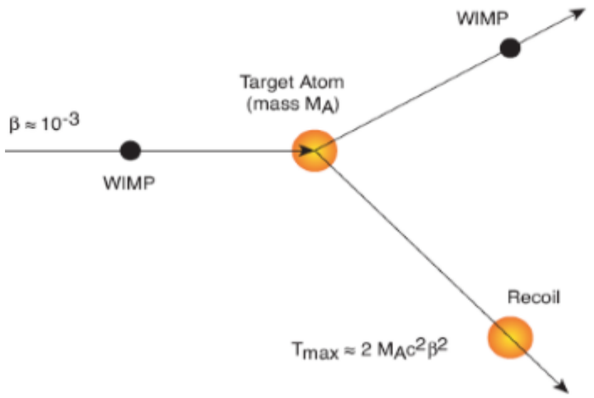


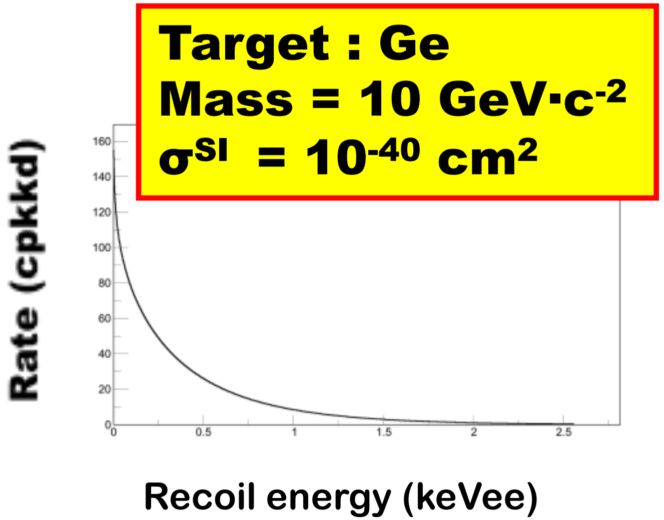
- Total space: 4000 m^3
- Main Lab Space: 6.5(W) x 6.5(H) x 42(L)

China Darkmatter Experiment (CDEX)



- **Nature of dark matter unknown.**
- **WIMPs is one kind of well motivated candidate.**





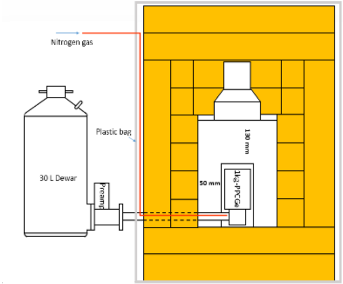
Point-contact HPGe detector (PCGe) :
✓Low energy threshold (~ 100eVee)
✓Very good energy resolution
✓Easy to scale up

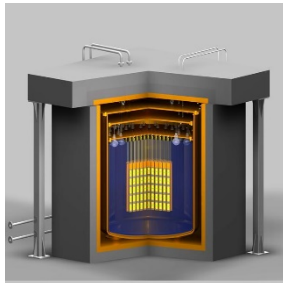
CDEX target:
Direct detection of low mass dark matter with tonne-scale PCGe array!

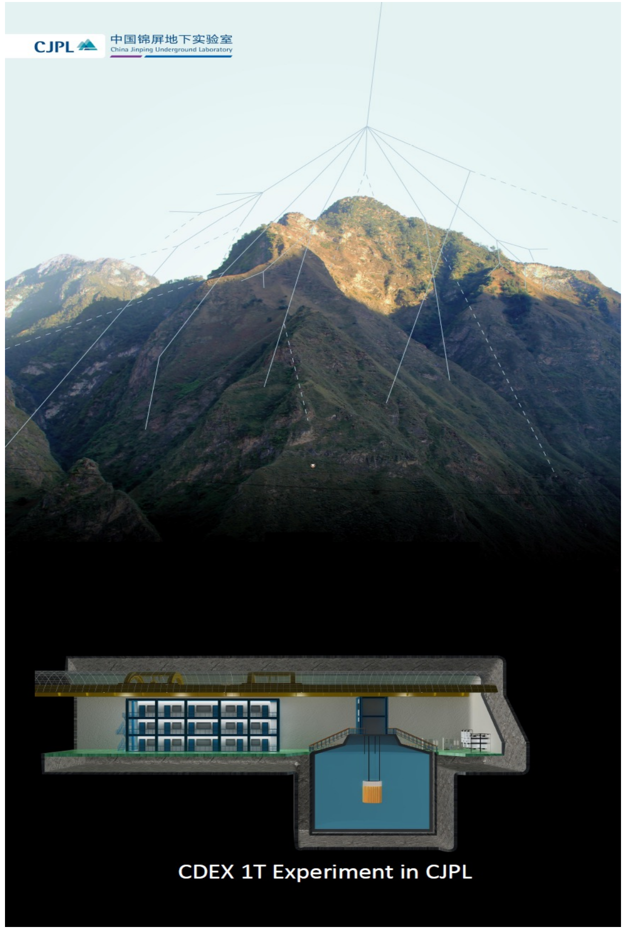
CDEX: China Dark matter EXperiment

CDEX development stages

- CDEX-1: Development of large-mass prototype PCGe detector, data analysis methods, and its background understanding and suppression;
- CDEX-10: Performances of HPGe array detector system and its passive/active shielding systems;
- CDEX-10X: Fabrication of HPGe, Ge crystal growth and ULB-Cu;
- ……
- CDEX-1T: Multi-purpose experiment for dark matter and double beta decay.







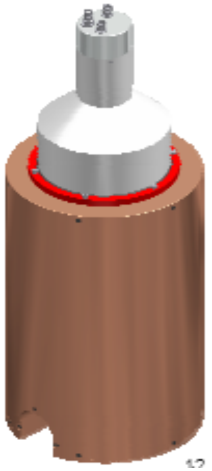
CDEX-1 experiment

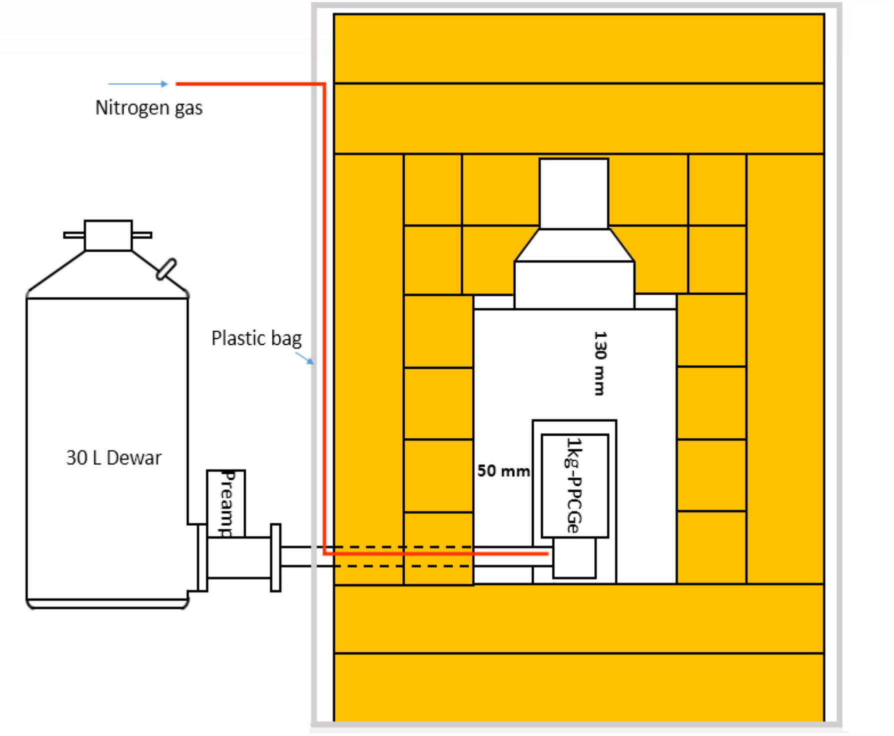
1. HPGe detector
   - ✓ Designed and studied the first 1kg-scale p-type point-contact Ge detector (1kg-PPCGe) based on our simulation and experience. C1A: readout from both P+ point and N+ Li drift layer.
   - ✓ Improved the second 1kg-PPCGe. C1B with lower Eth

2. NaI(Tl) used as anti-Compton detector
   - ✓ C1A without AC
   - ✓ C1A with NaI(Tl) AC
   - ✓ C1B with NaI(Tl) AC
   - ✓ C1 20g Ge + NaI(Tl)

1kg-PPCGe

NaI(Tl)

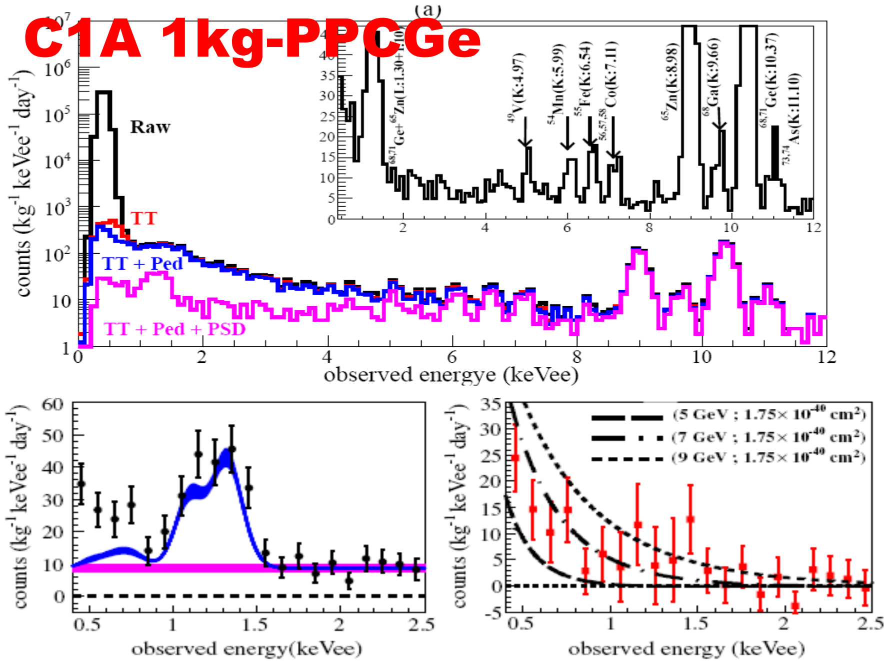


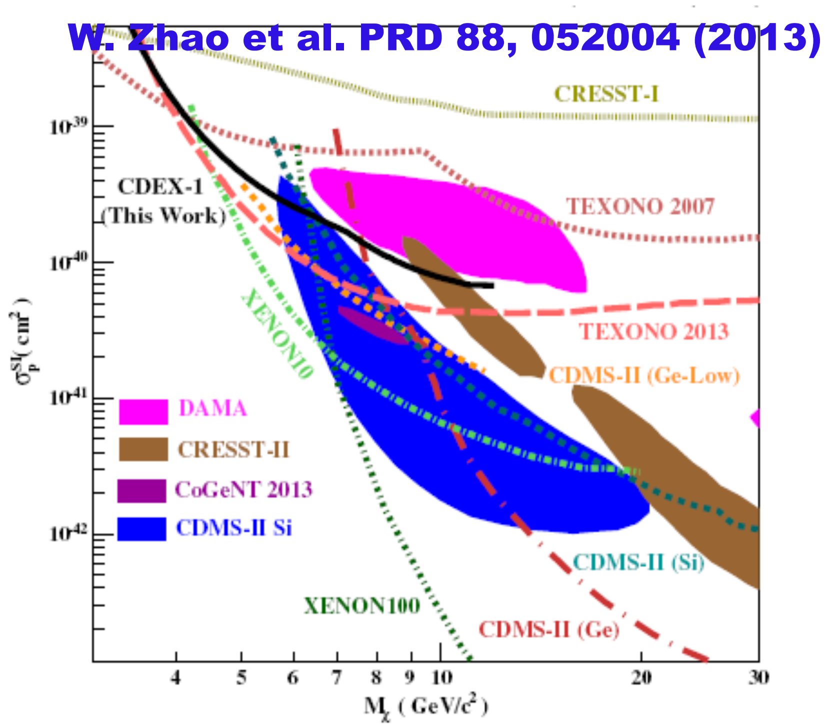


CDEX in CJPL-I

CDEX-1

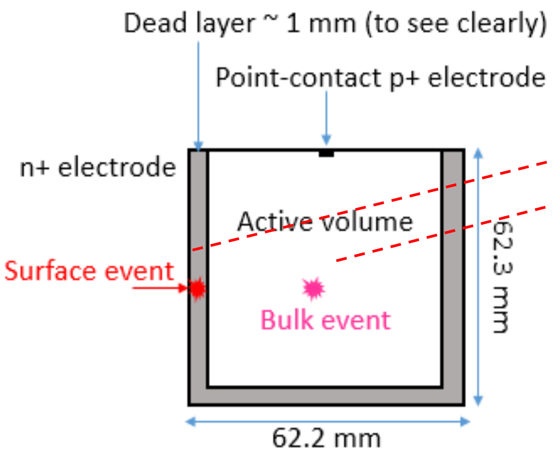
CDEX-1A experiment

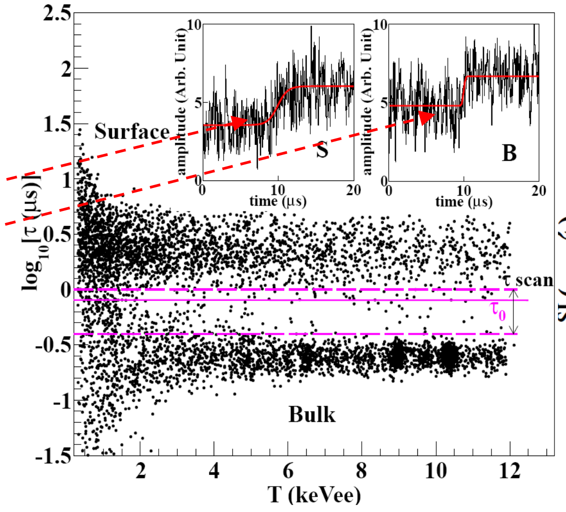


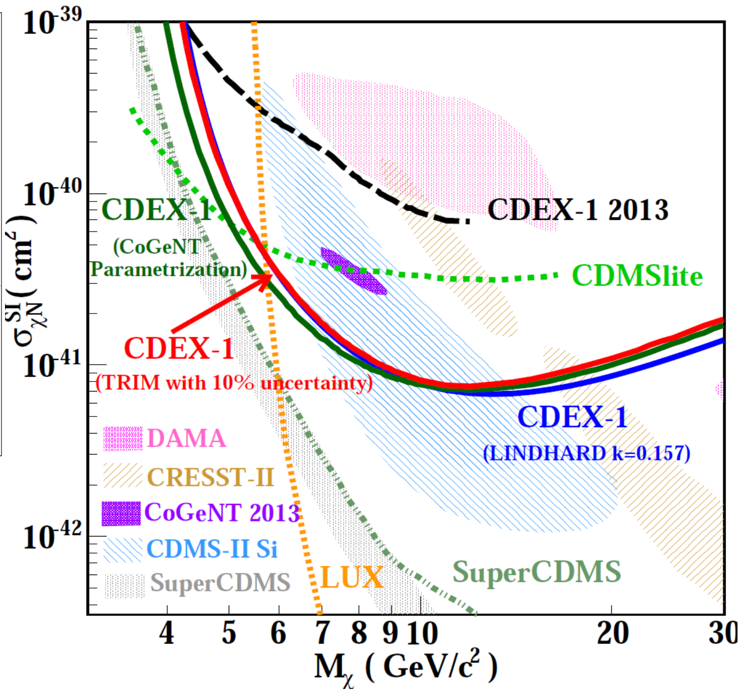


- ✓ Ge crystal mass: 994g
- ✓ Energy threshold ~400eV
- ✓ Background level @ 3-5keV: 10cpkkd
- ✓ K/L X-ray peaks from cosmogenic nuclei identified.
- ✓ The first large pPCGe design by CDEX successful;
- ✓ The first dark matter physical result from China.

CDEX-1A upgrade







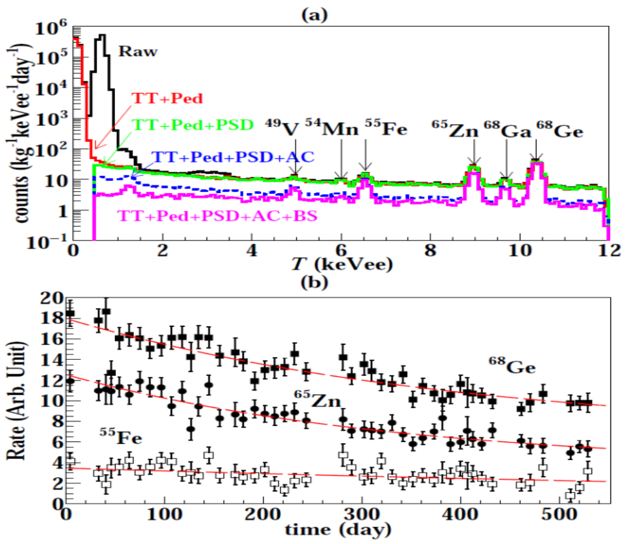
Q.Yue et al., PRD 90(RC) 091701

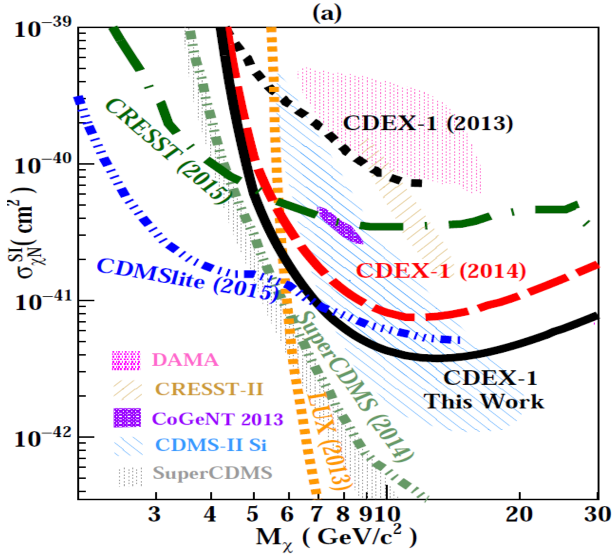
- **Bulk/Surf Discrimination**
- **C1A 1kg-PPCGe + NaI(Tl)**

✓ B/S disc. to get rid of the events with slow rise-time and partial charge collection;
✓ 1/3 background lower with/without AC detector;
✓ The best sensitivity by PCGe and Exclude the regions favored by CoGeNT.

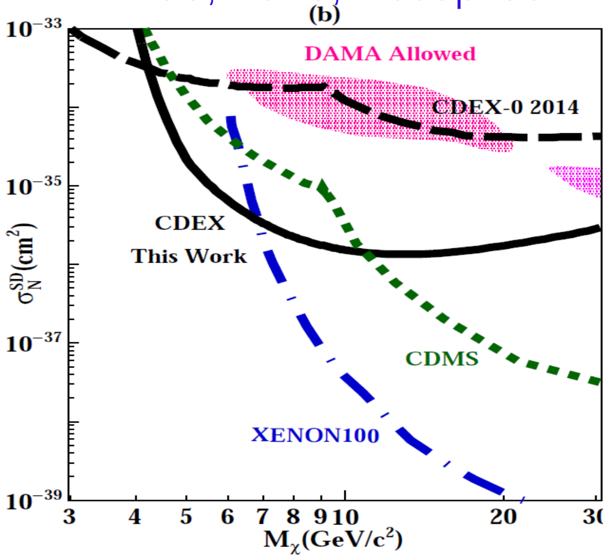
CDEX-1A new results

- CDEX-1A run > 500day, totally ~336 d·kg dataset;
- Flat background level decay from ~10 to ~4 cpkkd;
- Based on the decay of K/L x-ray peaks from the cosmogenic nuclei, The crystal history may be trced;
- ~2 times more sensitive than 2014 result;
- AM analysis with >1year data going on.



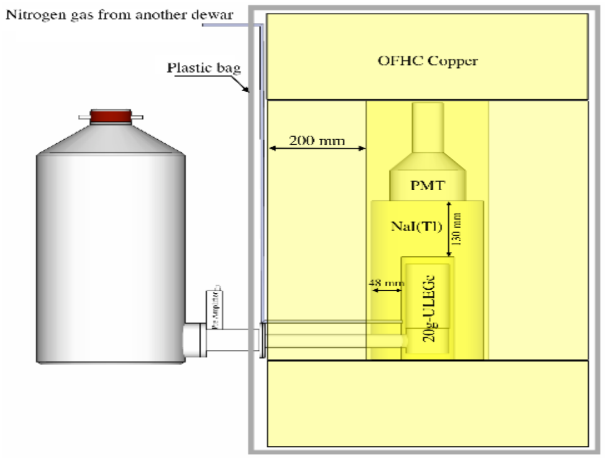


PRD93, 2015, Accepted

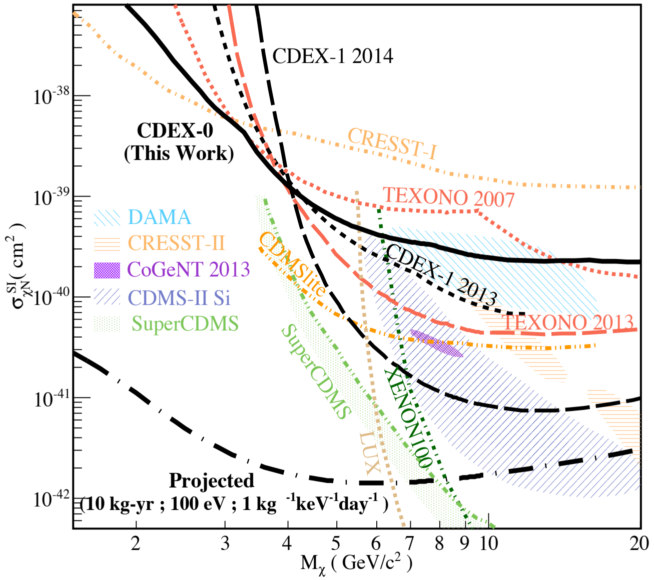


CDEX-0 result from 20g Array detector

CDEX-1 5g*4 + AC detector



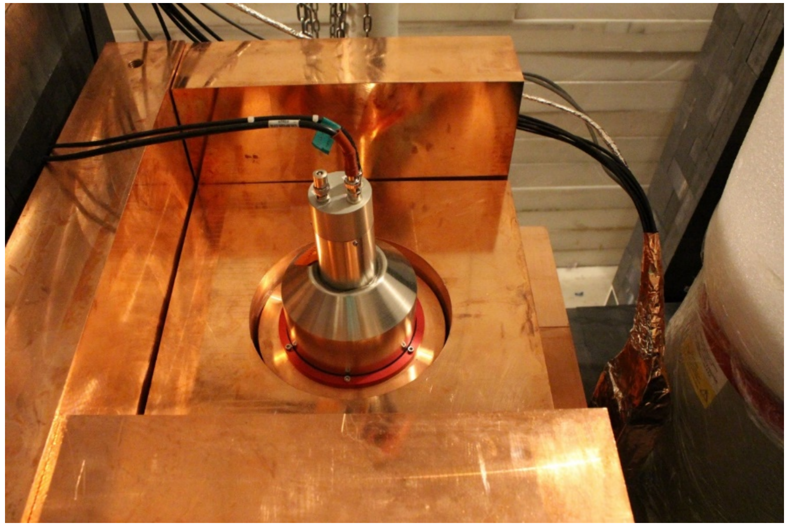
PRD90,032003,2014

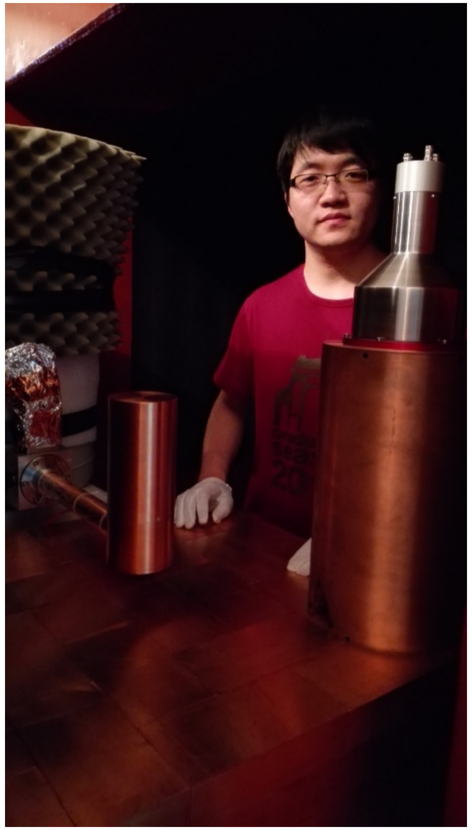


Highlight:

- ✓ **177eV lowest ionization energy threshold**
- ✓ **Good direction to lower energy threshold further**

CDEX-1B experiment

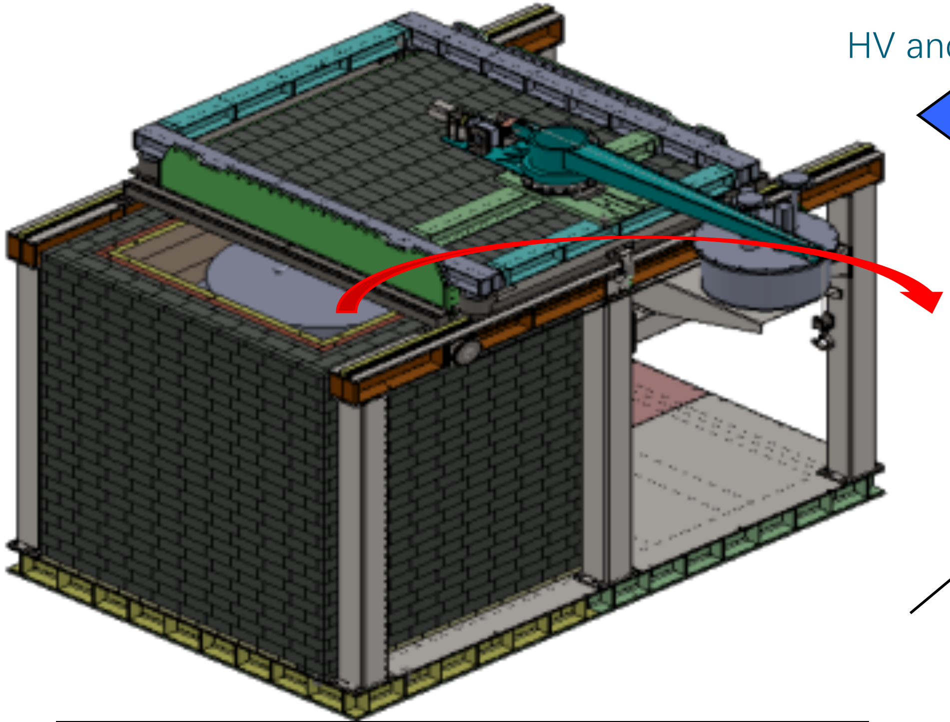


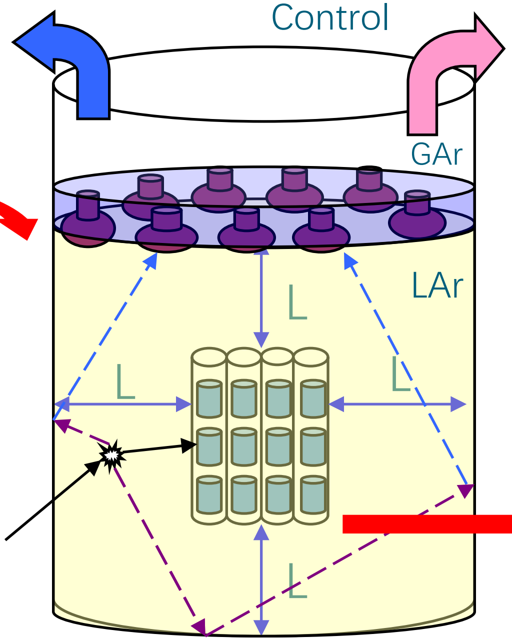


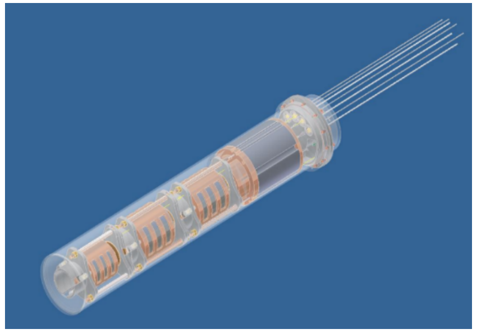
- ✓ Ge crystal mass: 1008g
- ✓ Energy threshold <300eV
- ✓ Background level @ 3-5keV: 3cpkkd
- ✓ K/L X-ray peaks from cosmogenic nuclei identified
- ✓ The first physical result under preparation

CDEX-10 experiment

- The important stage towards tonne-scale Ge experiment;
- PCGe array with lower energy threshold： <300eV;
- Performance study of the Ge array detector;
- Feasibility of LAr anti-Compton detector for CDEX.







3-PCGe element

CDEX-10 experimental setup

10kg-PCGe + LAr

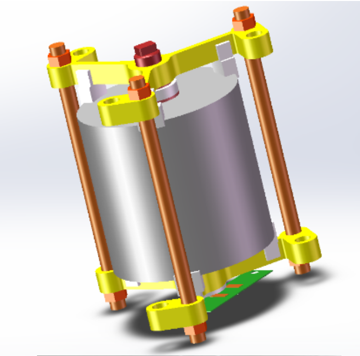
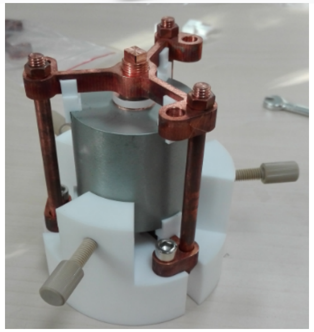
CDEX-10 Array detectors

CDEX-10 Array detectors

- 3 * 3 kg Array detectors;
- Eth<300eV;
- Better resolution in LN2 than with cooling finger.
- Under testing in CJPL

CDEX-10X

- ✓ Two 0.5kg PCGe with <350eV under preparation by CDEX;
- ✓ Totally new design by CDEX and background control with pure cable, PreAMP substrate and structure materials;
- ✓ Two PreAMP types: JFET and ASIC;
- ✓ ULB-Cu production by CDEX in CJPL this year.



PandaX collaboration

~50 people

Started in 2009

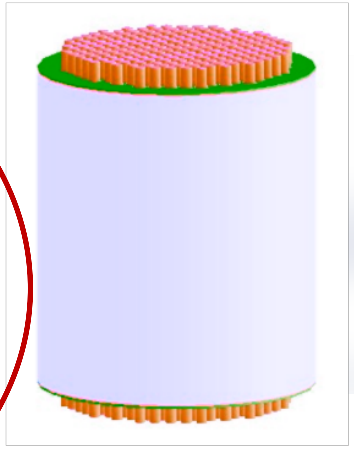
- Shanghai Jiao Tong University (2009-)
- Peking University (2009-)
- Shandong University (2009-)
- Shanghai Institute of Applied Physics, CAS (2009-)
- University of Science & Technology of China (2015-)
- China Institute of Atomic Energy (2015-)
- Sun Yat-Sen University (2015-)
- Yalong Hydropower Company (2009-)
- University of Maryland (2009-)
- Alternative Energies & Atomic Energy Commission(2015-)
- University of Zaragoza(2015-)
- Suranaree University of Technology(2015-)

PandaX experiment

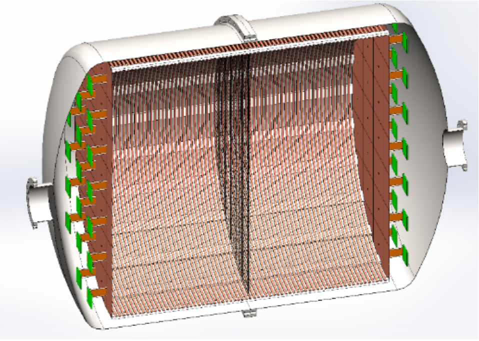
PandaX = Particle and Astrophysical Xenon Experiments

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017



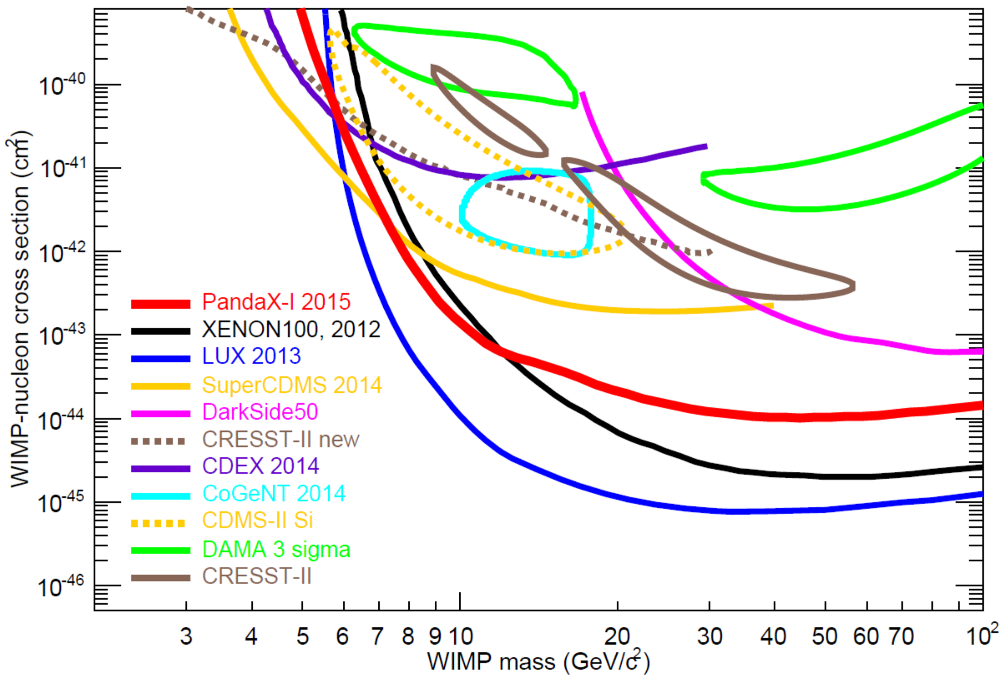
PandaX-xT:
multi-ton DM
future



PandaX-III:
200 kg to 1 ton
^{136}Xe 0vDBD
future

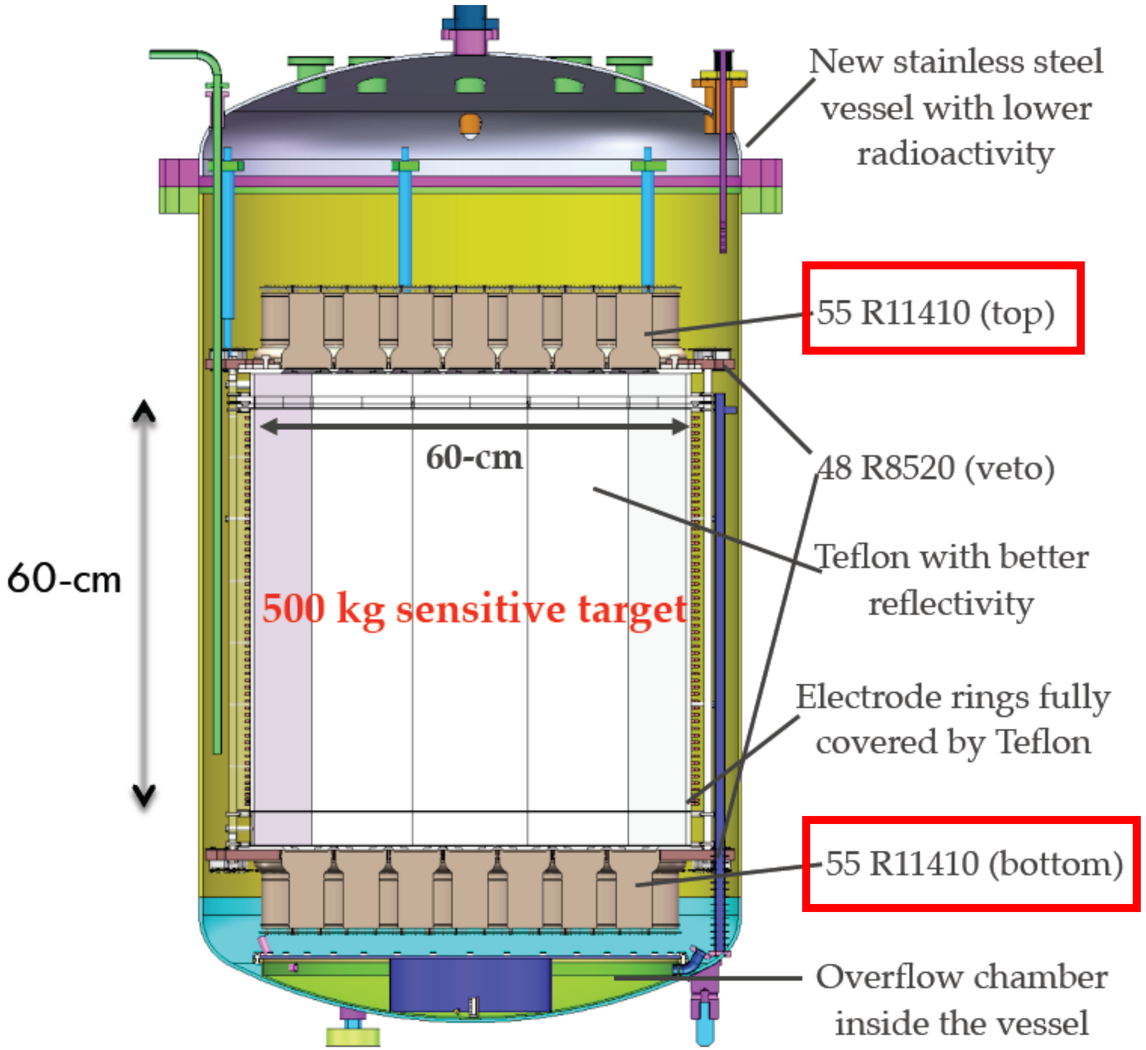
Final Results from PandaX-I

Phys. Rev. D **92**, 052004(2015)



- Completed in Oct. 2014, with 54.0 x 80.1 kg-day exposure
- Data strongly disfavor all previously reported claims
- Competitive upper limits for low mass WIMP in xenon experiments

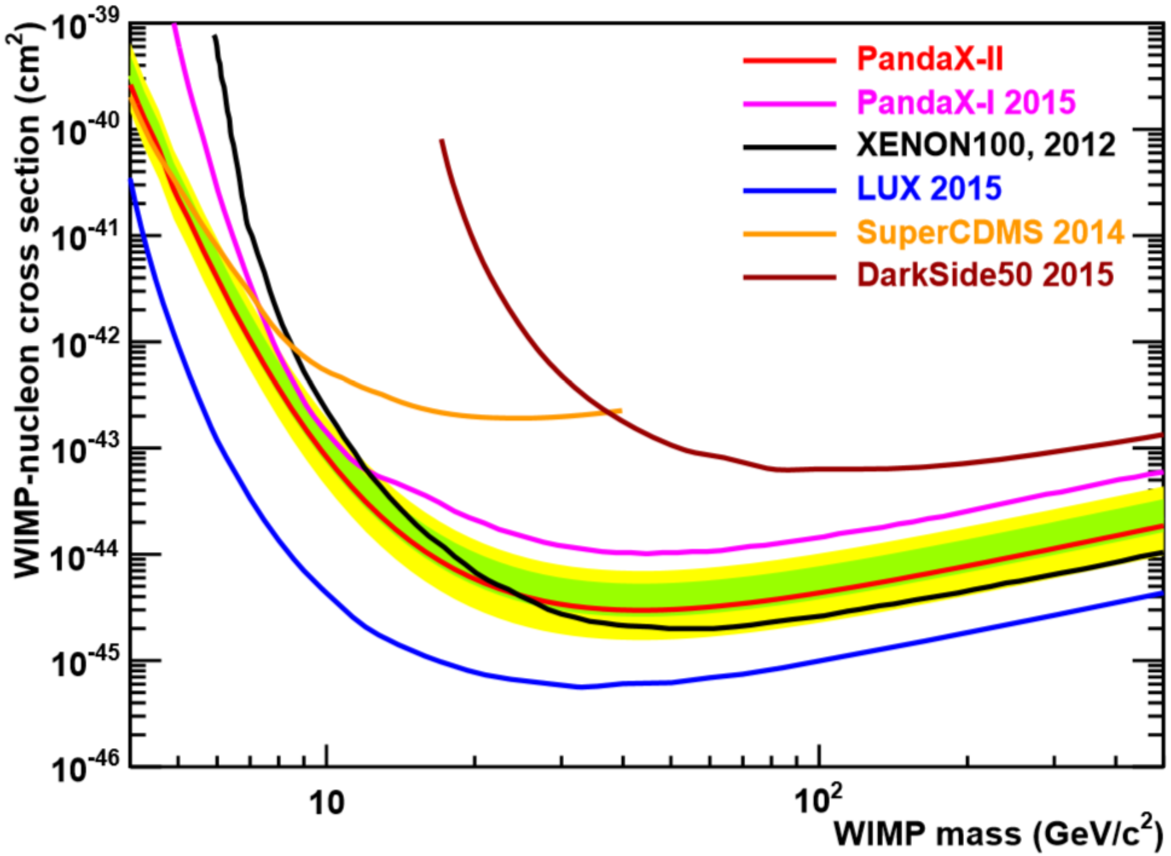
PandaX-II



- New inner vessel with clean SS
- New and taller TPC with brand-new electrodes
- More 3" PMTs and improved base design
- New separate skin veto region

Results from PandaX-II Commissioning

Phys. Rev. D. 39, 122009 (2016), Run 8



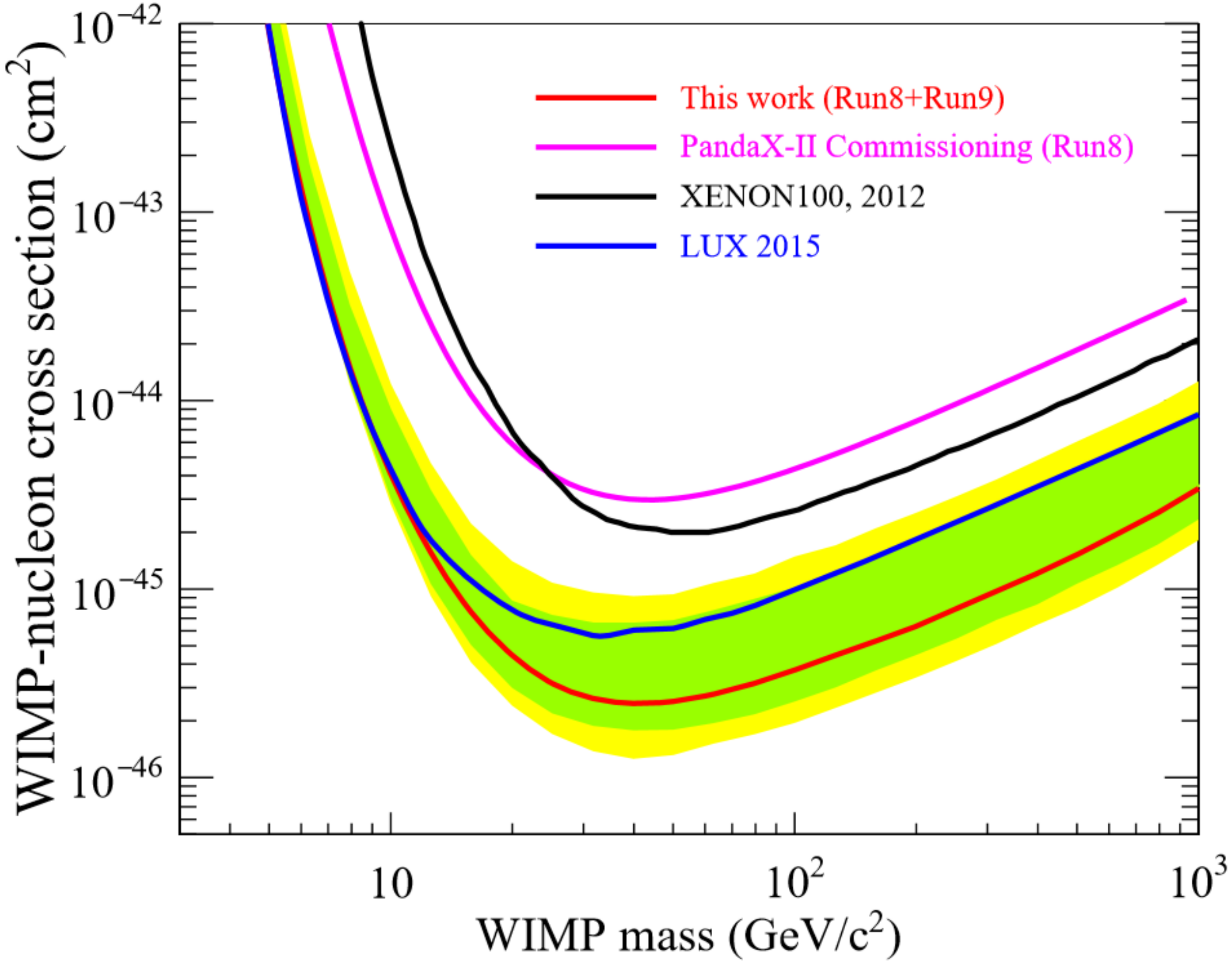
- Simple counting analysis based on an expected background of 3.2(0.7) evts and 2 observed evts
- Sizable (x2) difference of using original NEST or tuned NEST to predict DM distribution due to DM acceptance, but within 1σ band
- Low mass: competitive with SuperCDMS; high mass: similar exclusion limit as XENON100 225-day

Major upgrades in Run 9

Items	Status in Run 9
Krypton level	Reduced by x10
Exposure	Increased x4 (79.6 vs 19.1 day)
ER calibration	Now have tritium calibration
NR calibration	Statistics x6
Analysis	Improved position reconstruction
Background	Accidental background suppressed more than x3 using BDT

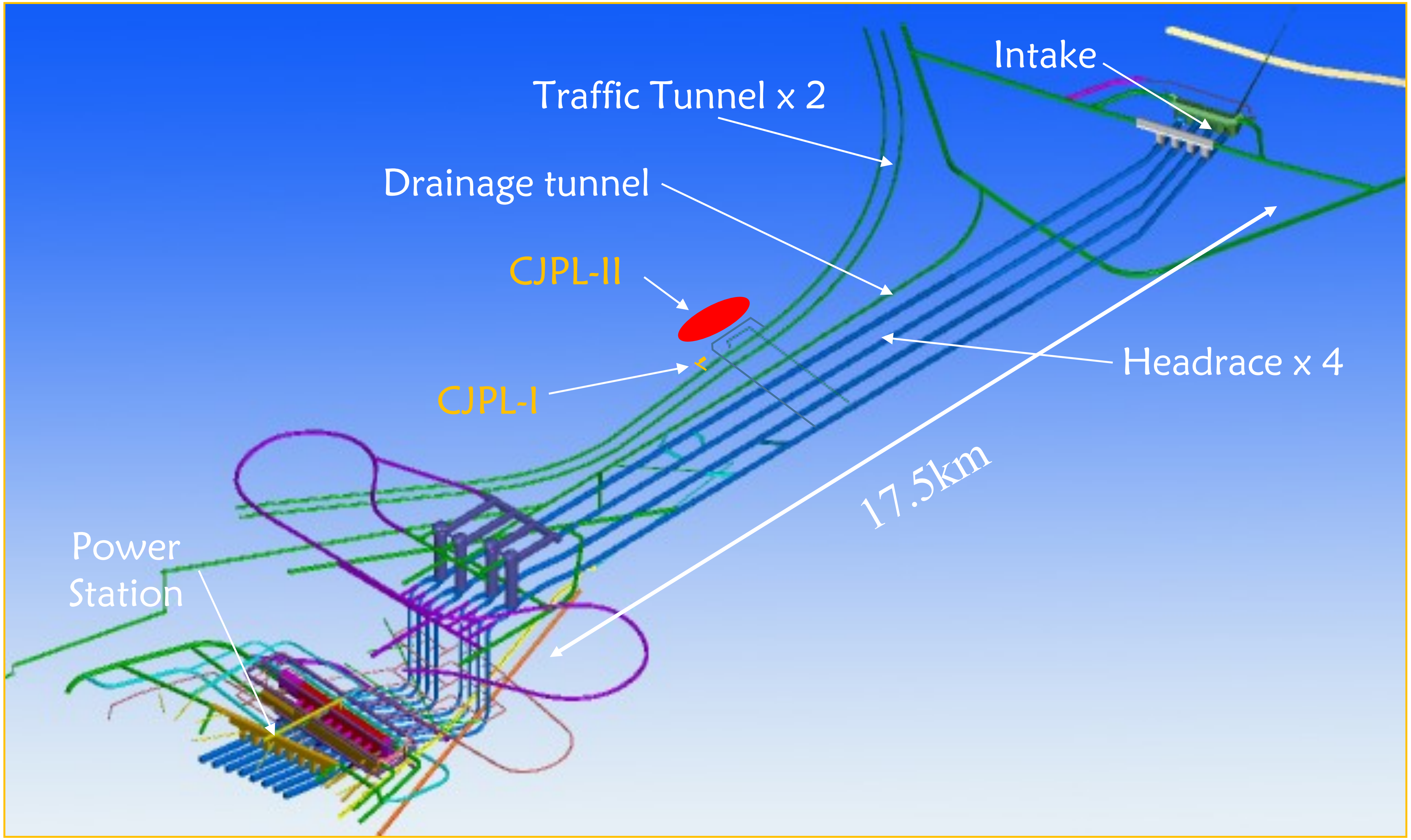
Combined results

arXiv: 1607.07400

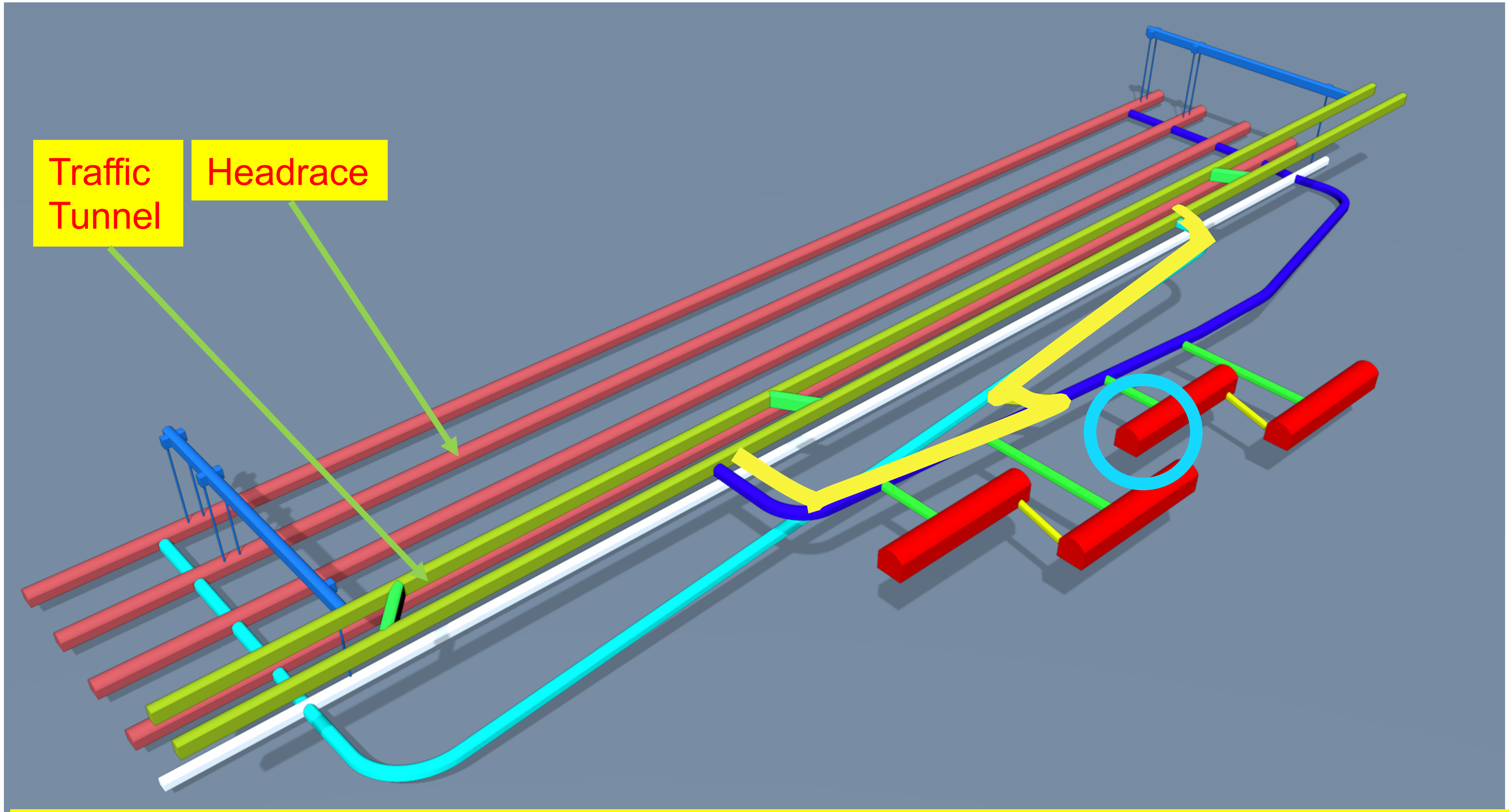


- Combination of Run 8 and Run 9 with an exposure of 3.3×104 kg-day.
- Minimum upper limit for isoscalar SI elastic cross section at 2.5×10^{-46} cm^2, more than a factor of 2 improvement compared to the LUX 2015 results

CJPL in Jinping tunnels

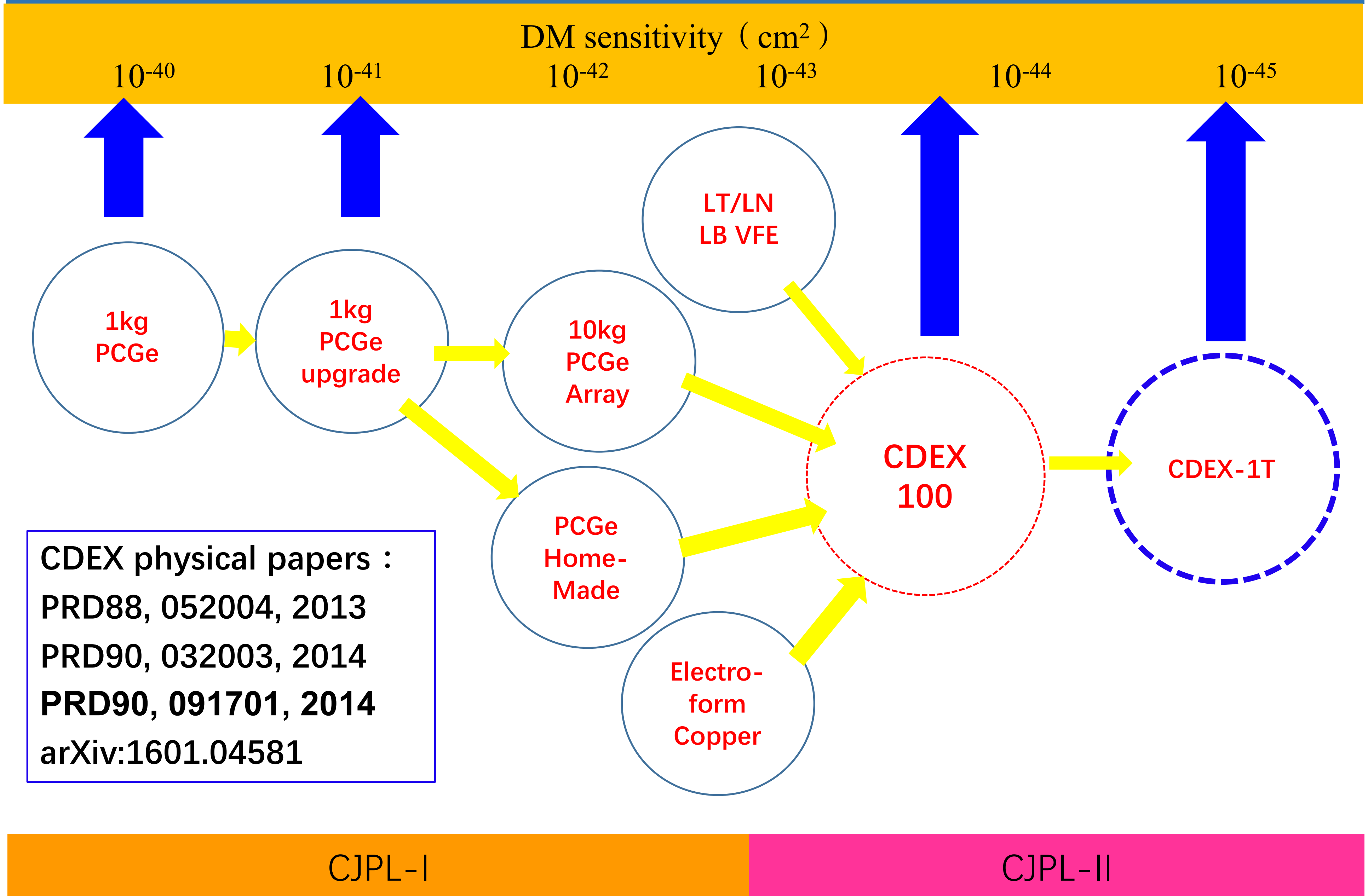


CDEX in CJPL-II



- **Four 14m*14m*130m main halls**
- **Total Volume ： ~300K m^3**

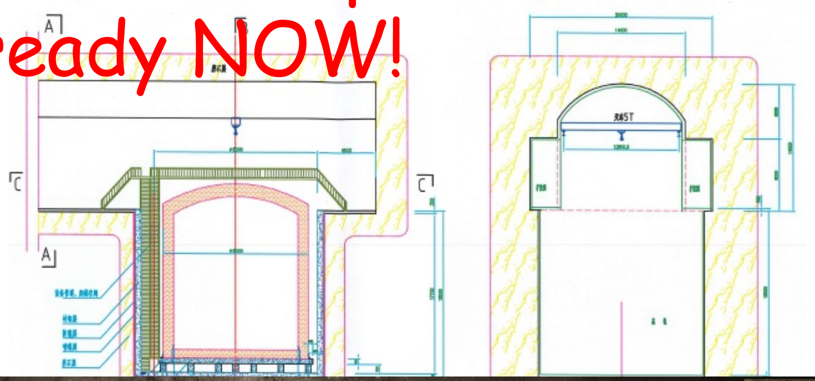
CDEX plan

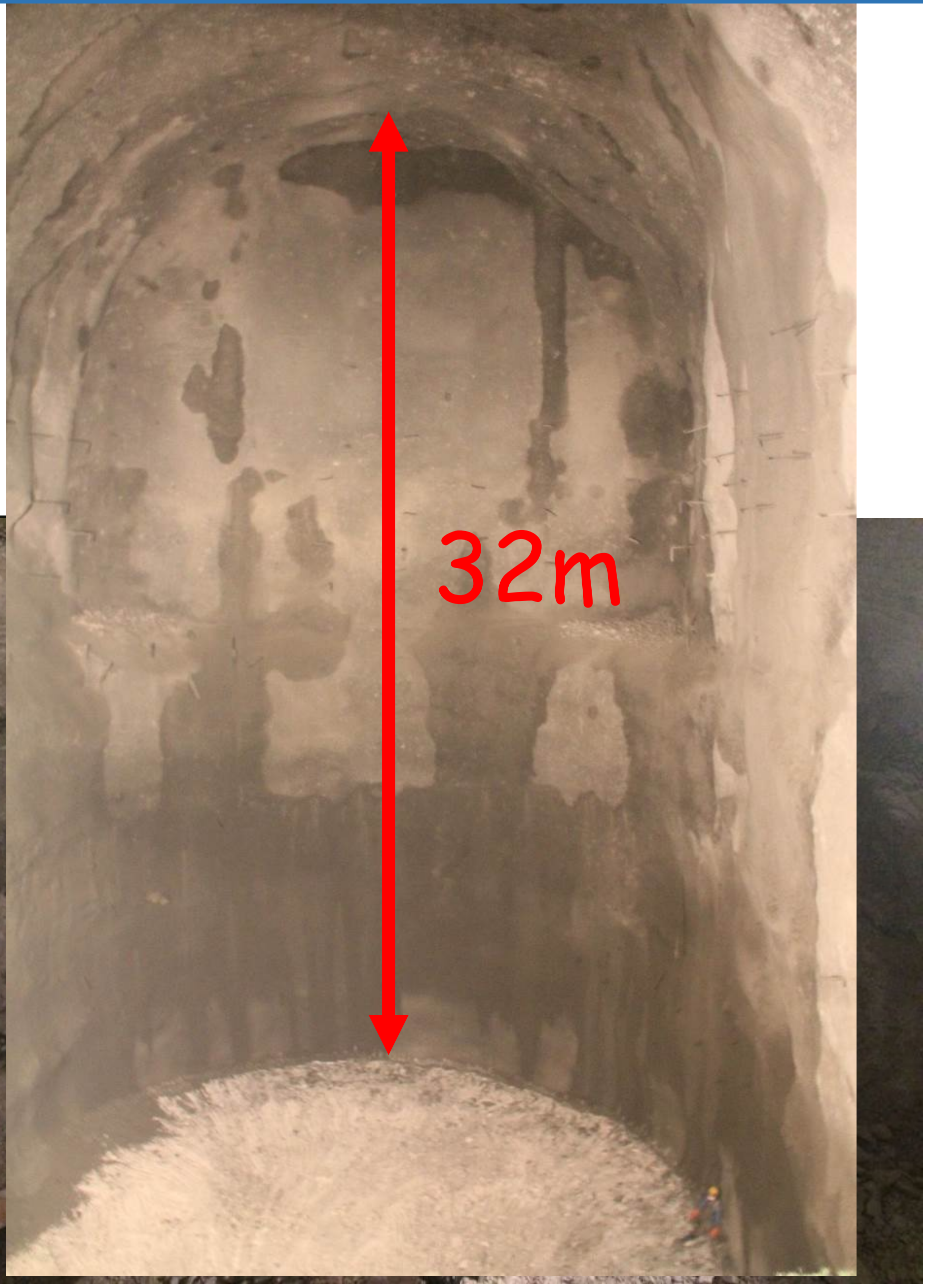


CDEX physical papers：
PRD88, 052004, 2013
PRD90, 032003, 2014
PRD90, 091701, 2014
arXiv:1601.04581

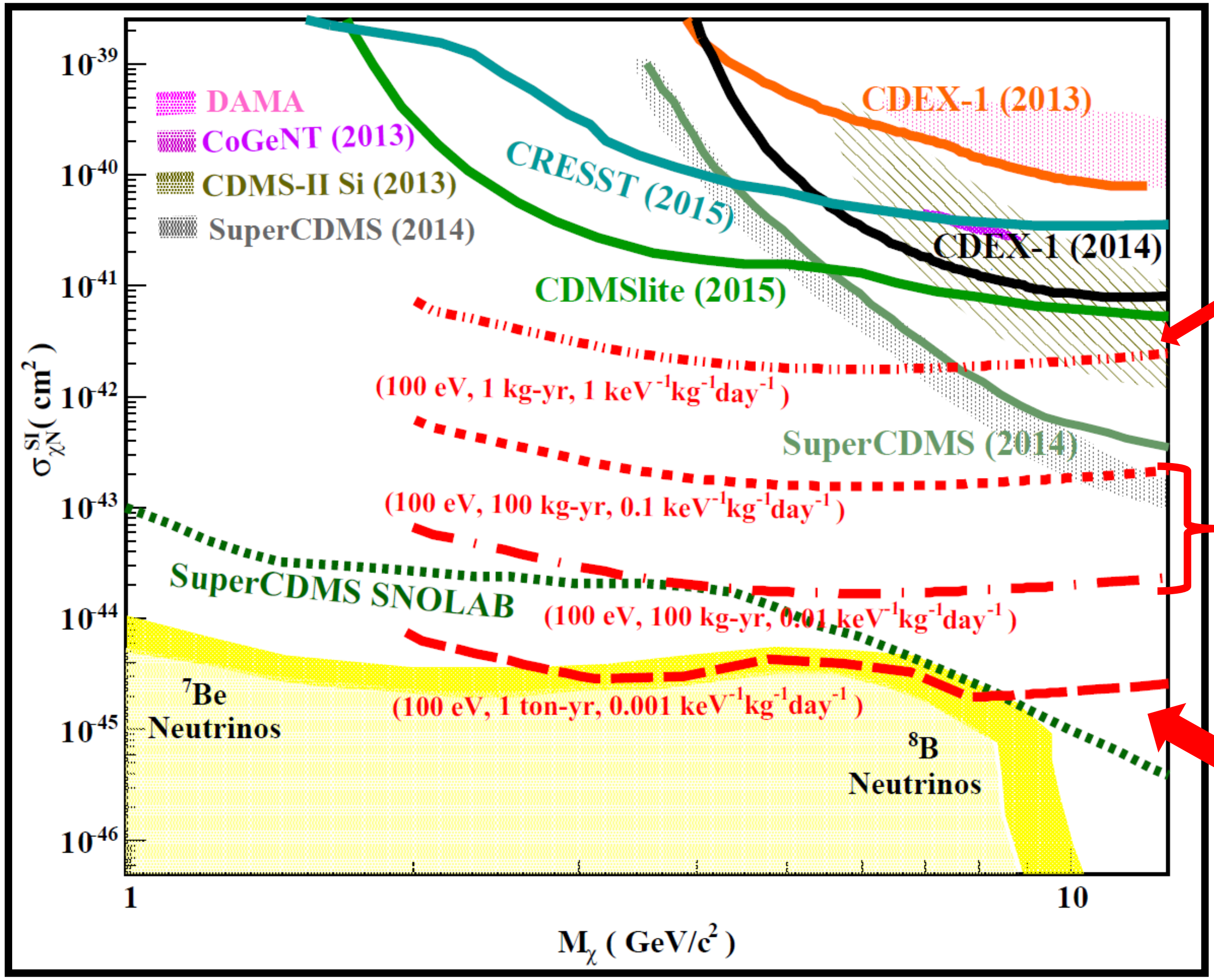
CDEX in CJPL-II

CDEX-1T space ready NOW!





CDEX-1T Multi-purpose experiment



CDEX-1 : Realistic Reach

CDEX-10/100 :

- Reach @ 0νββ Grade Bkg Control
- Spread -- H3 Bkg & Subtraction

CDEX-1ton :

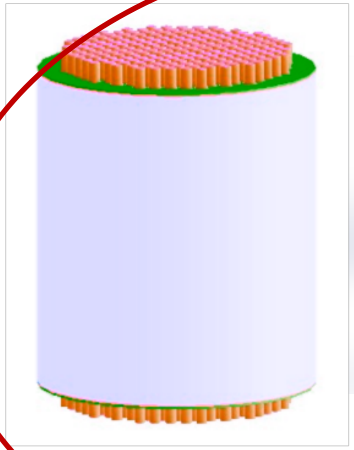
- Reach @ 0νββ Grade Bkg & Underground Ge-Growth, detector fabrication and ULB-Cu production

PandaX experiment

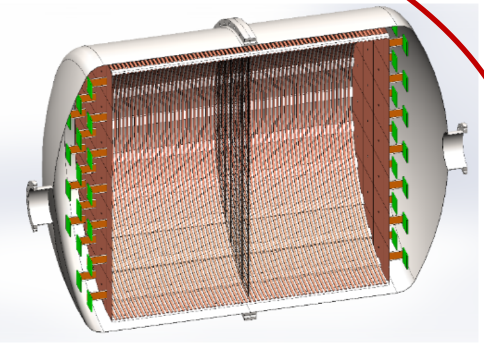
PandaX = Particle and Astrophysical Xenon Experiments

Phase I:
120 kg DM
2009-2014

Phase II:
500 kg DM
2014-2017

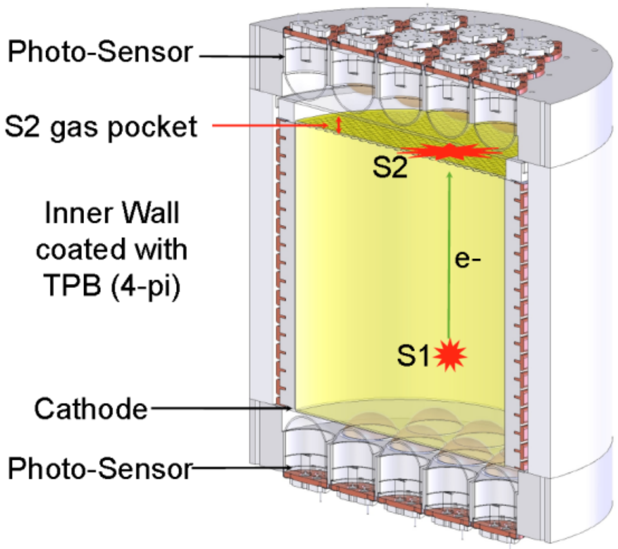


PandaX-xT:
multi-ton DM
future

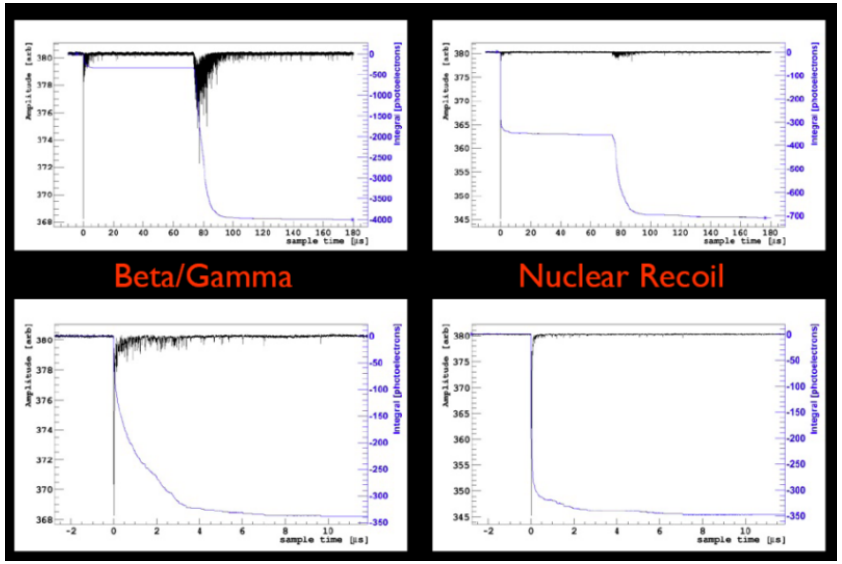


PandaX-III:
200 kg to 1 ton
^{136}Xe 0vDBD
future

液氩探测器优势



- 液氩是优秀的闪烁材料，在两相测量中利用S2/S1可去除本底100-1000倍，这一点和液氙探测器是相同的；
- 液氩发光衰减时间分为7纳秒快成分(单态发光)和1.6微秒慢成分(三态发光)，对于中子信号和光子信号，两种发光成分的比例是不同的，因而从波形上可以识别是哪一种事例。对于多于60光电子的光强，实验上证明了液氩具备10^8的伽玛-中子分辨能力；



液氩探测器能够测出更清楚的暗物质"脸谱"

液Ar与液氙探测器确定WIMP特性的互补

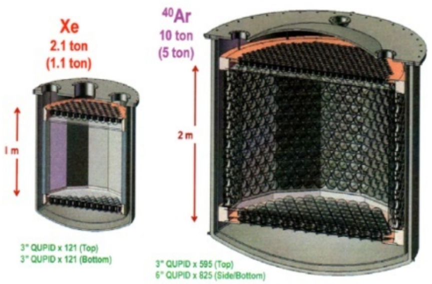


Fig. 1. Main parameters of the 1 ton/5 ton (fiducial) G2 system.

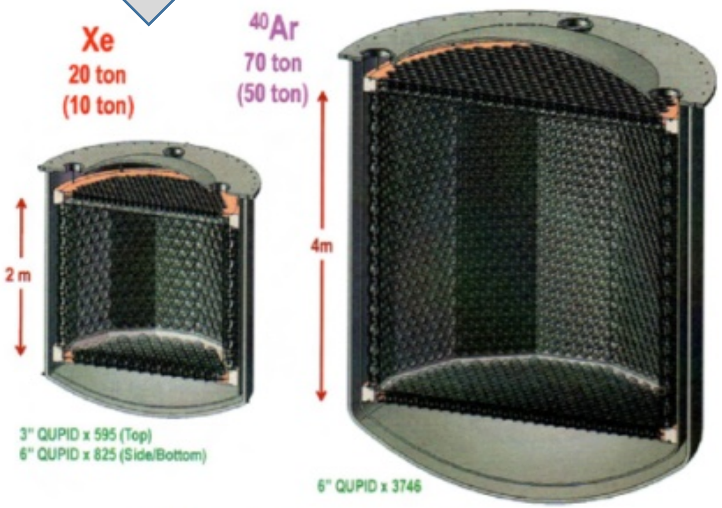


Fig. 2. Main parameters of the 10 ton/50 ton (fiducial) G3 system.

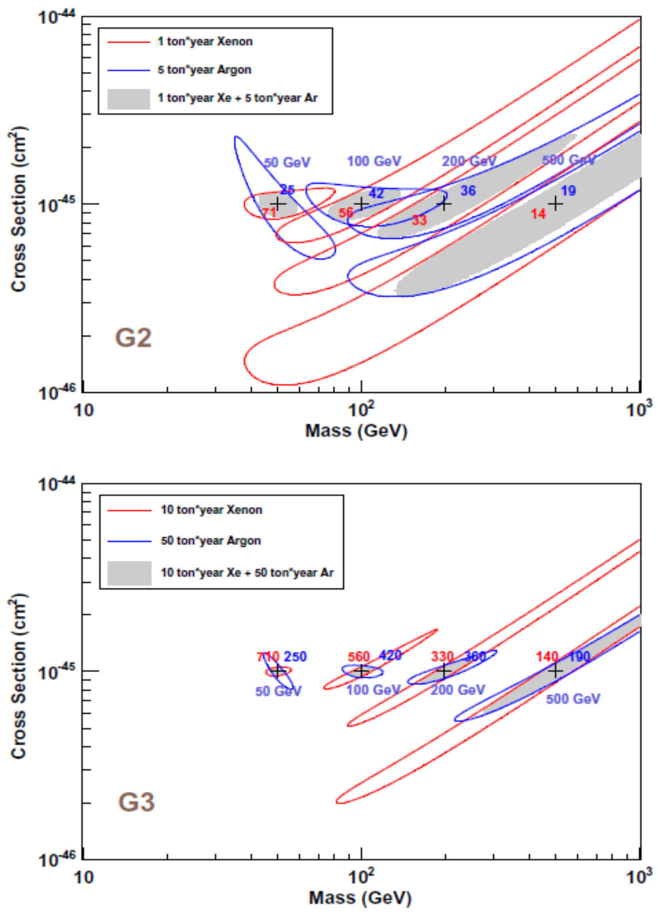
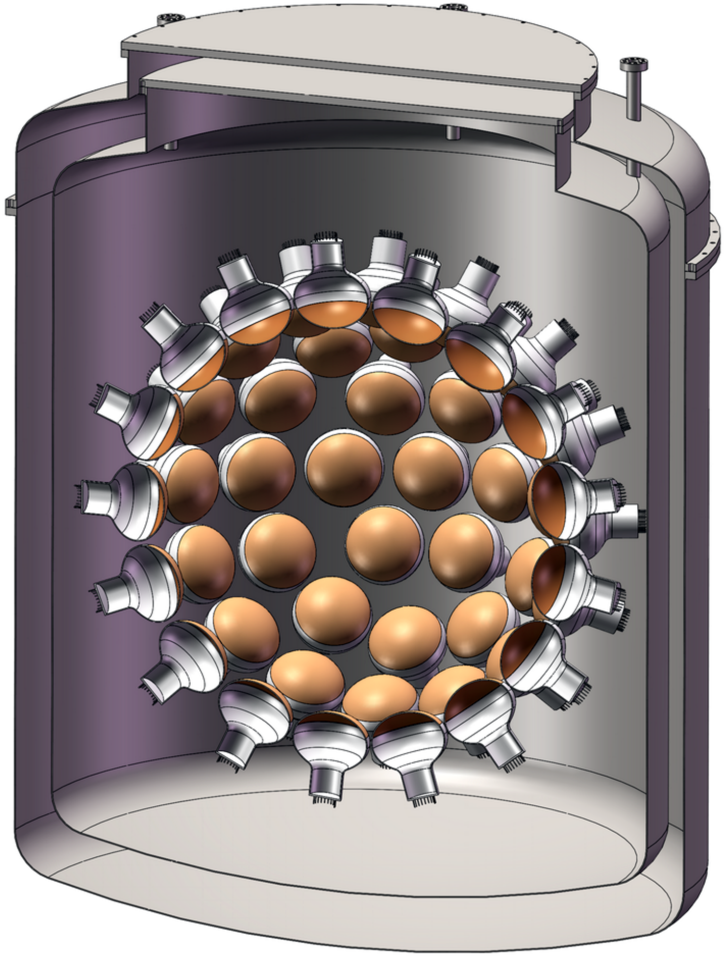
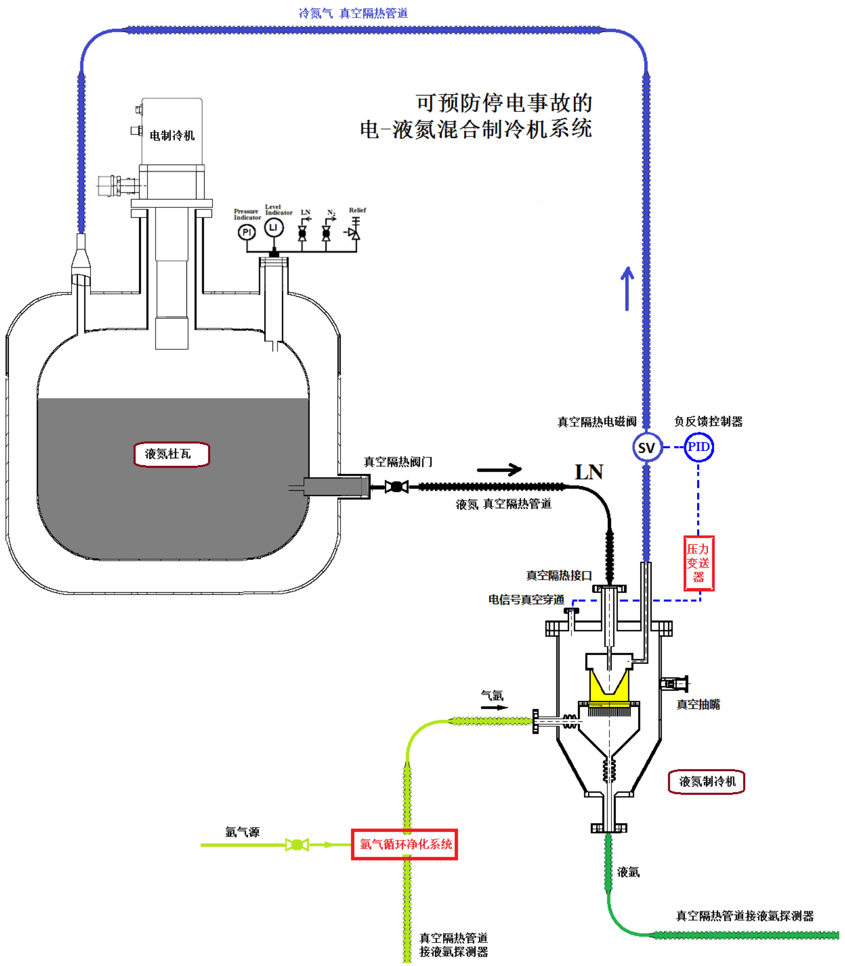


Fig. 12. Examples of overlap of 1σ Xe and Ar contours for WIMP masses 50–500 GeV (*upper*)cross-section 10^{-45} cm² with G2 system: 1 ton-y Xe & 5 ton-y Ar or cross-section 10^{-46} cm² with G3 system: 10 ton-y Xe & 50 ton-y Ar or cross-section 10^{-47} cm² with G4 system: 100 ton-y Xe & 500 ton-y Ar. (*lower*) cross-section 10^{-45} cm² with G3 system: 10 ton-y Xe & 50 ton-y Ar or cross-section 10^{-46} cm² with G4 system: 100 ton-y Xe & 500 ton-y Ar.

高能所液氩探测器实验室

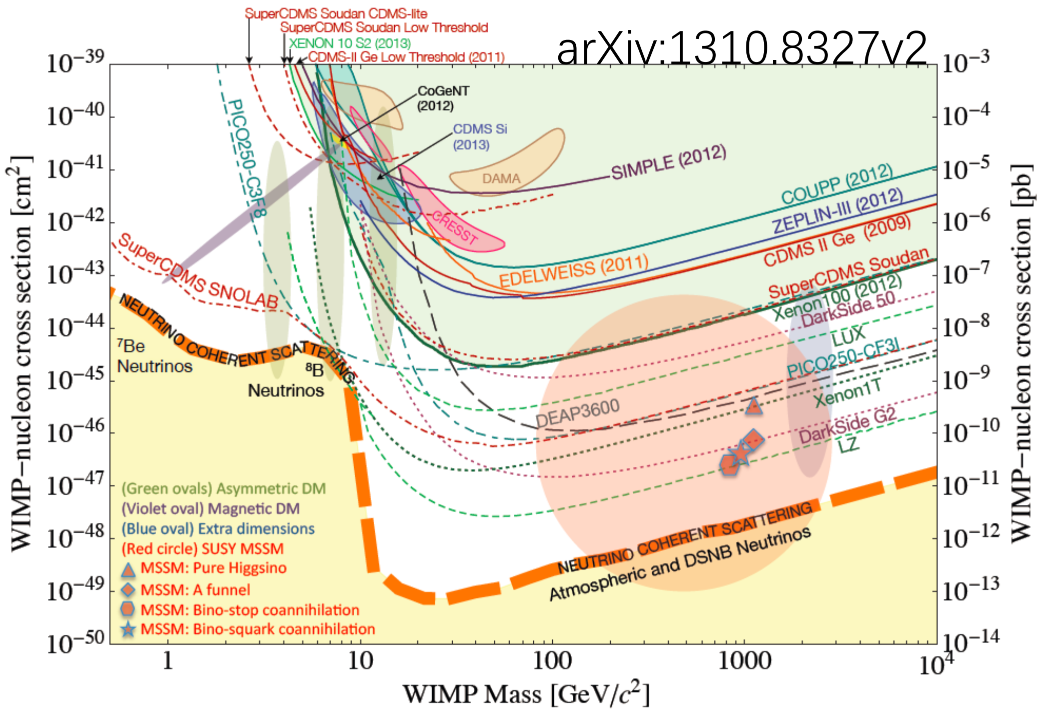
目前R&D: 1吨液氩探测器示意图





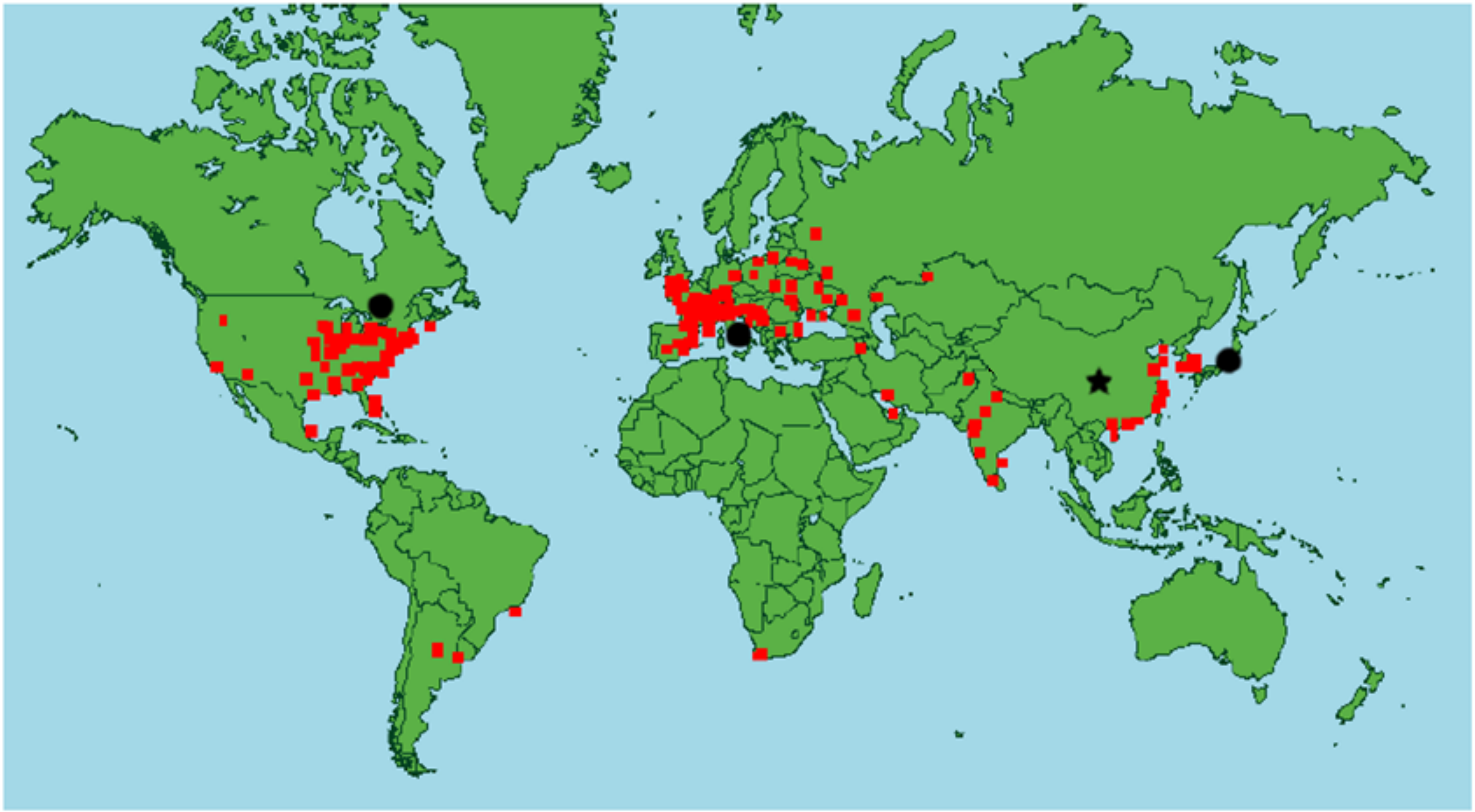
- 左图：吨级单相液氩探测器示意图,
- 右图：电-液氮混合制冷机概念设计图

目标: 锦屏液氩暗物质探测



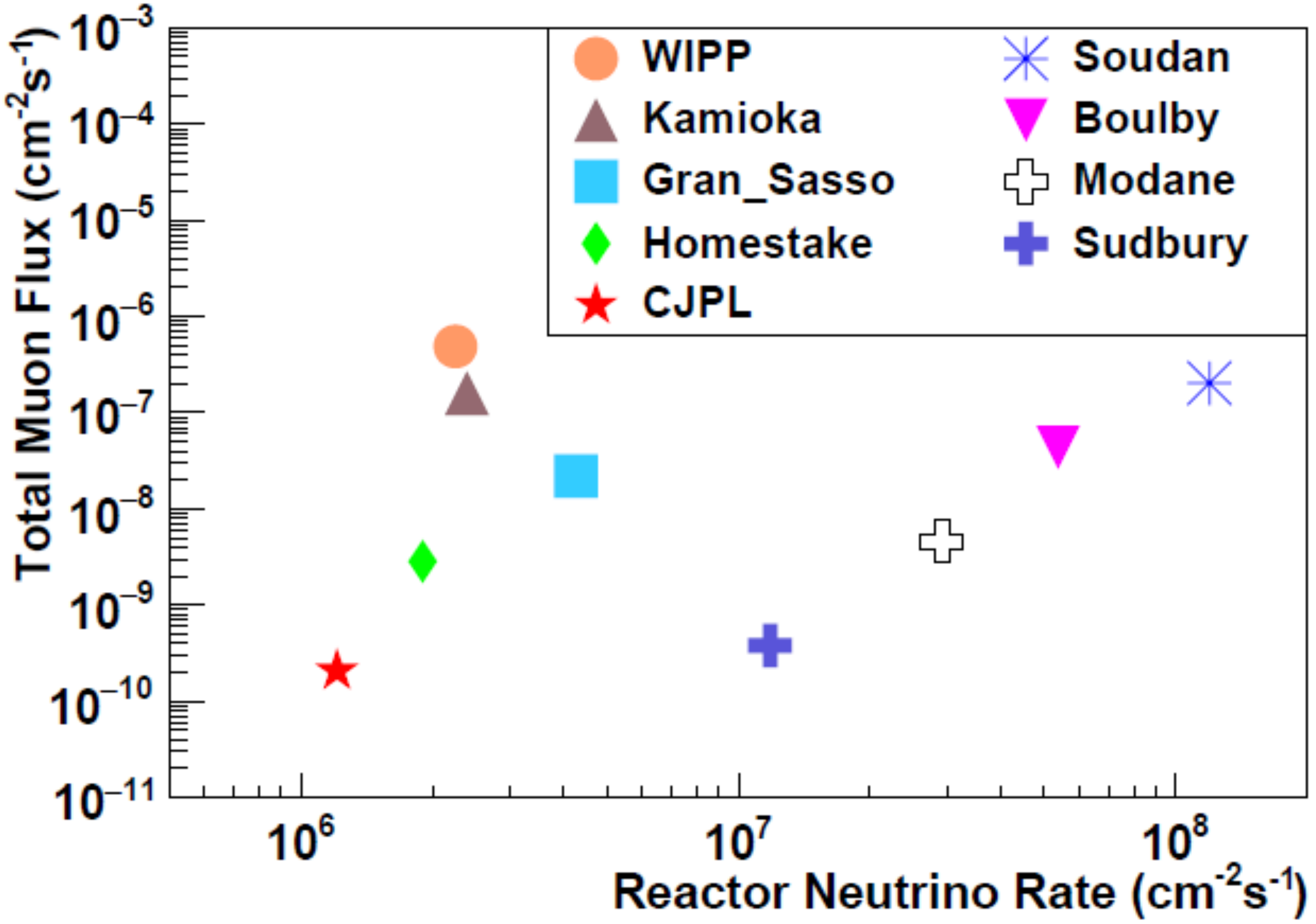
- 目前暗物质探测的灵敏度仍在提高，最终目标是实现暗物质的“终极探测”，达到中微子本底极限，这需要几百吨▪年的曝光量。
- 氩是惰性气体中价格最便宜，最易做成液体探测器的一种材料，已运用于加速器实验的量能器中，也是中微子探测和质子衰变探测的重要媒介。

反应堆本底



距最近的反应堆1200 km，低反应堆本底

优良的地下实验室



Total Muon Flux (cm-2s-1)
10−3
10−4
10−5
10−6
10−7
10−8
10−9
10−10
10−11
WIPP
Kamioka
Gran_Sasso
Homestake
CJPL
Soudan
Boulby
Modane
Sudbury
10^6
10^7
10^8
Reactor Neutrino Rate (cm-2s-1)

太阳标准模型(恒星演化模型)的四个要素： John Bahcall

1. 太阳供能方式：

质子-质子聚变链 pp

碳氮循环 CNO

2. 太阳内能量的传输机制：

辐射（内部），依赖于辐射透明度

对流（外部）

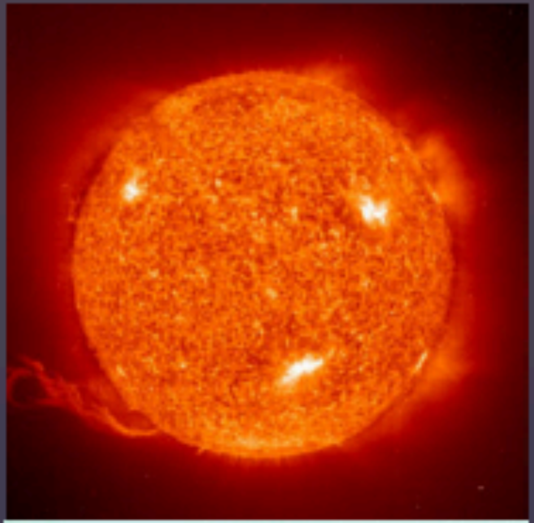
3. 太阳各处处于一个液态局域平衡状态：

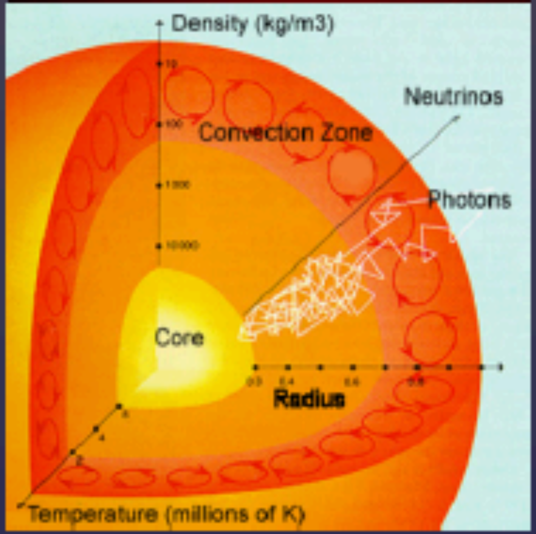
引力与辐射压力

4. 边界条件：

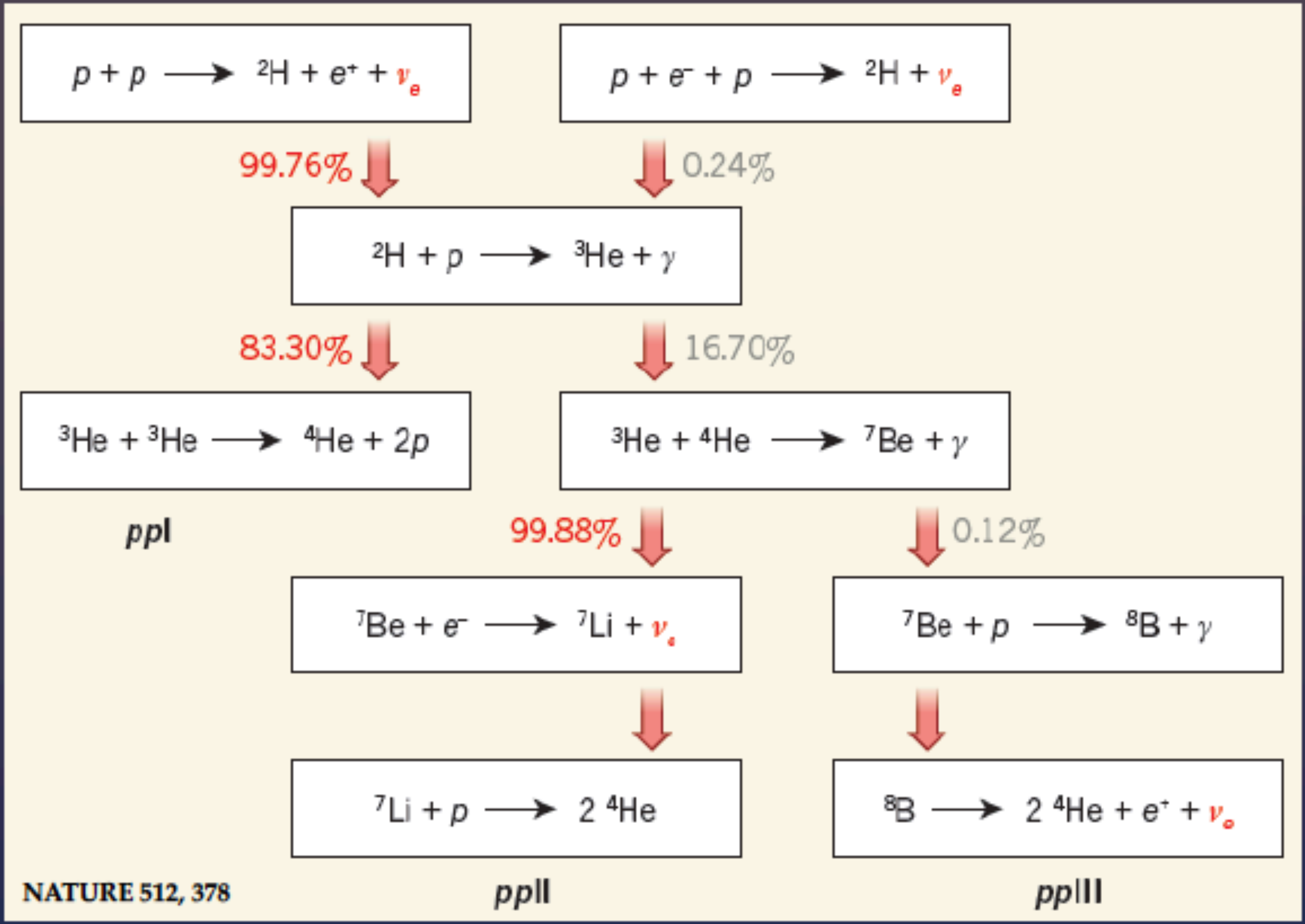
原初星的氢、氦、金属含量，

目前太阳半径，质量，亮度约束、年龄。

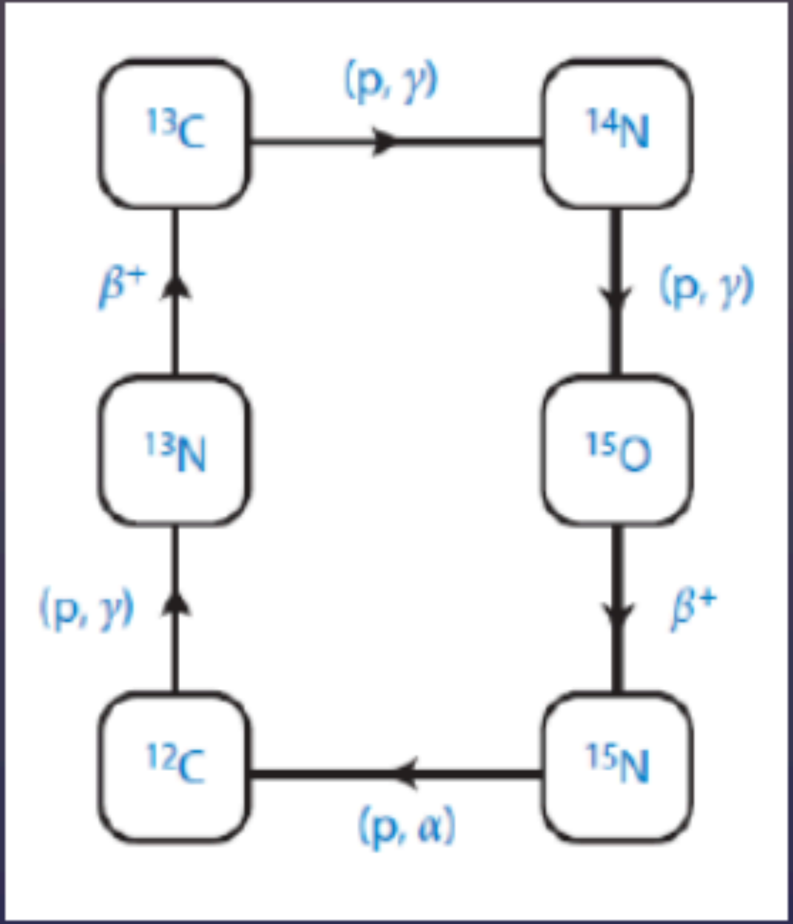


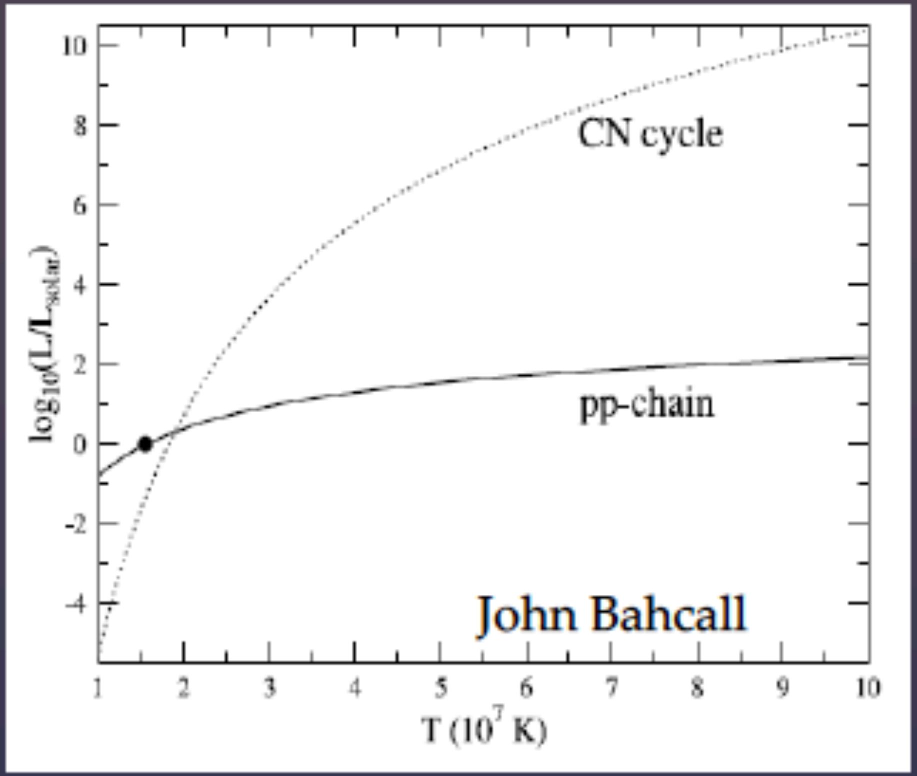


中微子产生-1：质子-质子聚变链 pp



中微子产生-2：碳氮循环 CNO





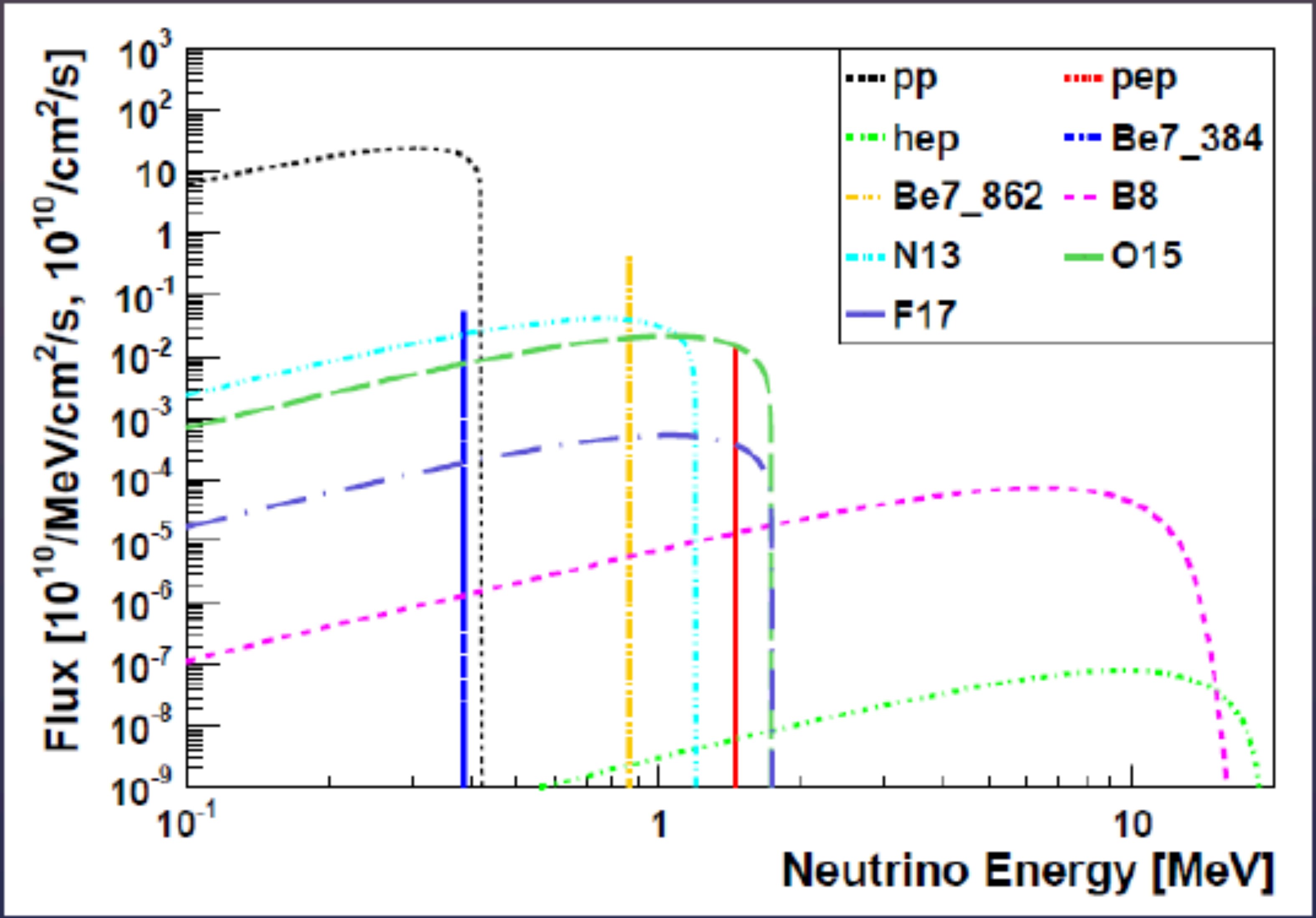
质子-质子聚变链：

（太阳温度下的主要过程）

碳氮循环：

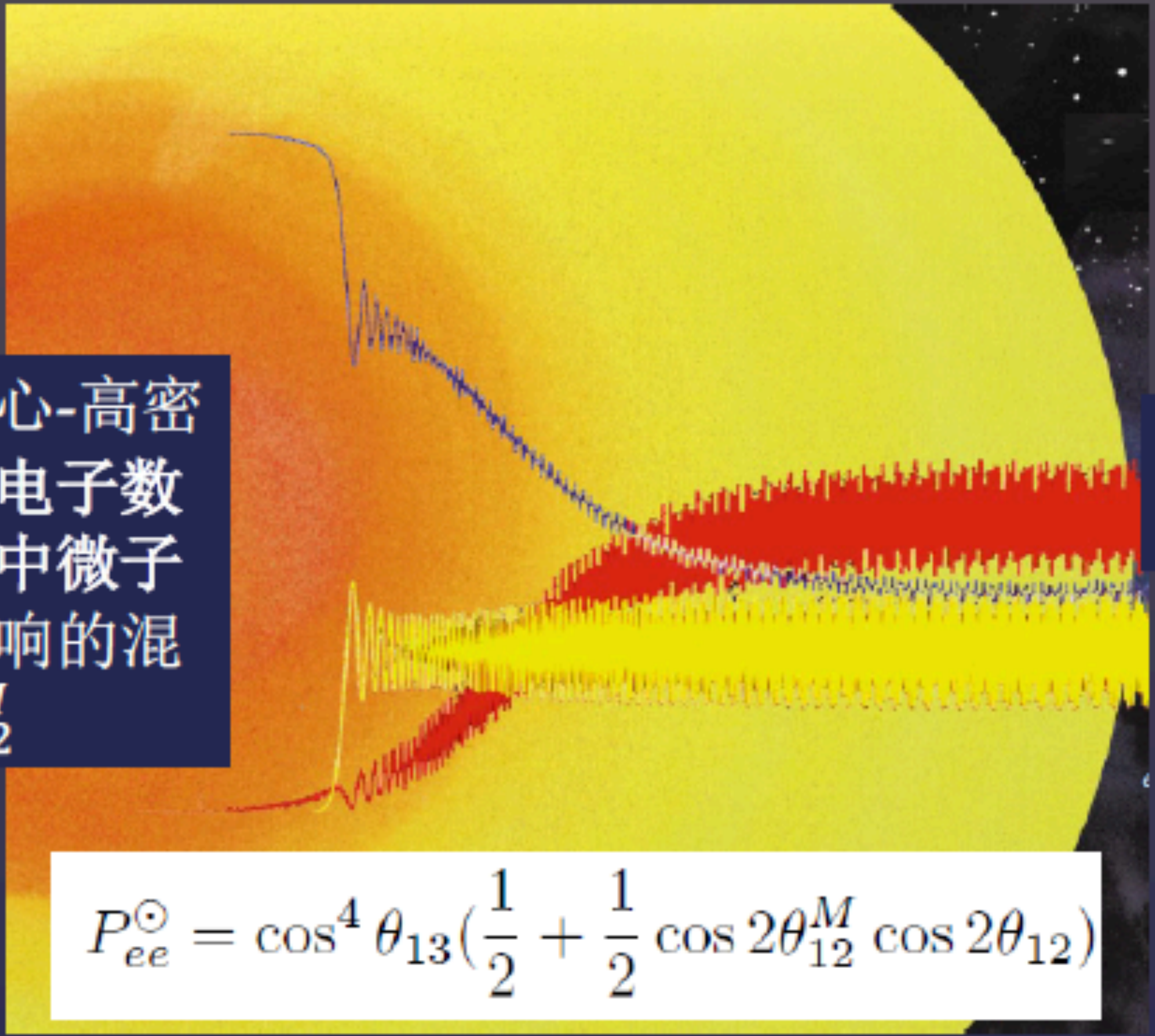
（高温主序星的主要模式）

太阳中微子能谱



Flux [10^10/MeV/cm^2/s, 10^10/cm^2/s]
10^3
10^2
10
1
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-7
10^-8
10^-9
10^-1
1
10
Neutrino Energy [MeV]
pp
pep
hep
Be7_384
Be7_862
B8
N13
O15
F17

太阳中微子振荡与传播



太阳中心-高密度：受电子数密度和中微子能量影响的混合角θ_{12}^{M}

外围：真空混合角θ_{12}

$$P_{ee}^{\odot} = \cos^4\theta_{13}\left(\frac{1}{2} + \frac{1}{2}\cos 2\theta_{12}^{M}\cos 2\theta_{12}\right)$$

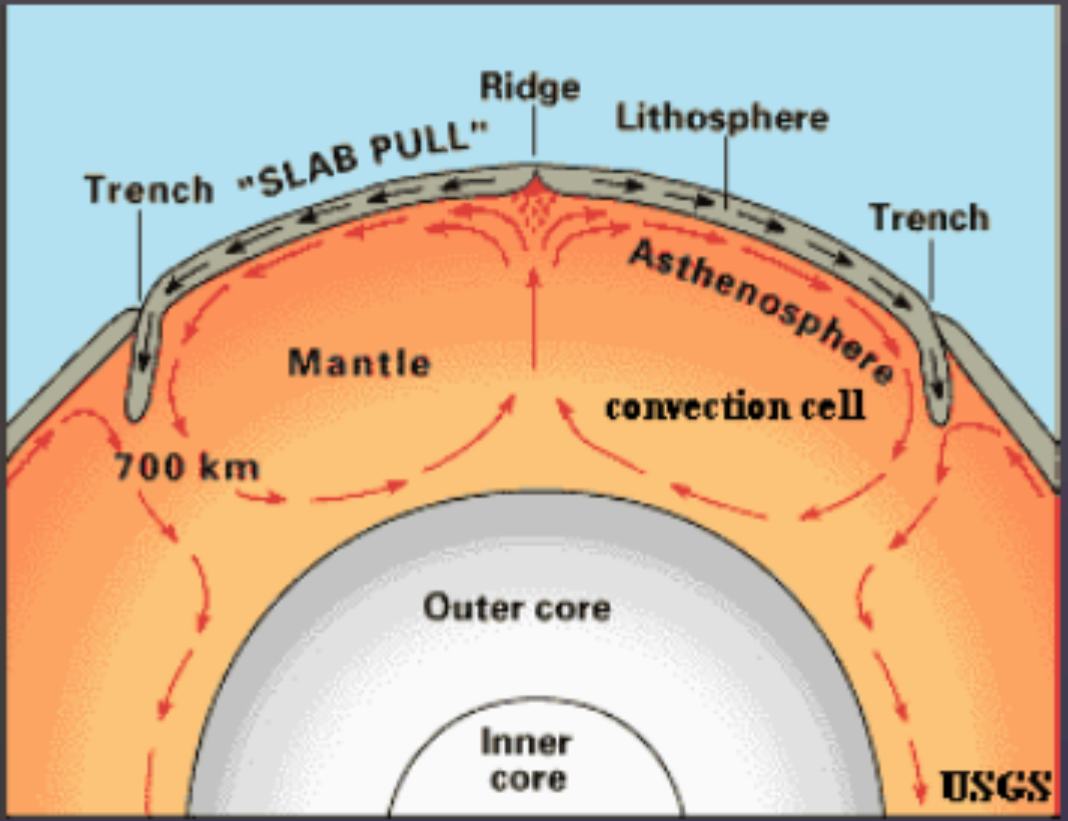
*如果中微子穿过地球，其通量将继续受到调制，幅度变化~3%

板块运动的原动力？

- 地球引力塌缩势能？
- 地球内部的核衰变，核裂变？

目前的知识：

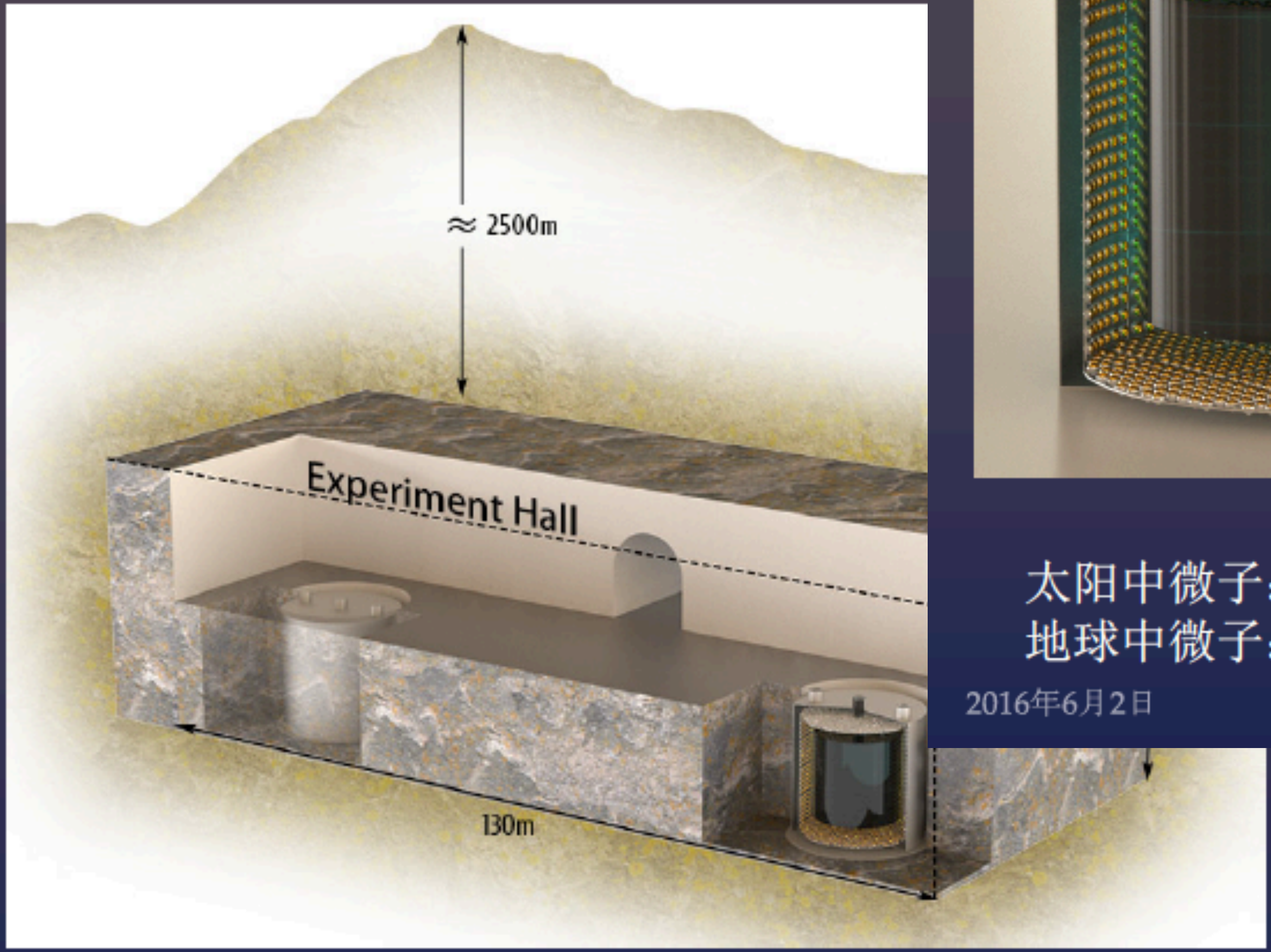
- 全球地热测量47±3 TW
- 对核衰变热的预期：
  - Cosmochemichal模型：10 TW
  - Geodynamical模型：15-30 TW
  - Geochemical模型：20 TW
- 地球中微子实验测量10-30 TW之间



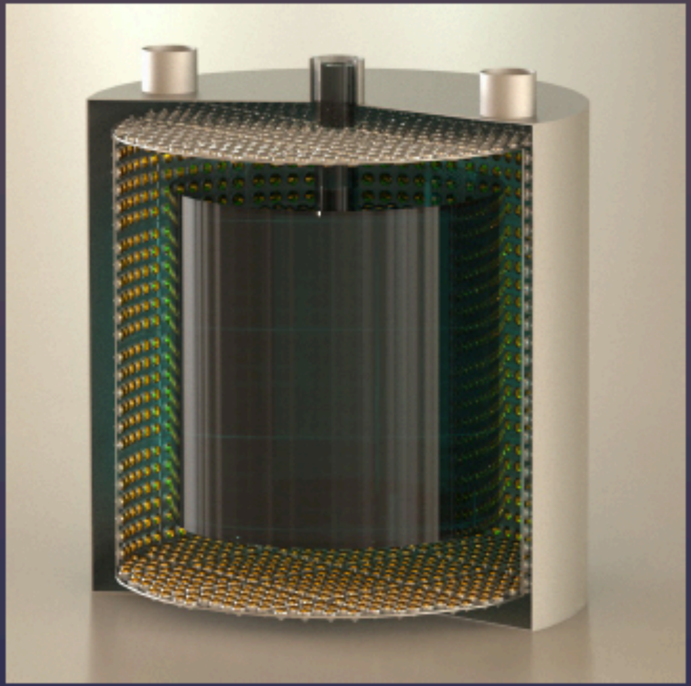
答案：

- 我们还在消耗地球形成之初的引力势能
- 核衰变情形基本未知
- 需要测量地球中微子

锦屏中微子实验



中微子探测器



- 共两个中微子探测器
- 每个的太阳中微子有效靶体积为1000吨，共2000吨
- 三层主要结构：钢桶，PMT层，亚克力桶
- 钢桶和亚克力间为纯水
- 亚克力容器内为液闪或水基液闪
- 总高H、外直径D约20米
- 能量分辨 > 500 PE/MeV
- 各方向外部光子缓冲 4米

太阳中微子：有效靶体积≈V(H-2×4米，D-2×4米) ≈1000吨
地球中微子：有效靶体积≈V(H-2×3米，D-2×3米) ≈1500吨

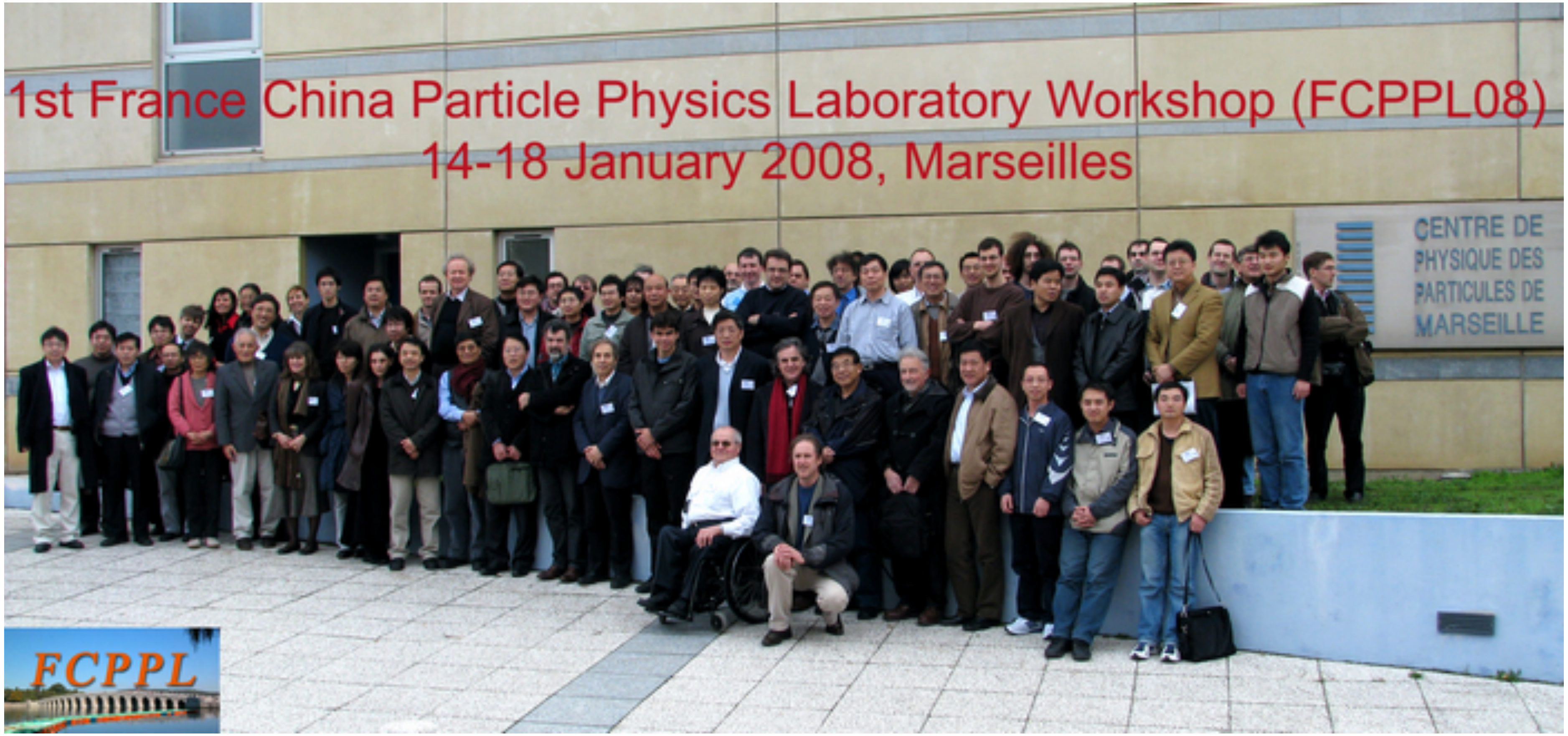
锦屏中微子实验调研-统计相对误差

	Neutrino component	Energy resolution 200 PE/MeV	500 PE/MeV	1000 PE/MeV
Fiducial mass 1000 ton	pp	0.02	0.007	0.005
	^{7}Be	0.007	0.006	0.005
	pep	0.07	0.05	0.04
	^{13}N	NA	0.5 (NA)	0.3 (0.4)
	^{15}O	0.3	0.2 (0.4)	0.1 (0.2)
	^{8}B	0.02	0.02	0.02
Fiducial mass 2000 ton	pp	0.01	0.005	0.004
	^{7}Be	0.005	0.004	0.004
	pep	0.06	0.03	0.03
	^{13}N	0.4	0.3	0.2 (0.3)
	^{15}O	0.2	0.1	0.08 (0.1)
	^{8}B	0.02	0.02	0.02
Fiducial mass 4000 ton	pp	0.01	0.004	0.003
	^{7}Be	0.004	0.003	0.003
	pep	0.04	0.03	0.02
	^{13}N	0.3	0.2 (0.3)	0.2 (0.3)
	^{15}O	0.1 (0.2)	0.07 (0.1)	0.06 (0.09)
	^{8}B	0.01	0.01	0.01

相对不确定性，例如0.3约对应 3σ

International Collaborations

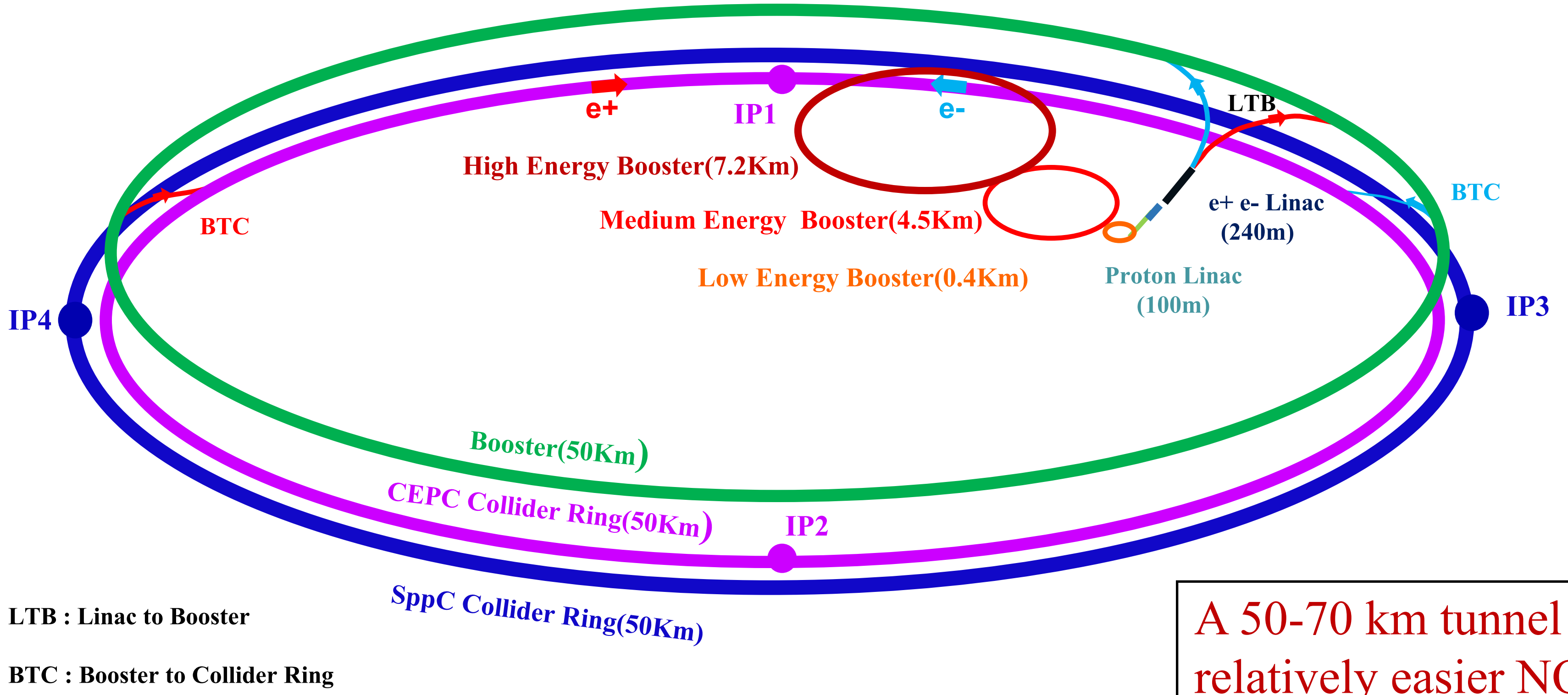
http://www.ihep.cas.cn/gjjl/hzxm/huitan/201111/t20111108_3392423.html



http://www.ihep.cas.cn/gjjl/hzxm/201404/t20140416_4091841.html

The Future: CEPC+SppC

- For about 8 years, we have been talking about "What can be done after BEPCII in China"
- Thanks to the discovery of the low mass Higgs boson, and stimulated by ideas of Circular Higgs Factories in the world, CEPC+SppC configuration was proposed in Sep. 2012



A 50-70 km tunnel is relatively easier NOW in China

Scientific Goals

- CEPC（e+e-: 90-250 GeV)
  - Higgs Factory: Precision study of Higgs(m_H, J^{PC}, couplings)
    - Same as SM prediction ? Other Higgs ? Composite ? New properties ? CP effect ？
  - Z & W factory: precision test of SM
    - New phenomena ? Rare decays ?
  - Flavor factory: b, c, τ and QCD studies
- SppC (pp: 50-100 TeV)
  - Directly search for new physics beyond SM
  - Precision test of SM
    - e.g., h^3 & h^4 couplings

Precision measurement & searches: Complementary with each other

Bob Wilson (first Director of Fermilab), when asked by a Congressional Committee *"What will your lab contribute to the defense of the US?"*, replied *"Nothing, but it will make it worth defending".*