宇宙重子缺失问题

Cosmic Missing Baryon Problem

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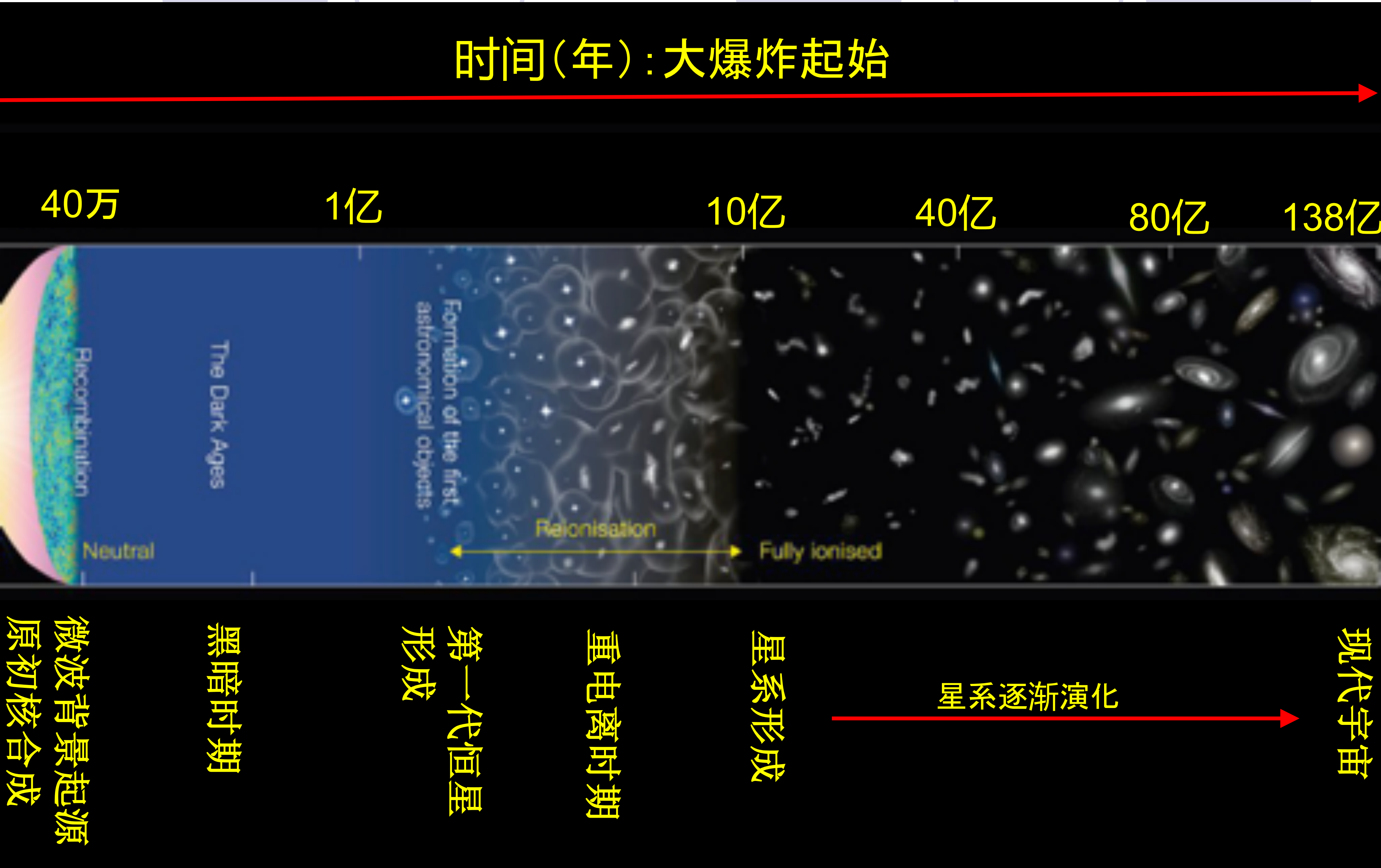
Where do we come from what are we where are we going

Paul Gauguin (1848—1903)

"I believe that this canvas not only surpasses all my preceding ones, but that I shall never do anything better—or even like it."

宇宙从哪里来？宇宙是什么？宇宙到哪儿去？



宇宙从哪里来？

1927年，Georges Lemaitre提出膨胀宇宙模型，后来演化为“大爆炸”理论。该理论的三大预言得到了观测的证实：

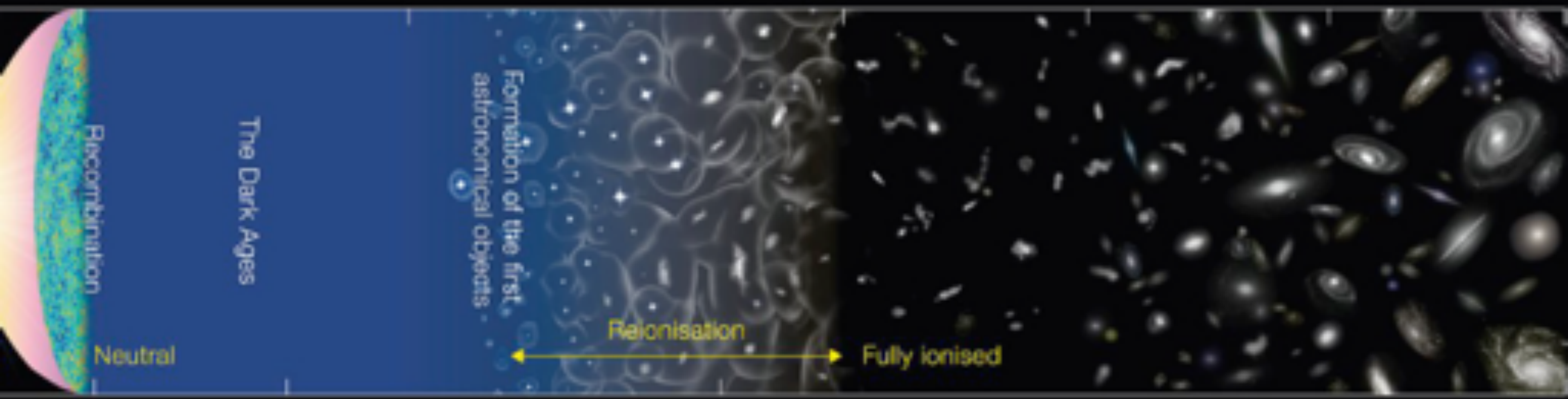
- **预言一：**哈勃为膨胀宇宙提高了观测证据
- **预言二：**观测证实原初核（即重子）合成产生的轻元素（包括氢、氘和氦）
- **预言三：**微波辐射背景
  - 发现：1978年诺贝尔物理奖
  - 物理性质的测量：2006年诺贝尔物理奖
  - 宇宙参数的精确测量：可能未来还会有更多

“大爆炸”理论是现代宇宙学研究的基石

宇宙是什么？宇宙到哪儿去？

时间（年）

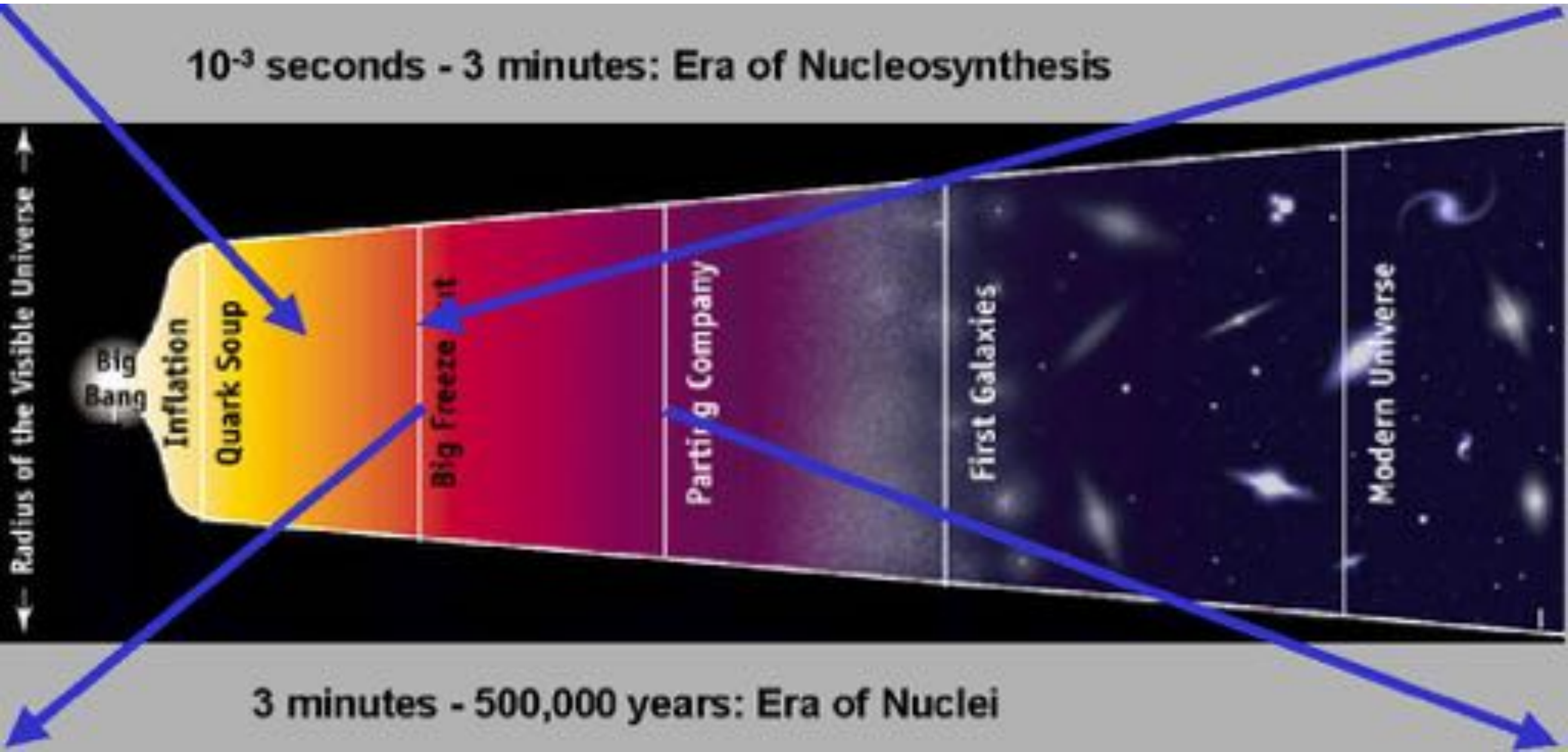
40万 1亿 10亿 40亿 80亿 138亿



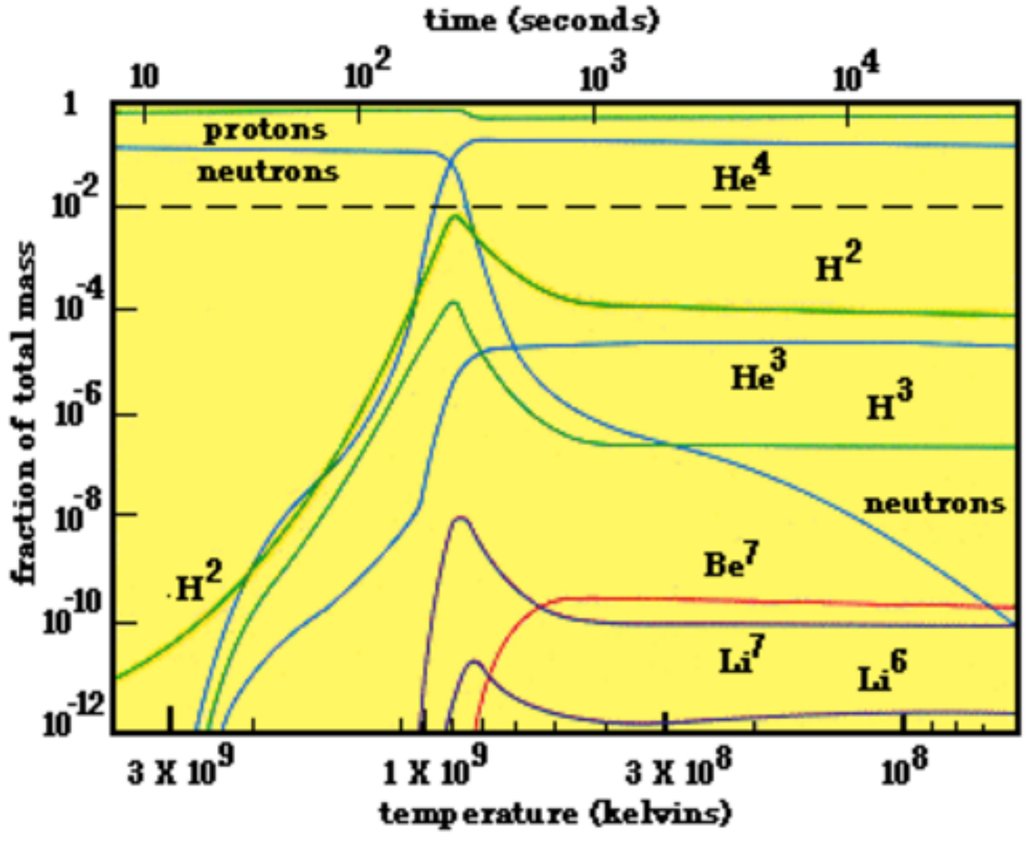
原初核合成

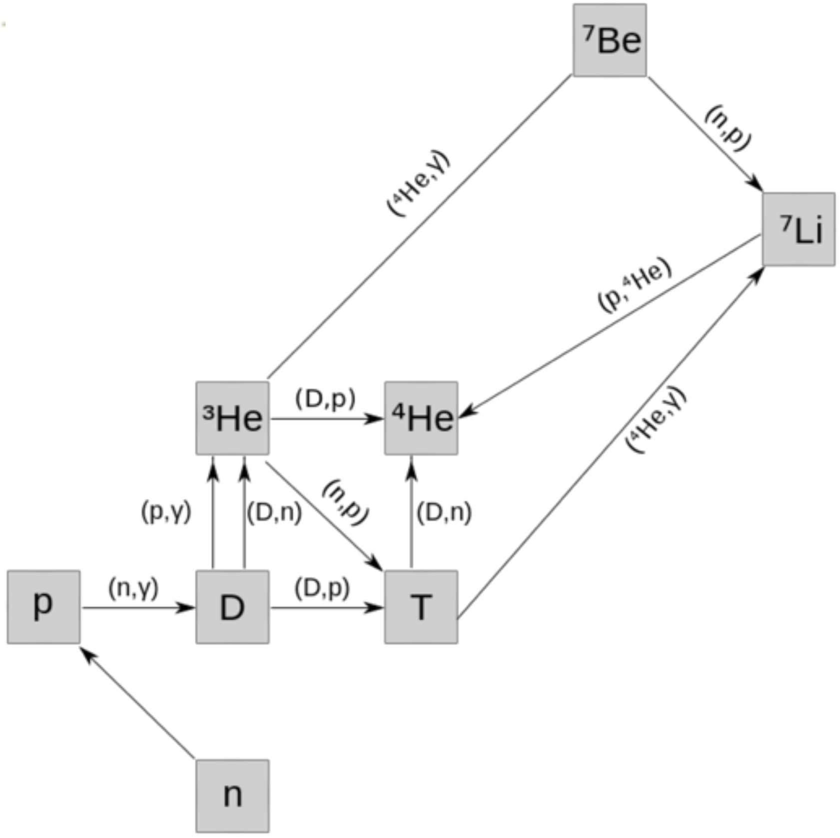
宇宙重子合成

重子是由三个夸克组成的粒子，如中子和质子



原初核元素合成

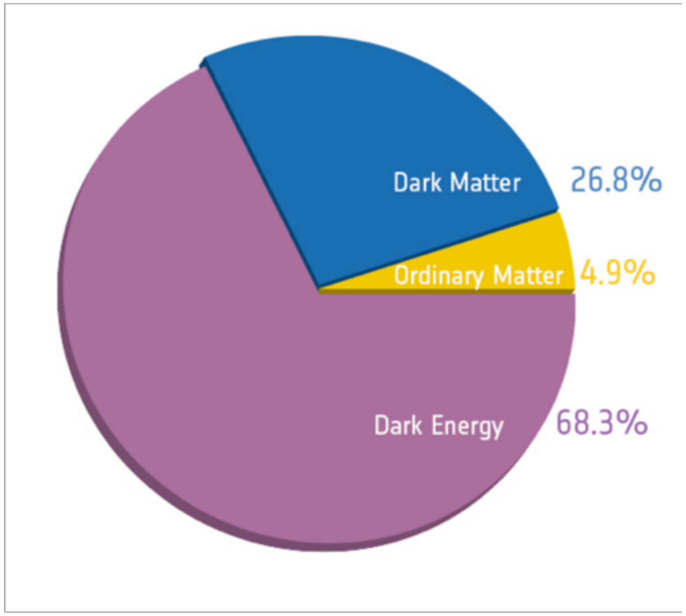

time (seconds)
10
10^2
10^3
10^4
1
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
fraction of total mass
protons
neutrons
He^4
H^2
He^3
H^3
neutrons
Be^7
H^2
Li^7
Li^6
3×10^9
1×10^9
3×10^8
10^8
temperature (kelvins)

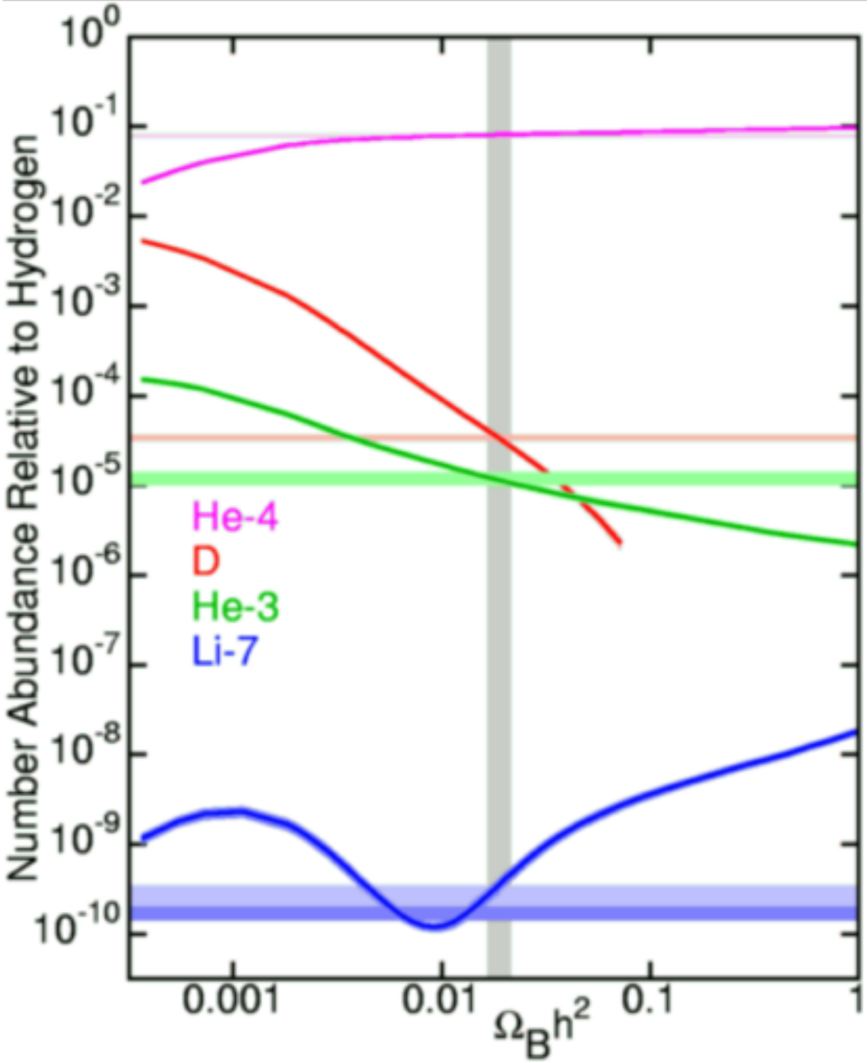

^7Be
(n,p)
(^4He,γ)
^7Li
(p,^4He)
^3He
(D,p)
^4He
(^4He,γ)
(p,γ)
(D,n)
(n,p)
(D,n)
p
(n,γ)
D
(D,p)
T
n

宇宙中的重子物质

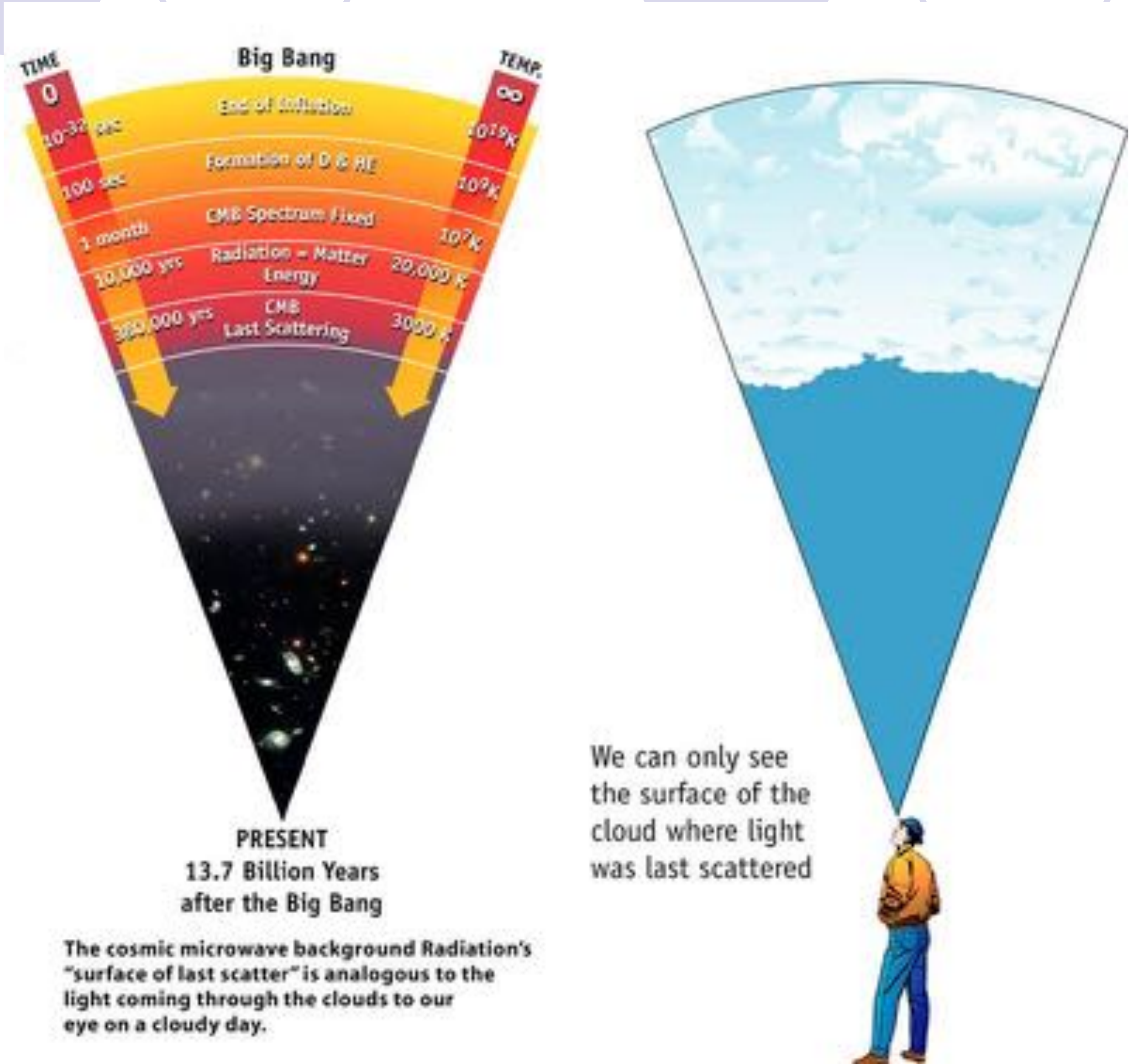
$\Omega_B h^2 = 0.0214 \pm 0.0020$

不同观测的到相同的结果!





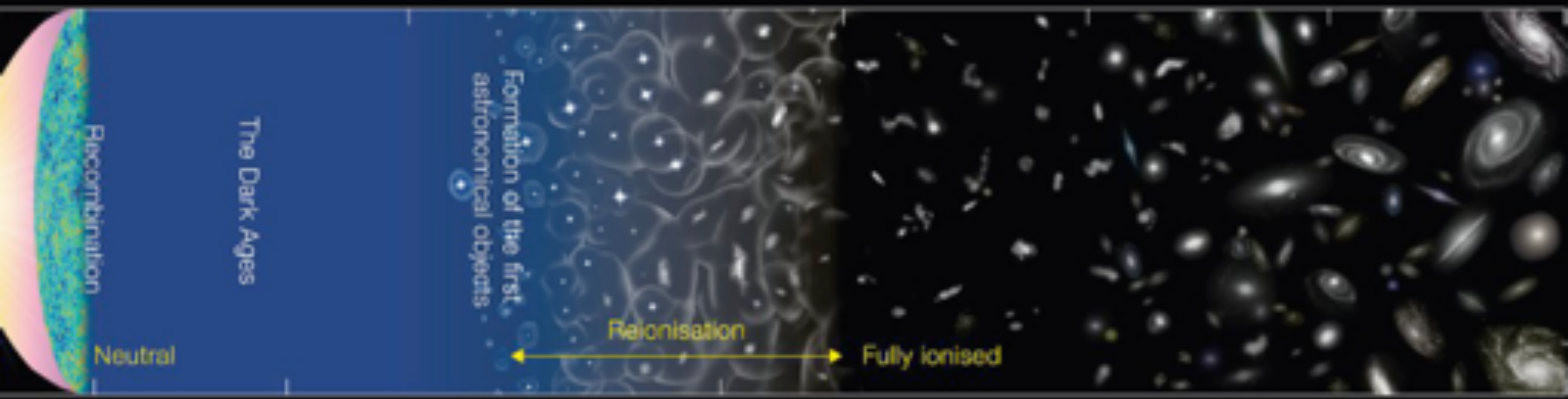
光子突破束缚。。。大致40万年时



宇宙是什么？宇宙到哪儿去？

时间(年):大爆炸起始

40万　1亿　10亿　40亿　80亿　138亿



微波背景起源

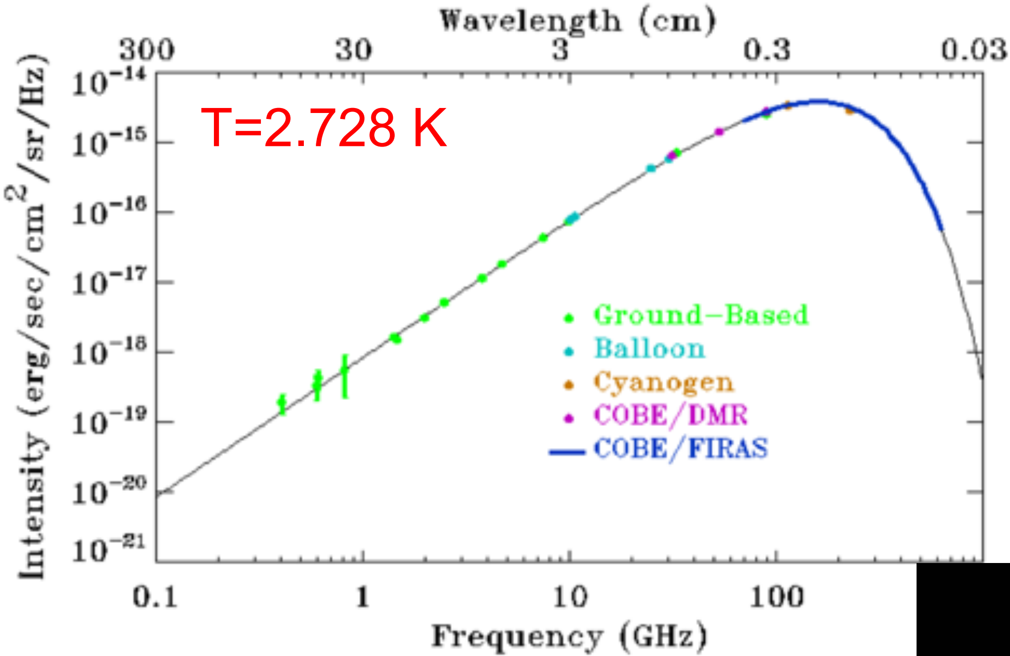
原初核合成

Nobel


COBE DMR Microwave Sky at 53 GHz
0
3.64 K

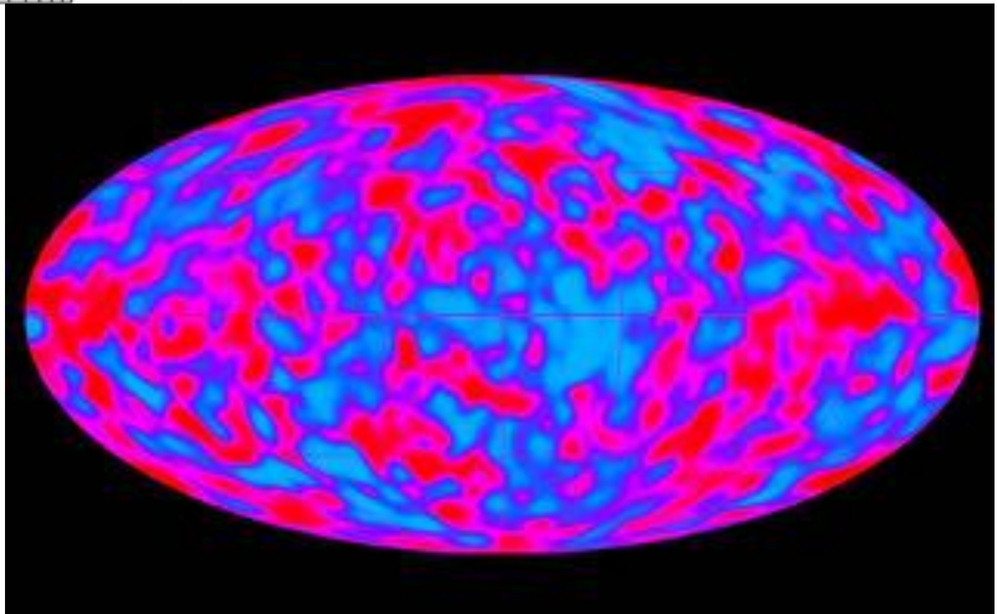

FIRAS
DIRBE
Deployable Sun, Earth, RF/Thermal Shield
DMR Antennas
Helium Dewar
Deployable Solar Panels
Earth Sensors
Deployable Mast
WFF Omni Antenna
TDRSS Omni Antenna
COBE

完美黑体辐射！

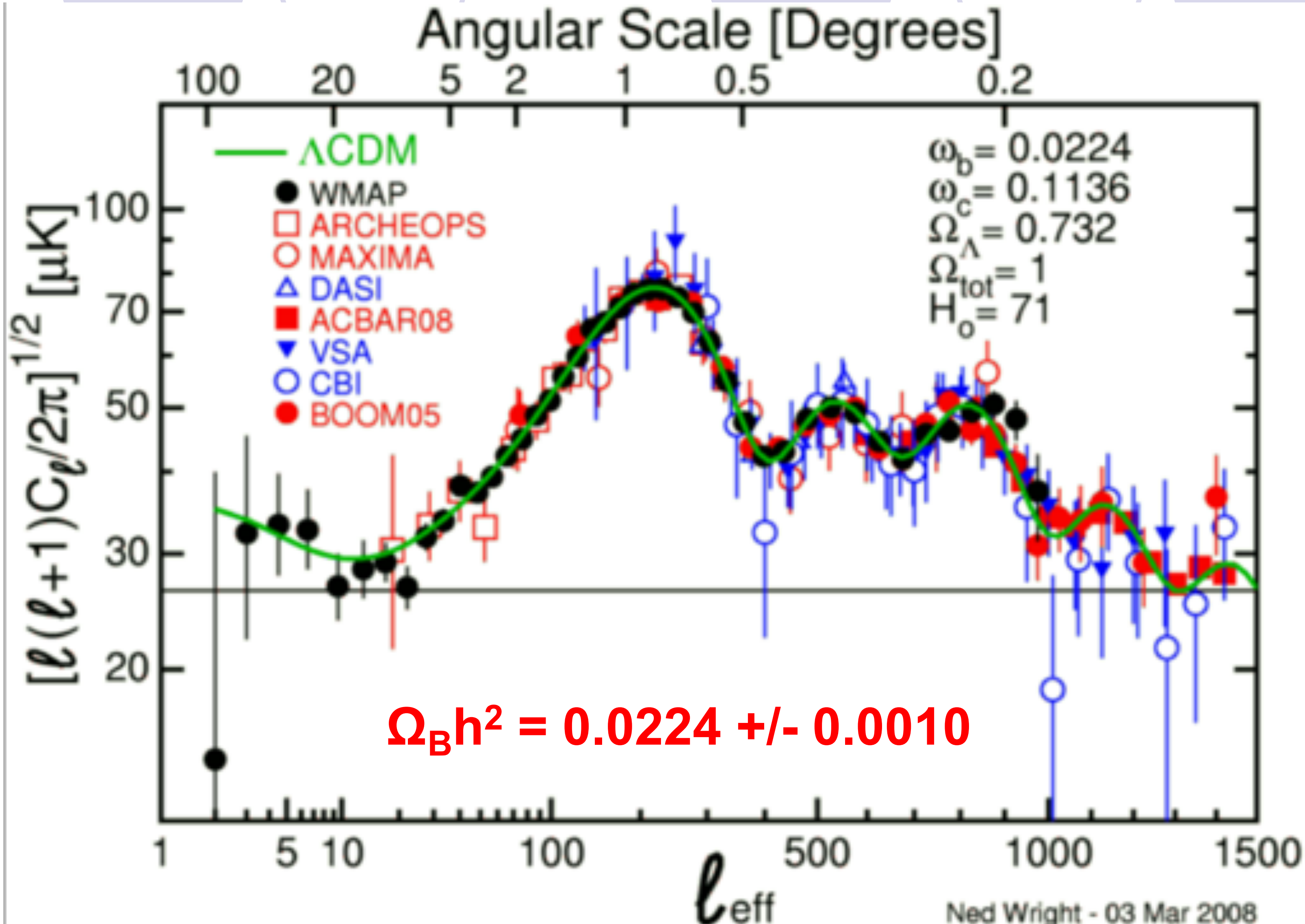


Nobel Prize in Physics in 2006

“Cosmic seeds”

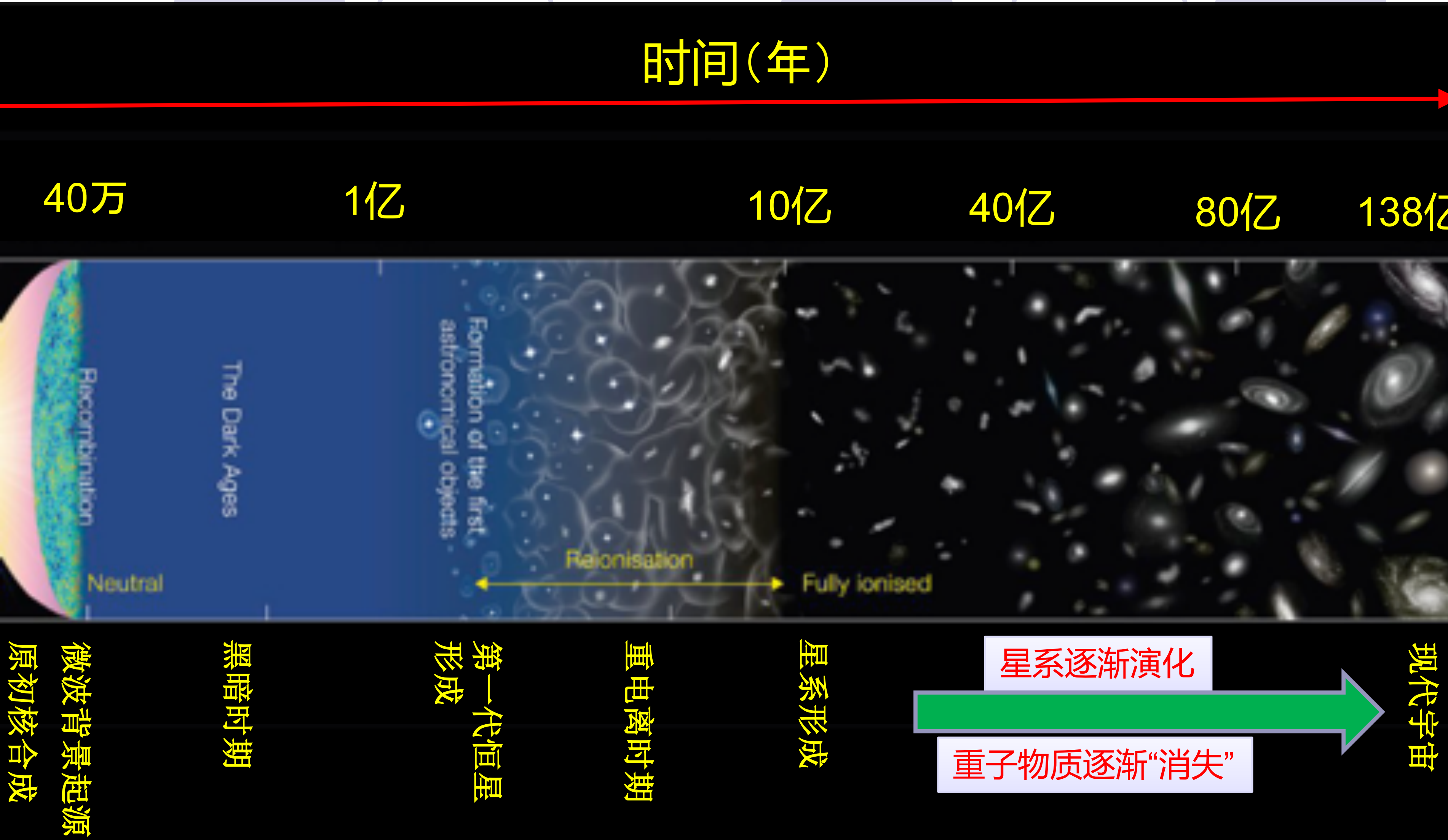


宇宙学进入精确测量时代



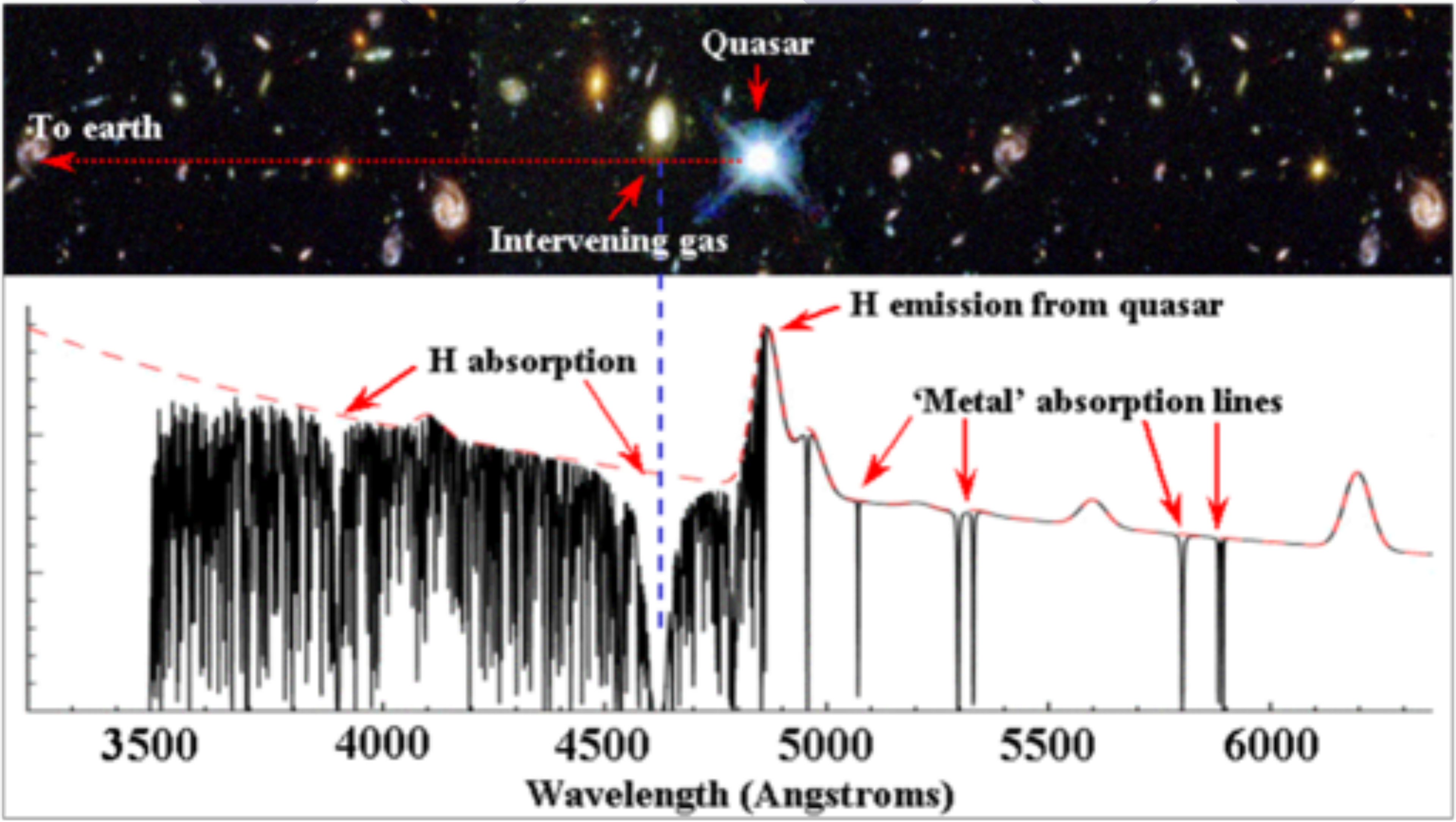
$$\Omega_B h^2 = 0.0224 +/- 0.0010$$

宇宙演化与重子``缺失”



理论预期：“缺失”的重子（组成元素周期表中元素的质子和中子）以低密度弥漫热气体的状态充满整个宇宙

宇宙重子普查



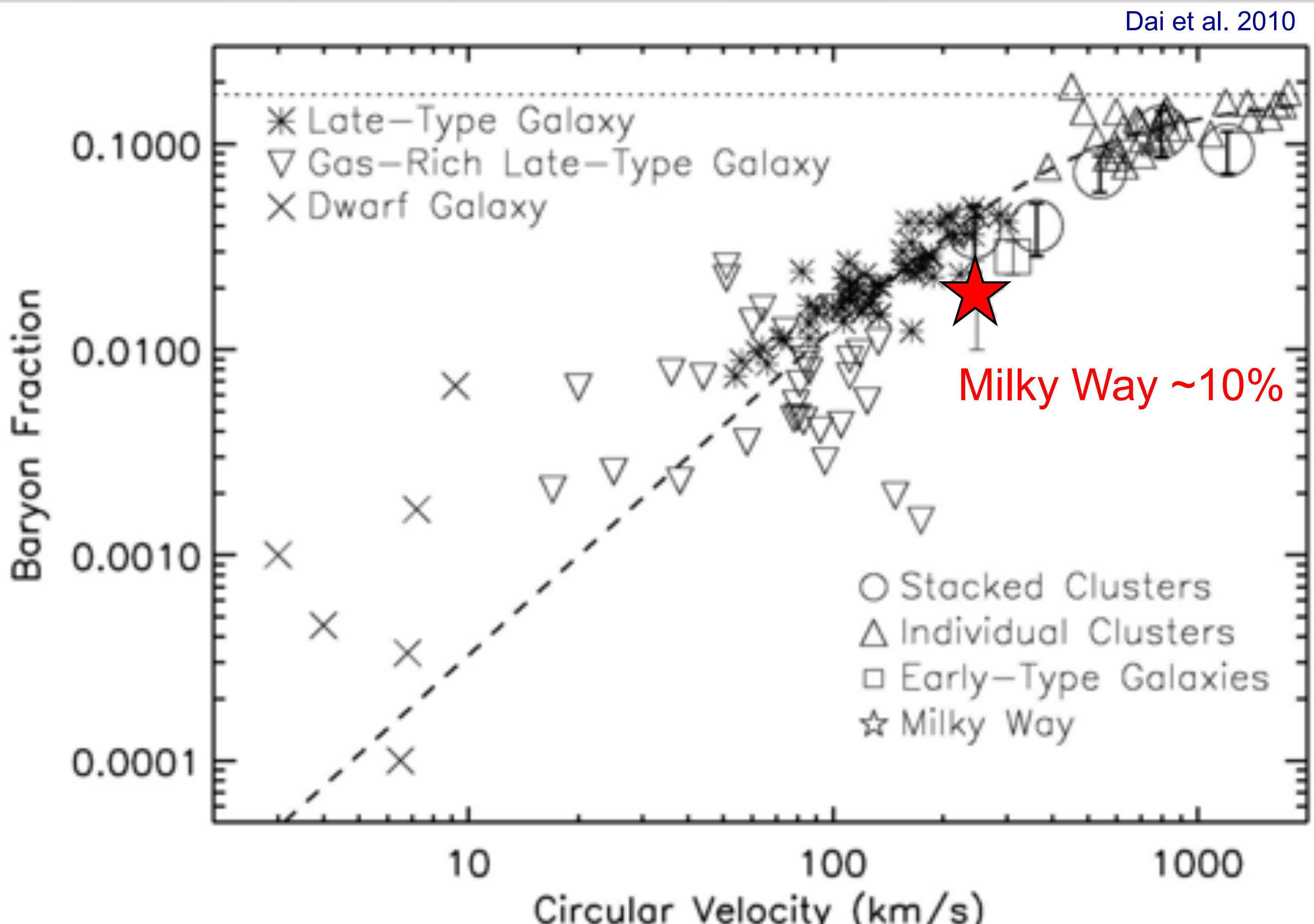
Quasar
To earth
Intervening gas
H emission from quasar
H absorption
'Metal' absorption lines
3500
4000
4500
5000
5500
6000
Wavelength (Angstroms)

Problem #1: Global missing baryons

- BBN baryons
  - At z~1100, they are fully accounted for with the observations of the cosmic microwave background.
  - At z > 2-3, they are mostly accounted for with observations of the Lyman alpha forest.
  - At z ~ 0, only about 50% of them are accounted for with optical and UV observations.

Where are the rest of the baryons?

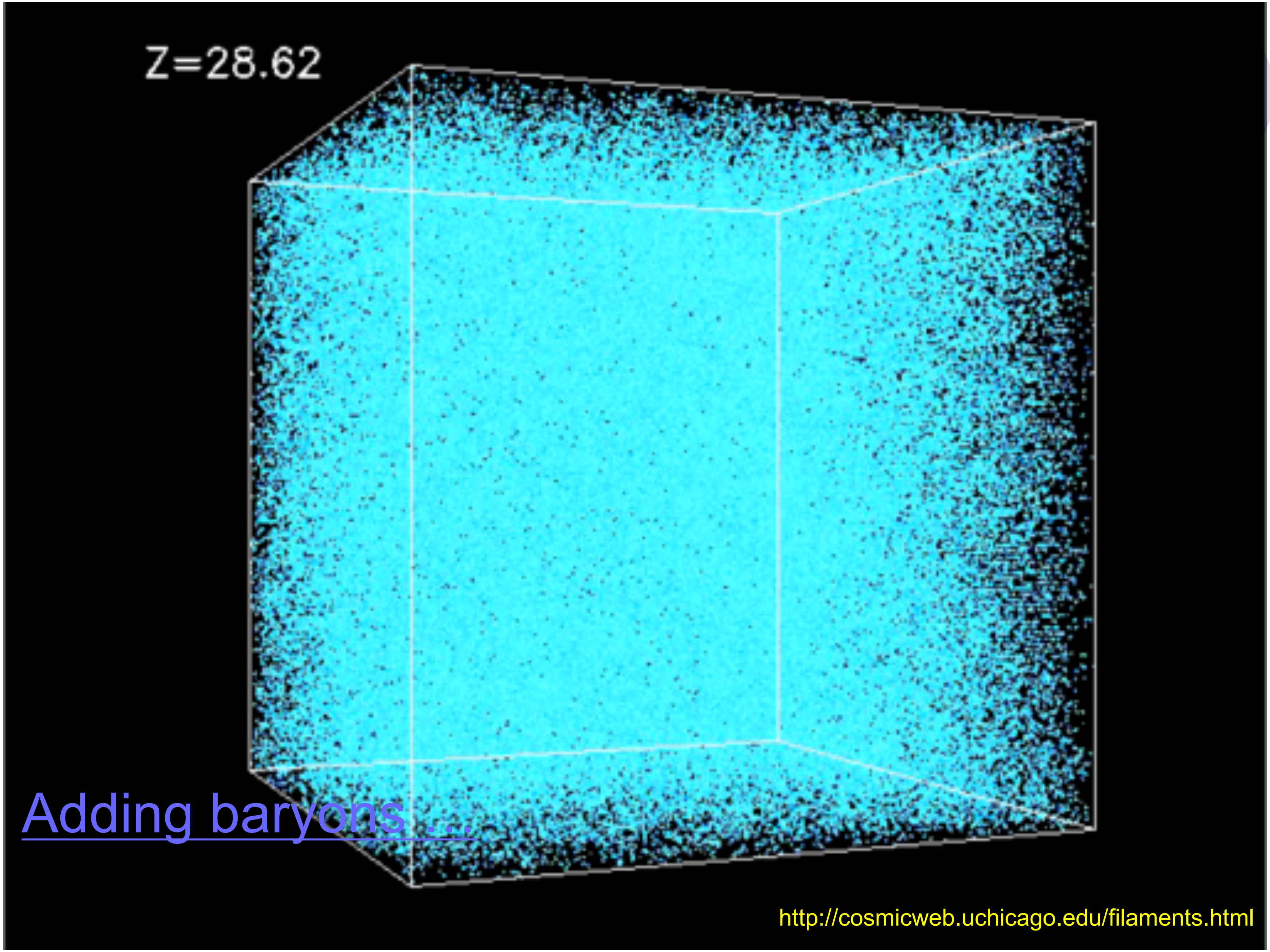
Problem #2: Local missing baryons



Problem #3: Missing metals

- Cosmic metallicity
  - Total mass of metals produced over cosmic time compared to the cosmic baryon density
  - Star formation history predicts 0.16 solar
- Measured metallicity
  - Consider metals in stars, metal absorption line systems, cold disk gas, hot group and cluster gas
  - The observed cosmic metallicity is about 0.015 solar

～90% of the metals are missing!



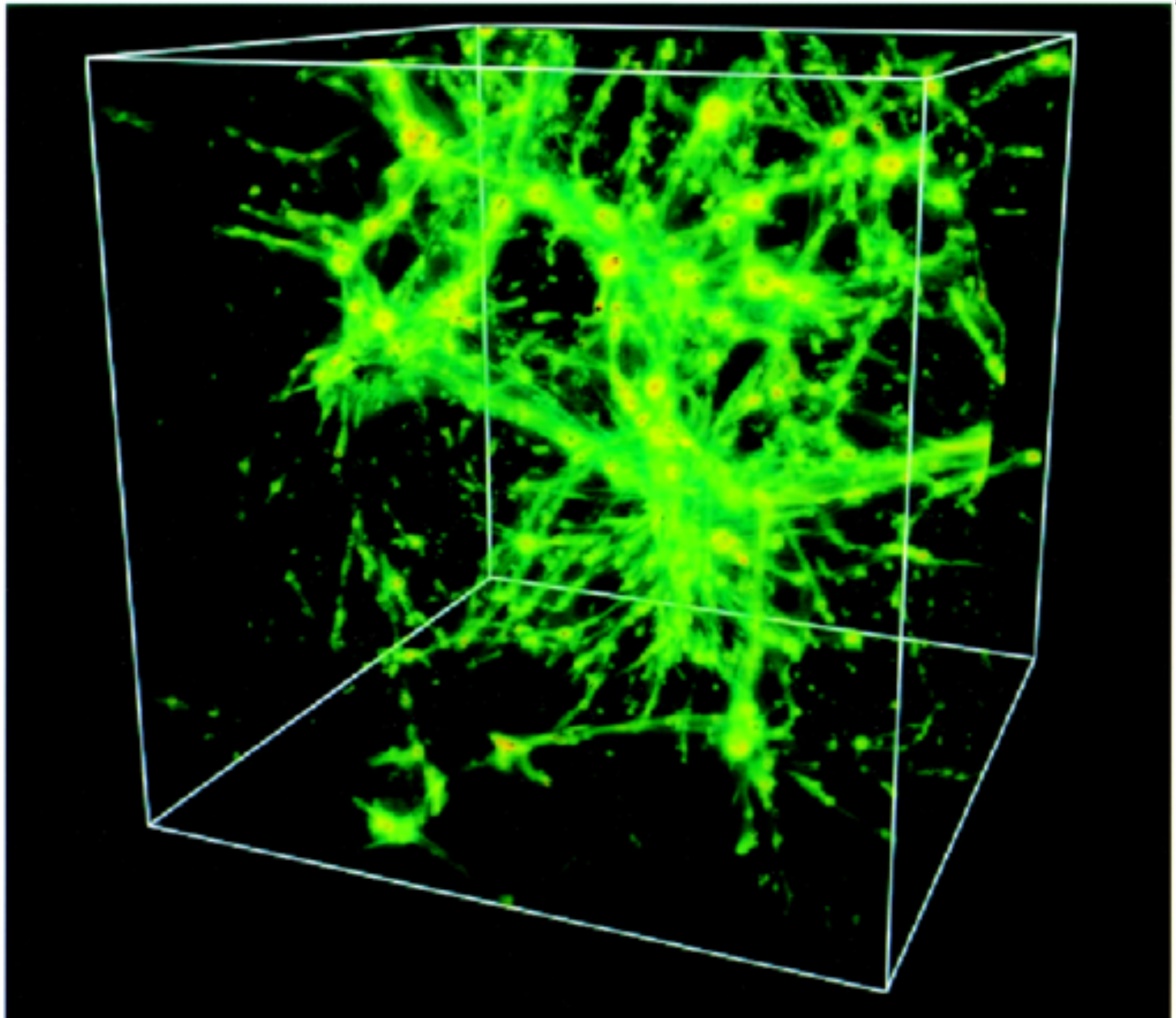
Adding baryons ...

http://cosmicweb.uchicago.edu/filaments.html

“Hidden”baryons in hot gas?

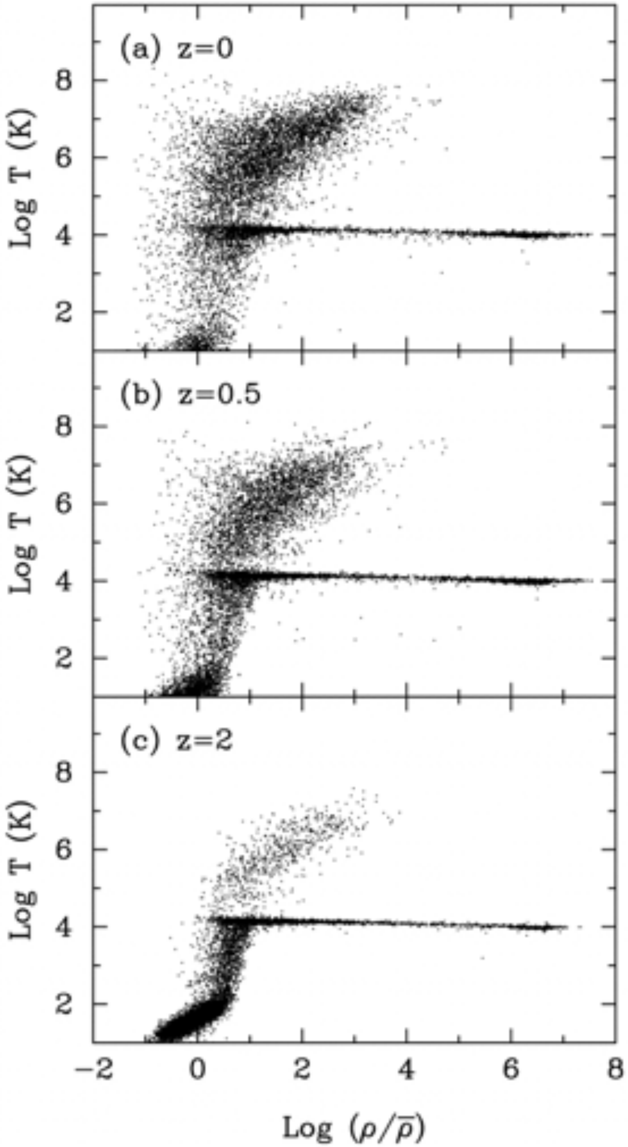
- Significant amount of hot gas is present in the cosmic filamentary structures.
  - Account for global missing baryons
- The hot halos of galaxies are more extended than previously detected.
  - Account for local missing baryons
- The hot gas has an average metallicity of 0.2-0.3 solar to account for the cosmic metallicity.
  - Account for global missing metals

理论数值模拟



Dave et al. 2001

Croft et al. 2001

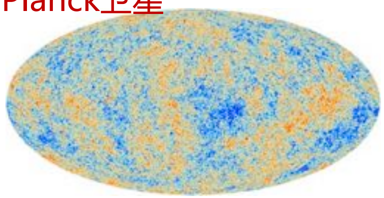


宇宙学发展的瓶颈

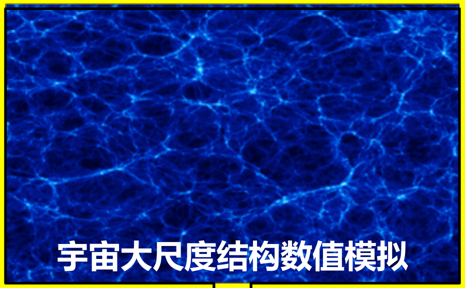
星系宇宙学领域发展瓶颈

理论

Planck卫星



宇宙微波背景辐射

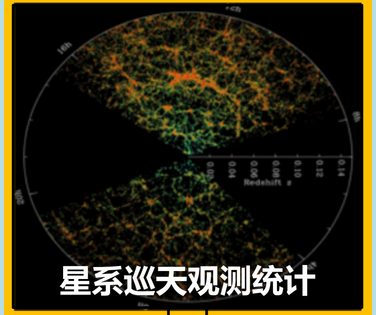


宇宙大尺度结构数值模拟

宇宙初始的物质密度场 → 宇宙暗物质密度场演化

重子缺失 ?

观测

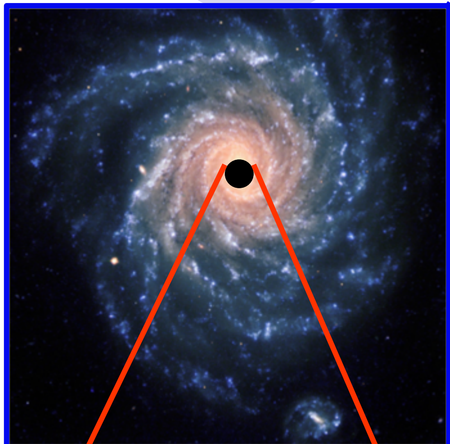


星系巡天观测统计

星系形成和演化

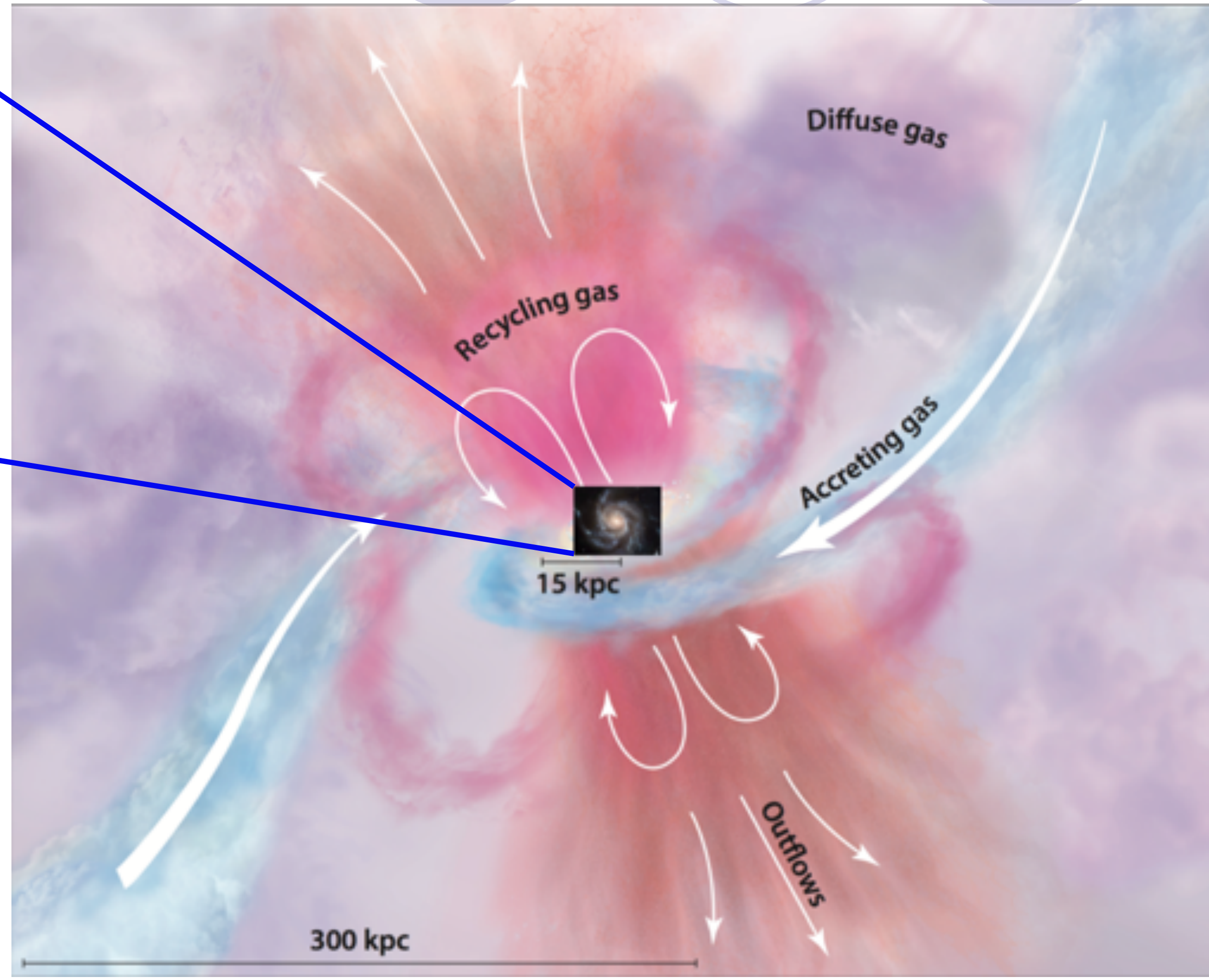
星系演化理论的瓶颈问题

恒星与星际介质循环



黑洞吸积物质和反馈能量

星系周和星系际介质在星系和暗物质晕内外循环



绝大部分是热气体

美国科学院（2010）天文十年规划报告

19个天文学重大问题

How did the universe begin?
What were the first objects to light up the universe and when did they do it?

How do cosmic structures form and evolve?
What are the connections between dark and luminous matter?

What is the fossil record of galaxy assembly and evolution from the first stars to the present?
How do stars and black holes form?
How do circumstellar disks evolve and form planetary systems?

How do baryons cycle in and out of galaxies and what do they do while they are there?
What are the flows of matter and energy in the circumgalactic medium?
What controls the mass-energy-chemical cycles within galaxies?

How do black holes wo
How do rotation and m
How do massive stars
What are the progenito
How diverse are planet
an exoplanet?
Why is the universe ac
What is dark matter?
What are the properties of the neutrinos?

1. 宇宙结构是如何形成与演化的?
2. 暗物质与重子物质是如何关联的?
3. 重子在星系内外如何循环以及各自作用?
4. 物质和能量如何在星系周介质传输?
5. 什么控制物质和能量在星系中循环?

- 探测宇宙和星系里“缺失”的重子
- 精确测量“缺失”重子的空间分布及物理和化学性质
- 研究影响星系的形成与演化的“反馈”物理过程

《科学》125个最重要科学问题

What is the universe made of?
What is the biolc
Why do humans
宇宙由什么组成?
To what extent are genetic variation and personal health linked?
Can the laws of physics be unified?
How much can human life span be extended?
What controls organ regeneration?
How can a skin cell become a nerve cell?
How does Earth's interior work?
... ... http://www.sciencemag.org/site/feature/misc/webfeat/125th/

我们从哪里来，我们是什么，我们到哪里去

BREAK

从科学目标到解决方法

HUBS卫星科学目标

科学目标

- 重子物质是否缺失？
- “缺失”重子空间分布及物理和化学性质
- 星系形成与演化“反馈”物理过程

观测需求

获取高能量分辨和高灵敏度的热重子的辐射能谱和图像

解决方法

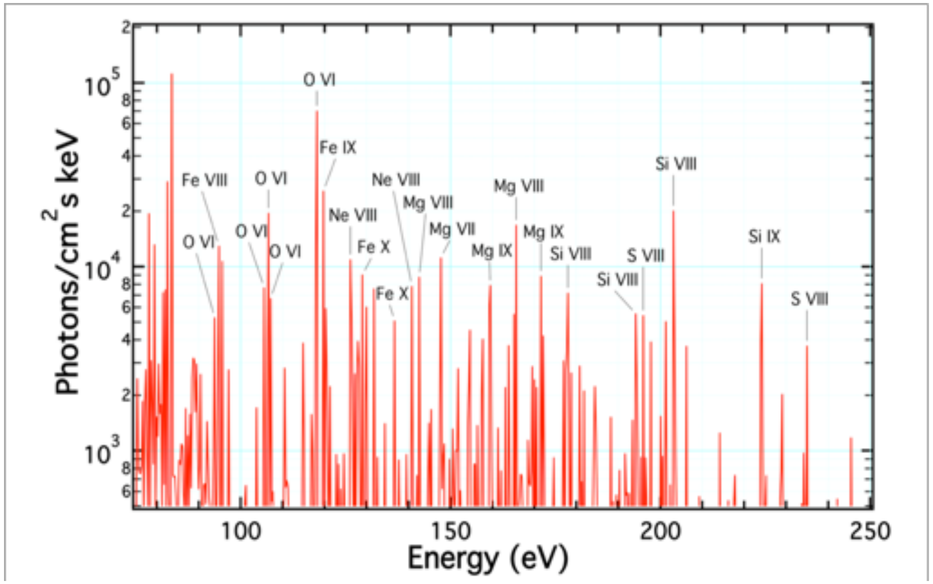
新型X射线高分辨率成像光谱仪

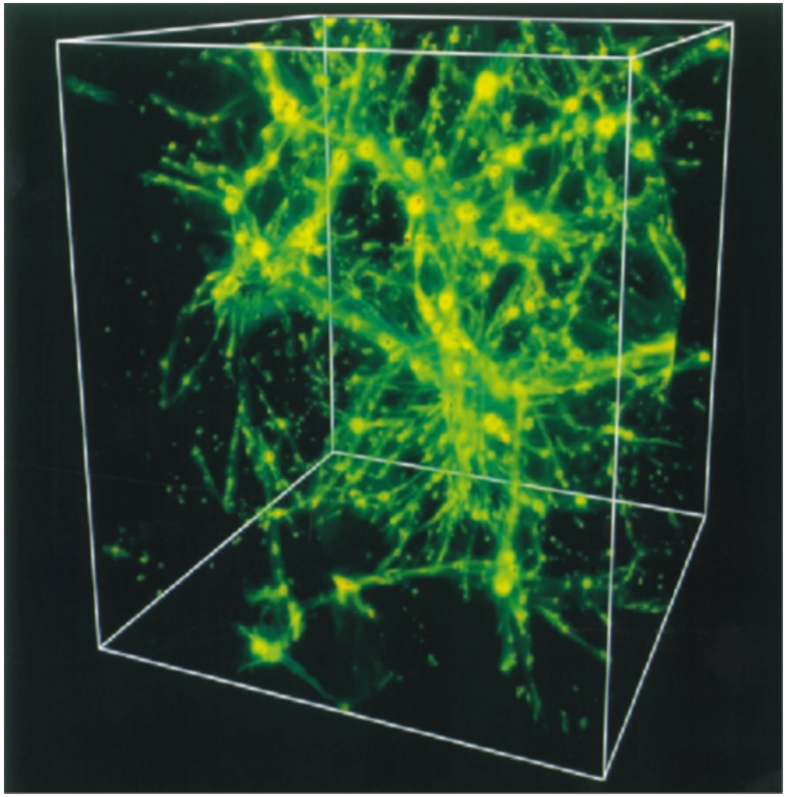
科学需求对探测技术的挑战

需要：高效率、高分辨率X射线成像光谱仪

但是，现有的光谱技术无法满足需求！

理论研究表明“缺失”的重子藏在温度大致为一百万度的热气体里，其辐射落在软X射线谱段。

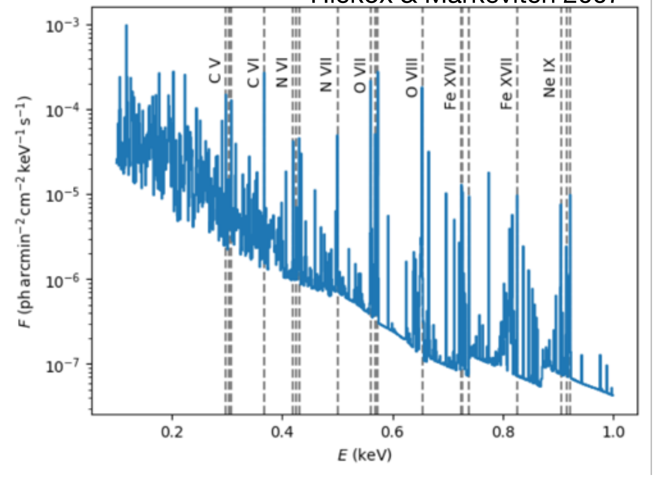


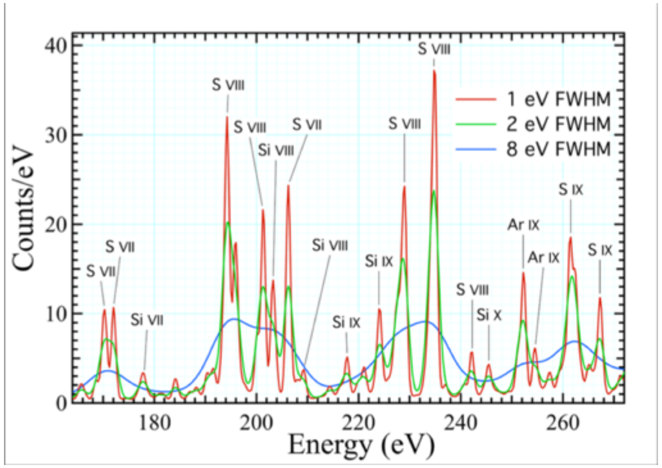


Why High-Resolution X-ray Spectroscopy?

- Strong foreground
  - Local Bubble+halo+SWCX
  - ROSAT, XQC
  - Need to separate redshifted lines
- Enhance S/N
  - Narrow-band imaging
  - Isolate lines
- Plasma diagnostics
  - X-ray spectrum of hot CGM/IGM is expected to be dominated by emission lines
  - Density, temperature, abundances

Hickox & Markevitch 2007

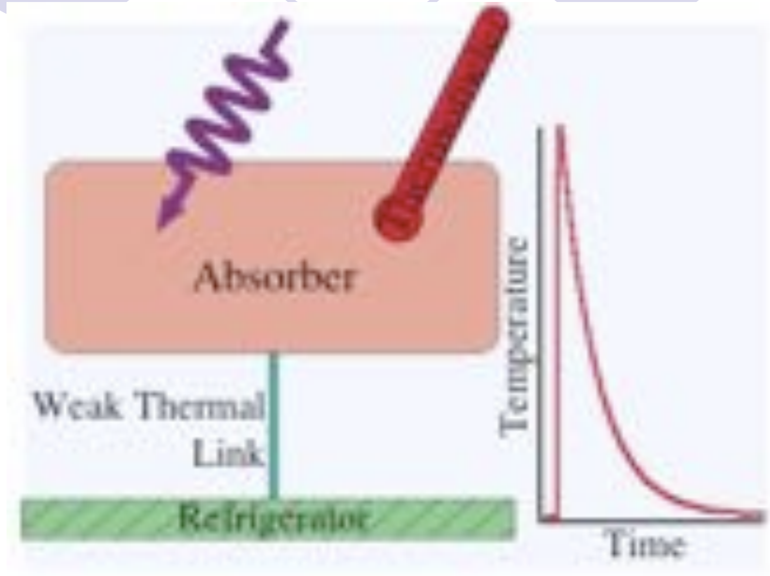




新型X射线成像光谱仪

<u>单光子微量能器</u>

- X射线吸收体
- 高灵敏度温度仪
- 吸收体和工作环境之间弱热连接:测量一个光子能量，释放热量并快速达到热平衡，准备测量下一个光子的能量

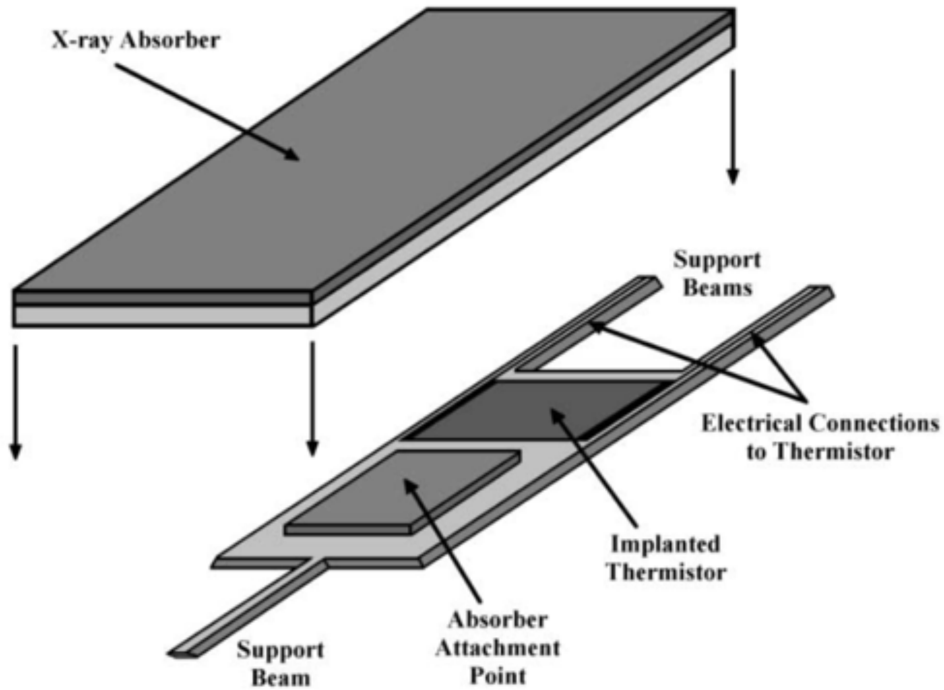


谱分辨率

$$\Delta E = \xi \sqrt{\frac{k_B T^2 C}{\alpha}}$$

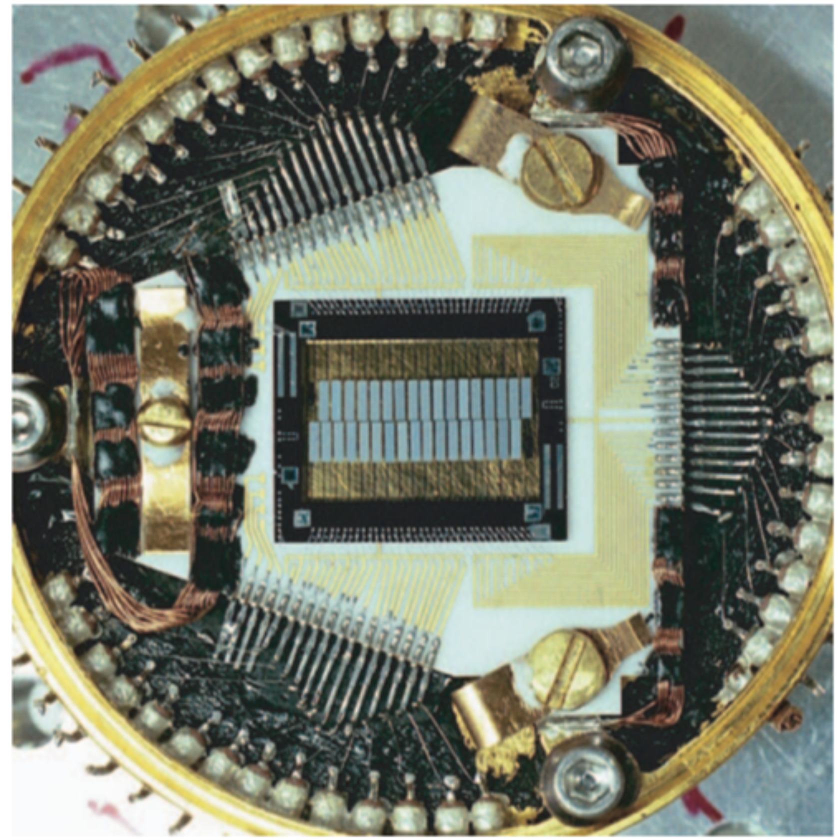
$$\alpha \equiv \frac{d \log R}{d \log T}$$

X射线微量能器



HgTe absorber attached to doped Si thermister.

Mccammon et al. 2002

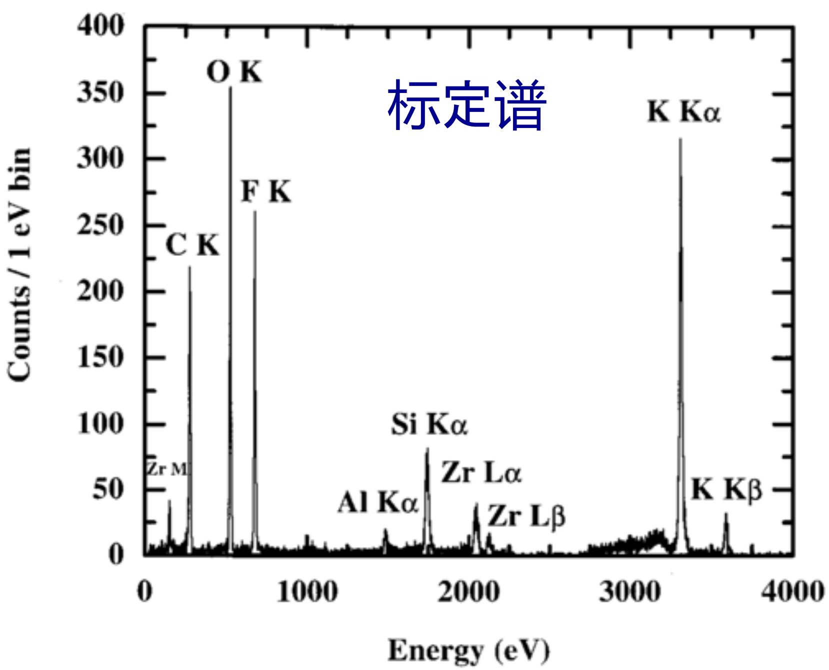


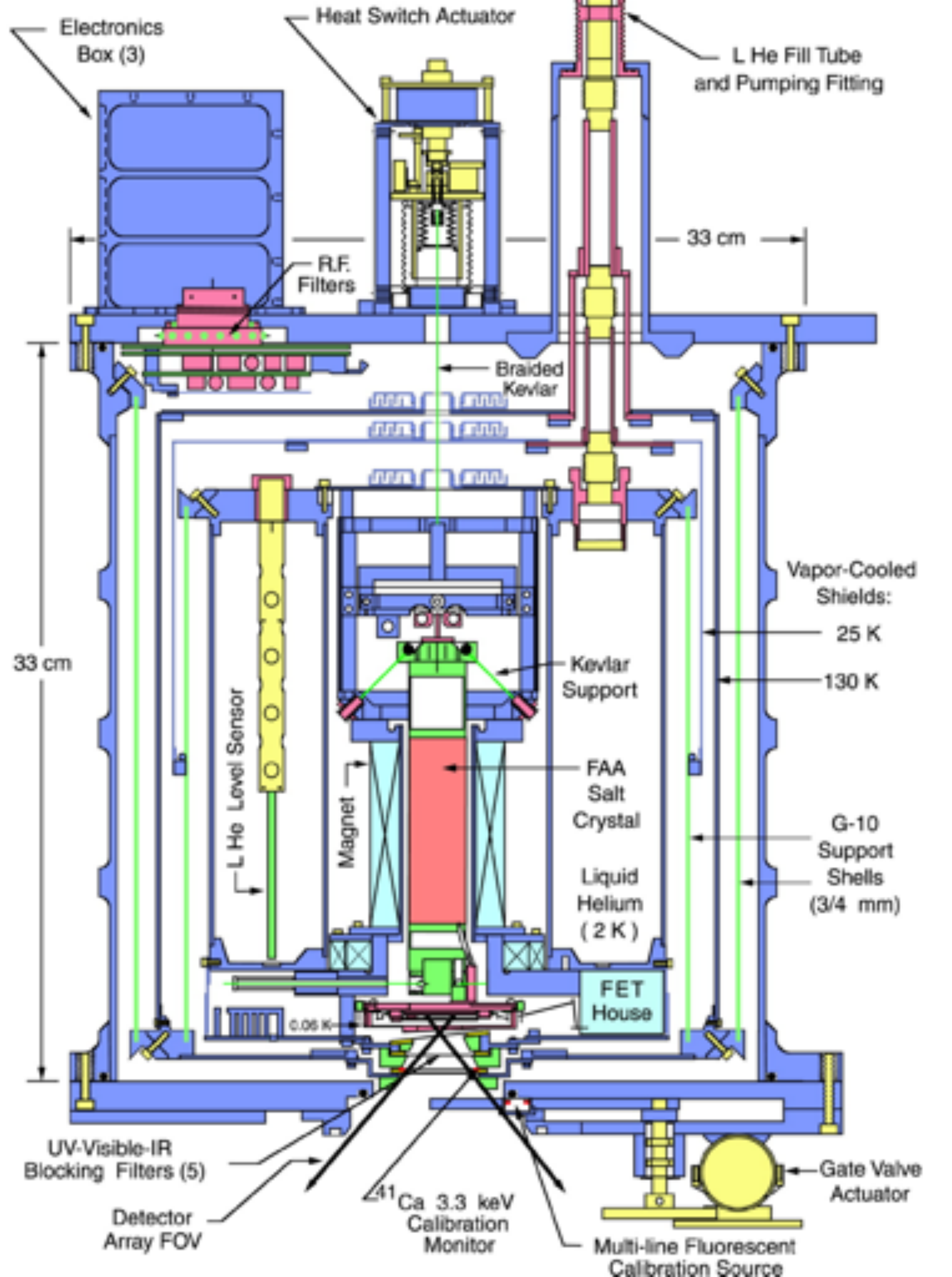
A 2x18 pixel flight array

$$R = R_0 \exp\left(T_0/T\right)^{1/2} \Rightarrow \alpha = -\frac{1}{2}\left(\frac{T_0}{T}\right)^{1/2}$$

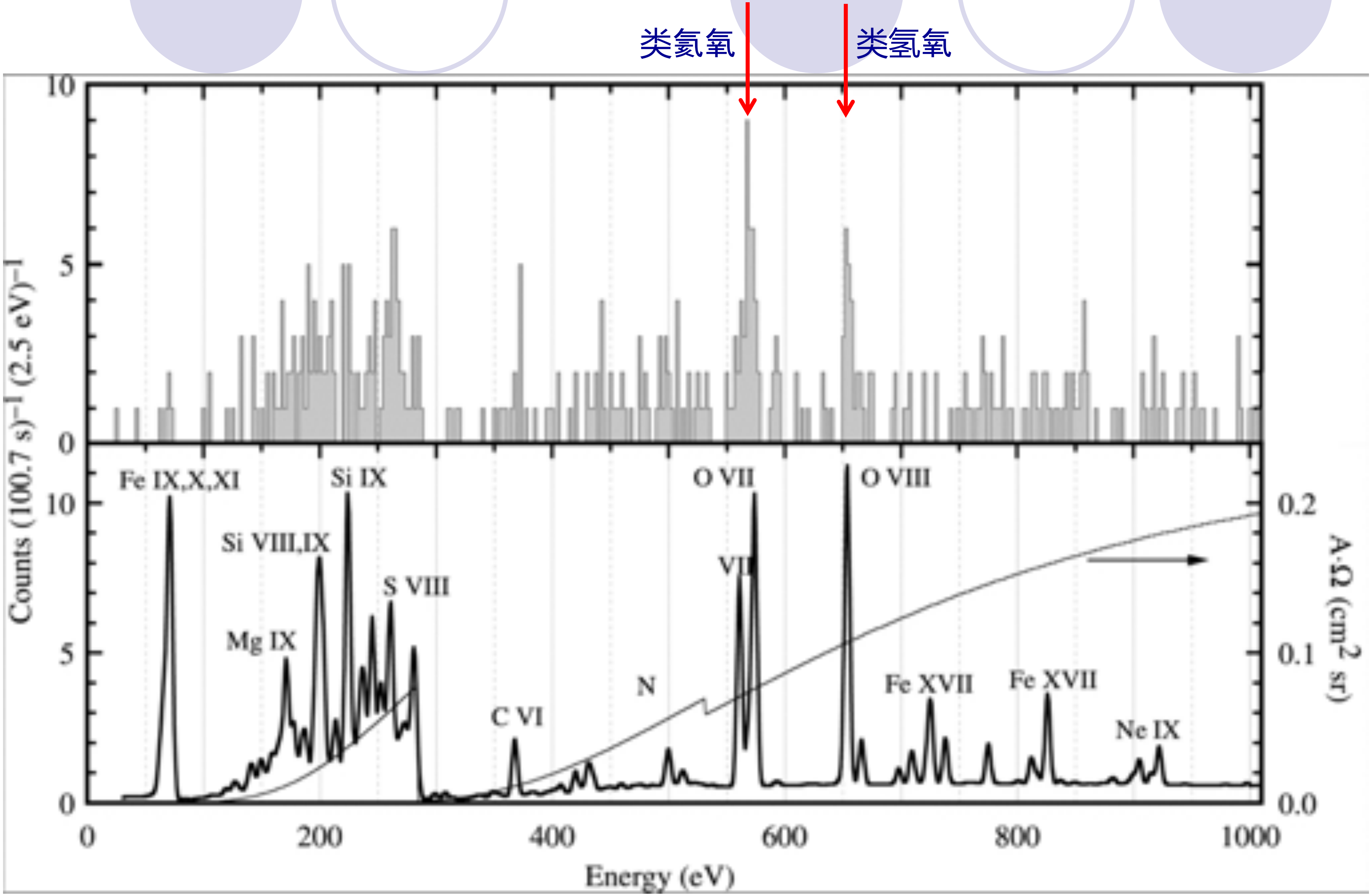
威斯康星大学的探空火箭实验

Mccammon et al. 2002

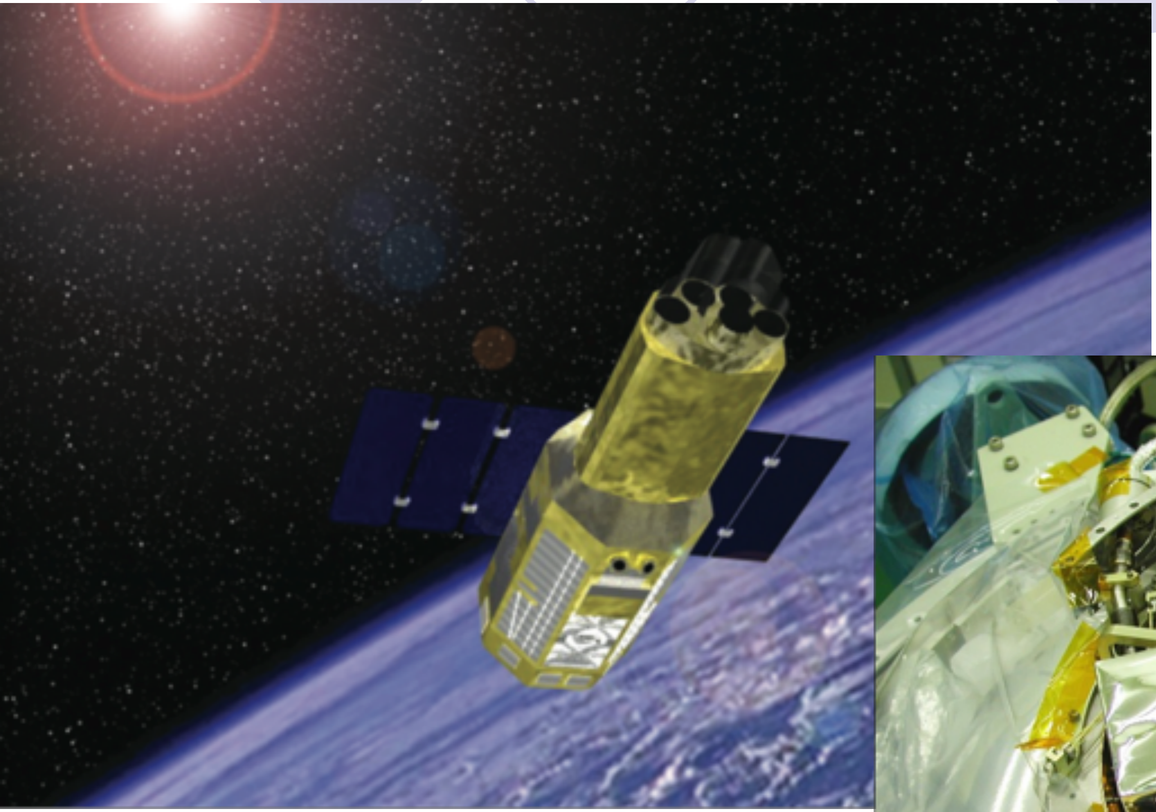


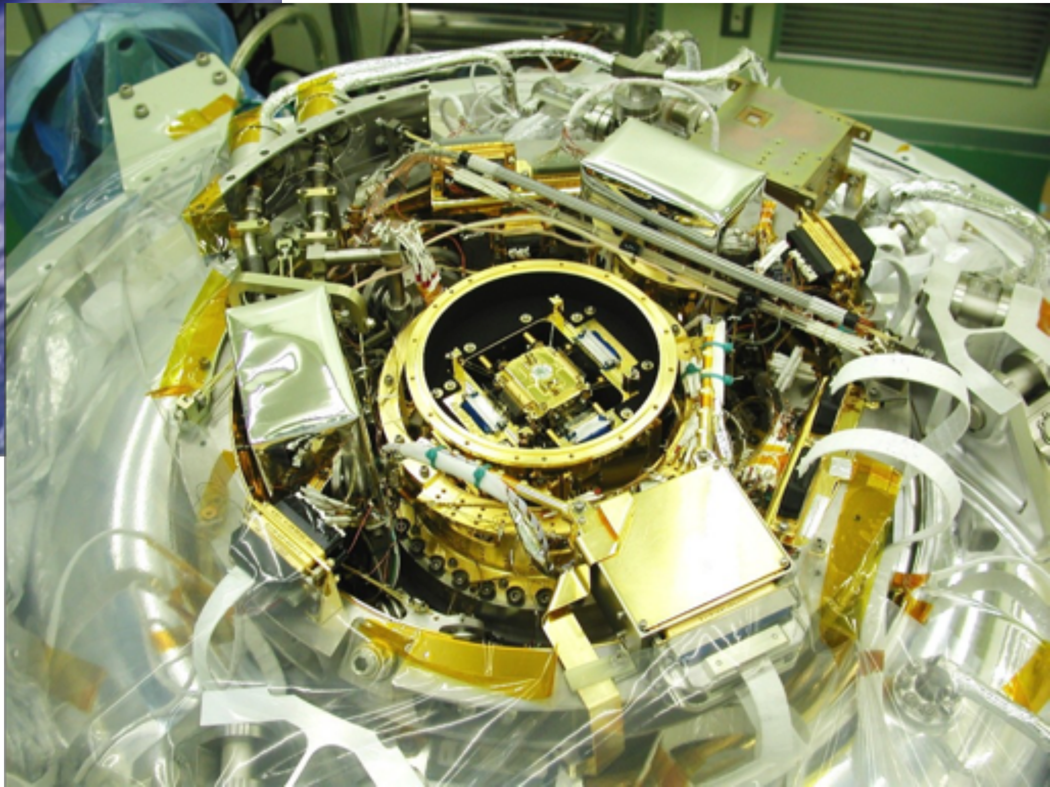


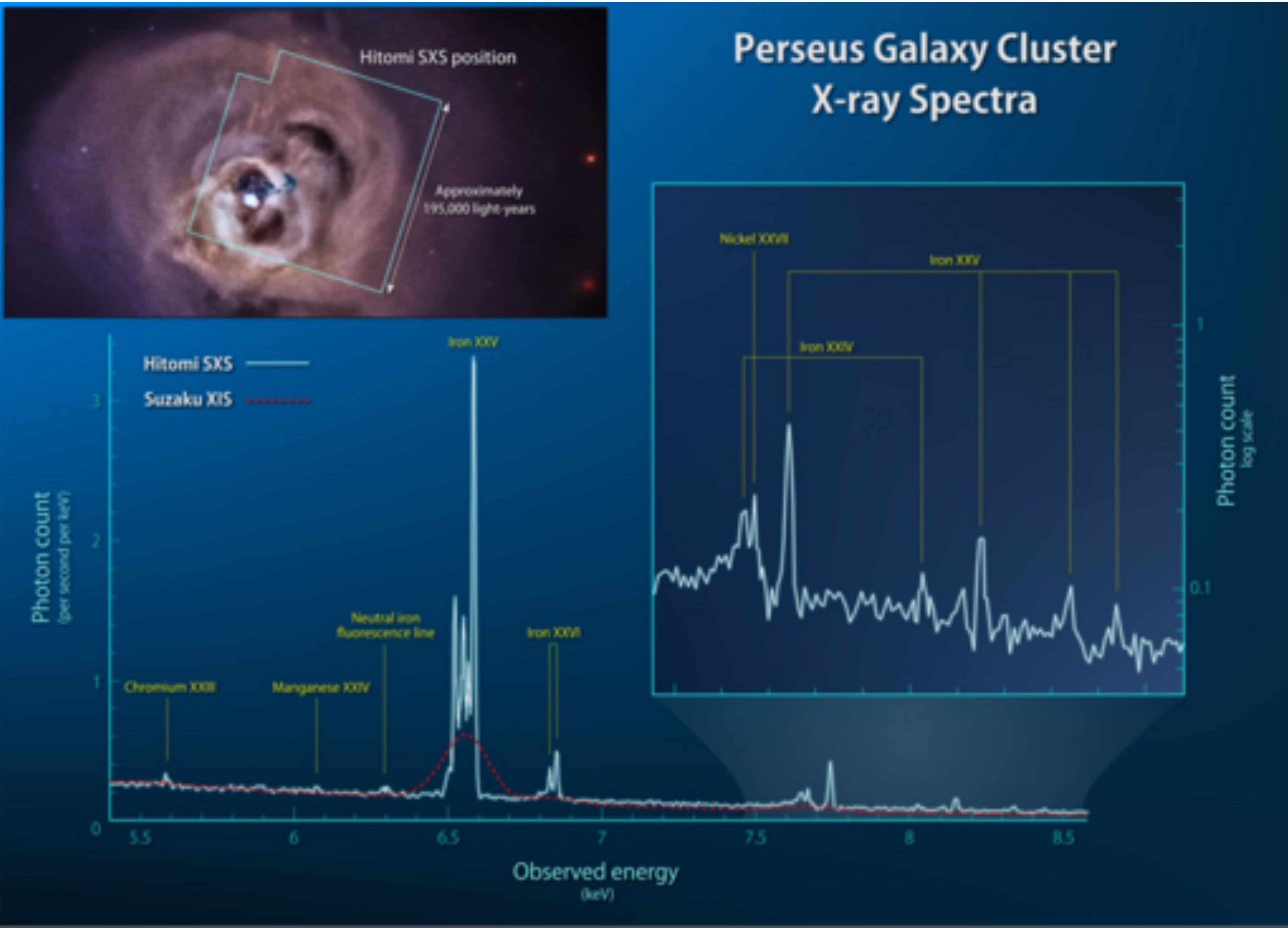
银河系内热气体的辐射谱



从探空火箭到卫星平台。。。



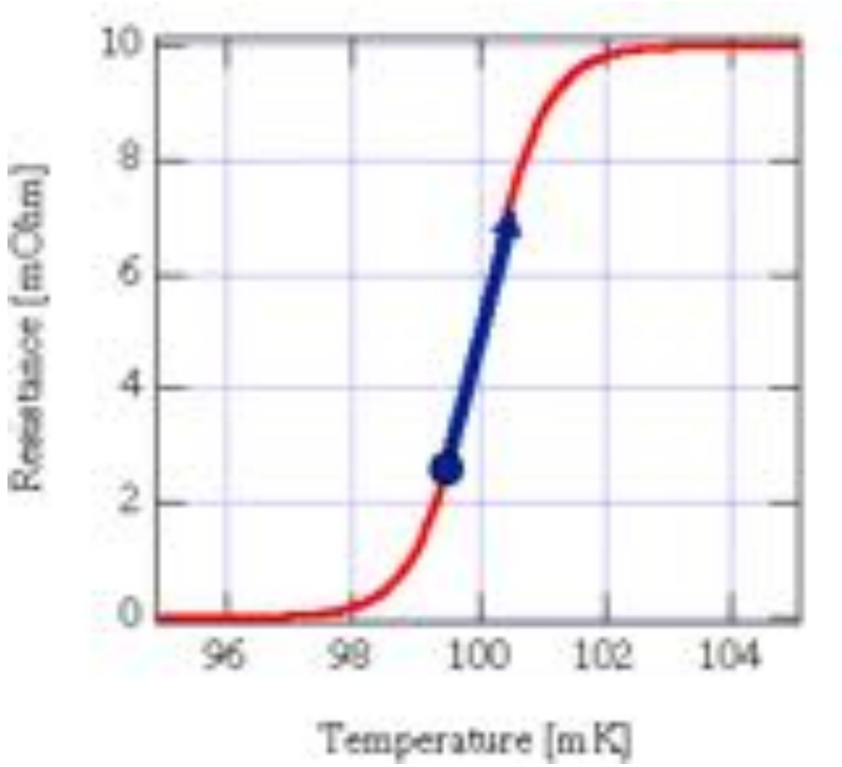




Perseus Galaxy Cluster
X-ray Spectra
Hitomi SXS position
Approximately
195,000 light-years
Hitomi SXS
Suzaku XIS
Photon count
(per second per keV)
Iron XXV
Neutral iron
fluorescence line
Iron XXVI
Chromium XXIII
Manganese XXIV
Observed energy
(keV)
5.5
6
6.5
7
7.5
8
8.5
0
1
2
3
Nickel XXVII
Iron XXV
Iron XXIV
Photon count
log scale
1
0.1

超导X射线微量能器

用超导转变边缘传感器(TES)做温度仪



能量分辨率

$$\Delta E = \xi \sqrt{\frac{k_B T^2 C}{\alpha}}$$

$$\alpha \equiv \frac{d \log R}{d \log T}$$

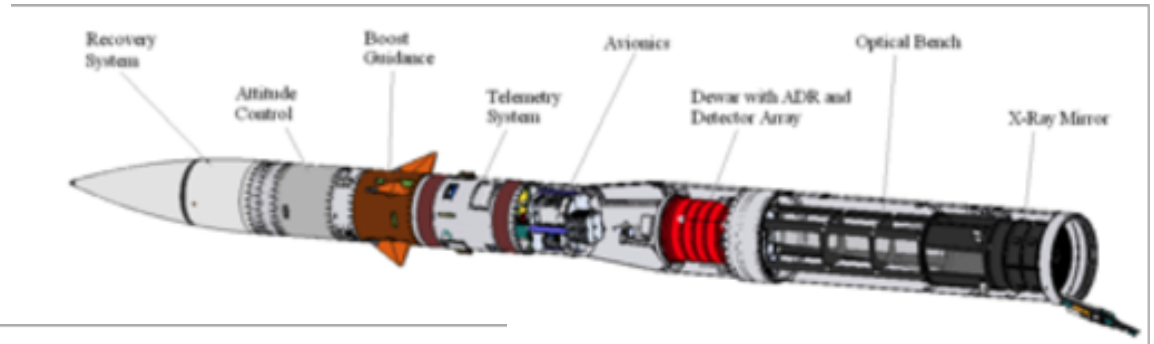
在过渡区域电阻对温度的变化极其敏感

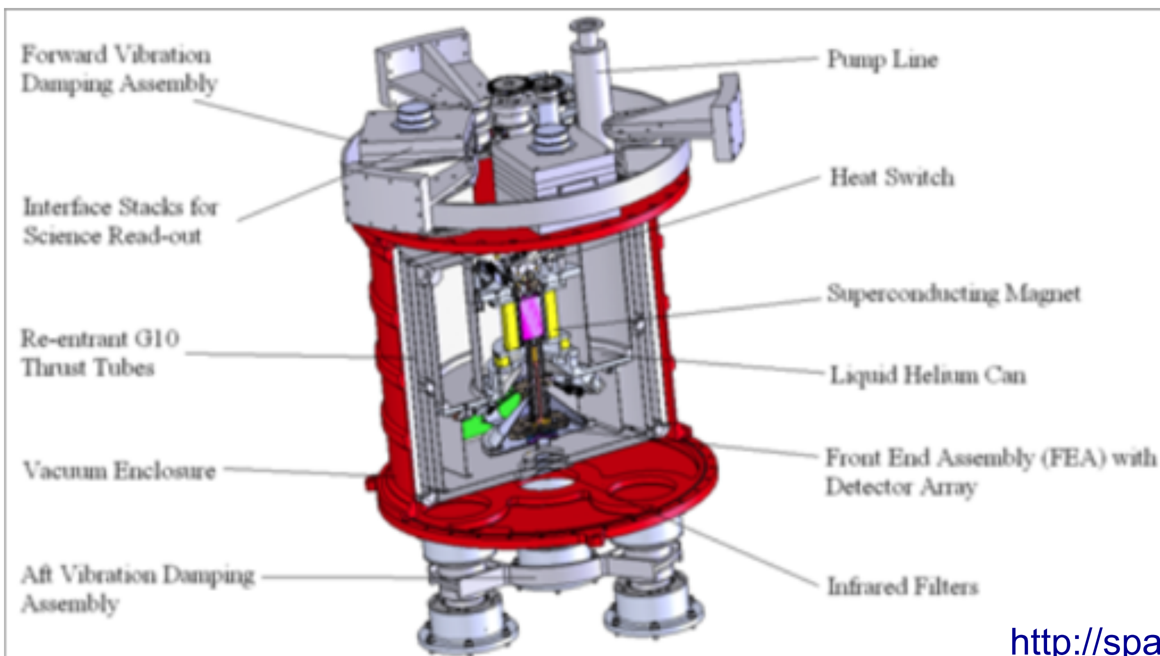
TES的技术优势

- The transition temperature is tunable with bilayer films, thanks to proximity effects.
  - Easy to match cryogenic operation
- TES arrays can be made in production mode, with mature film deposition and lithographic techniques.
  - Eliminate manual attachment of absorber to thermistor.
  - Achieve better uniformity.
  - Utilize 3-D structure to run electrical connection without sacrificing collecting area.
- Very large α can be achieved.
  - In principle, it leads to improved energy resolution.

TES的技术挑战

Extreme sensitivity to B field





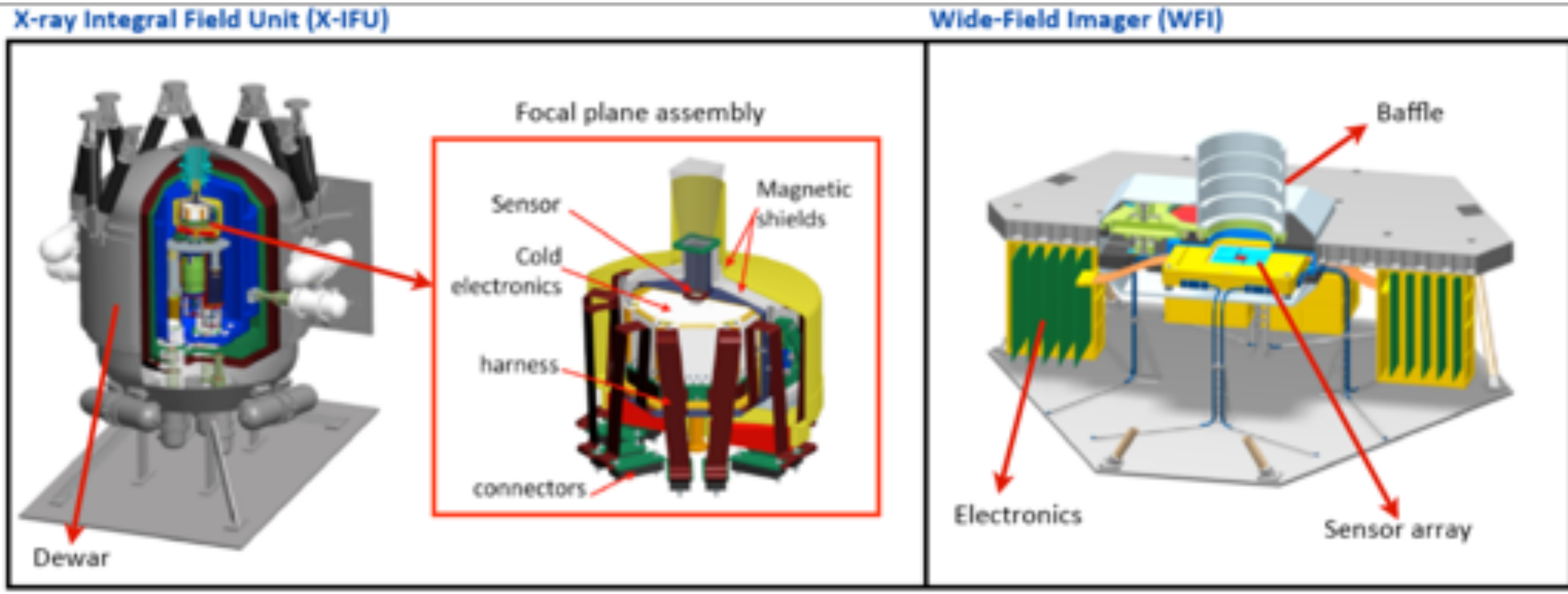
Micro-X rocket experiment

http://space.mit.edu/micro-x/hardware/hardware.html

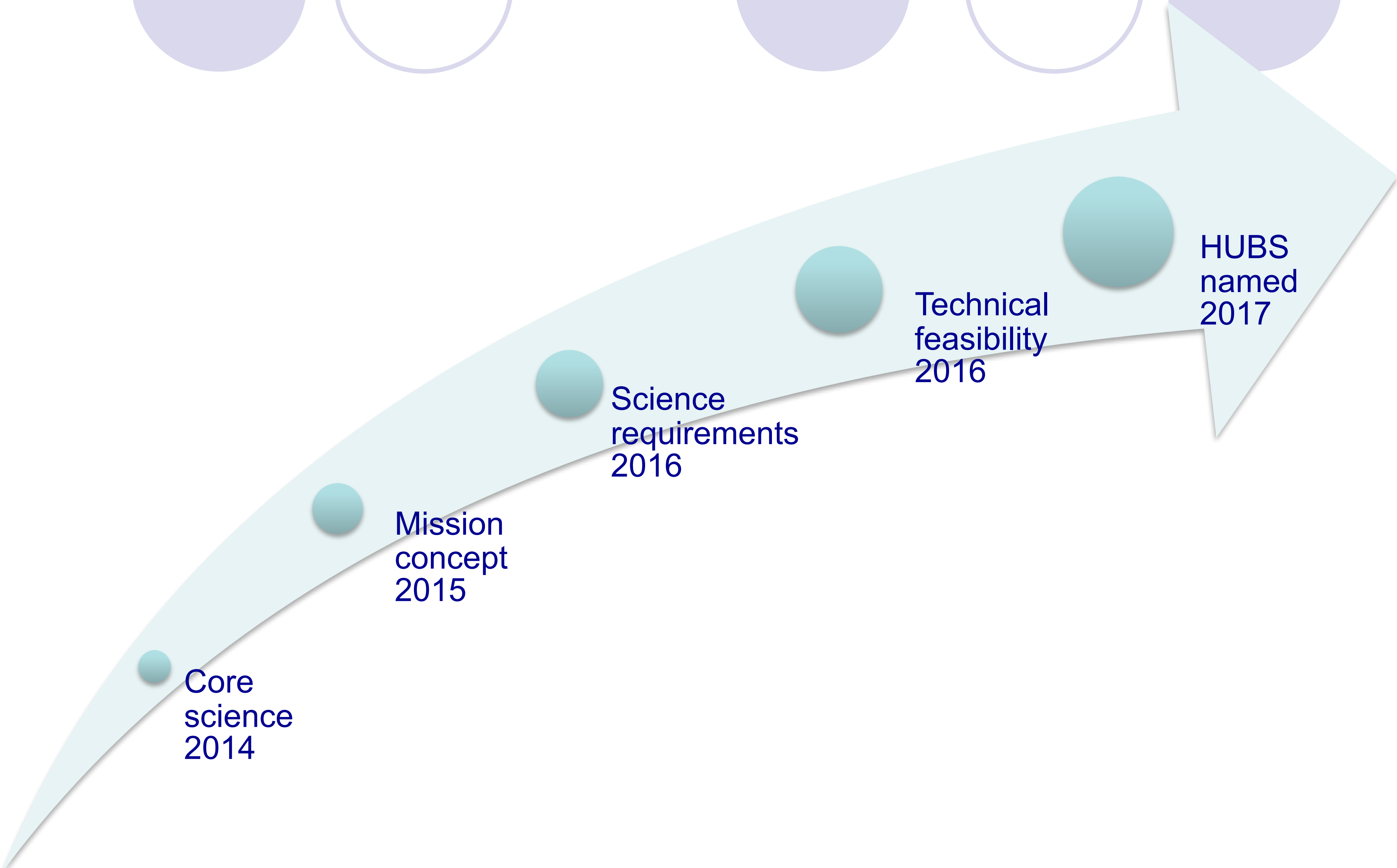
ESA's Athena Mission

… in early 2030

TES array of ~4000 pixels

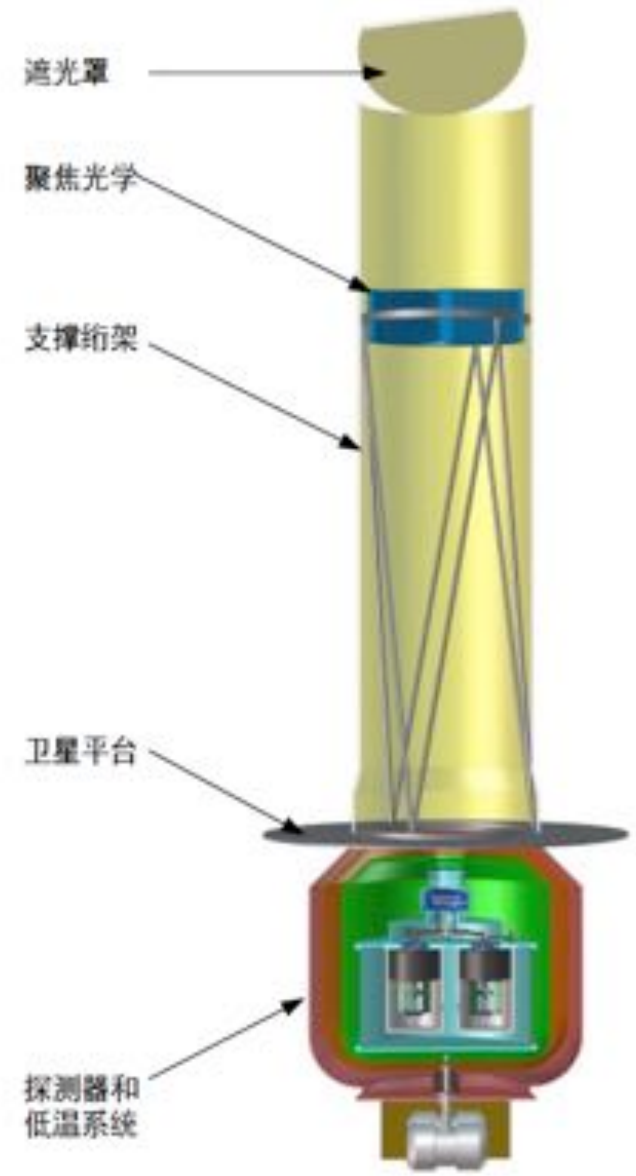


Hot Universe Baryon Surveyor (HUBS)



HUBS=宇宙热重子探寻计划

- 优化于软X射线的混合TES微量能器阵列
  - 谱段: 0.1-2 keV
  - 阵列: 60x60像素，能量分辨率 2 eV
  - 中心阵列: 12x12小像素代替3x3正常像素，能量分辨率 < 1 eV, 增强吸收线探测与分辨能力
- 大视场X射线聚焦望远镜
  - 有效面积: A_{eff} ~ $1000\ cm^2$
  - 视场: Ω_{FoV} ~ $1\ deg^2$
  - 角分辨率: ~ 1’
- 低倾角近地轨道
  - 降低粒子本底



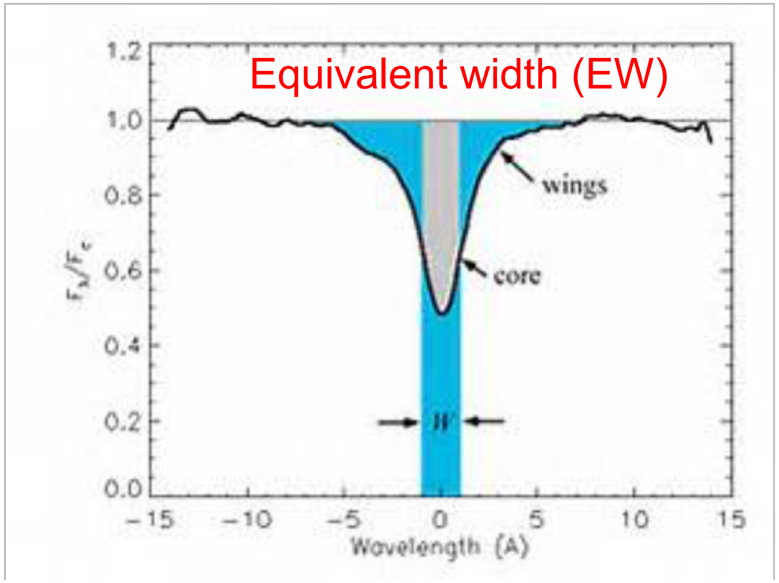
发射线与吸收线

- Emission lines
  - Proportional to emission measure.

$$I \propto \int_{path} n^2 \cdot dl$$

- Absorption lines
  - Providing column densities, but only 1-D info

$$I \propto \int_{LoS} n \cdot dl$$



Limited by the number of lines of sight

载荷探测指标

可探测到最弱发射线的强度：

$$EW \geq \left(\frac{S}{N}\right)\left(\frac{E}{I_c TRA_{eff}\Omega_{FOV}}\right)^{1/2}$$

S/N: 信噪比

E: 谱线的能量

T: 曝光时间

I_c: 连续谱强度

光谱仪设计指标： $FoM = RA_{eff}\Omega_{FOV}$

与国际相关卫星的比较：发射线

（棕色：已立项；蓝色：申请）

Mission	Launch date	Instrument	R@0.6 keV	A_{eff} @0.6 keV (cm^2)	Ω_{FOV} (deg^2)	FoM
XRISM	~2022	Resolve	100	70	0.0023	16
Athena	~2032	X-IFU	240	5000	0.0069	8280
Lynx	> 2040		200	10000	0.0069	13800
HUBS	～2028	XQSC	300	500	1	150000

吸收线探测指标

The detectability of weakest *absorption* lines is proportional to the square root of the product:

- Effective area
- resolving power

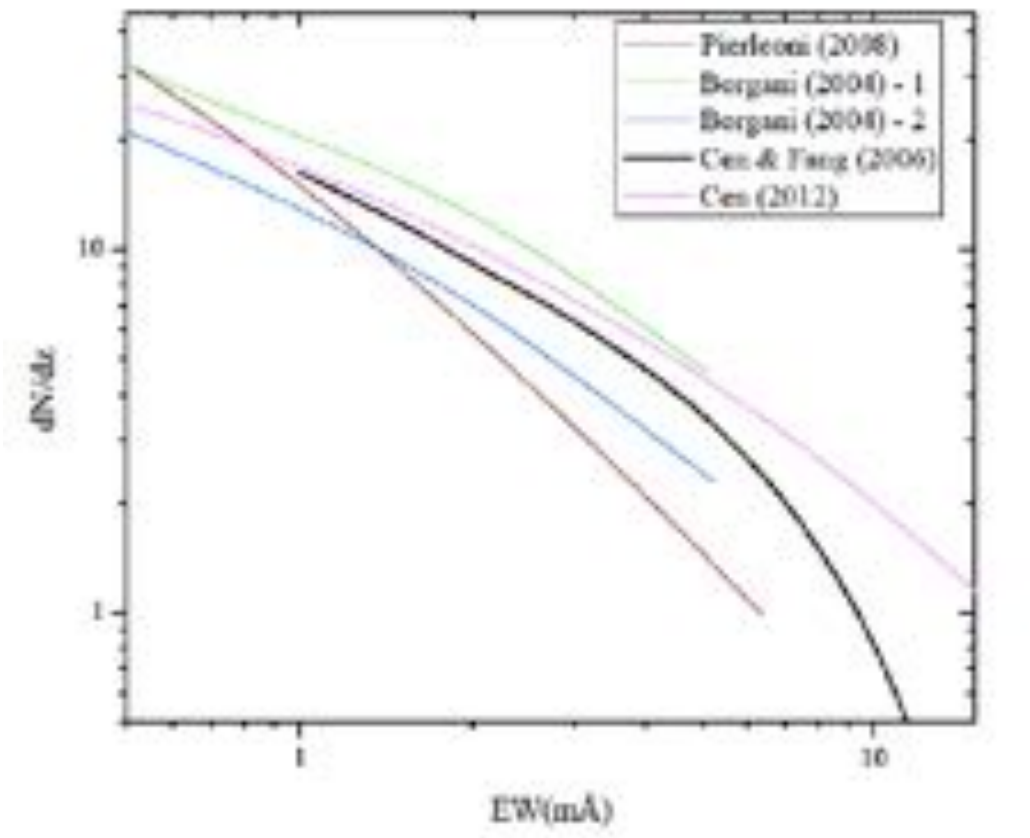
$$FoM = RA_{eff}$$

与国际相关卫星的比较：吸收线

Mission	Instrument	Technology	R@0.6 keV	A_{eff} @0.6 keV (cm^2)	FoM x1000	EW limit (mA)
Chandra	LETG/ACIS -S	Grating	600	10	6	48
XRISM	Resolve	Calorimeter	100	70	7	44
XMM-Newton	RGS	Grating	500	45	22.5	25
HUBS	XQSC	Calorimeter	600	500	300	6.8
Athena	X-IFU	Calorimeter	240	5000	1200	3.4
Arcus		Grating	2500	900	2250	2.5
Lynx		Grating	>5000	>4000	>20000	<0.8

预期吸收线的强度

- The strongest lines are seen in the outerskirts of groups or in the halos of galaxies.
- For O VII, few lines have EW greater than 10 mA.



Design requirement: *EW <10 mA*

HUBS关键技术的应用

- 尖端空间技术自主研发
  - X射线及红外超导探测器
  - 超导量子干涉器件（SQUID）的制作与集成
  - 长寿命、低振动、高效率机械制冷机(< 3 K)
  - 极低温(< 0.1 K) 制冷技术
  - 大视场X射线聚焦光学系统
- X射线、红外及微波天文观测应用
  - 除了X射线波段，超导探测器也被广泛应用于地面与空间红外探测及微波背景观测实验
- X射线微量能器在同步辐射、材料、医疗等其它领域的应用

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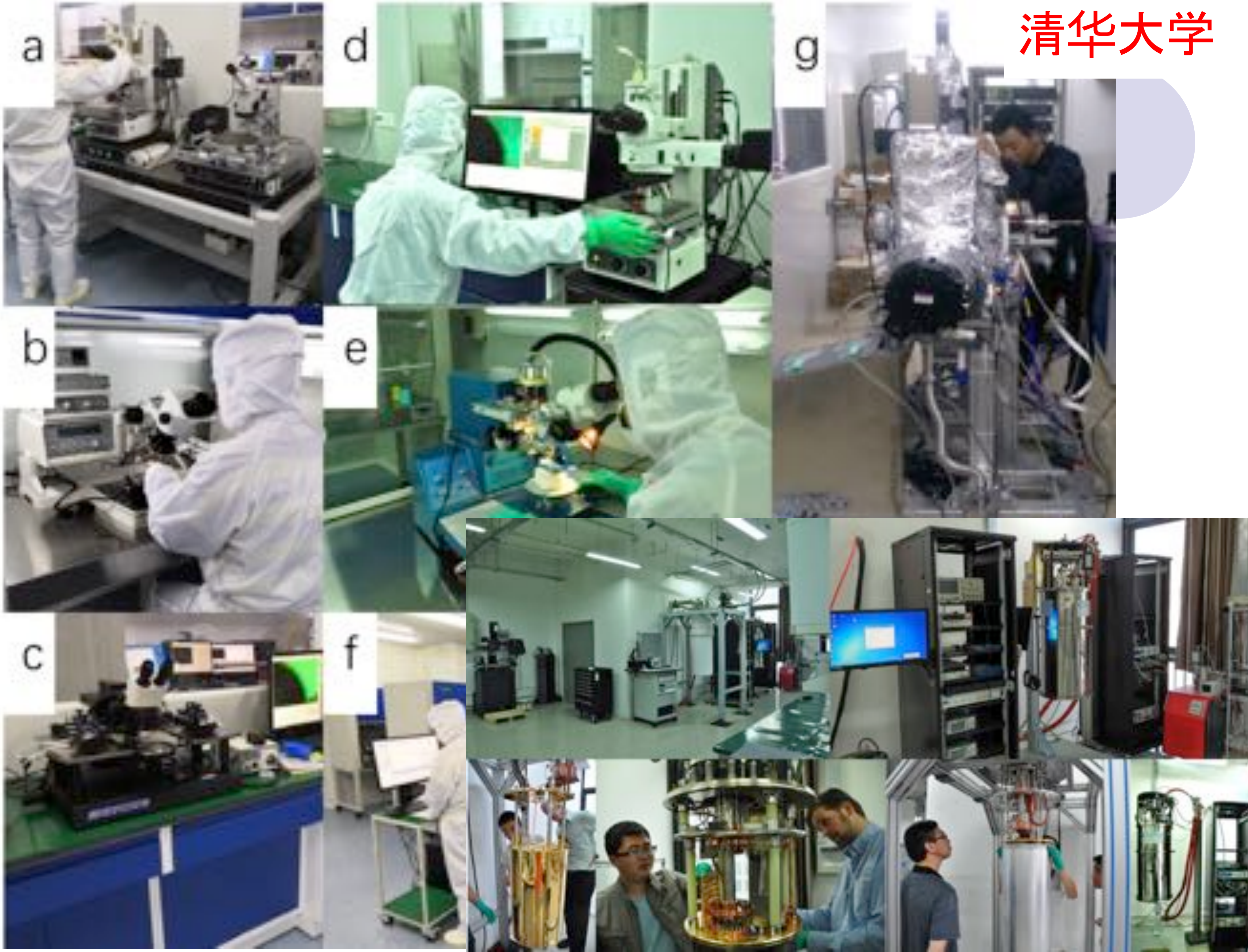

Concluding remarks

- High throughput, high resolution X-ray spectroscopy is needed to address a number of critical questions in astrophysics and cosmology.
  - Origin and distribution of hot baryons
  - Roles of feedback processes
  - Formation and evolution of galaxies
- The technologies required have advanced steadily to enable X-ray missions of all sizes.
  - TES array and SQUID readout technology
  - Development of cryogen-free coolers
  - Development of large FoV X-ray optics
- The impact of the development of cryogenic thermal sensors goes much beyond X-ray astrophysics.