

航天领域的辐射探测及发展现状

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4, 物理学院近代物理系, 中国科学技术大学

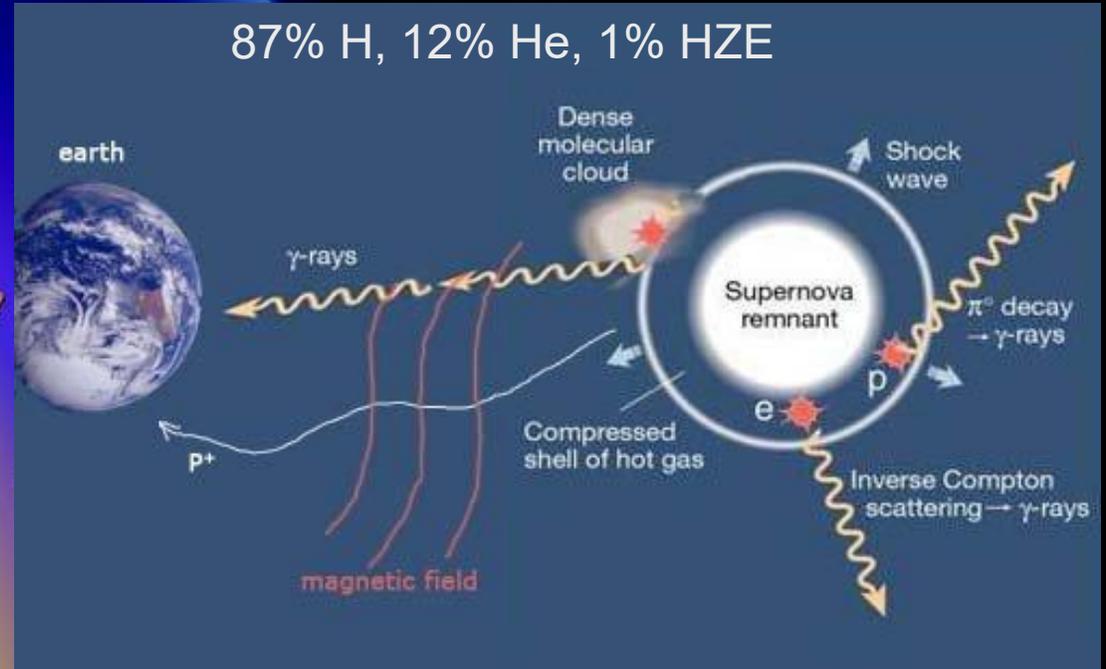
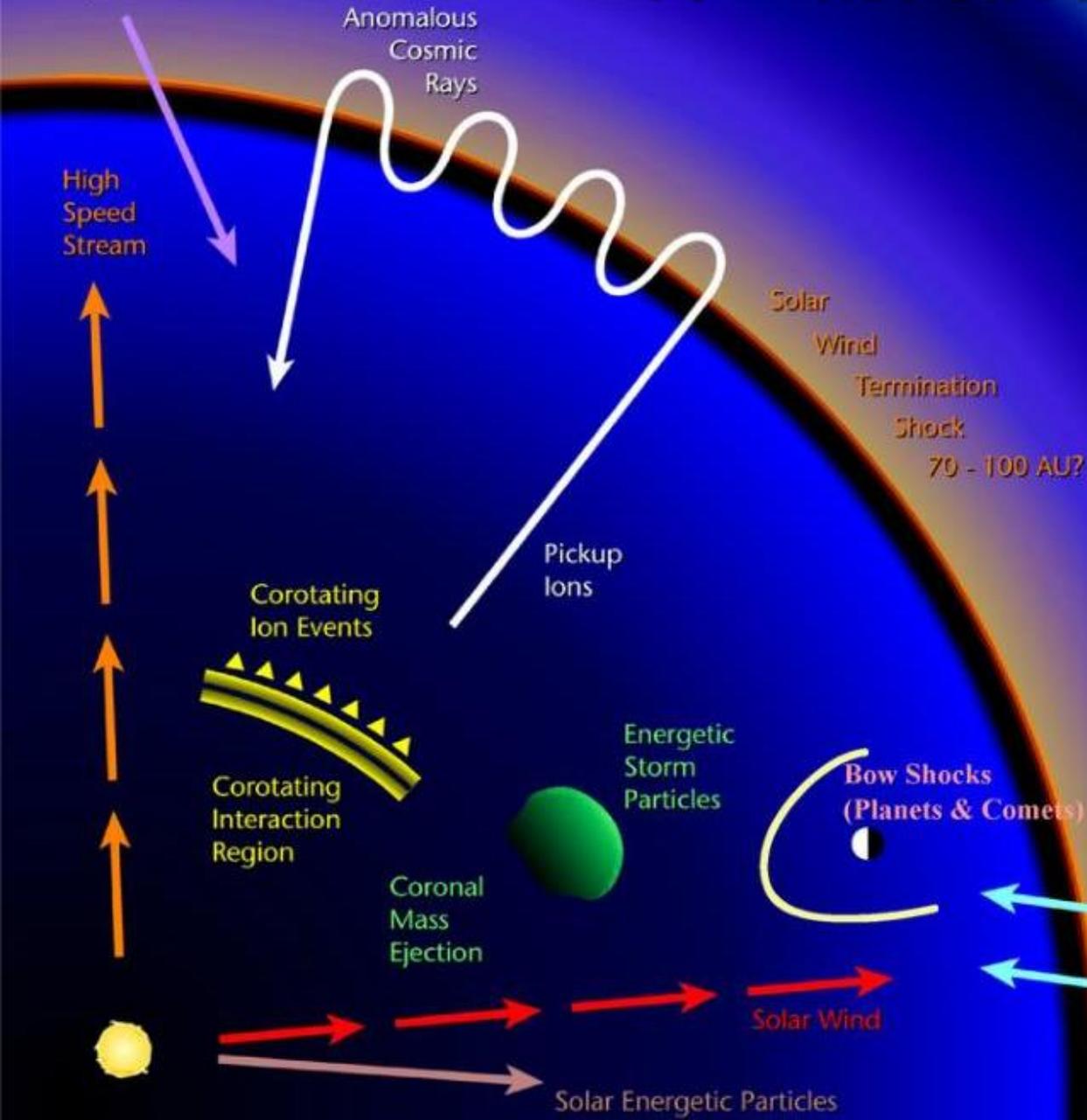


- **深空的高能粒子的特征：种类、来源、能量分布**
- **深空的高能粒子的辐射危害和预报需求**
- **空间辐射环境的模型预估（月球和火星的举例）**
- **空间辐射的现有测量（月球和火星的举例）**
- **空间辐射探测的未来需求**

深空的高能粒子种类和来源

Galactic Cosmic Rays

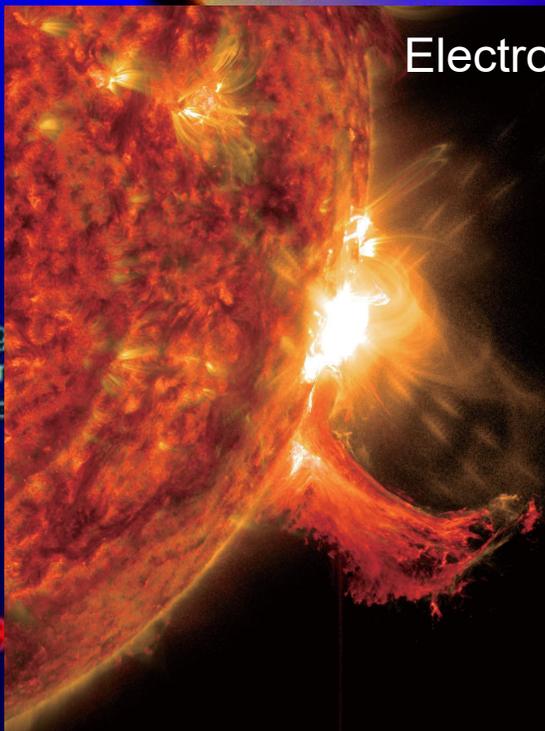
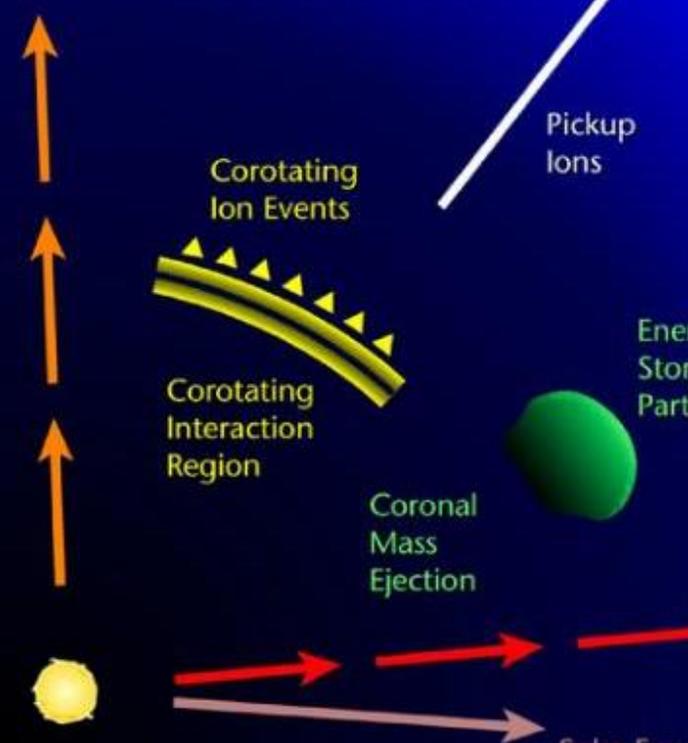
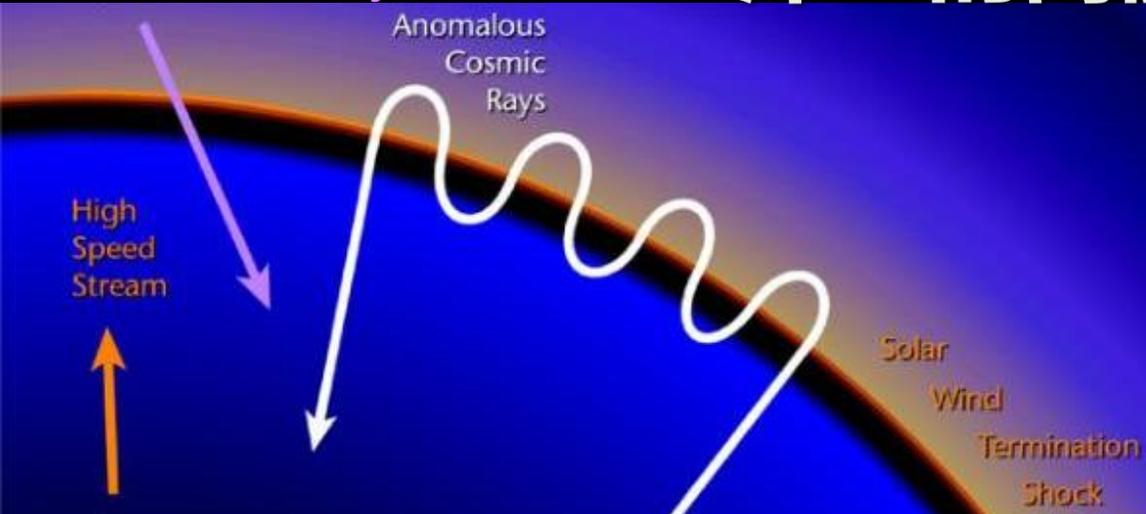
- Galactic Cosmic Rays (GCRs)
- Anomalous Cosmic Rays (ACRs)



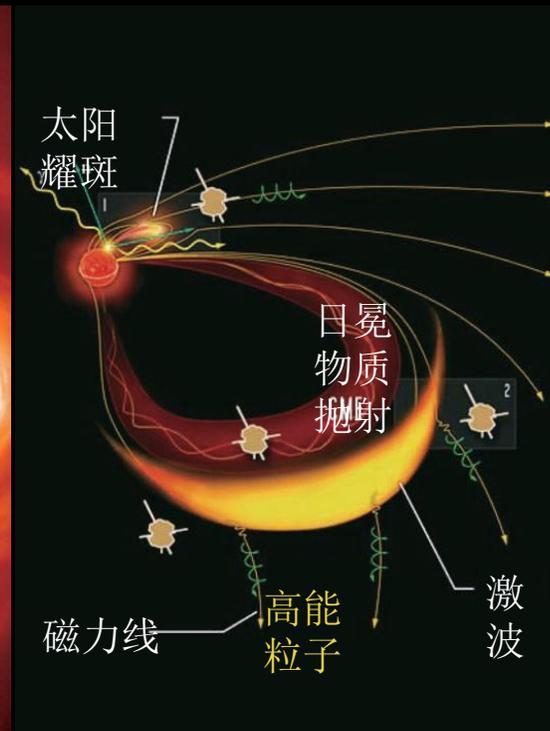
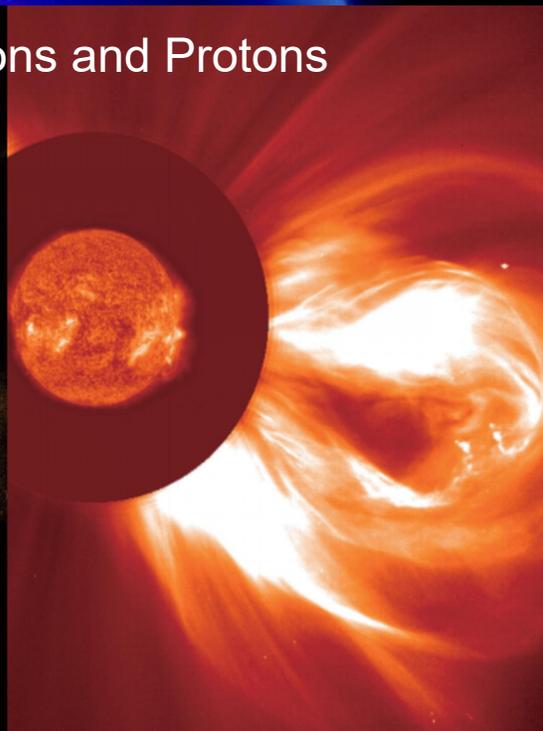
深空的高能粒子种类和来源

Galactic Cosmic Rays

- Galactic Cosmic Rays (GCRs)
- Anomalous Cosmic Rays (ACRs)
- Solar Energetic Particles (SEPs)
- Energetic Storm Particles (ESPs)

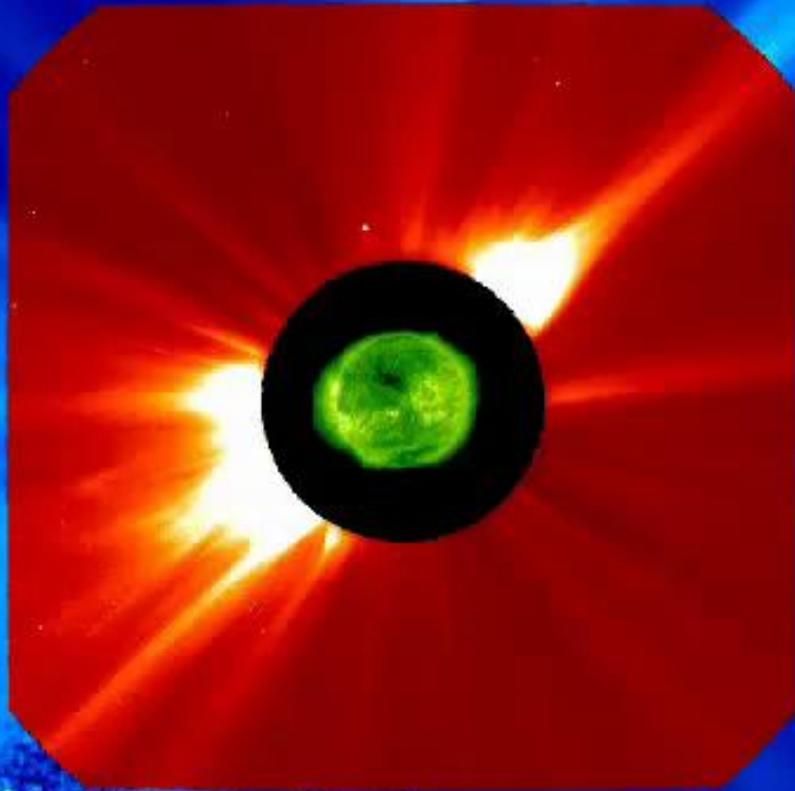


Electrons and Protons

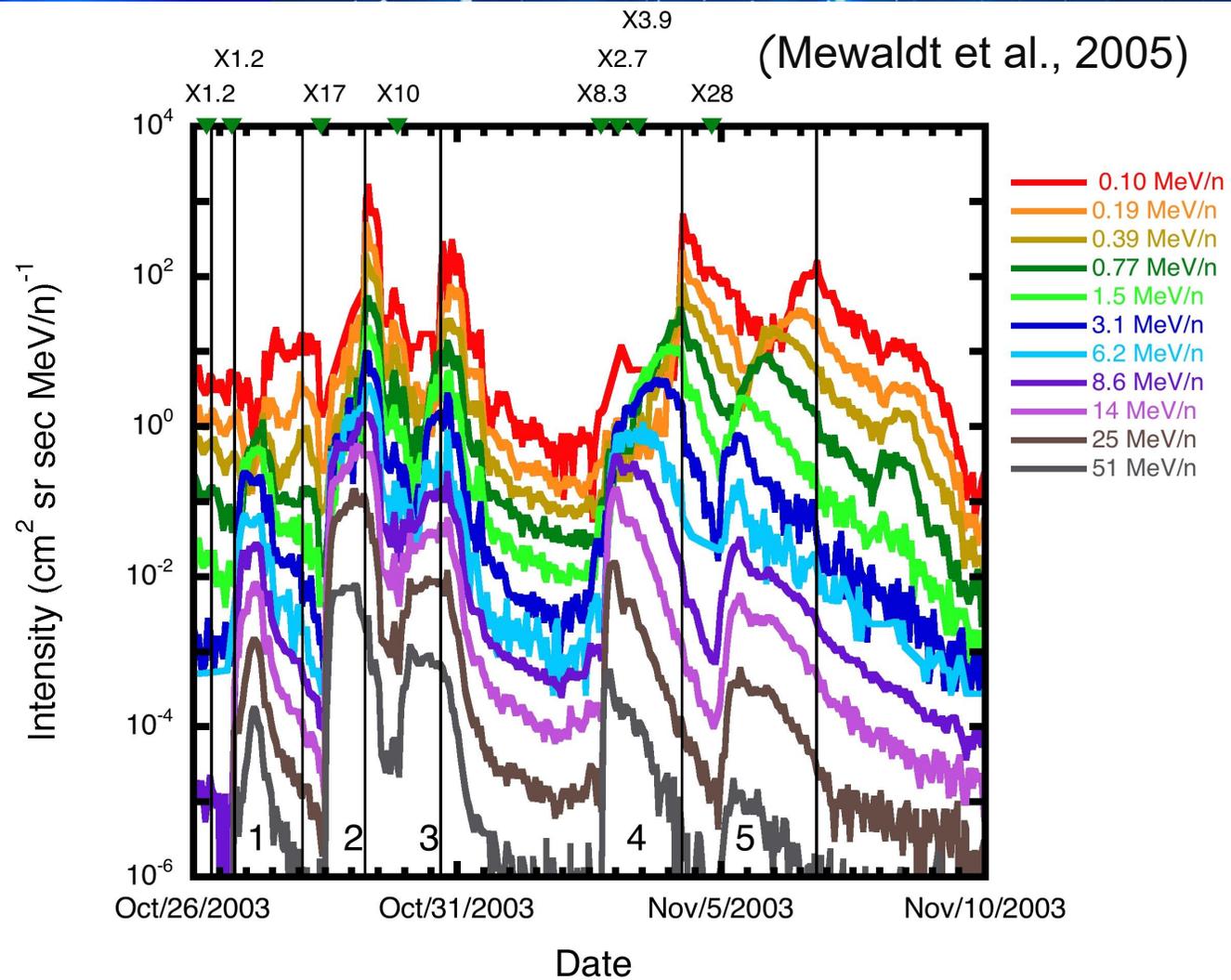


太阳高能粒子的产生和特征

连续多个SEP事件，MeV粒子通量增高数个量级



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深空高能粒子的能量特征

Long-term average of the particle spectrum in the heliosphere

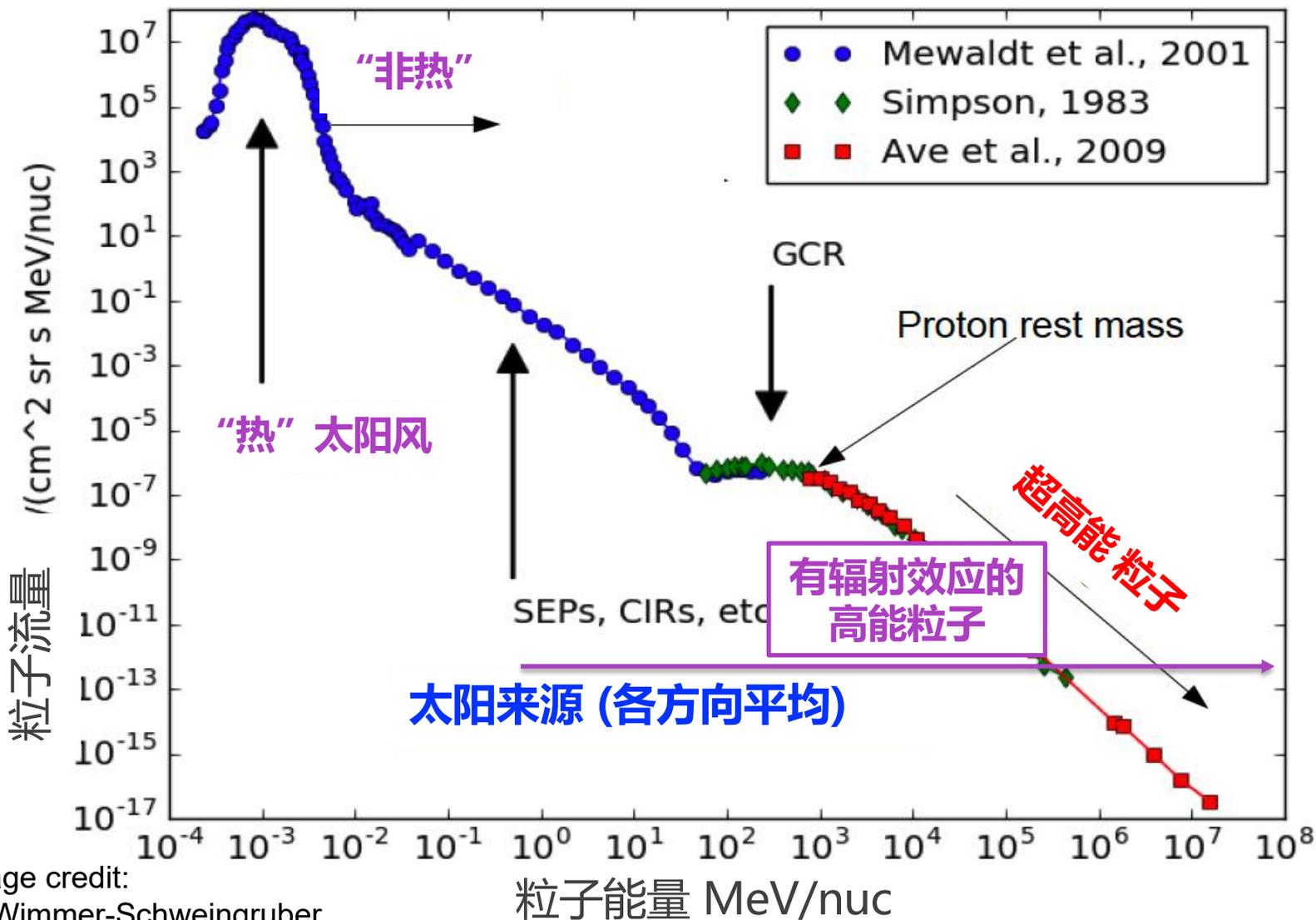
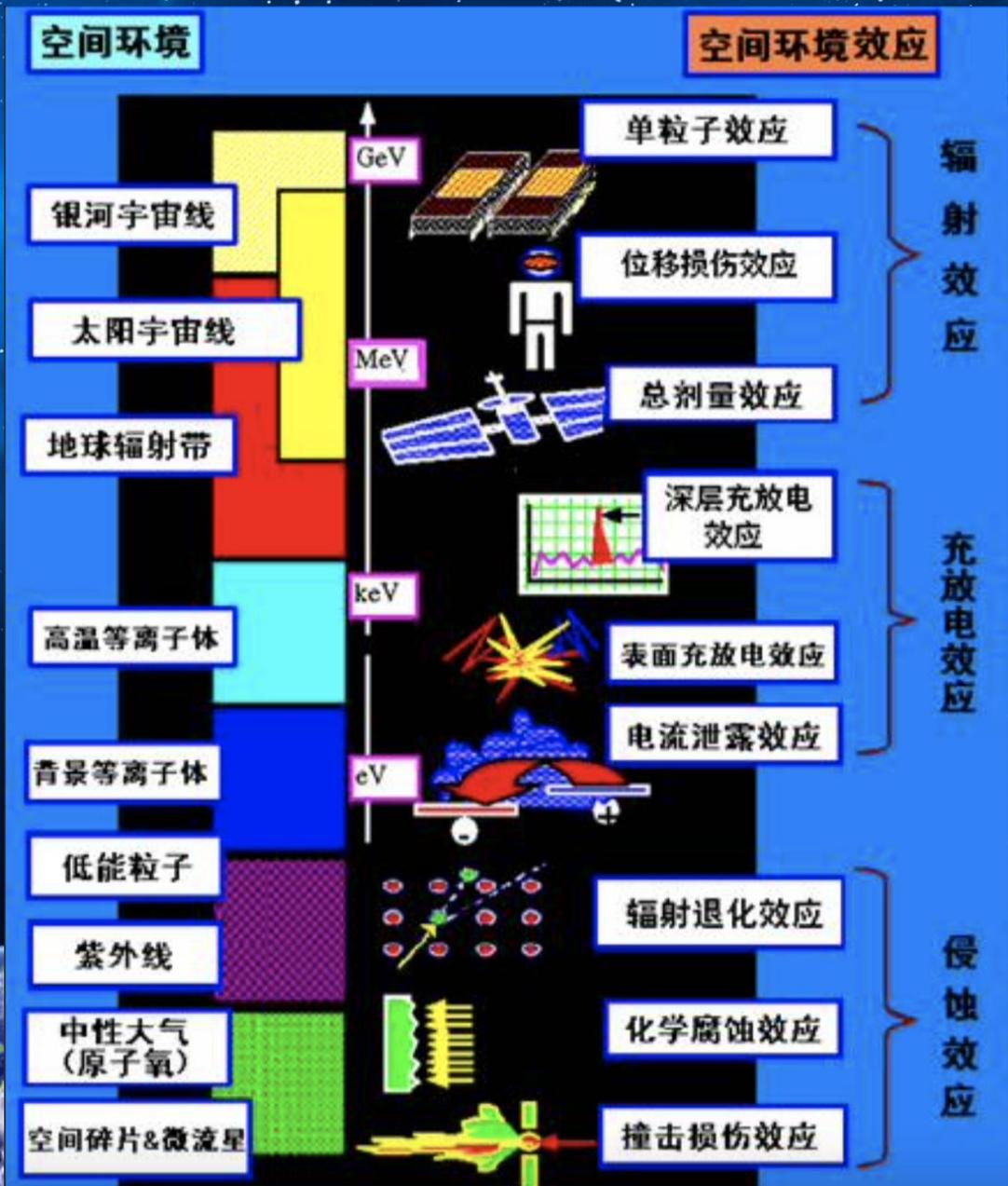


Image credit:
R. Wimmer-Schweingruber

深空高能粒子的辐射危害



RADIATION EFFECTS

Measurements in millisieverts (mSv). Exposure is cumulative.

HIGH RISK

- Potentially fatal radiation sickness. Much higher risk of cancer later in life.
- 10,000 mSv: Fatal within days.
- 5,000 mSv: Would kill half of those exposed within one month.
- 2,000 mSv: Acute radiation sickness.

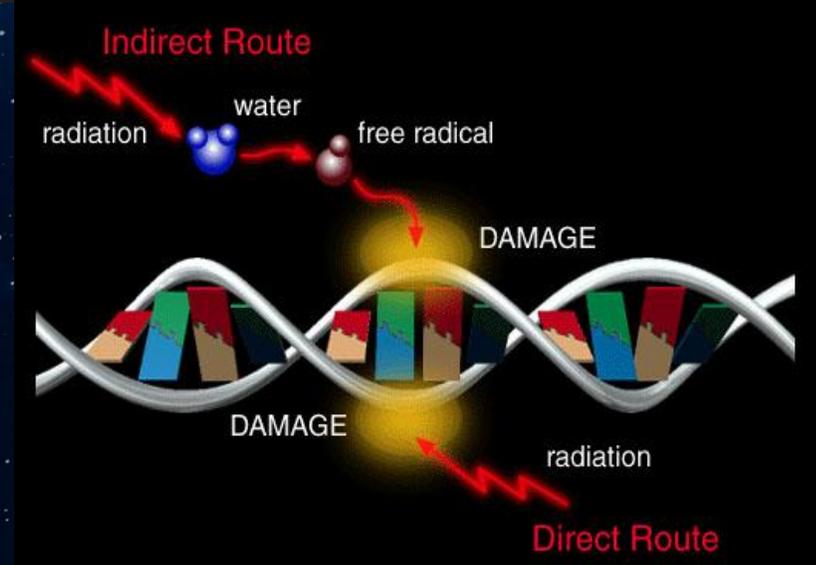
MODERATE RISK

- No immediate symptoms. Increased risk of serious illness later in life.
- 1,000 mSv: 5% higher chance of cancer.
- 400 mSv: Highest hourly radiation recorded at Fukushima. Four hour exposure would cause radiation sickness.
- 100 mSv: Level at which higher risk of cancer is first noticeable

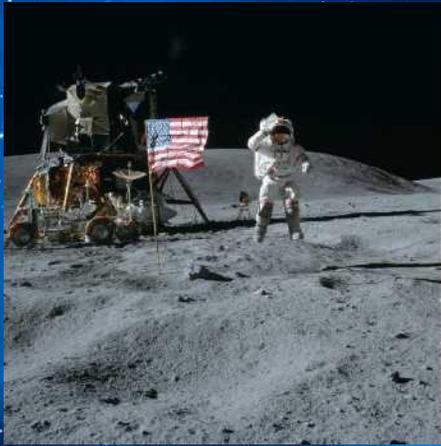
TOLERABLE LEVELS

- No symptoms. No detectable increased risk of cancer.
- 20 mSv: Yearly limit for nuclear workers.
- 10 mSv: Average dose from a full body CT scan
- 9 mSv: Yearly dose for airline crews.
- 3 mSv: Single mammogram
- 2 mSv: Average yearly background radiation dose in UK
- 0.1 mSv: Single chest x-ray

- EYES** High doses can trigger cataracts months later.
- THYROID** Hormone glands vulnerable to cancer. Radioactive iodine builds up in thyroid. Children most at risk.
- LUNGS** Vulnerable to DNA damage when radioactive material is breathed in.
- STOMACH** Vulnerable if radioactive material is swallowed.
- REPRODUCTIVE ORGANS** High doses can cause sterility.
- SKIN** High doses cause redness and burning.
- BONE MARROW** Produces red and white blood cells. Radiation can lead to leukaemia and other immune system diseases.



太阳高能粒子的预报需求：及时性（提前几周）

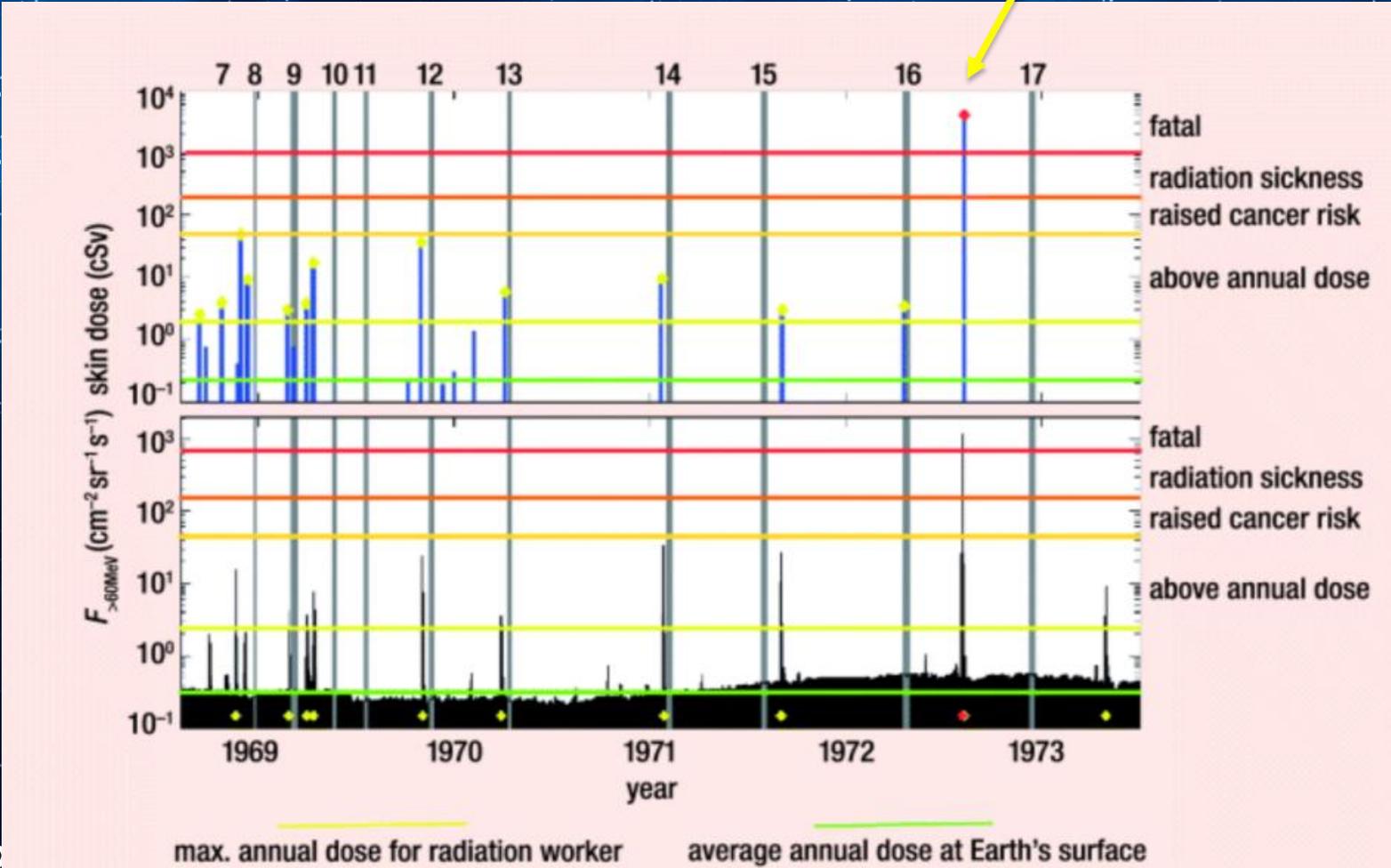


Apollo 16:
16 April 1972
21 April 1972

In between:
An enormous
solar explosion!

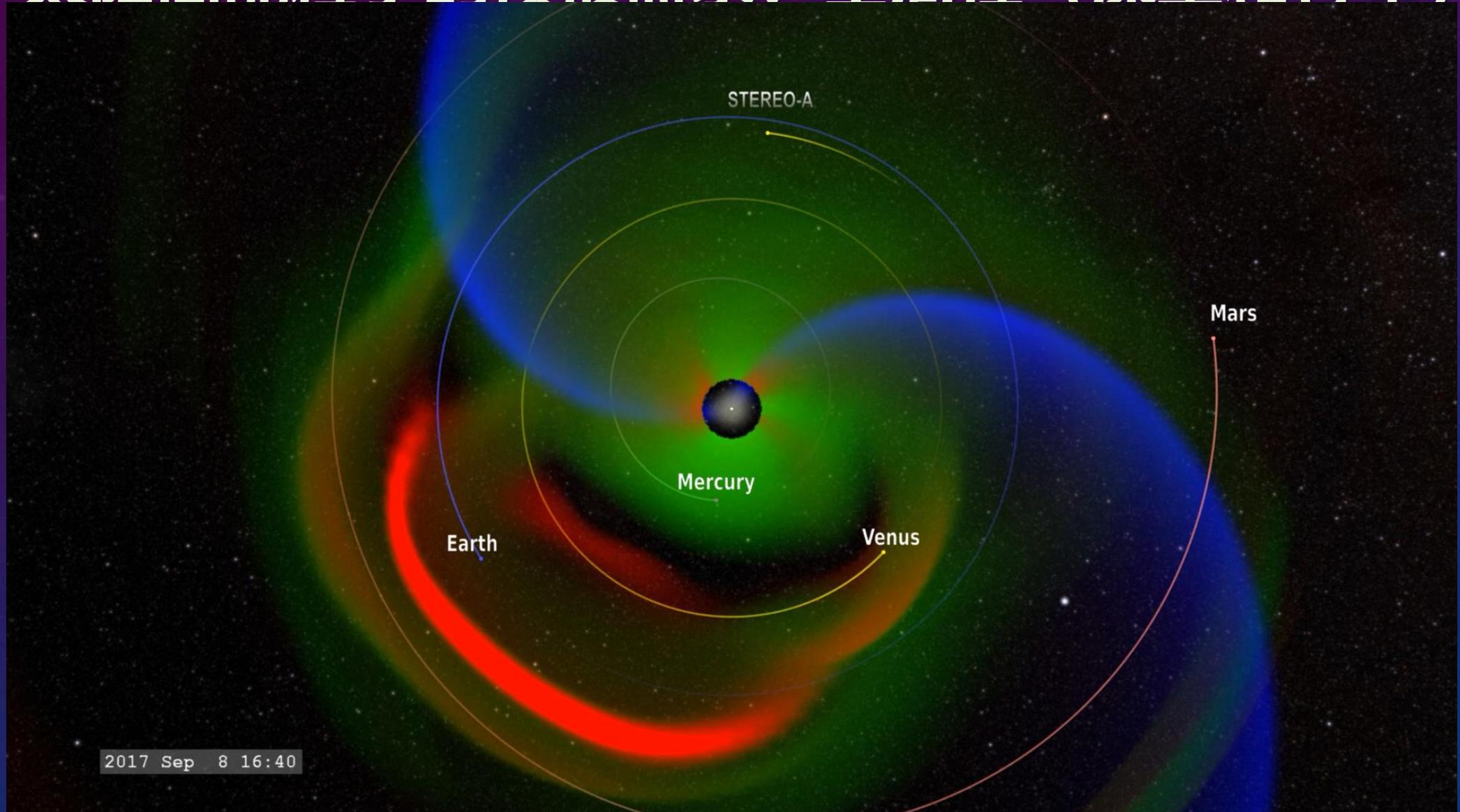


Apollo 17:
7 Dec. 1972
11 Dec 1972



Lockwood & Hapgood, 2007

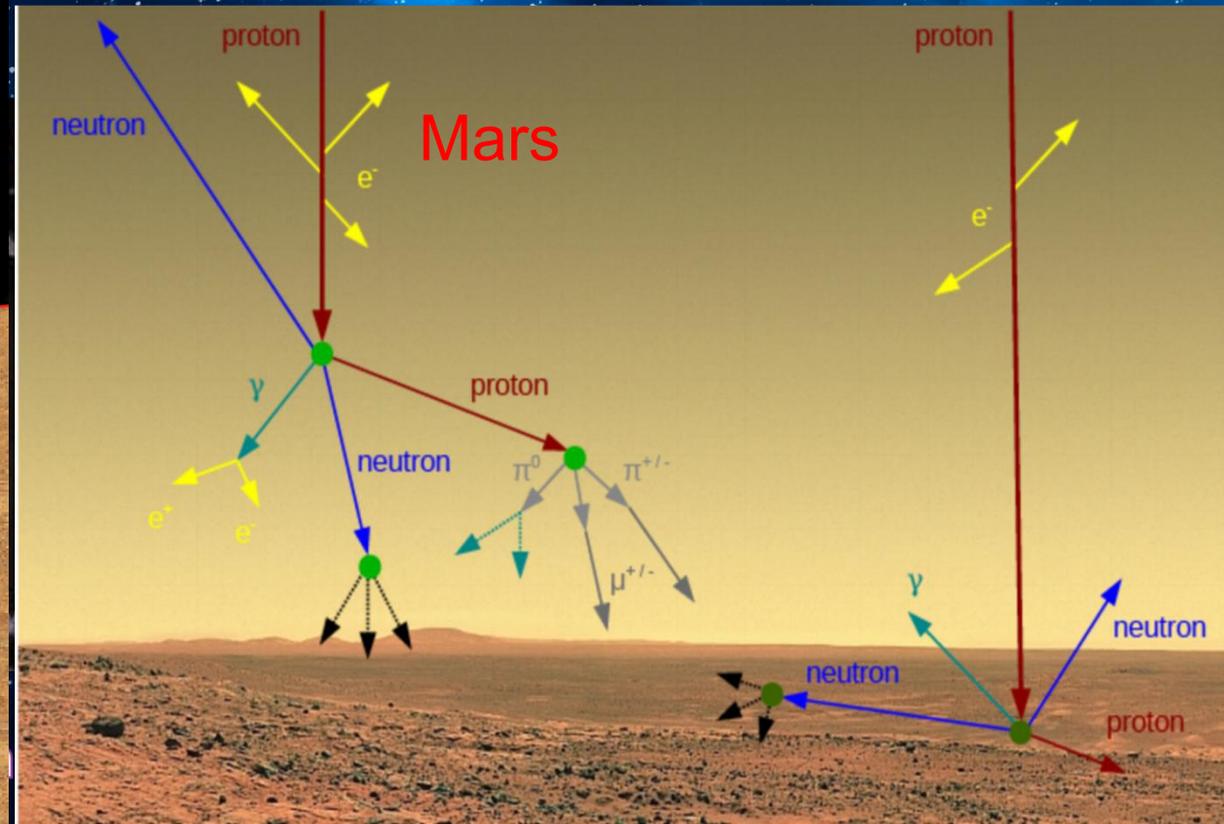
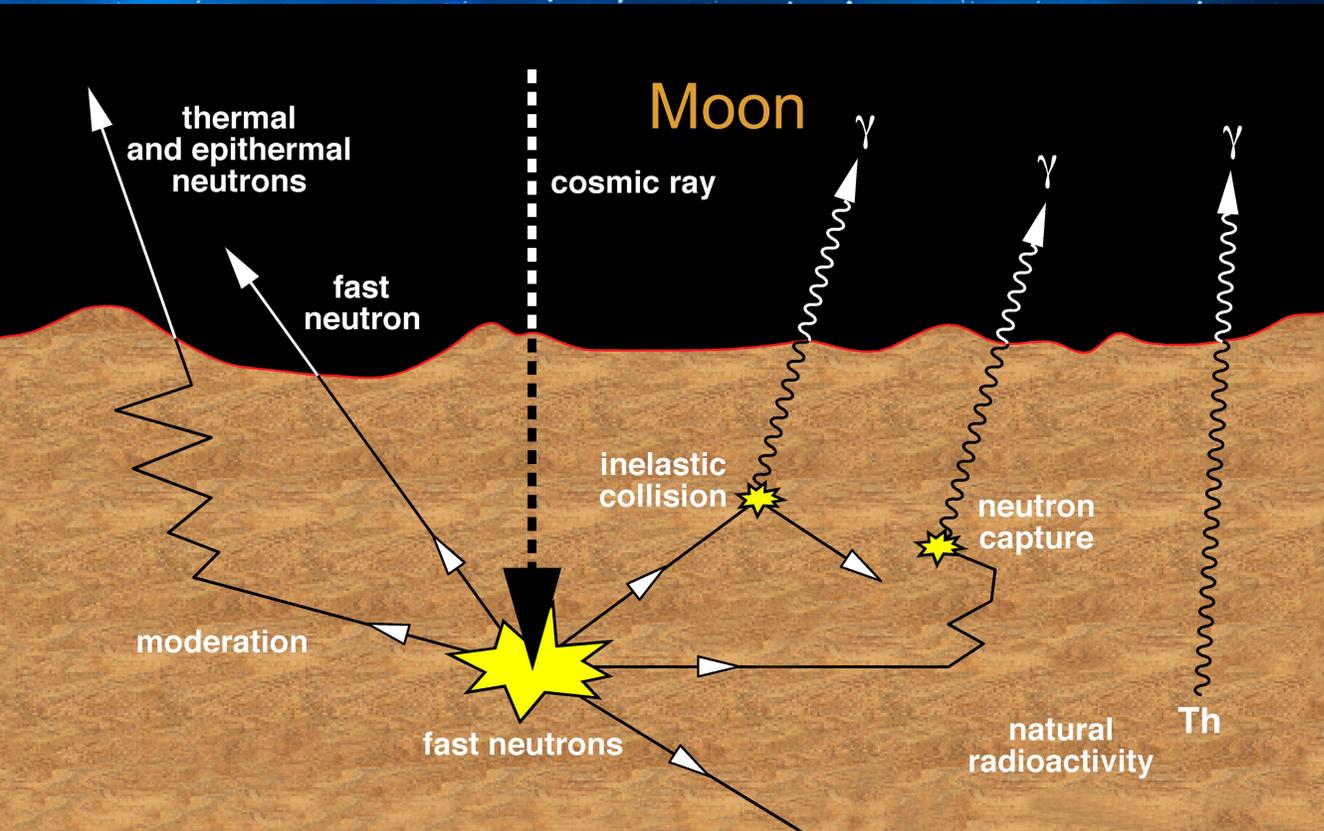
太阳高能粒子的预报需求：全局性（深空和行星）



Guo et al. 2018 Modeling the Evolution and Propagation of 10 September 2017 CMEs and SEPs Arriving at Mars Constrained by Remote Sensing and In Situ Measurement, Space Weather, 16

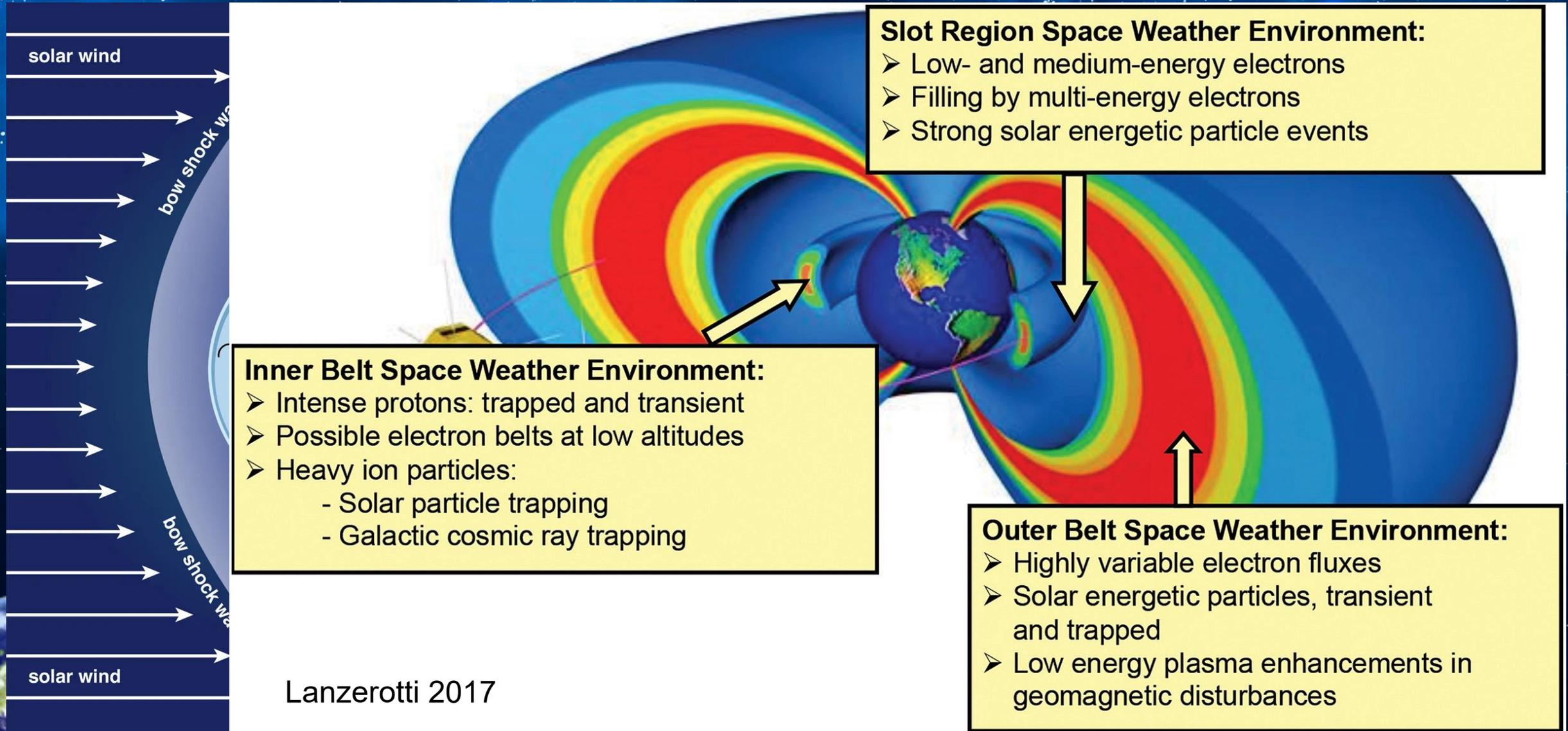
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地球、月球、火星空间辐射的比较研究

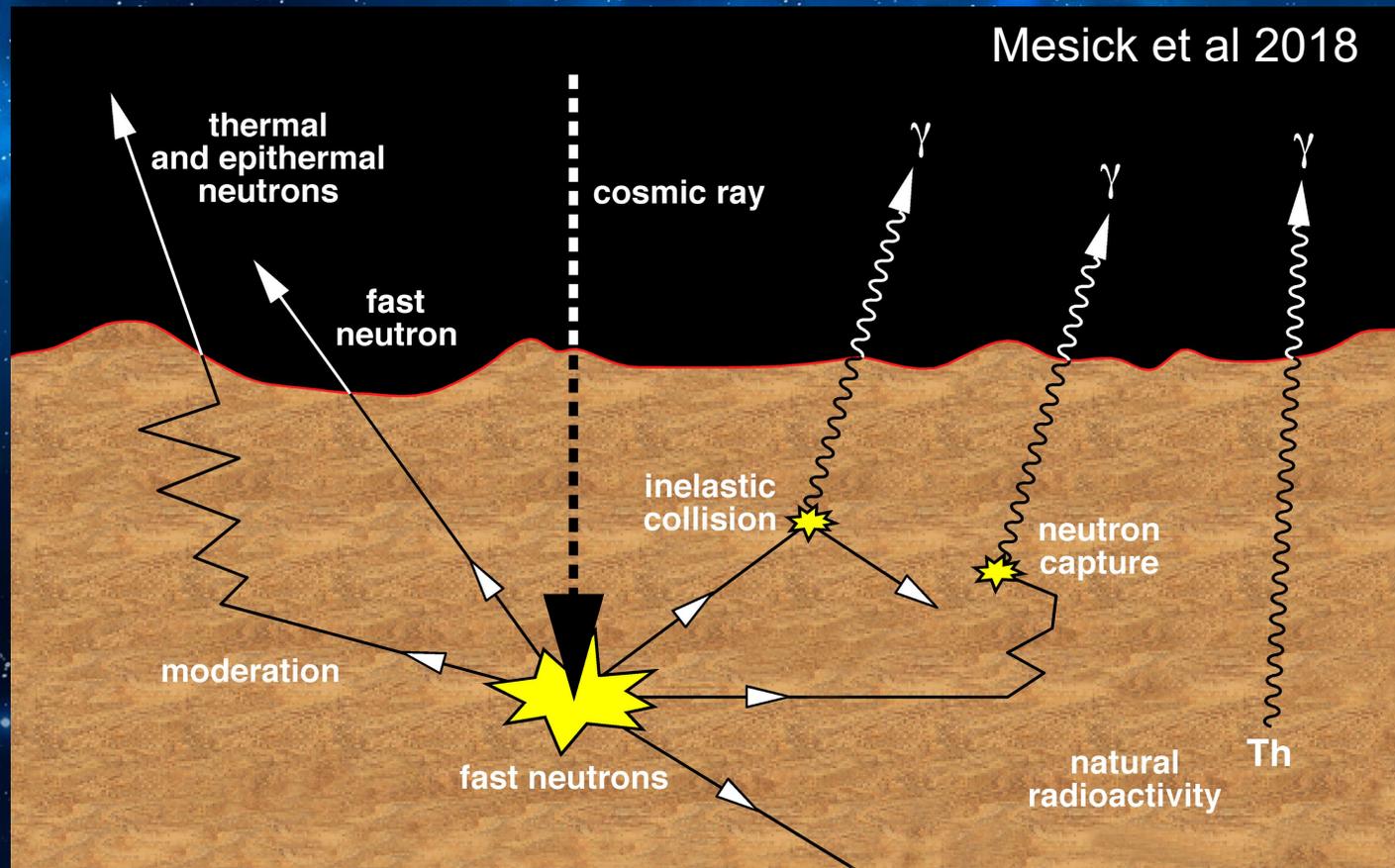


空间粒子可以在行星环境中产生大量次级粒子（包括生物辐射效应极强的中子），使其辐射环境和深空中大不一样

地球附近的高能粒子环境



月球空间的高能粒子环境

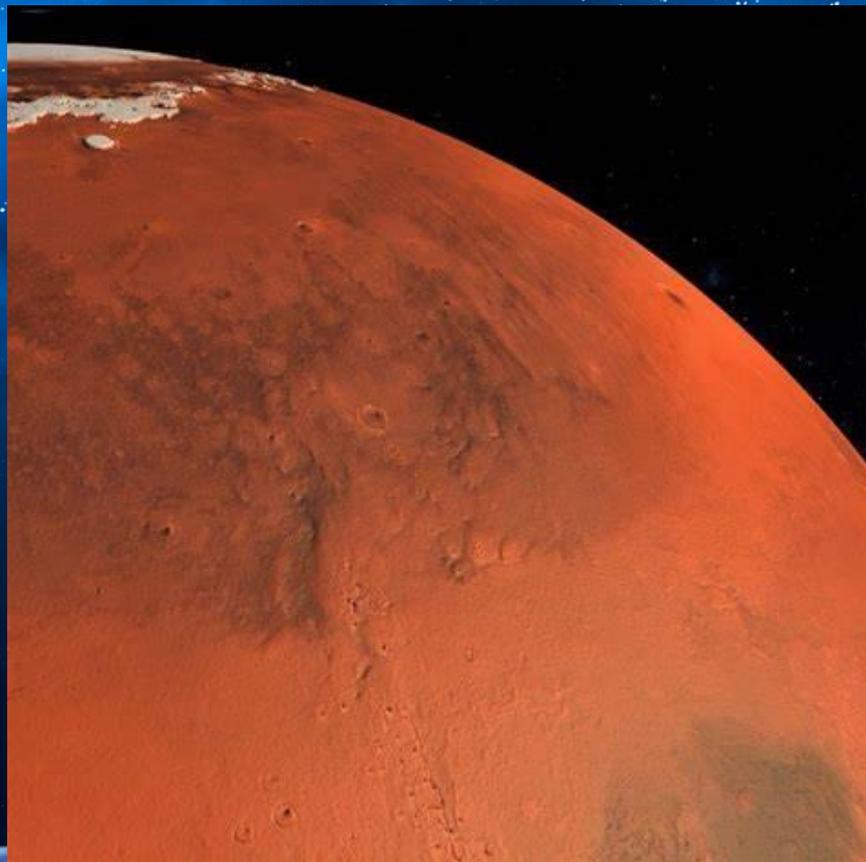


月球没有有效磁场/大气的保护

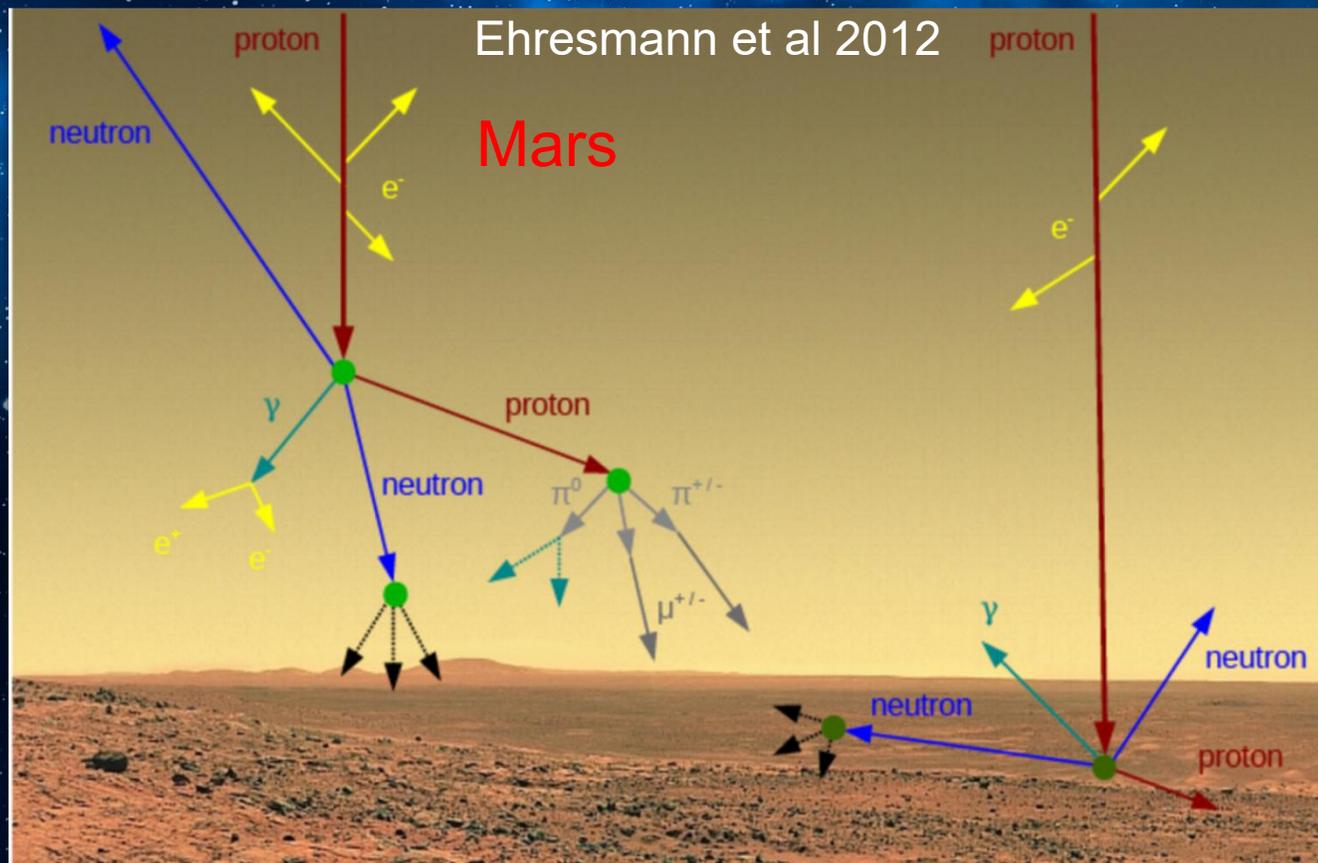


高能粒子直接与月壤相互作用，产生大量次级粒子

火星空间的高能粒子环境

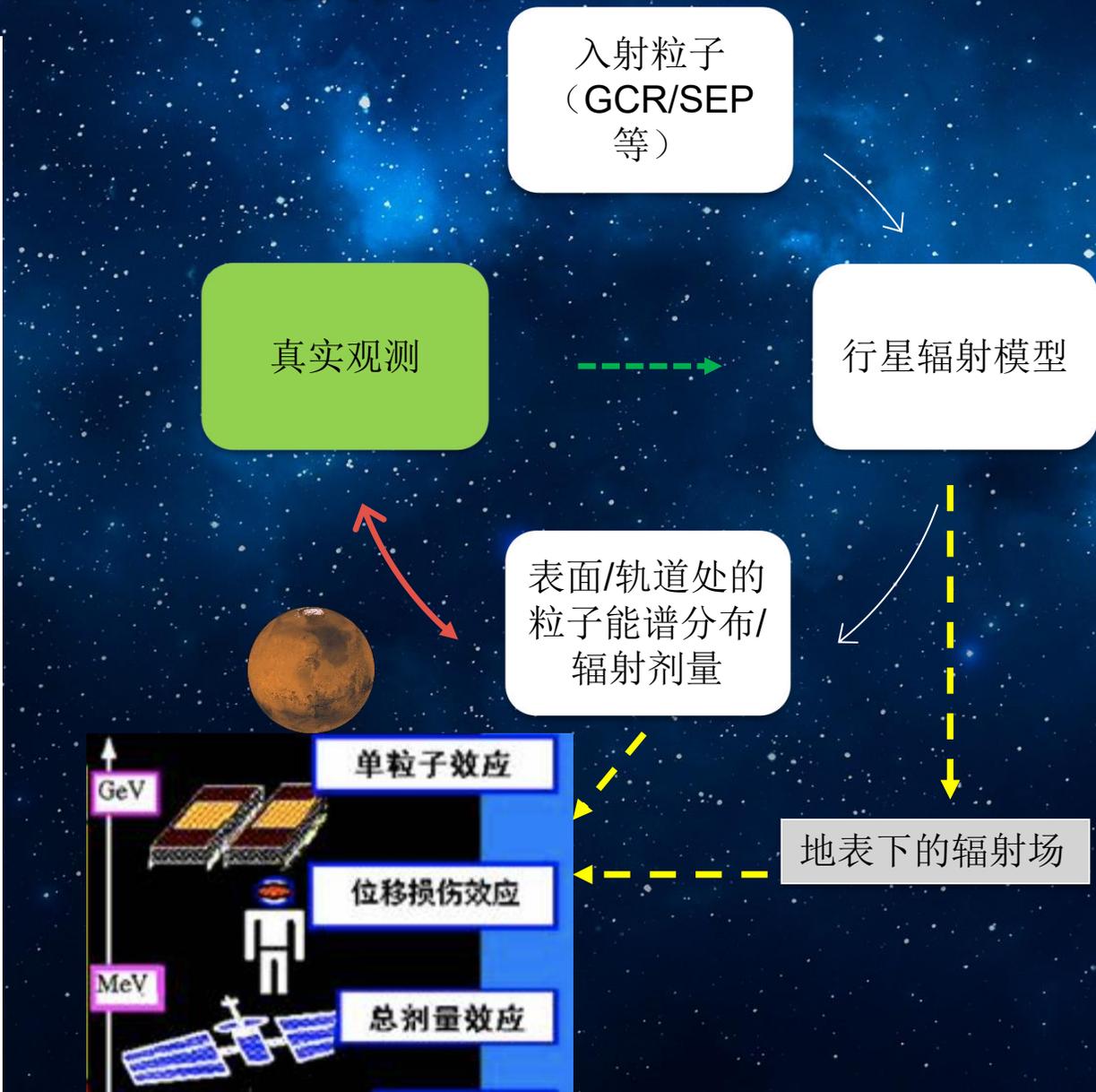
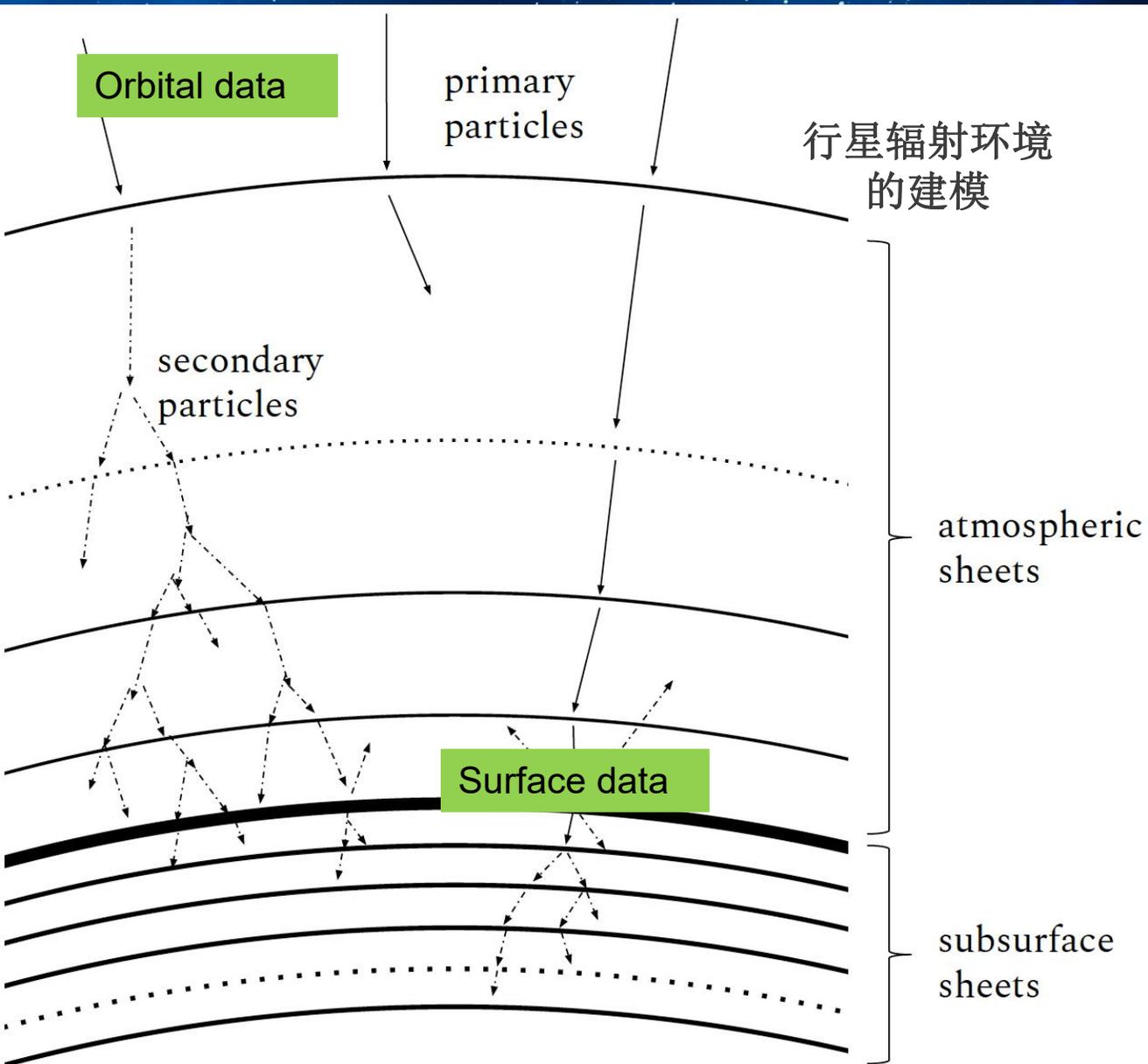


火星没有内禀磁场，却有稀薄的大气

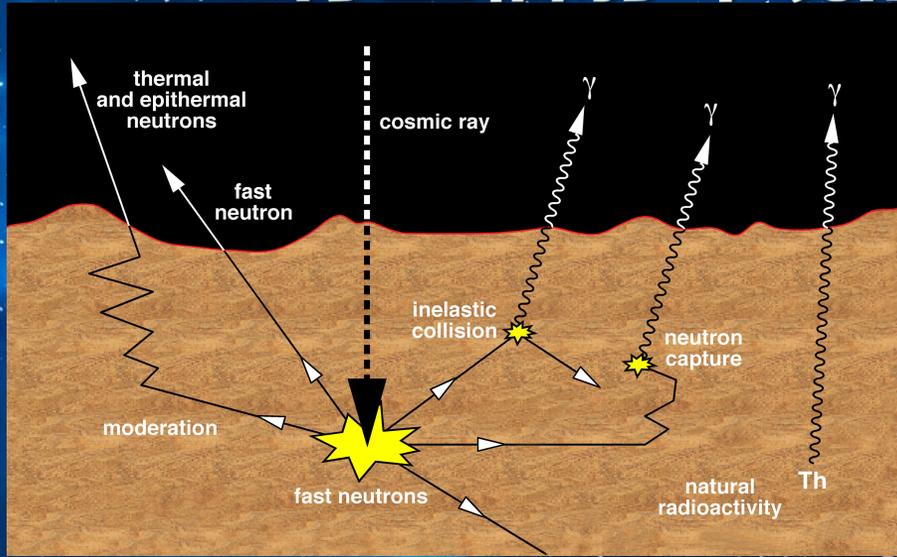


高能粒子可能穿过火星大气 (<0.01 bar) 到达火星表面，并与之相互作用，产生大量次级粒子

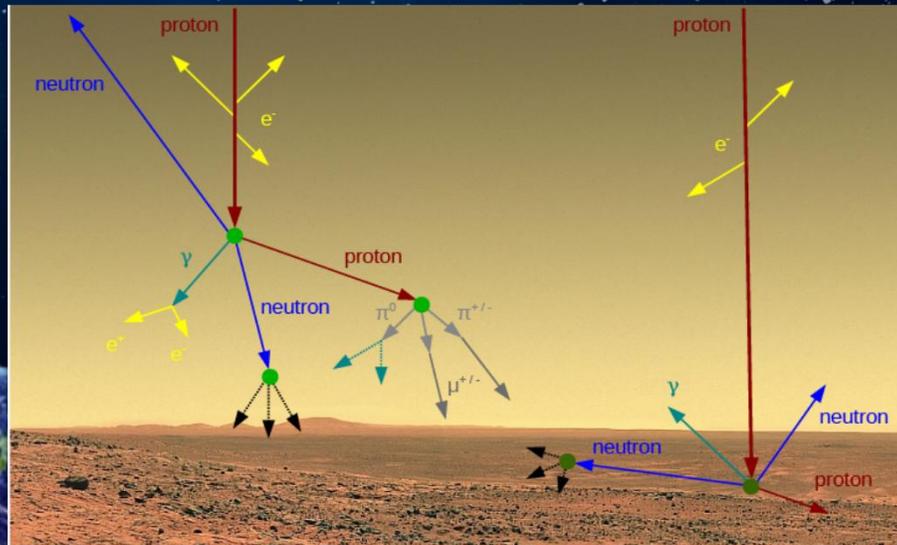
行星辐射环境的模型和数据需求



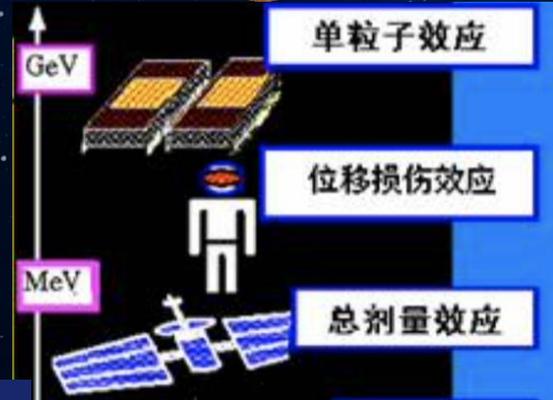
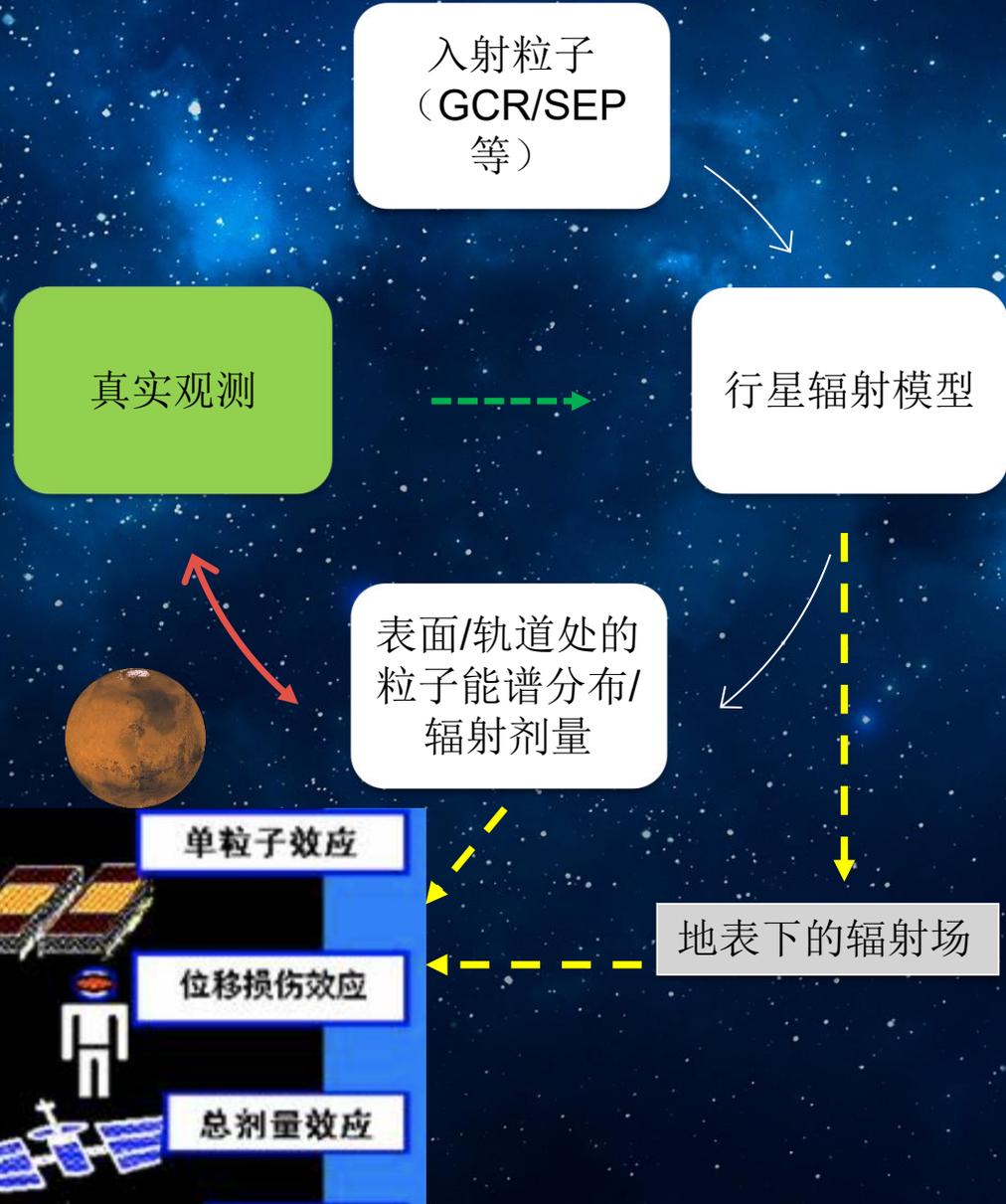
行星辐射环境的模型和数据需求



GEANT4 REDMoon模型 Dobynde & Guo, 2021



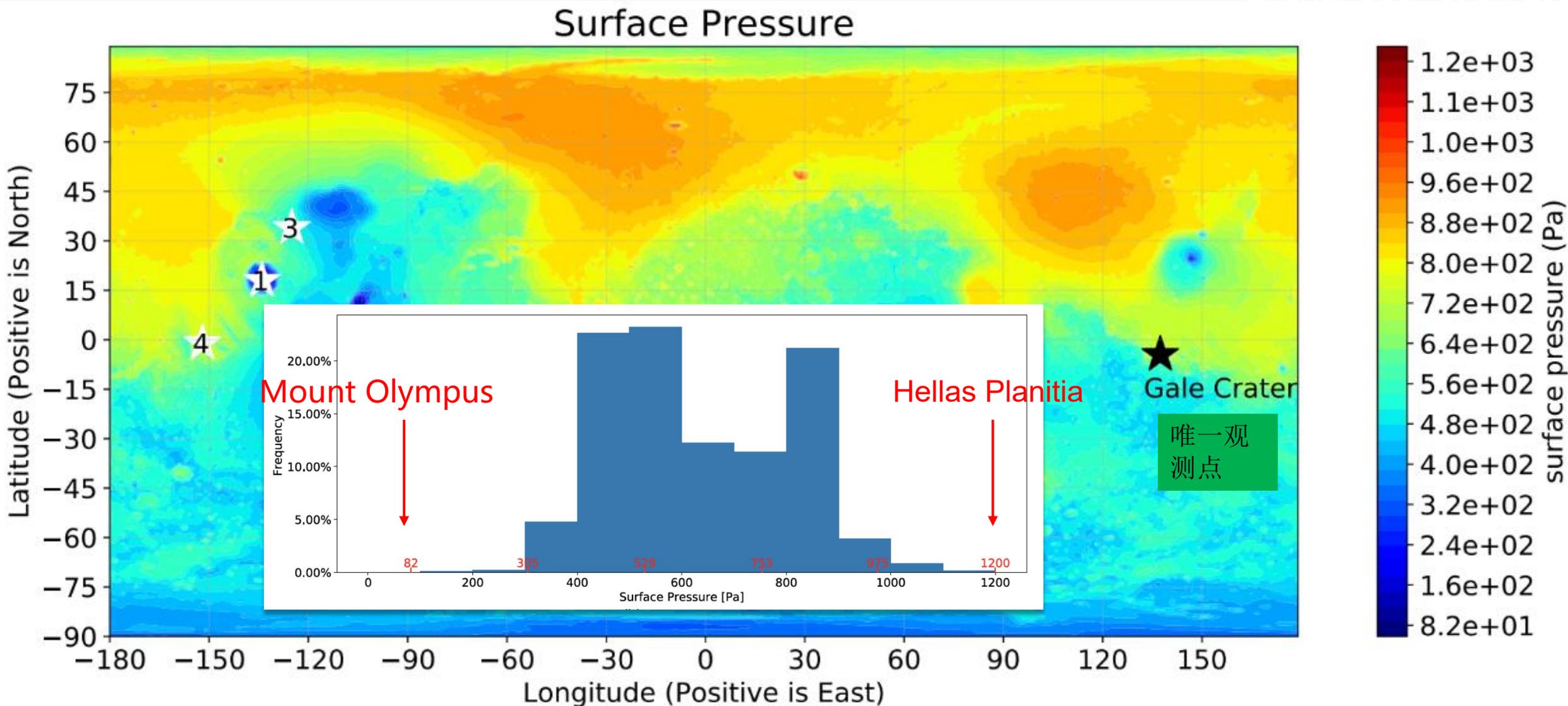
GEANT4 AtRIS模型: Guo et al. 2018, 2019; Zhang et al 2022



举例1：火星高能粒子辐射环境的全球模型

Guo* et al. 2018, 2019

Zhang, Guo* et al., 2022



Particles in deep space
(GCRs or SEPs)

Primary
GCRs
(mainly p^+ &
 He^{2+})

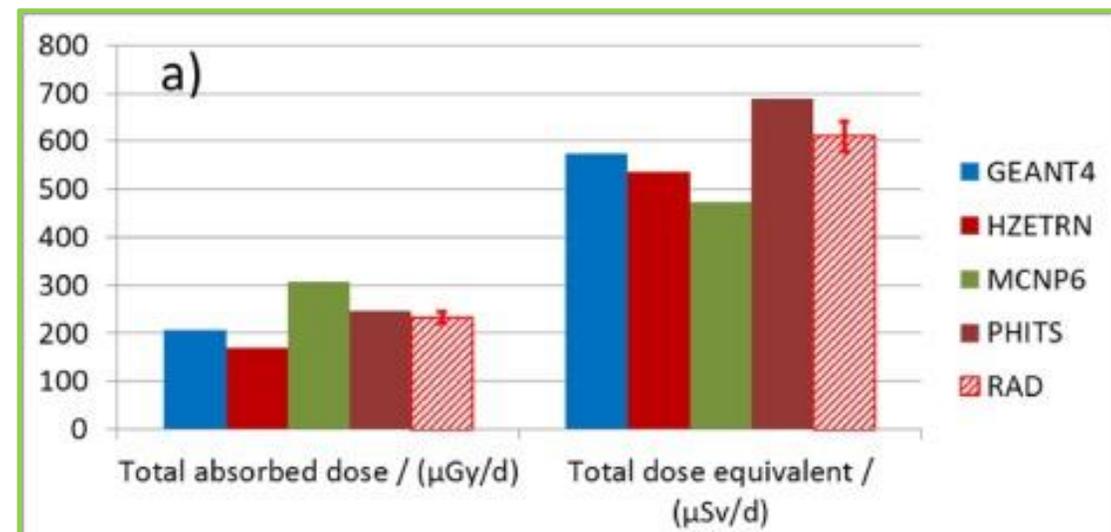
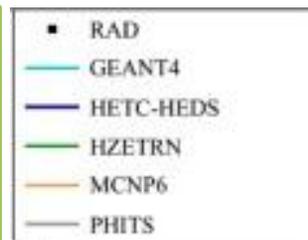
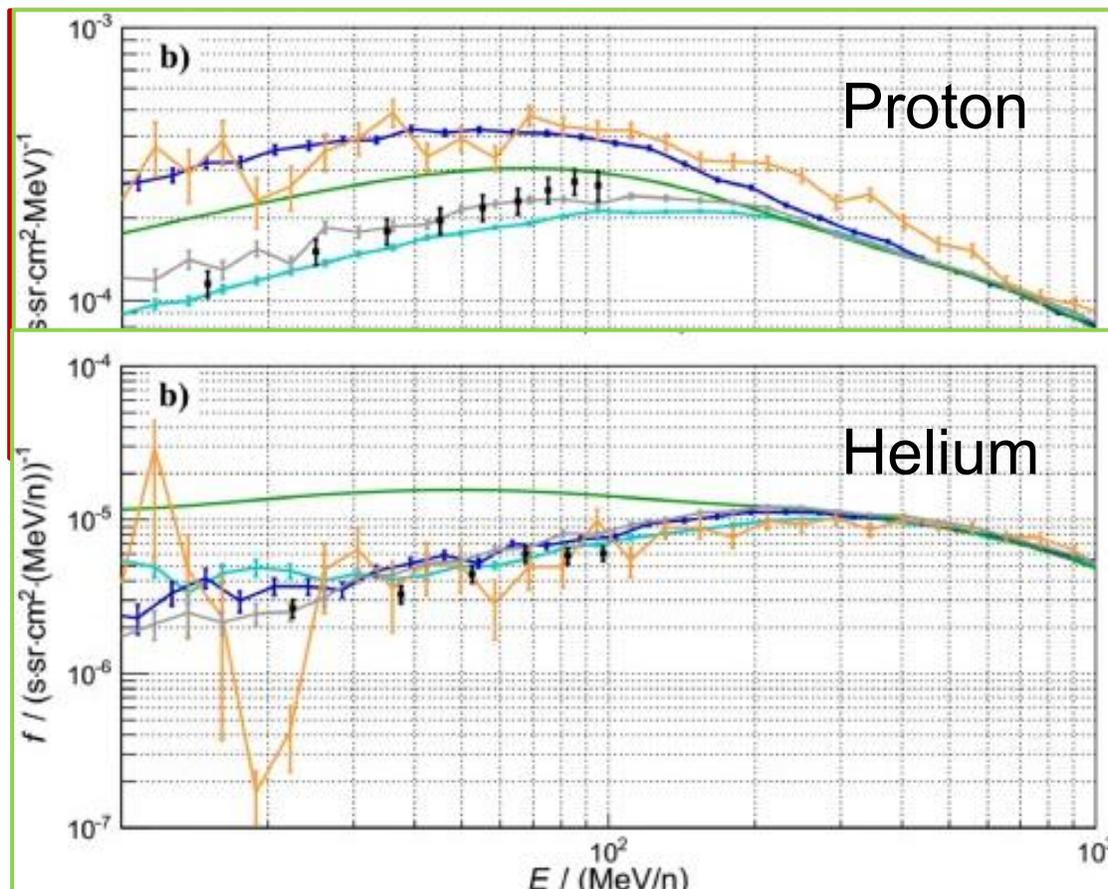
Particle transport
model (e.g.,
GEANT4)

GCR-induced Martian
surface particle spectra
of different types

Martian atmosphere &
regolith model (e.g.,
MCD)

Model validation
Matthiae 2016, 2018;
Guo+2019 SWSC

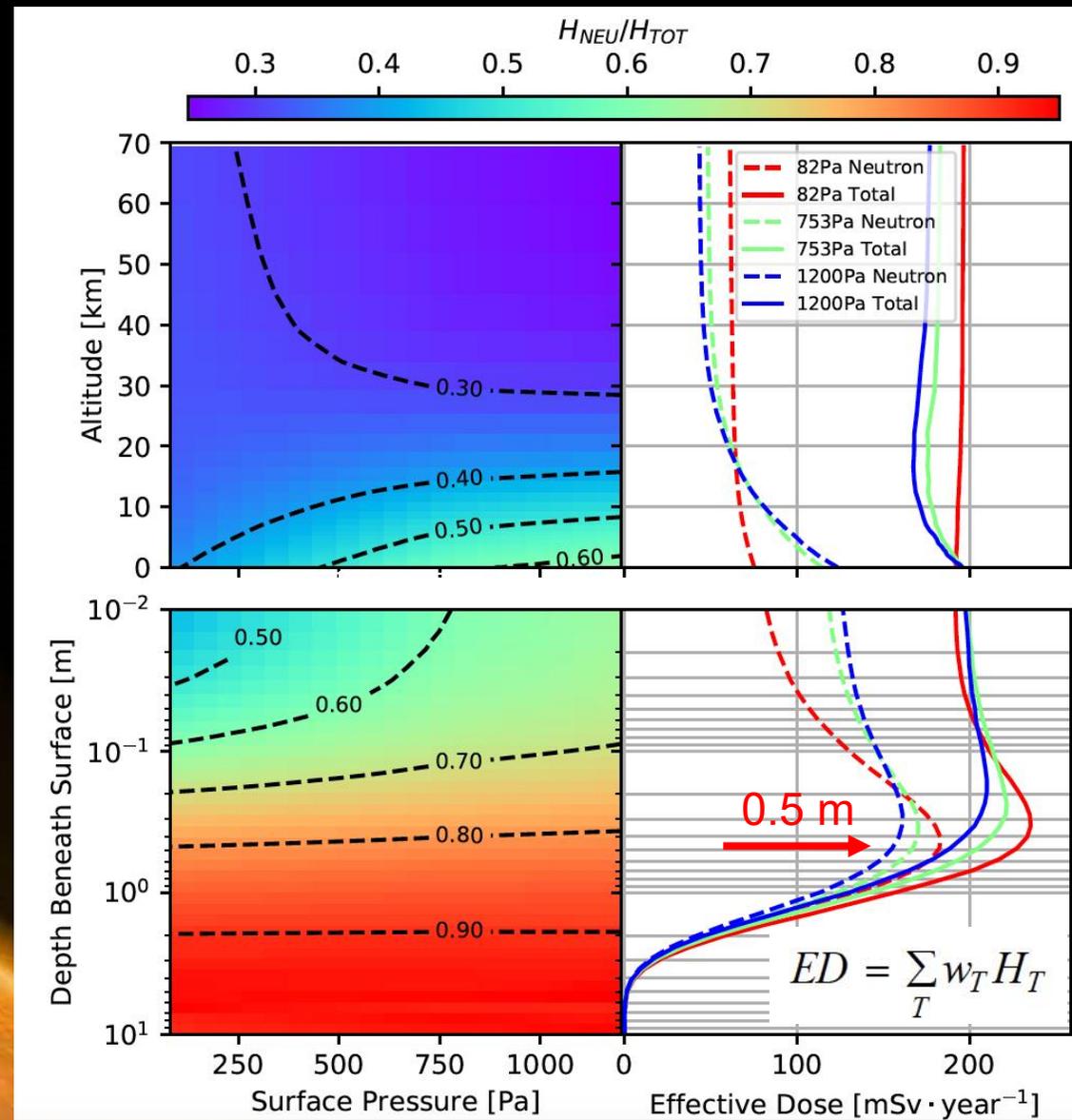
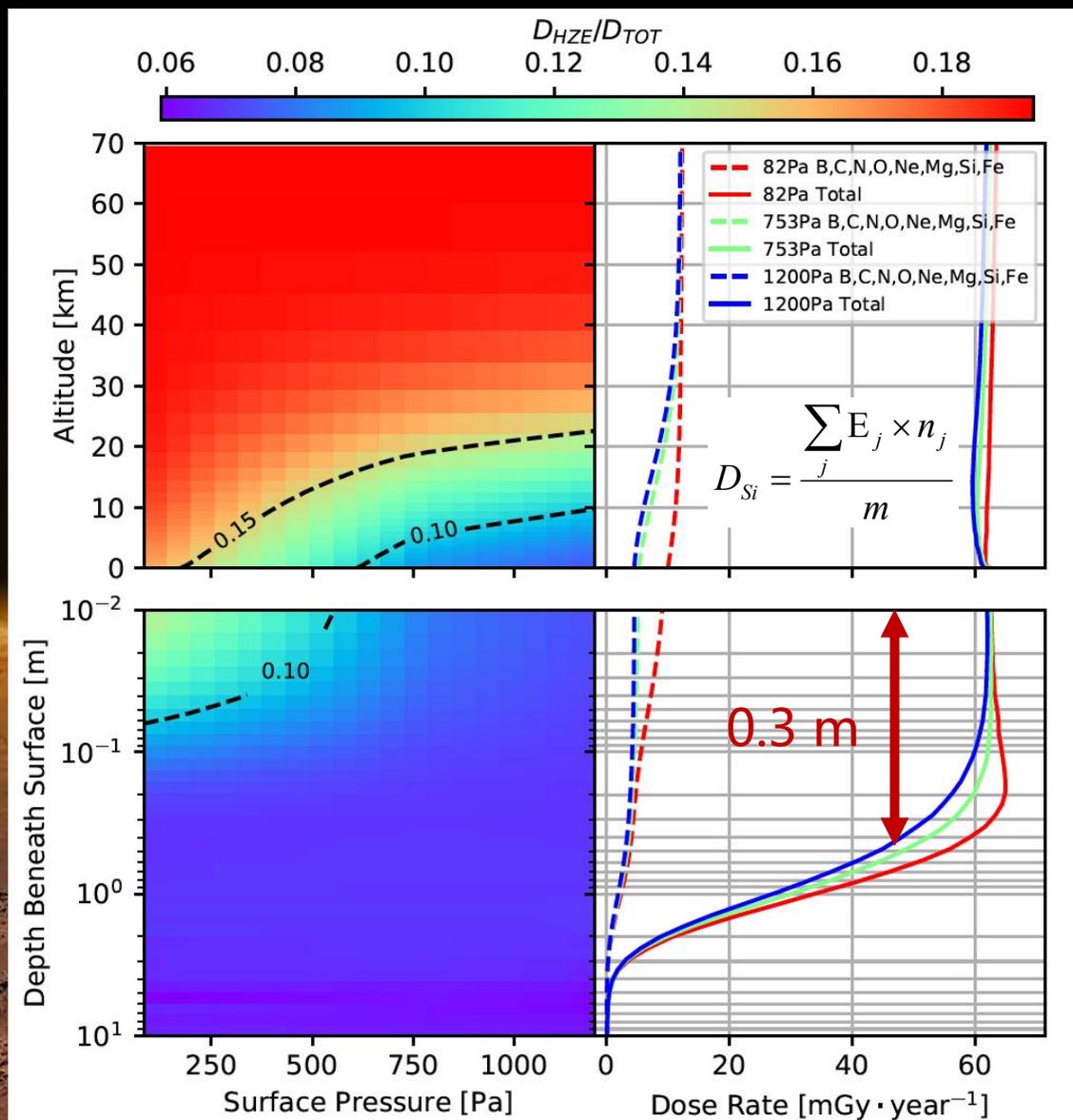
RAD measurement of surface
radiation under similar solar
modulation conditions
(*Ehresmann+2014, 2017,*
Kohler+2014, Guo+2017)



举例1：火星高能粒子辐射环境的模型预估

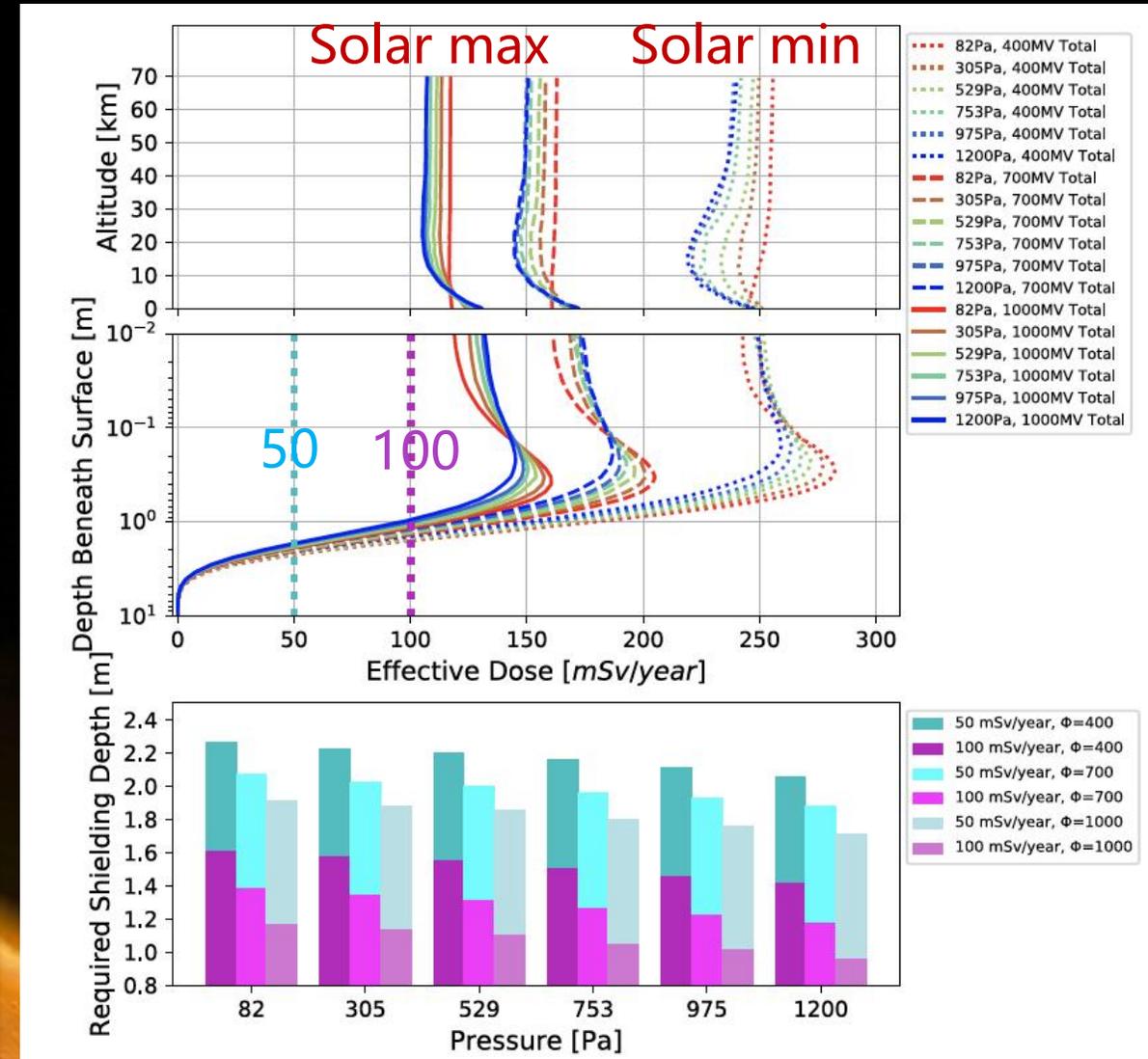
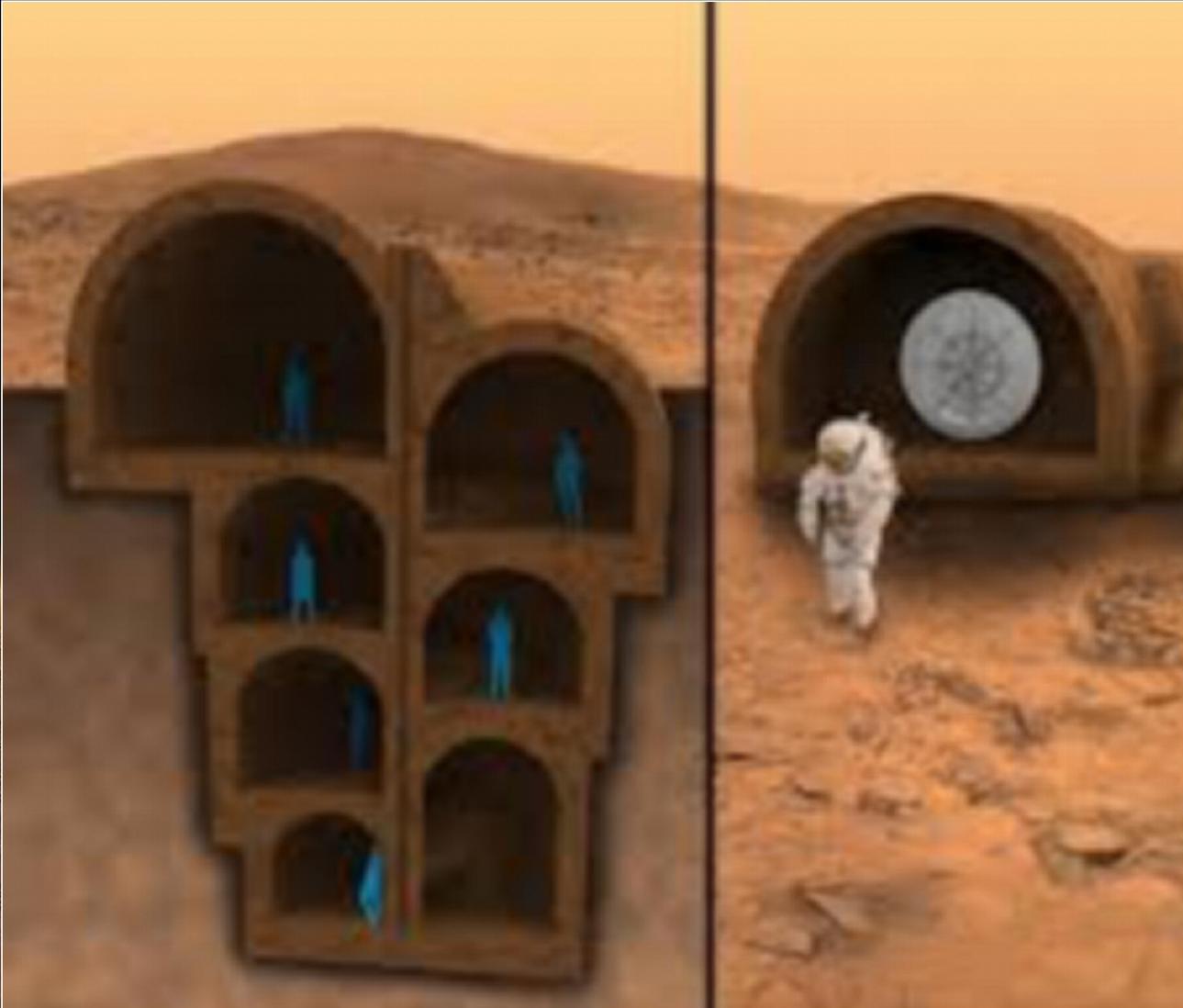
Z>2的高能带电粒子贡献超过10%

次级中子在火星土壤的贡献巨大



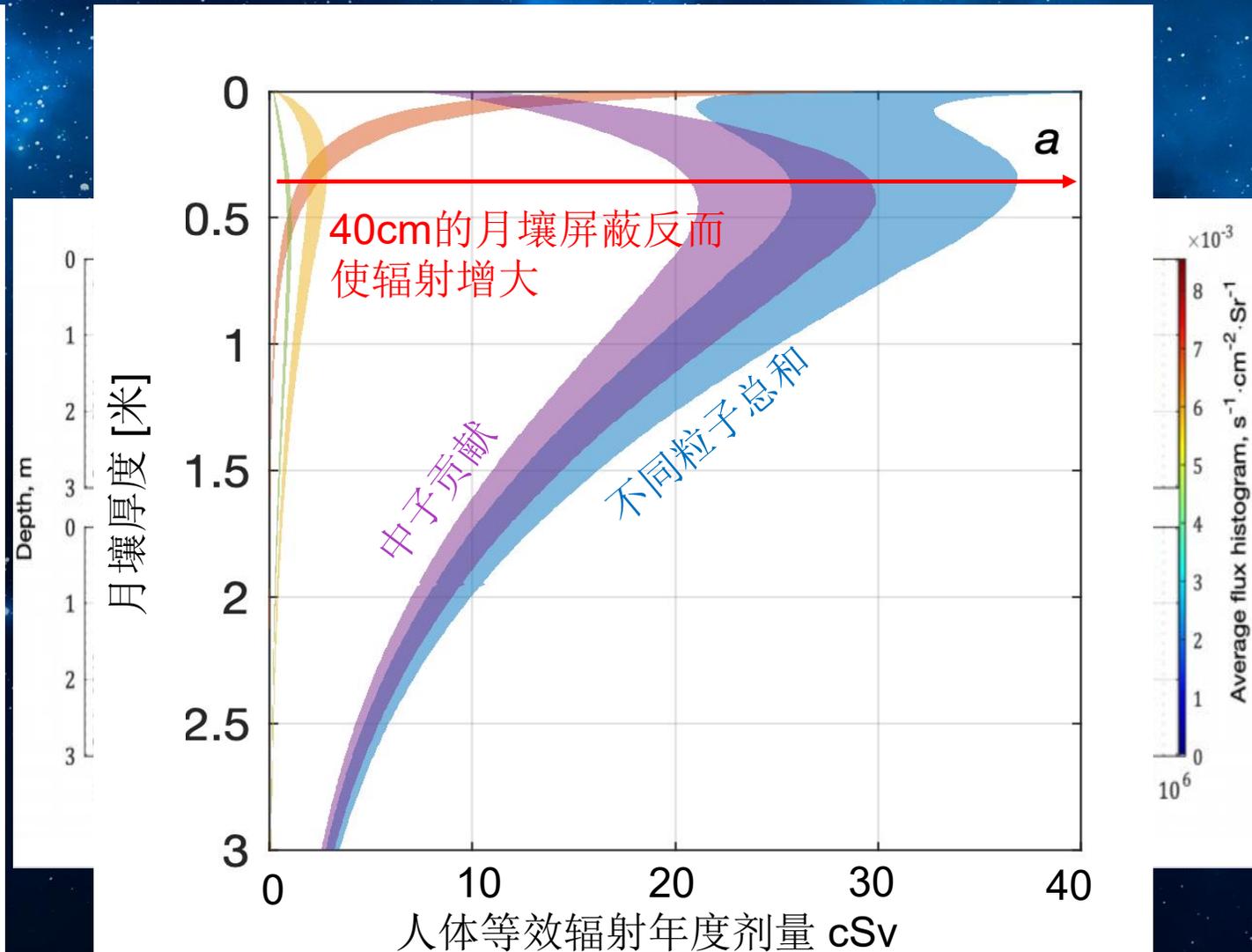
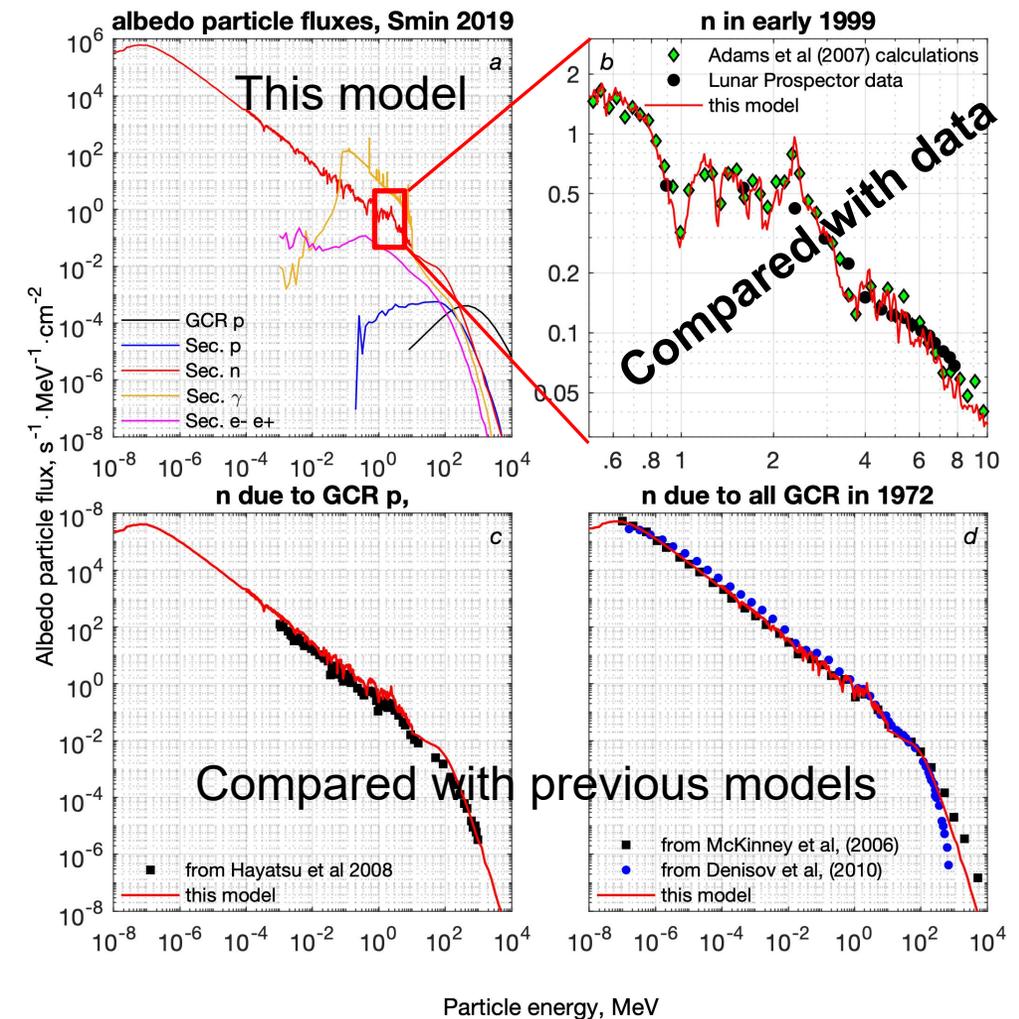
未来火星基地

During solar min and at high altitudes, more regolith shielding is needed

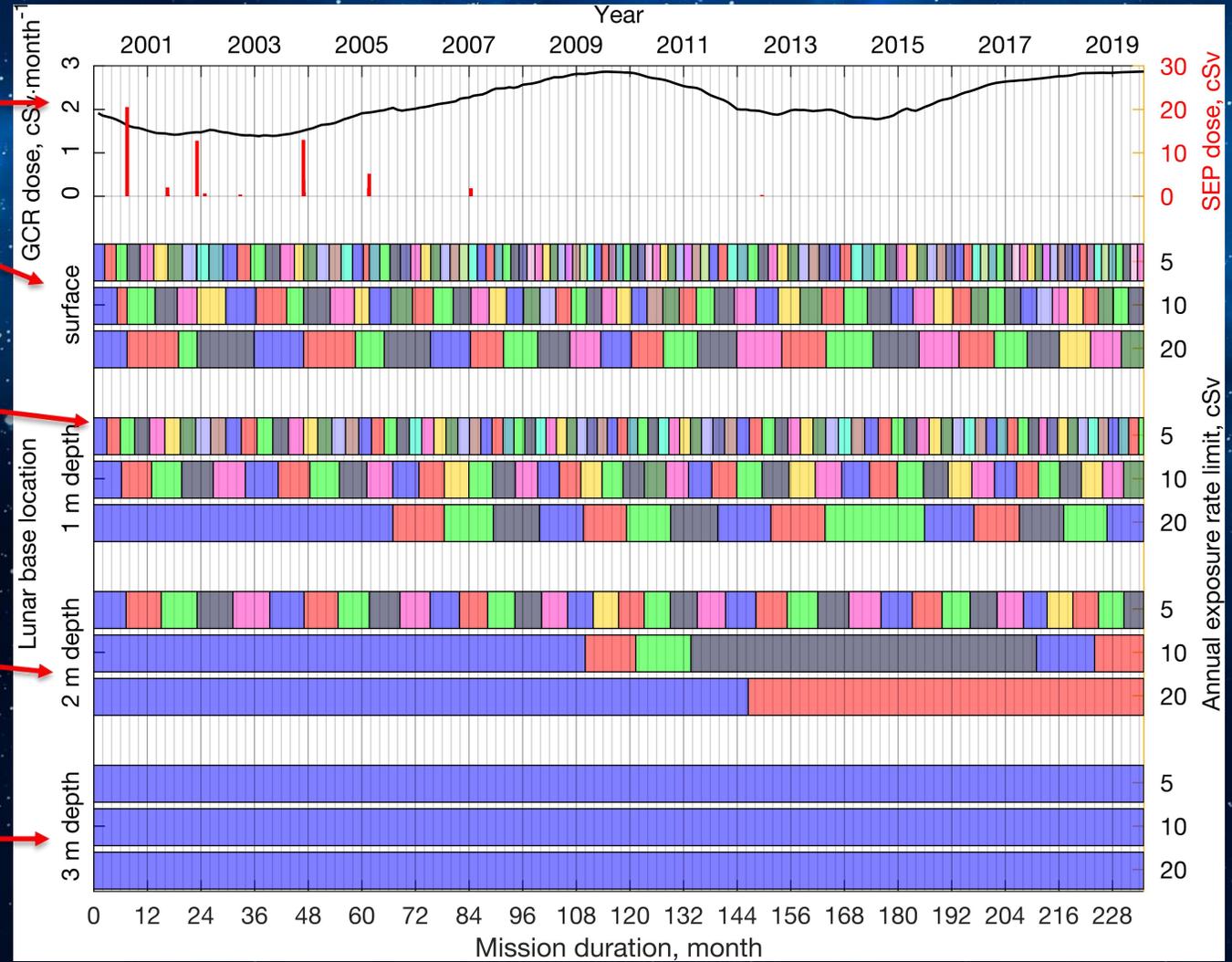
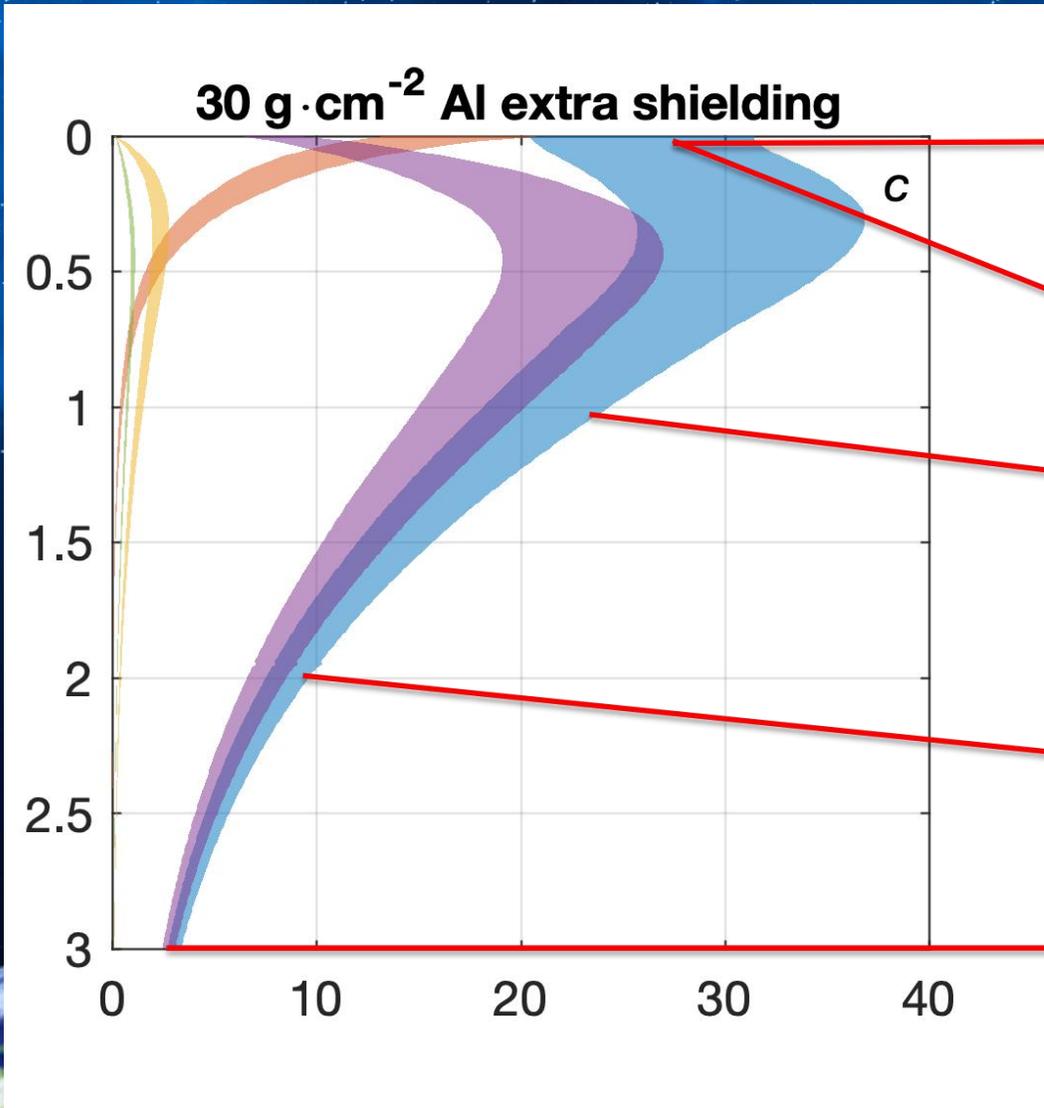


举例：月球的高能粒子辐射环境模型

Dobynde & Guo, 2021 JGR:planets



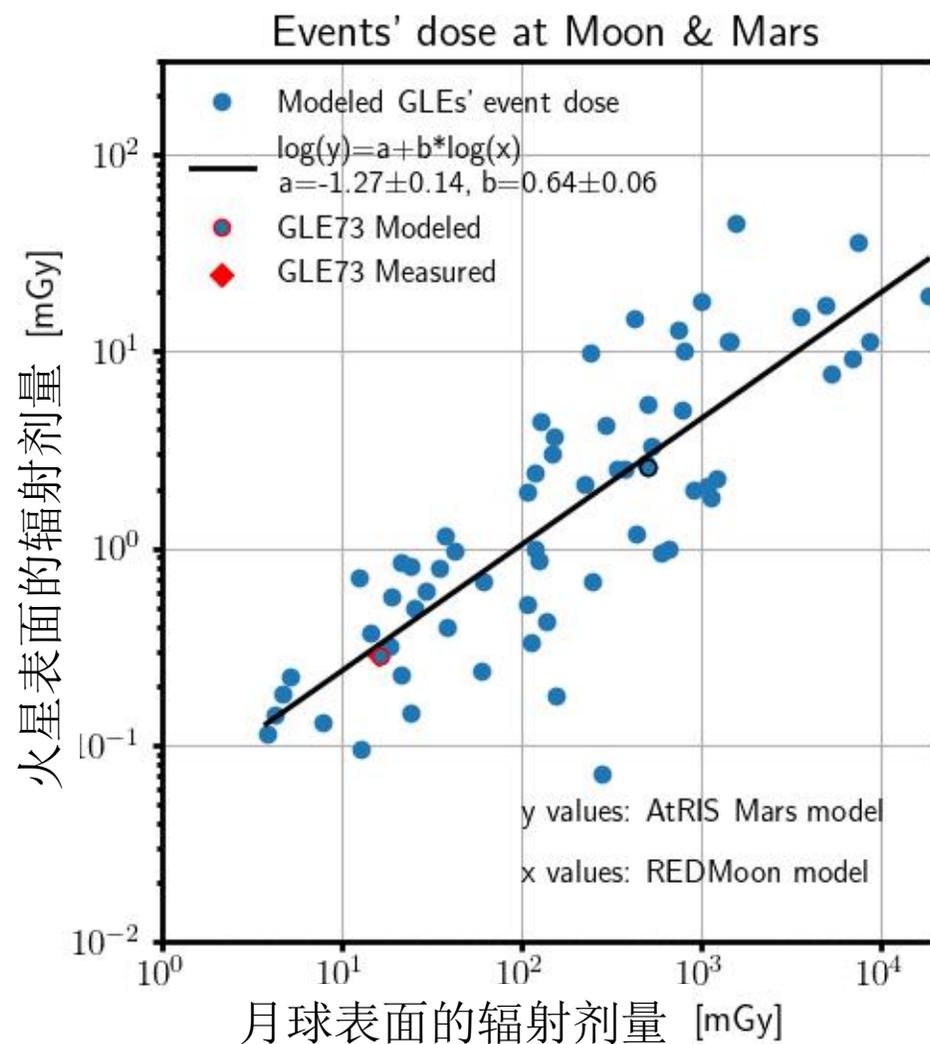
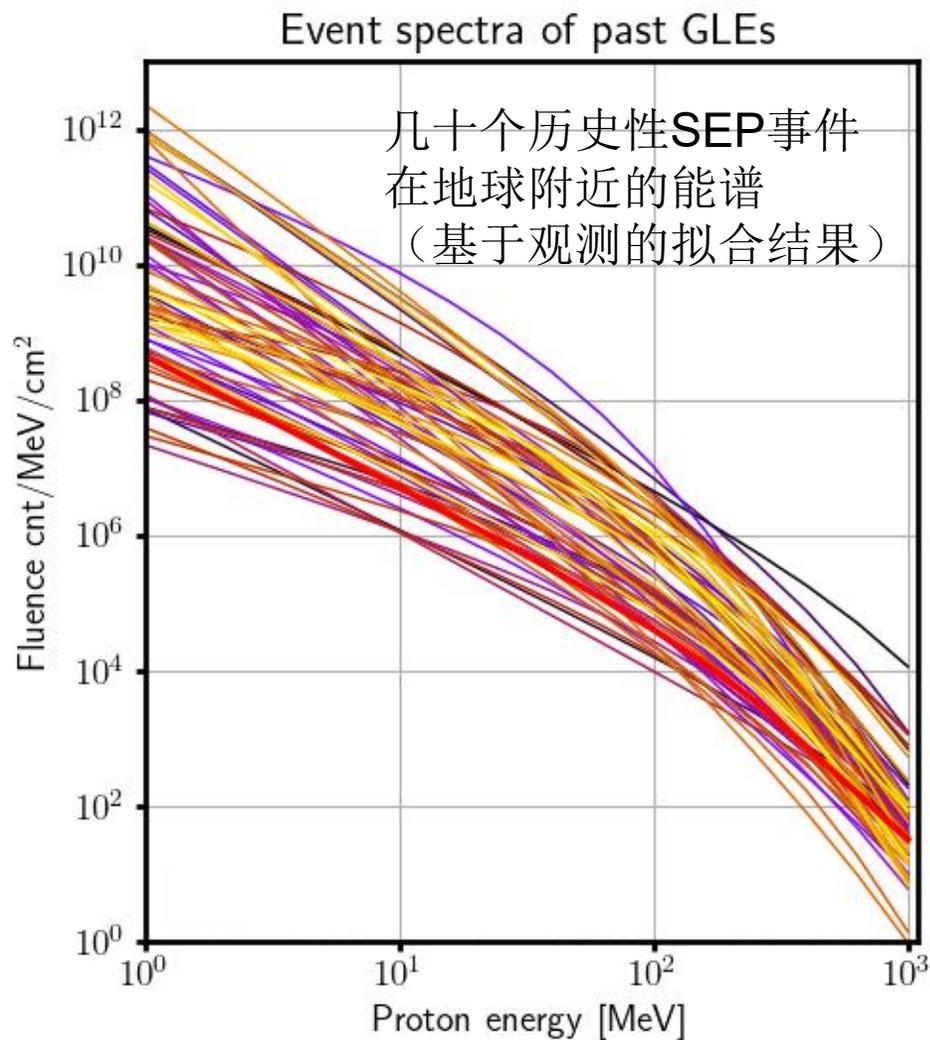
未来月球基地和探月窗口期



Dobynde & Guo, in preparation

模拟历史性SEP事件在火星和月球表面的辐射剂量

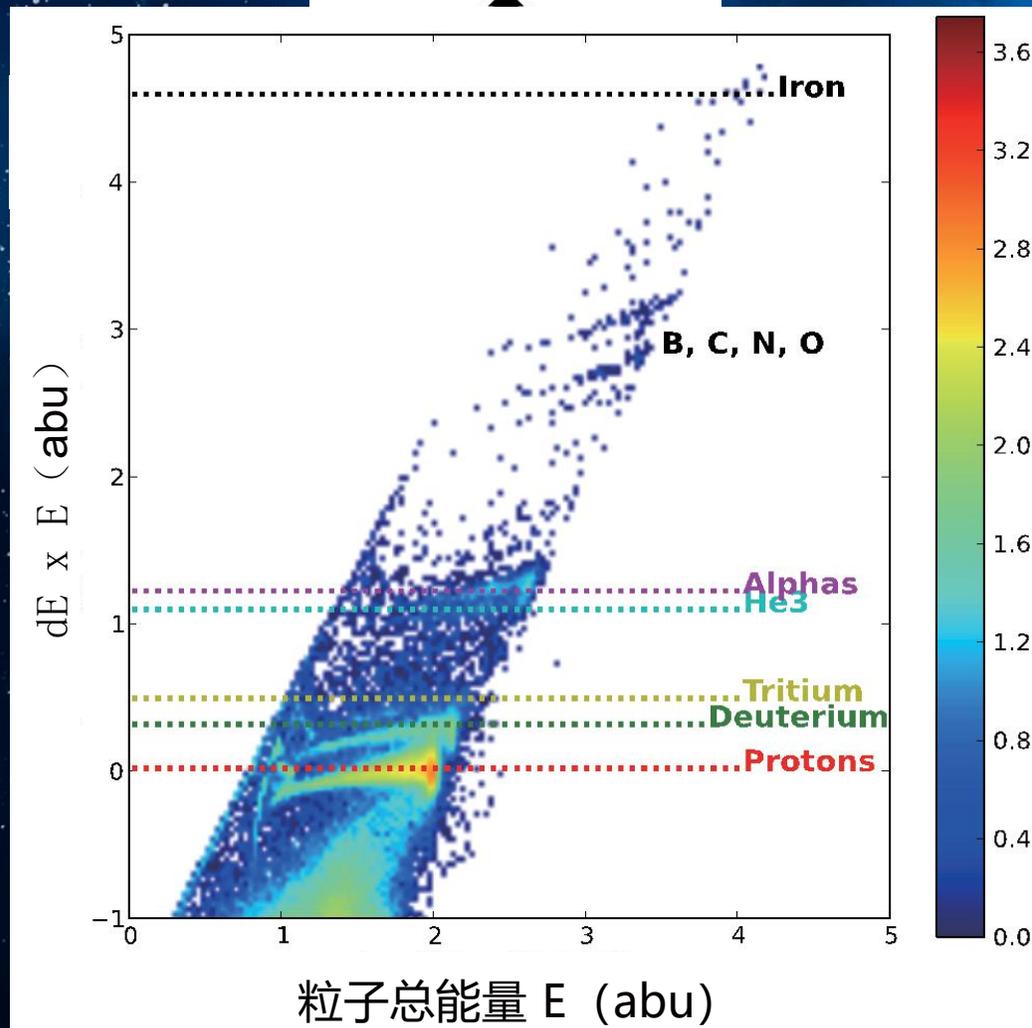
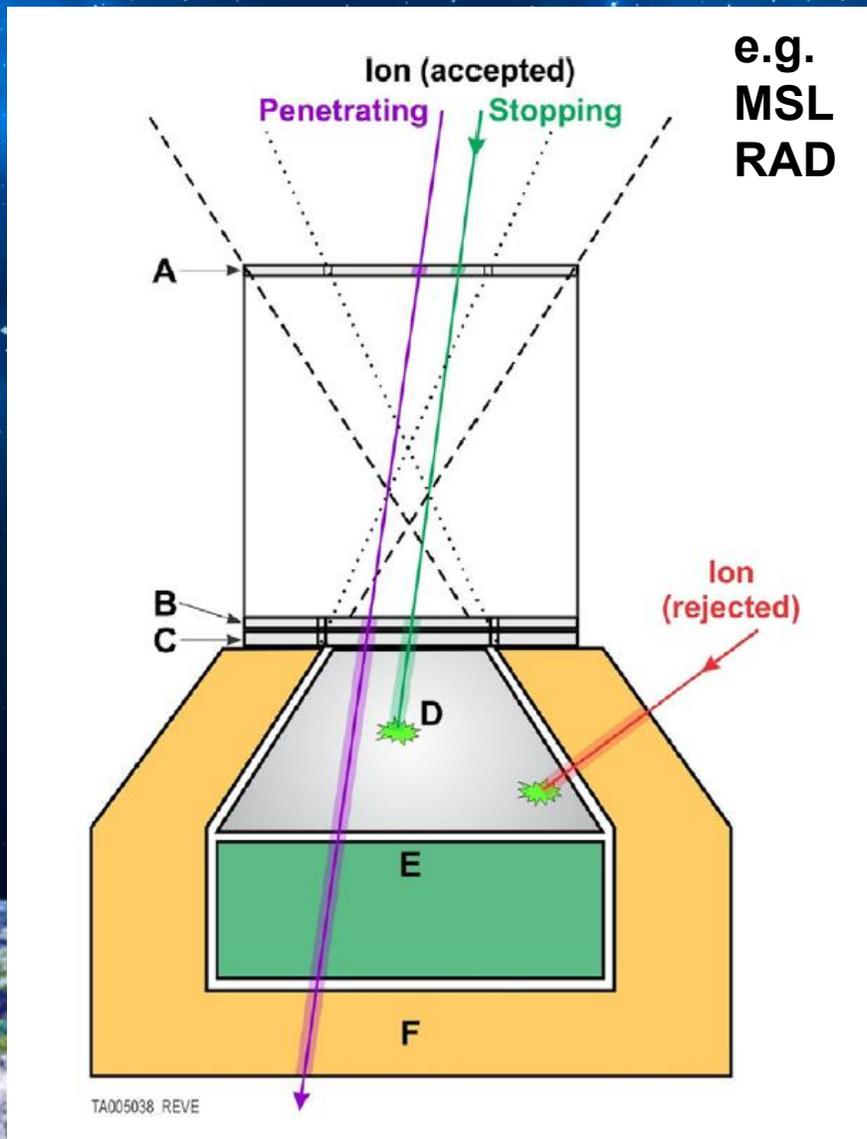
The SEP flux at Mars has been scaled by $1/R^2$



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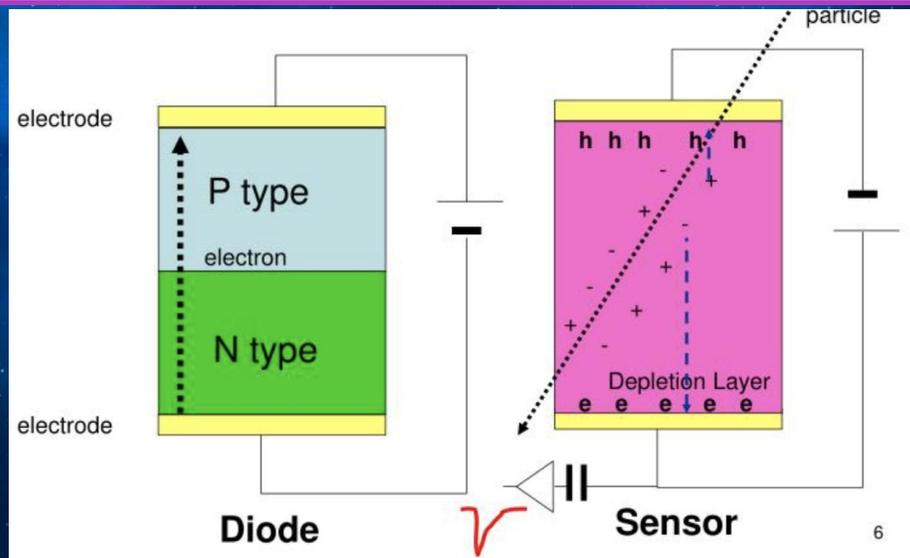
空间辐射的测量：带电粒子

$$\frac{dE}{dx} \cdot E \sim M \cdot Z^2$$



空间辐射的测量：辐射剂量

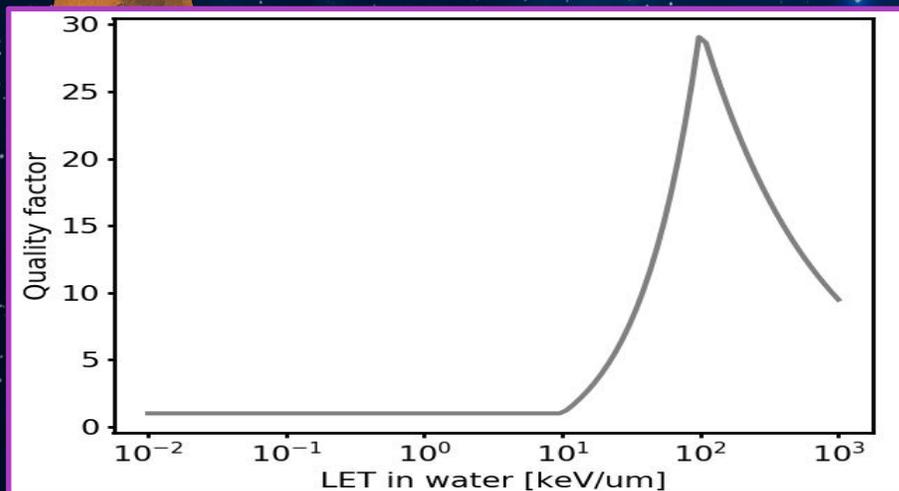
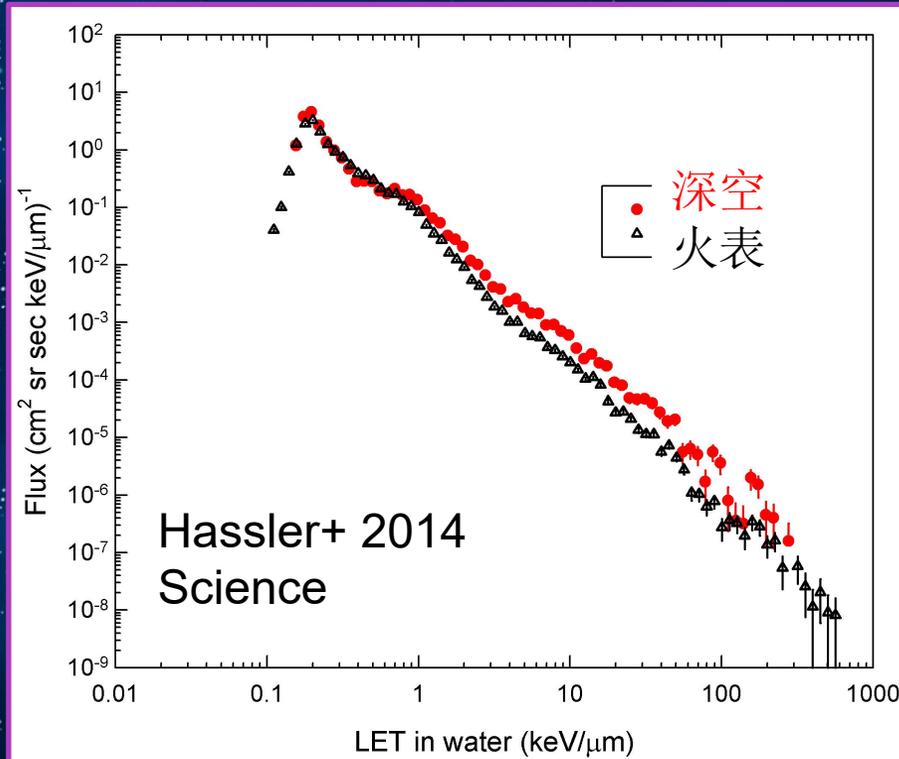
- Absorbed dose [吸收剂量], [1 Gy = 1 J/kg]



- LET (dE/dx) spectrum [LET 谱]

- Dose Equivalent [生物等效计量], Sv [1Sv = 1rem]

$$H = \langle Q \rangle \cdot D_{\text{water}}$$



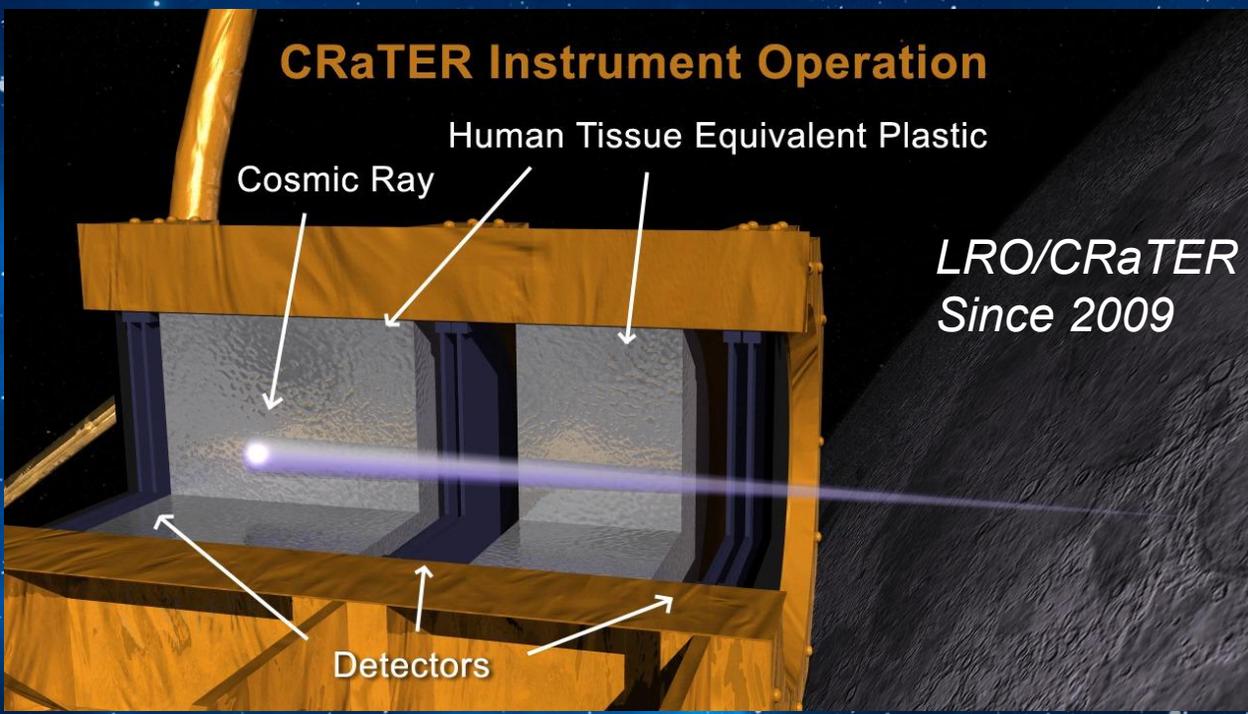
空间辐射的测量：中性粒子

探测对象	仪器名称	技术方案	技术指标	项目背景
中子	LEND	He-3管+闪烁体探测器	能量范围: 0.4eV~15MeV; 质量: 26.3kg 尺寸: 46×46×44cm ³ ; 功耗: 13W	2009年美国月球轨道环绕器LRO
	DAN	He-3管+真空中子管	能量范围: 0.001eV~100keV; 质量: 2.1kg(DE)+2.58kg(PNG) 尺寸: 20.4×6.1×21.2cm ³ (DE) 12.5×4.5×33.8cm ³ (PNG) 功耗: 4.5W(DE)+13W(PNG)	2011年美国火星科学实验室好奇号
	FREND	He-3管+闪烁体探测器	能量范围: 0.4keV~10MeV; 质量: 36kg 尺寸: 46.5×38×37cm ³ ; 功耗: 14W	2016年俄罗斯和欧洲联合任务ExoMars
伽马	MESSENGER GRS	高纯锗+塑料闪烁体	能量范围: 60keV~9MeV; 质量: 9.2kg 尺寸: 10×10×18cm ³ ; 功耗: 16.5W	2004年美国水星环绕器信使号
	SELENE GRS	高纯锗+BGO+塑料闪烁体	能量范围: 200keV~12MeV; 质量: 28.9kg 尺寸: 60×49×41cm ³	2007年日本月球环绕器月亮女神
	Chang'E-1 GRS	CsI闪烁探测器	能量范围: 0.3~10MeV; 质量: 31kg 功耗: 8.7W	2007年中国月球环绕器嫦娥一号
高能带电粒子/中性粒子	RAD	硅PIN+Csl晶体+塑料闪烁体	能量范围: 0.2~10MeV/n (带电粒子); 5~100MeV/n (中子、质子、氦) 质量: 1.56kg; 尺寸: 240cm ³ ; 功耗: 4.2W	2011年美国火星科学实验室好奇号
	LND	多层硅探测器	能量范围: 1~20MeV (中子); ~35MeV/n (质子、氦)	2019年中国月球嫦娥四号着陆器
	MEPA	硅探测器+ Csl晶体	能量范围: 0.1~12MeV (带电粒子); 2~100MeV (质子) 质量: ≤3kg; 尺寸: 27×18×14.8cm ³ ; 功耗: <10W	2020年中国天问一号火星探测器

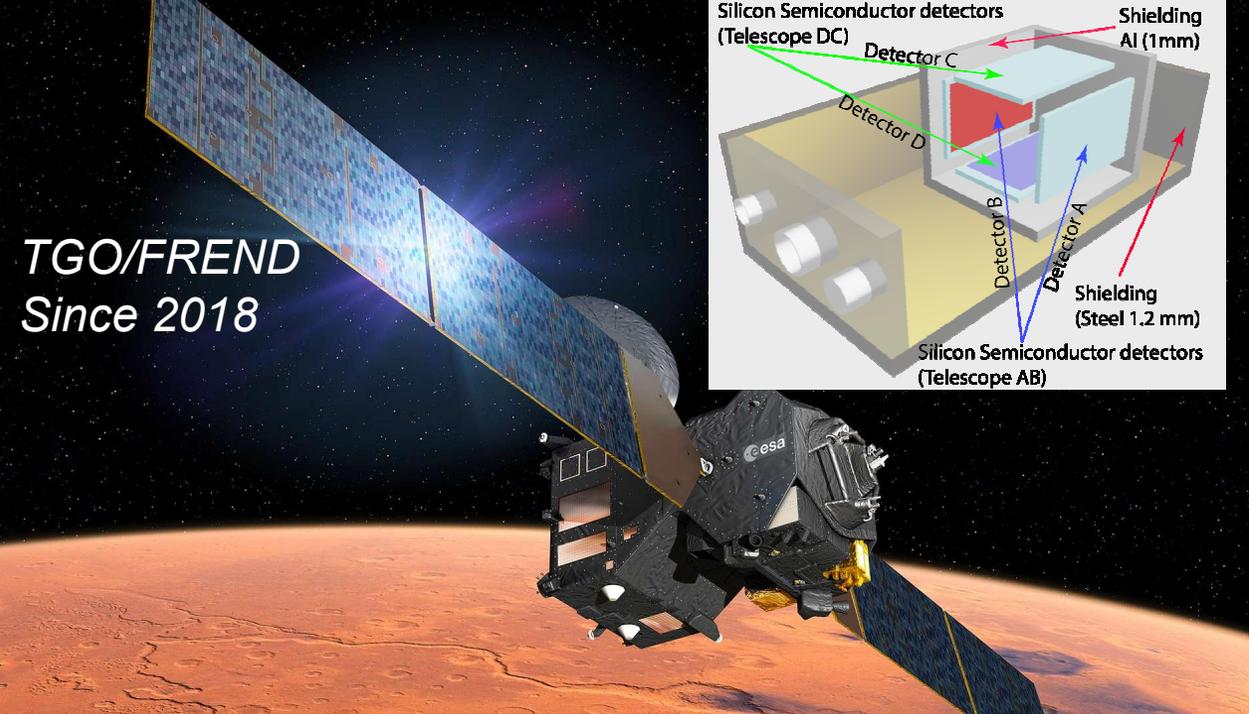
空间辐射的测量：中性粒子

仪器	中子探测方法	位置
LPNS[Feldman et al., 2004]	^3He 探测器	月球轨道
LEND[Mitrofanov et al., 2010]	^3He 探测器+闪烁体探测器	月球轨道
DAN[Litvak et al., 2008]	^3He 探测器	火星表面
RAD[Hassler et al., 2012]	闪烁体探测器	火星表面
FREND[Mitrofanov et al., 2018]	^3He 探测器+闪烁体	火星轨道
LND[Wimmer-Schweingruber et al., 2020]	Si探测器+Gd	月球表面
[Dudkin et al., 1990]	闪烁体+核乳胶探测器	
[Keith et al., 1992]	活化法(Au、Sc、Co ...)	近地轨道
SPECTR-N[Lyagushin et al., 1997]	核裂变法(^{235}U 、 ^{238}U ...)	近地轨道
BBND[Matsumoto et al., 2001]	^3He 探测器	

CRaTER Instrument Operation



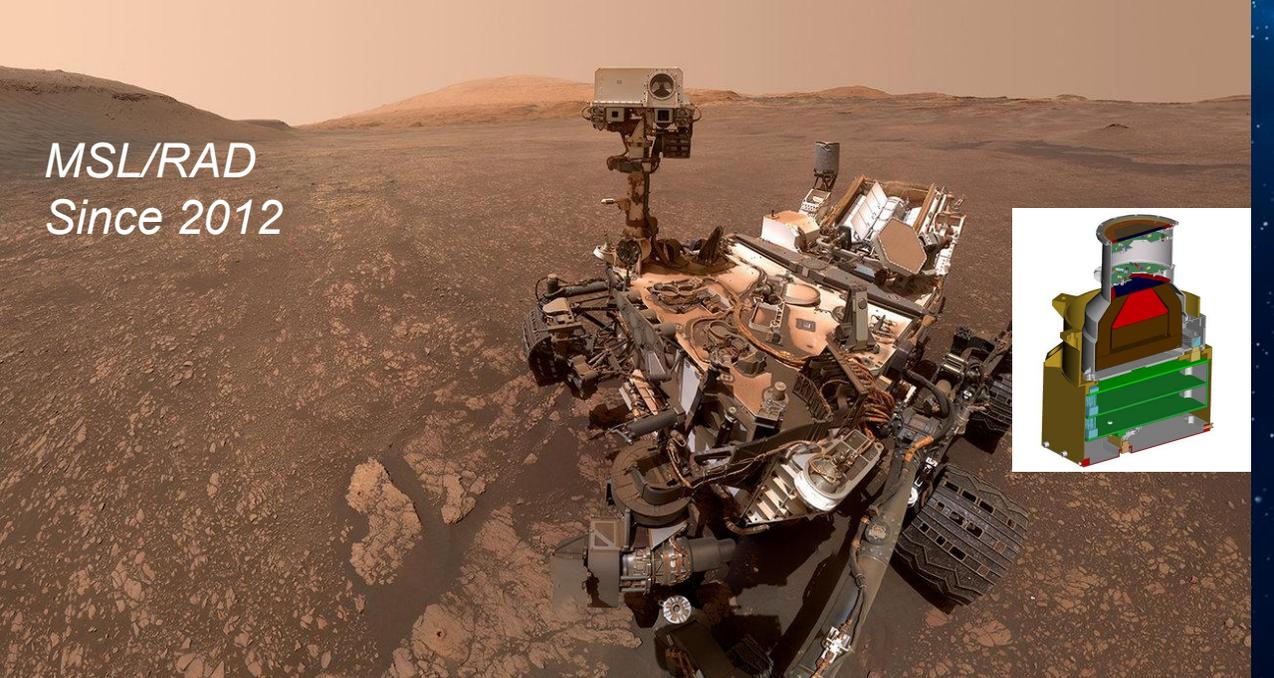
LRO/CRaTER
Since 2009



TGO/FREND
Since 2018

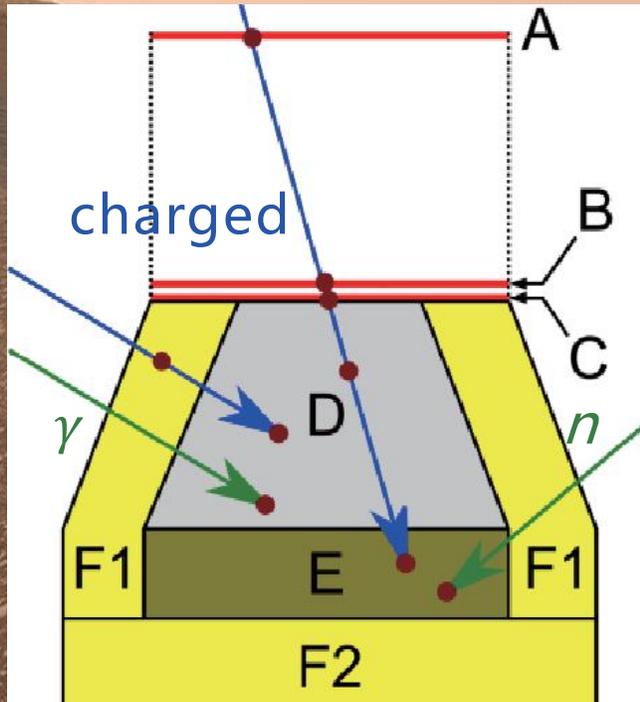


ChangE LND
Since 2019



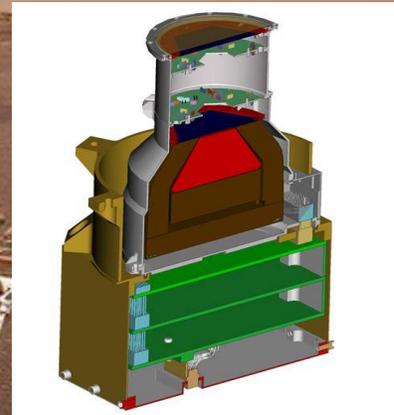
MSL/RAD
Since 2012

火星表面的辐射探测 (自2012年起)



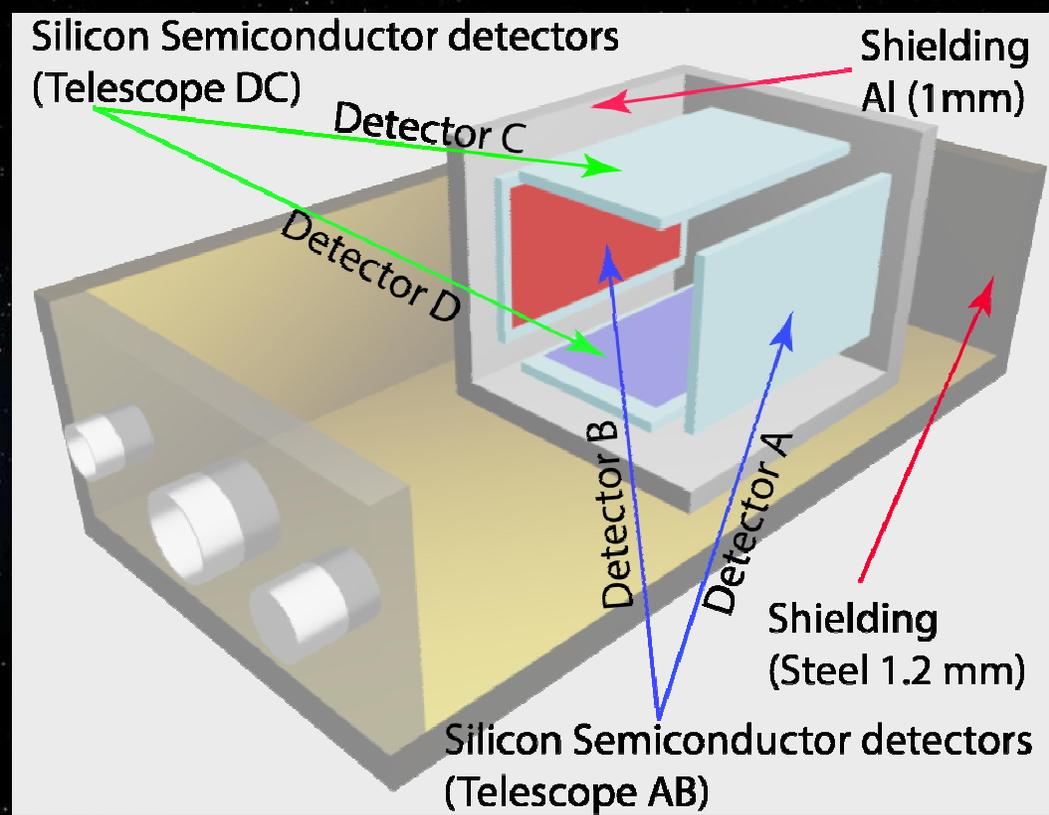
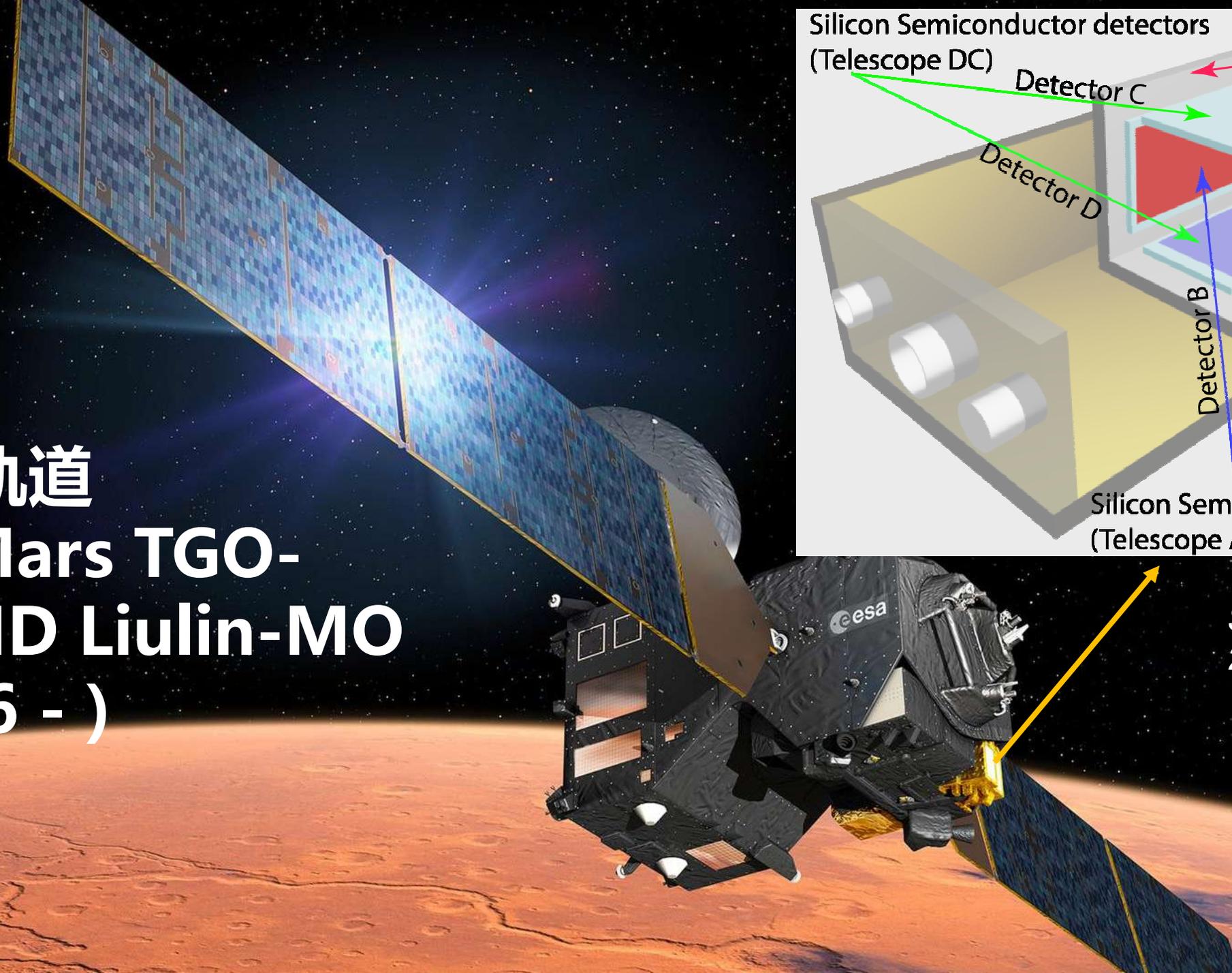
Zeitlin+ 2013 Science
Hassler+ 2014 Science
Guo+2021 A&A Rev (ref.
therein).

Radiation Assessment
Detector RAD



NASA MSL Curiosity Rover

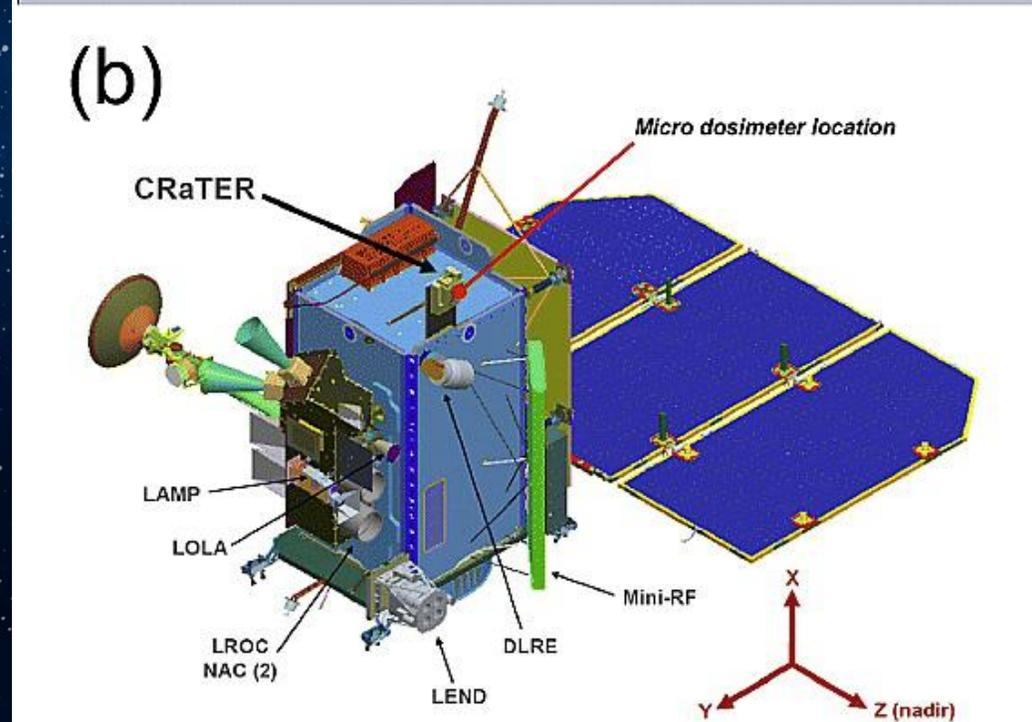
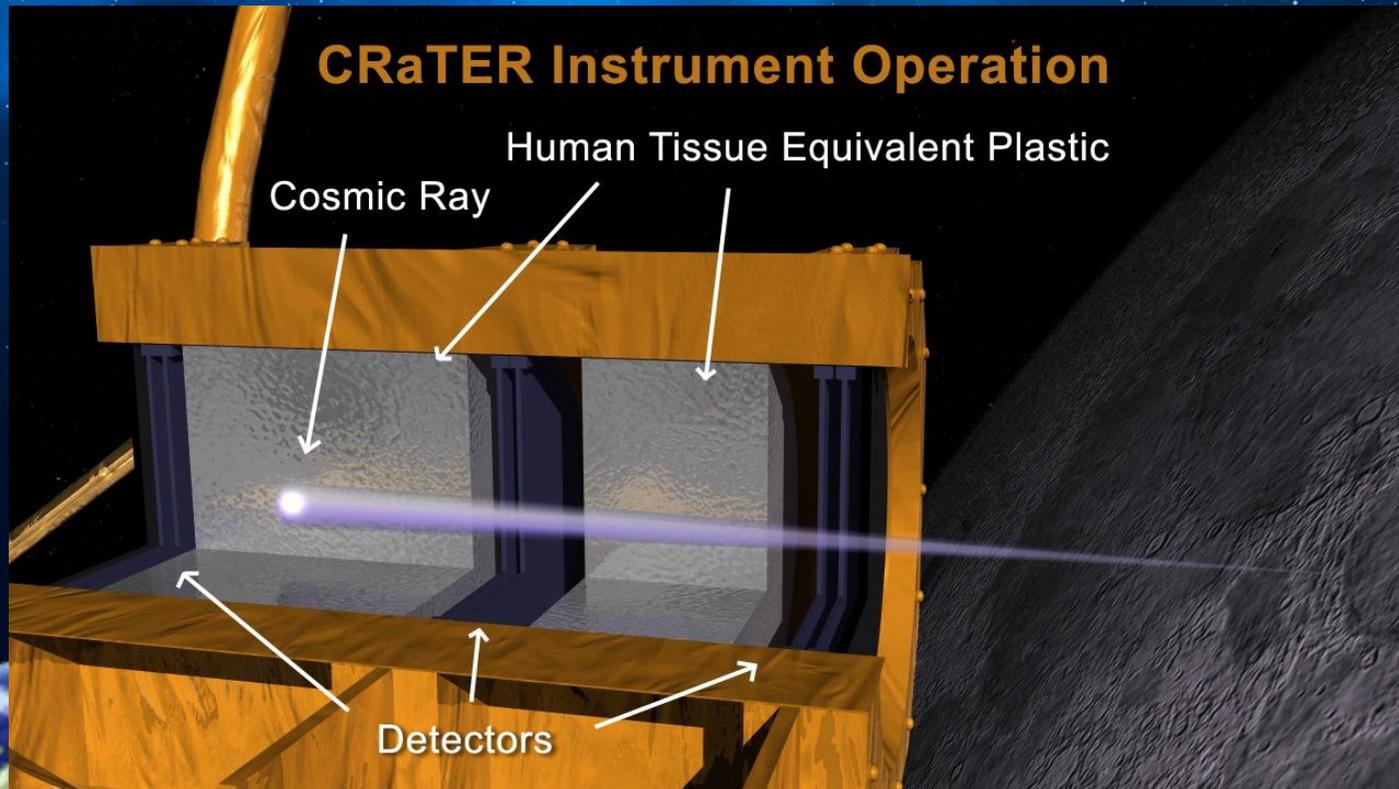
火星轨道 ExoMars TGO- FREND Liulin-MO (2016 -)



*Semkova et al,
2018, 2020, 2021*

月球轨道 LRO/CRaTER (2009-)

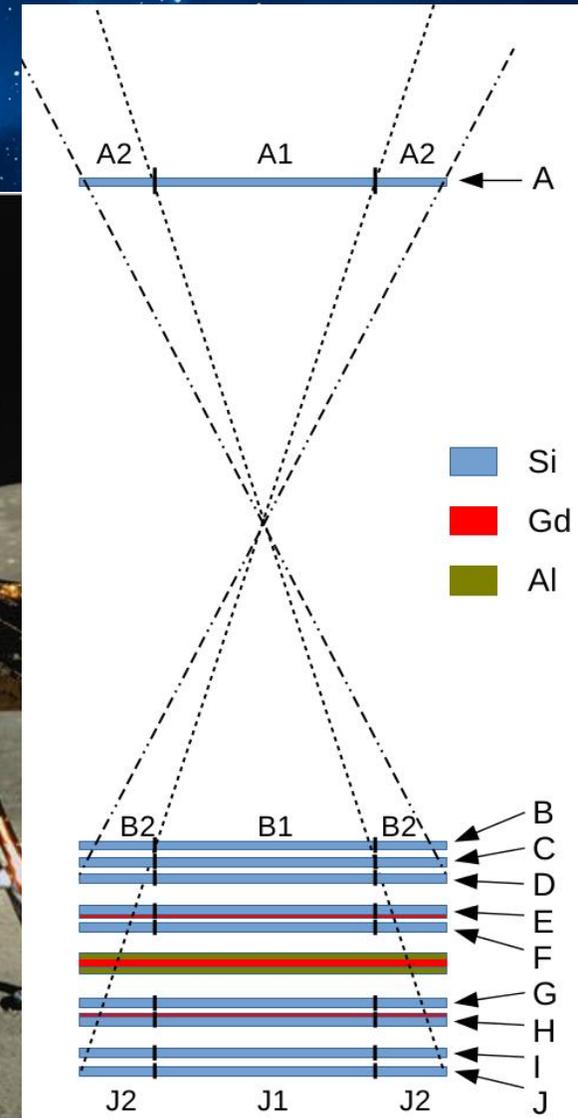
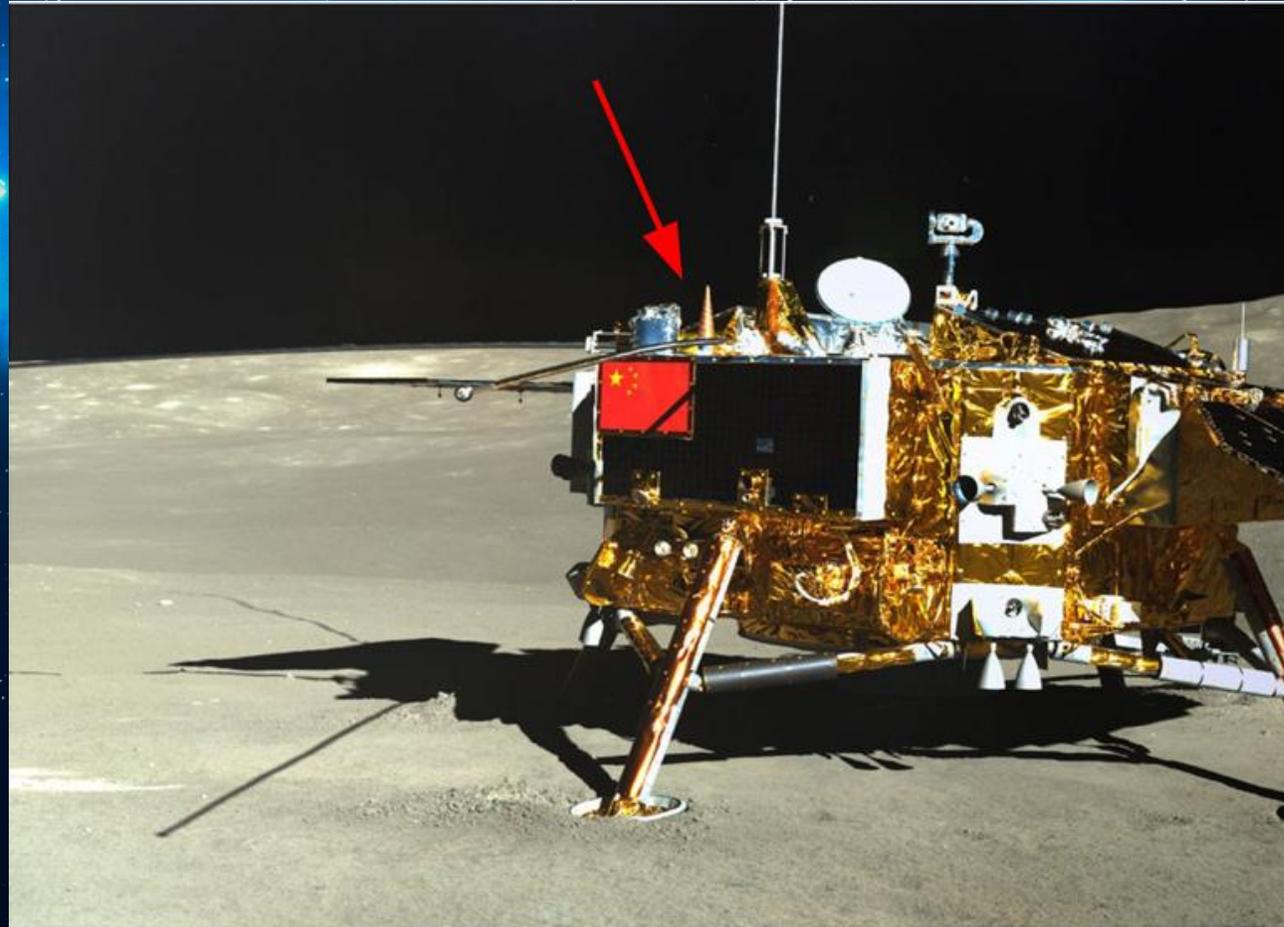
CRaTER (Cosmic Ray Telescope for the Effects of Radiation) characterizes the orbital lunar radiation environment and its biological impacts (Spence+ 2010)



ChangE4/LND (2019-)

LND (Lunar Neutron and Dosimetry Detector)

- Wimmer-Schweingruber+2020 Space Sci. Rev.
- Zhang et al. 2020, Sci. Adv.)
- Xu et al. 2020 ApJL



天问一号环绕器 (Tianwen-1 Orbiter)

Installation locations of instruments

References:

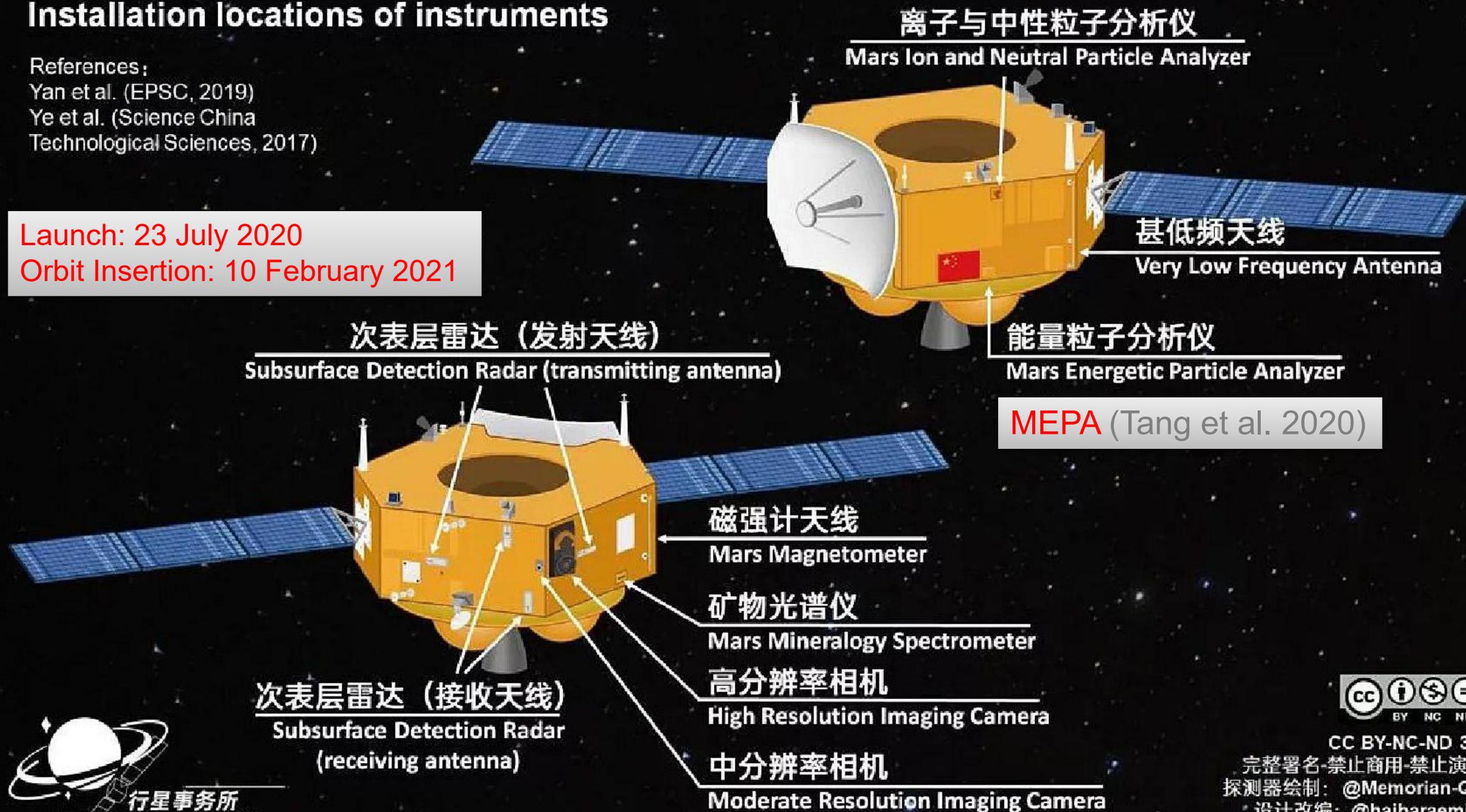
Yan et al. (EPSC, 2019)

Ye et al. (Science China

Technological Sciences, 2017)

Launch: 23 July 2020

Orbit Insertion: 10 February 2021



离子与中性粒子分析仪
Mars Ion and Neutral Particle Analyzer

甚低频天线
Very Low Frequency Antenna

次表层雷达 (发射天线)
Subsurface Detection Radar (transmitting antenna)

能量粒子分析仪
Mars Energetic Particle Analyzer

MEPA (Tang et al. 2020)

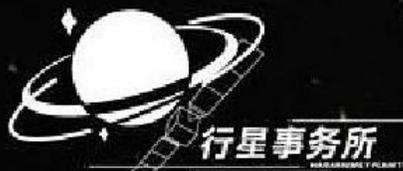
磁强计天线
Mars Magnetometer

矿物光谱仪
Mars Mineralogy Spectrometer

高分辨率相机
High Resolution Imaging Camera

次表层雷达 (接收天线)
Subsurface Detection Radar
(receiving antenna)

中分辨率相机
Moderate Resolution Imaging Camera



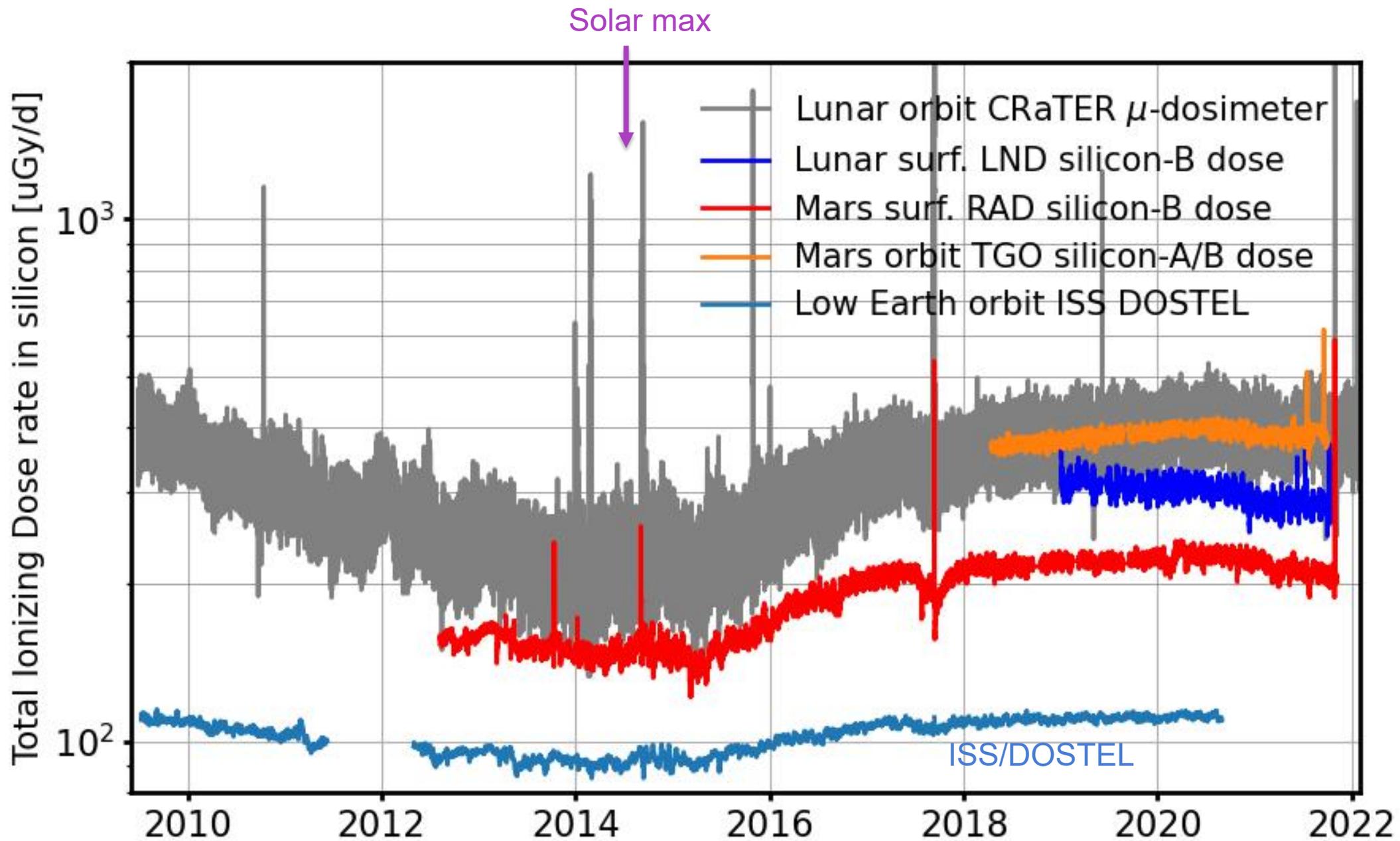
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完整署名-禁止商用-禁止演绎

探测器绘制: @Memorian-QN

设计改编: @haibaraemily

	仪器	辐射剂量	LET 谱 (in Si)	带电粒子	中性粒子
		$D_{Si} = \frac{\sum_j E_j \times n_j}{m}$			
月球轨道	LRO-CRaTER (Spence+ 2010)	Direct measurement at different shielding depths	0.1 - 2200 keV/ μ m	NA	NA
月球表面	Chang'E 4 LND (Wimmer+ 2020)	Direct measurement	40-780 keV/ μ m	Energy spectra (9-35 MeV protons and heavier ions)	fast neutron flux
火星轨道	TGO FREND Liulin-MO (Semkova+ 2020)	Direct measurement with paired detectors	0.1-136 keV/ μ m	Integrated flux	The FREND instrument on TGO measures thermal, epithermal and high energy neutrons
	Tianwen 1 MEPA (Tang+ 2020)	Indirect measurement	0.2-1200 keV/ μ m	Energy spectra (25-1.2 GeV protons)	NA
火星表面	MSL/RAD (Hassler+ 2012, Zeitlin+2016, Guo+ 2021)	Direct measurement at different shielding depths	0.2 - 1000 keV/ μ m	Energy-spectra (10-100 MeV/n for protons and ⁴ He and heavier ions)	Indirect measurement of high-energy neutron and gamma



空间辐射评估的未来需求

- 实现深空初始粒子的种类和能量的精确测量（非常关键的模型输入参数）
- 应用辐射传播模型来评估不同屏蔽下（飞船、空间站、行星环境下）的次级粒子的特征
- 实现对特定环境下不同次级粒子流量及能量的准确测量，尤其是生物辐射效应强的中子；并和模型的预估对比认证
- 对突发的太阳高能粒子事件，需要综合运用太阳和日地空间物理以及粒子物理的模型，并结合实时的观测对其实现准确和及时的预报
- 最终的目标：综合运用一系列物理的型和尽可能多的实测数据建立全空间、的随时间变化的动态的空间辐射数据库