

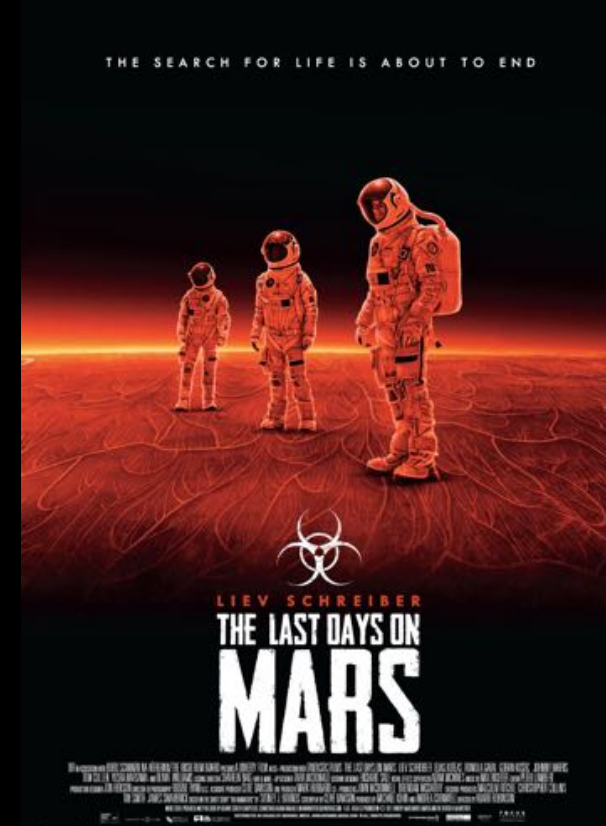
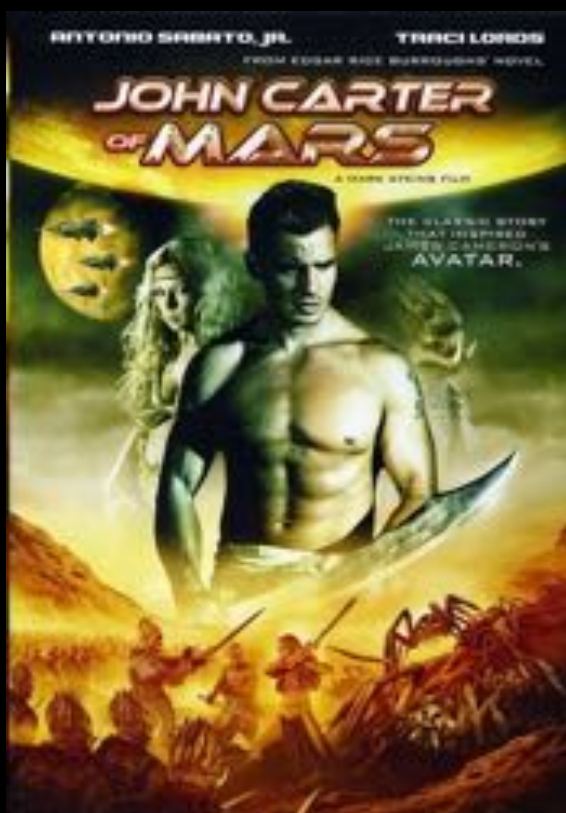
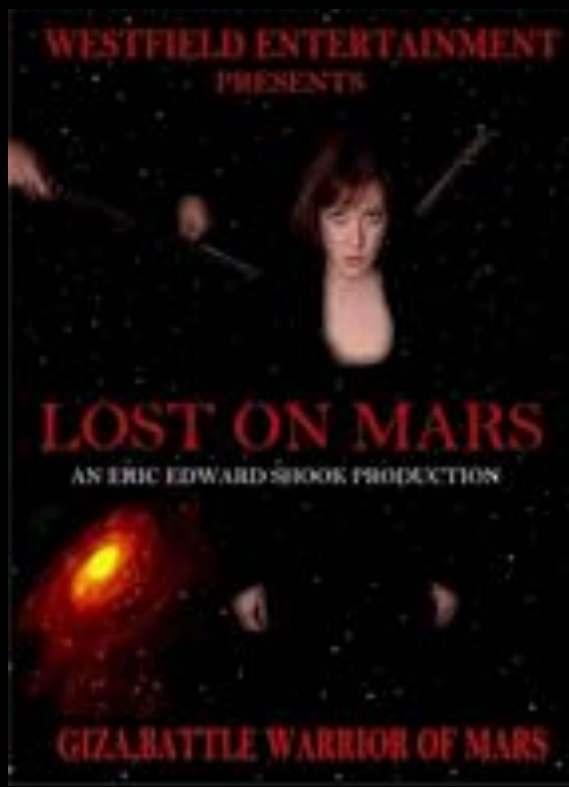
郭静楠 Jingnan Guo

探火任务面临的 空间环境危害 Space Weather Challenges for a Mars Mission



2020年行星科学暑期学校
中科院比较行星学卓越创新中心

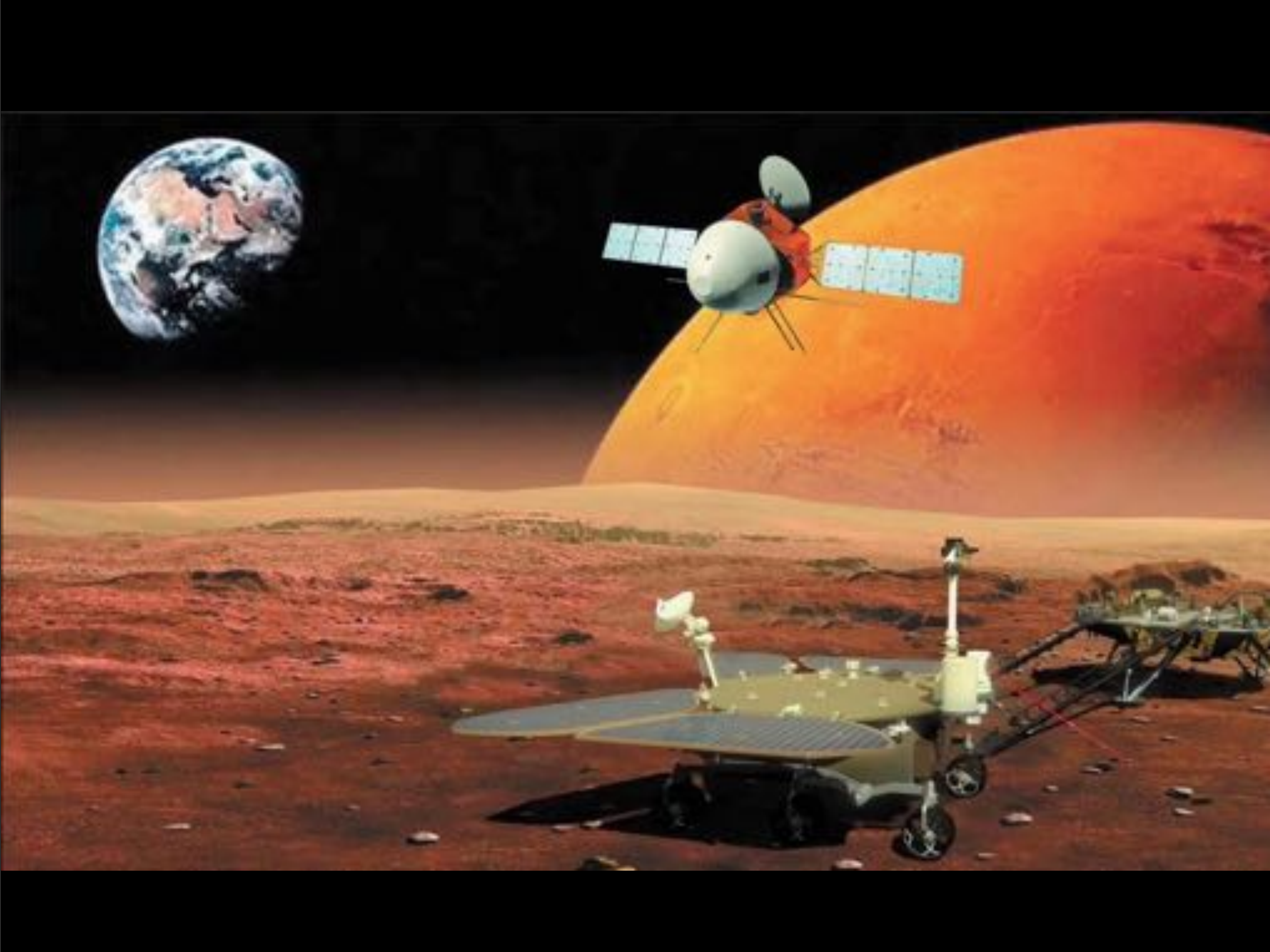
2020年07月25日
中国科学技术大学 地球和空间科学学院
jnguo@ustc.edu.cn



人类深空探索的步伐和目标

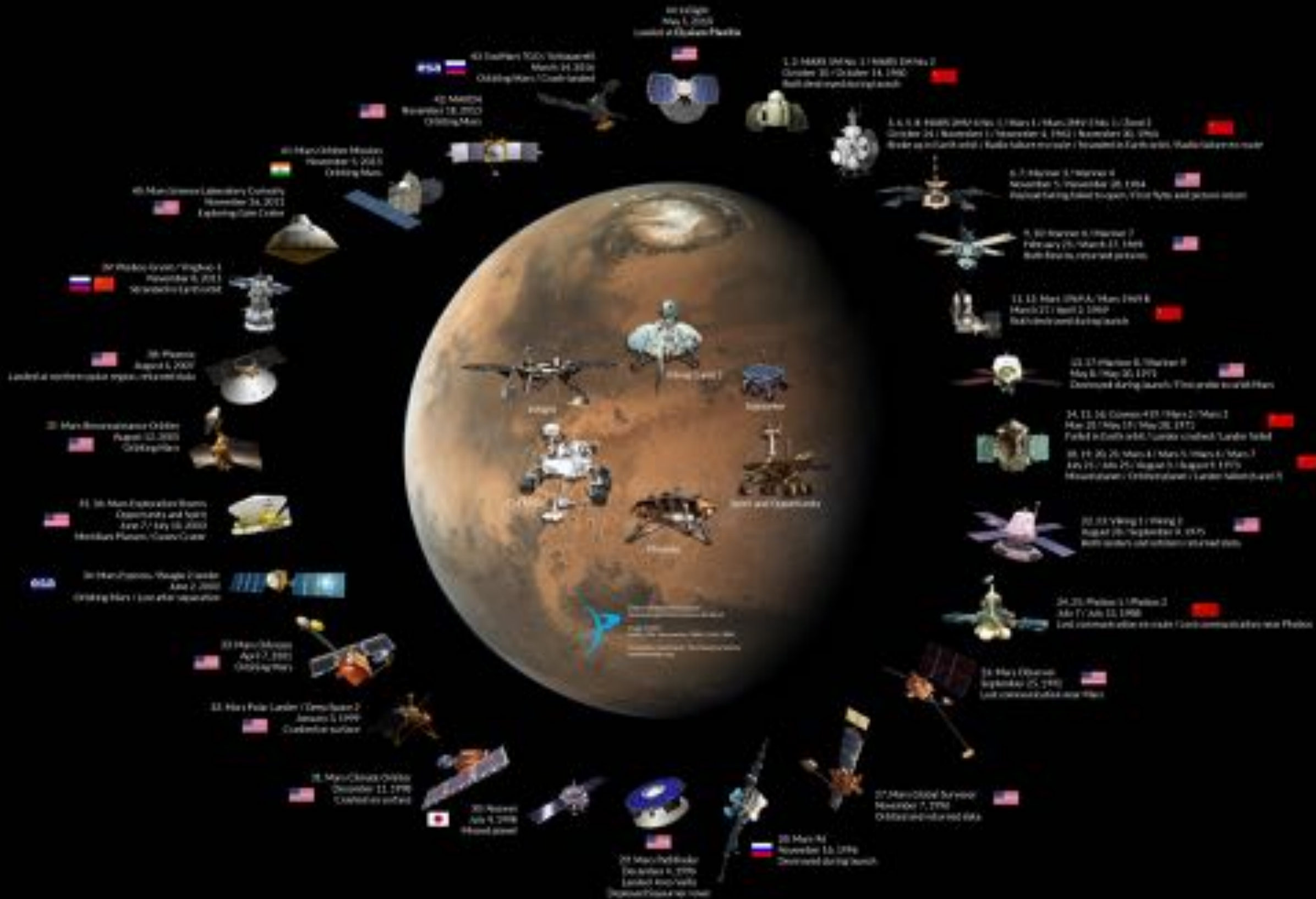
- 目前只有国际空间站（ISS）是外空的人类久居之所
- 一些国际宇航组织在计划人类重返月球的任务 (>2023)
- 火星是这一系列计划的终极目标 (>2030)





Mars Exploration Family Portrait

火星任务一览表



Mars Exploration Family Portrait

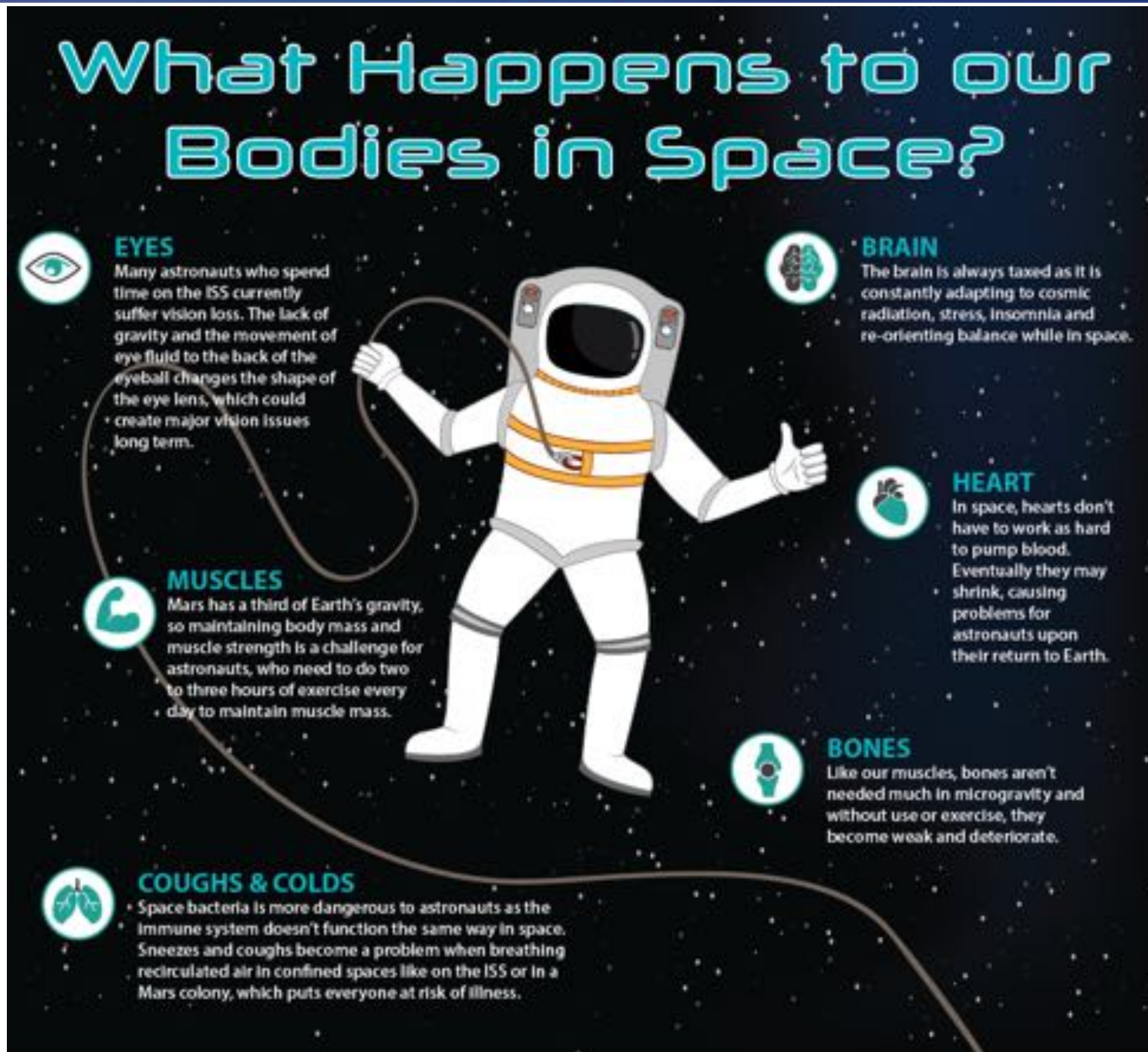
~ 50% chance of Failure Rate



成功的方式只有一种，失败的方式却有无数种

| | | | | | |
|--|------------------|-----------------------|-----------------------|--------------------|---|
| Mars 96 (M1 No.520)(Mars-96) ^[4] | 16 November 1996 | Russia Russia | Crucet Penetrators | Launch failure | Never left LEO |
| Mars Pathfinder | 4 December 1996 | NASA United States | Lander | Successful | Landed at 19.13°N 33.22°W on 4 July 1997 ^[10] |
| Sojourner | 4 December 1996 | NASA United States | Rover | Successful | The first rover on another planet, operated for 84 days ^[11] |
| Nozomi (PLANET-B) | 3 July 1998 | ISAS Japan | Orbiter | Spacecraft failure | Ran out of fuel before reaching Mars |
| Mars Climate Orbiter | 11 December 1998 | NASA United States | Orbiter | Spacecraft failure | Approached Mars too closely during orbit insertion attempt due to unit conversion error and burned up in the atmosphere |
| Mars Polar Lander | 3 January 1999 | NASA United States | Lander | Spacecraft failure | Failed to land |
| Deep Space 2 | 3 January 1999 | NASA United States | Penetrator | Spacecraft failure | Deployed from MPL, no data returned |
| Mars Odyssey | 7 April 2001 | NASA United States | Orbiter | Operational | Expected to remain operational until 2025. |
| Mars Express | 2 June 2003 | ESA Europe | Orbiter | Operational | Enough fuel to remain operational until 2026. |
| Beagle 2 | 2 June 2003 | ESA Europe | Lander | Lander failure | No communications received after release from Mars Express. Orbital images of landing site suggest a successful landing, but two solar panels failed to deploy, obstructing its communications. |
| Spirit (MER-A) | 10 June 2003 | NASA United States | Rover | Successful | Landed on January 4, 2004. Operated for 2208 sols |
| Opportunity (MER-B) | 8 July 2003 | NASA United States | Rover | Successful | Landed on January 25, 2004. Operated for 5351 sols |
| Rosetta | 2 March 2004 | ESA Europe | Gravity assist | Successful | Flyby in February 2007 en route to 67P/Churyumov–Gerasimenko ^[12] |

载人航天任务对宇航员身体健康的影响

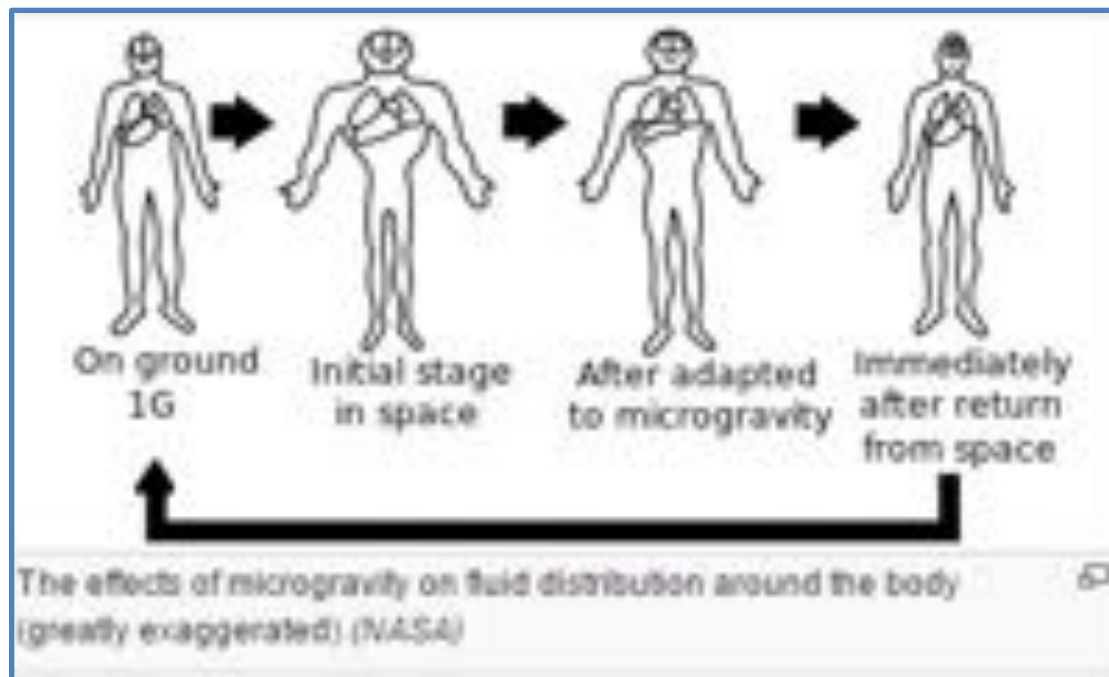


各种问题基本源于两种原因（及其叠加效应）

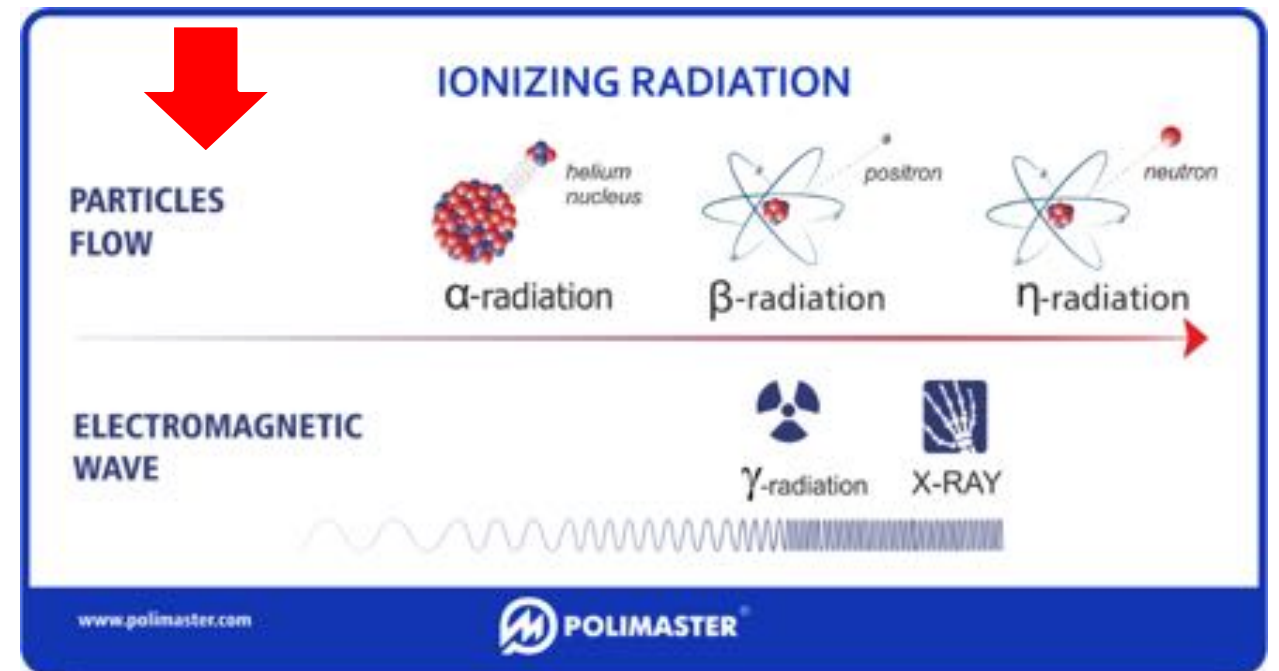
Microgravity
微重力

Space Radiation
高能粒子辐射

微重力影响血液和流体在人体中的循环和分布



空间高能粒子辐射



空间任务的各种风险评估（执行中/执行后）

Risks Assessments for all DRM*s (Jan 2015)

| Human Spaceflight Risks | In Mission Risk - Operatbns | | | | | | Post Mission Risk - Long Term Health | | | | | |
|---|-----------------------------|-----------------|--------------------|-------------------------|-------------------------------|-----------|--------------------------------------|-----------------|--------------------|-------------------------|-------------------------------|-----------|
| | Low Earth Orbit | Low Earth Orbit | Deep Space Surface | Lunar Flight/Habitation | Deep Space Journey/Habitation | Planetary | Low Earth Orbit | Low Earth Orbit | Deep Space Surface | Lunar Flight/Habitation | Deep Space Journey/Habitation | Planetary |
| | 6 Months | 12 Months | 30 Days | 1 year | 1 Year | 1 year | 6 Months | 12 Months | 30 Days | 1 year | 1 Year | 1 year |
| VMF | A | A | A | A | RM | RM | A | A | A | A | RM | RM |
| Renal Stone Formation | A | A | A | A | RM | RM | RM | RM | RM | RM | RM | RM |
| Inadequate food and nutrition | A | A | A | A | RM | RM | A | A | A | A | A | RM |
| Risk of Space Radiation Exposure | A | A | A | A | A | A | A | A | A | RM | RM | RM |
| Medications Long Term Storage | A | A | A | A | A | RM | A | A | A | A | A | RM |
| Acute and Chronic Carbon Dioxide | A | A | A | A | RM | RM | A | A | A | A | A | A |
| Inflight Medical Conditions | A | A | A | RM | RM | RM | A | A | A | A | RM | RM |
| Cognitive or Behavioral Conditions | A | A | A | A | RM | RM | A | A | A | RM | RM | RM |
| Risk of Bone Fracture | A | A | A | A | A | A | A | A | A | A | A | RM |
| Team Performance Degradation | A | A | A | A | RM | RM | A | A | A | A | A | A |
| Reduced Muscle Mass, Strength | A | A | A | A | A | RM | A | A | A | A | A | A |
| Reduced Aerobic Capacity | A | A | A | A | A | RM | A | A | A | A | A | A |
| Sensorimotor Alterations | A | A | A | A | A | RM | A | A | A | A | A | RM |
| Human-System Interaction Design | A | A | A | RM | RM | RM | A | A | A | A | A | A |
| Injury from Dynamic Loads | A | A | RM | RM | RM | RM | A | A | RM | RM | RM | RM |
| Sleep Loss | A | A | A | A | RM | RM | A | A | A | A | RM | RM |
| Altered Immune Response | A | A | A | A | RM | RM | A | A | A | A | A | RM |
| Celestial Dust Exposure | N/A | N/A | A | TBD | TBD | TBD | N/A | N/A | A | TBD | TBD | TBD |
| Host-Microorganism Interactions | A | A | A | A | RM | RM | A | A | A | A | A | RM |
| Injury due to EVA Operations | A | A | A | RM | A | RM | A | A | A | RM | RM | RM |
| Decompression Sickness | A | A | A | A | RM | A | A | A | A | RM | A | RM |
| Toxic Exposure | A | A | A | A | A | A | A | A | A | A | A | A |
| Hypobaric Hypoxia | A | A | A | A | A | A | A | A | A | A | A | A |
| Space Adaptation Back Pain | A | A | A | A | A | A | N/A | N/A | N/A | N/A | N/A | N/A |
| Urinary Retention | A | A | A | A | A | A | A | A | A | A | A | A |
| Hearing Loss Related to Spaceflight | A | A | A | A | A | A | A | A | A | A | A | A |
| Orthostatic Intolerance | A | A | A | A | A | A | A | A | A | A | A | A |
| Injury from Sunlight Exposure - retired | A | A | A | A | A | A | A | A | A | A | A | A |
| Risk of electrical shock - Retired | A | A | A | A | A | A | A | A | A | A | A | A |

A - Accepted

RM- Requires Mitigation

Green - controlled

Yellow - partially controlled

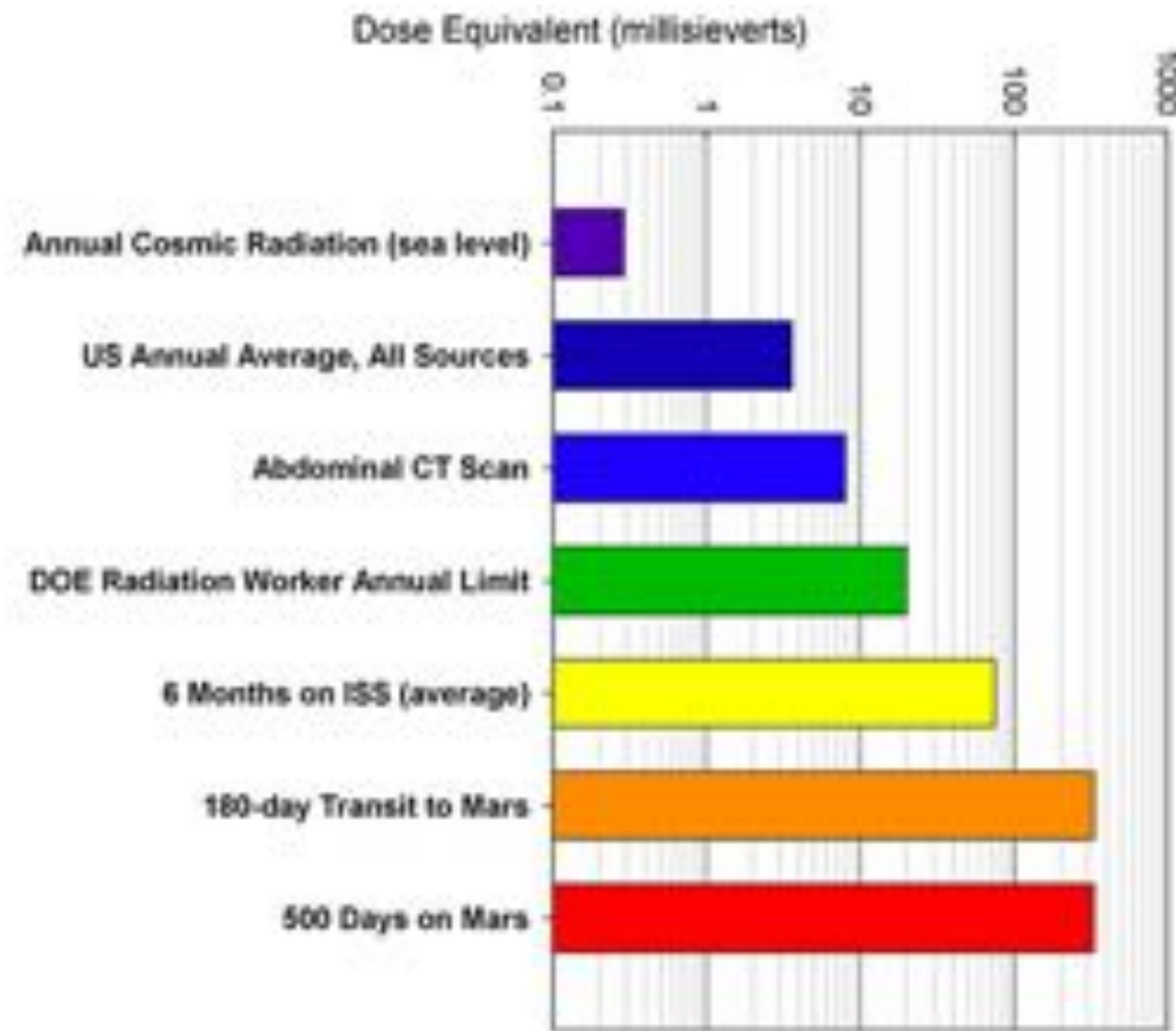
Red - uncontrolled

* Design Reference Mission

这里我们讨论空间辐射对火星探索任务的挑战

各种辐射剂 量比较

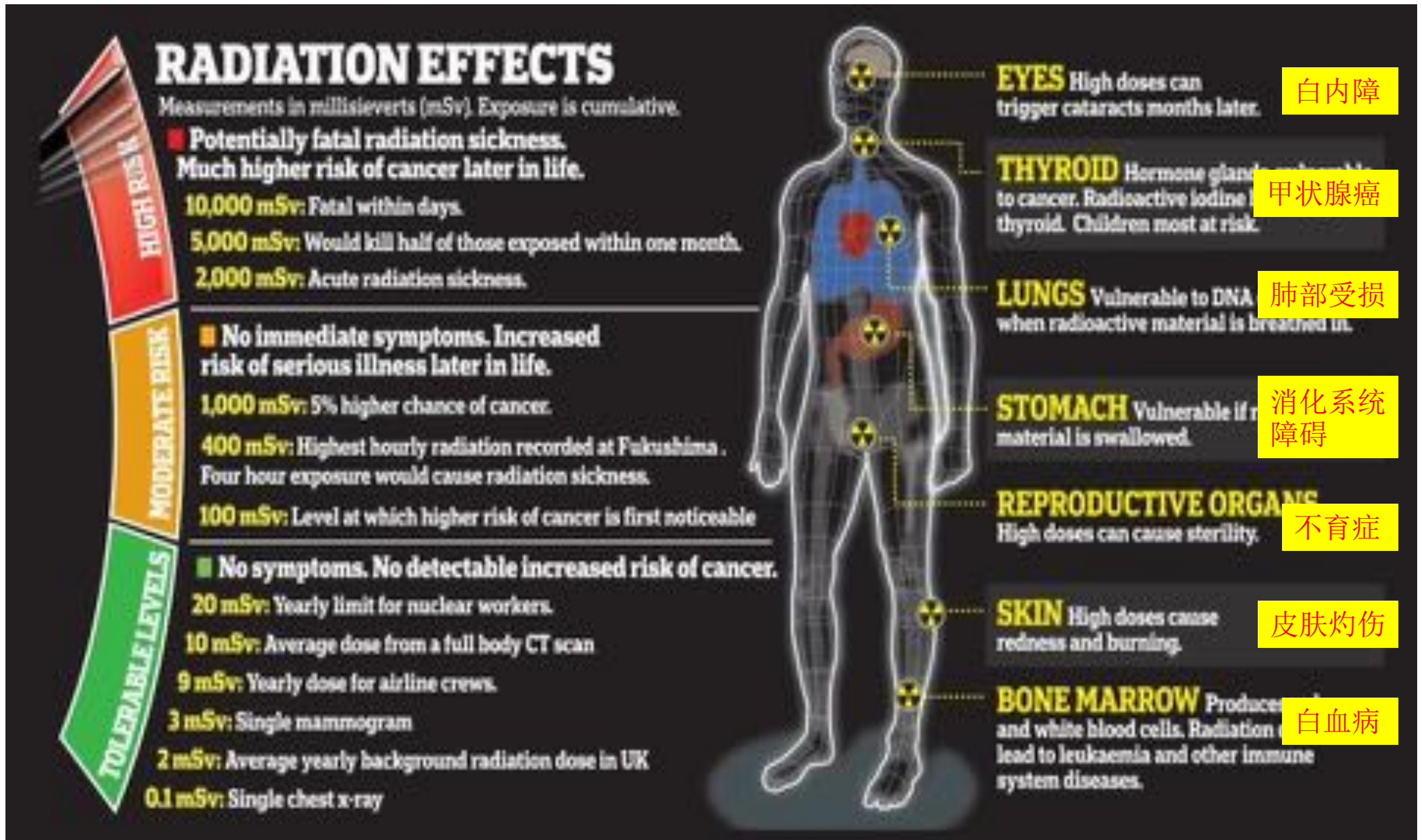
Hassler et al. 2014 Science



报告提纲

- 空间辐射的危害
- 空间辐射的种类
- 火星空间环境和辐射的测量
- 火星辐射的时空变化
- 太阳爆发和高能粒子事件
- 火星辐射仿真和防护方案

空间辐射的危害

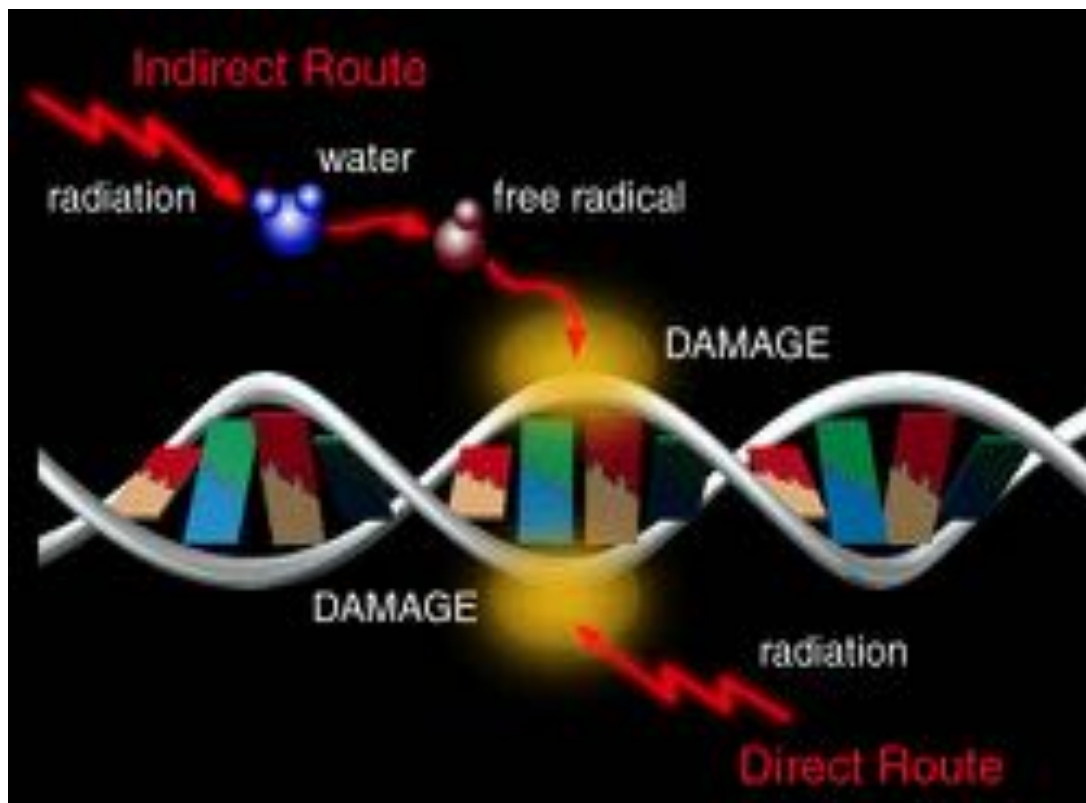


空间辐射长期致癌

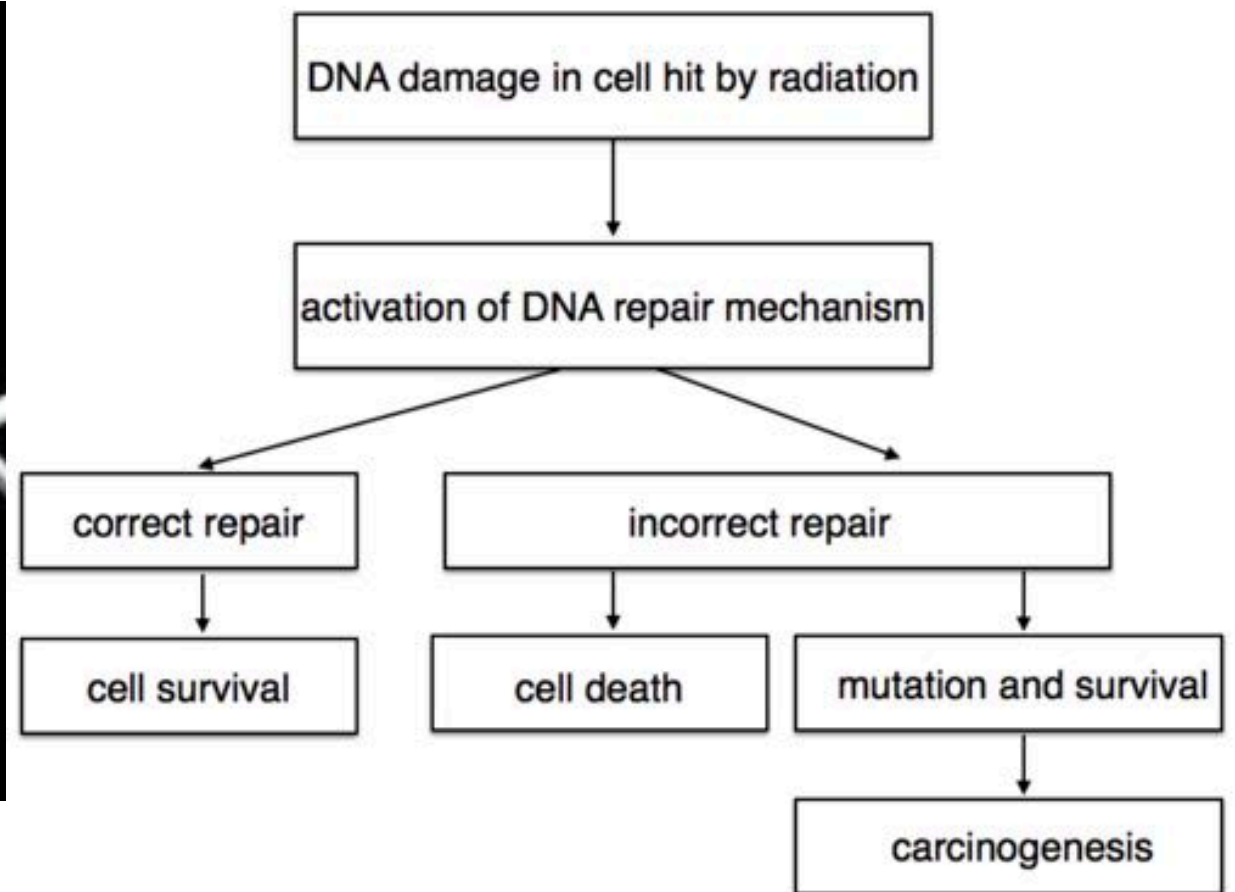
辐射和DNA作用（直接作用+间接作用）致其受损

辐射损害DNA

长期的DNA受损 导致癌症



SIMPLIFIED SCHEME



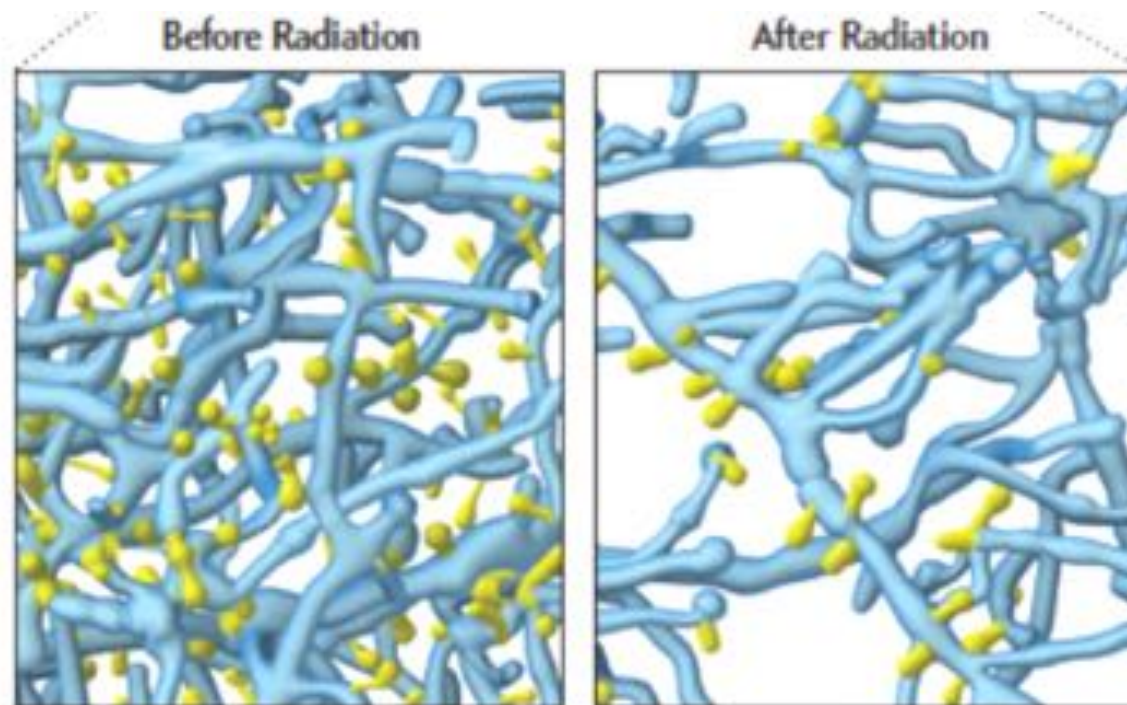
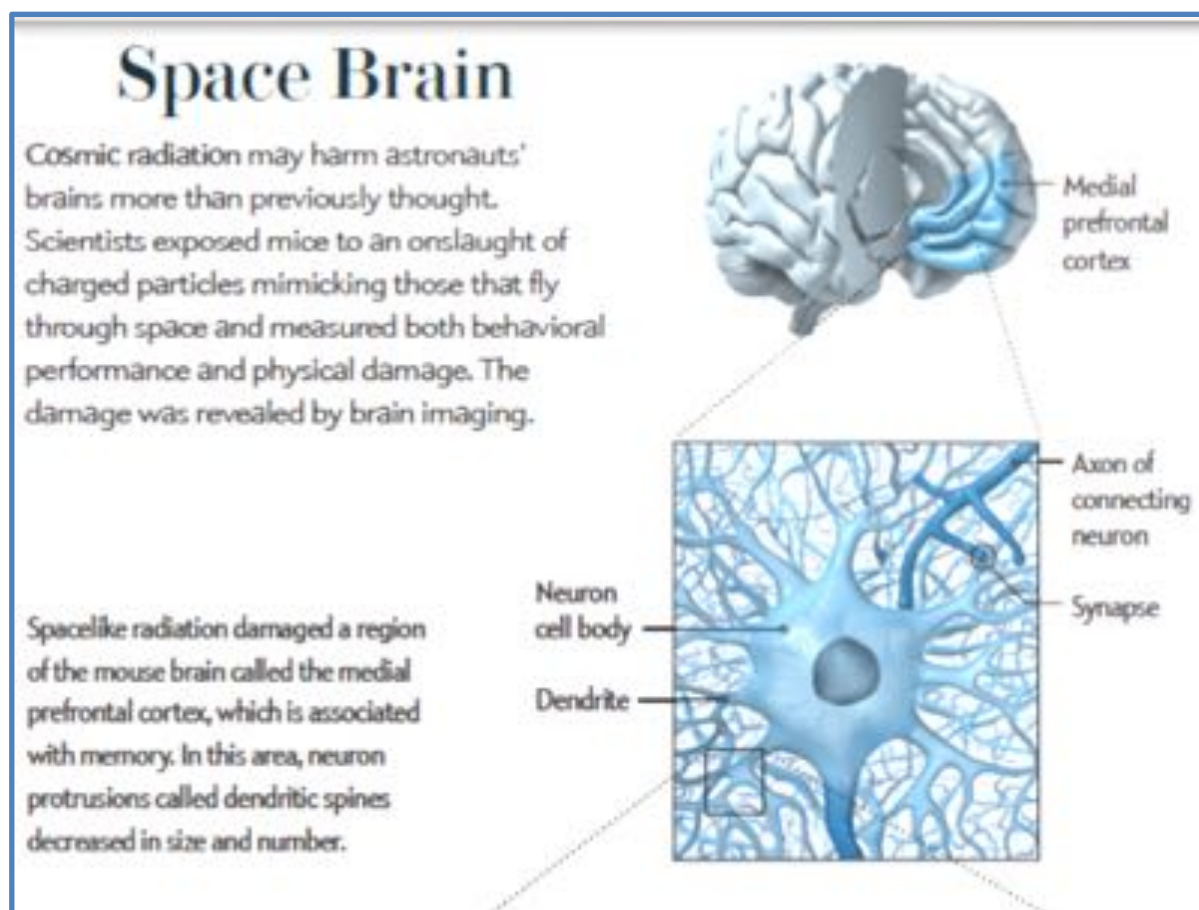
空间辐射损伤大脑

Limoli, Sci Amer 2017

Jandial et al., Surg Neurol Int, 2018

辐射损害神经中枢

辐射导致神经中枢的树突结构稀疏



神经中枢的树突接收其他神经元的化学信号，帮助我们学习和记忆。

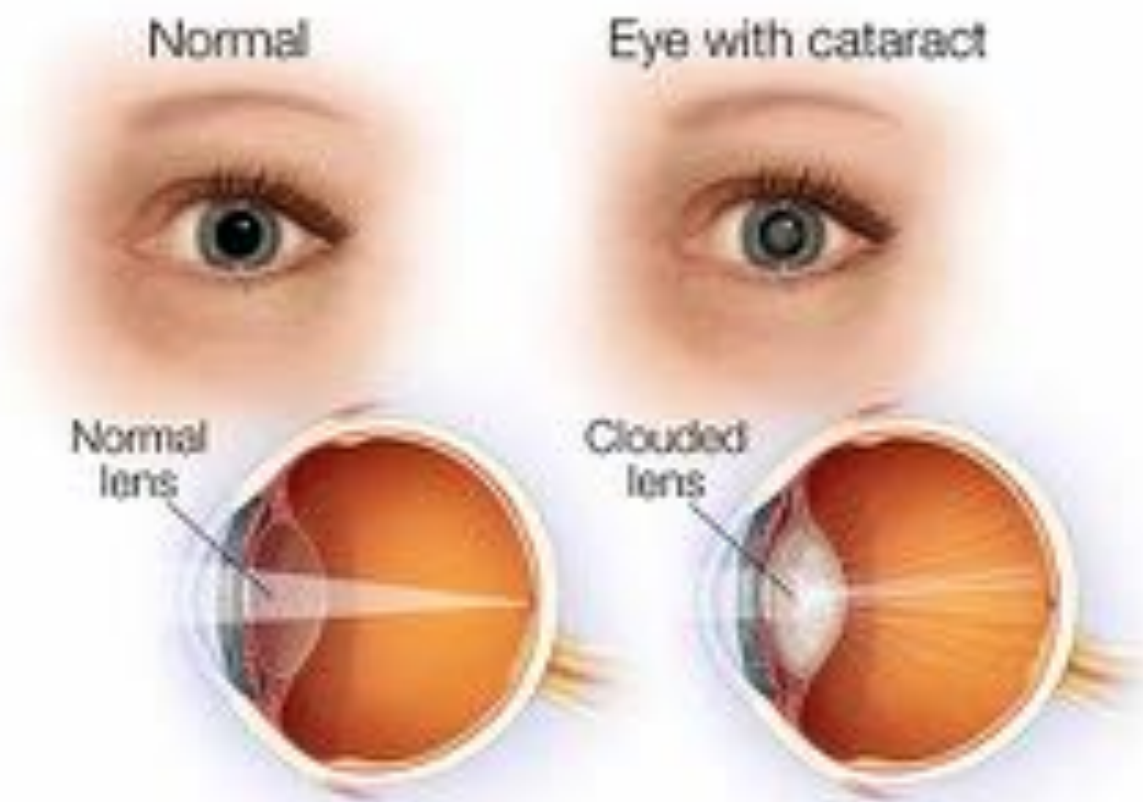
小白鼠在8个星期里暴露于30 cGray的辐射后，其树突减少了40%

空间辐射的其他危害

白内障（约40个宇航员在退役后的4-10年期间出现了此病症）

辐射危害

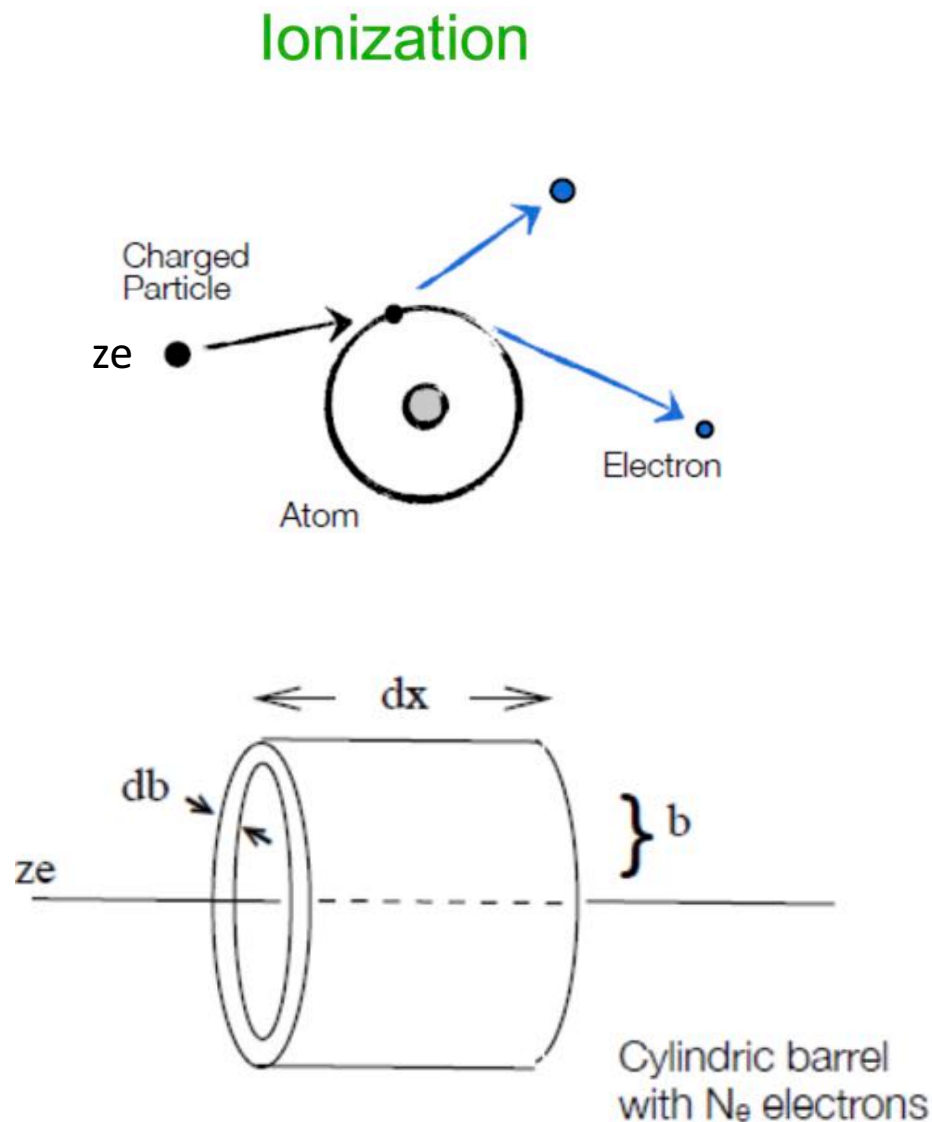
短时间，高剂量，也可直接导致辐射中毒



辐射如何和物质作用：带电粒子的激发电离过程

带电粒子和物质的相互作用：电离能损

H. Bethe (1930) and F. Bloch (1933)



带电粒子 ($ze, v=\beta c$) 和物质中的原子产生非弹性碰撞，损失能量，激发电子，改变自身方向。考虑到物质的密度和非弹性碰撞的概率，可以积分得到粒子穿过物质单位长度内的电离能损，考虑一些量子力学效应，可以推出Beche-Bloch 公式如下：

$$-\frac{dE}{dx} = \frac{4\pi e^4 N_A z^2 Z}{m c^2 \beta^2 A} \rho \ln \frac{2 m c^2 \beta^2 \gamma^2}{I} -$$

- relativistic terms

where

$\beta = v/c$ $N_A =$ Avogadro number
 $z =$ particle charge
 $m =$ particle rest mass
 $Z, A, \rho, I =$ atomic number, mass number, density and mean excitation energy of the medium

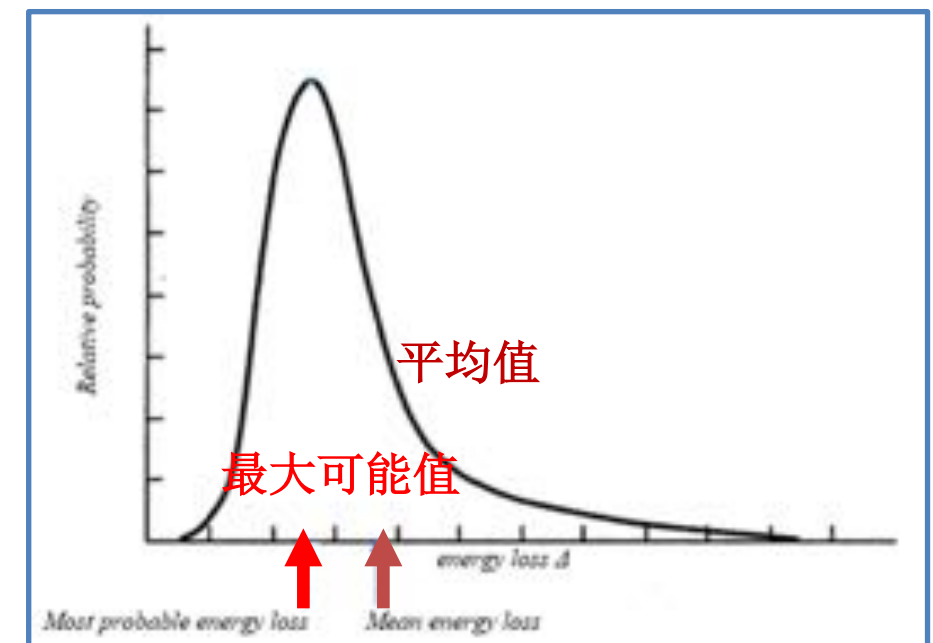
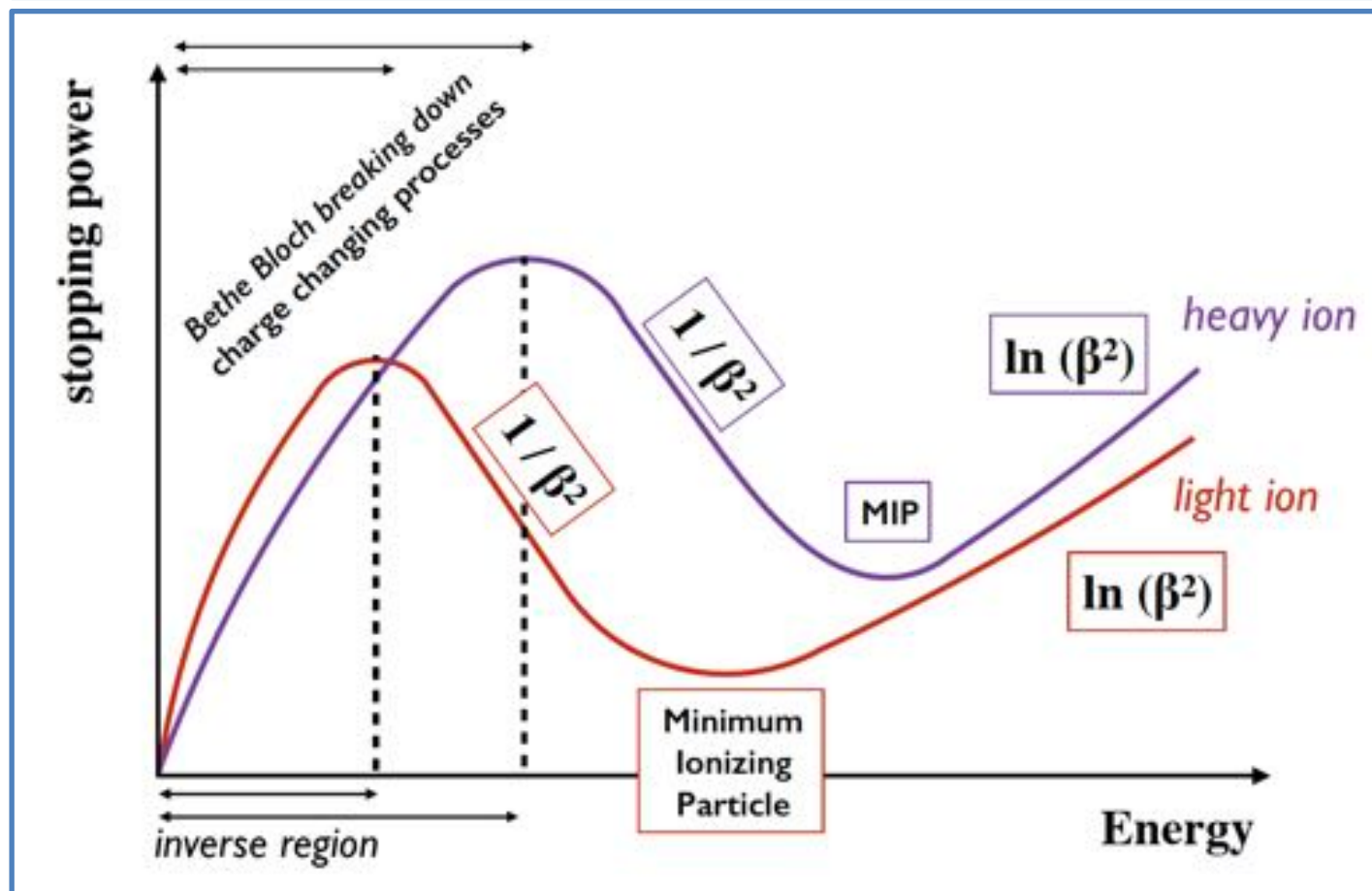
带电粒子的LET随能量变化

电离作用的Bethe-Bloch公式以及LET

能损的不确定性：Landau分布

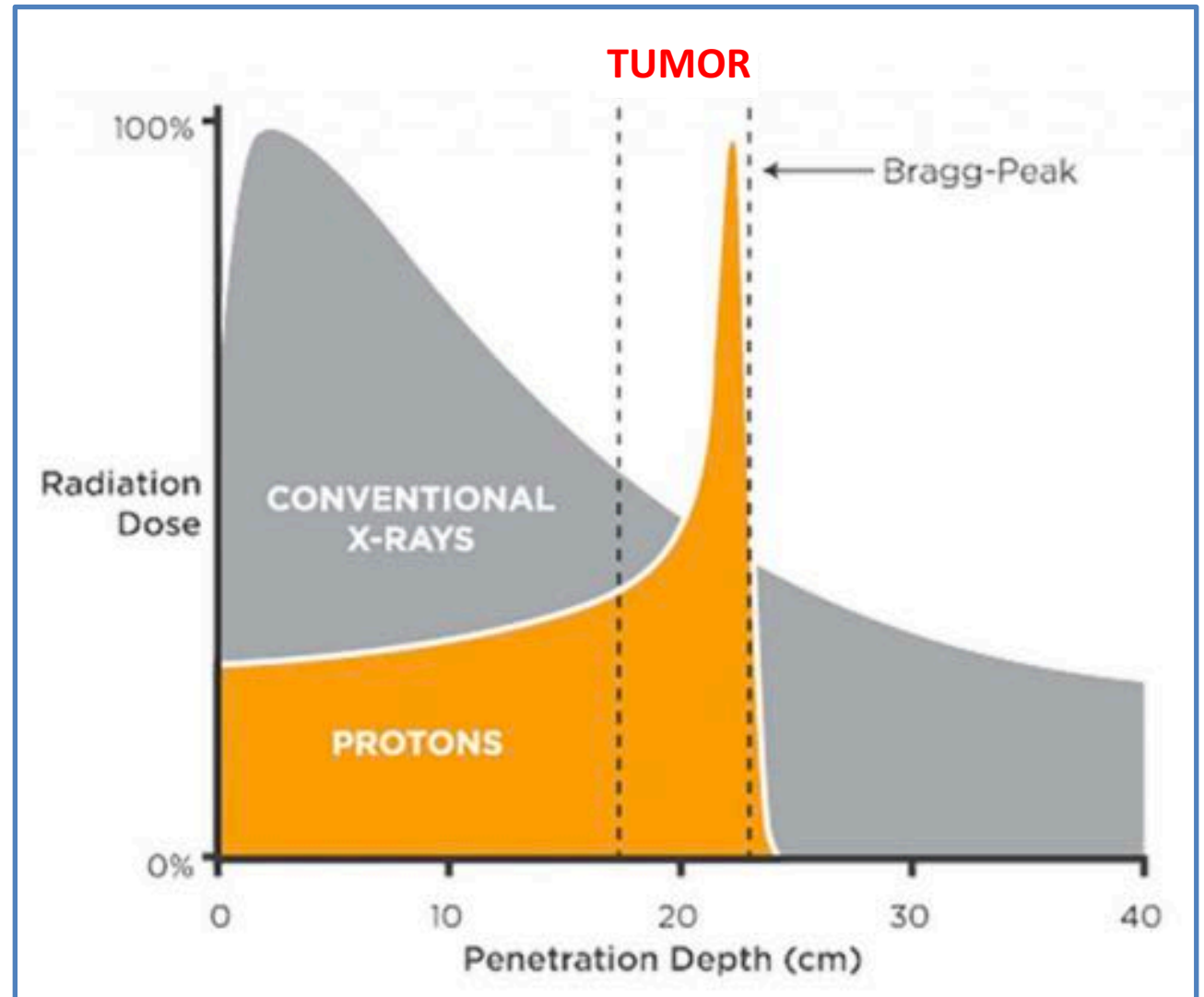
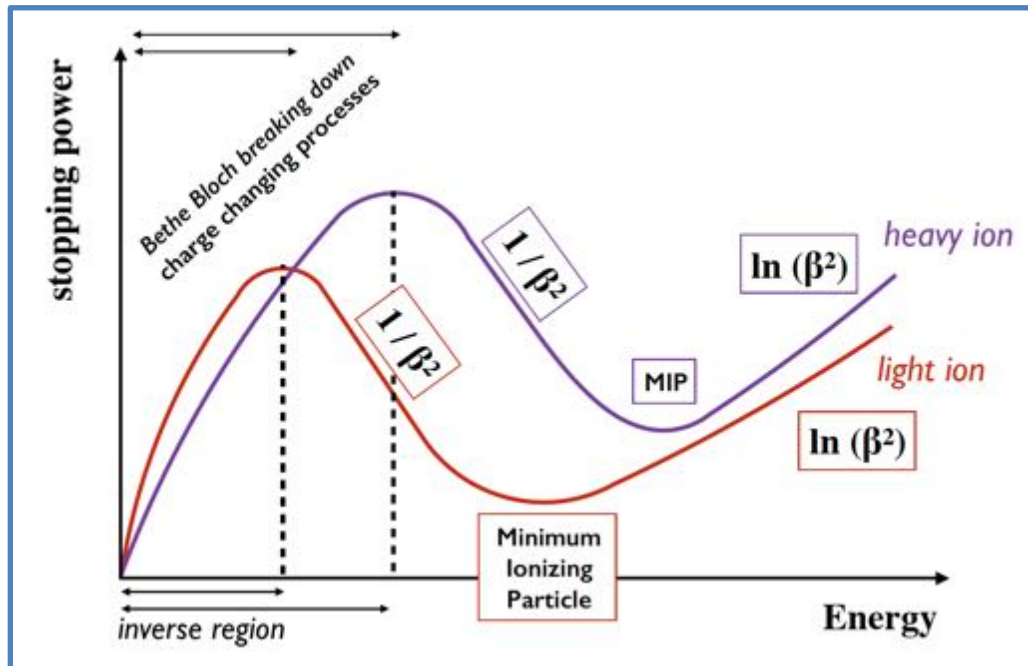
$$-\frac{dE}{dx} = \frac{4\pi e^4 N_A z^2 Z}{m c^2 \beta^2 A} \rho \ln \frac{2 m c^2 \beta^2 \gamma^2}{I} -$$

- relativistic terms



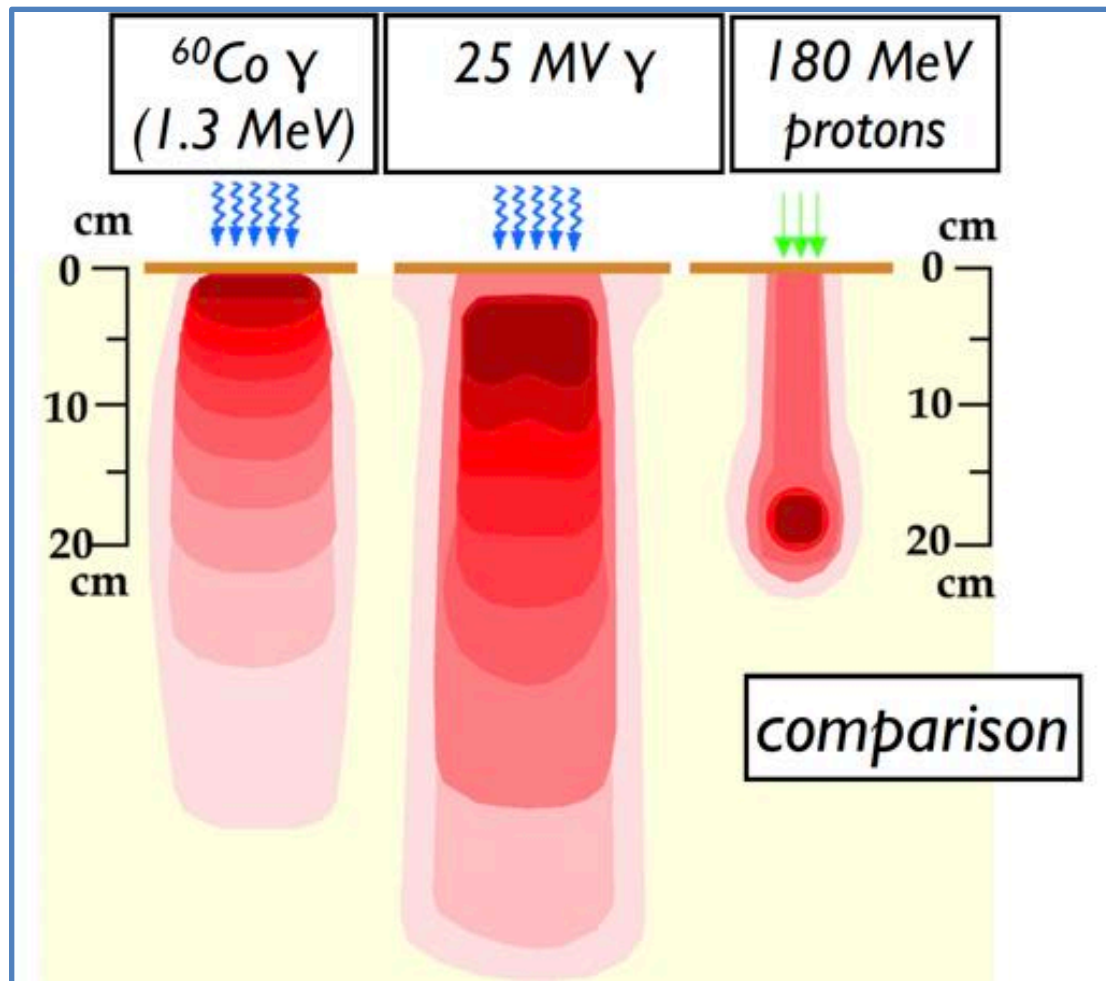
Bragg-Peak以及辐射的医学应用

带电粒子辐射可以用来精确的杀害癌症细胞

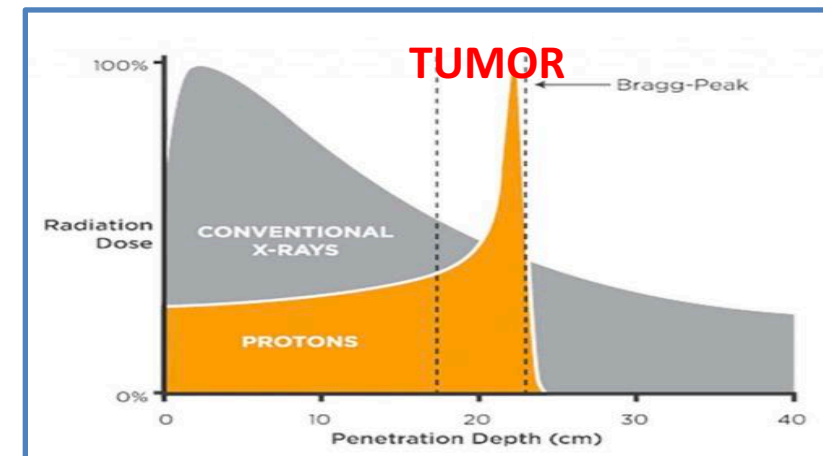


Bragg-Peak以及辐射的医学应用

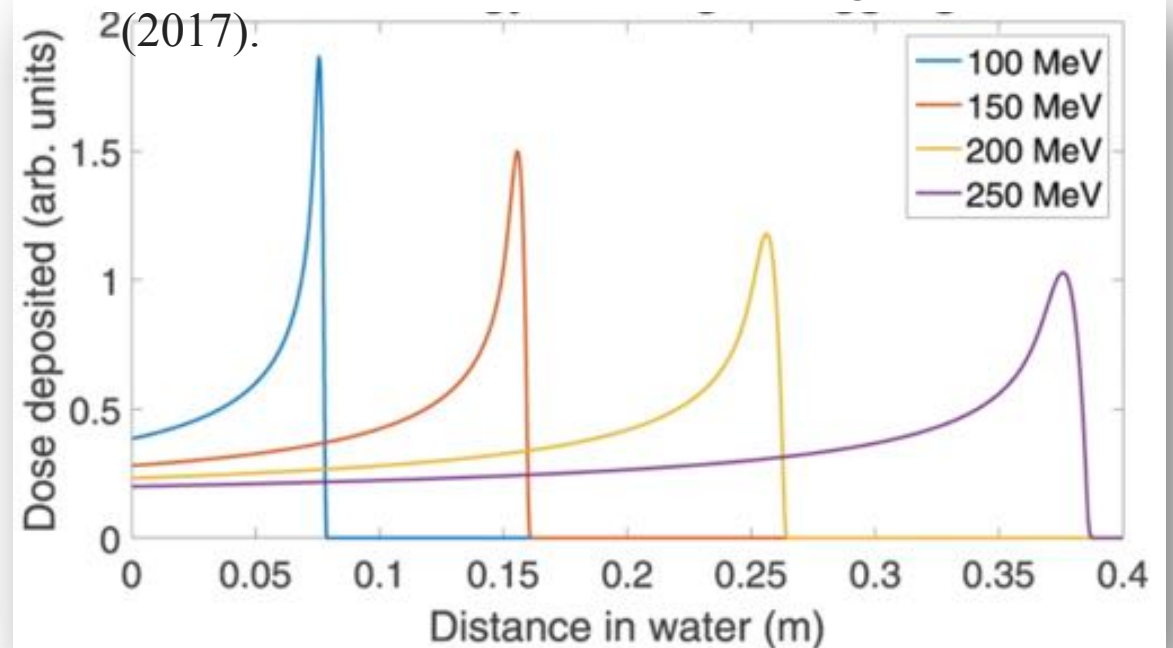
带电粒子辐射可以用来精确的杀害癌症细胞



Courtesy of Giorgio Baiocco (Uni. Pavia)



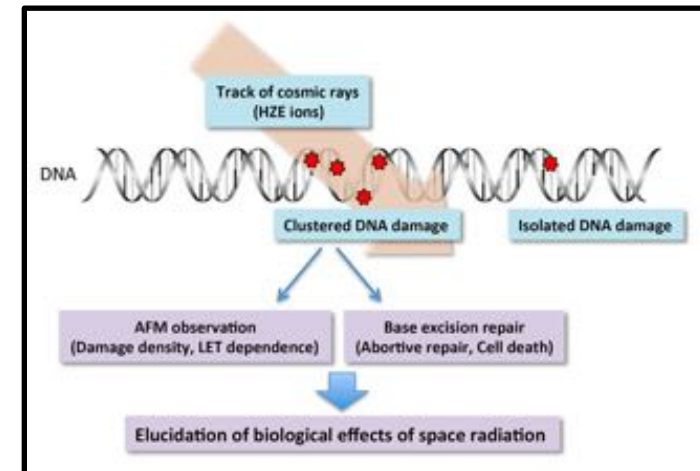
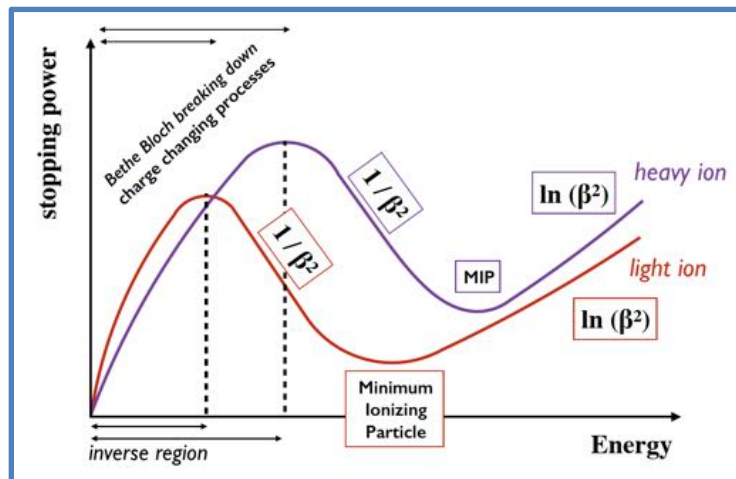
Grimes, D.R., Warren, D.R. & Partridge, M.



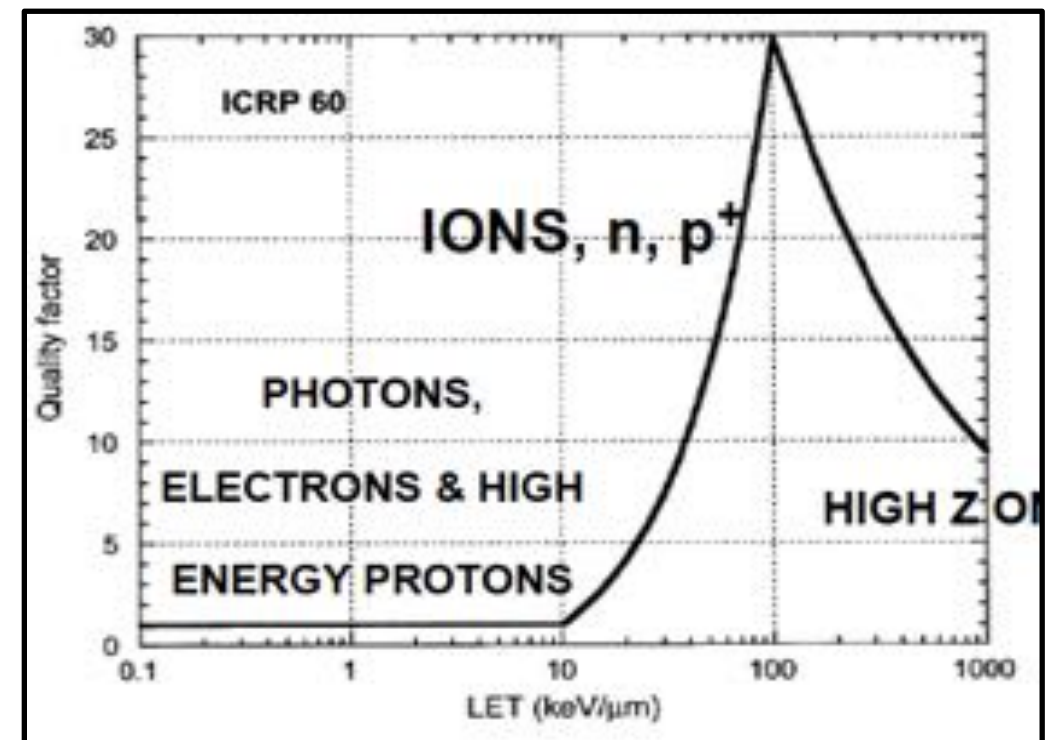
不同粒子的生物辐射效应不同

高能粒子LET及其对应的 biological quality factor

参考 International Commission on Radiological Protection 60



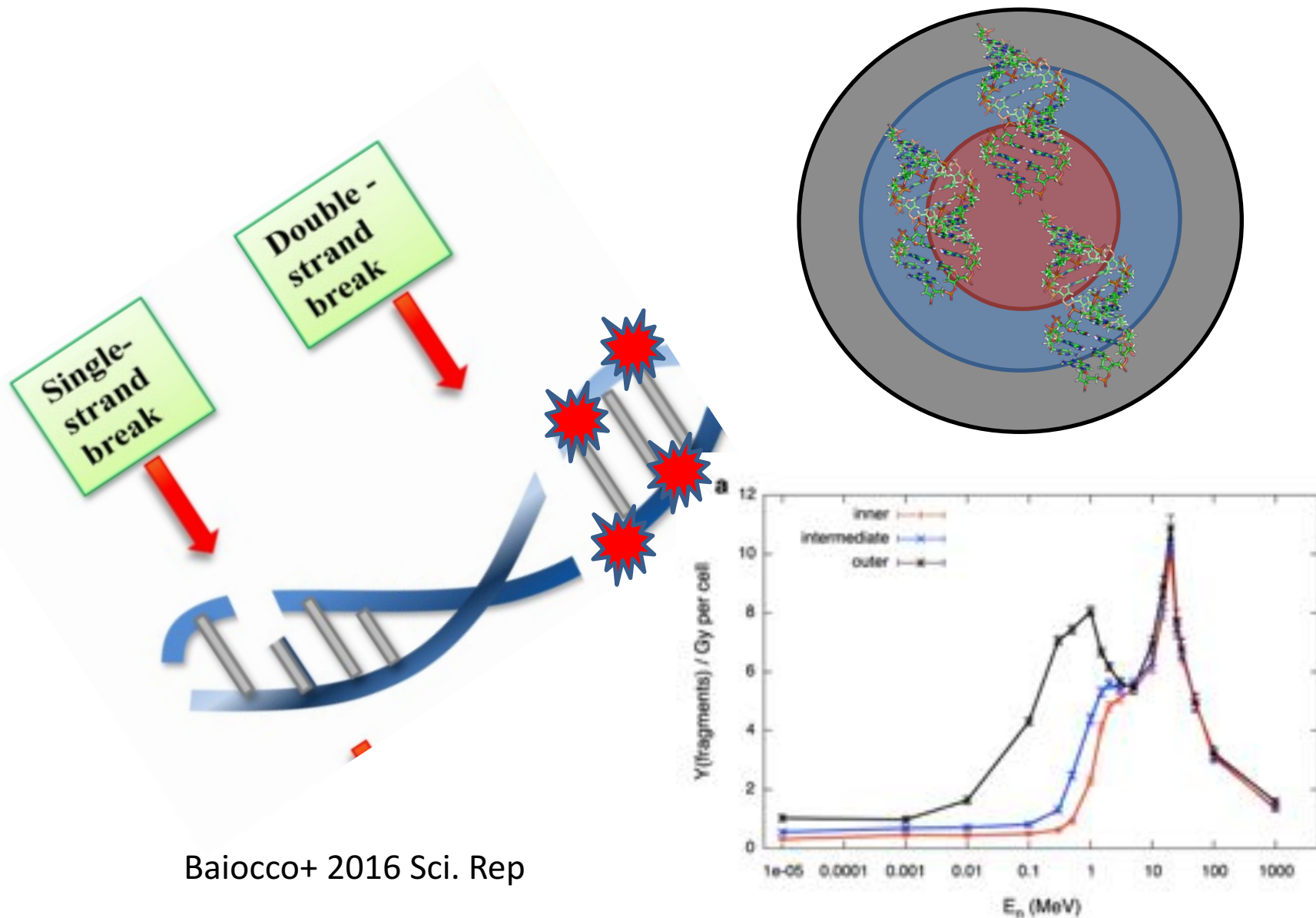
| Type of radiation | LET (keV/ μ m) |
|--------------------------------------|--------------------|
| cobalt-60 gamma-radiation | 0.3 |
| 250 kVp X-radiation | 2. |
| 10 MeV protons | 4.7 |
| 150 MeV protons | 0.5 |
| recoil protons from fission neutrons | 45. |
| 14 MeV neutrons | 12. |
| 2.5 MeV alpha particles | 166. |
| 2 GeV Fe nuclei | 1000. |



不同粒子的生物辐射效应不同

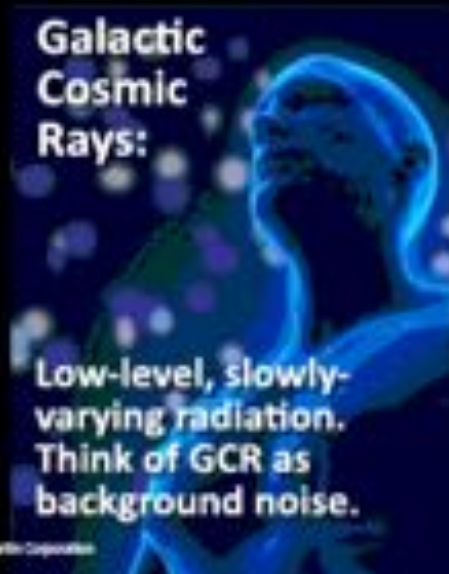
中子通过产生次级粒子引发的生物辐射效应

报告提纲



Baiocco+ 2016 Sci. Rep

- 空间辐射的危害
- 空间辐射的种类
- 火星空间环境和辐射的测量
- 火星辐射的时空变化
- 太阳爆发和高能粒子事件
- 火星辐射仿真和防护方案



Galactic Cosmic Rays/银河宇宙射线

- Origin: intra- or extra- galactic phenomena: supernova explosions
- Omnipresent background radiation, Low-intensity flux: few particles/cm²/s
- Wide variety of elemental species, including heavy ions
- Maximal flux at around 1 GeV/n energy
- Flux modulated by solar activities: maximal at solar minimum
- Dose: ~ 1 mSv/day



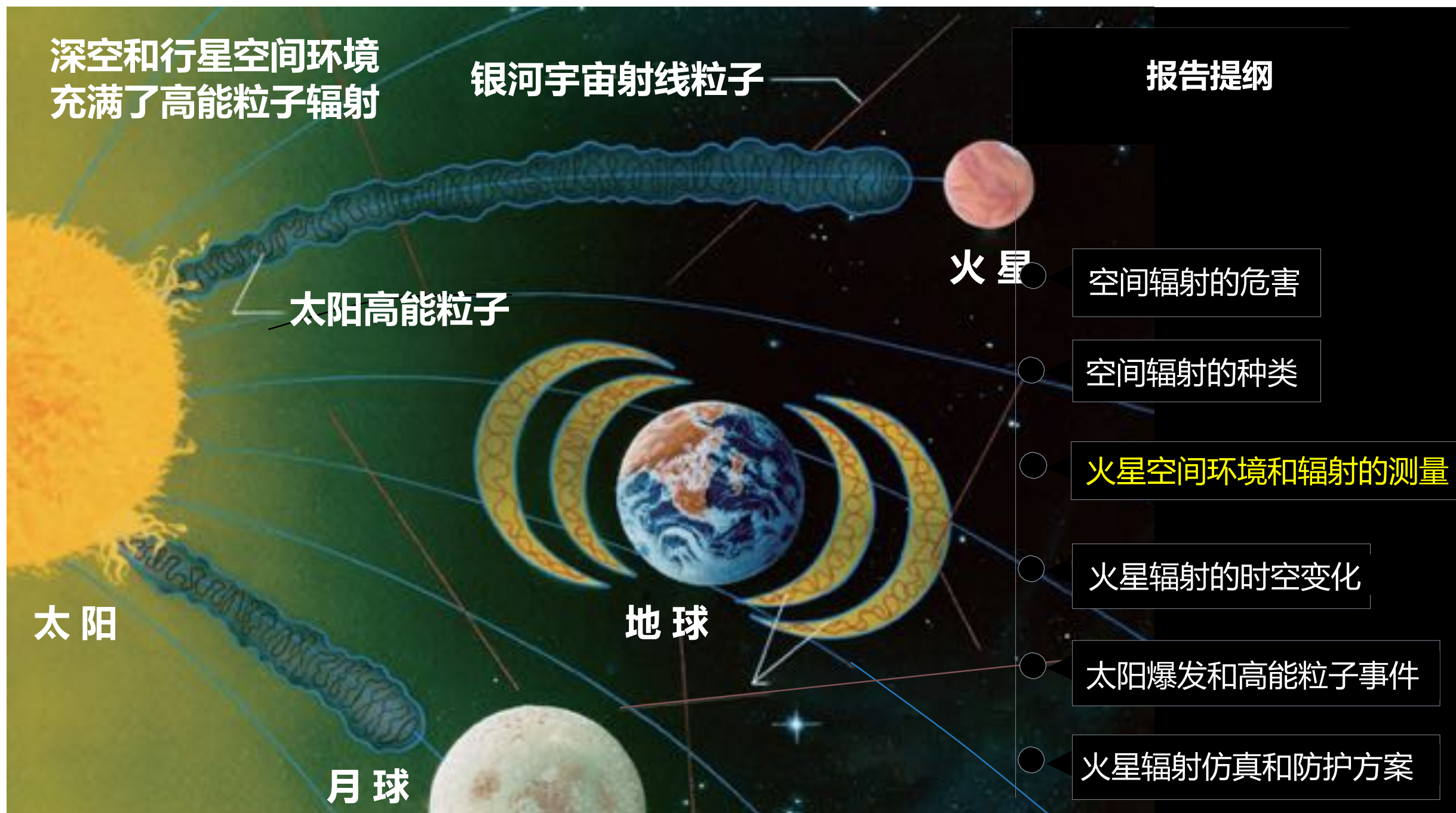
Solar Energetic Particles/太阳高能粒子

- Origin: sun eruptions (flares, CMEs, shocks)
- Related to solar activity (higher probability at solar max), but hardly predictable, with event duration from hours to days
- mainly protons (and Helium nuclei)
- Maximal flux for energies below 100 MeV
- Can reach huge fluxes (10¹⁰/cm²/s) at event maximum
- Dose: ~ Sv, highly dependent on the local shielding!

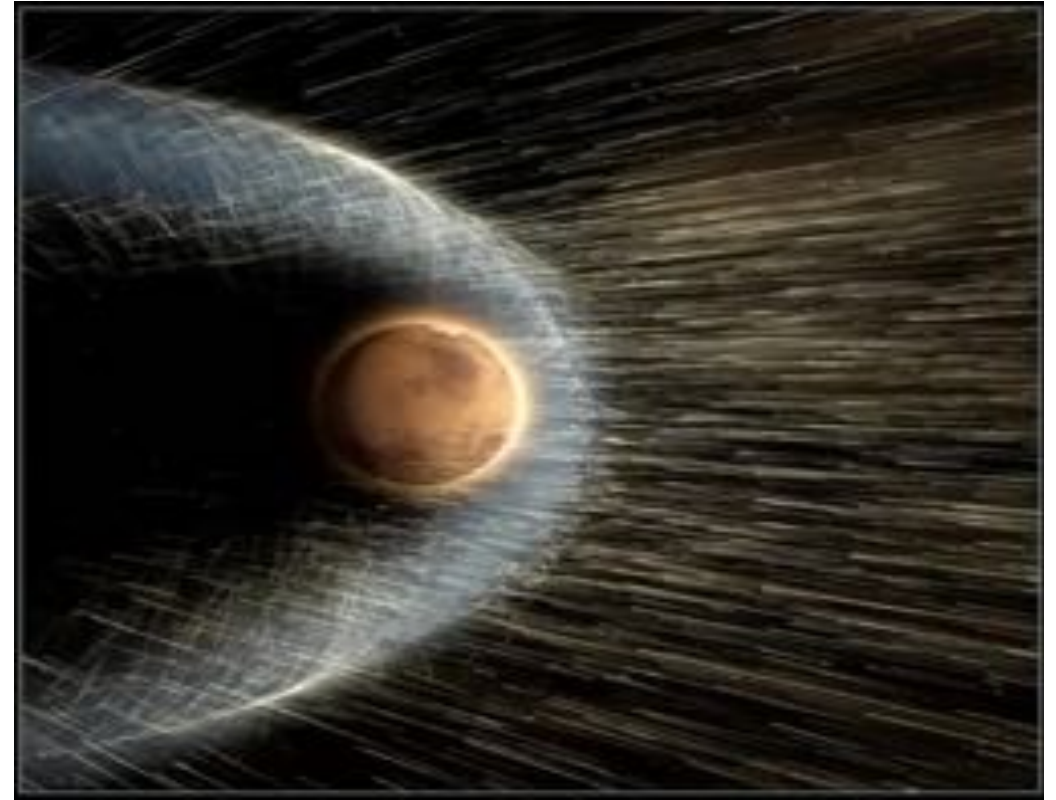
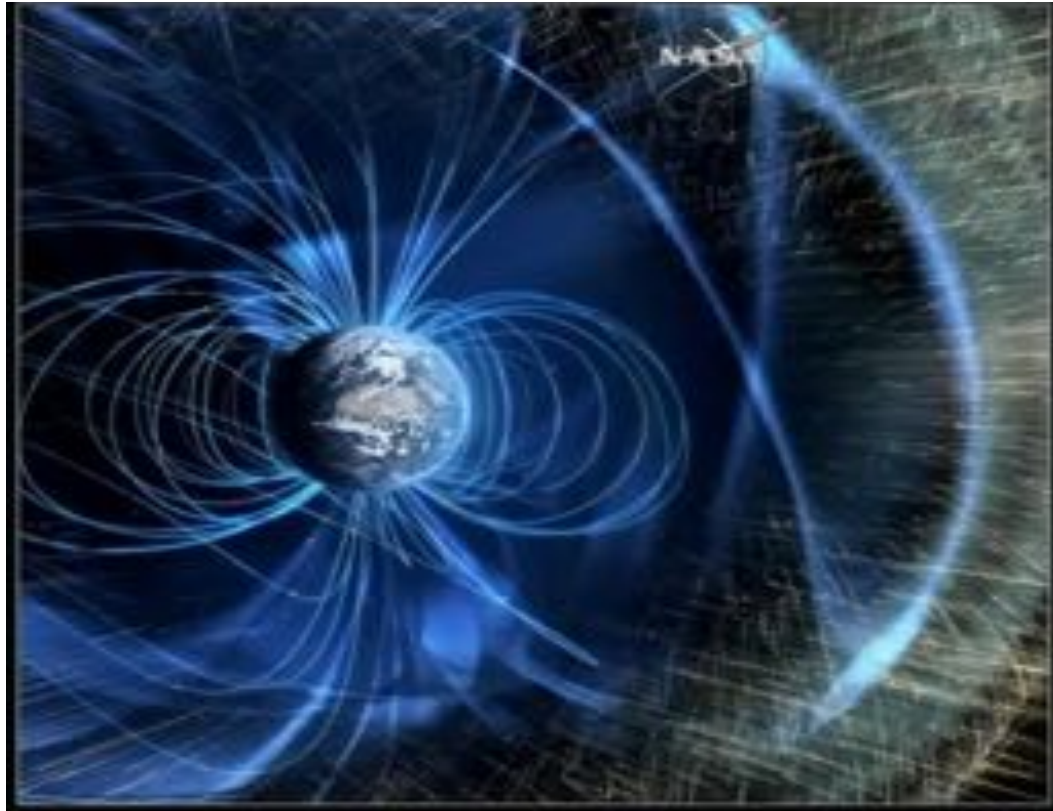
Geomagnetically Trapped Radiation

- Origin: particles trapped in the Earth magnetic field
- mainly protons and electrons
- Not a problem for deep space exploration beyond Earth magnetosphere

空间辐射的种类



火星比地球更受到空间天气和辐射的直接影响



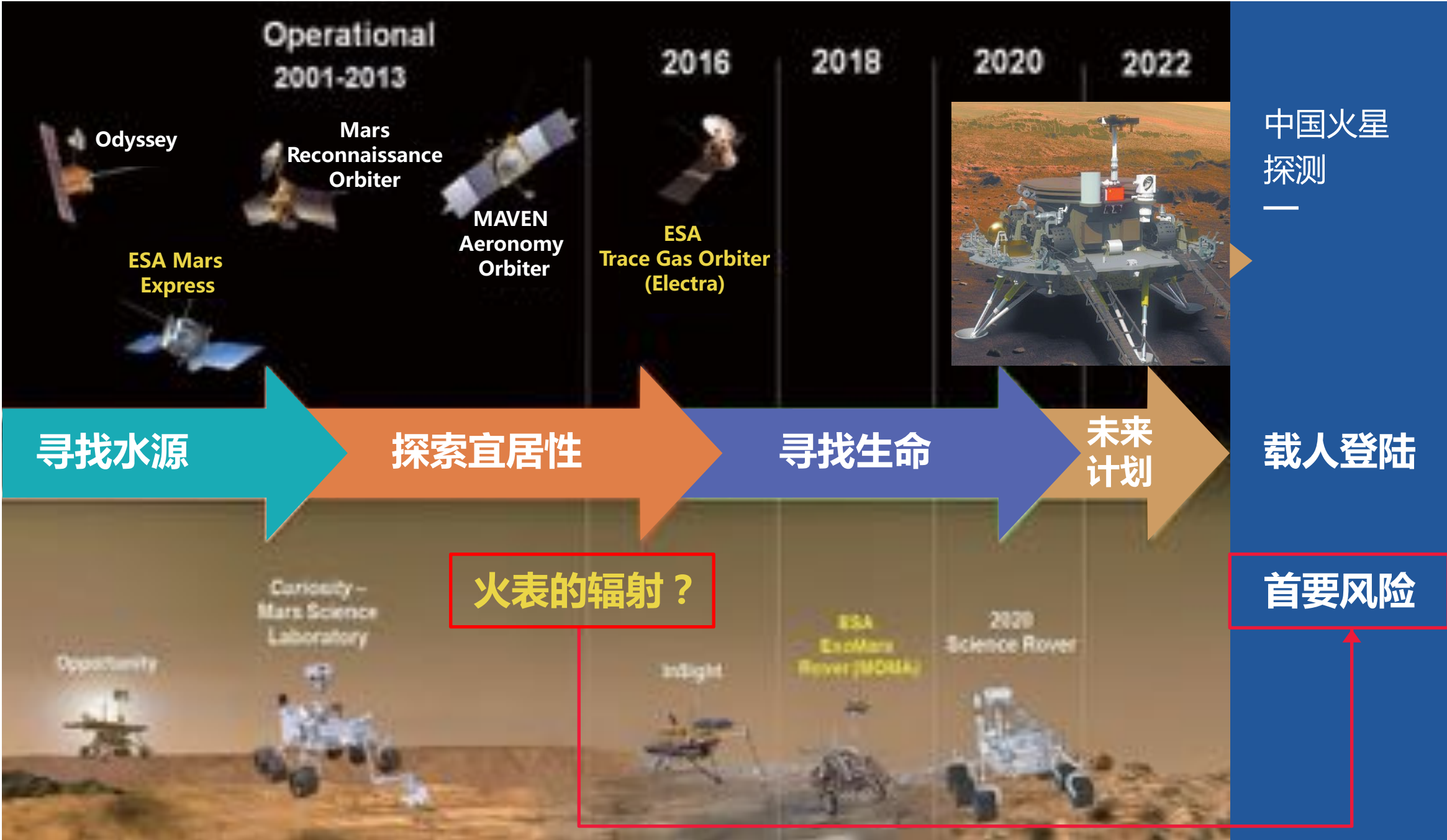
火星的大气也因此愈来愈稀薄

MAVEN 测得目前太阳风造成的火星大气损失率约为 10^{24} 原子每秒 $\sim 100\text{g/sec}$



(图片来自于Dr. Christina Lee from UC Berkeley)

火星探索的科学热点 (最近20年的火星项目)



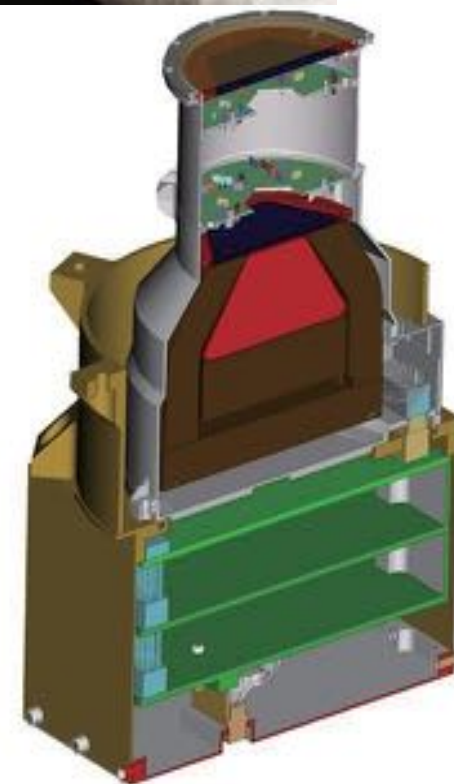
火星辐射的首次：MSL/RAD观测

— 2012年8月7日起，首次测量火星的辐射 —

高能粒子辐射 探测器
Radiation Assessment
Detector RAD



NASA好奇号火星车MSL



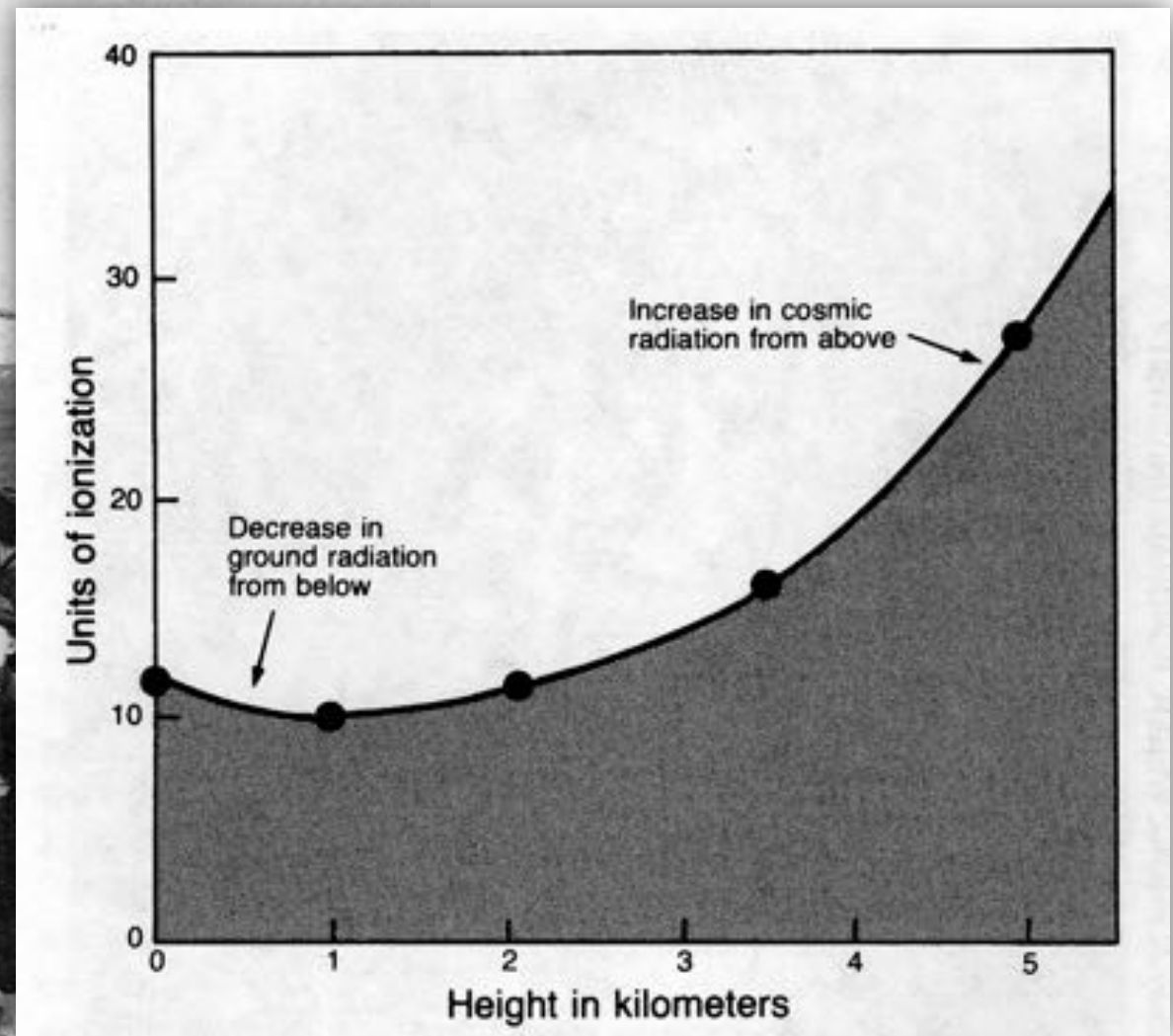
Hassler et al. 2014 Science

宇宙射线的发现恰在100年前的同一天

— 1912年8月7日，Victor Hess发现了空间辐射—



并因此获得诺贝尔奖



观测 标定 | RAD带电粒子的标定

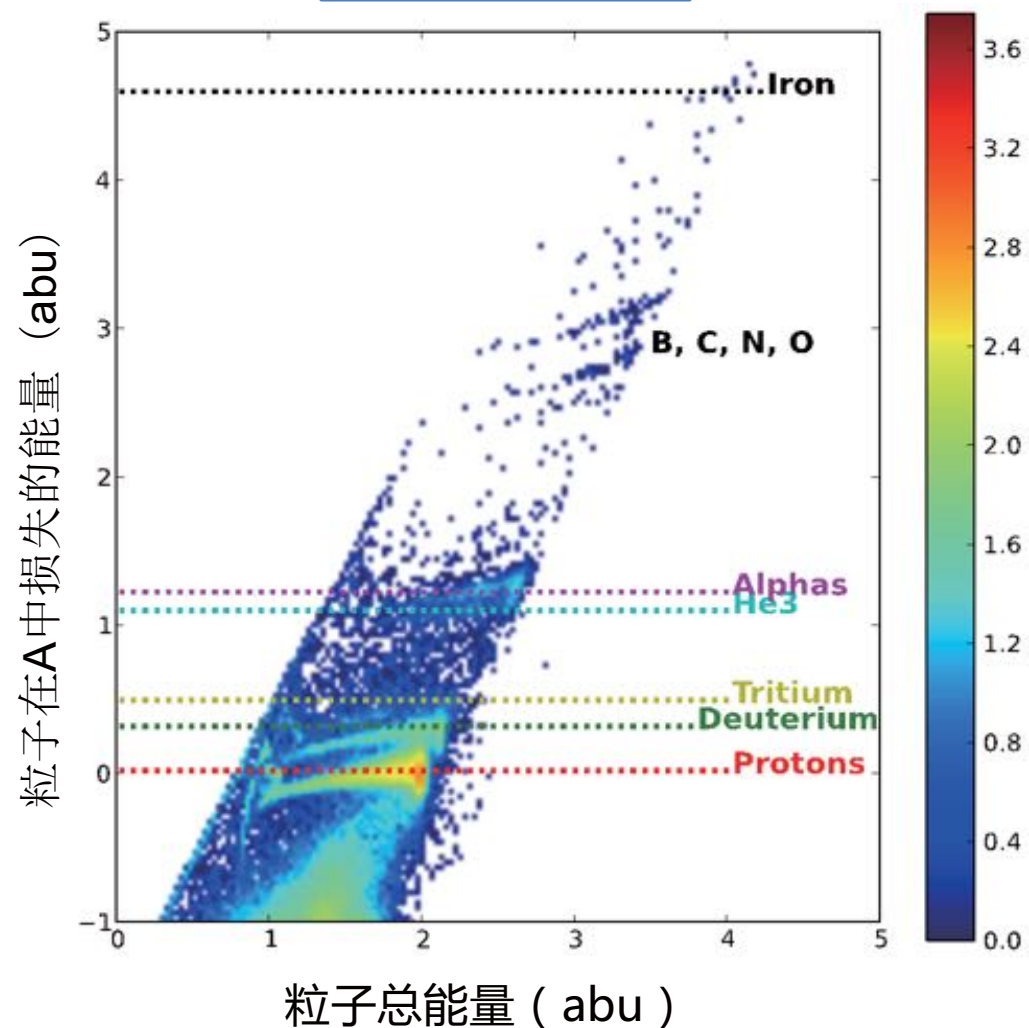
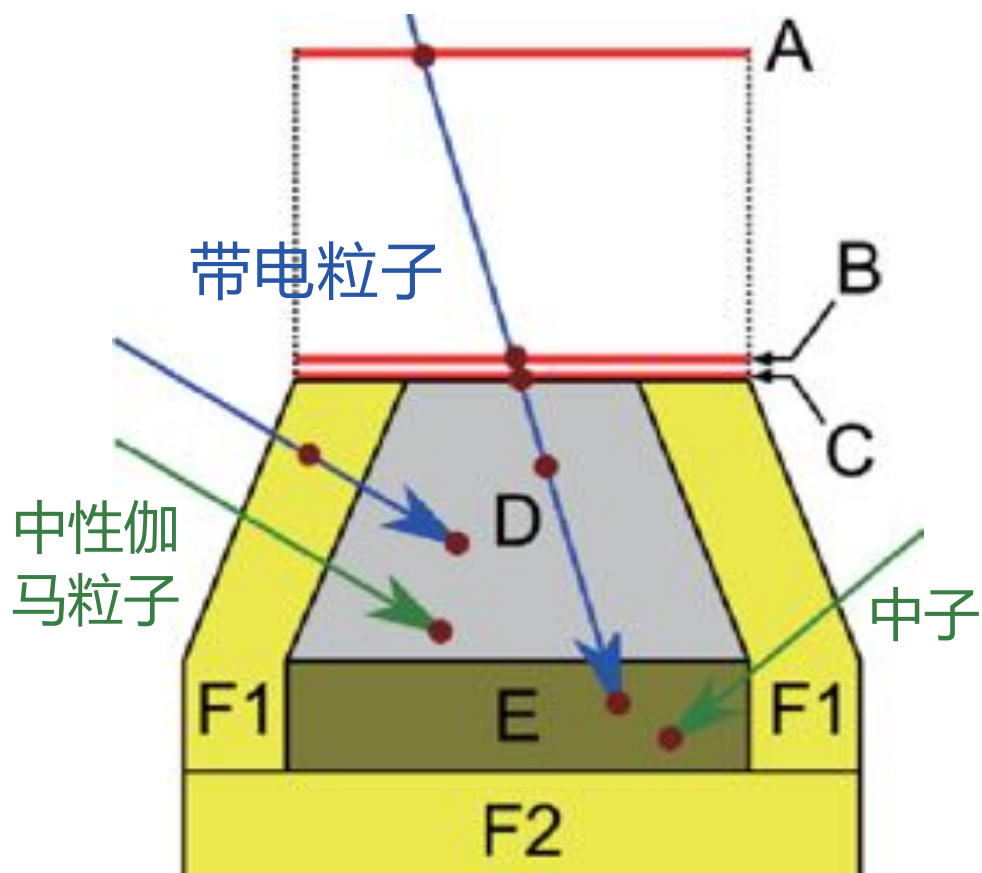
标定带电粒子能谱 Ehresmann+ 2014, 2016; Guo+ 2015 Rad. Prot. Dos

$$-\frac{dE}{dx} = \frac{4\pi e^4 N_A z^2 Z}{m c^2 \beta^2 A} \rho \ln \frac{2 m c^2 \beta^2 \gamma^2}{I} -$$

- relativistic terms

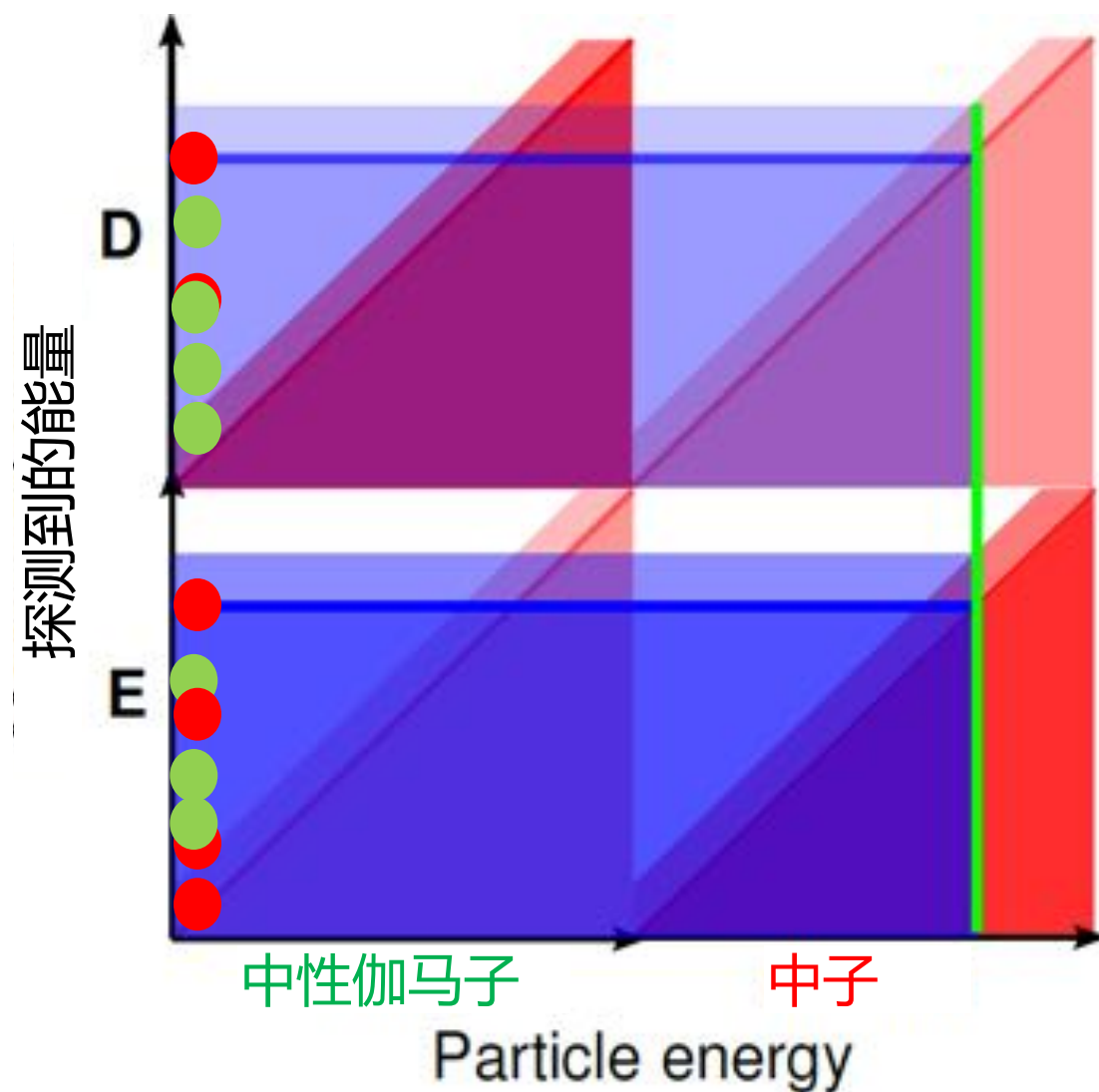
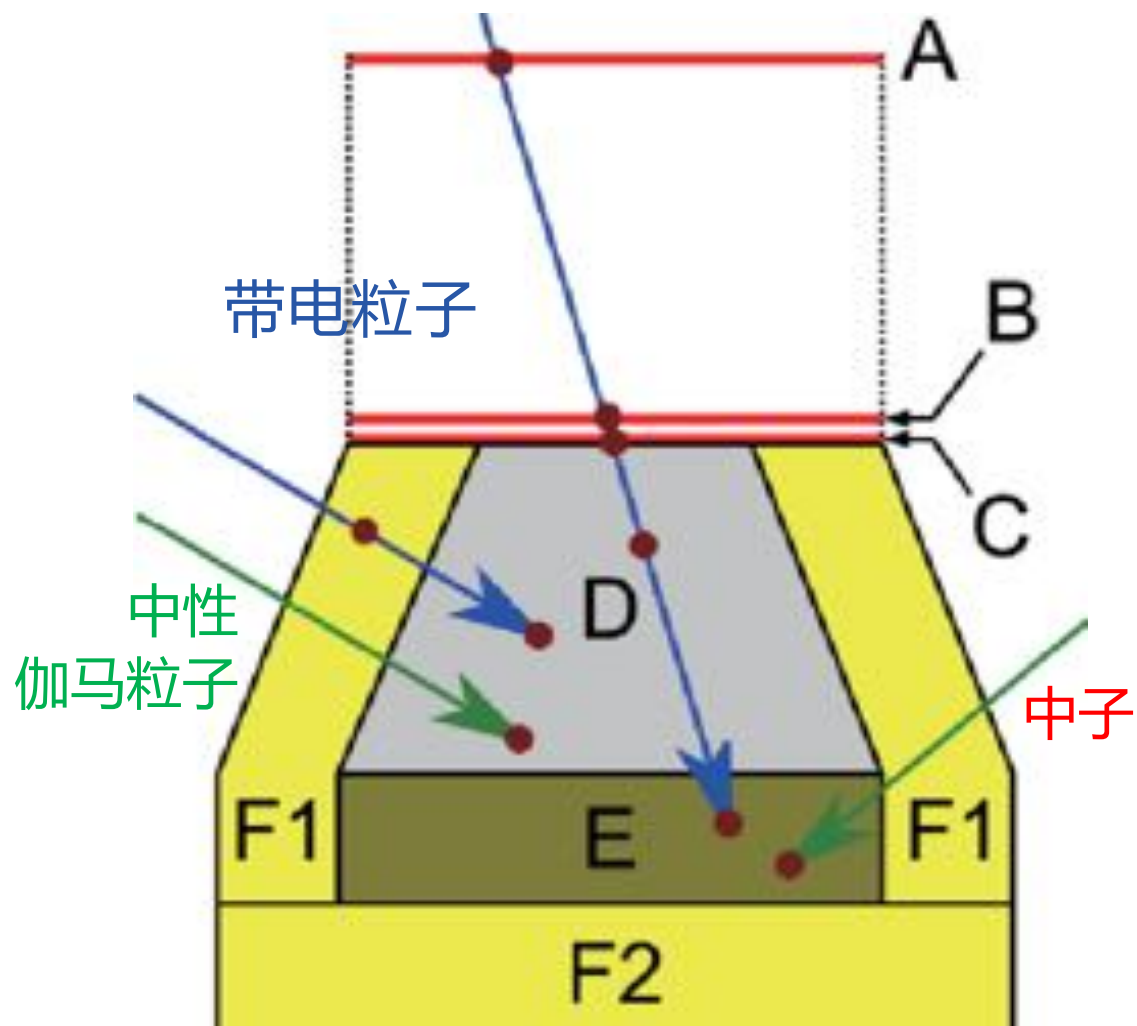


$$\frac{dE}{dx} \cdot E \sim M \cdot z^2$$



观测 标定 | RAD中性粒子的标定

标定中性粒子能谱 Koehler+ 2014 JGR; Guo+ 2017 LSSR

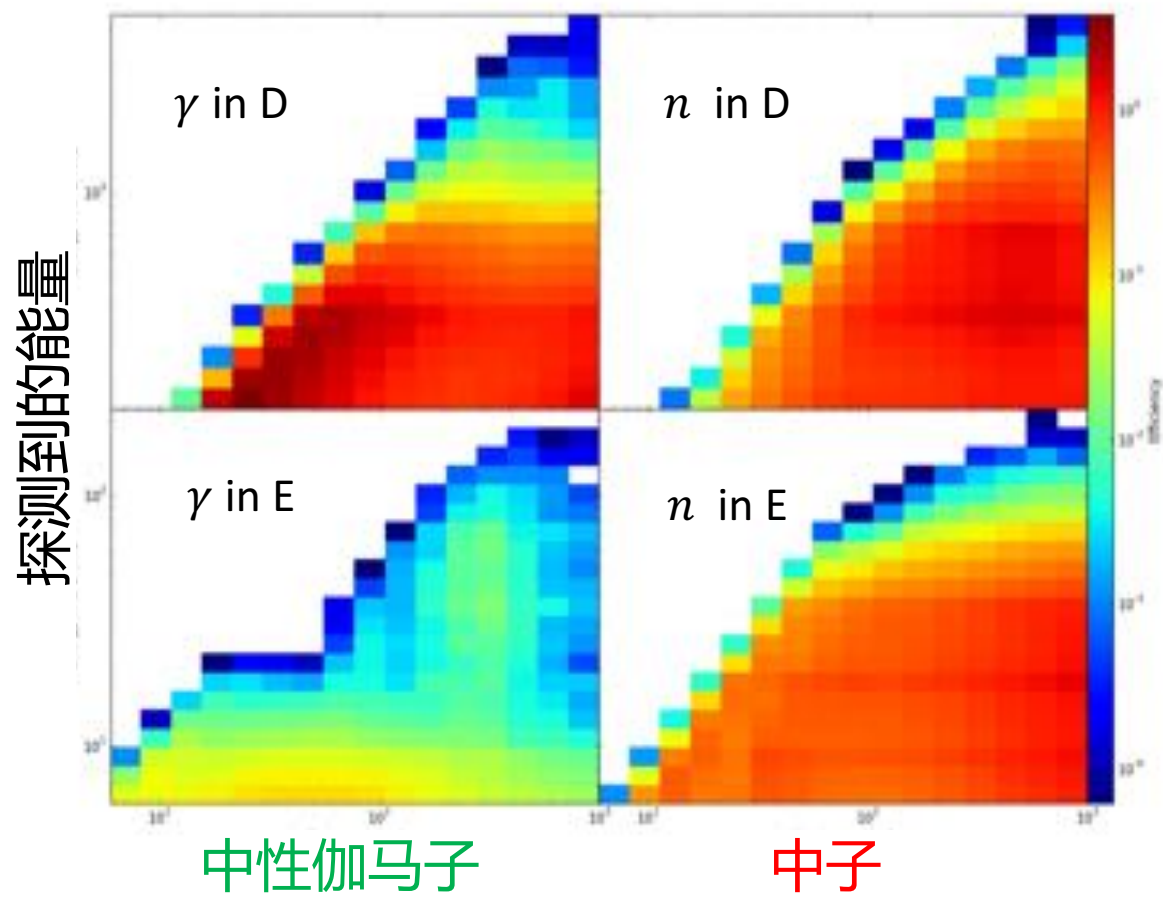


观测标定 | RAD中性粒子的标定

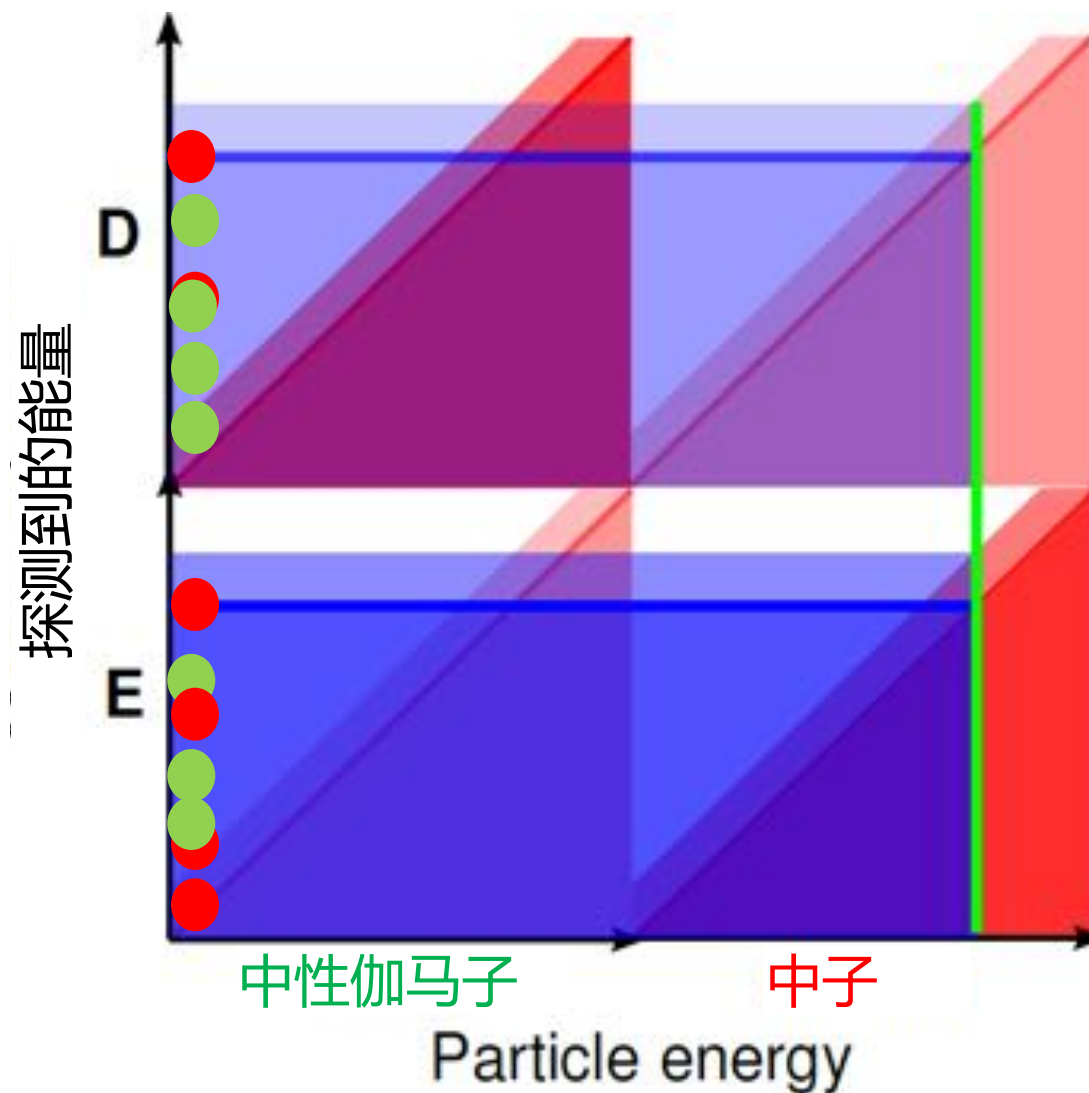
标定中性粒子能谱 Koehler+ 2014 JGR; Guo+ 2017 LSSR

$$\vec{z} = \mathbf{A} \cdot \vec{f}$$

$$\min \sum \left(\frac{\sum_j a_{ij} f_j - z_i}{\sigma_i^2} \right)^2, \quad \text{with } f_i > 0$$

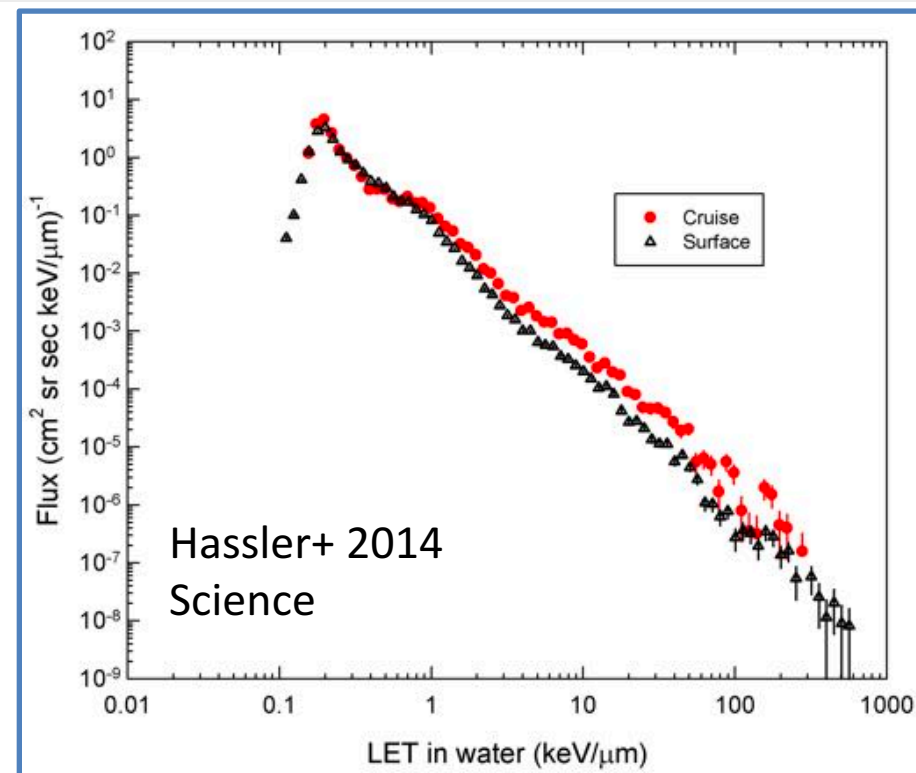
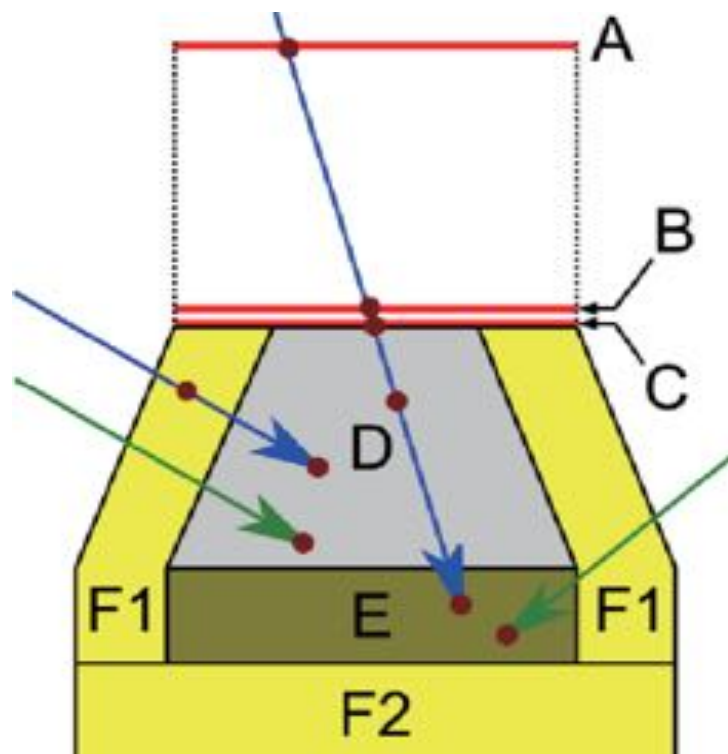


仿真模拟出响应矩阵A



观测 标定 | LET能谱的标定

标定LET能谱 求出等效生物辐射剂量 Zeitlin+ 2013 Science; Zeitlin+ 2019 LSSR

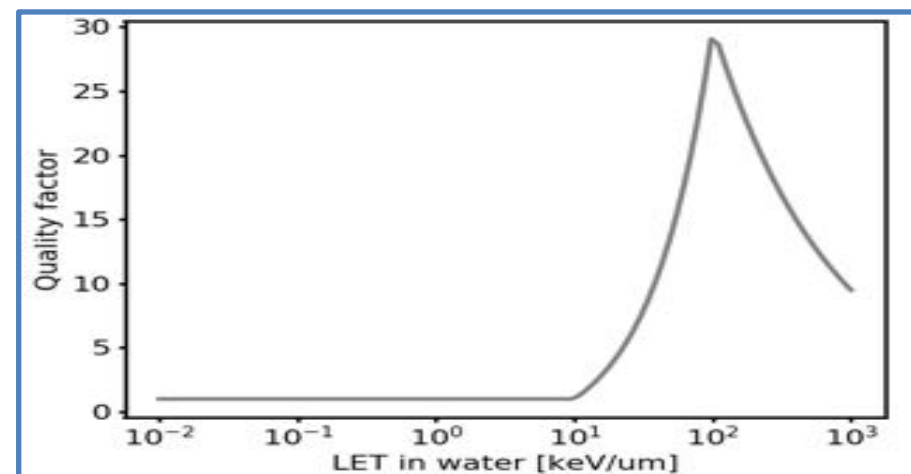


- Absorbed dose, Gy [1 Gy = 1J/kg = 100 rad]

$$D = \frac{dE}{dm}$$

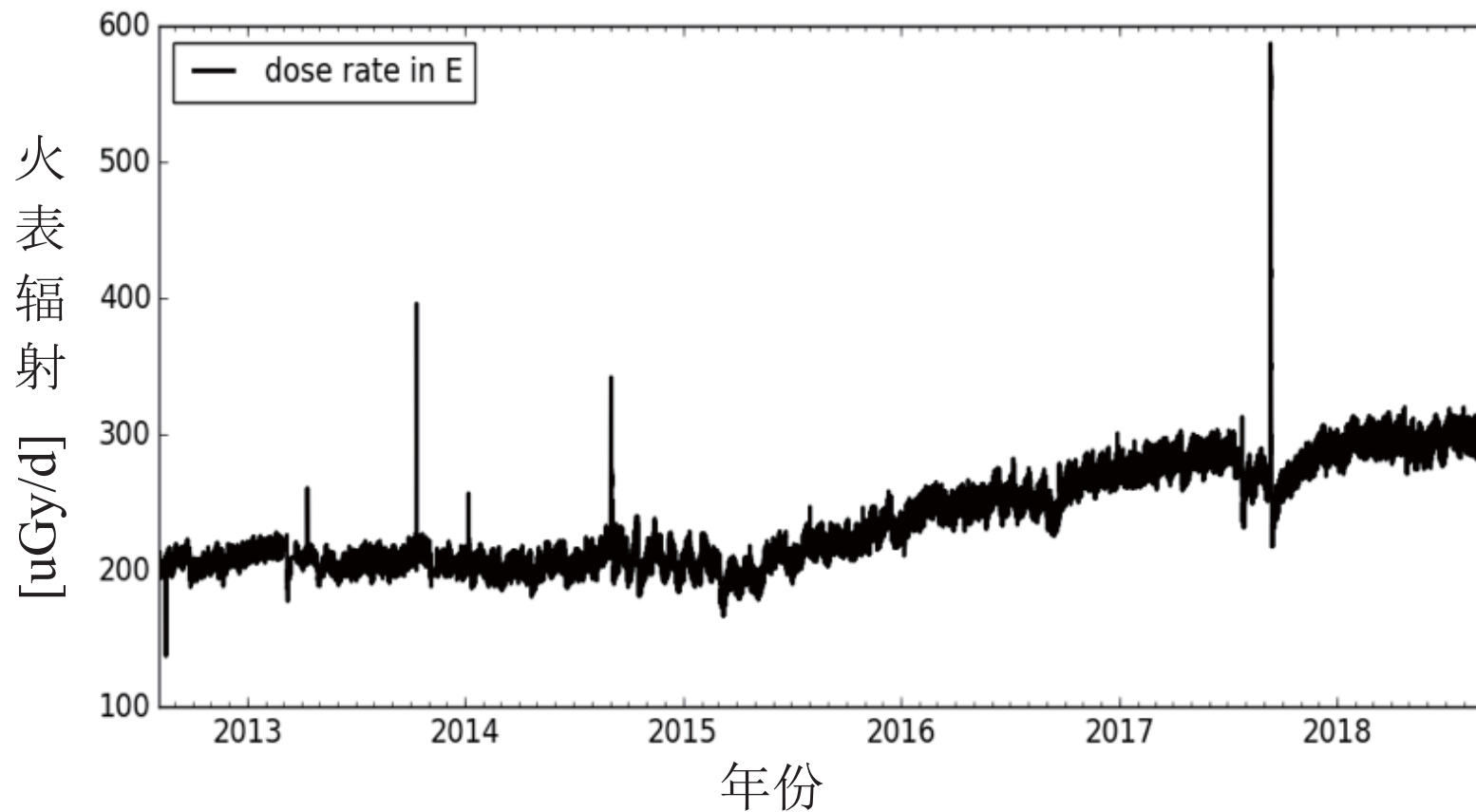
- Dose Equivalent, Sv [1Sv = 1rem]

$$H = \langle Q \rangle \cdot D$$



观测 | RAD 在火星表面测量的辐射剂量率

报告提纲



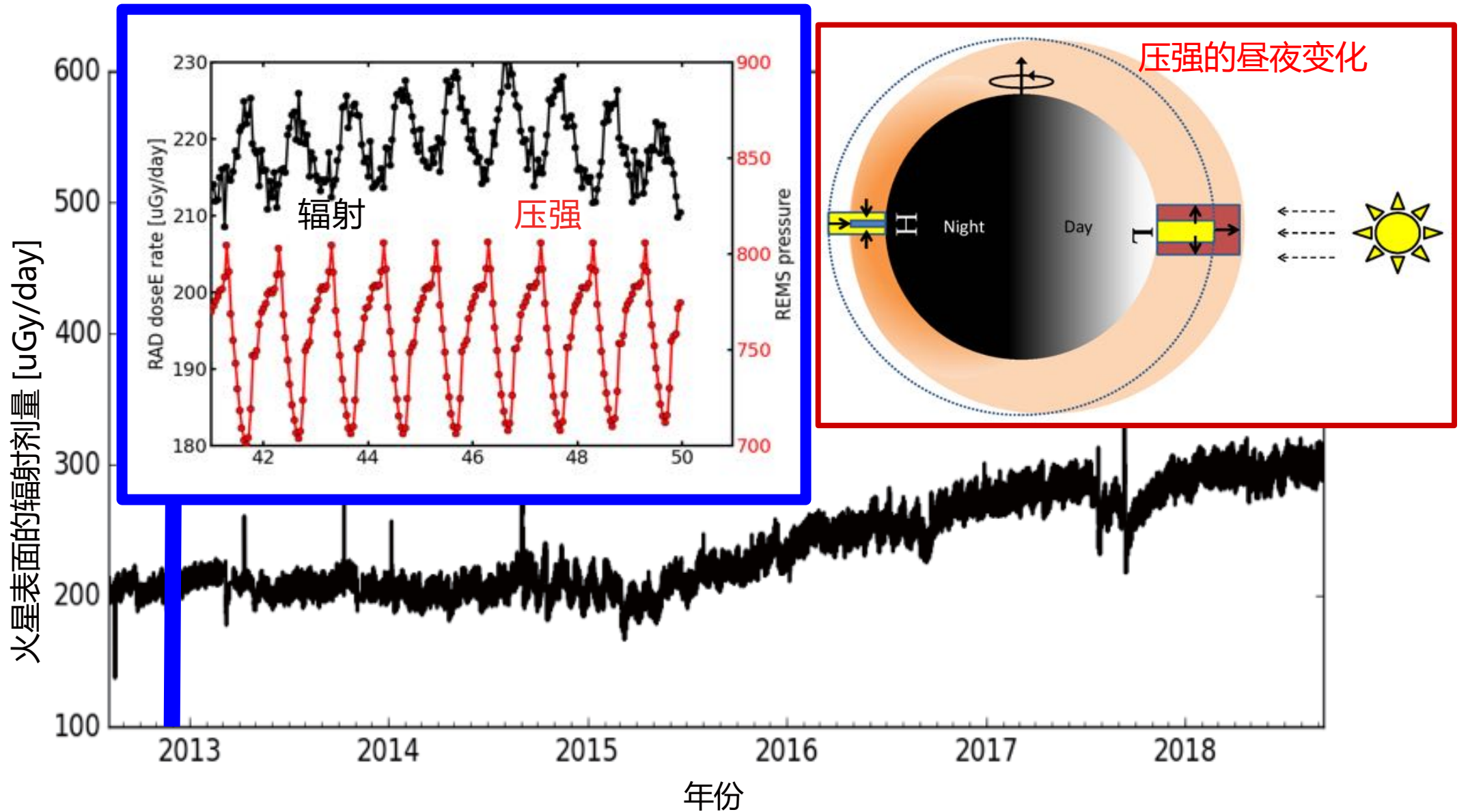
- 空间辐射的危害
- 空间辐射的种类
- 火星空间环境和辐射的测量
- **火星辐射的时空变化**
- 太阳高能粒子辐射事件
- 火星辐射仿真和防护

观测 | GCR辐射剂量受大气调节

火星大气昼夜变化
Rafkin+ 2014

辐射受
大气影响

大气压强（厚度）和表面辐射反相关

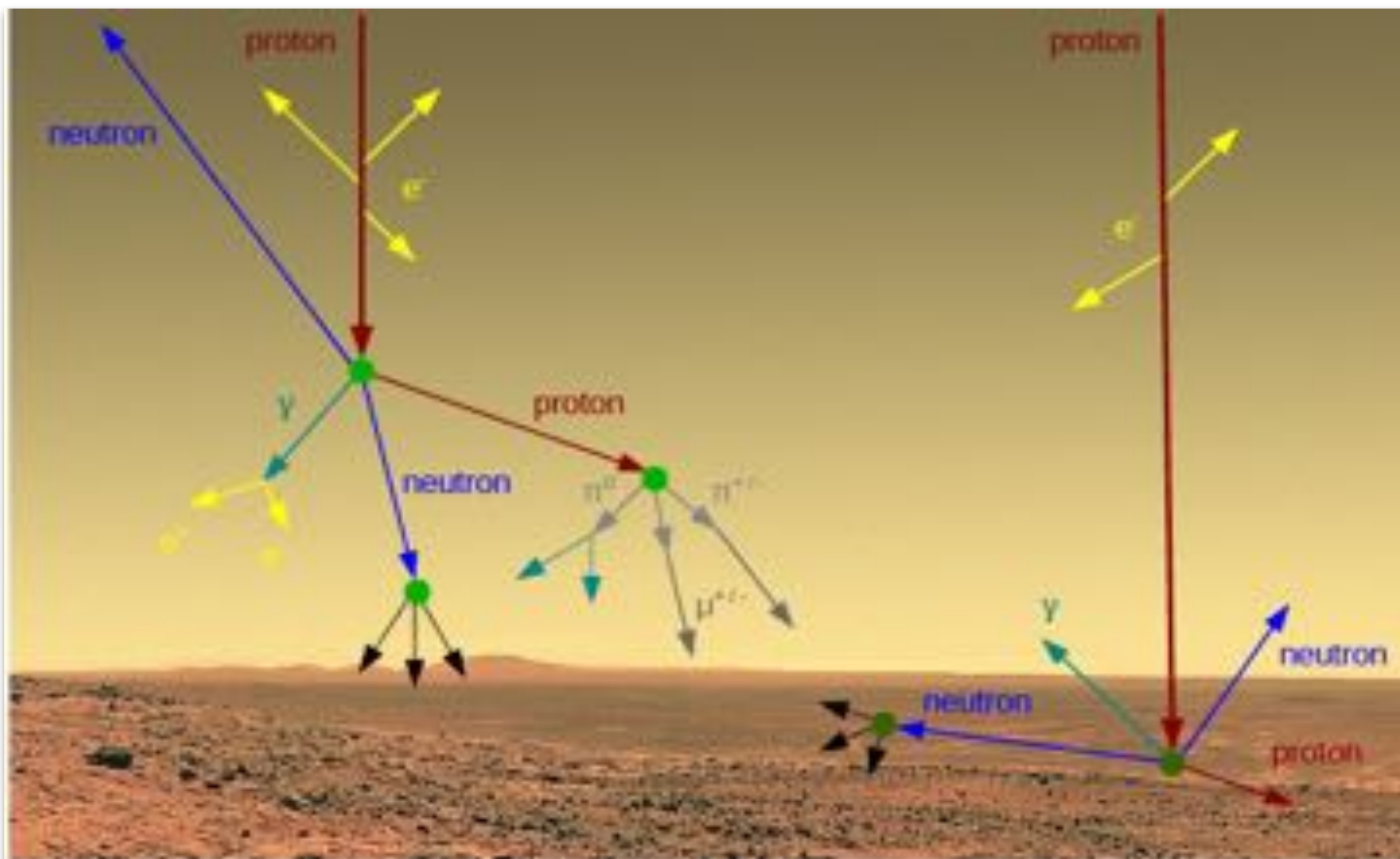


GCR粒子和大气相互作用

初始粒子会损失能量

辐射和
大气作用

初始粒子可以产生次级粒子

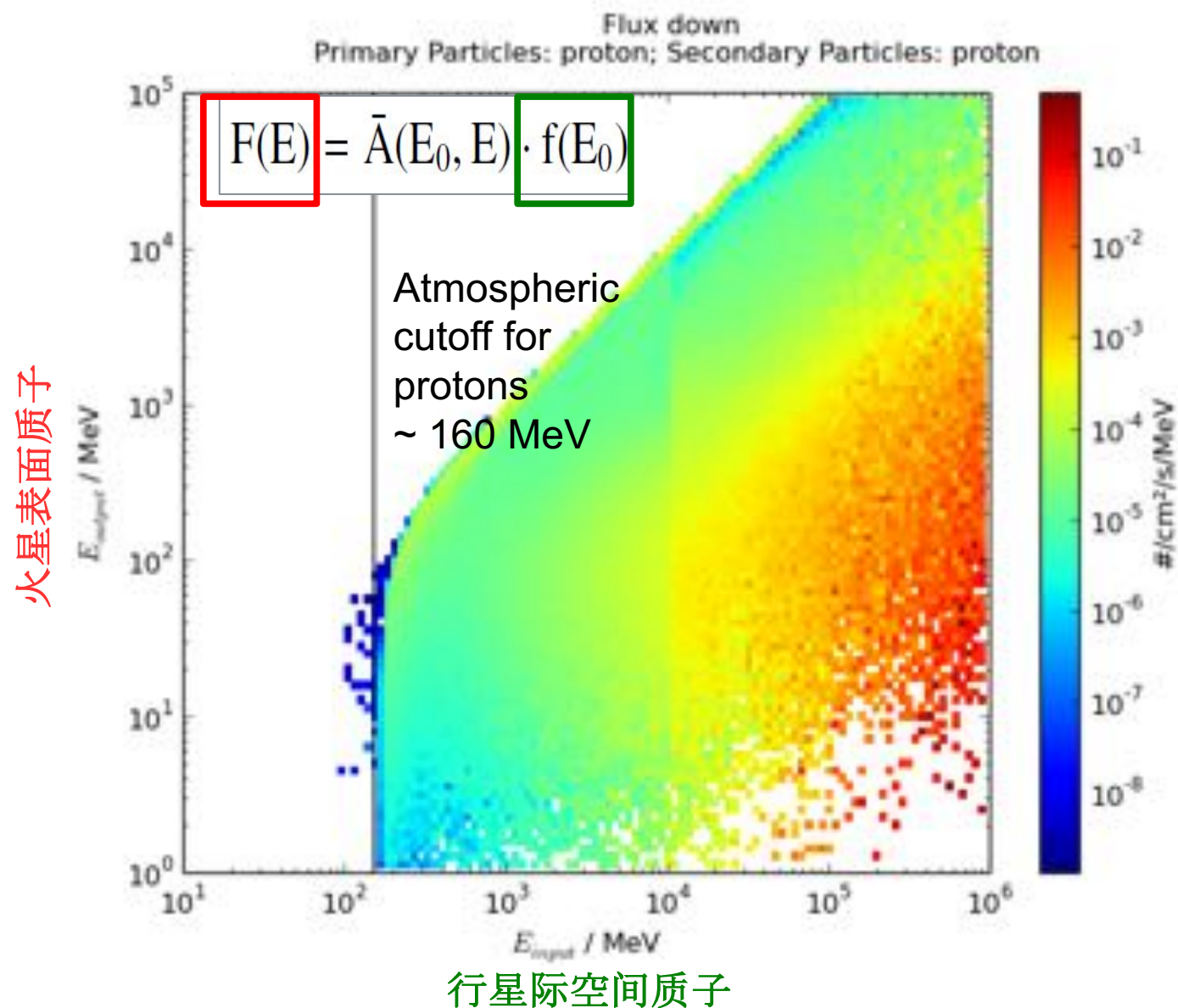


模拟粒子和大气相互作用

初始粒子和大气相互作用损失能量

辐射受
大气影响

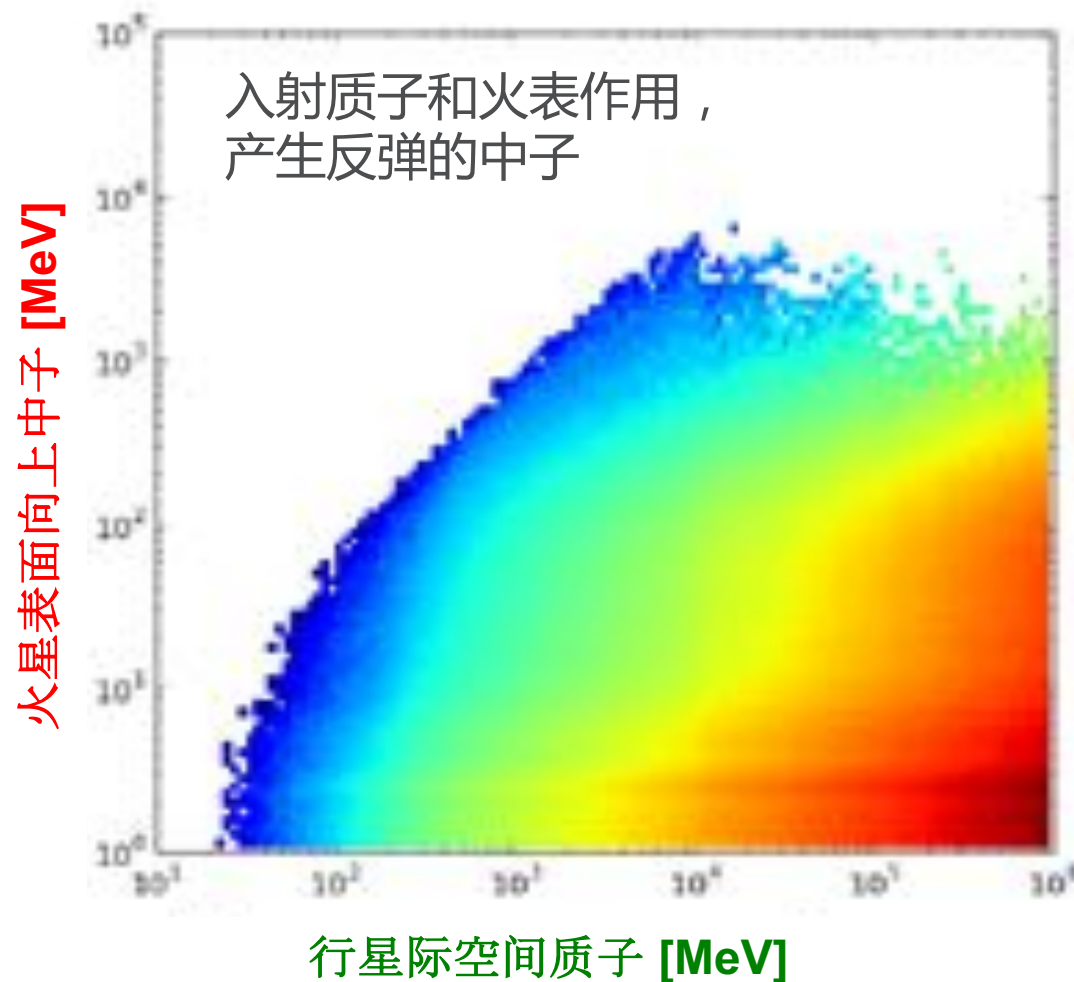
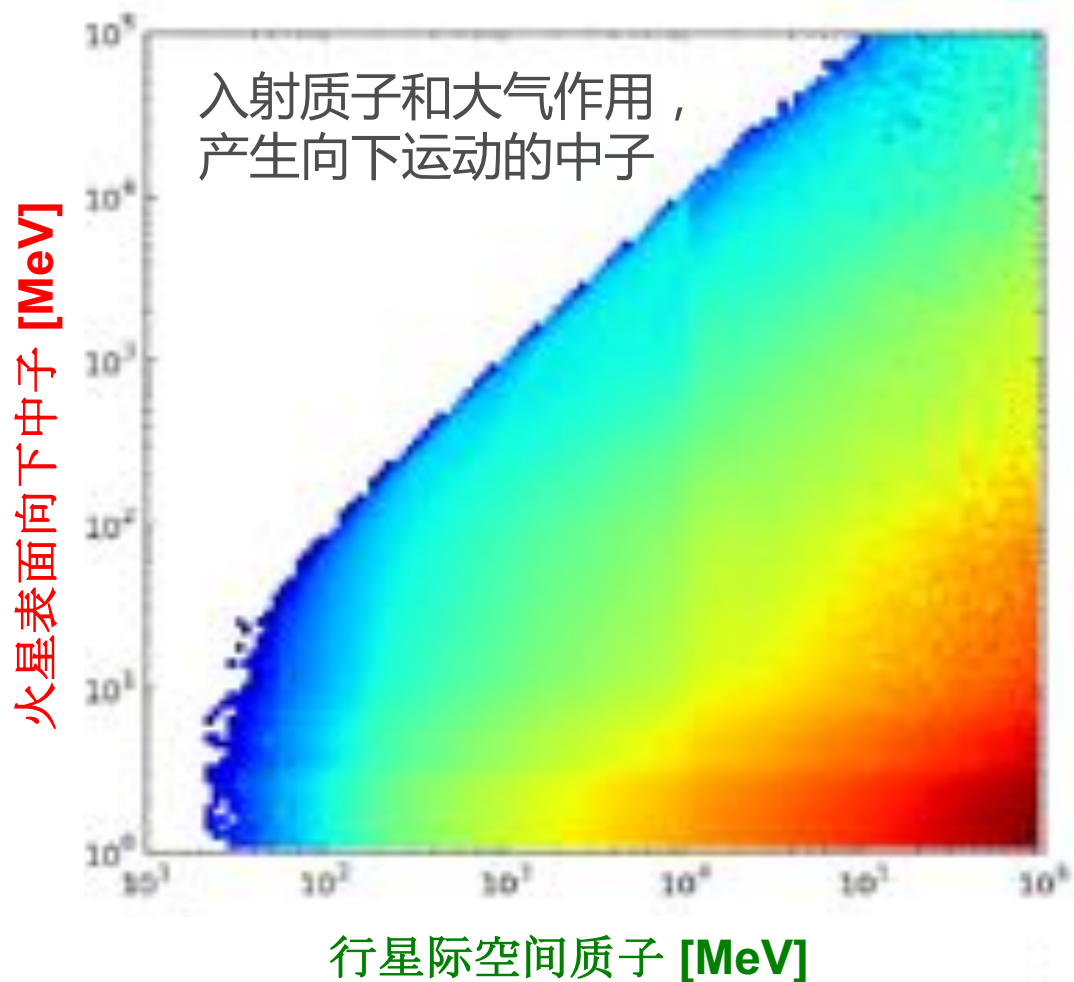
高能质子穿过火星大气的响应矩阵
Guo+ 2018 AJ; Guo+2019 SWSC



初始粒子和大气相互作用产生次级粒子

辐射受
大气影响

高能质子穿过火星大气产生
中子的响应矩阵

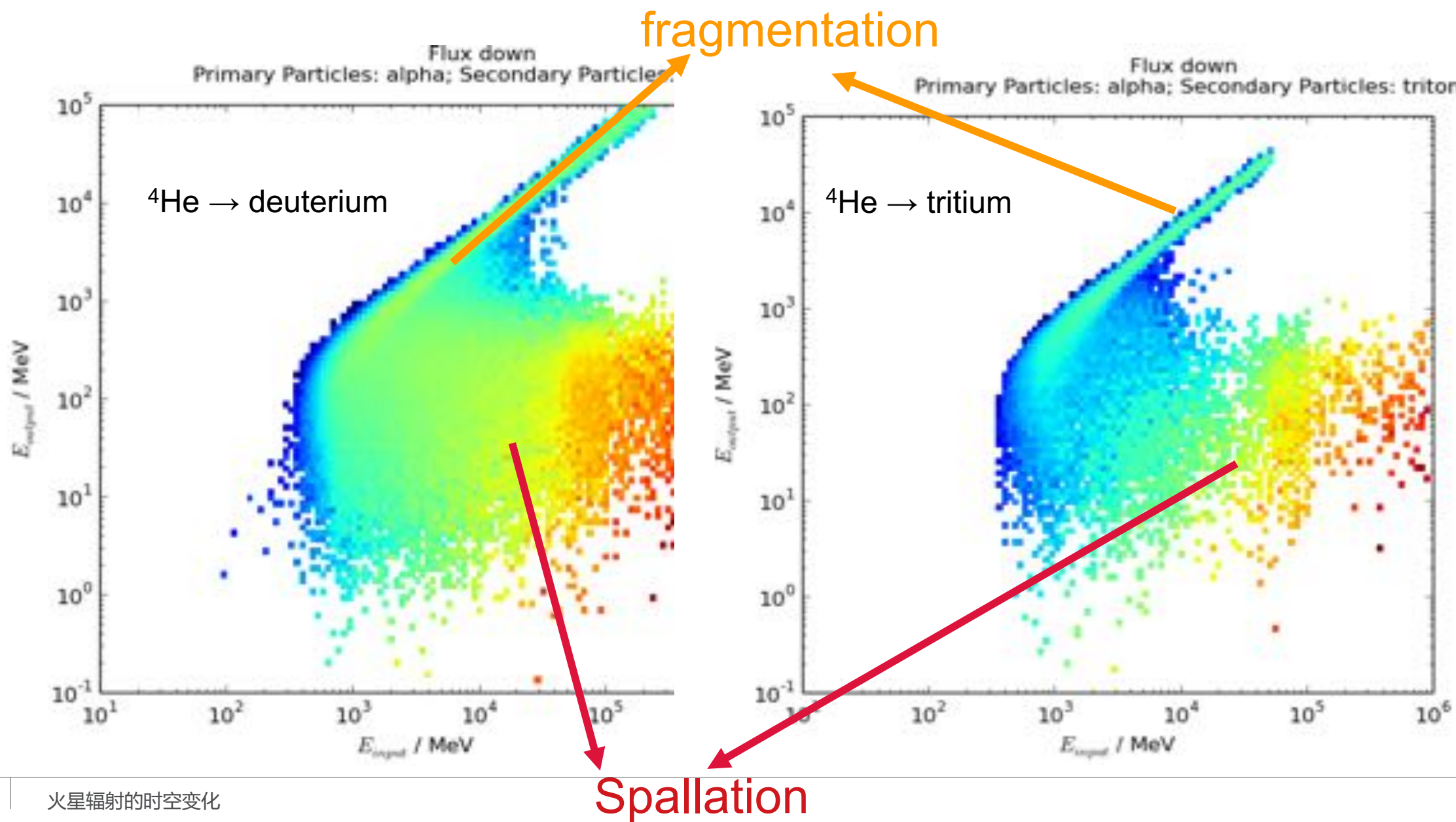


模拟粒子和大气相互作用

初始粒子和大气相互作用产生次级粒子

辐射受
大气影响

重离子穿过火星大气产生次级粒子

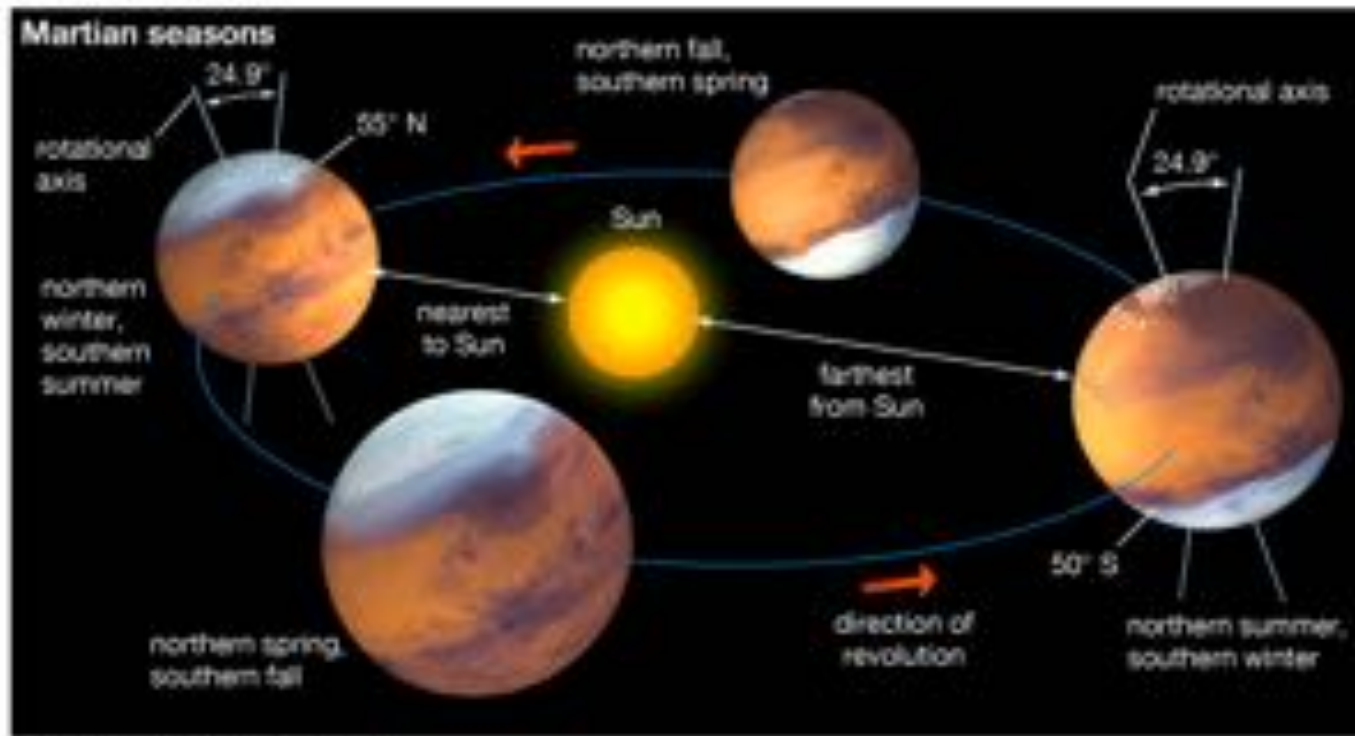


观测 | GCR辐射剂量受大气调节

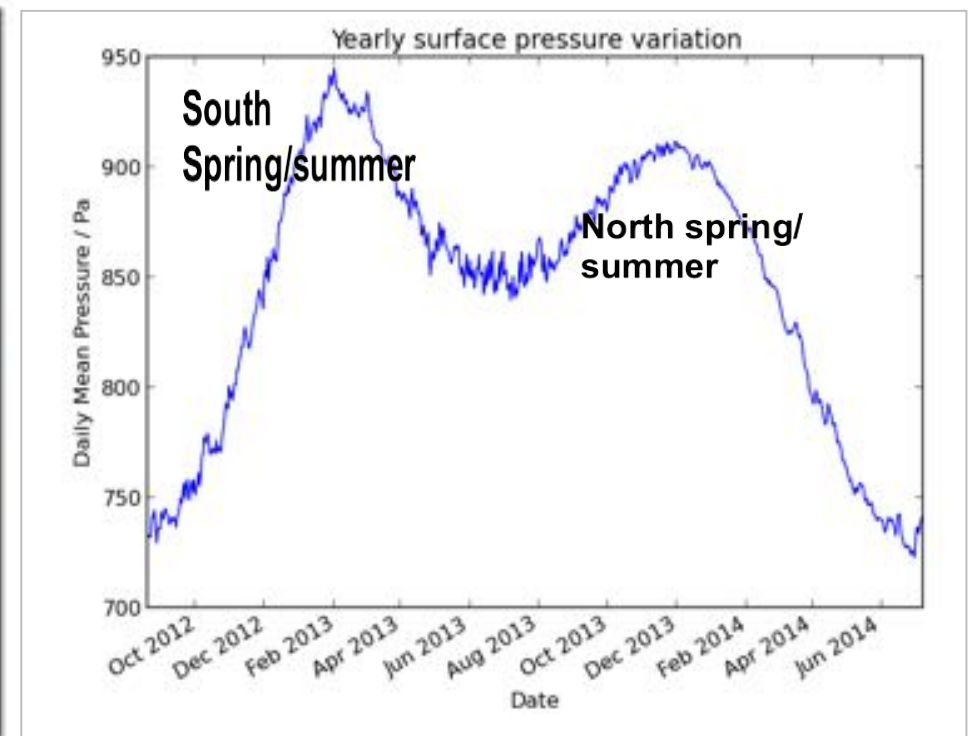
火星大气季节性变化
Tillman 1988; Zurek 1988

辐射受
大气影响

受两极CO₂冰层的季节性收缩调制



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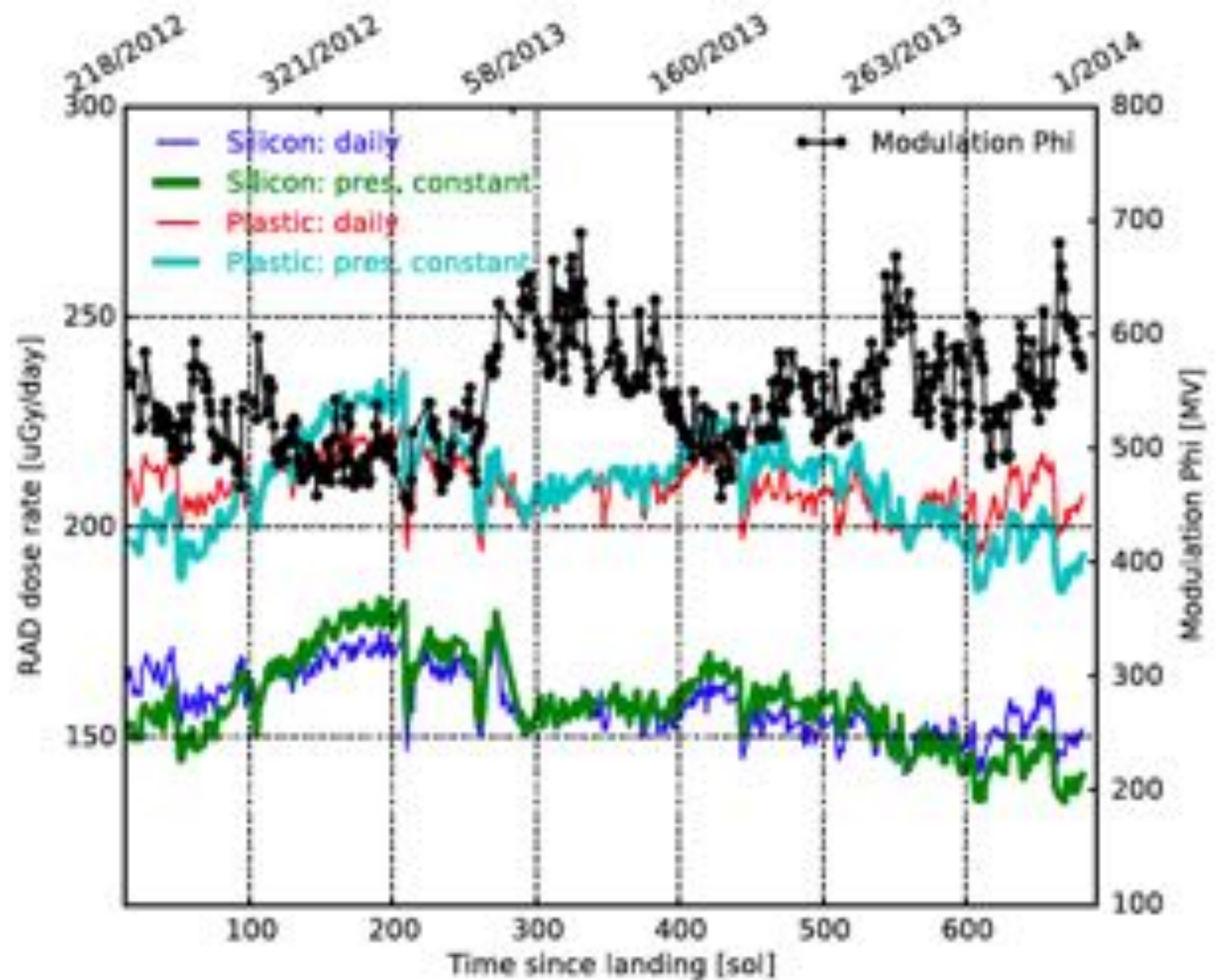
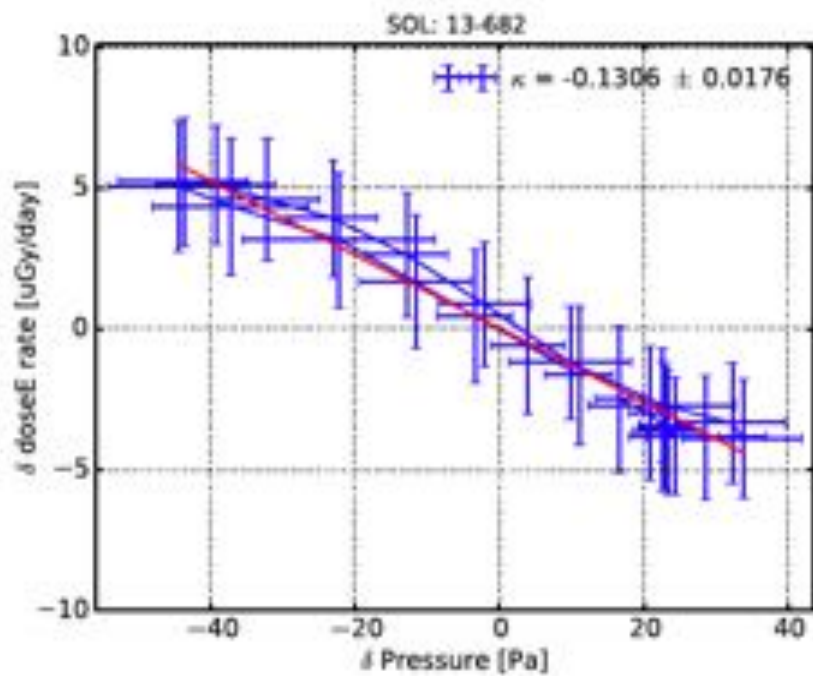


观测 | GCR辐射剂量受大气调节和太阳调制

大气季节性变化引发辐射变化
Guo+ 2015 ApJ

辐射受
大气影响

去除季节性影响后的GCR辐射
主要受太阳调制作用



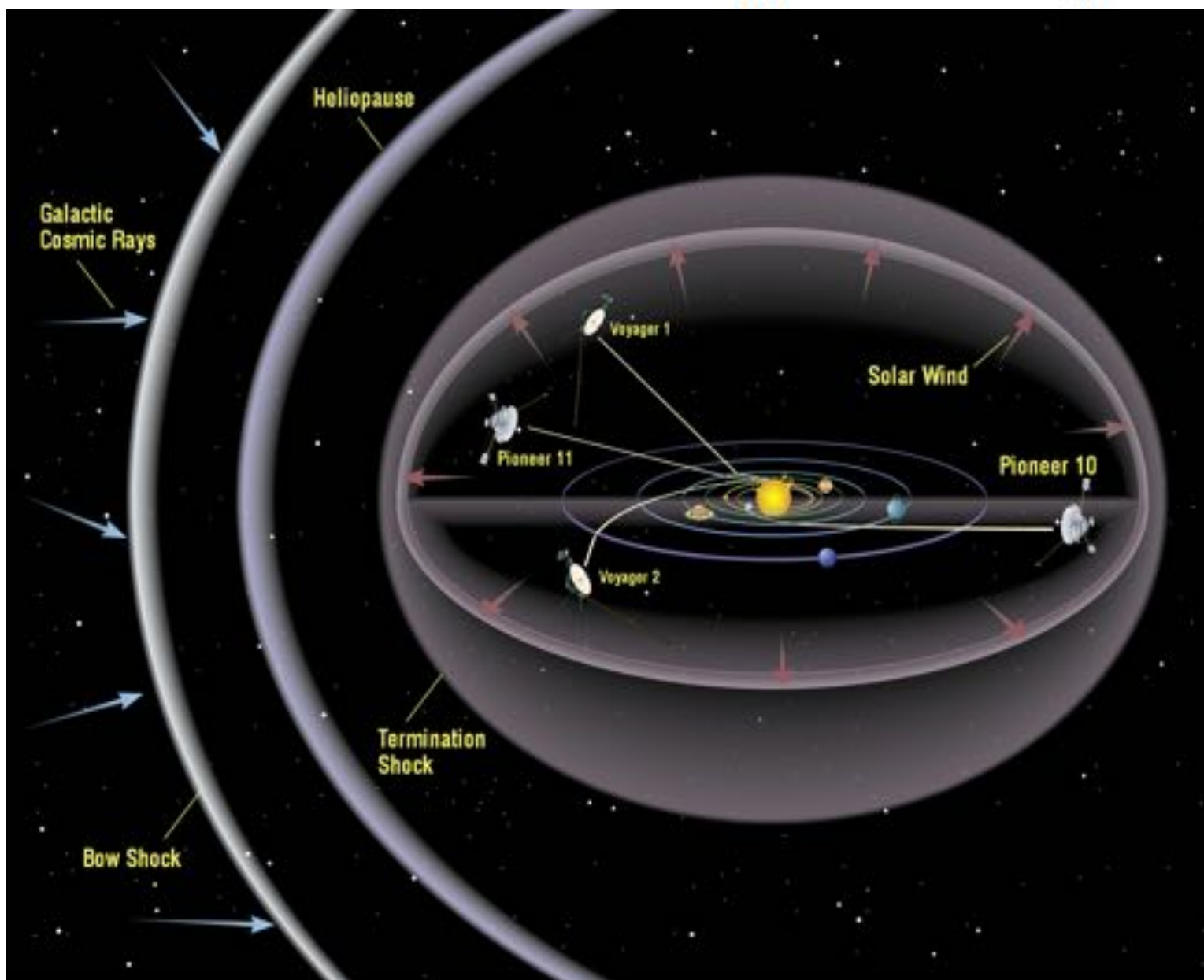
上图：从昼夜相关性里孤立出
大气对辐射的定量影响
(Super-posed Epoch)

右图：然后从长期演化中除去
季节性的大气的影响

宇宙射线粒子在向太阳系内传播的过程中，受行星际磁场影响而产生能谱变化。这一过程可由 Fokker-Planck Equation 描述 (Parker 1965, Planetary & Space Sci.)

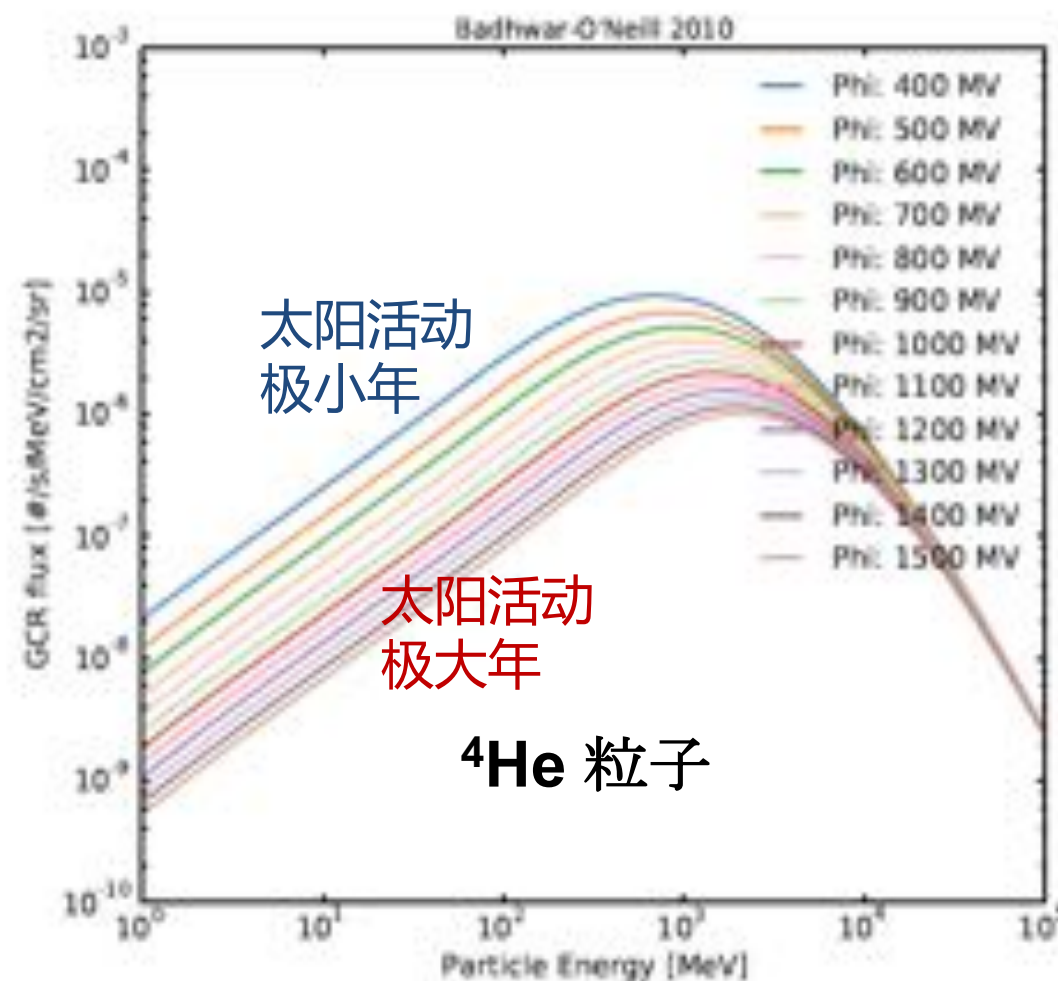
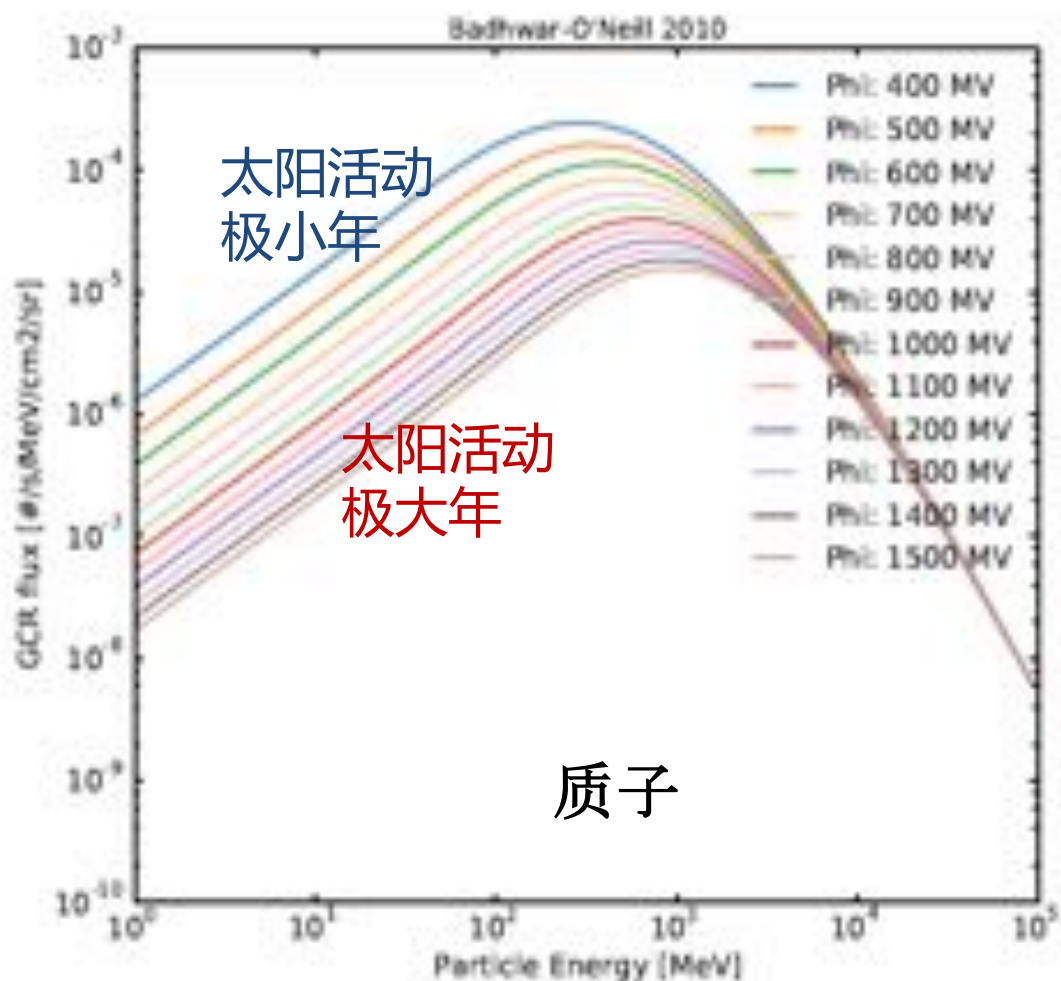
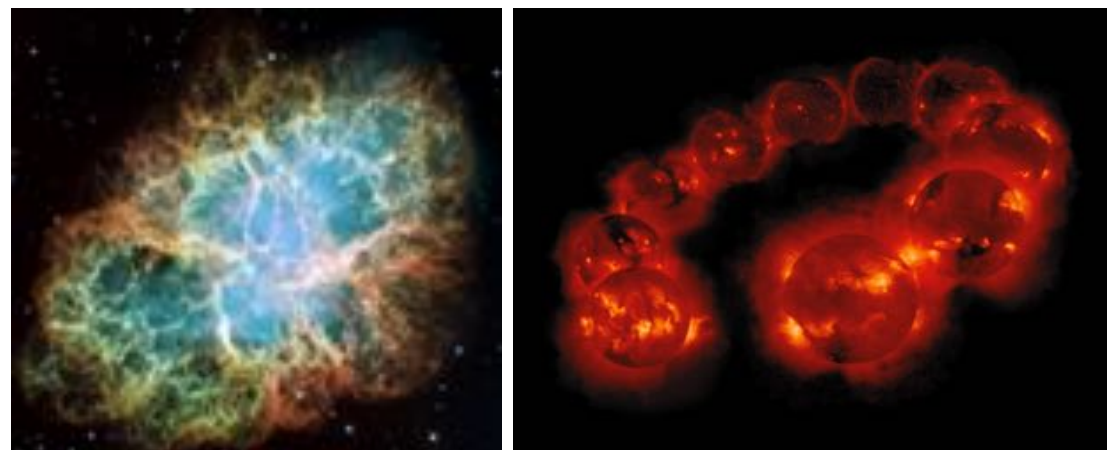
- i. 太阳风对流作用 outward solar wind convection
- ii. 粒子受磁场梯度和弯度作用产生漂移运动 gradient and curvature drifts
- iii. 粒子受磁场不均匀性和湍动影响的不规则扩散运用 diffusion through the irregular magnetic field
- iv. 绝热能损 adiabatic energy loss due to divergence of the expanding solar wind

$$\frac{\partial f}{\partial t} = - \left(\underbrace{\mathbf{V}}_i + \underbrace{\langle \mathbf{v}_D \rangle}_{ii} \right) \cdot \nabla f + \underbrace{\nabla \cdot \left(\overleftrightarrow{\kappa} \cdot \nabla f \right)}_{iii} + \underbrace{\frac{1}{3} (\nabla \cdot \mathbf{V}) \frac{\partial f}{\partial \ln P}}_{iv}$$



GCR辐射剂量受太阳调制

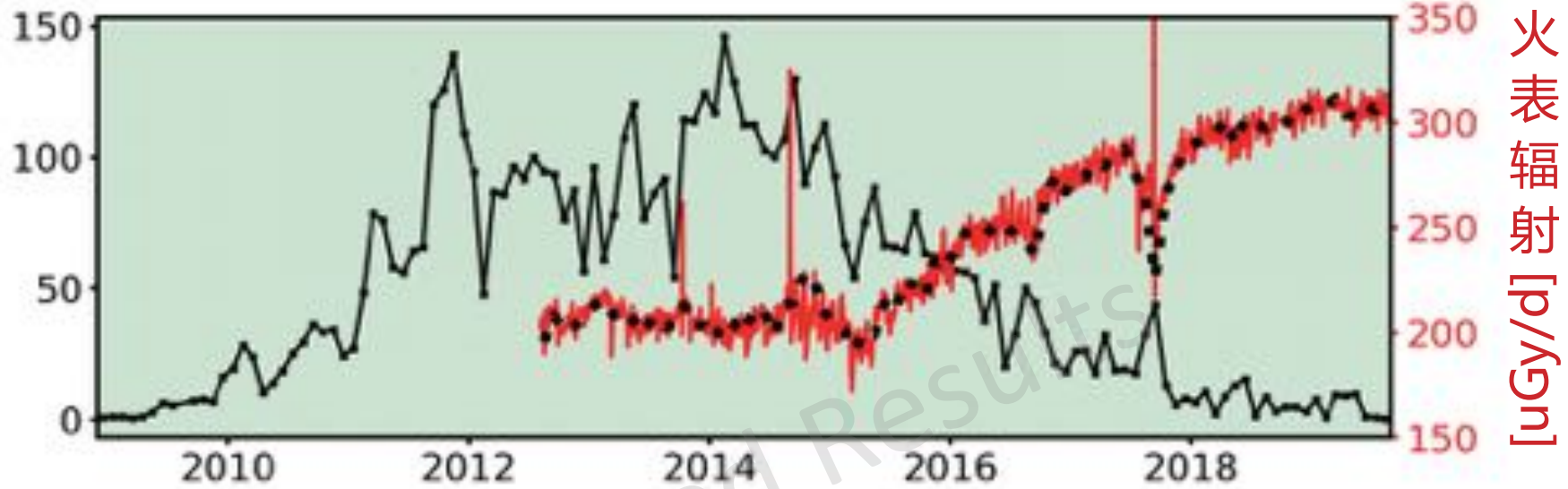
Badwahr O'Neil GCR 模型 (O'Neil 2010, 2014) : 初始粒子为被激波加速的、幂率谱分布的GCR初始能谱; 日球磁场为球形对称分布的空间磁场; 考虑粒子diffusion, convection, & adiabatic deceleration 过程, 可得到地球附近的粒子能谱。



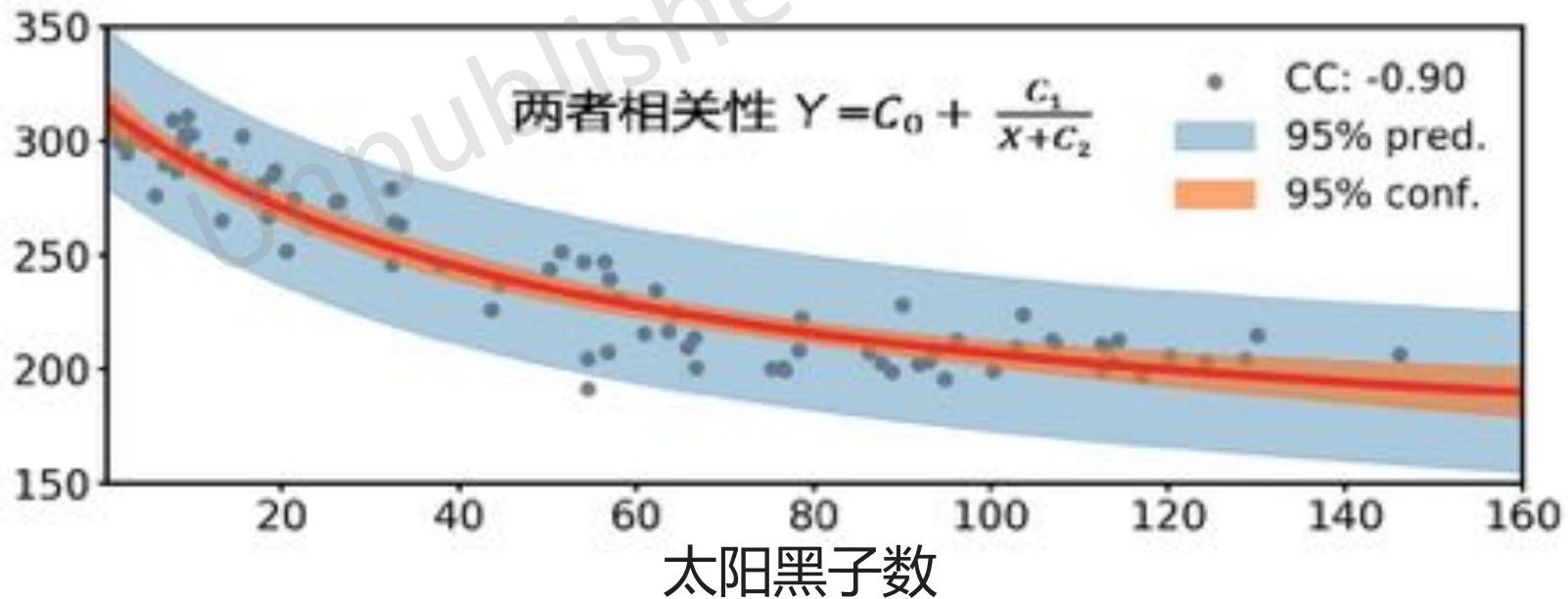
观测 | GCR辐射剂量受太阳调制

辐射随太阳活动的变化：基于数据的经验模型

24
周期
太阳
黑子
数

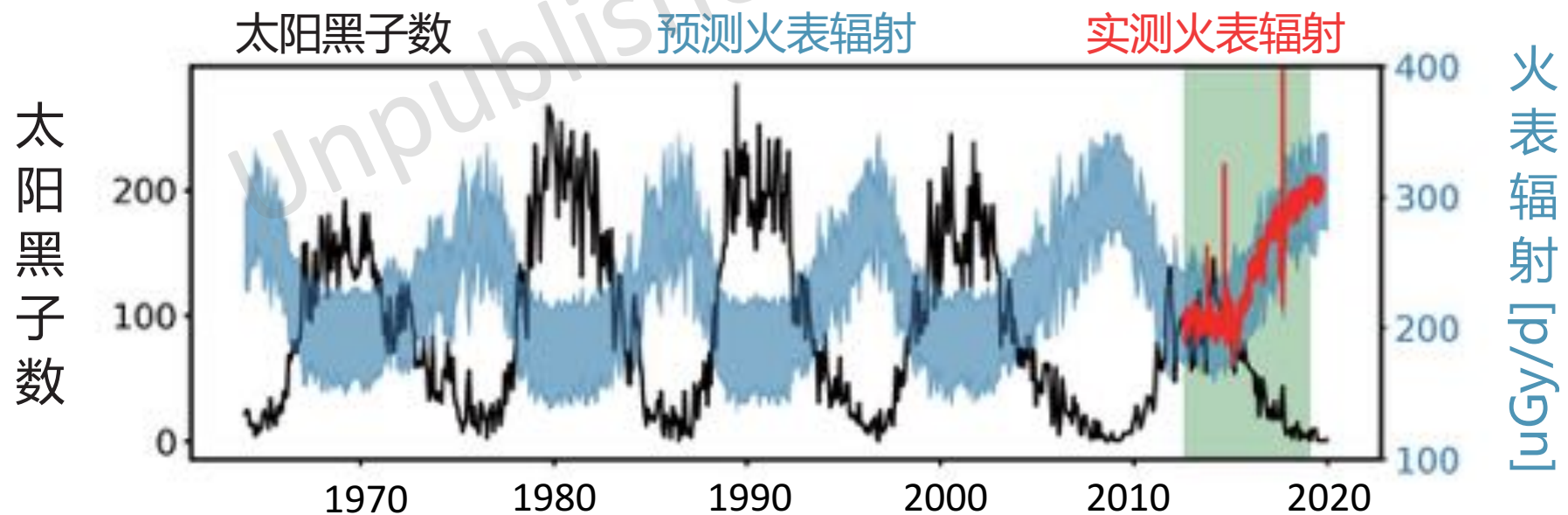
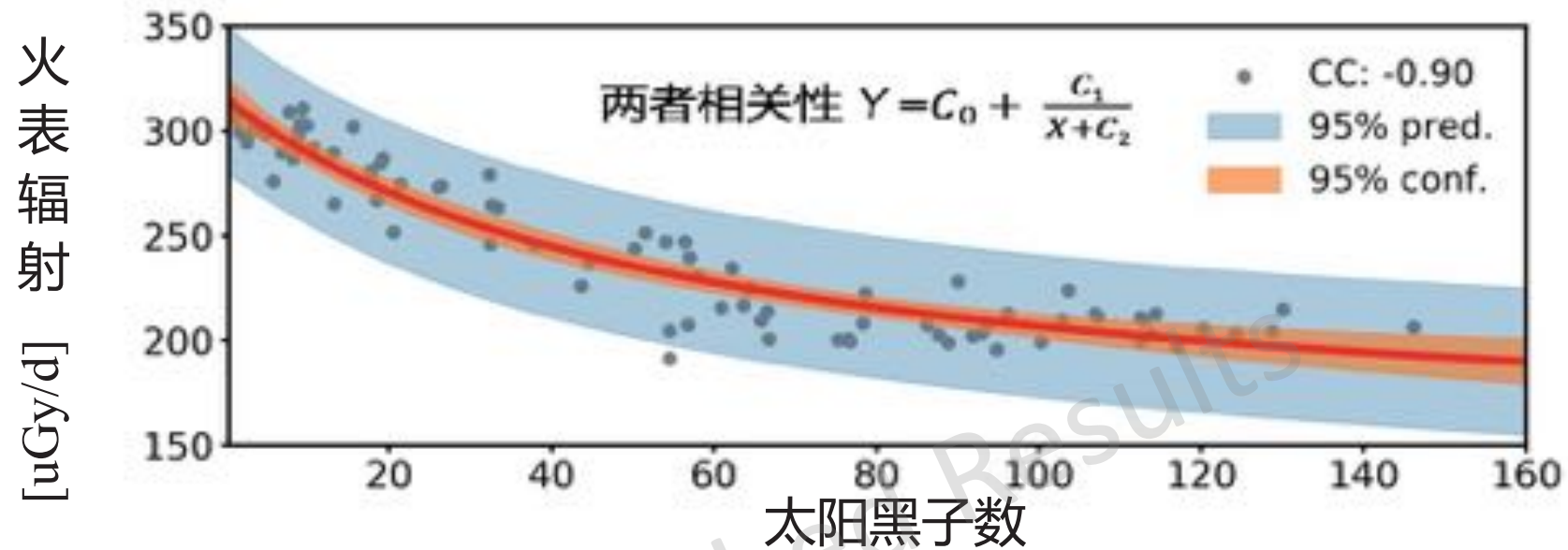


火
表
辐
射
[$\mu\text{Gy/d}$]



观测 | GCR辐射剂量受太阳调制

辐射随太阳活动的变化：用模型预测不同太阳活动下的辐射



然而。。。

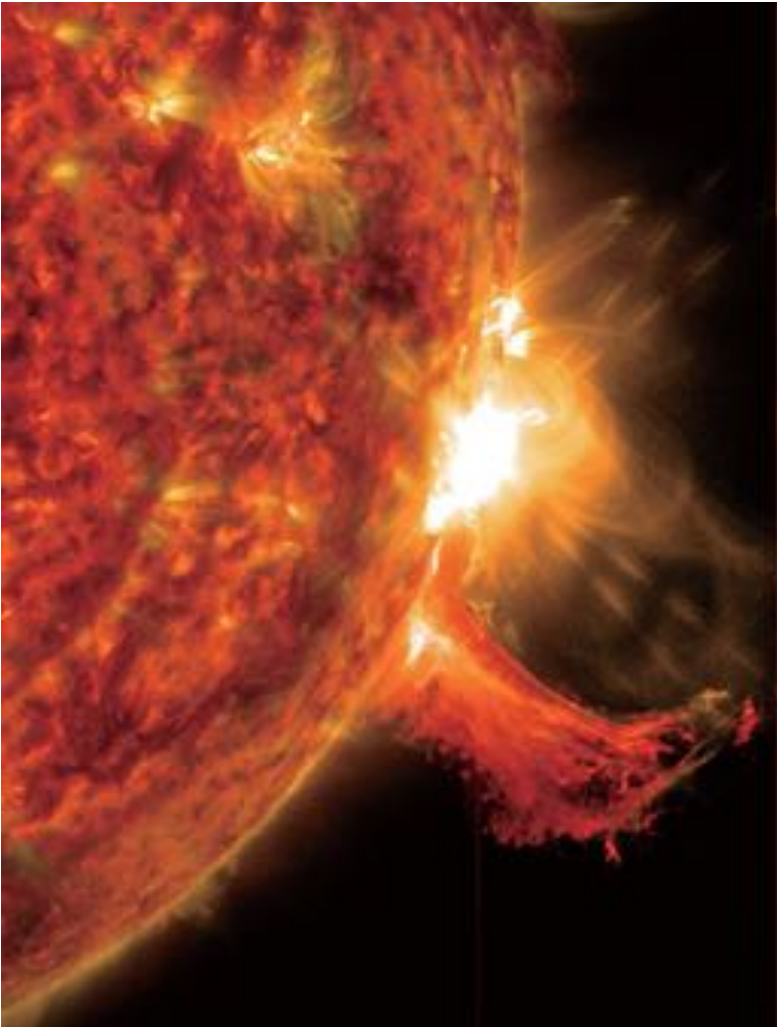
太阳极大年有更多的太阳高能粒子事件



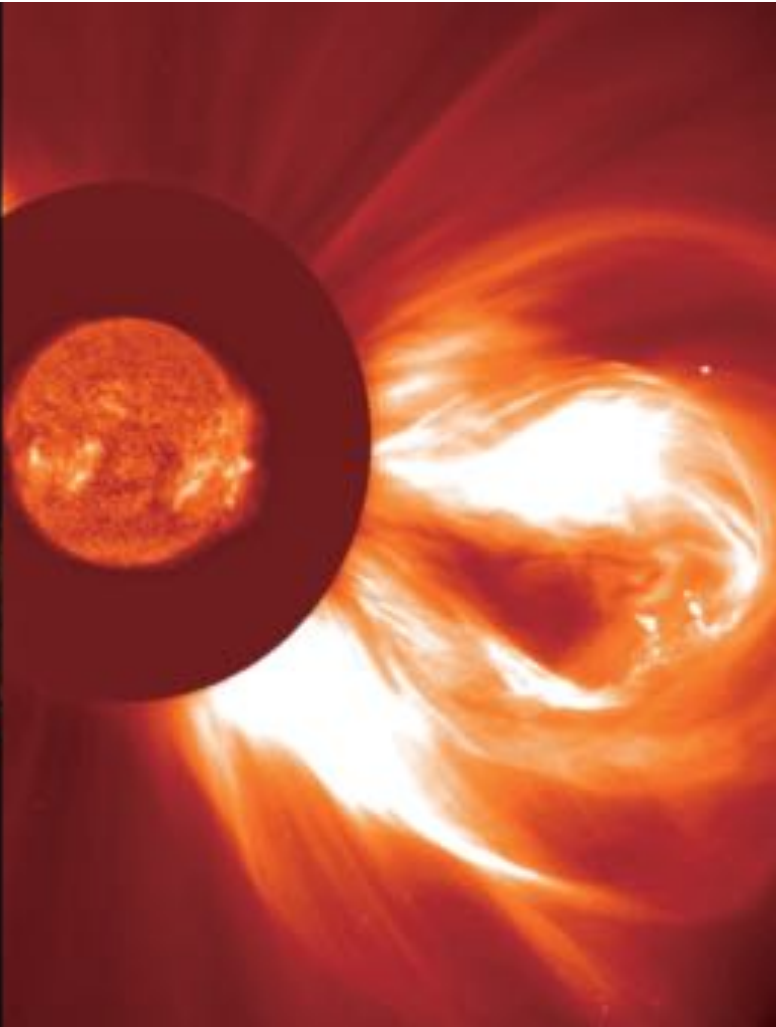
报告提纲

- 空间辐射的危害
- 空间辐射的种类
- 火星空间环境和辐射的测量
- 火星辐射的时空变化
- **太阳爆发和高能粒子事件**
- 火星辐射仿真和防护方案

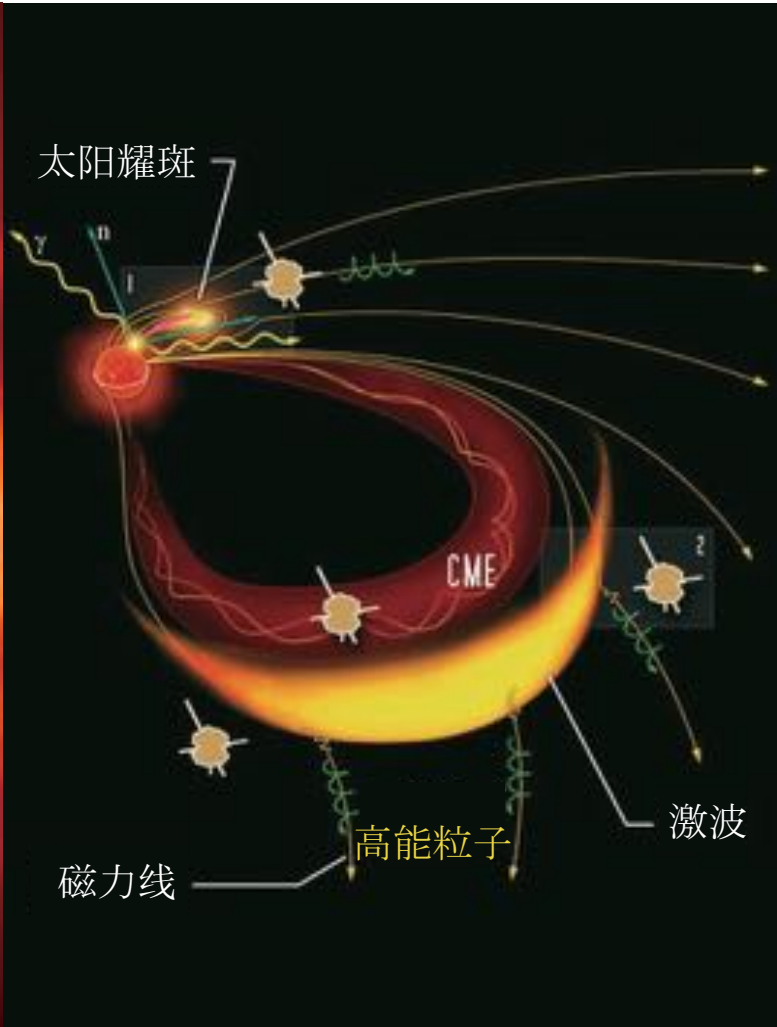
太阳爆发活动和高能粒子事件



太阳耀斑



日冕物质抛射/CME



产生高能粒子辐射

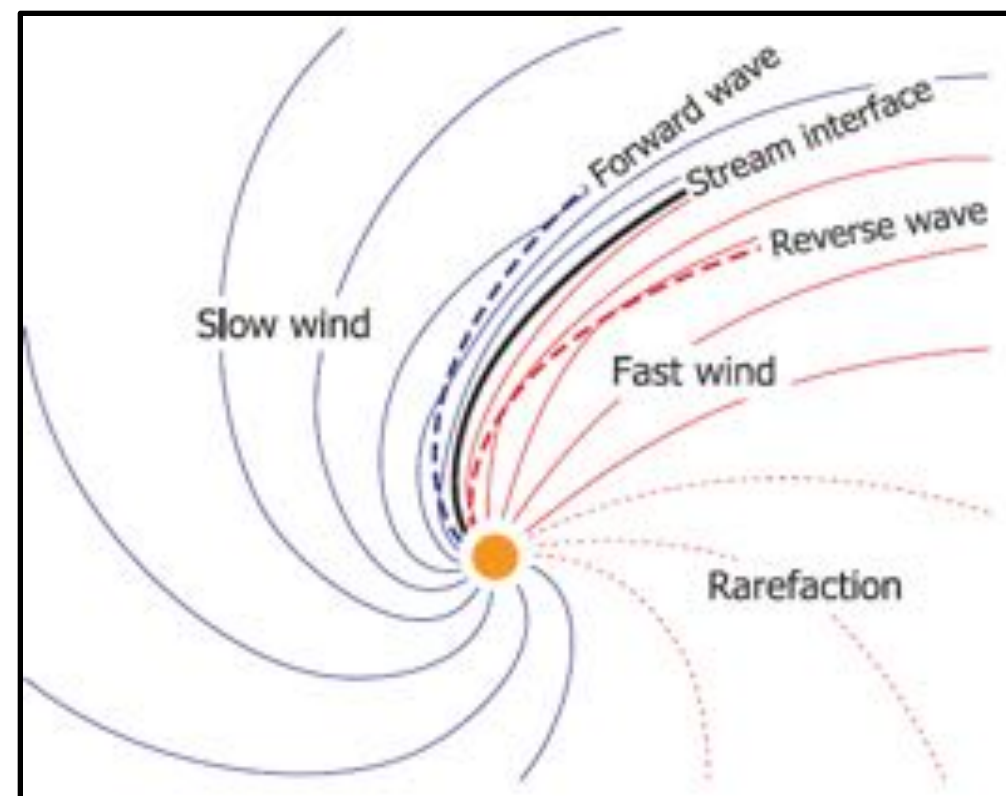
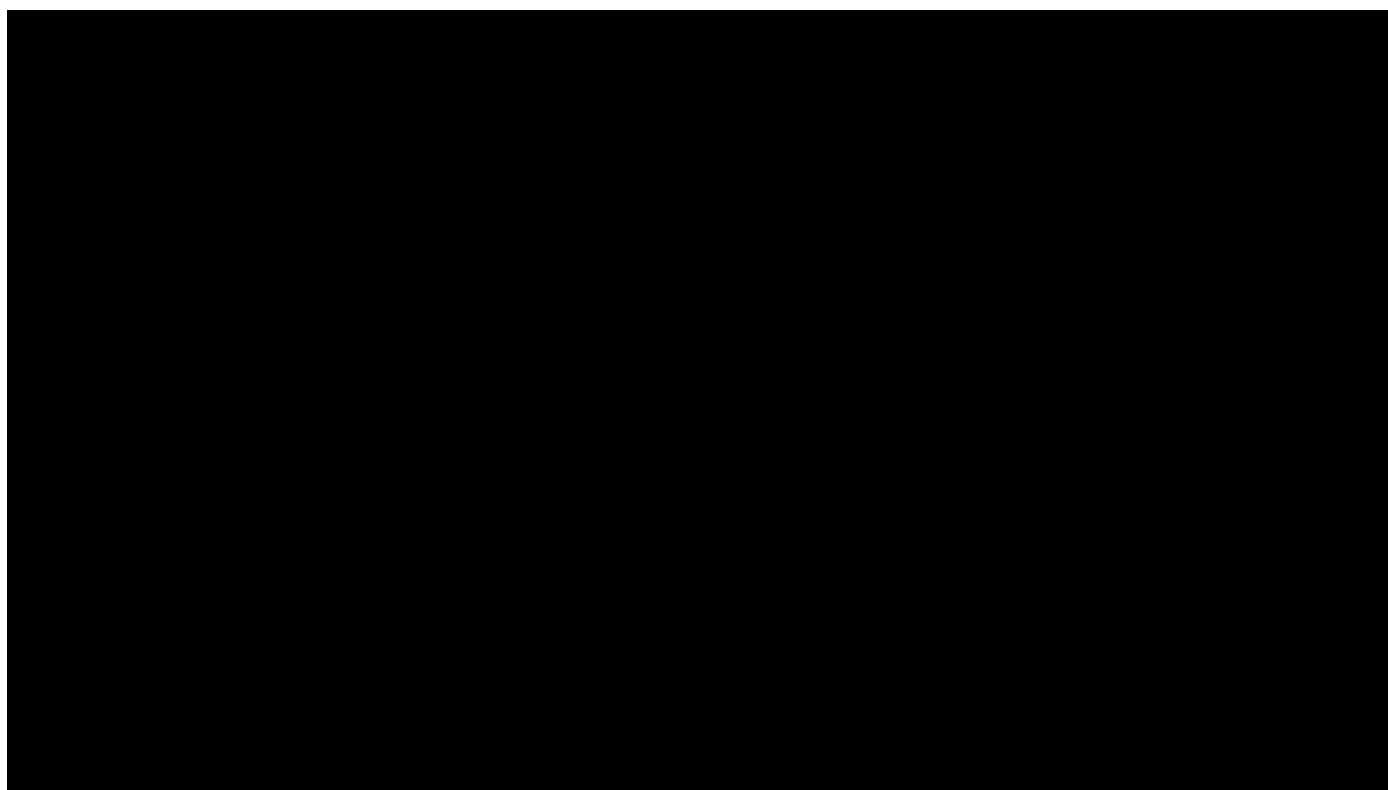
观测 | 行星际空间的日冕物质抛射会造成GCR流量的短期压抑

| Date | Detected By | Location in Space | Distance from the Sun |
|-------------------------|---|-------------------------|-----------------------|
| Oct. 14, 2014 | -- | Sun – CME Launches | -- |
| Oct. 16, 2014 | Venus Express <i>(indirect data)</i> | Venus | 0.72 AU |
| Oct. 16, 2014 | STEREO-A | The Far Side of the Sun | 0.96 AU |
| Oct. 17, 2014 | Curiosity | Mars | 1.41 AU |
| | MAVEN | | |
| | Mars Express | | |
| | Mars Odyssey | | |
| Oct. 22, 2014 | Rosetta | Comet 67P | 3.13 AU |
| Nov. 12, 2014 | Cassini | Saturn | 9.94 AU |
| Jan. 18 – Feb. 14, 2015 | New Horizons <i>(possible detection)</i> | En Route to Pluto | 31.49 AU |
| Late March 2016 | Voyager 2 <i>(possible detection)</i> | The Heliosheath | 111.06 AU |

行星际空间的日冕物质抛射经过火星到达太阳系边缘

太阳风和行星际空间的CIR结构

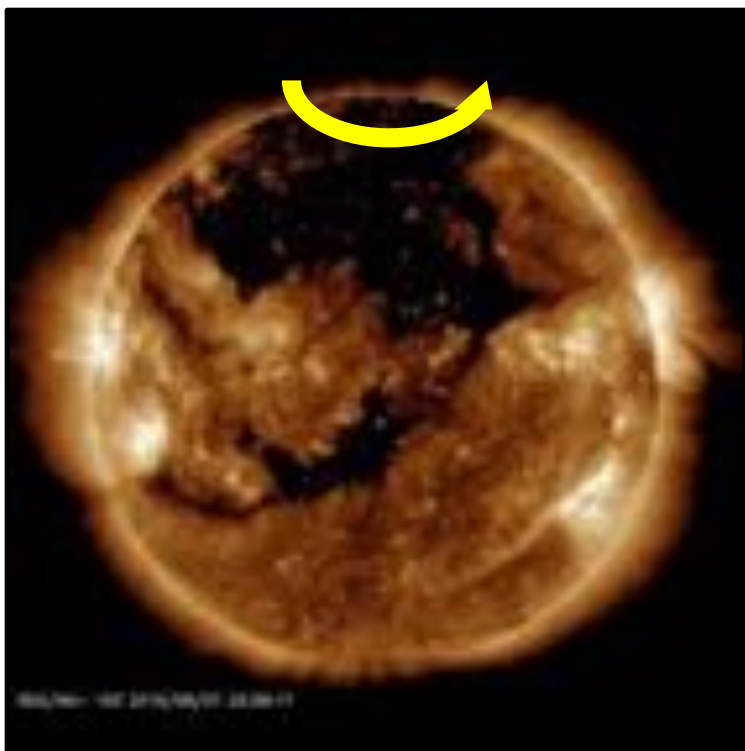
太阳风 和 Corotating Interaction Region / 共转相互作用区



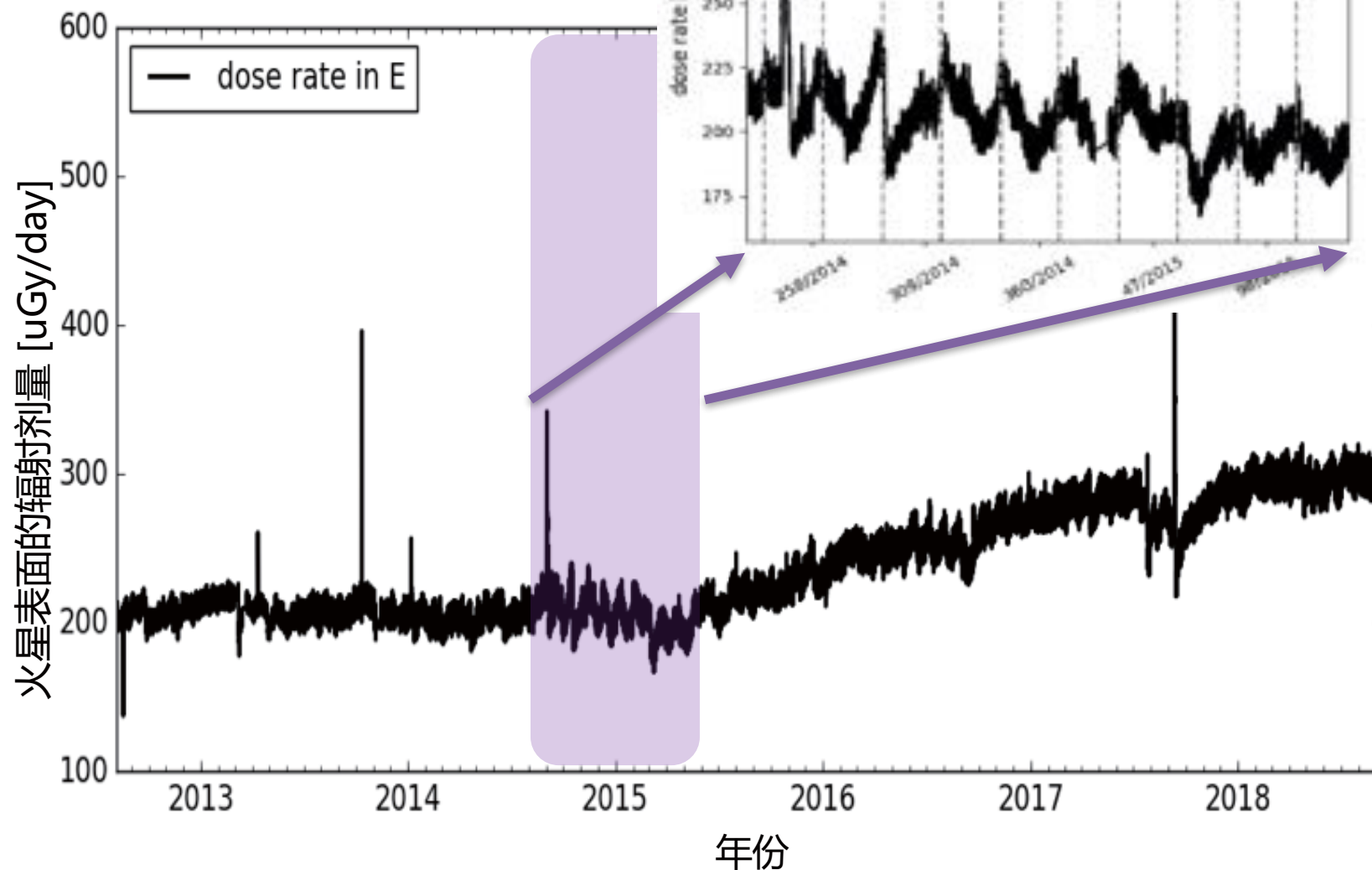
观测 | 行星际空间的CIR结构

CIR可造成背景GCR辐射的周期性震荡

- 我们在火星也观测到了这一特征



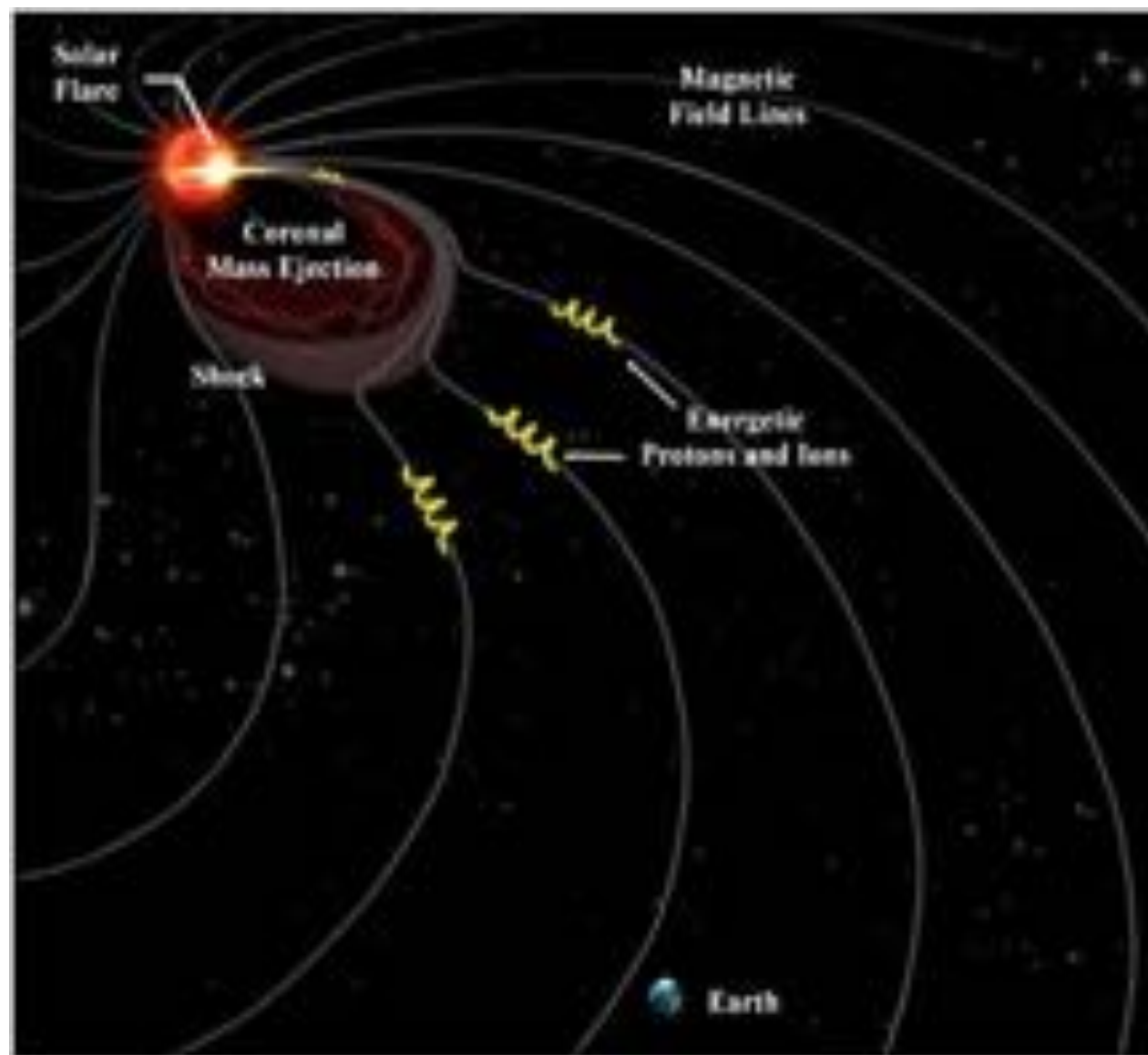
- 快太阳风来自于冕洞
- 冕洞随太阳自转



太阳高能粒子的辐射效应

深空和火表的高能粒子流量及辐射和地球以及地球附近的差别很大

- ❖ **源区**：不同观测者和粒子加速区（太阳耀斑, 日冕物质抛射, 激波）的磁场链接不同
- ❖ **传输**：不同的空间磁场结构和扰动导致不同能量和种类的粒子经历不同程度的横跨磁场的运输
- ❖ **局地作用**：粒子到达局地后，和火星大气或者宇宙飞船的电离作用和碰撞核作用会改变粒子的能量和种类



经典的SEP事件分为两类

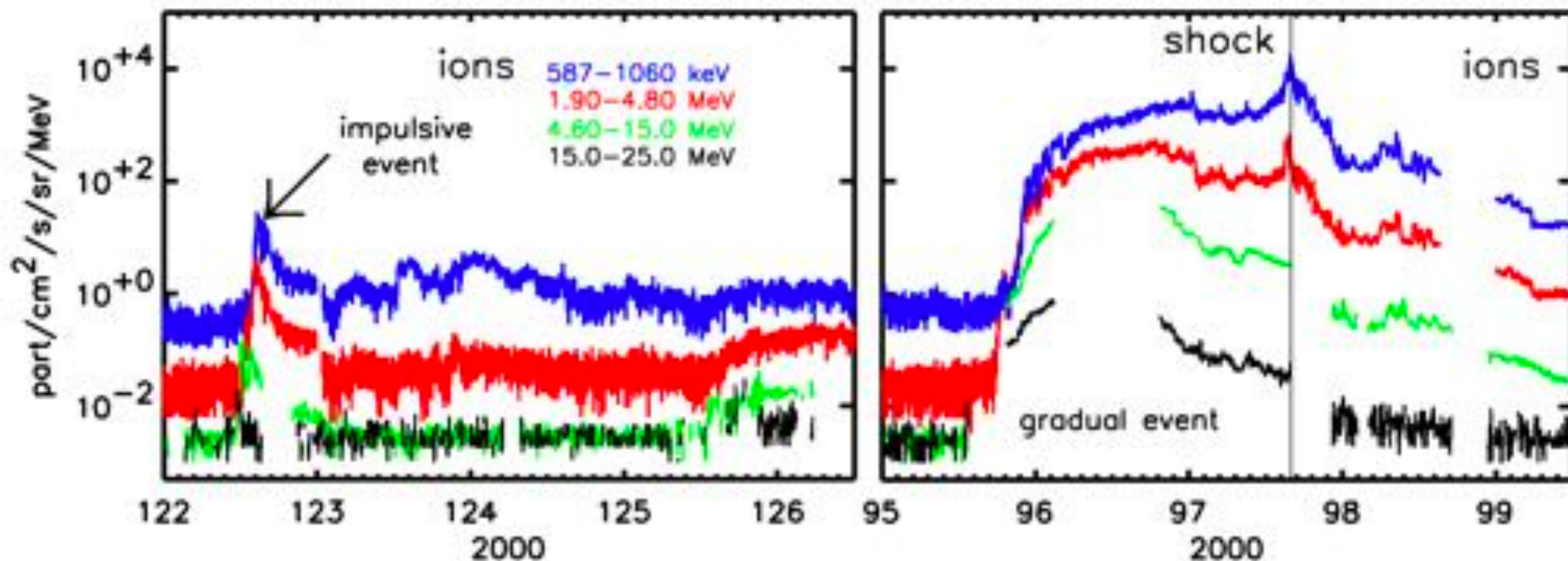
Impulsive Events :

- High e/p ratio
- Mainly low energy particles
- Enhanced ^3He , and heavy ions
- Narrow beam
- Type III radio bursts
- Mainly flare accelerated

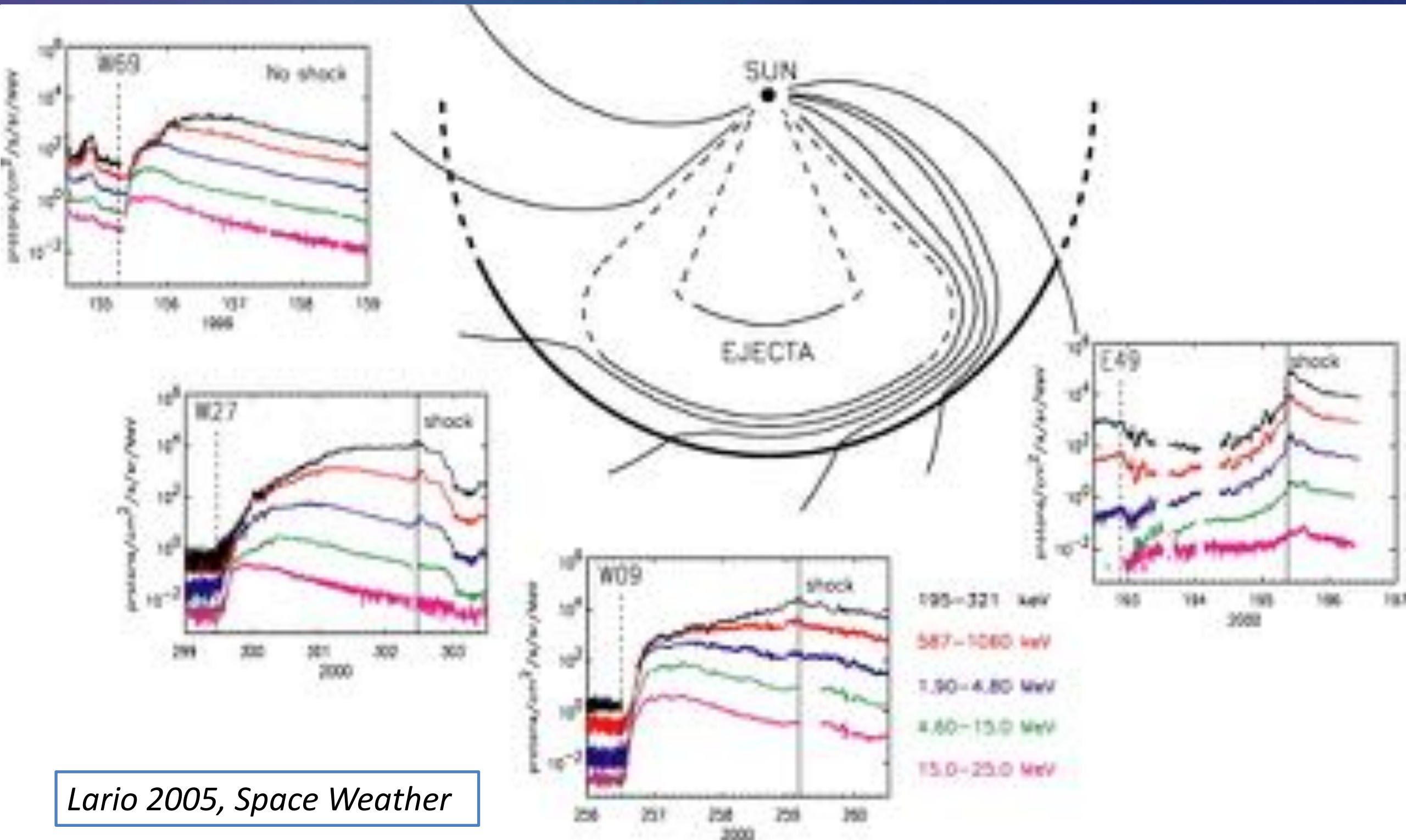
局地观测特征

Gradual events :

- Low e/p ratio
- Variable composition and charge
- Larger flares and CMEs
- Widely spread in the heliosphere
- Mainly accelerated by CME shocks
- Rather rare (1/month)

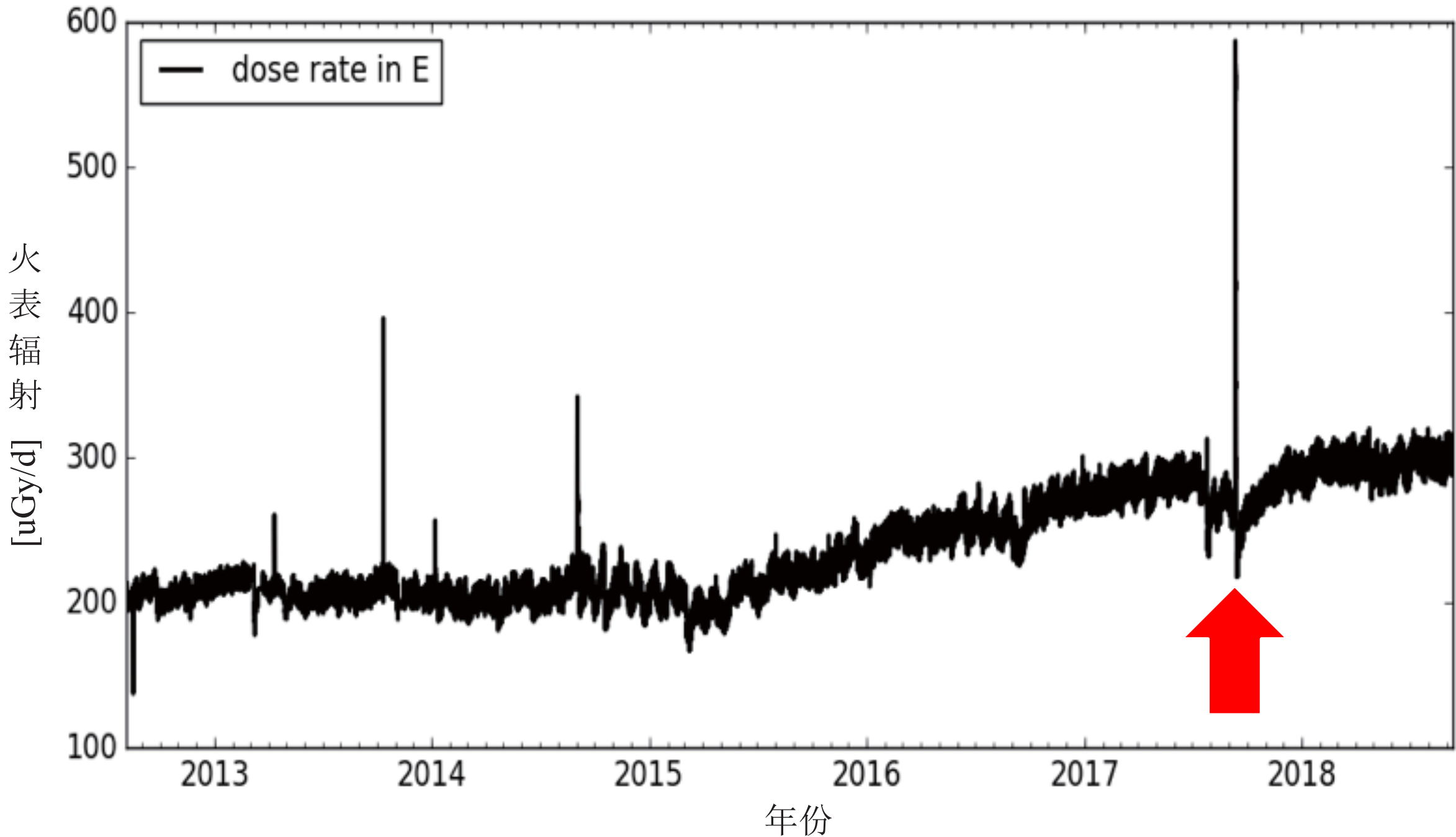


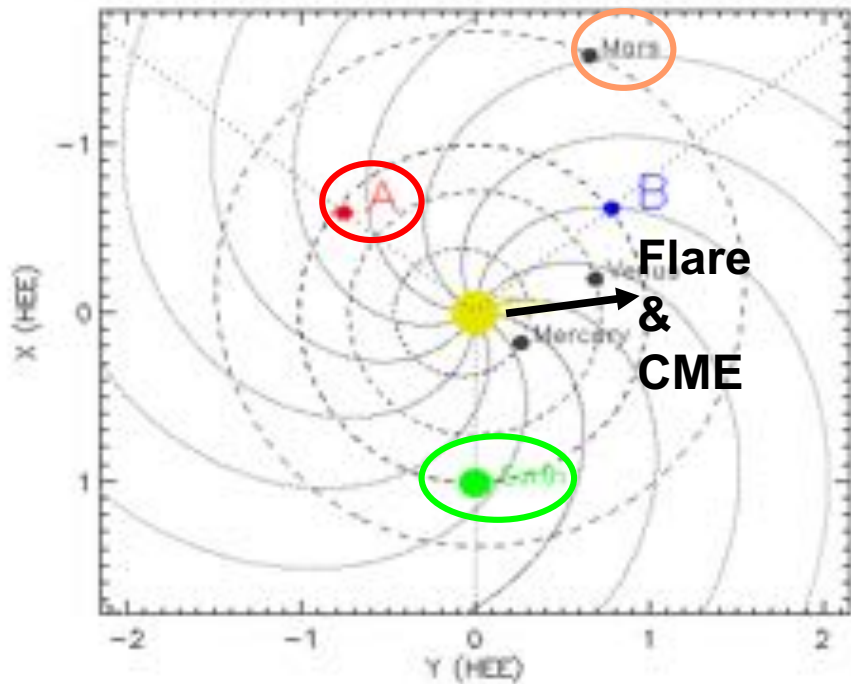
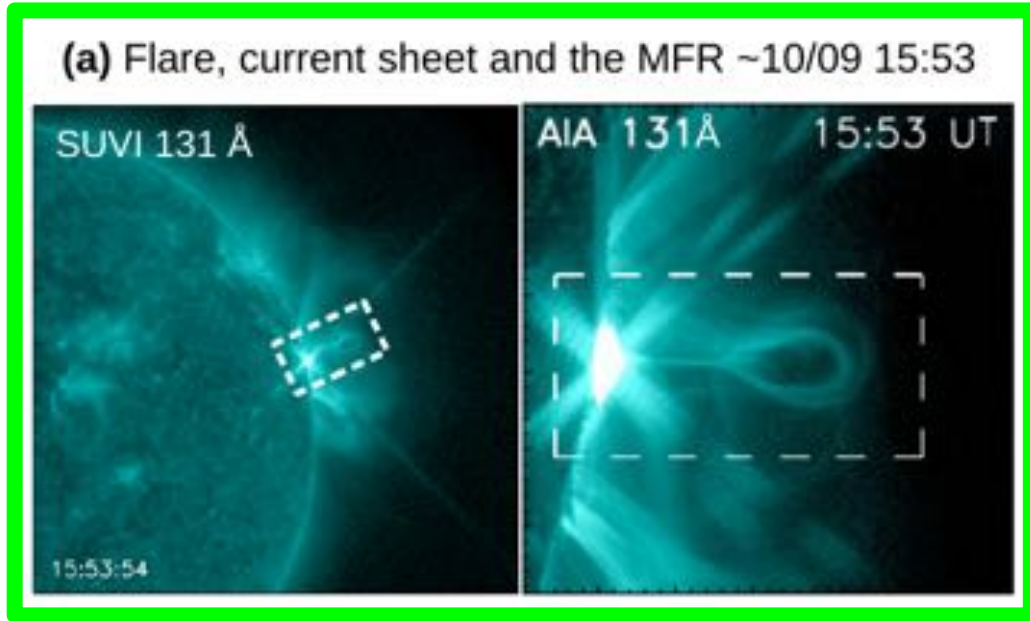
同一个SEP事件在不同的地方的局地特征也会不同



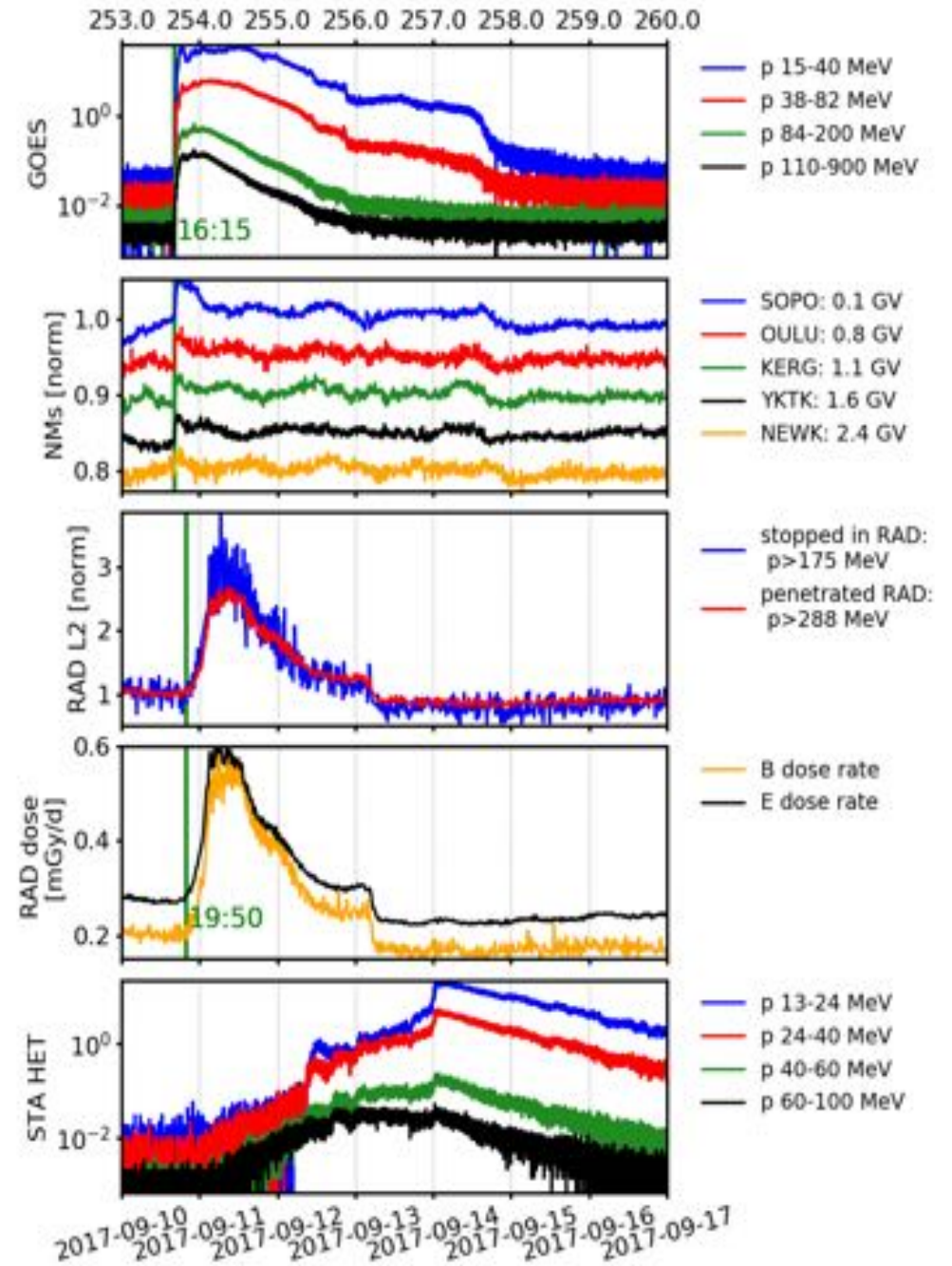
Lario 2005, Space Weather

观测 | 太阳爆发活动和高能粒子事件





GOES
Earth
NMs

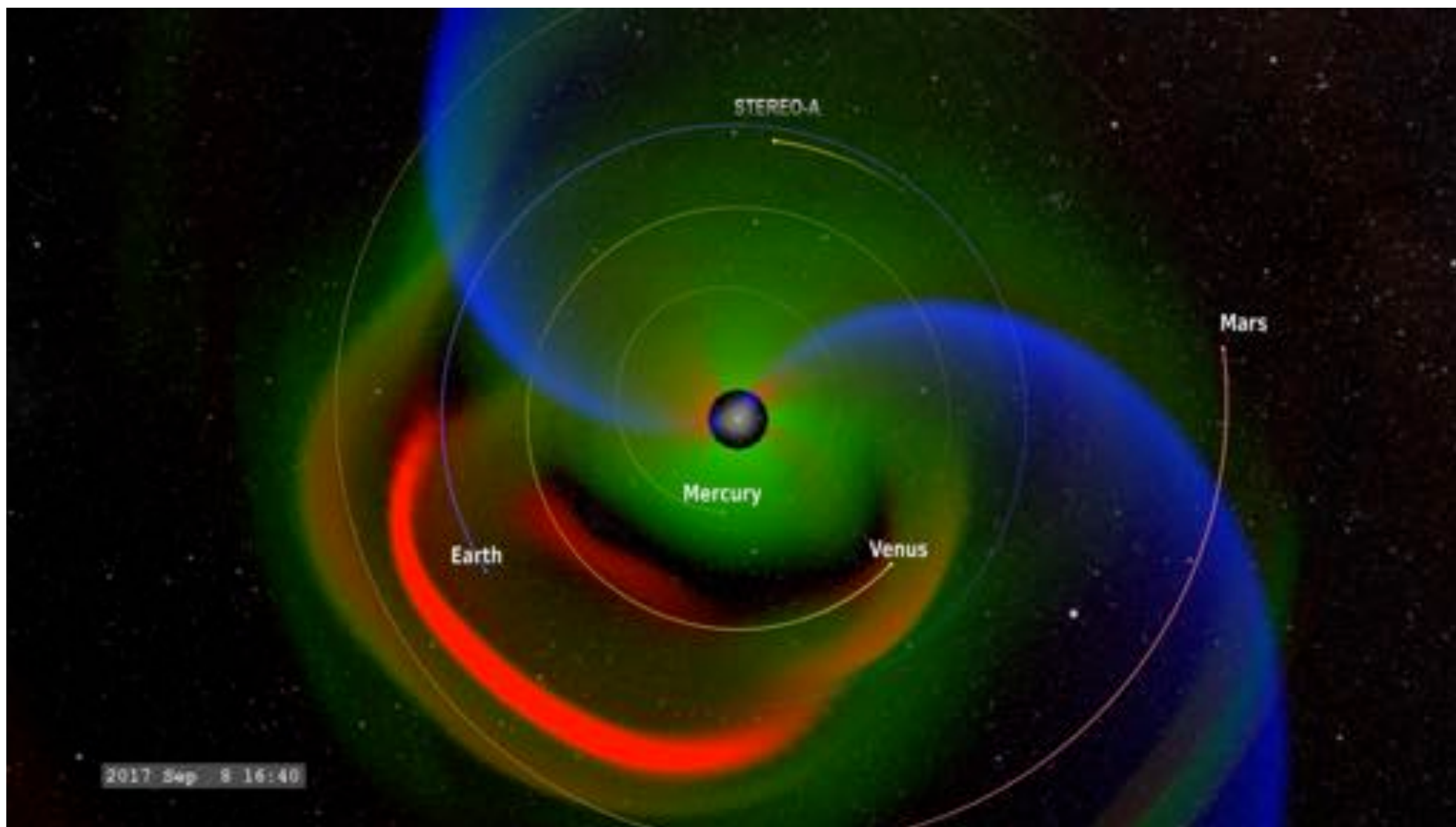


Mars
MSL/
RAD

STA
HET

太阳爆发活动和高能粒子事件

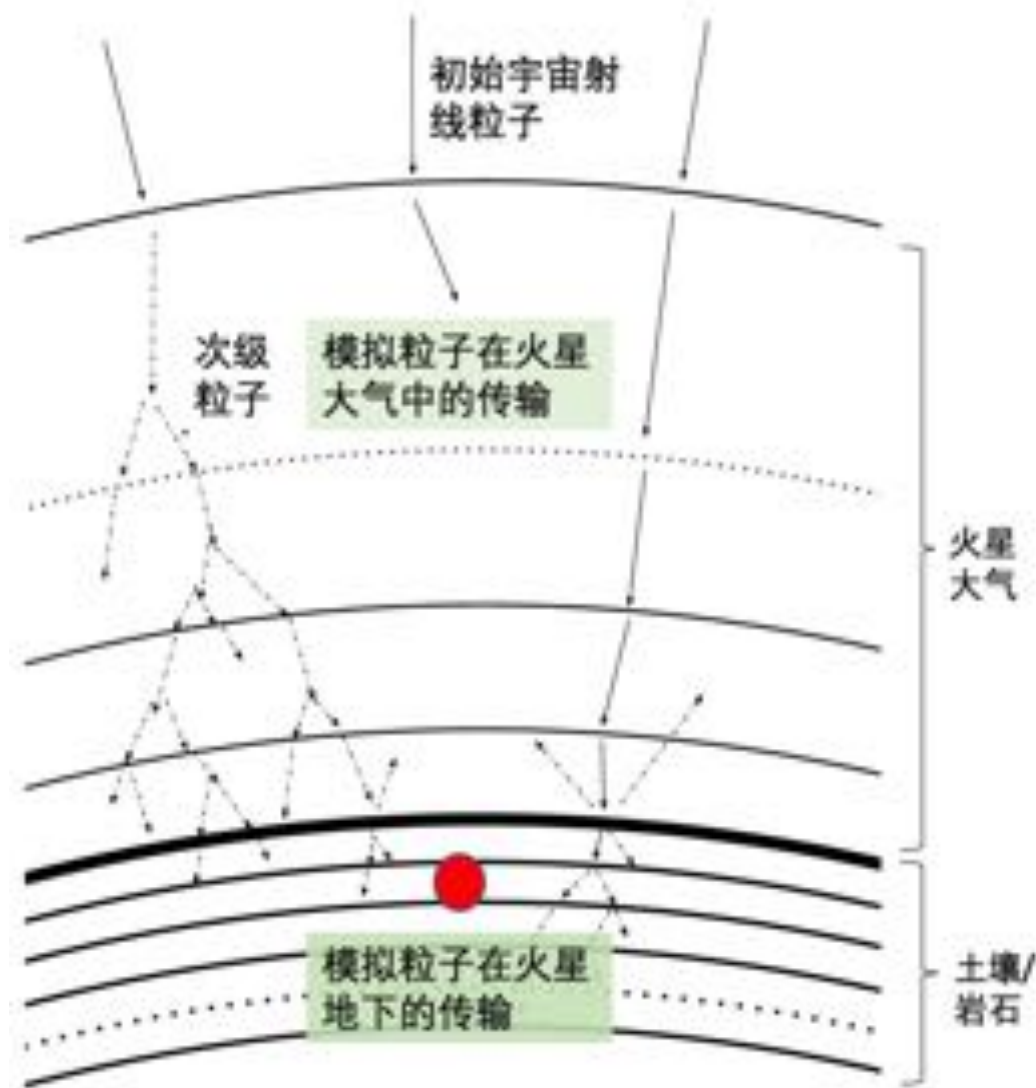
首次在两个行星表面同时探测到的太阳高能粒子事件



高能粒子在火星环境中传输的模型

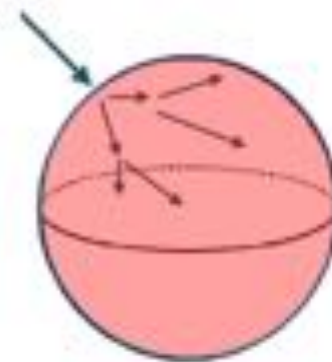
Guo+ 2019 SWSC, Roestel+ 2020 JGR

报告提纲



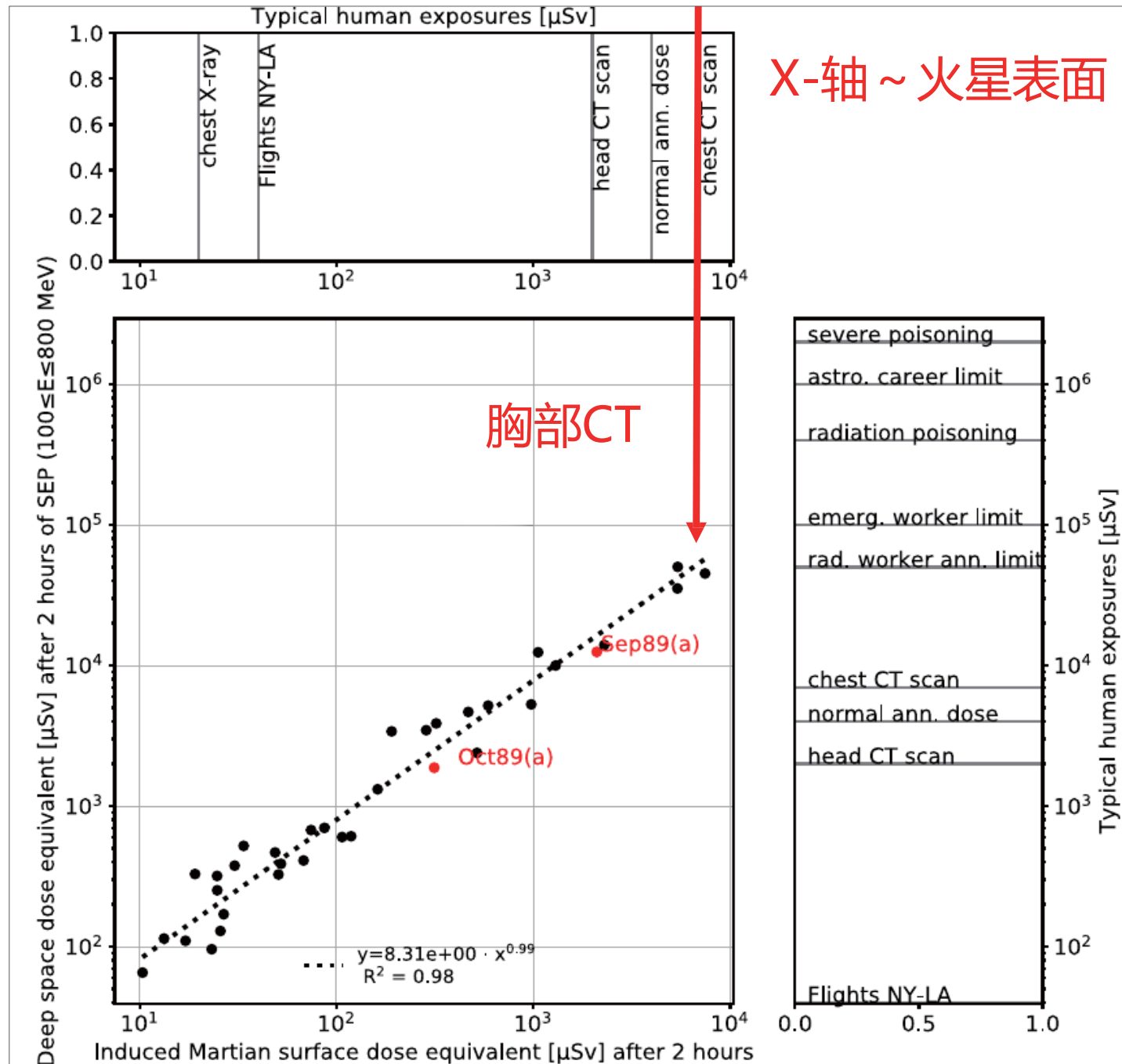
火星环境下的粒子进一步和人体作用引发生物辐射剂量

这一过程用近似人体上身躯干的“水球”（半径15 cm）来模拟



- 空间辐射的危害
- 空间辐射的种类
- 火星表面辐射的实测和标定
- 空间辐射的长期演化
- 太阳高能粒子辐射事件
- 火星辐射仿真和防护

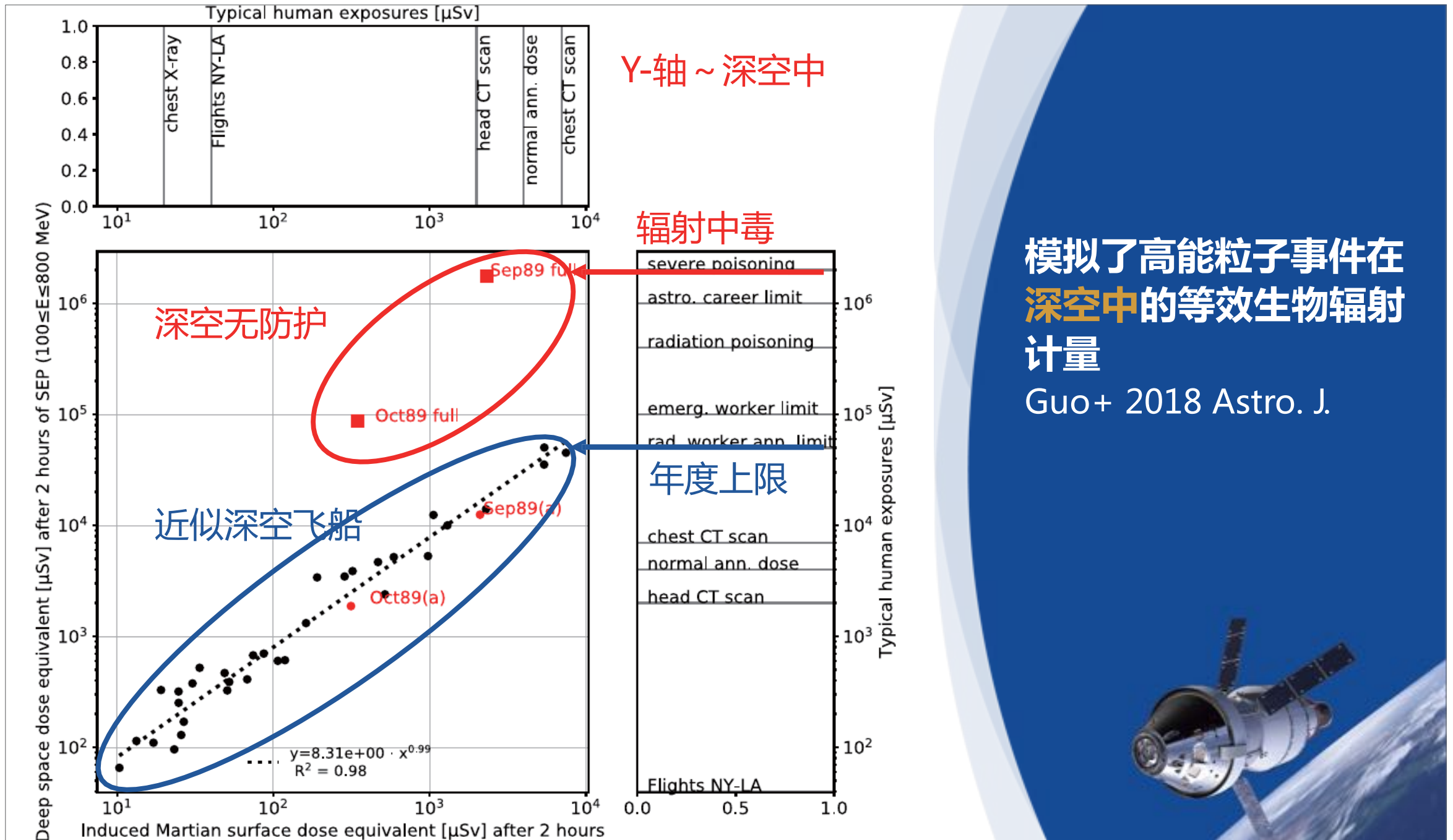
模型 | 深空和火星辐射环境的仿真



模拟了高能粒子事件在火星表面引发的等效生物辐射计量

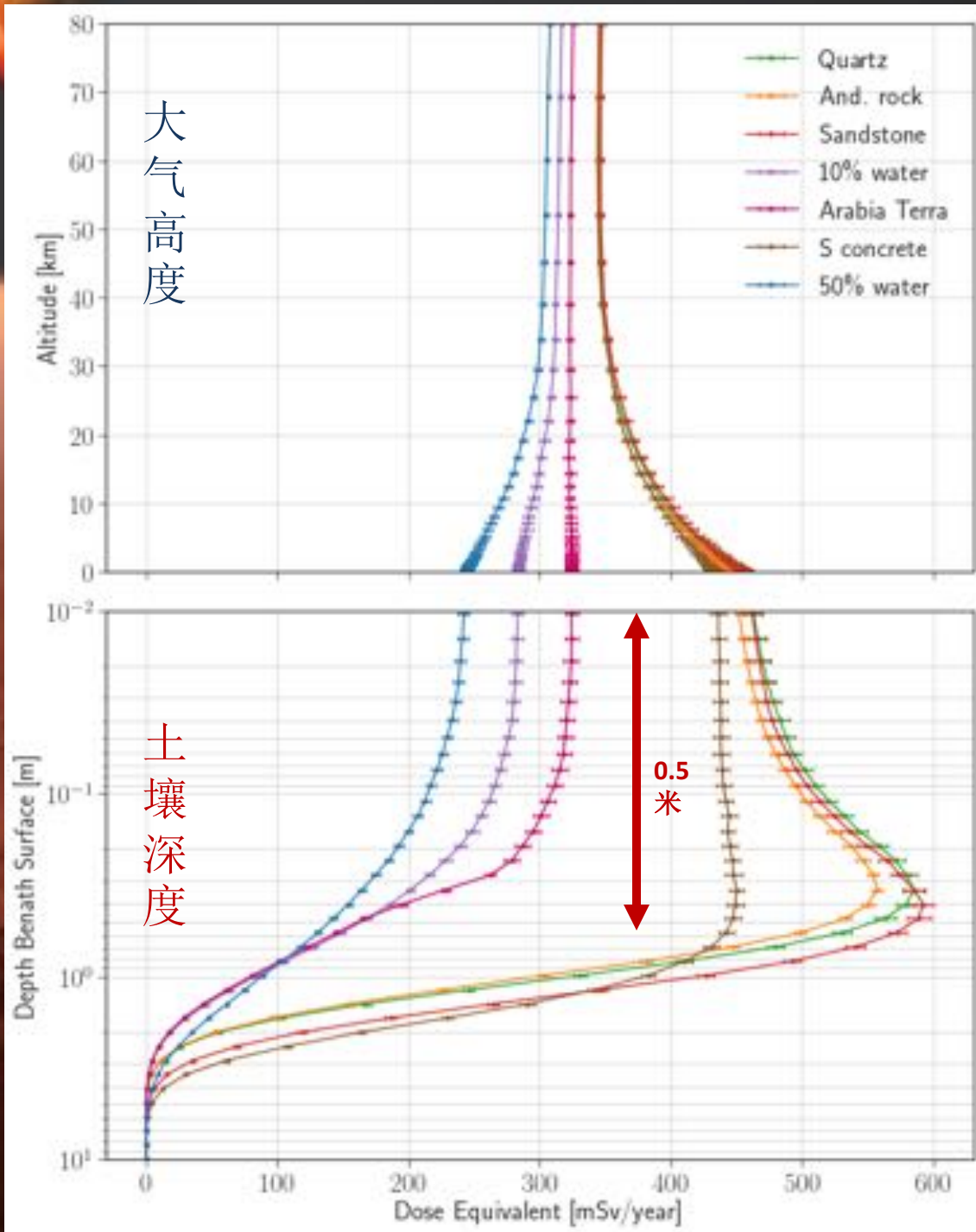
Guo+ 2018 Astro. J.

模型 | 深空和火星辐射环境的仿真



利用火星土壤做屏蔽

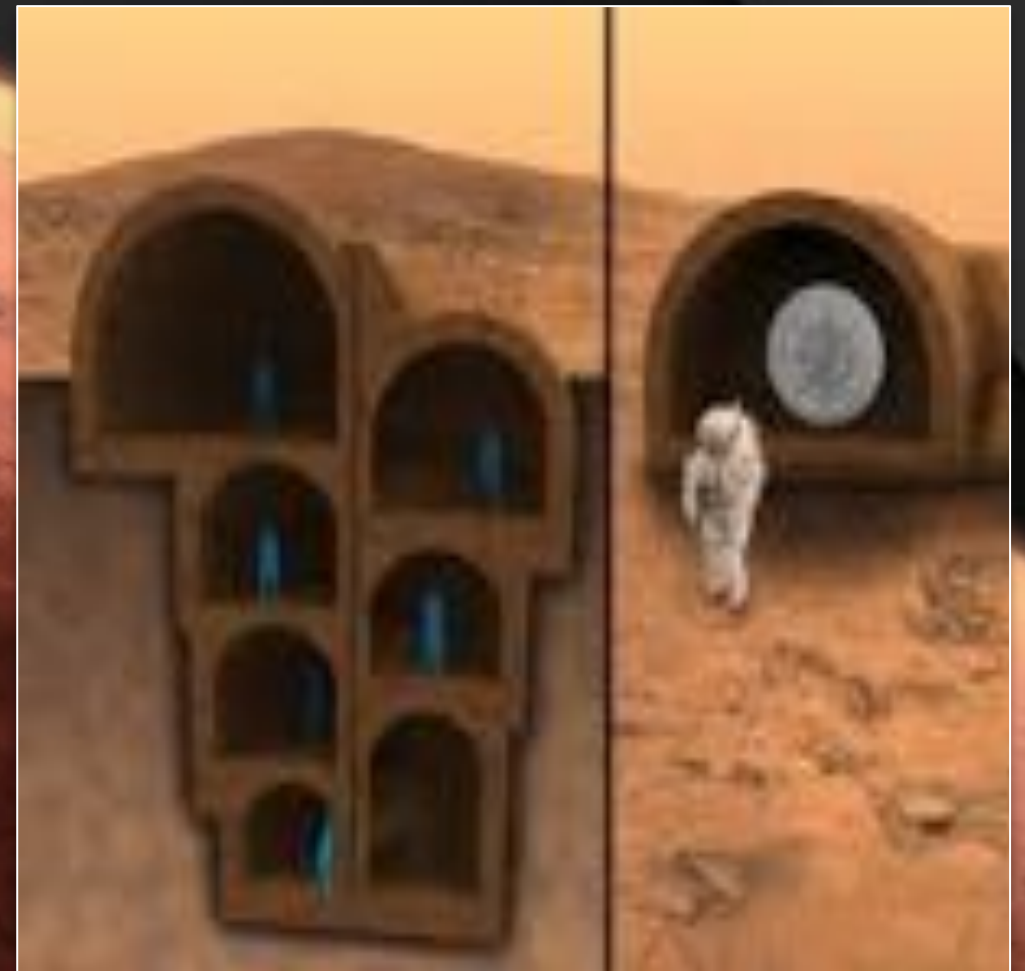
Roestl+ 2020, JGR: planets



大气高度

土壤深度

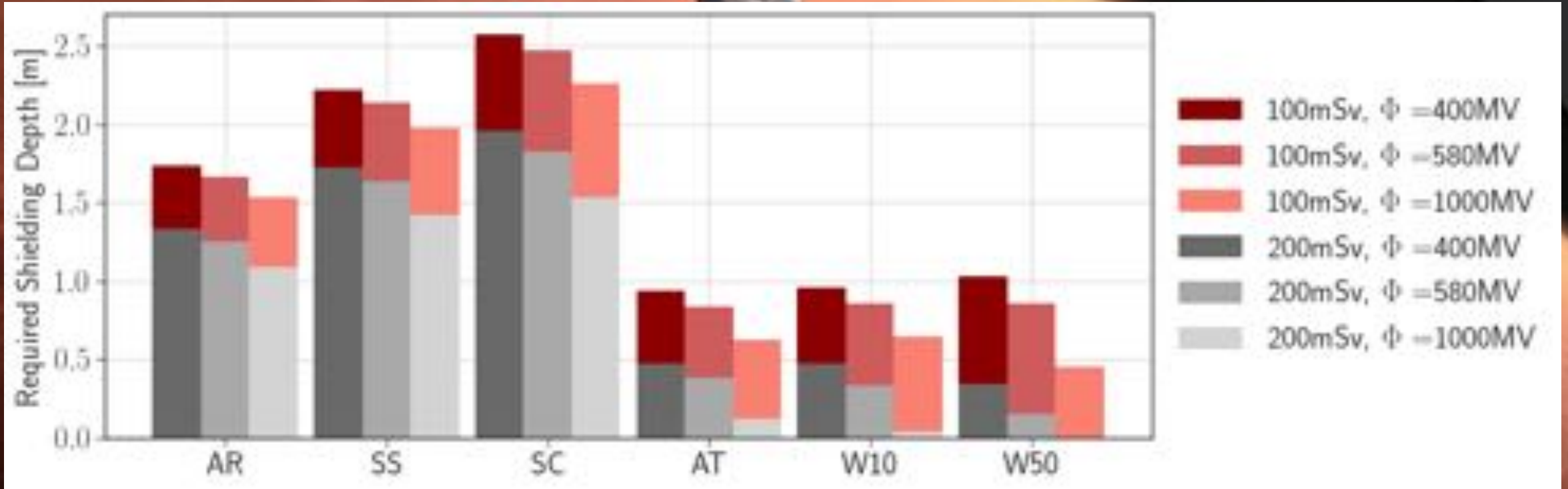
0.5
米



利用火星土壤 做屏蔽

Dry Regolith:
AR: andesite rock
SS: Sandstone
SC: Sulfur Concrete

Wet Regolith:
AT: Arabia Terra
W10: AR +10% water
W50: AR +50% water



总结

探火任务面临的太空辐射环境及优化方案

报告内容

空间辐射的危害

空间辐射的种类

火星空间环境和辐射的测量

火星辐射的时空变化

太阳爆发和高能粒子事件

火星辐射仿真和防护方案

- **GCR 银河宇宙射线辐射** 和太阳活动反相关；其定量的相关性依赖于局地的屏蔽环境（深空飞船，行星磁场，大气和土壤等）。这是因为带电粒子在穿过物质时，受其作用并通过电离损失和核反应而产生次级粒子，这一过程需要更多的测量和模拟来准确的标定。为有效的屏蔽GCR辐射，我们建议在太阳活动极大年开展远程的（载人）行星探测任务。
- **SEP 太阳高能粒子事件** 由于其突发性多变性的本质而很难预测。然而其危害却可能影响整个任务的成败。因而更准确的预报并结合实时性的防护措施非常重要，这需要我们更好的研究和预报太阳爆发过程（耀斑、CME），粒子的加速和传播机制，以及粒子在局地环境下的能谱变化。