太阳爆发现象中的未解之谜

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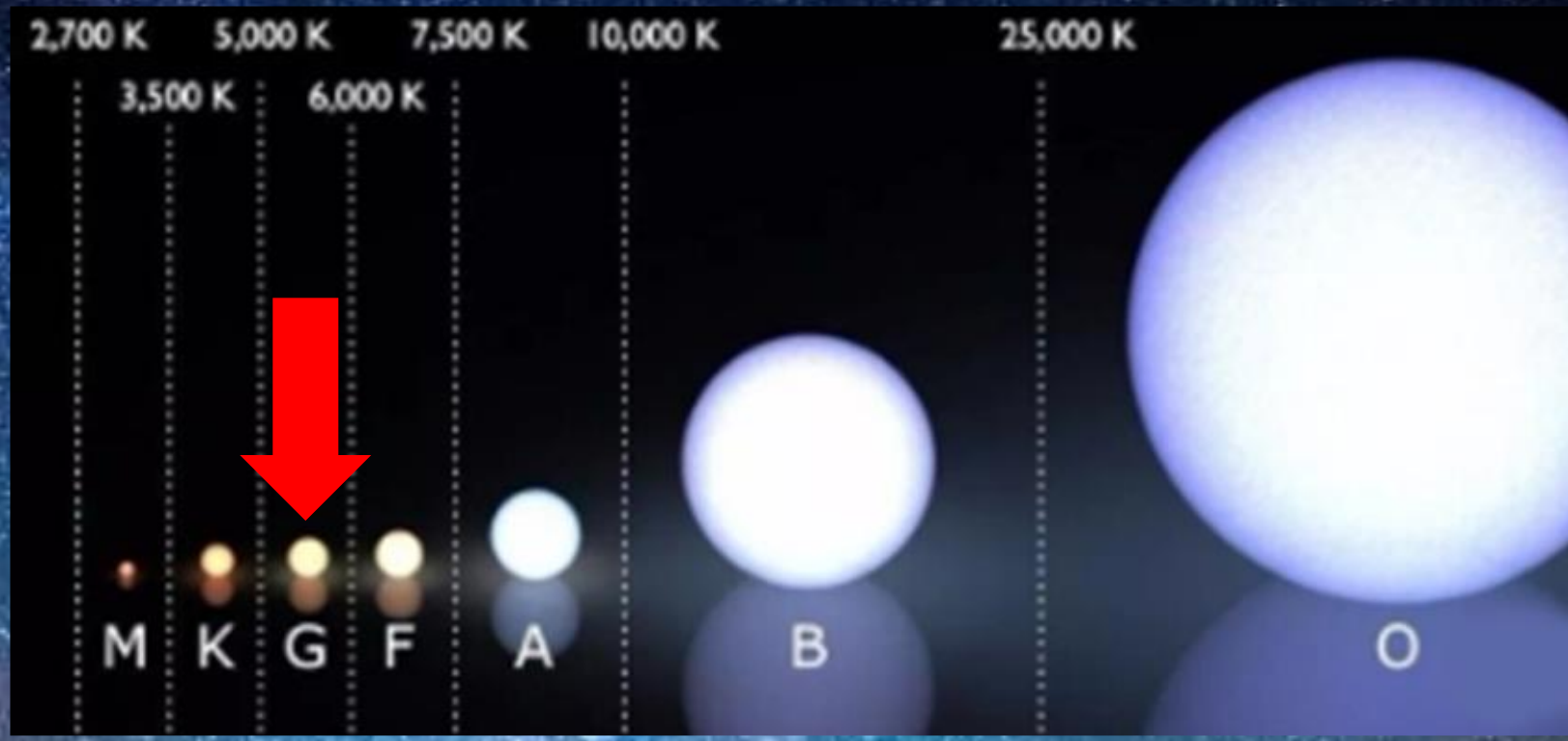
天文与空间科学学院



银河系有数千亿颗恒星

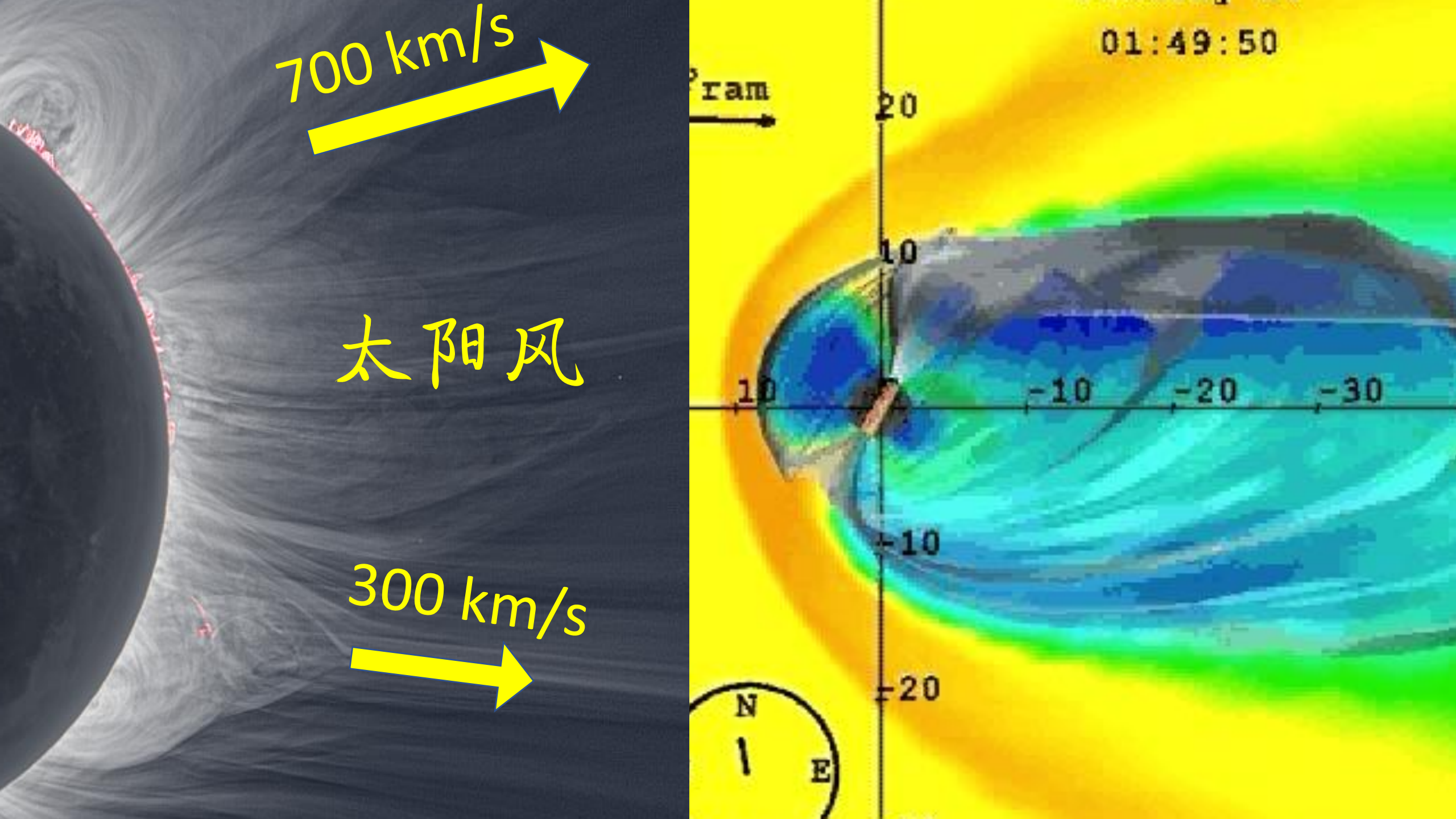
太阳概况

质量：1.99×10^{27}吨

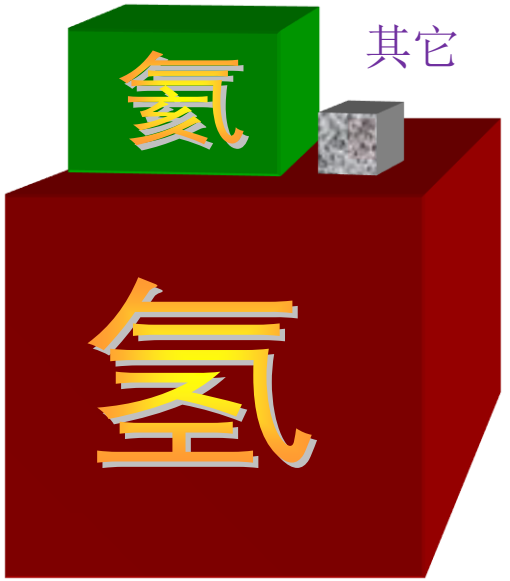
半径：69万公里

密度：平均1400公斤/立方米（10^{5}-10^{-4}）

温度：中心1千5百万度，表面5700度，日冕1百万度


700 km/s
太阳风
300 km/s
01:49:50
Pram
20
10
-10
-20
-30
10
-10
-20
N
E

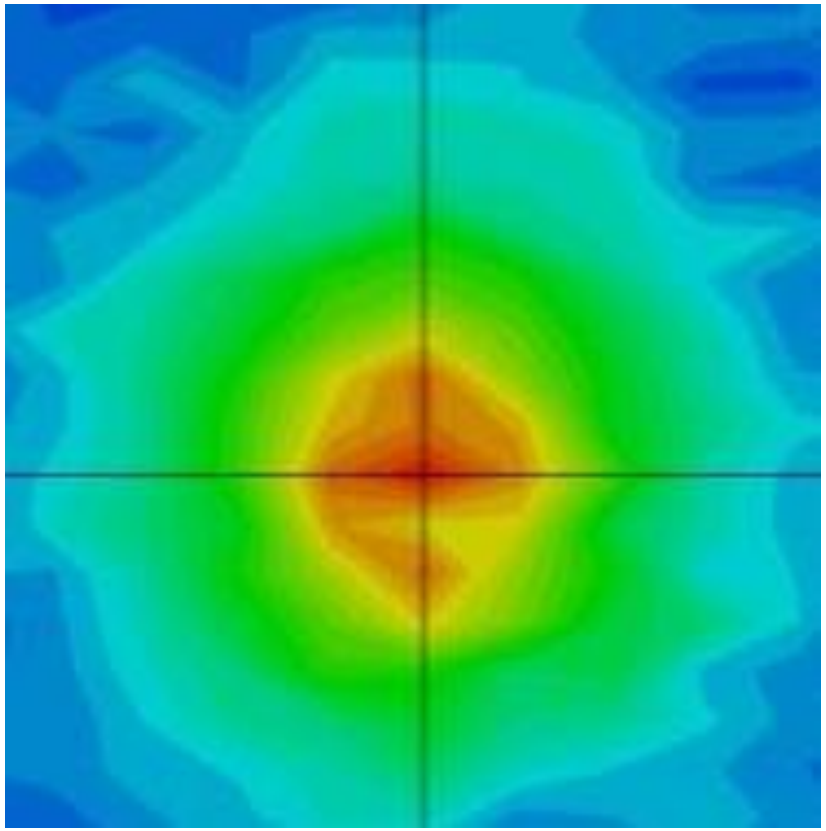
太阳的成分



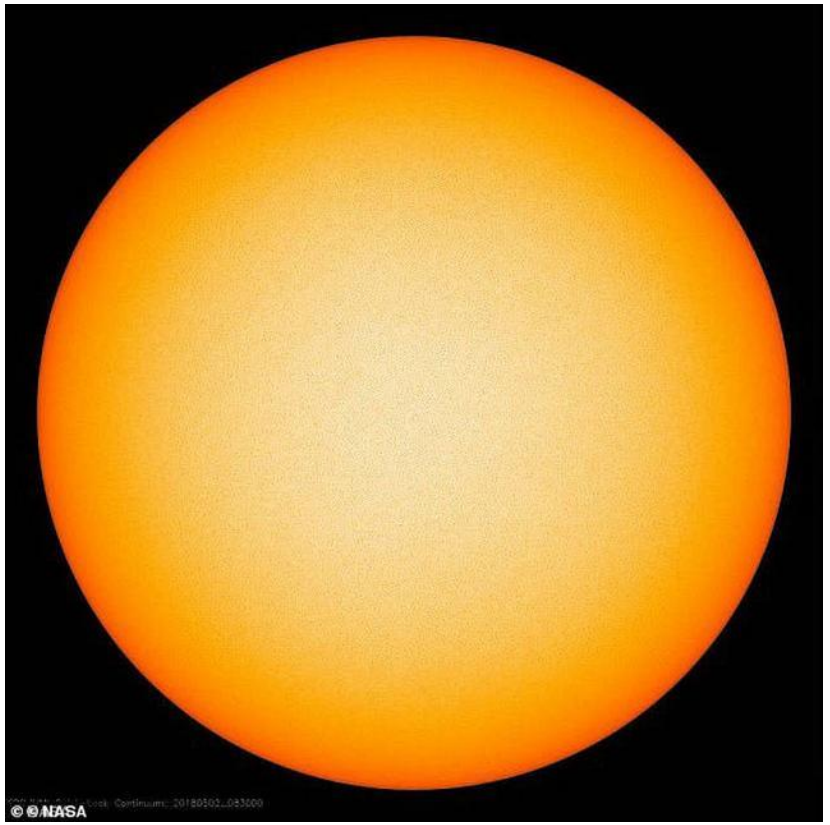
数量 氢气~91.2% 氦~8.7% 其它元素~0.1%
(含氧、碳、氮等)

质量 氢气~73.5% 氦~24.8%, 其余~1.7%

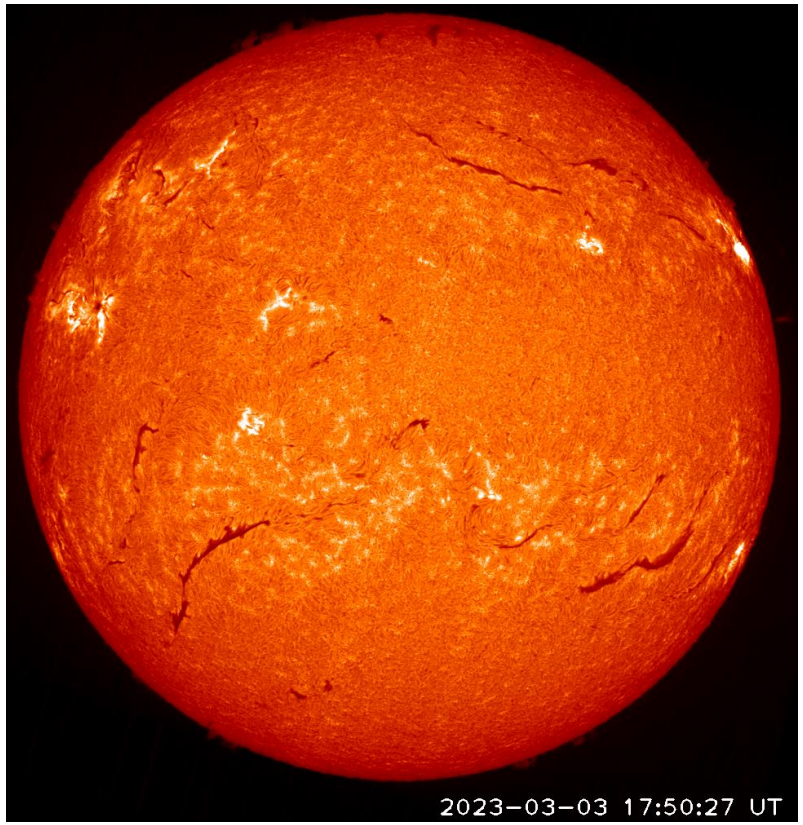
多波段图像中的太阳



中微子

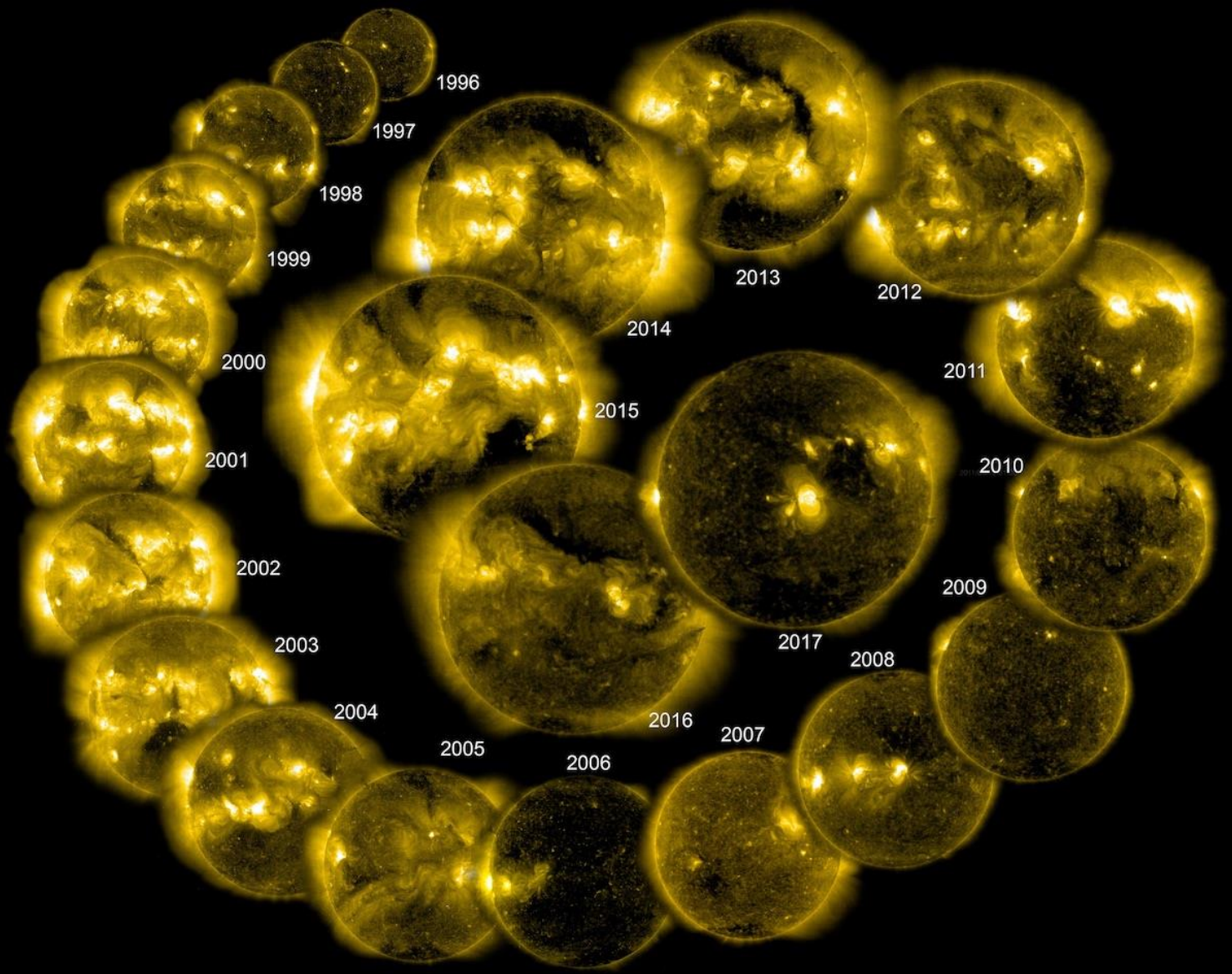


白光



Hα

紫外光


1996
1997
1998
1999
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2010
2011
2012
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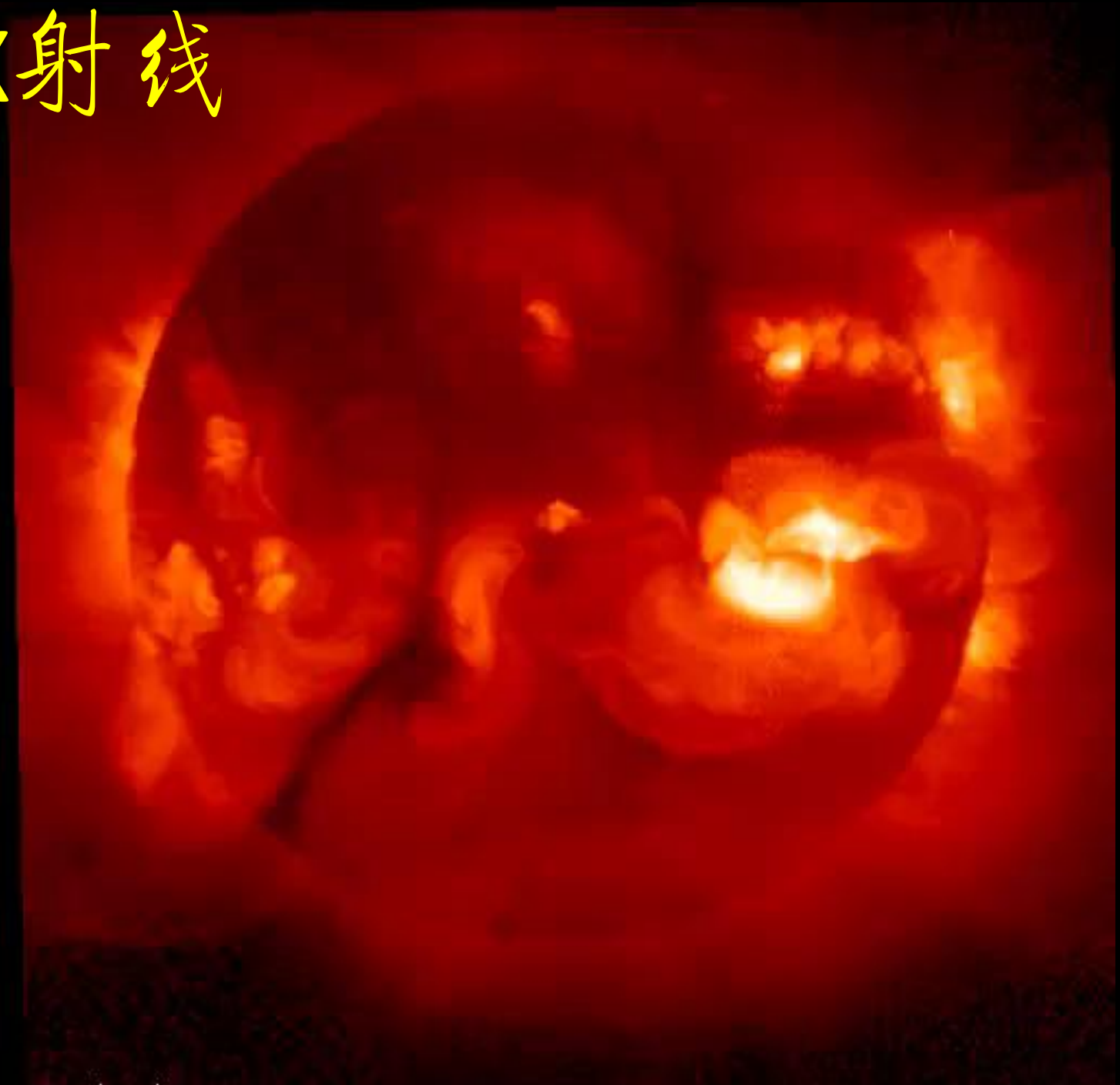
2015
2016
2017

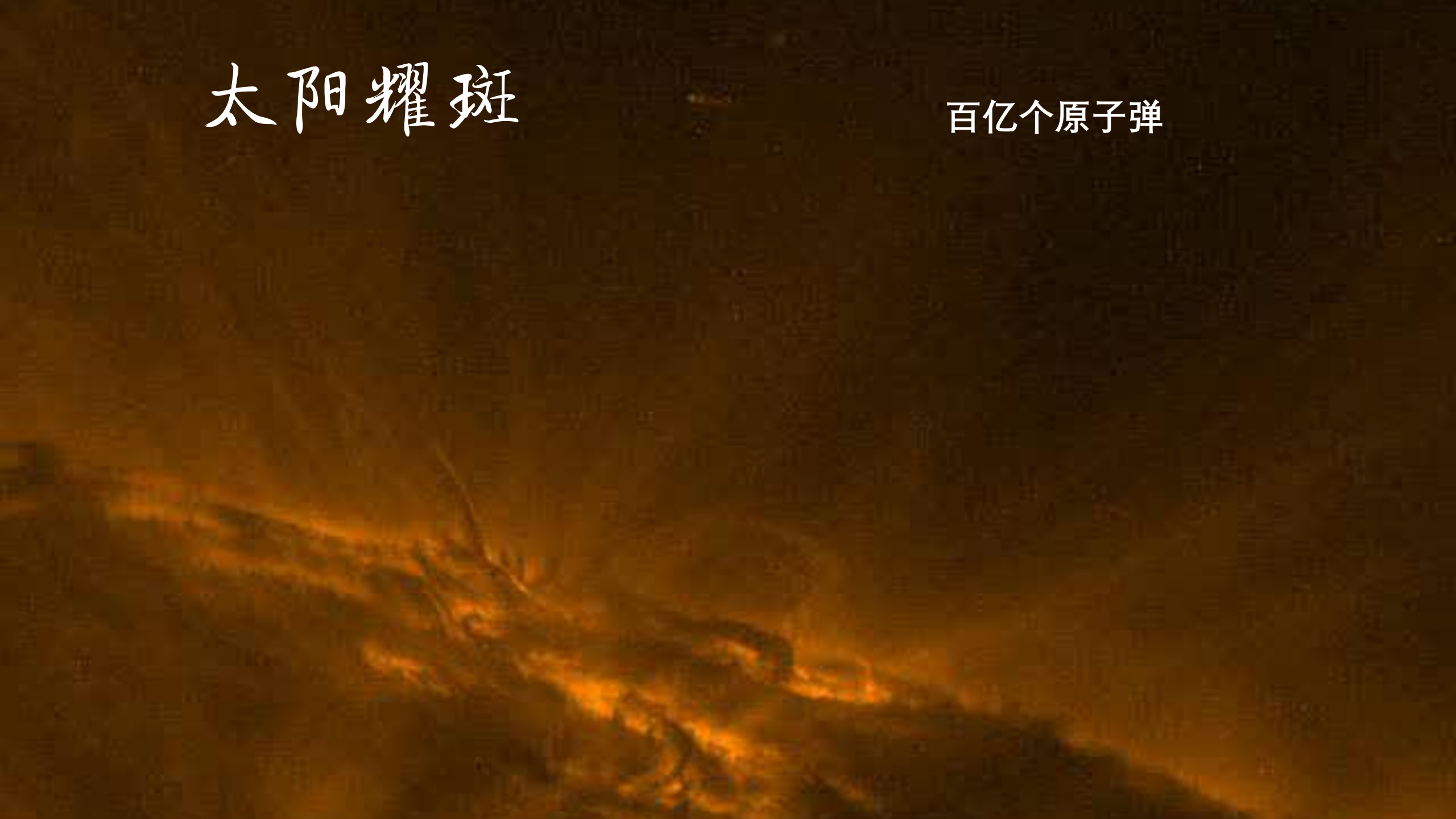
X射线



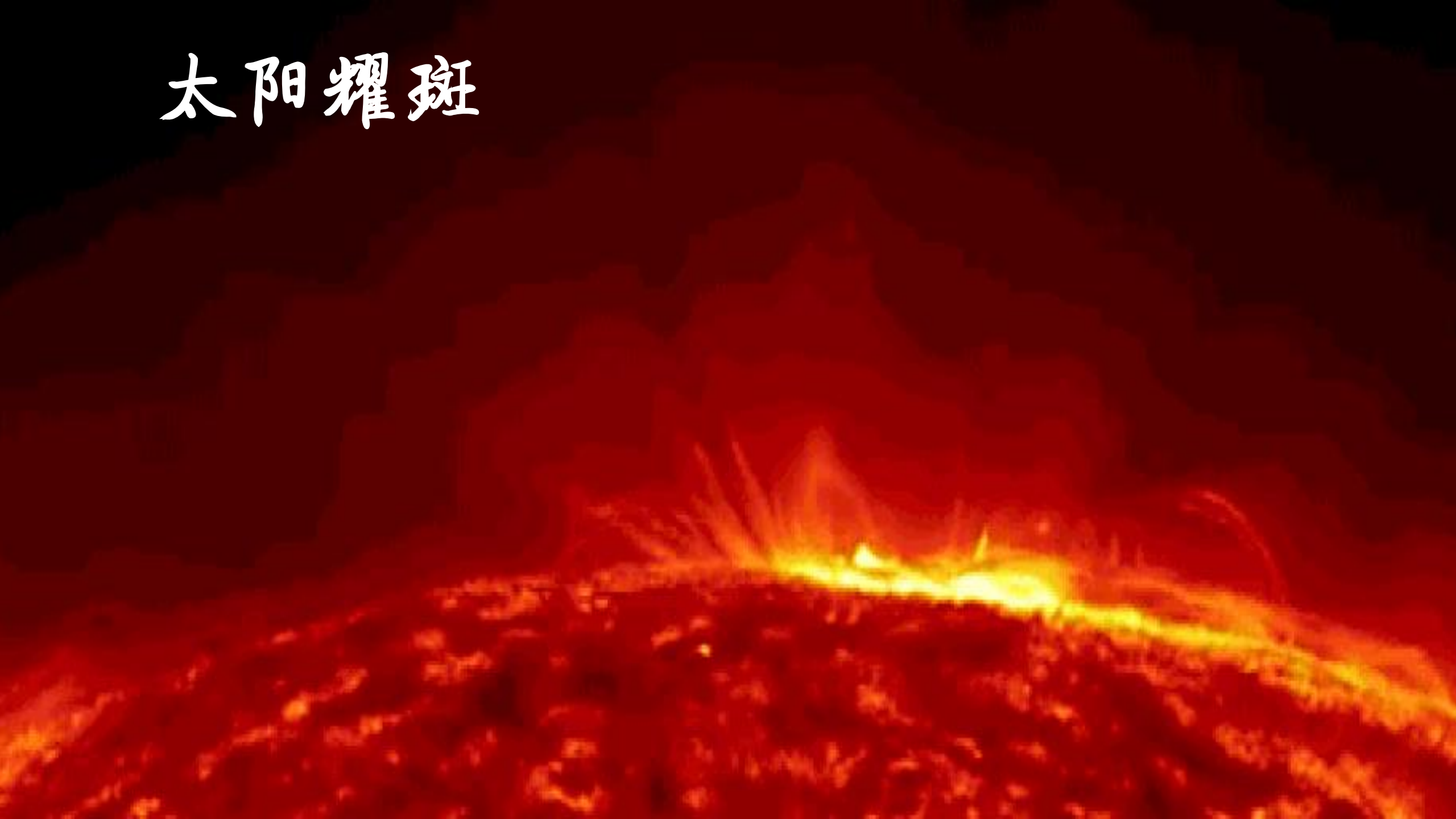

喷流 jet

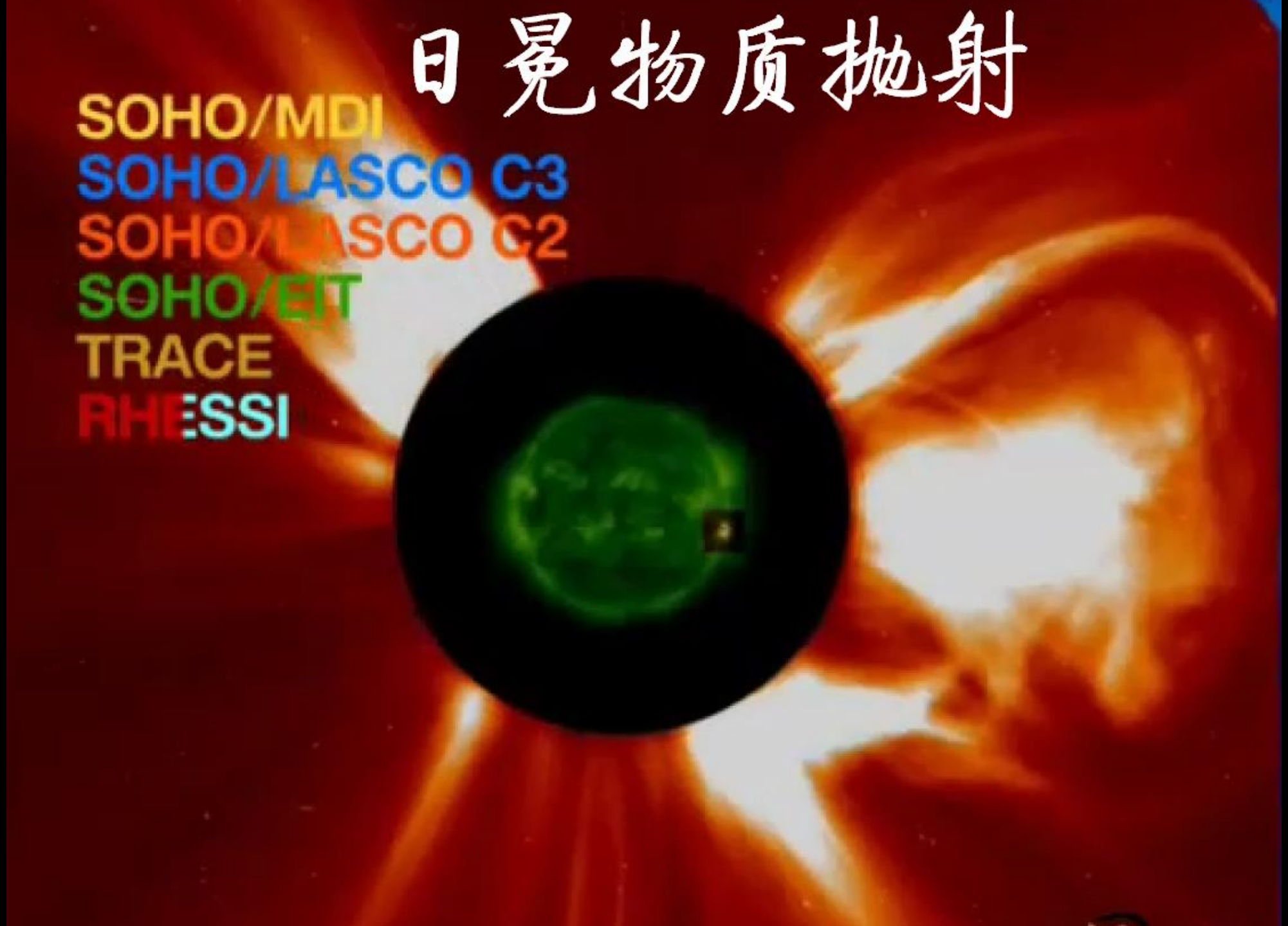
日珥抛射

1946 June 28

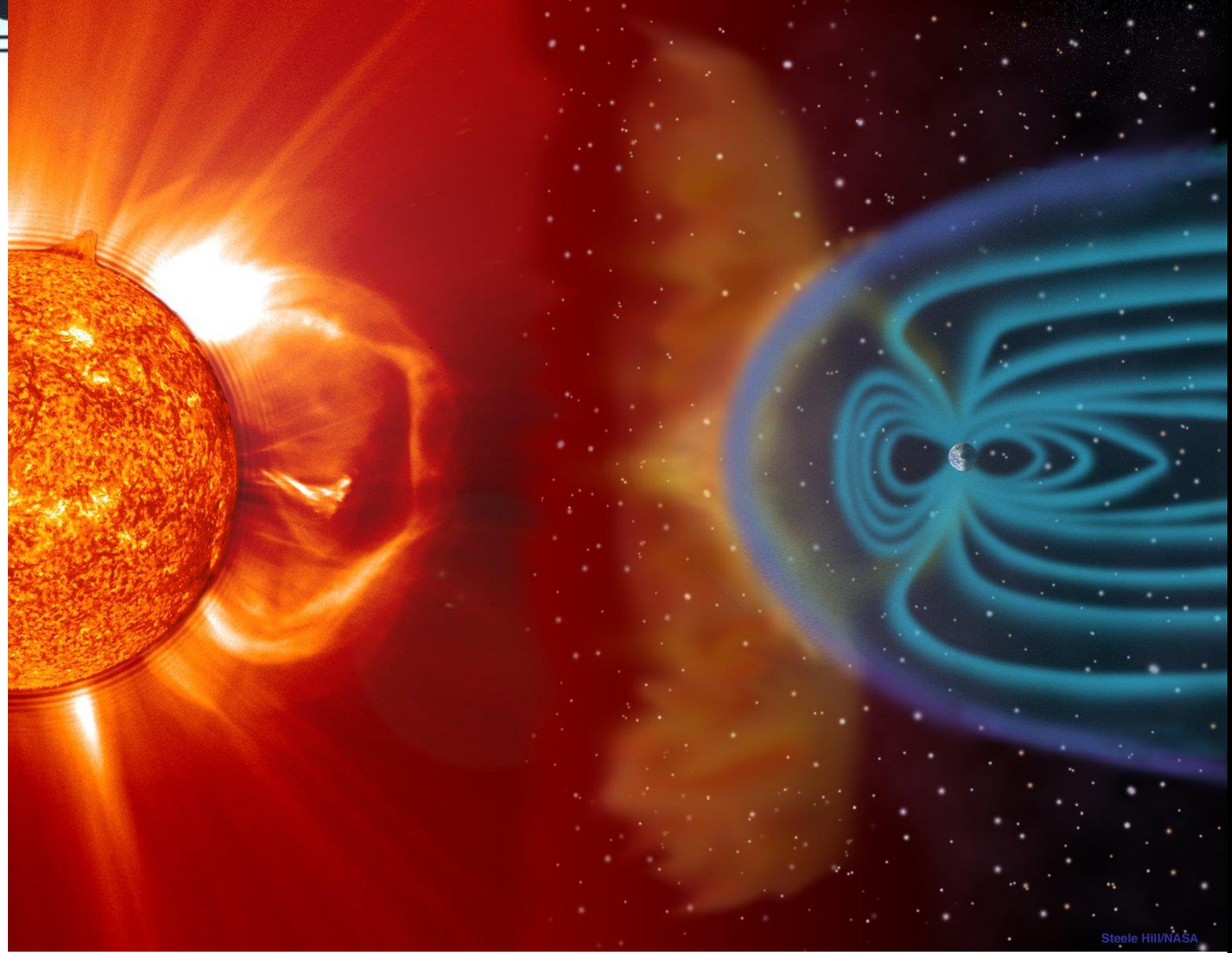

太阳耀斑
百亿个原子弹

太阳耀斑



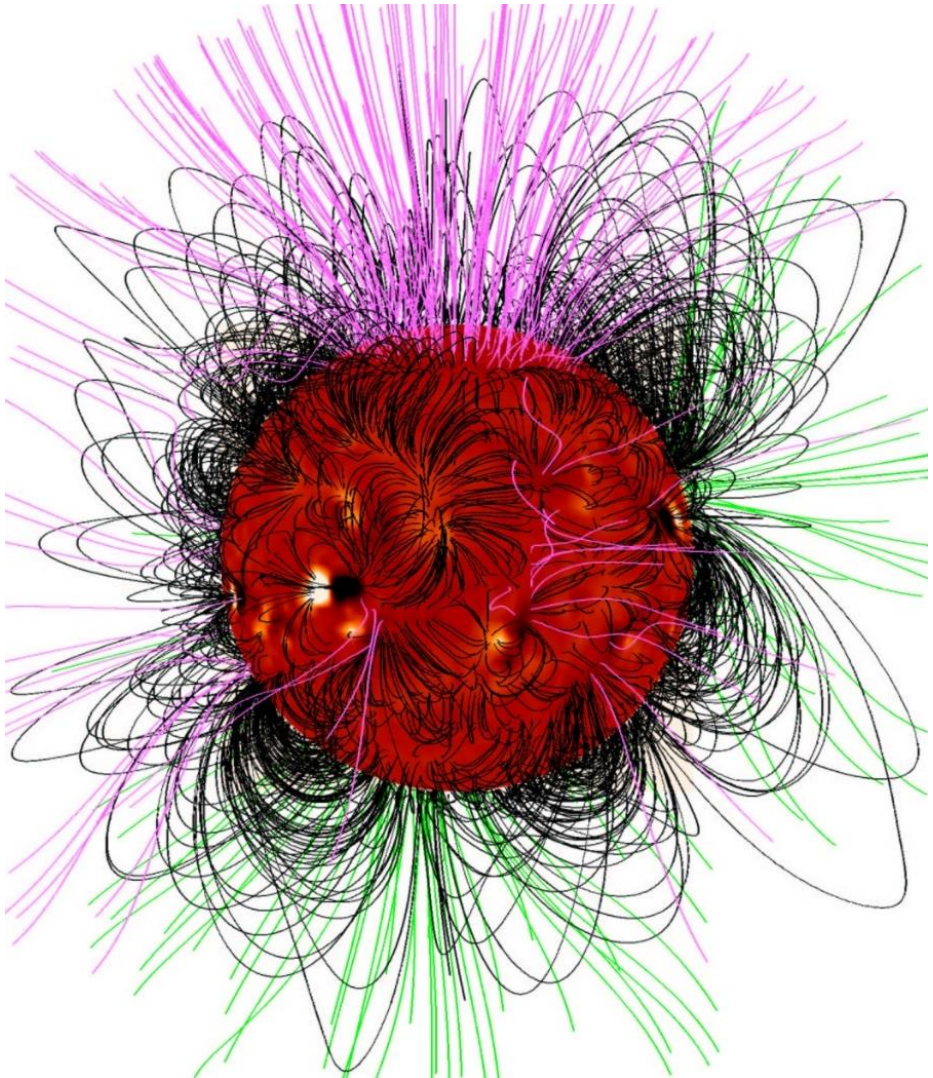

日冕物质抛射
SOHO/MDI
SOHO/LASCO C3
SOHO/LASCO C2
SOHO/EIT
TRACE
RHESSI

太阳风暴



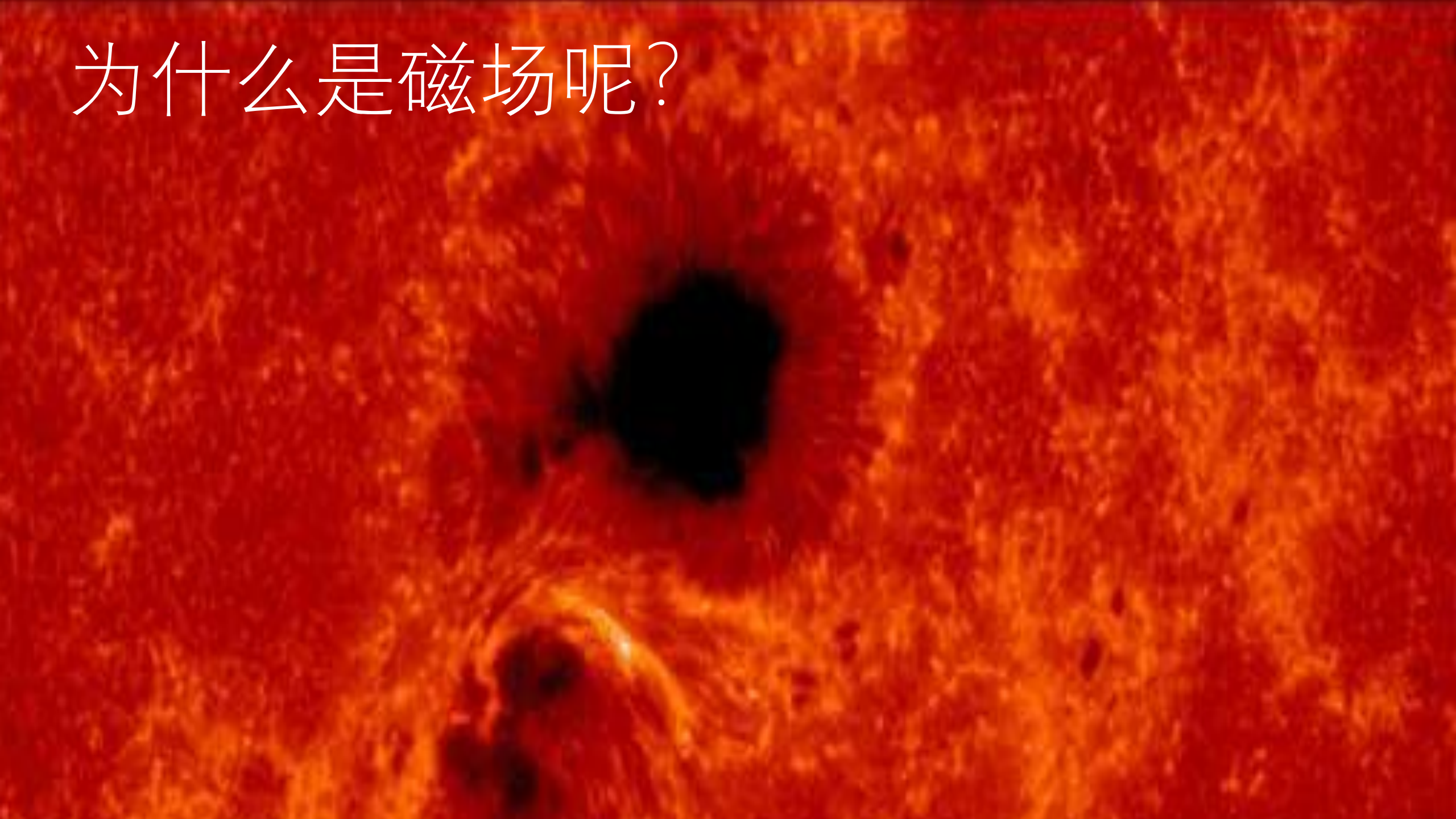

每年产生的破坏达几十亿元

能源是什么？



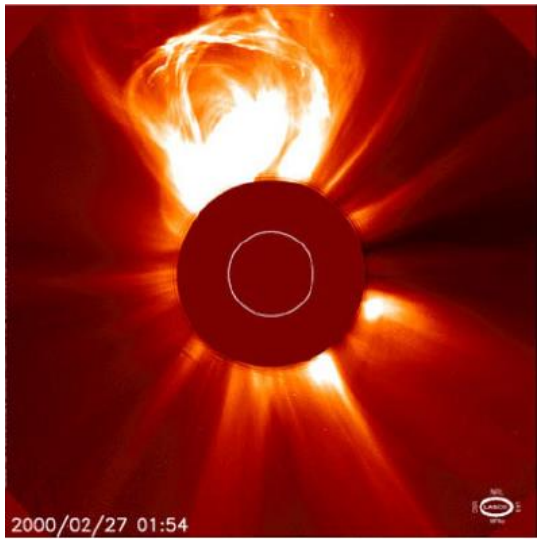
磁场！

为什么是磁场呢？



为什么是磁场呢？

能量密度



$E=10^{32}$ erg

$V=10^{24}$ m^3

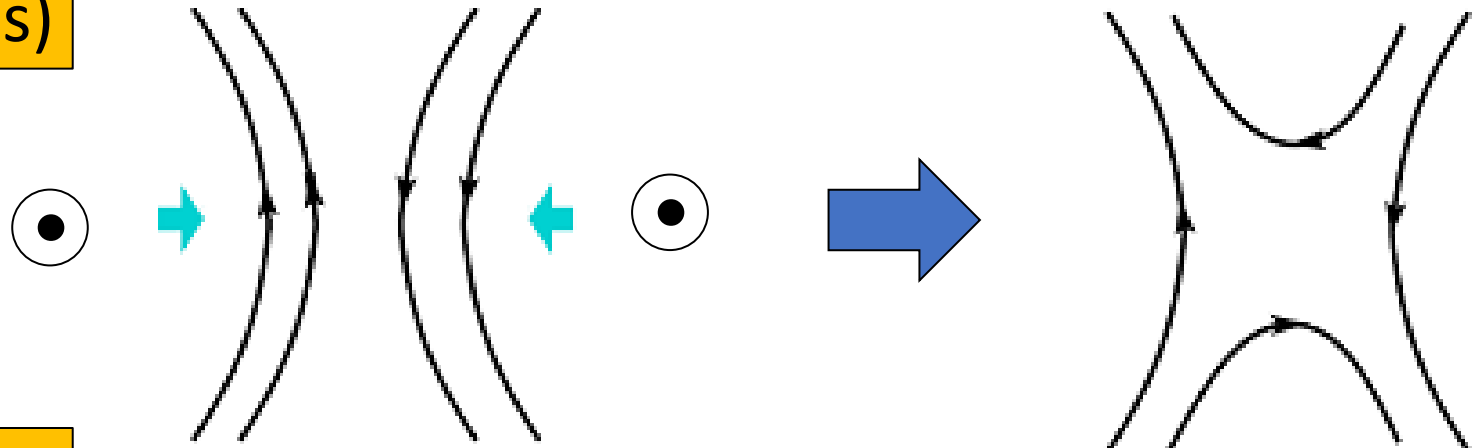
$\rho=10$ J m^{-3}

Form of energy	Energy density (J m^{-3})	Observed averaged value
Kinetic ($\frac{1}{2}m_p n V^2$)	8×10^{-4}	$n = 10^{15}$ m^{-3}, $V = 1$ km s^{-1}
Thermal (nkT)	1×10^{-2}	$T = 10^6$ K
Potential ($nm_p gh$)	5×10^{-2}	$h = 10^5$ km
Magnetic ($B^2/2\mu_0$)	40	$B = 10^{-2}$ T

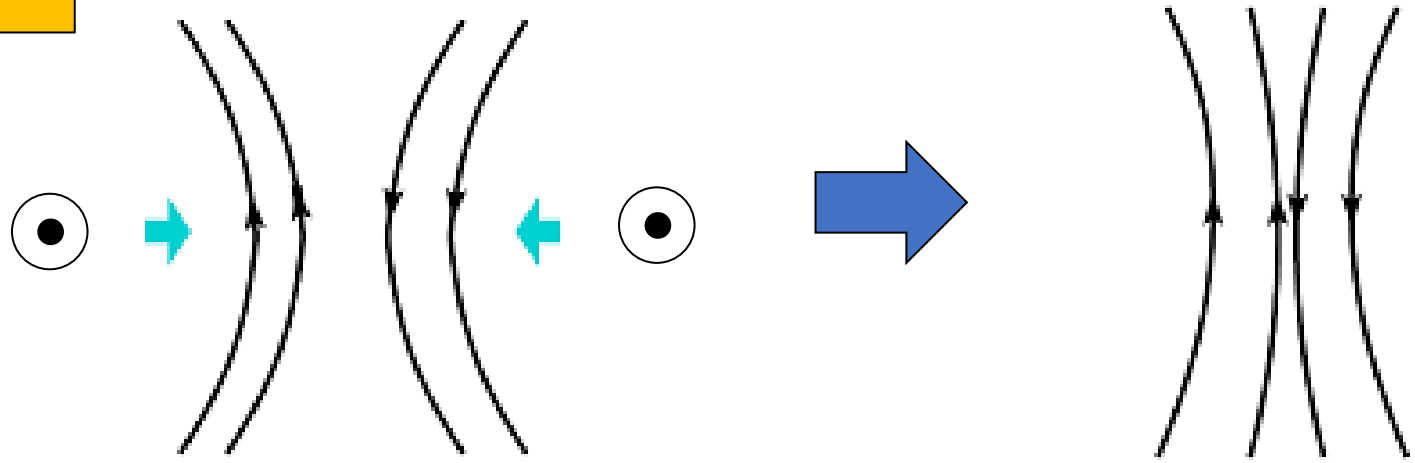
Chen, P. F. 2011, Living Reviews in Solar Physics, 8, 1

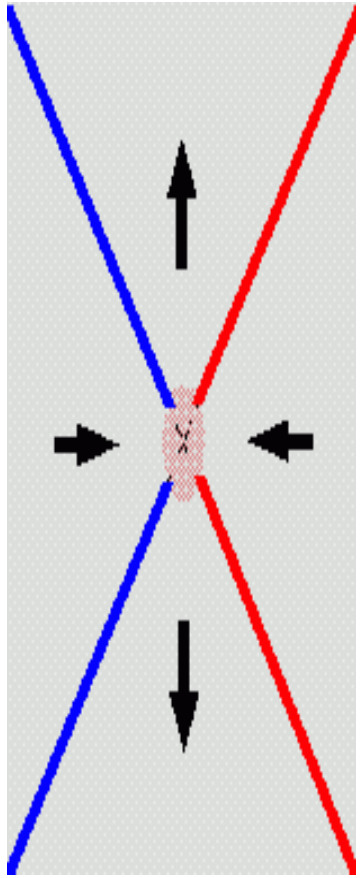
磁重联 Magnetic reconnection

In vacuum
(or neutral gas)



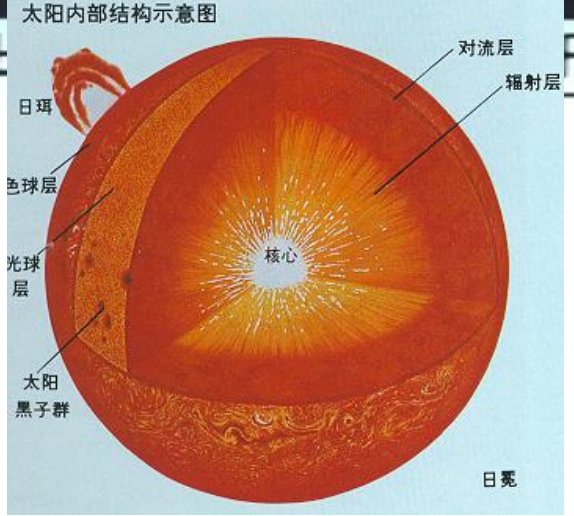
In plasma
with low η

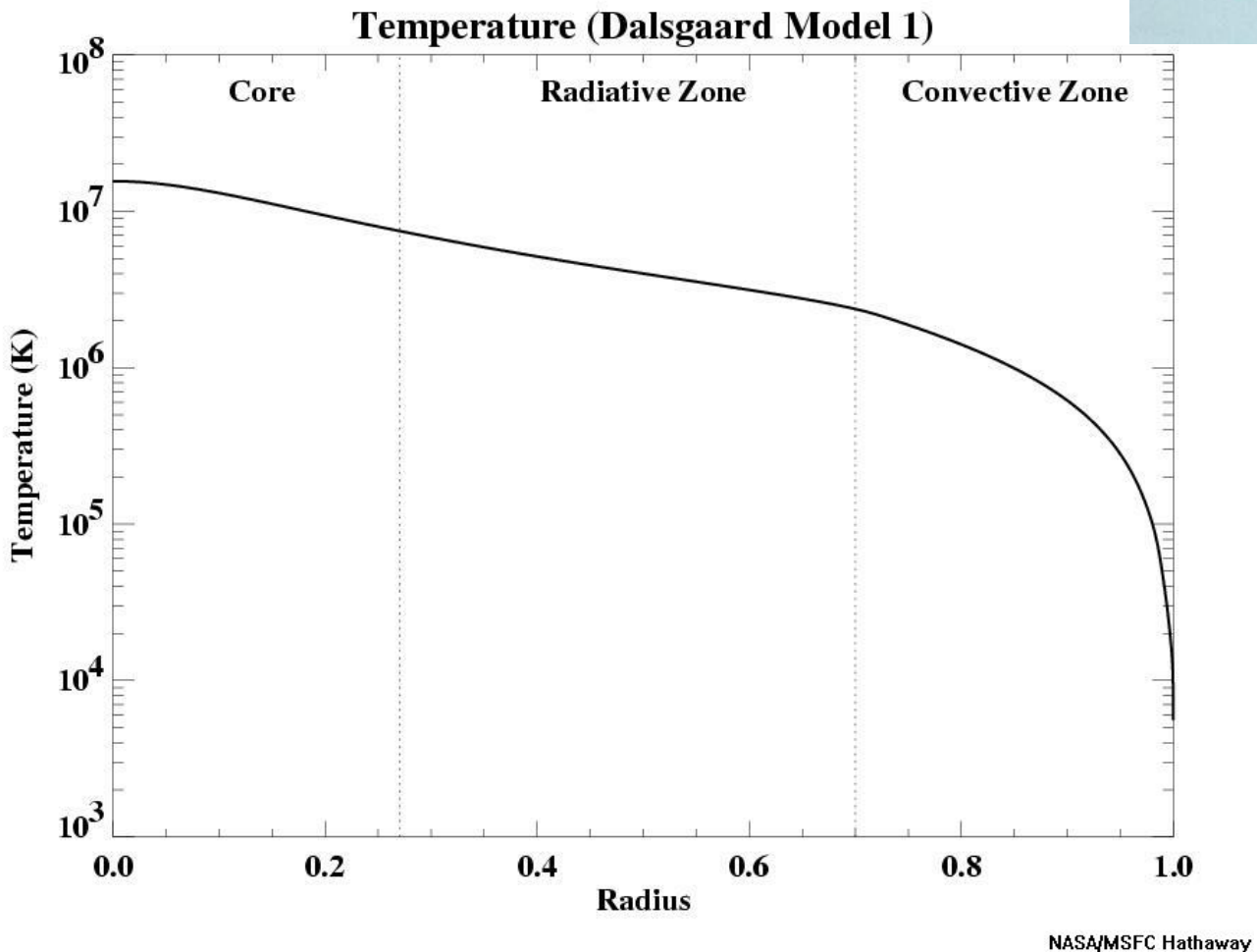


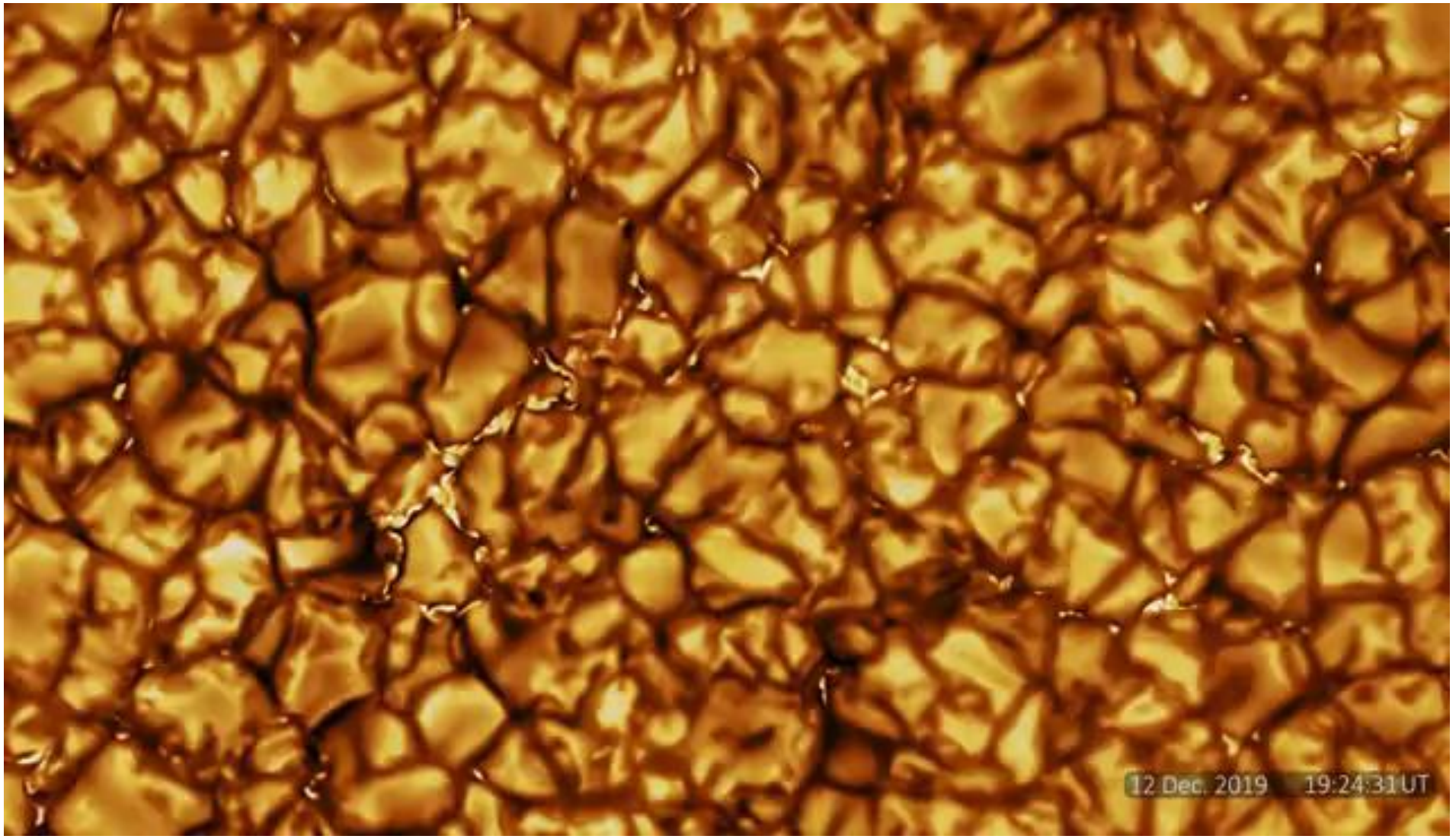


太阳磁场是怎么产生的？

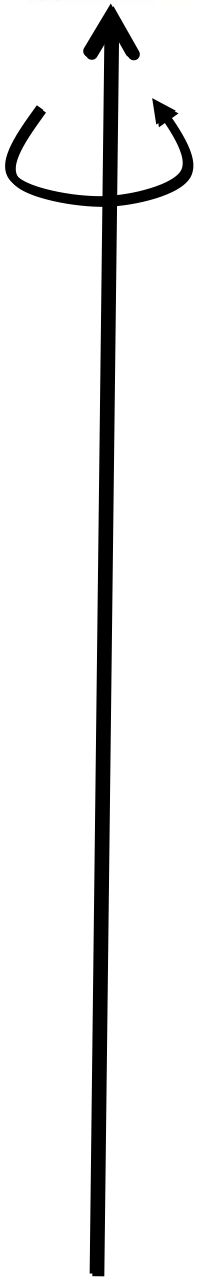
太阳内部的结构

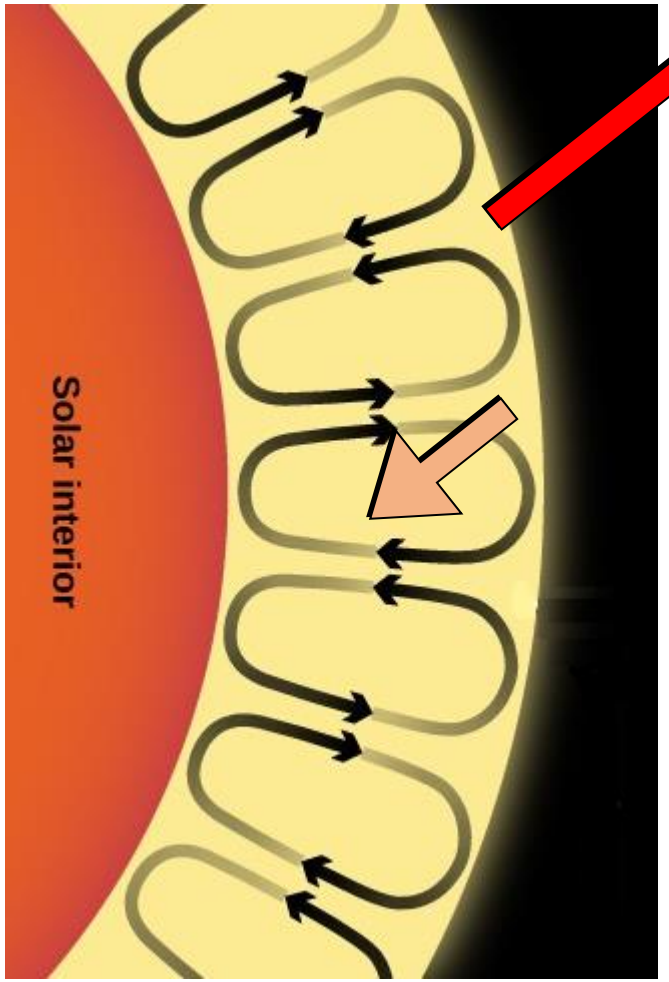

太阳内部结构示意图
对流层
辐射层
日珥
色球层
光球层
核心
太阳黑子群
日冕

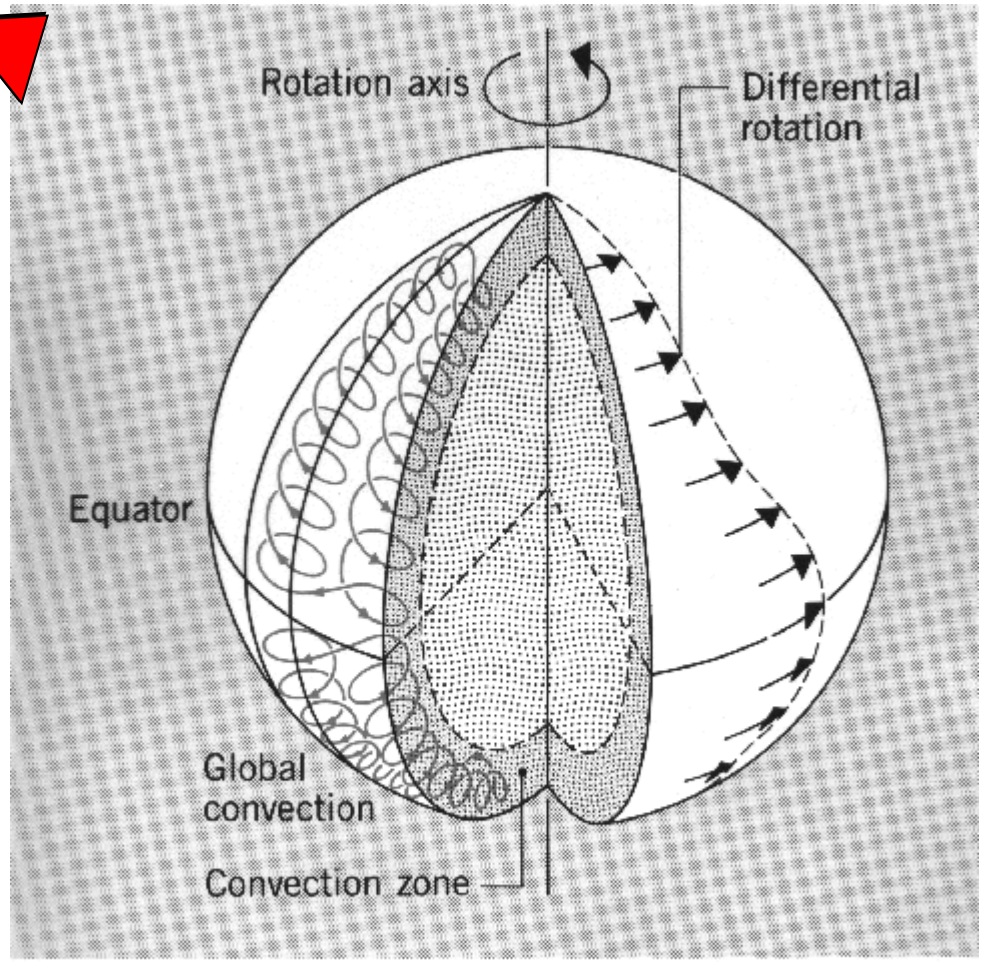

Temperature (Dalsgaard Model 1)
Core
Radiative Zone
Convective Zone
Temperature (K)
10^8
10^7
10^6
10^5
10^4
10^3
0.0
0.2
0.4
0.6
0.8
1.0
Radius
NASA/MSFC Hathaway


12 Dec. 2019 19:24:31UT

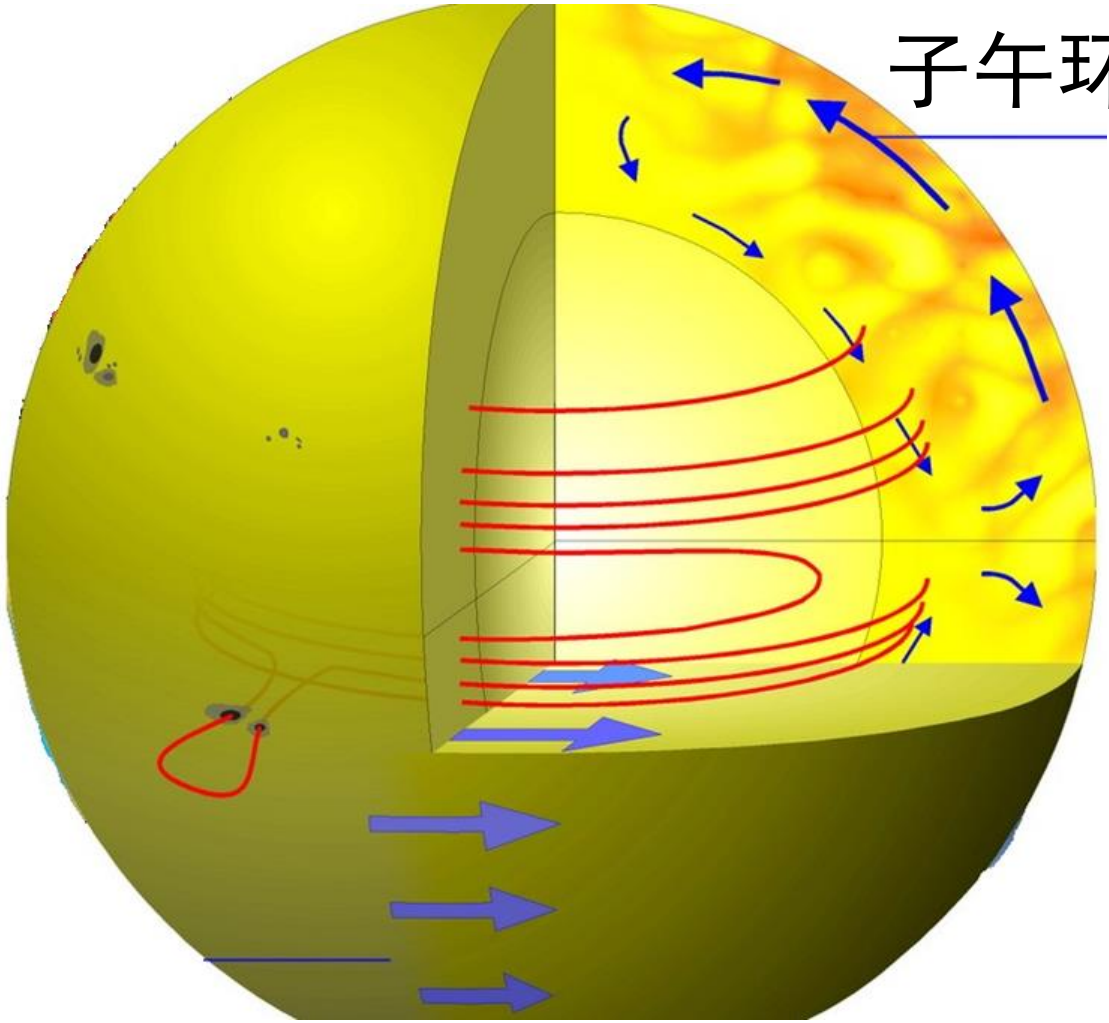
$$F = -2m\,\boldsymbol{\omega} \times \mathbf{v}$$

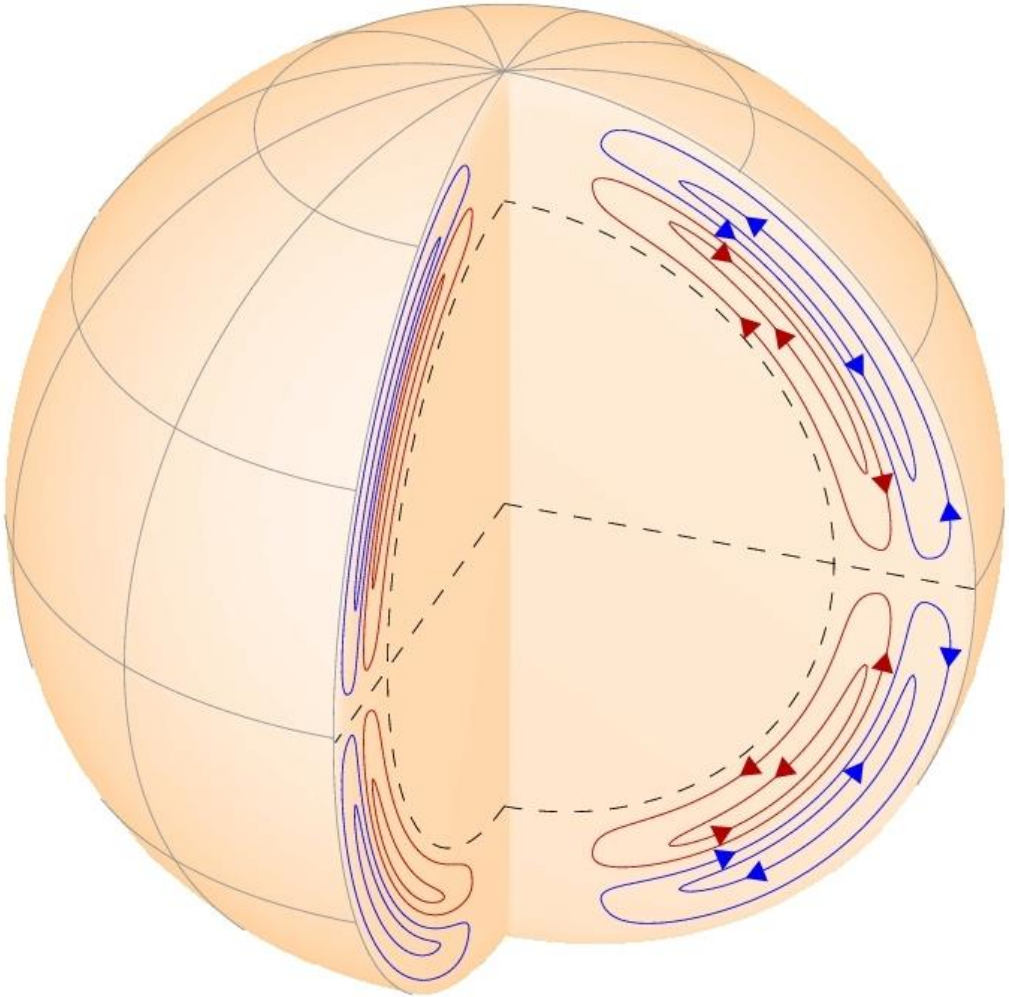






Convection and the solar magnetic field.

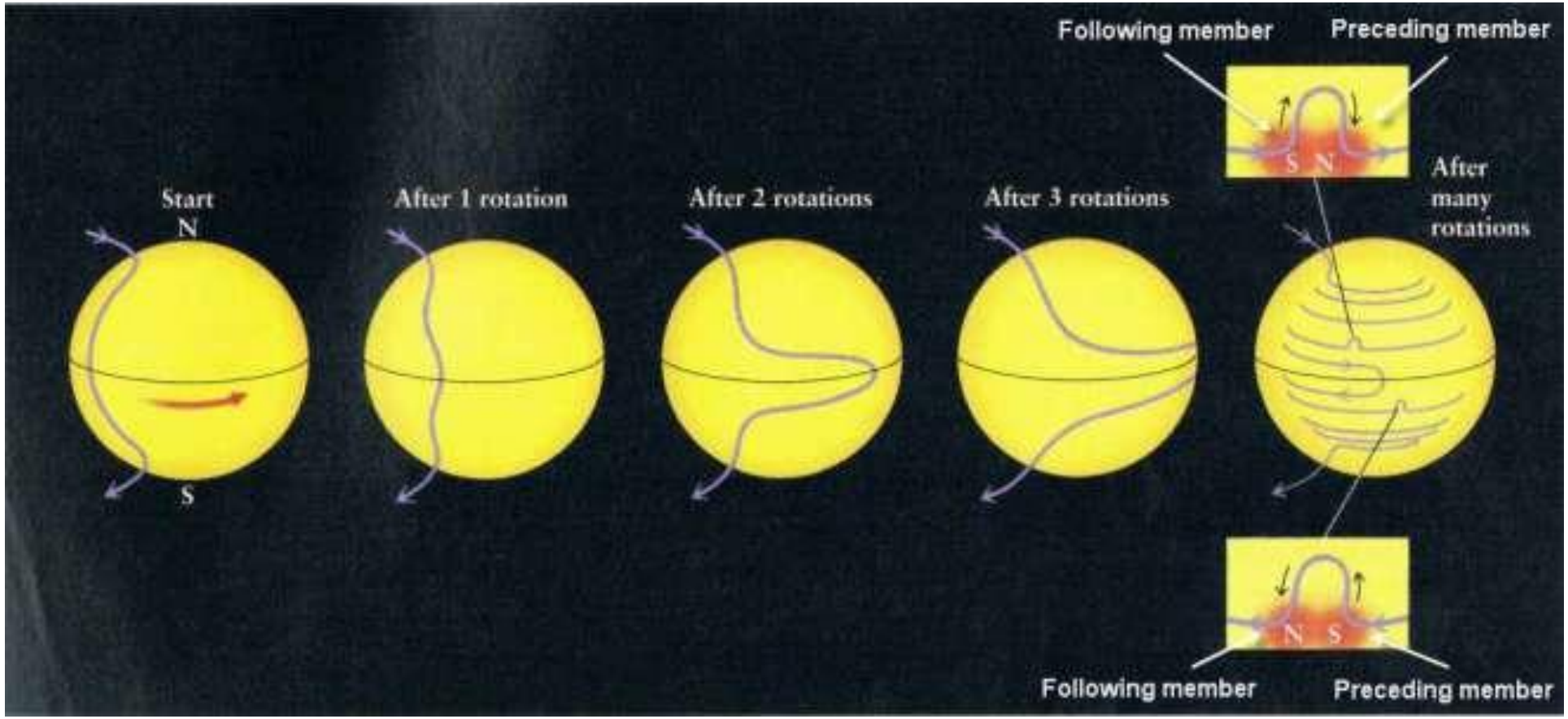


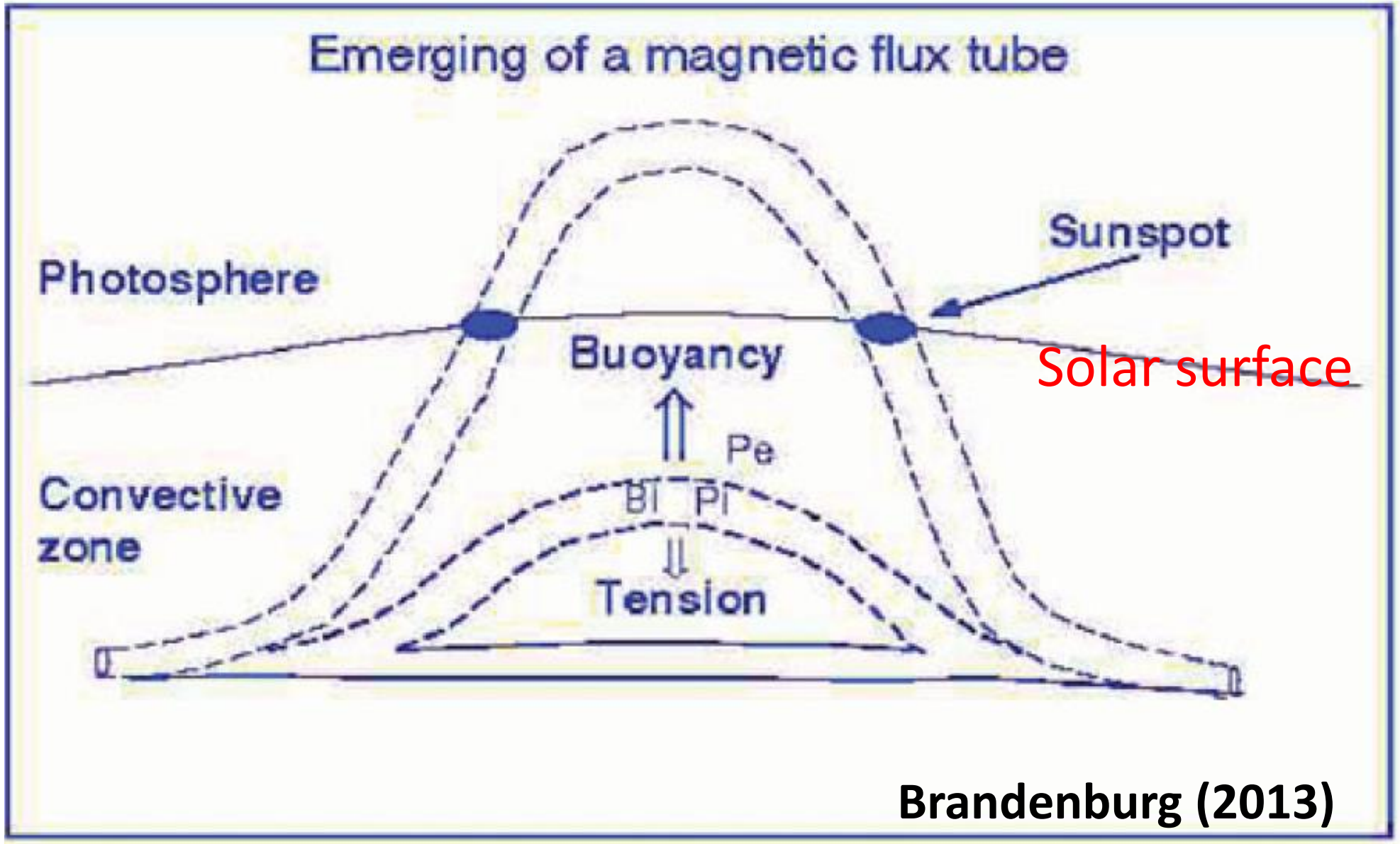


Zhao et al. (2013)

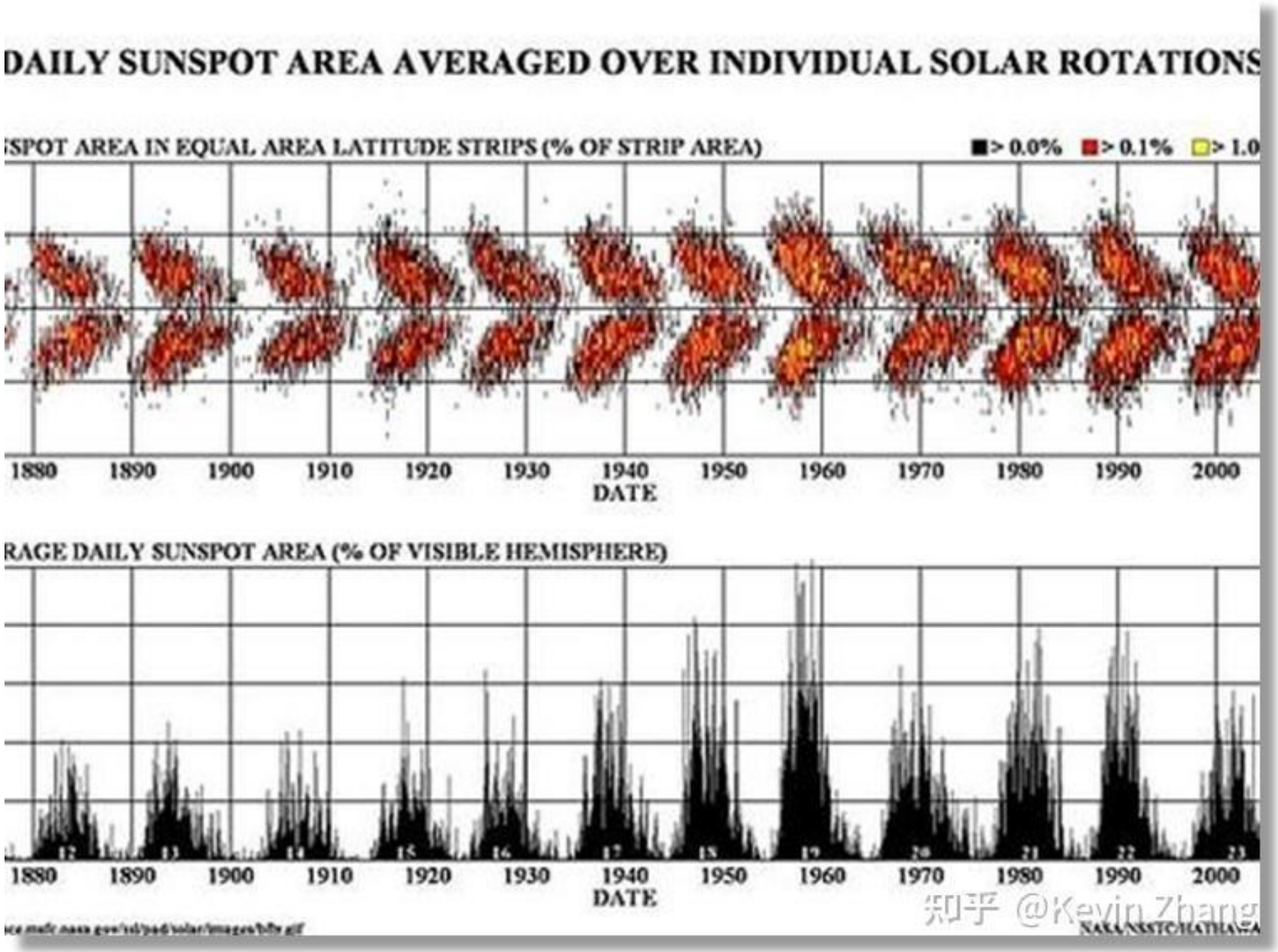
Gizon et al. (2020)

发电机理论 Dynamo theory

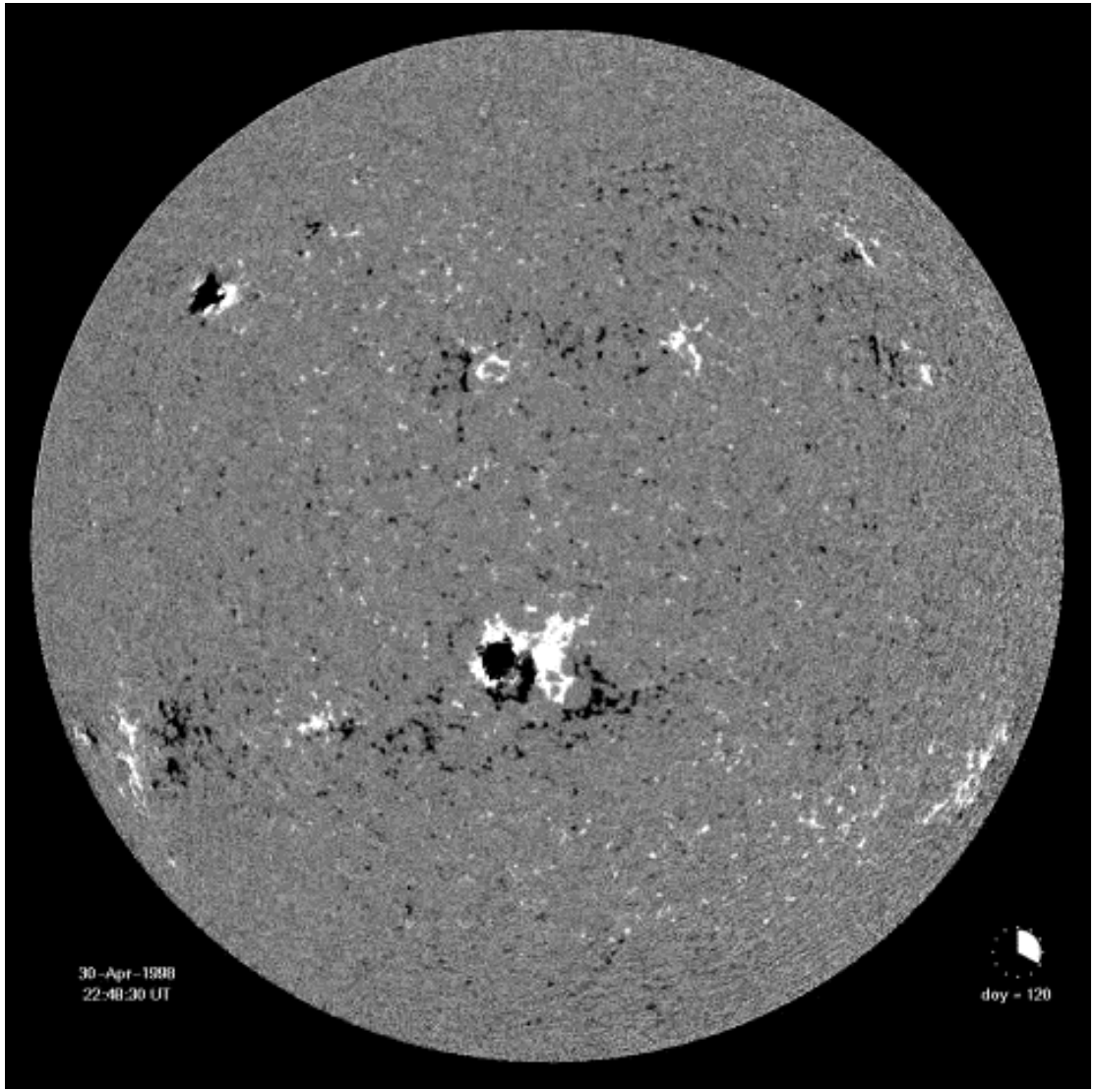




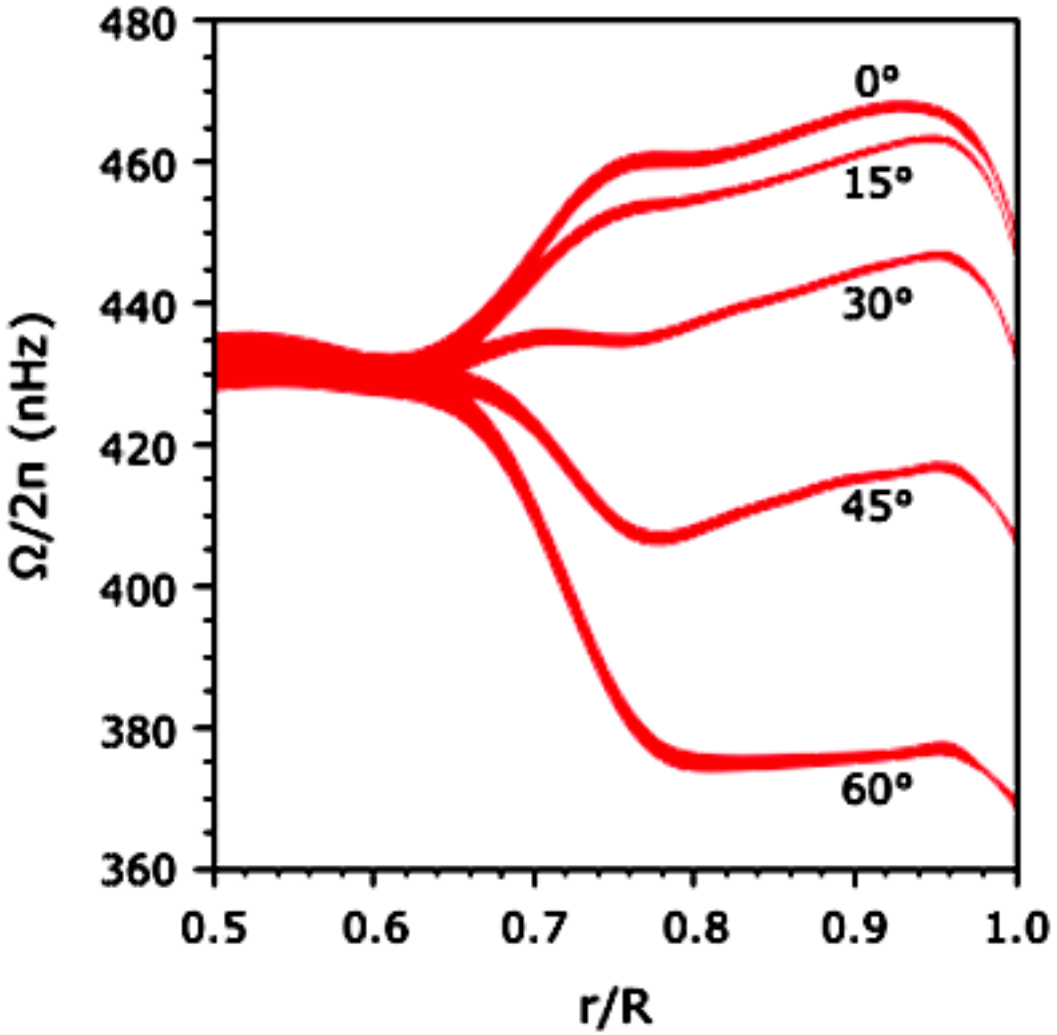
Brandenburg (2013)


DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS
SPOT AREA IN EQUAL AREA LATITUDE STRIPS (% OF STRIP AREA)
> 0.0%
> 0.1%
> 1.0
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
DATE
RAGE DAILY SUNSPOT AREA (% OF VISIBLE HEMISPHERE)
12
13
14
15
16
17
18
19
20
21
22
23
1880
1890
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
DATE
知乎 @Kevin Zhang

谜之一：磁场在哪里产生？



Radial Distribution of the Angular Velocity



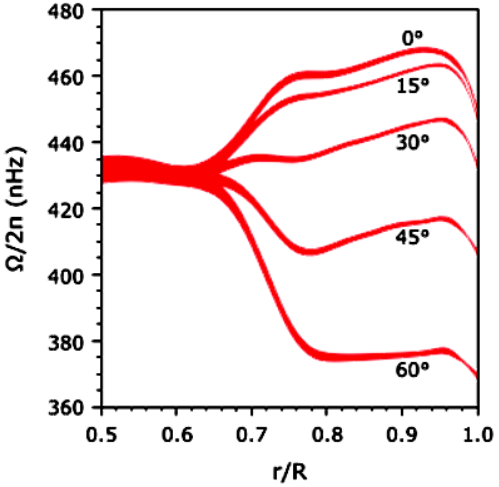
0.7*R* for global dynamo

0.95R for local B

Charbonneau (2020)

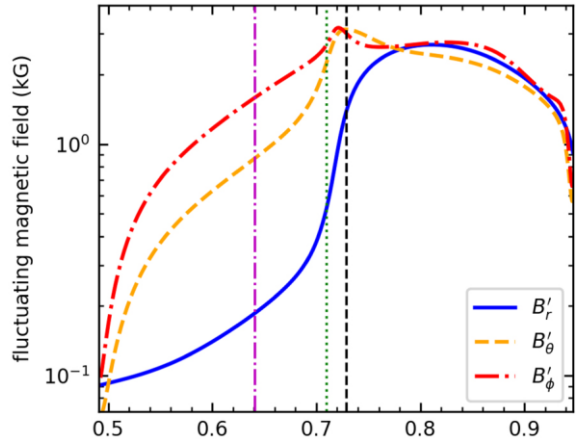
The solar dynamo begins near the surface

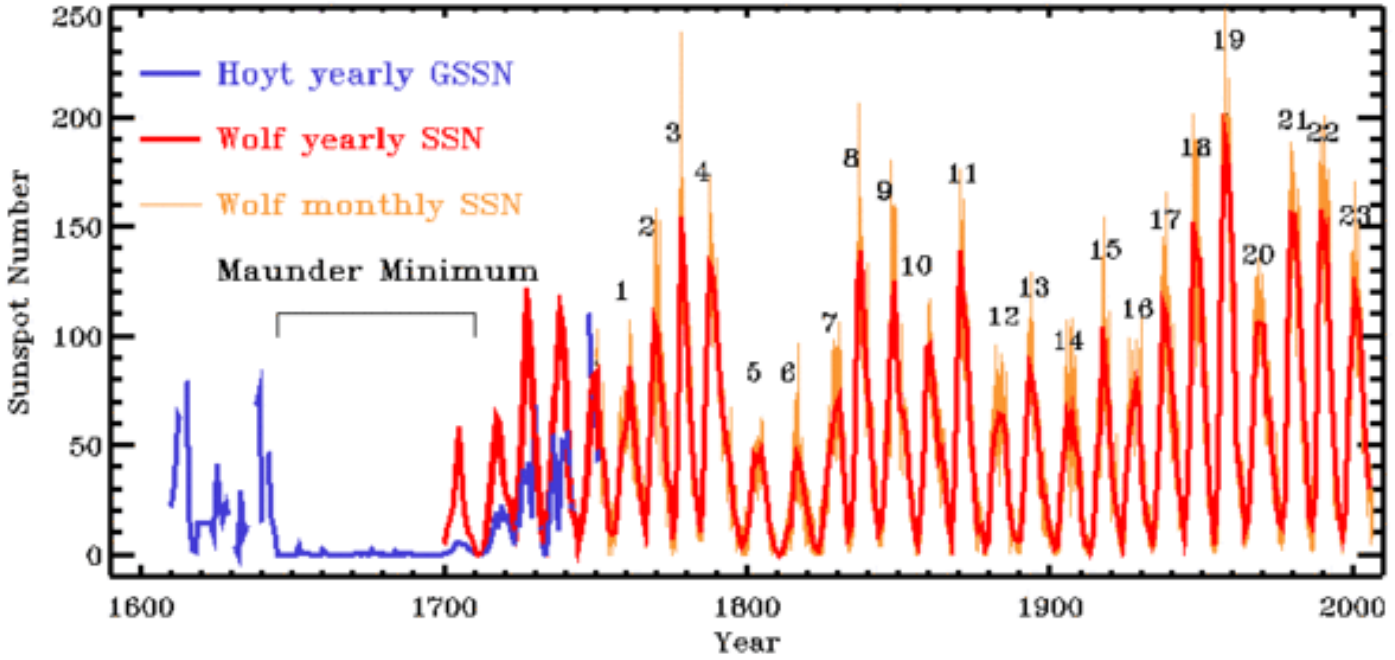
Vasil et al. (2024, Nature)



Dynamo Action in the Radiative Interior

Matilsky et al. (2022, ApJ)



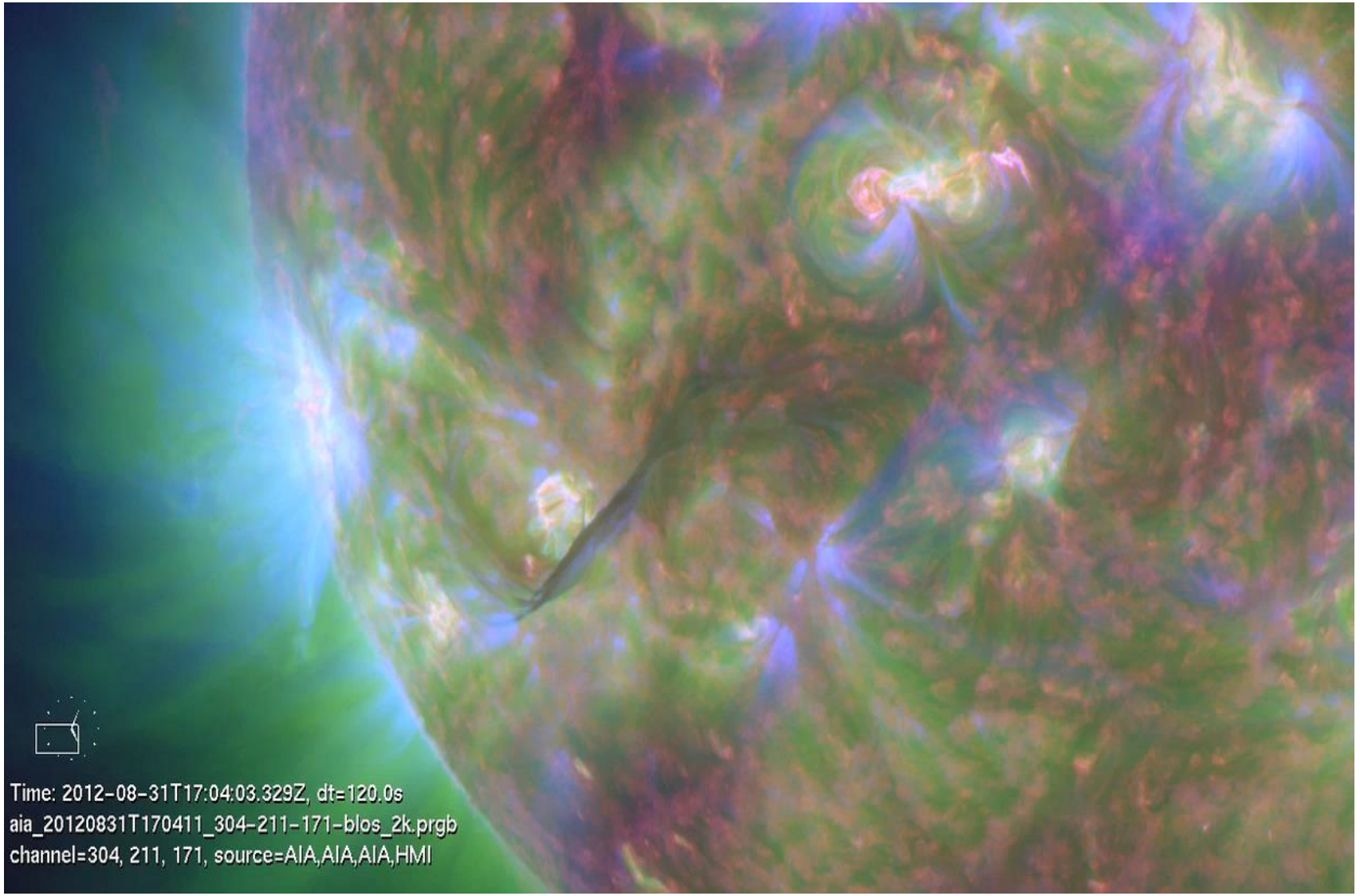


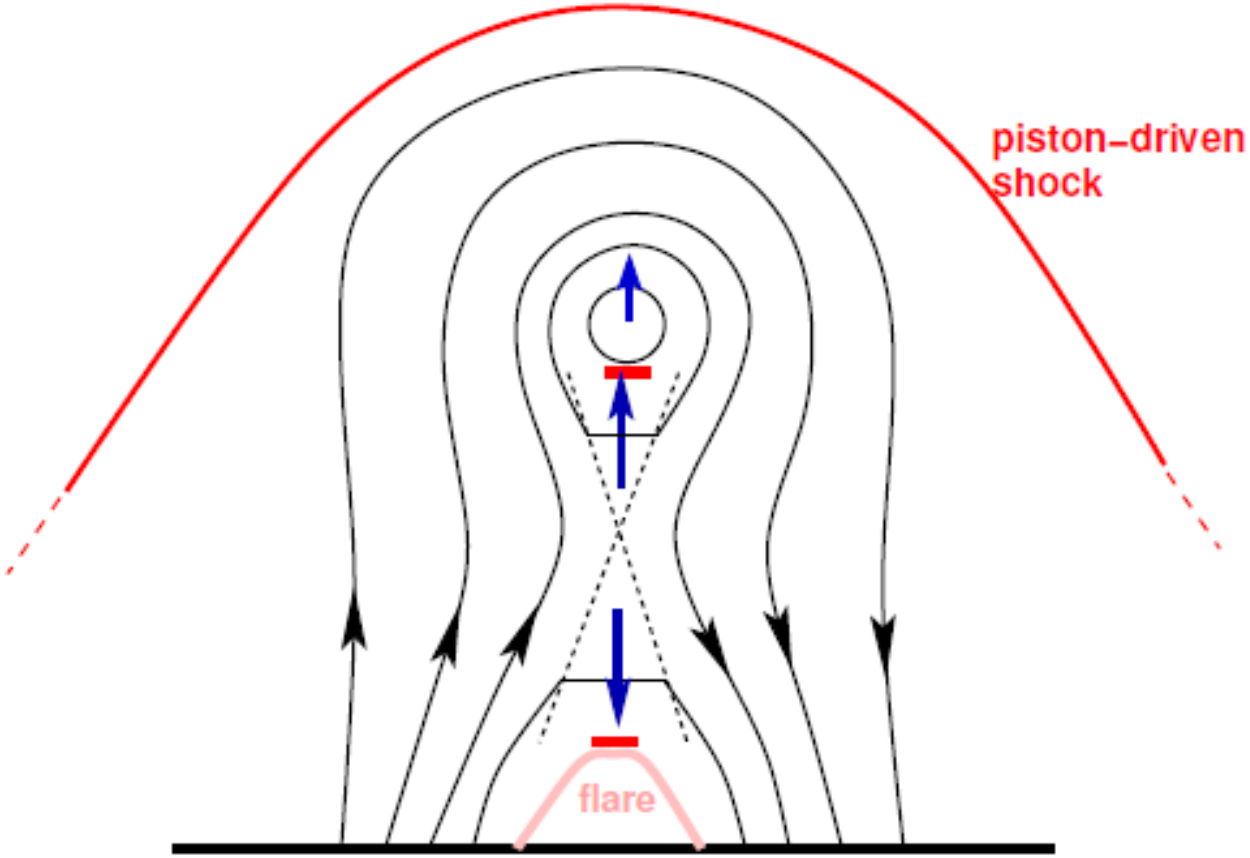
It is not possible to rule out a different rotation for the core ($0.19<r/R_{\odot}<0.3$).

Eff-Darwich & Korzennik (2013, SP)

Can future neutrino measurements say something?

谜之二：爆发是如何触发的？

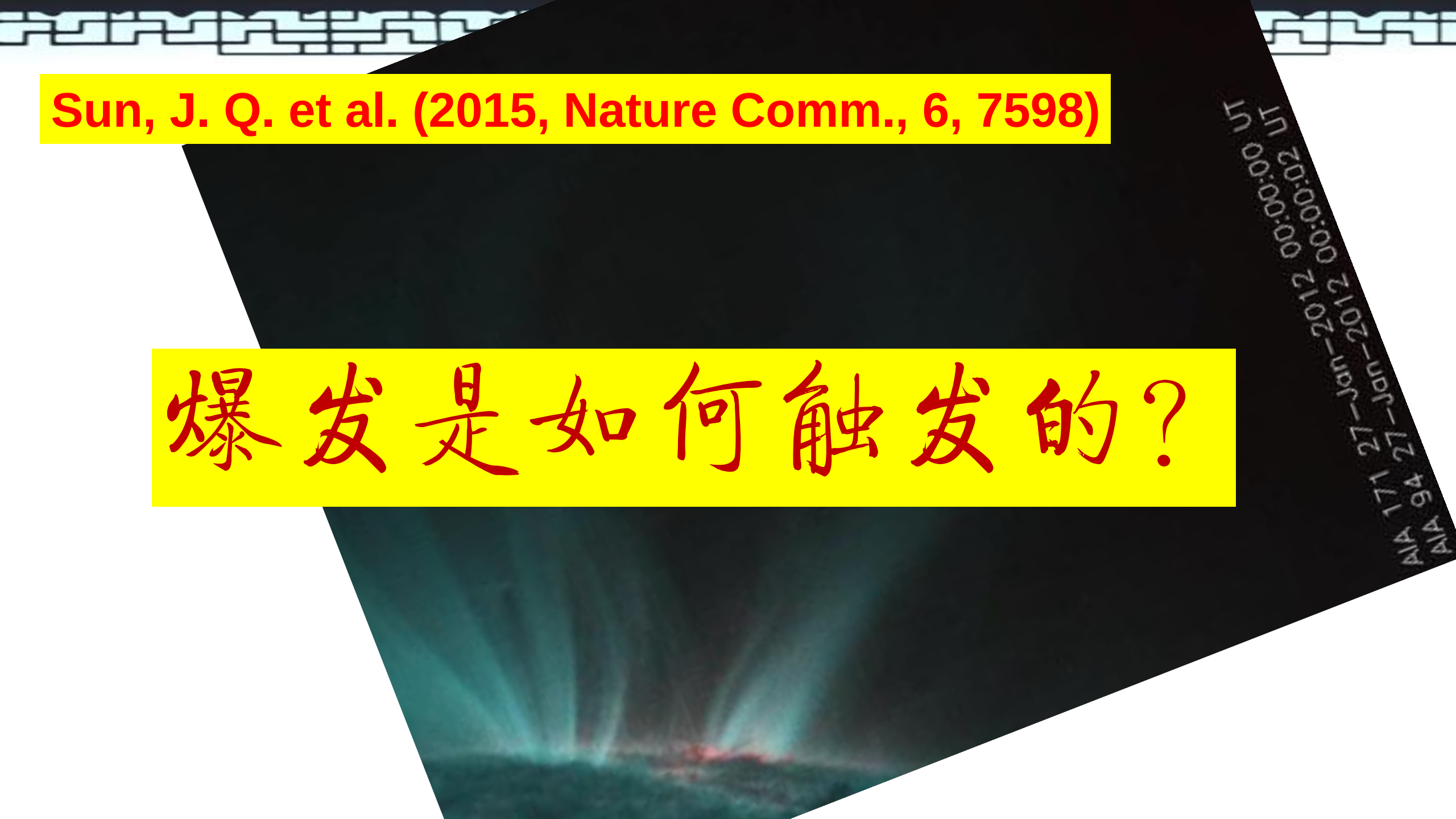




Standard model

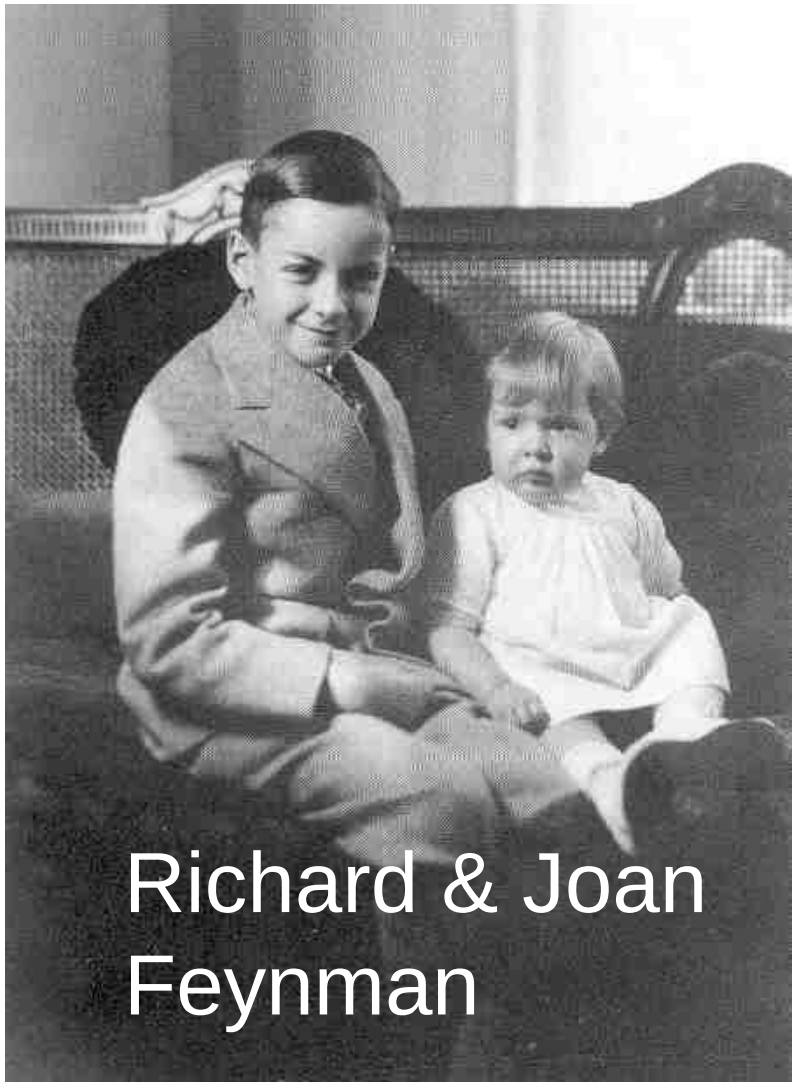
Chen, P. F. 2011, Living Reviews in Solar Physics, 8, 1

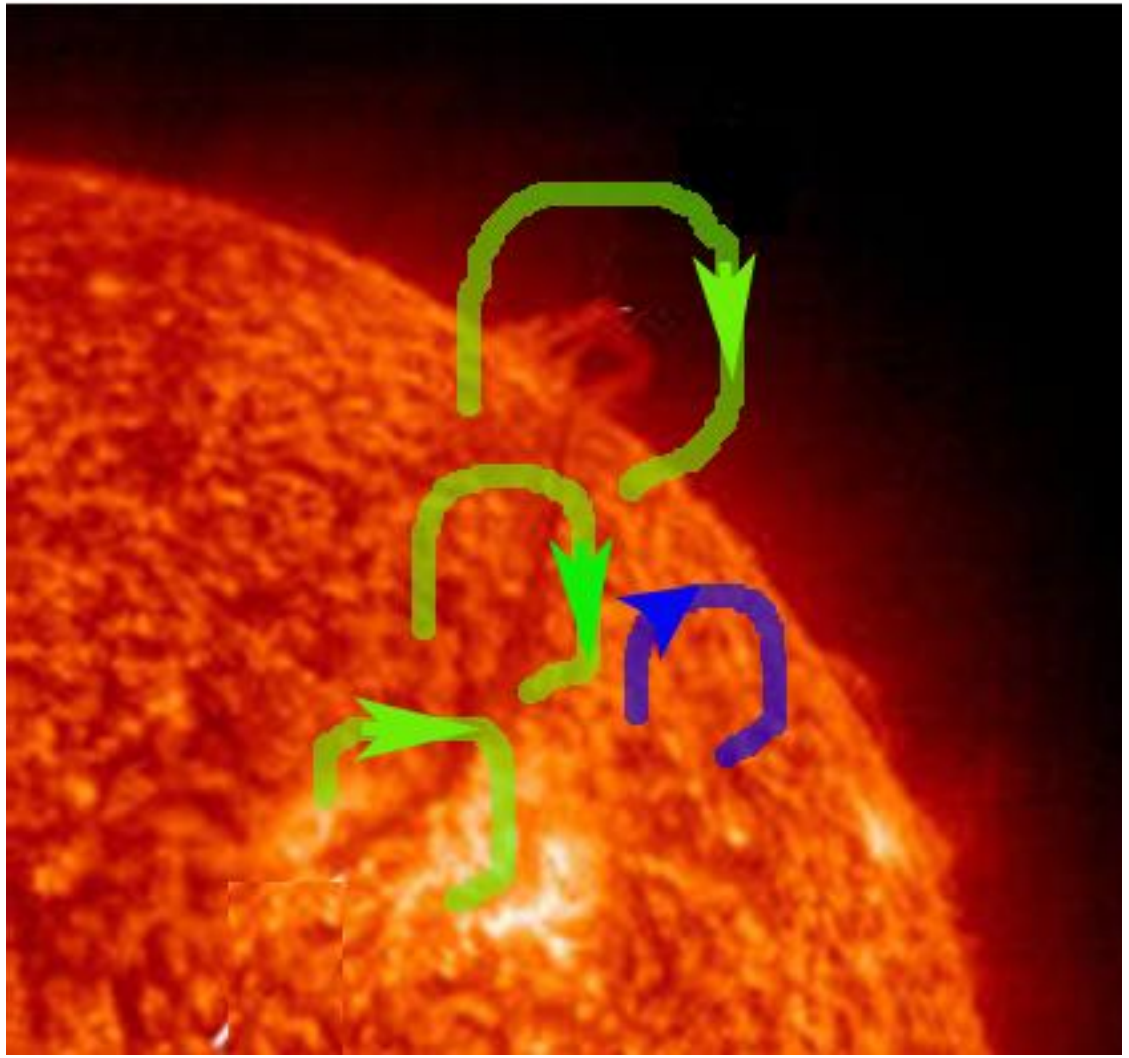
Sun, J. Q. et al. (2015, Nature Comm., 6, 7598)



爆发是如何触发的？

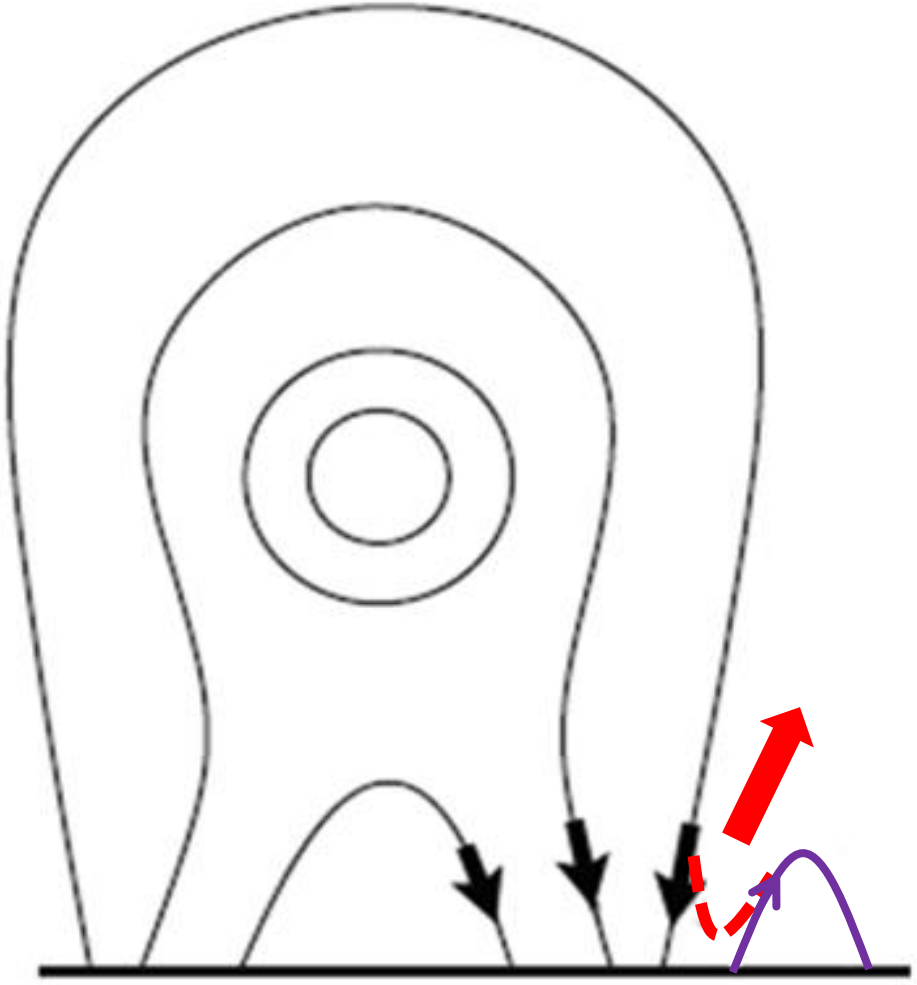
费曼的发现

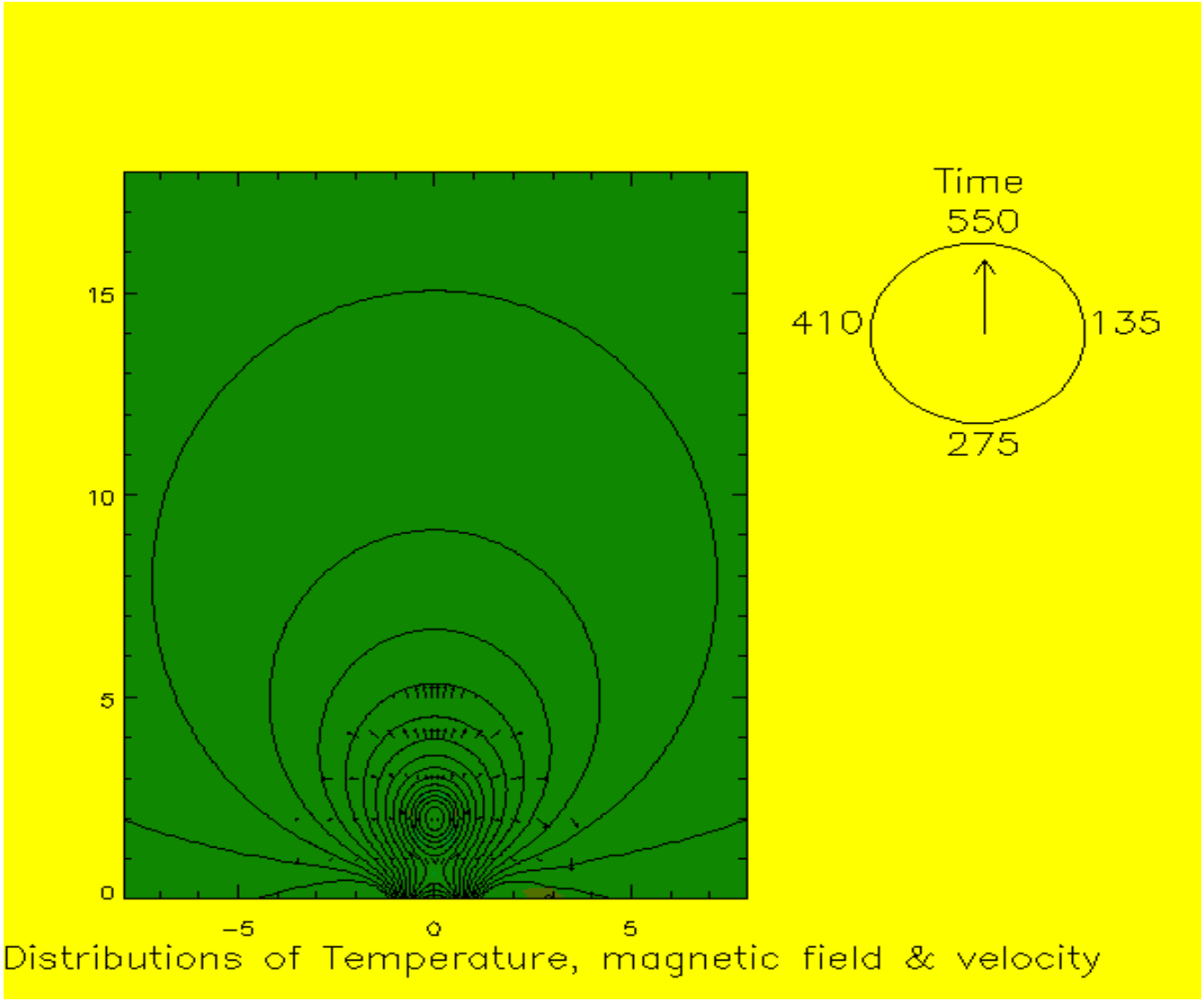




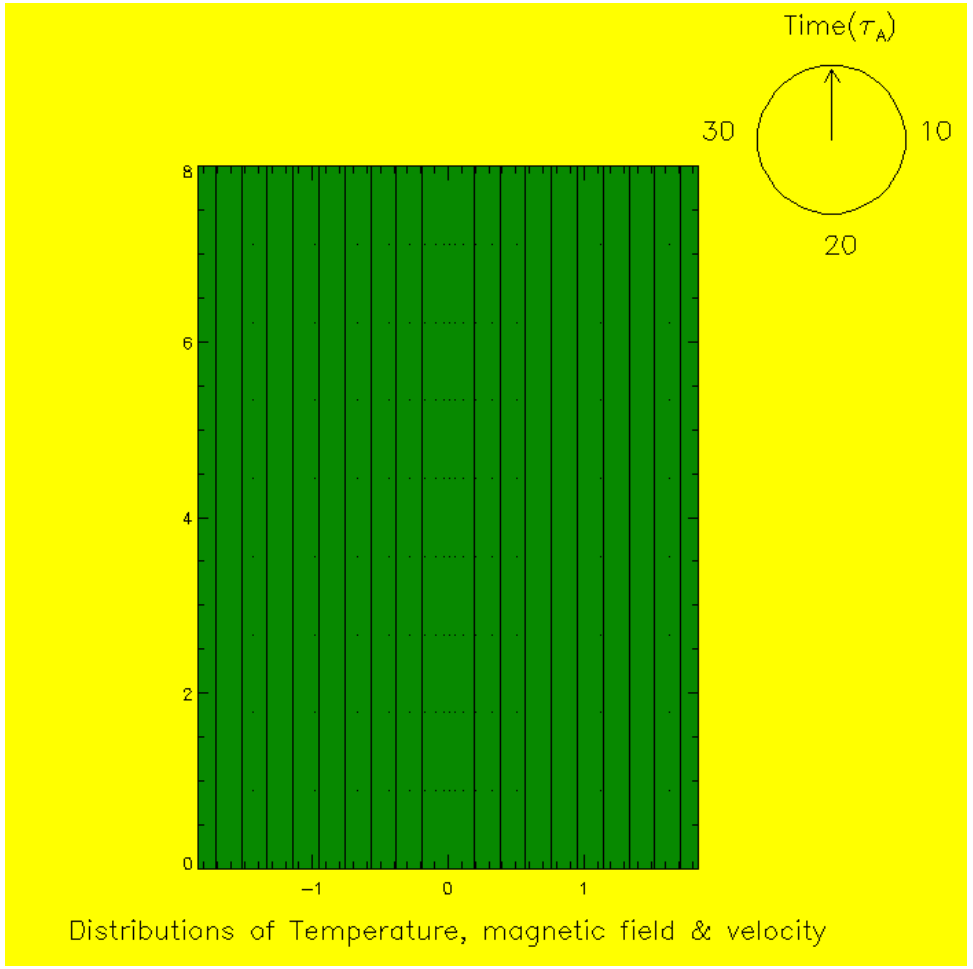
日冕物质抛射爆发前一天会出现新的磁场浮现

Chen & Shibata (2000, ApJ, 545, 524)





谜之三：磁重联中的能量分配

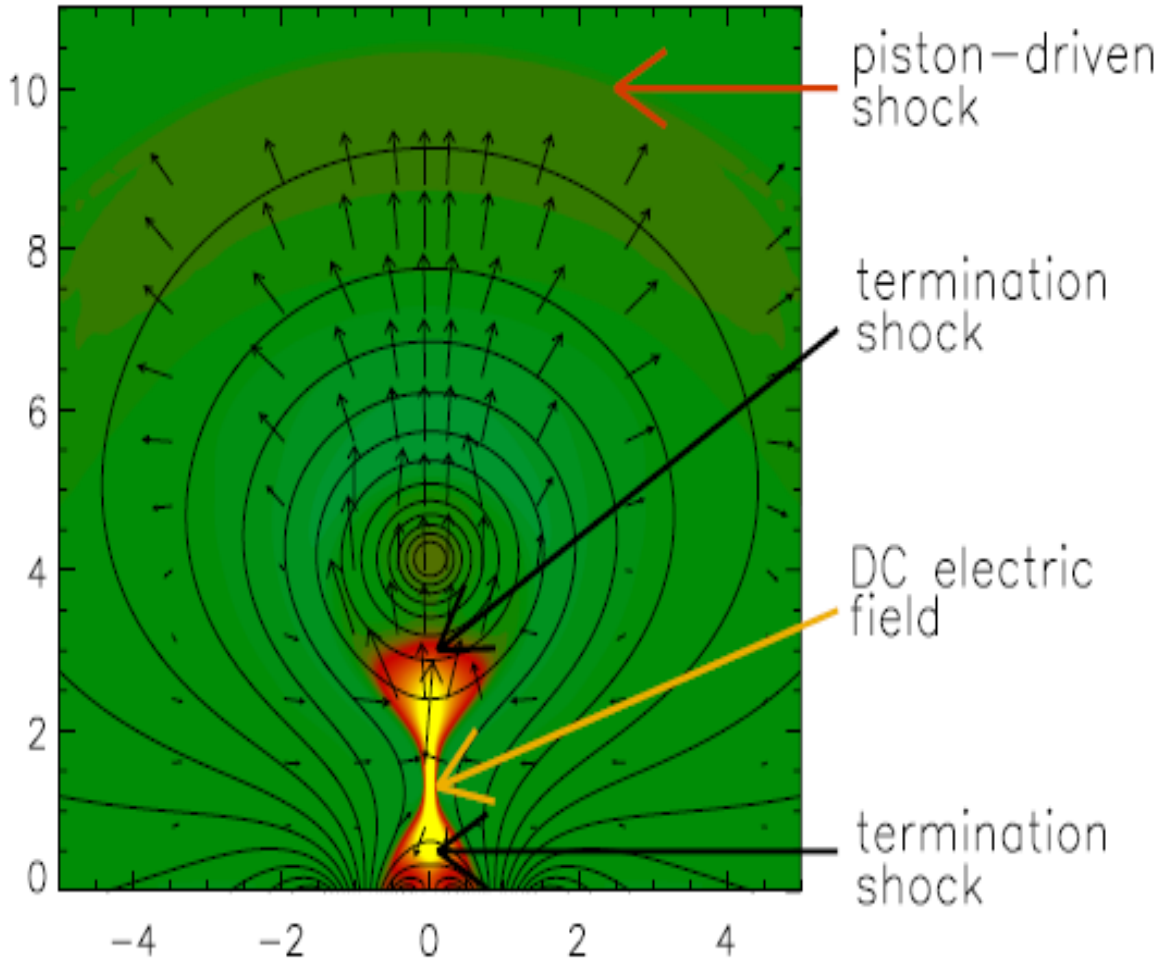


(1) 动能

(2) 热能

(3) 高能粒子非热能

Chen et al. (1999, ApJ, 513, 516)



1. 电场

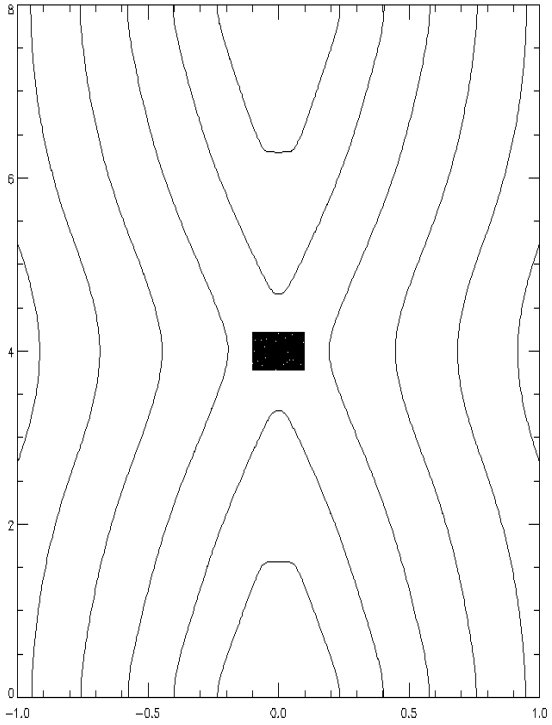
2. 激波

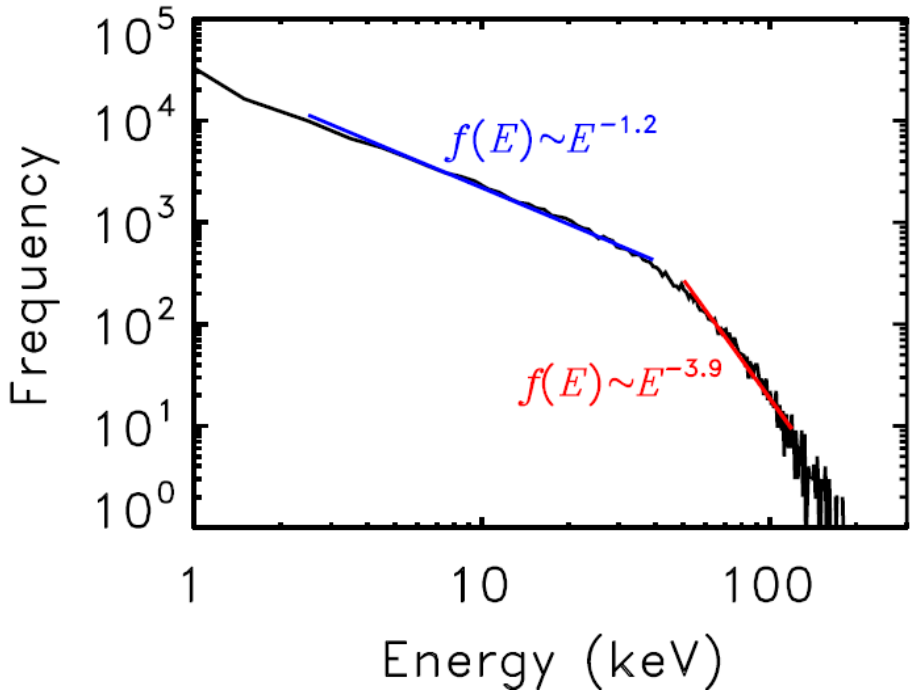
3. 湍流

Chen, P. F. + 2007, Adv. Space Res., 39, 1421

通常的研究手段

1. 数值模拟

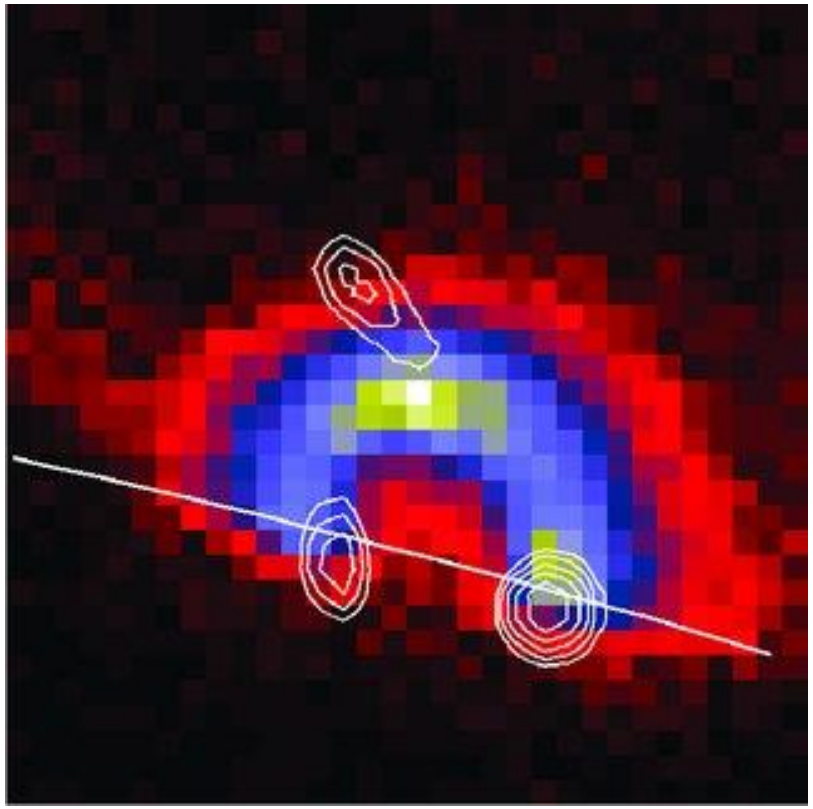




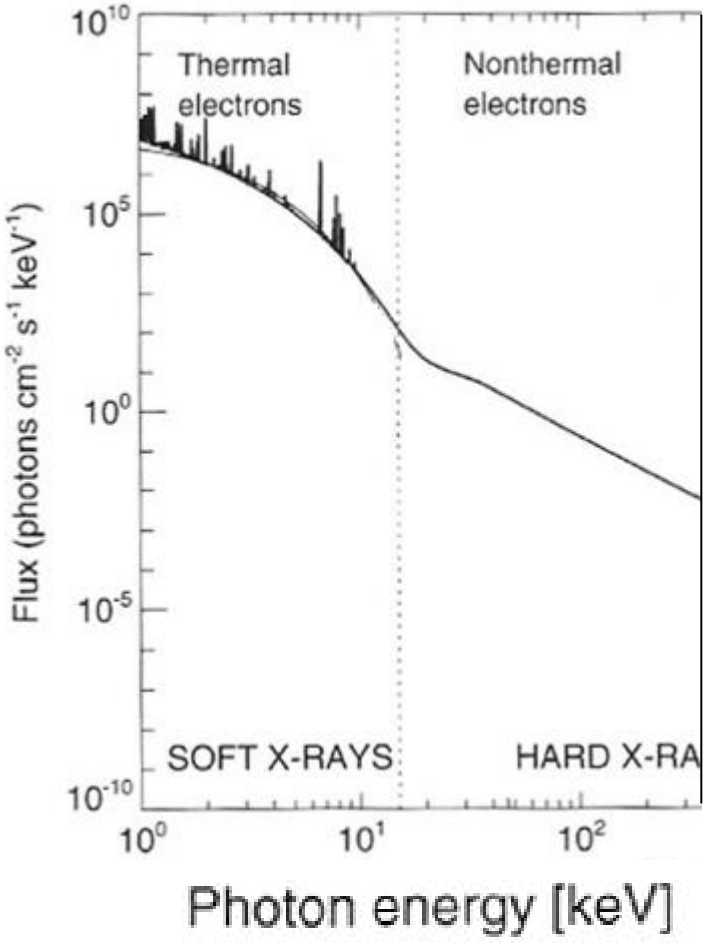
Liu W. J. et al. (2009)

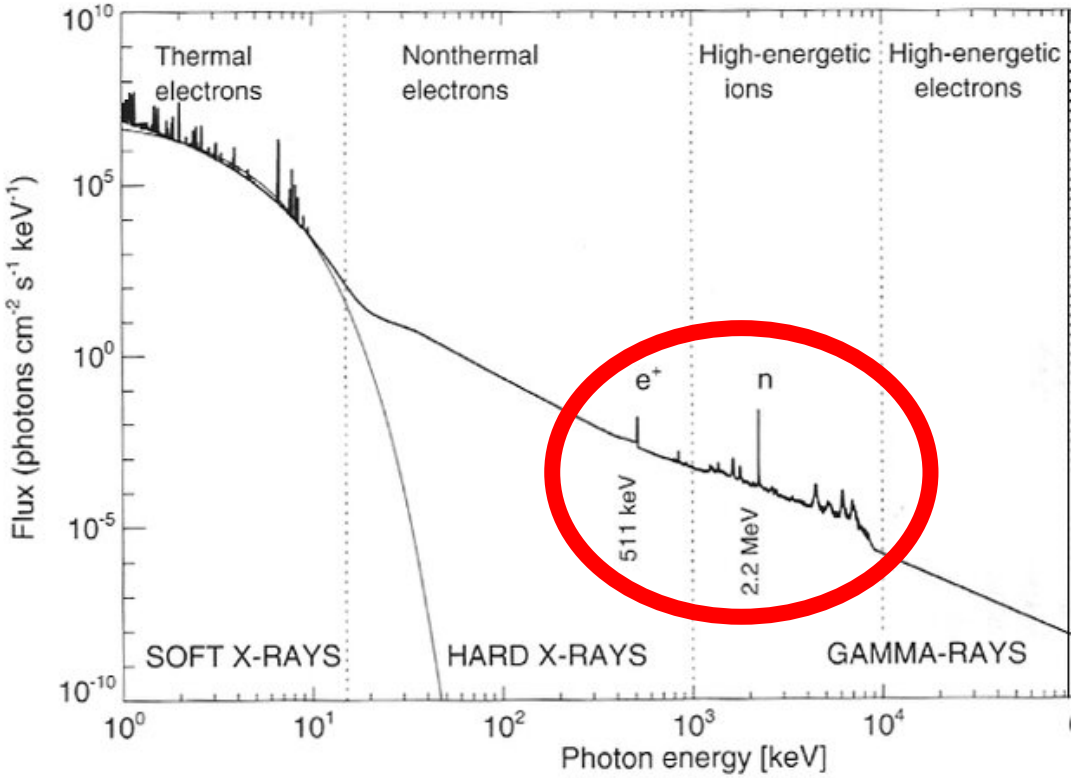
通常的研究手段

2. HXR观测

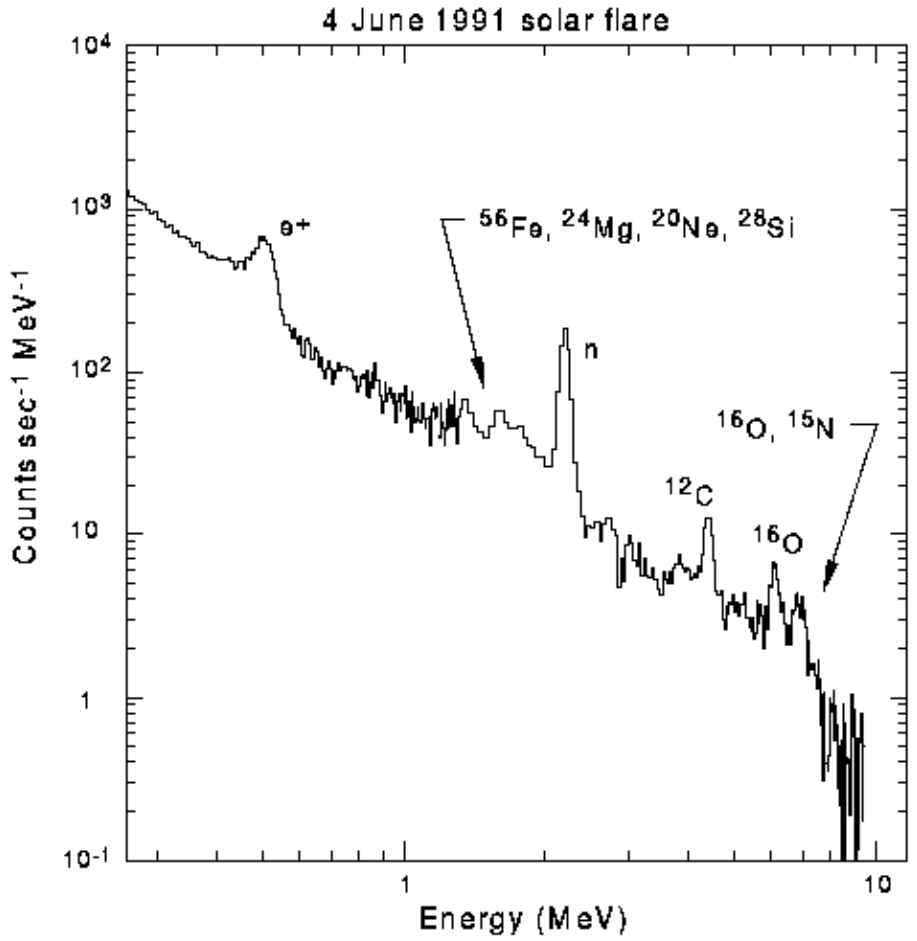


Masuda et al. (1995)





Lin et al. (2002)



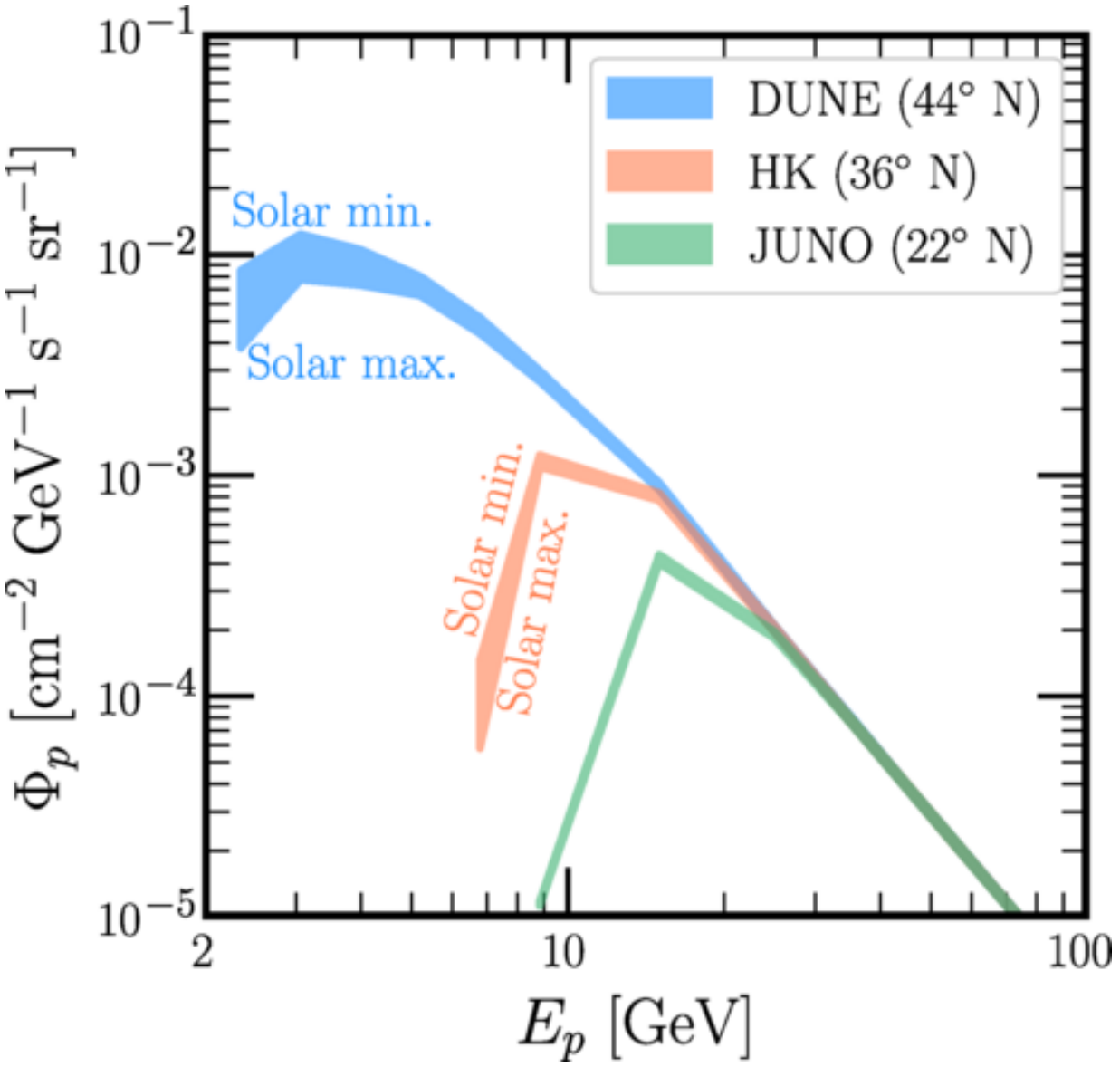
Murphy et al. (1997)

加速的粒子: p, ^{3}He, ^{4}He, C, N, O, Ne, Mg, Si, and Fe

Fargion (2004): No possibility of detecting solar flare neutrinos even with Hyper-Kamiokande.

de Wasseige (2016): predicts 398–770 cm^{-2} neutrino fluence at Earth in the 10–100 MeV range.

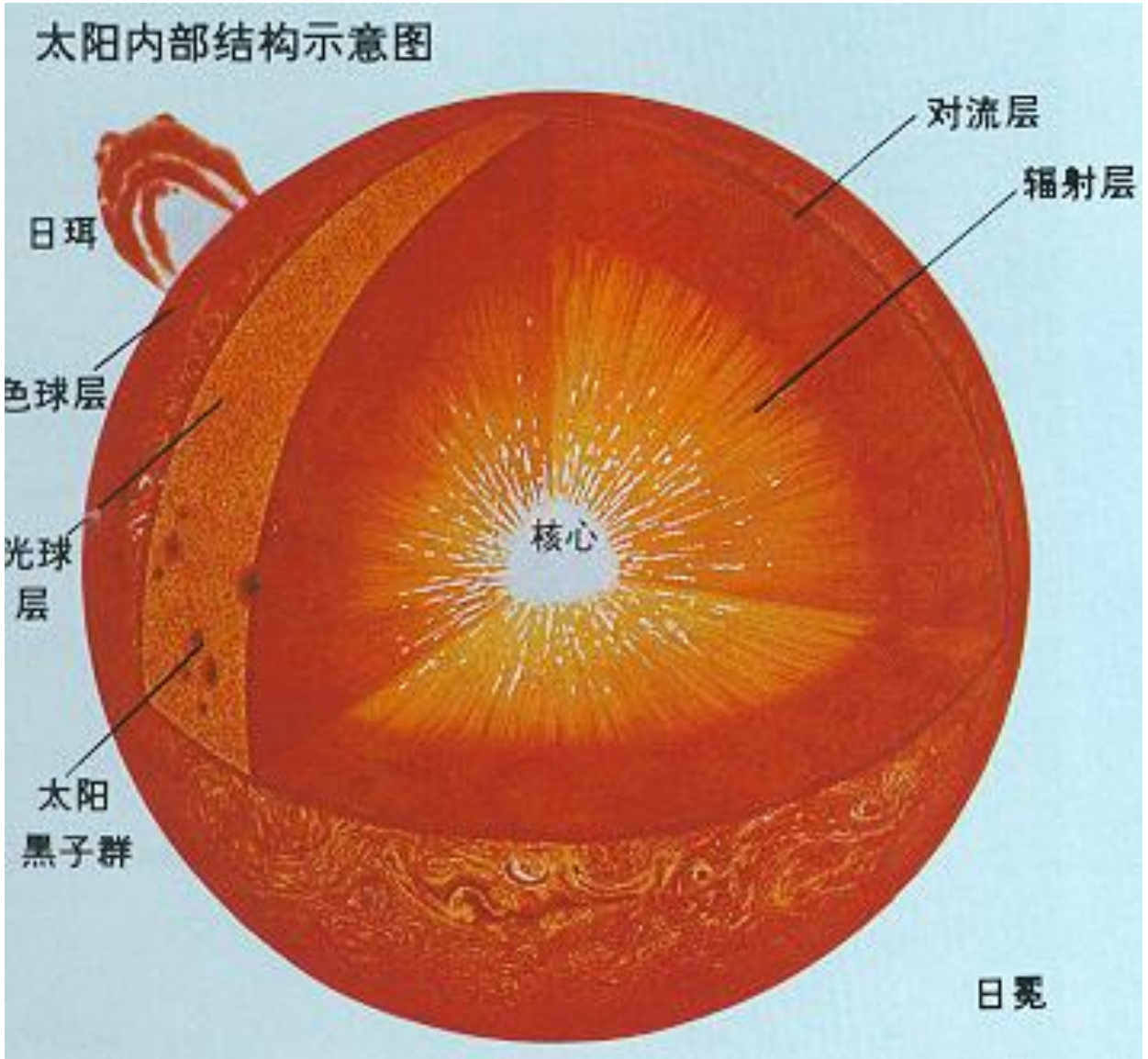
Abe et al. (2022): no excess

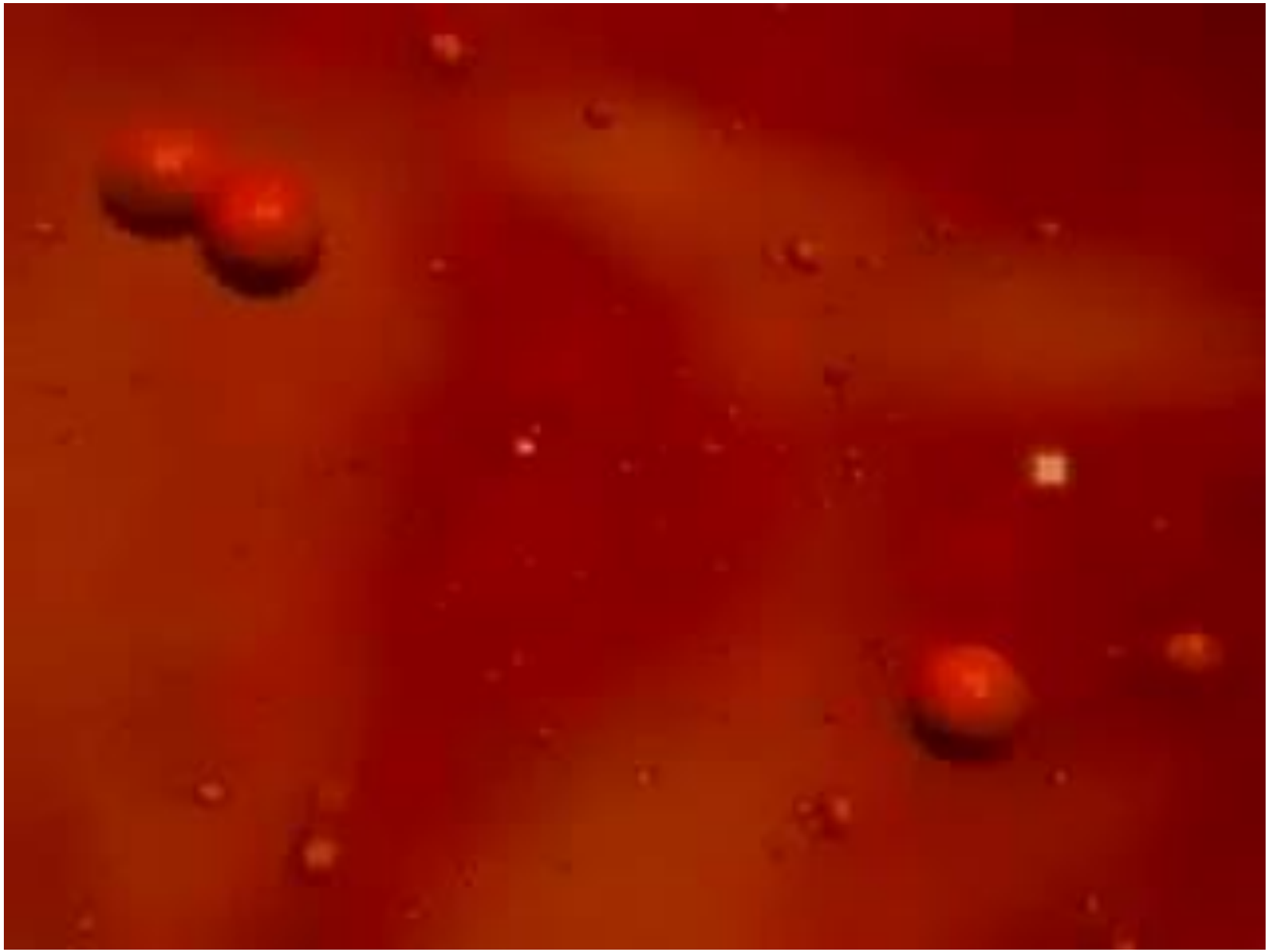

DUNE (44° N)
HK (36° N)
JUNO (22° N)
Solar min.
Solar max.
Solar min.
Solar max.
Φ_p [cm^{-2} GeV^{-1} s^{-1} sr^{-1}]
E_p [GeV]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
2
10
100

±5% for DUNE

中微子探测可能涉及的几个物理问题

（1）标准模型vs非标准模型



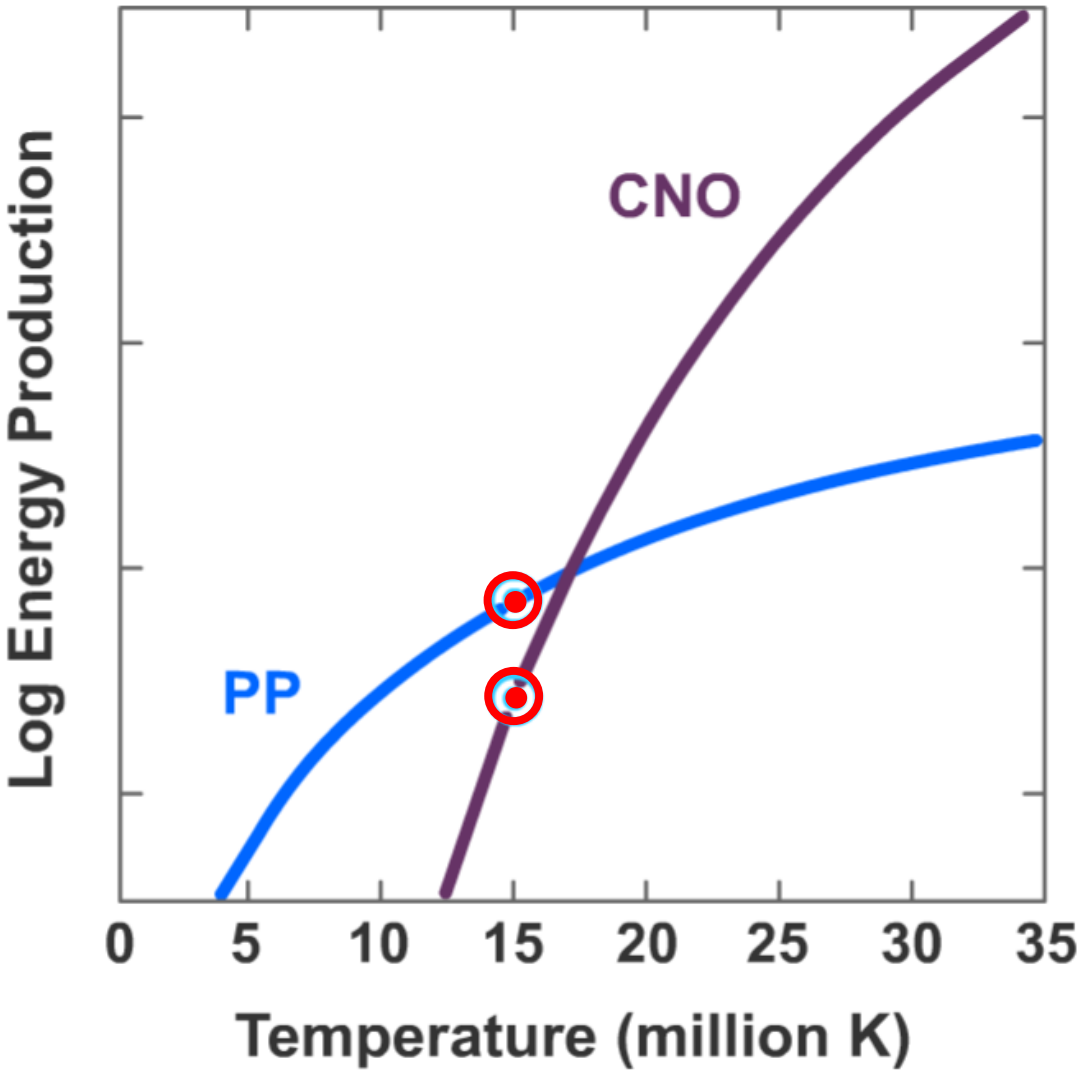


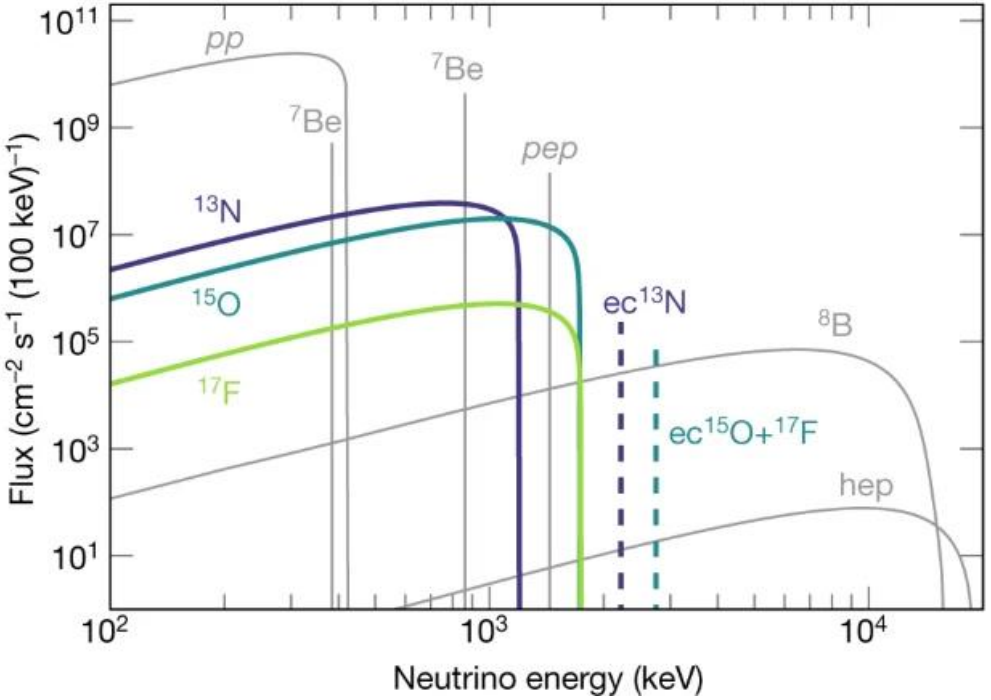
4个氢原子

1个氦原子

质量减少
0.007倍

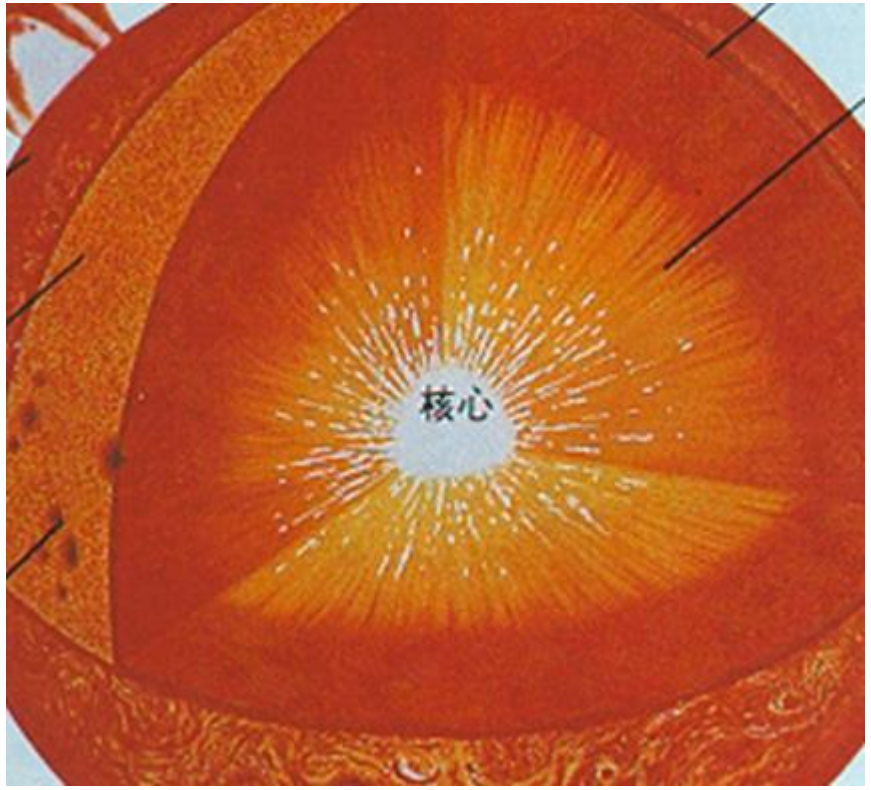
$$E = mc^2$$





The Borexino Collaboration, 2018, 2020, Nature

99% from the pp chain
1% from the CNO cycle

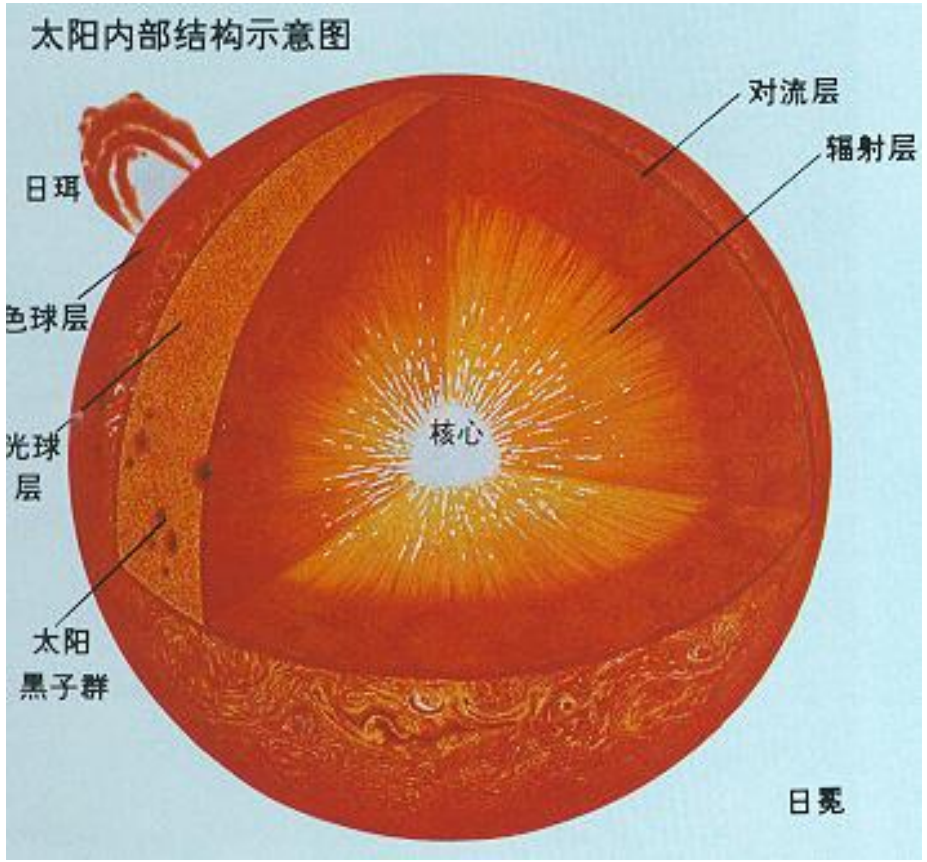


An efficient factory for keV-scale physics beyond the Standard Model, e.g., solar axions and dark photons.

Gustafson et al. (2024)

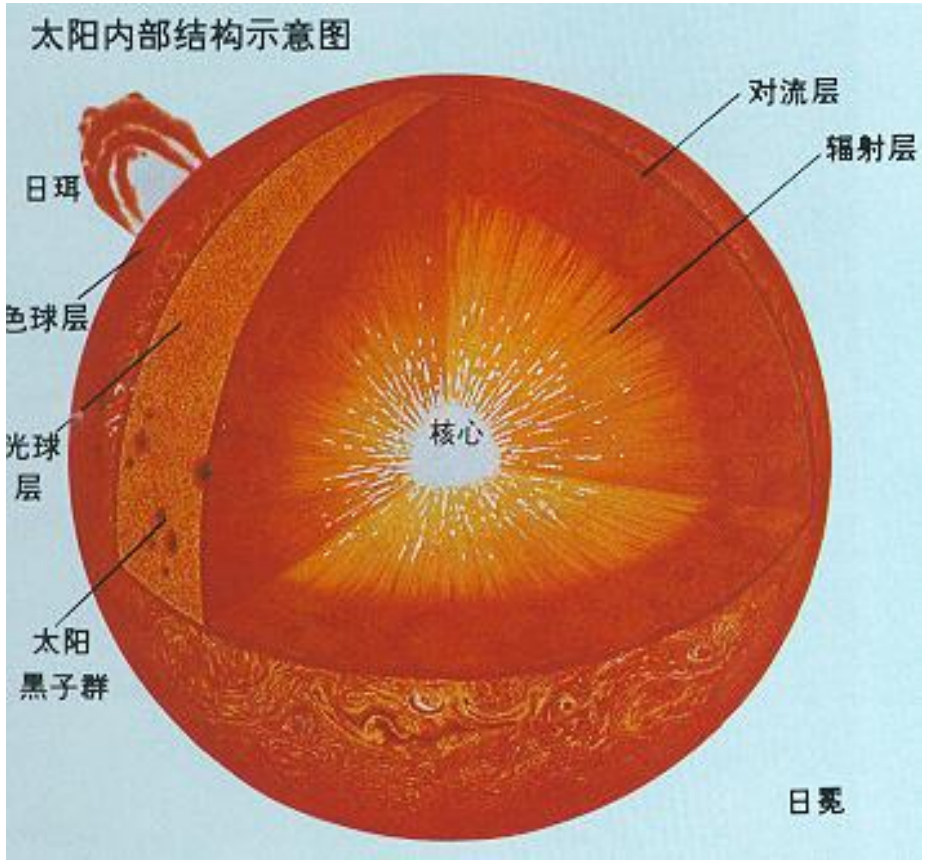
Xu, Wang, Chen (2023)

（2）内重力波



目前太阳的内部结构来自太阳表面p模波的反演，大部分p模波来自外层，故对内层反演的精度较低。太阳内部深层次还有内重力波（g模），局限在内层，目前没有确凿的观测证据。周期在几十分钟及以上。希望能测到g模波对中微子强度的调制。

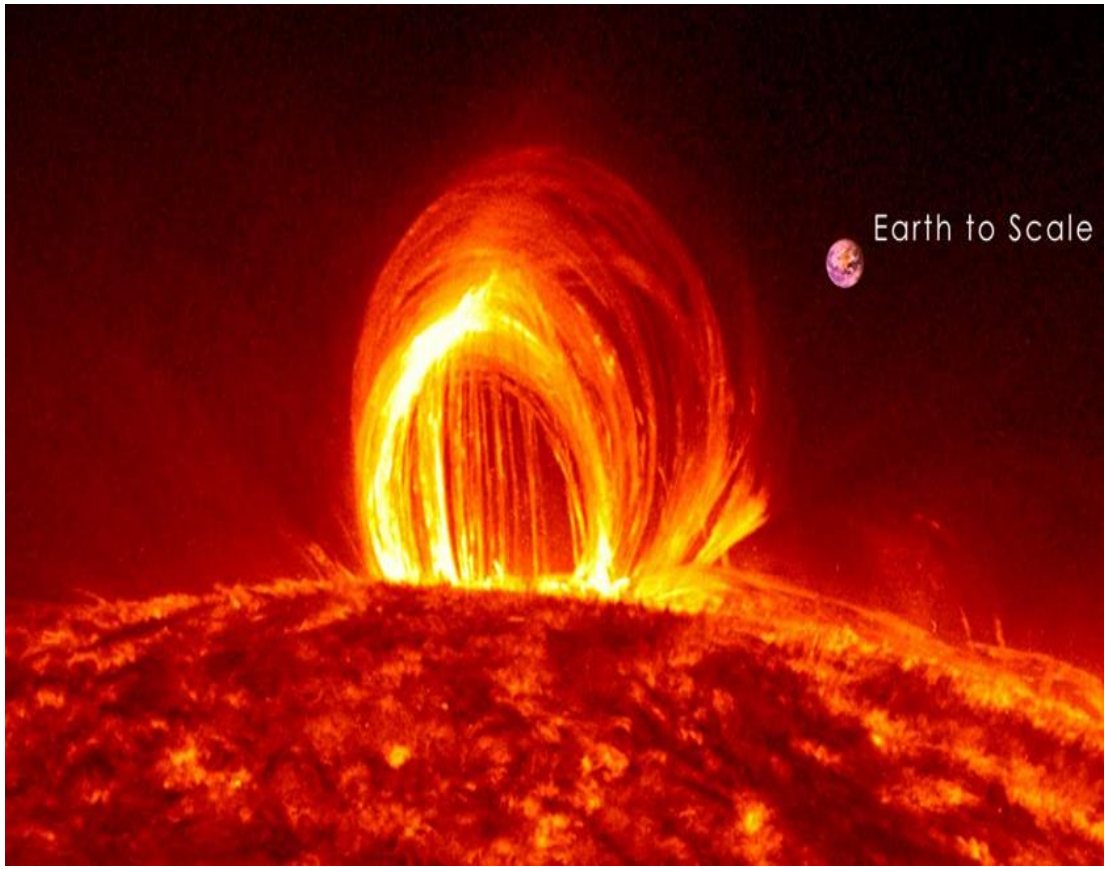
（3）核心和辐射区是否刚体自转？



目前倾向认为它们是刚体自转，但不排除自转速度有差异。若有差异，有人提出交界处可能也有发电机过程，使得太阳黑子出现万年尺度的起伏。

g模波对中微子强度的调制会受到这种差异的影响。

（4）太阳耀斑产生的中微子



目前尚未探测到。

太阳耀斑中微子将提供粒子加速的重要信息。

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谢谢大家！

欢迎提问！