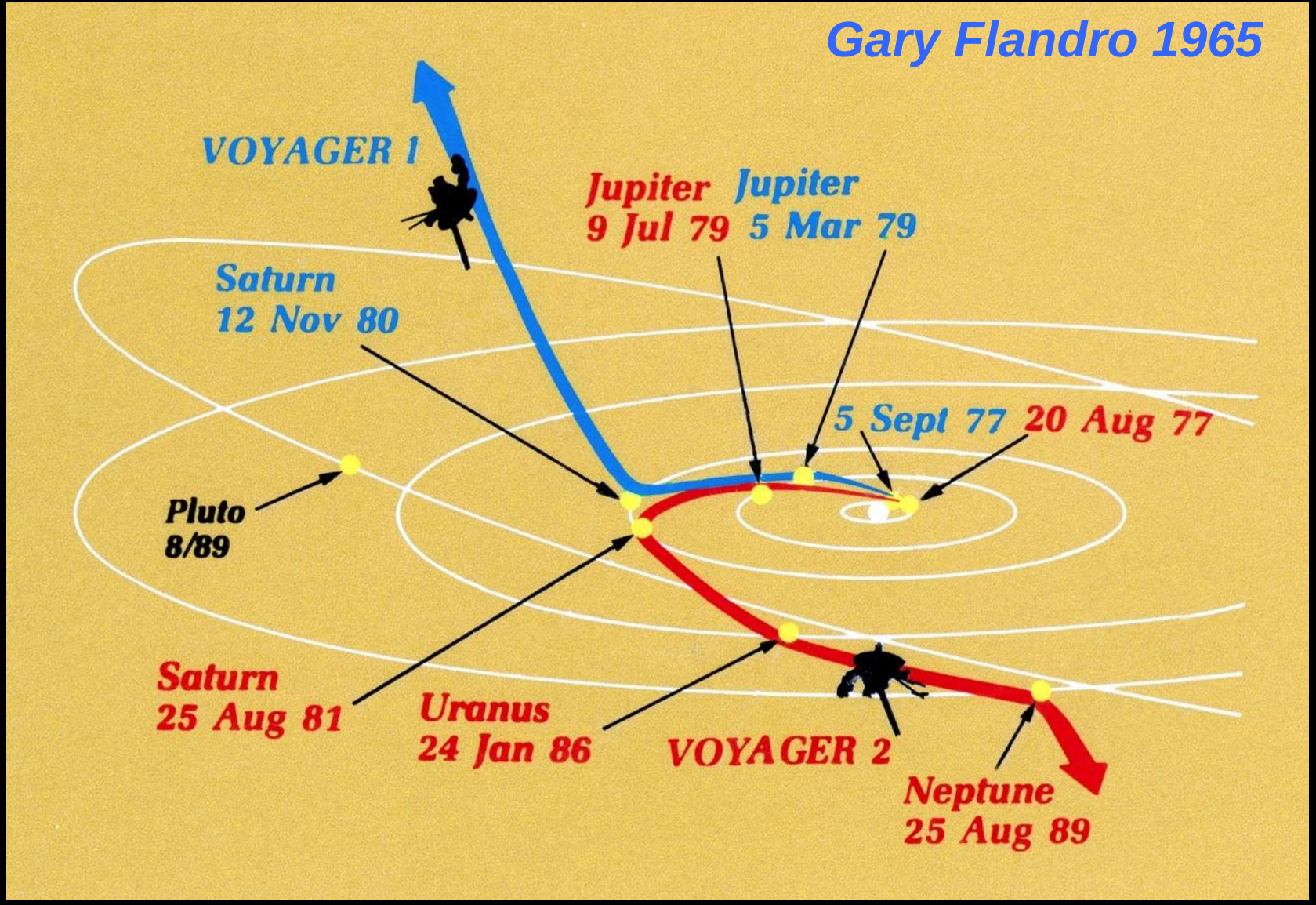
The Voyager Odyssey

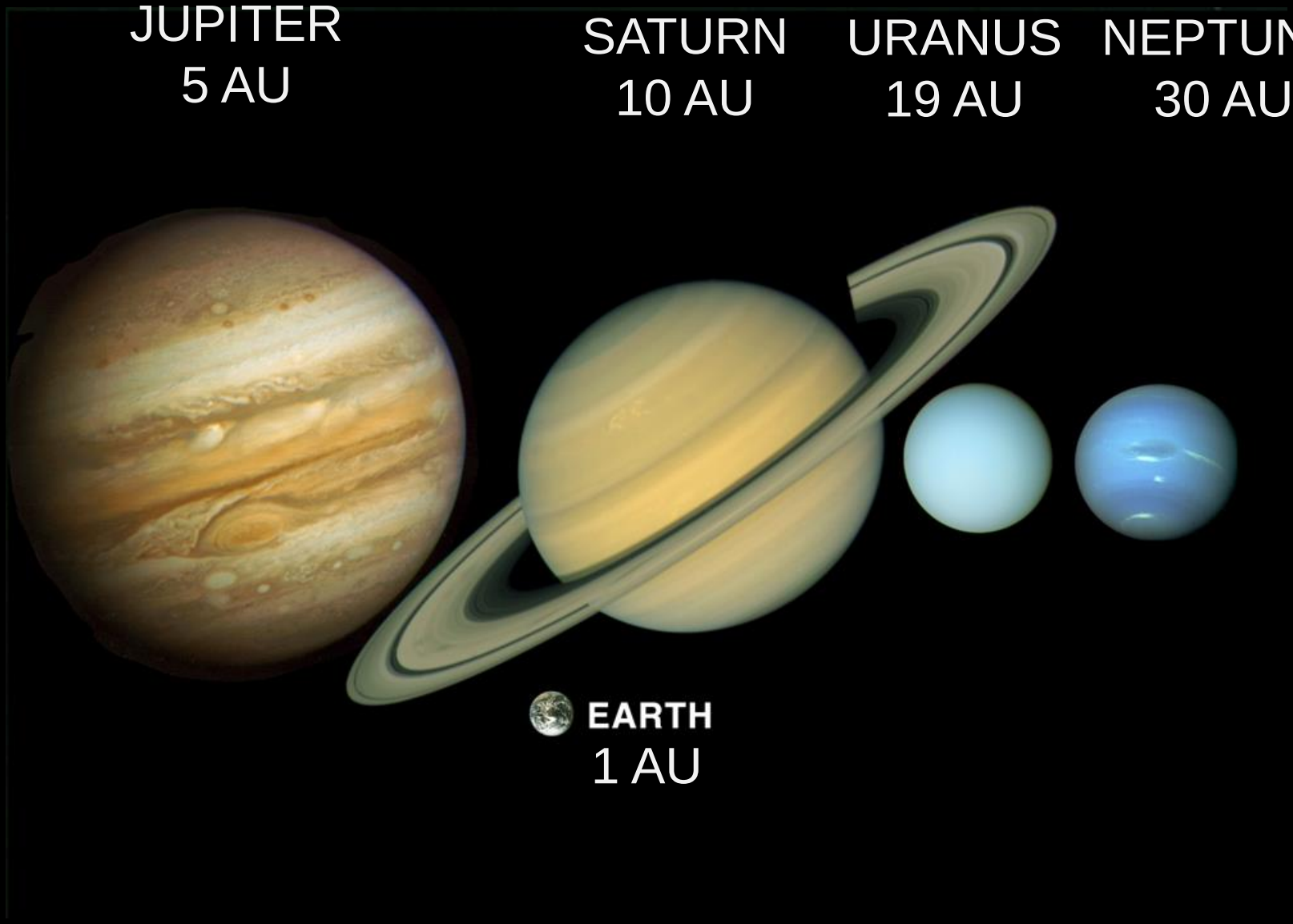
AMS Days at CERN

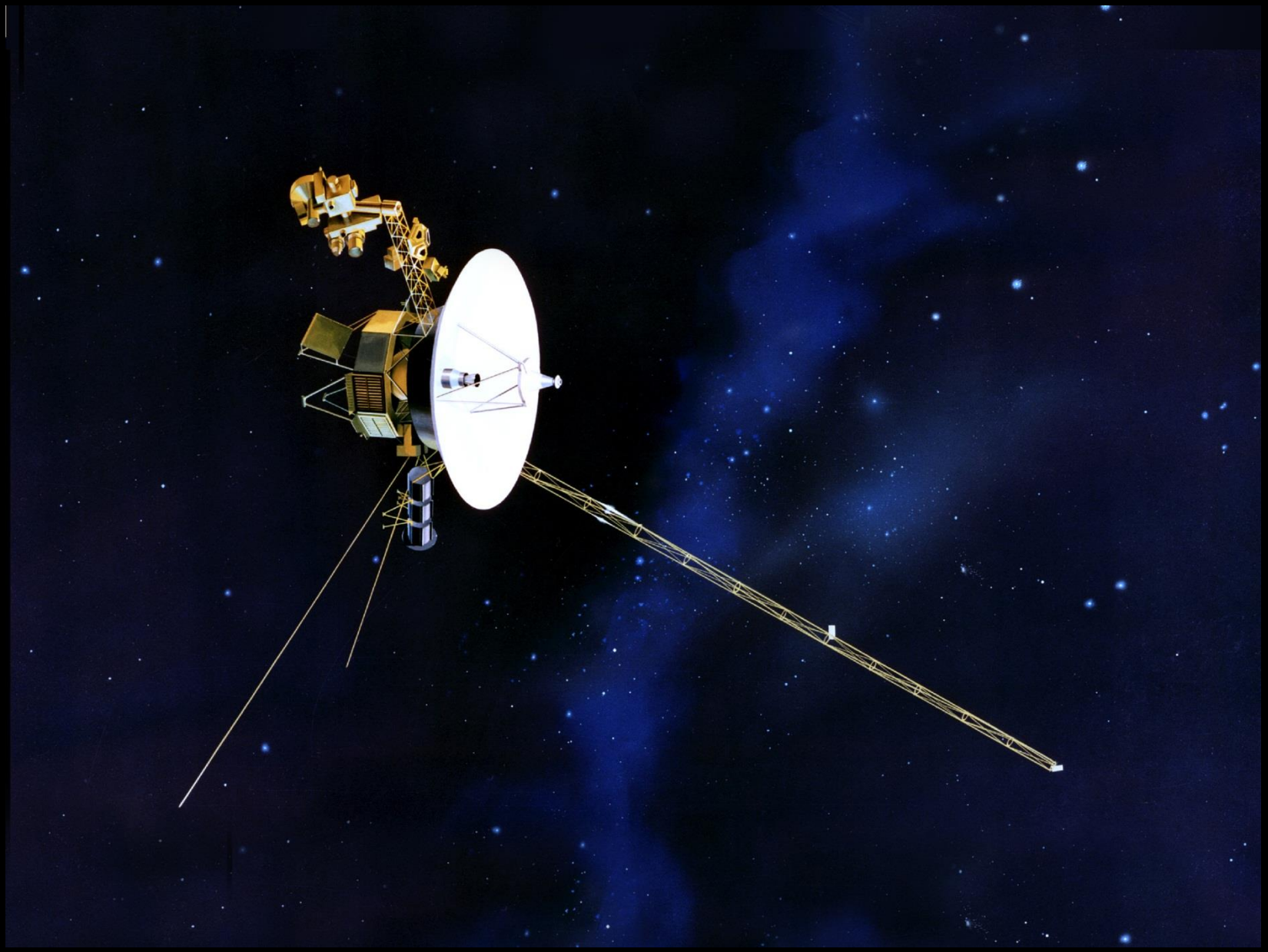
April 16, 2015

Edward C. Stone



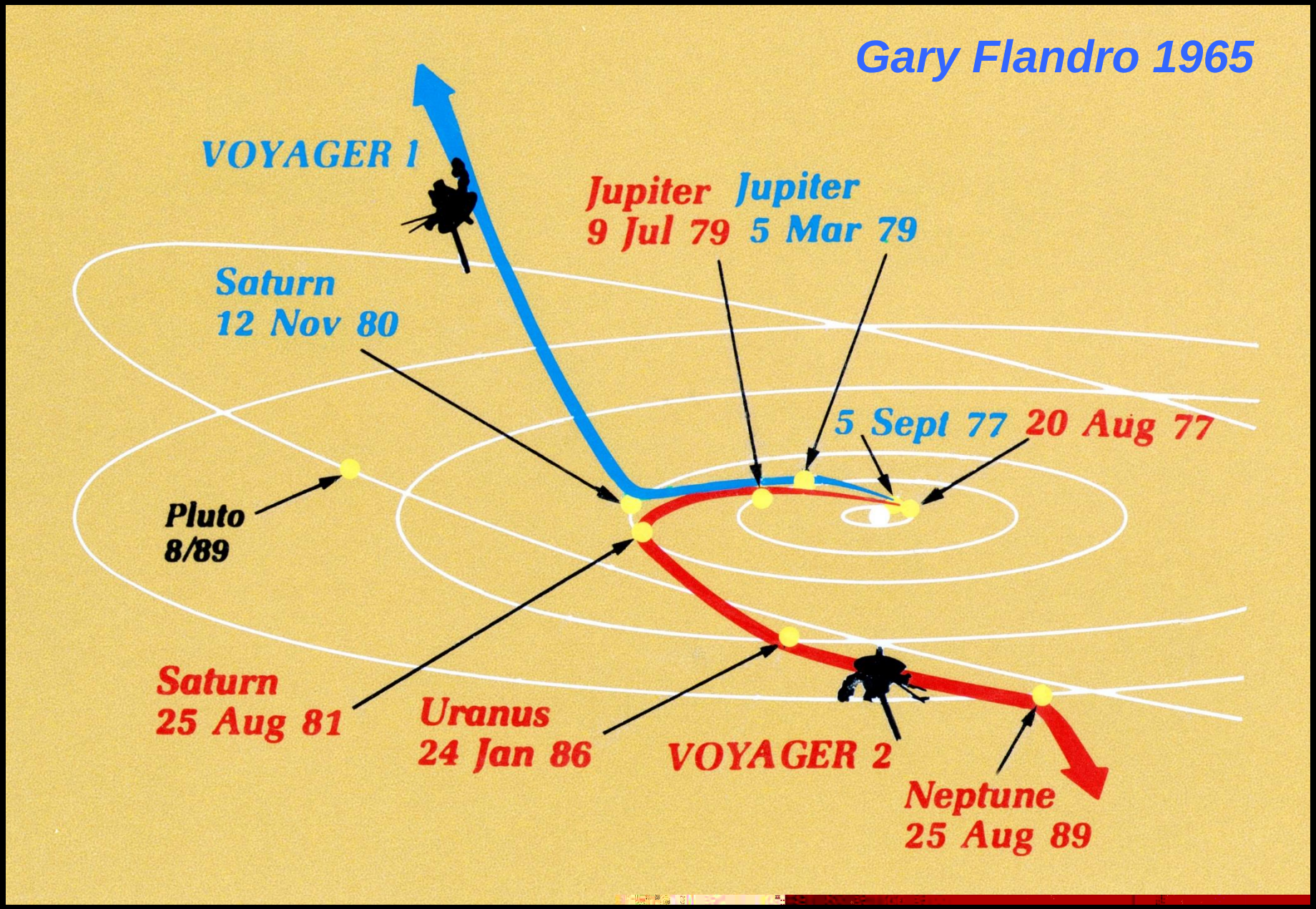
Once every 176 years the giant planets are lined up for a Grand Tour, and in 1977 the Voyagers were launched on humankind's longest journey

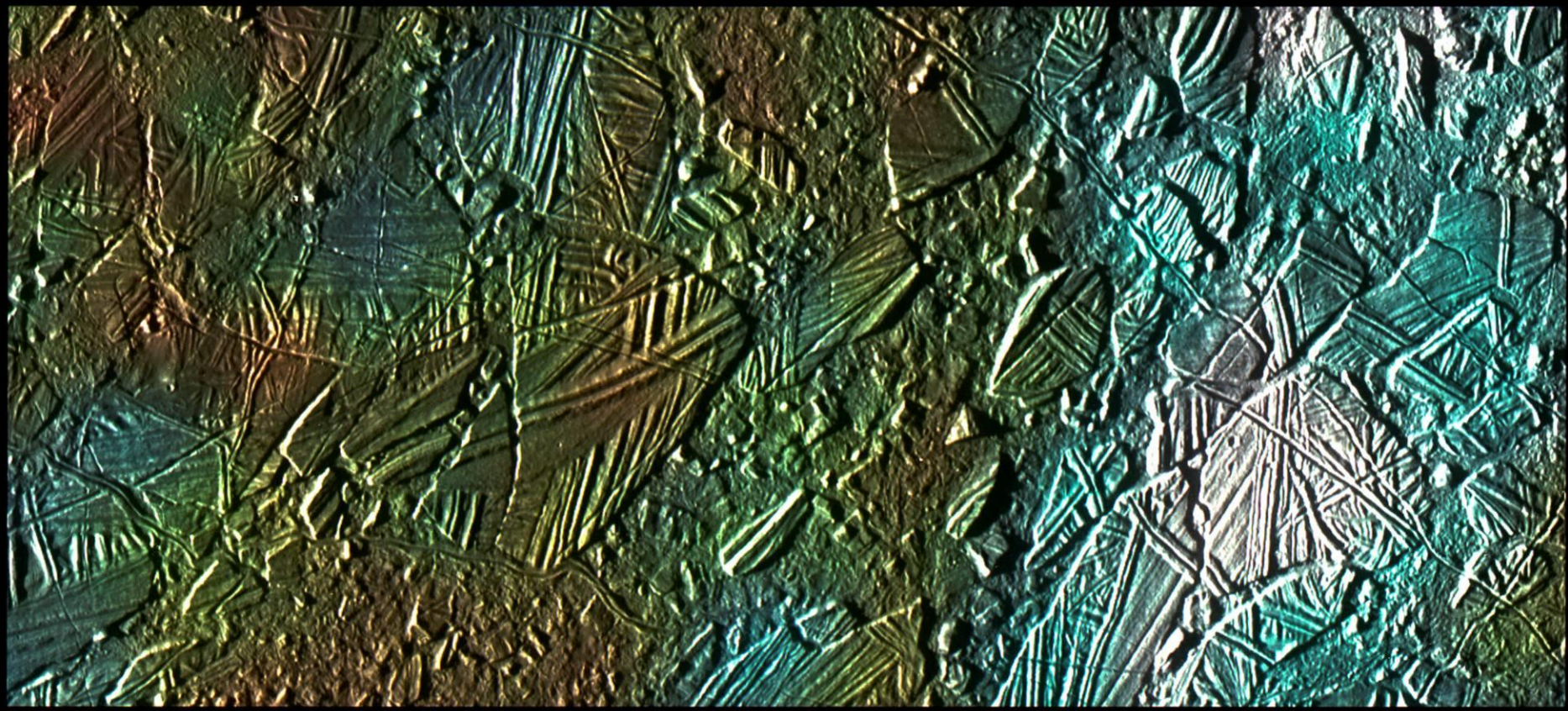

JUPITER
5 AU
SATURN
10 AU
URANUS
19 AU
NEPTUNE
30 AU
EARTH
1 AU



Voyager Interstellar Mission

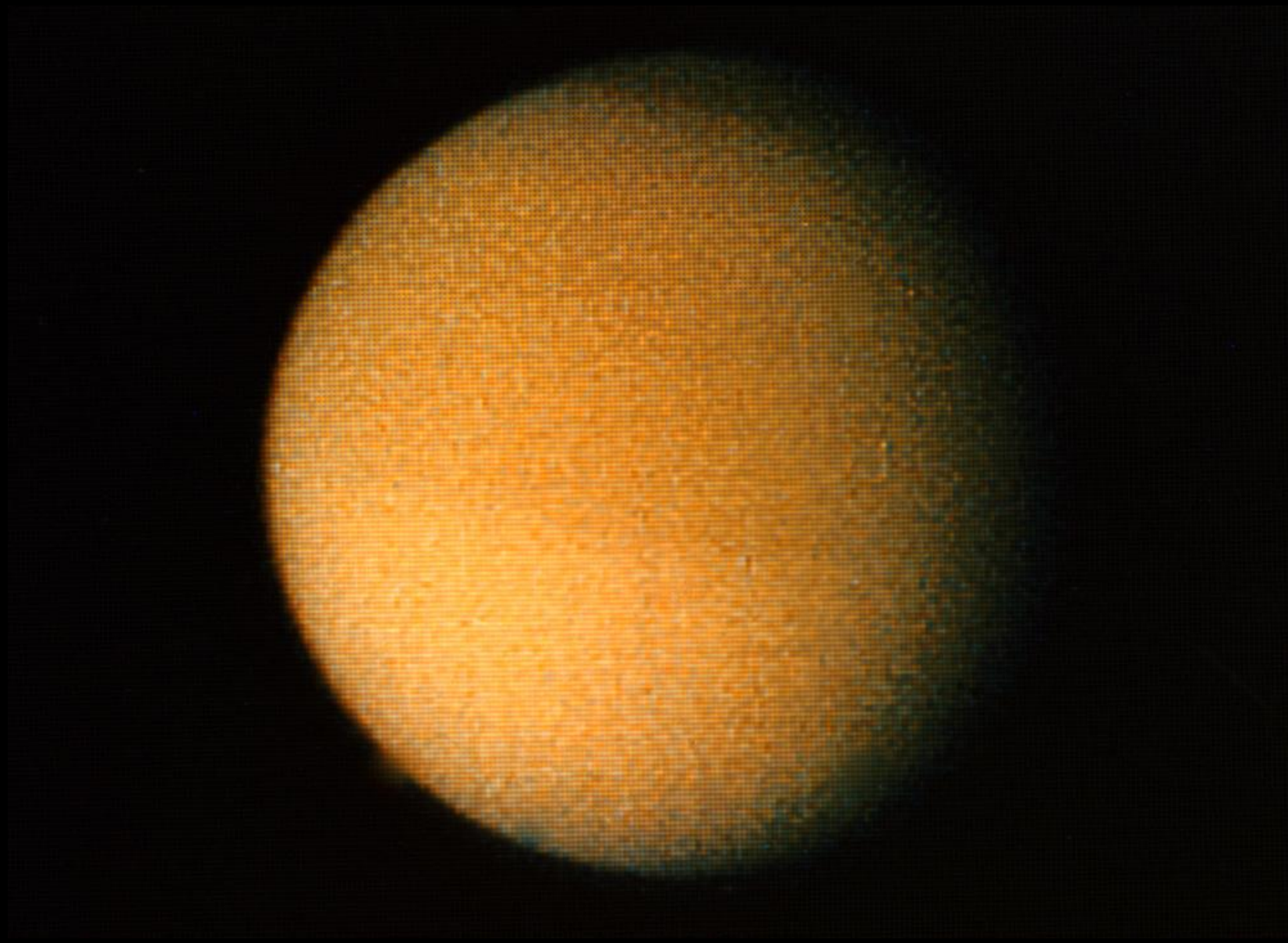
- Plasma Science (Voyager 2)
  - J.D. Richardson, J. W. Belcher, L. F. Burlaga, A.J. Lazarus, R. McNutt, E.C. Sittler, Jr., C. Wang
- Low-Energy Charged Particles
  - S.M. Krimigis, T.P. Armstrong, R.B. Decker, G. Gloeckler, D.C. Hamilton, M. E. Hill, L.J. Lanzerotti, B.H. Mauk, R. McNutt, E.C. Roelof
- Cosmic Rays
  - E.C. Stone, A.C. Cummings, N. Lal, F.B. McDonald, W.R. Webber
- Magnetometer
  - N.F. Ness, L.F. Burlaga
- Plasma Waves
  - D.A. Gurnett, W.S. Kurth


Gary Flandro 1965
VOYAGER 1
Jupiter
9 Jul 79
Jupiter
5 Mar 79
Saturn
12 Nov 80
5 Sept 77
20 Aug 77
Pluto
8/89
Saturn
25 Aug 81
Uranus
24 Jan 86
VOYAGER 2
Neptune
25 Aug 89

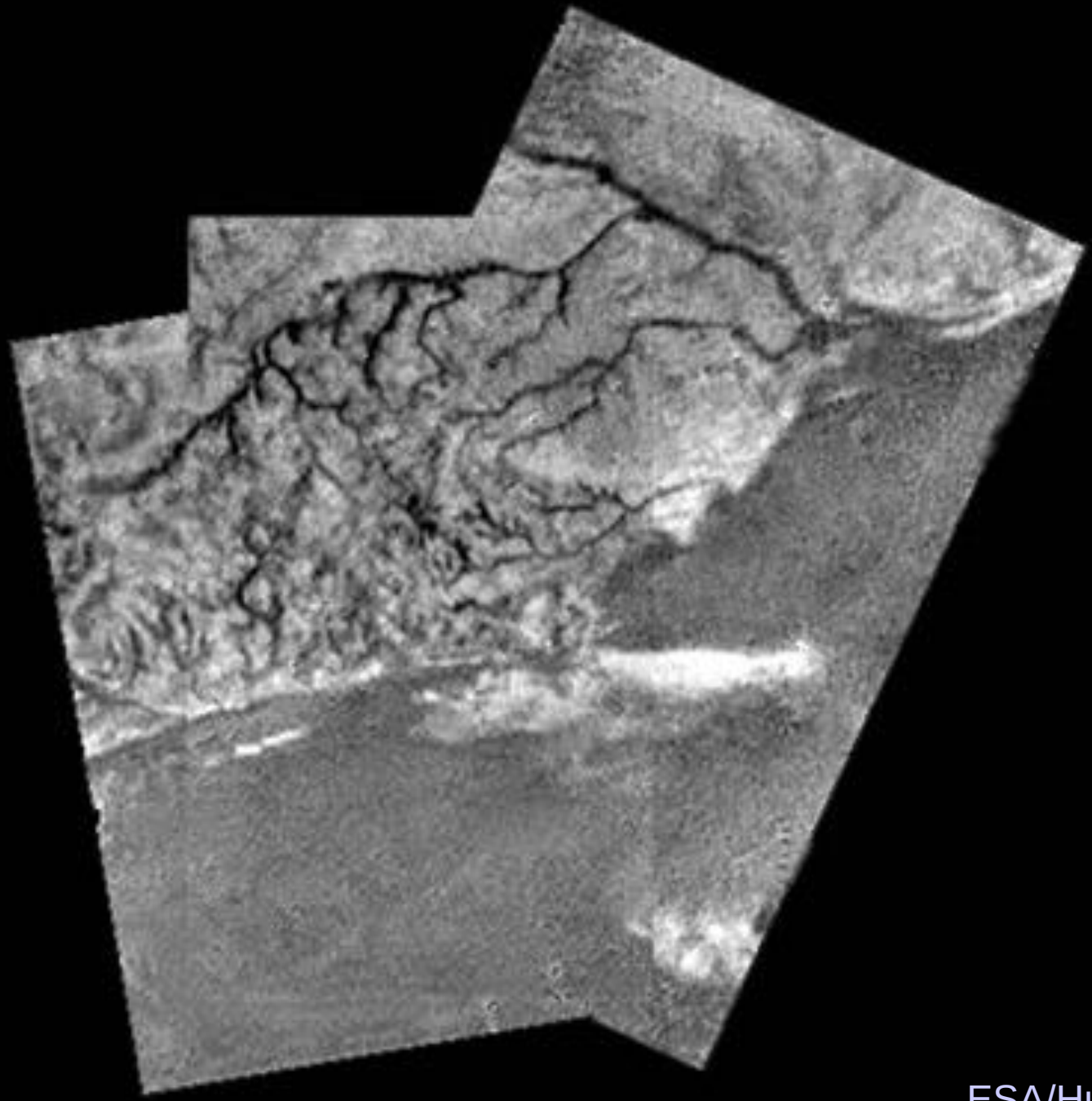


Europa (Galileo)

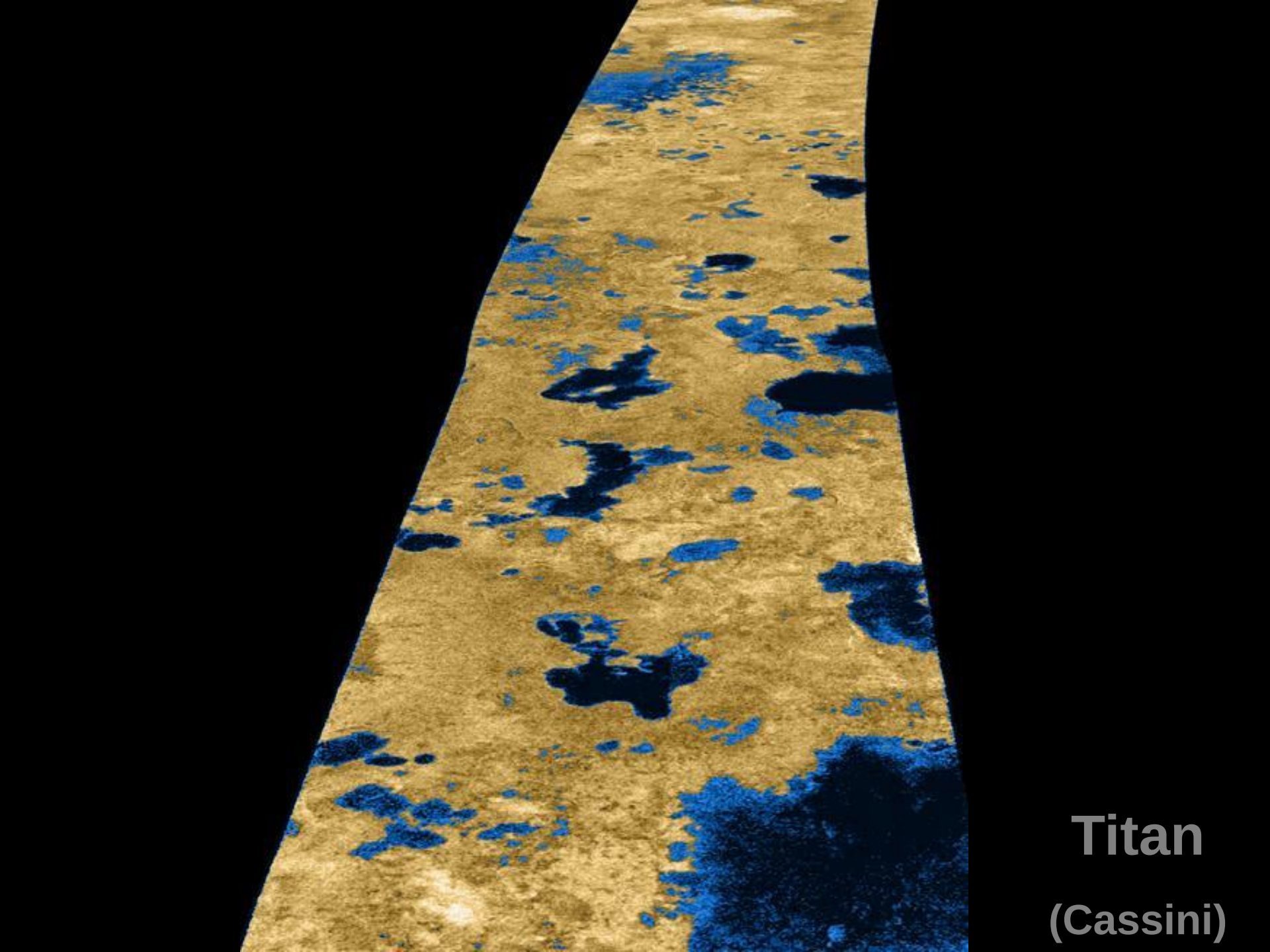
Saturn



Titan

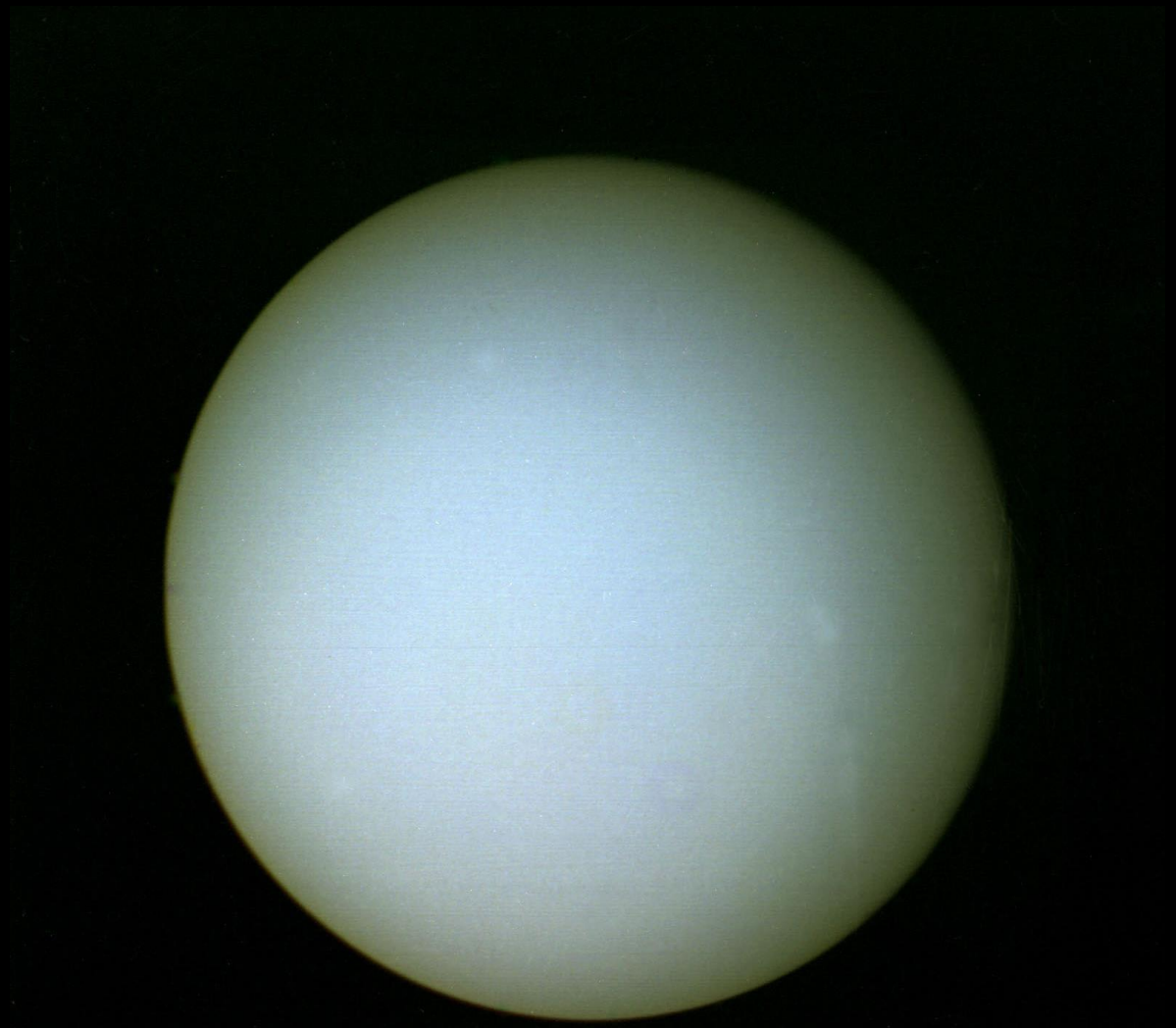


ESA/Huygens Probe

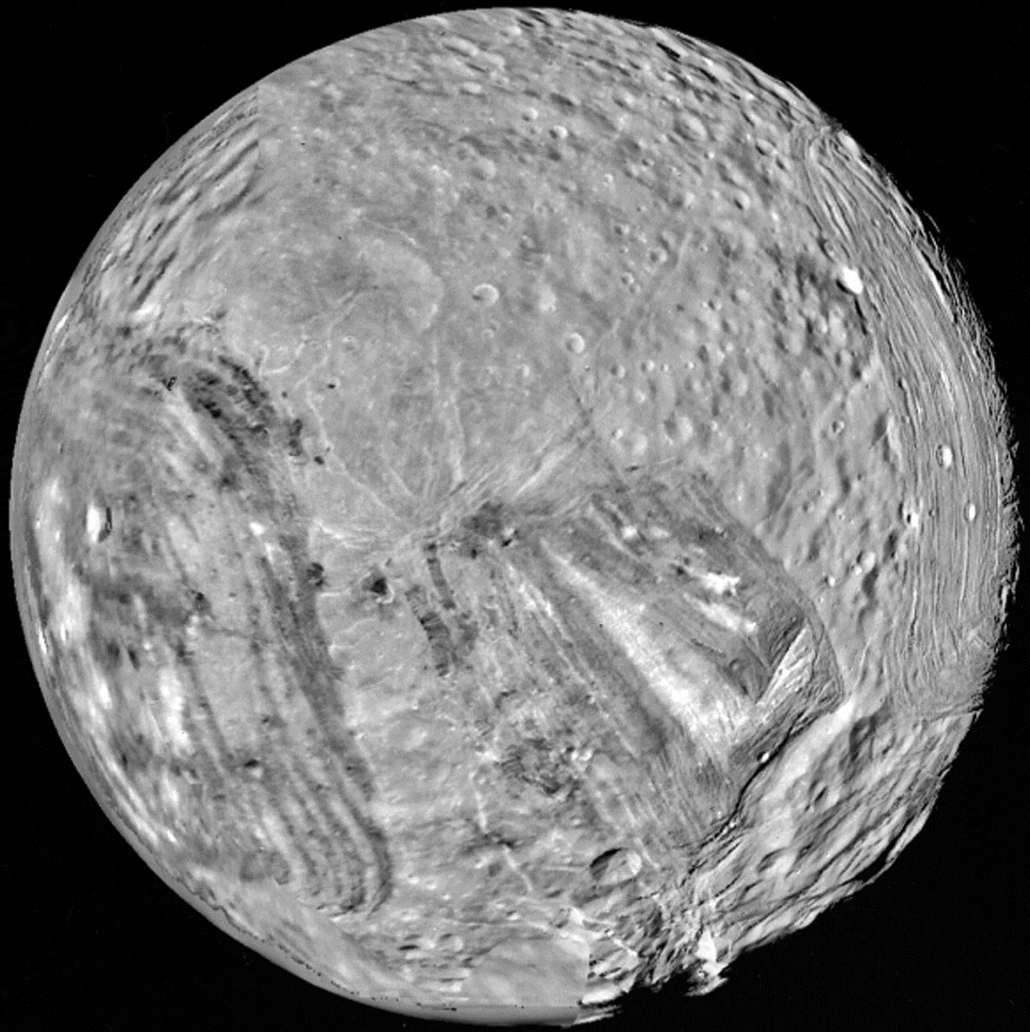


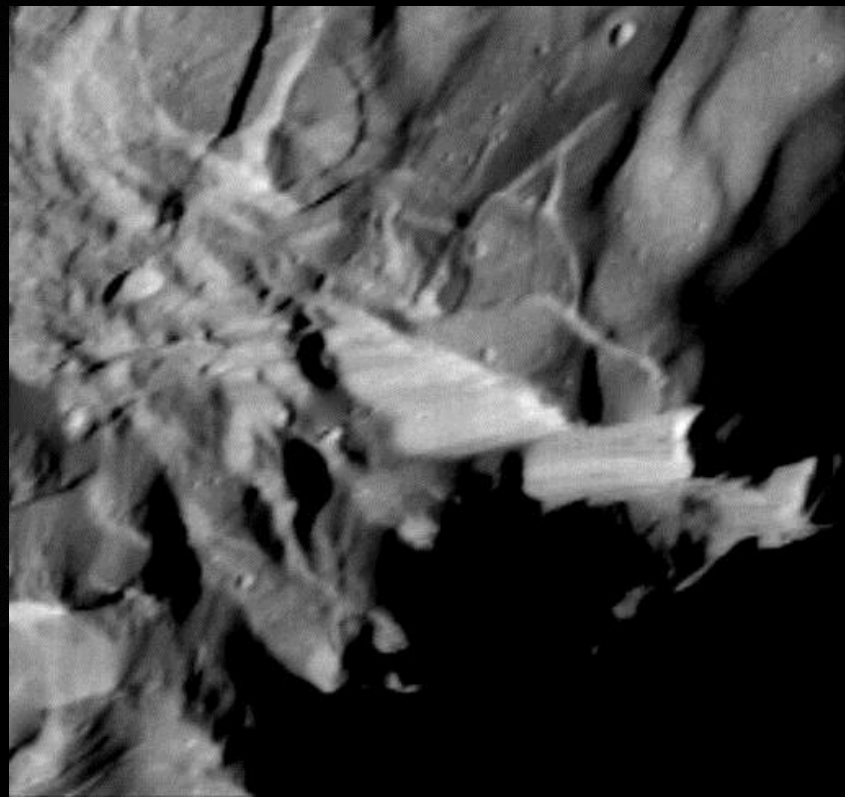
Titan

(Cassini)

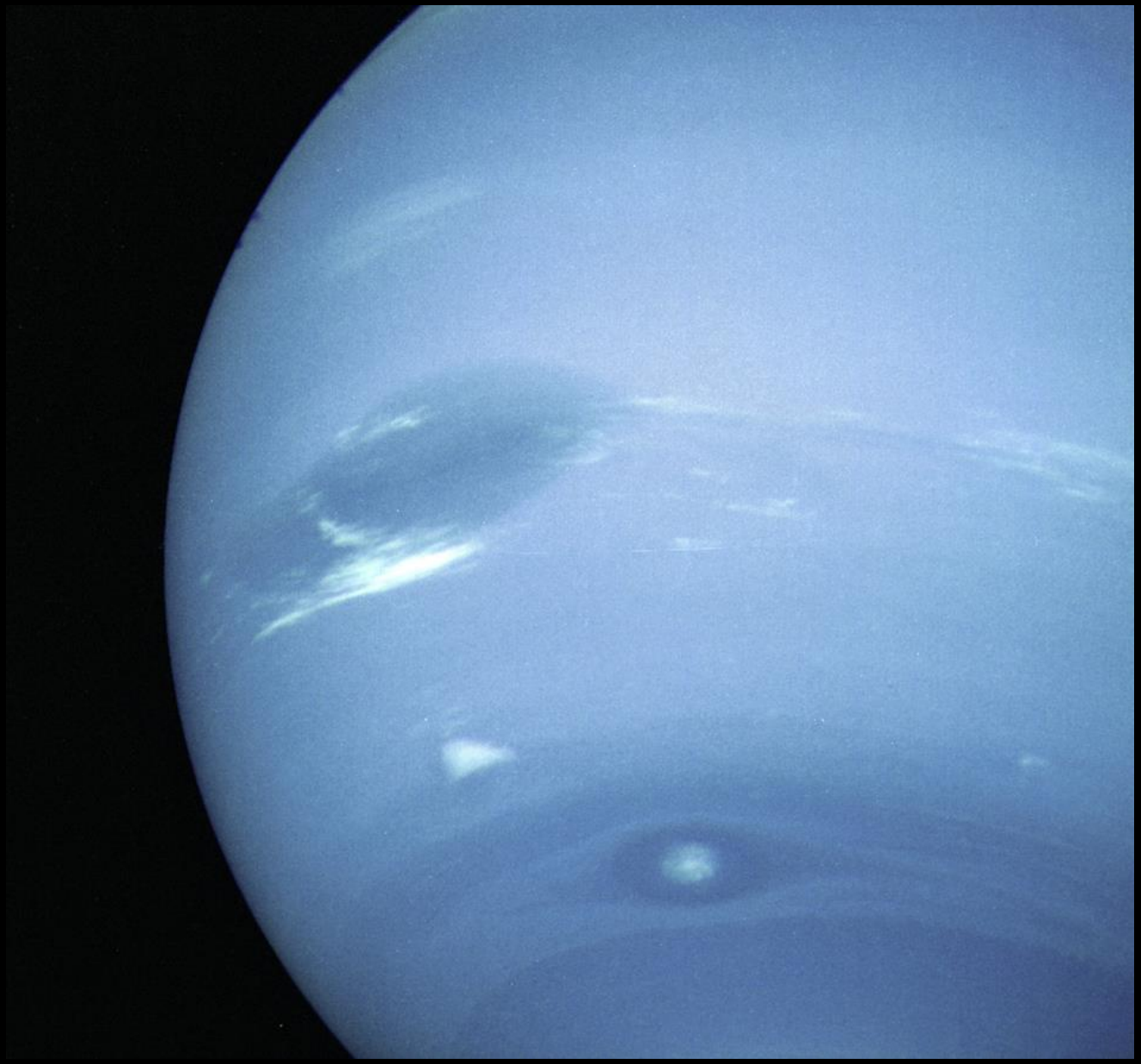


Uranus 19 AU

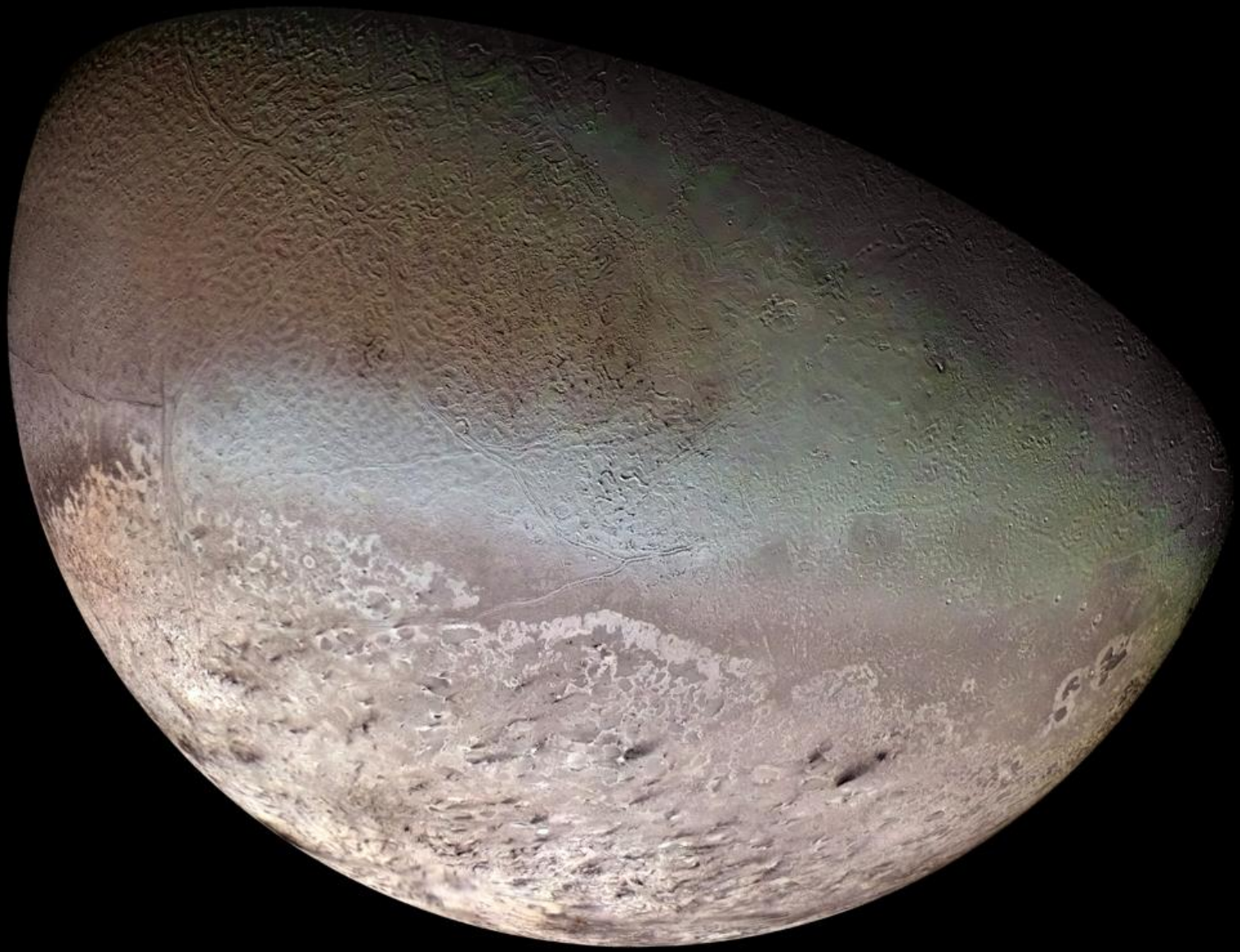




Miranda

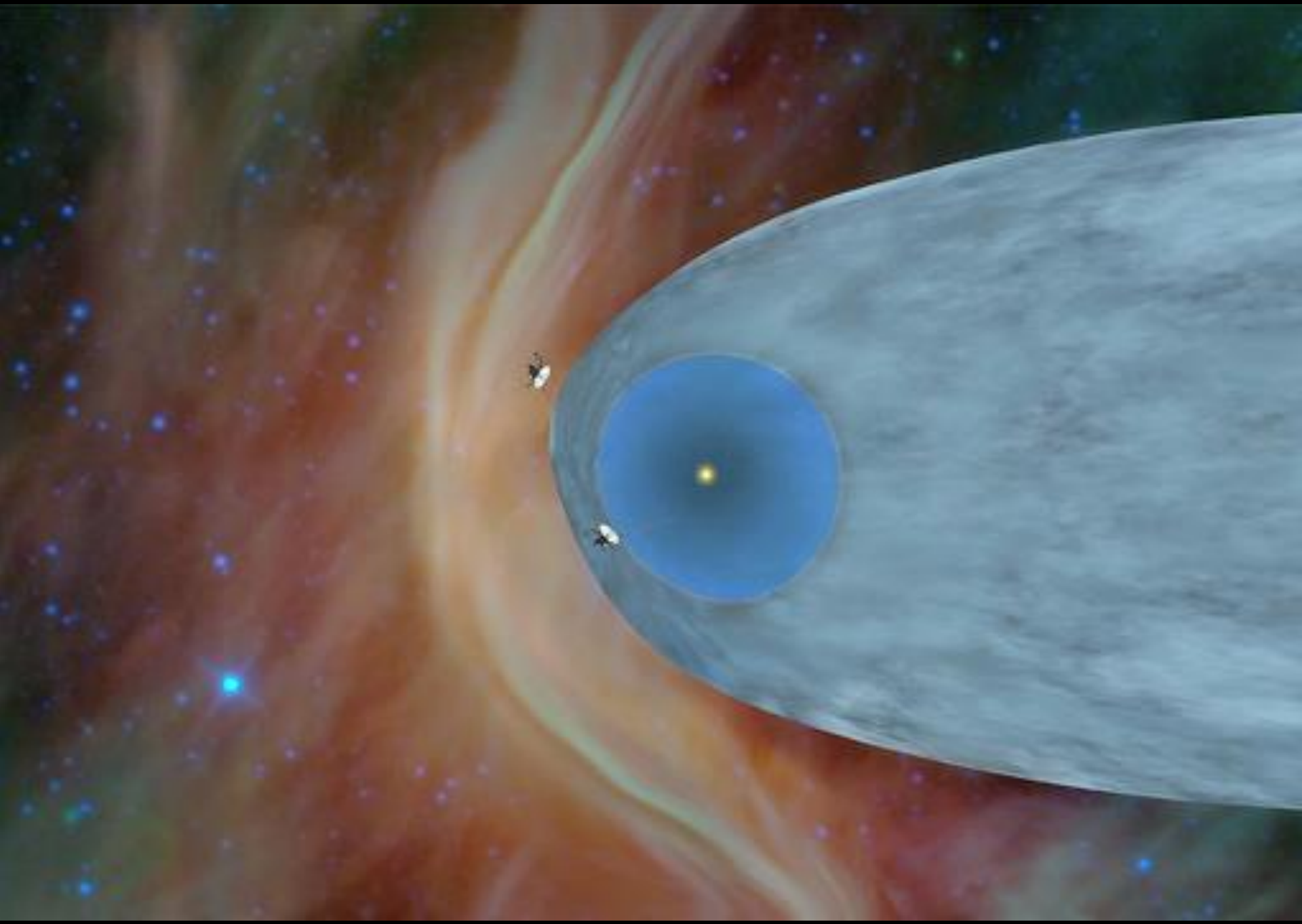


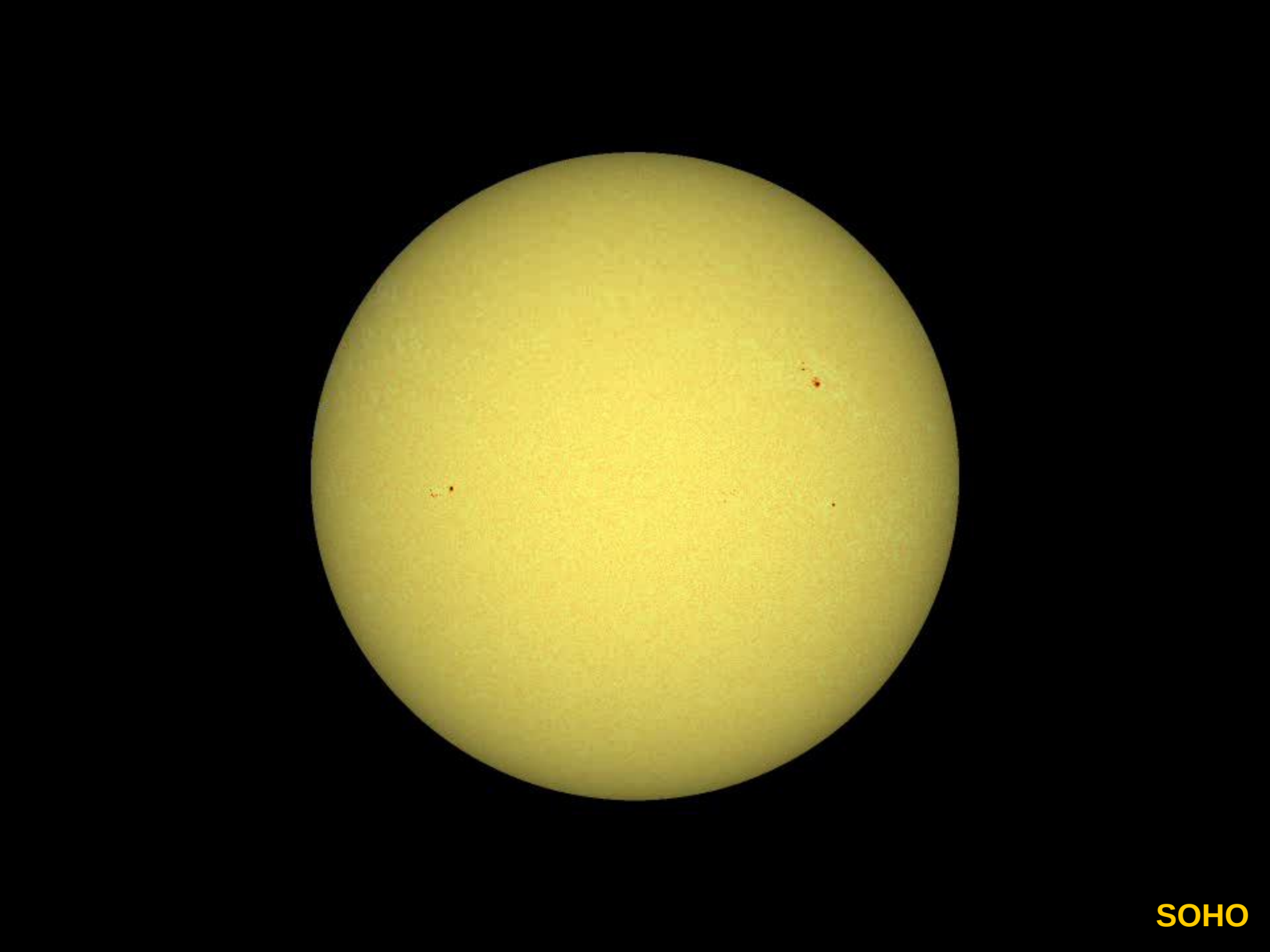
Neptune



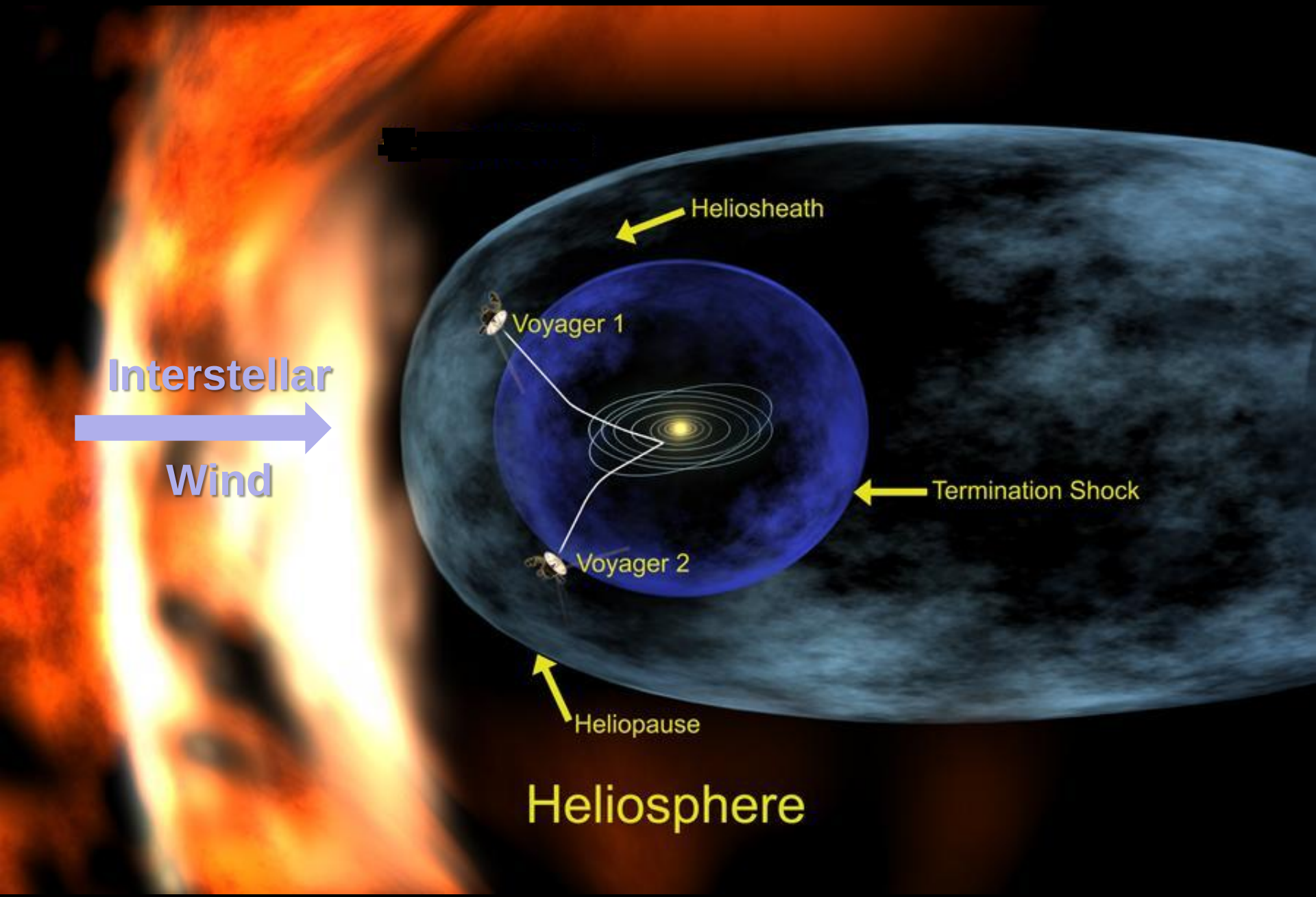
Triton

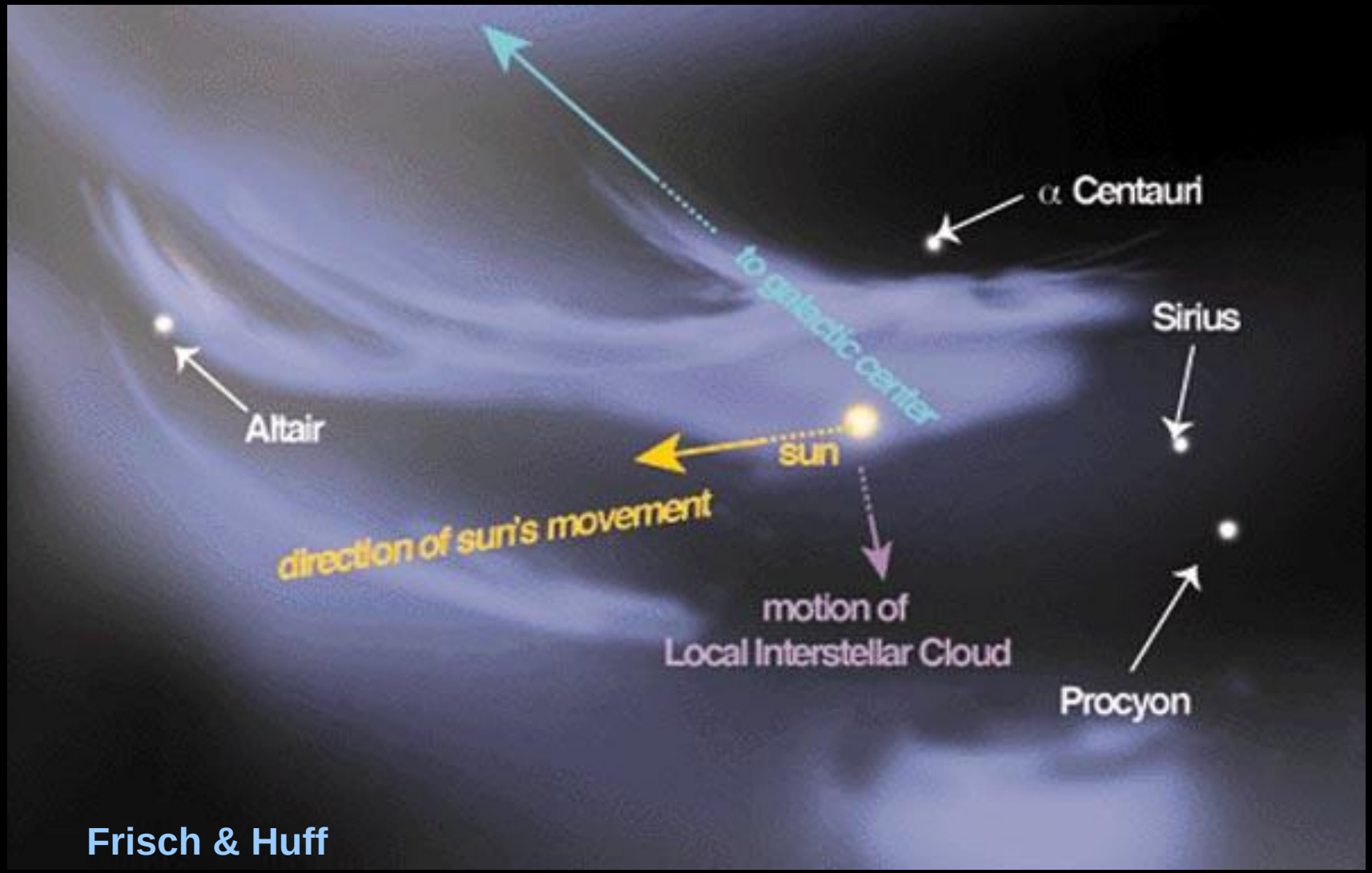
A New View of the Solar System




SOHO

SOHO

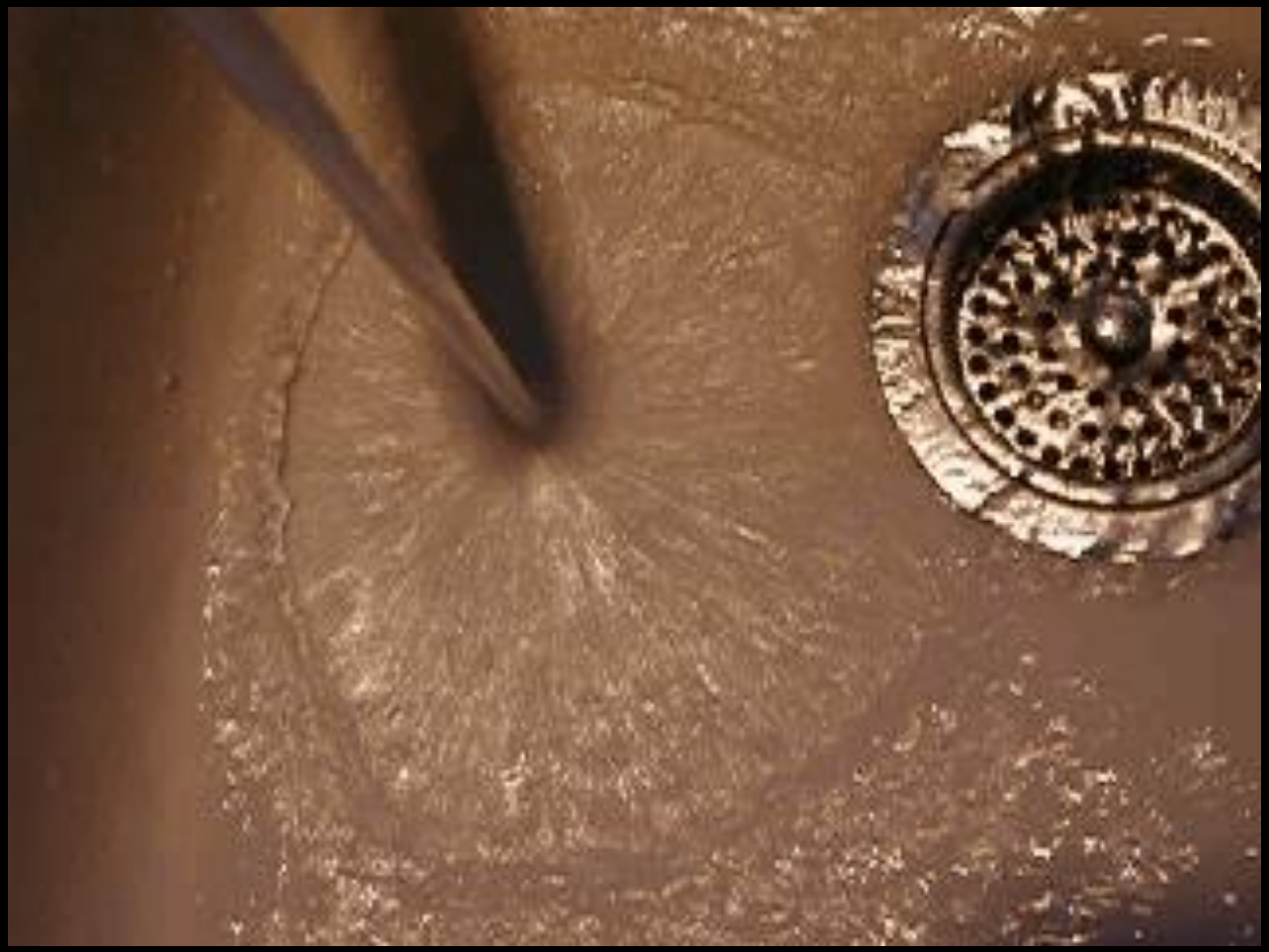

Heliosheath
Voyager 1
Interstellar
Wind
Termination Shock
Voyager 2
Heliopause
Heliosphere


α Centauri
to galactic center
Sirius
Altair
sun
direction of sun's movement
motion of
Local Interstellar Cloud
Procyon

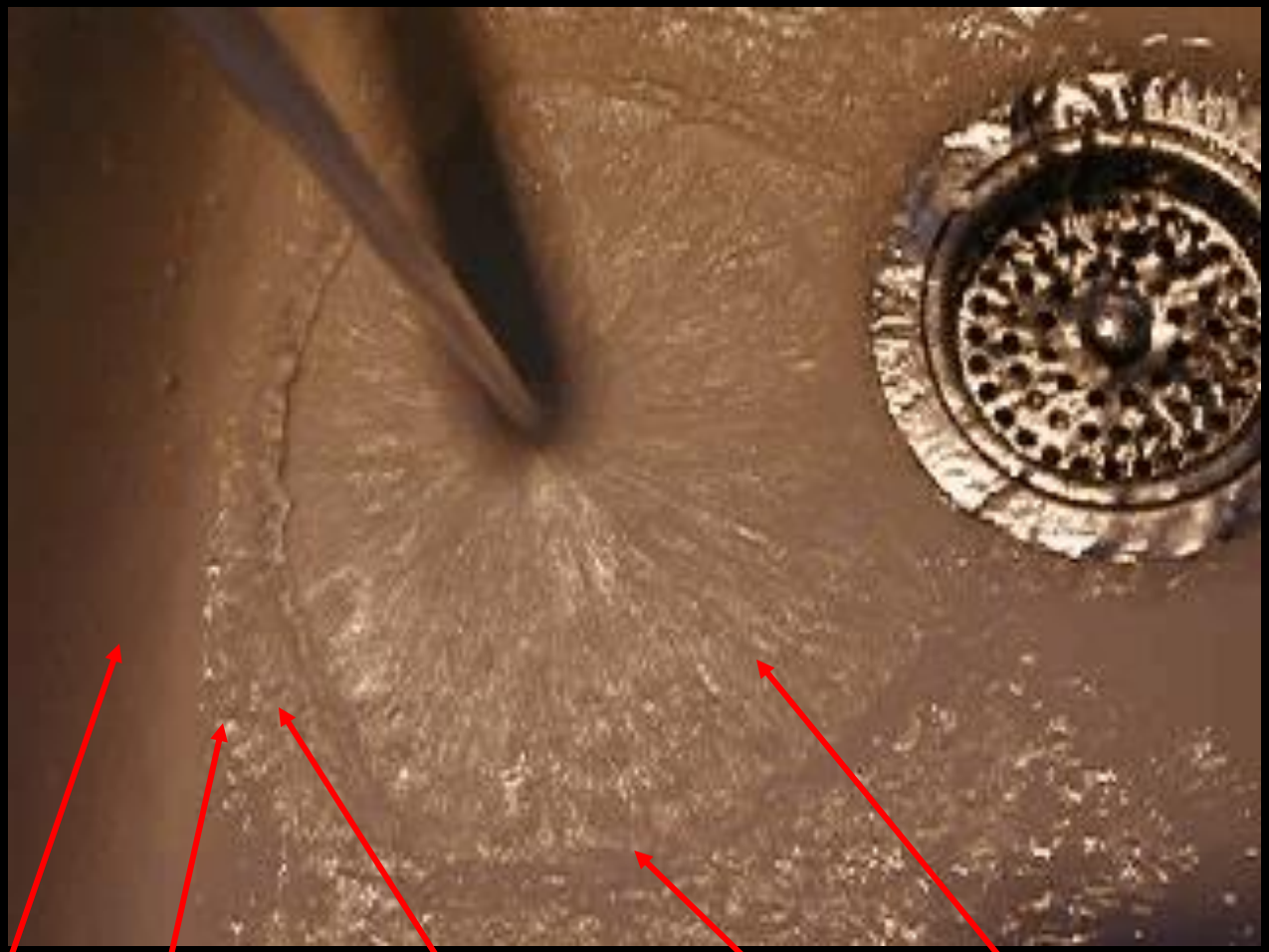
Frisch & Huff

Zank

HST- Orion Nebula



The Heliosphere in a Kitchen Sink



Supersonic Solar Wind

Interstellar Space

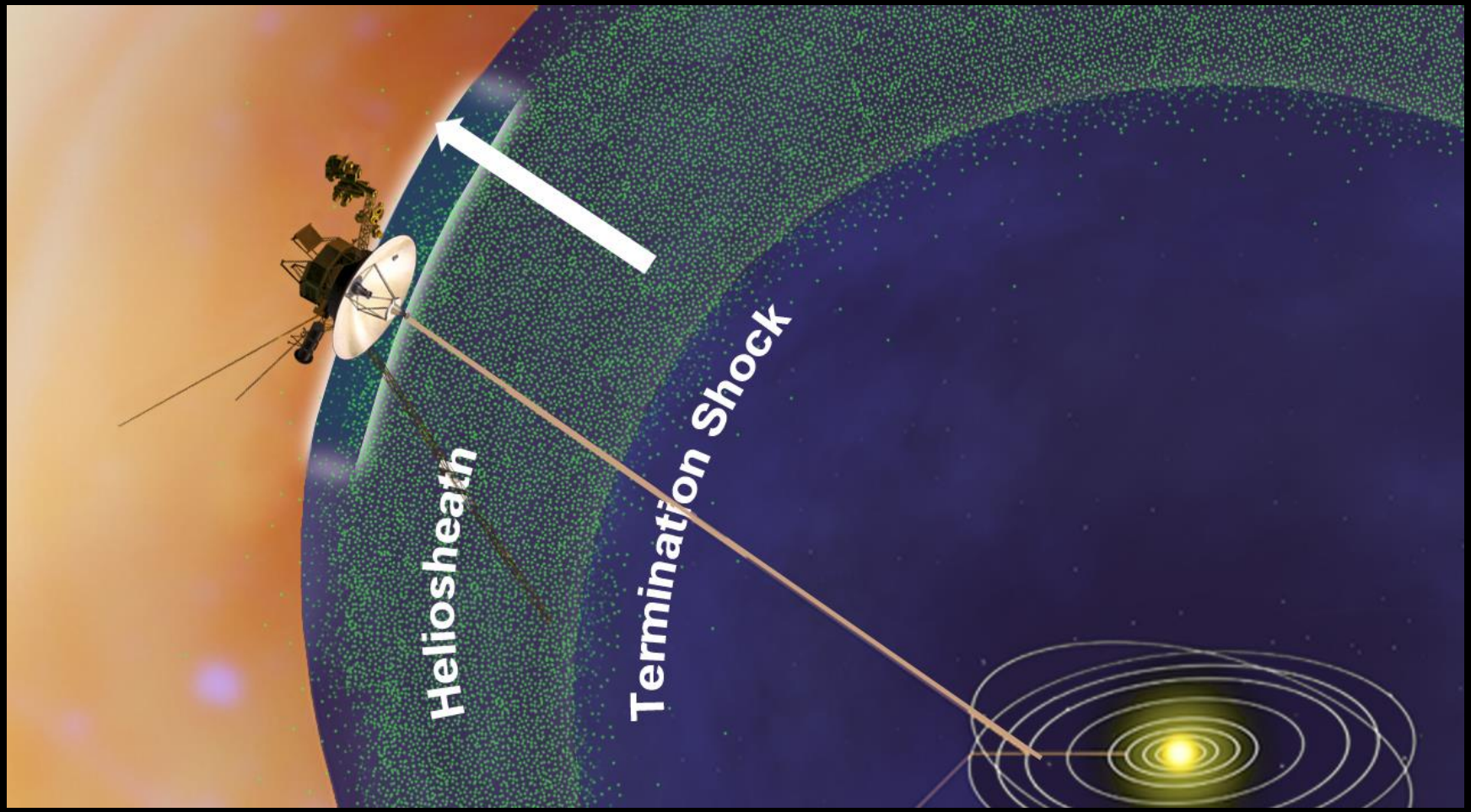
Shock- wind abruptly slows

Slow wind turns, flows toward drain

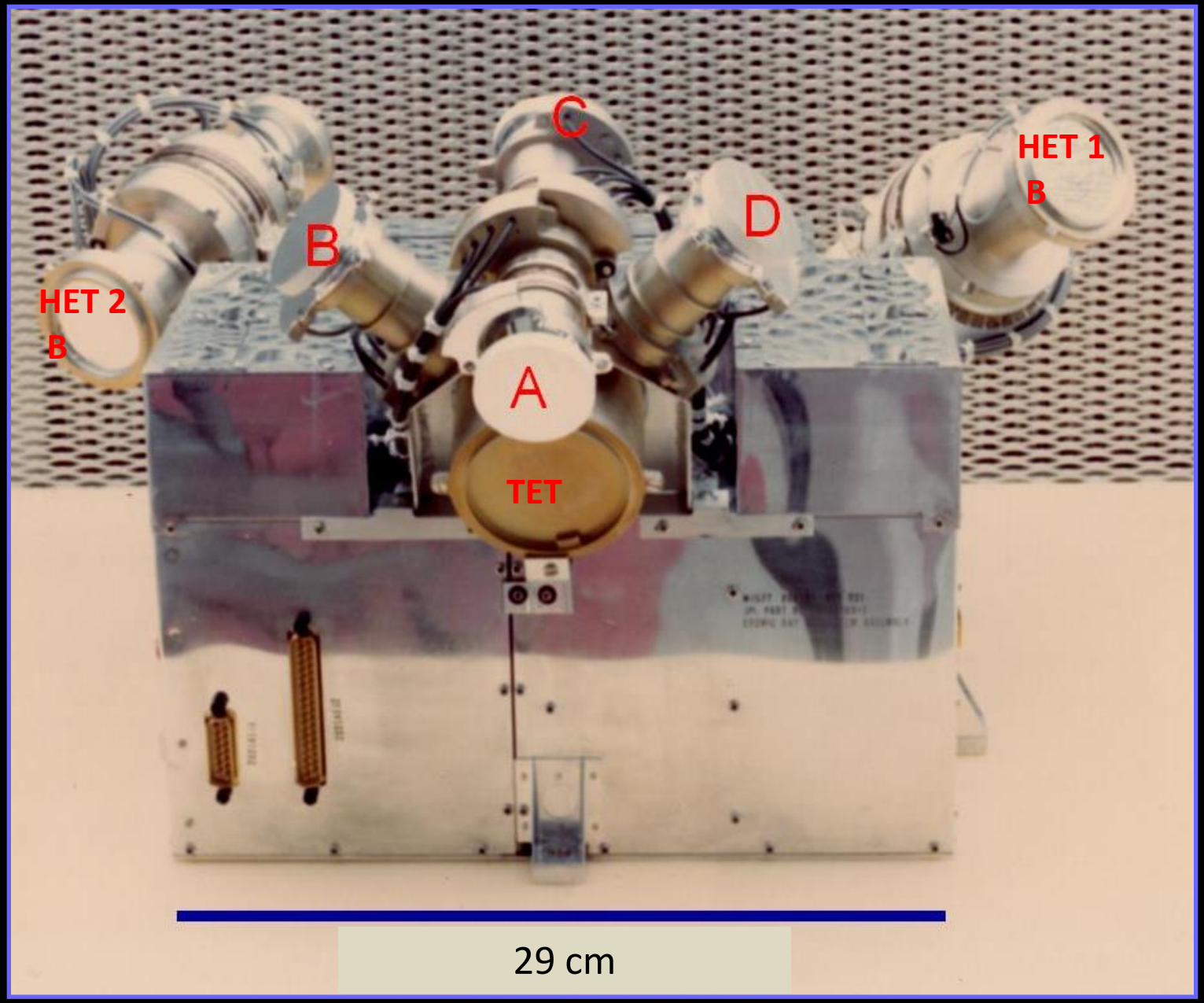
Heliopause, boundary of solar wind bubble

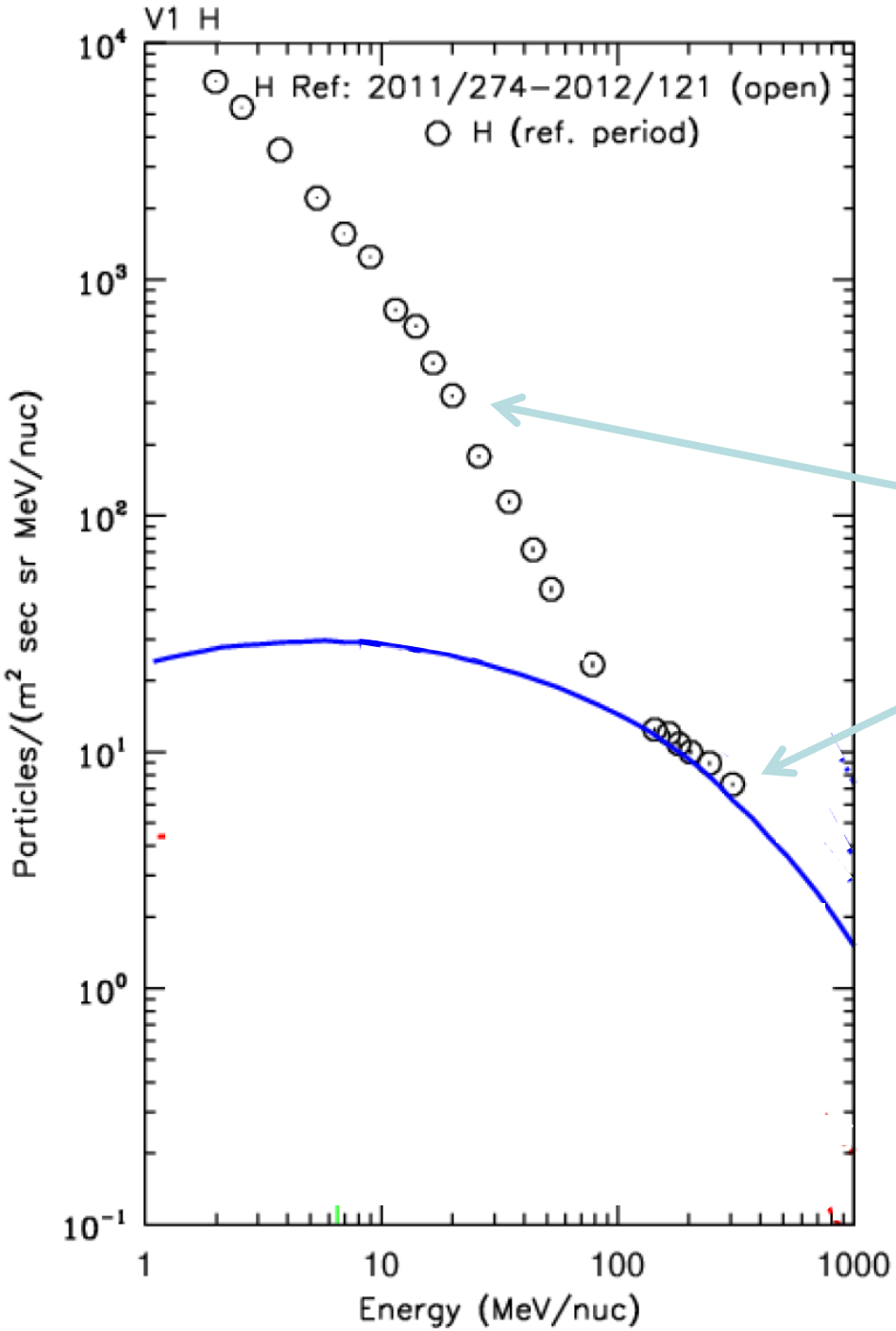
Energetic Ions Leak Out of the Bubble and Disappear

(ionized atoms with ~5% speed of light)



Voyager Cosmic Ray Telescopes





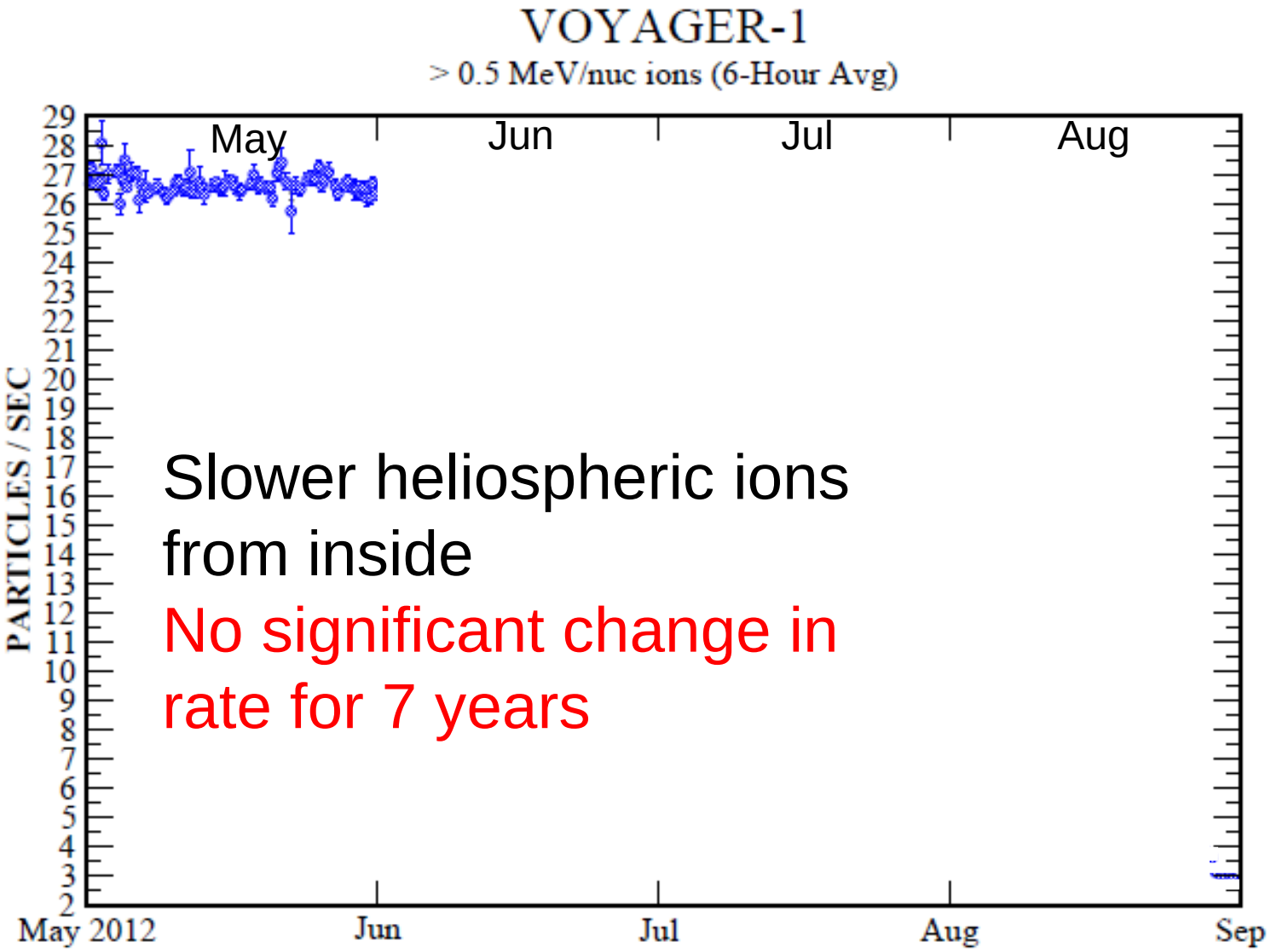
H spectrum for 2011/272- 2012/121 before V1 entered interstellar space

<100 MeV are from inside the heliosphere

>200MeV are galactic cosmic rays from outside

<100 MeV cosmic rays excluded

Ip & Axford 1985
Leaky Box


VOYAGER-1
> 0.5 MeV/nuc ions (6-Hour Avg)
May
Jun
Jul
Aug
PARTICLES / SEC
29
28
27
26
25
24
23
22
21
20
19
18
17
16
15
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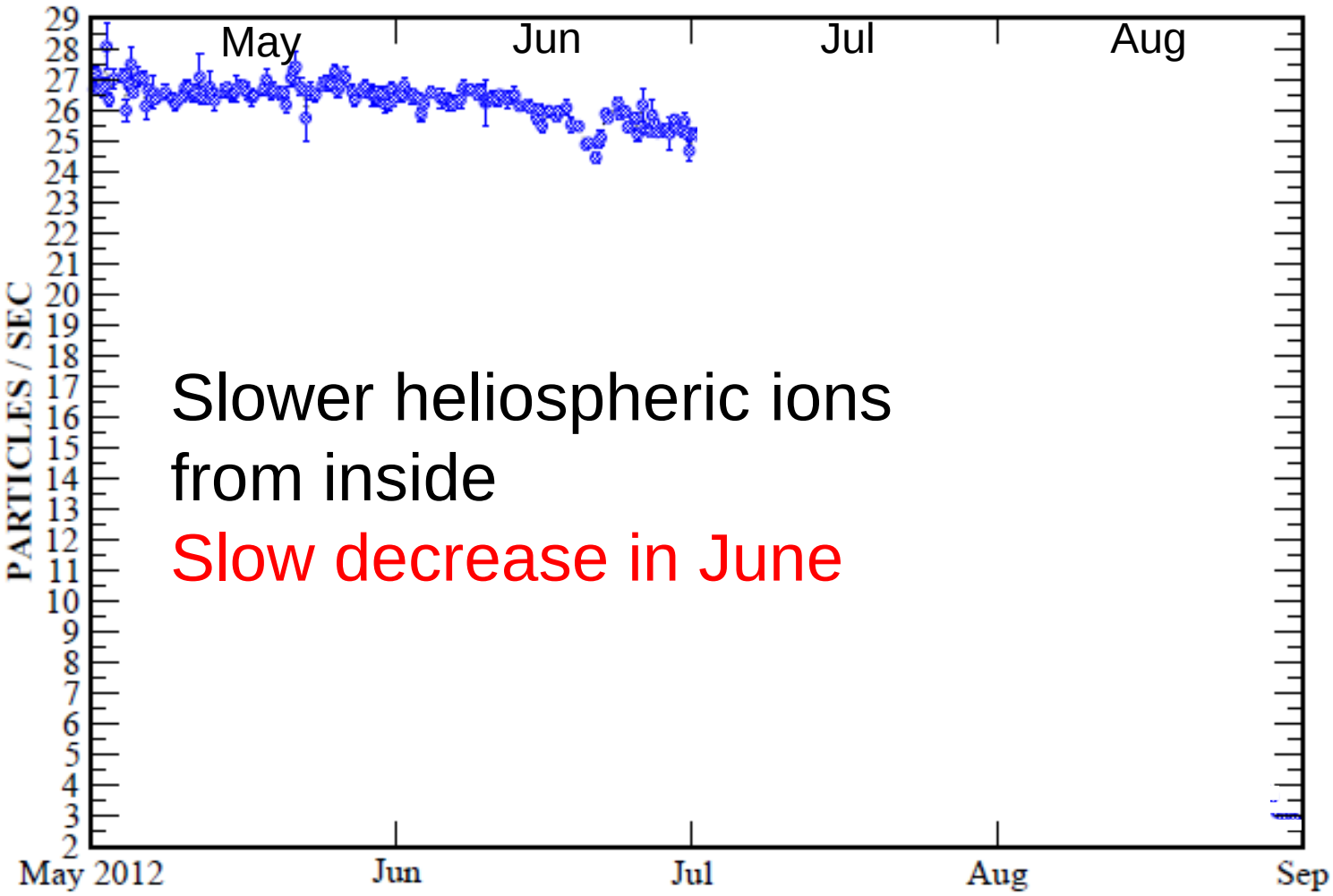
7
6
5
4
3
2
May 2012
Jun
Jul
Aug
Sep
Slower heliospheric ions from inside
No significant change in rate for 7 years

2012

CRS

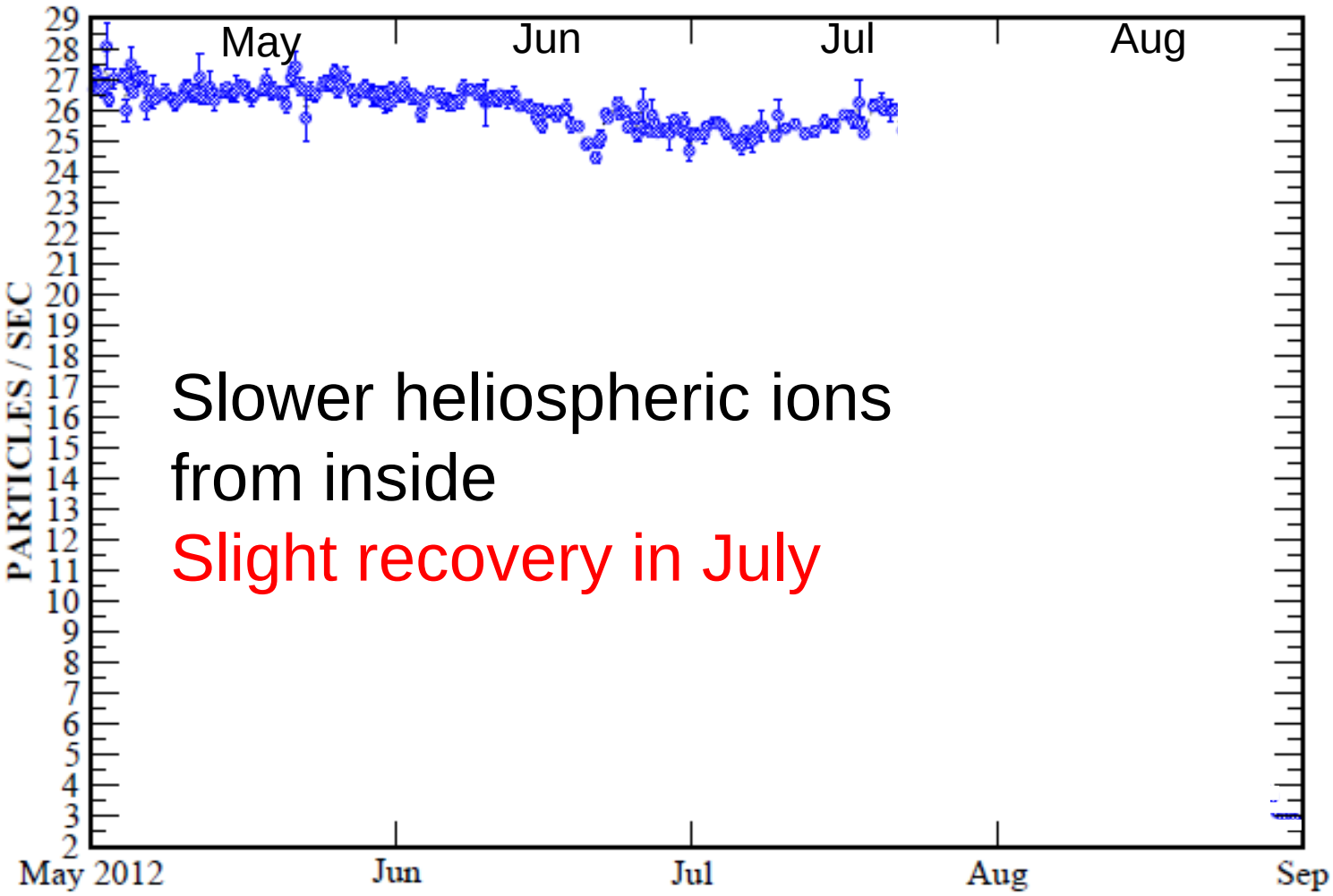


Slower heliospheric ions from inside

Slow decrease in June

2012

CRS

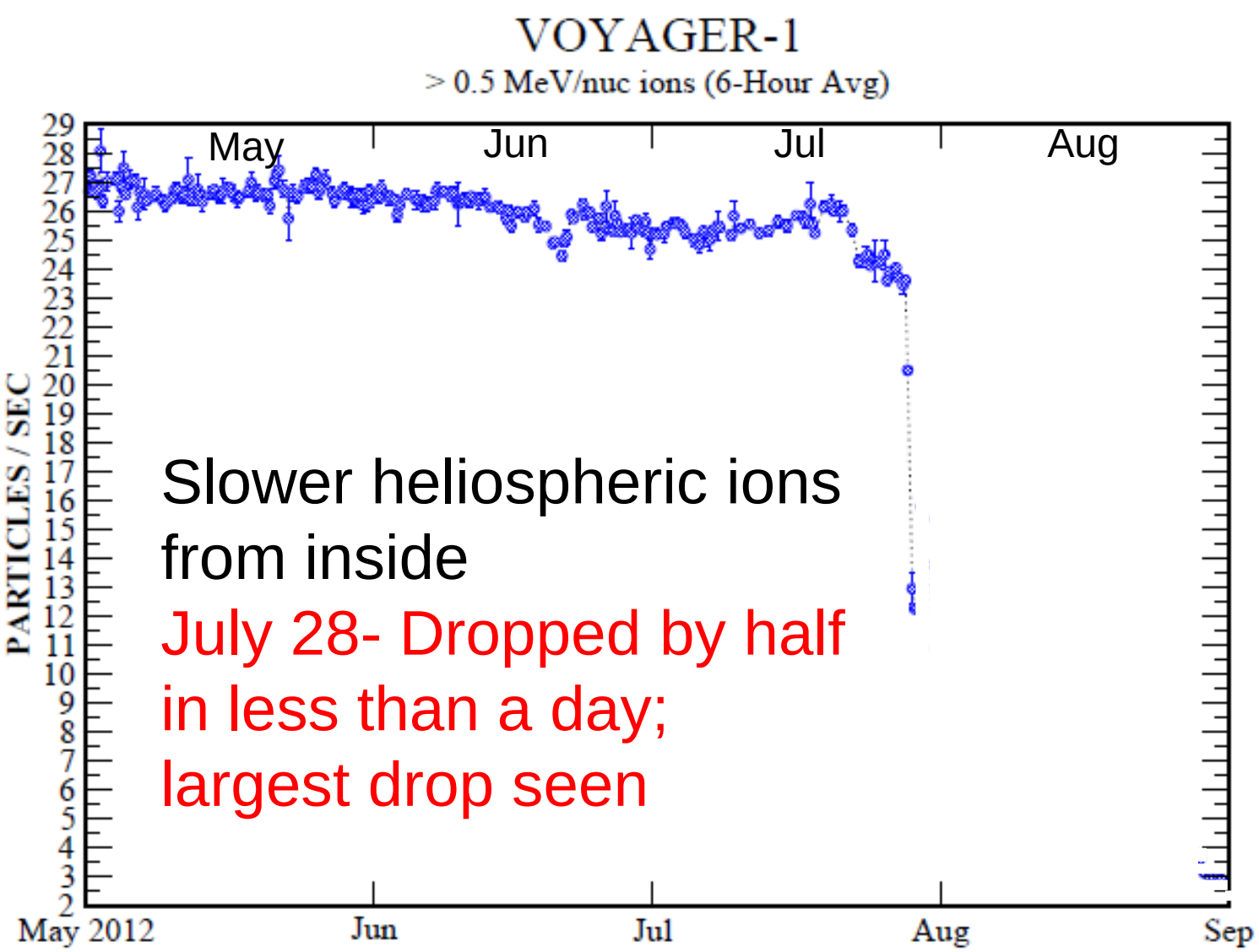


Slower heliospheric ions from inside

Slight recovery in July

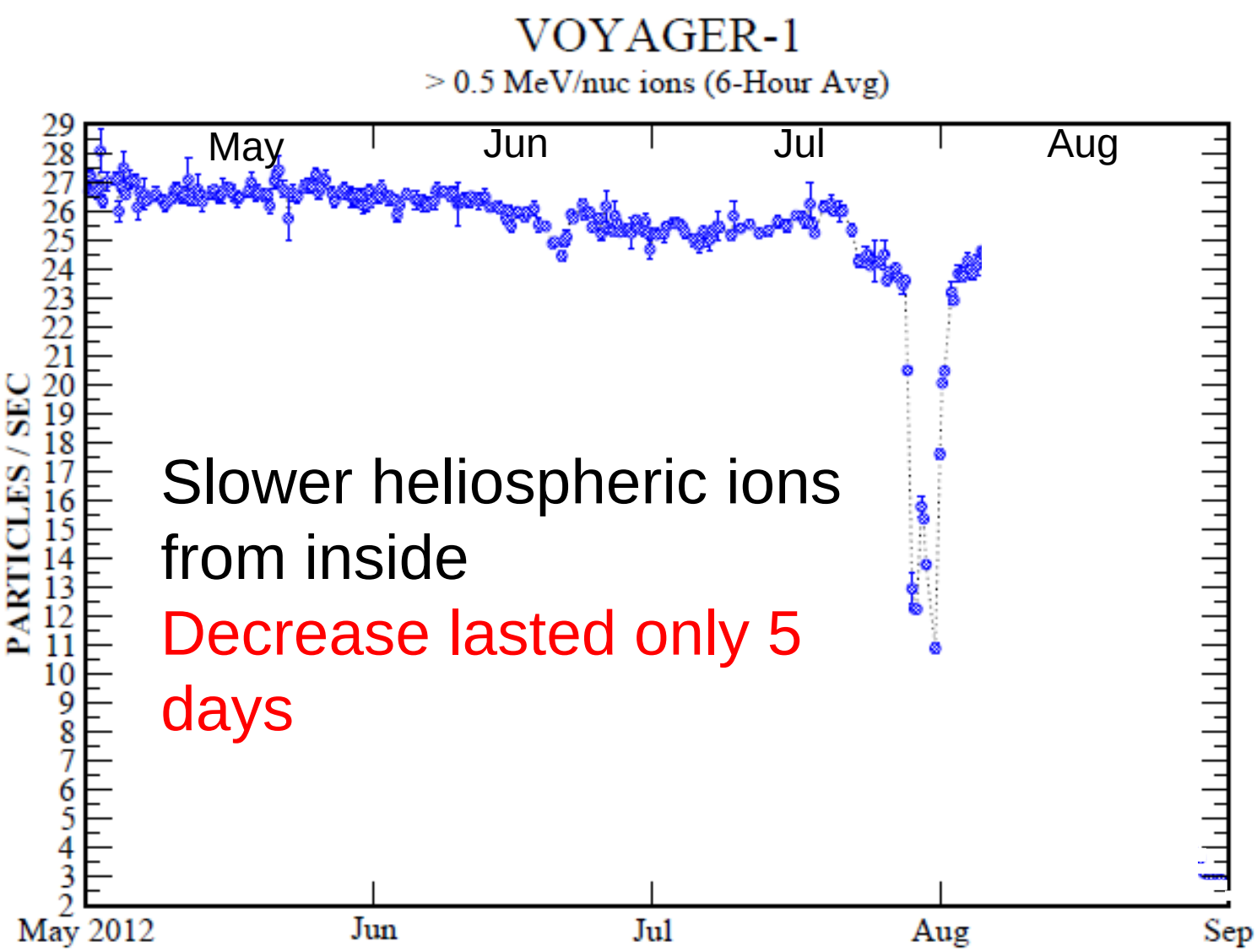
2012

CRS


VOYAGER-1
> 0.5 MeV/nuc ions (6-Hour Avg)
PARTICLES / SEC
May
Jun
Jul
Aug
May 2012
Jun
Jul
Aug
Sep
Slower heliospheric ions from inside
July 28- Dropped by half in less than a day; largest drop seen

2012

CRS


VOYAGER-1
> 0.5 MeV/nuc ions (6-Hour Avg)
May
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PARTICLES / SEC
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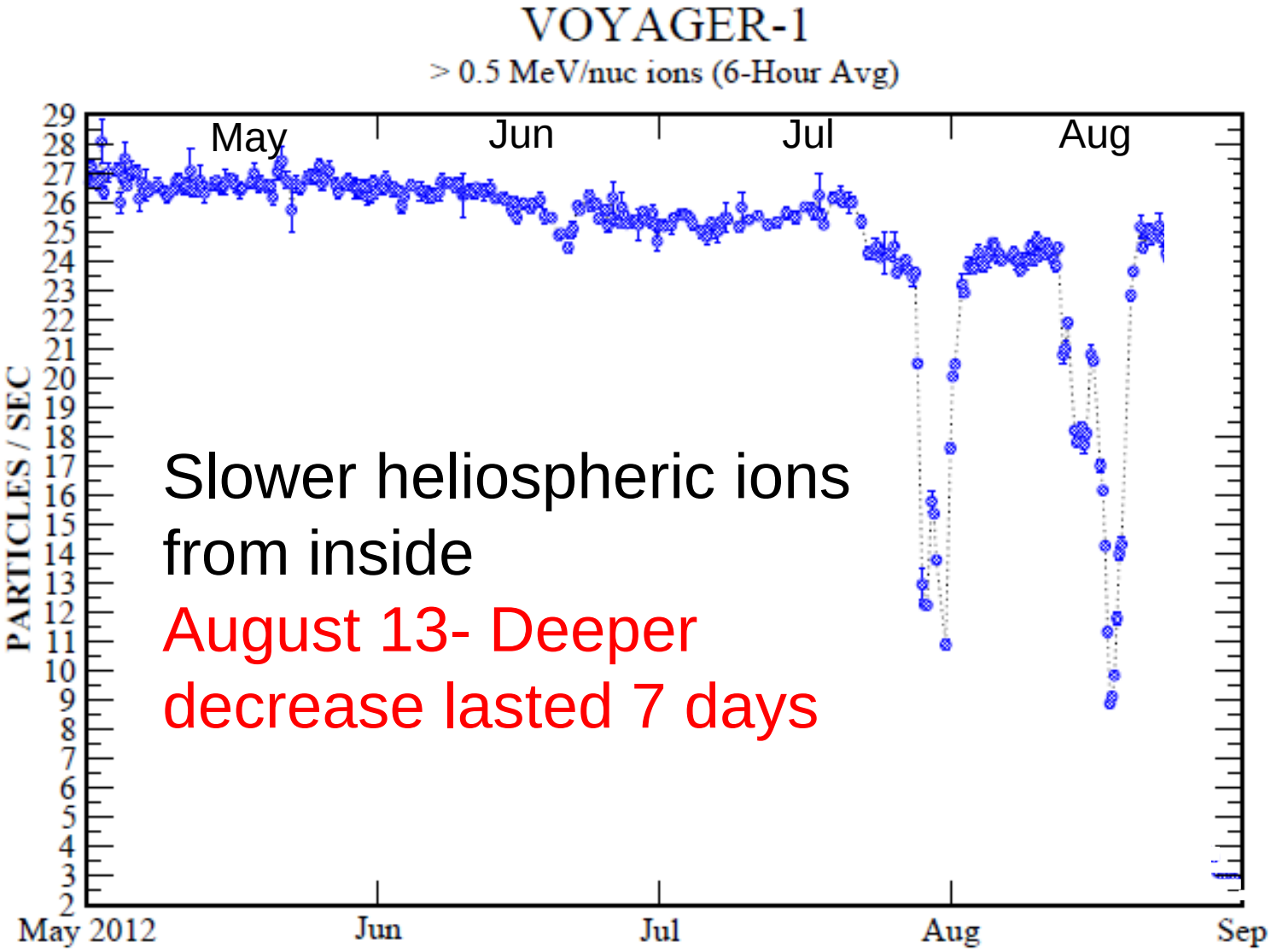
2
May 2012
Jun
Jul
Aug
Sep
Slower heliospheric ions from inside
Decrease lasted only 5 days

2012

CRS


VOYAGER-1
> 0.5 MeV/nuc ions (6-Hour Avg)
May
Jun
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PARTICLES / SEC
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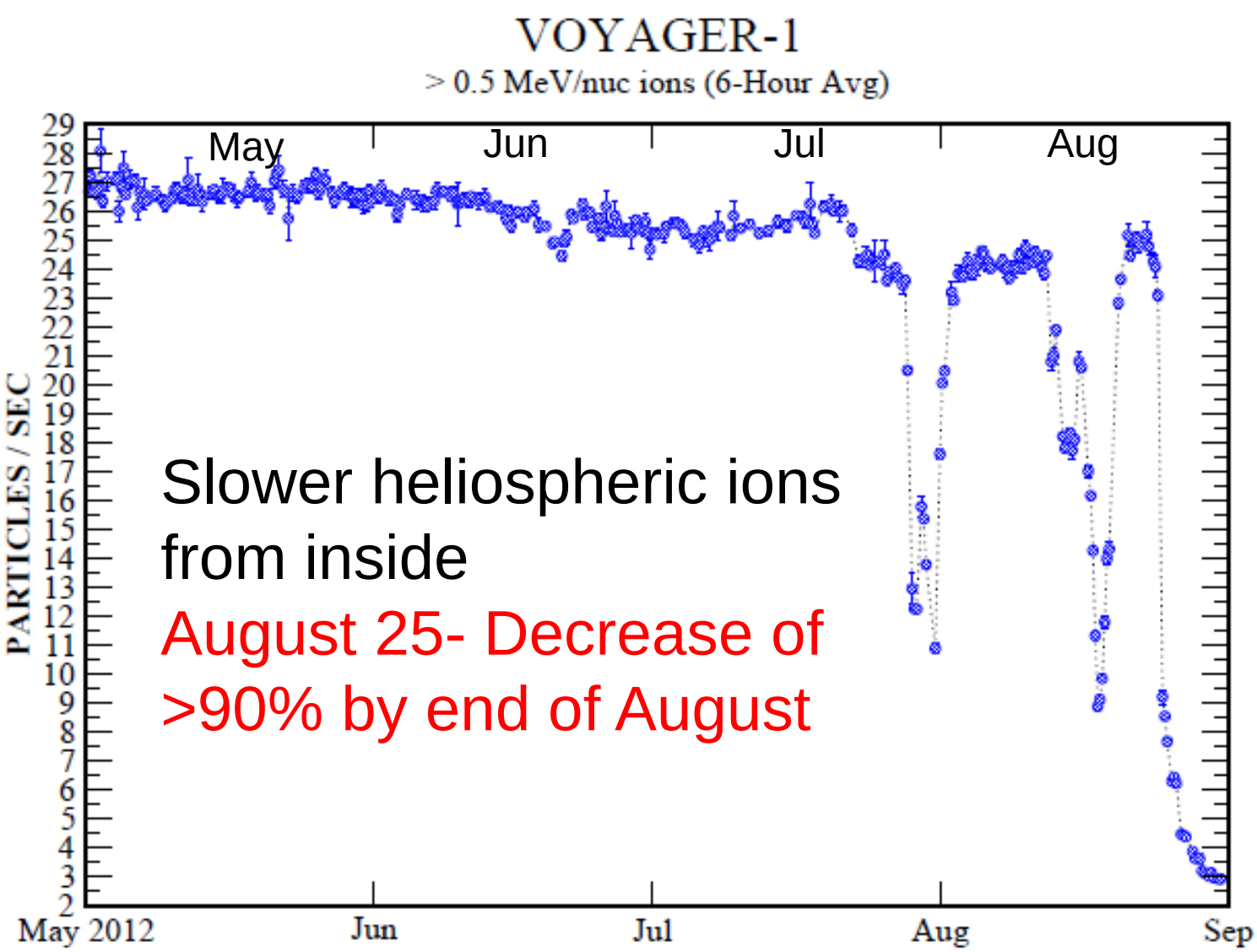
2
May 2012
Jun
Jul
Aug
Sep
Slower heliospheric ions from inside
August 13- Deeper decrease lasted 7 days

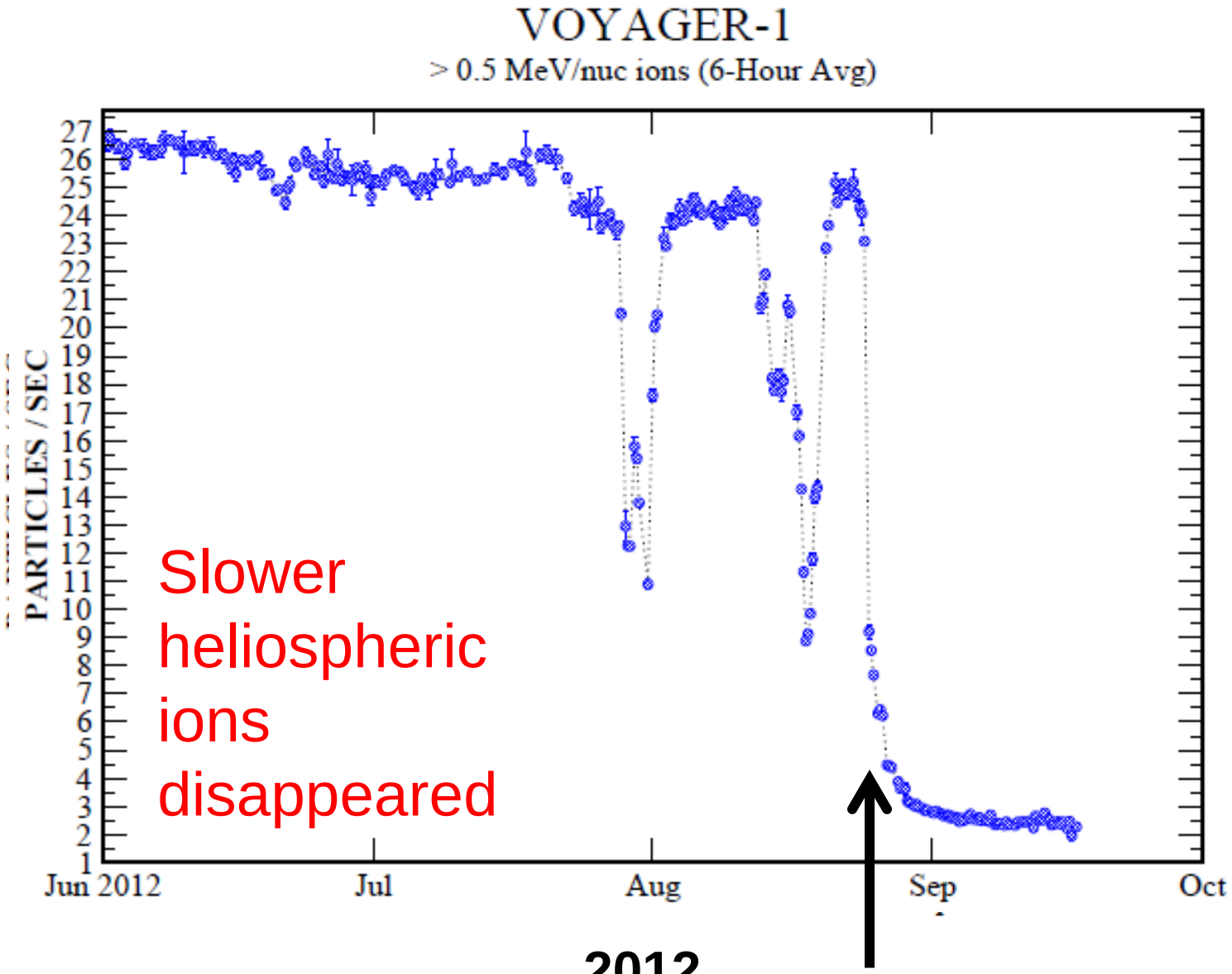
2012

CRS


VOYAGER-1
> 0.5 MeV/nuc ions (6-Hour Avg)
PARTICLES / SEC
May
Jun
Jul
Aug
May 2012
Jun
Jul
Aug
Sep
Slower heliospheric ions from inside
August 25- Decrease of >90% by end of August

2012

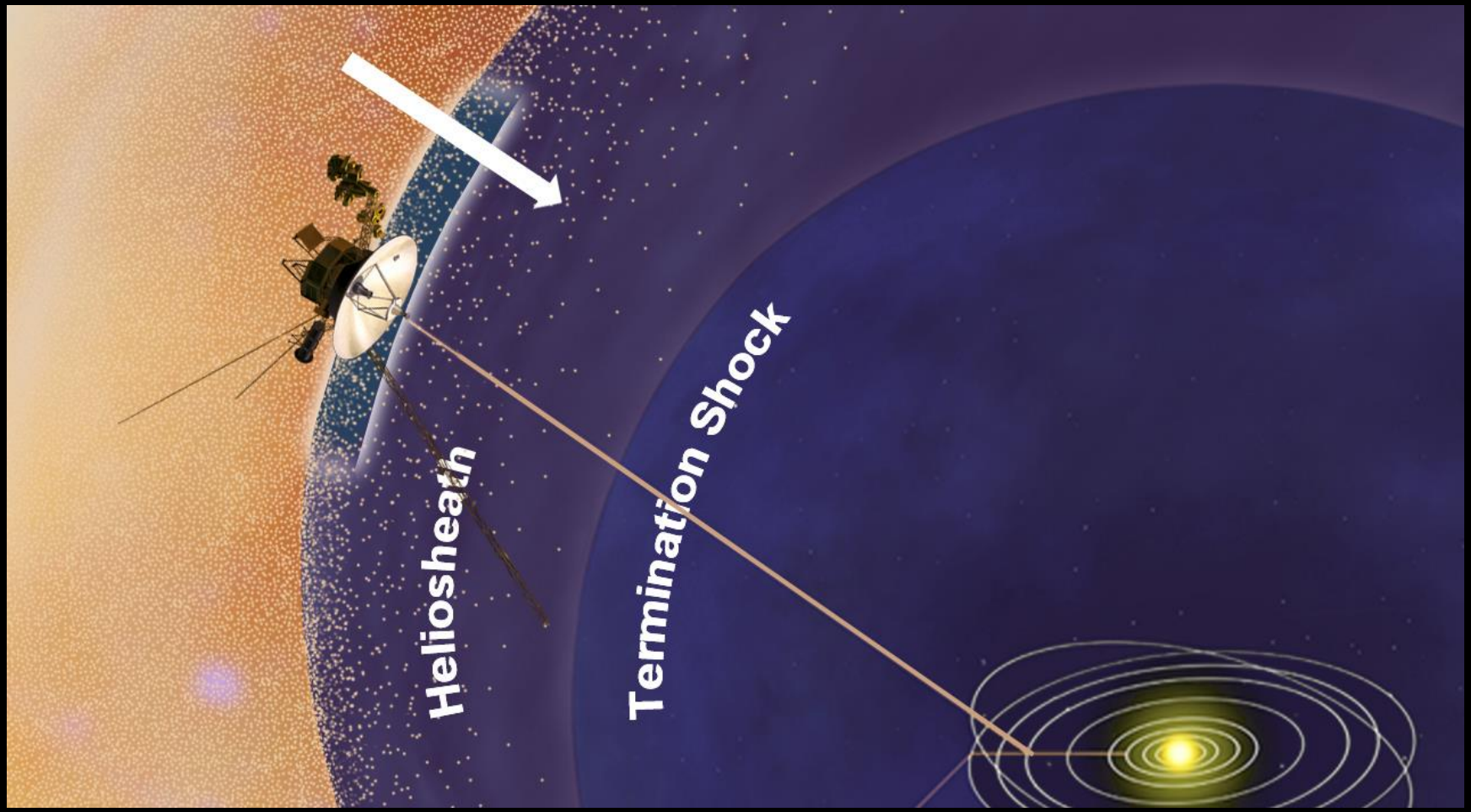
CRS



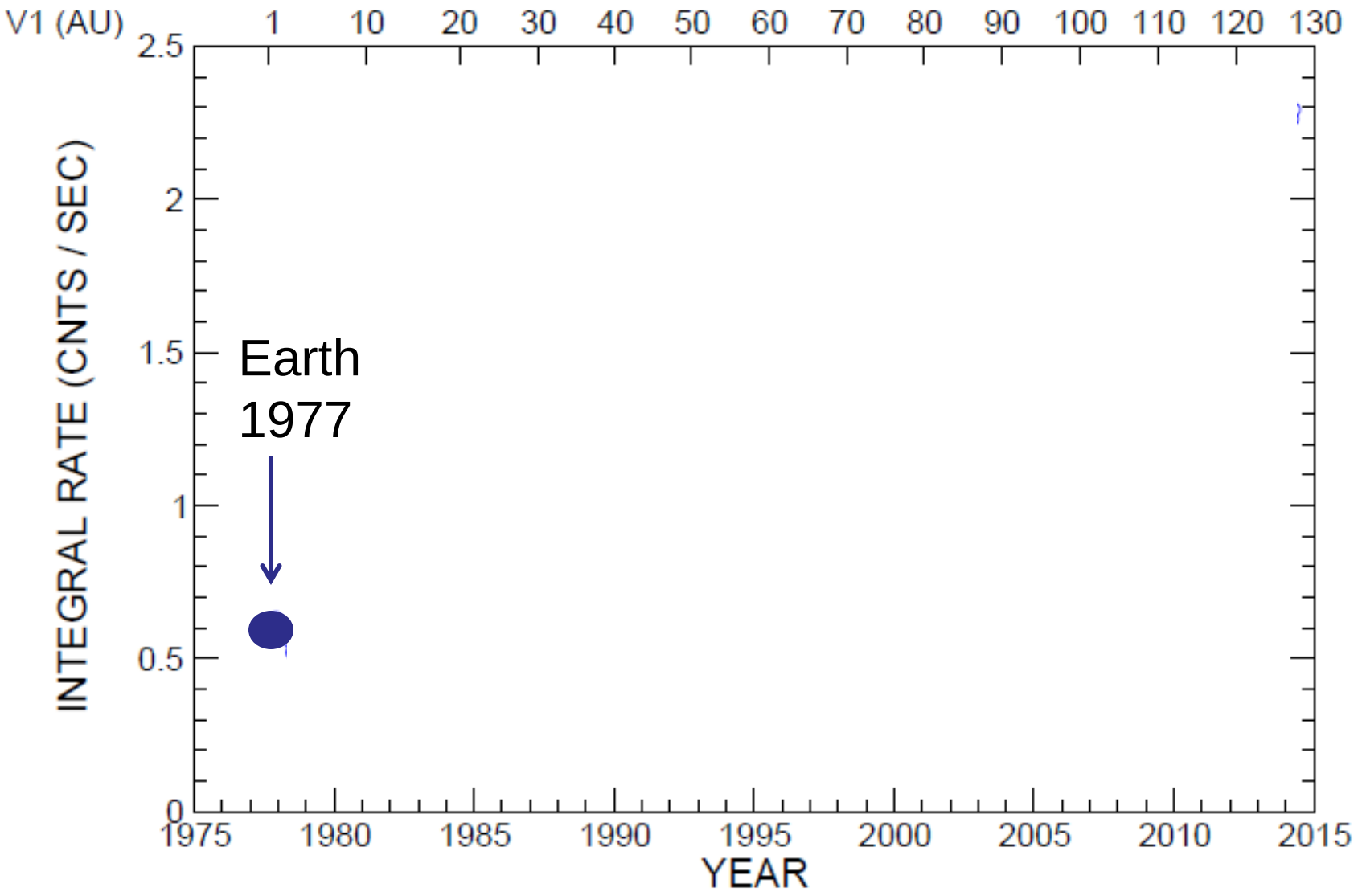
Interstellar space August 25, 2012

CRS

Galactic cosmic rays diffuse inward, but many are carried back out by the solar wind

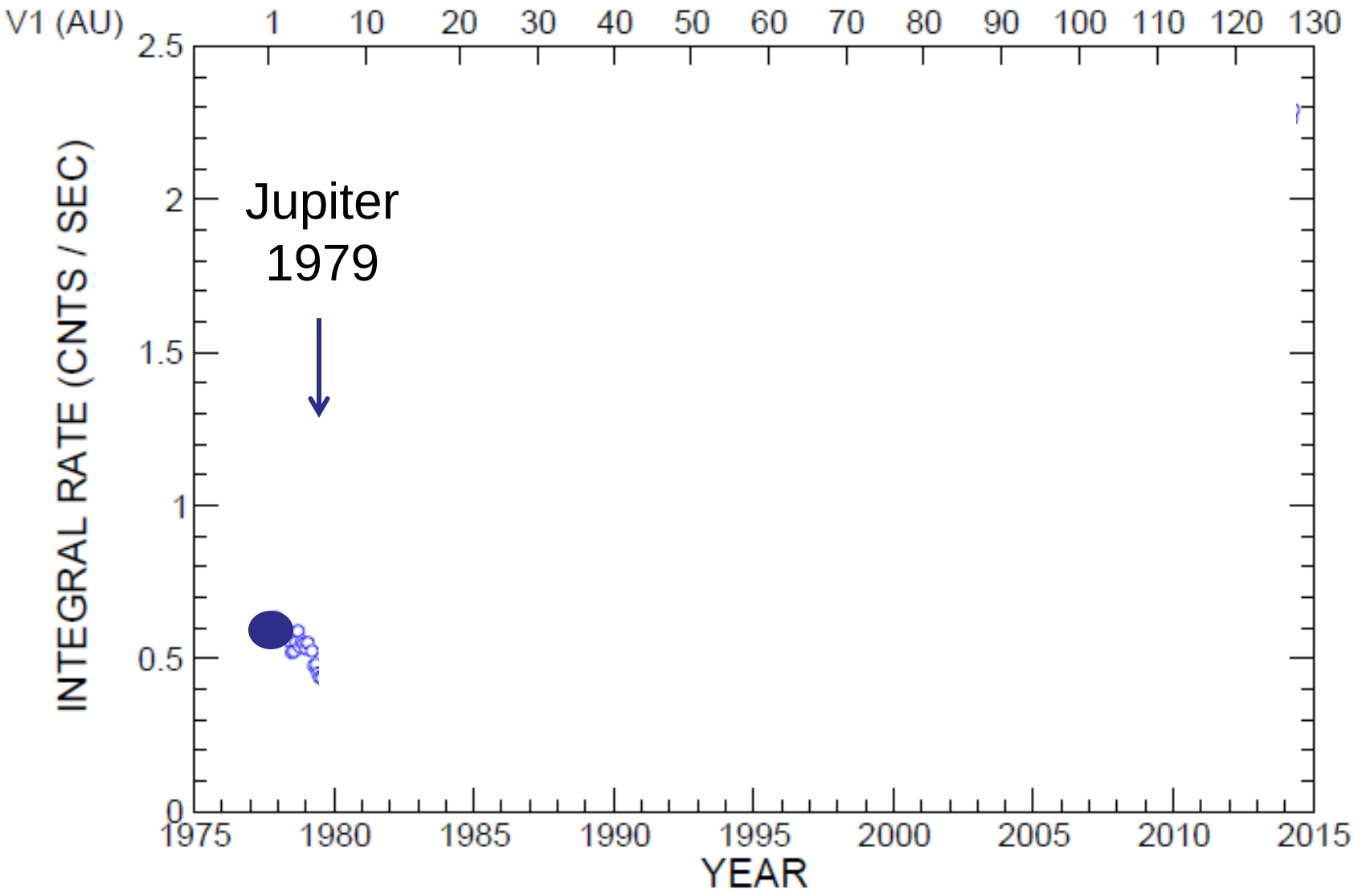


Cosmic Rays from Milky Way Galaxy



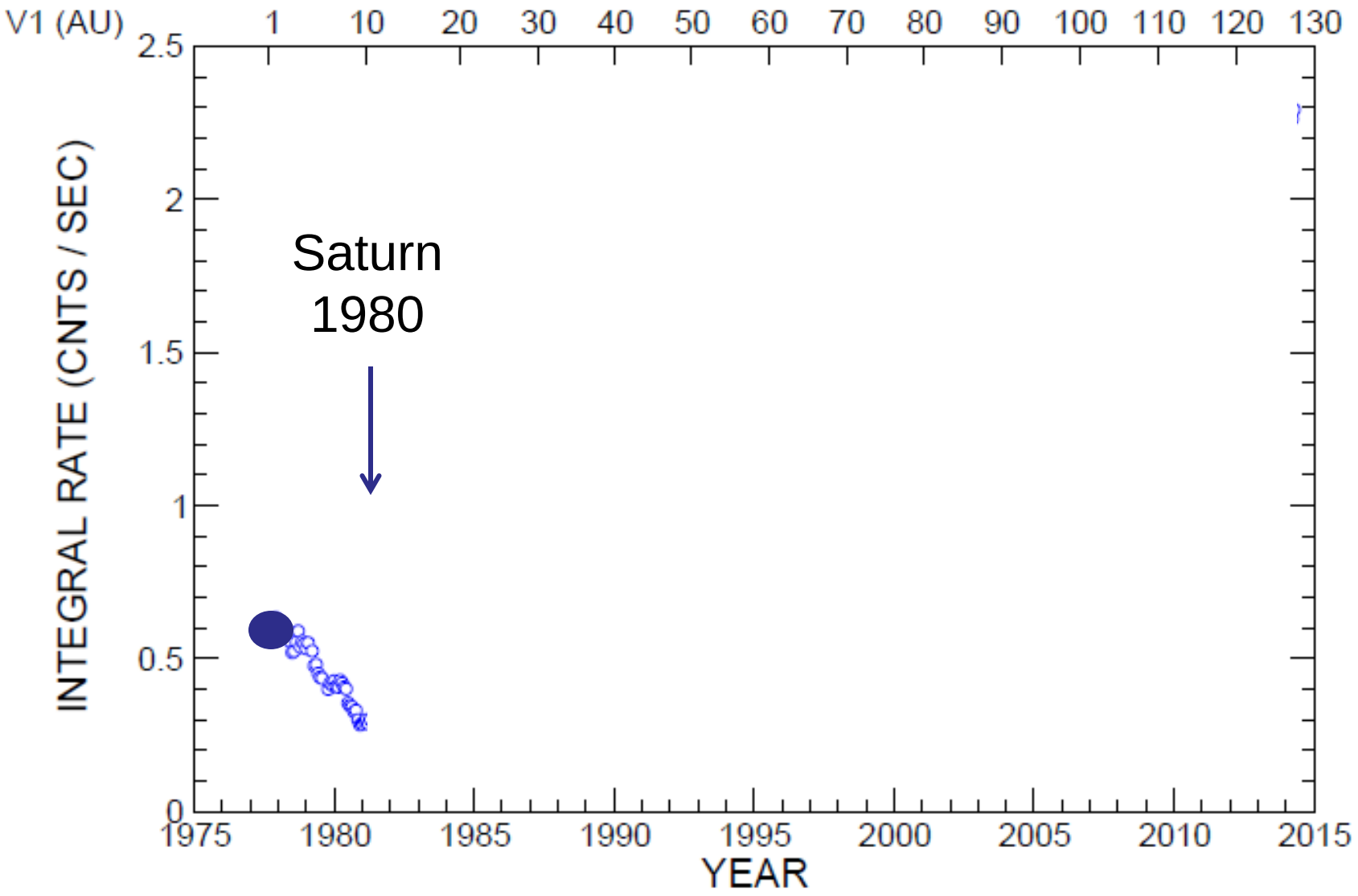
CRS

Cosmic Rays from Milky Way Galaxy



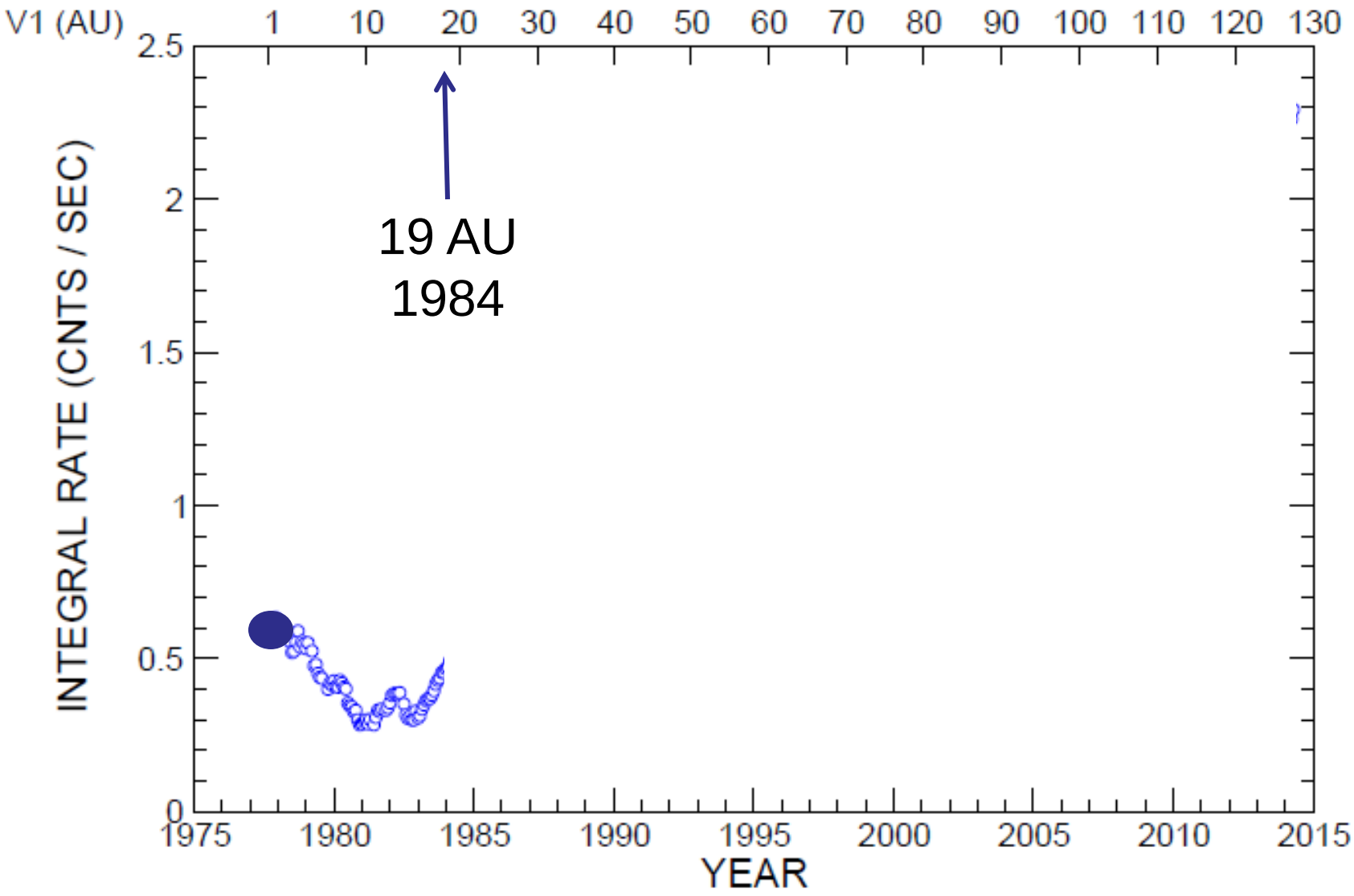
CRS

Cosmic Rays from Milky Way Galaxy



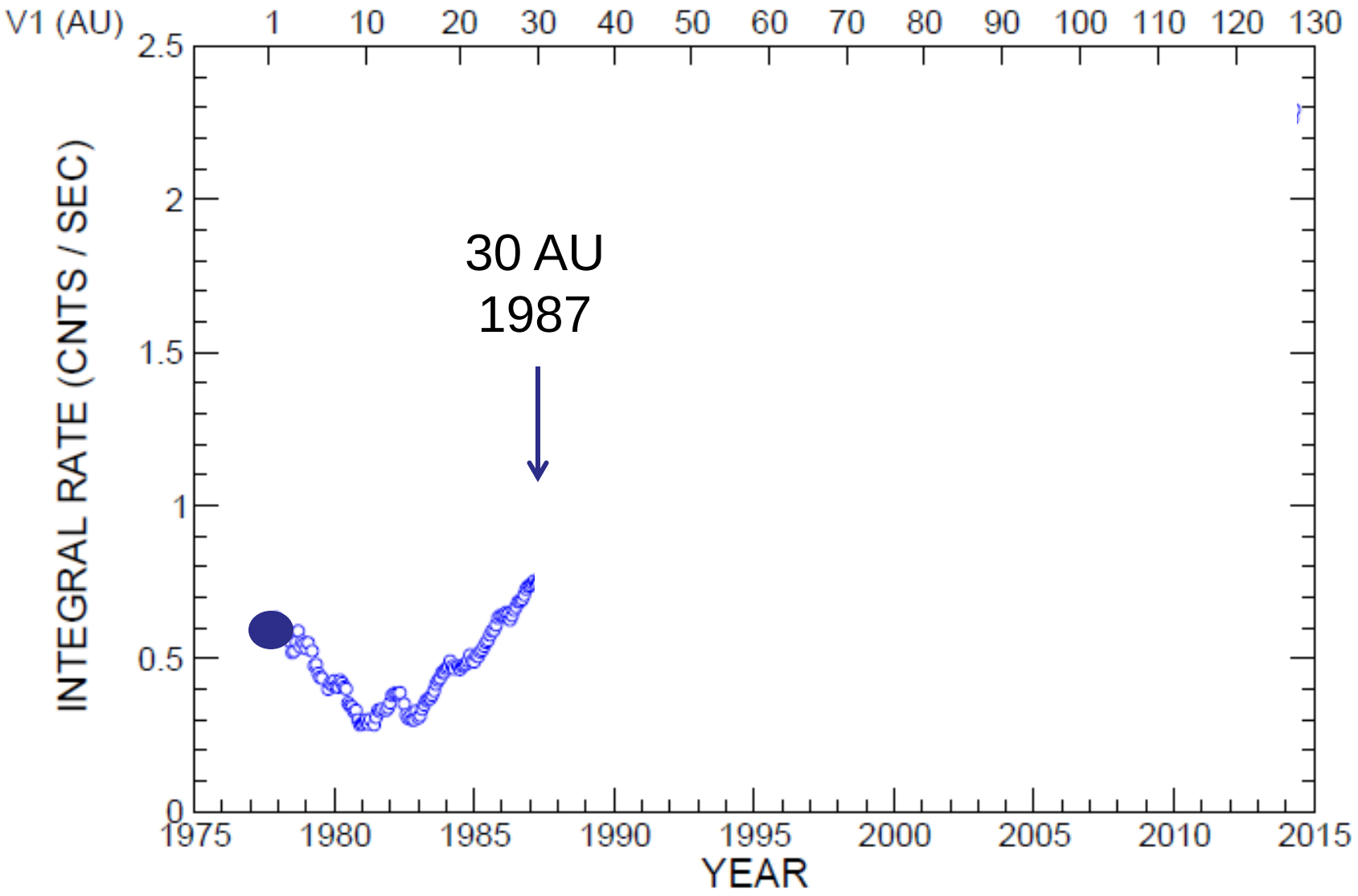
CRS

Cosmic Rays from Milky Way Galaxy



CRS

Cosmic Rays from Milky Way Galaxy



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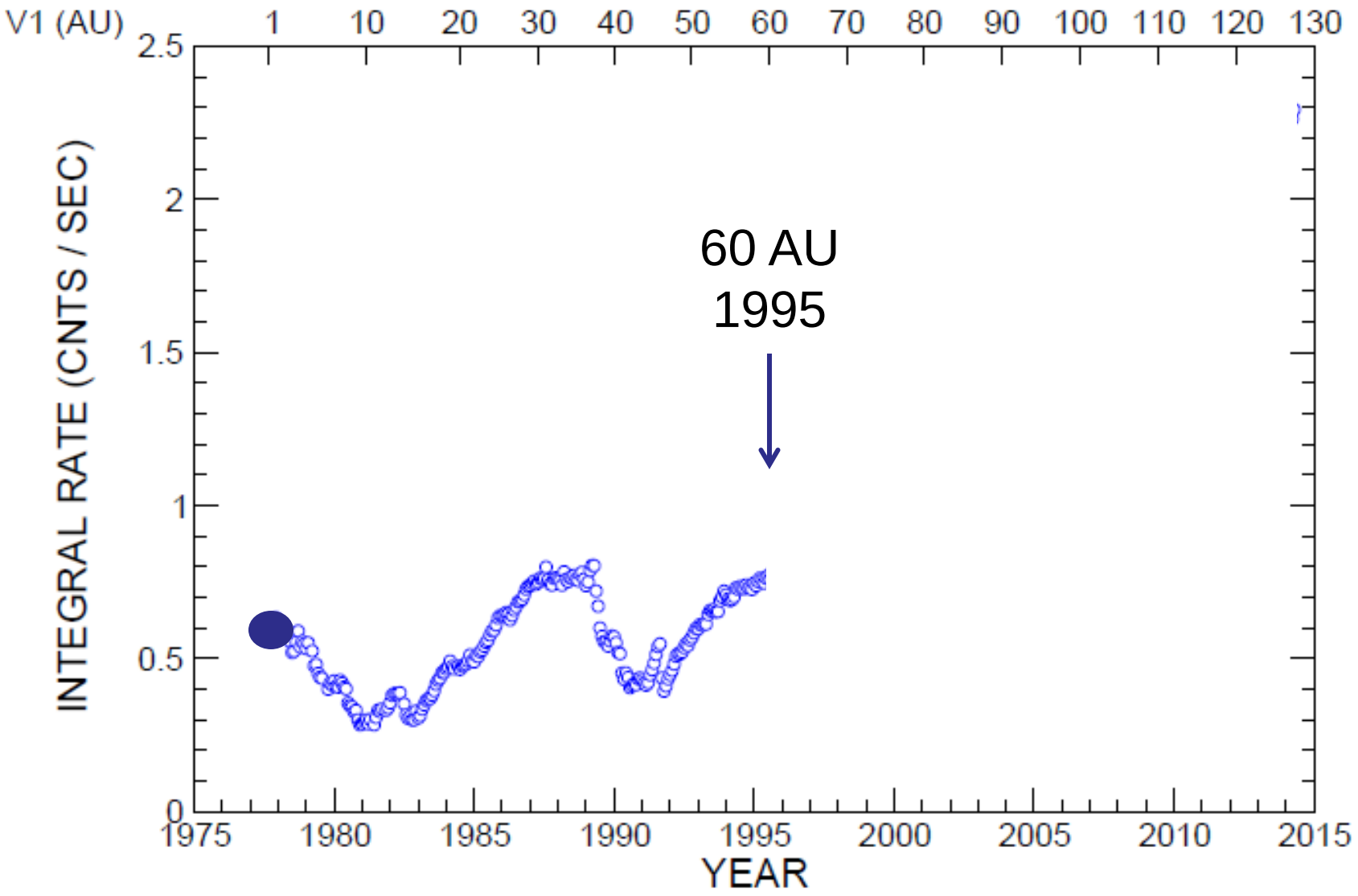
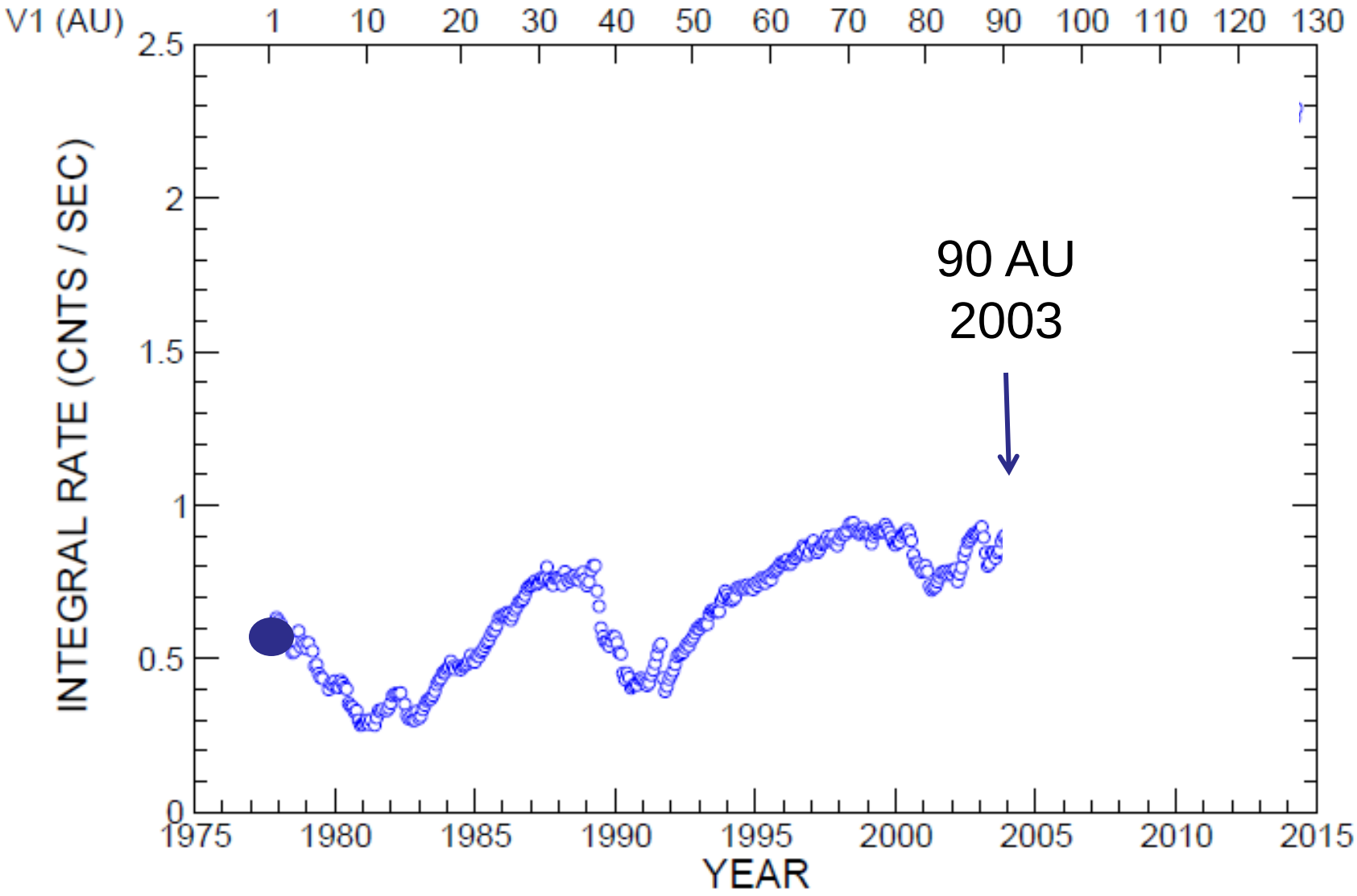
Cosmic Rays from Milky Way Galaxy



Cosmic Rays from Milky Way Galaxy



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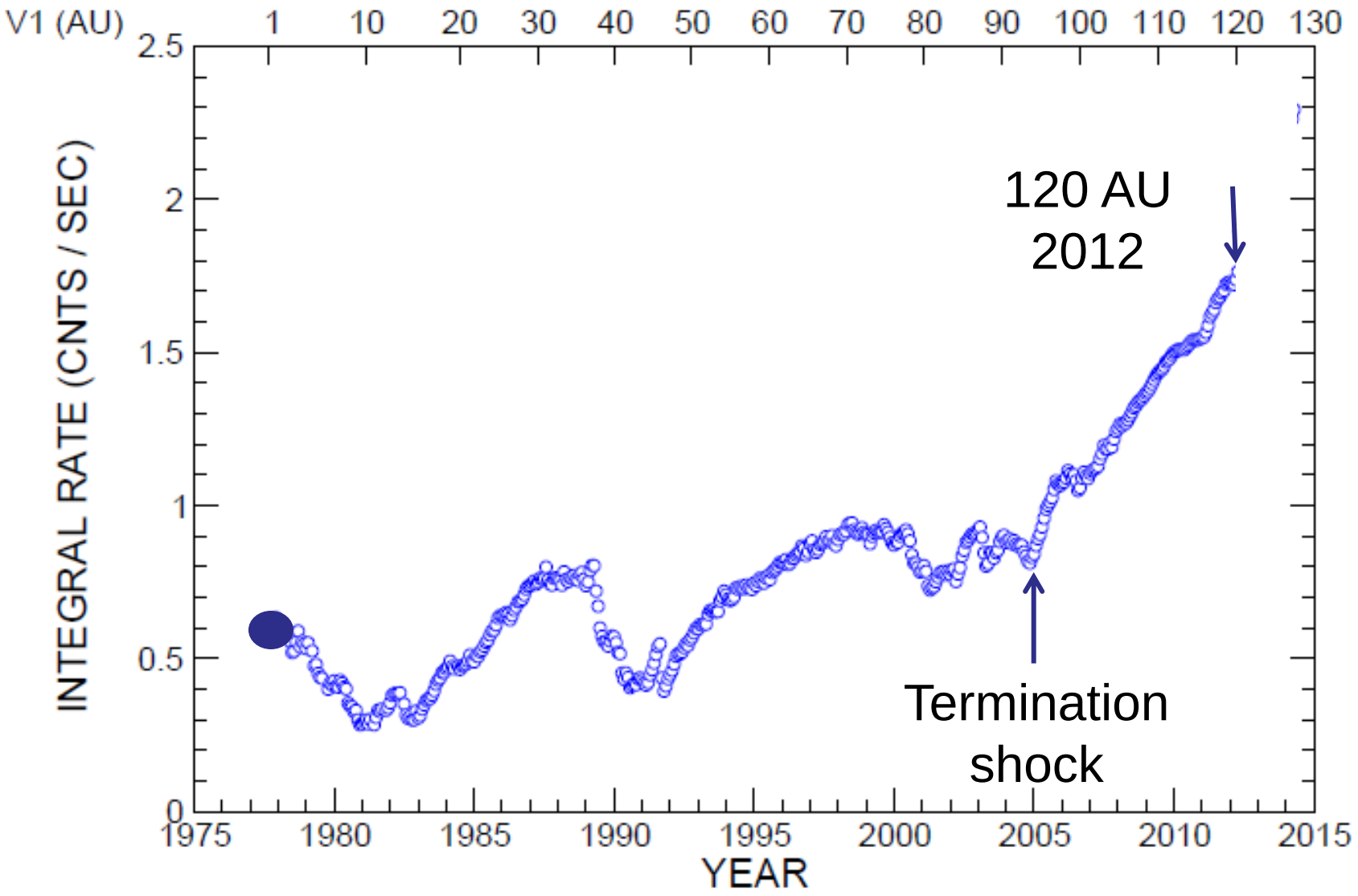
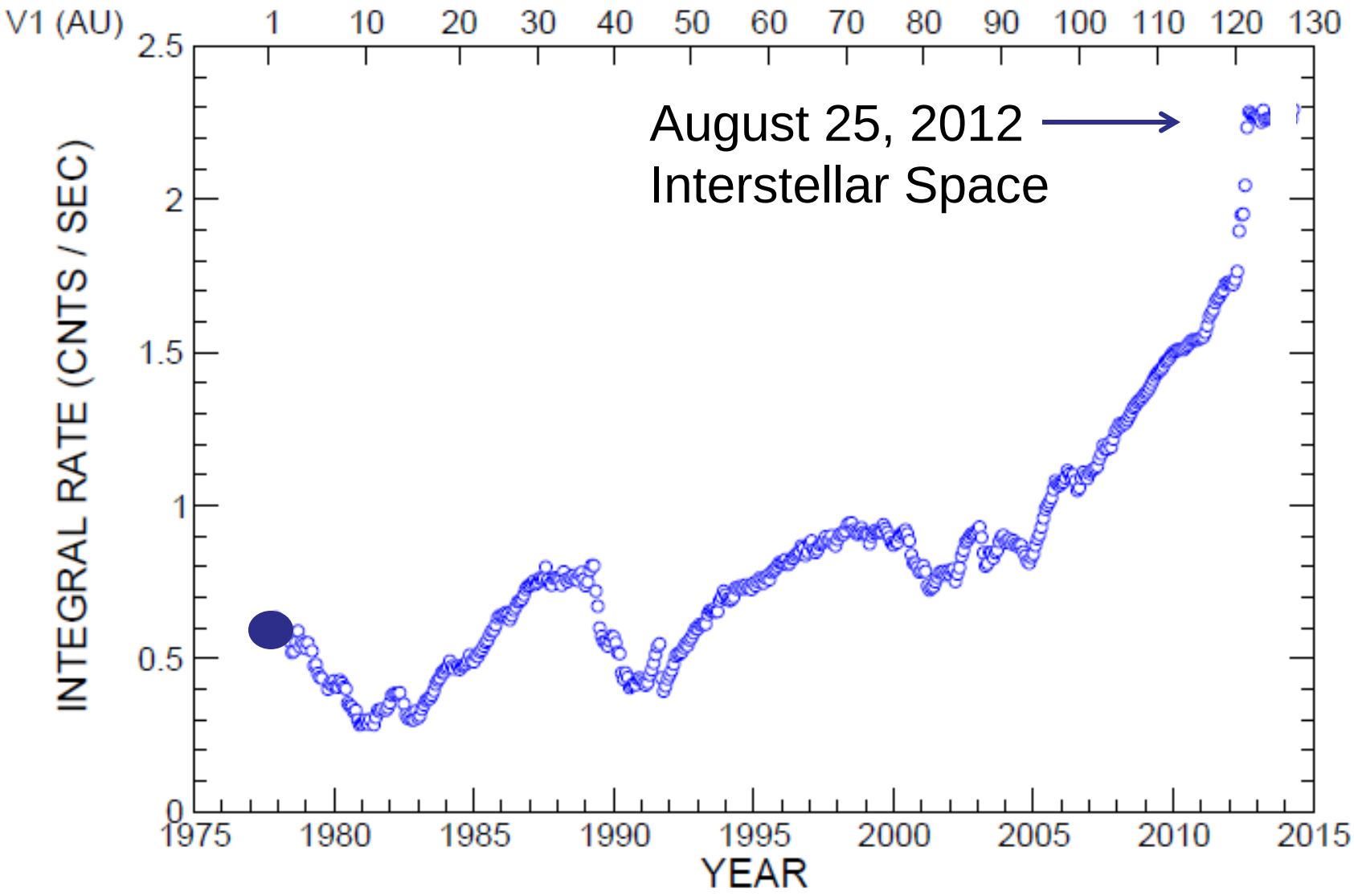
Cosmic Rays from Milky Way Galaxy



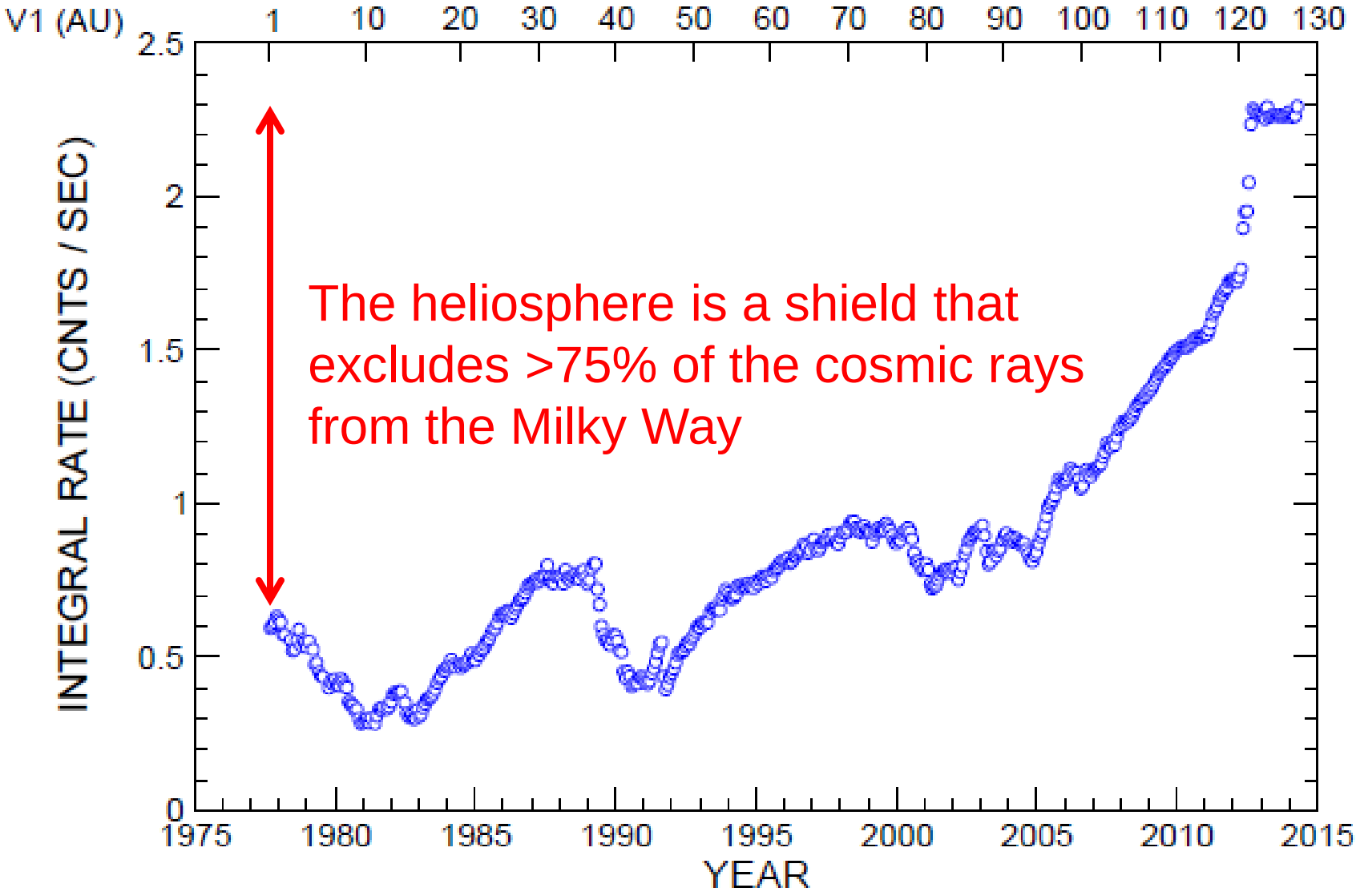
CRS

Cosmic Rays from Milky Way Galaxy

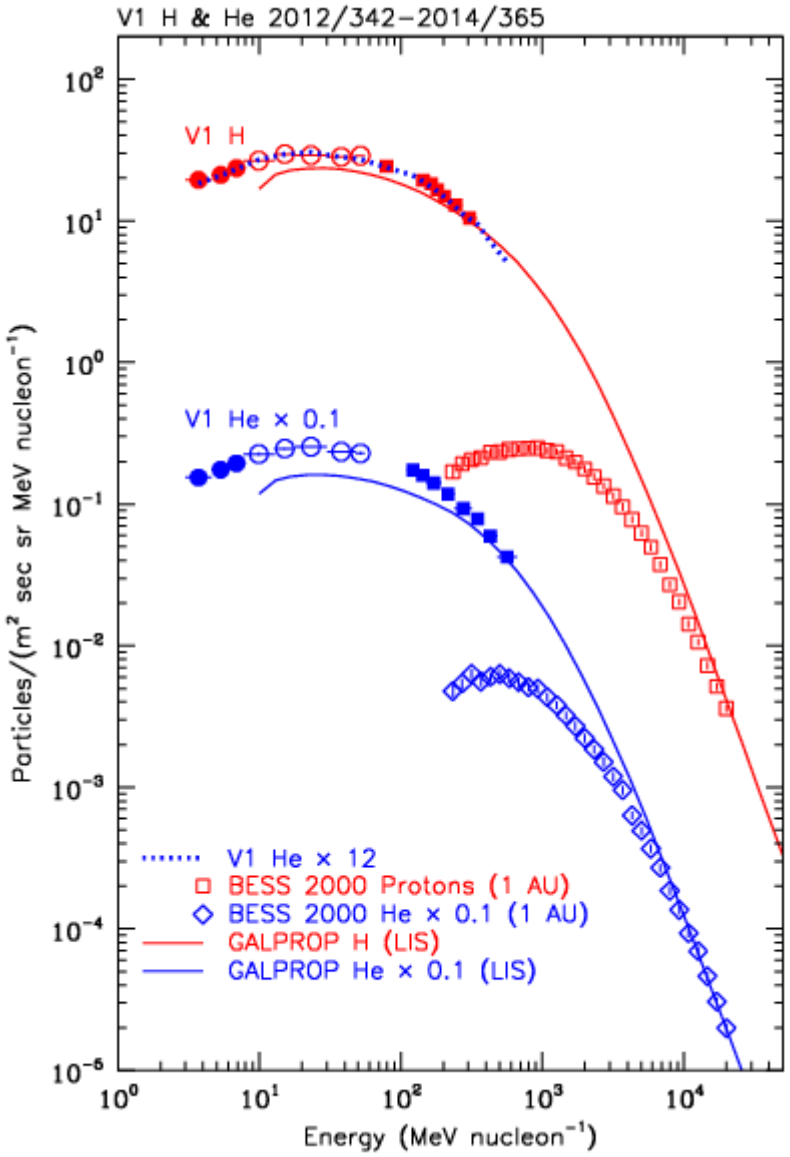


CRS

Cosmic Rays from Milky Way Galaxy



CRS



V1 H, He spectra for 2012/342-2014/365.

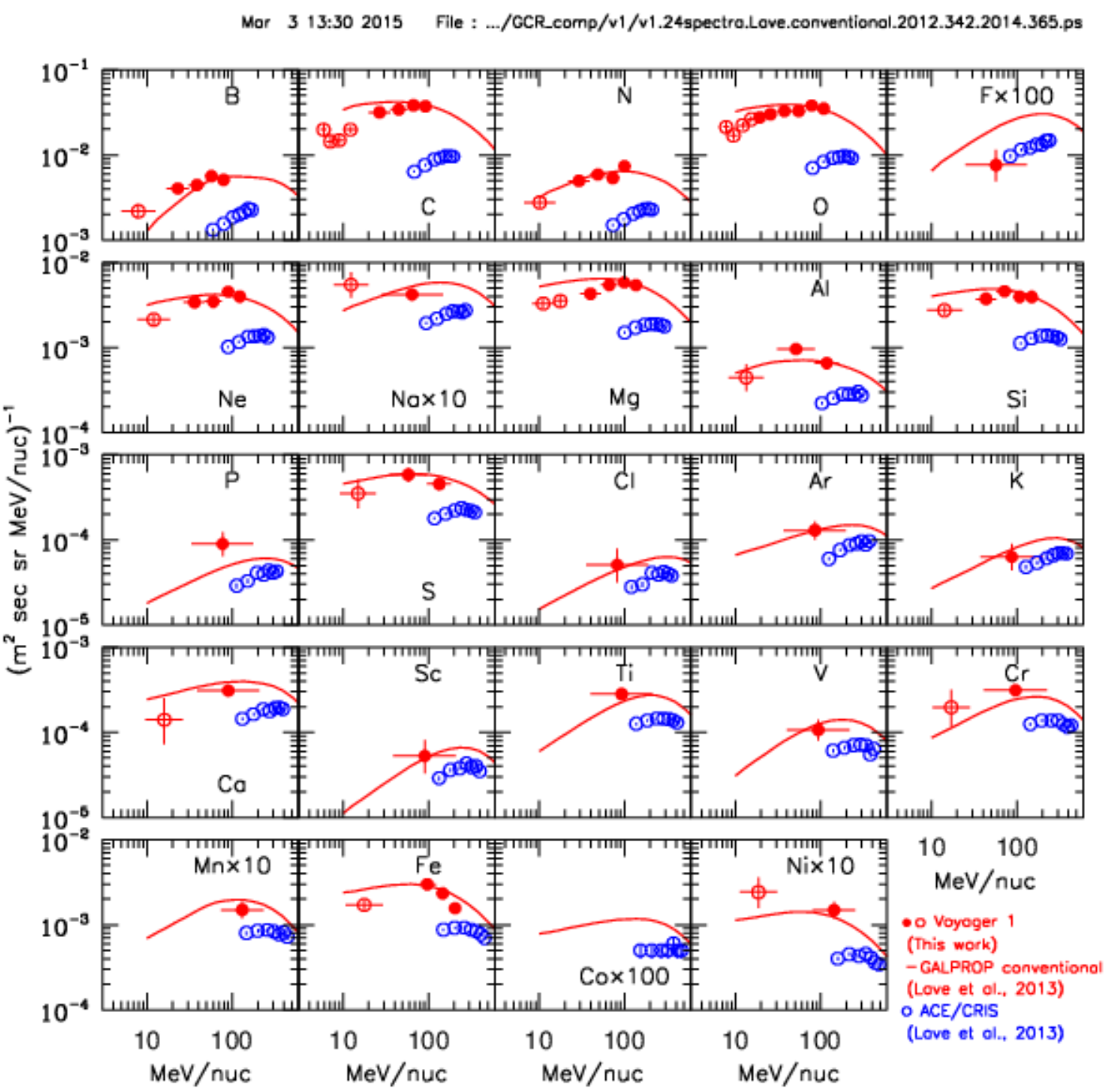
Also shown for reference are higher energy data at 1 AU from BESS (Shikaze et al., 2007).

Interstellar GALPROP spectra (see Lave et al., 2013, conventional + diffusive reacceleration model) fit to spectra at 1 AU

V1 spectra flatten below ~hundred MeV/nuc – so not close by a recent source of GCRs.

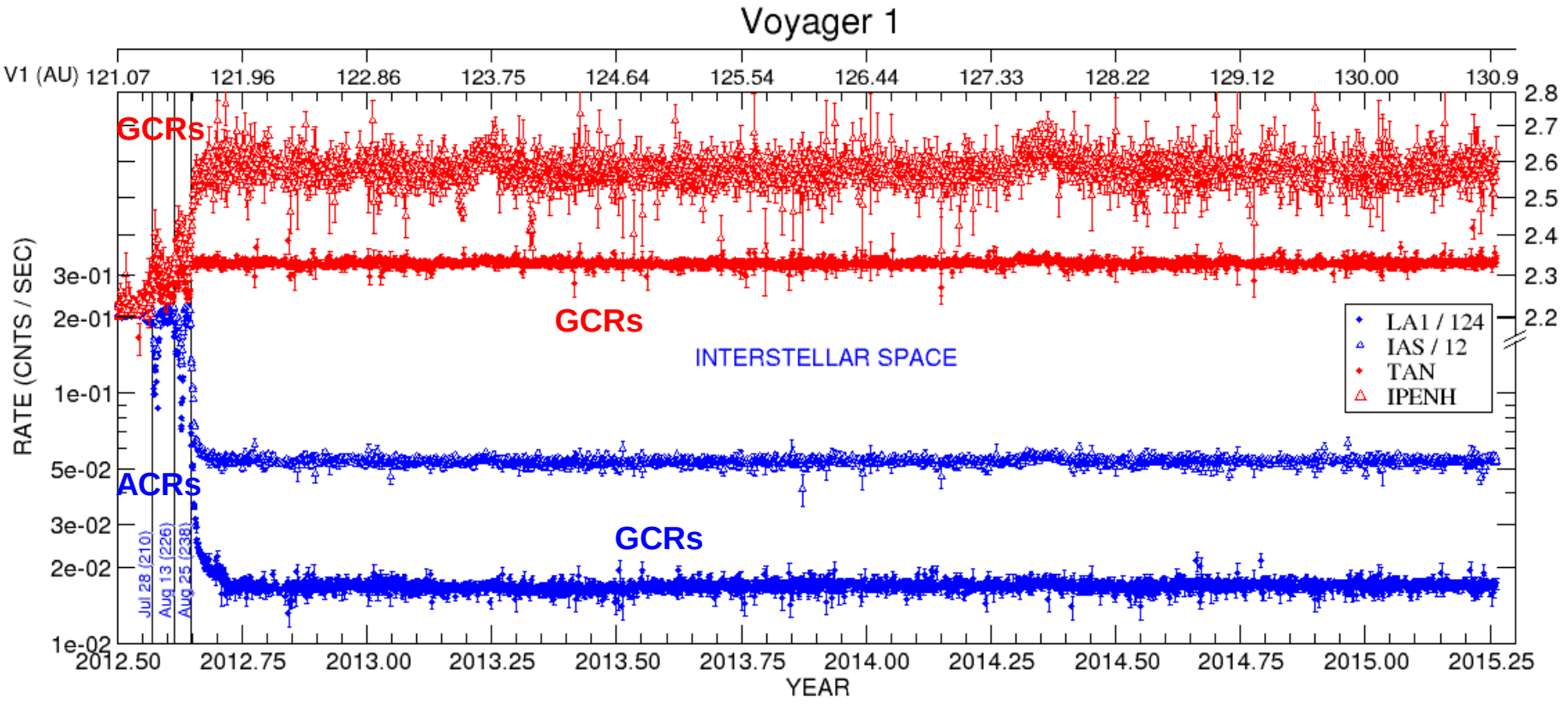
GCR H, He spectra in the LISM peak at ~10-40 MeV/nuc with H/He ratio = ~12 at ~3-300 MeV/nuc (see blue dotted line).

Same spectral shape for H and He indicates not modulated in solar wind.



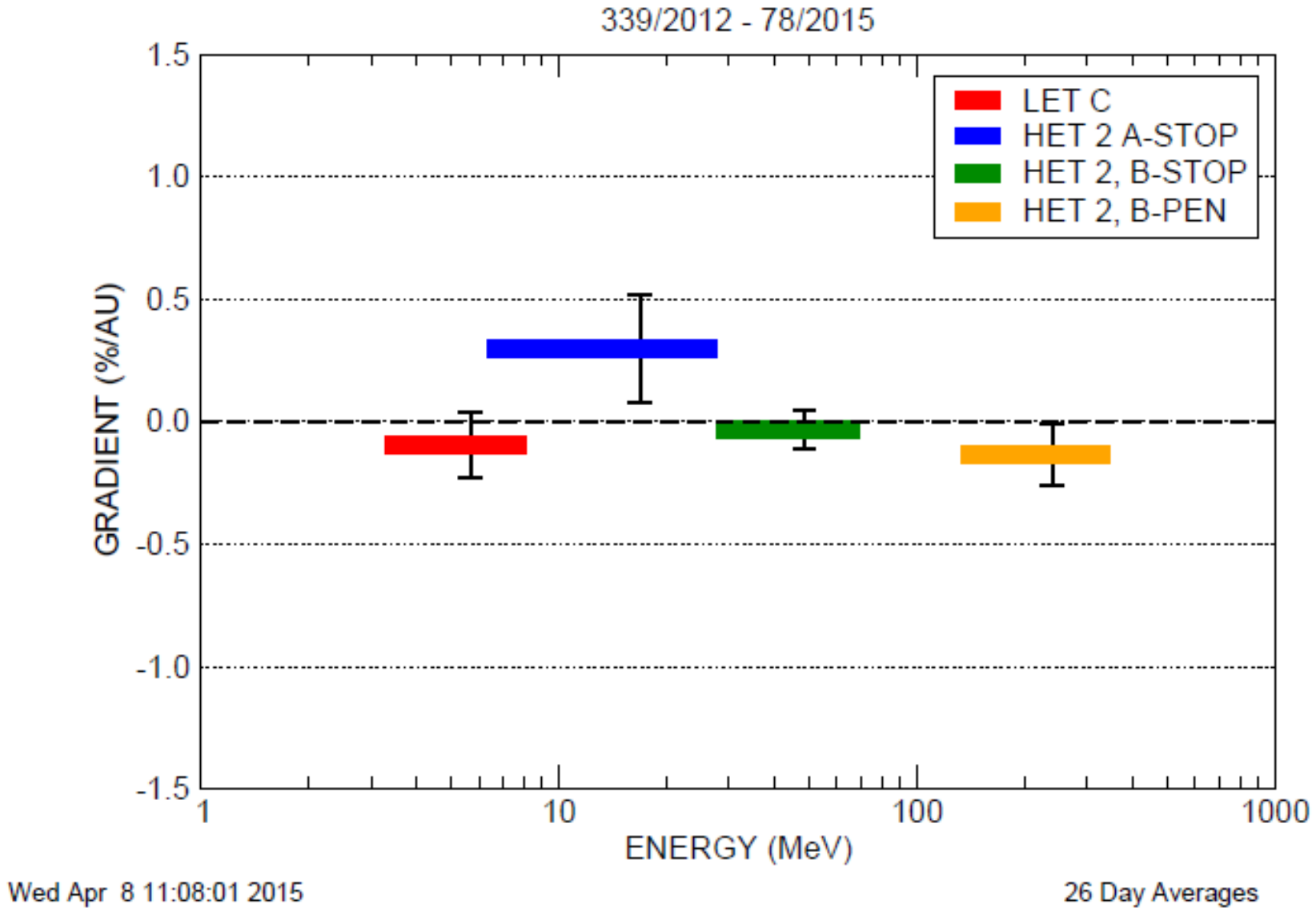
V1 spectra for 2012/342-2014/365 for 24 elements (red) together with ACE data at 1 AU and GALPROP LISM spectra described in Lave et al. 2013.

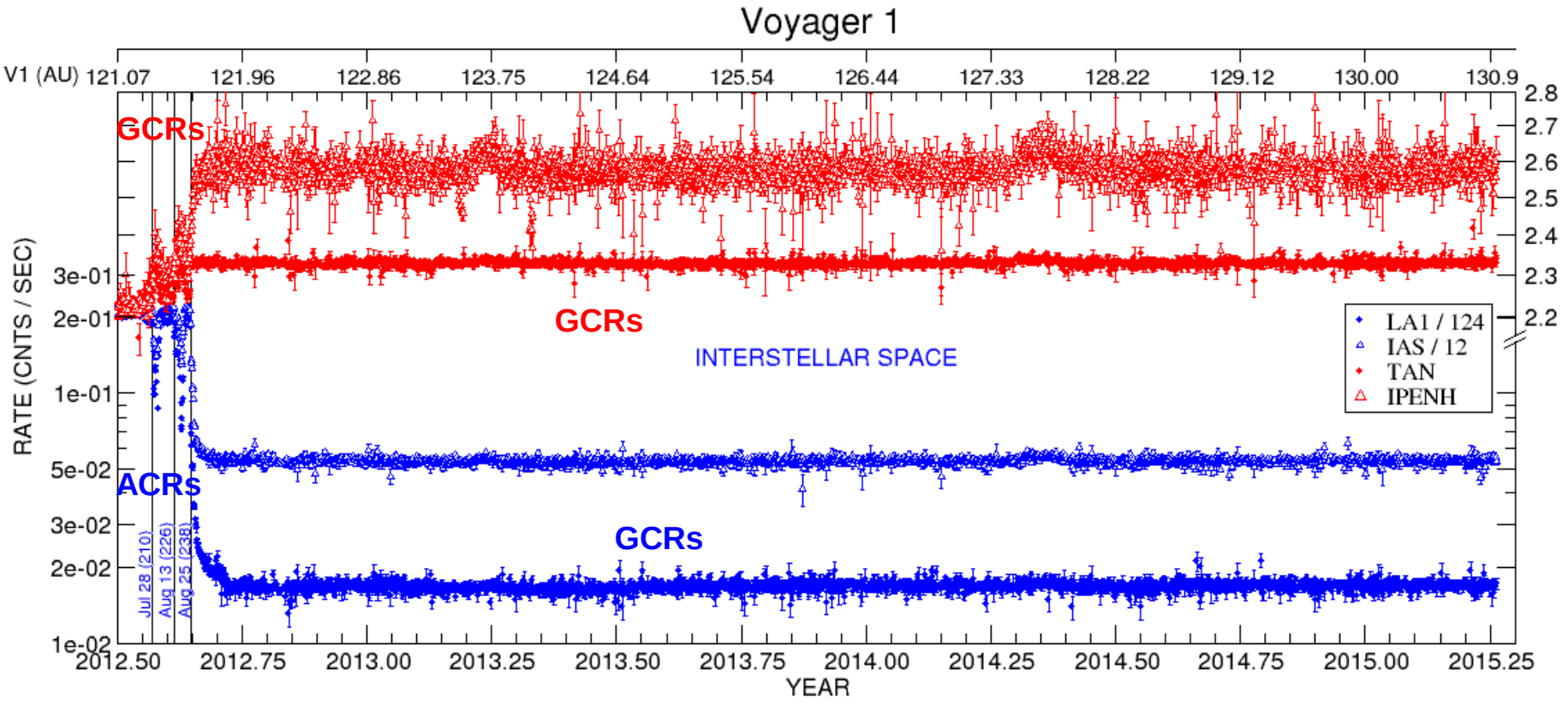
To first order, the off-the-shelf GALPROP model is doing a reasonable job – biggest discrepancies at the lower energies.



6 Hour Averages
Wed Apr 8 19:10:47 2015

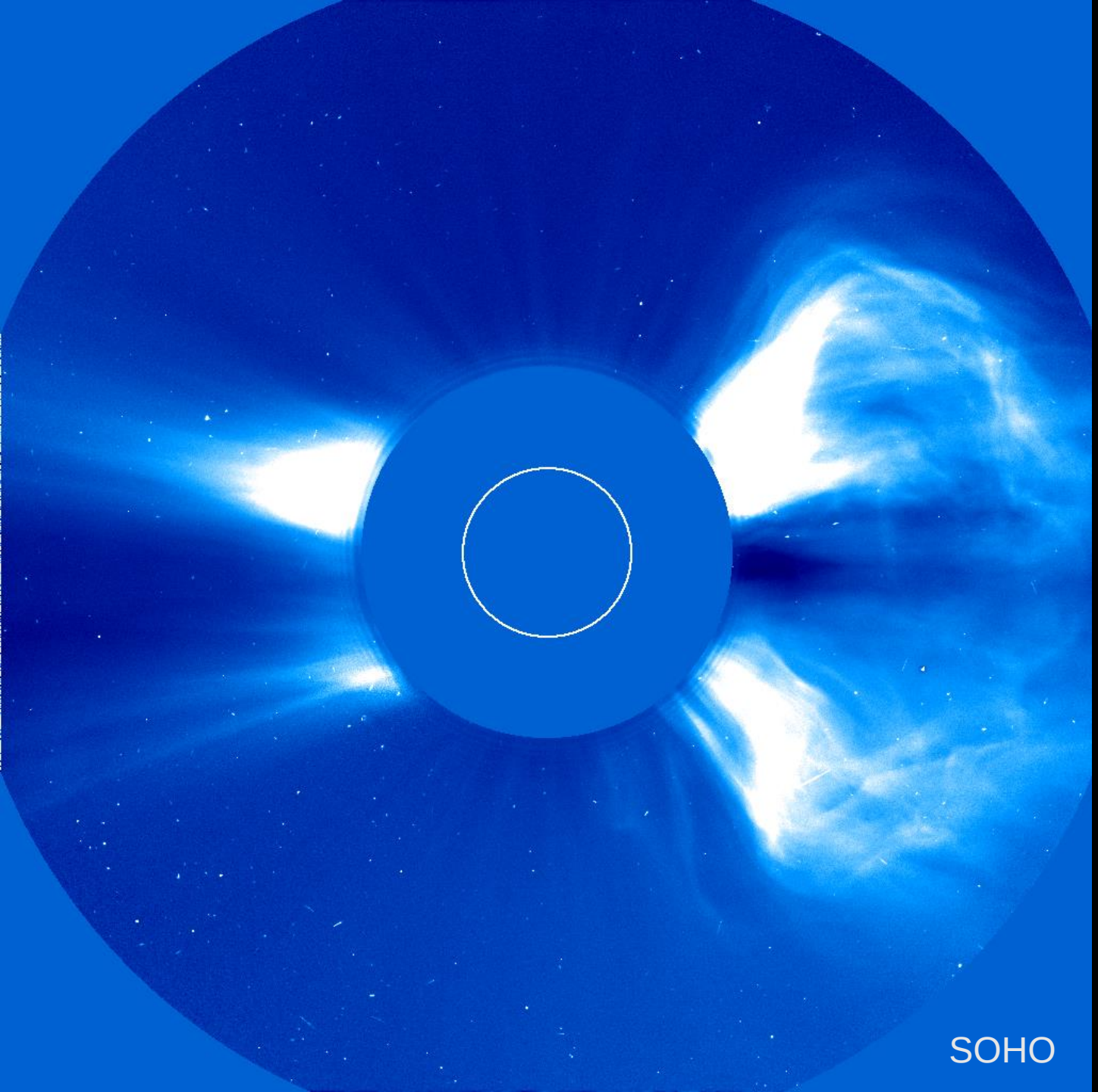
No significant gradients


339/2012 - 78/2015
LET C
HET 2 A-STOP
HET 2, B-STOP
HET 2, B-PEN
GRADIENT (%/AU)
1.5
1.0
0.5
0.0
-0.5
-1.0
-1.5
1
10
100
1000
ENERGY (MeV)
Wed Apr 8 11:08:01 2015
26 Day Averages



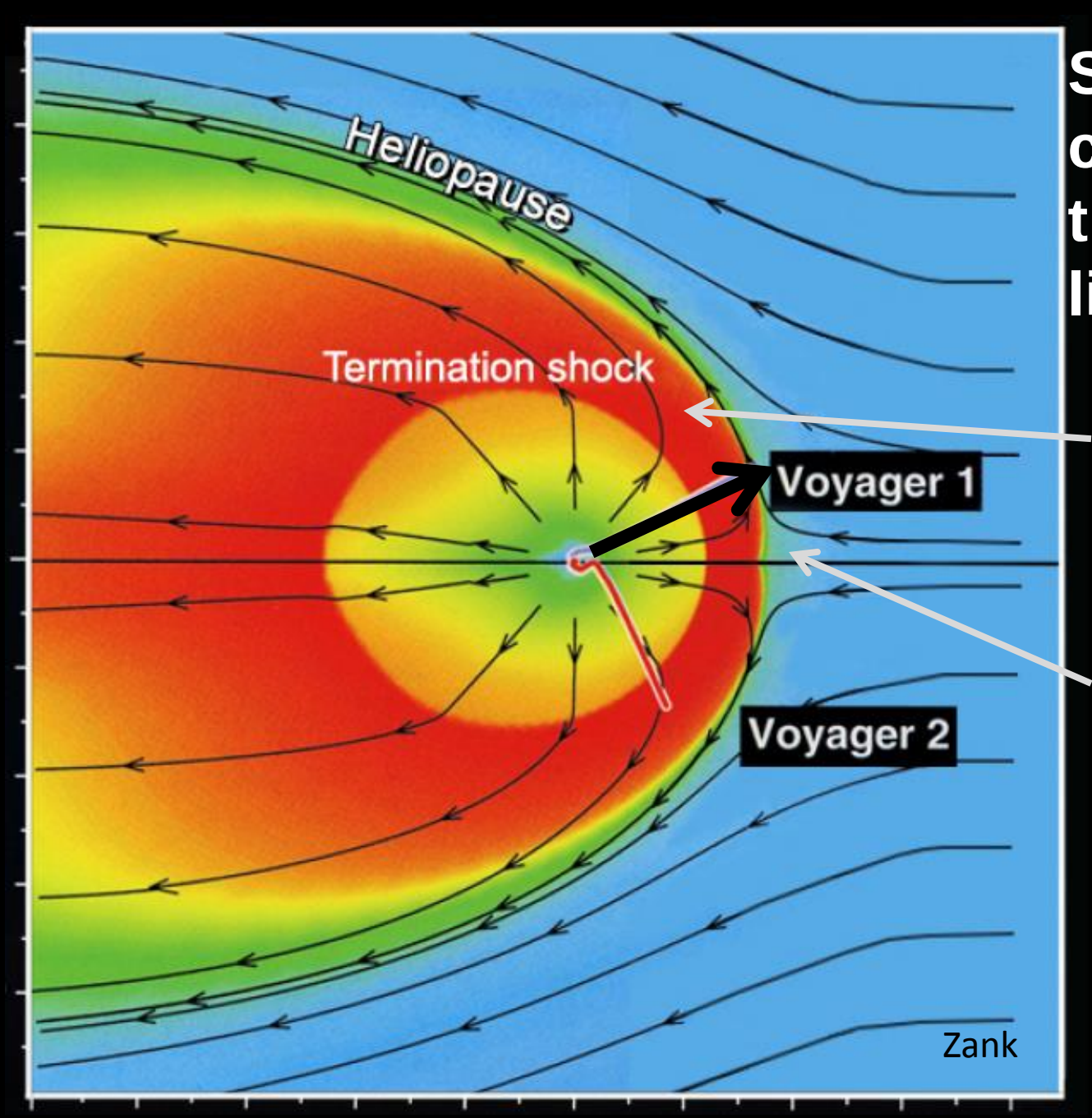
6 Hour Averages
Wed Apr 8 19:10:47 2015

No significant gradients



Coronal Mass Ejection

More than 1,000,000 miles/hour

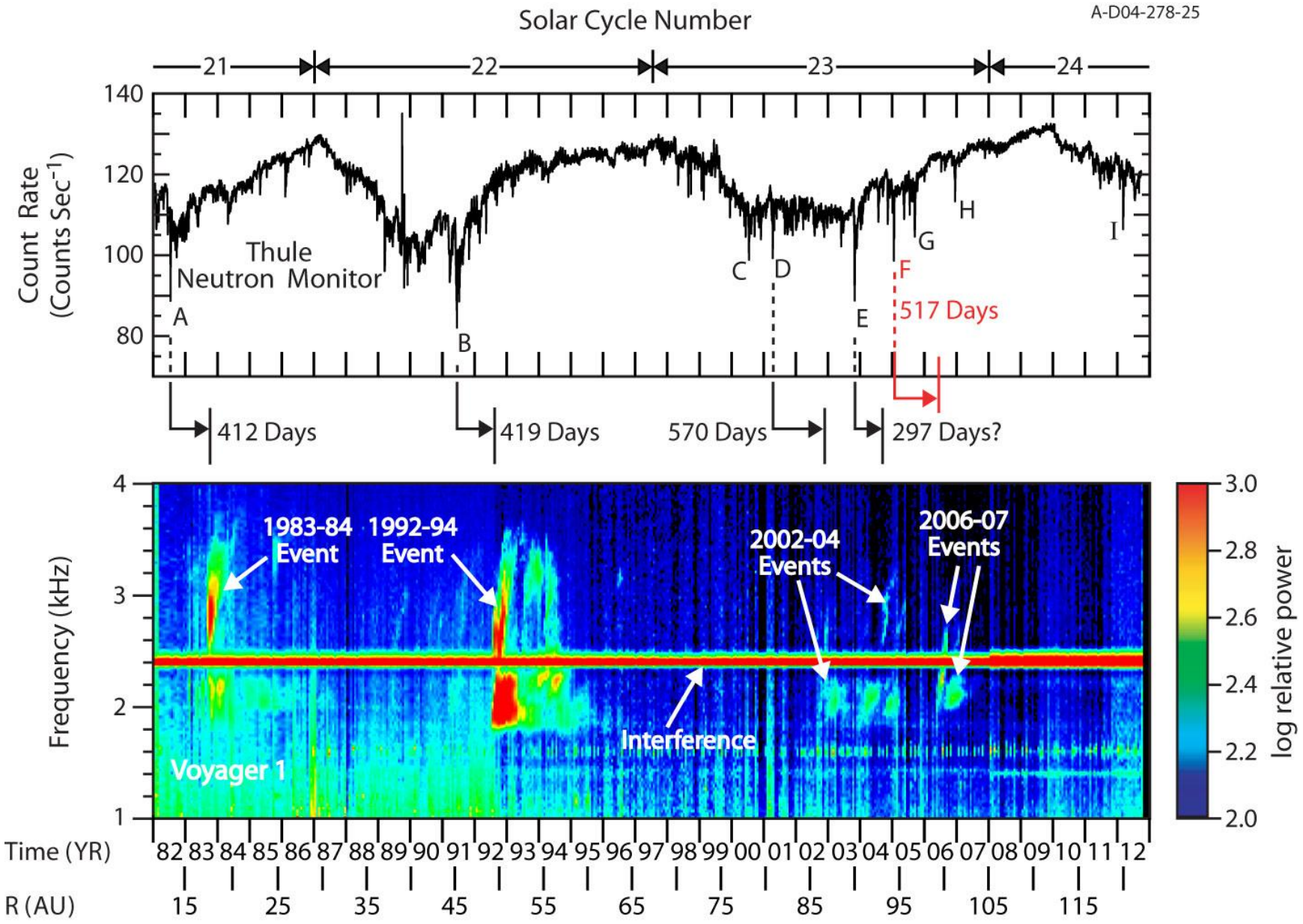


Solar tsunami causes ions in the wind to ring like a bell

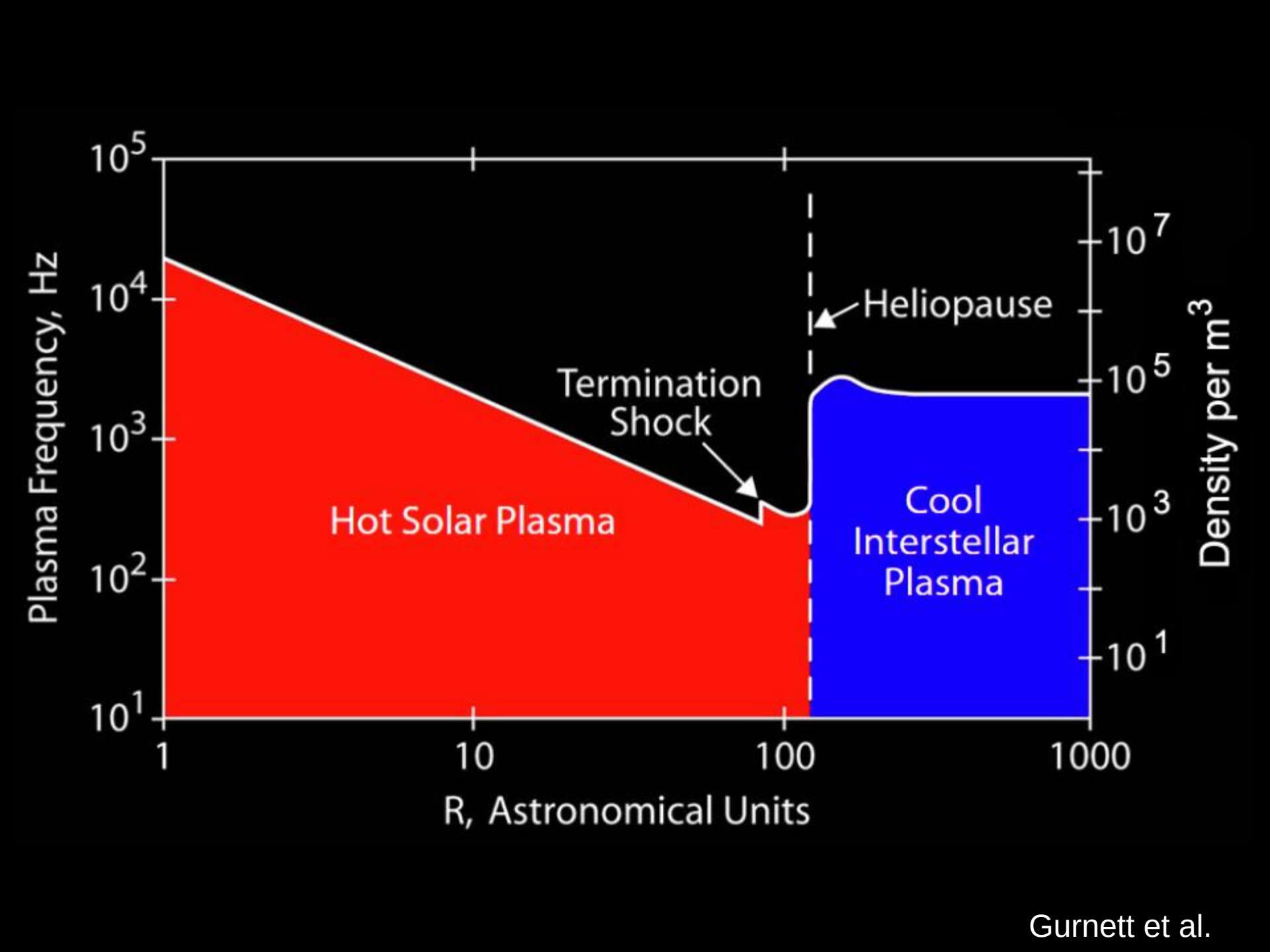
Density inside ~1000 m^{-3}
300 Hz

Density outside ~100,000 m^{-3}
3000 Hz

The Latest Voyager 1 Spectrogram

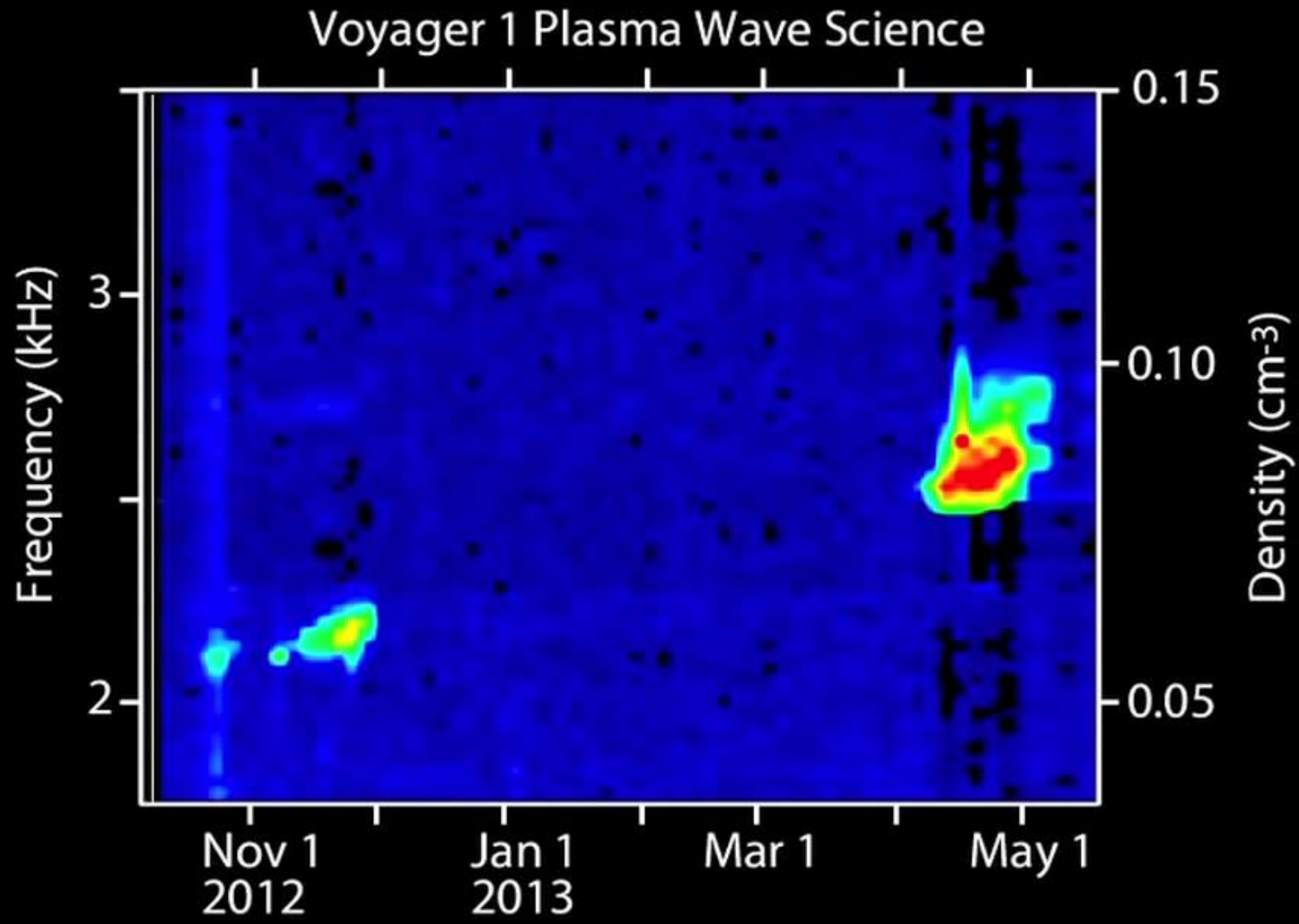


Gurnett & Kurth



Gurnett et al.

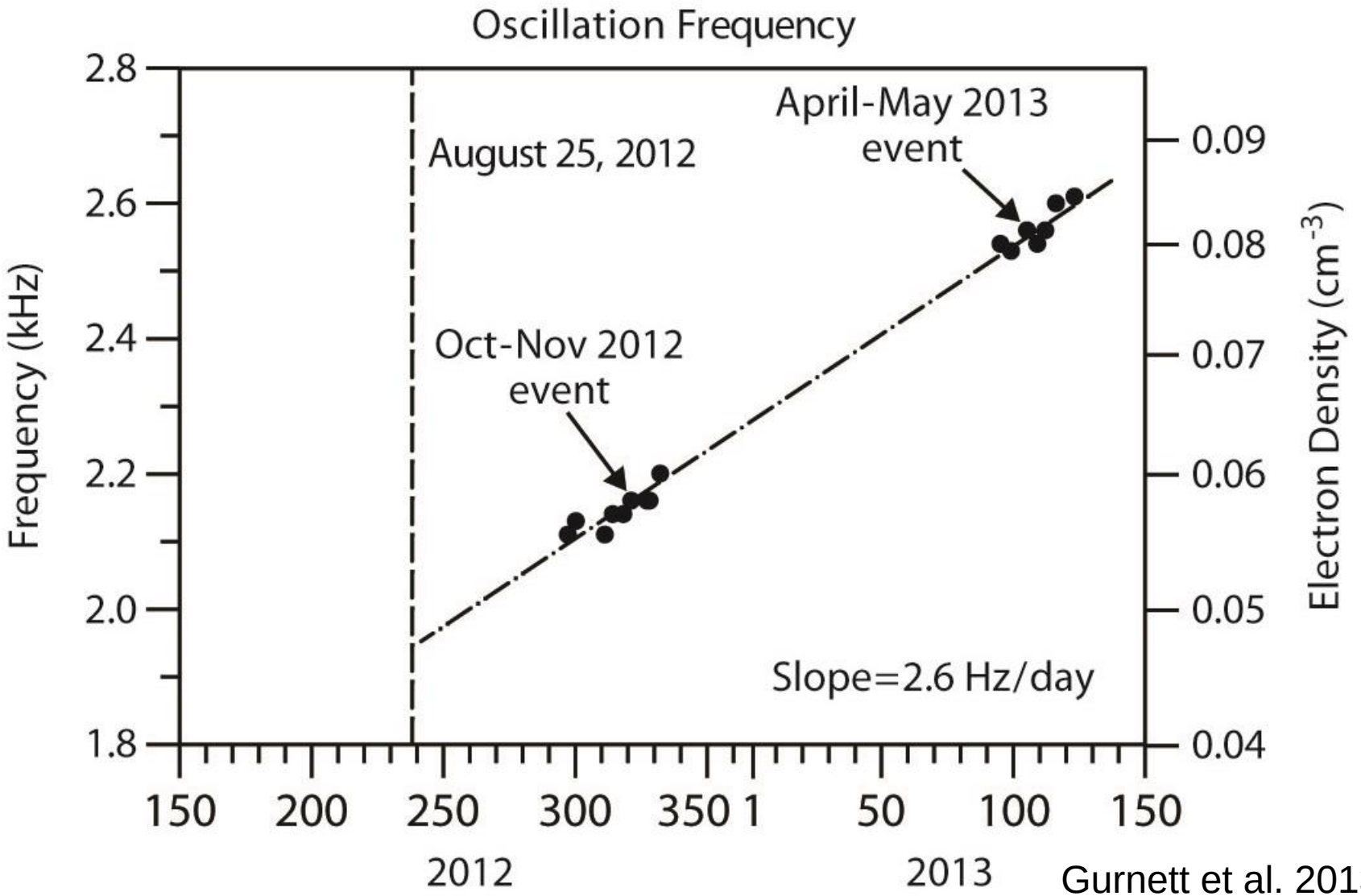
The Sounds of Interstellar Space



Gurnett et al.

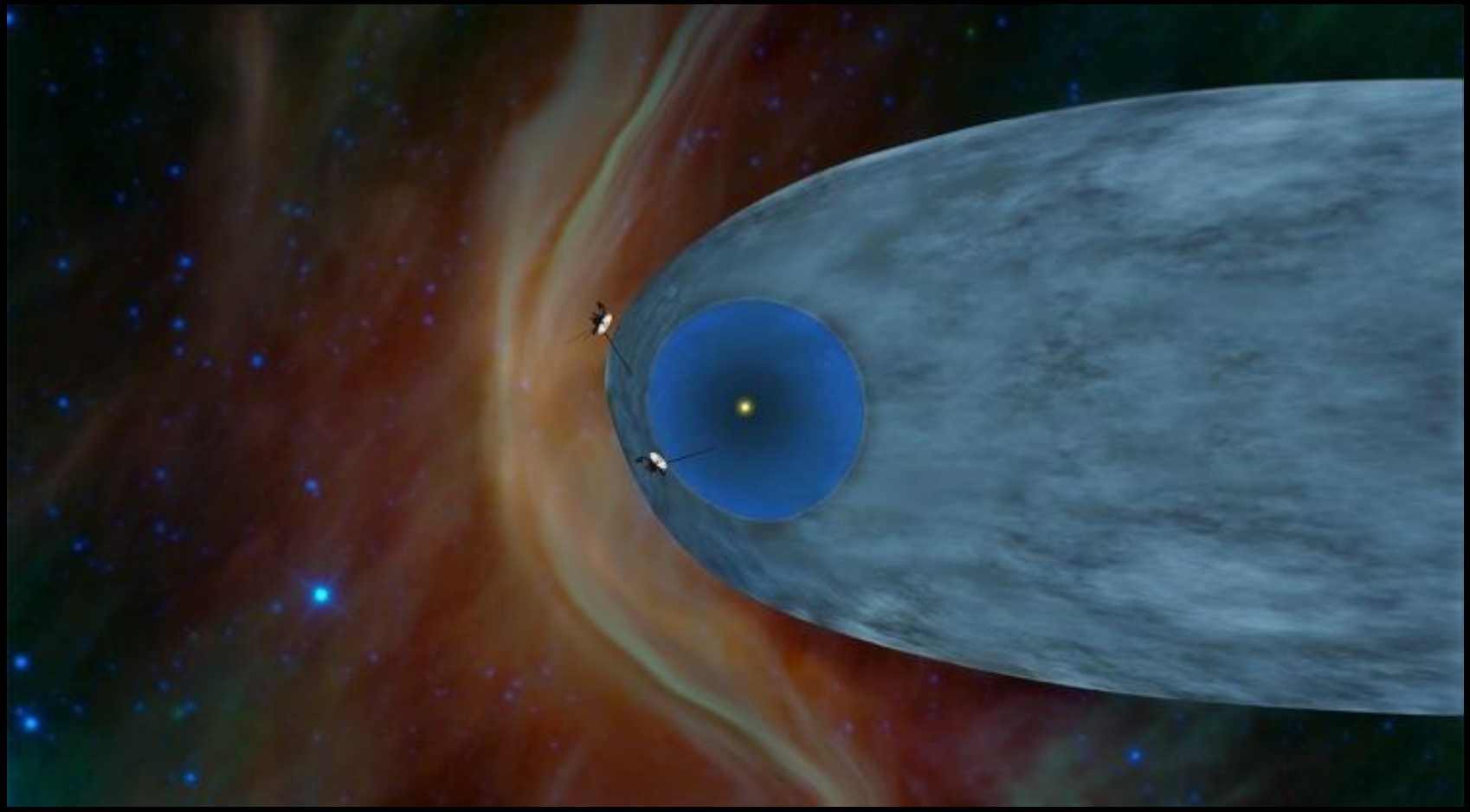
The Density Ramp

What causes it? When will it reach the top?

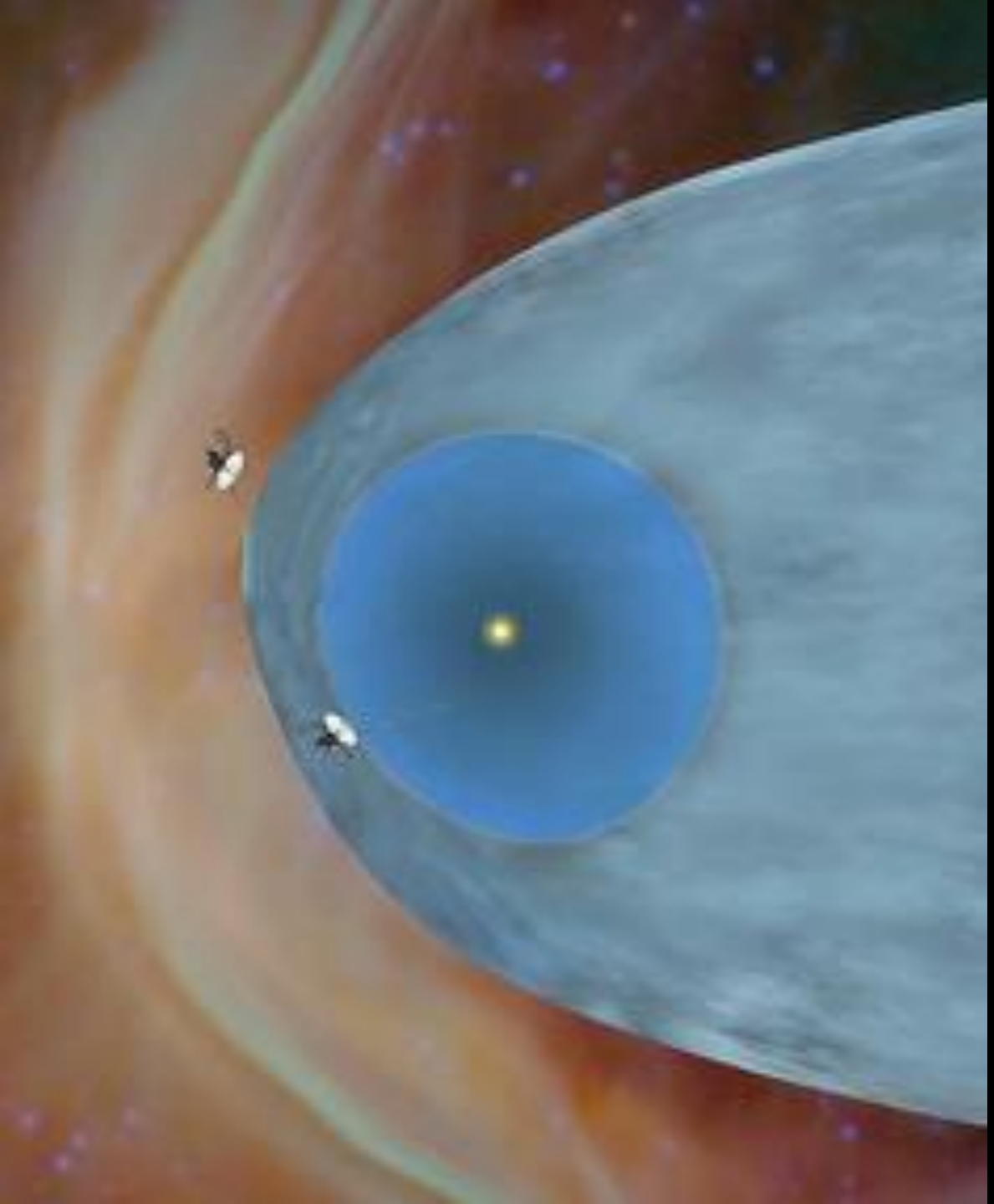


Gurnett et al. 2013

HST- Orion Nebula

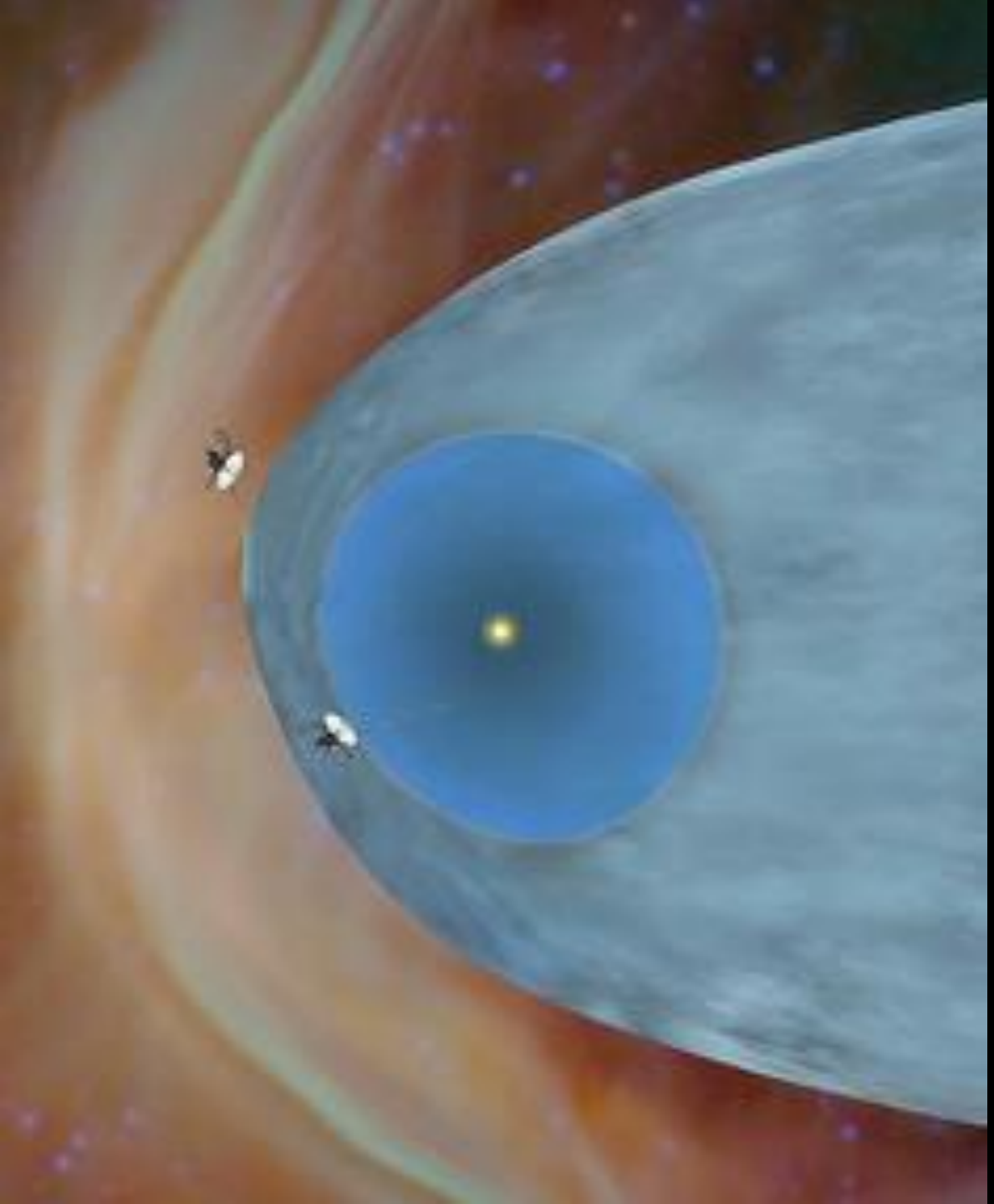


On August 25, 2012, at 18 billion kilometers from the Sun, Voyager 1 entered the space between the stars



Voyager 1 131.0 AU
19.7 billion km

Voyager 2 107.7 AU
16.2 billion km
~2 years to
interstellar space?



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~2 years to
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Instrument power-
sharing begins
2020

Last instrument off
2025

The Voyager Odyssey continues