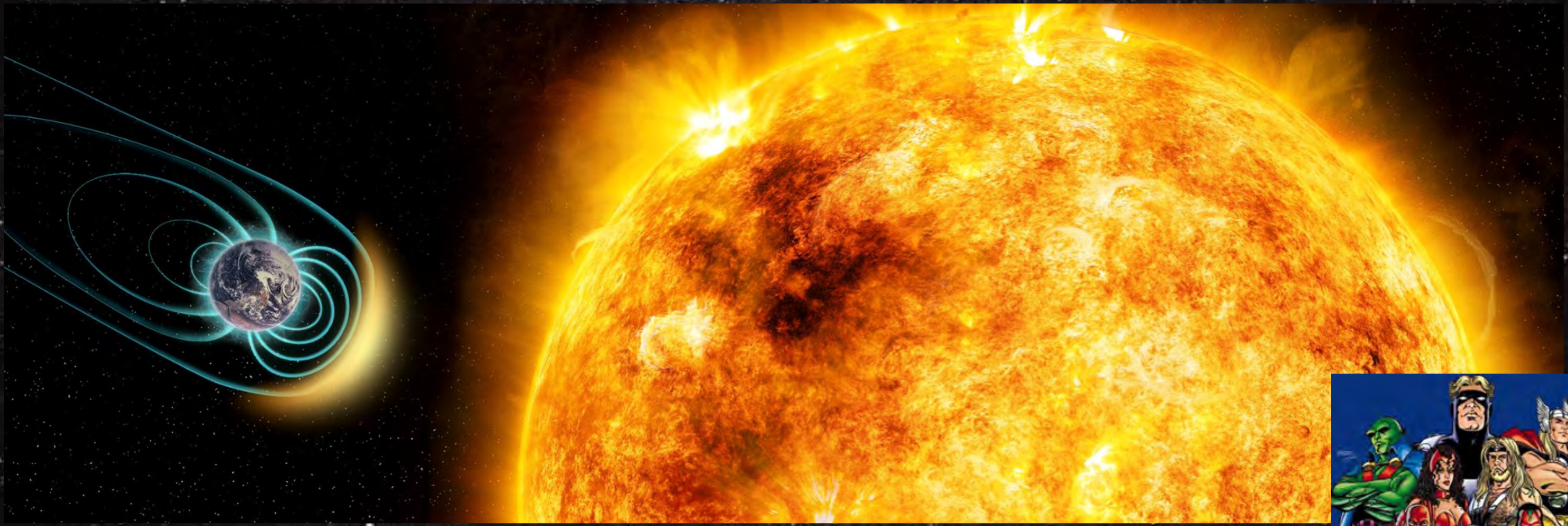
NASA/XRP HIF IRAD SEEC HST-XMM Newton TESS NICER

The Sun-Earth System in Time: Searching For Habitable Rocky Exoplanets



Vladimir Airapetian

NASA/GSFC/SEEC & AU and the Team of Superheroes

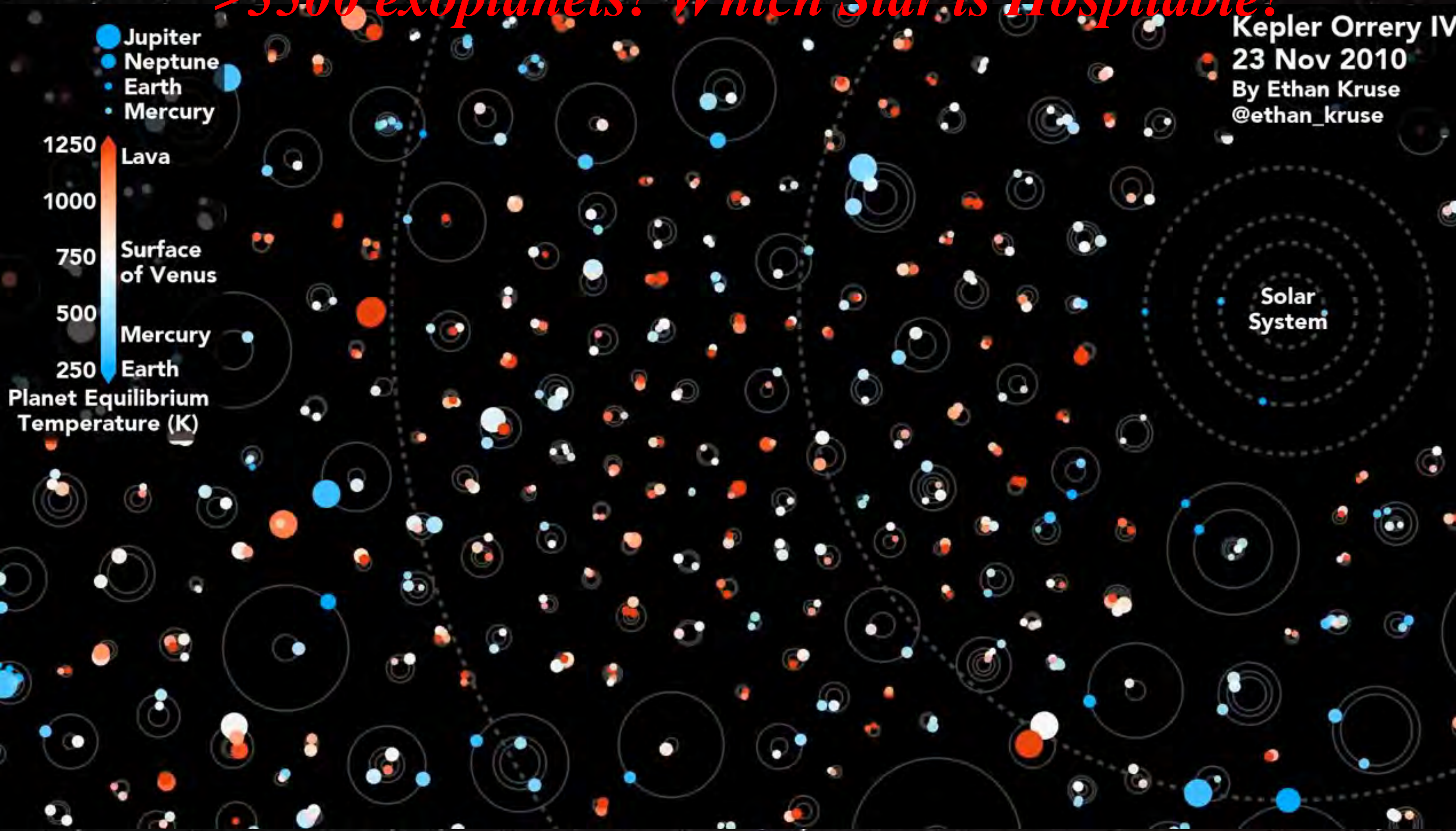
Glocer, Kang, Jin, Hu, Gronoff, Namekata, Notsu, France, Chen, Pettit, Kobayashi, Garcia-Sage, Kuang, Yamashiki, Gudel, Boro Saikia, Pavlov, Mitchel, De Nolfo

4th Jack Eddy Symposium, Oct 29- Nov 3, 2023

OUTLINE

- Is Earth a Unique Planet?
- Reconstructing Space Weather from Young Solar Analogs (observations and models)
- Impact of XUV flux and CMEs on exoplanetatry magnetospheres
- Impact of superflares on chemistry and climates of rocky planets: 775AD event as a proxy
- Chemical signatures of prebiotic planets in the era of JWST via laboratory experiments

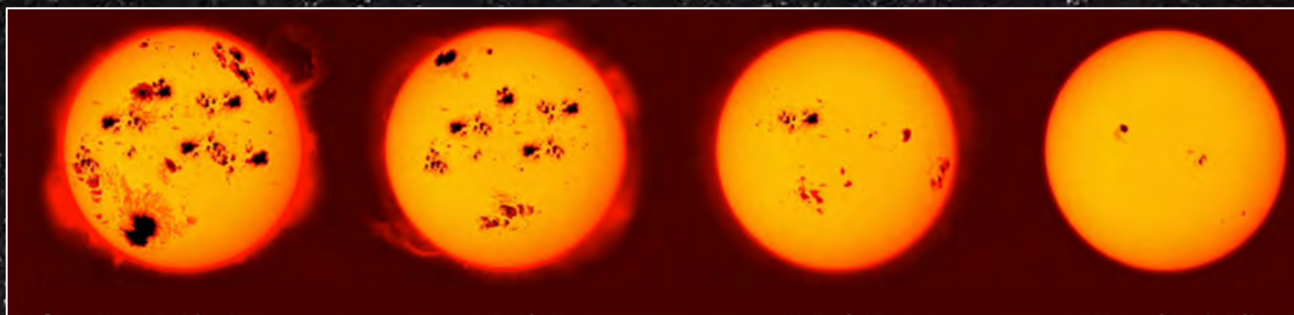
How Can We Detect a Habitable Planet Out of the Zoo of >5500 exoplanets? Which Star is Hospitable?



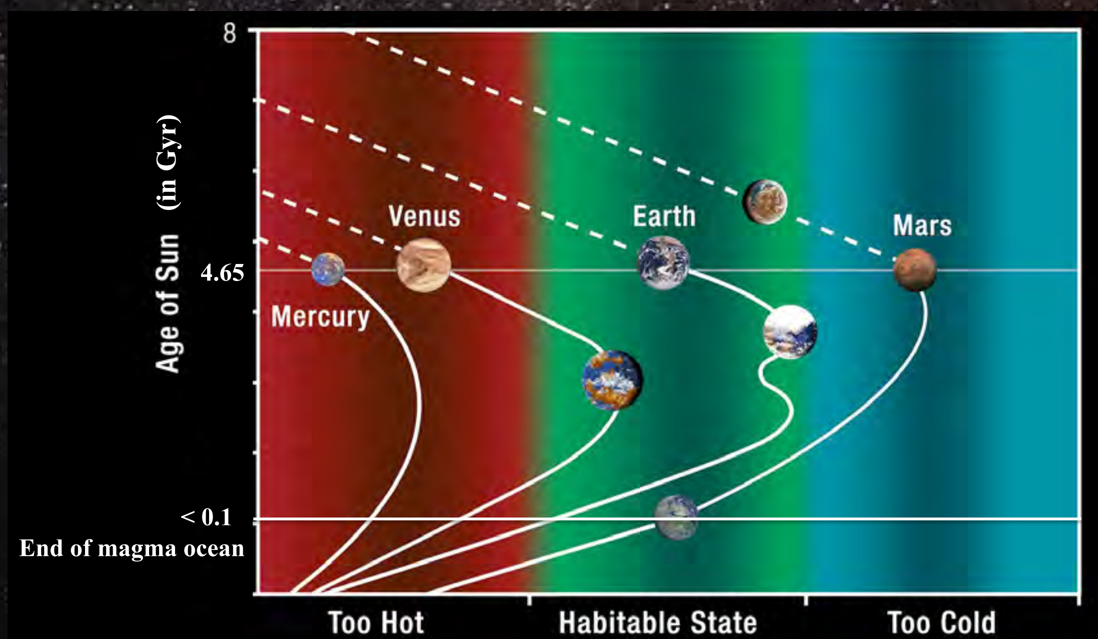
Is Earth a Unique Planet?
Is Earth-Sun a Unique System?

~~Is Earth a Unique Planet?~~
Is Earth-Sun a Unique System?

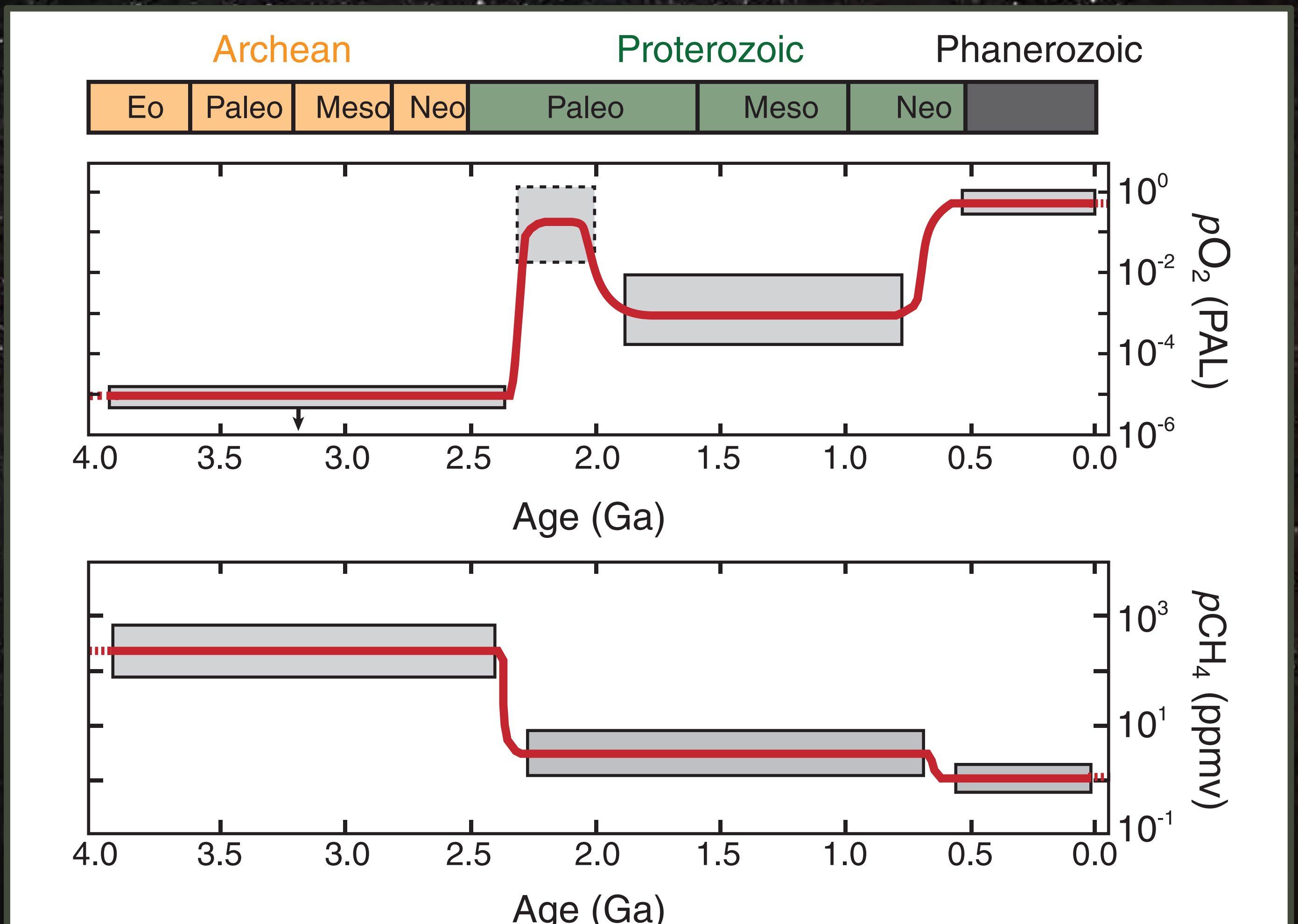
We need to understand how habitability state evolved in the Solar System



<300 Ma *~650 Ma* *~2 Ga* *Today*



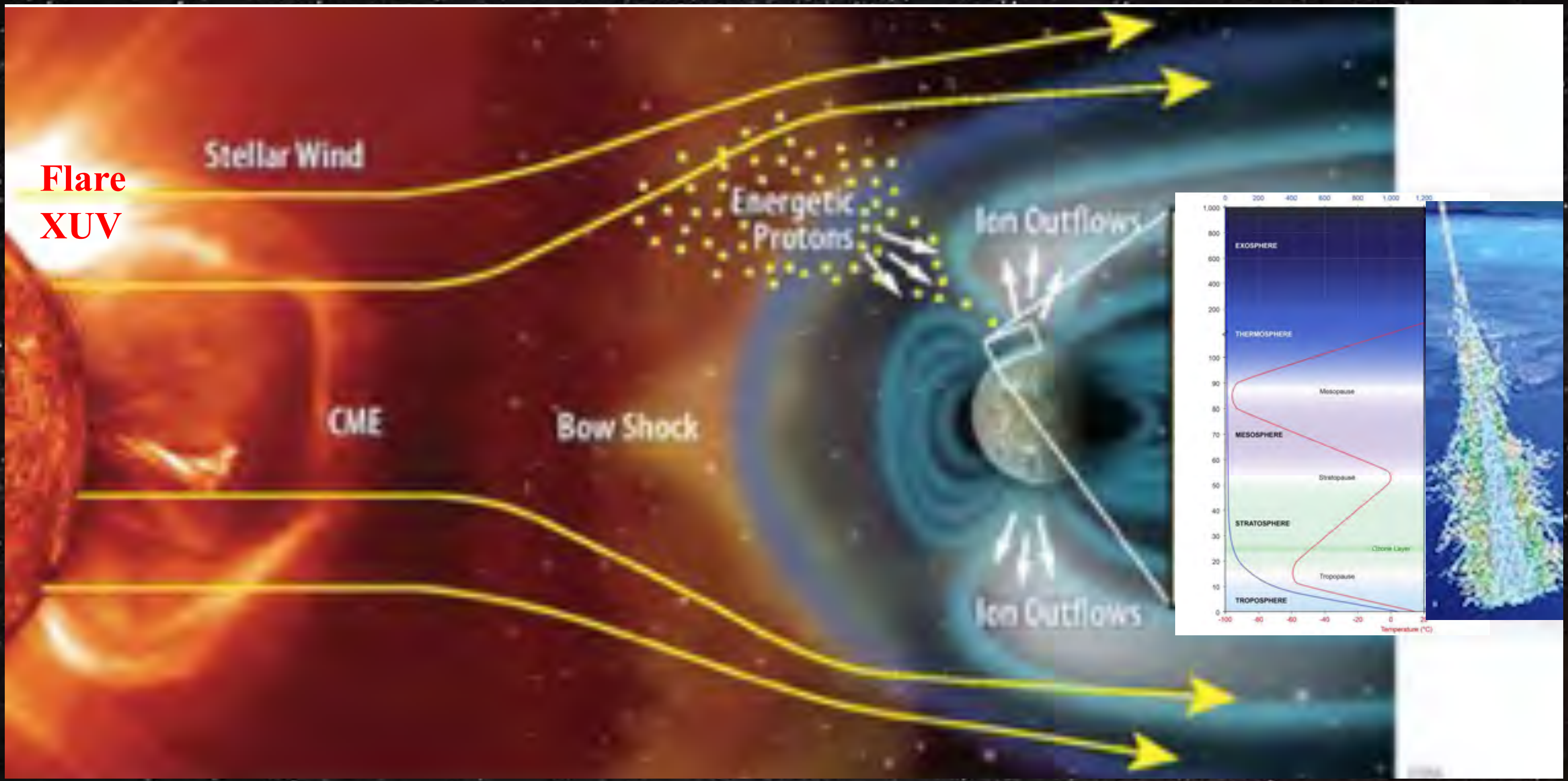
Earth Through Time: Which Version Are We Going To Search For?



Reinhard+17

Strategy:

Study Evolution of Earth-Sun Systems via Space Weather to Filter Out Uninhabitable Worlds



Review Airapetian+20, Int Journal of Astrobiology 2020

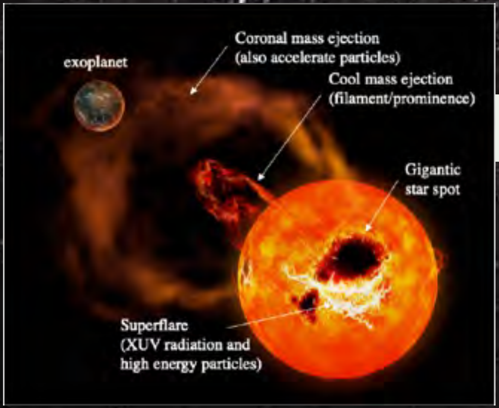
Why Do We Need to Study Stellar CMEs ?

- ***CMEs can directly affect the exoplanetary environments via escape and chemistry, and thus "habitability"***

[cf. Hazra & Vidotto+22; Airapetian+16]

- ***CMEs may affect the stellar mass/angular momentum evolution***

Driven by the development in exoplanet research, finding stellar CMEs becomes more and more important



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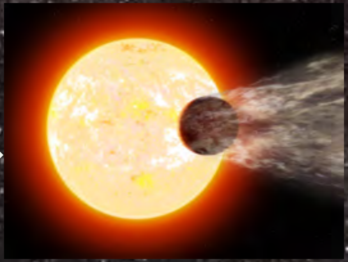
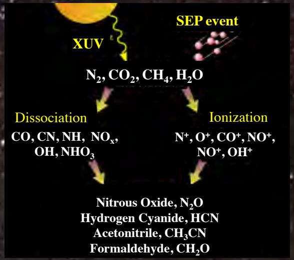
CME/SEP

Atmospheric heating/erosion



Chemistry change



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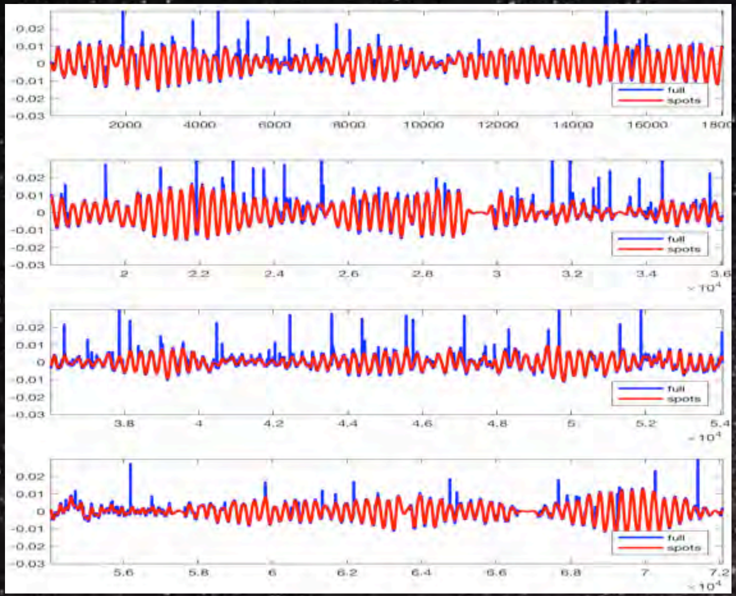
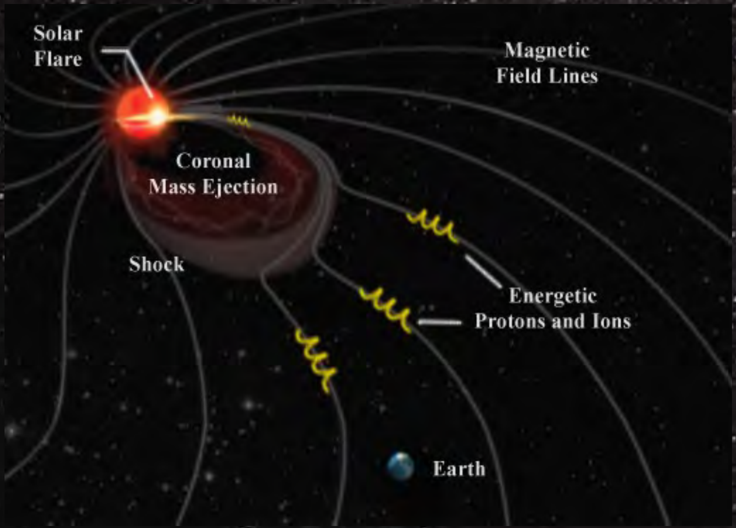
CME mass loss

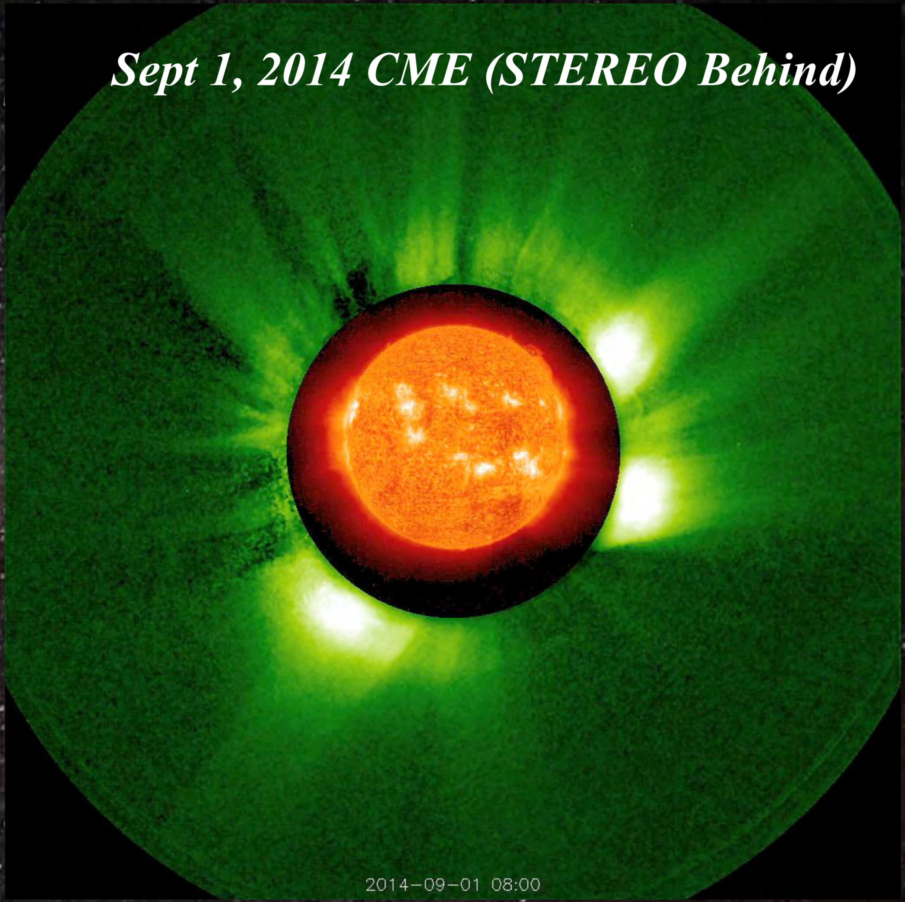
Stellar mass & angular momentum evolution

Osten & Wolk 2015

Flares, CMEs & StEPs from Young Suns

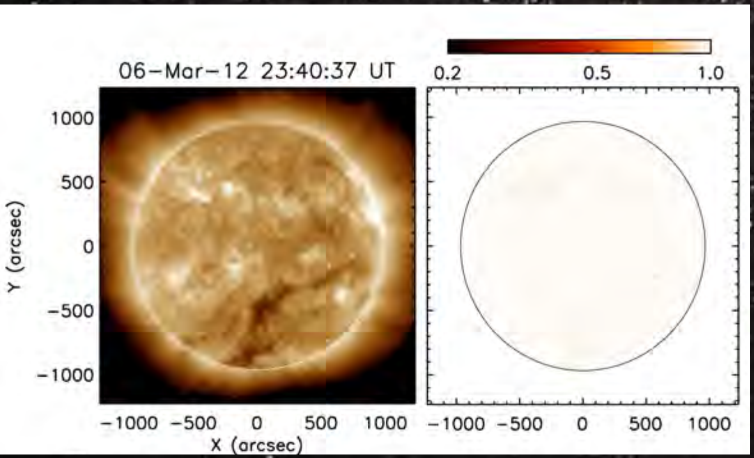




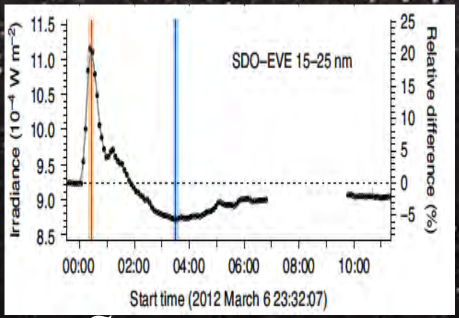


XUV dimming

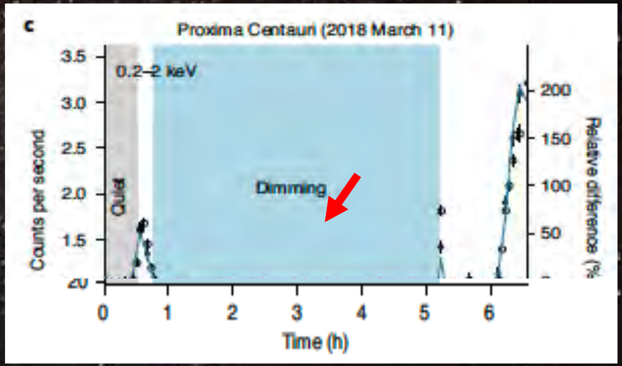
- X-ray, EUV, NUV dimming (escape of coronal material) are highly related to the occurrence of CMEs, ⇒ recently reported on active M/K-dwarfs [Veronig et al. 2021, Nat. Astron., Loyd et al. 2022].
  - So far, only ~22 events are reported
  - Advantage: high correlation between dimming and the occurrence of solar CMEs [Veronig et al. 2021]
  - ⇒ Very strong indication of stellar CMEs (based on the solar obs.)
  - Disadvantage: - May depend on the definition of quiescent stellar XUV level Note: may not necessarily indicate CME occurrence? (see, talk by Julián D. Alvarado-Gómez)



Solar EUV dimming observed by SDO



Sun-as-a-star EUV obs

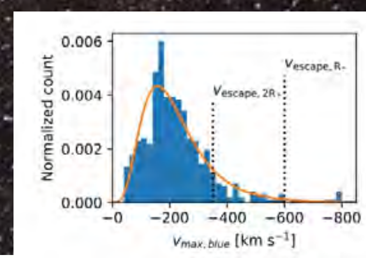


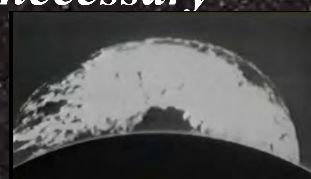
Dimming!!

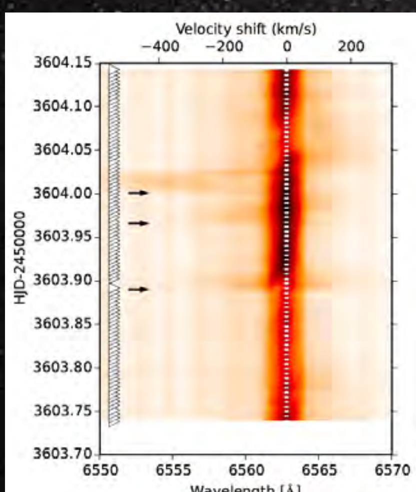
Blue-shifted Balmer/XUV lines on M/K/giant stars

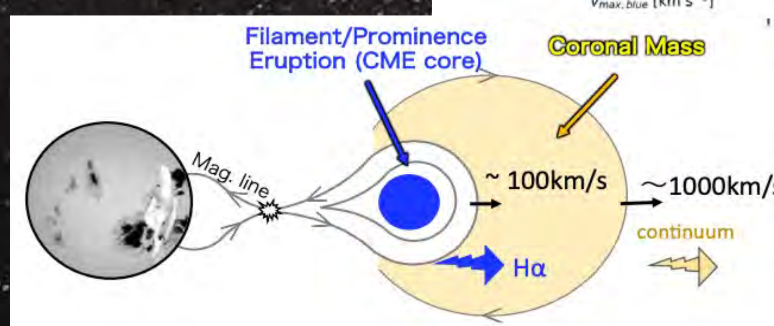
Blue-shift emission of Balmer/UV lines on M/K-dwarfs are promising detections of “prominence eruption”[Houdebine+1990, Vida+16, 19, Leitzinger+14, Honda+18, Maehara+21, and more!!]

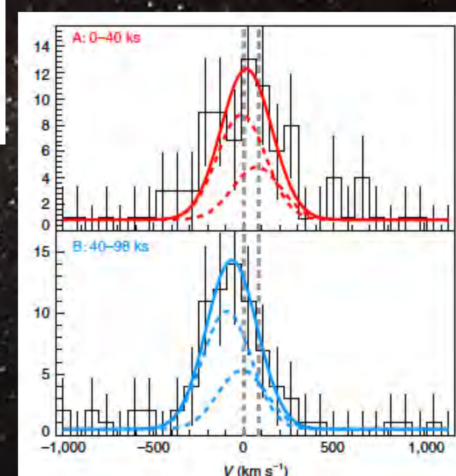
- *Advantage: relatively easy to detect from ground-based observations (> 200 candidates; Leitzinger et al.)*
- *Disadvantage: Only “emission” profile → sometimes difficult to distinguish from “flare” radiations (evaporations)*
  - *Just <u>a lower-part of CMEs</u> & <u>LOS velocity</u>*
  - *Can we infer CME occurrence only from H-alpha obs? → numerical work/solar obs. is necessary*



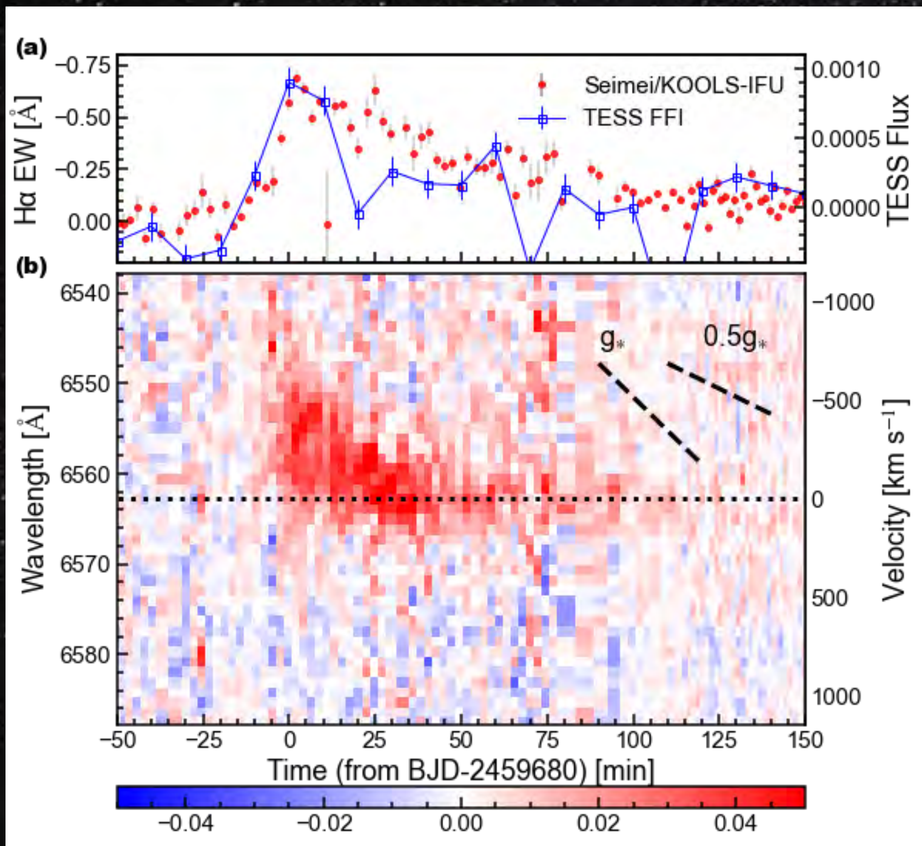


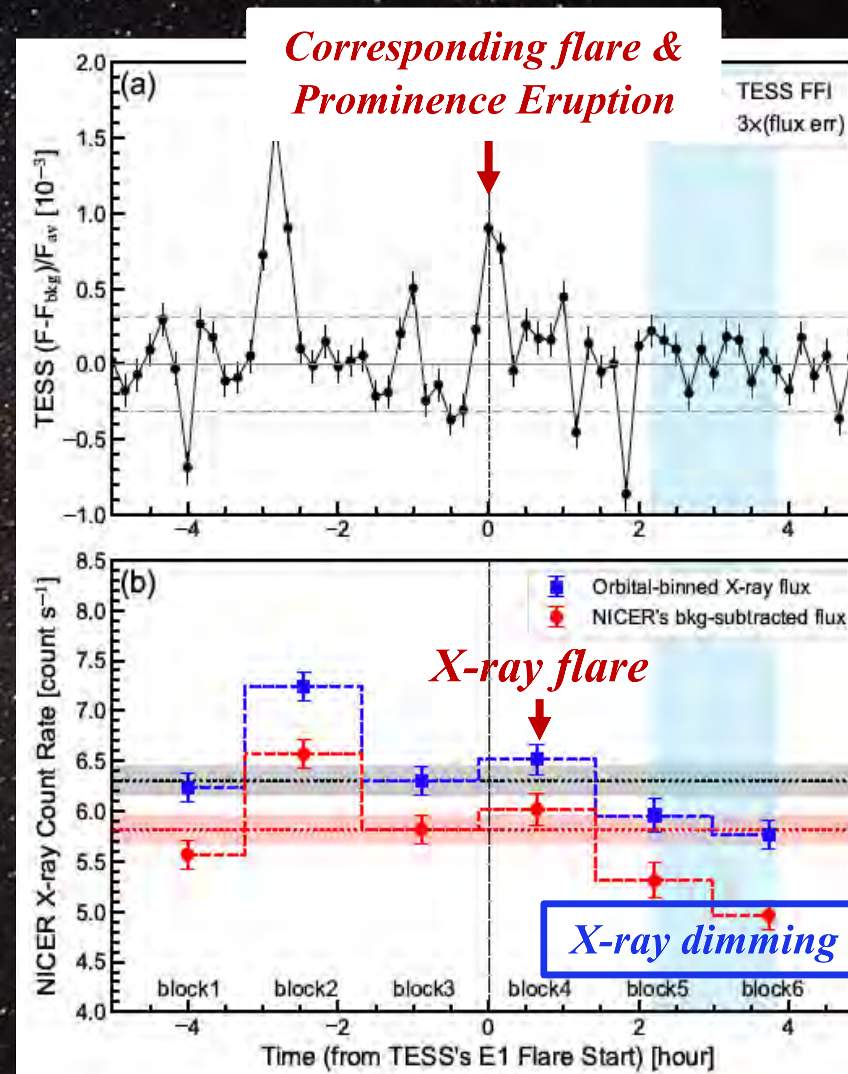






Searching for SW Around Other Suns: Blue-shifted Hα and X-ray dimming as CME signatures on EK Dra

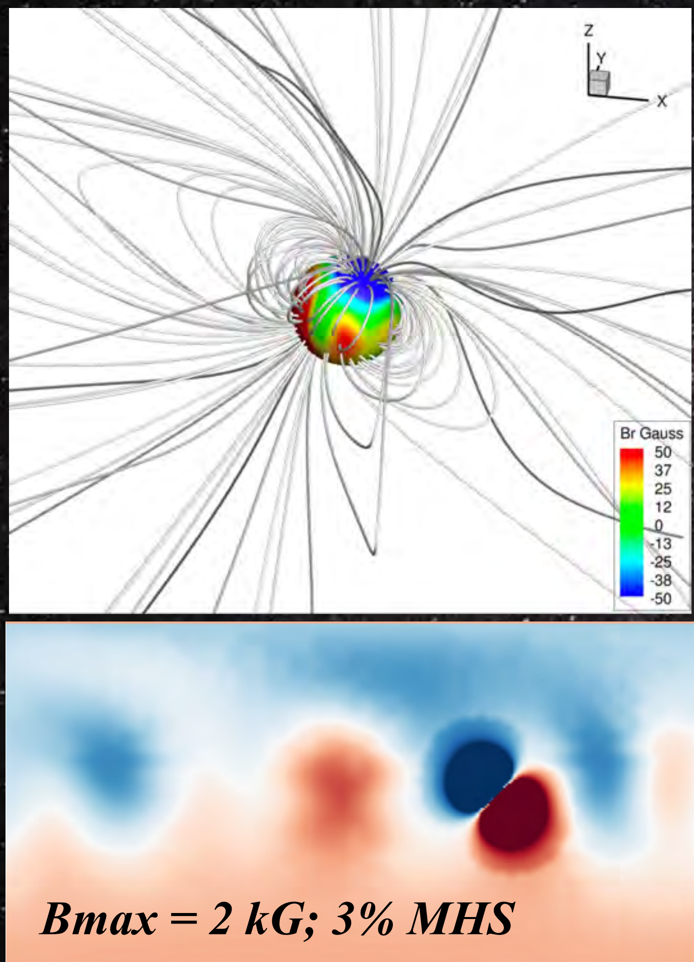




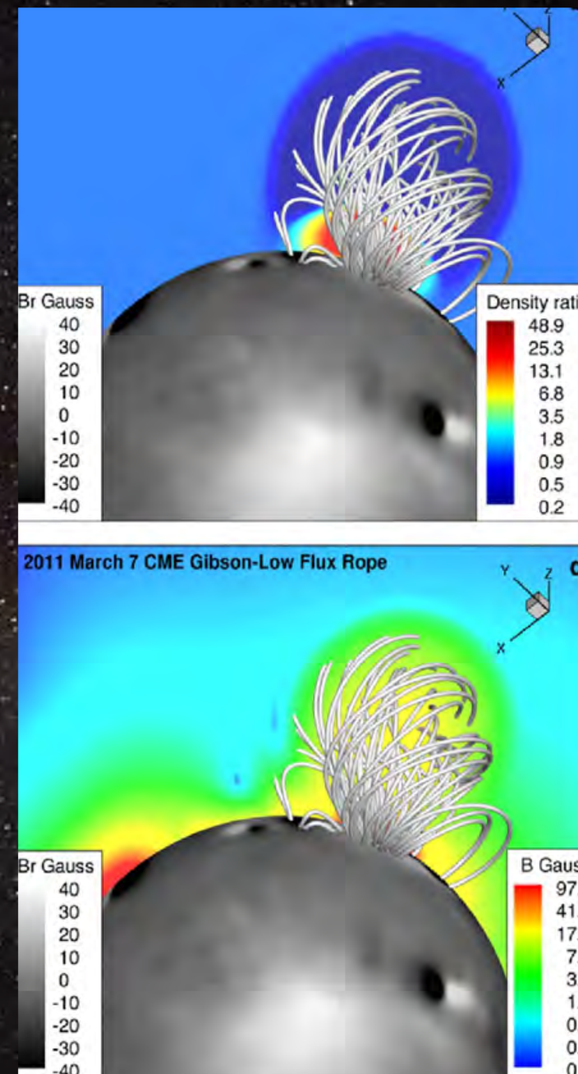
Namekata, Airapetian.. Notsu+23

3D MHD AWSoM Model: Magnetic Flux Rope

ZDI magnetogram and a bipolar AR

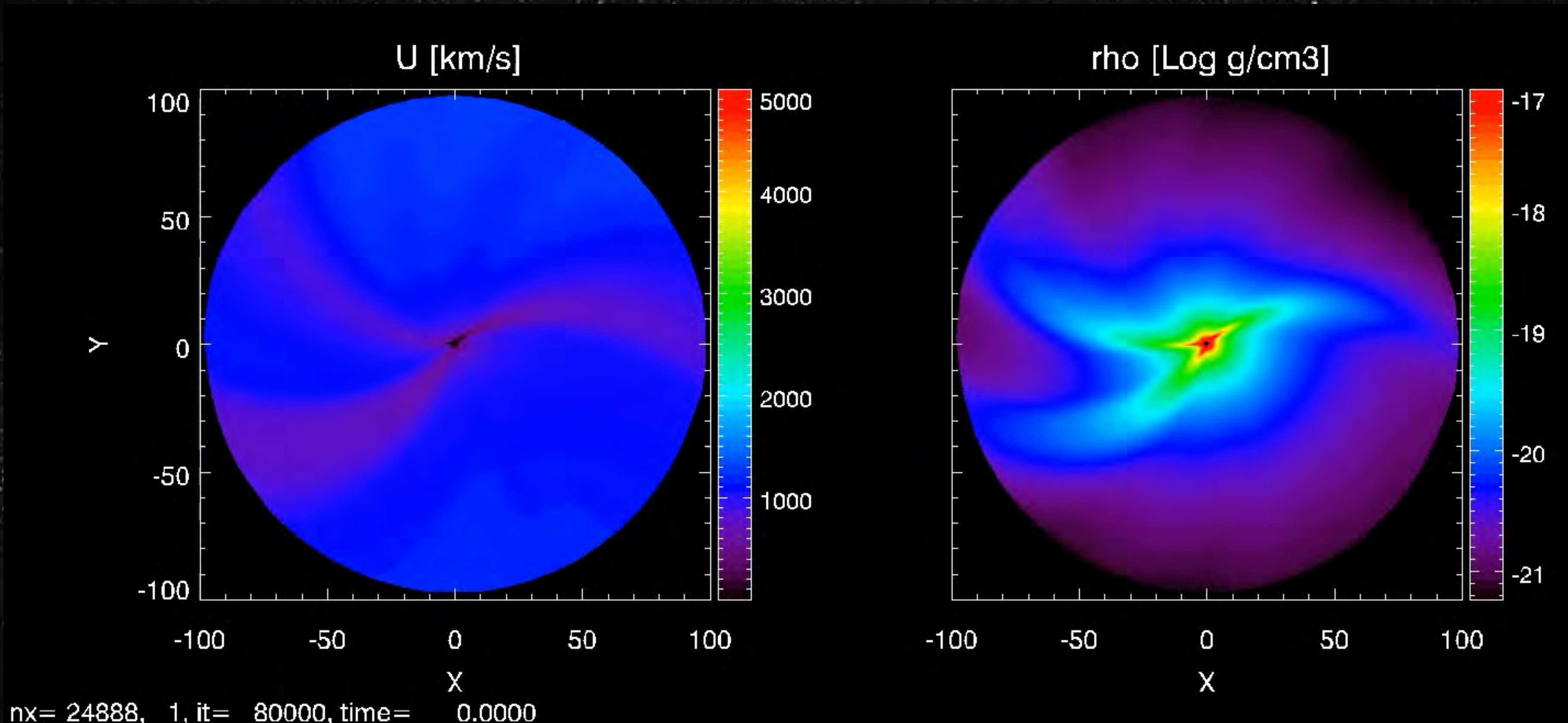


Twisted unstable magnetic flux, 2 x 10^{34} erg



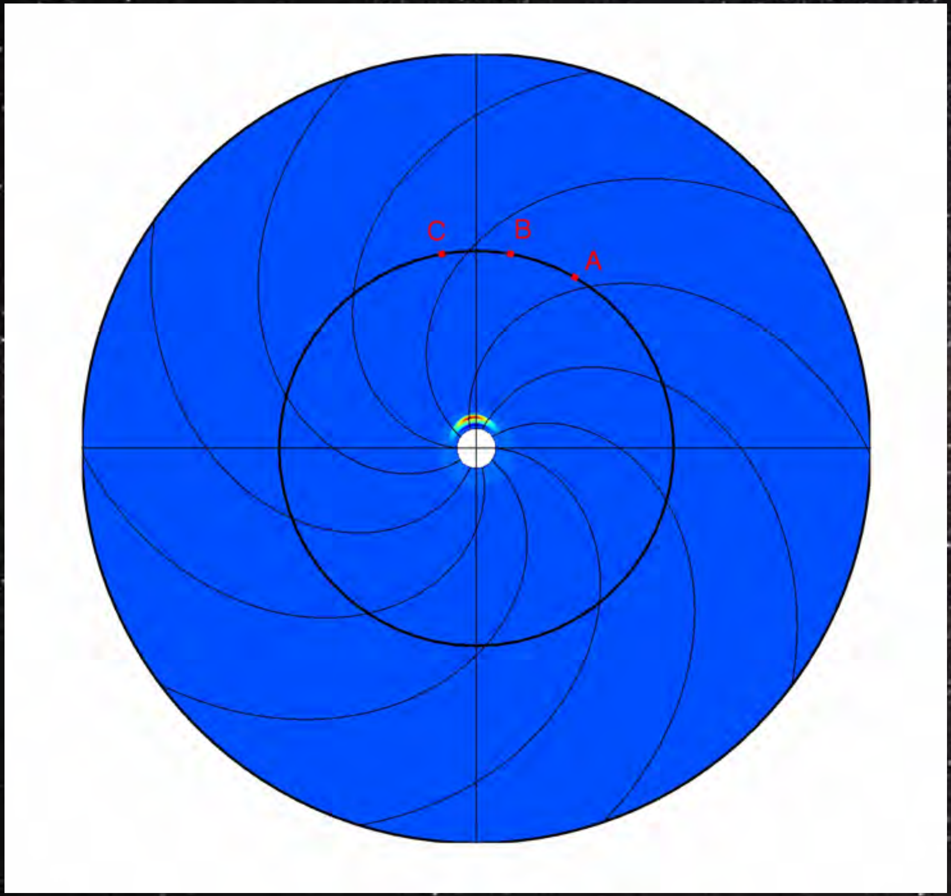
Ejected Flux Rope - Stellar CME shocks

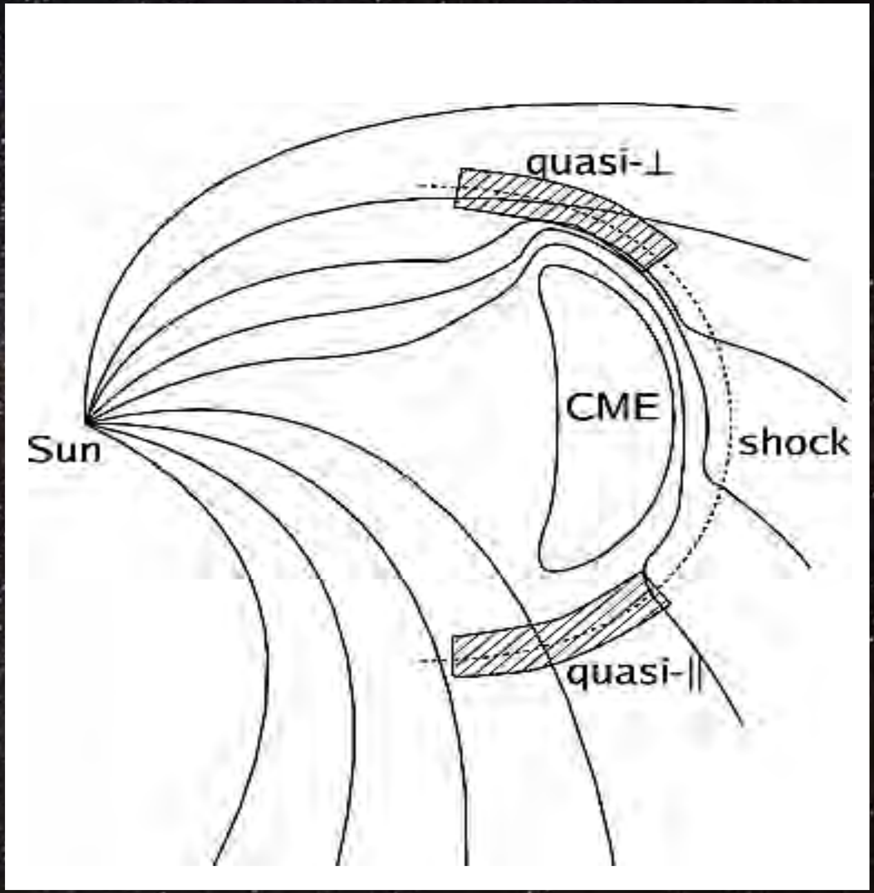
Jin, Hu, Airapetian in progress+23



- *We use the AWSoM to model initiation & propagation of a stellar CME*
- *6 hr CME simulation in the coronal region, 2013.9 epoch*
- *Flux rope energy is ~2.7x10^{34} ergs, CME speed is ~5000 km/s at t=30 min*
- *CME shock data used as input for the particle acceleration model (iPATH)*

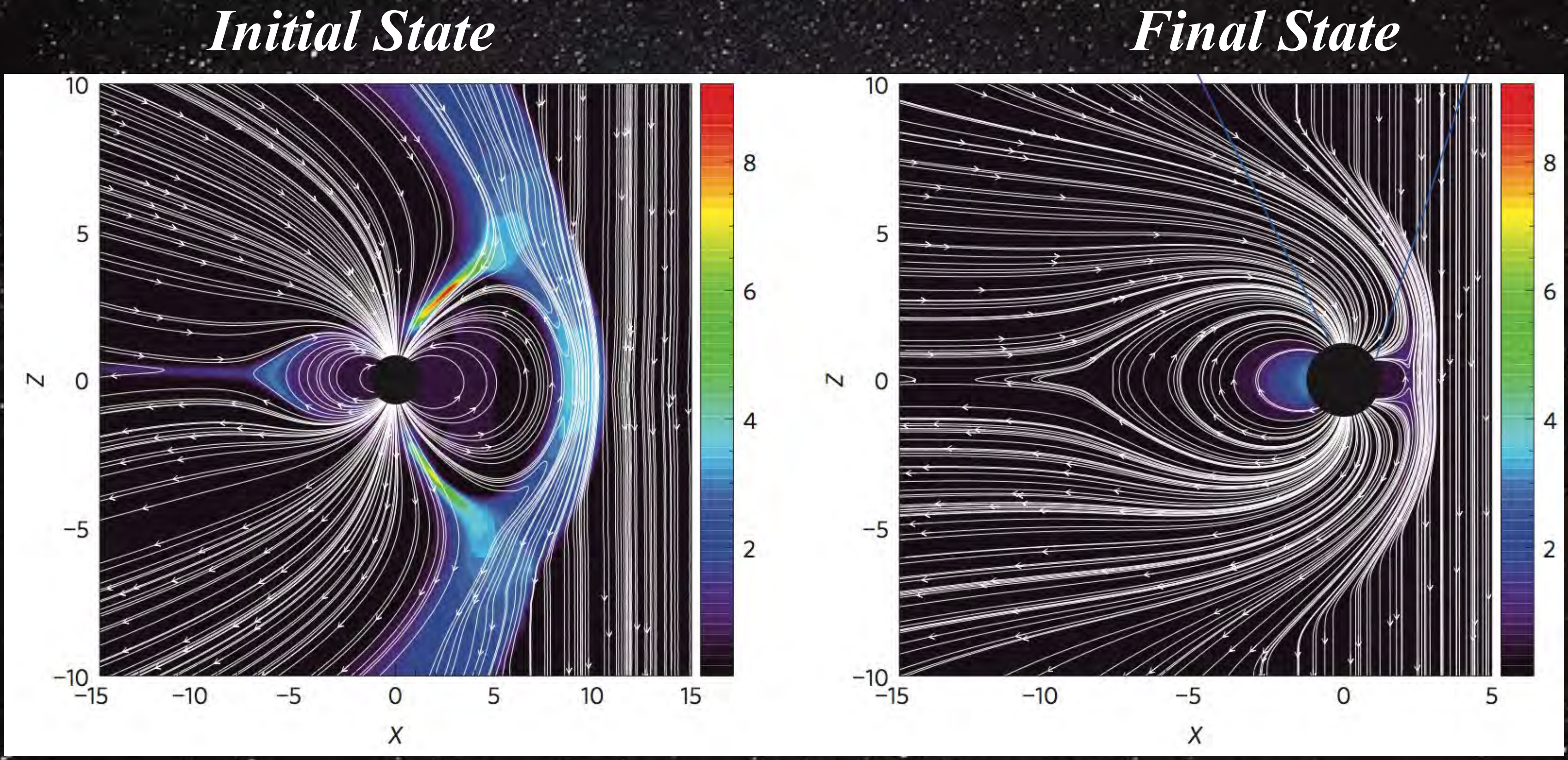
CME shocks as the source of accelerated particles



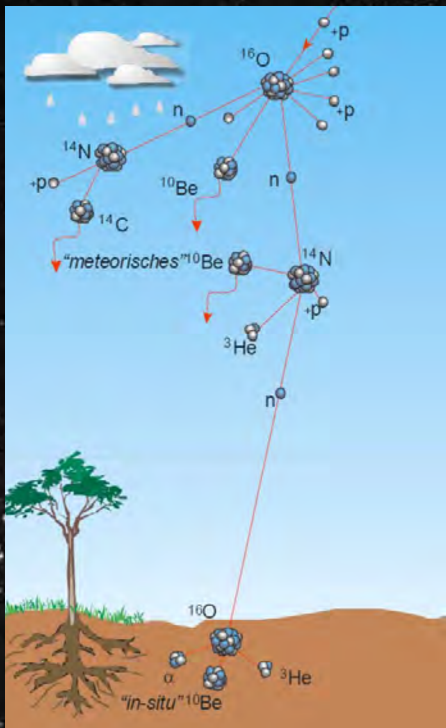


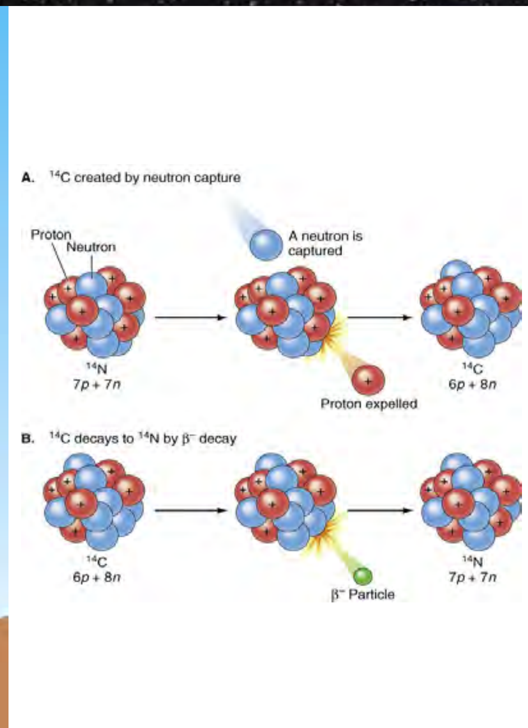
CMEs Compressed Early Earth Magnetosphere opening up 70% of the magnetic field

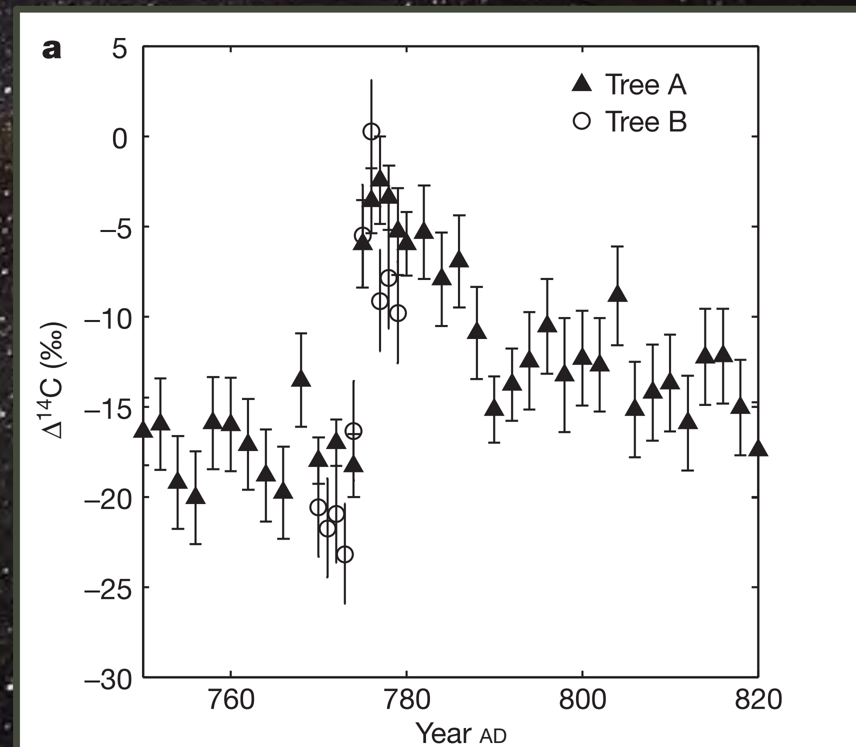
Airapetian et al. 2016, Nat Geoscience



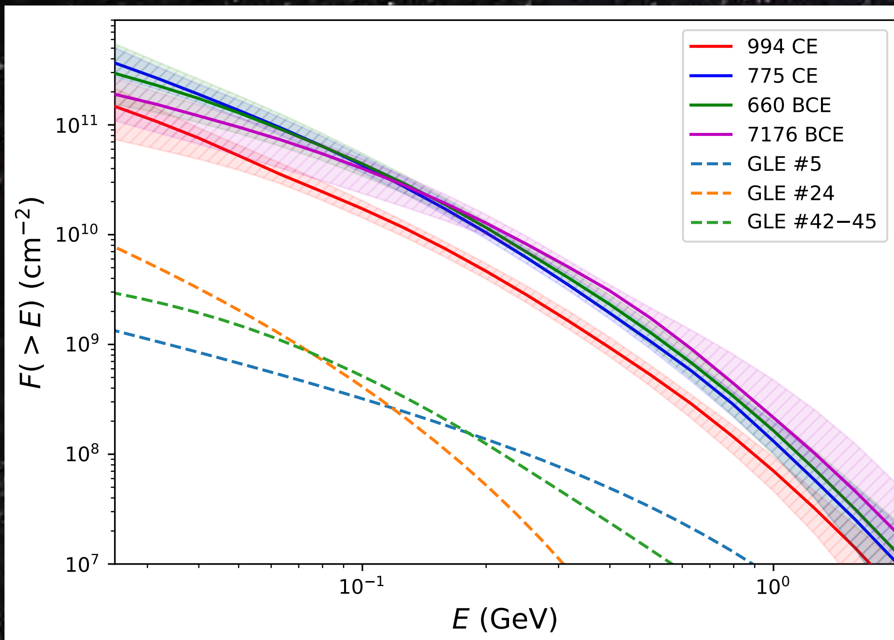
Solar Superflare of 775AD via Cosmogenic Isotopes as a Proxy of Stellar Superflares



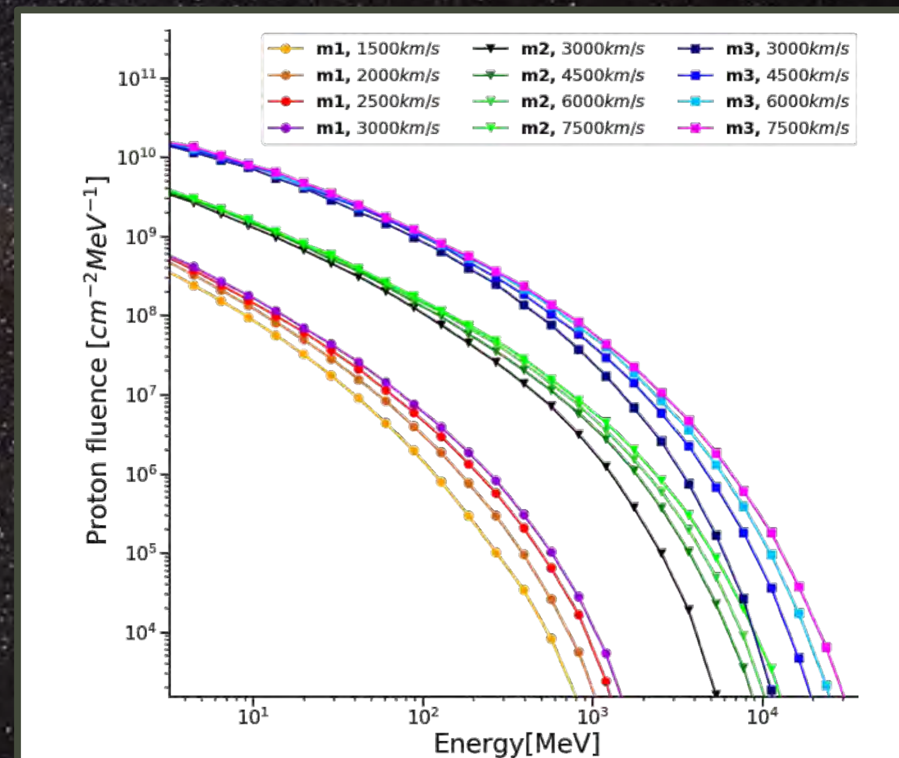




SEP Energy Spectra of Solar and Stellar Superflares



Koldobskiy++23



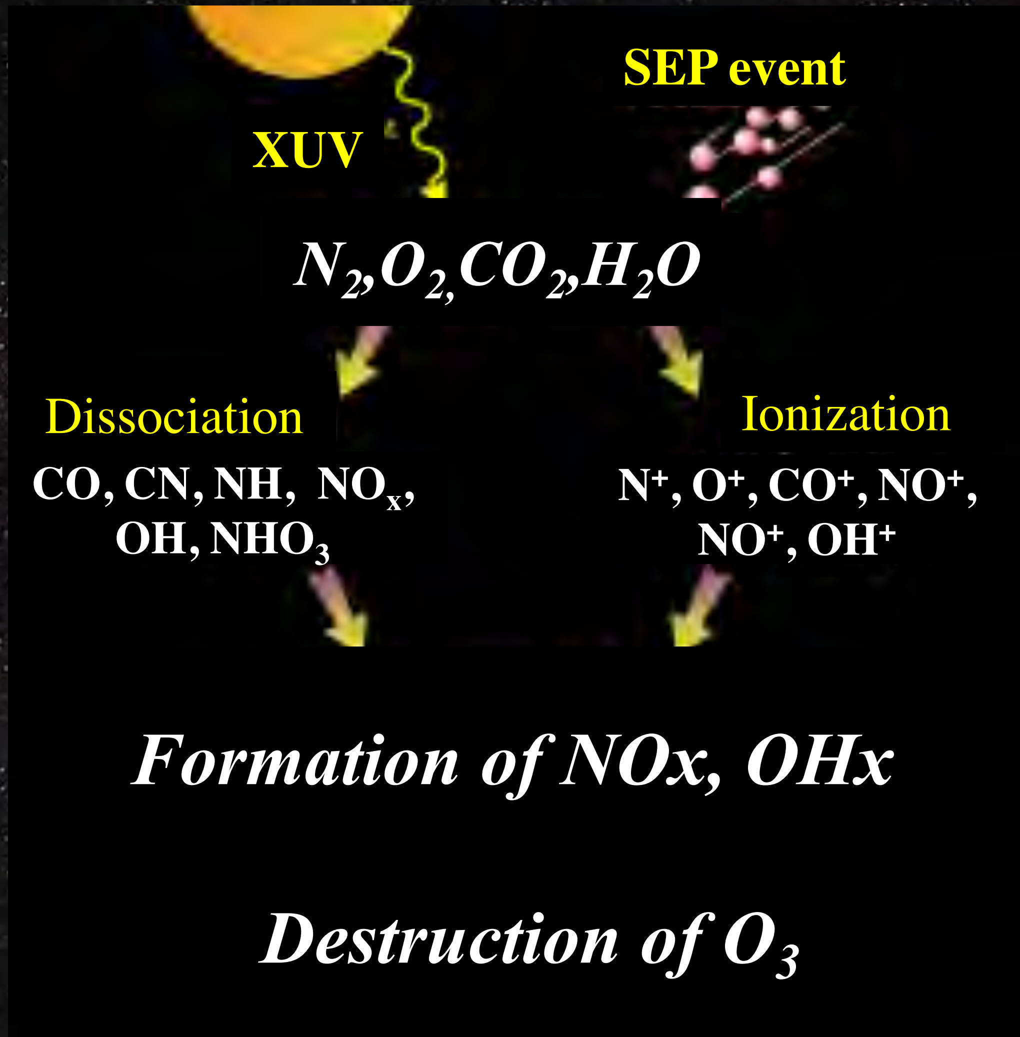
Hu, Airapetian+23

3D GM + WACCM Model of 775AD CME&SEP Impact

Airapetian, Chen+23

- *Use SEP energy spectrum as Input for WACCM code*
- *High Top (0-150 km) version of the Community Earth System Model v1.2 (NCAR, Neal+10; Marsh+15)*
- *Fluid dynamics and thermodynamics eqs with self-consistent coupling of dynamics, chemistry, radiation.*
- *Horizontal resolutions of 1.9° x 2. 5°*
- *The vertical domain extends (145 km) with 66 levels.*
- *The vertical resolution is between 0.5 and 2 km in the troposphere and stratosphere (~0.5 H above the stratosphere).*
- *All simulations are integrated for at least 2 Earth years.*
- *Protons are injected at latitudes (>60^0) across longitudes,*

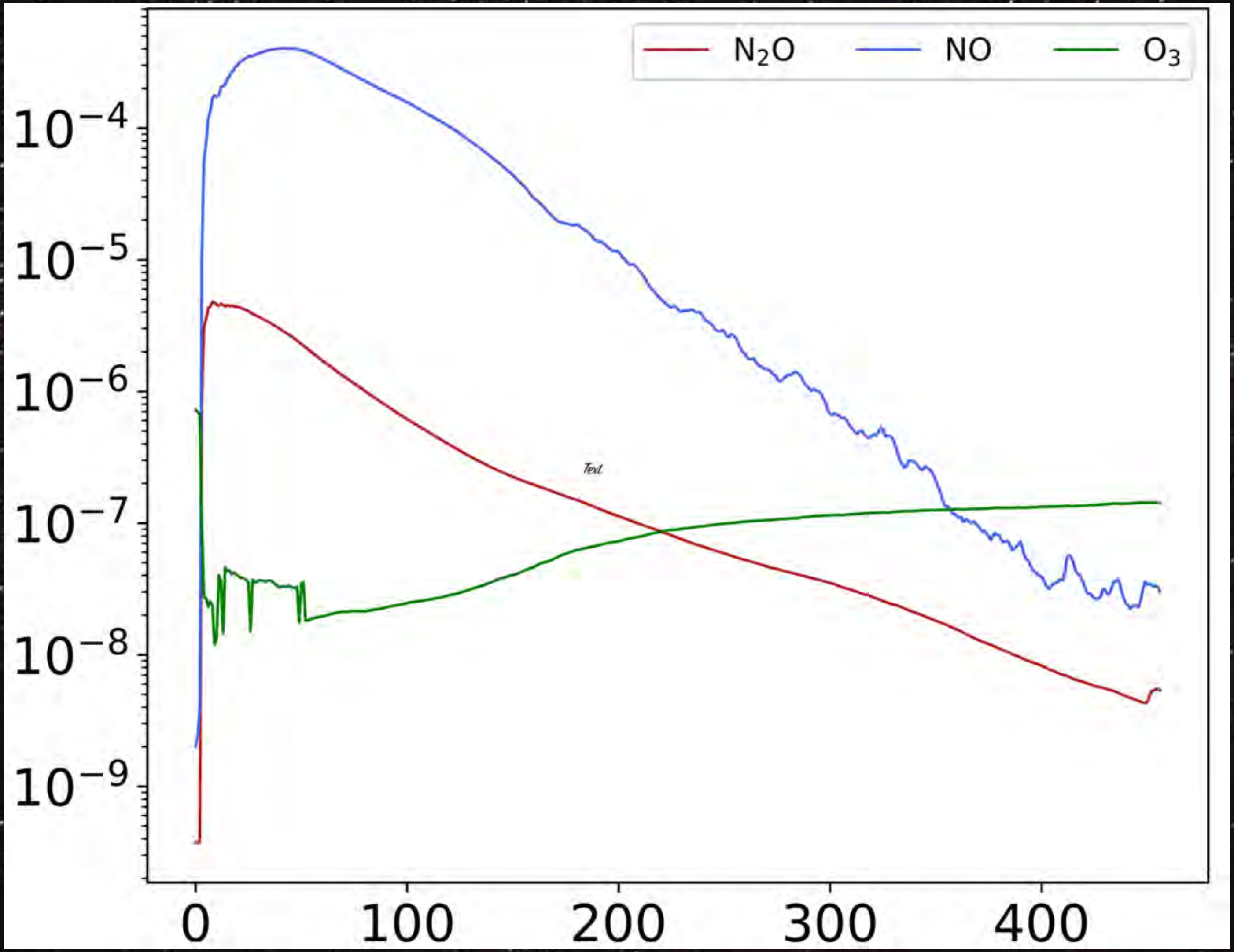
SW Driven Chemistry



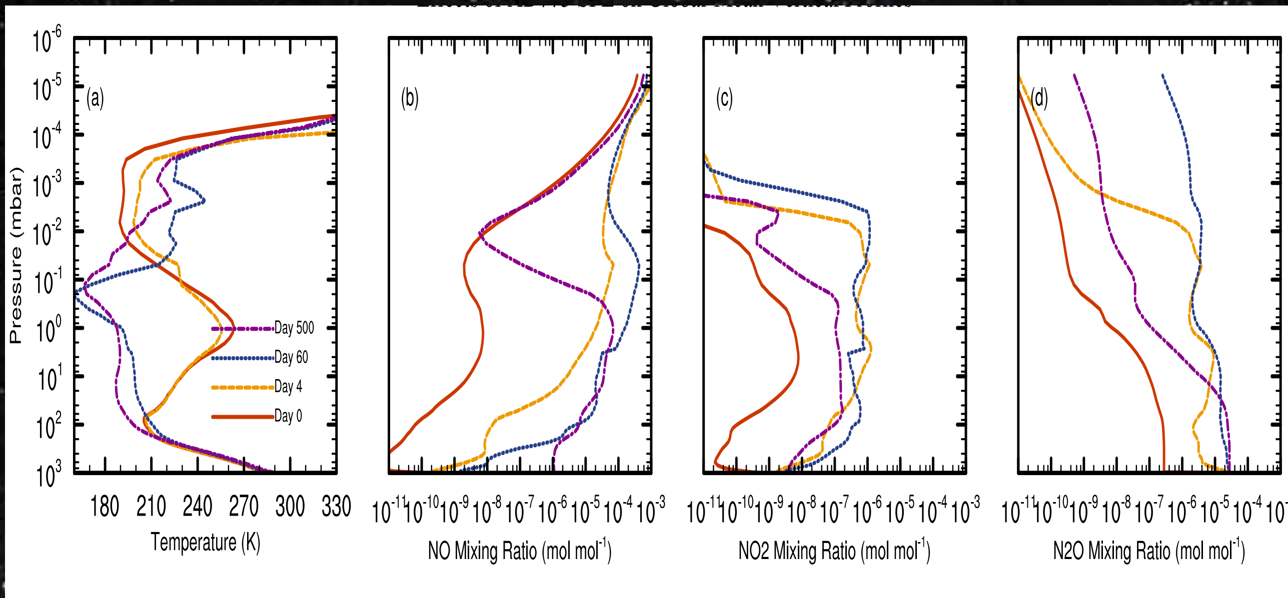
Destroyed O_3, Formed: N_2O, NO_2

Signatures of Photosynthetic Biosphere vis Superflares

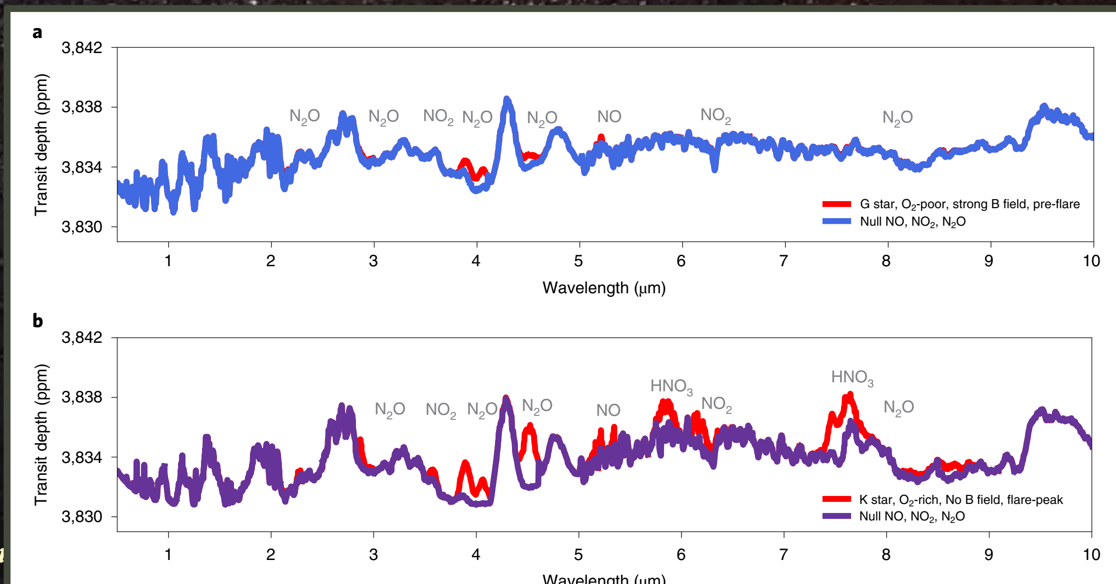
1 bar (0.7 N_2 -0.2 O_2) Airapetian, Chen+23



Global-Mean Vertical Profiles and IR spectra

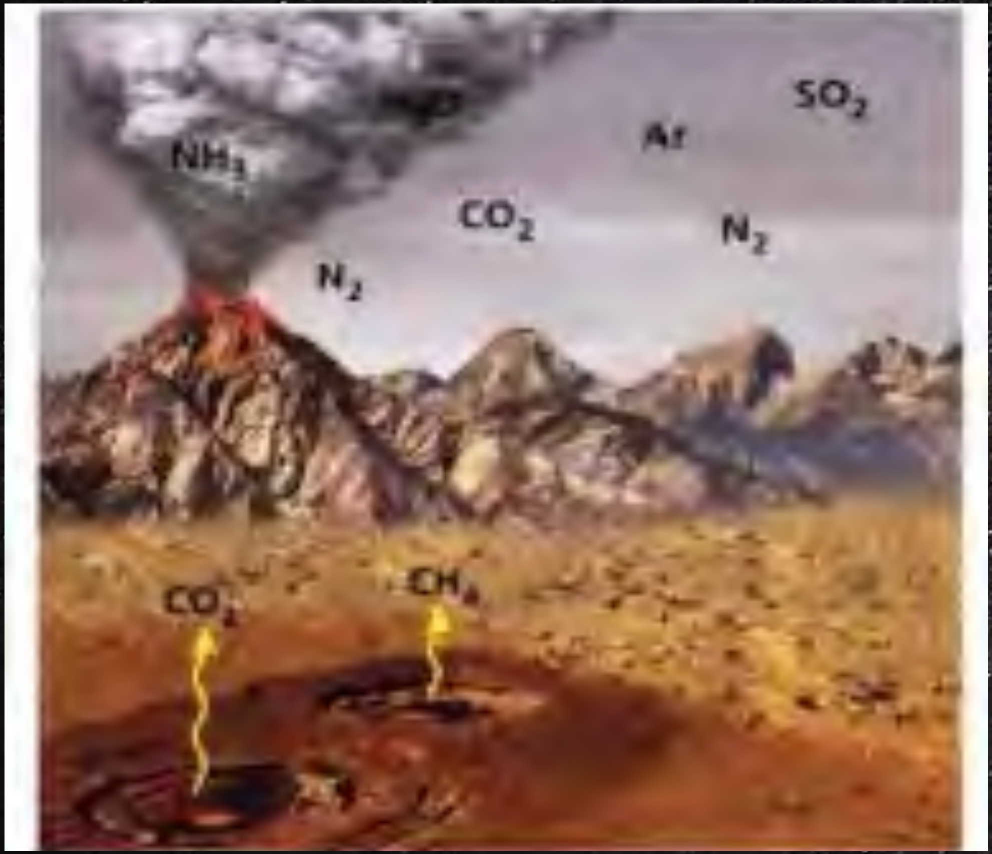


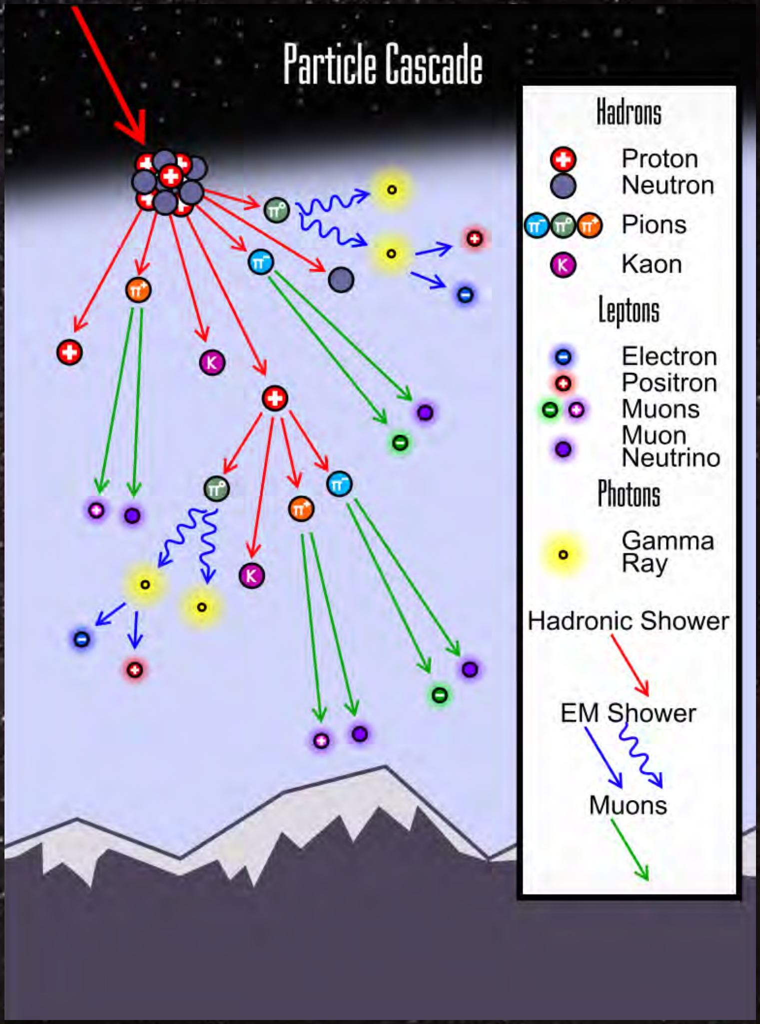
Airapetian+23, in prep



Chen+21

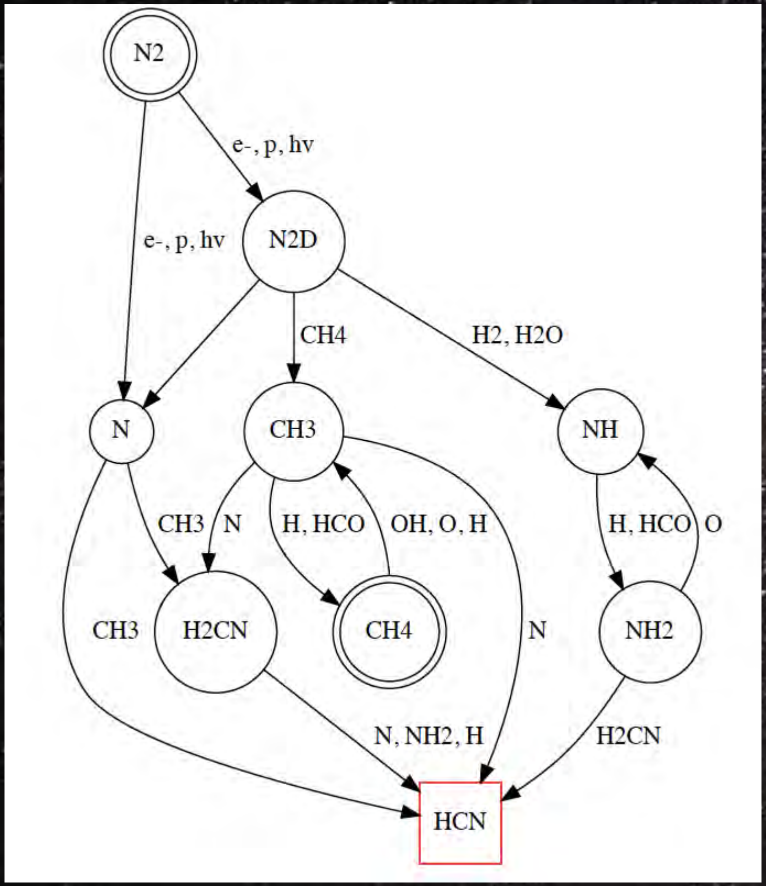
Impact of SEPs on Young Volcanic Earth and rocky exoplanets

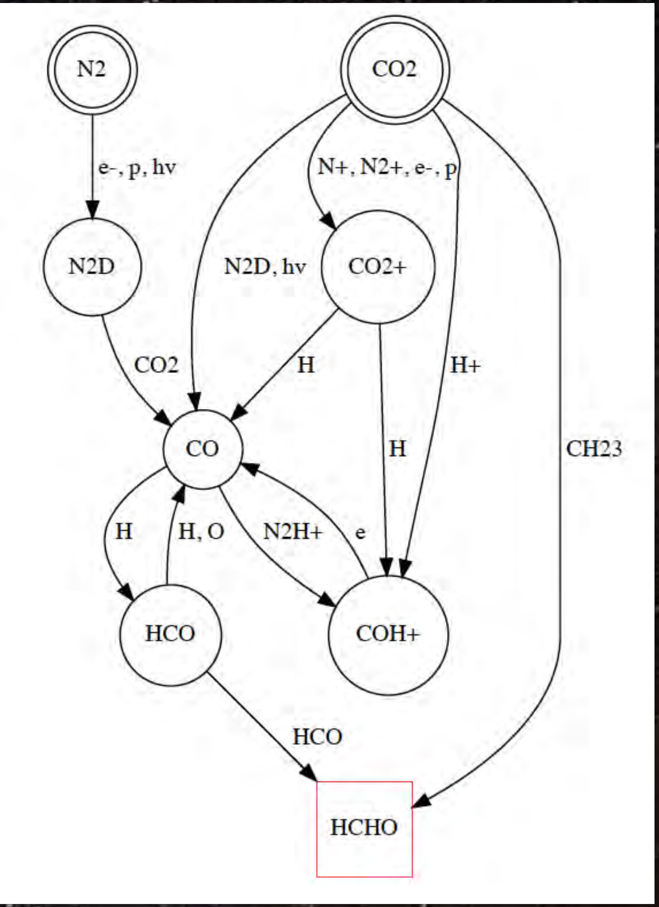




Hydrogen cyanide and Formaldehyde in early Earth's atmosphere

1 bar (0.8 N_2, 0.2 CO_2) Hayworth+2023

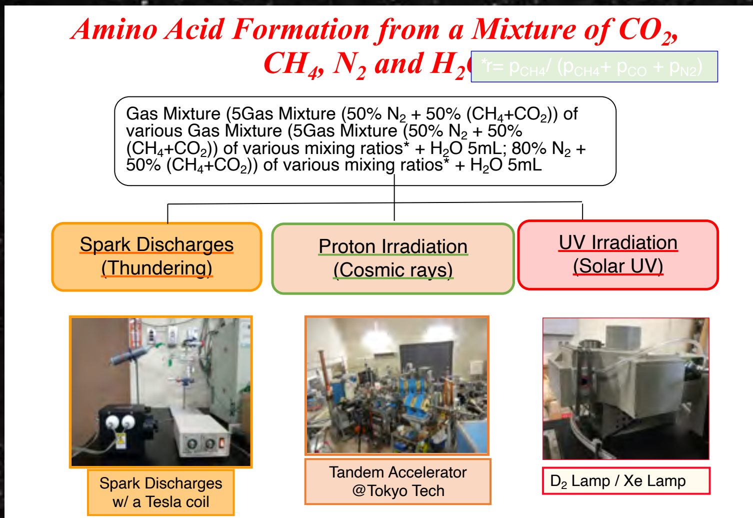


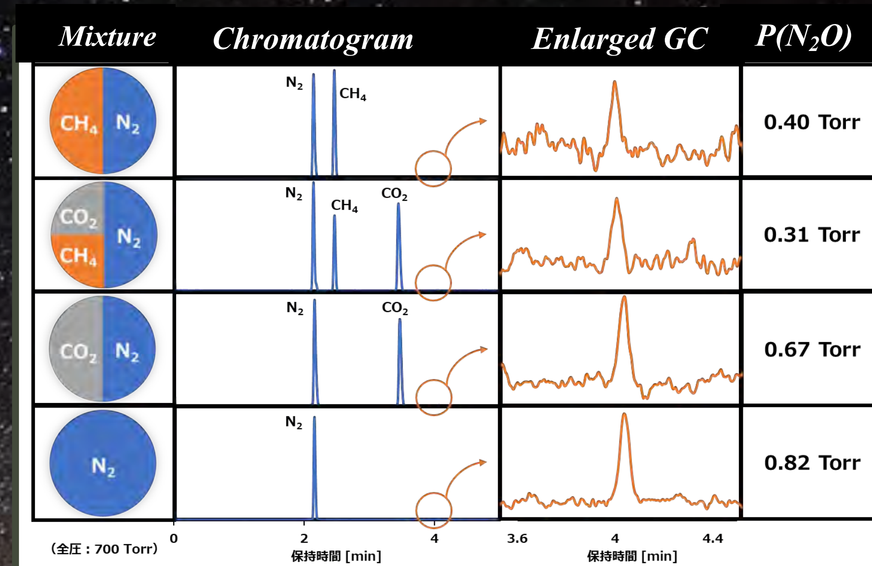


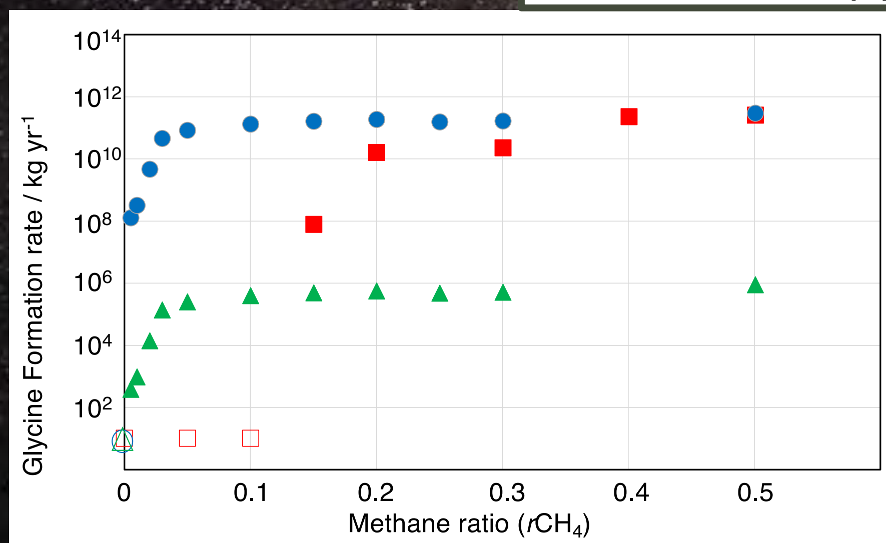
Flux before SEP: ~1.2 x 10^2 mol/cm^2/s
After SEP: ~6.2 x 10^8 mol/cm$^{2/}$s

Flux Before SEP: ~7.4 x 10^7 mol/cm^2/s
After SEP: ~2.0 x 10^{11} molecules/cm^2

Laboratory Experiments at Tokyo Tech

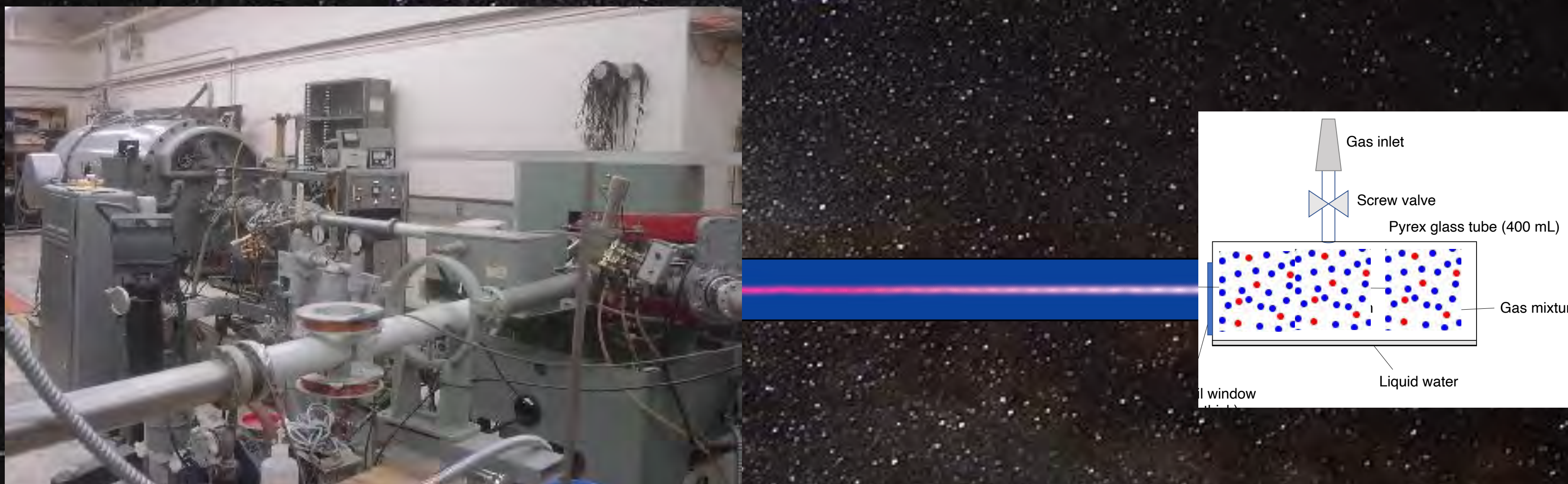






Kobayashi, Airapetian+32

ExoPlanetary Particle Irradiation Chemistry (EPIC) Lab at NASA GSFC



4th Jack Eddy Symposium, Oct 29- Nov 3, 2023

Conclusions

- ***Need to understand the evolution of (exo)planetary habitable state via star-planet interaction with SW***
- ***CME- & CIR-driven SEPs supply free energy to initiate a chain of reactive chemistry***
- ***Photo-collisional chemistry produce pre-biosignatures - N_2O, powerful GH gas, NO_2 , HCN, CH_2O, the precursors of RNA and DNA***
- ***EPIC Project for Experimental Irradiation Facility to Study Pre-biosignatures of Young Rocky Exoplanets***

Thank You For Your Attention!