Transient Mass Loss in Active Stars and Observation Methods

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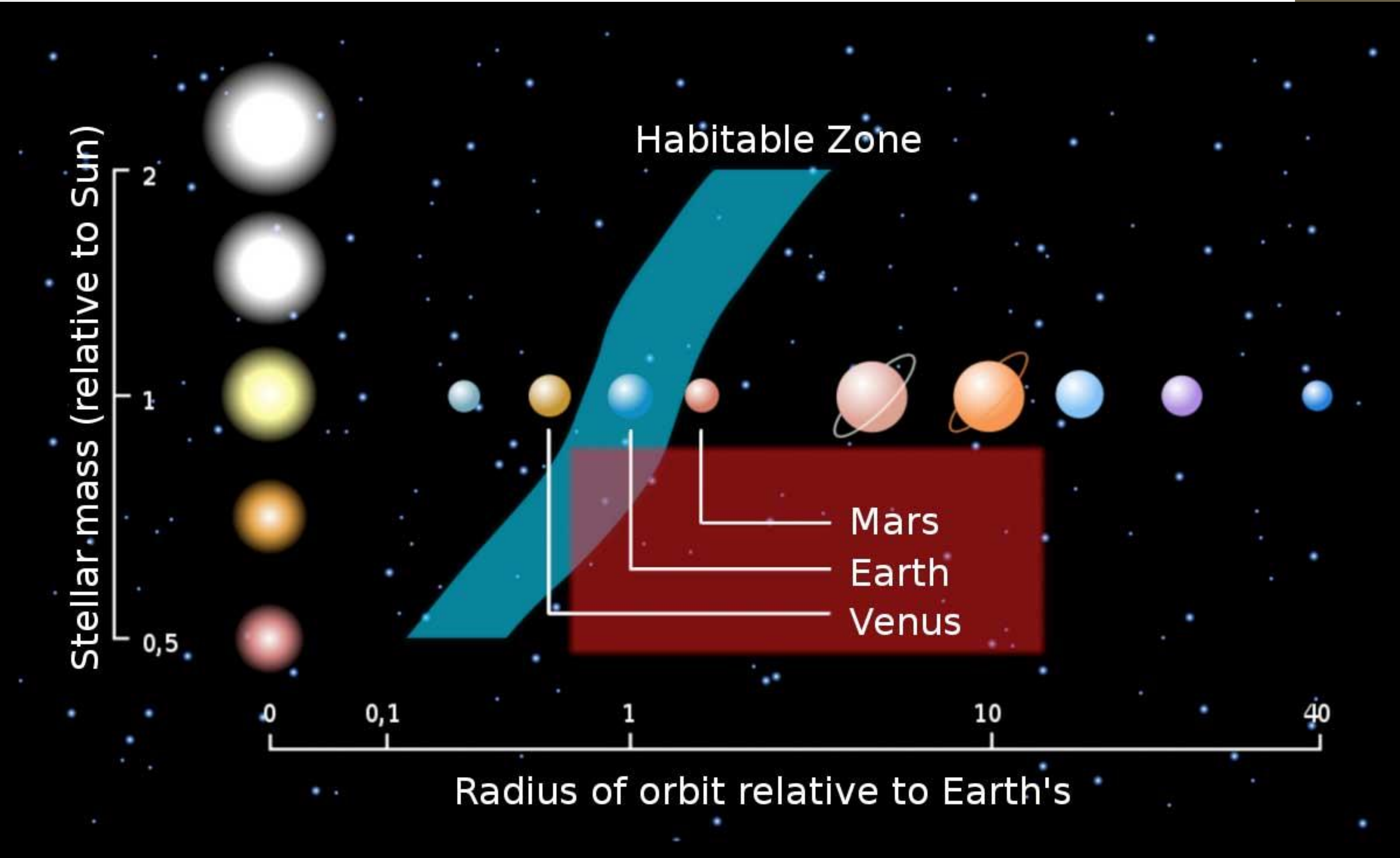
Outline

- Exoplanets and Habitability Concerns
- Coronal Mass Ejections
  - Traditional Detection Methods
  - CME-Flare and Solar-Stellar Connections
- Type II Radio Burst
  - Solar Example
  - Modeling and concerns
- Pretend the Sun is a Star
  - Multi-wavelength analysis and initial results
- LOFAR
  - Results and Additional Considerations

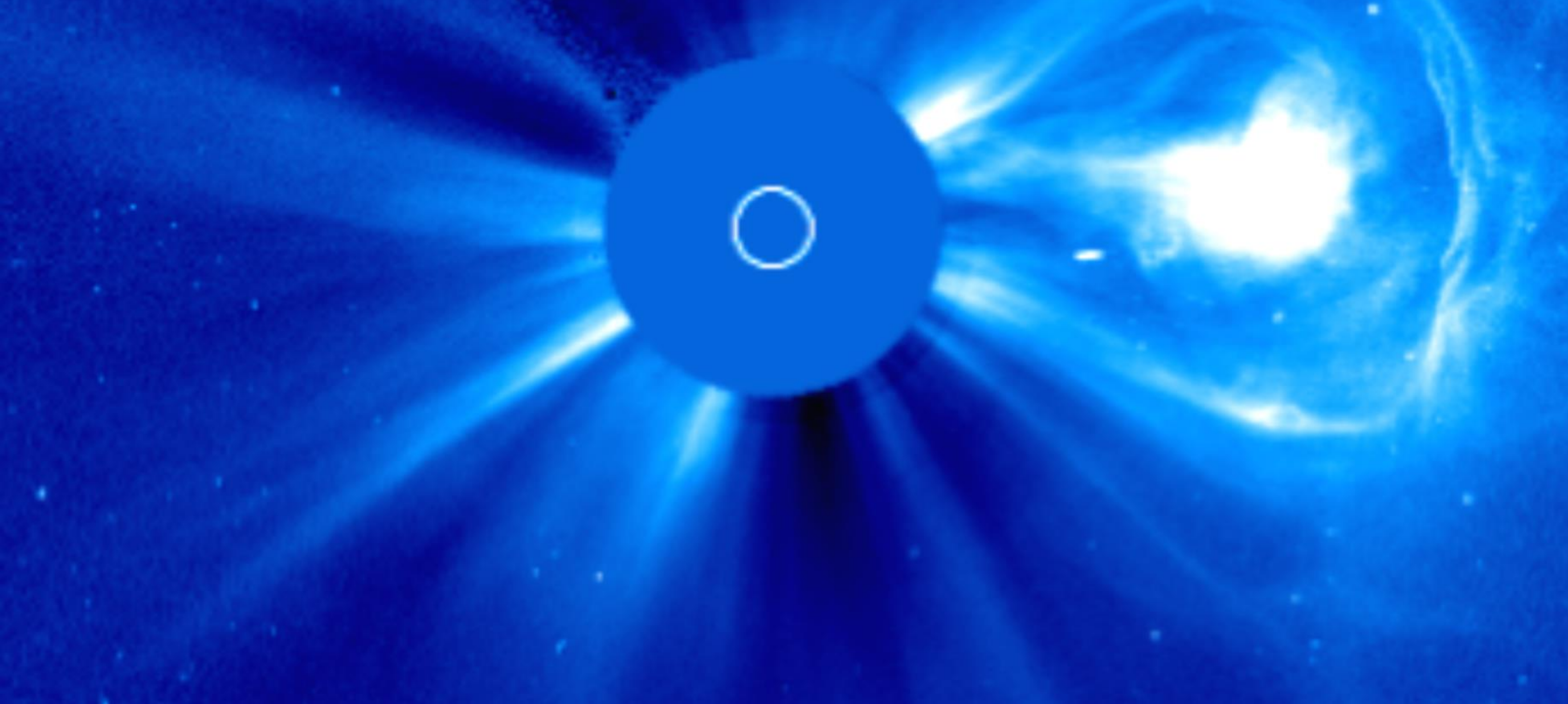
Habitable Zone



Coronal Mass Ejections (CME)

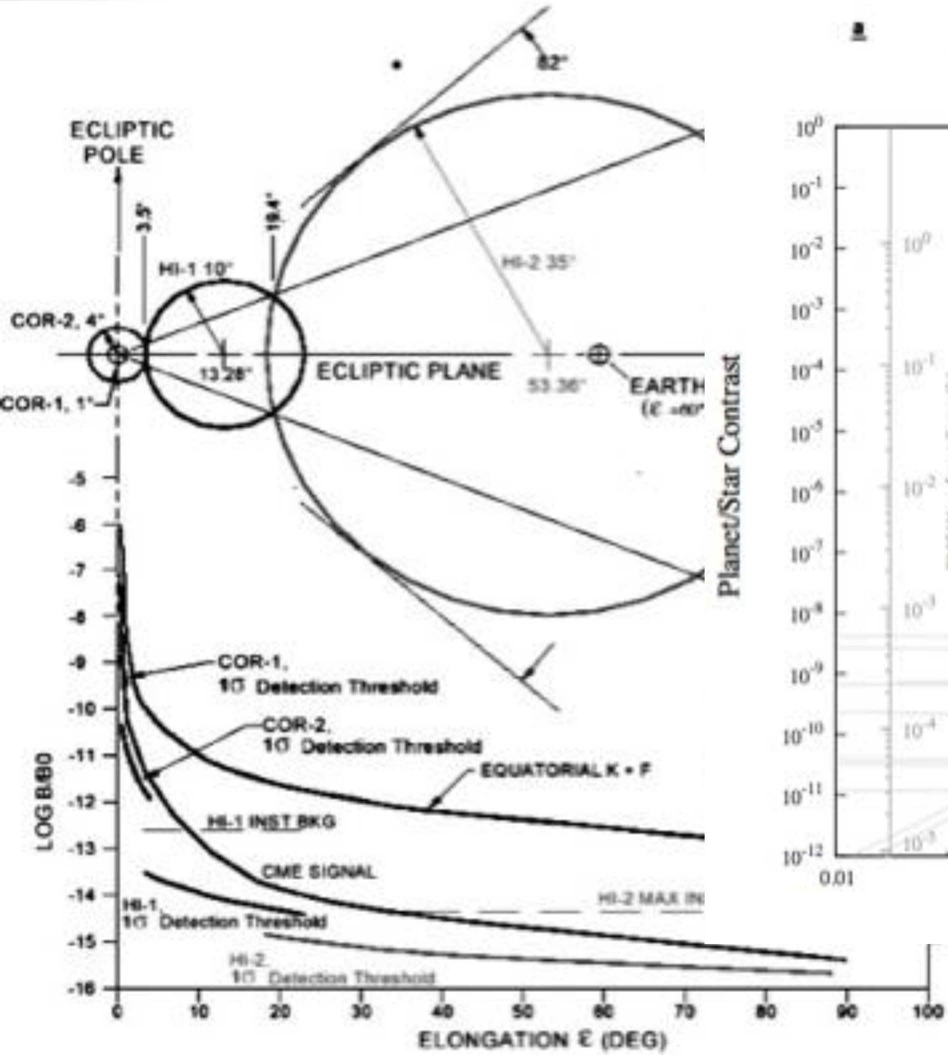
LASCO C3 (4-30 $R_{\odot}$) Image of a solar CME

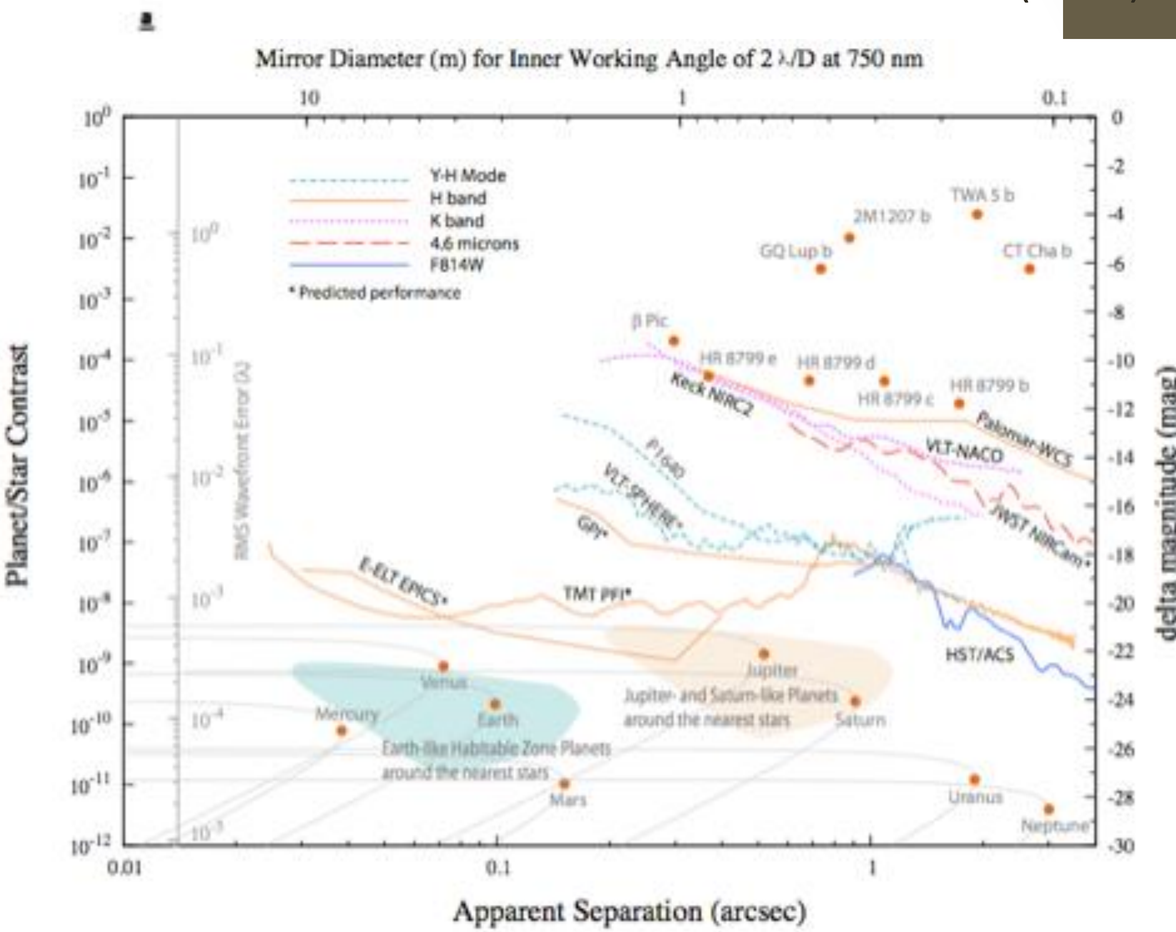
- $M > 10^{13}$ kg
- V ~ 100 – 3000 km/s
- 1-5 times a day



Solar vs. Astronomical Coronagraphs

Mawet et al. (2012)





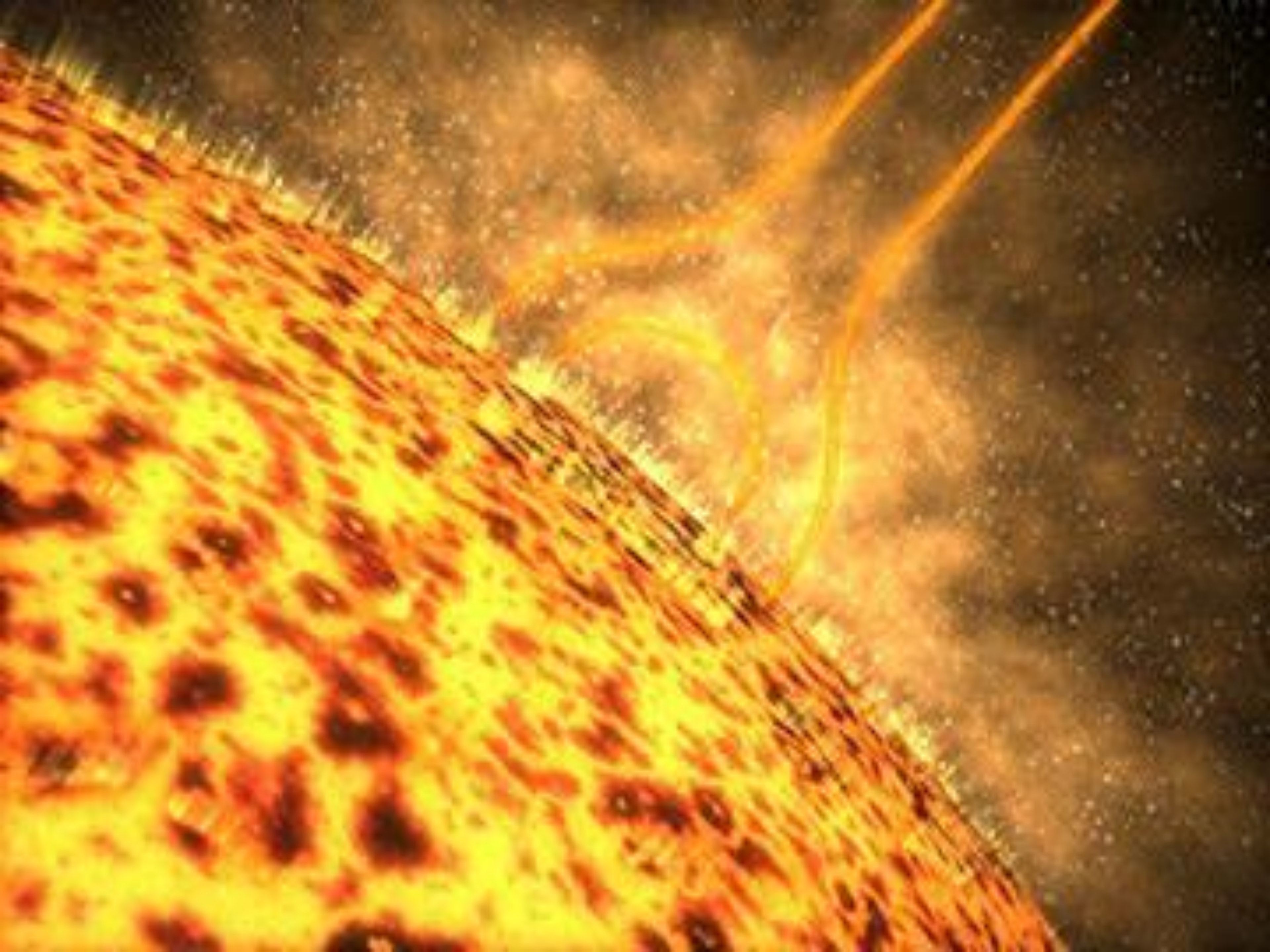
Stellar CME at 2 R_* at 5 pc:
Separation of 0.5 mas = 0.0005 as.

Harrison et al. (2005) specs for STEREO coronagraphs

Eruptive Events

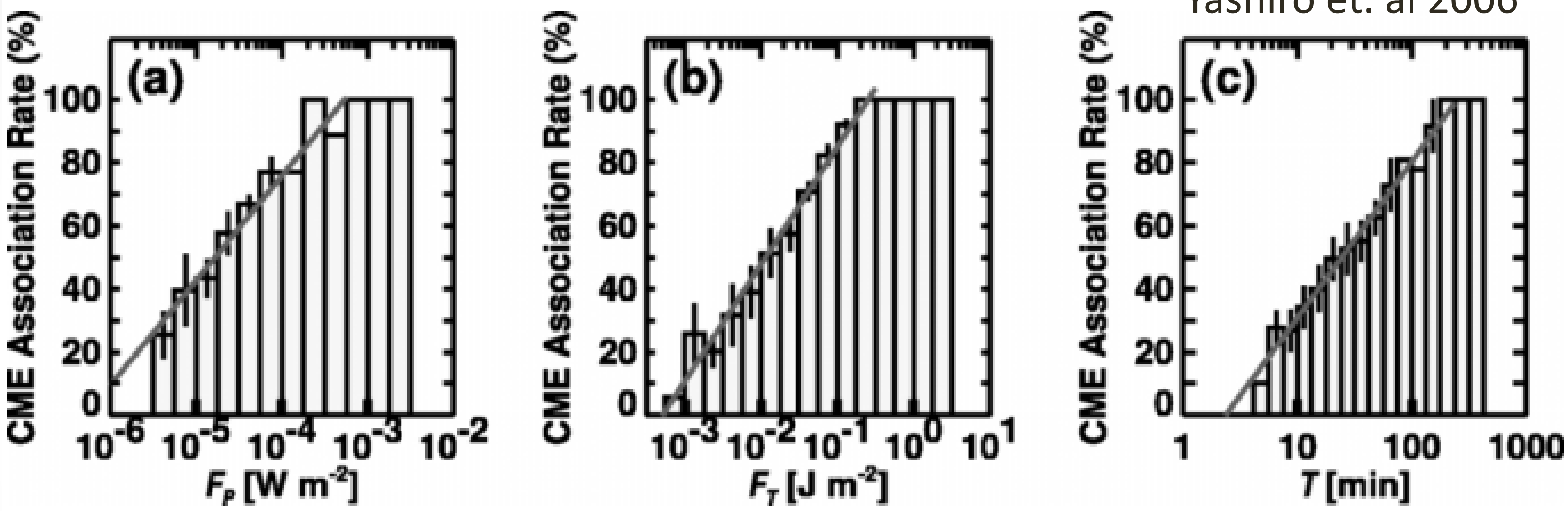
Observational Signature	Sun	Stars*
Flare	✓	✓
Nonthermal Hard X-ray Emission	✓	?
Incoherent Radio Emission	✓	✓
Coherent Radio Emission, m-dm-cm	✓	✓
FUV Emission Lines (transition region)	✓	✓
Hot Blackbody Optical-UV	✓	✓
Coronal Emission Lines and Continuum	✓	✓
Optical/UV Chromospheric Emission Lines	✓	✓
Coronal Mass Ejection	✓	?
Radio Type II Burst	✓	?
High Velocity Outflows from Escaping Material	✓	?
Scintillation of Background Radio Sources	✓	?
Coronal Dimming's	✓	?
NH Increases in X-Ray Flare Spectra	?	?
Pre-flare dips prior to Impulsive Phase	?	?
Effects of CMEs on Stellar Environment	✓	?
Flare/CME Connections	✓	?

Reference is Osten 2017, in **Impacts of Exoplanetary Space Weather on Climate and Habitability of Terrestrial Type Exoplanets (in prep.)**



CME Connections to Flares (solar)

Yashiro et. al 2006



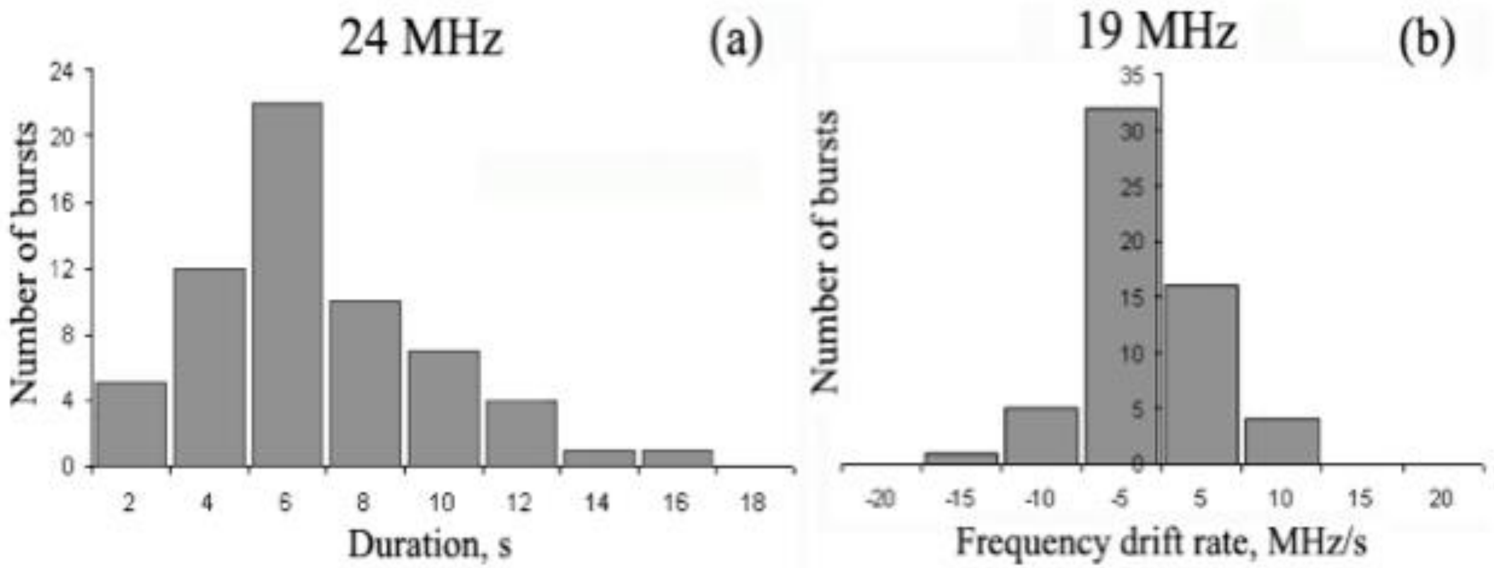
$$\frac{1}{2} M_{CME} v^2 = \frac{E_{rad}}{\epsilon f}$$

$$M_{CME} = K_M E_{GOES}^{\gamma}$$

Osten & Wolk 2015,
based on Emslie et al. 2012
and Drake et al. 2013

Aarnio et al. 2012
Drake et al. 2013

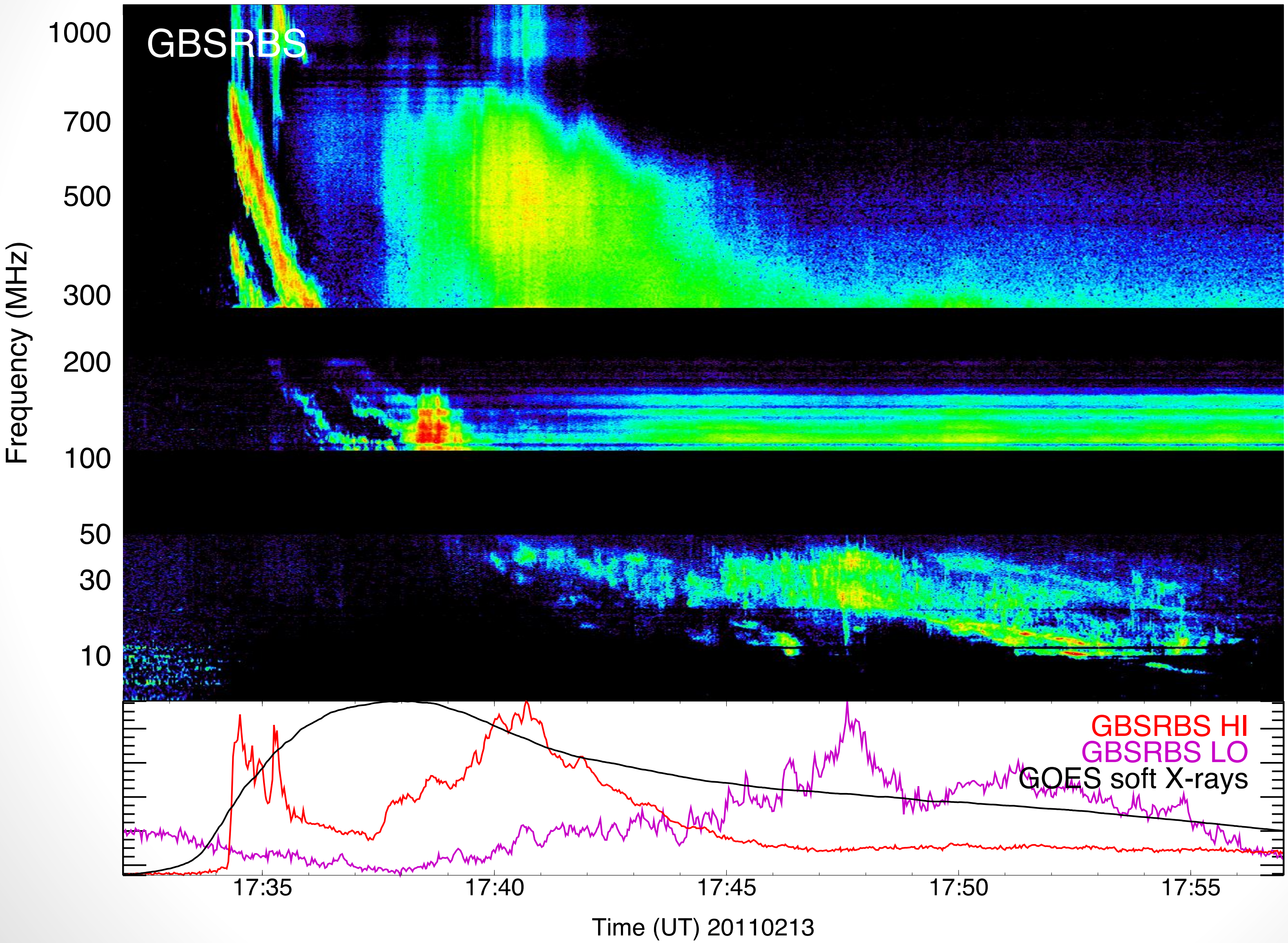
Low Freq. (16.5 – 33.0 MHz) Bursts on AD Leo



Konovalenko et al. (2012)

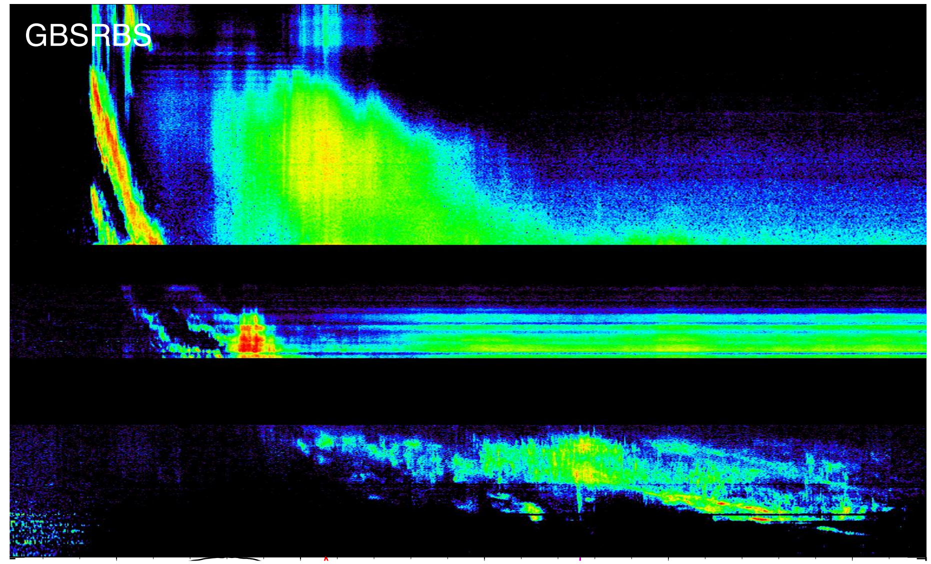
Solar Type II Burst

Feb. 13, 2011



Description of the Type II burst

$$v_A = 2.03 \times 10^{11} \frac{B}{\sqrt{n}}$$

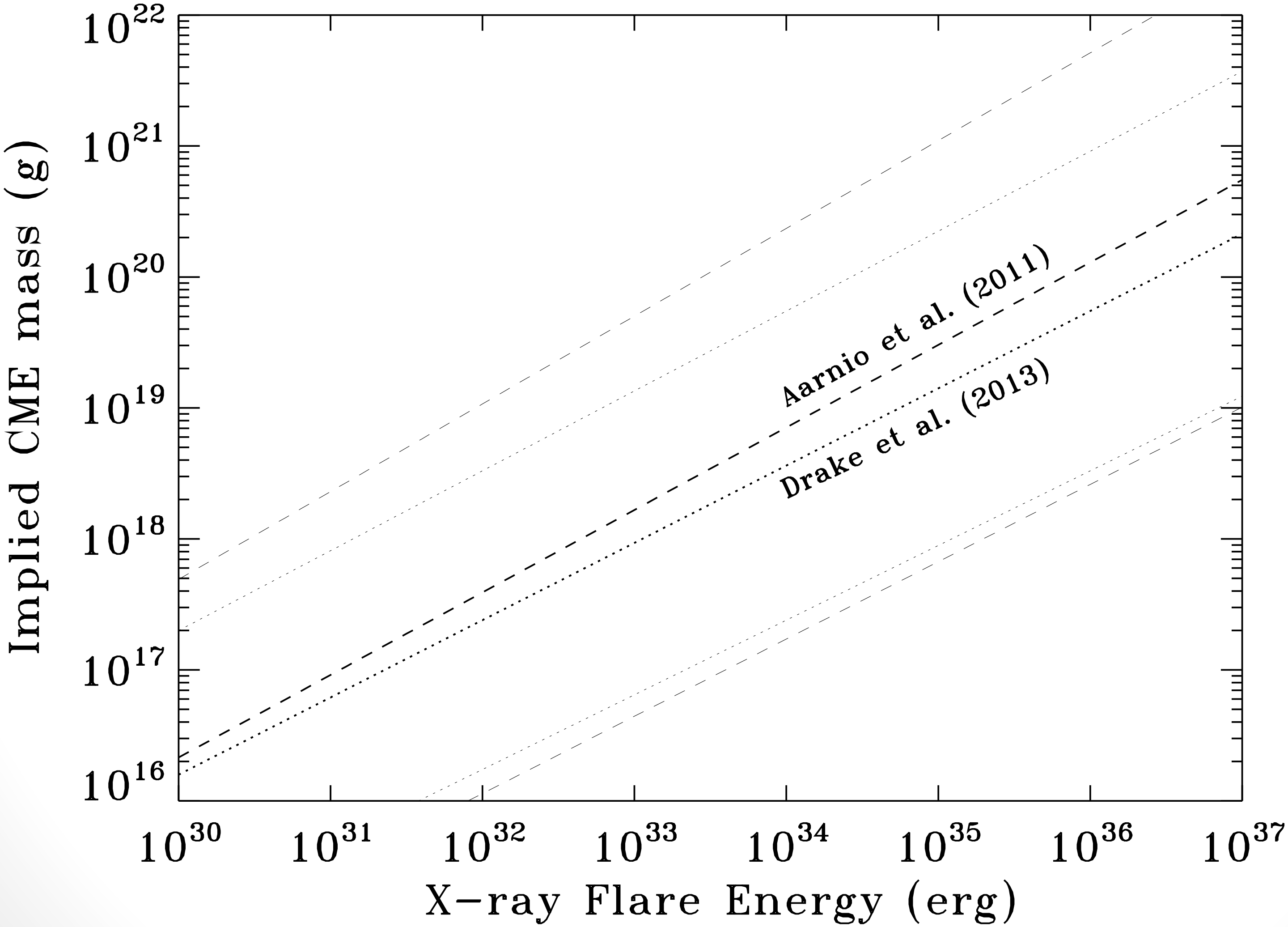


$$\nu_p = \sqrt{\frac{ne^2}{\epsilon_0 m_e}}$$

$$\frac{d\nu}{dt} = \frac{\partial \nu}{\partial n} \frac{\partial n}{\partial h} \frac{\partial h}{\partial s} \frac{\partial s}{\partial t}$$

$$= \left(\frac{\nu}{2n}\right) \left(-\frac{n}{H_0}\right) (cos\theta) \left(v_s\right) = -\frac{\nu v_s cos\theta}{2H_0}$$

CME Mass from Flare Energy



Connecting CMEs and Flares

- Empirical Relation (Aarnio 20011, Drake 2013)

$$M_{CME} = AE^{\gamma}$$

- Energy Equipartion (Osten, Wolk 2015)

$$\frac{1}{2} M_{CME} v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}}$$

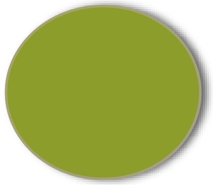
$$E_{GOES} = \left[\frac{A \epsilon v^2}{2} f_{GOES} \right]^{\frac{1}{1-\gamma}}$$

$$v = \sqrt{\frac{2}{A \epsilon f_{GOES}}} (E_{GOES})^{\frac{1-\gamma}{2}}$$

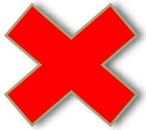
Solar Comparison

The criteria used for data selection:

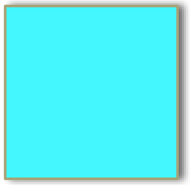
1. Flare is M or X-class
   - Peak flux above 10^{-5} or 10^{-4} W/m^2
2. Associated CME observed at LASCO
3. The CME had a type II burst associated to it



Listed as `poor' in the SOHO/LASCO catalog

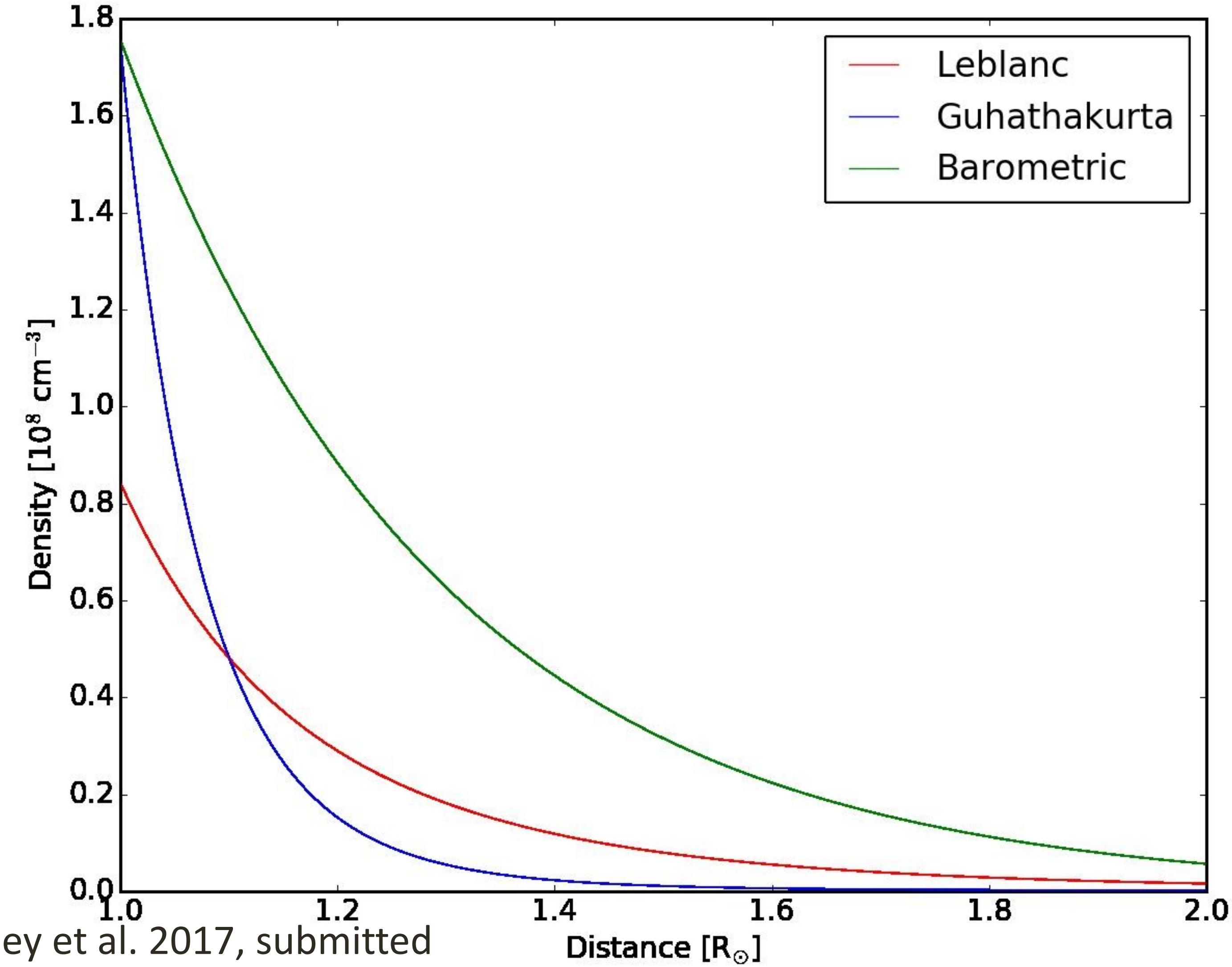


Non-exponential shape



Multiple signals, but chose the exponential shaped event.

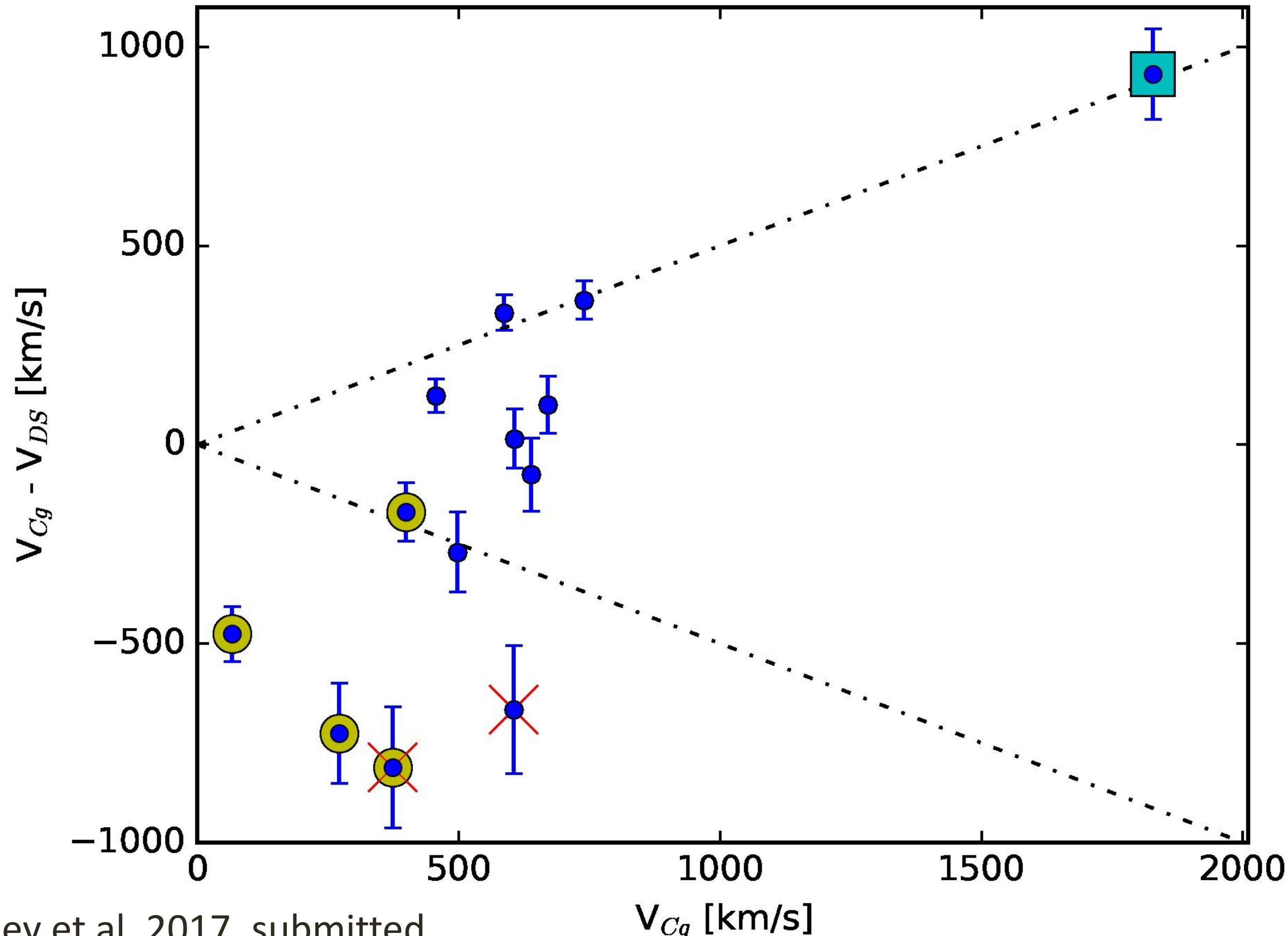
Barometric Model



Crosley et al. 2017, submitted

Velocity

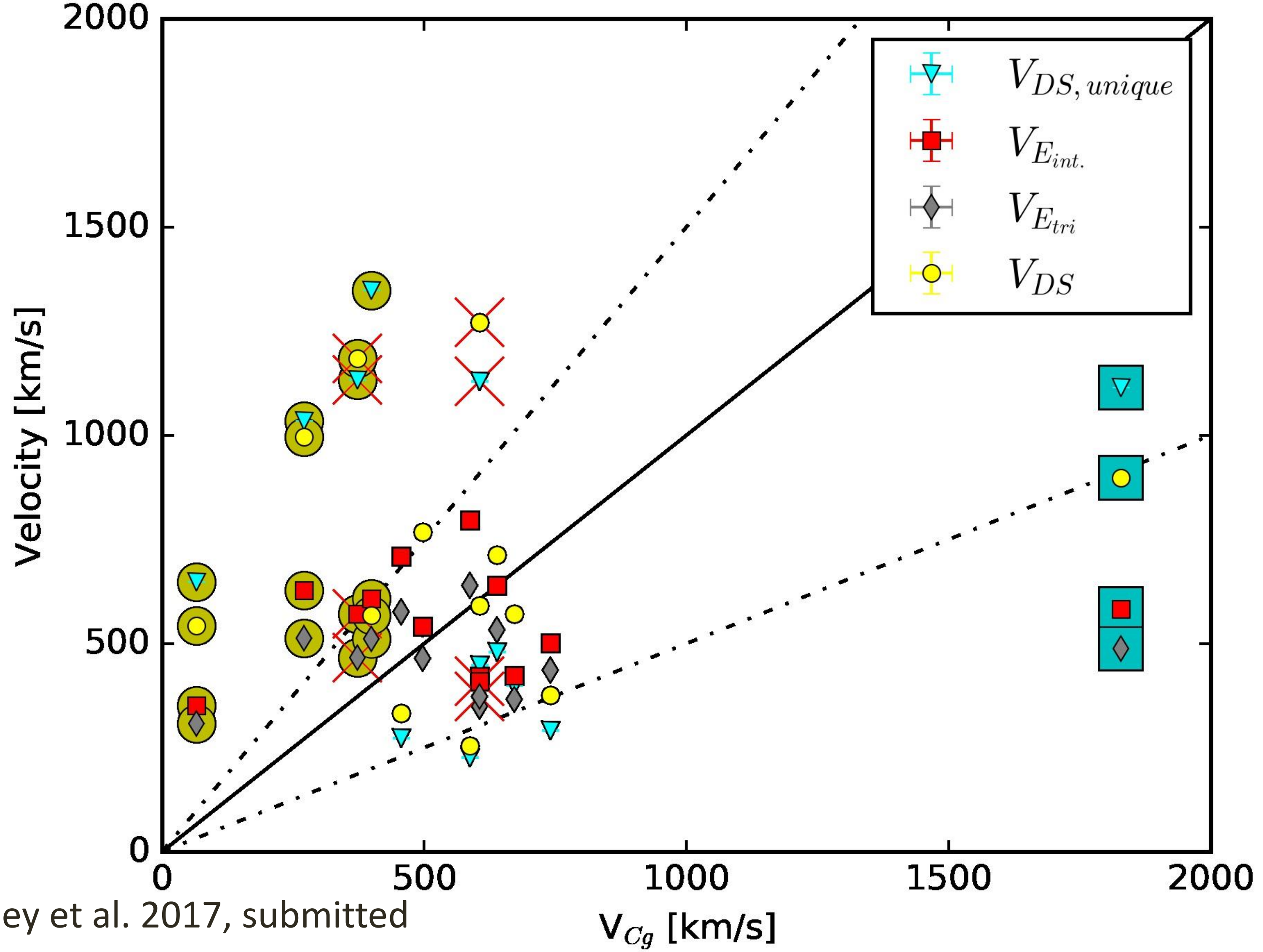
$$\frac{d\nu}{dt} = -\frac{\nu v_s cos\theta}{2H_0}$$



Crosley et al. 2017, submitted

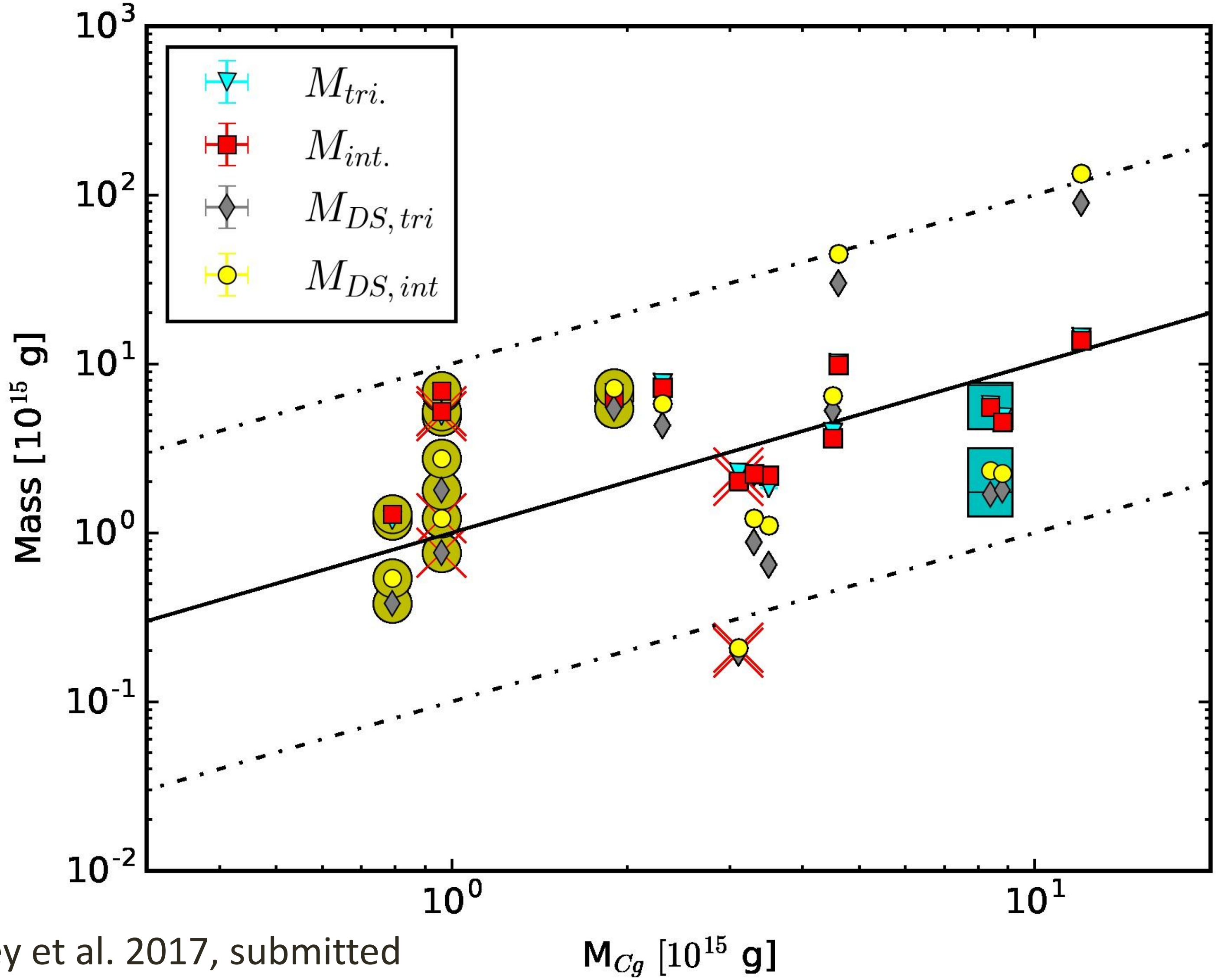
Comparing Vel.

$$v = \sqrt{\frac{2}{A\epsilon f_{GOES}}}(E_{GOES})^{\frac{1-\gamma}{2}}$$



Crosley et al. 2017, submitted

Mass

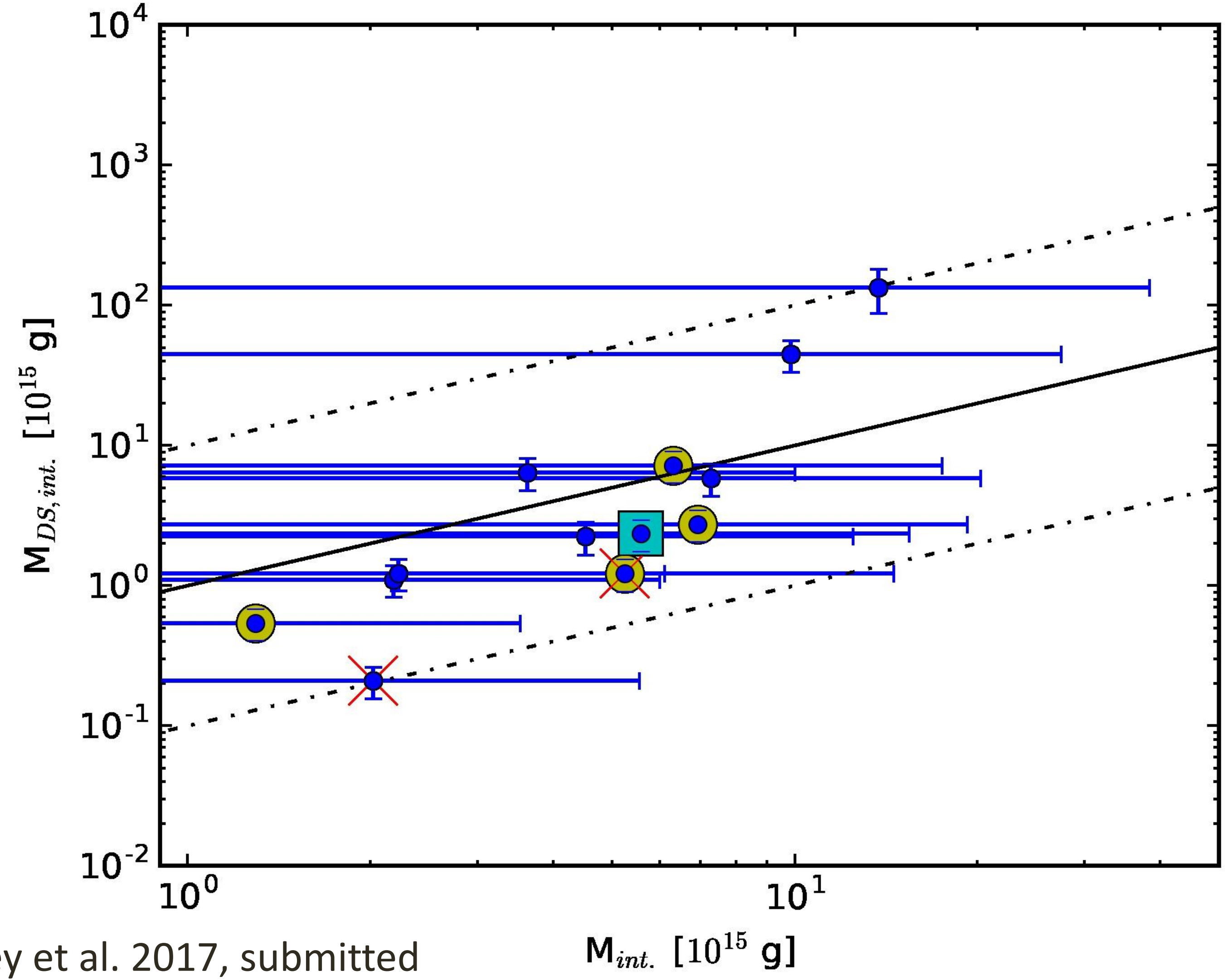


Crosley et al. 2017, submitted

Comparing Mass

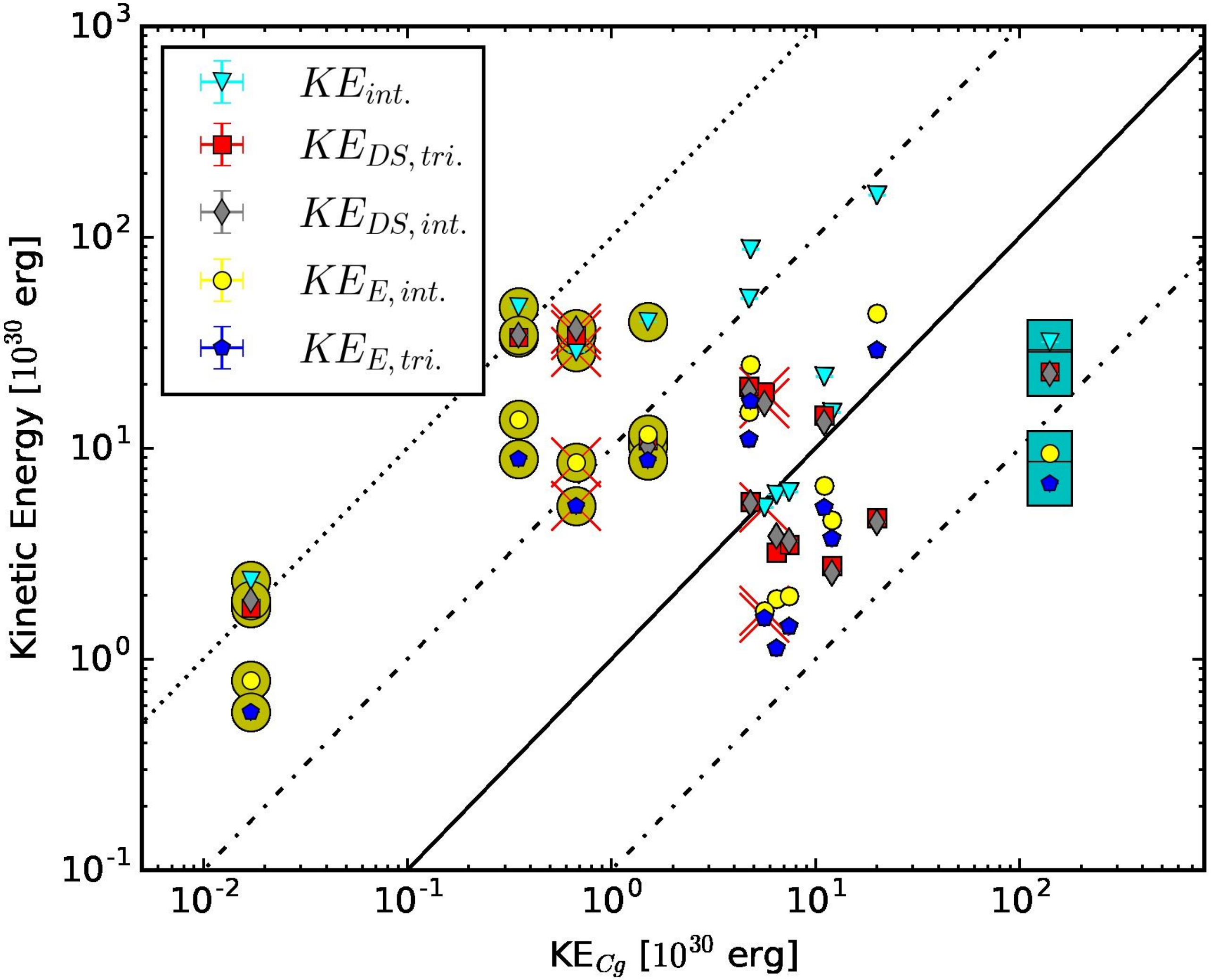
$$\frac{1}{2}M_{CME}v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}}$$

$$M_{CME} = AE^{\gamma}$$



Crosley et al. 2017, submitted

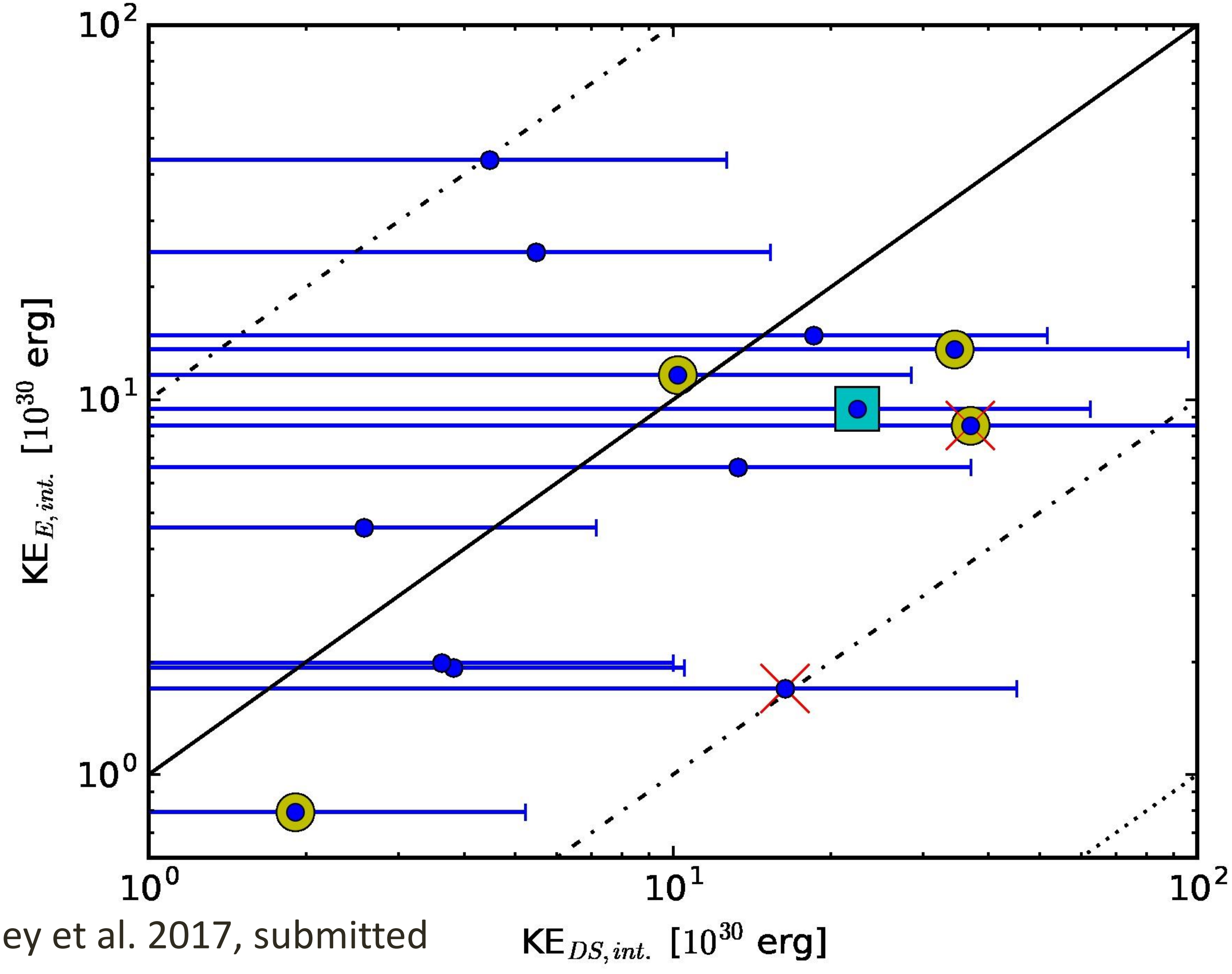
Kinetic Energy



Crosley et al. 2017, submitted

Comparing KE

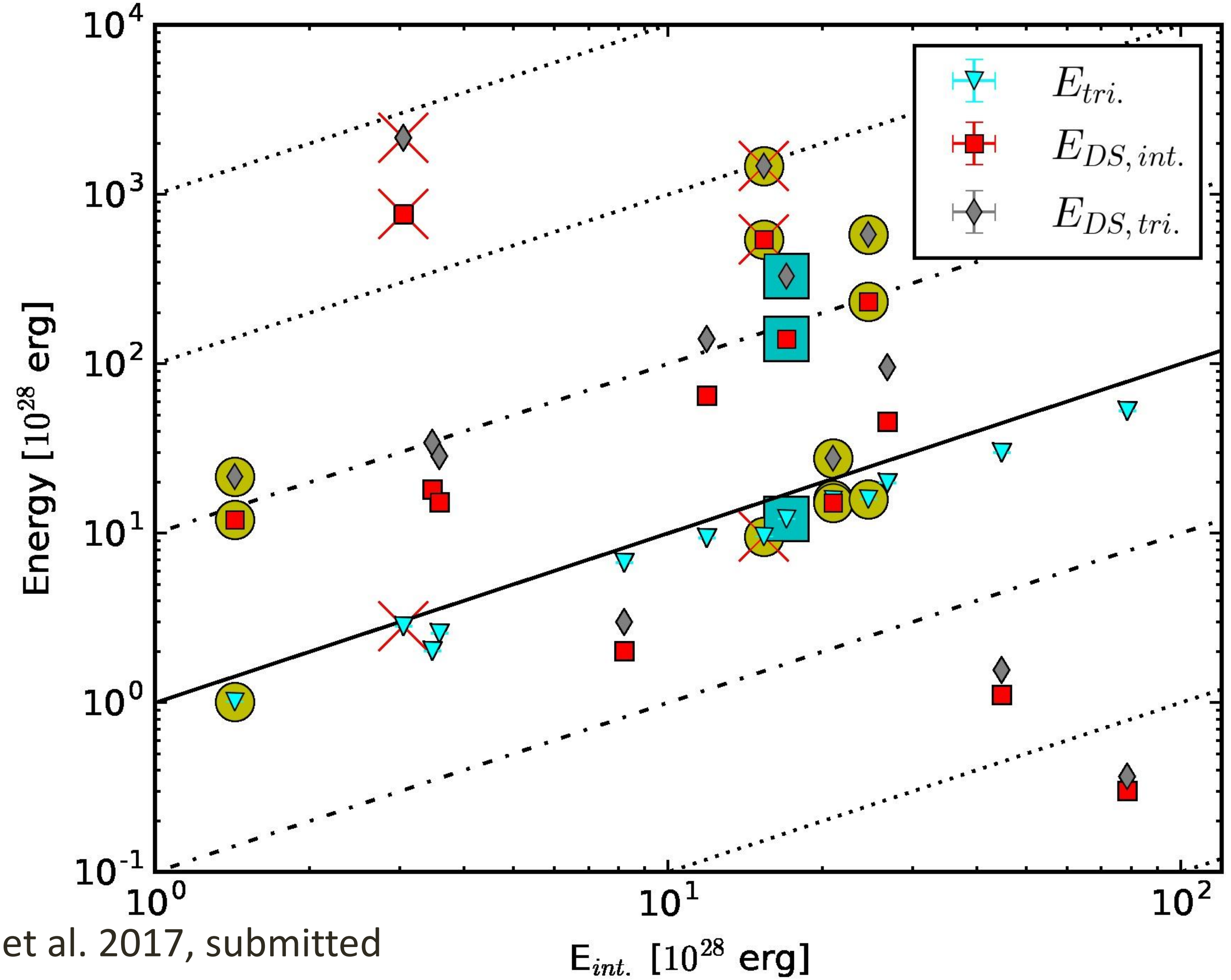
$$\frac{1}{2}M_{CME}v^2 = \frac{E_{GOES}}{\epsilon f_{GOES}}$$



Crosley et al. 2017, submitted

Energy

$$E_{GOES} = \left[\frac{A\epsilon v^2}{2} f_{GOES}\right]^{\frac{1}{1-\gamma}}$$



Crosley et al. 2017, submitted

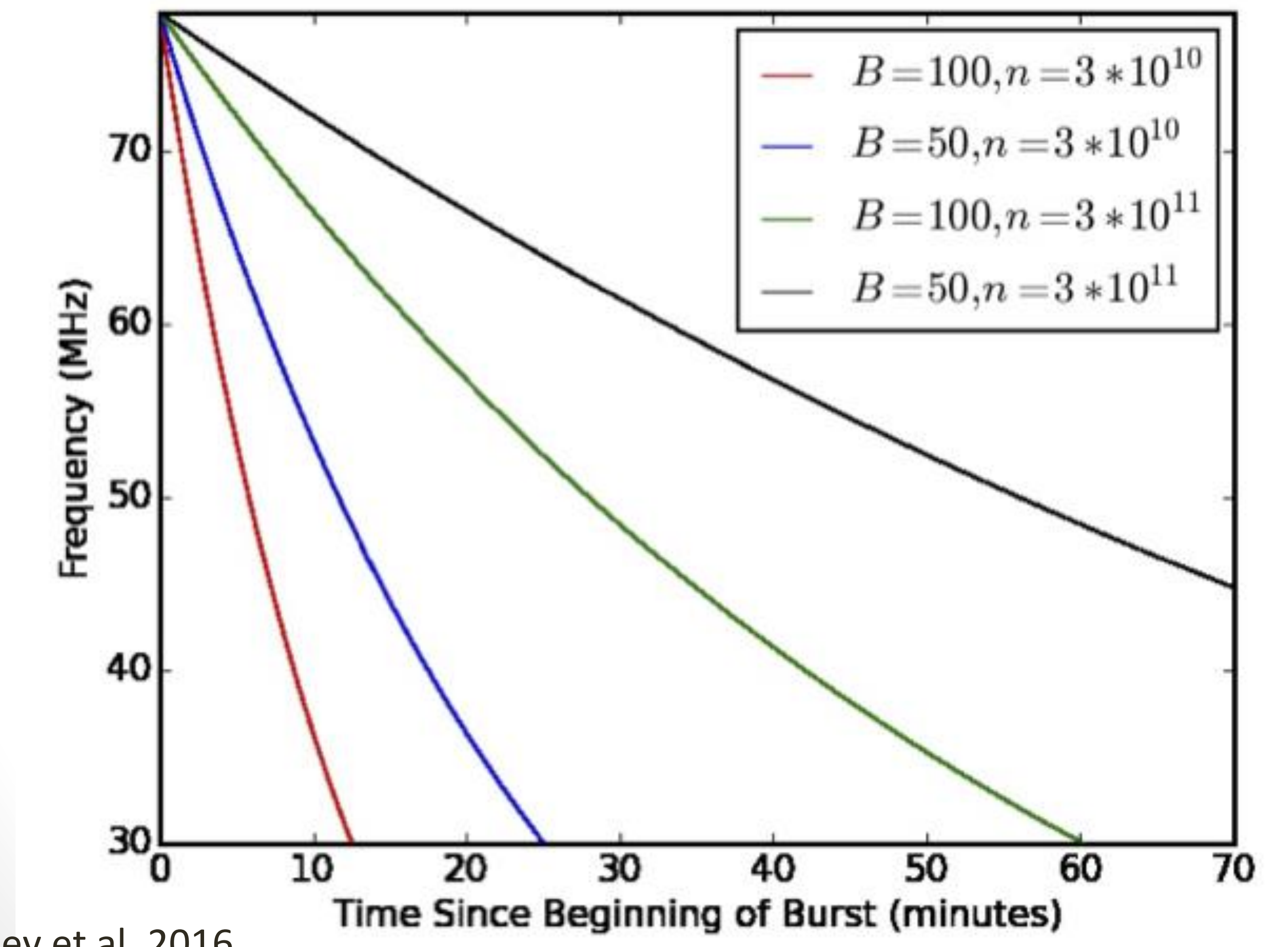
LOw Frequency ARray (LOFAR)

- LBA 10-90 MHz
- HBA 110-190 MHz
- Beam-Formed Mode
  - Combine collecting area into coherent `array beams'
    - Correct for geometric and instrumental time an phase delays for pointing
    - Restricted FoV, but full cumulative sensitivity of the combined stations
  - 5.12μs time resolution (van Haarlem et al. 2013)
  - 0.763-195 kHz frequency resolution (van Haarlem et al. 2013)
  - On and Off beam observation mode

YZ Canis Minors (CMi)

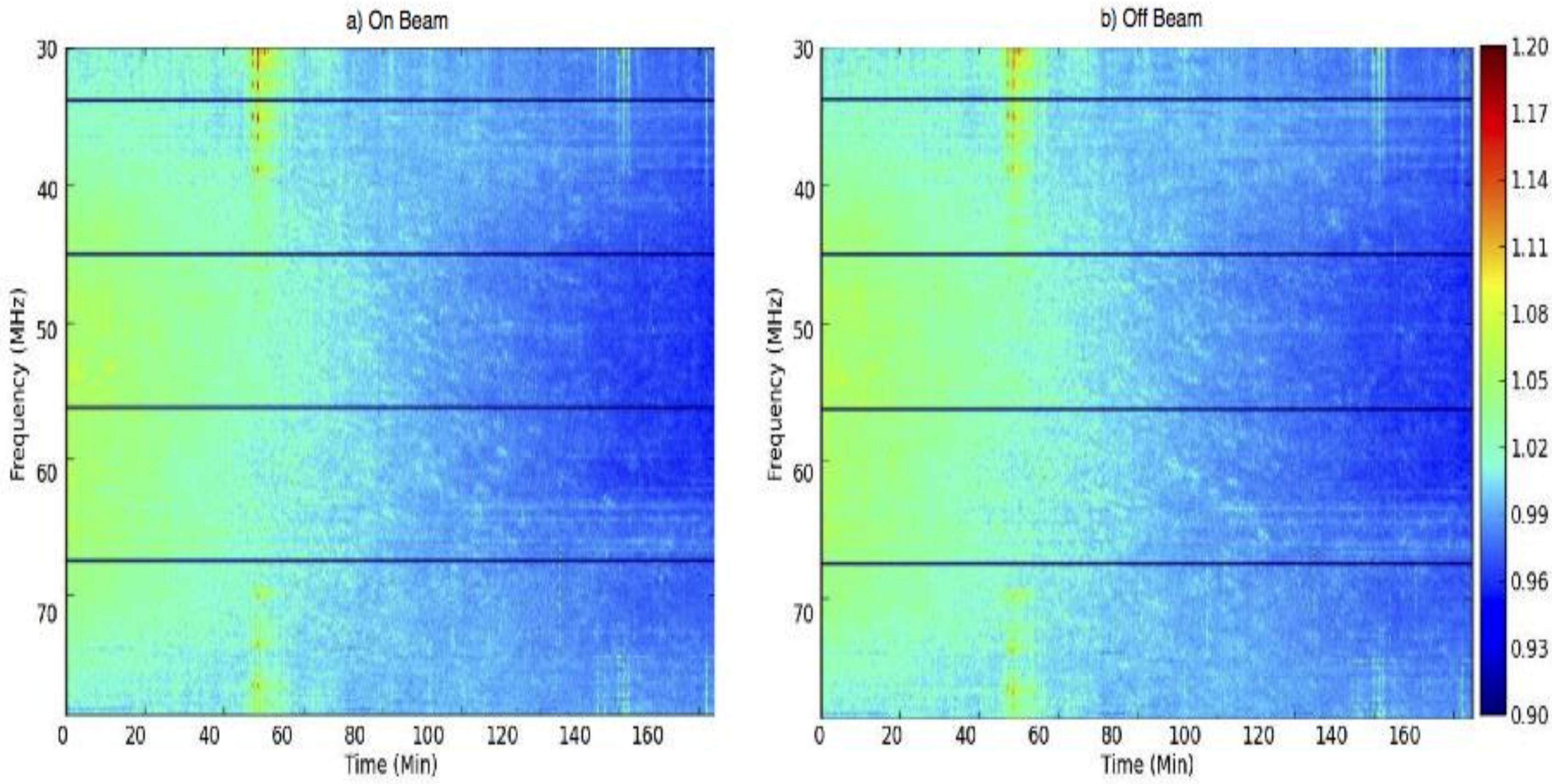
- 5.93 pc away (Perryman et al. 1997)
- 0.34 $M_{\odot}$ (Lim et al. 1987)
- ~0.36 $R_{\odot}$ (Mullan et al. 1992)
- B at flare sites between B = 50 – 100G (Raassen et al. 2007)
- n of $3x10^{10}$ cm^{-3} for quiescent state to < $5x10^{12}$ for hotter plasma (Ness et al. 2004)
  - expect bursts between ~1500 -10 MHz
- Coronal T of 10^7 K (Dupree et al. 1993)
- 0.4 flares/hour with energies above U-band energy of 5 x 10^{31} (Lacy et al. 1976)
- Low frequency (1500 – 300 MHz) microwave events observed (Kundu & Shevgaonkar 1988)

What Can We Expect?



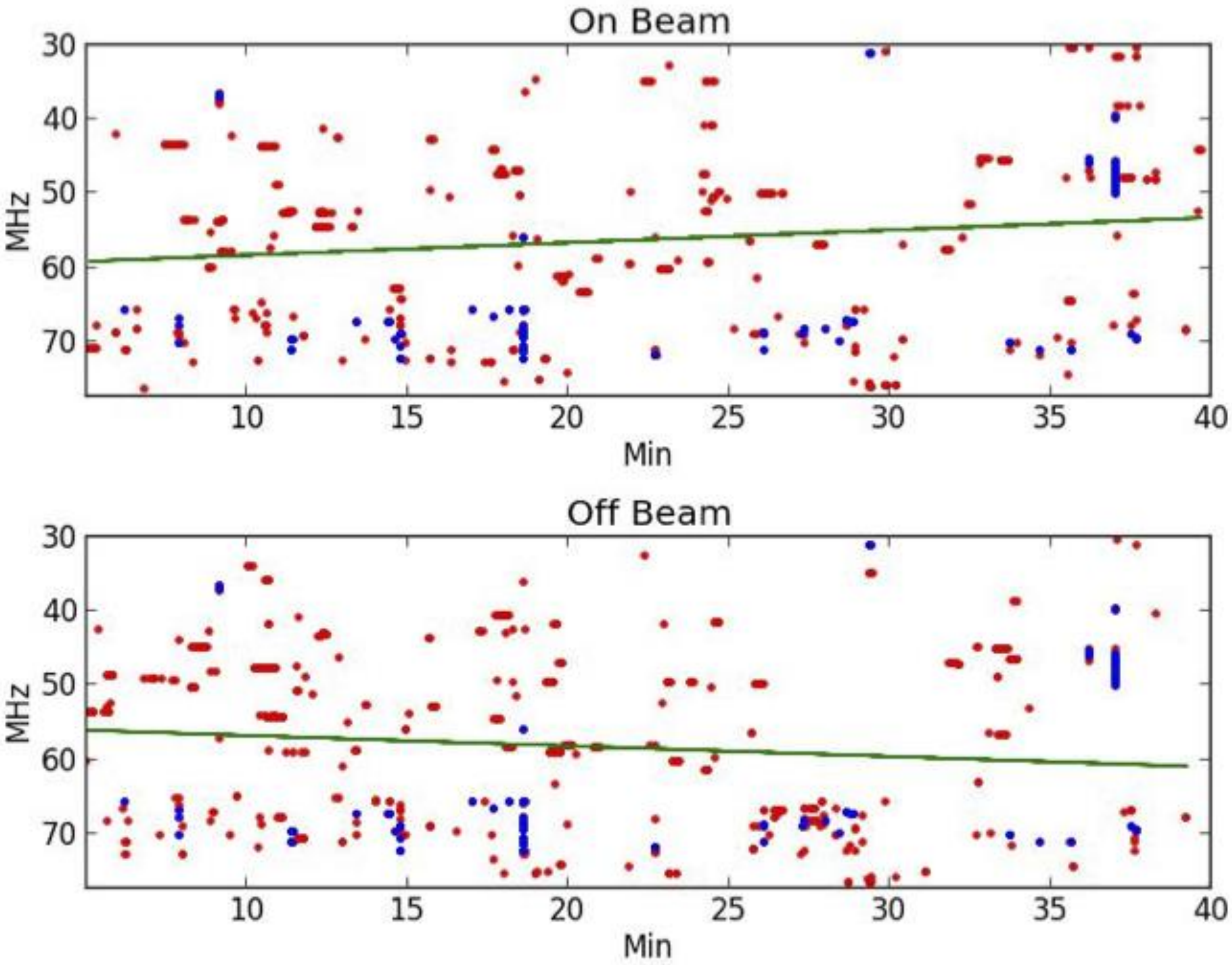
Crosley et al. 2016

LBA Example



Crosley et al. 2016

Measuring Drift Rate

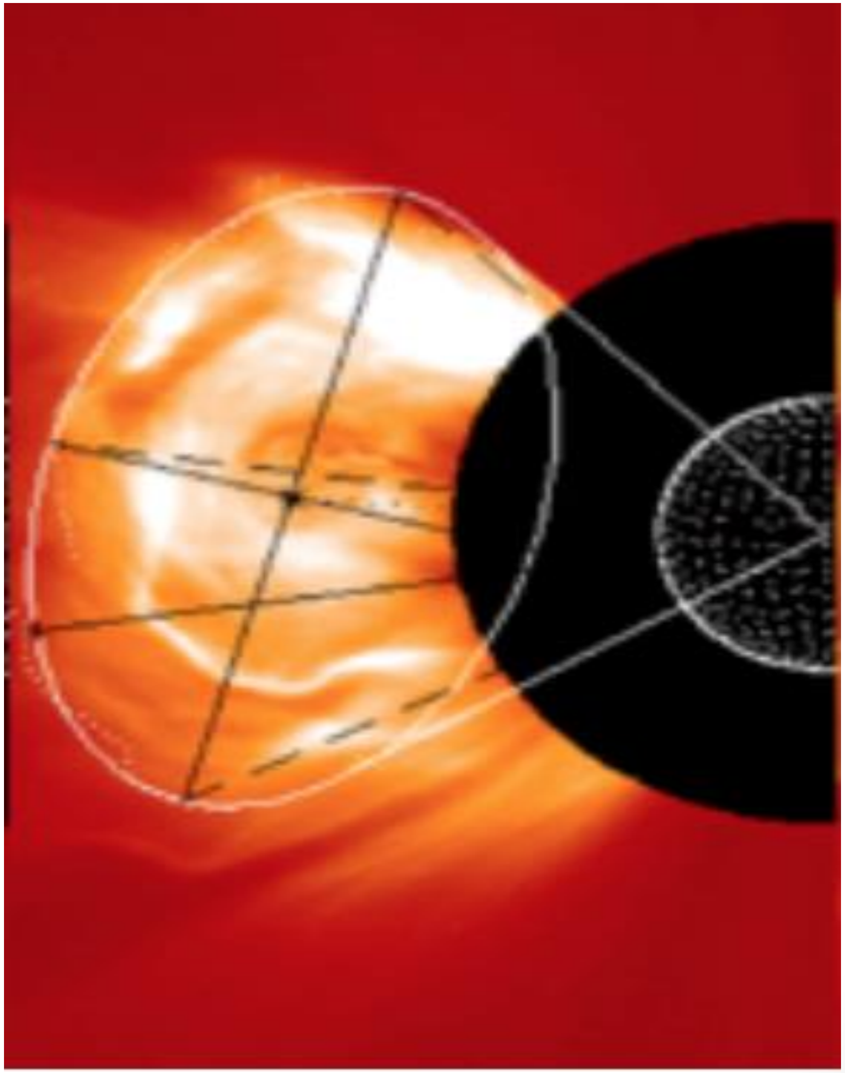


Crosley et al. 2016

Geometric Considerations

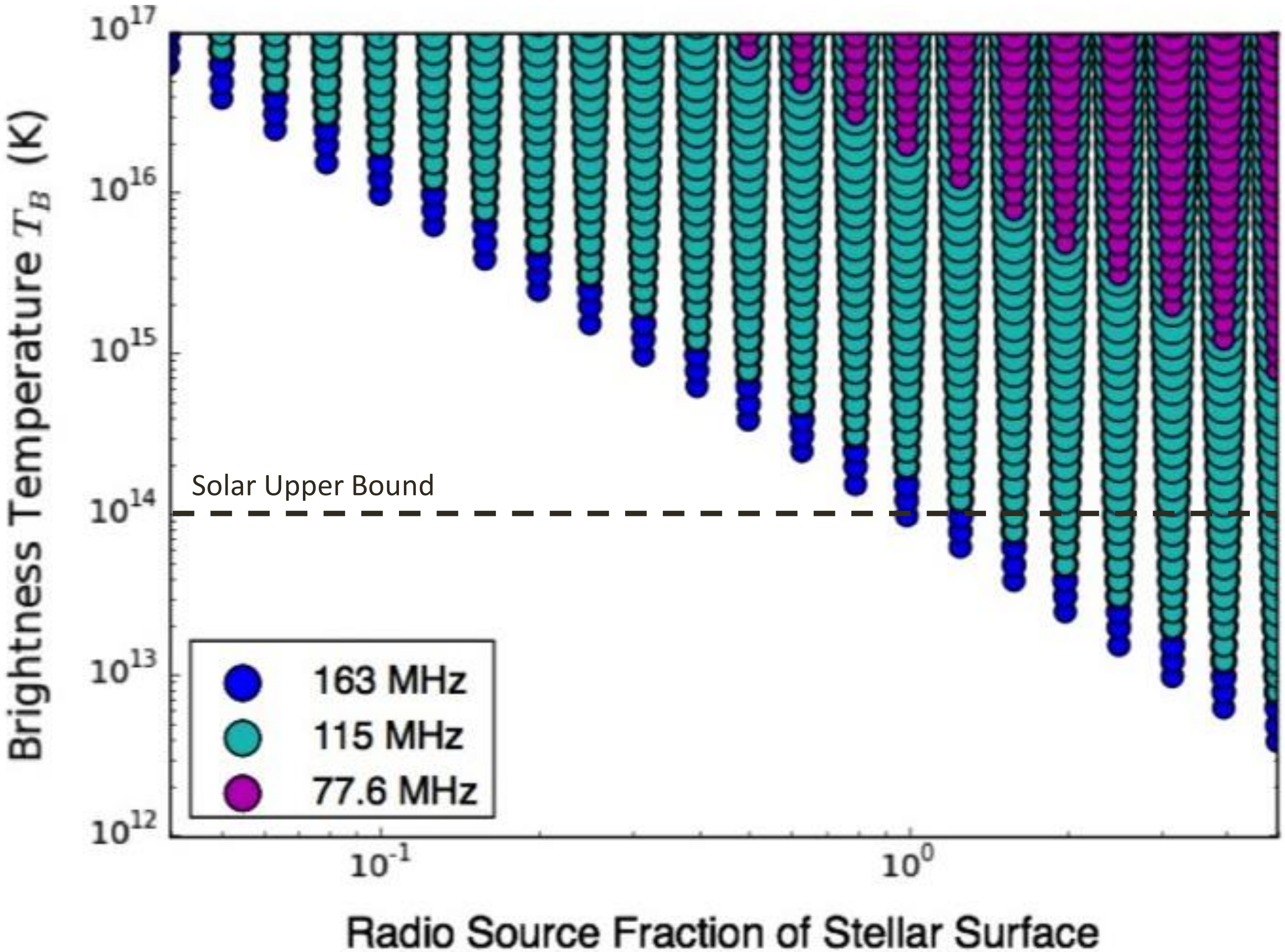
- On Sun, preferentially shock towards base of corona
- Susino et al. 2015 found an example solar CME which was fully super Alfvénic at 4 solar radii

$$S_\nu \propto \frac{\nu^2}{c^2} \int T_b d\Omega$$



Byrne 2012

Observational Uncertainties



$$S_\nu \propto \frac{\nu^2}{c^2} \int T_b d\Omega$$

Crosley et al. 2016

Moving Forward

- 60 Hours of EQ Peg Observations
  - Partial multi-wavelength observations
- Pursue large field surveys?
- More sensitive Observatories to push limits further

- Thank you!