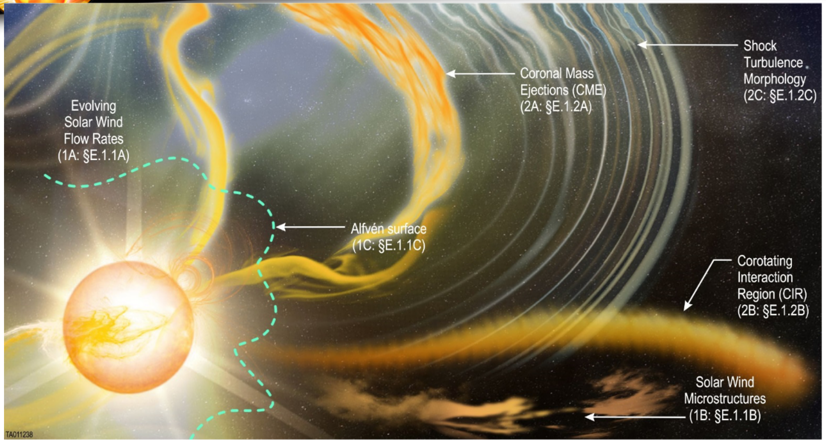
Polarimeter to Unify the Corona and Heliosphere

WG2C, Mihir Desai

PUNCH Workshop, August 11, 2021

PUNCH Science Objectives & WG2C – Science Topics



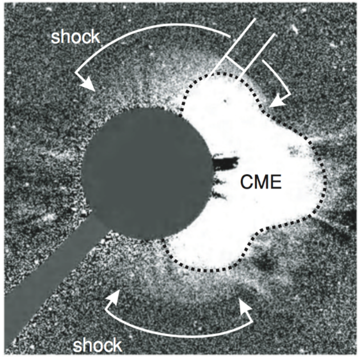
Objective 1: Understand how coronal structures become the ambient solar wind

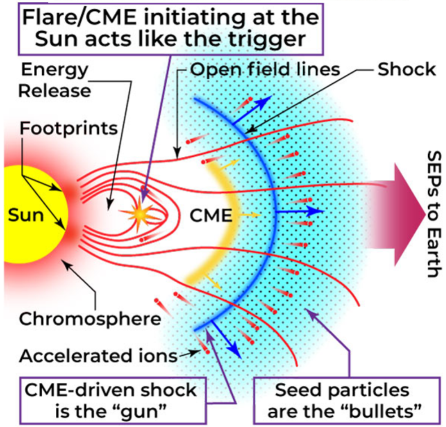
Objective 2: Understand the dynamic evolution of transient structures in the young solar wind

A. How do coronal mass ejections (CMEs) propagate and evolve in the solar wind?

B. How do quasi-stationary corotating interaction regions (CIRs) form and evolve?

C. **How do shocks form and interact with the solar wind across spatial scales?**





Moses et al. 2015; Vourlidas et al.,

- **CMEs and Shocks (Interactions with WG2-A):**
  - CME structure, CME-shock Identification, Quantitative Image Analyses, Shock shape, properties
  - Dave Webb, Jackie Davies, Glenn Laurent, Barbara Thompson
- **Shock Evolution from ~5-10 au and beyond**
  - Solar Wind variability, CME shock evolution in coronal and heliospheric imagery, PSP, SolO
  - Nicholeen Viall, Alexis Rouillard, Dusan Odstrcil

Shock Properties as function of time, radial distance, and azimuth

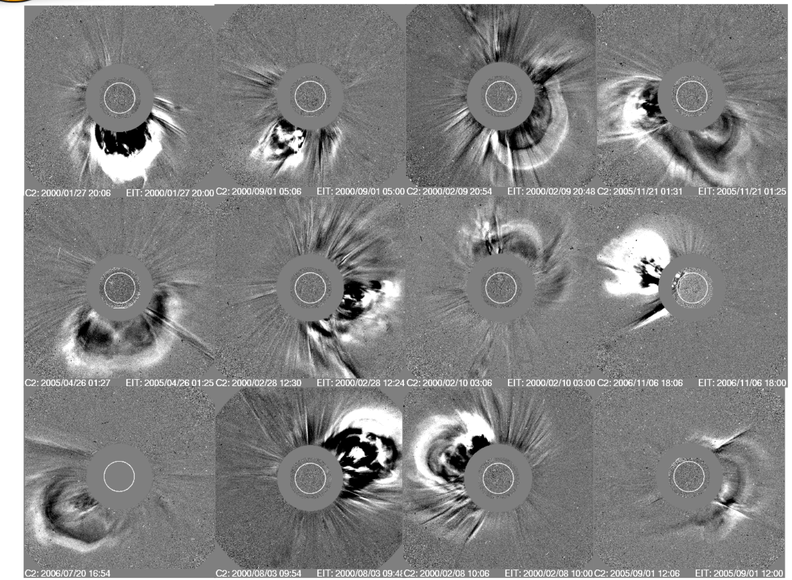
- Shock Analyses, Shock Physics, turbulence, small-scale dynamics, Space Weather Applications, Comparisons with Radio data, PSP, SolO
- William Matthaeus, Huw Morgan, Iver Cairns, Vic Pizzo

SEP acceleration:

- Relationship between shock shape, Properties and upstream turbulence and observations at PSP, SolO, and 1 AU
- Mihir Desai, William Matthaeus, Iver Cairns, Alexis Rouillard

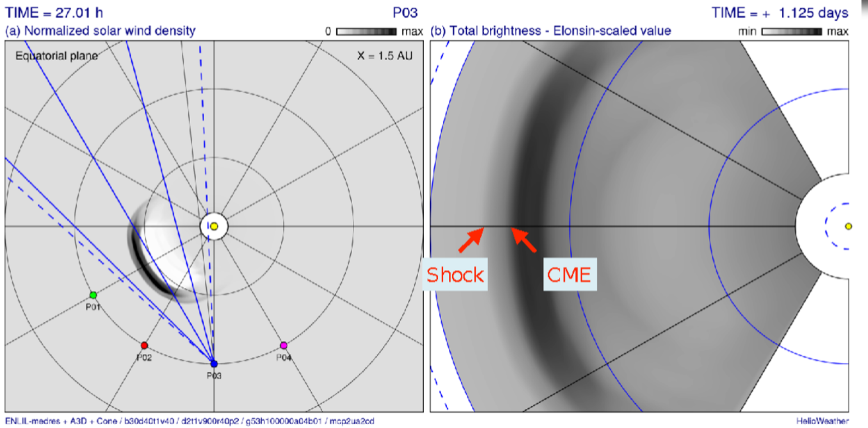
PUNCH connects CME & shock formation, 3D structure, evolution, SEP acceleration and Space Weather

Identify, Track & Model CMEs, Shocks, and their shapes

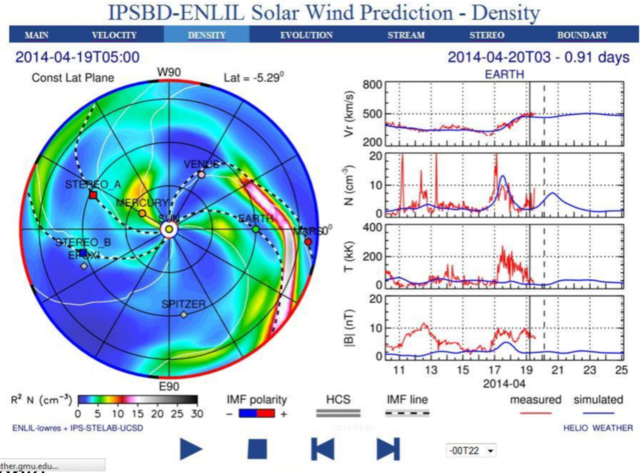


Courtesy: Robin Colaninno

Courtesy: Dusan Odstrcil

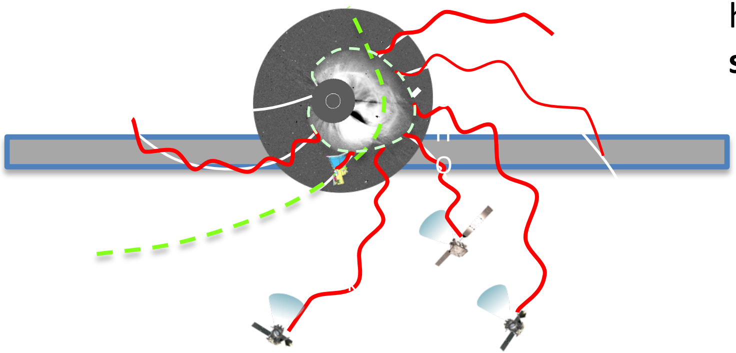


Courtesy: Bernie Jackson



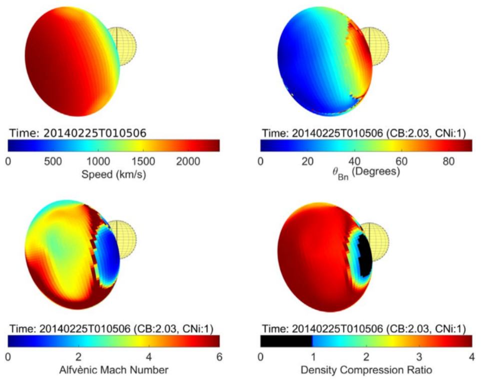
Use/Disclaimer Statement if applicable

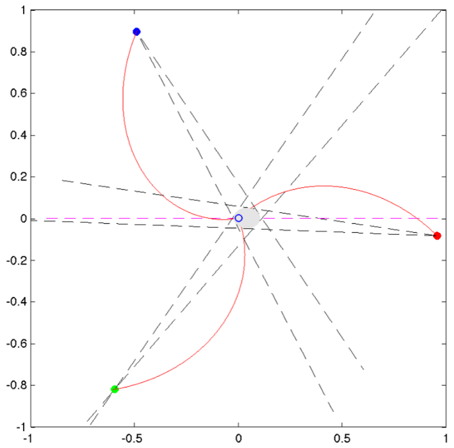
Shock Evolution modeling and validation



Slide Courtesy: Alexis Rouillard

Combined with numerical modelling of the background corona and heliosphere we can derive the time-evolving 3-D **properties of coronal shock waves:**

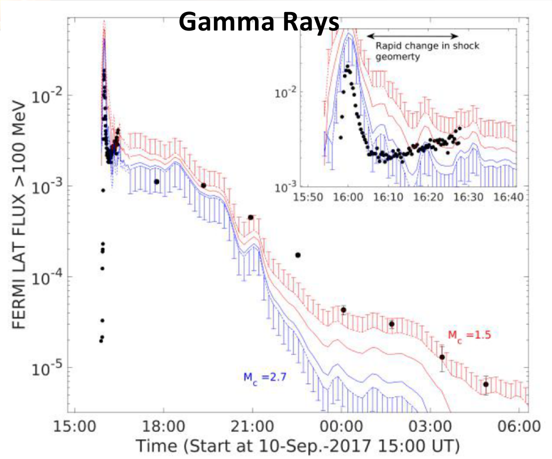


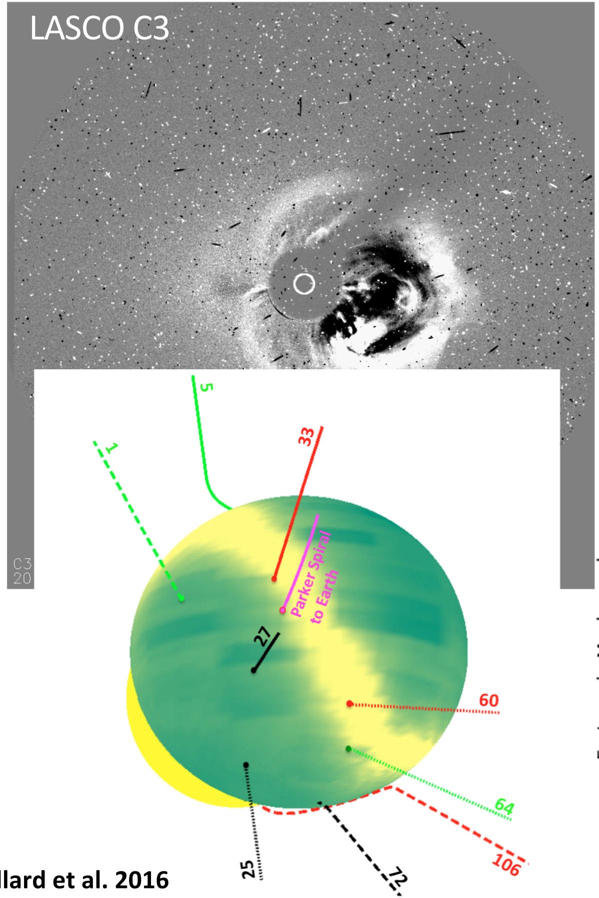


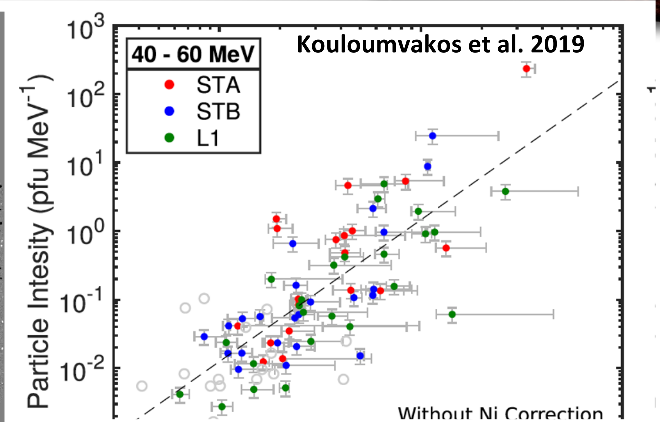
To connect coronal shocks with in situ measurements of SEPs we model the interplanetary magnetic field:

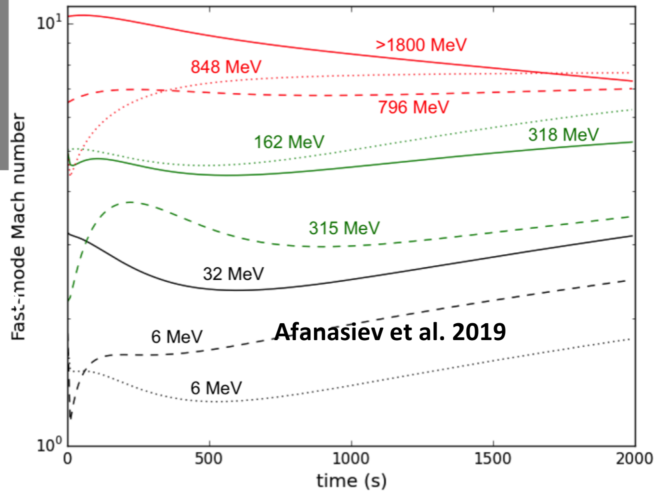
PUNCH will provide critical data to improve all these modelling steps!

Link γ-ray sources, CMEs, Shocks & SEPs









→ **PUNCH in concert with improved modeling will link CMEs, shocks and SEPs Critical for Space Weather models and predictions**

Courtesy: Alexis Rouillard

Rouillard et al. 2016

PUNCH Measurements & Performance

Q2C: How do shocks form and interact with the solar wind across spatial scales?

Formation, cross-scale spatial structure, and shock parameter (Mach ratio) of forward shocks driven by strong CMEs or CIRs.	Distortion (e.g., crinkles, bends) and brightness jump of shock fronts across a wide field of view via 3D polarization analysis, image deblurring,autocorrelation and structure functions.

Connection between shock formation, structure, evolution and SEPs and Space Weather

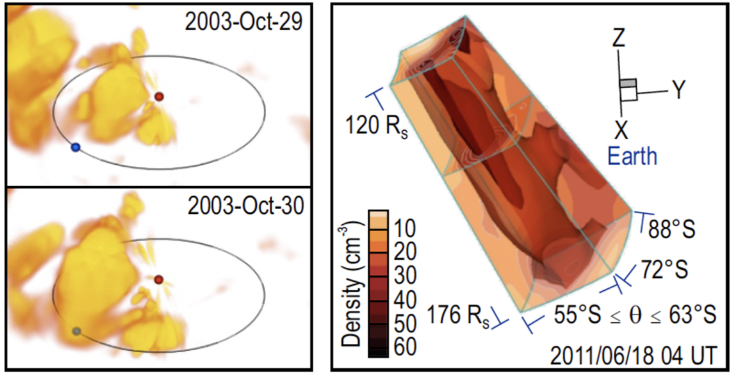
PUNCH Analyses Techniques

3D polarization analysis, auto-correlation & structure functions, and co-added image deblurring. Global heliospheric models are used for context and event analysis.

D: Kinematic Tomography Yields Detailed 3D Information (2A, 2B, 2C)

Large scale inversions from IPS show heliospheric evolution

Fine scale inversions from SMEI reveal substructure features in a micro-stream associated with a coronal jet



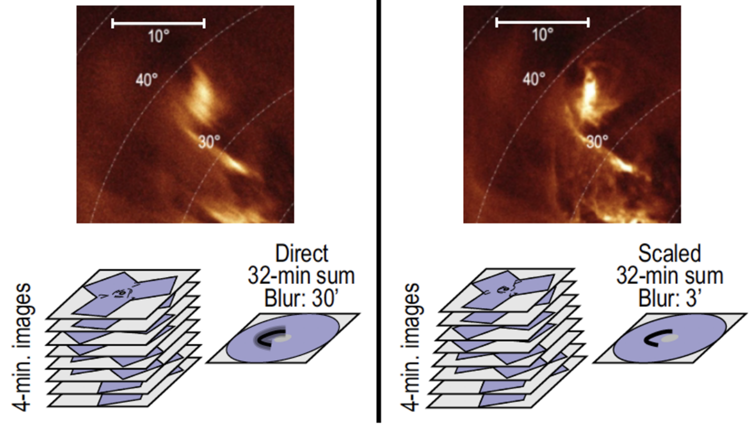
Jackson et al. (2006) Yu et al. (2014)

PUNCH uses proven tomographic techniques to determine global and fine-scale structure via kinematic constraints, as demonstrated here using published data from IPS and SMEI. With >30x improvements in SNR and two polarization channels, PUNCH enables far more detailed, precise tomography of ejecta and the solar wind.

C: Co-Added Image Deblurring Preserves Spatial Resolution (1B, 2A, 2C)

Long or summed exposures blur CMEs and wind features

PUNCH deblurring preserves CME structure



PUNCH rapid cadence enables co-added image deblurring, permitting high resolution, deep field imaging. This proven technique (DeForest et al 2016) enables deep imaging of detailed structure in the solar wind and transients (Questions 1A, 2A, 2B, 2C).

Connection between shock formation, structure, evolution and SEPs and Space Weather

Tools and Observations for WG2C

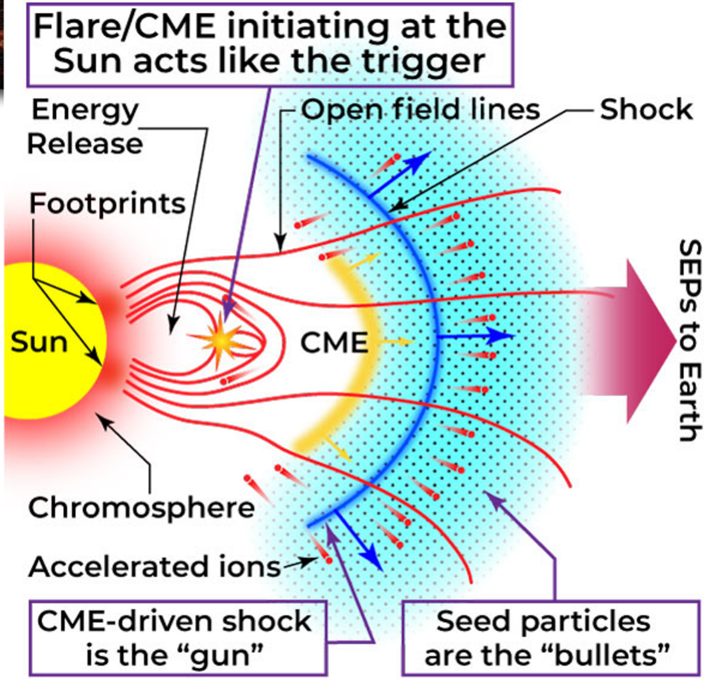
- Synthetic Data (already developed)
  - Understand the physics and limitations of CME/CIR models
  - Generate synthetic shocks that PUNCH will detect
  - Model radial falloff in density, relation to coronal holes, streamers, and 3D Reconstruction
    - Shock expansion speed
    - Density maps combined with background models to predict transport of strong compressions
- PUNCH Observations
  - Morphology along the front and its evolution.
  - Excess density maps and their evolution

Connection between shock formation, structure, evolution and SEPs and Space Weather

WG2C Goals for PUNCH

- Have well-vetted tools capable of
  - Identifying CMEs, CIRs, and shocks in PUNCH data
    - Malanushenko WG2A, de Koning WG2B
  - Quantifying Shock Properties, Structure & Evolution
    - Robin, Laurent, Jackson
  - Modeling and Mapping to PSP, Solar Orbiter
    - Rouillard, Odstrcil, Matthaeus
  - Relating to turbulence ahead of shock
    - Matthaeus, Cair

Image credit: adapted from Moses et al. 2015



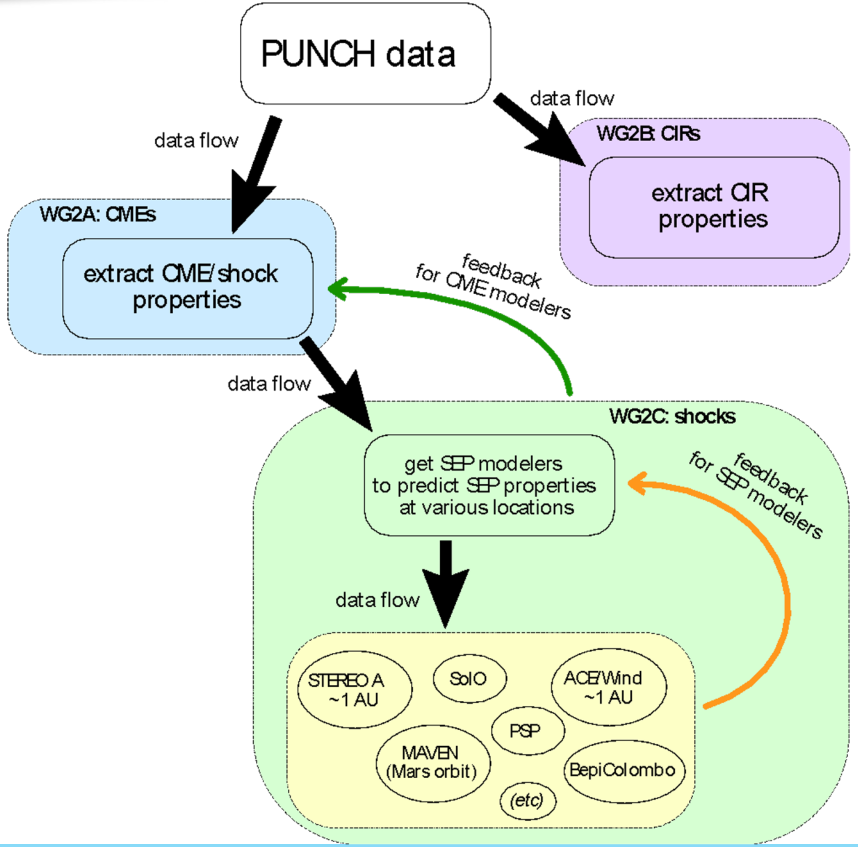
Morphological evolution of density structures associated with hydrodynamic and turbulent instabilities in CME fronts and CIRs; association (or lack) of instability onset and shock "crinkles" with SEPs.	Measure, for the first time in high resolution, shock evolution in the solar wind. Identify role of large-scale turbulence to SEP production, and importance of spatial instabilities to shock evolution.

Ongoing and Future work

- Develop and refine methods for generating reliable CME shock data and their evolution as a function of heliospheric location
  - Generate synthetic CME-shock data and match to observed data -- e.g., STEREO-HI shock observations
  - Predict evolution of key parameters like density, velocity etc. depending on where the shock is observed
  - Predict what PSP, ACE, STEREO, Solar Orbiter should see
  - Compare and Refine Models
  - Include shock-turbulence interactions
  - Combine with SEP models
  - Implications for in-situ SEPs

Connection between shock formation, structure, evolution and SEPs and Space Weather

WG2 Activities & Team Member Roles



Connection between shock formation, structure, evolution and SEPs and Team Roles

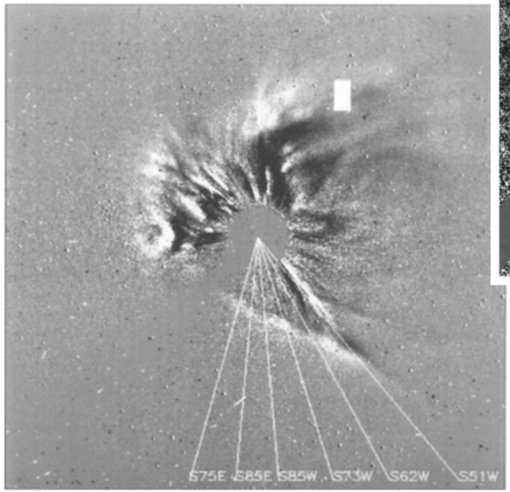
Scientist	Role
Mihir Desai	WG leader; Shock structure; SEP acceleration
Sarah Gibson	Working Group coordination
Glenn Laurent	Quantitative image analysis
William Matthaeus	Turbulence theory and interpretation; PSP/ISOIS liaison; in-situ comparison
Dusan Odstrcil	Heliospheric modeling (ENLIL)
Barbara Thompson	Shock structure; image analysis
Nicholeen Viall	Analyze and interpret PUNCH data on solar wind variability
Vic Pizzo	Shock analysis; Space weather applications
Iver Cairns	Shock physics and CME; solar wind structure and turbulence; Coordination with radio observations
Jackie Davies	CME-shock interaction analysis
Huw Morgan	Analysis of small-scale dynamics
Alexis Rouillard	Analysis of solar wind variability and shocks in coronal and heliospheric imagery

Thank You & Questions!

Connection between shock formation, structure, evolution and SEPs and Space Weather

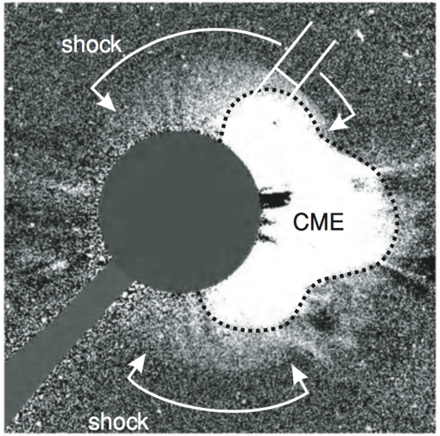
Early Shock Observations

"Amber Waves of Grain"

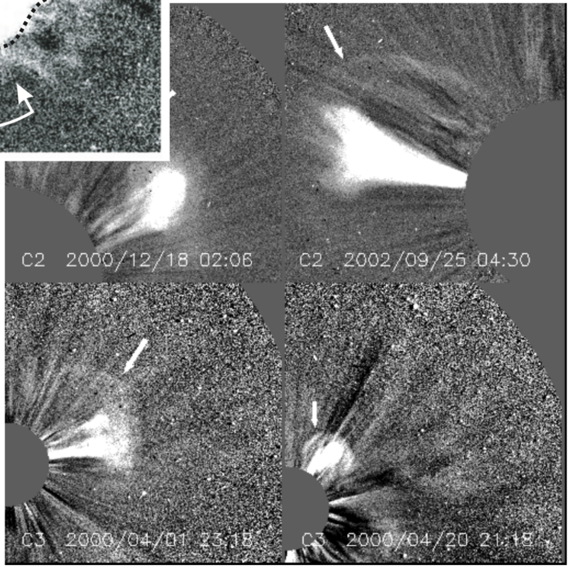


Sheeley, N.R., Hakala, W.N., and Wang, Y.-M.: 2000, Detection of coronal mass ejection associated shock waves in the outer corona, ApJ **105**, 5081-5092

Slide Courtesy: Robin Colaninno



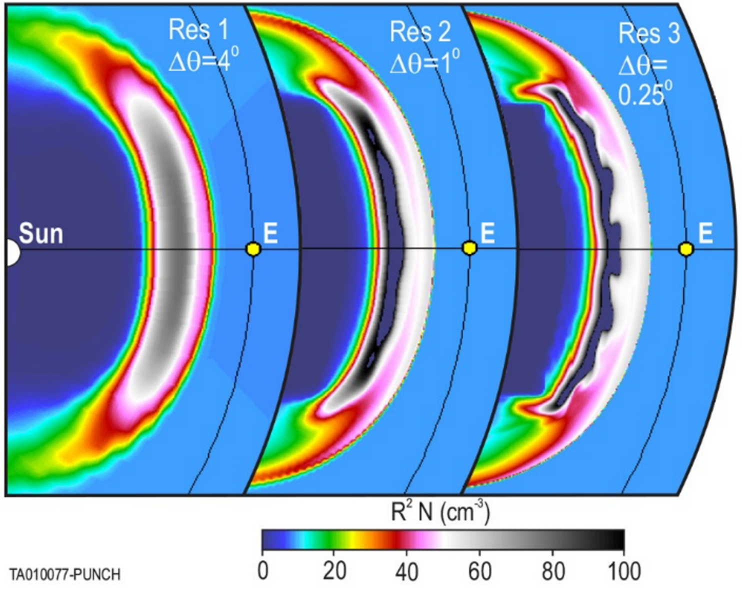
Vourlidas, A., *et al.*: 2003, Direct Detection of Coronal Mass Ejection-Associated Shock in Large Angle and Spectrometric Coronagraph Experiment White-Light Images ApJ **598**, 1392-1402



2C: Shock Dynamics & Morphology

How do shocks form and interact with the solar wind across spatial scales?

- Simulations suggest that CMEs are strongly affected by turbulent instabilities across their shocks.
- Corrugations of shock fronts may be responsible for the acceleration of solar energetic particles (SEPs) and type II radio bursts.
- The current generation of coronagraphs and heliospheric imagers are not designed to capture shock evolution, interactions and possible instabilities, due to sensitivity and motion blur effects.



Odstrcil, 2011

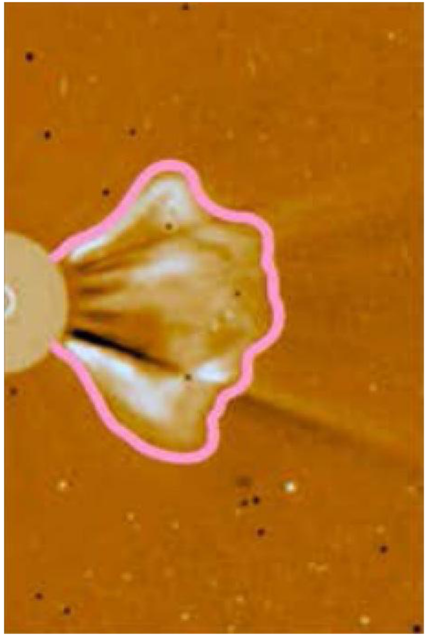
PUNCH observes global shock structure and resolves shock-turbulence interactions.

2C: Shock Dynamics

Science Activities for Baseline Closure on Question 2C

Develop a data-driven, cross-scale picture of shock formation and turbulence using spatial irregularities and brightness variations

PUNCH provides a cross-scale picture of shock formation and shock turbulence interaction, and CME/CIR interactions. This enables breakthrough science in a previously inaccessible observational regime, exploring the role of solar wind variability on interplanetary shock behavior, with implications for SEP acceleration and radio emission.



Tappin and Simnett, 1997

PUNCH is ideally suited for cross-scale analysis, with global field of view and high spatial/temporal resolution.

WG2C: Science Question & Closure

How do shocks form and interact with the solar wind across spatial scales?

PUNCH provides a cross-scale picture of shock formation and shock turbulence interaction, and CME/CIR interactions. This enables breakthrough science in a previously inaccessible observational regime, exploring the role of solar wind variability on interplanetary shock behavior, with implications for SEP acceleration and radio emission.

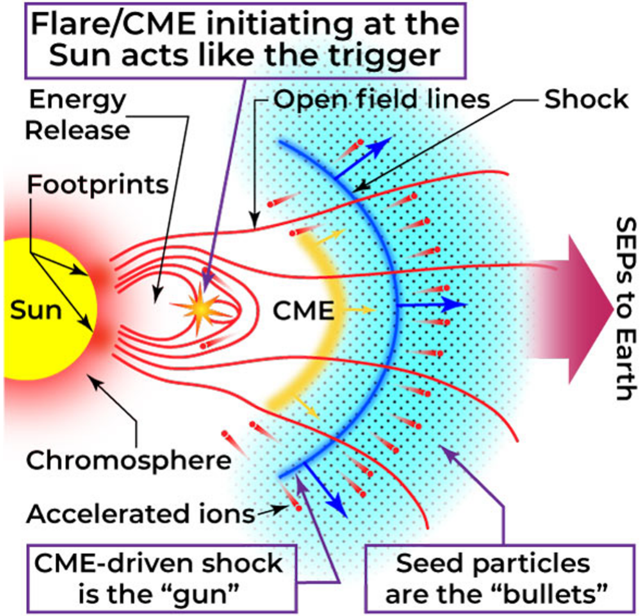


Image credit: adapted from Moses et al. 2015

Connection between shock formation, structure, evolution and SEPs and Space Weather