PSTI UCLA
Plasma Science and Technology Institute

Outstanding Problems in Astrophysical Plasmas and Magnetic Fields on all Scales

21 September 2015

Plasma Fest

The baryonic universe consists almost entirely of plasmas !

- stellar (solar) atmospheres
- stellar interiors
- pre-recombination universe
  (< 380,000 years ABB)
- post-reionization universe
- HII regions
- stellar (solar) winds
- accretion disks around compact objects
- supernova remnants
- intergalactic medium
- pulsar wind nebulae
- astrophysical jets
- cosmic rays
- coronal gas
- synchrotron nebulae
- relativistic shocks

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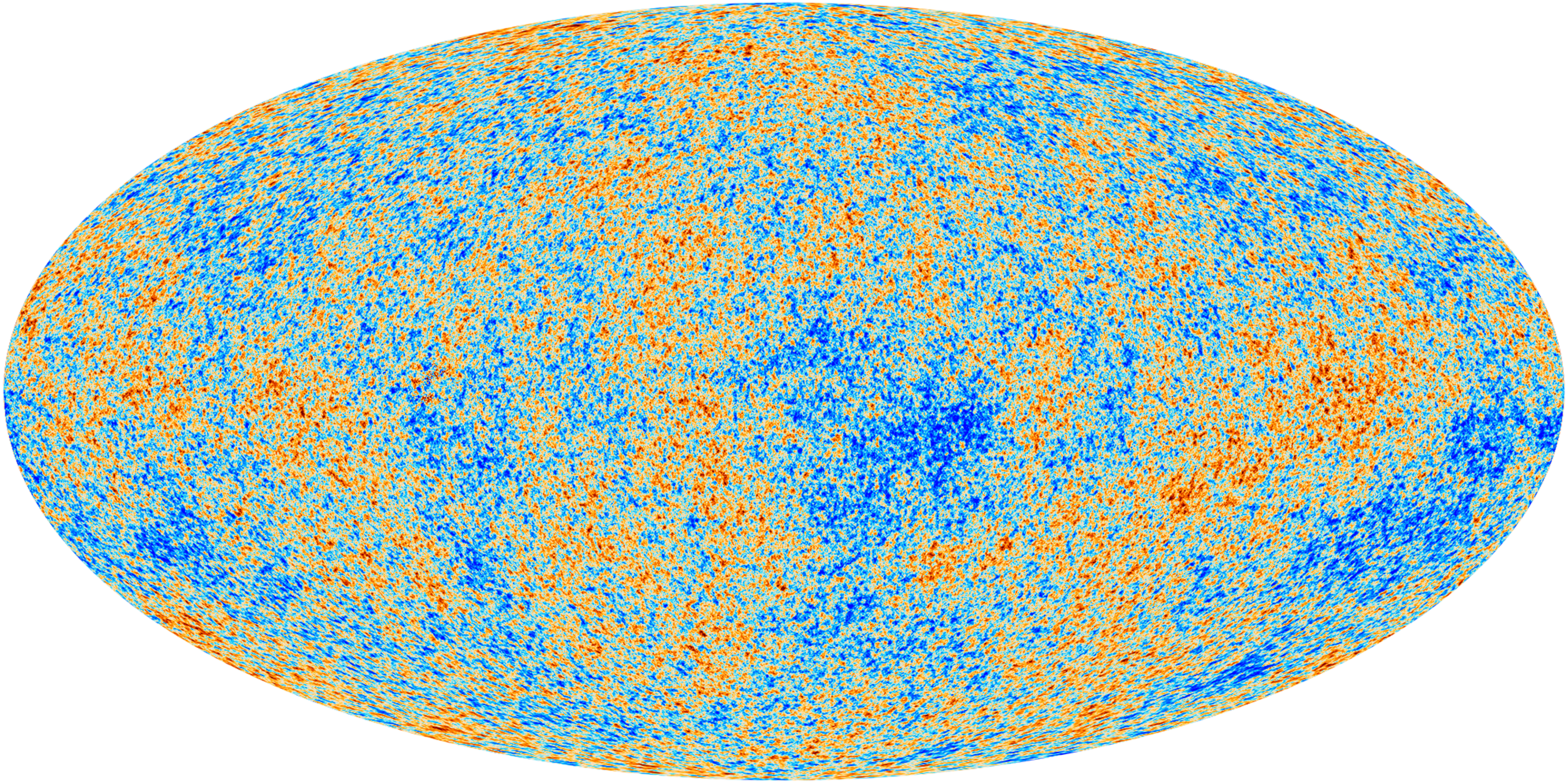
→ Even neutral gas clouds have a plasma description because of residual ionization and the coupling between ions and neutrals

Research on astrophysical *plasmas* very closely coupled to research on *magnetic fields*

- jets, flares, loops, filaments → all organized or generated by magnetic fields
- magnetosphere-wind and magnetosphere-accretion-flow interactions
- disk evolution → magnetic field fosters angular momentum transport via magnetic tension and MHD instabilities that generate turbulent viscosity.
- modern star formation theories all include magnetic braking mechanisms to facilitate accretion.
- Plasma generation in pulsar magnetospheres critical for their evolution

Themes of astrophysical plasma research at UCLA

- **early universe –**
    - Cosmic microwave background – Ned Wright
    - cosmic dark ages and re-ionization – Steve Furlanetto
    - origin of magnetic fields in the universe – Ferd Coroniti, Smadar Naoz
- **Galactic Center Group –** Morris, Andrea Ghez, Tuan Do, Gunther Witzel
    - accretion onto the central black hole
    - synchrotron filaments and the Galactic center magnetosphere
    - jets
    - stellar and galactic winds
    - supernova shocks
    - HII regions
- **pulsars & pulsar wind nebulae –** Ferd Coroniti, Brad Hansen



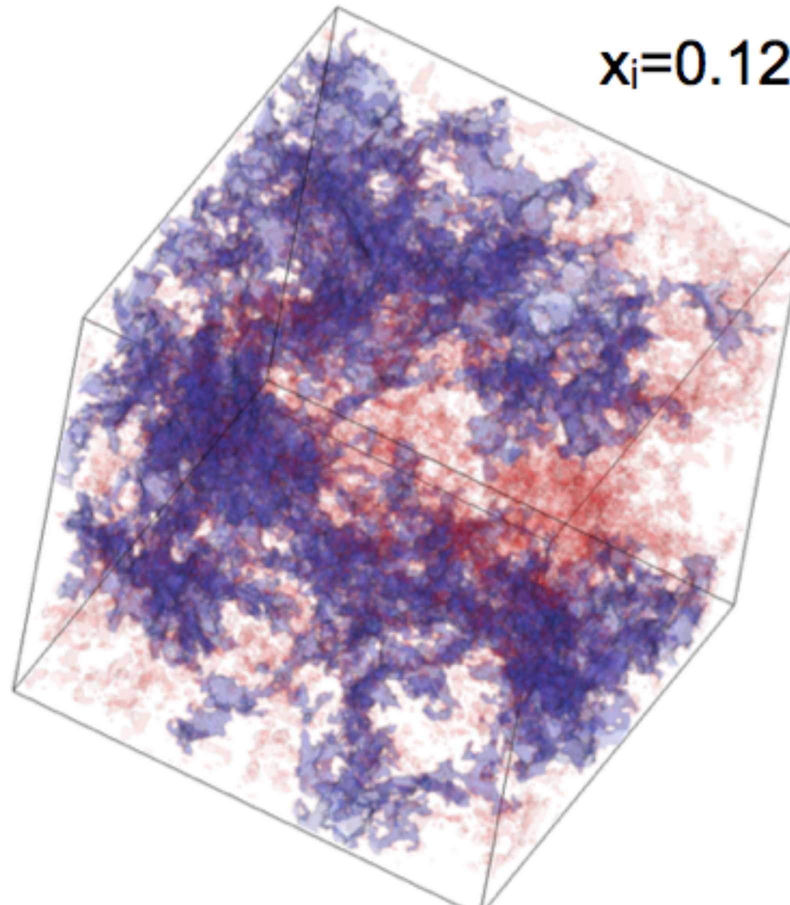
Planck all-sky image of CMBR

ESA and the Planck Collaboration

Plasmas and Magnetic Fields During Structure Formation

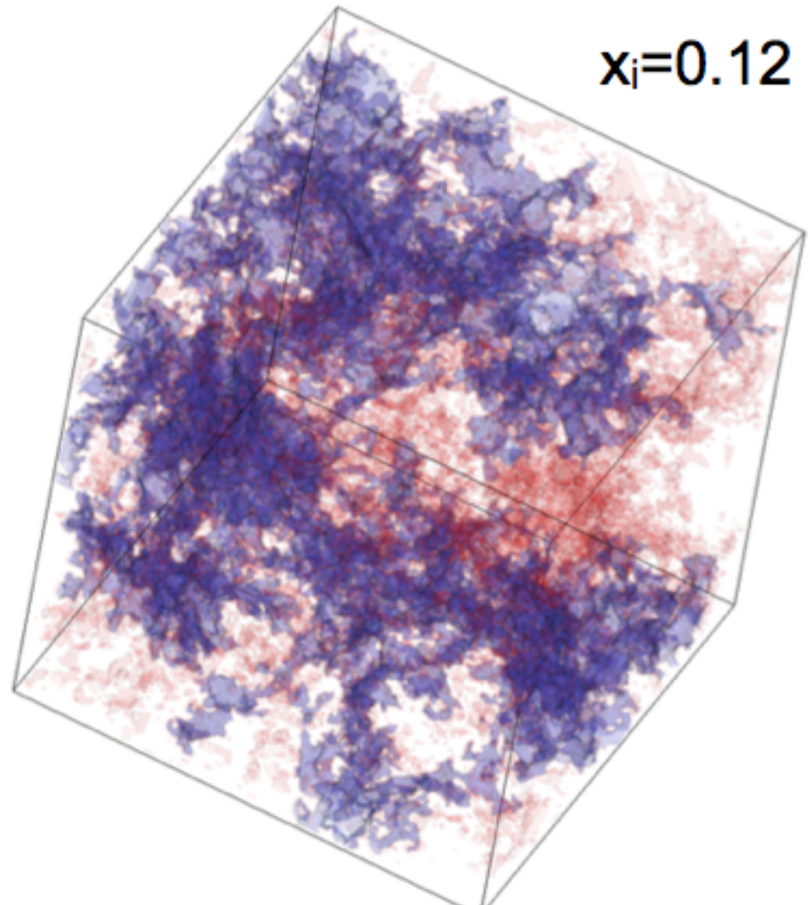
Astronomy Group: Furlanetto

- Furlanetto's primary concern is with the low-density intergalactic medium and its interaction with galaxies
  - How important are cosmic rays?
- ***Reionization*** is the epoch at which the first galaxies ionize the IGM (and heat it)
  - Red and blue: ionized regions



Astronomy Group: Furlanetto

- Key plasma questions:
  - How does the IGM get heated?
  - Do cosmic rays affect the IGM?
  - What creates intergalactic magnetic fields?
  - How do accretion disk sources ionize and/or heat the Universe?



Generation of Primordial Magnetic Fields on Linear Overdensity Scales

Smadar Naoz* and Ramesh Narayan

Harvard-Smithsonian Center for Astrophysics, Institute for Theory and Computation, 60 Garden Street, Cambridge, Massachusetts 02138, USA

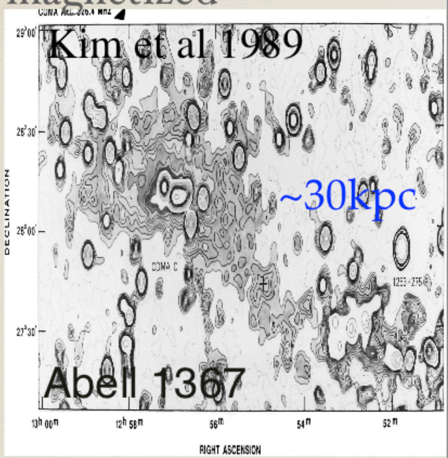
(Received 1 April 2013; revised manuscript received 17 May 2013; published 29 July 2013)

Magnetic fields appear to be present in all galaxies and galaxy clusters. Recent measurements indicate that a weak magnetic field may be present even in the smooth low density intergalactic medium. One explanation for these observations is that a seed magnetic field was generated by some unknown mechanism early in the life of the Universe, and was later amplified by various dynamos in nonlinear objects like galaxies and clusters. We show that a primordial magnetic field is expected to be generated in the early Universe on purely linear scales through vorticity induced by scale-dependent temperature fluctuations, or equivalently, a spatially varying speed of sound of the gas. Residual free electrons left over after recombination tap into this vorticity to generate magnetic field via the Biermann battery process. Although the battery operates even in the absence of any relative velocity between dark matter and gas at the time of recombination, the presence of such a relative velocity modifies the predicted spatial power spectrum of the magnetic field. At redshifts of order a few tens, we estimate a root mean square field strength of order 10^{-25}–10^{-24} G on comoving scales ~ 10 kpc. This field, which is generated purely from linear perturbations, is expected to be amplified significantly after reionization, and to be further boosted by dynamo processes during nonlinear structure formation.

Primordial Magnetic Fields
Smadar Naoz's group

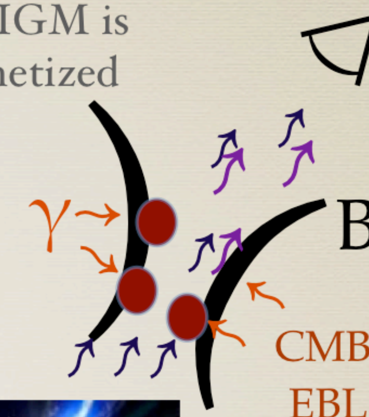
Observation: the Universe is magnetized:

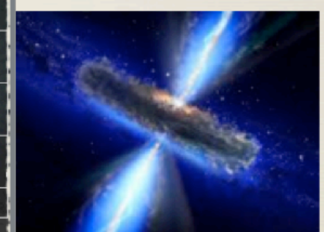
Galaxy clusters are magnetized



Galaxies, new and old are magnetized

The IGM is magnetized





Research question: How were these magnetic fields generated?

Plasma instabilities at the early Universe and their effect on structure formation

Naoz & Narayan 2013, PRL: Plasma instabilities, such as the Biermann battery, at the early Universe can generate the primordial magnetic fields

$$\dot{B} \sim \bar{T}\nabla\delta_e \times \nabla\delta_T$$

Before re-ionization: $B \sim 10^{-25}$-10^{-24} G

After re-ionization $B \sim 10^{-18}$ G

Shear-shock generated magnetic fields:

THE ASTROPHYSICAL JOURNAL, 780:146 (6pp), 2014 January 10 doi:10.1088/0004-637X/780/2/146

ON THE POSSIBLE ORIGIN OF THE LARGE SCALE COSMIC MAGNETIC FIELD

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Received 2013 September 11; accepted 2013 November 21; published 2013 December 19

ABSTRACT

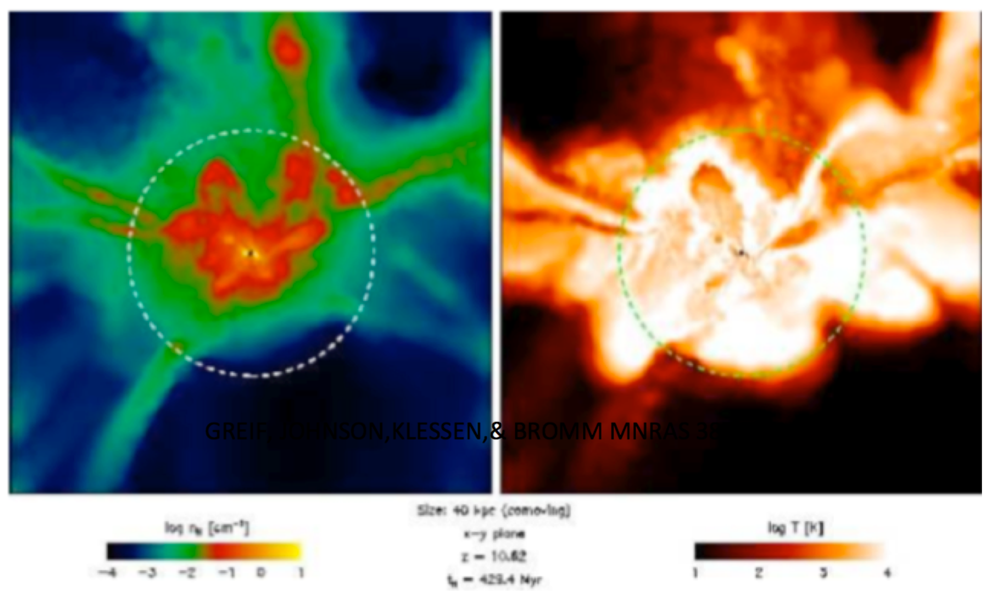
The possibility that the large scale cosmic magnetic field is directly generated at microgauss, equipartition levels during the reionization epoch by collisionless shocks that are forced to satisfy a downstream shear flow boundary condition is investigated through the development of two models—the accretion of an ionized plasma onto a weakly ionized cool galactic disk and onto a cool filament of the cosmic web. The dynamical structure and the physical parameters of the models are synthesized from recent cosmological simulations of the early reionization era after the formation of the first stars. The collisionless shock stands upstream of the disk and filament, and its dissipation is determined by ion inertial length Weibel turbulence. The downstream shear boundary condition is determined by the rotational neutral gas flow in the disk and the inward accretion flow along the filament. The shocked plasma is accelerated to the downstream shear flow velocity by the Weibel turbulence, and the relative shearing motion between the electrons and ions produces a strong, ion inertial scale current sheet that generates an equipartition strength, large scale downstream magnetic field, $\sim 10^{-6}$ G for the disk and $\sim 6 \times 10^{-8}$ G for the filament. By assumption, hydrodynamic turbulence transports the shear-shock generated magnetic flux throughout the disk and filament volume.

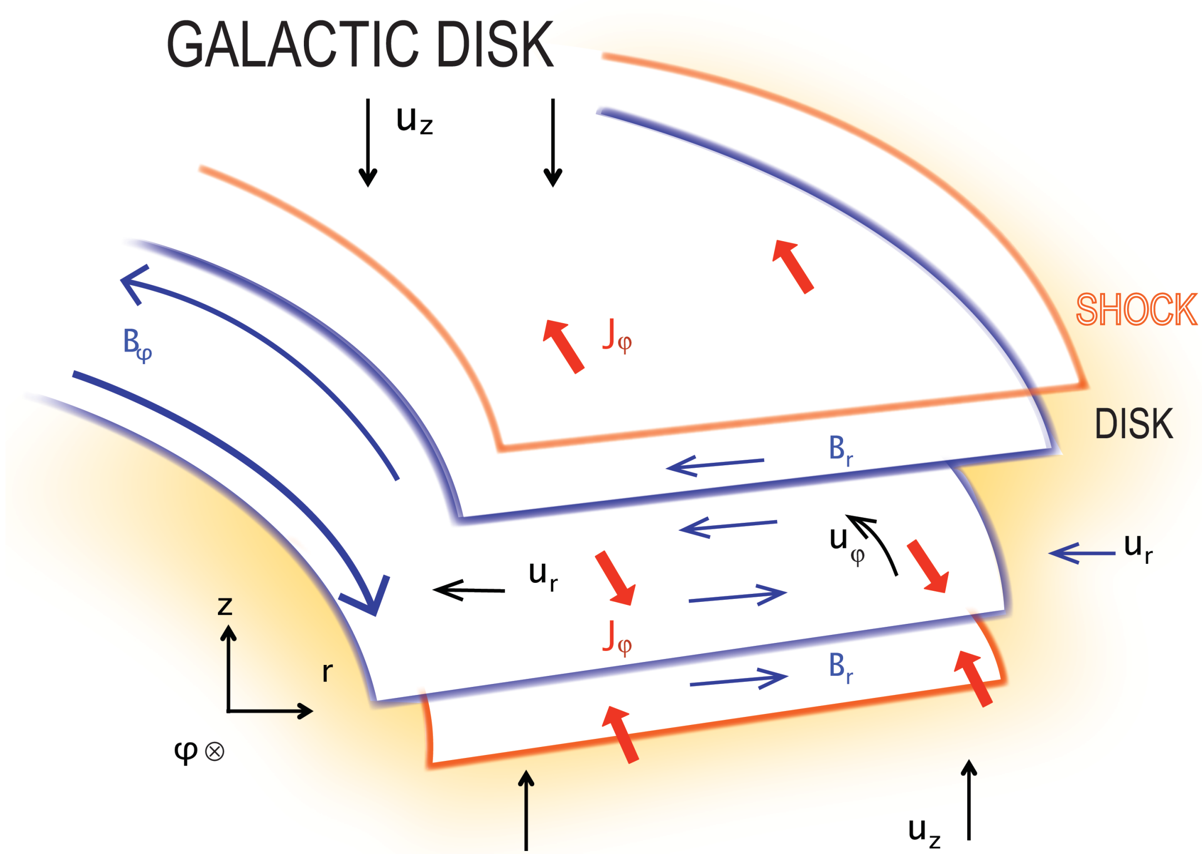
GENERATION OF STRONG LARGE SCALE MAGNETIC FIELD

- NEED A SHEAR FLOW BETWEEN IONS AND ELECTRONS TO CREATE A LARGE SCALE CURRENT.
- LIKELY SOURCE FOR THE SHEAR MOTION IS NEUTRAL FLOWS THAT ARE COLLISIONALLY COUPLED TO THE PLASMA AND PROVIDE THE ENERGY TO CREATE B.
- THE MIXTURE OF ENERGETIC NEUTRAL FLOWS AND COLLISIONLESS FULLY IONIZED PLASMA OCCURS DURING THE ERA OF REIONIZATION ($6 < z <$ 20-30) WHEN POP III STARS START TO IONIZE THE PROTOGALACTIC REGION THAT IS BEING FORMED BY INFLOW ALONG THE COSMIC WEB.

FIRST COOLING FLOW GALAXY

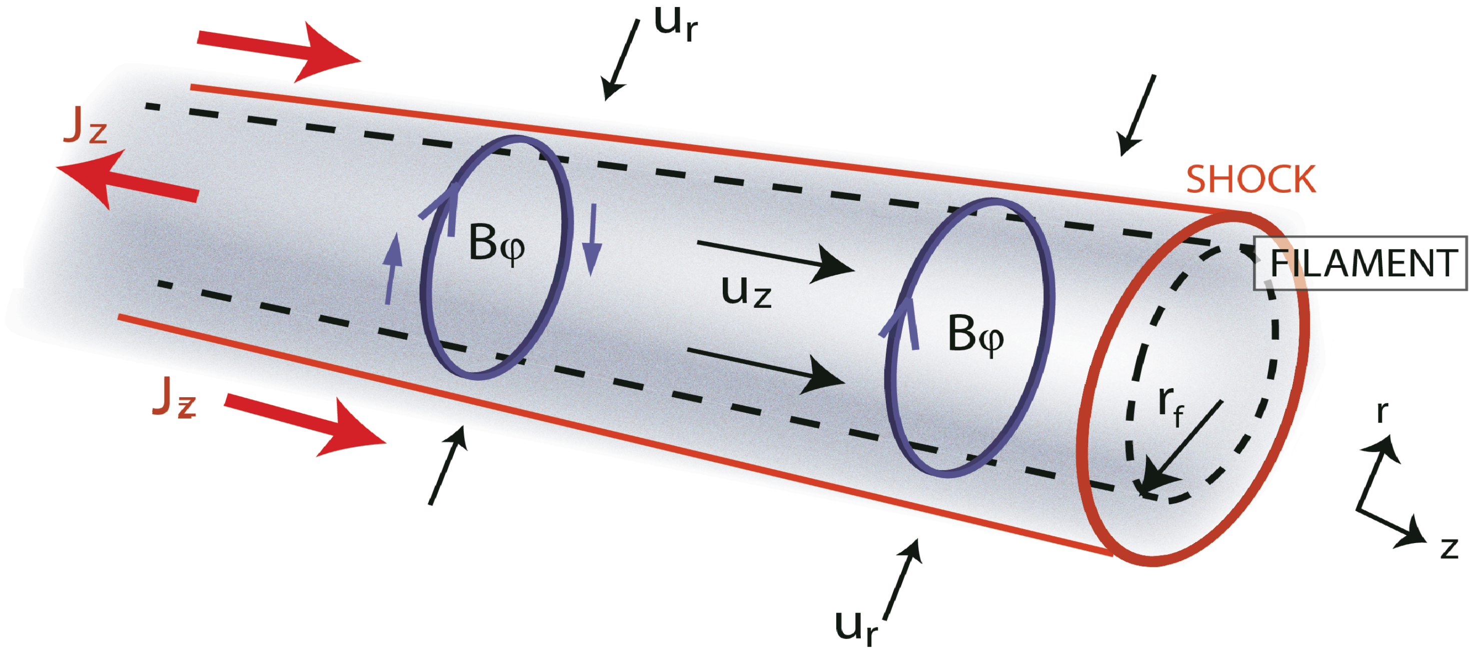
GREIF, JOHNSON,KLESSEN,& BROMM MNRAS 387, 1021, 2008





Can generate an equipartition-strength, large-scale downstream magnetic field of 10^{-6} gauss

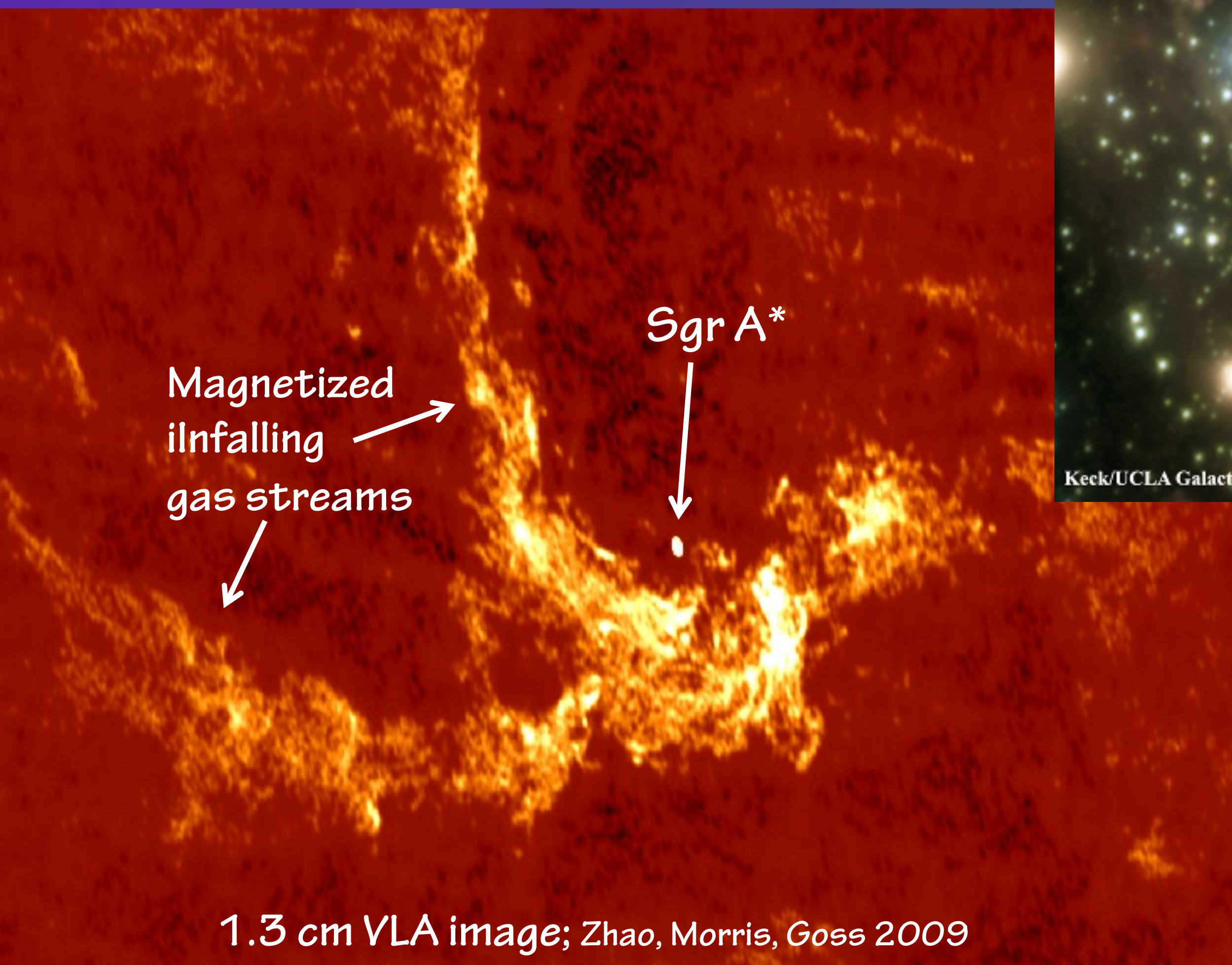
COSMIC WEB FILAMENT



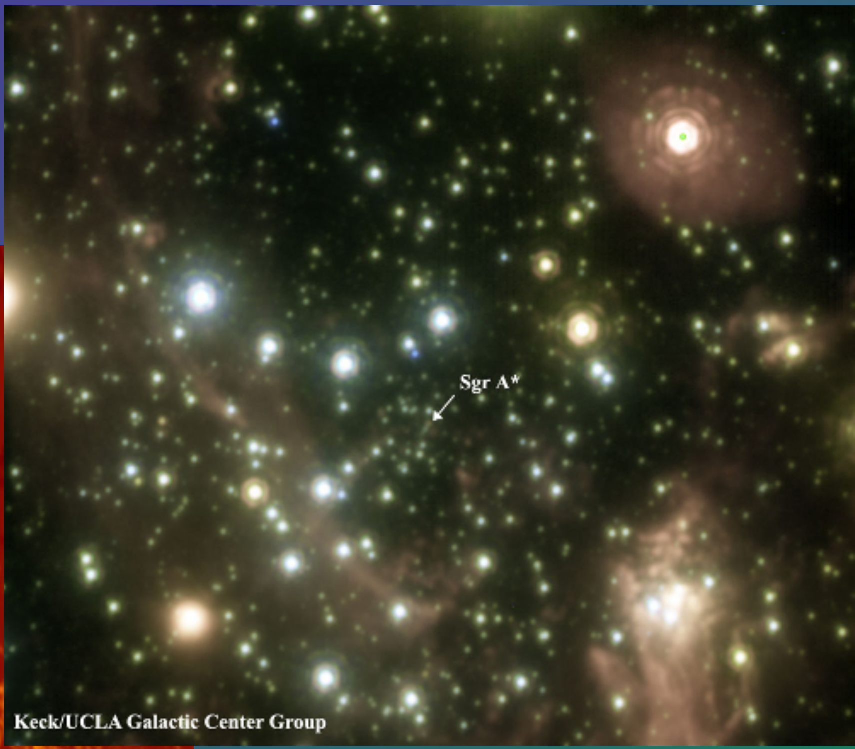
Generates an equipartition-strength, large-scale downstream magnetic field of ~ 10^{-7} gauss

Plasmas and Fields in the Galactic Center

Accretion onto the Central Black Hole



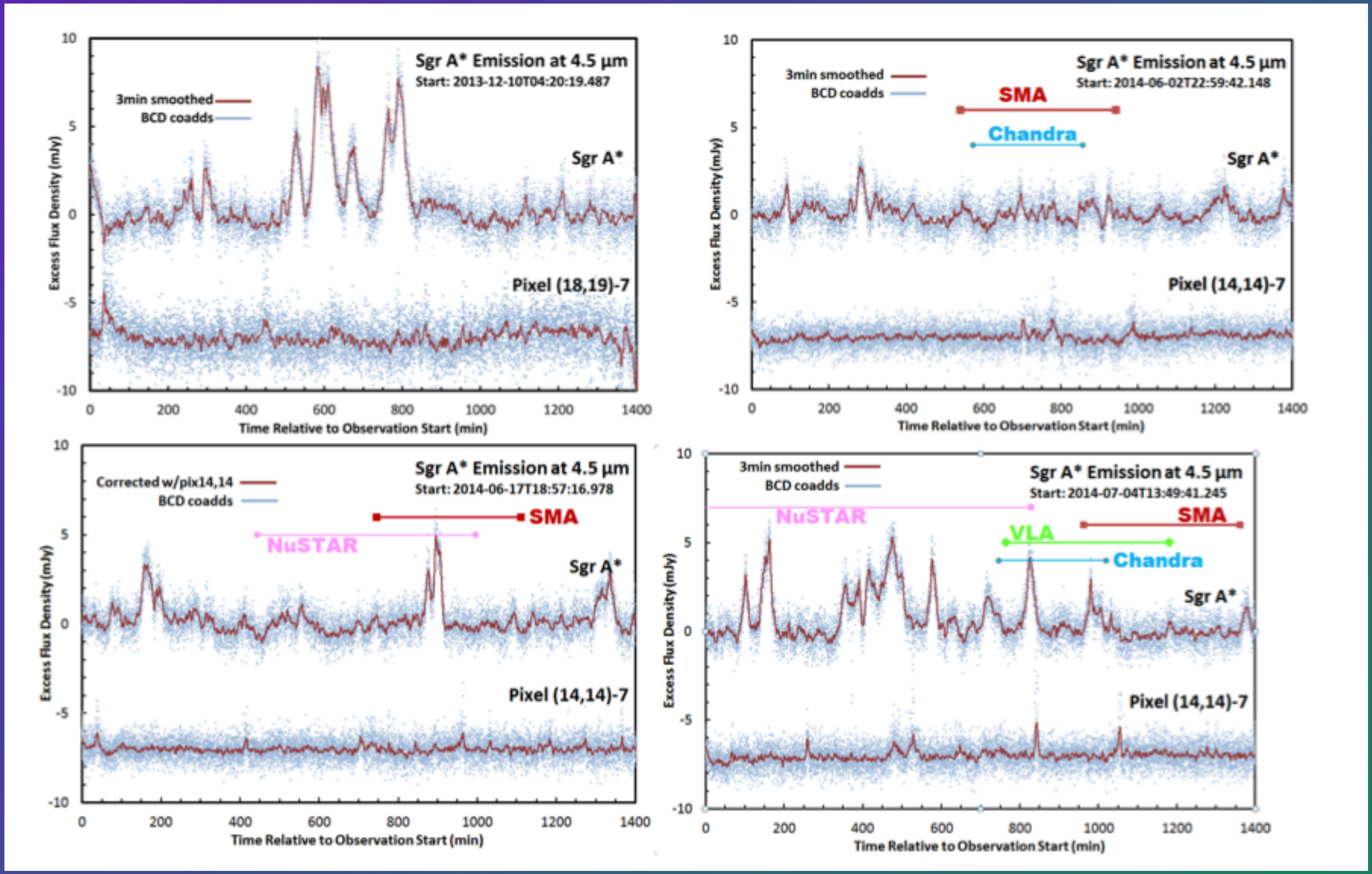
1.3 cm VLA image; Zhao, Morris, Goss 2009



2.2 µm Keck AO image
stellar winds from massive stars

Accretion signatures – light curves of Sgr A*

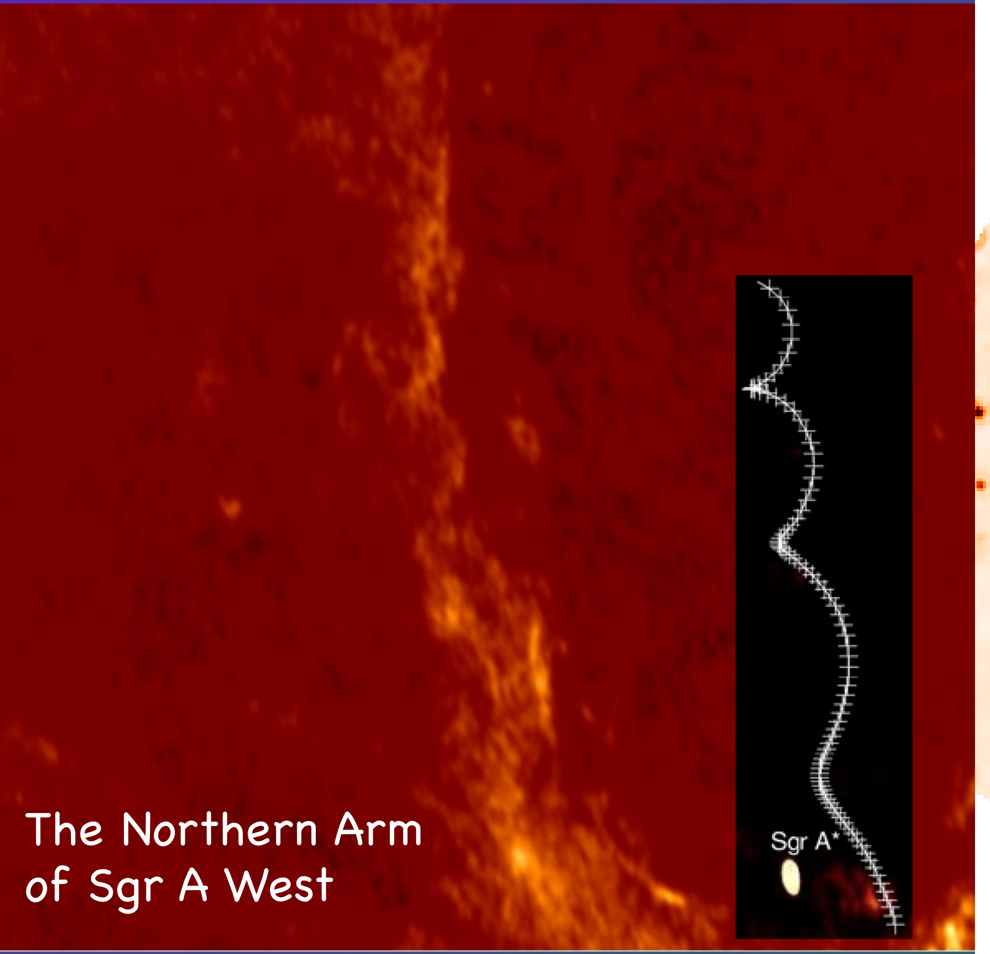
with Spitzer at 4.5 μm (Hora et al. 2014; Witzel et al. in preparation)



Source of variability unknown – unsteady accretion? MRI? Jet? Lensing? Tidally disrupted objects?

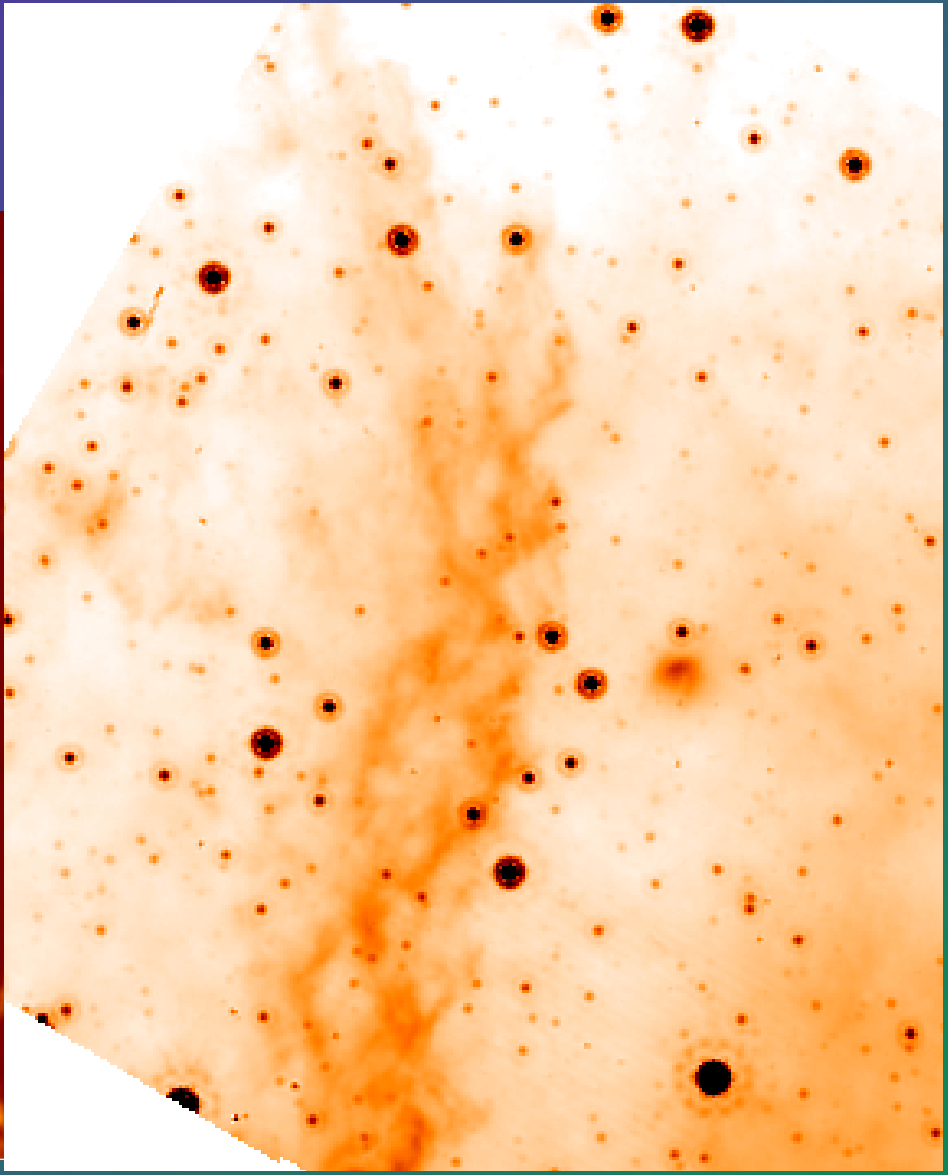
Helical Features

0.25 pc scale

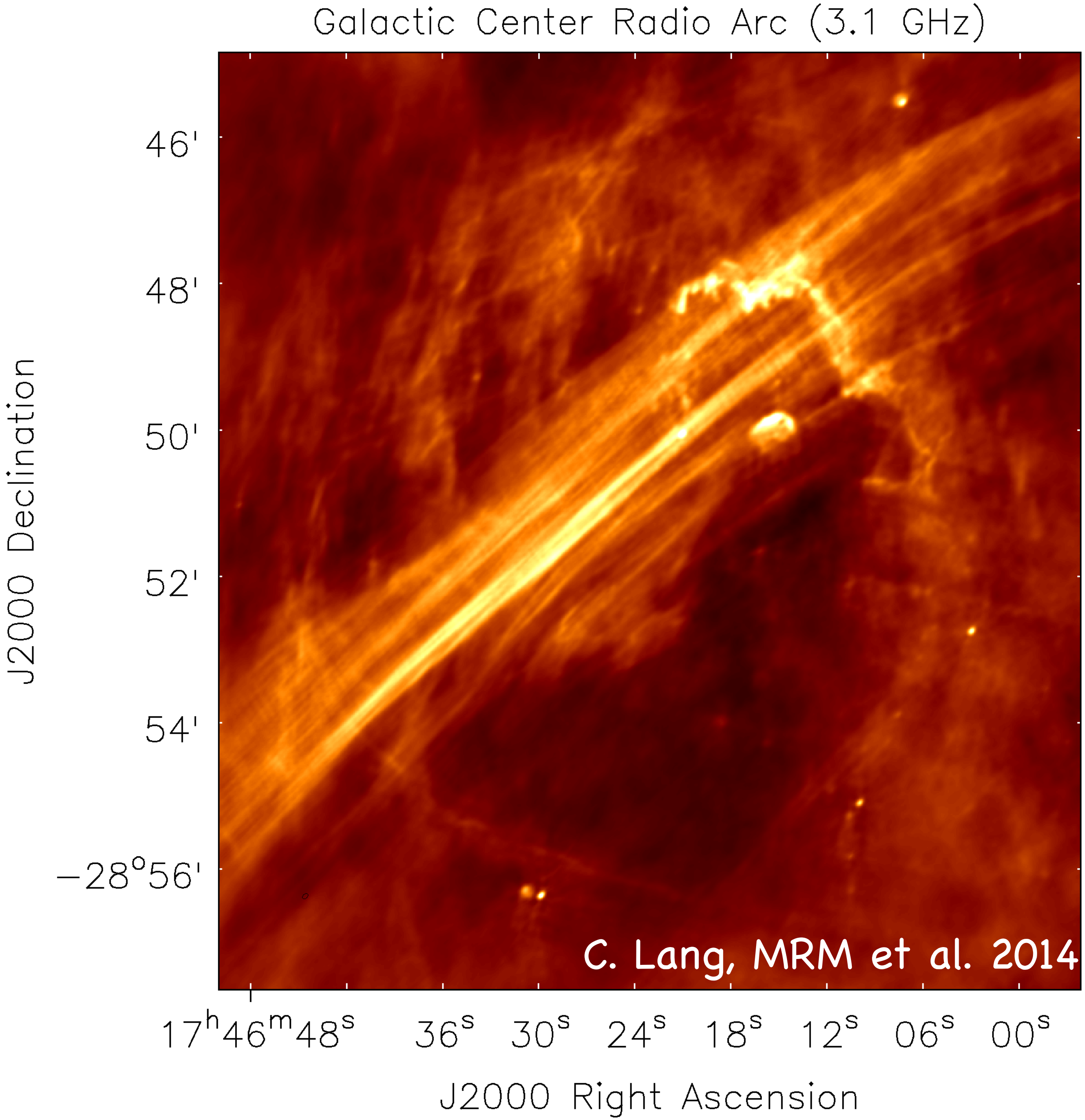


1.3 cm VLA; Zhao, MRM + 2009

100 pc scale – Double Helix

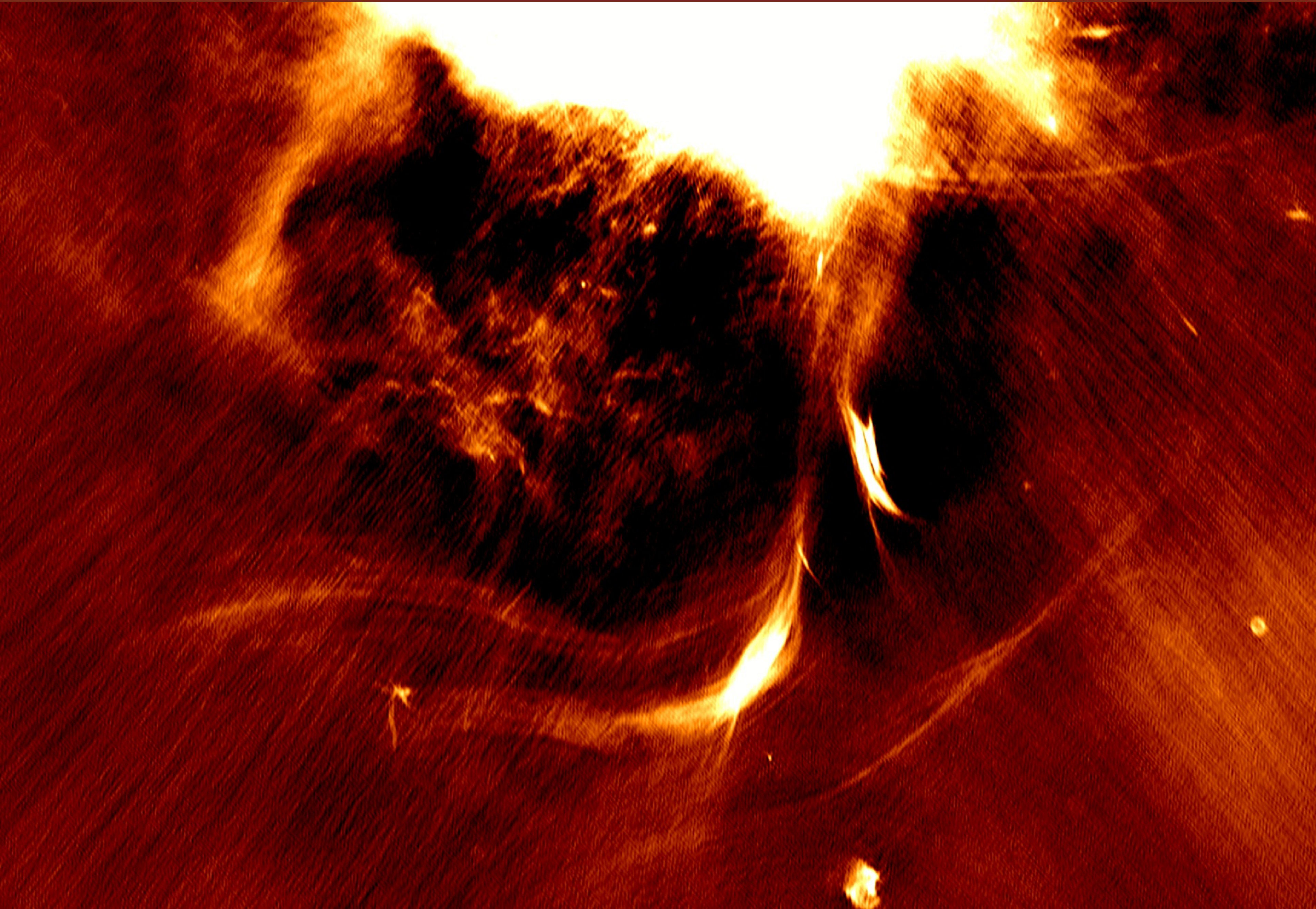


Spitzer/MIPS 24 μm; MRM, Do, Uchida 2006



Galactic Center Radio Arc (3.1 GHz)
46'
48'
50'
52'
54'
−28°56'
J2000 Declination
17h46m48s
36s
30s
24s
18s
12s
06s
00s
J2000 Right Ascension
C. Lang, MRM et al. 2014

The “Southern Curl” – a larger-scale magnetic distortion



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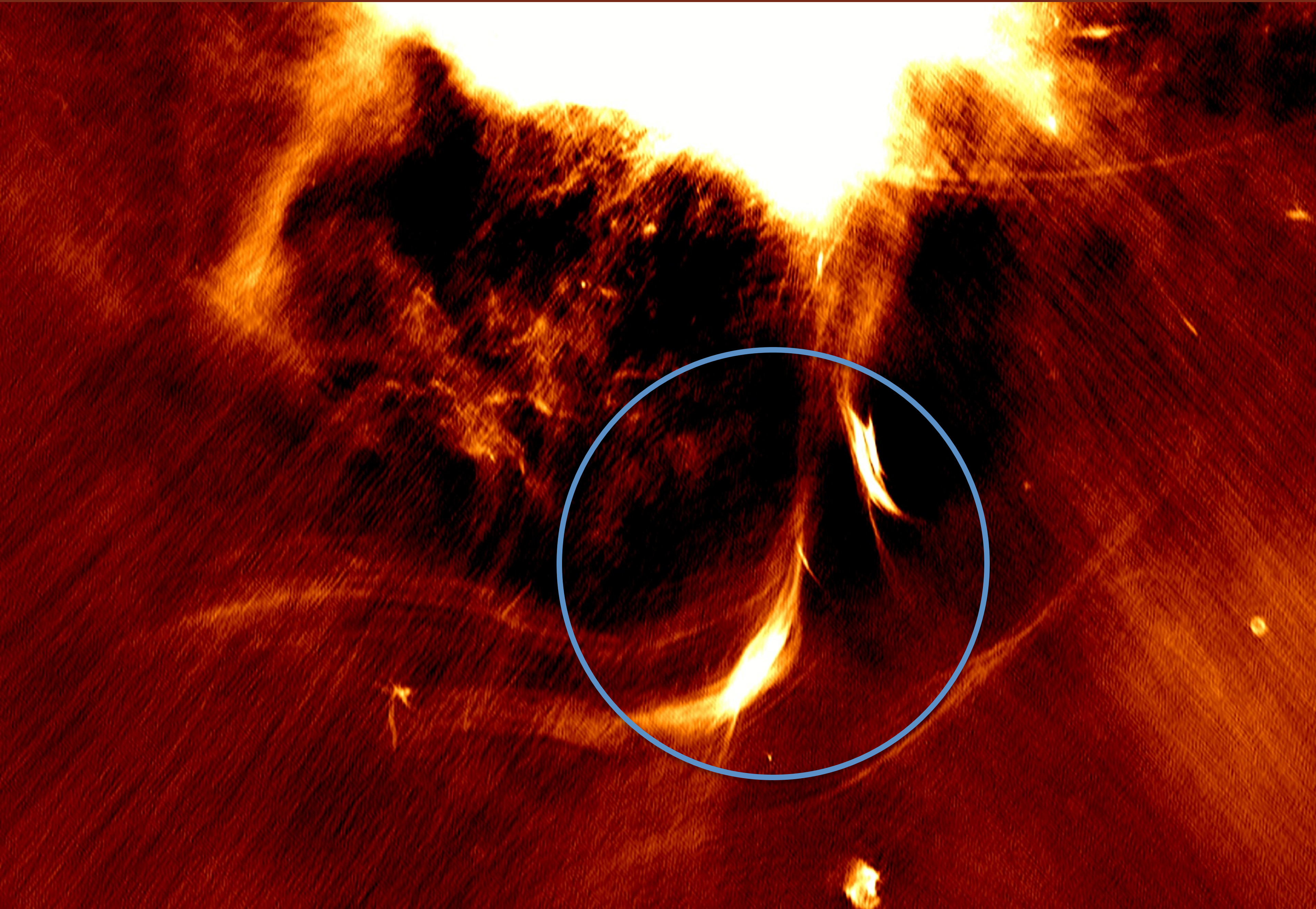

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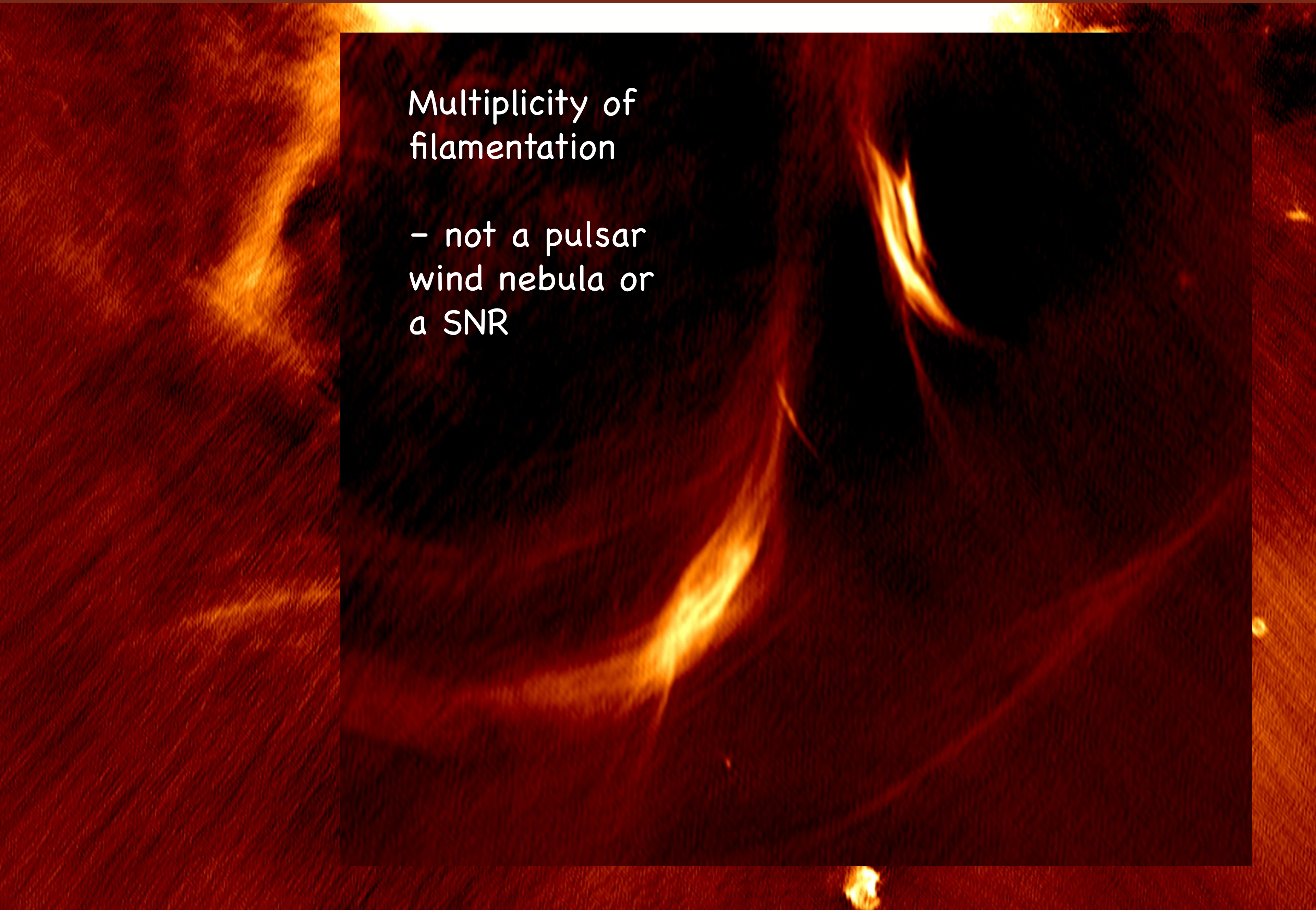


Multiplicity of filamentation

– not a pulsar wind nebula or a SNR

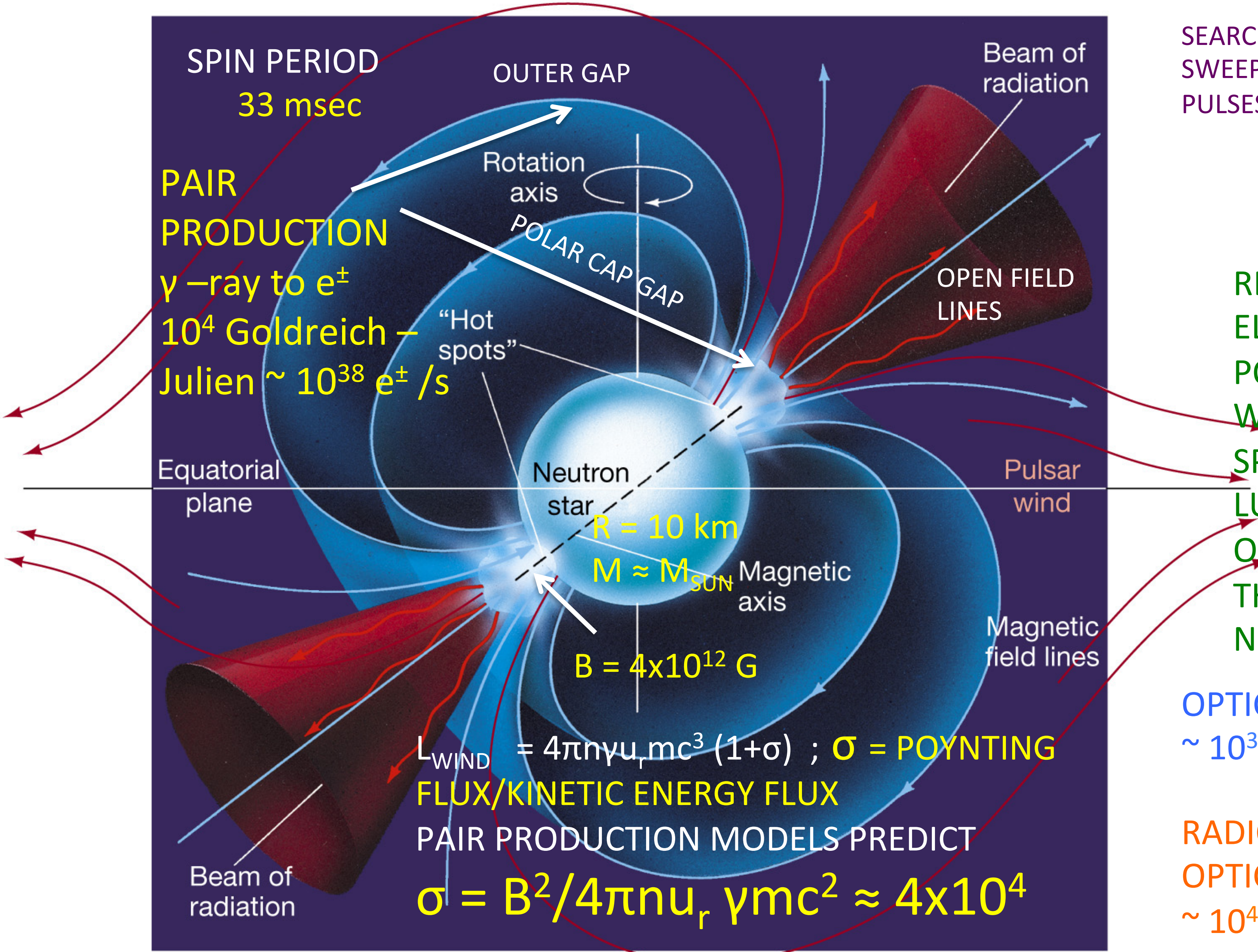
Pulsars and Pulsar Wind Nebulae

The Crab Nebula – Ferd Coroniti

Neutron Star Mergers – Brad Hansen

CRAB PULSAR

SPINDOWN POWER $L = I\Omega \, d\Omega/dt = 5\text{x}10^{38}$ ergs/s

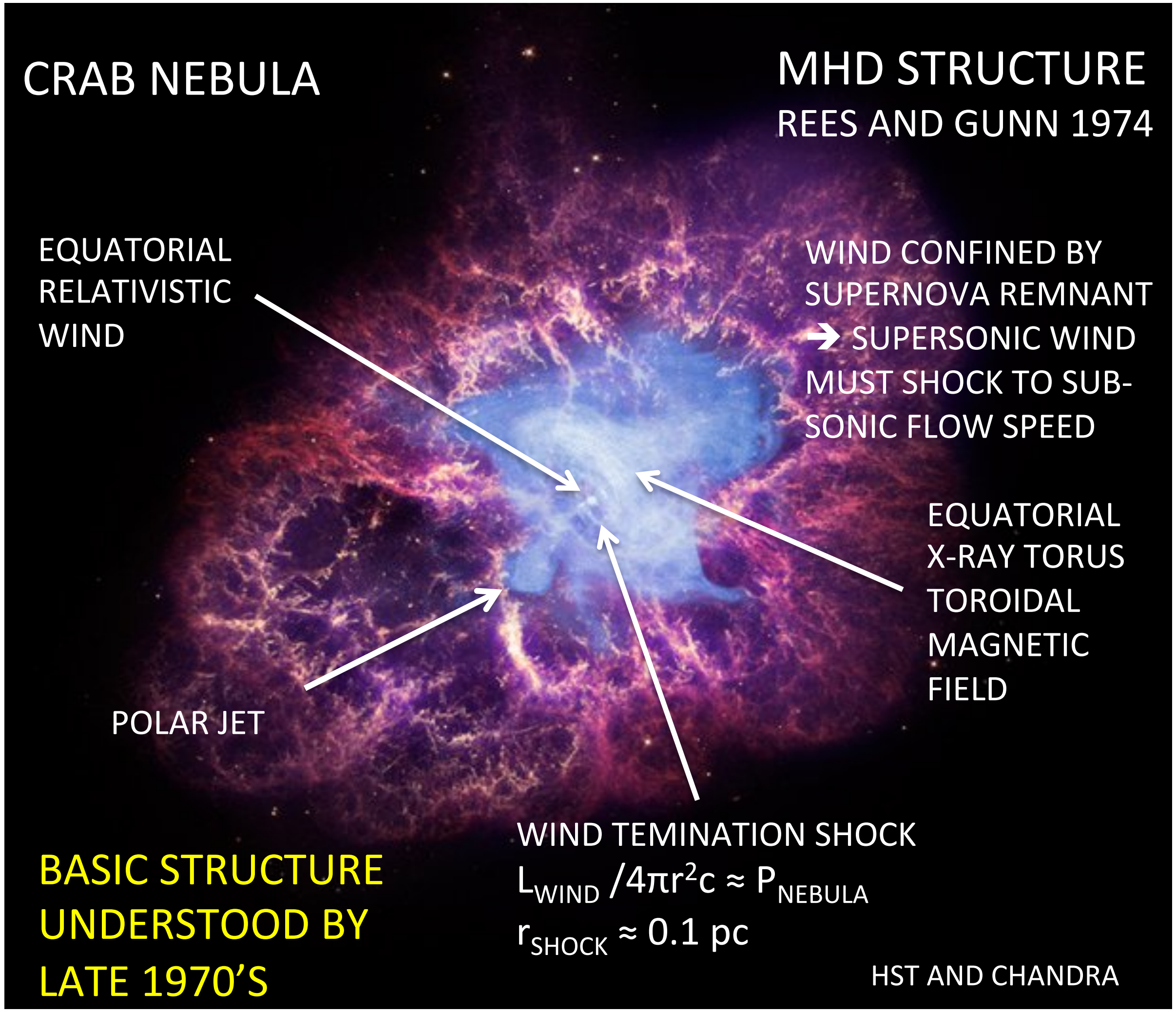


SEARCH LIGHT SWEEP PRODUCES PULSES

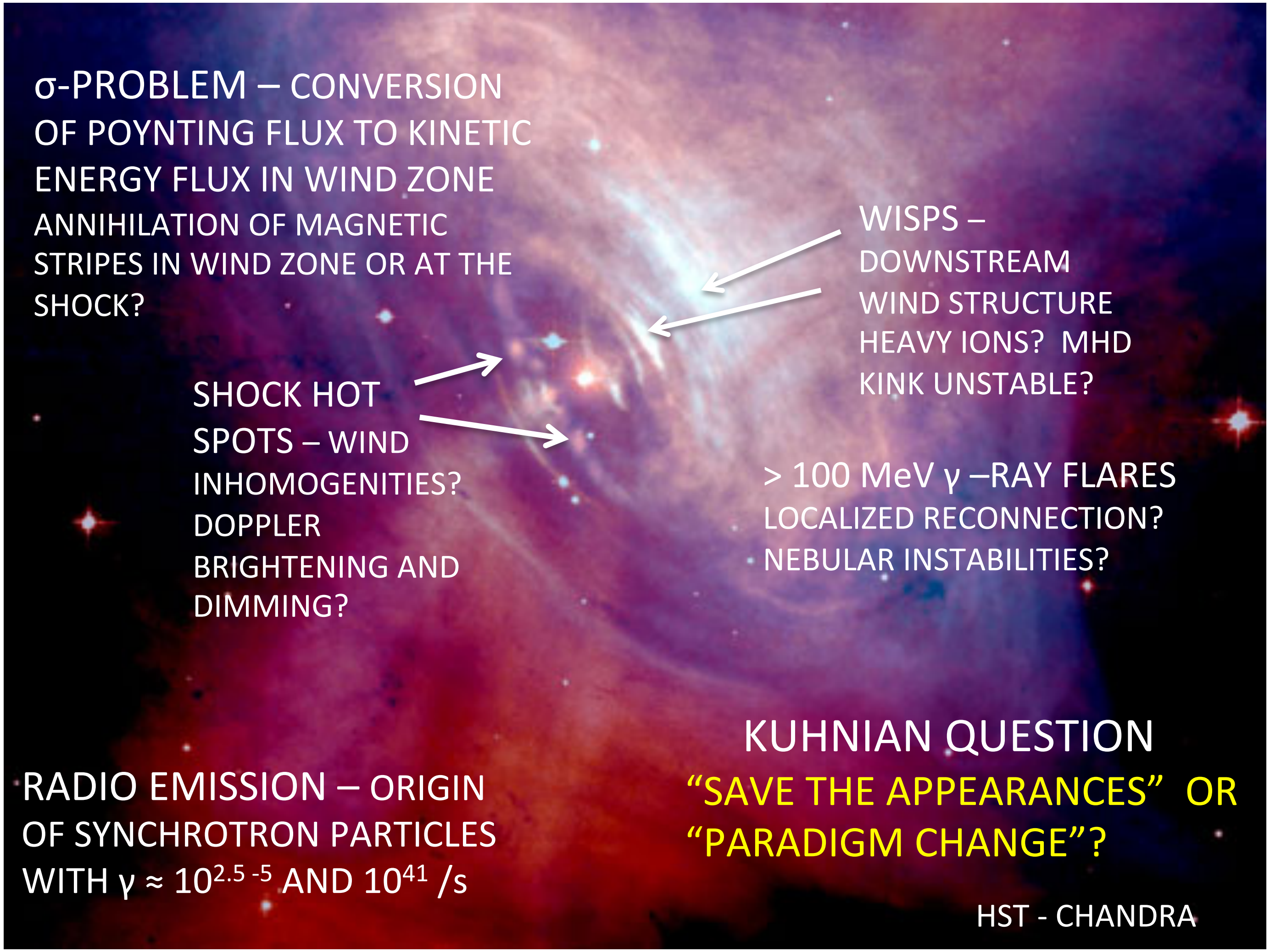
RELATIVISTIC ELECTRON-POSITRON WIND CARRIES SPIN-DOWN LUMINOSITY OUTWARD TO THE CRAB NEBULA

OPTICAL TO γ-RAY
~ 10^{38} $e^{\pm}$ pairs/s

RADIO TO OPTICAL
~ 10^{41} $e^{\pm}$ pairs/s

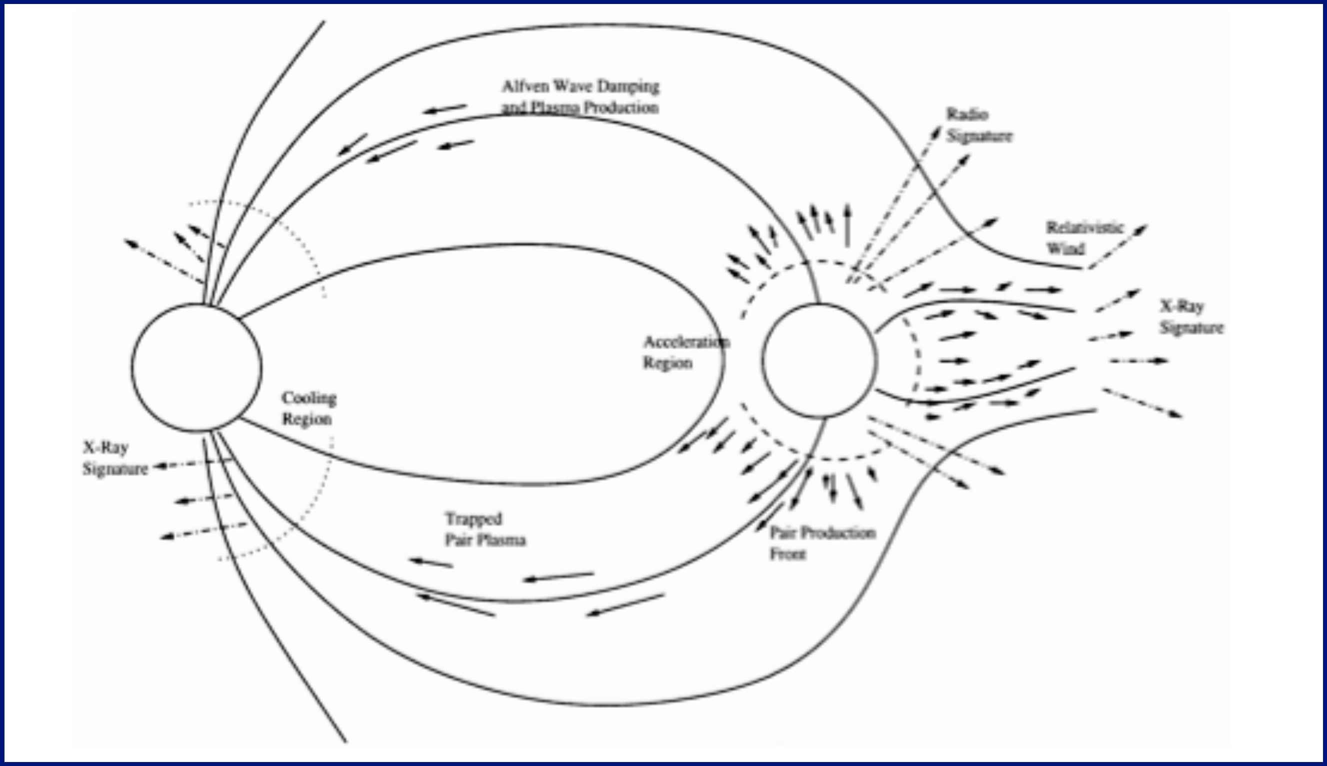

CRAB NEBULA
MHD STRUCTURE
REES AND GUNN 1974
EQUATORIAL RELATIVISTIC WIND
WIND CONFINED BY SUPERNOVA REMNANT
➔ SUPERSONIC WIND MUST SHOCK TO SUB-SONIC FLOW SPEED
EQUATORIAL X-RAY TORUS
TOROIDAL MAGNETIC FIELD
POLAR JET
WIND TEMINATION SHOCK
$L_{WIND} / 4\pi r^2 c \approx P_{NEBULA}$
$r_{SHOCK} \approx 0.1$ pc
BASIC STRUCTURE UNDERSTOOD BY LATE 1970'S
HST AND CHANDRA

CRAB NEBULA CONUNDRUMS



Brad Hansen: Transient Electromagnetic Signals from Neutron Star Mergers

Hansen & Lyutikov (2001)
MNRAS, 322, 695



Advanced LIGO hopes to find signatures of gravitational waves from neutron star mergers in the next few years. What are the potential electromagnetic counterparts? Plasma generation during inspiral and during the post merger settling of the neutron star may determine the nature of these transients.

Active Galactic Nuclei:

- massive magnetized accretion disks around supermassive black holes
- Is the magneto-rotational instability sufficient to account for the multi-wavelength variability?
  Matt Malkan
- What emission process accounts for the spectral energy distribution? Ned Wright