Composition, Particle Physics & Sources of UHECRs

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4th Workshop on Air Shower Detection at High Altitude
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Galactic Magnetic Field

A new era:

It is now possible to estimate magnetic deflections in the Galactic Magnetic Field

Glennys Farrar and Ronnie Jansson

Center for Cosmology and Particle Physics
New York University

RJ & GF, Ap.J. 757, 14 (2012) coherent & striated
RJ & GF, Ap.J.Lett. 761, L11 (2012) random & n_{cre}
GF, RJ, I Feain & B. Gaensler JCAP (2012) Cen A

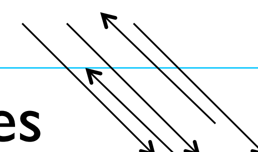
35 parameter model of the GMF

χ^2/dof = 1.064 for > 10k dof

40,000 **Rotation Measures** of distant quasars $\sim \int_z^\infty dz\, n_e(\mathbf{x})\, B_{\|}(\mathbf{x})$

WMAP total & **polarized synchrotron** emission of Milky Way (>10^5 datapoints) $\sim \int_z^\infty dz\, n_{cre}(\mathbf{x})\, B_{\perp}^2(\mathbf{x})$

Complementary!

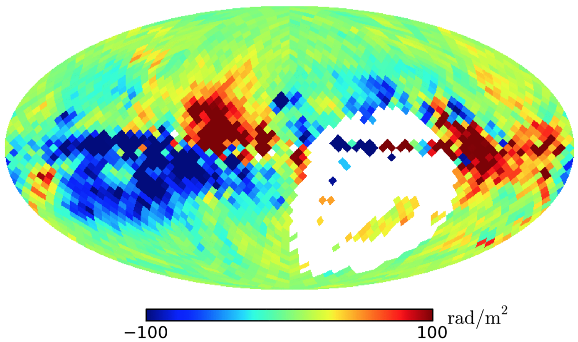


JF12 model has coherent, *"striated"* and random pieces

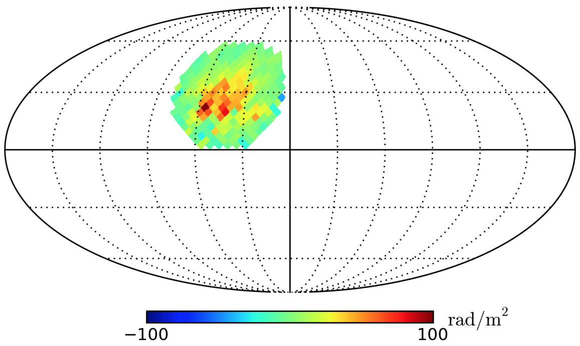
- Disk with spiral arms
- Toroidal Halo
- Out-of-plane "X" field

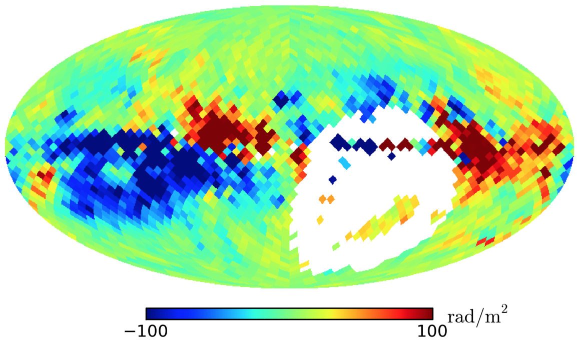
fit => $B_{stri} \approx \pm 1.2\, B_{reg}$

Nitty-gritty I: RMs



- 40403 extragalactic RMs
  - some are duplicate measurements of same source
- Map to 8 10^{-4} sq-deg Healpix pixels; 50M
  - if multiple measurements, take the best quality ones
  - average. => 38627 pixels with RMs
- Remove outliers
  - for each pixel, measure mean & variance of neighbors
  - remove pixels > 3 sigma from local mean; iterate
  - 666 pixels removed
- **Bin to 2067 pixels** (13.4 sq-deg) sky has 3072; some have
- **Measure variance from sub-pixels**
- Subtract foregrounds (GIMMs) Wolleben et al (2010)

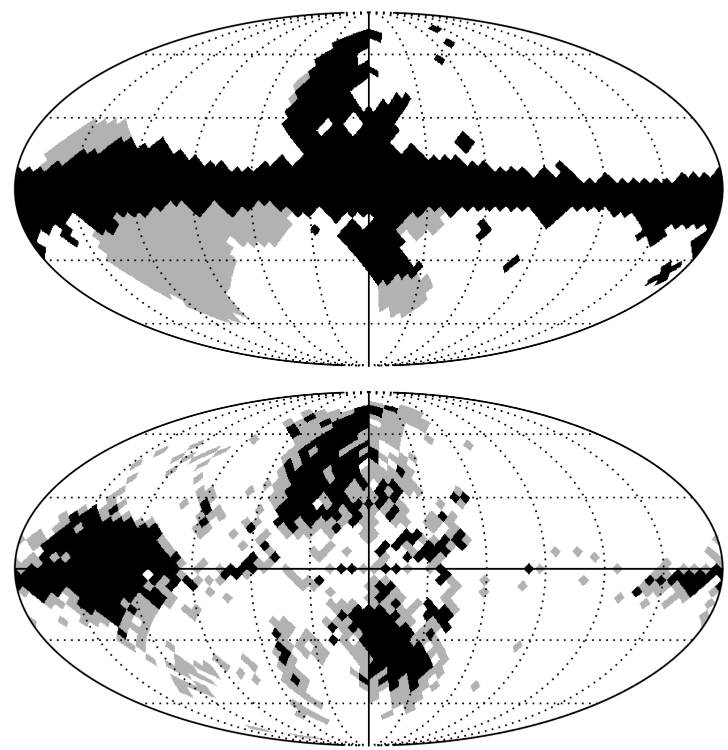




Nitty-gritty II: Synchrotron Maps

- WMAP 7-yr K-band, 22 GHz synchrotron maps
- Bin to 2067 pixels (13.4 sq-deg)
- Measure variance from sub-pixels
- Foreground
  - contributes ~$1/r^2$; need masking (?)
  - try 4 masks:
    - WMAP polarization (black, upper plot) 27%
    - extended WMAP to remove hi-PI regions attributable to local structures (grey) 35%
    - Pull > 3 (black, lower plot) or > 2 (grey)

$$p = \sqrt{(Q^2 + U^2)/(\sigma_Q^2 + \sigma_U^2)}$$



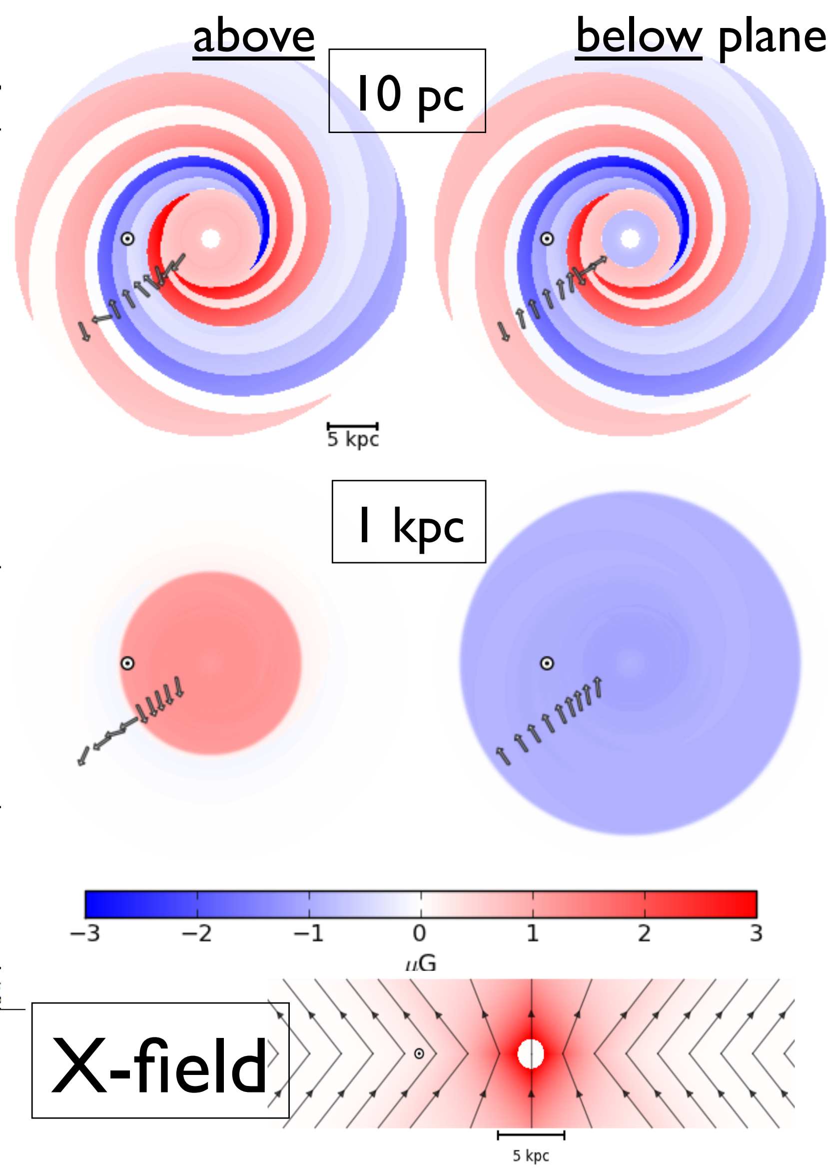
JF12 Coherent GMF Model

BEST-FIT GMF PARAMETERS WITH $1-\sigma$ INTERVALS.

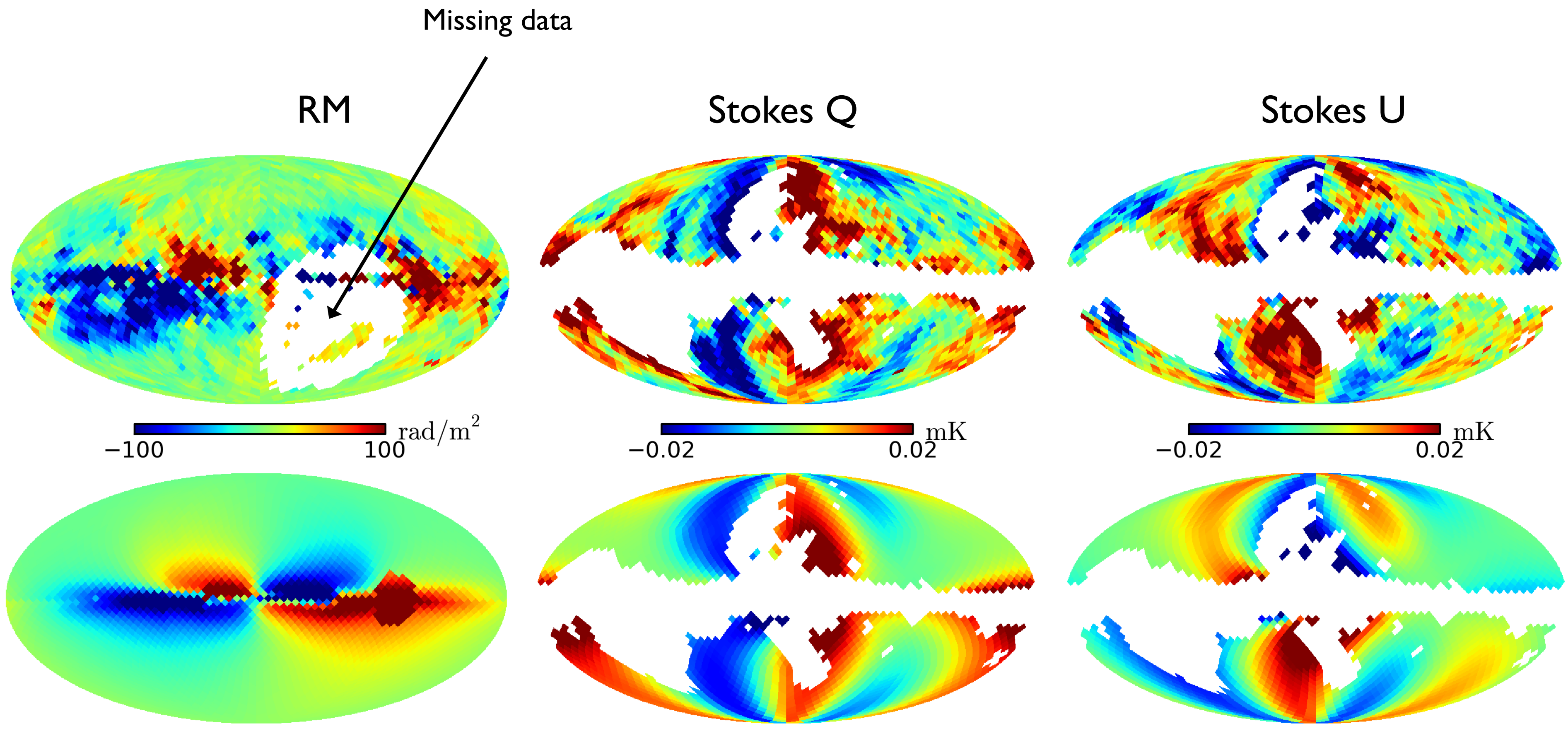
Field	Best fit Parameters	Description
Disk	$b_1 = 0.1 \pm 1.8\,\mu$G	field strengths at $r = 5$ kpc
	$b_2 = 3.0 \pm 0.6\,\mu$G	
	$b_3 = -0.9 \pm 0.8\,\mu$G	
	$b_4 = -0.8 \pm 0.3\,\mu$G	
	$b_5 = -2.0 \pm 0.1\,\mu$G	
	$b_6 = -4.2 \pm 0.5\,\mu$G	
	$b_7 = 0.0 \pm 1.8\,\mu$G	
	$b_8 = 2.7 \pm 1.8\,\mu$G	inferred from $b_1, ..., b_7$
	$b_{\rm ring} = 0.1 \pm 0.1\,\mu$G	ring at 3 kpc $< r <$ 5 kpc
	$h_{\rm disk} = 0.40 \pm 0.03$ kpc	disk/halo transition
	$w_{\rm disk} = 0.27 \pm 0.08$ kpc	transition width
Toroidal halo	$B_{\rm n} = 1.4 \pm 0.1\,\mu$G	northern halo
	$B_{\rm s} = -1.1 \pm 0.1\,\mu$G	southern halo
	$r_{\rm n} = 9.22 \pm 0.08$ kpc	transition radius, north
	$r_{\rm s} > 16.7$ kpc	transition radius, south
	$w_{\rm h} = 0.20 \pm 0.12$ kpc	transition width
	$z_0 = 5.3 \pm 1.6$ kpc	vertical scale height
X halo	$B_{\rm X} = 4.6 \pm 0.3\,\mu$G	field strength at origin
	$\Theta^0_{\rm X} = 49 \pm 1^\circ$	elev. angle at $z = 0, r > r^c_{\rm X}$
	$r^c_{\rm X} = 4.8 \pm 0.2$ kpc	radius where $\Theta_{\rm X} = \Theta^0_{\rm X}$
	$r_{\rm X} = 2.9 \pm 0.1$ kpc	exponential scale length
striation	$\gamma = 2.92 \pm 0.14$	striation and/or $n_{\rm cre}$ rescaling

NOTE. — For the parameter $r_{\rm s}$ only a lower 68%-bound is given.

$$L(z,h,w) = \left(1 + e^{-2(|z|-h)/w}\right)^{-1}$$



Observed vs. Simulated data, JF12



13 parameter Random GMF Model

R. Jansson + GRF, Ap. J. Lett. (2012)

Disk Component

8 arms as in JF12; B~1/r;

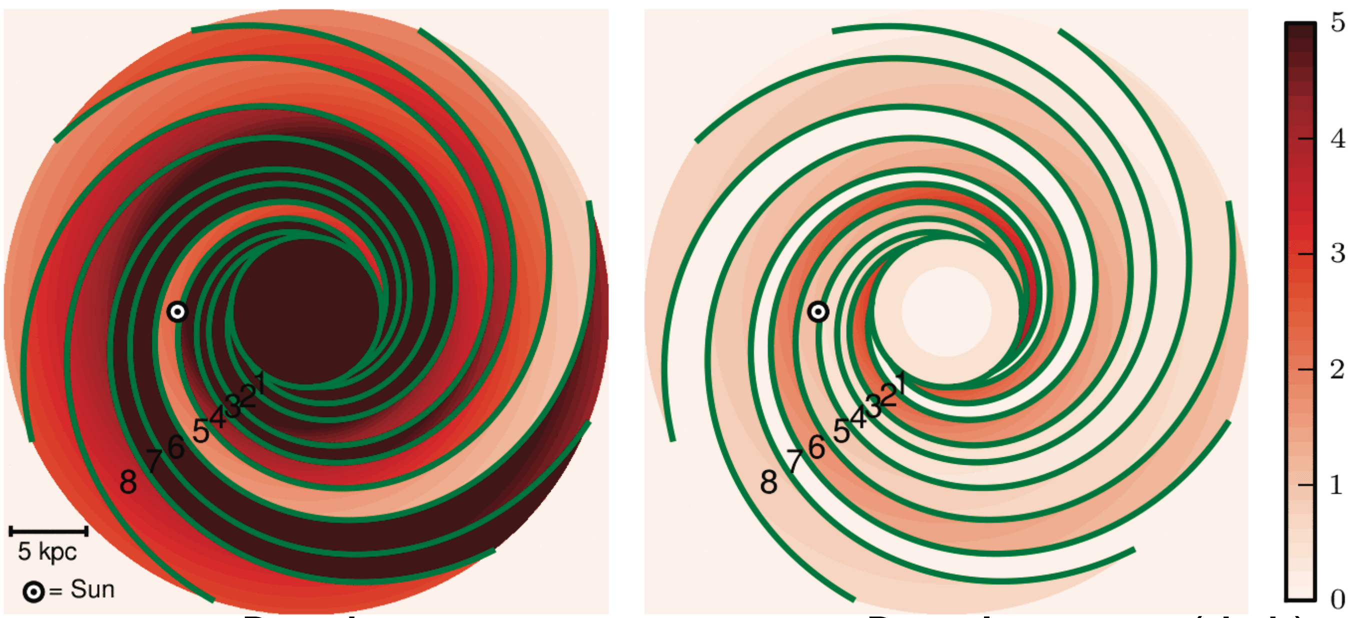
fit separately for B_{rms} in each arm

Central region: constant B_{rms}

Gaussian vertical profile; 600 pc

Halo: strength, scale height, radial scale

Field	Best-fit Parameters	Description
Disk component	$b_1 = 10.81 \pm 2.33\,\mu$G	Field strengths at $r = 5$ kpc
	$b_2 = 6.96 \pm 1.58\,\mu$G	
	$b_3 = 9.59 \pm 1.10\,\mu$G	
	$b_4 = 6.96 \pm 0.87\,\mu$G	
	$b_5 = 1.96 \pm 1.32\,\mu$G	
	$b_6 = 16.34 \pm 2.53\,\mu$G	
	$b_7 = 37.29 \pm 2.39\,\mu$G	
	$b_8 = 10.35 \pm 4.43\,\mu$G	
	$b_{int} = 7.63 \pm 1.39\,\mu$G	Field strength at $r < 5$ kpc
	$z_0^{disk} = 0.61 \pm 0.04$ kpc	Gaussian scale height of disk
Halo component	$B_0 = 4.68 \pm 1.39\,\mu$G	Field strength
	$r_0 = 10.97 \pm 3.80$ kpc	Exponential scale length
	$z_0 = 2.84 \pm 1.30$ kpc	Gaussian scale height
Striation	$\beta = 1.36 \pm 0.36$	Striated field $B_{stri}^2 \equiv \beta B_{reg}^2$



Random Regular (disk)

χ^2= 1.065 per d.o.f.

(2957 d.o.f.)

Observed vs model for Random Field

22 GHz Synchroton Total Intensity

note plots are saturated

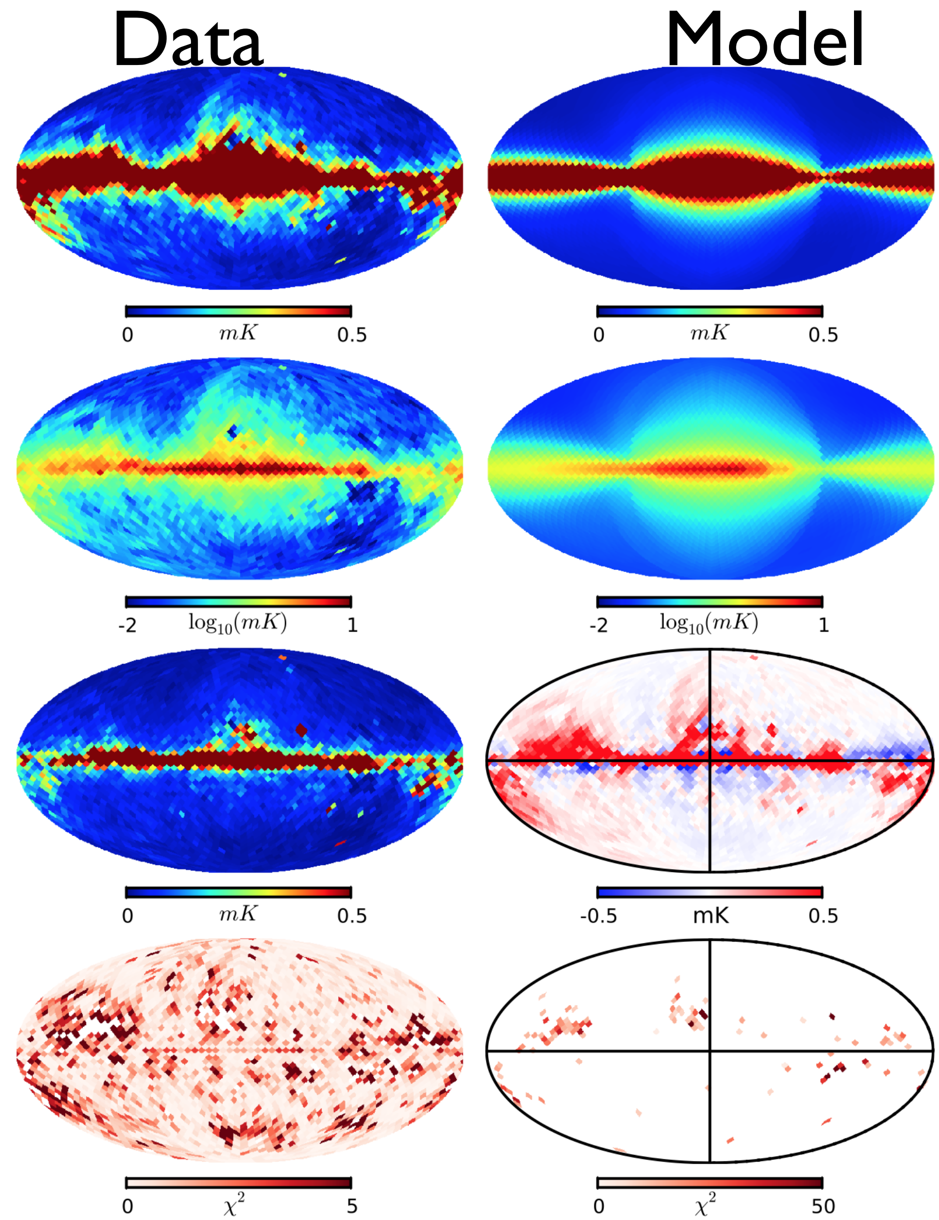
Log_{10} Intensity

Left: Variance σ for I

Right: data – model

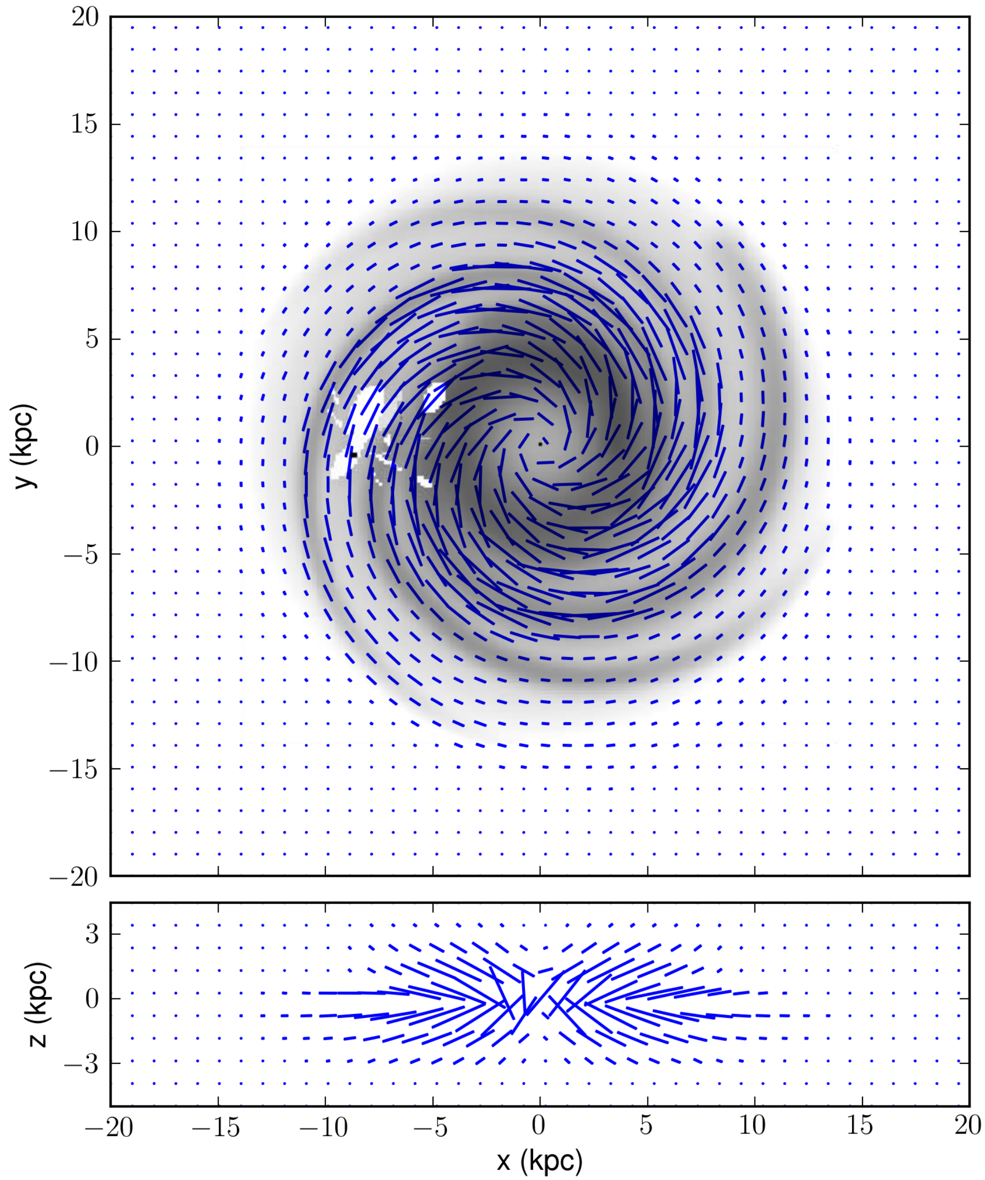
L: chi-sq of fit in each pixel

R : chi-sq of dropped outliers



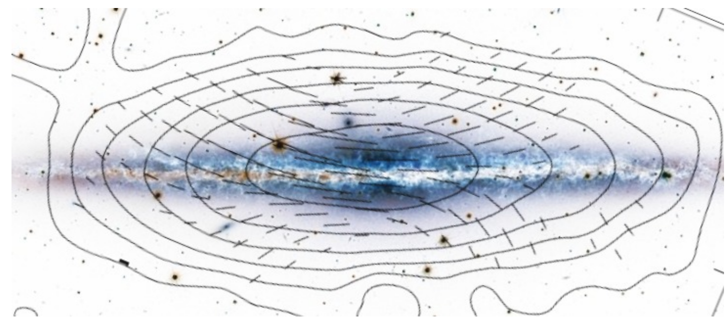
To an extragalactic radio observer, the Milky Way

looks like the galaxies we observe!

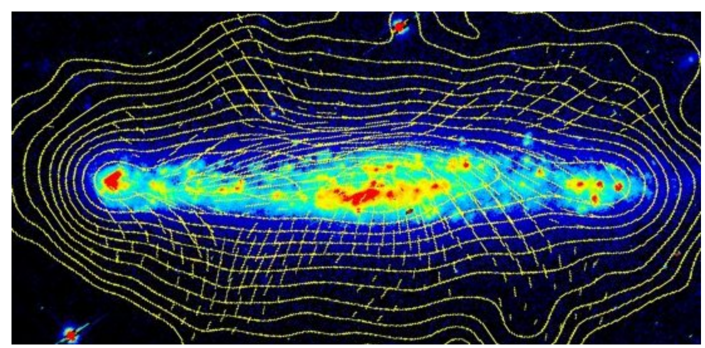


Milky Way analogues:

NGC 891

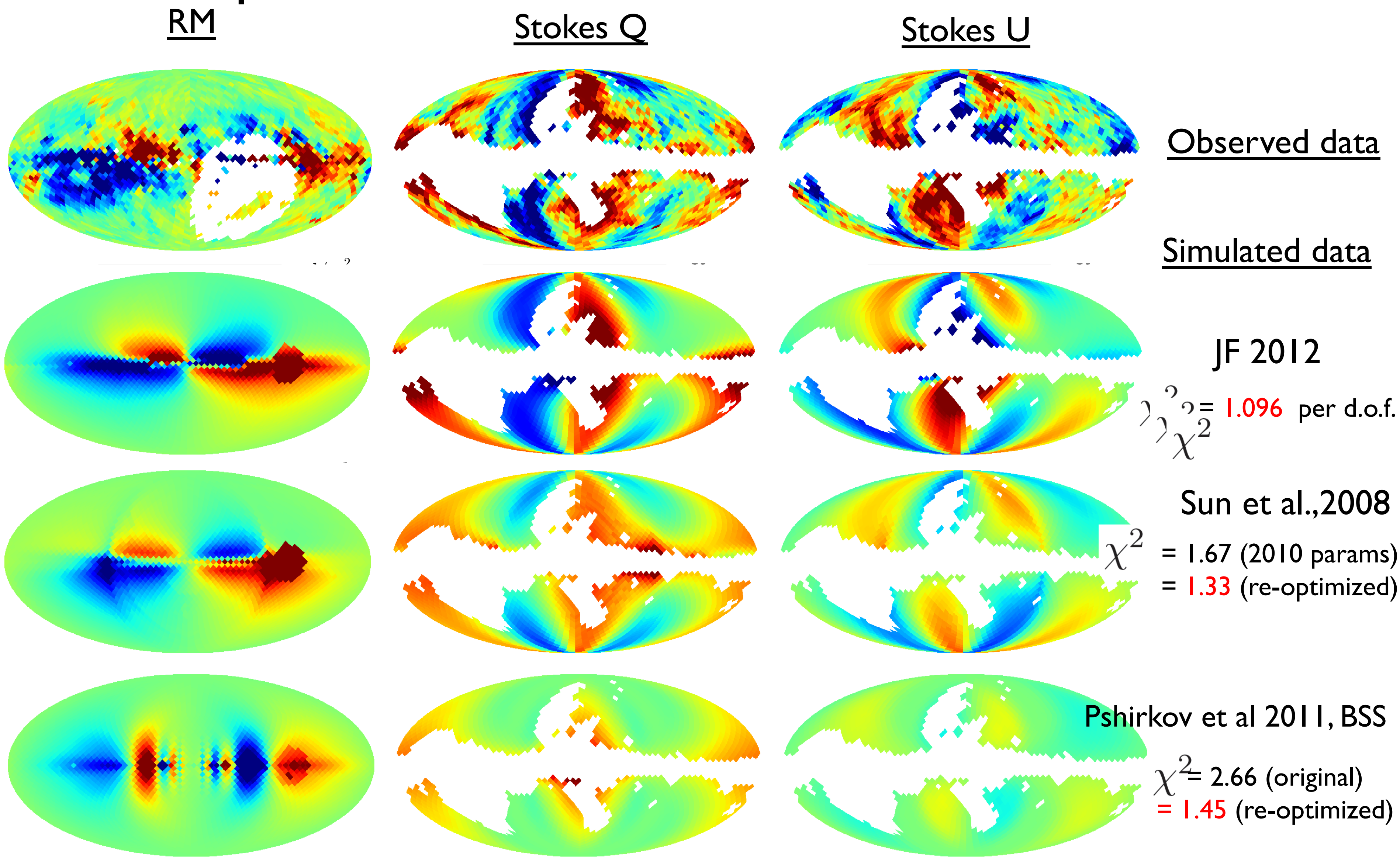


NGC 5775



Old models fit poorly, JF12 fits well

χ^2 per d.o.f. = 1.096, with 6605 observables

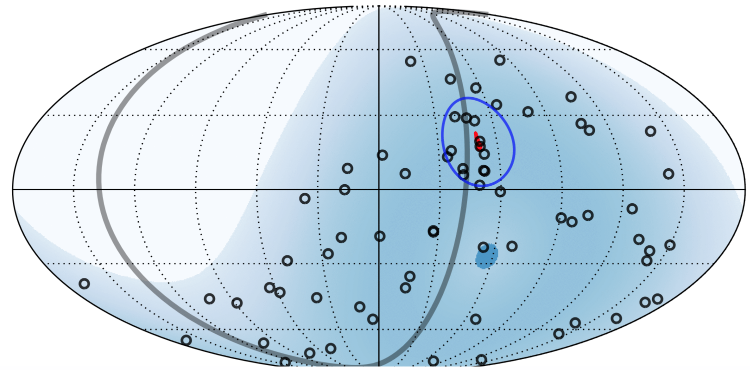


Cosmic Ray Deflections

UHECR deflection in Cen A region

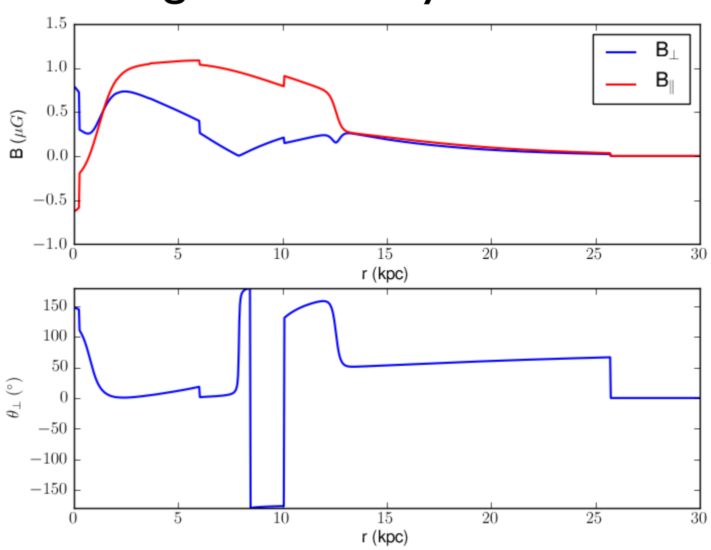
GRF, Ronnie Jansson, Ilana Feain & Bryan Gaensler JCAP 2012

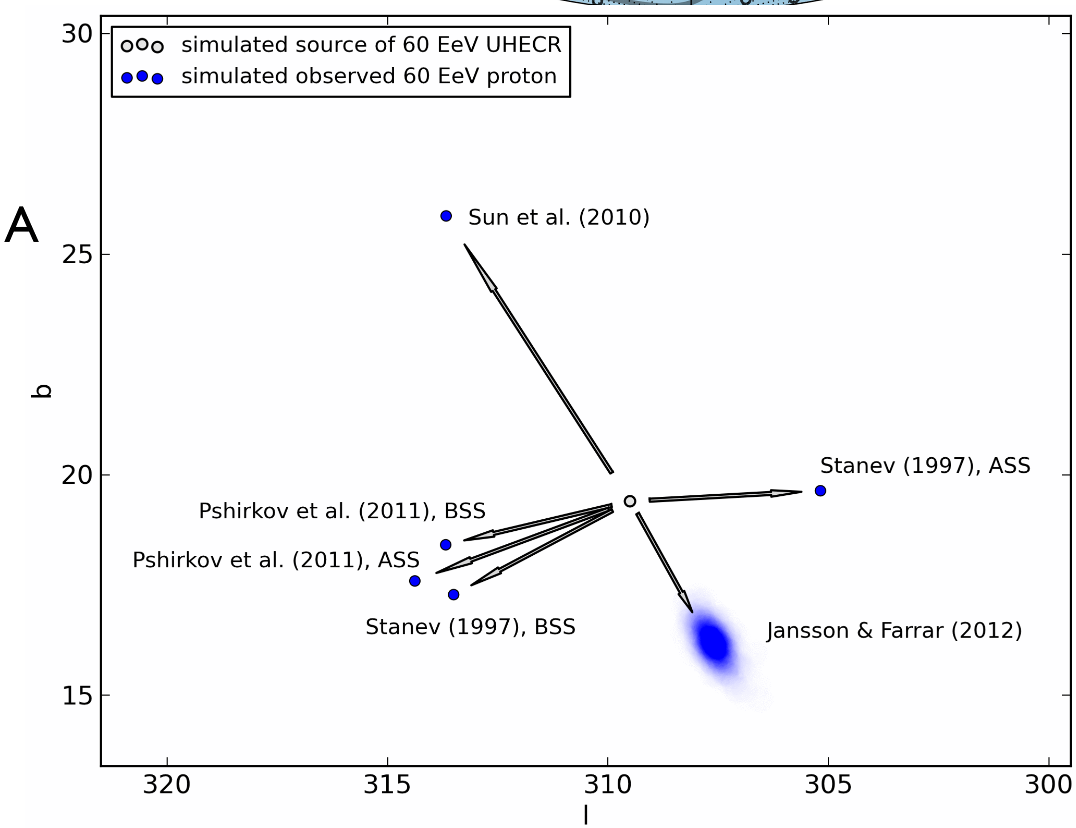
Cosmic Ray deflection depends strongly on magnetic field model.



(Not sufficient to fit Q,U!)

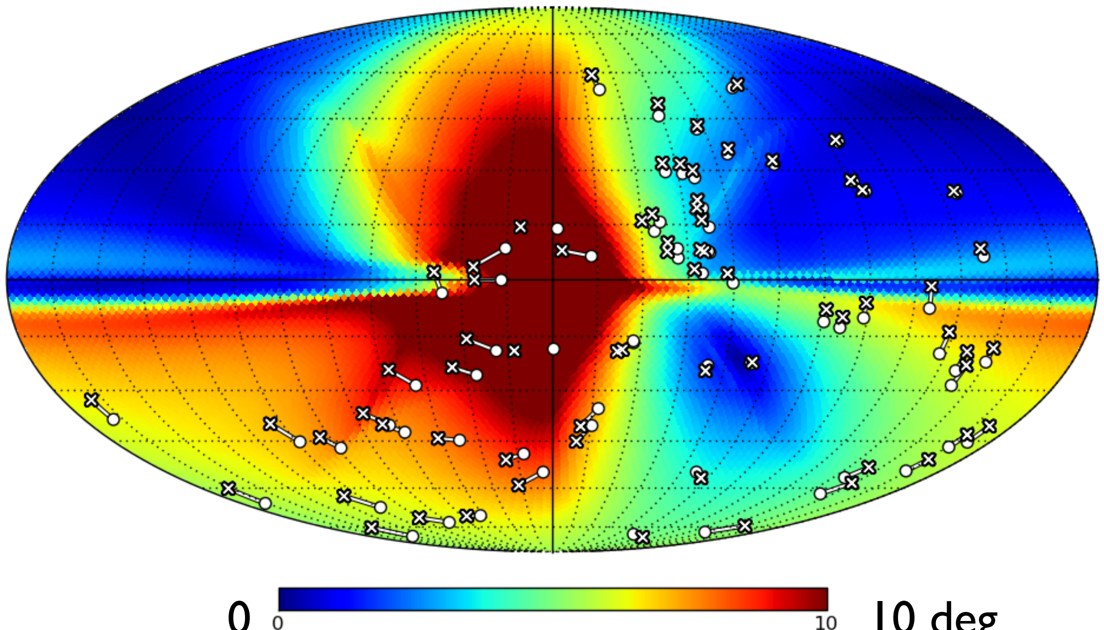
Line-of-sight B seen by CR from Cen A





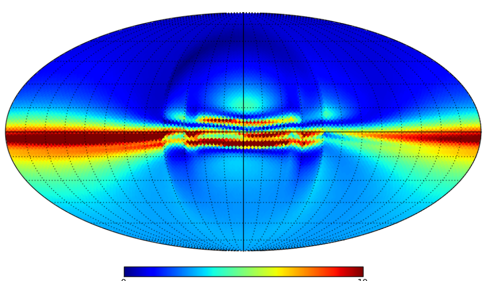
Different GMF models predict very different UHECR deflection

JF12

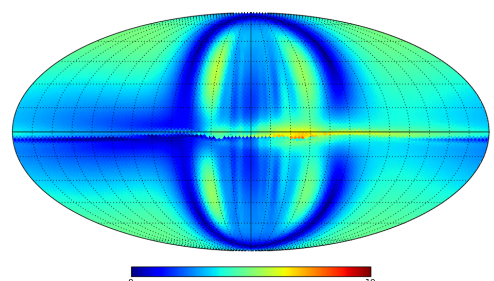


60 EeV/Z

0 10 deg



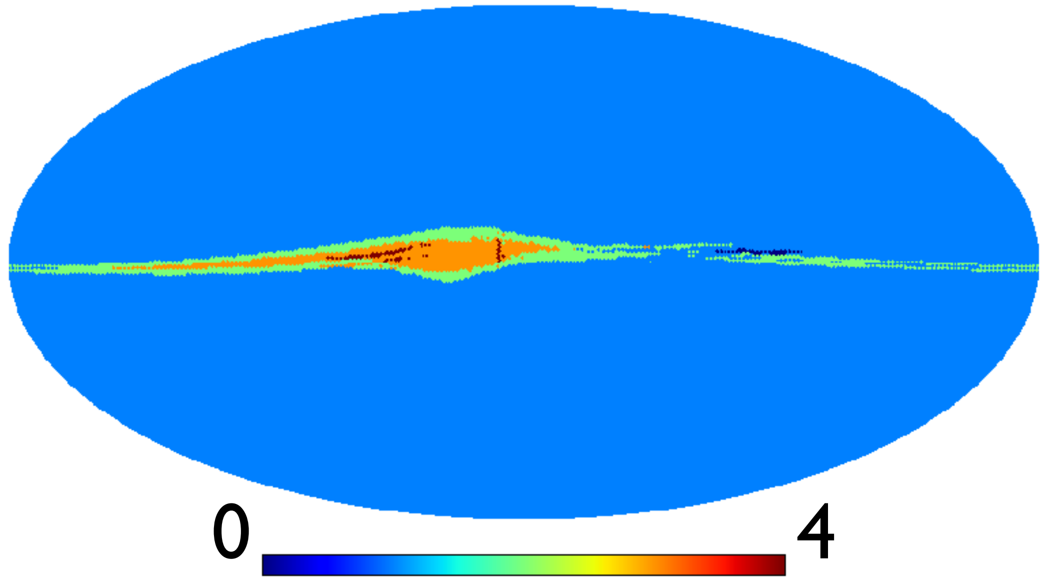
Sun et al. (2008)



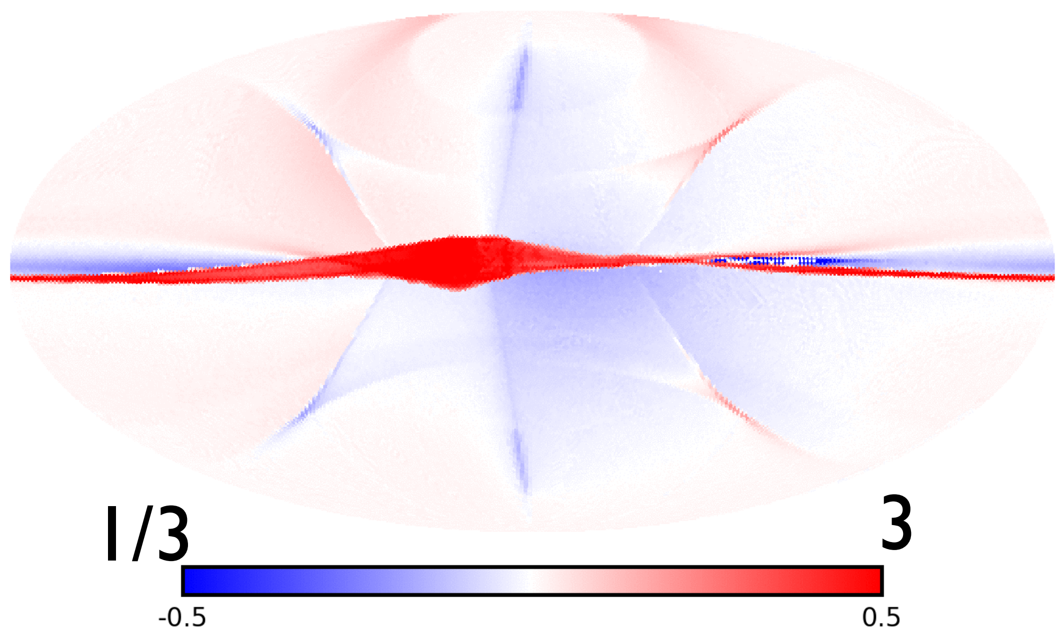
Pshirkov et al 2011, BSS

Images & Amplification

- Sources near the Galactic Plane have multiple images, even at 60 EV



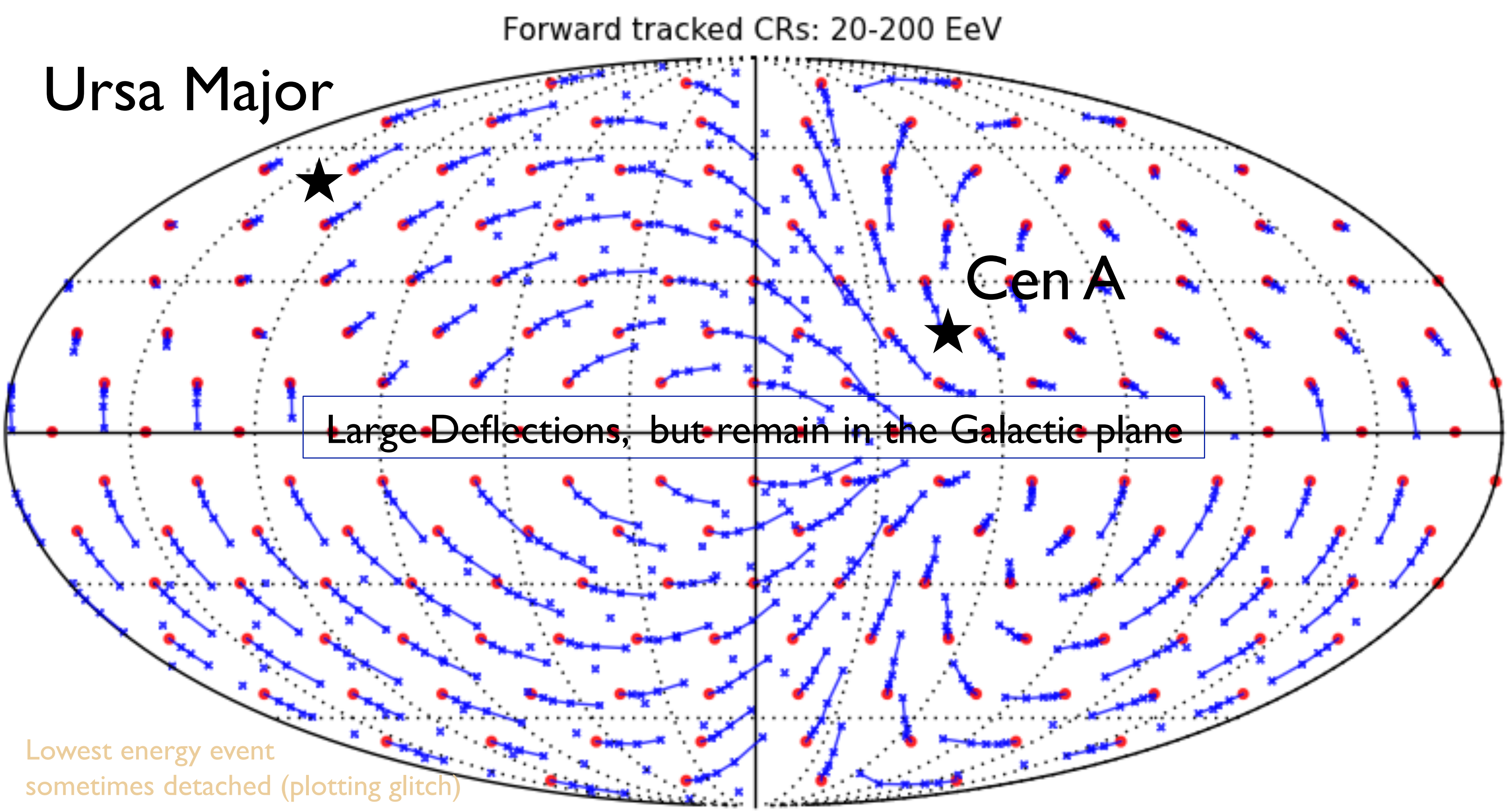
- Some sources are amplified by factor ~ 10!



(Jansson & Farrar, in prep)

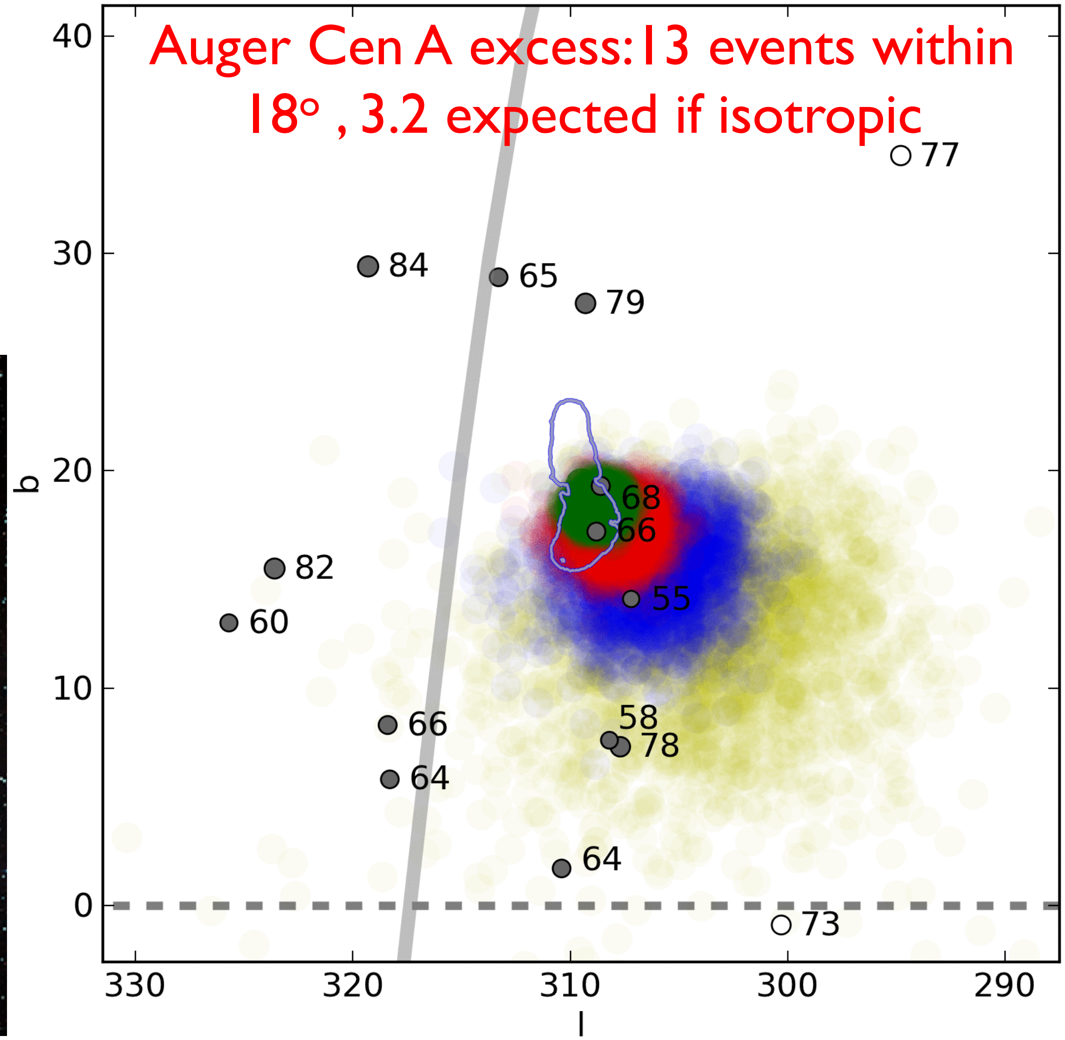
Deflection Map

20-200 EeV protons in JF12 coherent field



UHECR locus from Cen A

Farrar, Janssen, Feain, Gaensler 2012



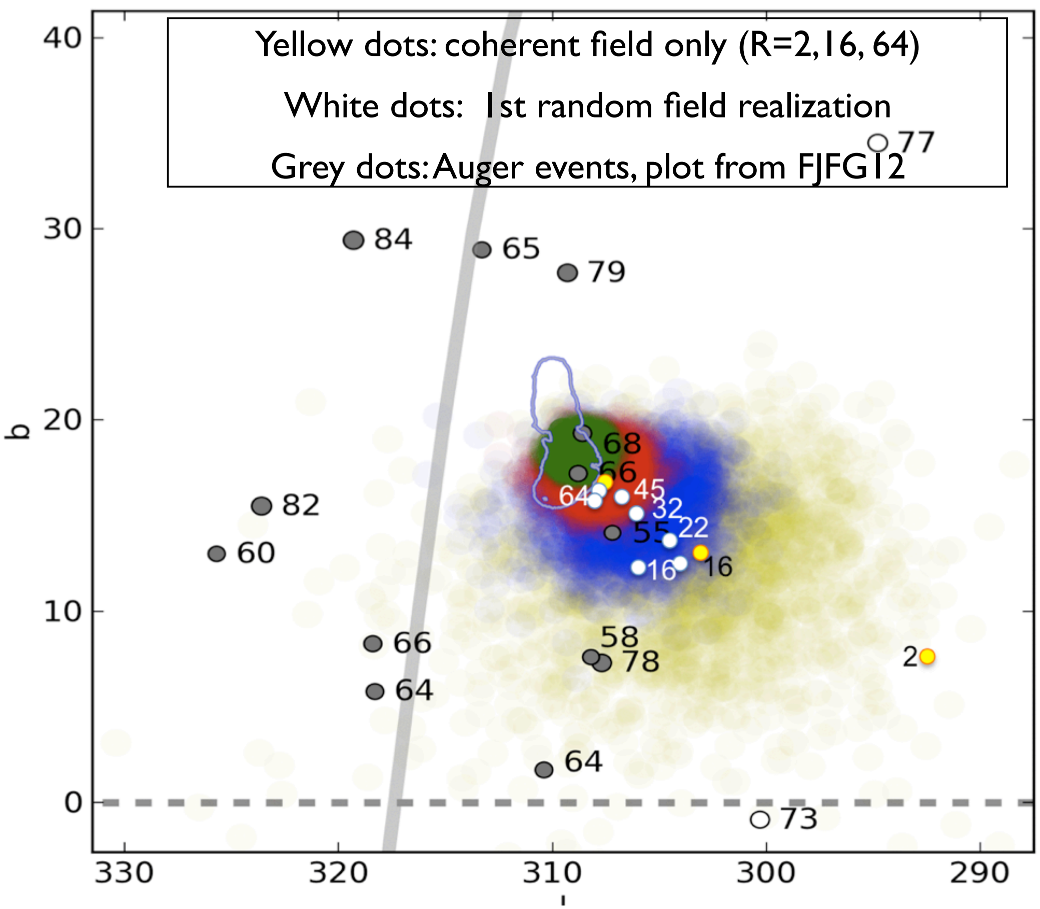
- UHECR Deflection in GMF for E/Z = 160, 80, 40, 20 EeV (spread comes from random)
- Auger energy uncertainty ~ 20-25%, GMF has to be > 80 nG to impact locus
- 3 CRs can be protons from Cen A
- 3 more CRs can be from Cen A if they have Z = 2-4

Forward Tracking from Cen A

down to 2 EV, including the striated & random fields

Azadeh Keivani (LSU) + GF

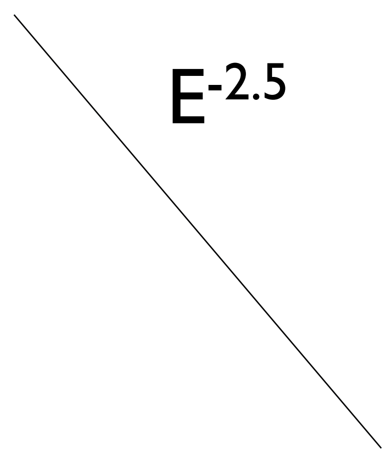
- Just 2 field realizations done so far, more running.
- Arcs are intrinsically thin... as seen in data; multiplets can appear to thicken.
- Even for Fe, deflection <20 deg.

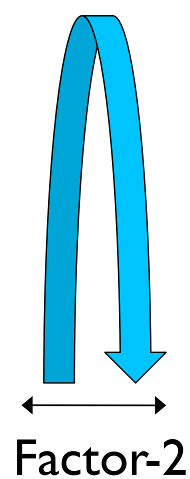


Bursting vs Continuous Source?

Power-Law at source => Peaked at observer,

if burst duration << time-delay smearing





Observational Constraints on UHECR sources (conservative)

- UHECR energy injection rate:

  $\sim 10^{44\text{-}45}$ erg Mpc^{-3} yr^{-1}

- UHECR effective source density

  $> \sim 3\ 10^{-5}$ Mpc^{-3} (could be lower if high Z)

- N.b., UHECR arrival time delay $\sim 10^{4\text{-}5}$ yr

  => bursting source ok if rate > $3\ 10^{-10}$ Mpc^{-3} yr^{-1}

"Classical" models *alone* don't work

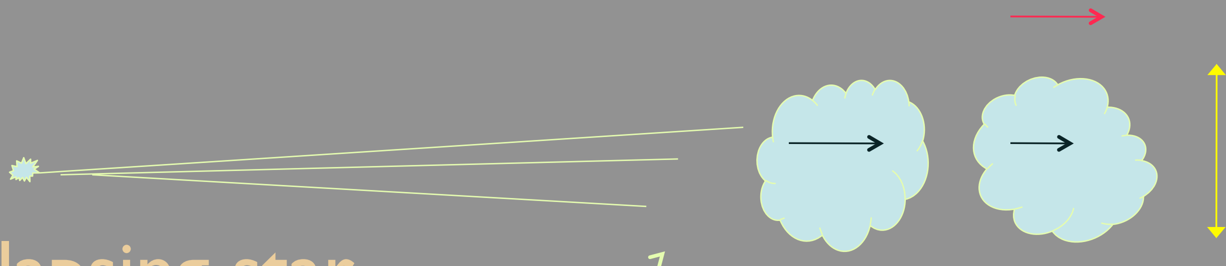
- GRB (Waxman, 95):
- **local rate too low**
  - Implies UHECRs should come from a few, isolated sources
  - Not enough total UHECR power
- **Ice Cube limit on ν's accompanying GRBs** **arXiv: 1204.4219**

- AGN jets, radio galaxies:
- **too few are powerful enough** (unless high Z reduces constraint on source density)
  - Implies UHECRs should come from a few, isolated sources

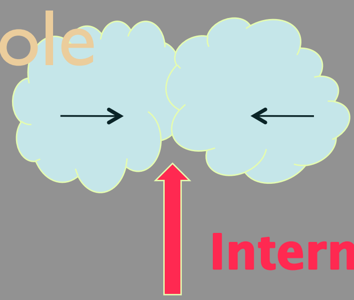
UHECR acceleration

Illustrative case – internal shocks

in GRB (ultra-relativistic) or AGN (mildly relativistic) jets



Collapsing star
or accreting
Supermassive
Black Hole



CM moves with
bulk Lorentz factor
Γ

Theoretical Constraint

GRF + A. Gruzinov "AGN flares and Cosmic Ray Bursts" ApJ 2008

To confine UHECRs:

$$RB \gtrsim 3 \times 10^{17}\, \Gamma^{-1}\, E_{20}.$$

=>

$$L_{\rm bol} \sim \frac{1}{6} c\Gamma^4 B^2 R^2 \gtrsim 10^{45} \Gamma^2\, E_{20}^2\, {\rm erg/s}.$$

MUST HAVE

Bolometric Luminosity > 10^{45} erg/s

ONLY ACHIEVED IN THE HIGHEST LUMINOSITY AGNs

Need a new class of SOURCEs

- AGN-bursts (GF & A. Gruzinov, 2008)
  - major disk instability or tidal disruption event in weak AGN
  - induces quasar for ~ 1-6 months
  - **rate & flux are reasonable**
  - photon counterparts should be observable (SDSS)

- Stellar tidal disruption events (FG08)
  - induces quasar for ~ 1-6 months
  - photon counterparts should be observable (SDSS)
  - **van Velzen et al 2011: 2 TDEs observed in SDSS Stripe 82**

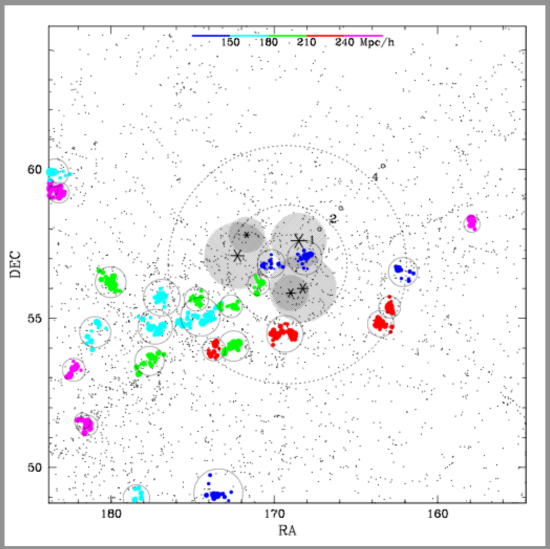
    => correct rate & flux!

Consequences of UHECR-burst scenario

- UHECRs:
  - Present AGN luminosity not a measure of flux in UHECRs.
  - Events from a single source display bursting spectrum
  - Composition may include heavy nuclei
- Predicts new class of optical and x-ray bursts:
  - SDSS: Search of archival data performed
  - N.b., Accompanying photon bursts arrive ~10^{4-5} years before UHECRs!

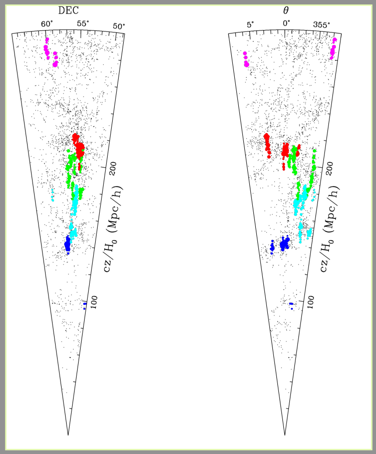
Evidence for a bursting source
The "Ursa Major" UHECR Cluster

- 4 events in AGASA + HiRes (94 total) *HiRes 05*
  Same position within < 1°
  Chance probability: 2 10^{-3} *GRF 05*
  Not in Auger field of view :-(

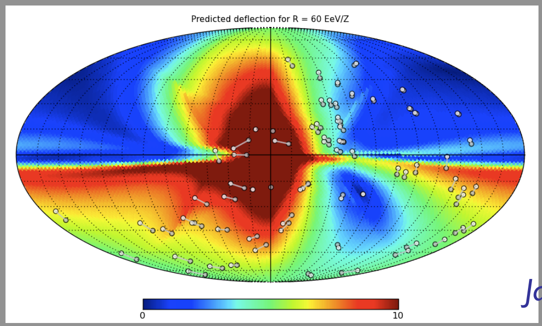


GRF, Berlind, Hogg 06

- SDSS => foreground empty!
  Extragalactic deflection low
  GRF, Berlind, Hogg 06



  & GMF deflection low too



Jansson-GRF 2012

- *Spectrum suggests bursting source*
  - *Energies same within factor-2*
  - *No events at lower energy*
- New: Swift-BAT hard x-ray source at location predicted from UHECR deflections z = 0.047

Energy spectrum of CRs from an individual bursting source:

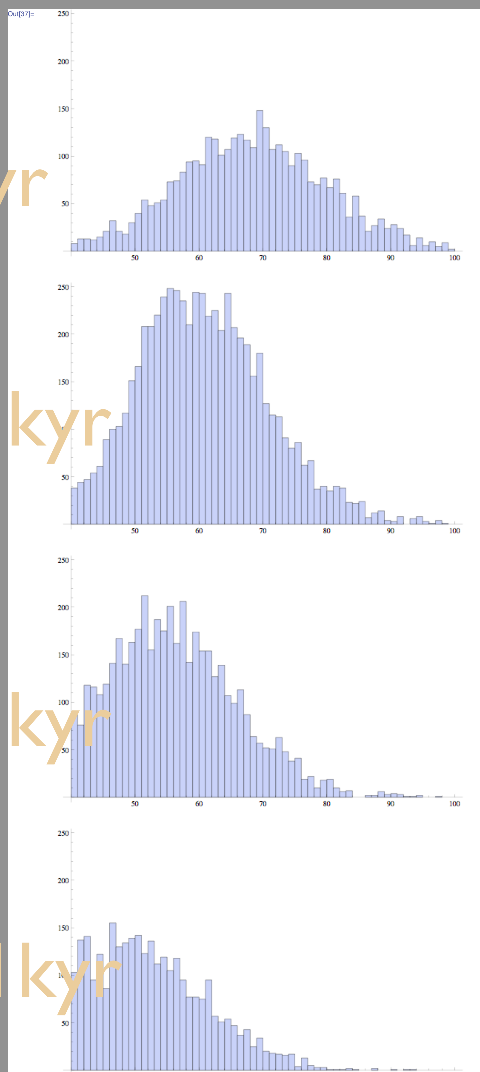
GRF 07; GF in prep

T=0-3kyr

T=30-31kyr

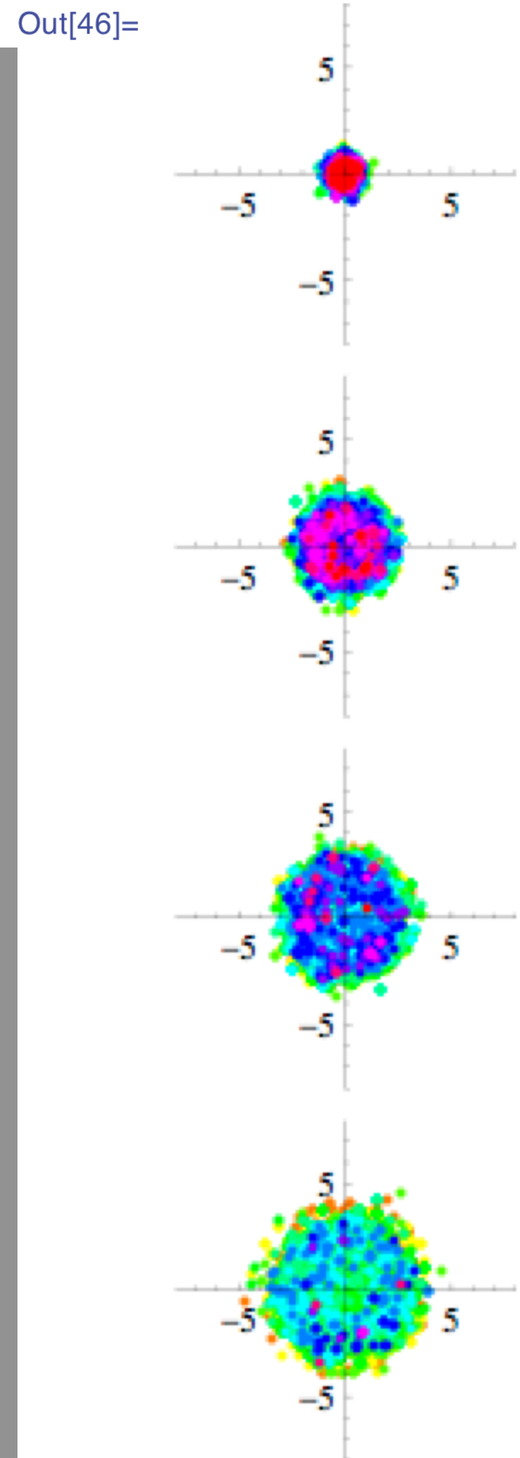
T=60-61kyr

T=90-91kyr



←Spectrum

Arrival Direction →



Ursa Major Cluster CR Energies:

38, 53, 55, 77 EeV

+ 1 event in HiRes < 30 EeV

$E_{UHECR} \approx 10^{49}$ erg $(D_{200})^3 f_{GZK}$

Too low for GRB

Tidal Disruption Flares *Observed*

- 5 strong candidates
  - **2 optical flares in SDSS stripe 82**

THE ASTROPHYSICAL JOURNAL, 741:73 (24pp), 2011 November 10 doi:10.1088/0004-637X/741/2/73

OPTICAL DISCOVERY OF PROBABLE STELLAR TIDAL DISRUPTION FLARES

SJOERT VAN VELZEN[1,2,3], GLENNYS R. FARRAR[1,4], SUVI GEZARI[5], NIDIA MORRELL[6], DENNIS ZARITSKY[7],
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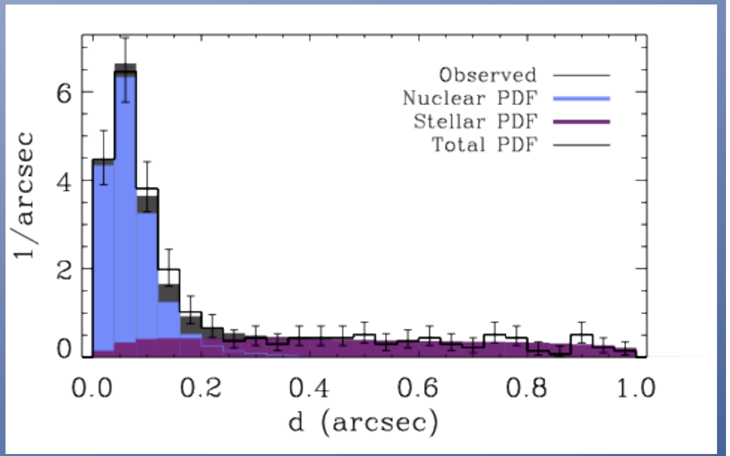
[4] Department of Physics, New York University, NY 10003, USA

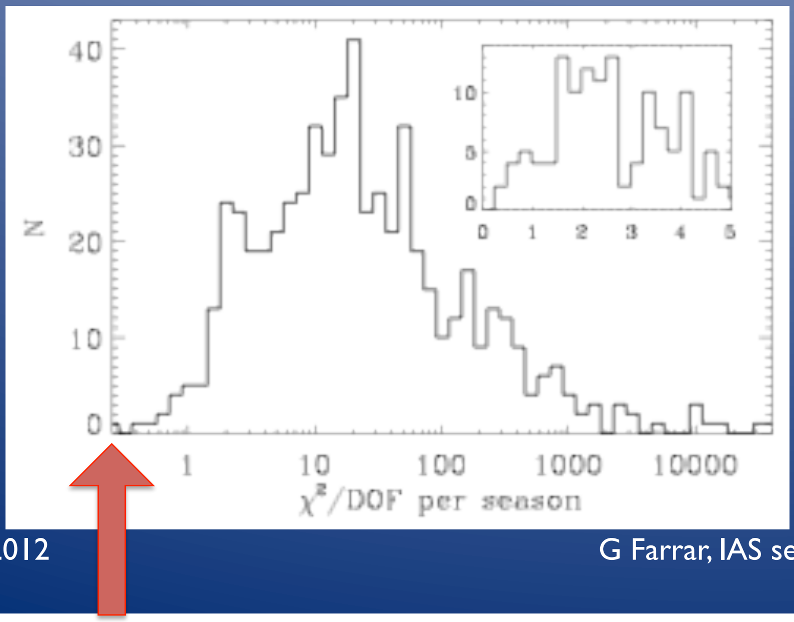
  - 2 "blazar mode" flares discovered in 2011 by Swift with extensive multi-wavelength follow-up
  - UV-Optical TDF, Gezari et al, Nature May 2, 2012
    - Saw peak of flare
  - (plus earlier candidates in UV and X-ray)
- Supermassive BH's disrupting a star
- "transient quasar" – accelerate UHECRs?

Optical Tidal Disruptions

van Velzen, GRF, et al, ApJ 2011

- 2.6M galaxies, 70 obs (SDSS Stripe 82)
- **Unbiased selection** of flare candidates
  - Hi-res nuclear cut to reduce SNe bkg
  - Color locus to exclude QSO hosts
  - Variability cut to remove variable AGNs

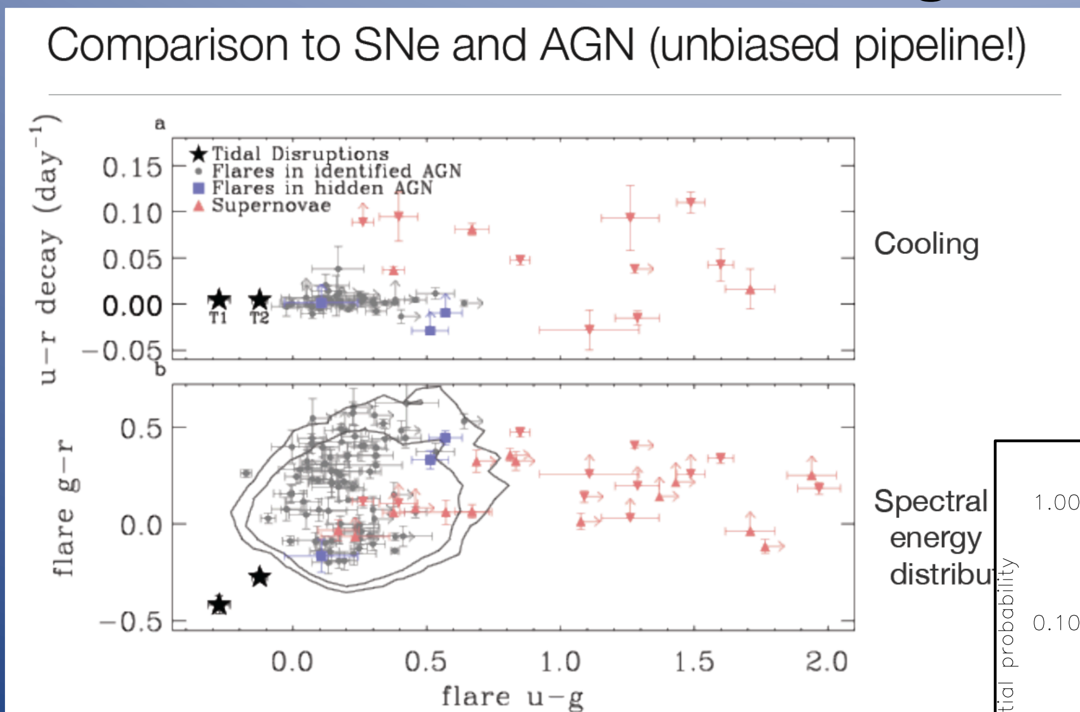


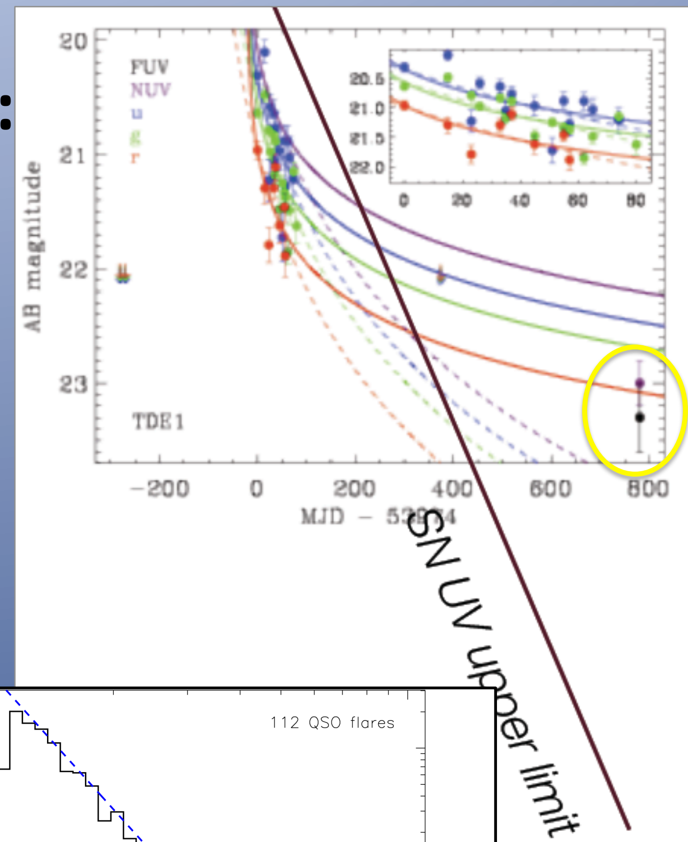


=> 2 TDF candidates

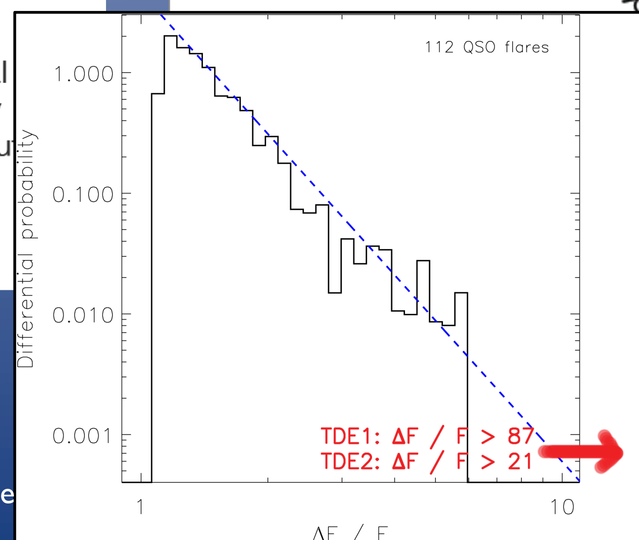
Candidate flares: unlike SNe or AGN

- **Late time UV brighter than any SN:**
- **Distinctive color and cooling:**





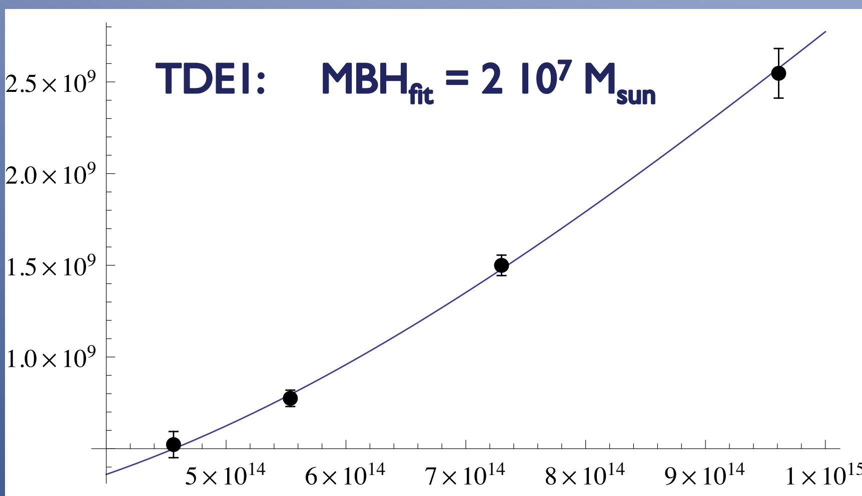
- Stronger flares than any AGN:

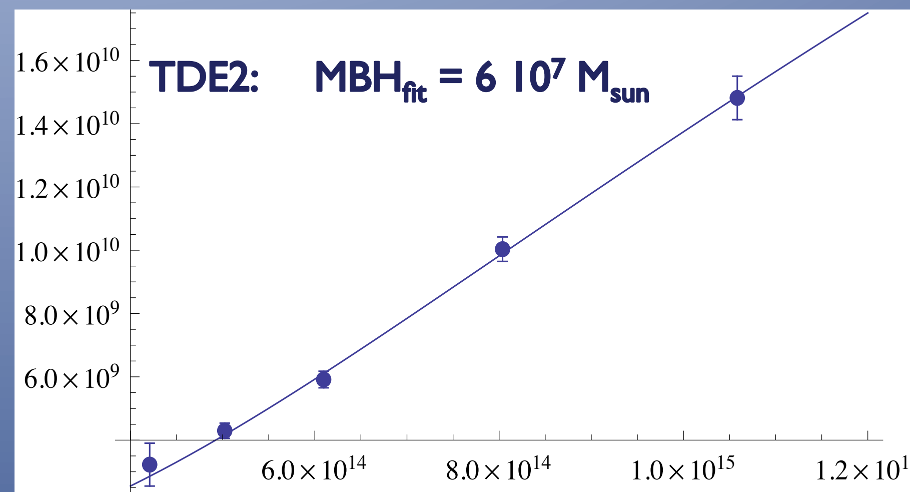


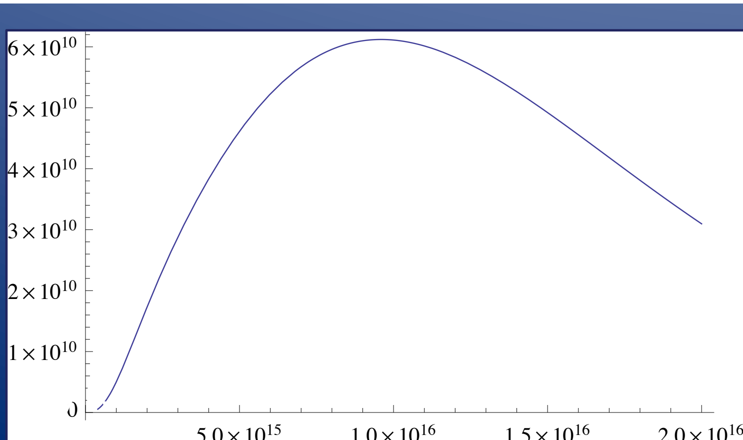
SDSS TDFs can accelerate UHECRs!

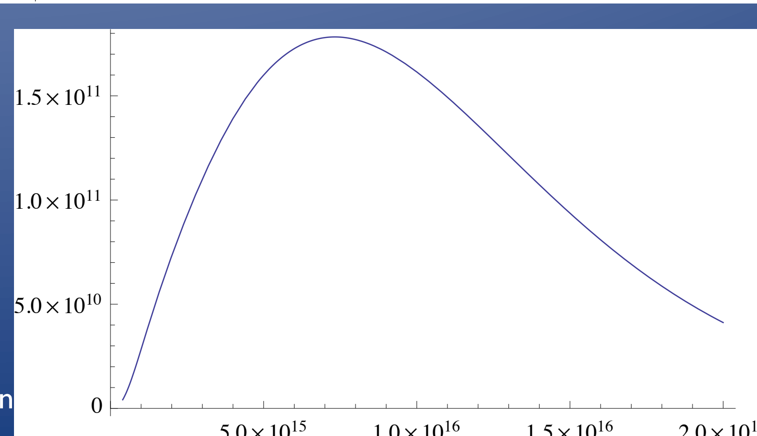
$L_{bol,peak} > 10^{47}$ erg/s, $L_{bol} > 10^{45}$ erg/s for ~ 1 year

(GRF in prep)









Tidal Disruption Flares satisfy UHECR source requirements

- $L_{bol} > 10^{45}$ erg/sec
- TDEs give observed UHECR energy injection rate:

  ~ $10^{44\text{-}45}$ erg Mpc^{-3} yr^{-1}

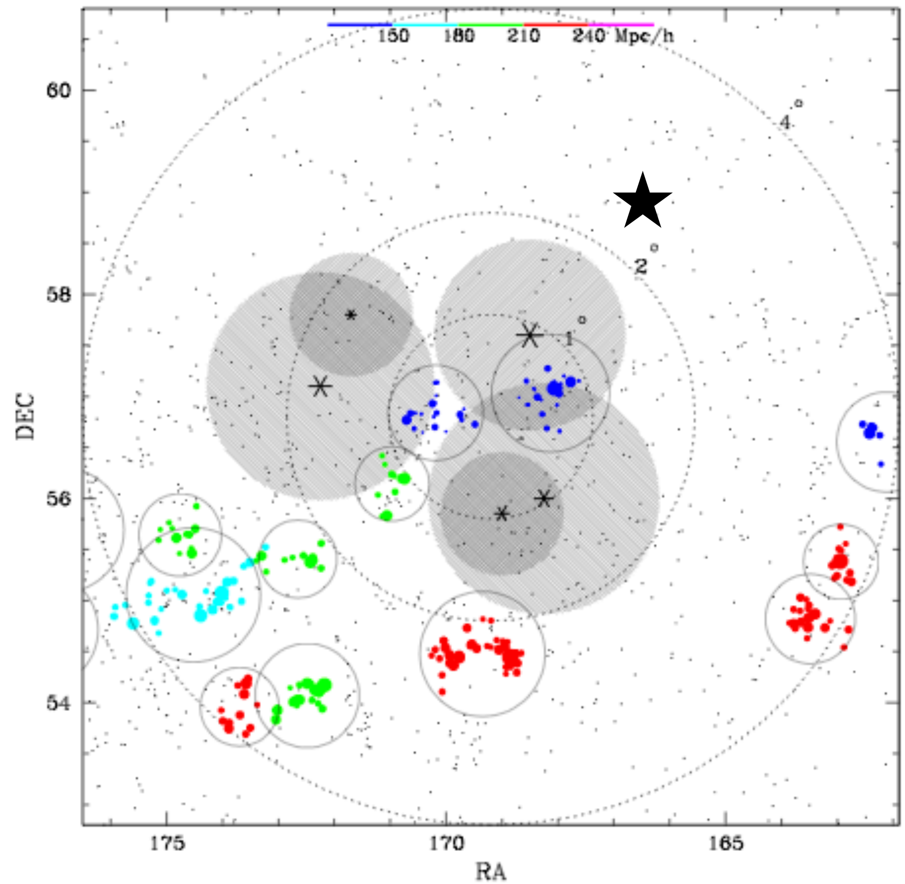
- TDE rate consistent with UHECR effective source density > 3 10^{-5} Mpc^{-3} (n.b., typical propagation delay ~ $10^{4\text{-}5}$ yr)

The Ursa Major Cluster

- 5 events seen in HiRes (2) & Auger (3)
- 34, 35, 36 & 50 EeV (rescaling E's by CERN UHECR12)

  ~13 EeV may be chance

- Swift-BAT hard X-ray AGN:
  - only AGN anywhere nearby
  - Swift-BAT Hard X-ray AGN
  - Recent Chandra observation
  - 200 Mpc; void in foreground
  - JUST WHERE THE SOURCE SHOULD BE!



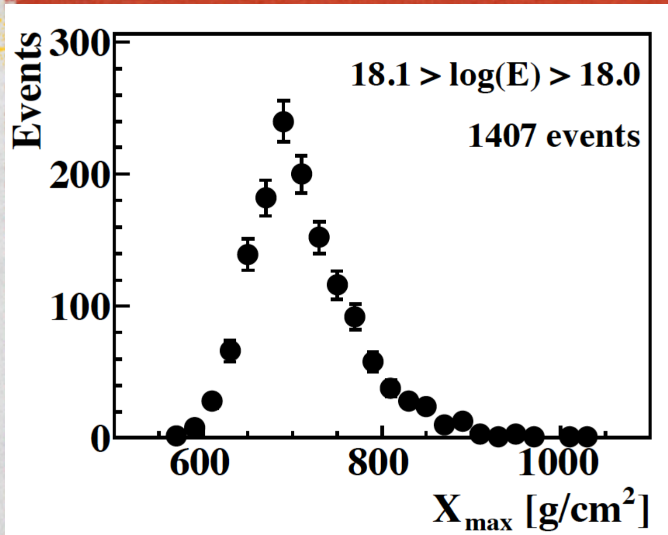
VHE gamma Signatures of Tidal Disruption Burst

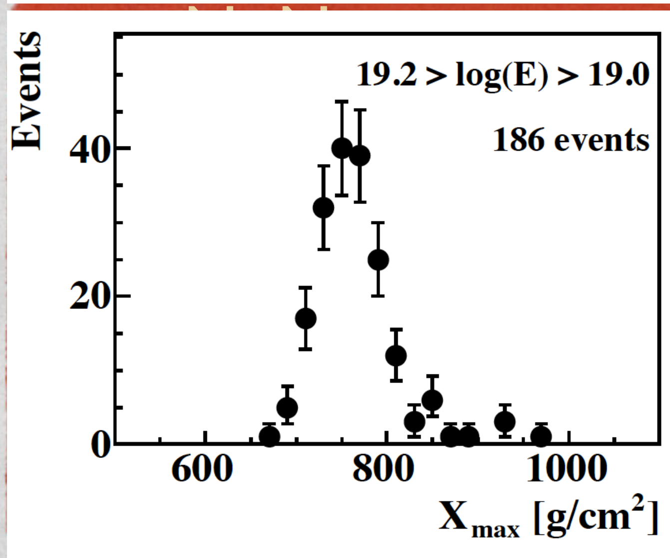
~ 1 month duration

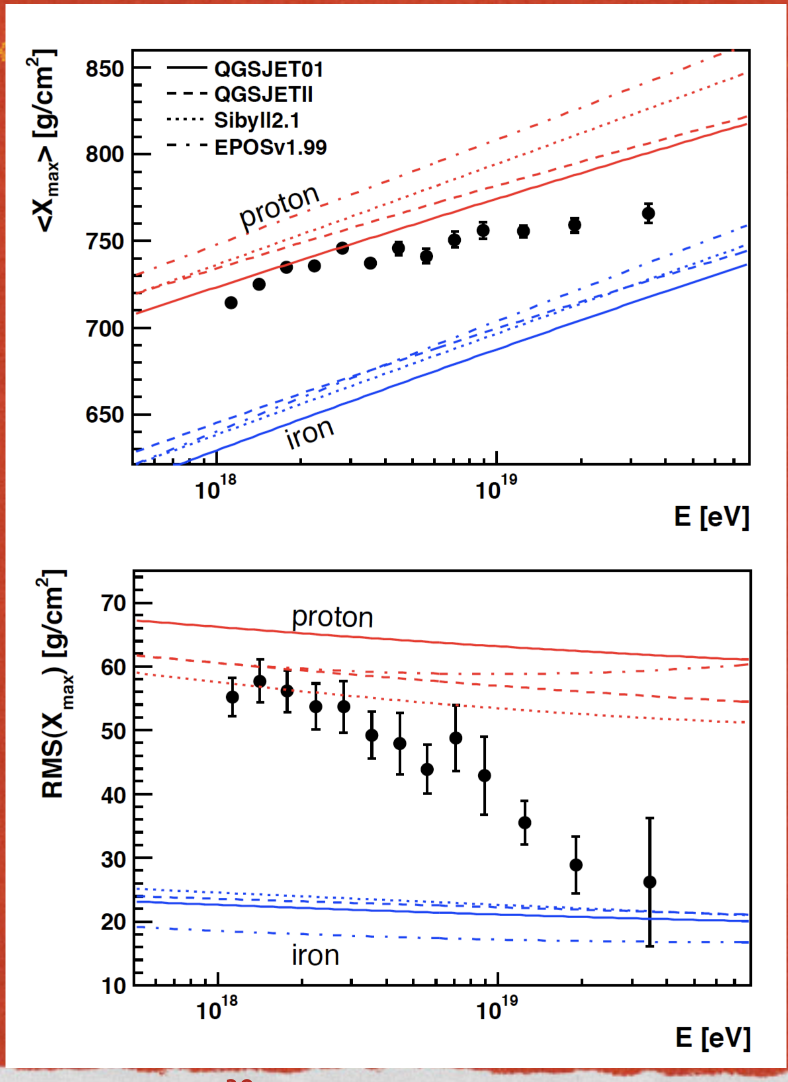
Ursa Major CR spectrum favors BURSTING SOURCE

Composition ⇔ Particle Physics

Depth of Shower Maximum X_{max} & its increase with Energy







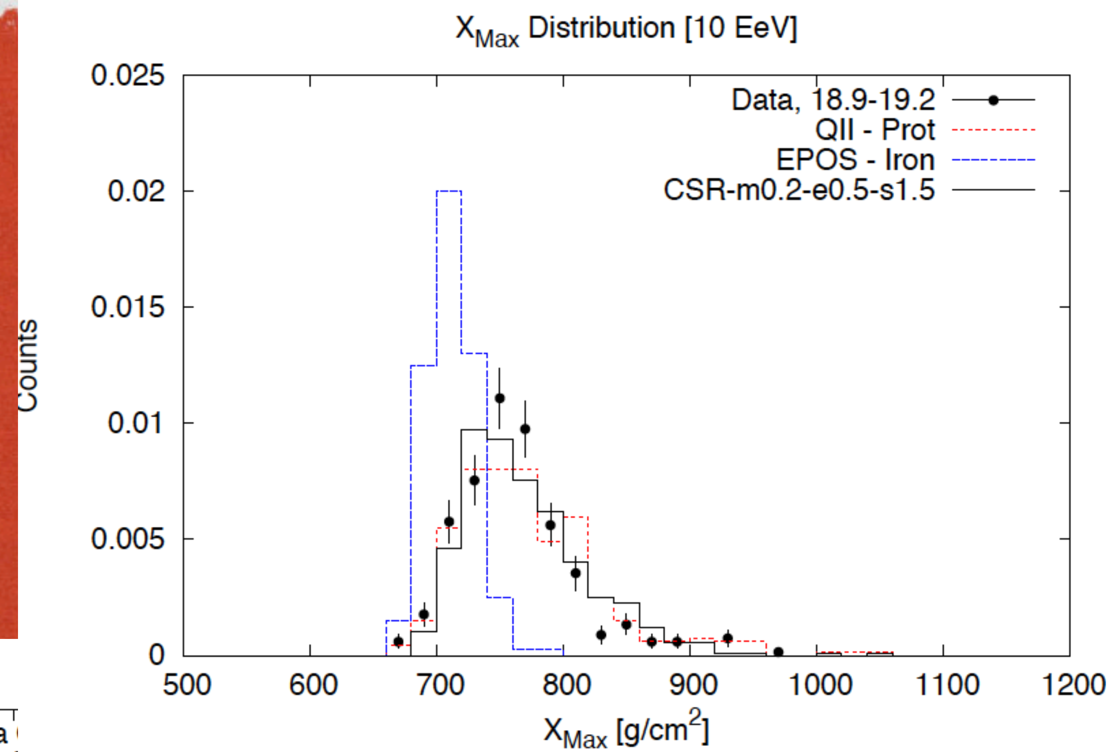
P -> p+Fe?

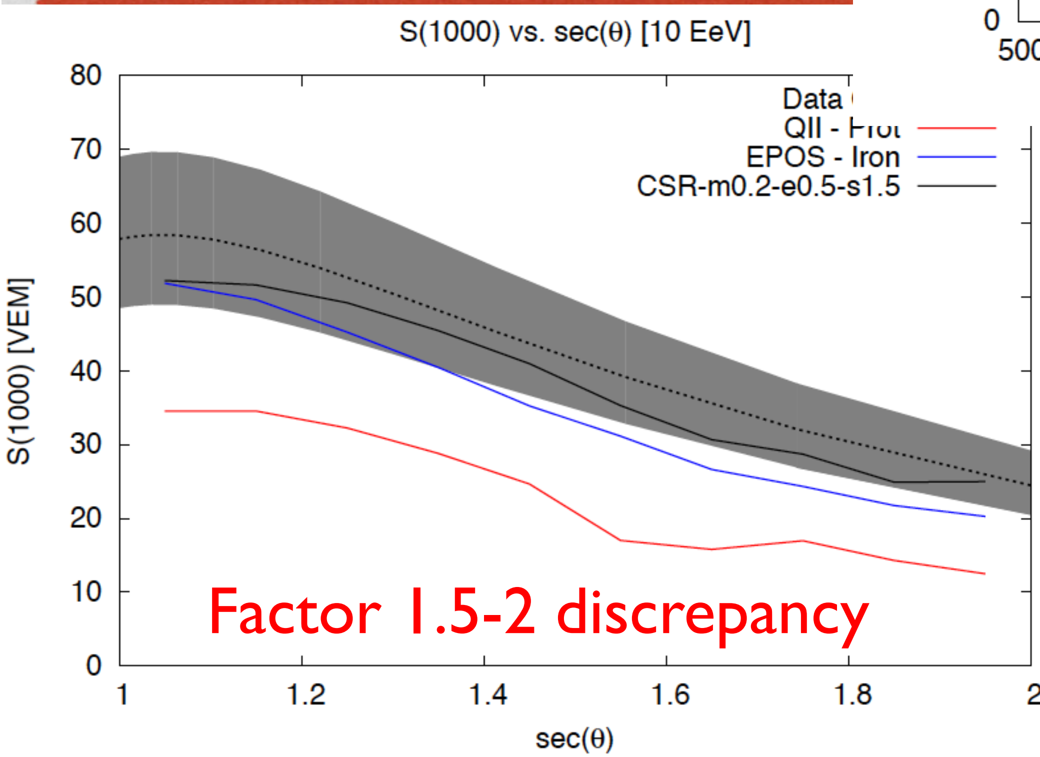
No!

Low RMS => narrow composition range.
Strong constraint on Astrophysics

Depth of Shower maximum

- Composition
- Particle physics





Factor 1.5-2 discrepancy

Must get BOTH Xmax and **zenith angle (CIC) right**

- at the same time.

PRESENT MODELS DO NOT !

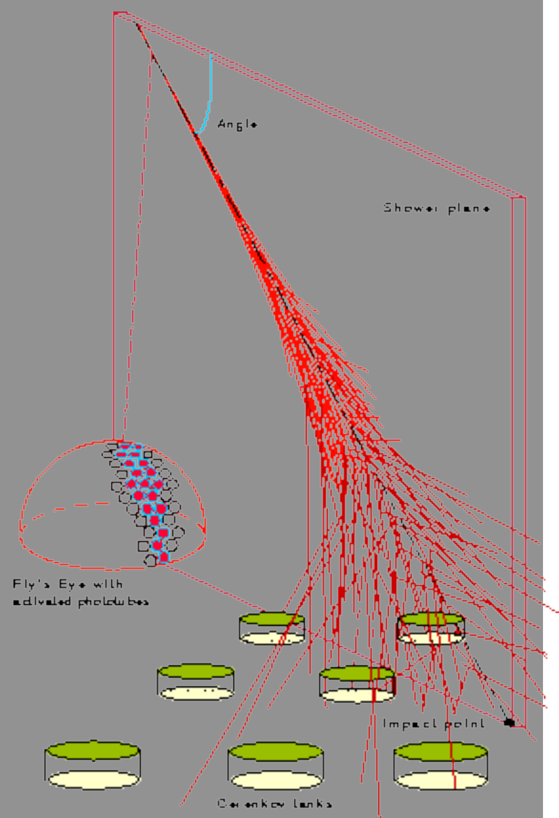
Breaking the degeneracy between models

- 4 toy models to fit CIC + Xmax
- S_{1000} -X_{max} plane scatter plot will help discriminate

GRF & Jeff Allen, in preparation

Simulating UHE air showers

- Use "event generators"
  - Designed to fit accelerator data
  - Experimental constraints incomplete; LHC helps
  - Huge extrapolation in energy
    (100's of interactions above LHC energies)
- First collision: E_{CM} > 100 TeV
  - May be highly inelastic 1000's of secondaries
  - OR diffractive (if p) 10's of secondaries
  - Imprints composition information
  - Largely determines X_{max}



Keep in mind…

- 10 EeV = 10^{19}eV ⇔ Sqrt[s_{NN}] = 140 TeV

- Average 10^{19} eV shower (QGSJetII) has

  2 20 200 secondary interactions

  above 10^{18} 10^{17} 10^{16}eV

- A substantial extrapolation beyond constrained physics!

What knobs can be turned?

- Primary Composition
- Cross section (direct measurement only below 10^{17}eV)
- Fraction of quasi-diffractive (high elasticity) events: f_{el}
- Multiplicity of non-diffractive events
- Particle content: strangeness fraction, meson-baryon ratio
- Reducing the π^0 fraction is the only thing that helps!

Conventional physics does not allow the π^0 fraction to be changed much

- Isospin invariance => $\pi^0 = \pi^+ = \pi^-$
- Isospin breaking (e.g., from resonance production and decay) is small
- Pion fraction is nearly universal
  - Z^0-decay:
  - Final states of hadron collisions (central region)
  - Even QGP
- If accounting for UHECR showers requires significantly lower π^0 fraction, that means it requires New Physics!

Models

- Chiral Symmetry Restoration (CSR) -- proton
- Matter-induced pi0 stabilization (pi0S)
- Heavy quark enhancement (DB)
- Ad-hoc conversion of pions to kaons & baryons

New models:

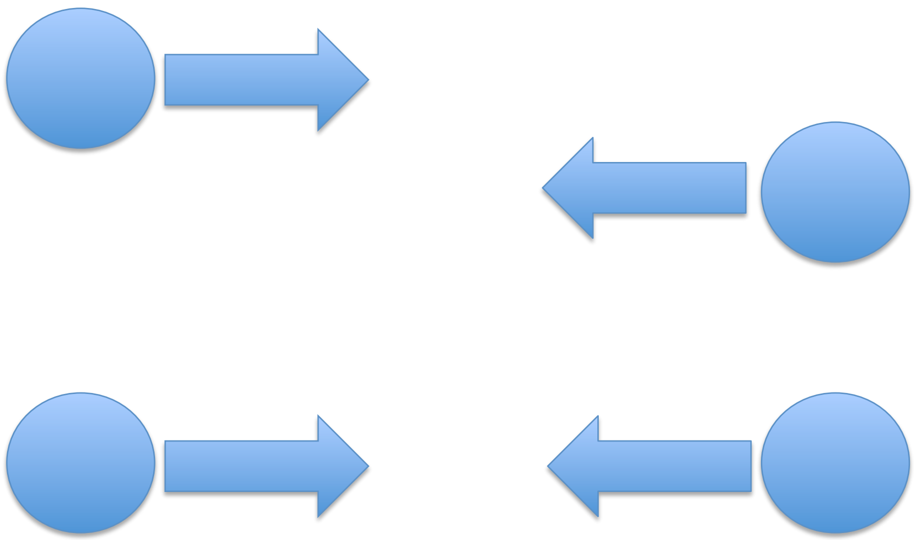
Proton-only composition isn't ruled out, for now

Future hybrid data can distinguish between composition & new physics

Chiral Symmetry Restoration

- proton primaries
- meson production suppressed
- peripherality-dependent production of CSR
- can fit <Xmax> & RMS at all E

Chiral Symmetry Restoration(-inspired) Model



Peripheral collision:

Standard Physics

$f_{el} > f_{min}(E)$ -- use EPOS

Central collision:

Chiral Symmetry Restored

$f_{el} < f_{min}(E)$ – use CSR

Chiral Symmetry Restored Phase

- Convert fraction f_{mes} of mesons to nucleon or anti-nucleon
- Increase multiplicity by factor f_{mult}

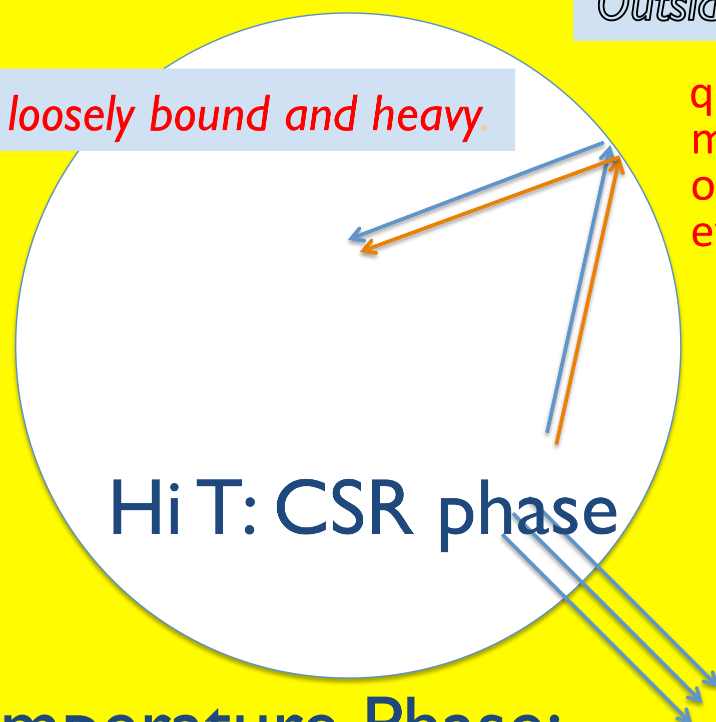
Lattice QCD predicts Chiral Symmetry is restored at $T_{CS} \geq T_{deconf} = T_{QGP}$

Possible mechanism for meson suppression in CSR phase

Outside, mesons are very light

Inside, q-qbar is loosely bound and heavy

q-qbar wavefunctions don’t match at boundary => mesons only produced after CSR phase evaporates.



Baryon wavefunctions inside and outside match, so baryons can escape

Low Temperature Phase:
chiral symmetry spontaneously broken

Matter-induced Index of Refraction in QCD

- Coherent interaction of particles including π^0's with ambient matter generates an index of refraction $n = 1 + \varepsilon$ (c.f. Fermi!)
- Changes E-p relation, making decay $\pi^0 \rightarrow \gamma\gamma$ KINEMATICALLY IMPOSSIBLE above $E/m = \varepsilon^{-1/2}$
- DEPENDS ON ENERGY OF π^0, not of interaction

Egalitarian quark production at VHE

- As the energy increases, the “penalty” for producing heavy quarks decreases (a known phenomenon at high pt, conjecture may also occur at VHE)
- LHC expts find enhanced K/pi ratio; fit that and increase with energy
- Convert light mesons to Charm and Bottom mesons with a probability that increases with energy; fit to get required muon content.

Modern-Politics Model

- Convert pions to K's and baryon-antibaryons at all energies above fixed-target experiments (E_{lab} ~TeV)
- Adjust fraction converted to fit UHECR shower data
- Don't worry about consistency with lab experiments (why pay attention to facts????)

Diverse Behaviors wrt Energy

Energy Dependence

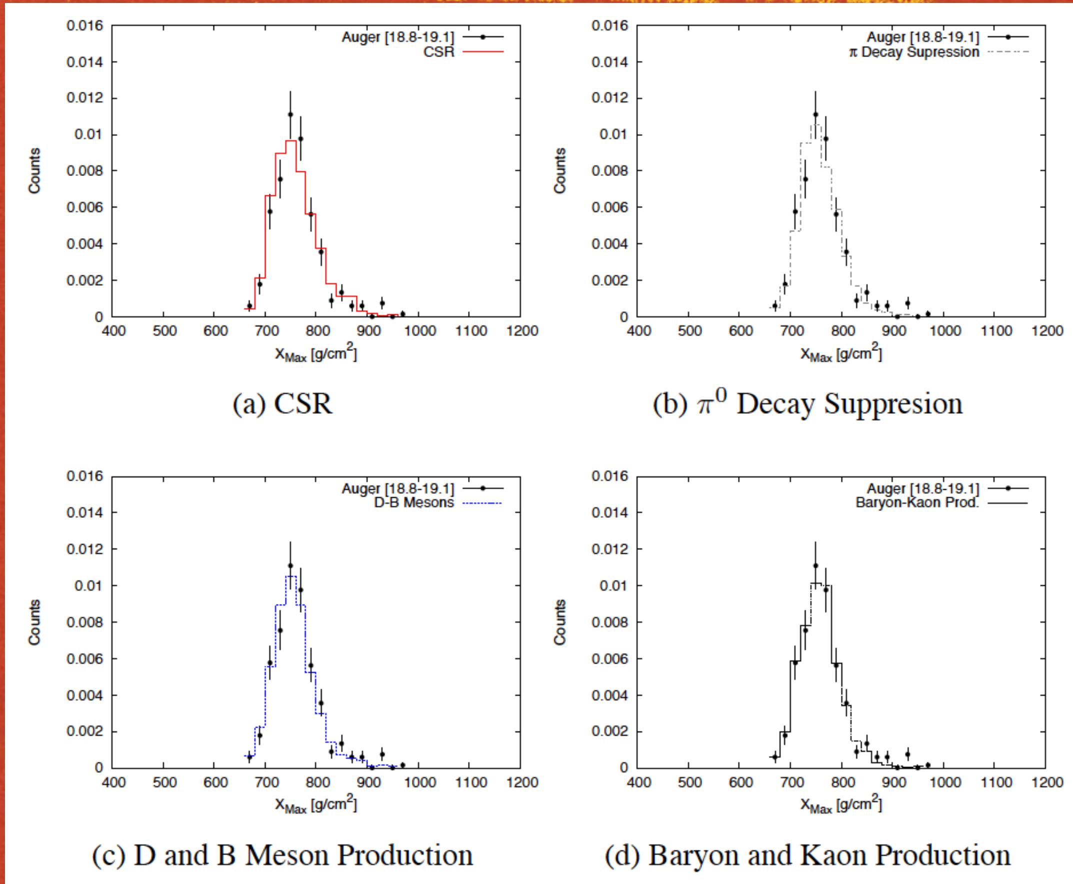
- IndexRefraction: only depends on particle energy, not interaction energy; abrupt transition to new regime.
- CSR: turns on gradually above 10^{17} eV, depending on peripherality of collision
- K-B (modern politics): modification at low as well as high energy
- DB mesons: relatively smaller change to physics than CSR; modifications occur at high energies

Composition

- CRS: proton only
- others: fix composition to fit Xmax

Step 1: Xmax at 10 EeV

- CSR: pure proton
- Fit each of others to mix of p, He, N and Fe



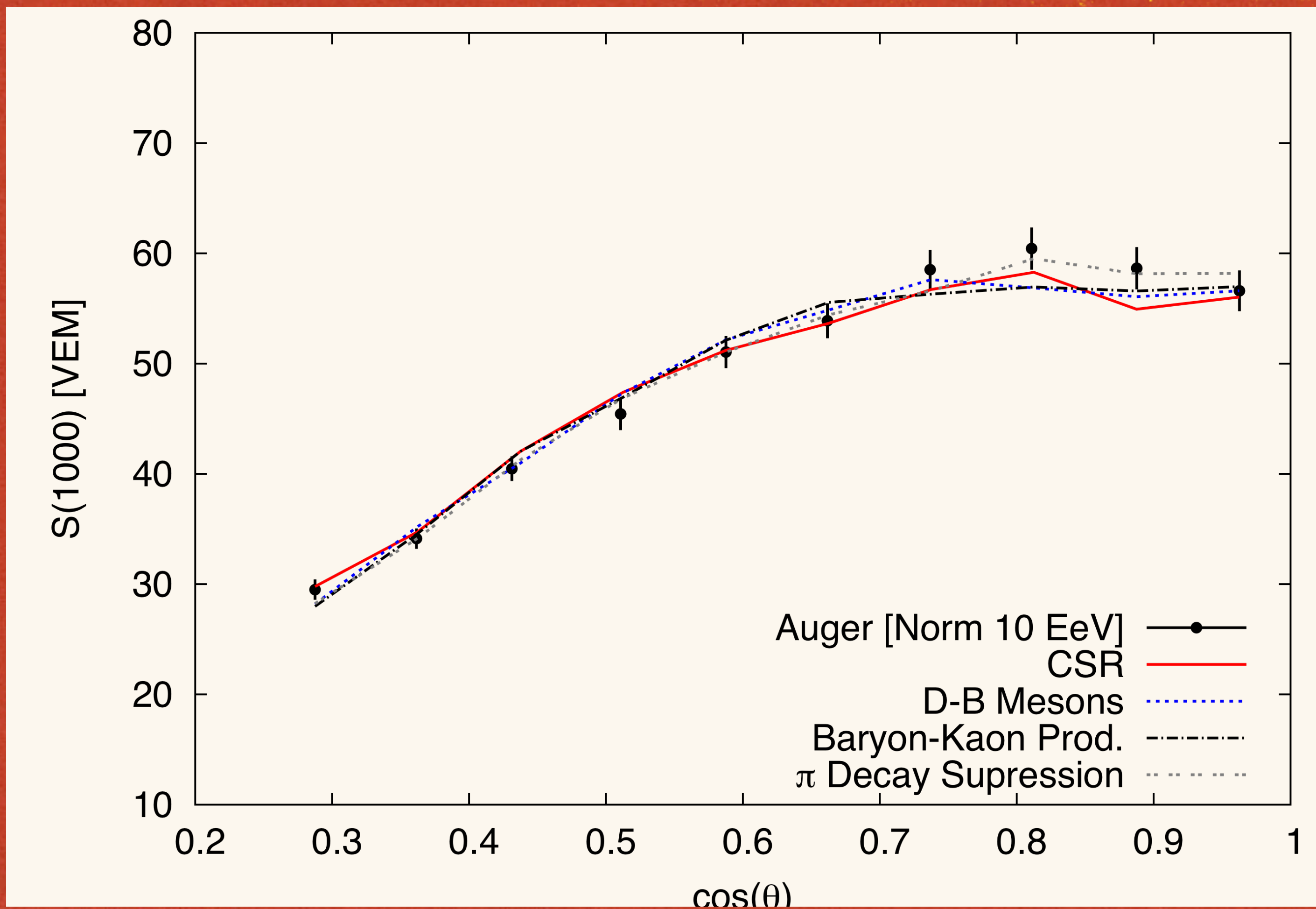
(a) CSR

(b) π^0 Decay Suppresion

(c) D and B Meson Production

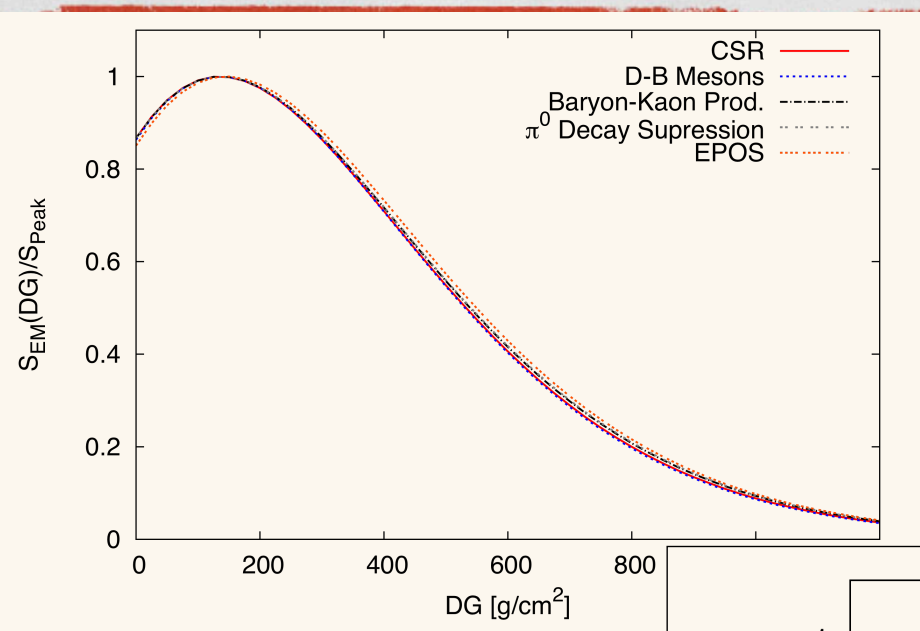
(d) Baryon and Kaon Production

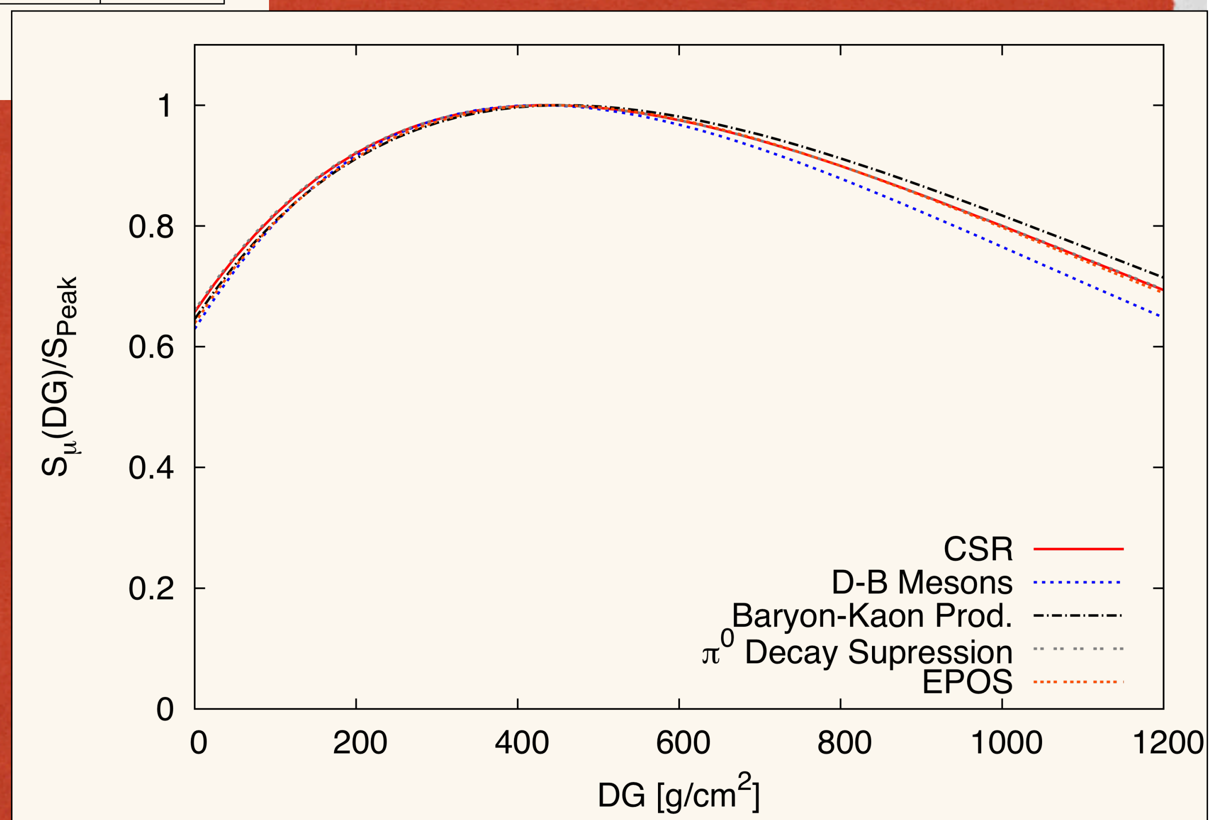
II: CIC (muon content)



Model Parameters

Model	Composition	Eng. Threshold	Modification
CSR	100p	10^{17} eV	80% mesons -> baryons ~20% of events at 10^{17} ev ~90% of events at 10^{19} eV
MSPD	6% p 7% He 40% C 47% Fe	~$10^{16.5}$ eV	Pions do not decay
D-B Meson	5% p 12% He 78% C 5% Fe	10^{17} eV	2/3 of mesons -> D-B mesons
Pi -> K, B	4% p 15% He 62% C 19% Fe	All Eng.	5% of forward pi's to Baryons 8% of all pi's to kaons



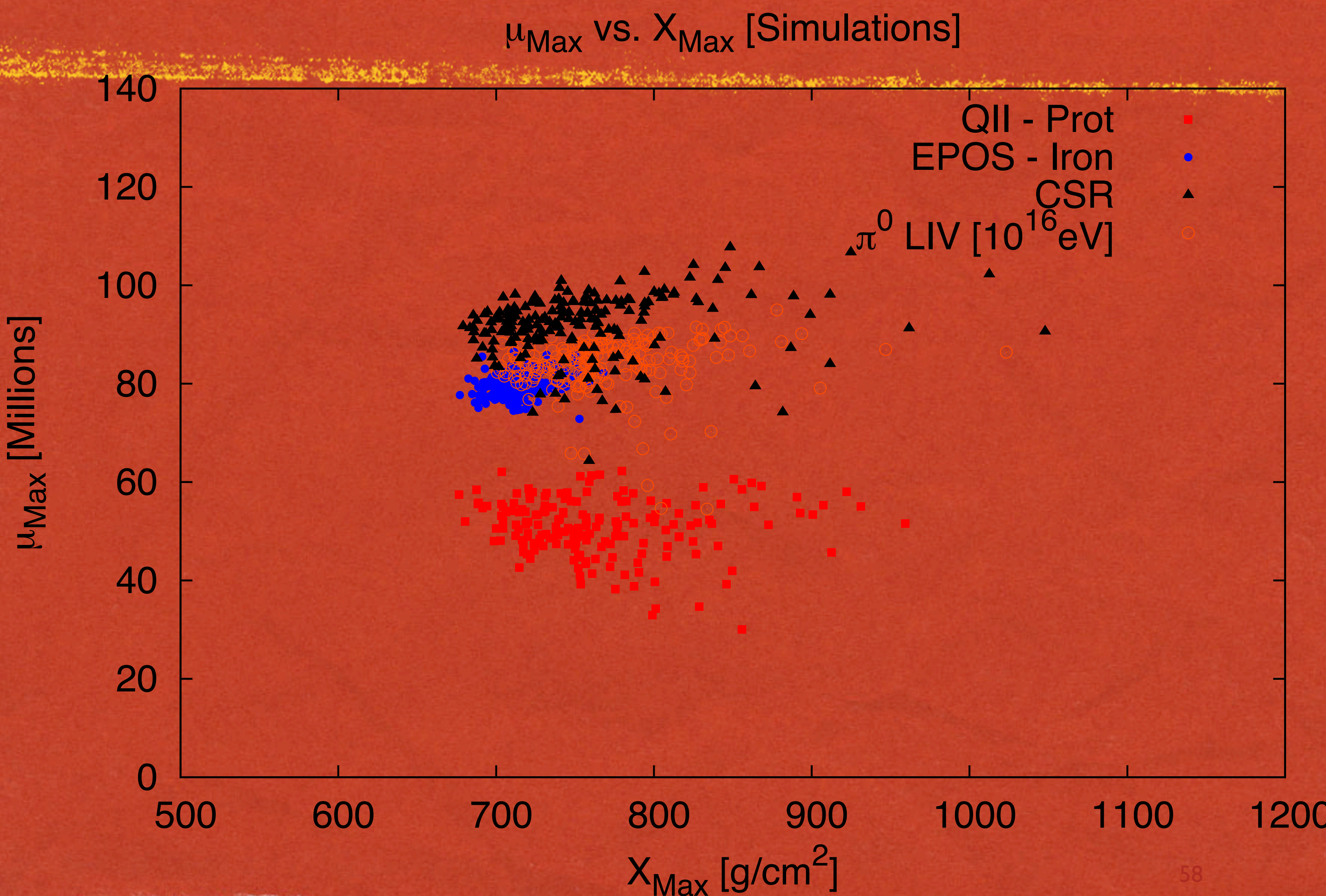


Differences between models are very subtle.

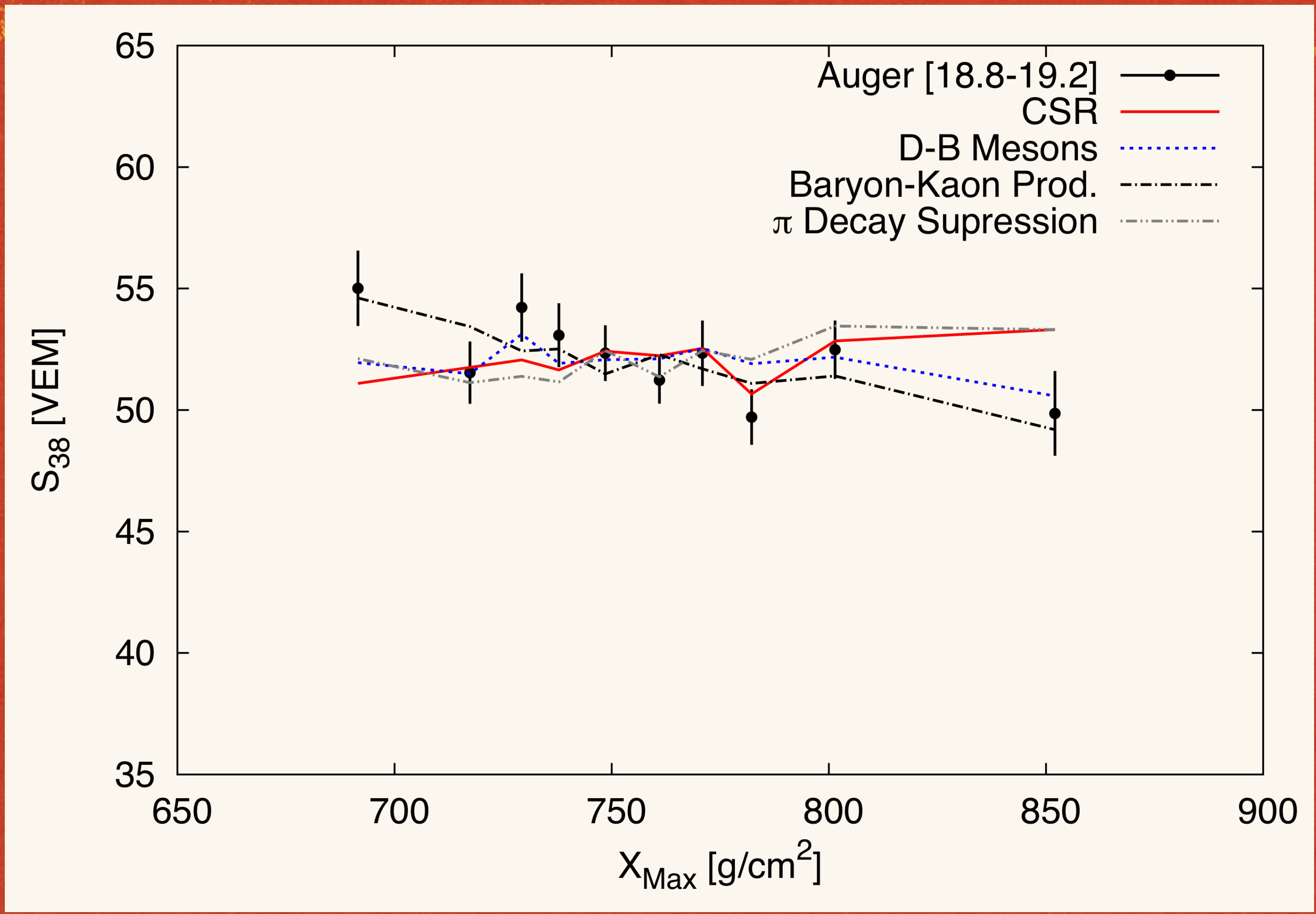
How to discriminate? SX plot!

- Scatter plot for individual hybrid events
- Correlation between ground signal and Xmax
- Big statistics: separate into Energy and zenith bins
- Present statistics: Rescale to common energy and DG (analogous to using S_{38} instead of S_{1000})

Hybrid events can discriminate models



S-X plot



Auger [18.8-19.2]
CSR
D-B Mesons
Baryon-Kaon Prod.
π Decay Supression
S38 [VEM]
XMax [g/cm2]
65
60
55
50
45
40
35
650
700
750
800
850
900

Summary

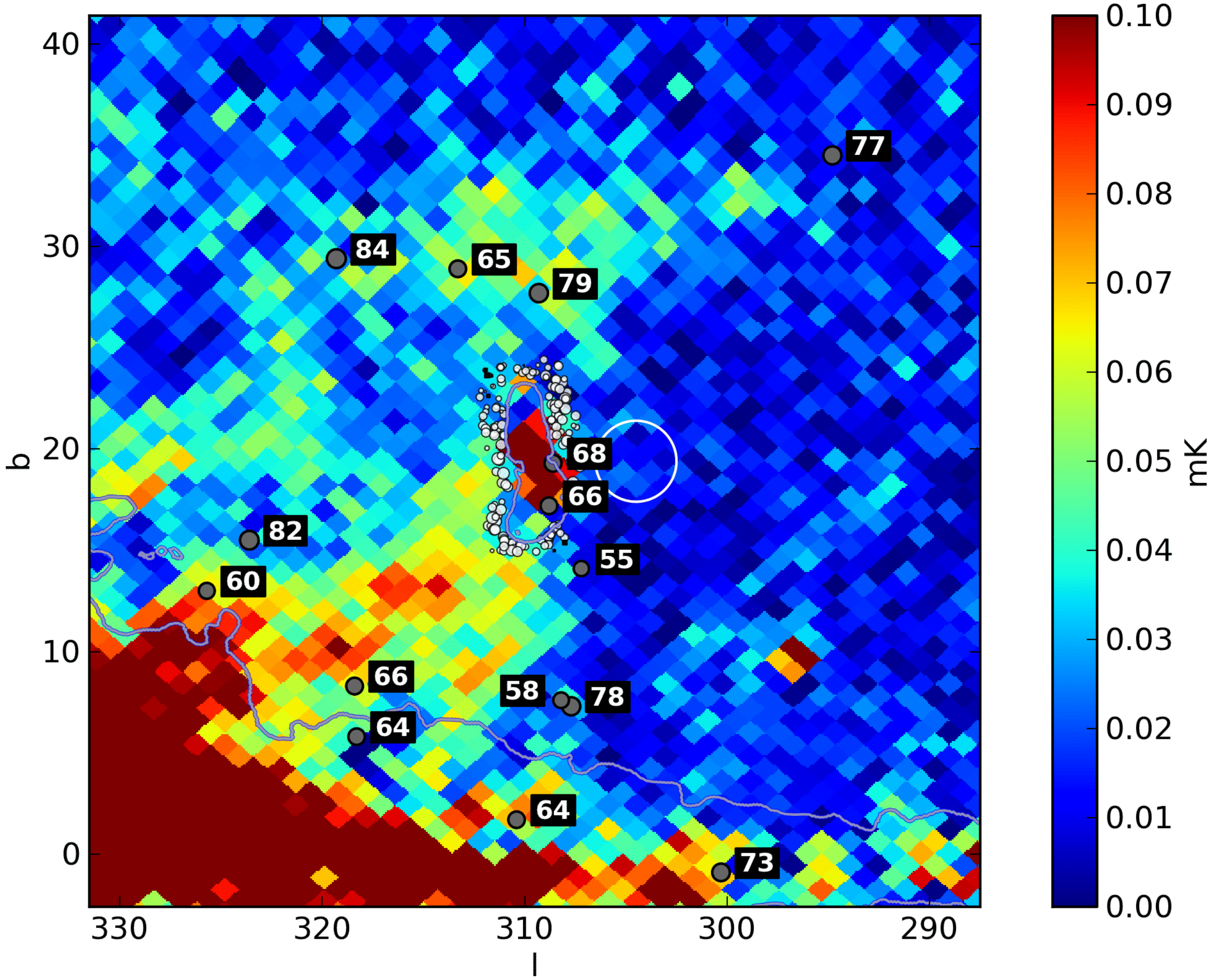
- Composition & Particle Physics
  - Examples prove that models can be made consistent with present data. Radically new physics may be required.
  - Hybrid data will be able to decide between models [&MPD!]
  - Composition will be determinable.
- Sources Galactic Magnetic Field
  - Trustworthy GMF => correlation studies will be much more powerful and reliable. New phase of analyses underway.

Conclusion

We're at the threshold of a Golden Age of UHECR particle & astrophysics

JF12 predictions in Cen A direction

excellent fit -- FJFG12



Entry plane maps, multiple images