Future of Dark Matter Astro-Particle Physics @ ICTP, October 11th 2013

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TIDAL COSMIC RAYS IN GALACTIC FLY BYS

Tijana Prodanović, University of Novi Sad

Tamara Bogdanović, Georgia Institute of Technology
Dejan Urošević, University of Beogradu
Aleksandra Dobardžić, University of Belgrade
Levan Kakabadze (coming to a PhD near you)
Brian Fields, University of Illinois at Urbana-Champaign
Vasiliki Pavlidou, University of Crete

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SEARCHING FOR DARK MATTER

- **(In)Direct**
- Experiments – DAMA, LHC, SuperCDMS, IceCube etc.
- Gamma-ray signals – lines or excess in background

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SEARCHING FOR DARK MATTER

- **(In)Direct**
- Experiments – DAMA, LHC, SuperCDMS, IceCube etc.
- Gamma-ray signals – lines or excess in background

- **See anything weird?**

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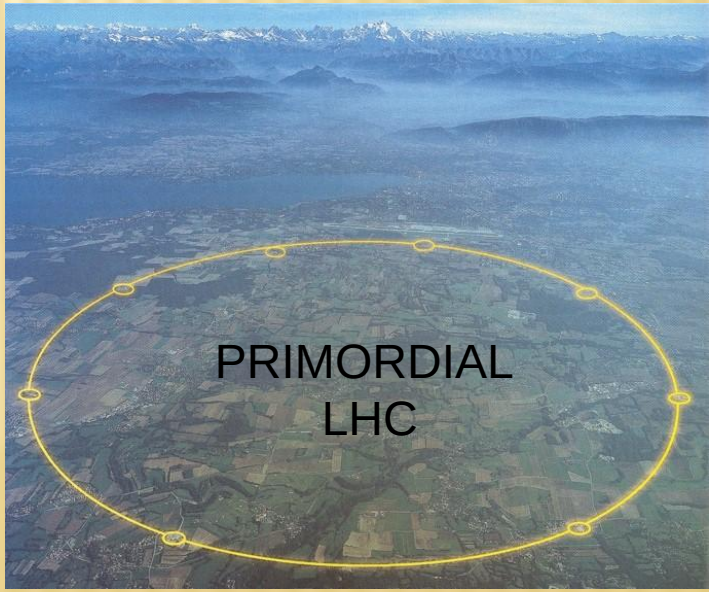
I SEE WEIRD LITHIUM

- One of the primordial elements (D,He,Li)
- Primordial nuclear reactor
- Initial conditions+physics →abudances↔observations
- Big Bang Nucleosynthesis testing physics and cosmology



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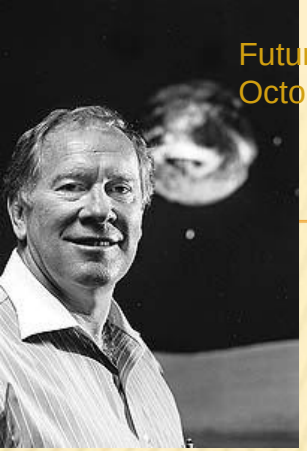
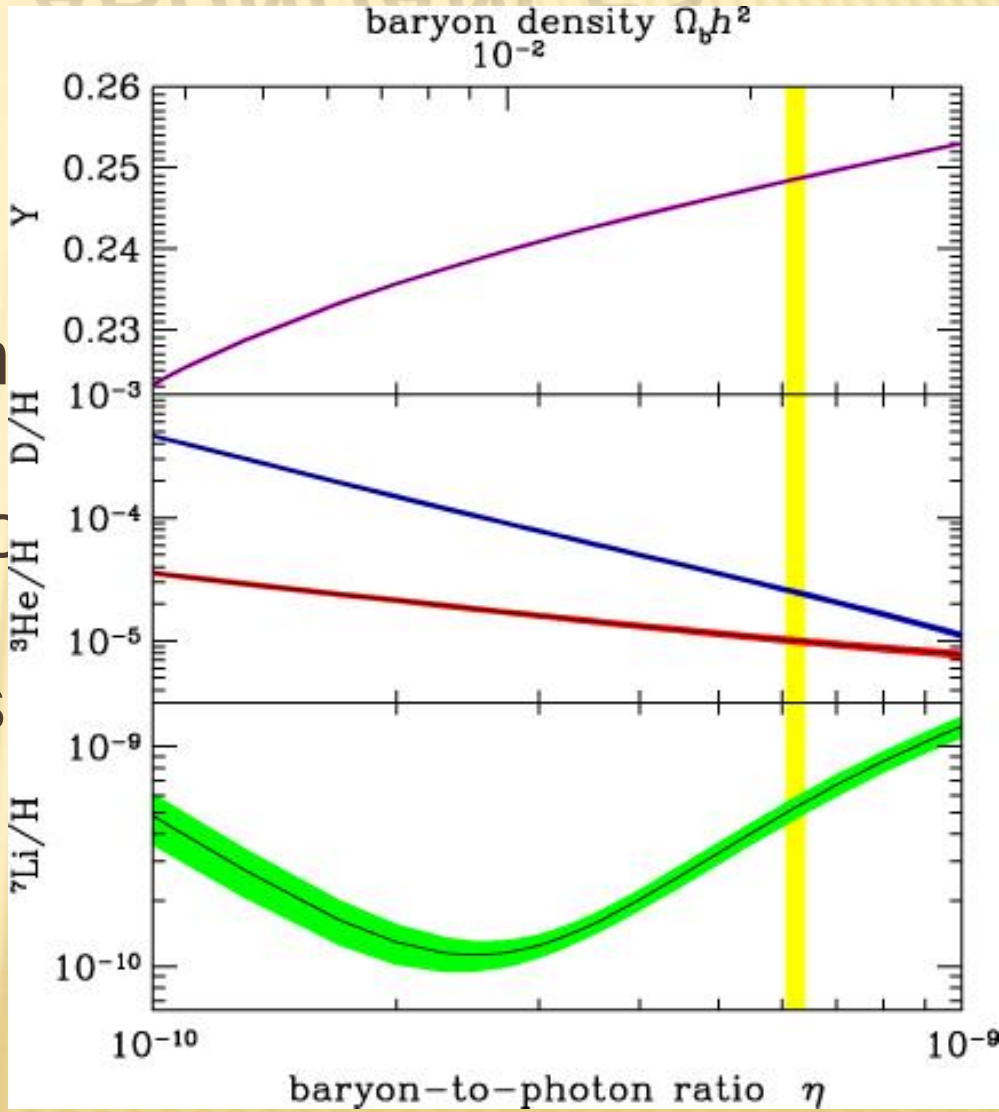


PRIMORDIAL ABUNDANCES

- Schramm plot
- Abundance vs baryon density
- Curves: BBN predictio
- 1σ uncertainty – nuclear reaction rates
- CMB (*WMAP*: Dunkley 2008)
  – fixes baryon density
- Read off abundance
- Simple!(?)



Cyburt et al. 2004, 2008

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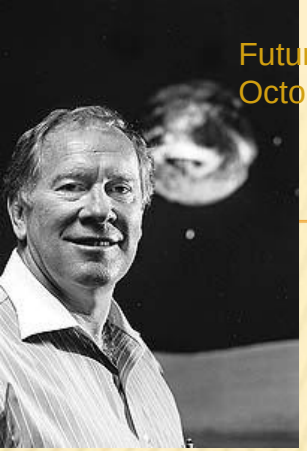

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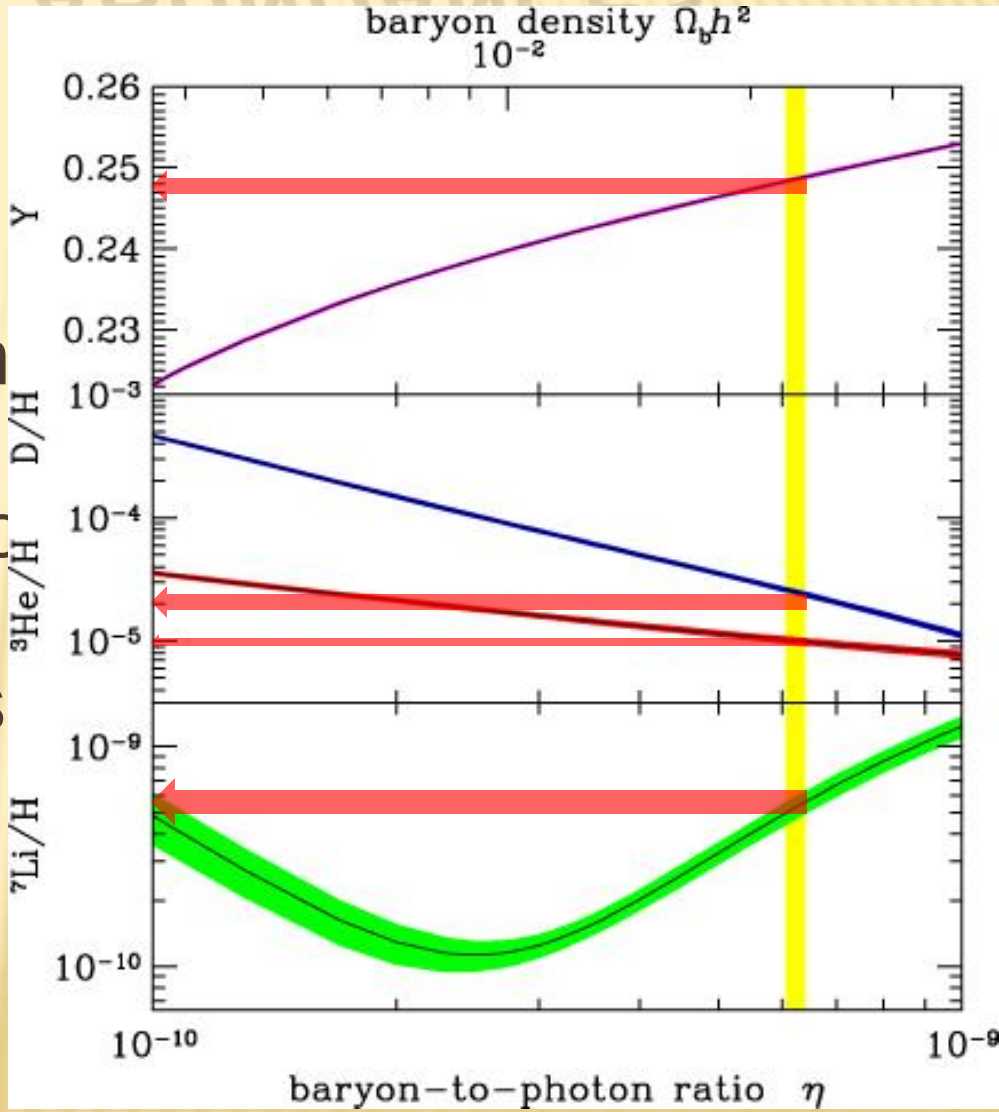

Cyburt et al. 2004, 2008

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THEORY VS OBSERVATIONS?

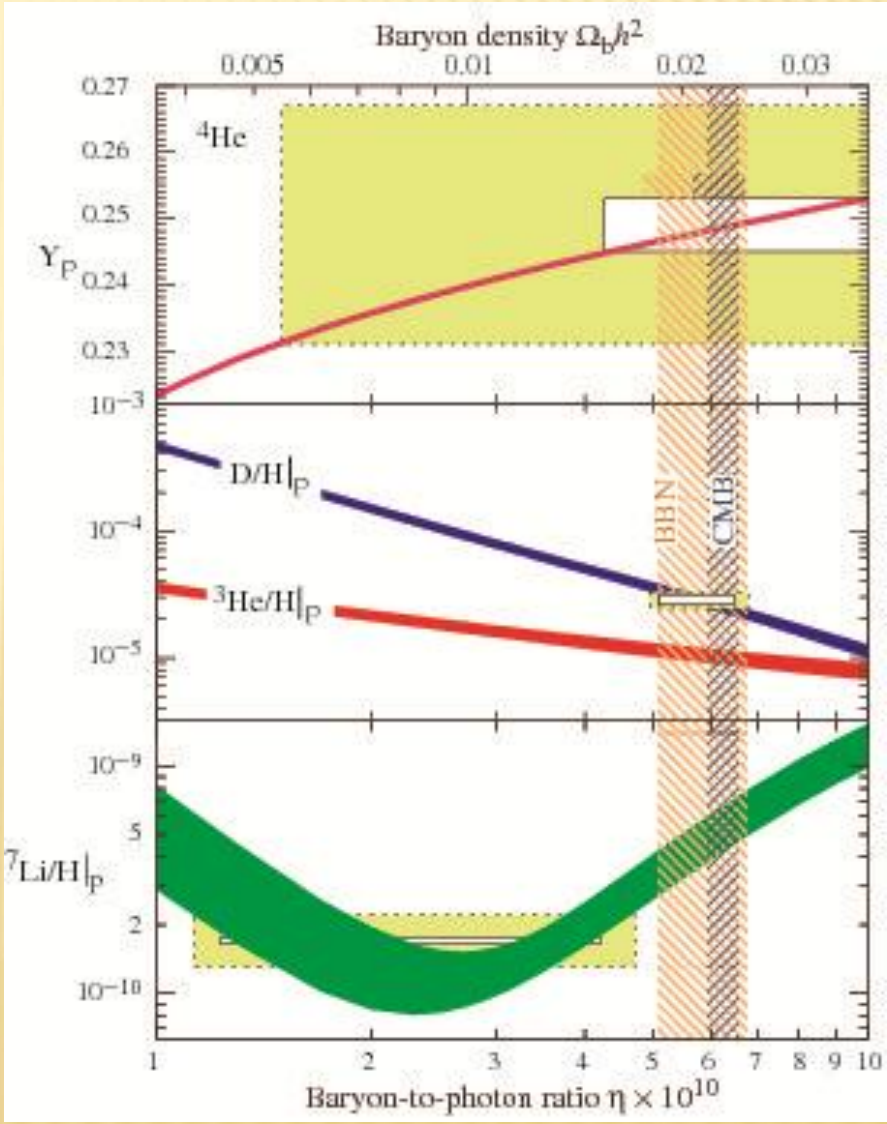
- BBN theory curves
- CMB – baryons
- Observations - boxes

- ^{4}He – OK ☺
- D – right on! ☺
- ^{7}Li – problem! ☹

Factor of 3-4 discrepancy!

LITHIUM PROBLEM!

- **Note: Planck gives lower baryon density – slightly lower Li discrepancy!**



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SOURCES OF LITHIUM

- ^{7}Li sources
  - BBN
  - **cosmic-ray interactions** (ingredients: shock waves, magnetic field, charged particles) (Reeves 1970)
    - fusion $\alpha + \alpha \rightarrow {}^{6,7}\mathrm{Li}$
    - spallation $p, \alpha + \mathrm{CNO} \rightarrow \mathrm{LiBeB}$
  - type II supernovae (neutrino process – neutrino-induced spallation in C shell – ^{11}B, ^{10}B i ^{7}Li)
- ^{6}Li sources
  - **cosmic-ray interactions mainly** (Reeves 1970)
  - in accretion disks of micro quasars (Iocco & Pato 2012)

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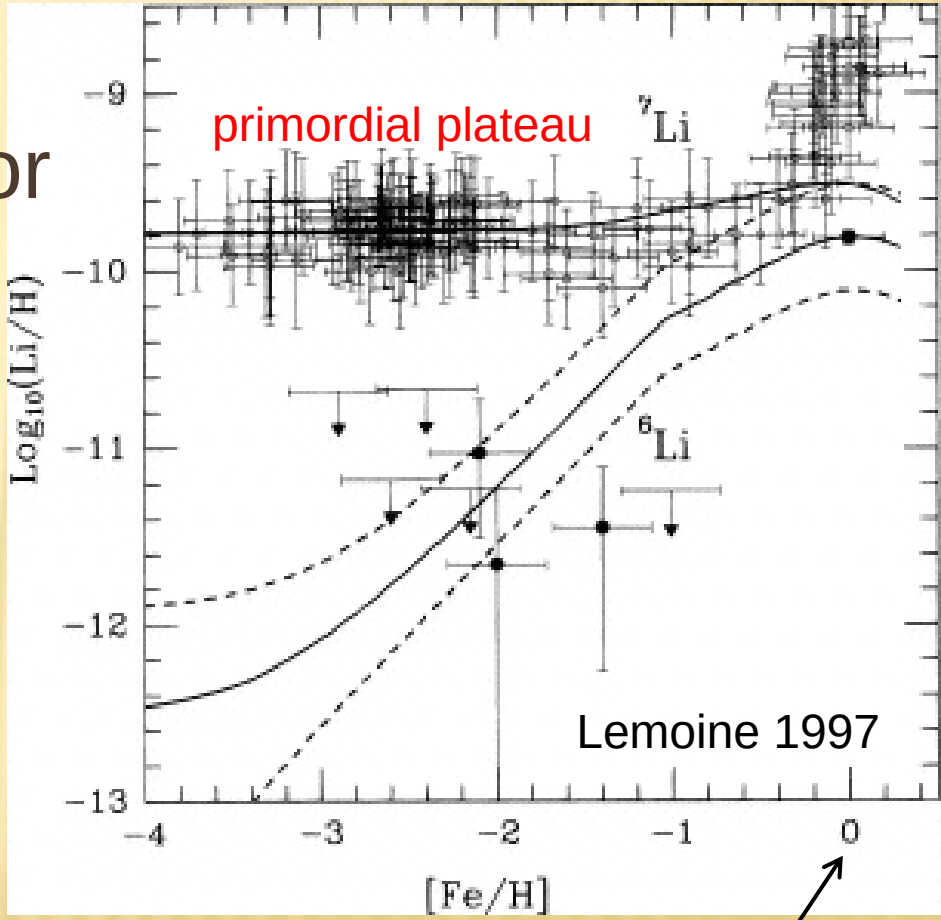
MEASURING PRIMORDIAL LITHIUM

- Spite & Spite 1982
- Old, warm, metal-poor halo dwarfs
- (Almost) uniform Li abundances over a range of low metallicities
- Very low scatter!
- Primordial **plateau**



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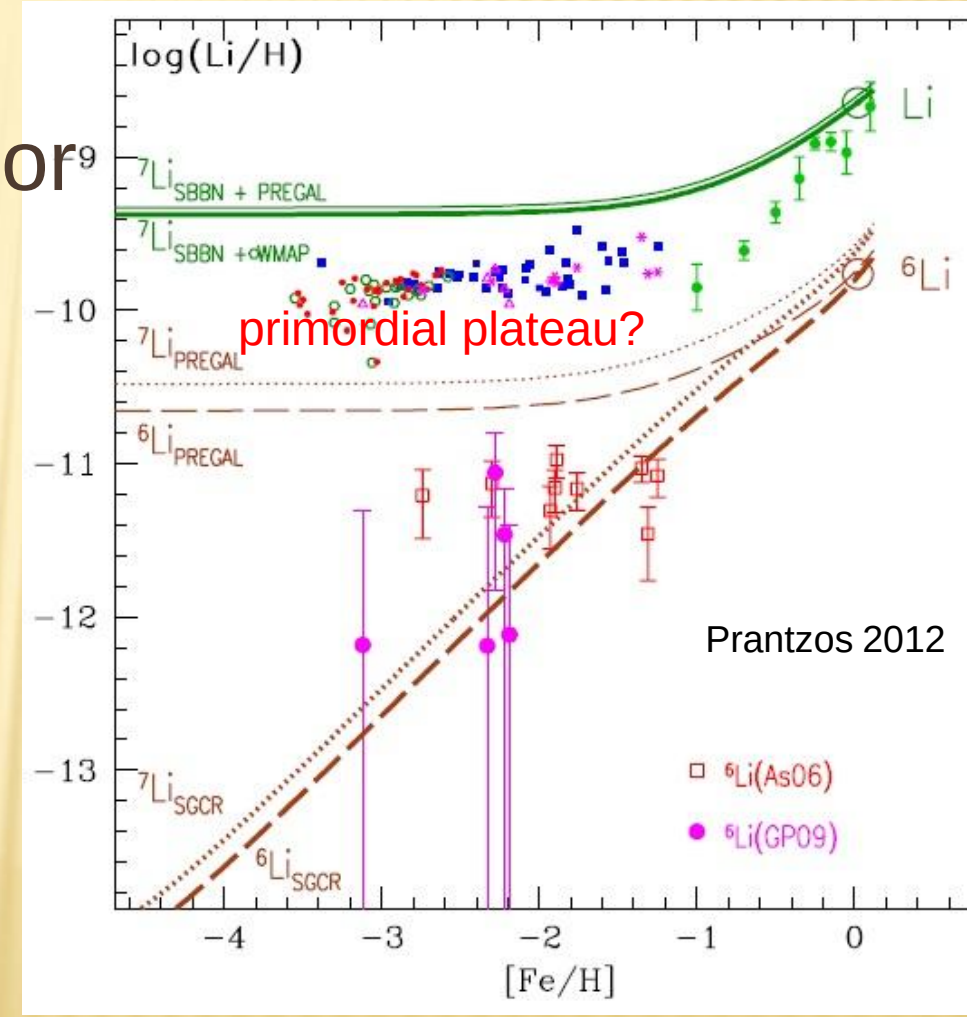

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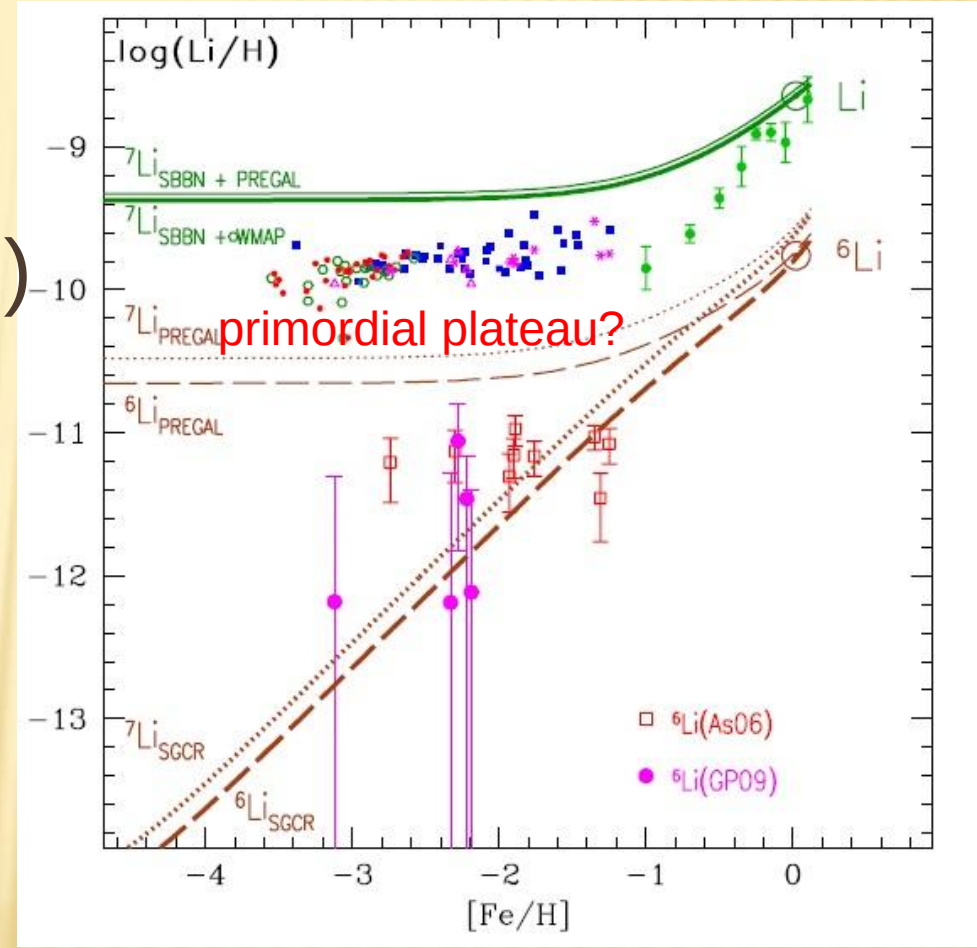
LITHIUM PROBLEM

- Spite "plateau" ~ **2- 4 times lower** than predicted (CMB+BBN) primordial abundance

$$\left(\frac{^7Li}{H}\right)_p = \left(5.24^{+0.71}_{-0.62}\right)\times 10^{-10}$$

$$\left(\frac{^7Li}{H}\right)_{obs} = \left(1.23^{+0.68}_{-0.32}\right)\times 10^{-10}$$



Li is destroyed instead of expected post-BBN production!?

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WHO IS TO BLAME?

- **Observations?**
- Measured abundances are wrong?
- Stellar modeling problems?

- **Theory?**
- Measured aboundances are ok?

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WHO IS TO BLAME?

- **Observations?**
- Measured abundances are wrong?
- Stellar modeling problems?

- **Theory?**
- Measured aboundances are ok?
- Find a way to destroy Li pre-galactically
- New physics?

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MAIN ISSUES

- How big of a problem?
  - **Contamination** due to other sources of ^{6,7}Li?
  - Lithium problem even worse?
- Sure we should not blame stellar observations?
  - Need idependent **confirmation**
- Stellar or early, new physics destruction?
  - Measured abundances are below predicted values over a large range of low metallicities
  - Uniform destruction of Li in different stars at different metallicities?

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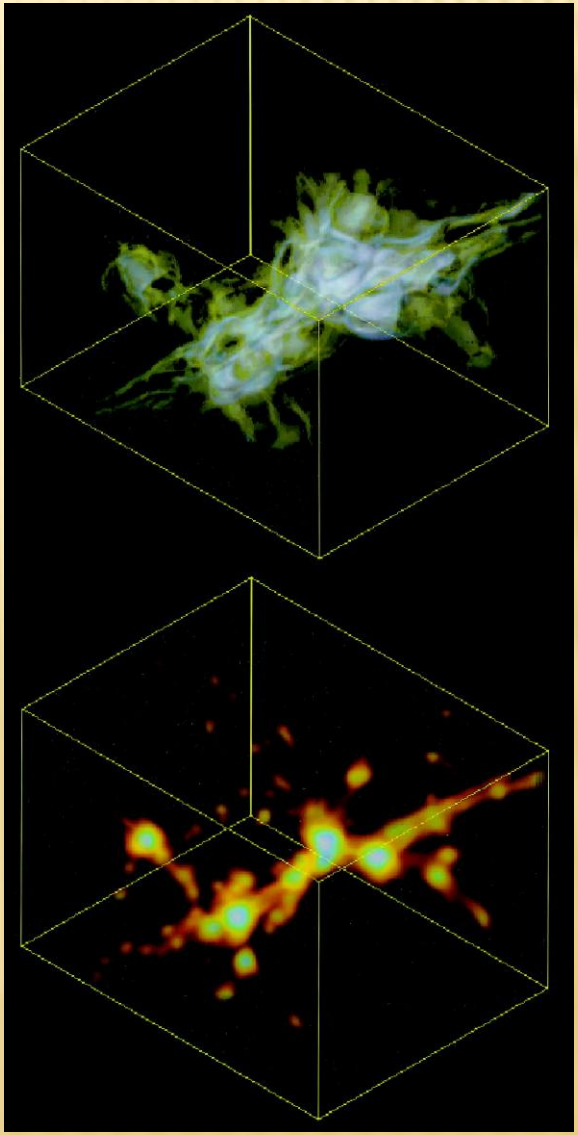
CONTAMINATION?

- Cosmological cosmic rays
  - Shock waves during structure formation (eg. Miniati 2000)
  - Hope to observe on clusters (eg. Colafrancesco & Blasi 1998, Brunetti et al 2012)
  - Li (6,7) production
  - Such Li is a contaminat to primordial Li content in halo stars (Suzuki & Inoue 2002)
  - Must correct for – larger discrepancy!
  - Note: Also adding to extragalactic gamma-ray background – foreground for DM signals! (Loeb & Waxman 2000)

Miniati et al. 2000



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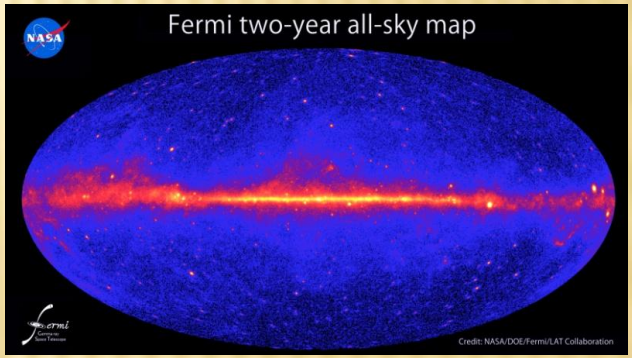
CONSTRAIN CONTAMINATION!

- **Can use gamma-rays as a probe!**
- Same source from hadronic CRs
- Lithium-gamma-ray connection

$$\frac{\gamma_\pi}{\mathrm{Li}} \propto \frac{1}{y_{\alpha,ism} y_{\alpha,cr}} \frac{\langle \sigma_\gamma \rangle}{\langle \sigma_{\alpha\alpha} \rangle}$$

(Fields & Prodanović 2005)



- Use extragallactic gamma-ray background (EGRB) to constrain pre-Galactic Li production
- But must have **a model of structure formation cosmic ray contribution to the EGRB** (Dobardžić & Prodanović 2012, Kakabaze et al. in preparation)

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CONSTRAIN CONTAMINATION!

- **Can use gamma-rays as a probe!**
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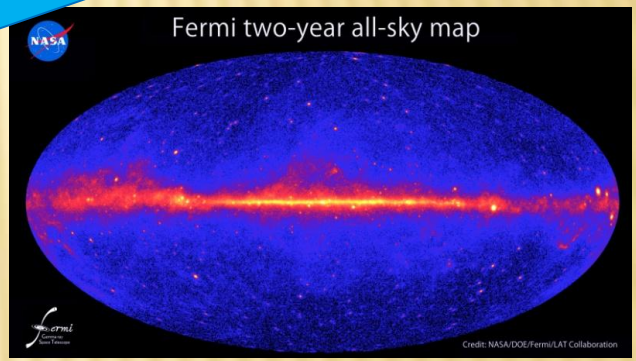
See Aleksandra's Poster!

$$\frac{\gamma_\pi}{\alpha,cr}\ \langle\sigma_{\alpha\alpha}\rangle$$

(…olds & Prodanović 2005)



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FIND NEW SITES!

- New site where Li was measured !
- Small Magellanic Cloud (Howk et al 2012)
  - Metallicity ~ 0.20 solar
  - Measured gas phase Li abundance in its ISM (and isotopic ratio!)
  - No worry about stellar modeling
  - Independent test of the state of the Lithium problem!

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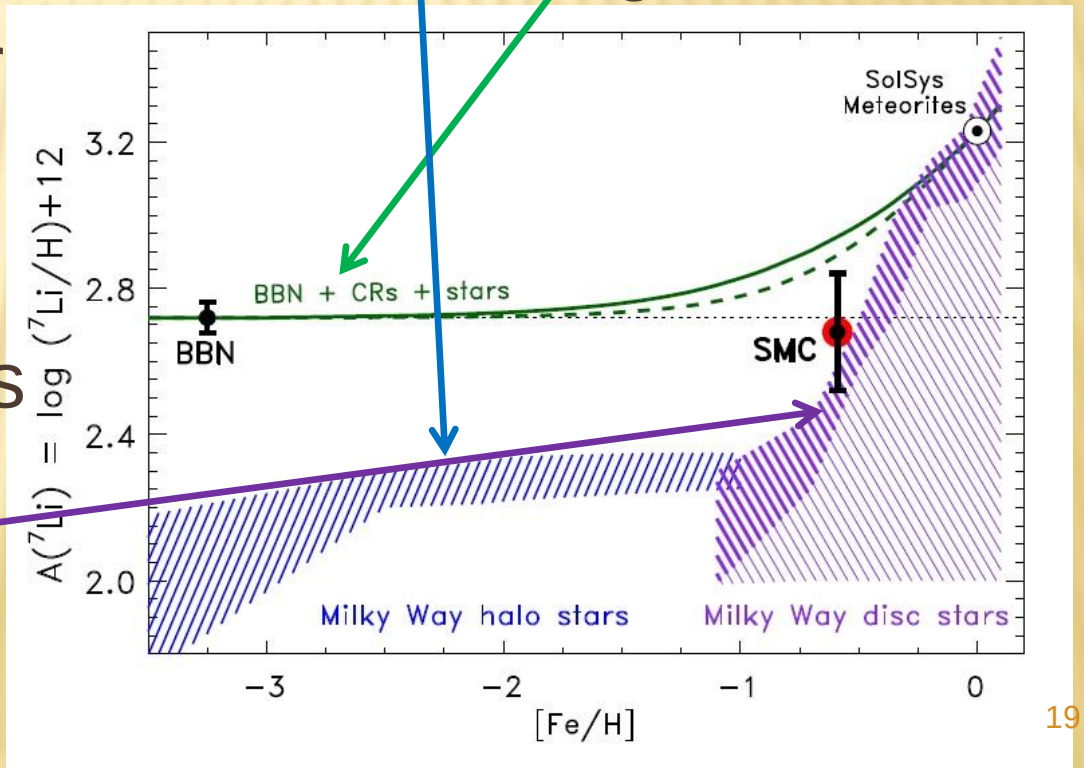
SMALL MAGELLANIC CLOUD

- Howk et al. 2012, *Nature*
- Measured abundance consistent with teoretical primordial value (above observed plateau)
- Li problem cause – stellar modeling?
- But little room for post-BBN production of Li in CR interactions

post-BBN



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BUT...CLOSE FLY-BYS

- Interractions, collisions and close fly-bys impact galaxy morphology
- Especially pronounced on small satellite galaxies disrupted by large ones (eg. SMC & MW)

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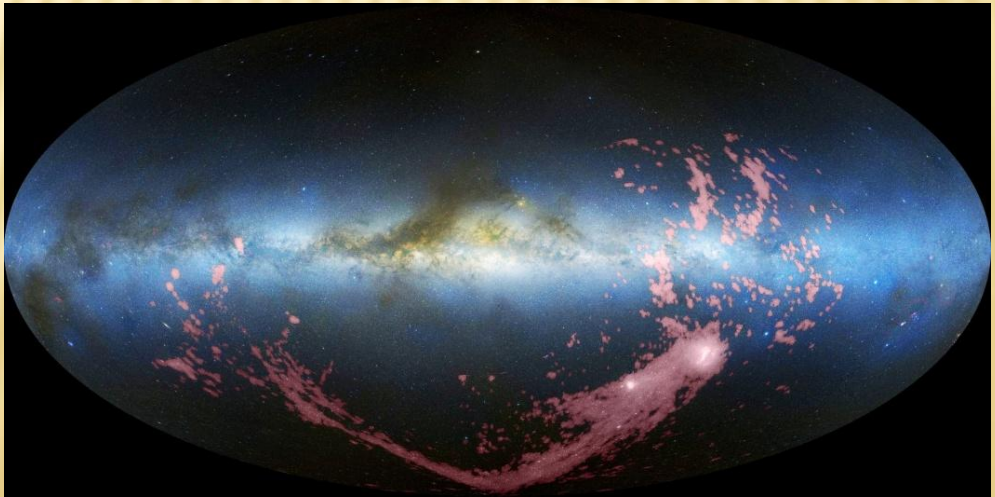
TIDAL SHOCK WAVES

- Galaxy interactions – strong shock waves on large scales (cf. Cox et al. 2006)
- Close fly-bys – tidal shock waves
- “Magellanic stream” – due to tidal interaction between Magellanic clouds ~ 2Gyr ago? (Diaz & Bekki 2012)



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TIDAL COSMIC RAYS

- Tidal shock waves + magnetic fields = **tidal cosmic rays (TCR)**
- Nucleosynthesis – LiBeB production
- In low metallicity systems
  - no CNO
  - only ^{6,7}Li production – **contamination! Must correct for!**
- Gravitational interactions energetically sufficient

$$E_{kin,SMC-MW} \sim 10^{58}\,\mathrm{erg} \qquad E_{^6Li,SMC} \sim 2\times10^{56}\,\mathrm{erg}$$

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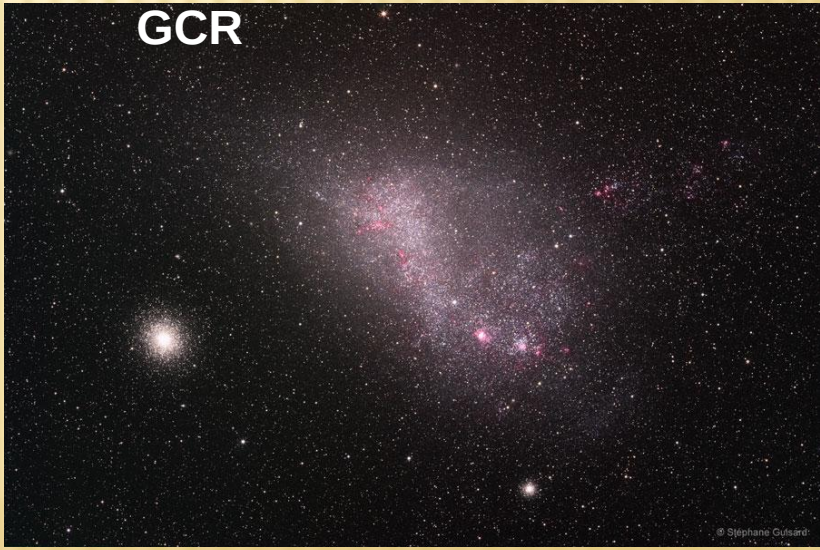
TCR & LITHIUM

- How much Li can be produced in these interactions?
- Toy model – compare to/scale with supernova shock waves

VS



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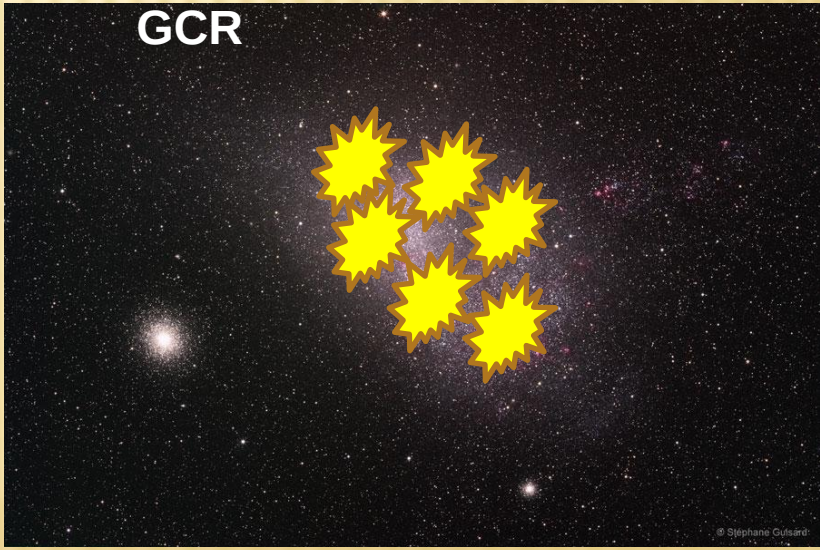

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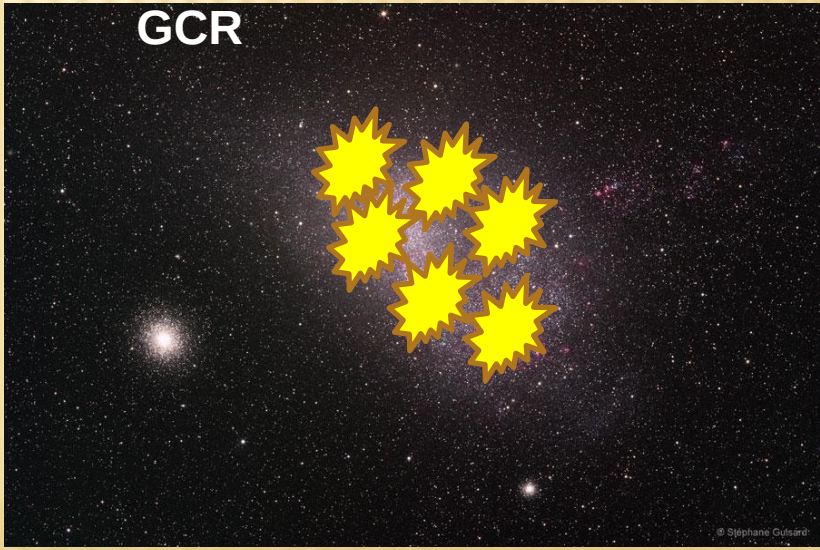

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TCR & LITHIUM

- How much Li can be produced in these interactions?
- Toy model – compare to/scale with supernova shock waves

vs

• Short but intensive cosmic-ray injection
•Large scale shock waves
•Not dirrectly/imediately accompanied with metallicity increase

• Continuous injection of cosmic rays
•Small scale shock waves
•Directly accompanied with metallicity increase

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TCR & LITHIUM

- **To have $Li_{TCR} = Li_{GCR}$**
  - how large TCR flux would be needed?
  - how large should a scale of tidal shock be?
- Fraction of total gas mass of the system that tidal shocks sweep over

$$N_{\mathrm{Li}} \propto n_{ISM} N_{CR} \tau_{CR}$$

system metallicity

ISM gas number density

particle acceleration efficiency at shock waves

$$\frac{M_{TCR,gas}}{M_{gas}} = 8\left(\frac{0.2M_{sol}}{M_{\mathrm{Fe},SN}}\right)\left(\frac{y_{\mathrm{Fe}}}{y_{\mathrm{Fe},sol}}\right)\left(\frac{\tau_{TCR}}{10^9\,yr}\right)^{-1}\left(\frac{n_{ISM}}{1cm^{-3}}\right)\left(\frac{R_{SNR}}{10\,pc}\right)^{3}\left(\frac{\eta_{GCR}}{\eta_{TCR}}\right)$$

Fe mass ejected by 1 supernova

TCR population lifetime

SNR radius up to which particles are efficiently accelerated

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TCR, LITHIUM & SMC

- At solar metallicity, entire system needs to be tidally shocked 8 times in order for TCRs to produce same amount of Li as GCRs!
- **SMC** (metallicity ~ 1/5 solar)
  - **Only 2 interactions are sufficient for TCRs to make as much Li as GCRs!**

$$M_{TCR,gas} / M_{gas,SMC} \approx 2$$

  - SMC has suffered at least 2 interactions with LMC and 1 with MW!

- But main caveat: TCR duty-cycle could be 10x lower and TCRs 10x less efficient (need numerical modeling)

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IMPLICATIONS: ISOTOPIC RATIO

- If no TCRs were accelerated in SMC
  - Expected isotopic ratio $\left({}^6\mathrm{Li}/{}^7\mathrm{Li}\right)_{SMC,GCR} \approx 0.06$
- If siqnificant fraction (eg. 50%) of total Li abundance in the SMC gas was due to
  - Isotopic ratio $\left({}^6\mathrm{Li}/{}^7\mathrm{Li}\right)_{SMC,GCR+TCR} \approx 0.1$
- Observed isotopic ratio (Howk et al. 2012)

$$\left({}^6\mathrm{Li}/{}^7\mathrm{Li}\right)_{SMC,obs} \approx 0.13 \pm 0.05$$

- **Observations are consistent with having another cosmic ray population in SMC!**

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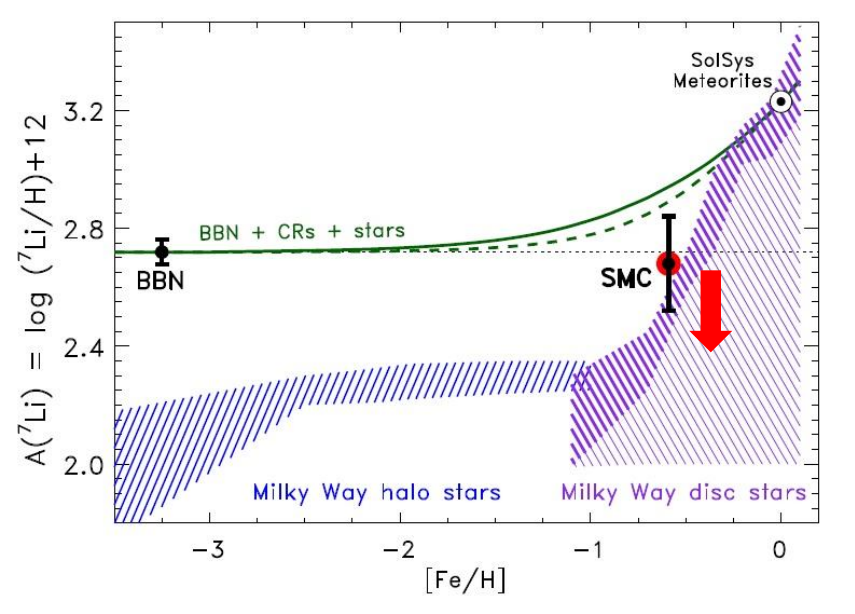
IMPLICATIONS: CONTAMINATION

- If significant fraction of total Li abundance in the SMC is due to TCRs
- Li problem remains!
- **Solution in non-standard physics?**



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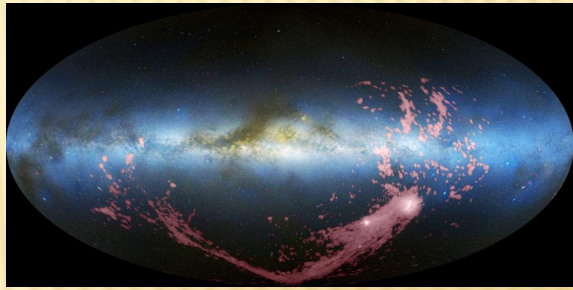
CONCLUSION



- Primordial lithium problem
  - predict 4x more Li than observed
  - stellar destruction or new physics?
- Li observed in SMC gas – ok if post-BBN production low
- But SMC “survived” few close encounters
- Tidal shock waves - **Tidal cosmic-rays!**
- 2 close fly-bys sufficient for TCRs to make same quantity of Li as GCRs made over the system history!
- Truly primordial SMC Li even lower!
- **Implies solution in the form of new physics!?**

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GRACIE! ☺

QUESTIONS?

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BACKUPS

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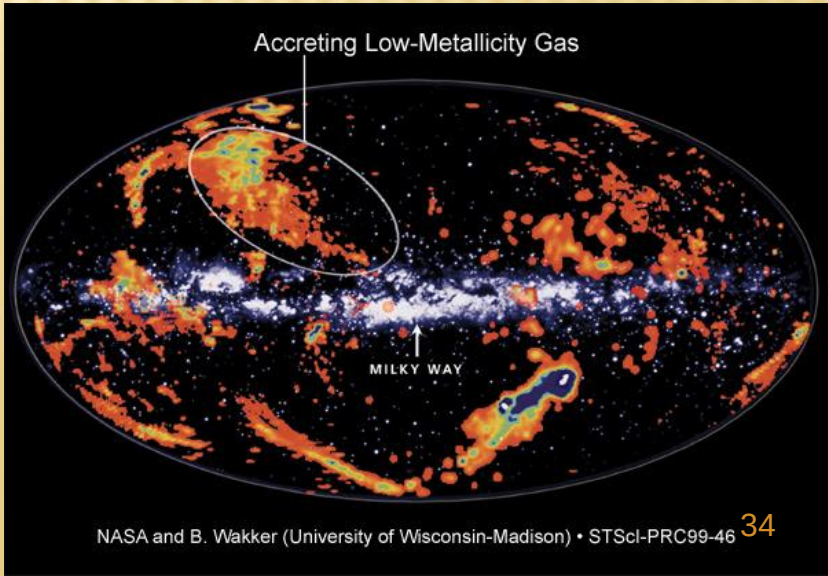
FIND NEW SITES!

- Find a better site for measuring Li!
- High Velocity Clouds (Prodanovic & Fields 204)
  - (In some cases) Low metallicity (~ 10% solarne)
  - Little dust
  - Not complicated by stellar modeling
  - Idependent test of pre-galactic Li production
- But High ionization, low density, difficult to observe



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NEW (ASTRO) PHYSICS

- Lithium problem not solved
- No conventional solution...so far
- ^{7}Li problem must be solved without endangering concordance with other elements!
- Bonus: Find sink of ^{7}Li which is a source of ^{6}Li?
- Dark matter affecting BBN epoch?

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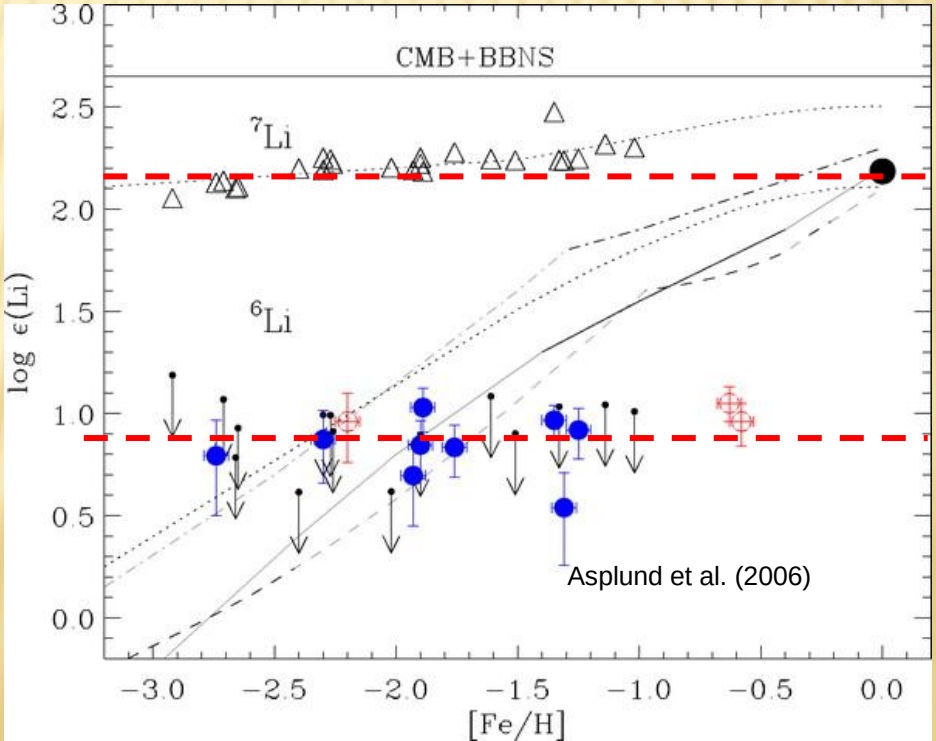
LITHIUM PROBLEM EVEN WORSE?

- ^{6}Li "plateau"? Not made during BBN!
- Post-BBN production in CR interactions
  - Galactic CRs - ^{6}Li increases with metallicity
  - Cosmological CR? – ^{6}Li independent of metallicity

^{7}Li plateau

^{6}Li plateau



Expected but low

Unexpected

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^{7}Li plateau

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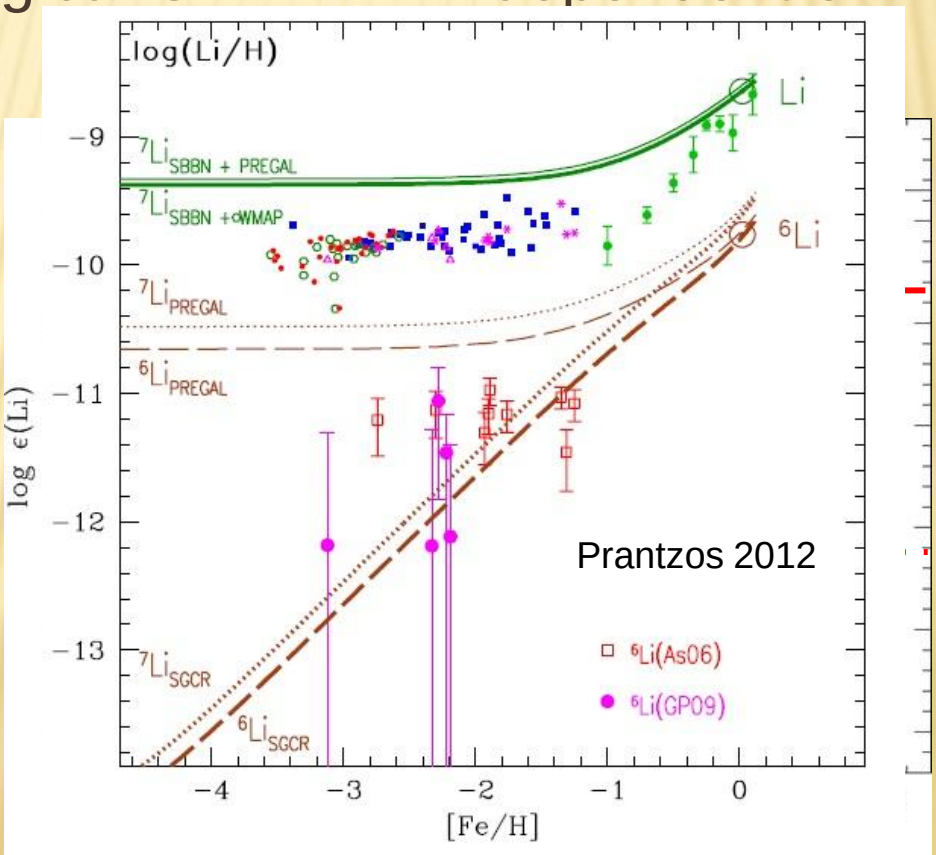

Expected but low

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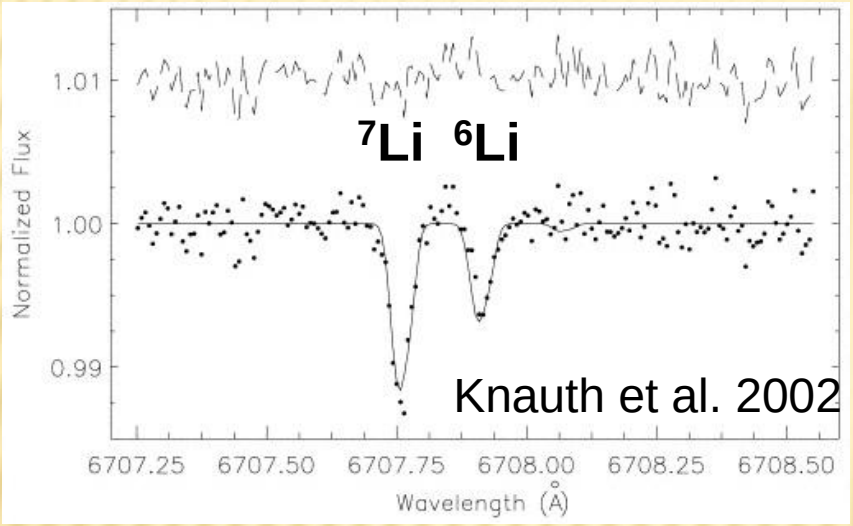
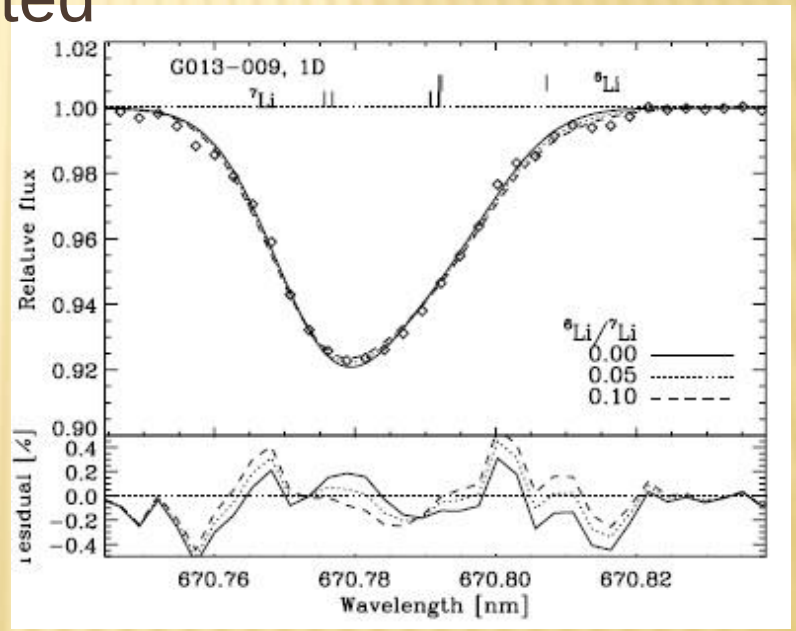
LITHIUM OBSERVATIONS

- Easy in insterstellar medium gas! ☺
  - Both isotopes nicely deparated





Asplund et al. 2006

- Complicated in stars ☹
  - ^{6}Li shows as small asymmetry on ^{7}Li line – isotopic ratio infered from this

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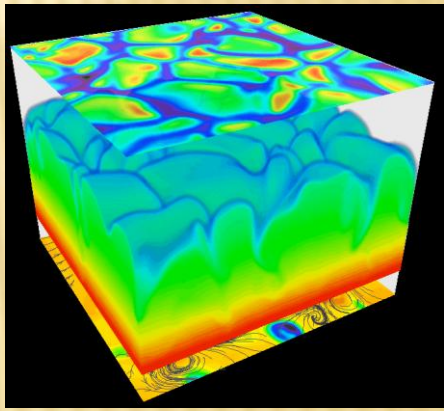
SOLUTION?: LITHIUM OBSERVATIONS

- Absorption lines in stellar atmospheres
- Modeling! Non-LTE, 1D vs. 3D
  - Li mostly ionized in atmospheres
  - Must determine Li II/Li I ratio
  - Strong temperature dependance



- Much larger temperature needed to solve Li problem? $\Delta T \sim$ 500-600K?
  - Affects other element abundances (Be, B, O)
  - Casagrande et al. 2010 – new, detailed analysis of T scale gives at most $\Delta T \sim$ 200K

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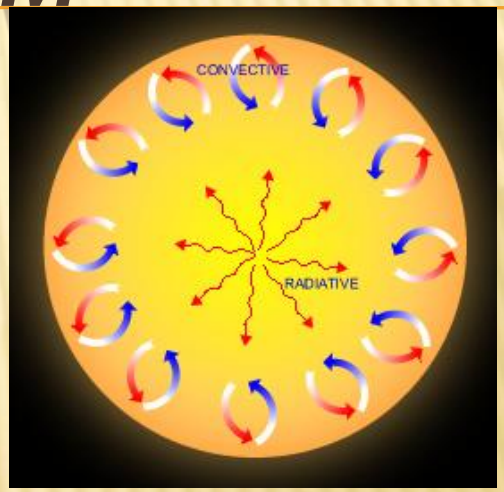
SOLUTION?: MIXING LITHIUM



- Lithium easily burned in stars

$$T > 2.5\times10^6 \Rightarrow {}^7Li + p \rightarrow 2\,{}^4He$$

$$T > 2\times10^6 \Rightarrow {}^6Li + D \rightarrow 2\,{}^4He$$

- Destroyed by convection!
  - Deeper mixing of surface material – Li burning
  - If ^{7}Li is destroyed – ^{6}Li destroyed even more!
- **But not enough and not uniformily!**
  - Different stars – different convective zones
  - Should see larger scatter around “plateau”!

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IMPLICATIONS: RADIO EMISSION

- Enhanced radio signal due to TCR presence
  - expect strong synchrotron emission
  - Note: tidal shock waves would trigger star-formation, followed by enhanced GCR flux, but at the later epoch
- Enhanced radio signal detected from M51 interacting system!
  - especially pronounced in smaller of interacting galaxies!
  - due to TCRs?

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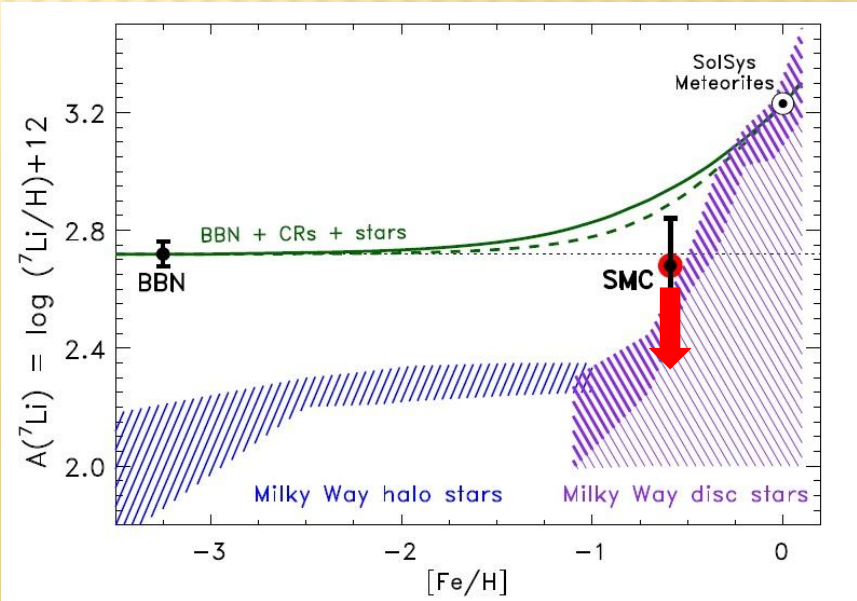
IMPLICATIONS

- If significant fraction of total Li abundance in the SMC is due to TCRs
  - Li measured in SMC gas is not representatiove of close-to-primordial abundance and should not be compared to MW as it is – must make downward correction for this contamination!
  - Li problem remains!
  - Observations and stellar destruction not a problem!



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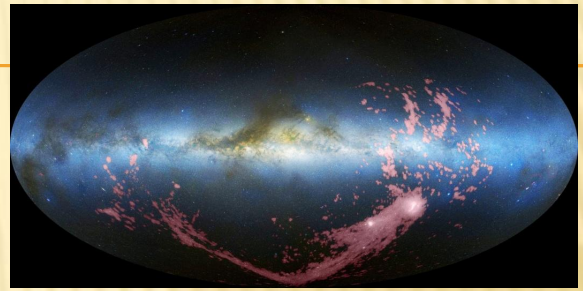
CONCLUSION



- SMC “survived” few close encounters with LMC and MW
- Tidal shock waves - **Tidal cosmic-rays!**
- 2 close fly-bys sufficient for TCRs to make same quantity of Li as GCRs made over the system history!
- SMC Li contaminated by TCRs
- Truly primordial SMC Li even lower!
- **Implies solution in the form of new physics!?**