NSTX-U

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The nearly continuous improvement of discharge characteristics and edge stability with increasing lithium coatings in NSTX

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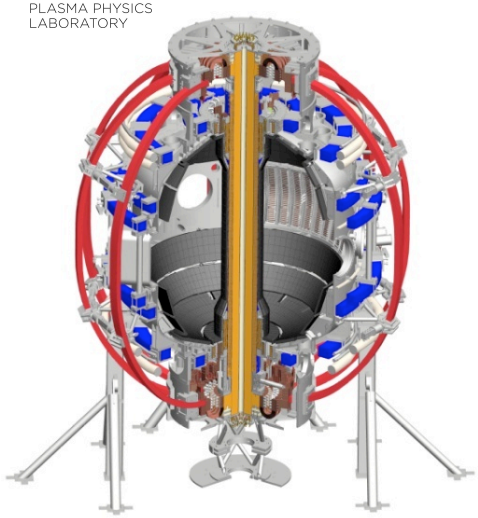
PPPL PRINCETON PLASMA PHYSICS LABORATORY

24th IAEA Fusion Energy Conference

8-13 October 2012, San Diego, CA



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ASCR, Czech Rep

Power and particle exhaust a key challenge for future devices

- Liquid metals are being studied at PPPL as an alternative to solid PFCs for future devices

- NSTX used lithium wall coatings (evaporative and liquid) to test the efficacy of lithium in particle and power exhaust
  - Lithium has effective deuterium retention -> low recycling
  - Lithium will be important research line in NSTX-Upgrade, which is scheduled to commence operation in 2014

Plasma characteristics and edge stability improved nearly continuously with increasing lithium coatings

- Lithium evaporated before discharge; amount scanned

- Global characteristics changed
  - Recycling: D_α declined in all measured views
  - Energy confinement (τ_E, H-factor) improved, consistent with reduced transport at lower ν^*
  - *When discharges were ELM-free, radiated power increased with time (we tested several techniques to ameliorate this problem)*

R. Maingi, PRL 2011
R. Maingi, NF 2012
S. Kaye, EX/7-1
W. Guttenfelder, TH/6-1

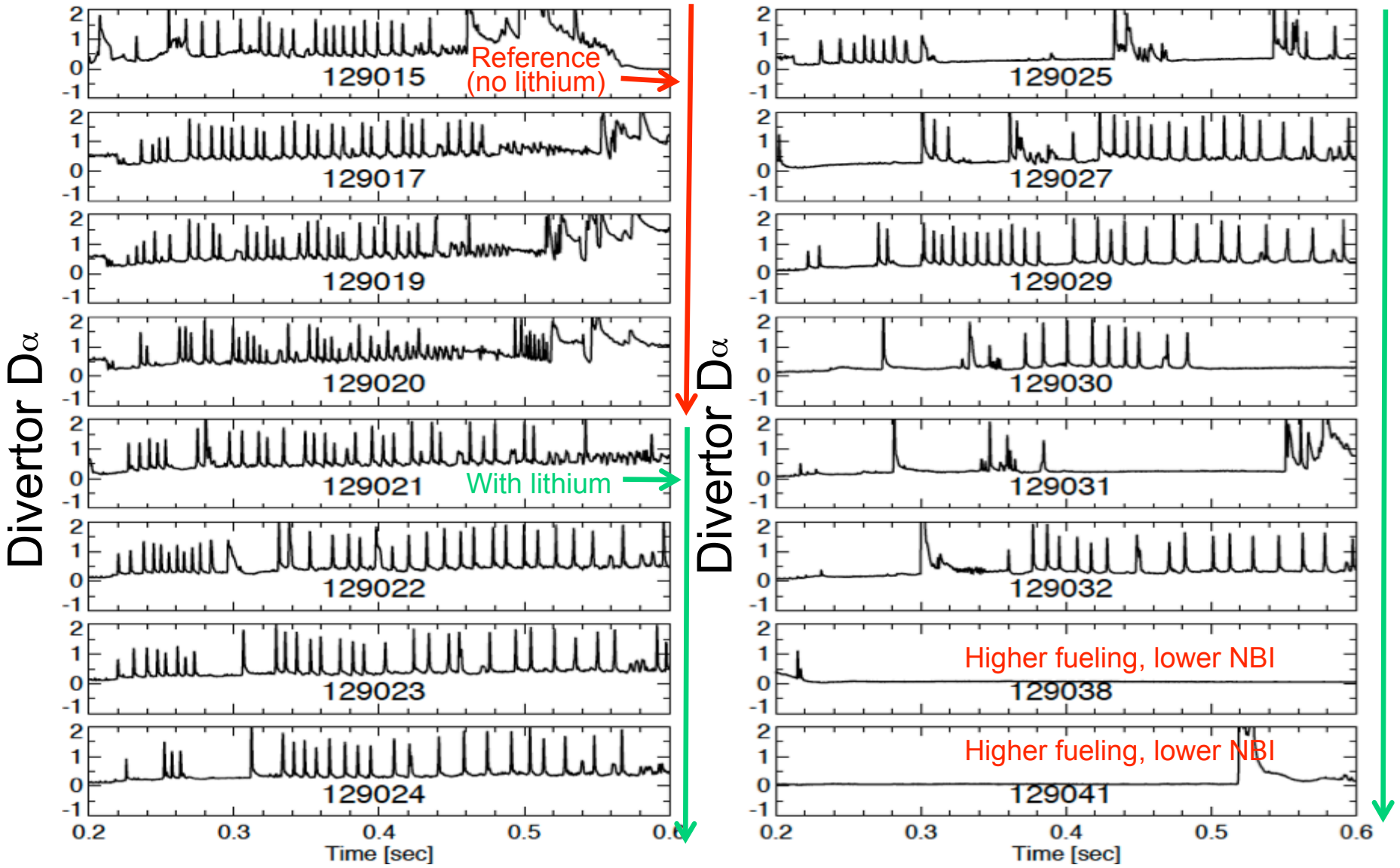
- Edge particle and thermal transport declined
- ELM frequency decreased before going to 0
  - Edge stability gradually improved

J. Canik, EX/P7-16
J. Canik, PoP 2011
D. Boyle, PPCF 2011
C.S. Chang, TH/P4-12
A. Diallo, EX/P4-4

➢ *No liquid lithium divertor (LLD) in these experiments*

M. Jaworski, EX/P5-31

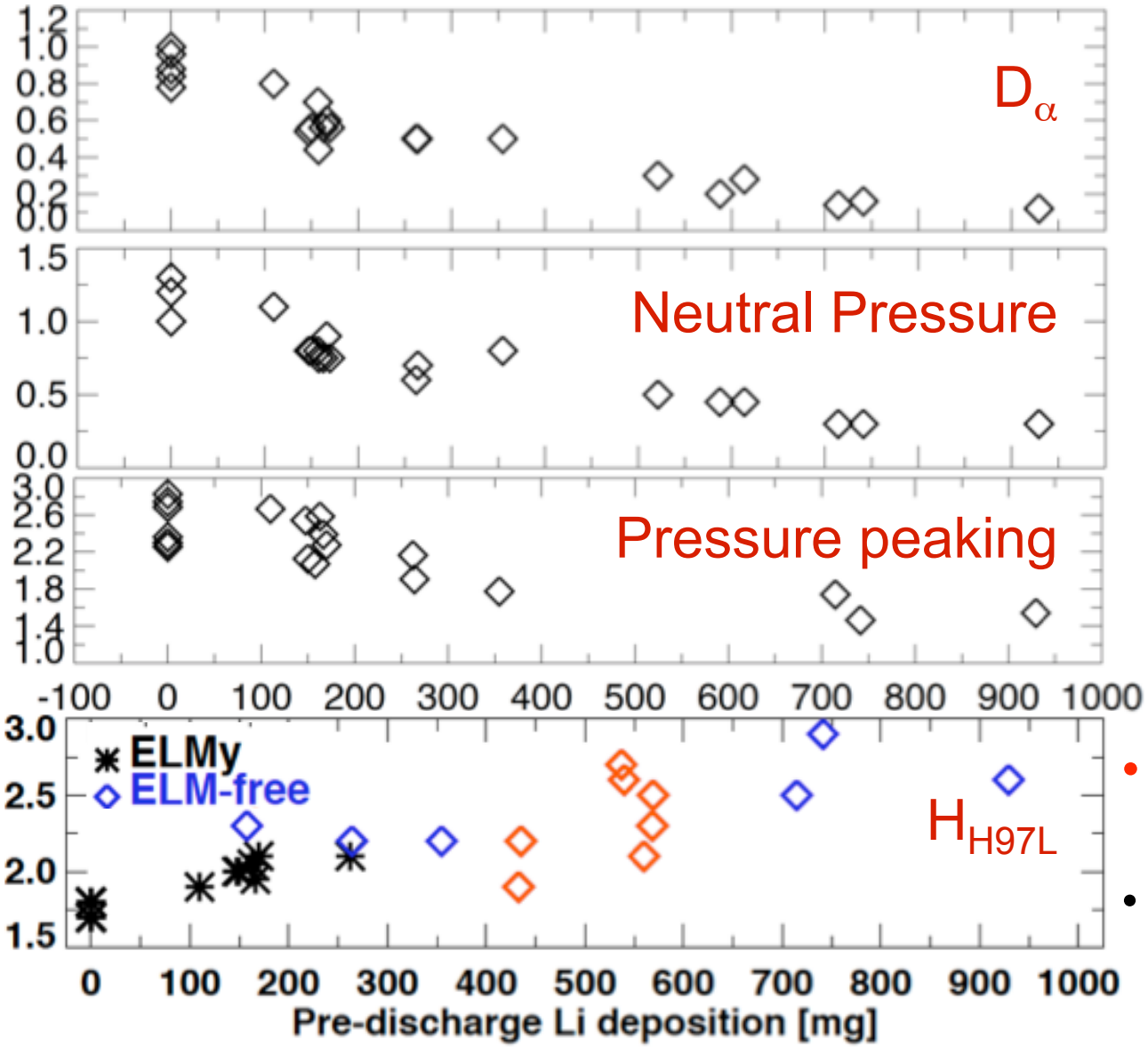
ELMs eliminated gradually during experiment



Outline

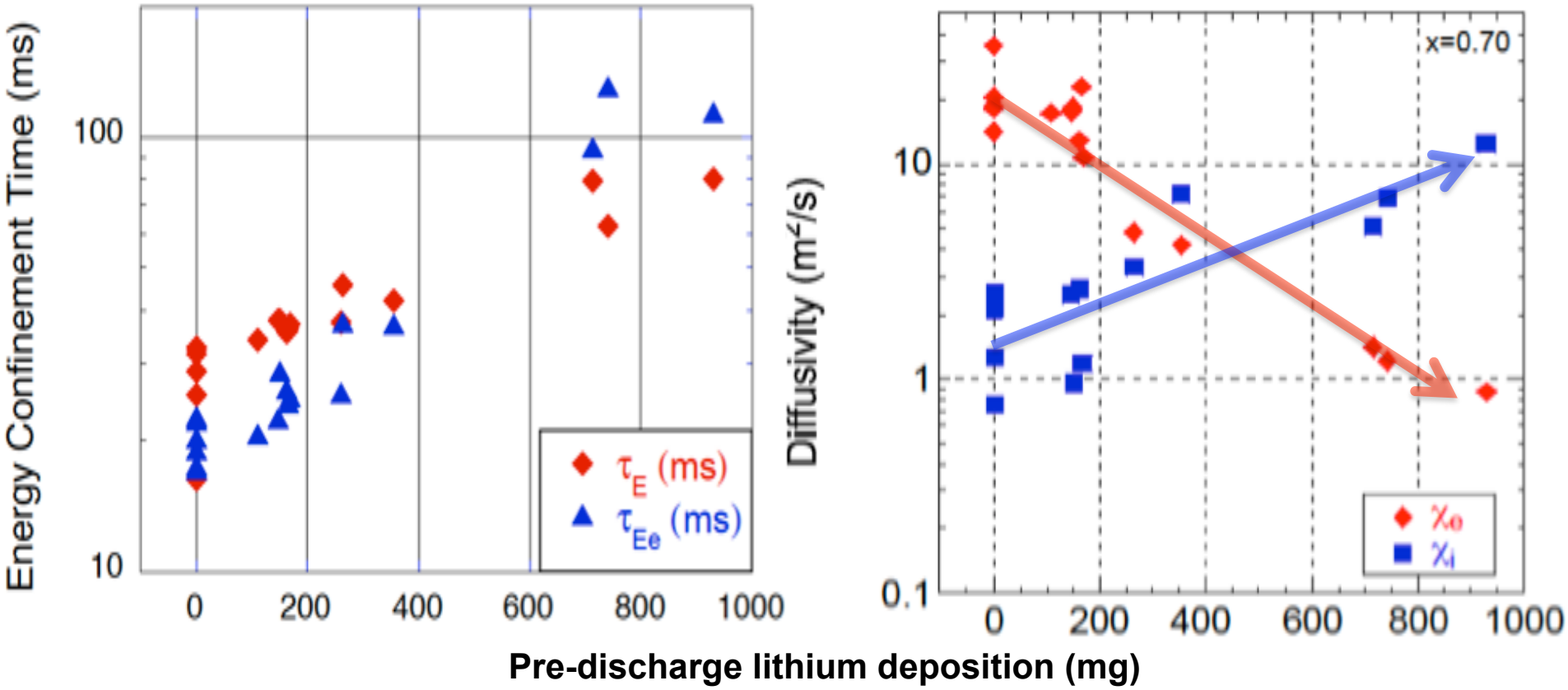
- Global changes and SOLPS interpretive modeling
- Micro-stability and ELM stability calculations
- Flowchart describing role of lithium

Recycling, neutral pressure, and pressure peaking decreased nearly continuously with increasing lithium; H_{H97L} increased



- **H_{H98y2} range from 0.8-1.4**
- Data in orange from other experiment

Energy confinement increased and edge electron transport decreased with pre-discharge lithium evaporation



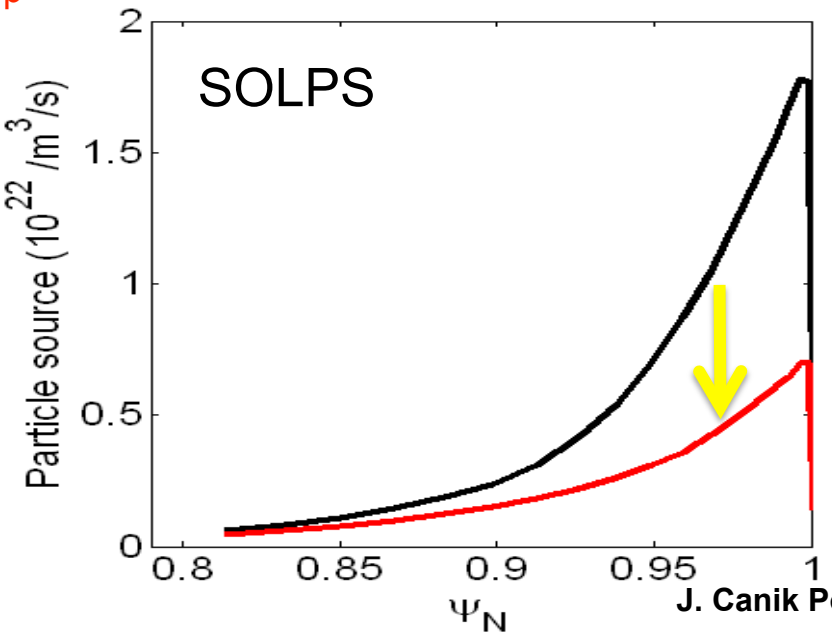
- Edge ion transport increased

TRANSP

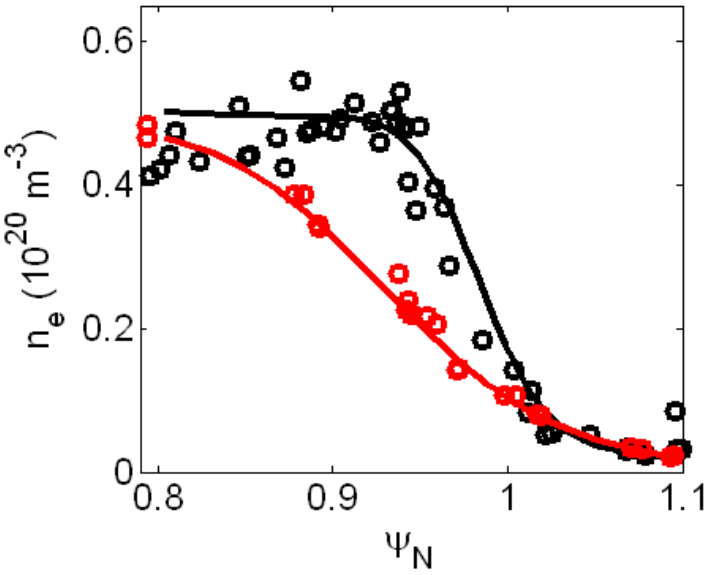
R. Maingi, PRL 2011, S. Kaye, IAEA 2012 EX 7/1

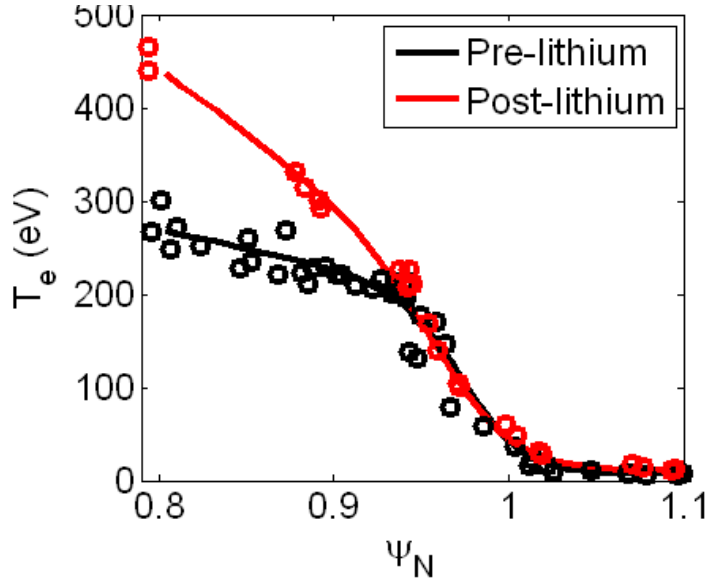
SOLPS interpretive simulations indicate particle fueling source from recycling was reduced with lithium

- Target recycling coefficient varied to match peak divertor D_α
- Separatrix position adjusted as needed to match divertor peak heat flux
- Radial profile of D_{eff}, χ_e^{eff}, χ_i^{eff} varied to match midplane n_e, T_e, T_i, for the computed recycling source profile
- R_p dropped from 0.98 to 0.9 with lithium



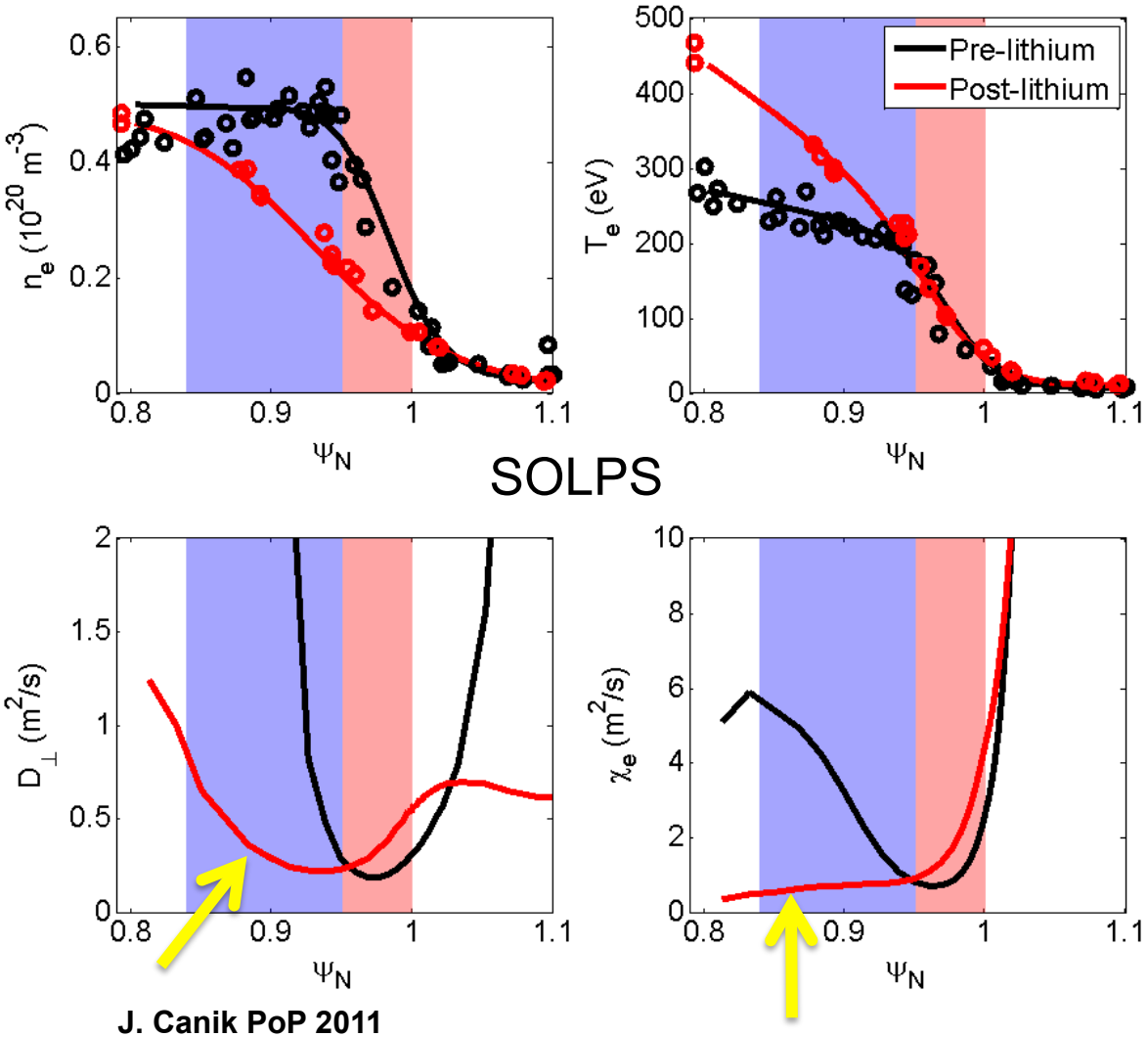
J. Canik PoP 2011





Recycling and edge transport changes interpreted with SOLPS simulations

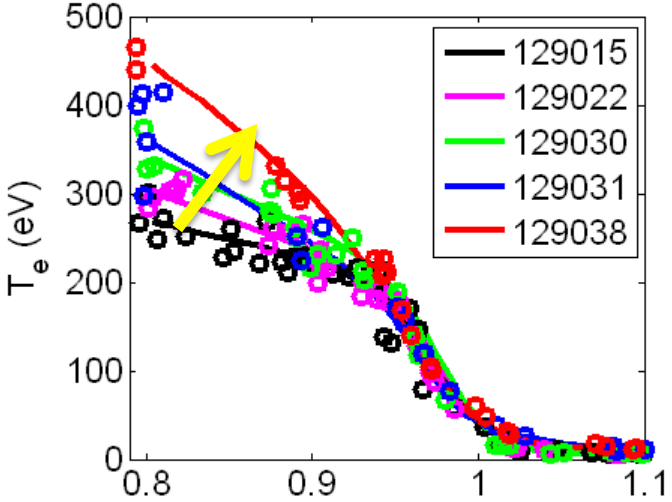
- Pre-lithium case shows typical barrier region inside separatrix
- Change in n_e profile with lithium from $0.95<\psi_N<1$ consistent with drop in fueling at ~ constant transport
- Spatial region of low transport expanded with lithium
  - Low $D_\perp$, χ_e persist to inner boundary of simulation (ψ_N~0.8)

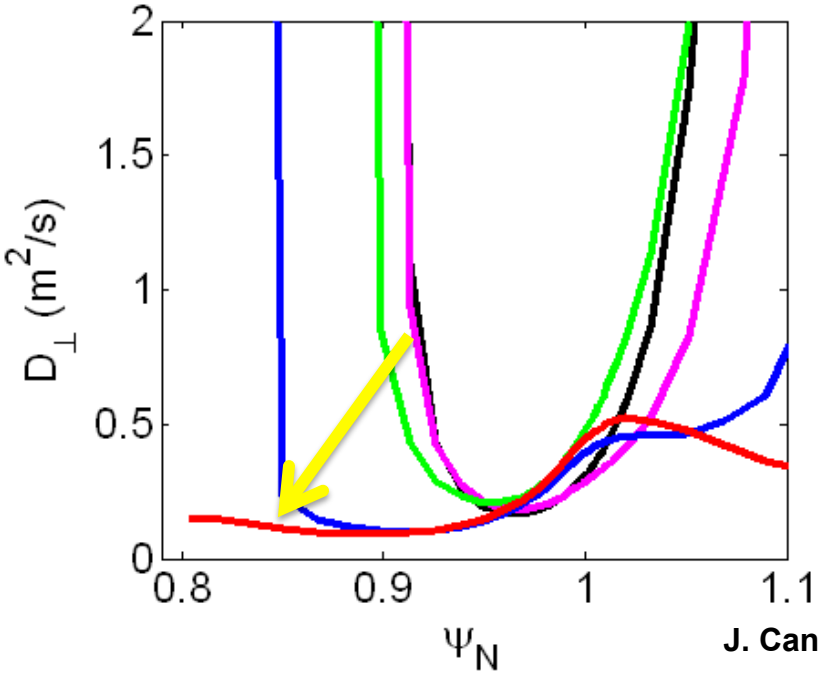


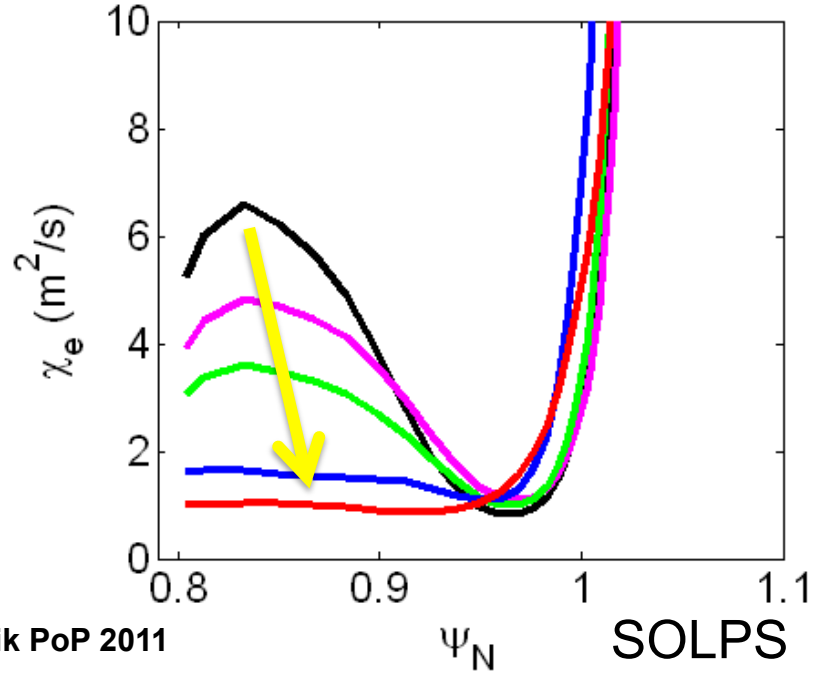
J. Canik PoP 2011

Spatial extent of low D, χ_e region expanded continuously with increasing pre-discharge lithium

- Several shots analyzed with SOLPS with increasing lithium (direction of arrow)
- T_e gradient clamped in last 5% of ψ_N, but increased from ψ_N=0.8-0.95
- First three discharges were ELMy, last two ELM-free







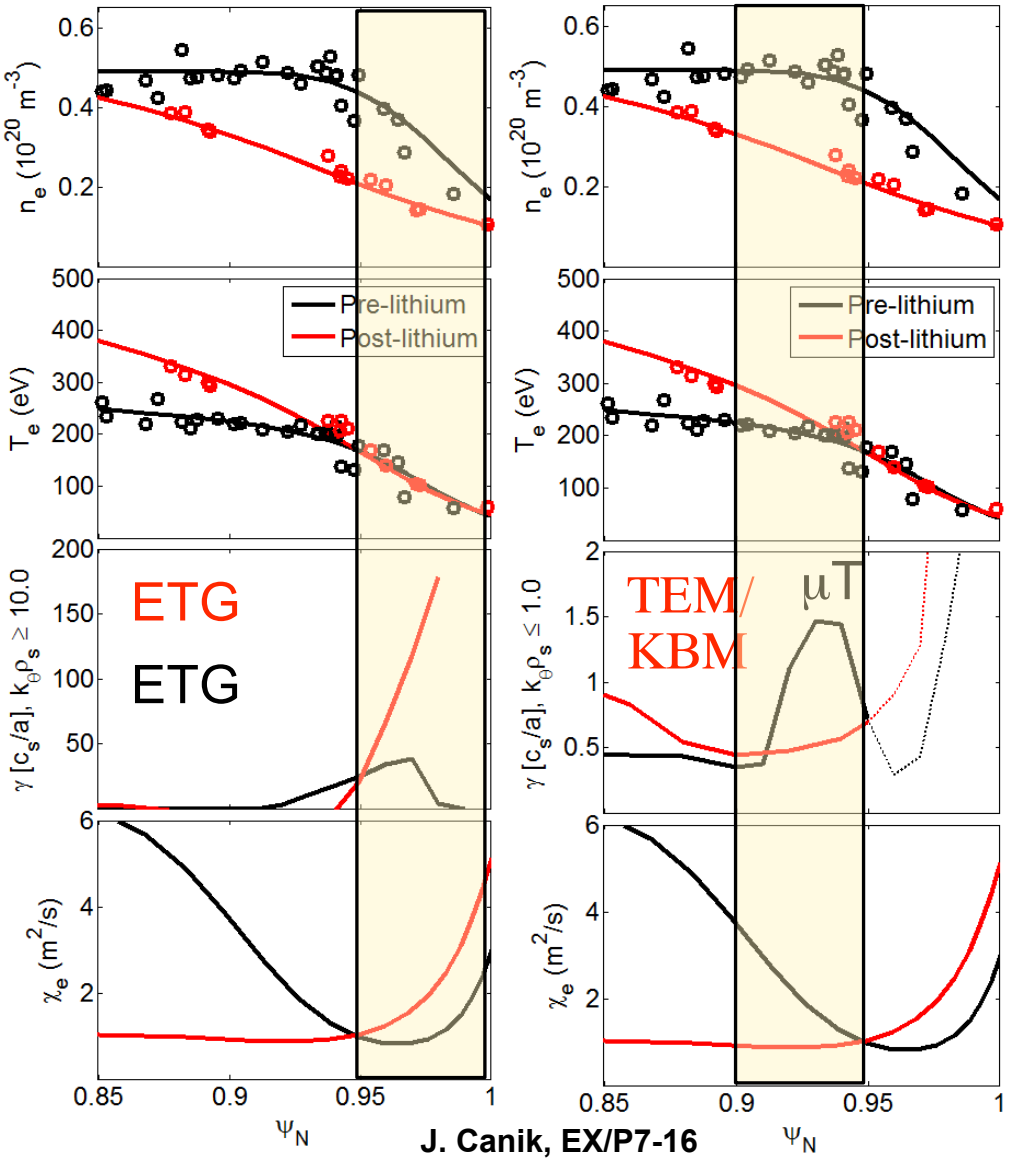
J. Canik PoP 2011

Outline

- Global changes and SOLPS interpretive modeling
- Micro-stability and ELM stability calculations
- Flowchart describing role of lithium

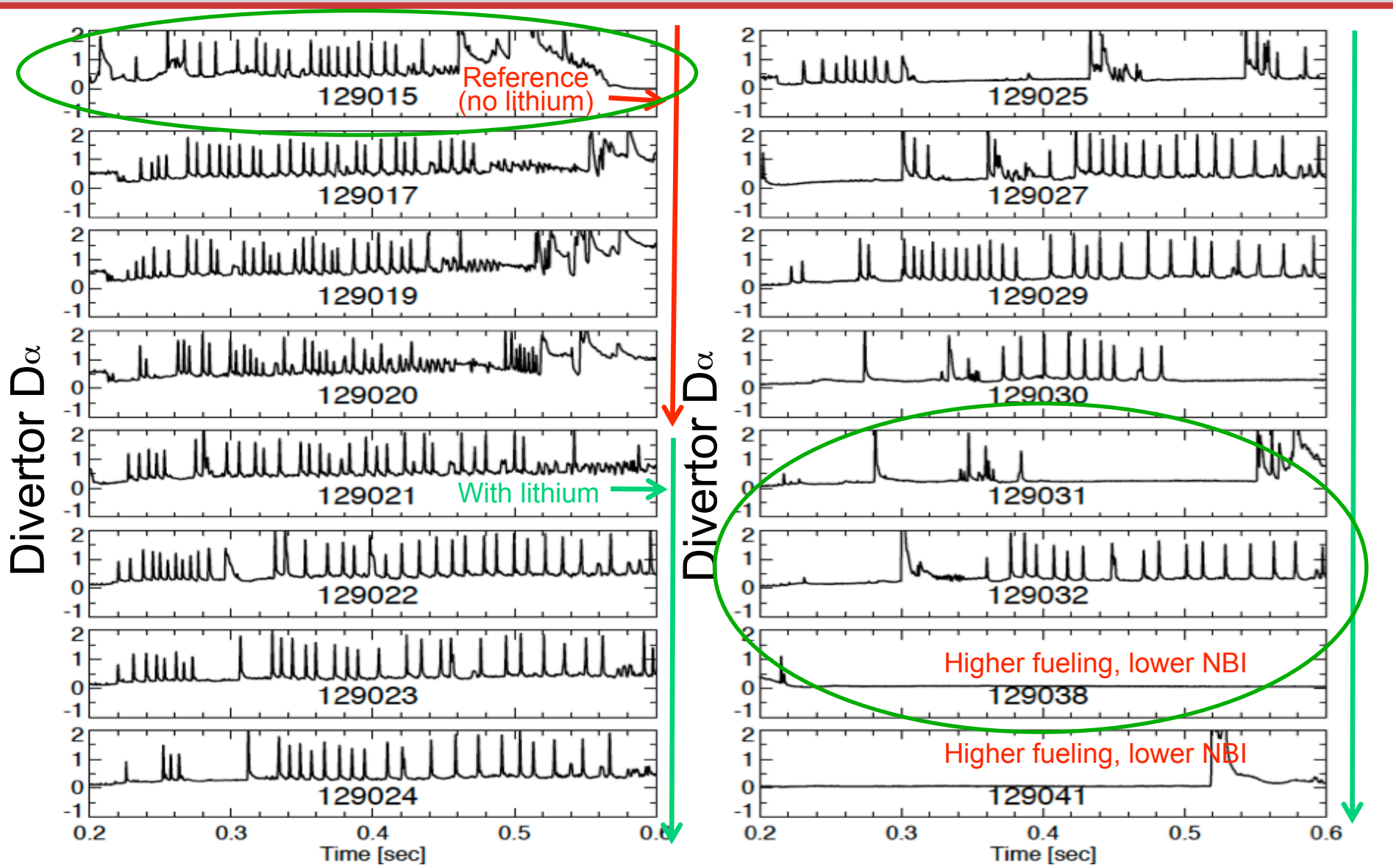
Work in progress: change in edge density gradient with lithium coatings alters the edge micro-stability properties

- From ψ_N = 0.95-1, n_e gradient reduced with lithium
  - ETG more unstable, correlates with higher χ_e
- From ψ_N = 0.8-0.95, n_e gradient increased with lithium
  - μT more stable over outer part of range, correlates with lower χ_e
- Both μT and ETG are plausible candidates – drive transport in electron channel
- These are linear GS2 calcs – need non-linear calcs for actual heat flux
- E x B shear rate higher w/Li

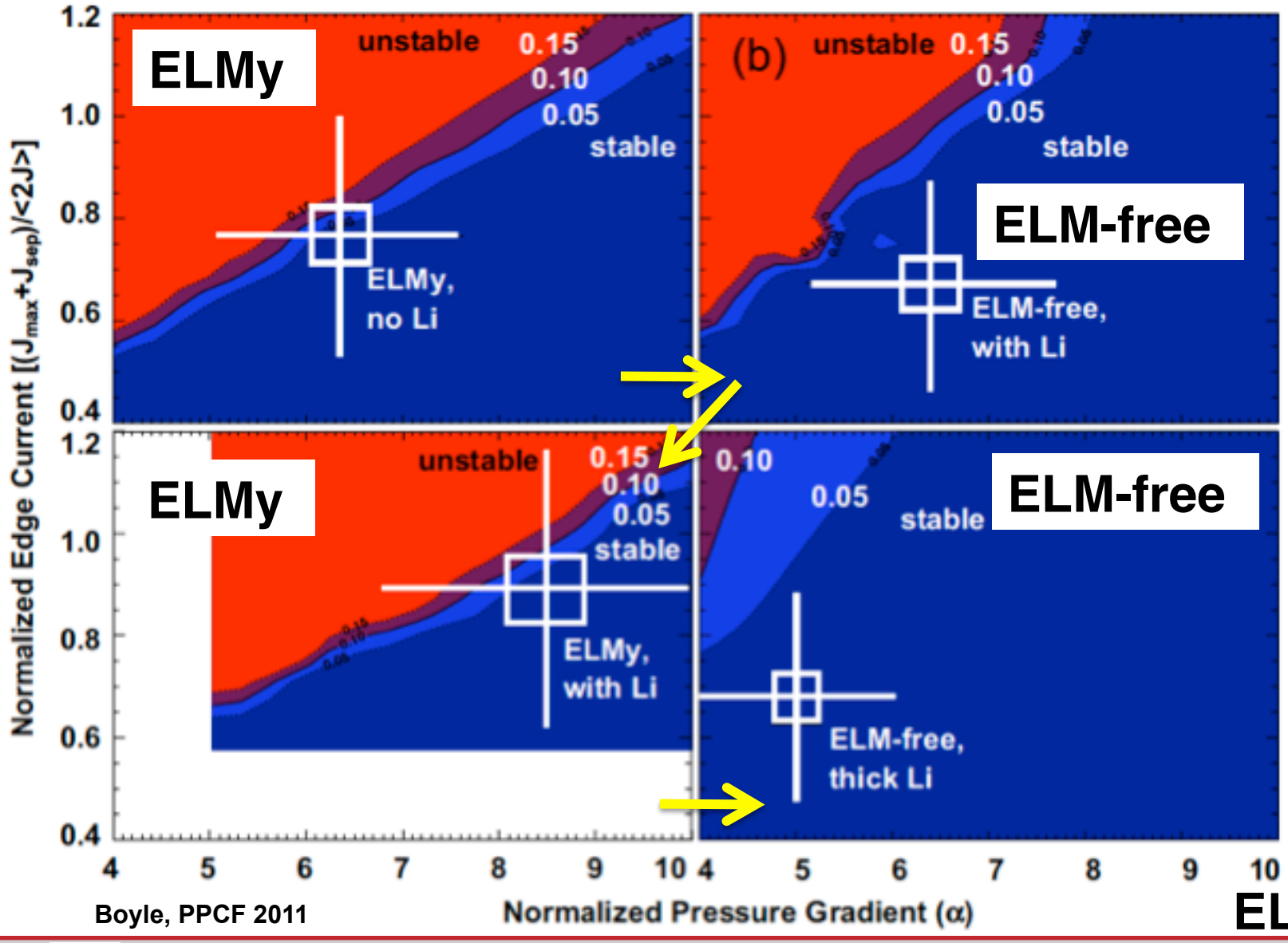


J. Canik, EX/P7-16

ELM elimination was not quite monotonic



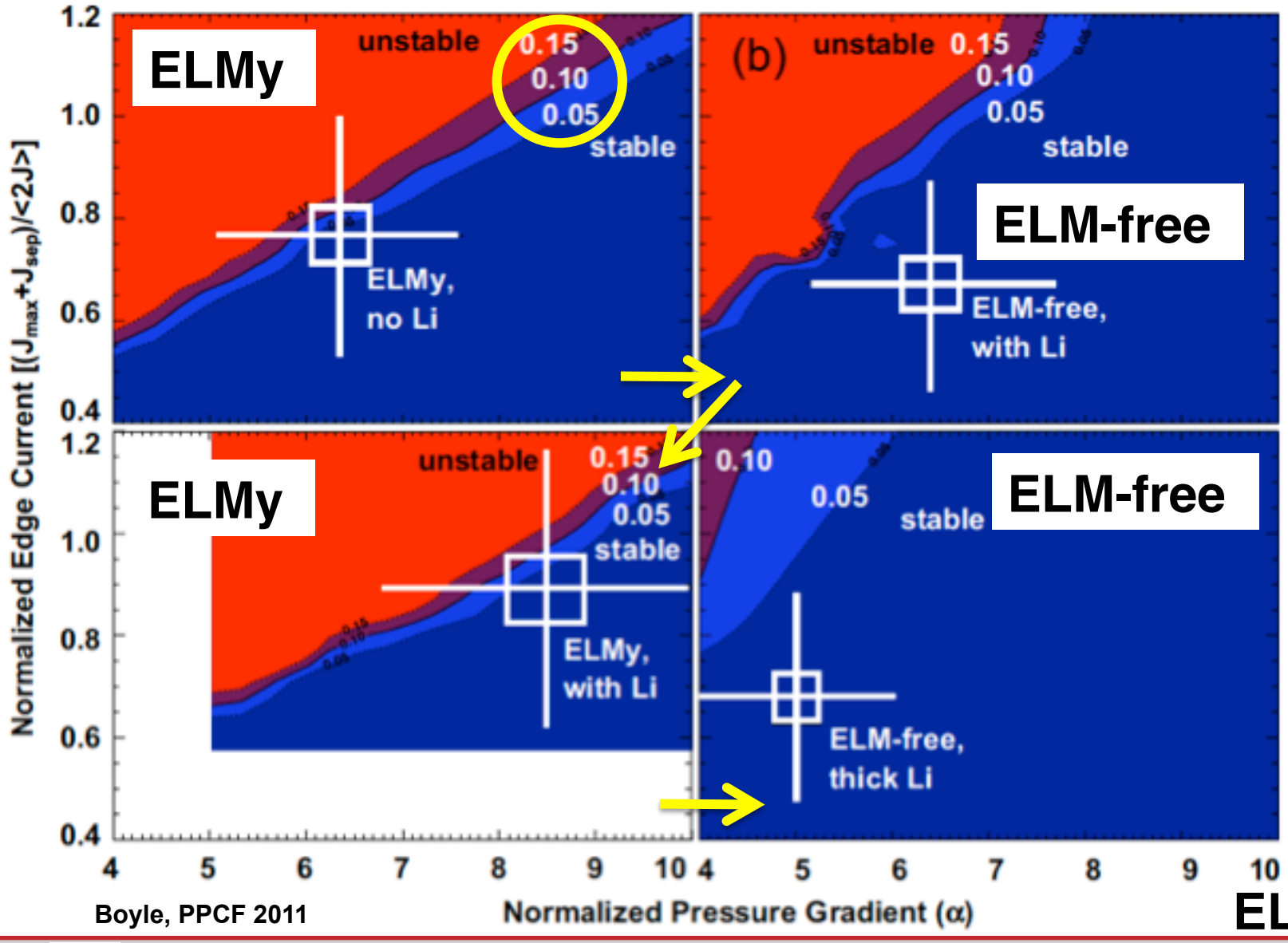
ELMy discharges closer to kink/peeling stability boundary than ELM-free ones



Boyle, PPCF 2011

ELITE

Ideal growth rates low: why instabilities not stabilized by diamagnetic flow?

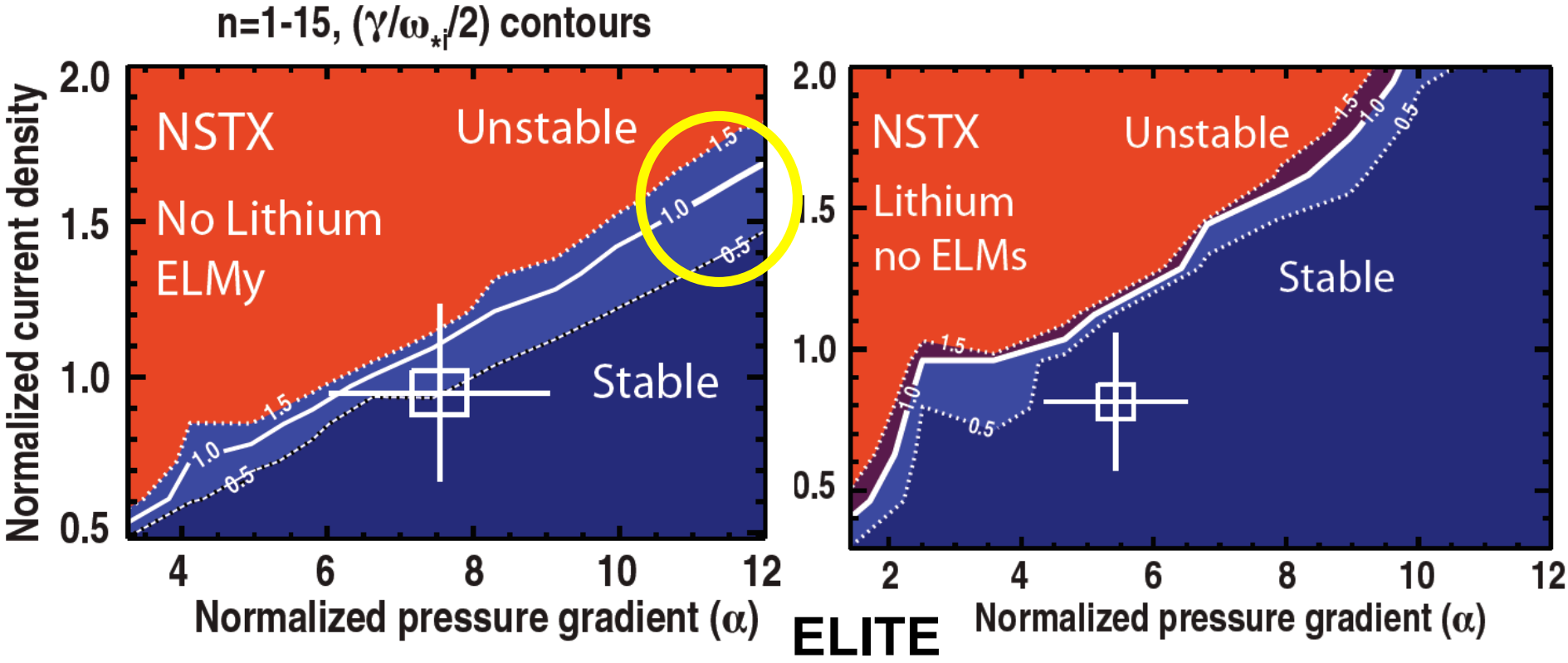


Boyle, PPCF 2011

ELITE

Revised bootstrap current calculation from XGC *and* extended ELITE calculation (n=1-15) increased growth rates

- Bootstrap current increased by 30% — XGC: C.S. Chang, TH/P4-12
- Growth rates for n=1, 2 were larger than for n=3 — Groebner, EX/11-4
- ELMy discharges at the ideal instability boundary
- ELM-free discharges still in stable operating space



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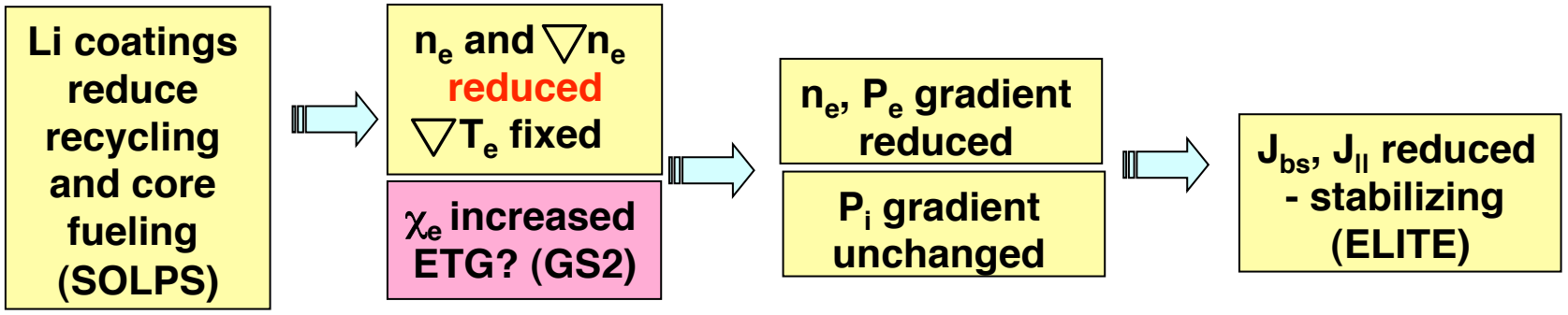
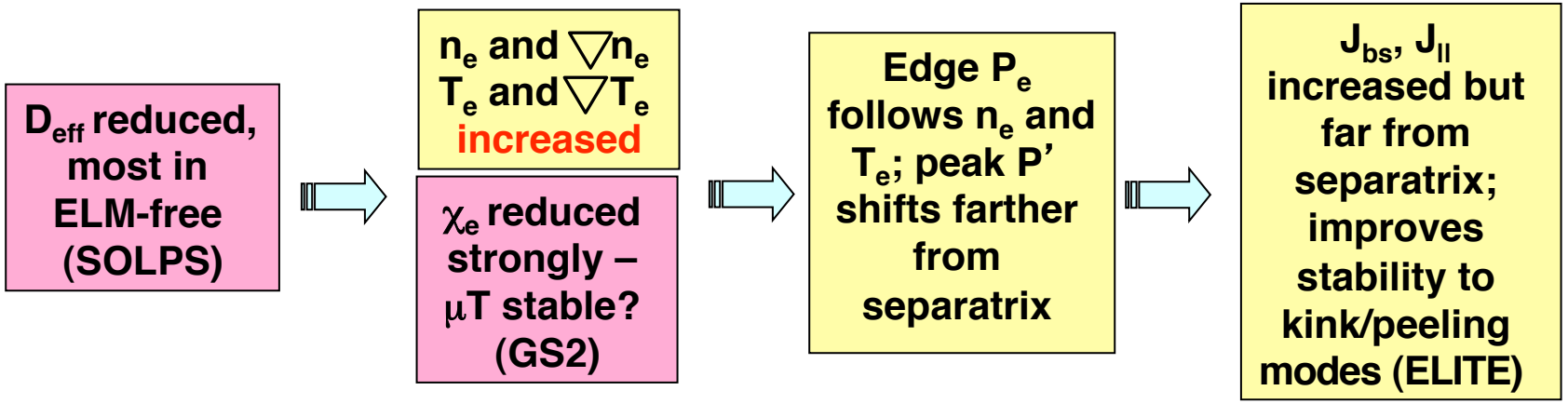
What is the role of lithium?
To reduce recycling and associated fueling

ψ_N from 0.95-1 (recycling region)



ψ_N from 0.8-0.94



The observed 'continuous' dependence was surprising, because we expected only the top monolayers to play a role

- Nominal divertor film thicknesses of 60-500 nm obtained during the lithium evaporation scan
- Calculations for NSTX divertor shows ion implantation depth < 5 nm, i.e. << 60 nm – 500 nm coating thickness
  - ➢ SO: the effect was expected to saturate for nominal film thickness > 10 nm
- Possibility uncovered by lab measurements: more lithium results in Oxygen segregation to the surface, which increases the film capacity to retain deuterium

C.N. Taylor, JNM 2011
J.P. Allain, PoP 2012

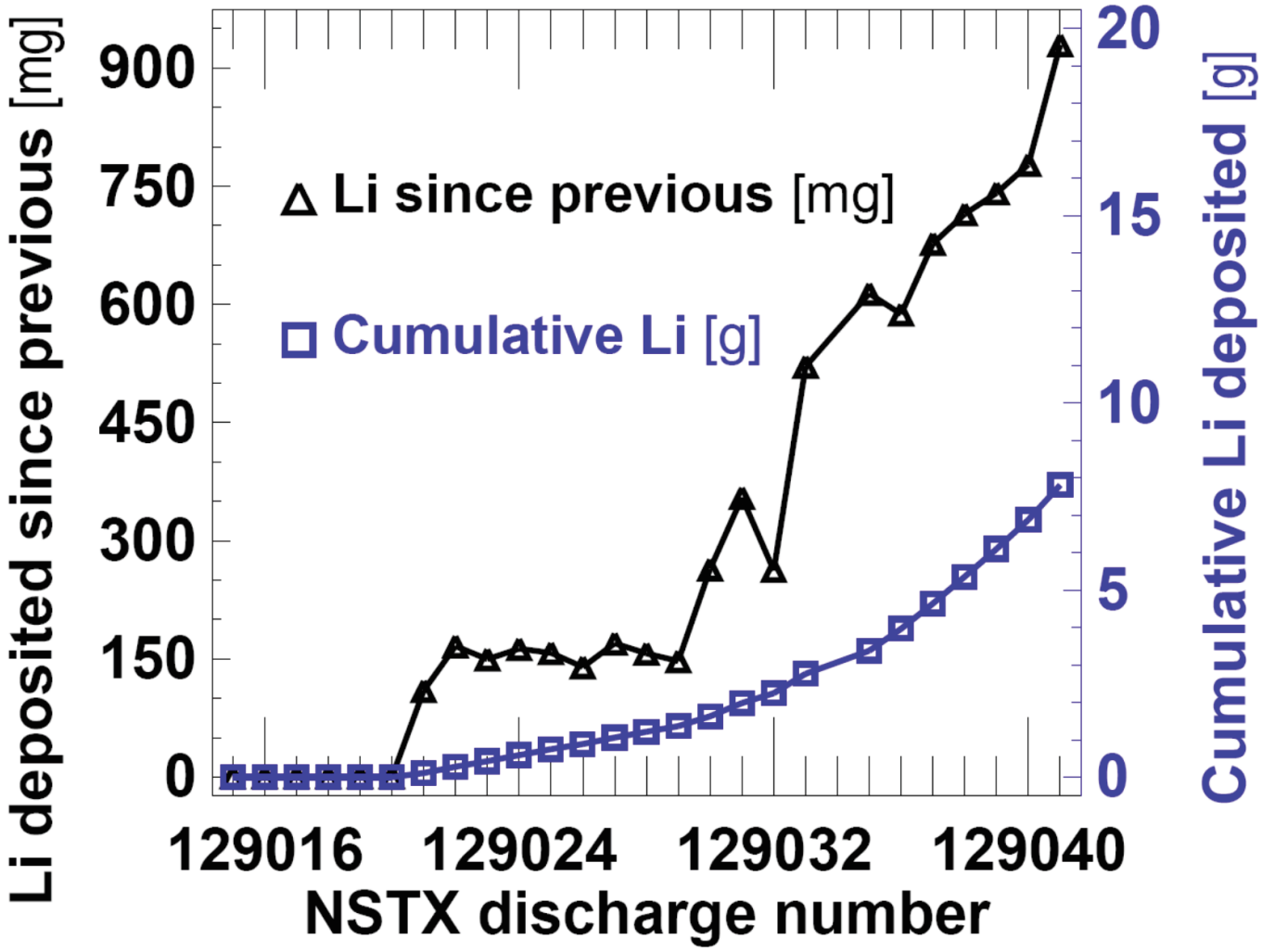
Global characteristics changed and edge electron transport declined with increasing Li deposition; ELMs eliminated

- Last 5% of ψ_N: recycling source drop leads to drop in density and pressure gradient
  - T_e gradient clamped, consistent with more unstable ETG
  - Drop in J_{BS}, stabilizing to kink/peeling modes
- ψ_N from 0.8-0.95: particle transport drops
  - T_e gradient increased, consistent with more stable μT
  - Increased pressure and gradient, but current driven modes still stable
    - *Higher gradients allowed farther from separatrix*
- Density profile and particle transport change key first step
  - Underlying physics of particle transport change needs to be identified

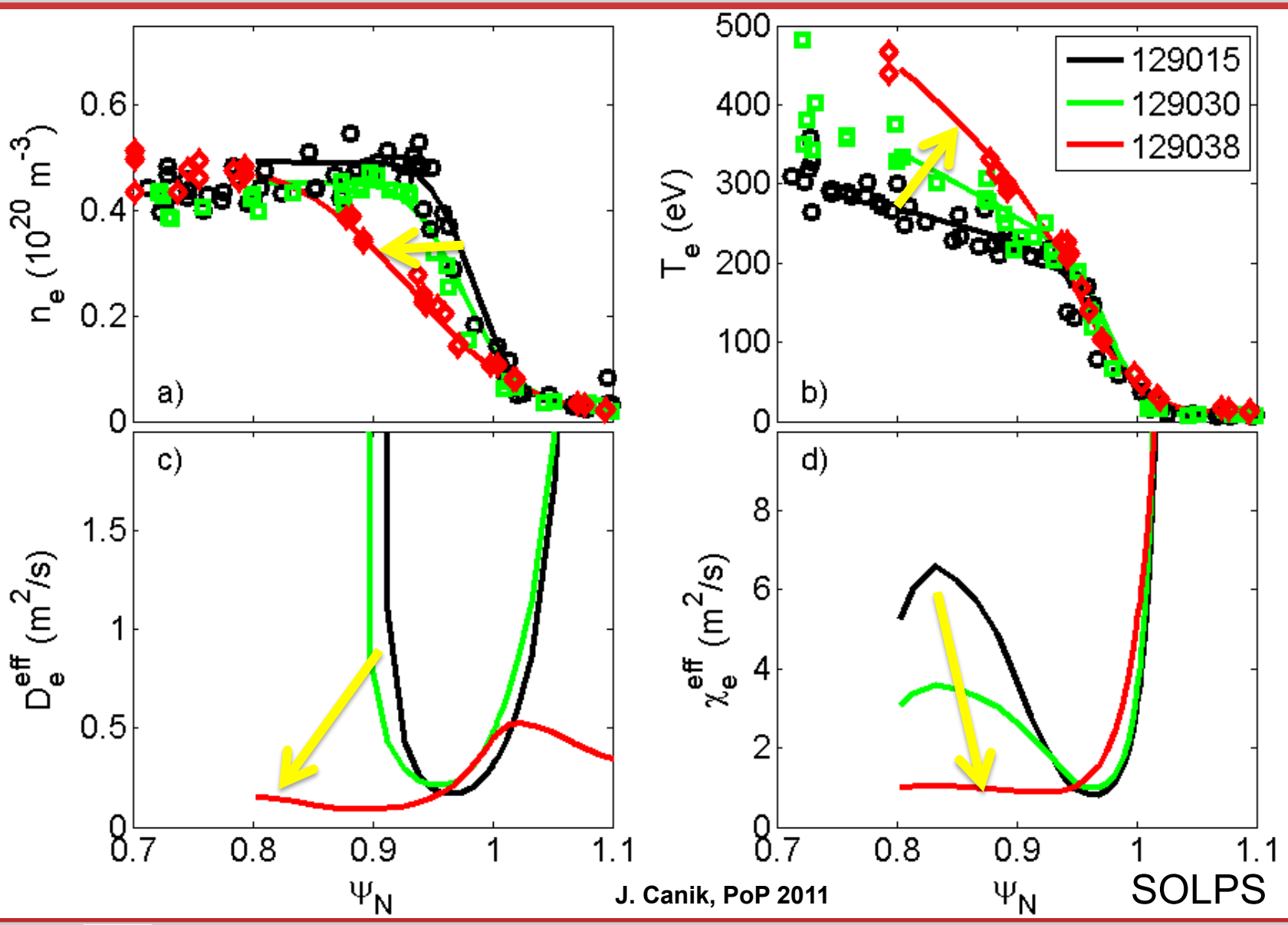
THANK YOU FOR YOUR ATTENTION!

Pre-discharge lithium evaporation varied during experiment - first lithium usage in this particular run campaign

- Lithium evaporation before discharges with two overhead ovens

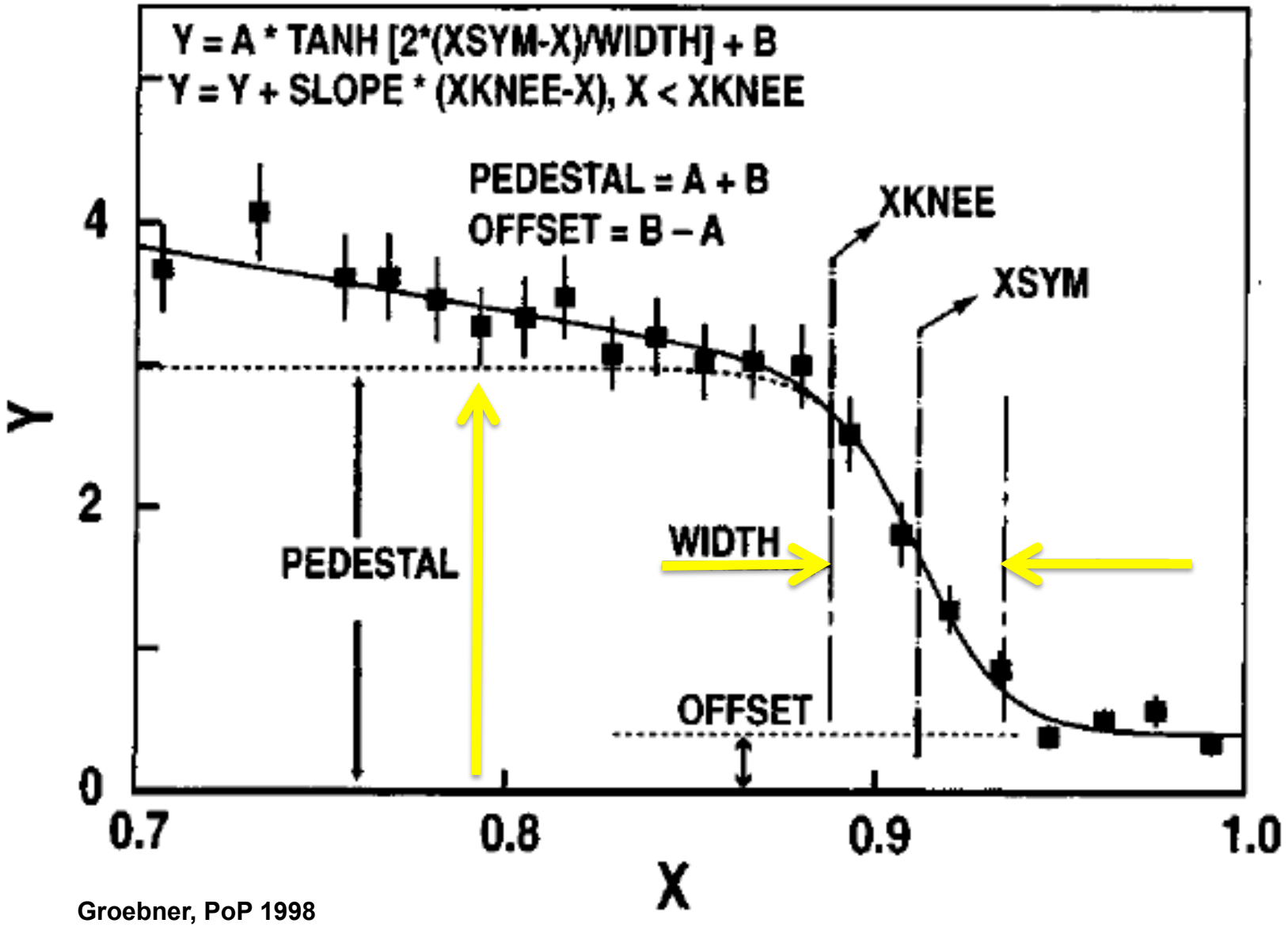


Transport barrier widens continuously with increasing pre-discharge lithium, i.e. pedestal-top D, χ_e reduced



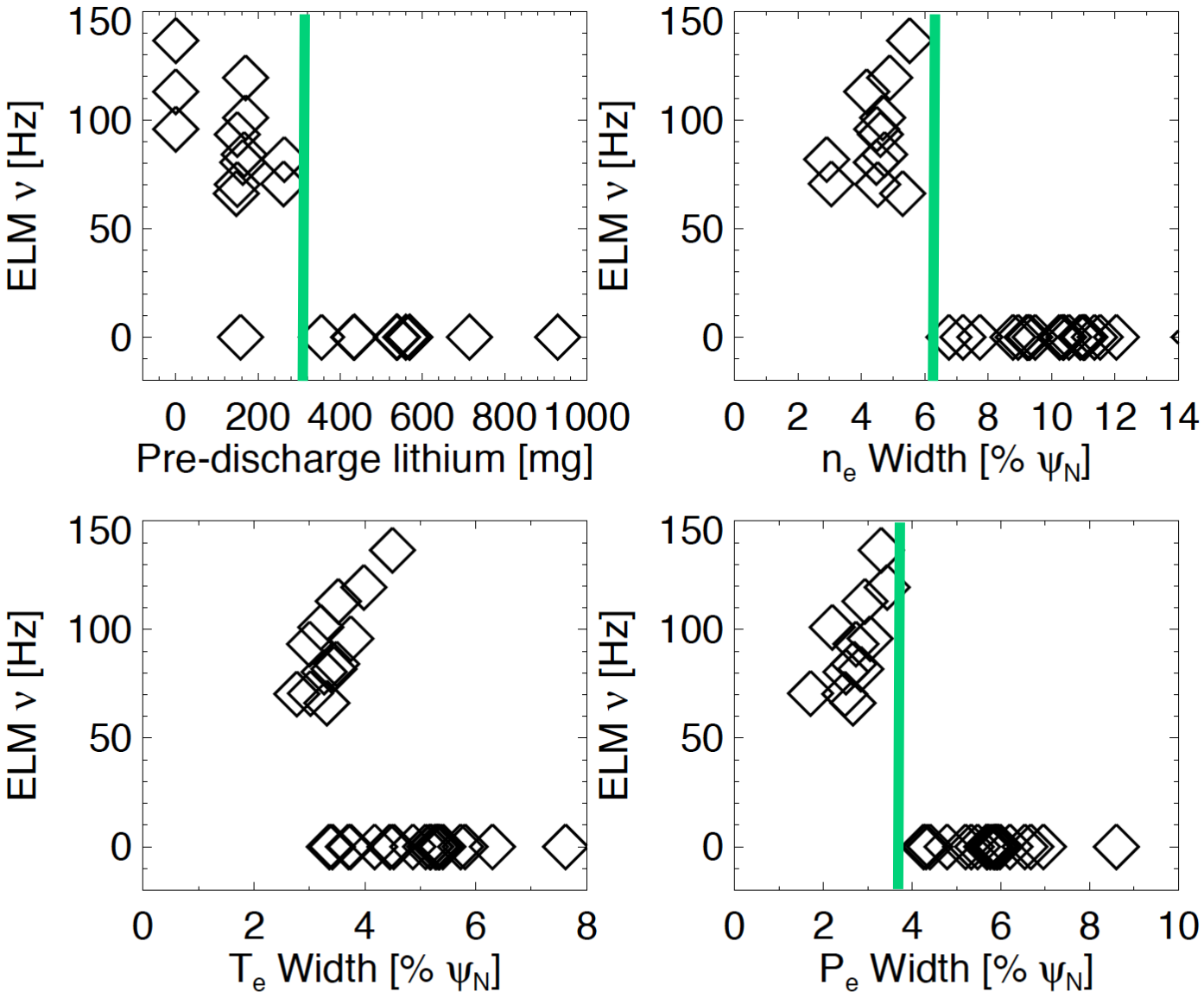
J. Canik, PoP 2011

Edge density, temperature, and pressure profiles fitted to "standard" modified hyperbolic functional form

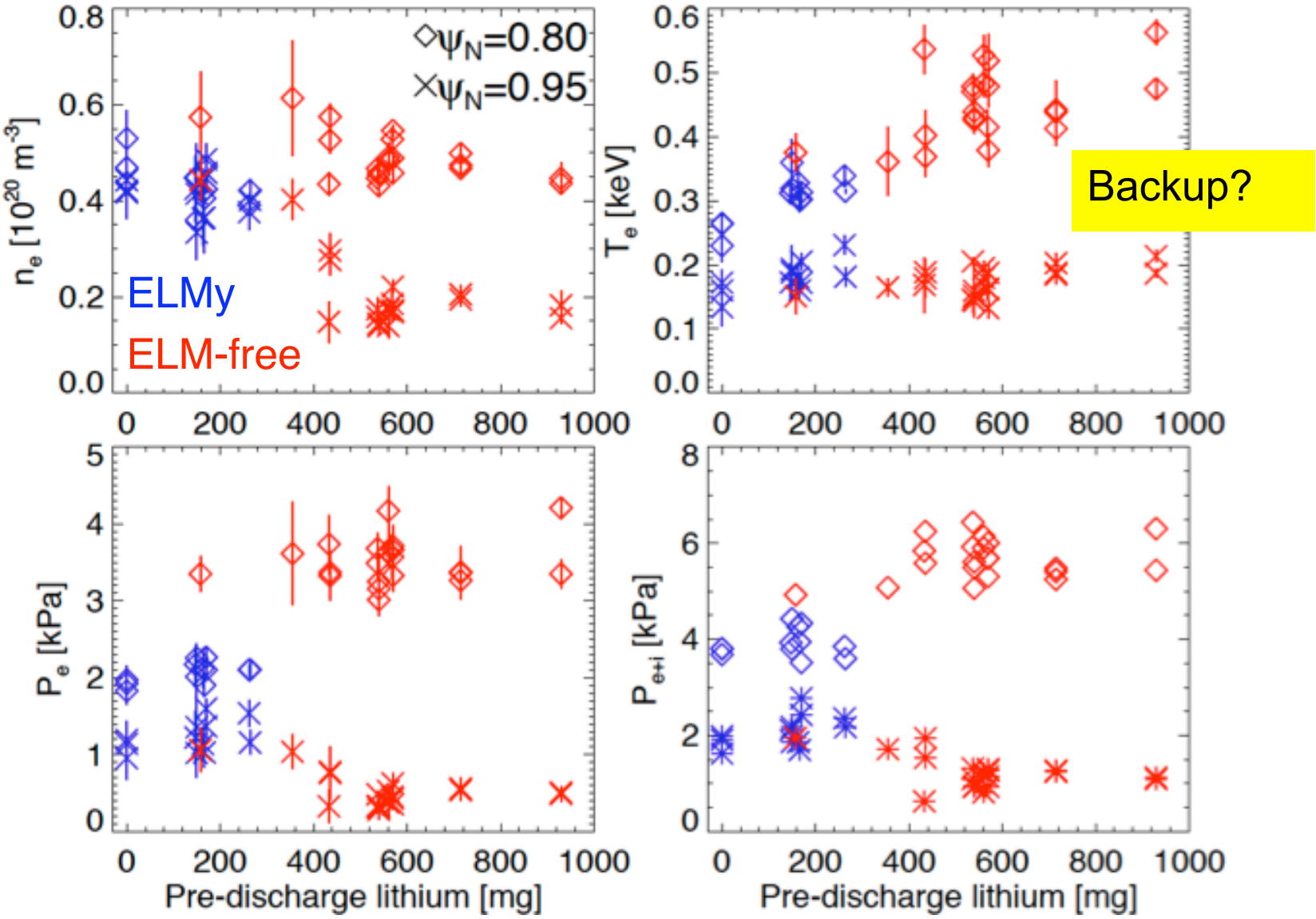


Groebner, PoP 1998

n_e and P_e "mtanh" profile widths separate ELMy and ELM-free data



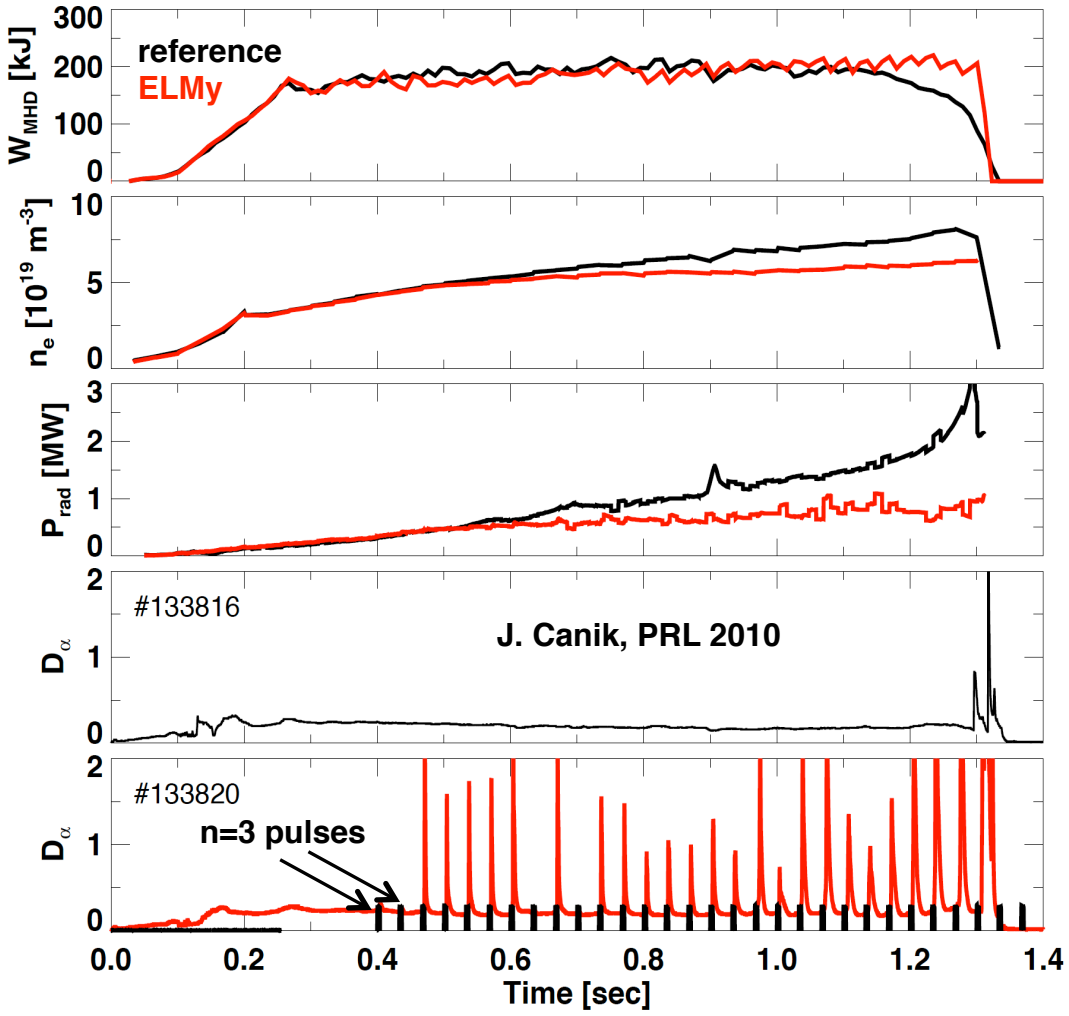
Density and pressure drop with lithium coatings at ψ_N=0.95, but increase at ψ_N=0.80 with increasing lithium



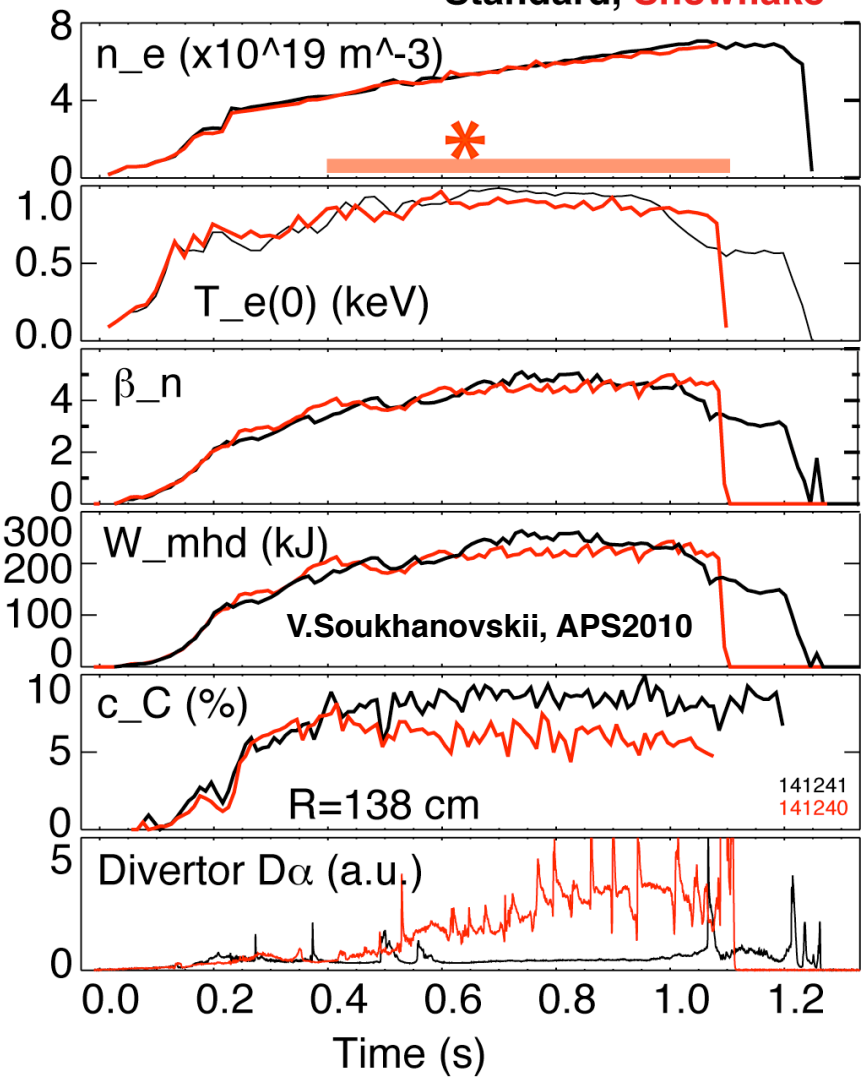
Backup?

3D external fields used to trigger ELMs, while "Snowflake Divertor" used to reduce edge impurity source

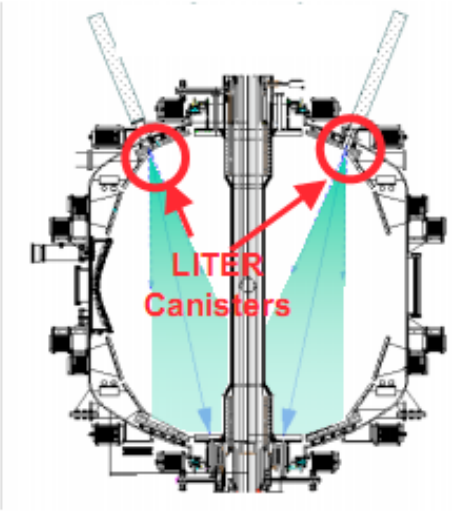
Type I ELMs triggered for impurity control (post-lithium, n=3)

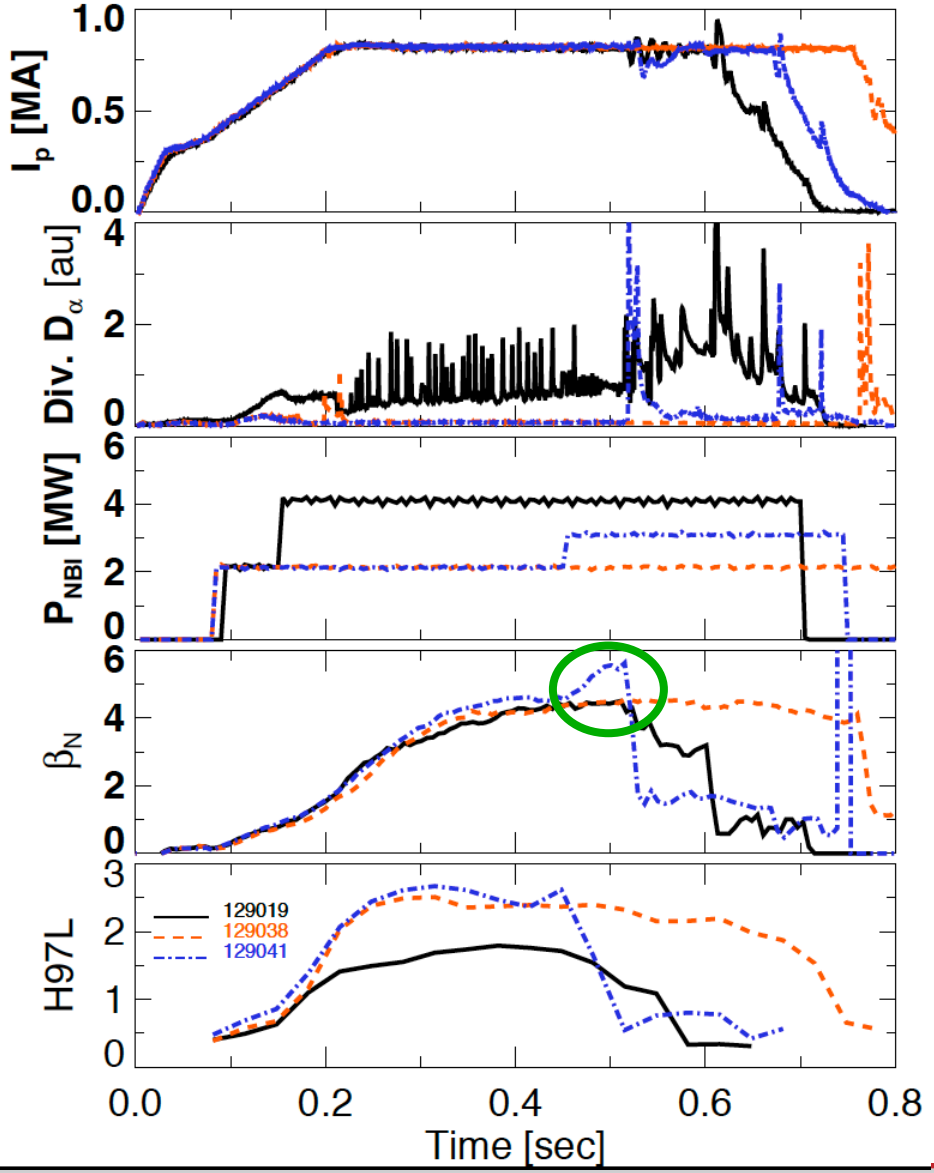


Snowflake Divertor



Edge stability limits pushed beyond global stability limits with lithium coatings in NSTX

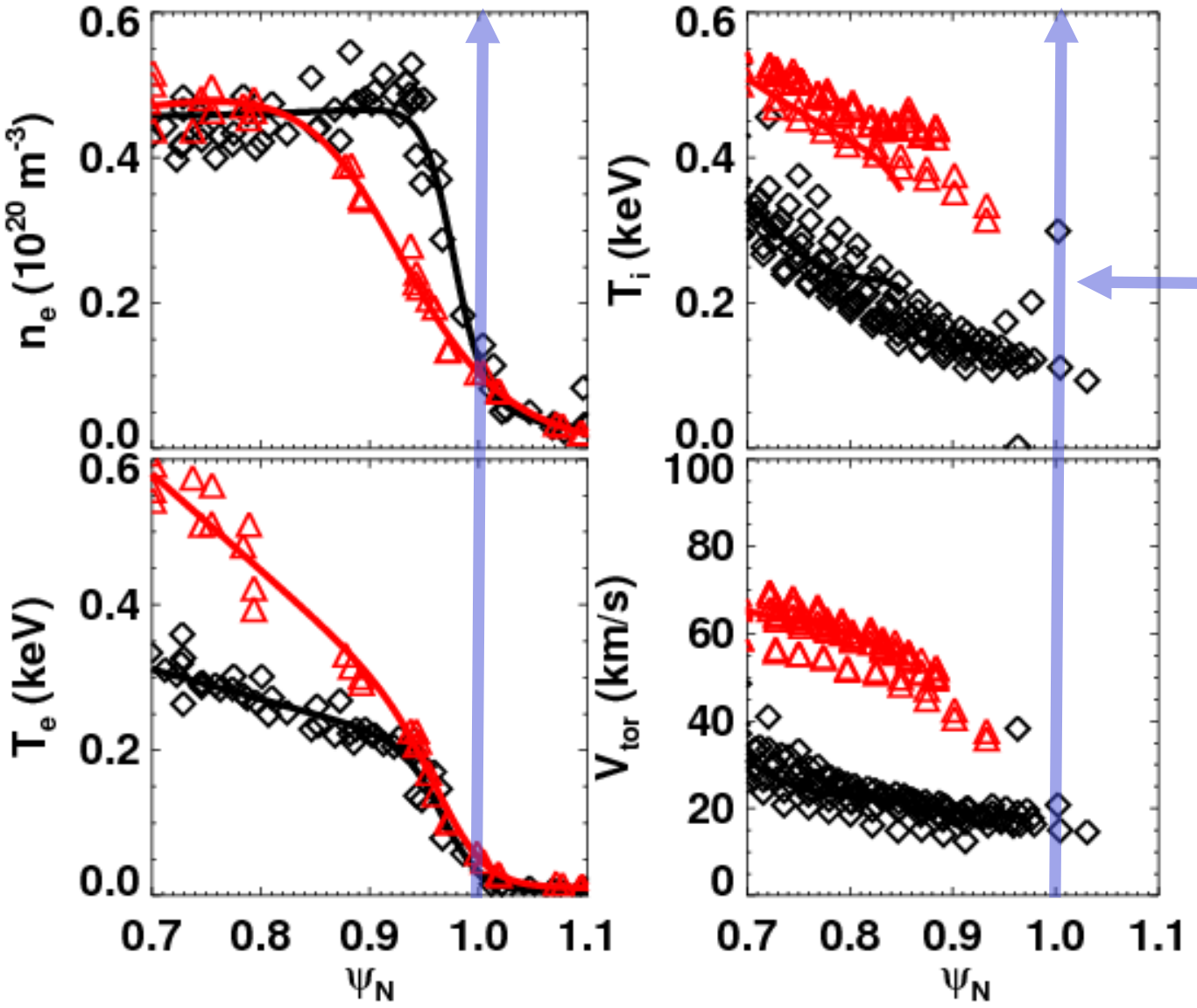




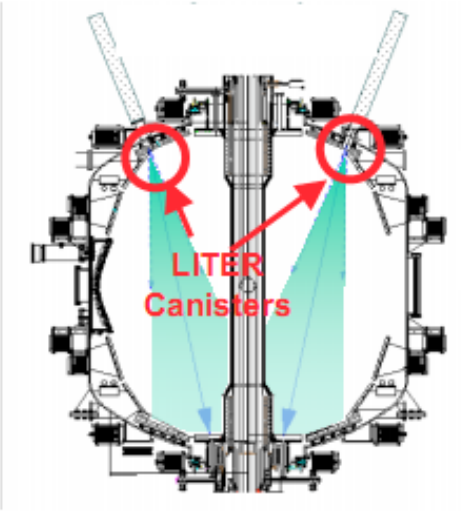
- Without Li, With Li, With Li
- ELM-free, reduced divertor recycling
- Power scan to identify β limit
- Core β limit observed, but no ELMs

D. Mansfield, JNM 2009
R. Maingi, PRL 2009

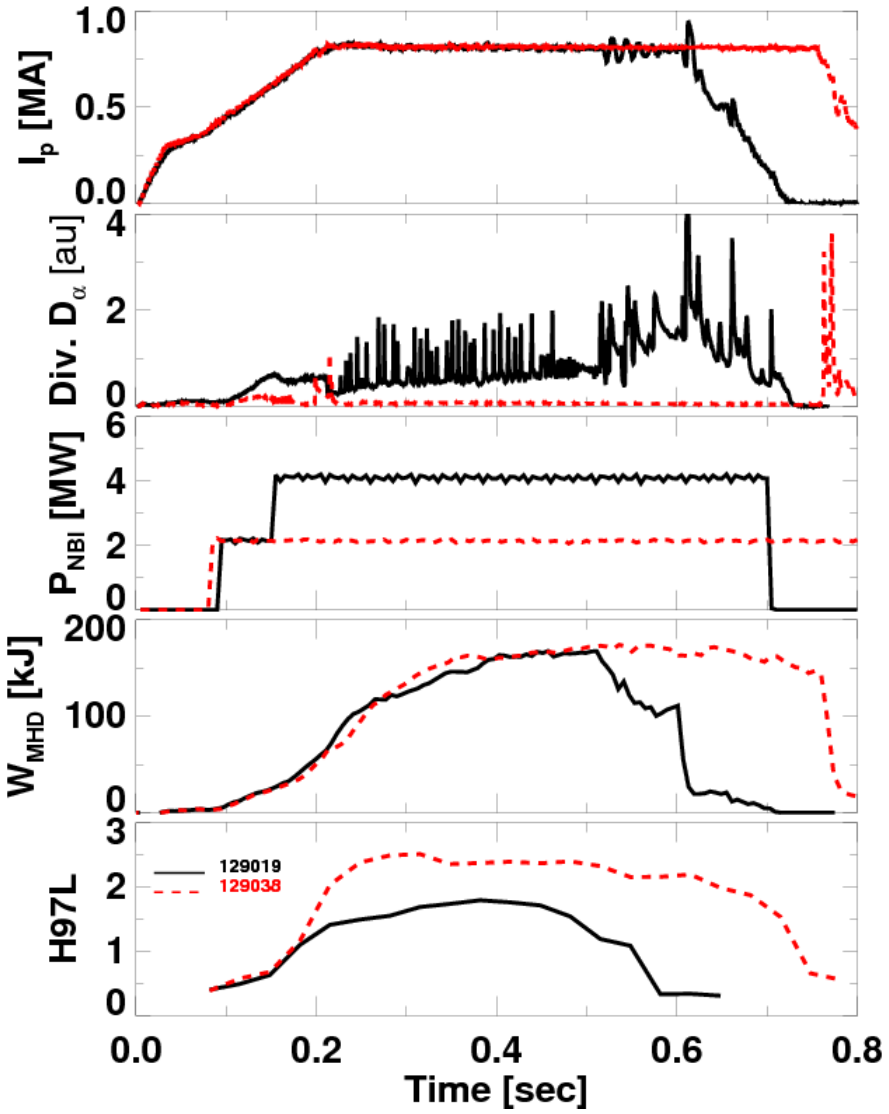
T_e, T_i increased and edge n_e decreased with lithium coatings



Type I ELMs eliminated, energy confinement improved with lithium wall coatings; (ELMs eliminated up to β_N limit)



~ 700mg Li between 129037 and 129038

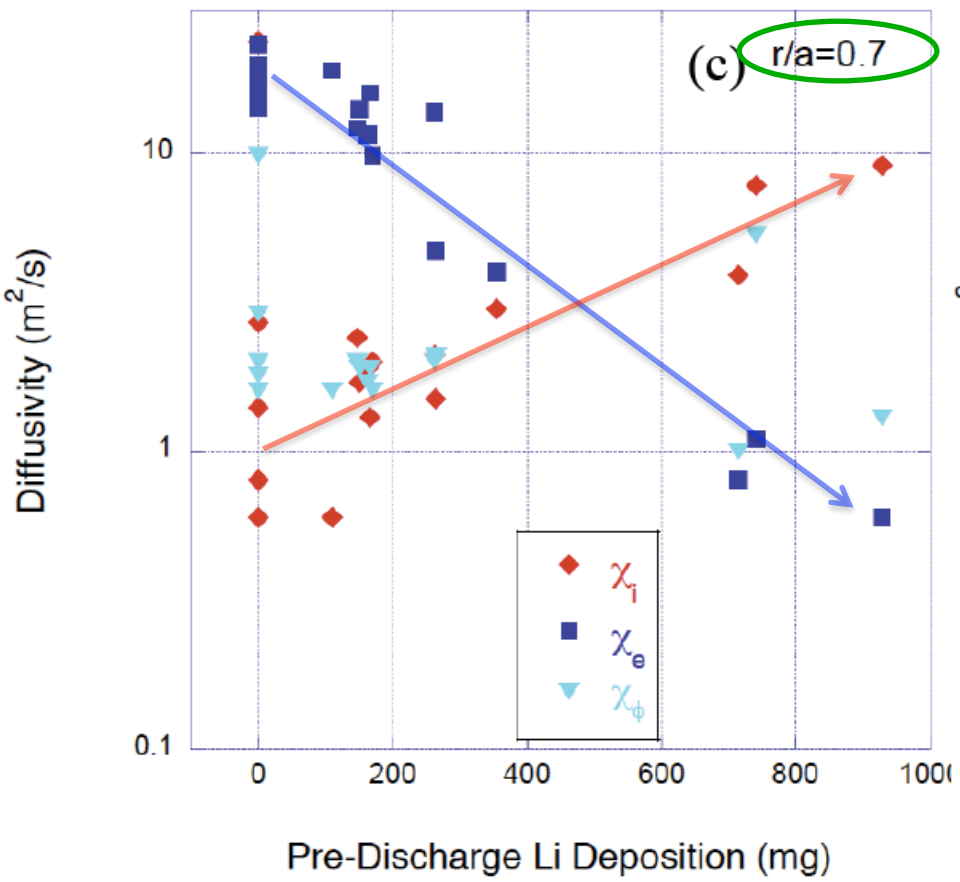


- Without Li, With Li *(pre-LLD)*
- ELM-free, reduced divertor recycling
- Lower NBI to avoid β limit
- Similar stored energy
- H-factor 40%↑

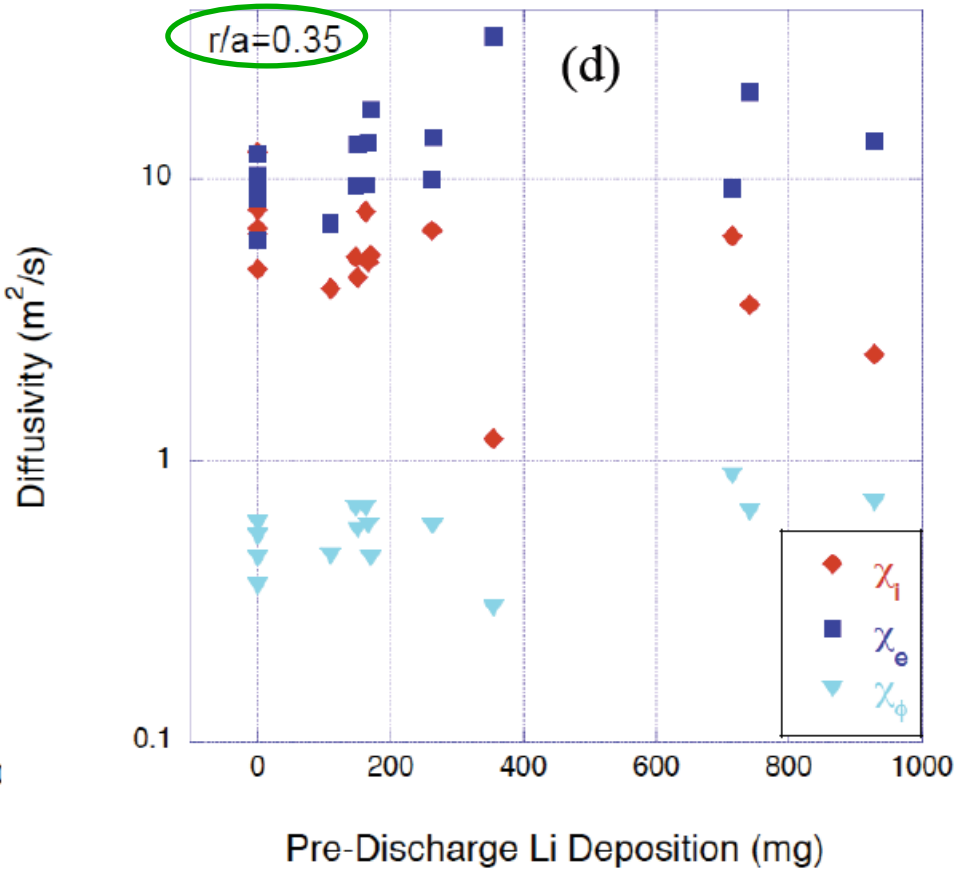
H. Kugel, PoP 2008
R. Kaita, IAEA 2008
M. Bell, PPCF 2009
D. Mansfield, JNM 2009
R. Maingi, PRL 2009

Edge χ_e goes down and χ_i goes up; core χ's unchanged

Edge

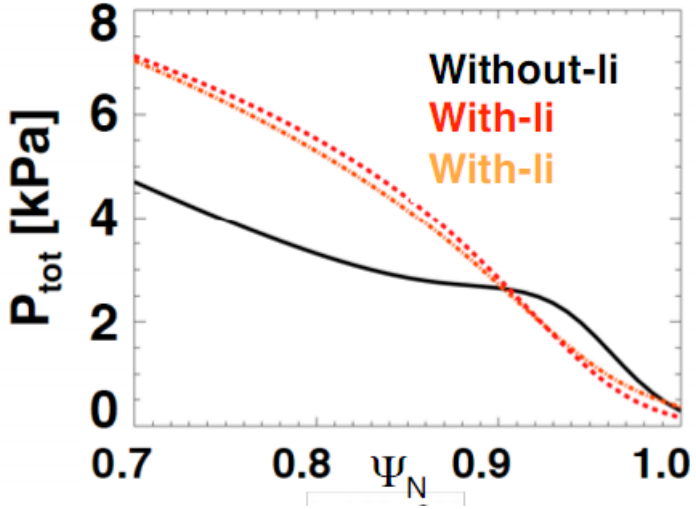


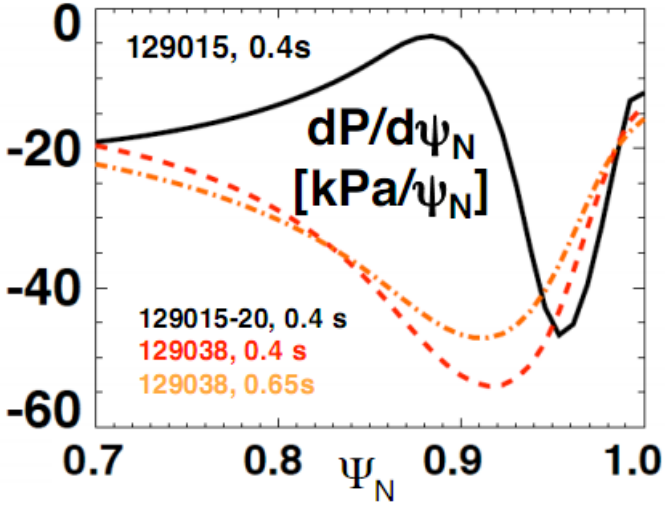
Core

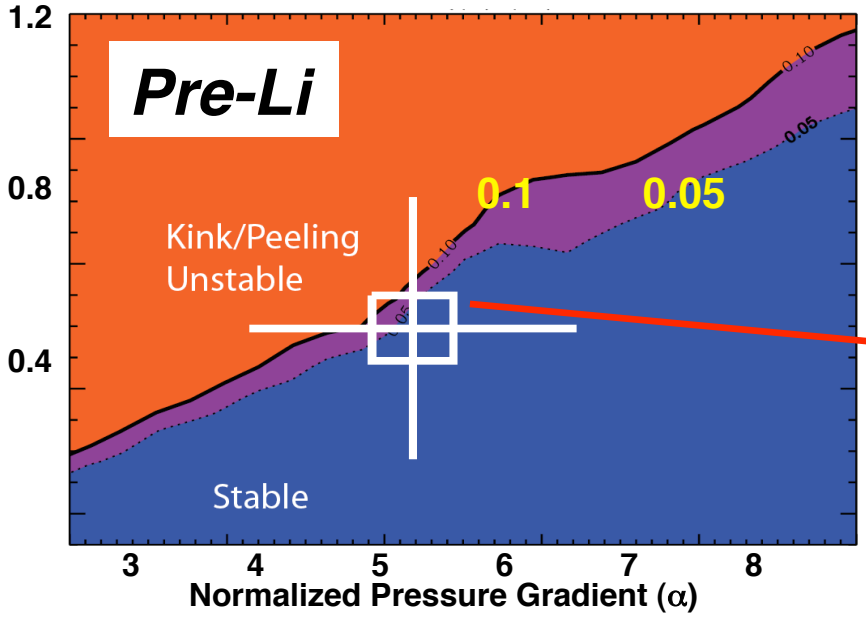


- Global increase in τ_E correlates with drop in edge χ_e
- Consistent with change in χ_e, D from SOLPS simulations

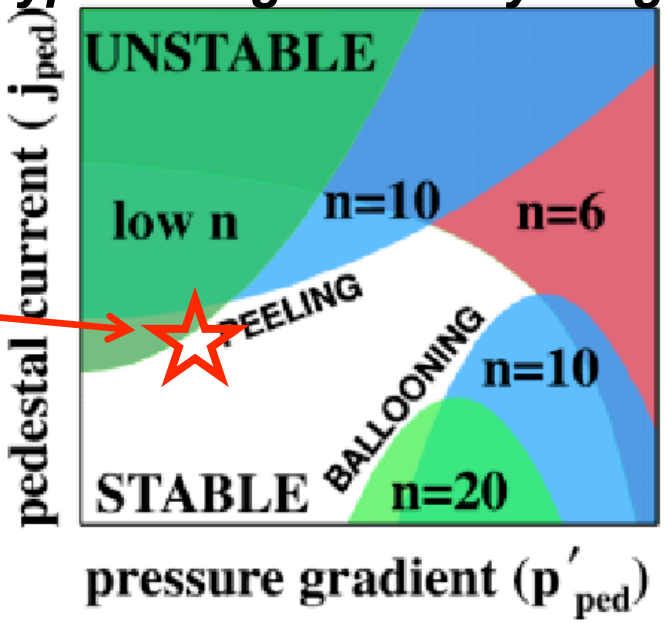
Pre-lithium discharge near the kink/peeling boundary (end points of lithium scan)





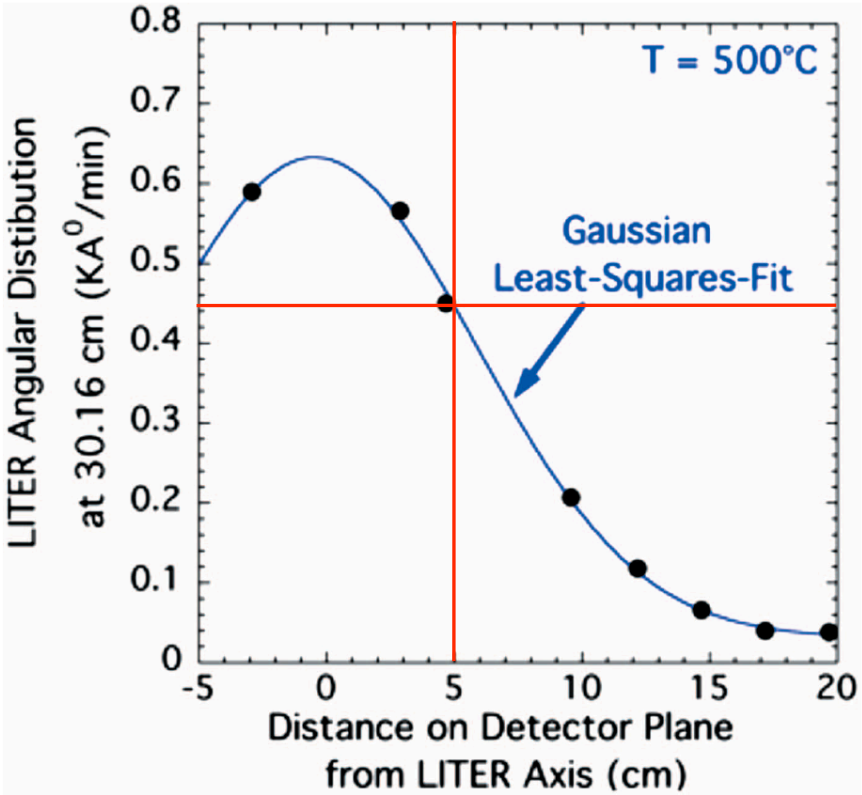


Typical Edge Stability Diagram

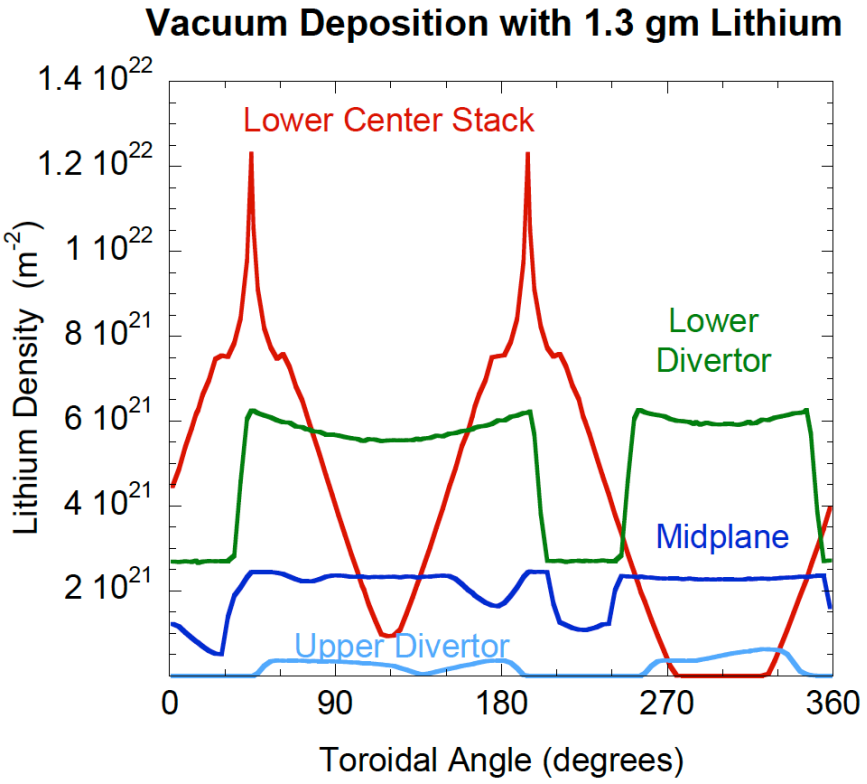


LiTER deposition has toroidal and poloidal variation

- 30cm distance from LiTER to surface
- in NSTX, x-axis should be multiplied by 10x
- For R_{OSP}~0.8m, deposition 1/3 less than max.

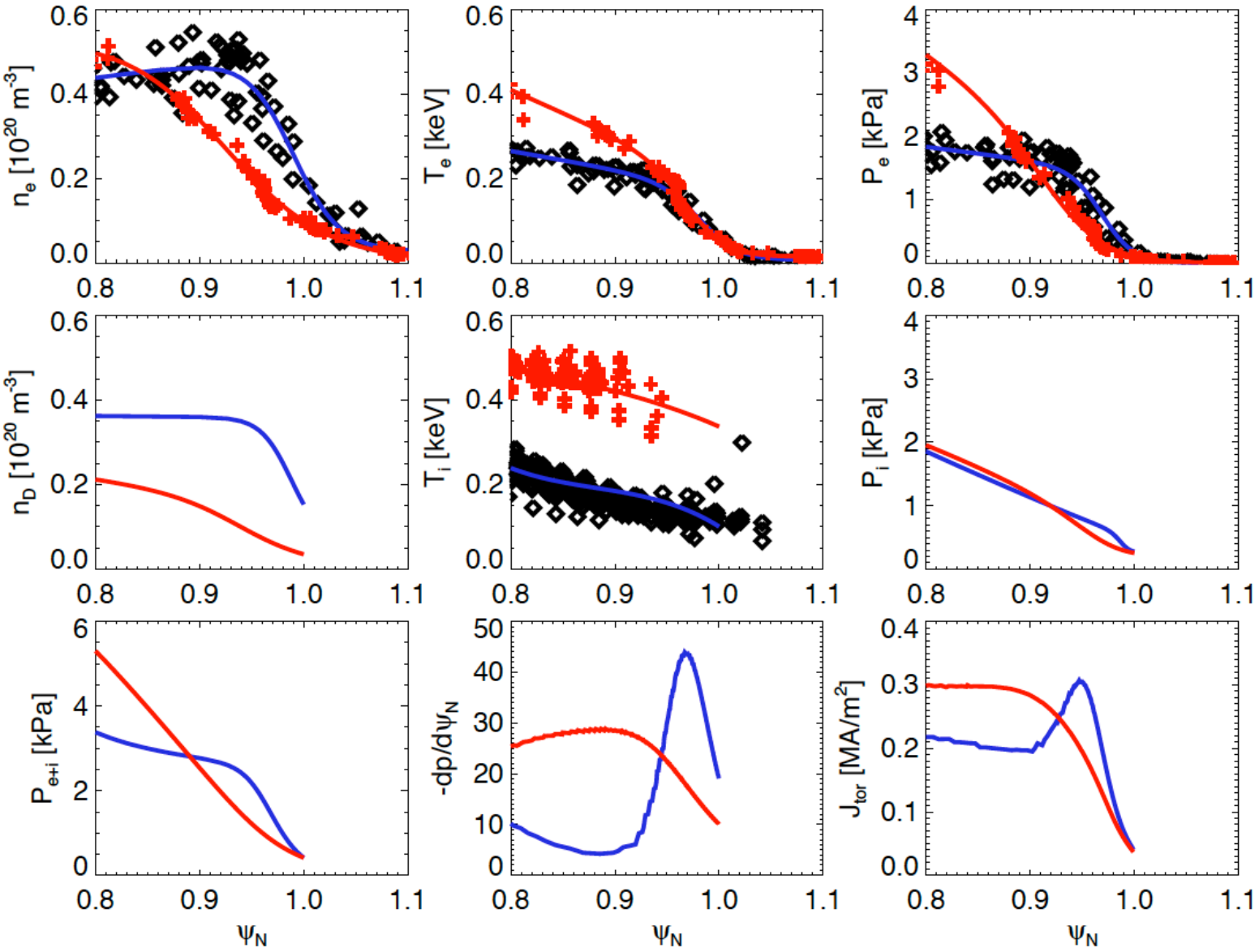


H. Kugel PoP 2008

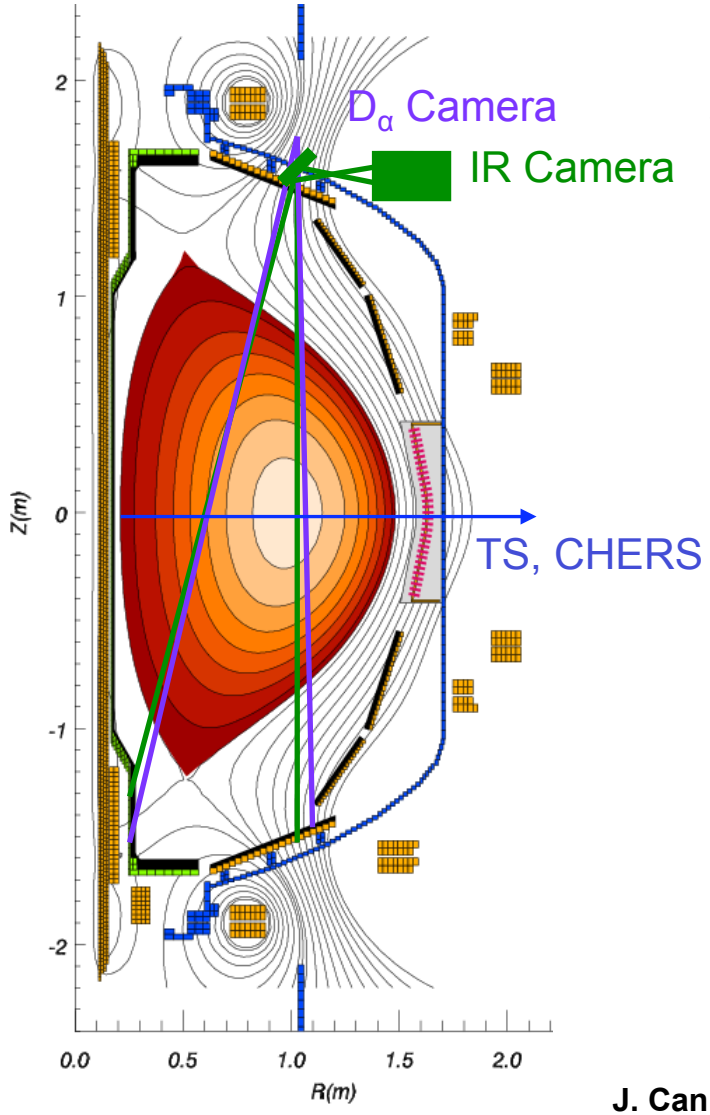


* From H. Kugel, source?

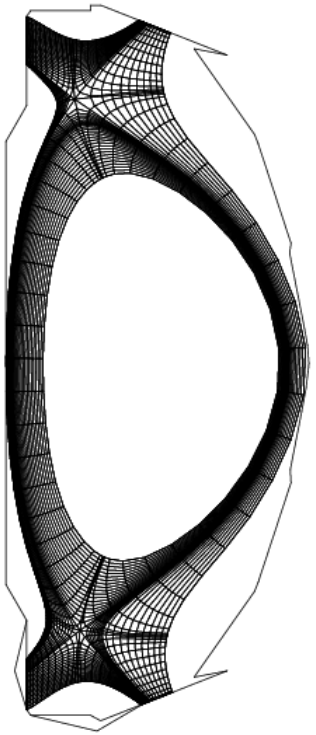
Lithium substantially affects edge profiles



Divertor recycling and far edge cross-field transport quantified with data-constrained SOLPS modeling



SOLPS Grid

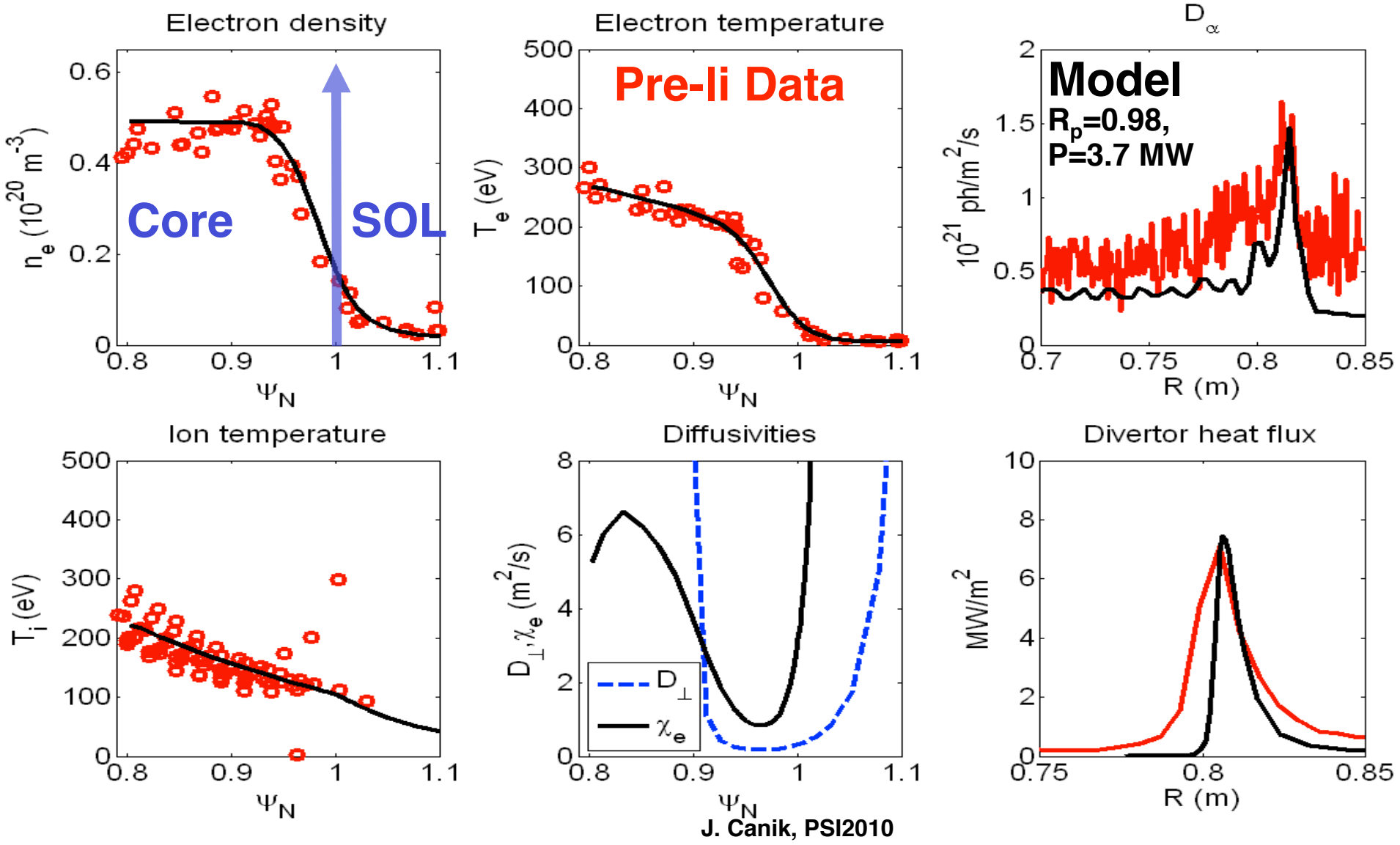


J. Canik PoP 2011

- SOLPS (B2-EIRENE: 2D fluid plasma + MC neutrals) used to model NSTX experimental data
  - Iterative Method
  - ✓ Neutrals, impurities contributions
  - ✓ Recycling changes due to lithium

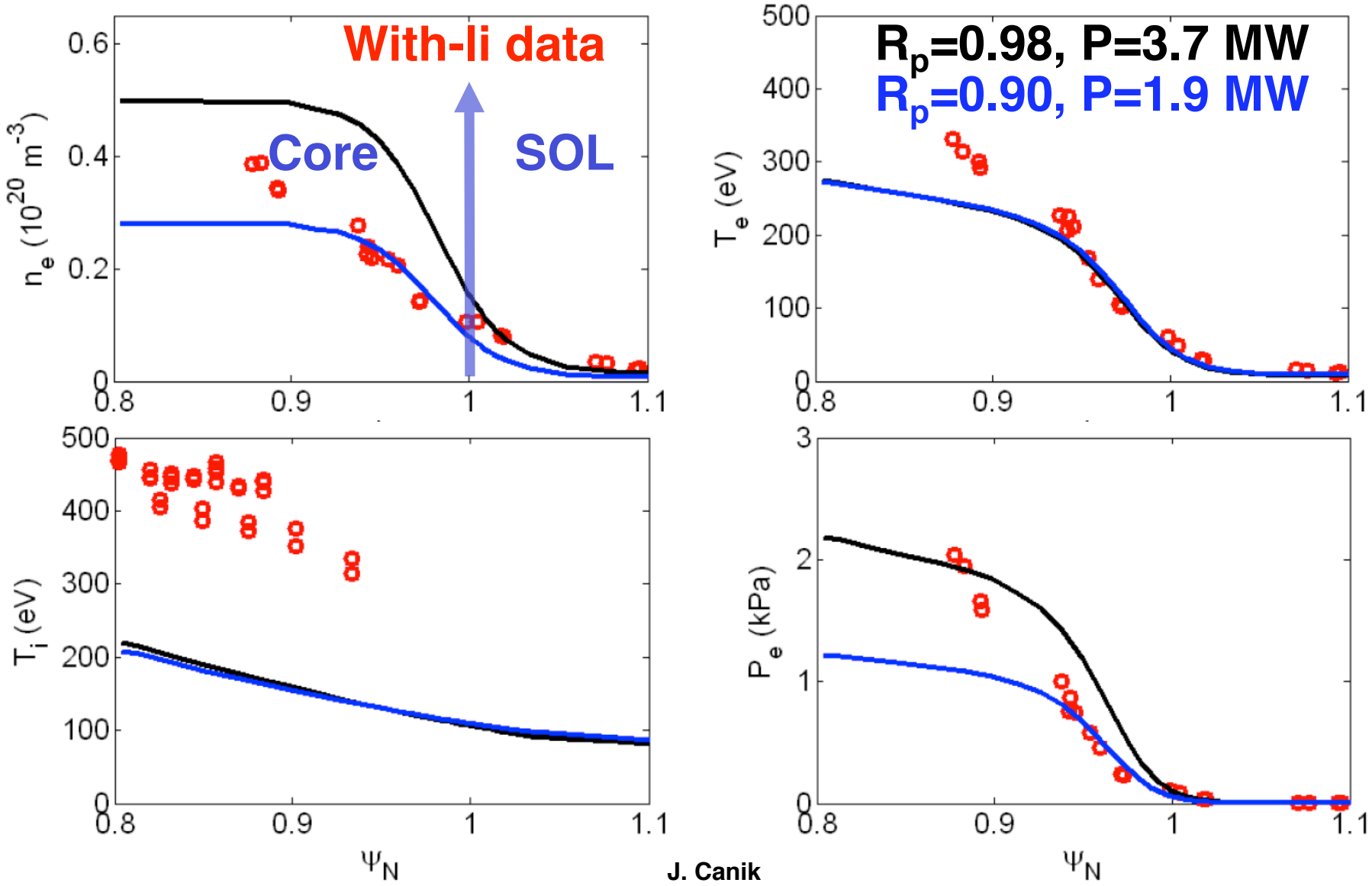
Parameters adjusted to fit data	**Measurements used to constrain code**
Radial transport coefficients $D_\perp$, χ_e, χ_i	Midplane n_e, T_e, T_i profiles
Divertor recycling coefficient	Calibrated D_α camera
Separatrix position/ T_e^{sep}	Peak divertor heat flux

2-D modeling used to model power and particle balance of baseline ELMy discharge



J. Canik, PSI2010

With-lithium discharge profiles not reproduced with simple recycling coefficient change



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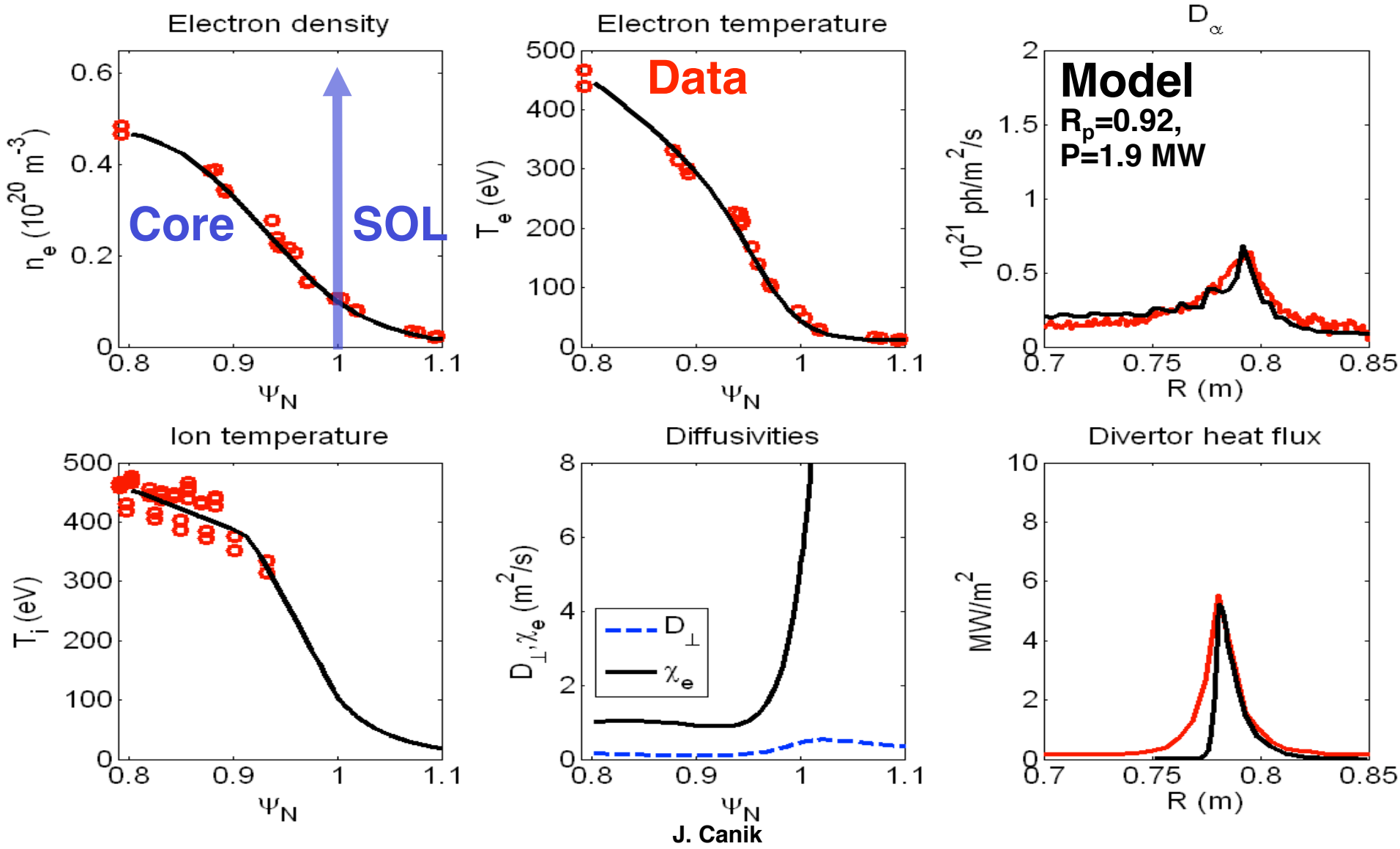
With-lithium discharge profiles better matched with transport and recycling coefficient change

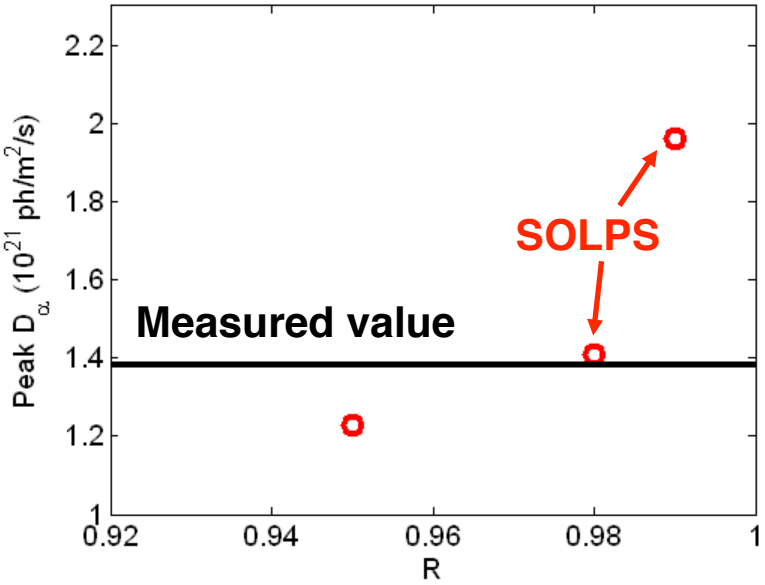


J. Canik

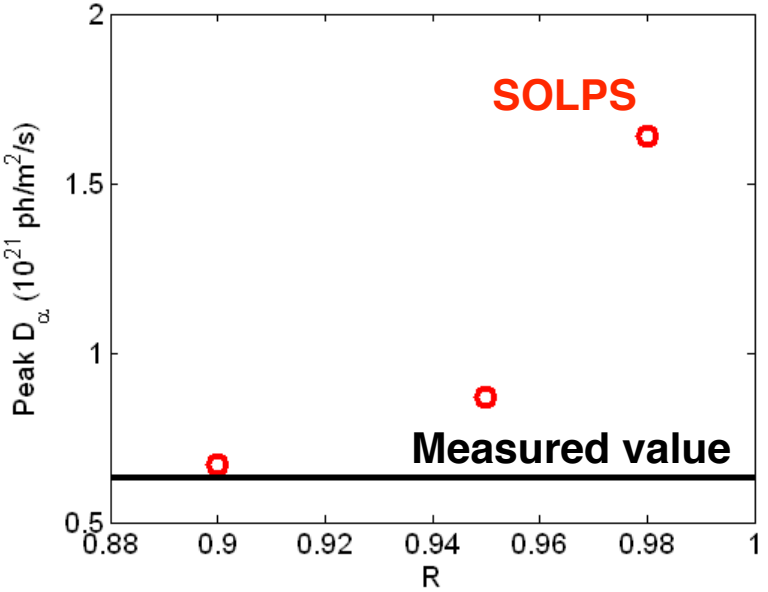
Peak D_α brightness is matched to experiment to constrain PFC recycling coefficient: lithium reduces R from ~.98 to ~.9

- For each discharge modeled, PFC recycling coefficient R is scanned
  - Fits to midplane data are redone at each R to maintain match to experiment
- D_α emissivity from code is integrated along lines of sight of camera, compared to measured values
  - Best fit indicates reduction of recycling from R~0.98 to R~0.9 when lithium coatings are applied

Pre-lithium

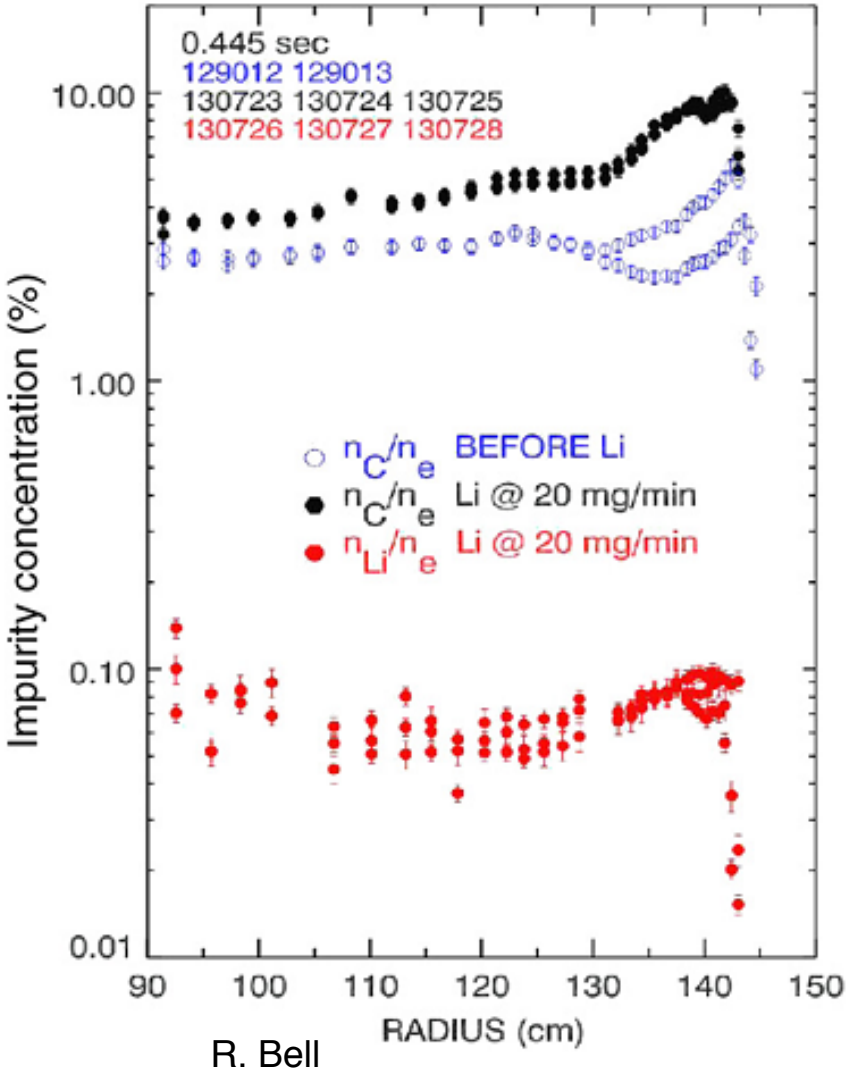


Post-lithium



Carbon is the dominant impurity species with lithium coatings

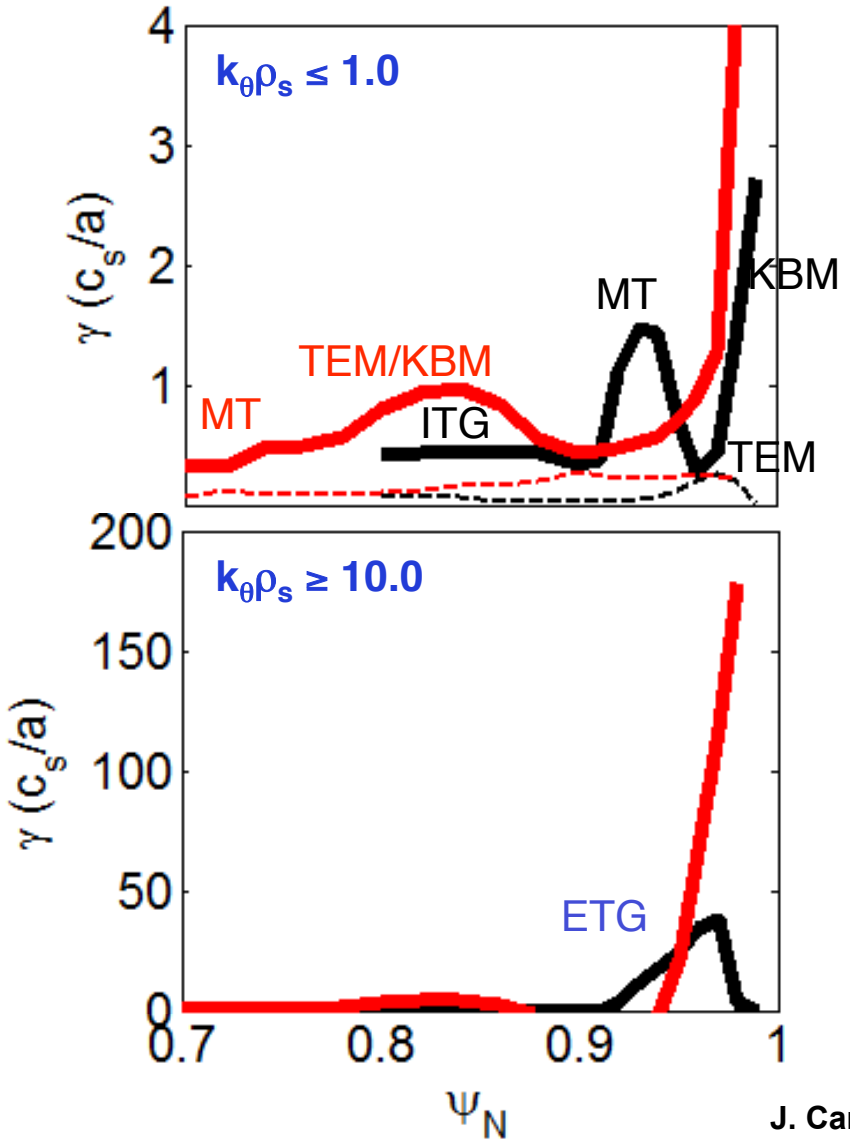
- Measured lithium concentration is much less than carbon
  - Carbon concentration ~100 times higher
  - Carbon increases when lithium coatings are applied
  - Neoclassical effect: higher Z accumulates, low Z screened out
- Increase in n_C may be due to lack of ELMs
  - Can be mitigated by triggering ELMs

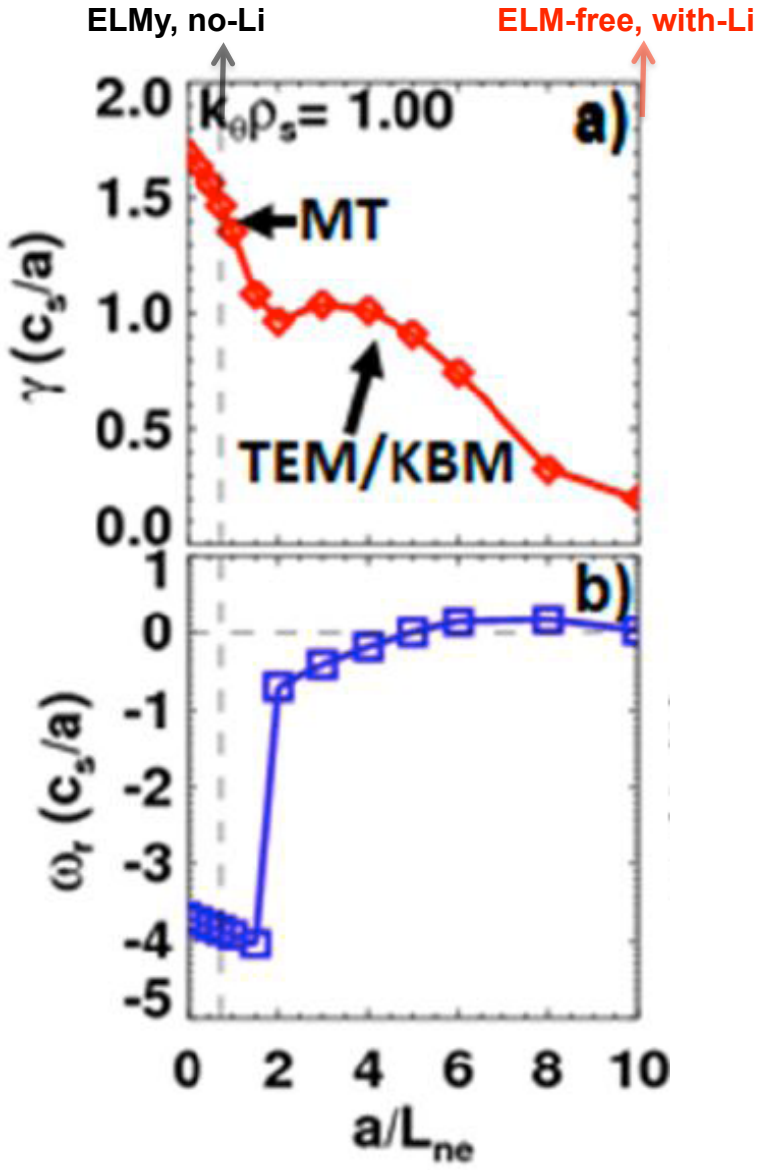


R. Bell

M. Bell, PPCF **51** (2009) 124054

Increased density gradient with lithium reduces micro-tearing drive; (ETG important in far edge in clamping T_e gradient)

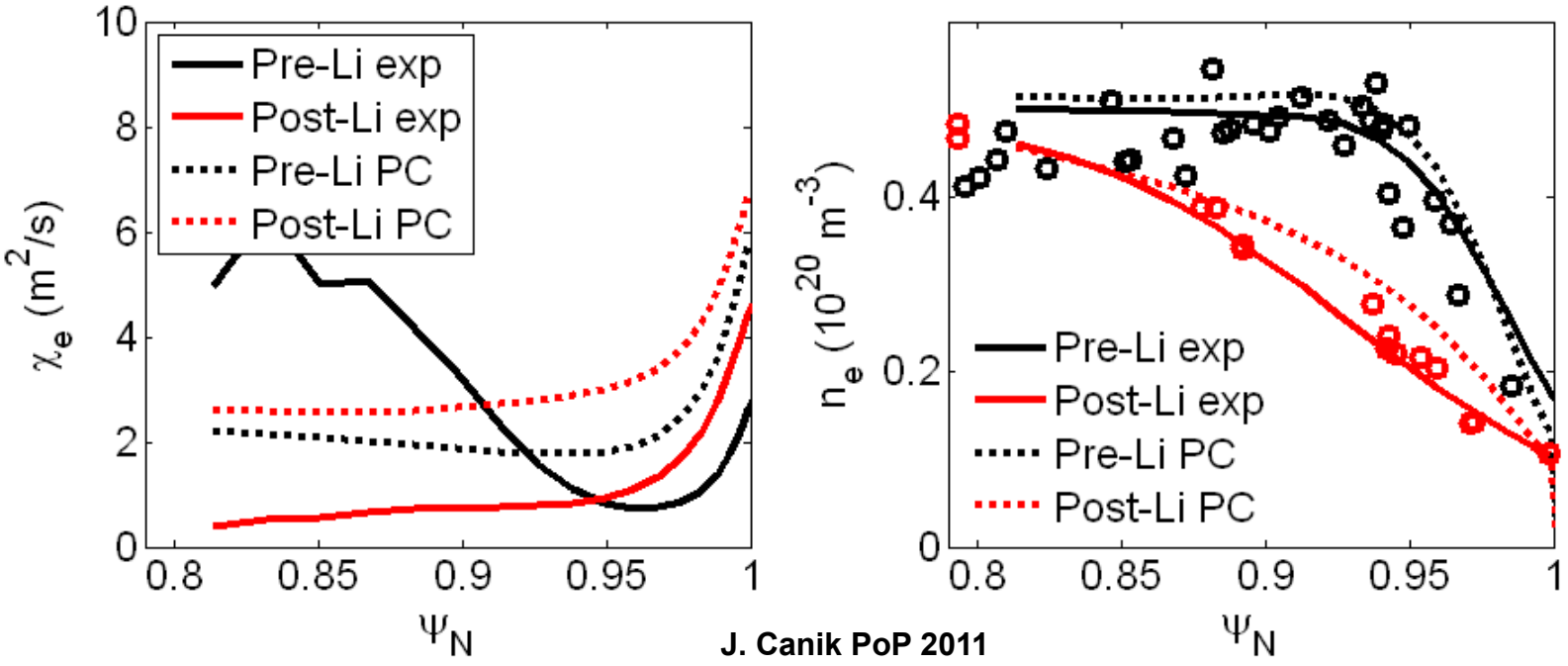




J. Canik, EX/P7-16

Measured pedestal modifications are semi-quantitatively consistent with paleoclassical transport

- Pedestal structure model based partly on paleoclassical transport proposed
  - J.D. Callen, UW-CPTC 10-9
  - Depends on resistivity profile->Z_{eff} changes important
- Model recovers χ_e magnitude, shape, rise near separatrix, as well as modest increase with lithium outside ψ_N~0.95
- Density profile shape changes with lithium also captured by model



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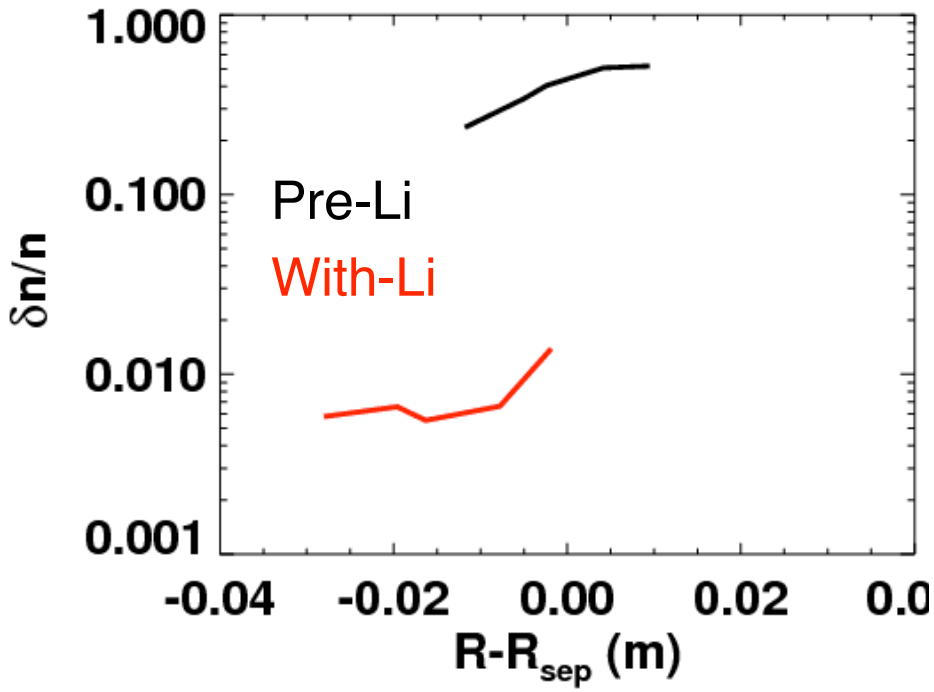
Edge fluctuations reduced with lithium coatings

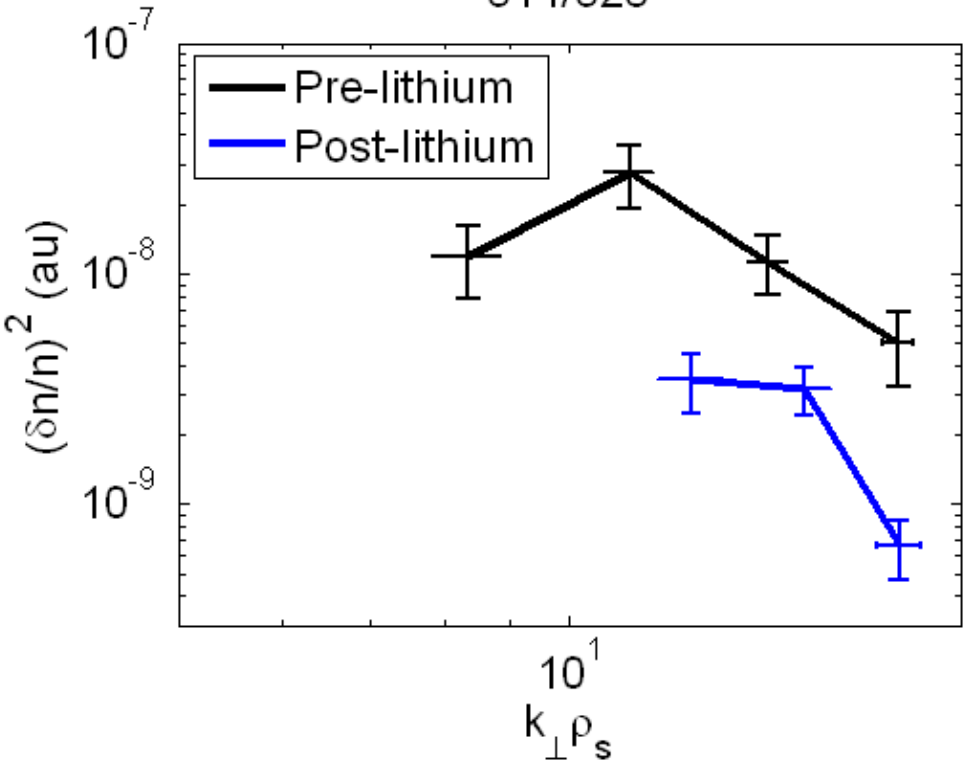
Reflectometry near n_e pedestal top



High-k scattering

Top of n_e pedestal

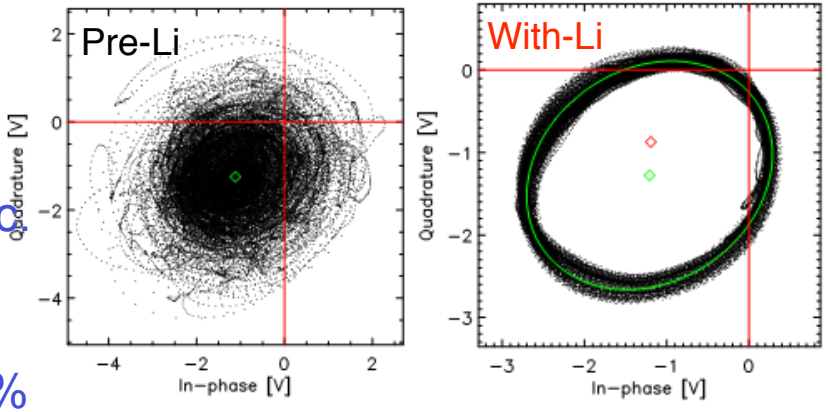
314/328

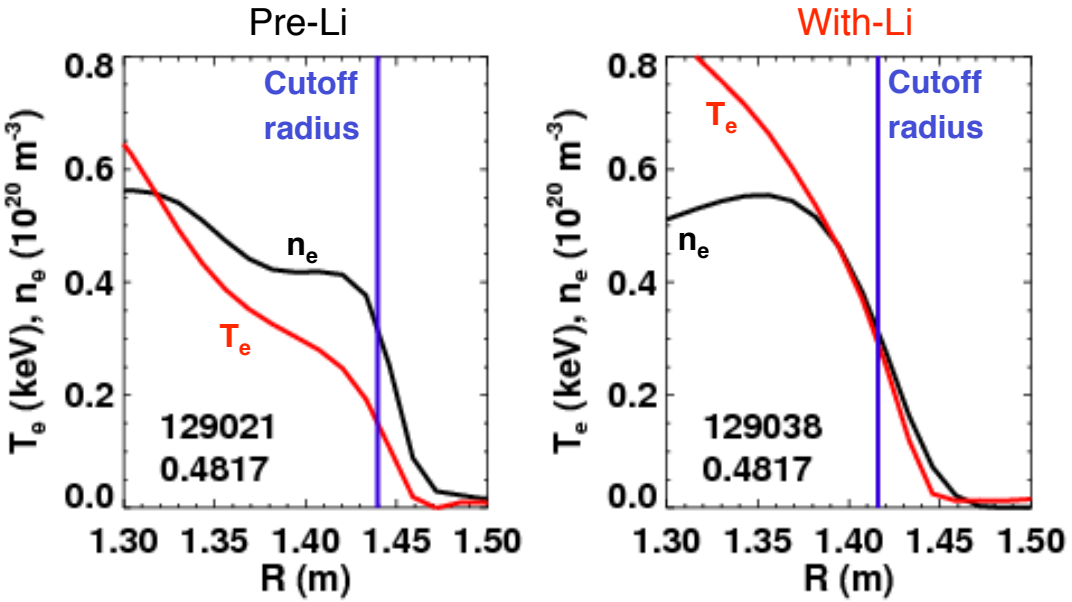


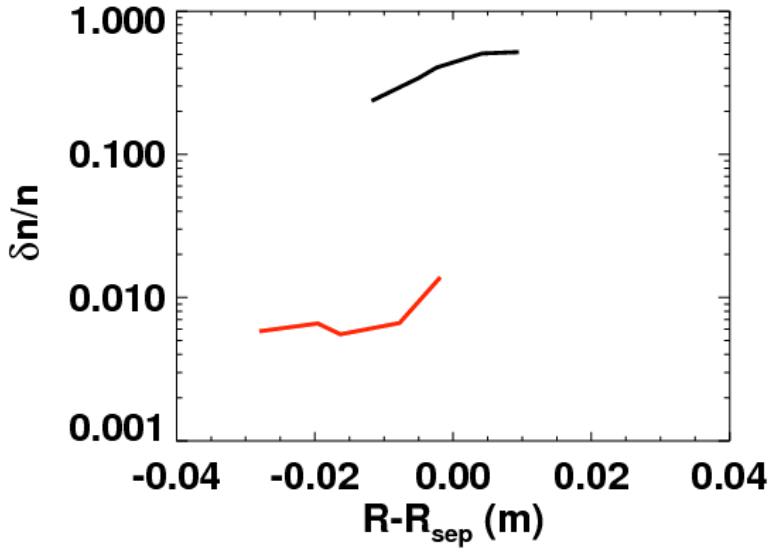
J. Canik PoP 2011

Edge reflectometry near pedestal top shows reduced density fluctuations with lithium

- Reduced transport in inner region->higher pedestal top pressure
- Reflectometer shows reduced fluctuation level
  - Pre-lithium: strong amplitude and phase fluc
  - Post-lithium: little amplitude fluctuation
  - 3D simulations using Kirchoff integral indicate turbulence level reduced from ~10% to ~1% with lithium



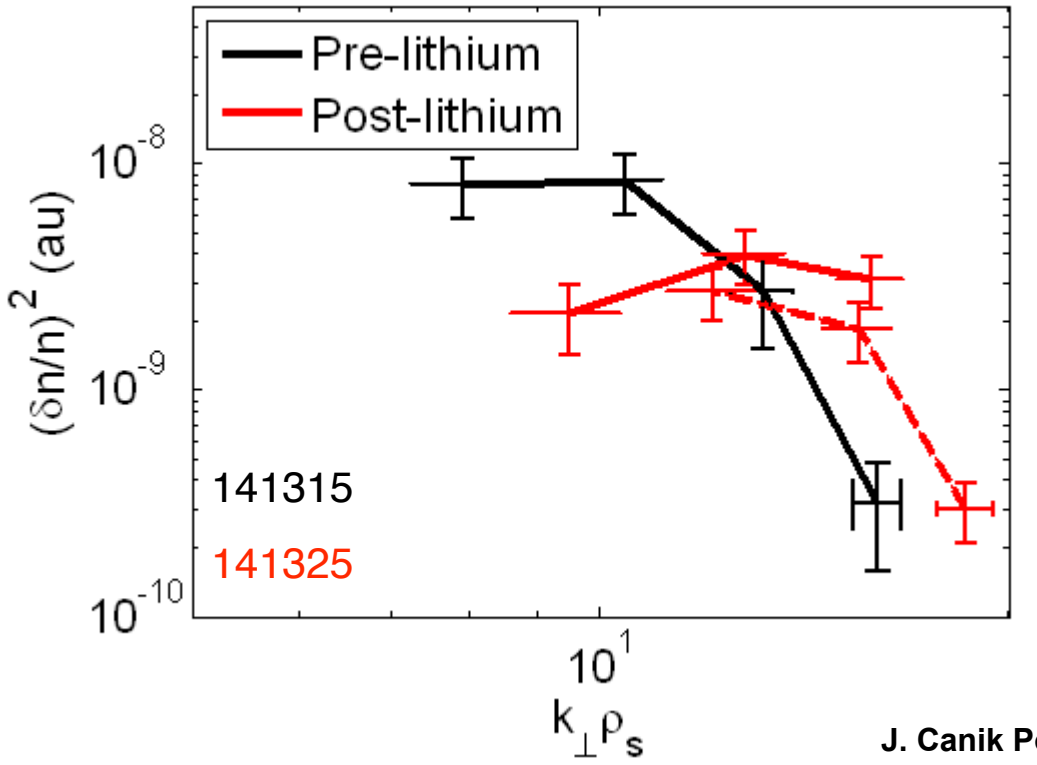




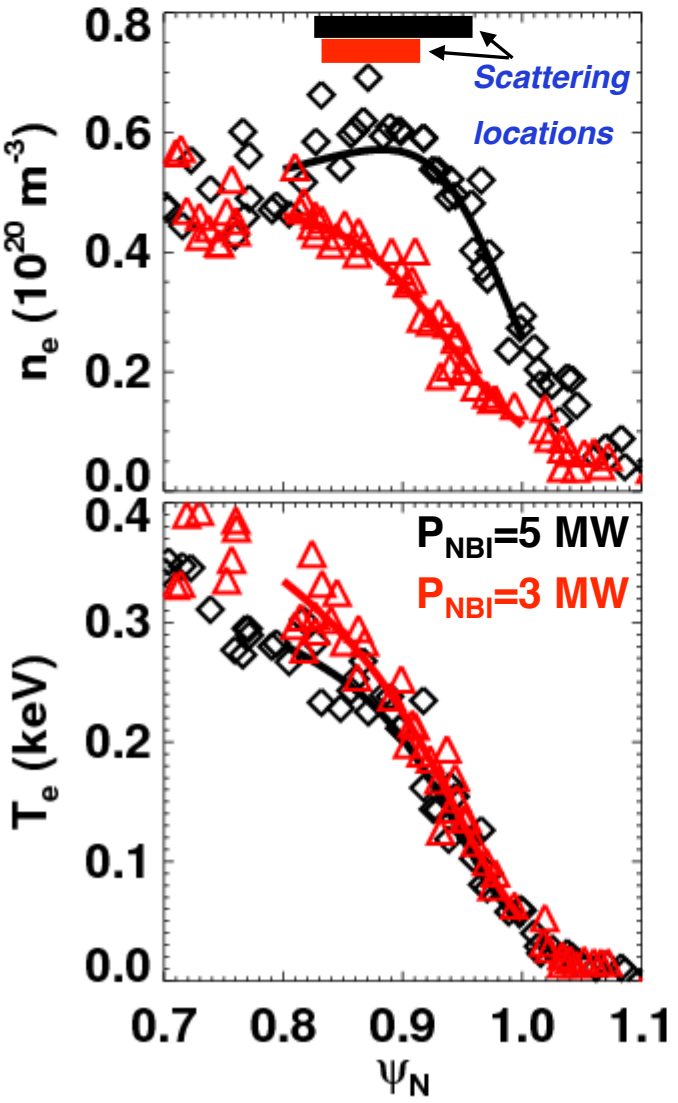
J. Canik PoP 2011

High-k scattering diagnostic shows little change in fluctuation amplitude at $k\rho_s > 10$

- Pre-to-post lithium transition repeated, similar profile changes observed
- Fluctuations similar for $k\rho_s > 10$, some reduction at lower k for the with-lithium case

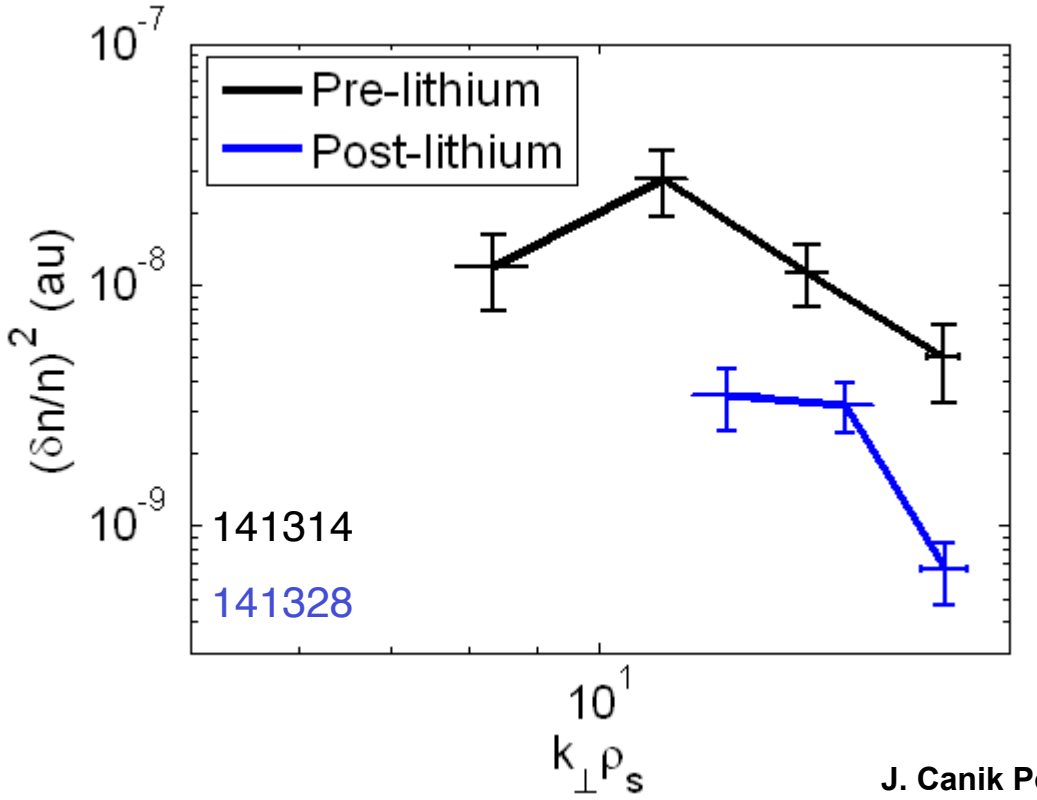


J. Canik PoP 2011

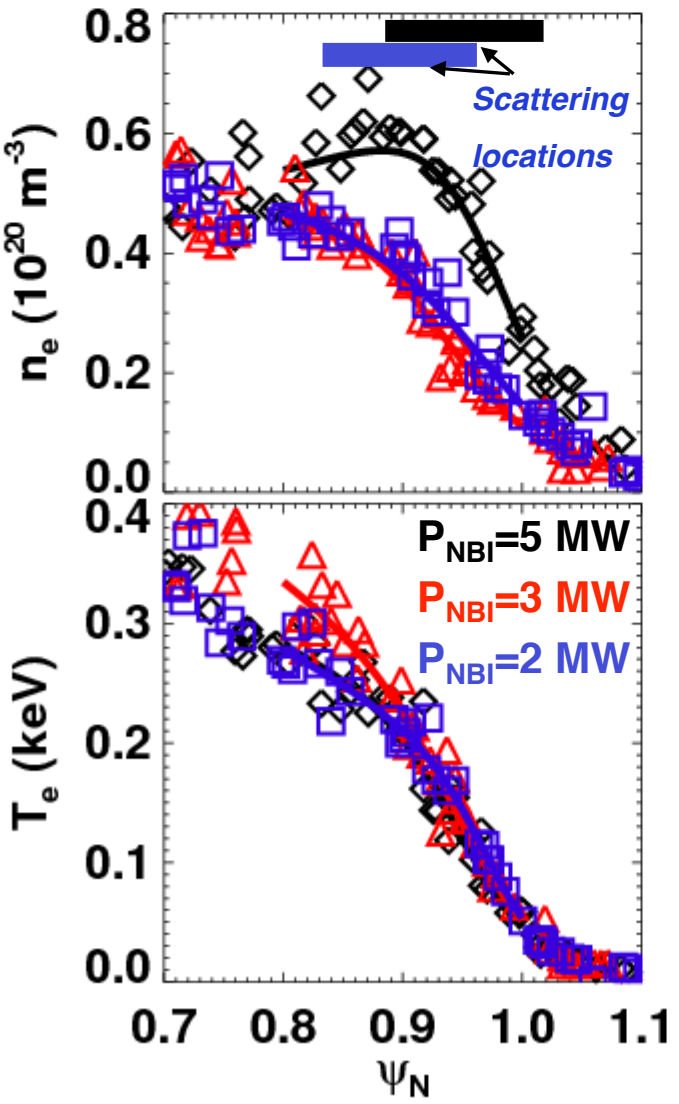


With power reduced so T_e profile matches pre-lithium case, fluctuation amplitudes show broad reduction

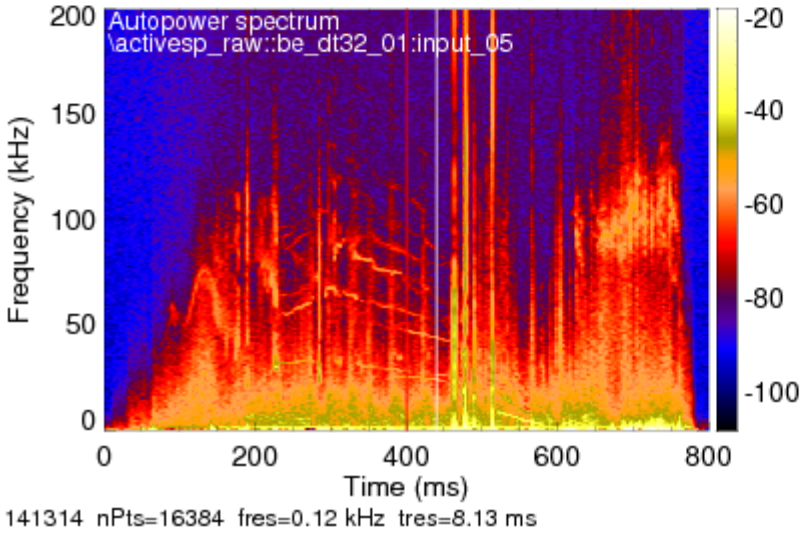
- Power reduced to 2 MW
- T_e profile similar to pre-lithium
- Fluctuation amplitude reduced across measured $k\rho_s$

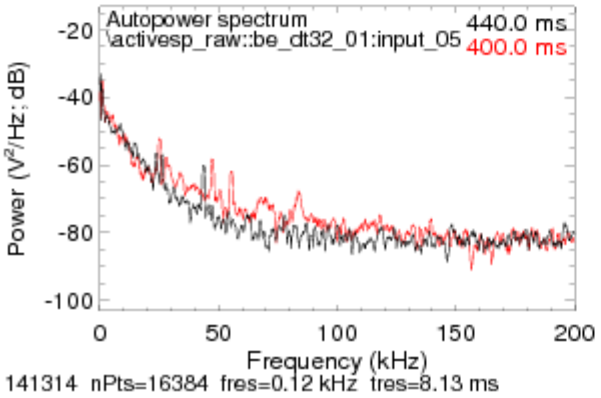


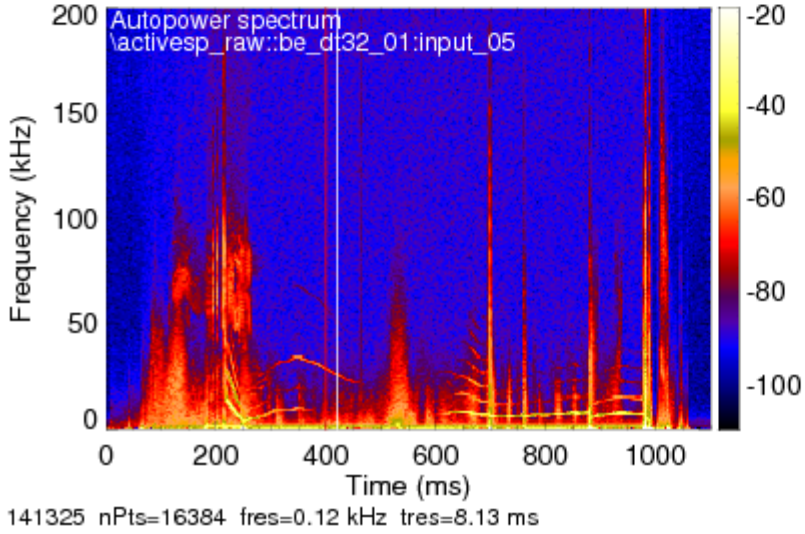
J. Canik PoP 2011

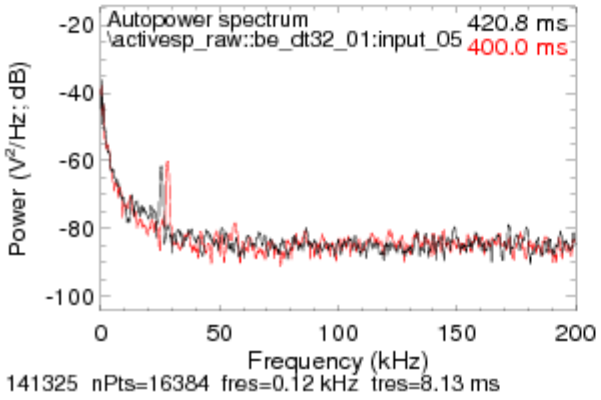


BES also shows reduced turbulence levels in post-lithium discharges









***Courtesy D.R. Smith, UW**