What we (don't) know about tokamak edge plasma transport from experiment and modeling

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nstx118152_gpi_hmode_nbi.avi

Zweben NSTX GPI H-mode+NBI

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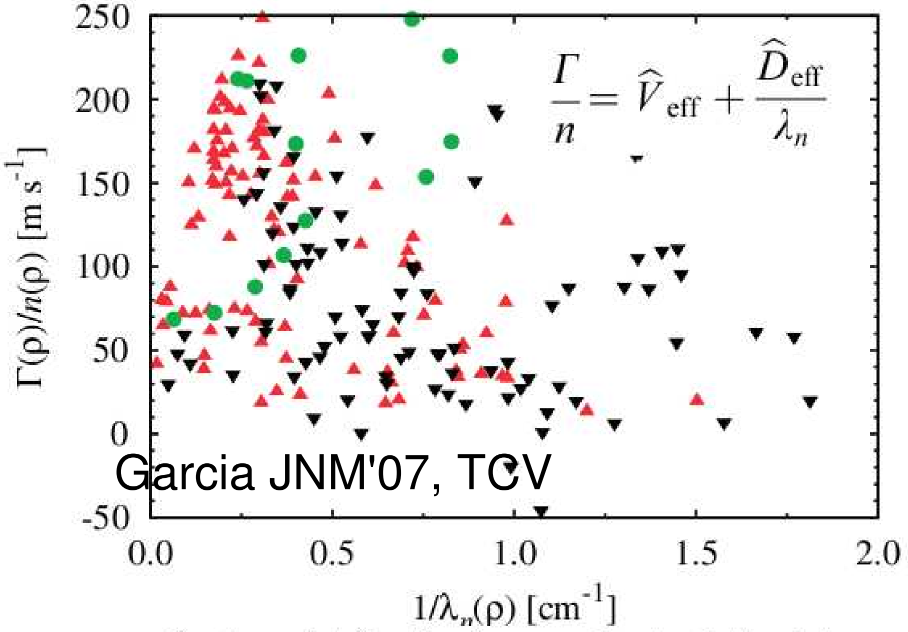
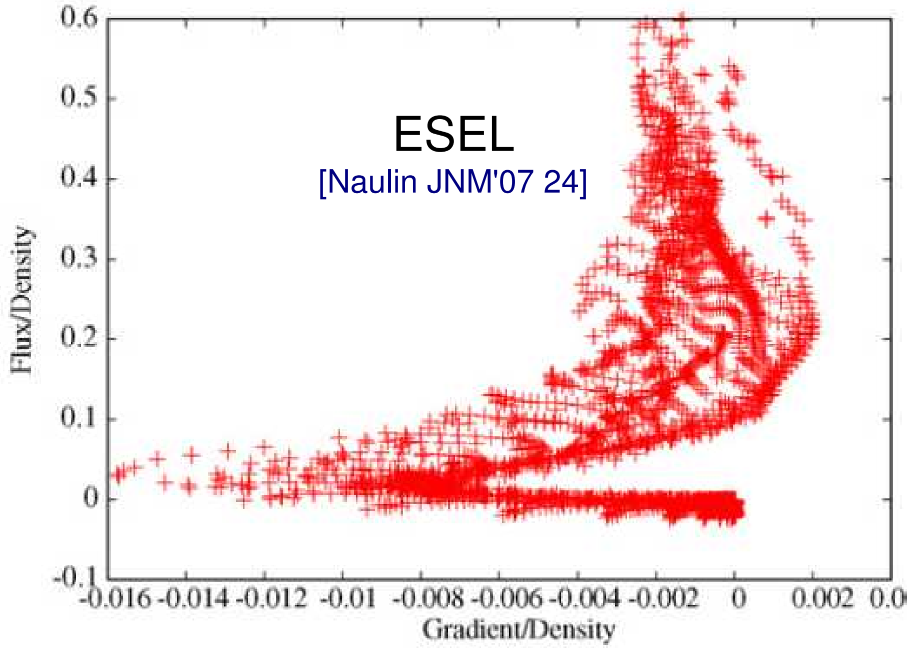
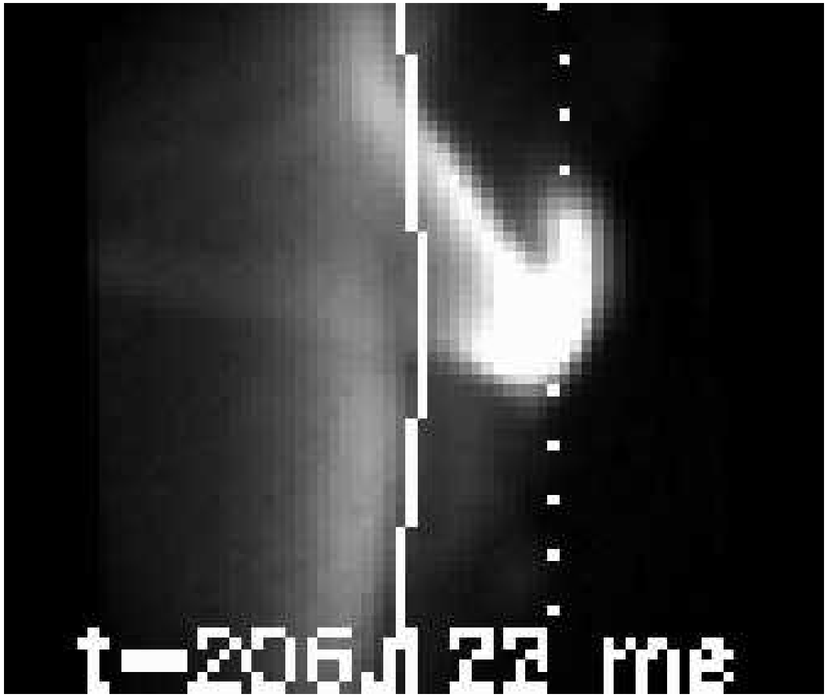
Experimental observations

- Central transport is mostly diffusive
- SOL transport is neither convective nor diffusive: it's non-local!



Scatter plot for the flux–gradient relationship.

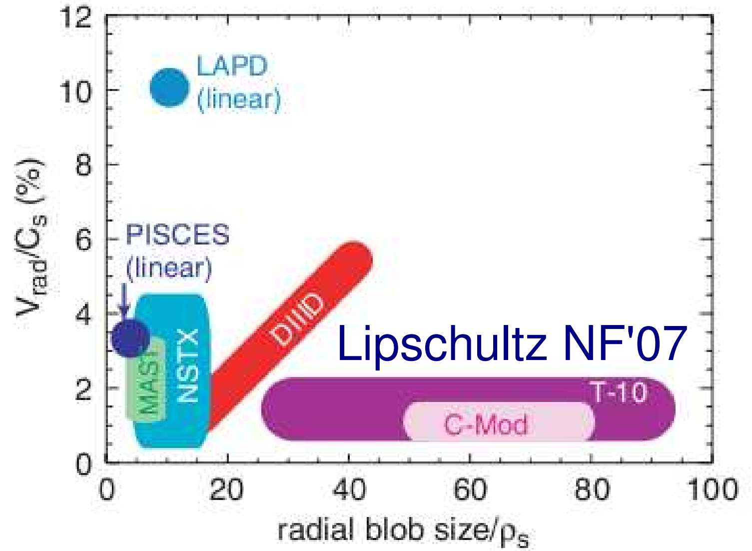




nstx118152_gpi_hmode_nbi.avi

Zweben NSTX GPI H-mode+NBI

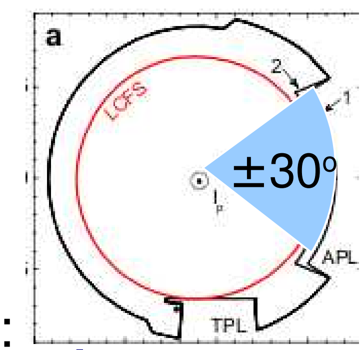
Blobs characteristics



- Largest dimensions: $d_{||}^{ls}$>10m, d_z/d_r~1
- Fractal structure ($f^{-\beta}$ up to 2.5 decades)

  due to splitting up (energy cascade)
- Velocities: v_r<+1km/s, $|v_\theta|\leq$5km/s, $v_{||}=c_{is}$
- Lifetime: enough to reach the wall (before divertor);

  autocorrelation time $t_{AC}^{-2} = t_{life}^{-2} + (v/d)^{-2}$



[J. Gunn JNM'07 484]

- Amplitude: (2-3)·$\sigma_T/T \sim \sigma_n/n = 0.2_{LCFS} \rightarrow 1_{wall}$, $C(n_e, T_e) > 0.5$
- Generation: not understood, 1st experimental observation:
  - drift-interchange wave crest in Torpex (non-tokamak), [Furno *etal.* PoP'08 055903] FurnoBlob.wmv

- Propagation: due interchange instability $E_z = \nabla_R B$x**B => $\mathbf{v_R} = \mathbf{E_z}x\mathbf{B}$ and** $\nabla_R p$ where $\nabla_R p/p > \nabla_R B/B$ [Garcia JPP'01 81], ie. ~30° @ LFS
  - Other forces than $\nabla_R B$: neutral wind, divertor plate tilt, centrifugal, $\nabla_R T$.

What's missing from experimentalists?

- 2D images using visible camera (or visible tomography)
  - Plasma enlighten by neutrals using
    - Gas-puffing in SOL
    - NBI: BES in SOL & pedestal
  - Difficult signal interpretation: $S = n_0 n_e^{0.5\text{-}0.8} T_e^{0.3\text{-}1.4}$ [Zweben PoP\02]; ongoing attempt on canceling the T_e-dependence (CIEMAT)
  - Correlation 50% between camera signal and I_{sat} [Alonso PhD thesis, Tim Happel]
  - Large effort should be put into the image data processing and signal calibration (eg. using probe $S = f(\text{fast } T_e, I_{sat})$)
- 1D HIBP – very difficult to reach large S/N in SOL
- 0D probes ($n_e T_e^{1/2}$, ϕ-2.8T_e, $\mathbf{v_{||}/c_{si}}$)
  - no other diagnostic can resolve n & T with the necessary spatial (<3mm) and temporal (<3μs) resolution.
  - What is T_e, T_i at wall & divertor? Experiment: T_e>5eV, models <1eV. T_i>>T_e. Measure T_i!
  - the $v_{||}$ info can be useful for testing 3D codes, not exploited yet!

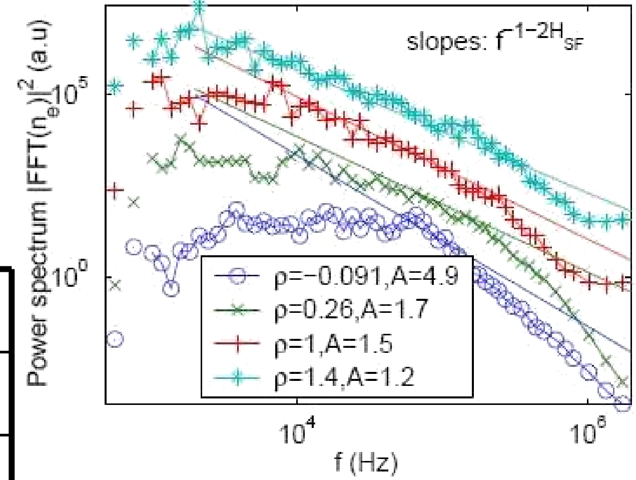
SOL turbulence terminology

Spatial dimension	**Name**	**Observed by**	**Characteristic**
0D (in time)	Intermittent event, burst	Langmuir probe	Non-Gaussian PDF, *fractal PS~f^{β}*
1D parallel	Filaments	twin Langmuir probes or camera	Long correlations or || long structures
1D radial	Avalanche, streamer, density finger	Sandpile model fluid model	Cluster dynamics
2D simulations	**Blob, coherent structure**	Models of isolated blobs	Propagation dynamics due ∇_RBxB and ∇_Rp
2D experiment	plasmoid, avaloid, IPO, eddy (vortex)	Fast visible camera, LP matrix [videoMaqueda]	1x2cm^2, ~1km/s, …

All terms relate to a particular observable characteristic of a blob, driven by a single phenomena – the **interchange turbulence**.

Blob is an atom of edge tokamak plasma turbulence

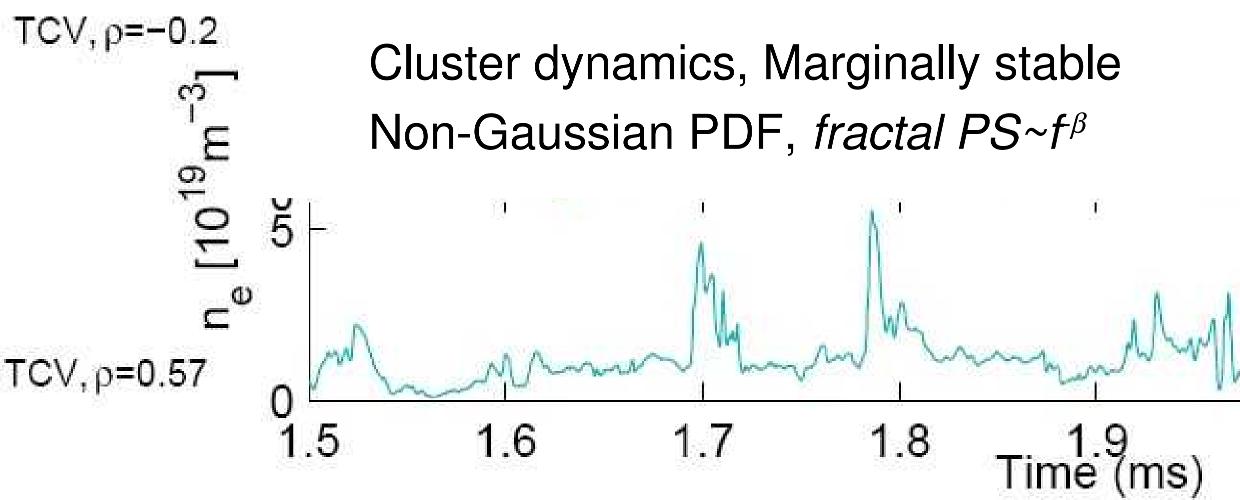
Sandpile analogy

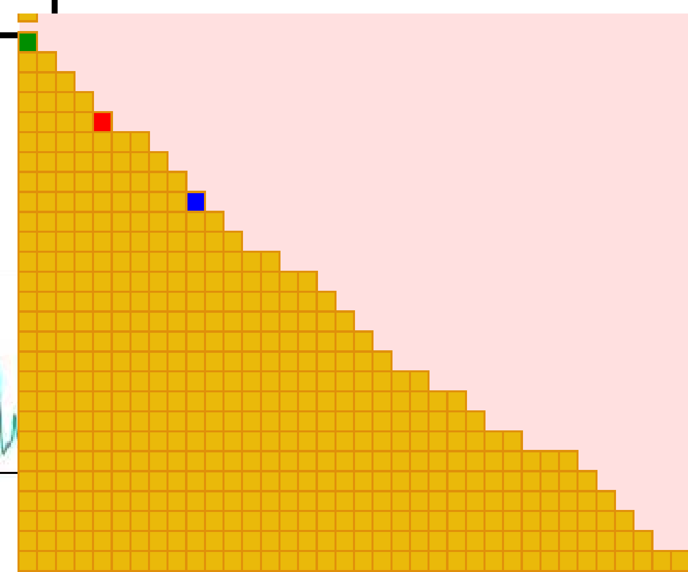


Sandpile	Tokamak edge
Sandpile slope	$\nabla_r p$
Sand grains	Individual ions on Larmor orbits
Force of gravity	Curvature and ∇_rBxB
Static friction	Instability threshold $\nabla_R p \cdot \nabla_R B > 0$
Dynamic friction	Dissipation at small scales and velocity shear

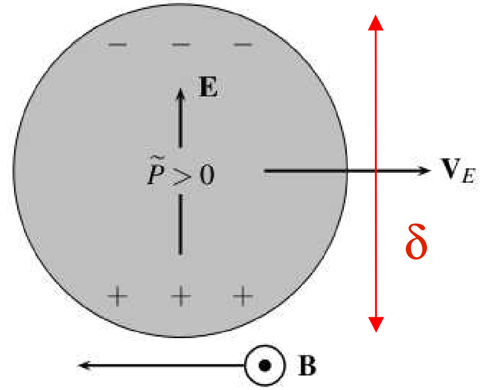
Cluster dynamics, Marginally stable

Non-Gaussian PDF, *fractal PS~f*$^{\beta}$





Model of Interchange instability



Inside LCFS, plasma stable due to helical B-field (safety factor q). In SOL, q is insufficient!

Take existing 2D fluid ESEL model based on interchange motions:

Curvature and ∇BxB drift

↓

vertical charge separtion

↓

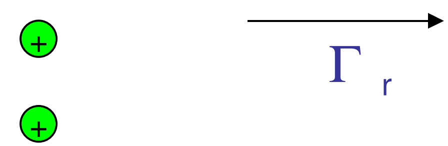
Generation of E_z

↓

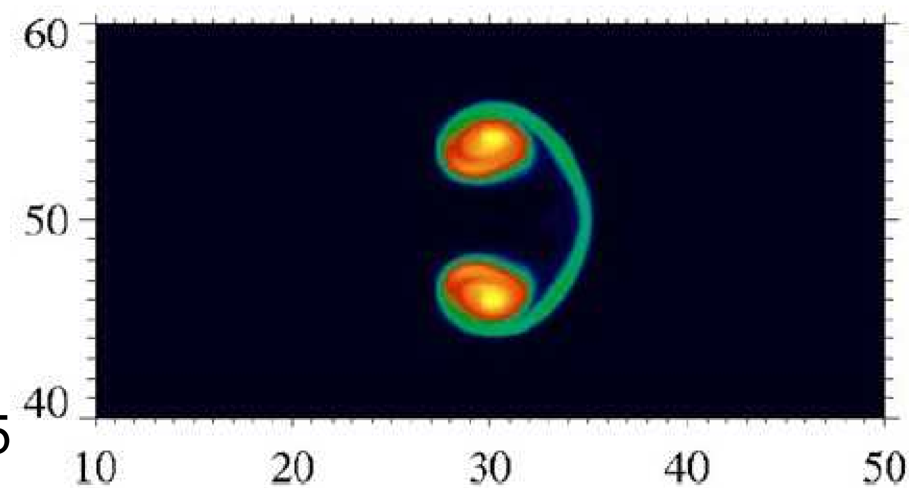
ExB drift outwards

↓

Unstable at LFS due ∇p

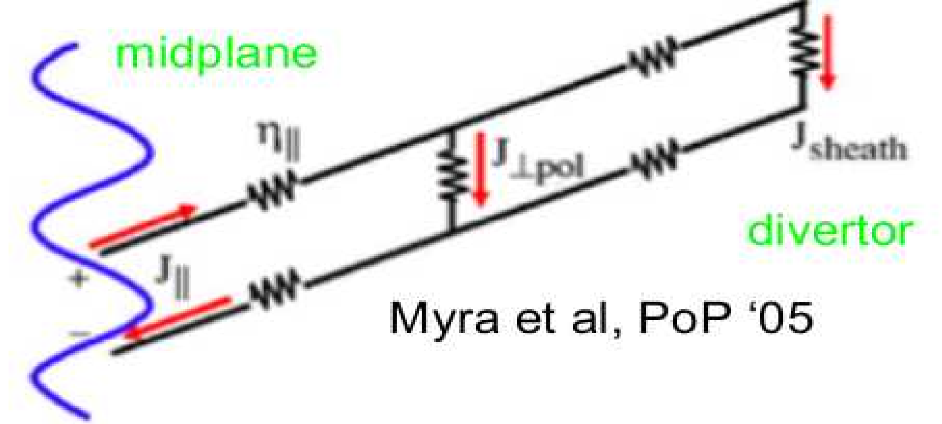


driven by ∇_RBxB+RxB and ∇_Rp where $\nabla_R p \cdot \nabla_R B>0$, ie. LFS.



Garcia, PoP'05

Fluid simulations of a single blob

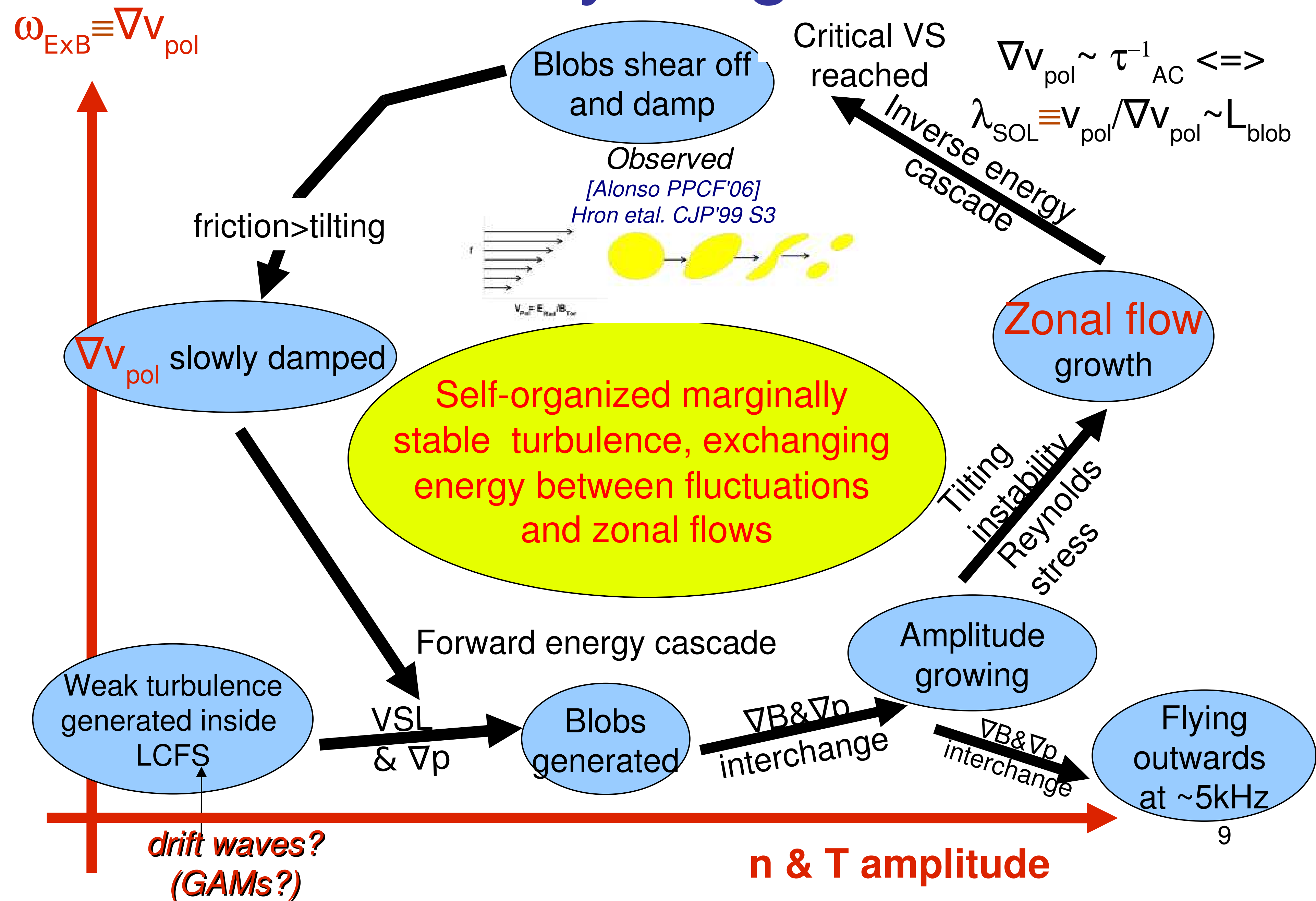


Myra et al, PoP '05

- Blobs' radial velocity scaling:
  1) Assuming sheath dissipation:
     $v_r \sim 2c_s(\rho_s/\delta)^2 L_{||}/Rn_b/n_t \sim 100$m/s, *[Krasheninnikov PLA'01 368]*.
     Blob unstable to Kelvin-Helmholtz => shape evolution
  2) Assuming $j_{sh}=0$ (ie. $\nu^* >> 1$) => $v_r \sim c_s(2\delta/R^* \delta n/n)^{1/2}$ *[Garcia etal, PoP'06 082309]*
  – X-point detaches midplane from divertor [Russel PRL'04] :-)
- Experimental tests favor the 2nd model: $v_r \propto \nabla I_s$ [for ELMs *Goncalves PPCF'03*], for blobs directly [Schmid PPCF'08 045007]
- Blob spinning supposed to stop $v_r(E_z)$: only if $\delta T/T>1$ [Myra PoP'04]; preliminary observed in ESEL
- Evolve blobs into mushrooms? Yes, observed. Shape invariant if $\delta \sim \delta_* = \rho_s (L_{||}^2/\rho_s R)^{1/5} \sim 4$cm [Yu PoP'03 4413].

SOL instability diagram

In analogy as for ELMs $j_p(\nabla p)$ [Connor PoP'98]



European SOL fluid codes overview

- Long time-series of measurable quantities are necessary for direct comparison of modeling with experiment. Computer power limitations:
- 10^4 ion orbits (0.2ms) to see 1 blob to develop its shape and move its own size. 5D Gyrokinetic codes insufficient
- 10^5 ion orbits to see 10 blobs = 2ms for some statistics. In 3D: DiESEL (64 || CPUs for 1 month)
- 10^6 necessary to fully develop marginally stable turbulence with velocity shear from tilting and self-consistent radial profiles.
  – 2D ESEL, BESEL – extensive experimental verification on TCV (& JET); 3 CPU's in 3 days.
  – 2D Sarazin&Ghendrih experimental verification ??

RISØ

The ESEL model

scalars from experiment
$T_{LCFS}, n_{LCFS}, B_{LCFS}, R+a, L_{||}, m_i, m_e, Z_i$, gap

[*Fundamenski, Nucl. Fusion 2007 417*]: neoclassical transport: collisional ⊥ and acoustic (||)

Diffusion $D_n, D_T, D_\Omega \sim 10^{-2} m^2/s$ and || damping $\tau_n, \tau_T, \tau_\Omega$

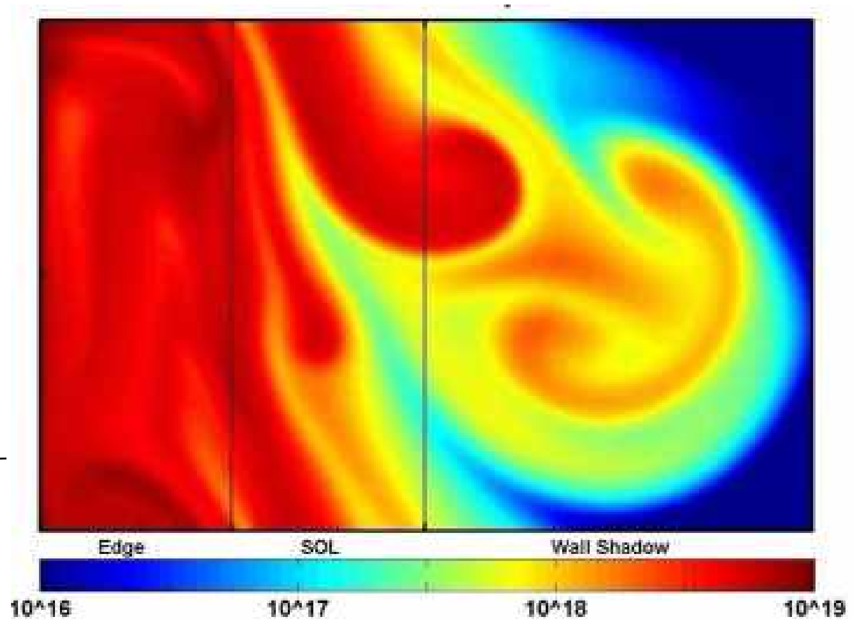
ESEL simulation [OE Garcia. Phys. Plas. **12**,062309 (2005)]

- MFF UK + IPP + Denmark
- Electrostatic 2D fluid model solves selfconsistently turbulence in n, T_e, Ω.
- Simplifications: parallel losses by linear damping, drift approximation, finite ρ_{Li} effects neglected, only LFS

$\nabla_r v_{pol}$ generated at LCFS due tilting instability

Actual development: joining with SOLF1D to solve

- parallel dynamics
- Includes Ti => plasma wall sputtering
- It's 1000x slower => it's a 100CPUweeks!



Density[m^{-3}]

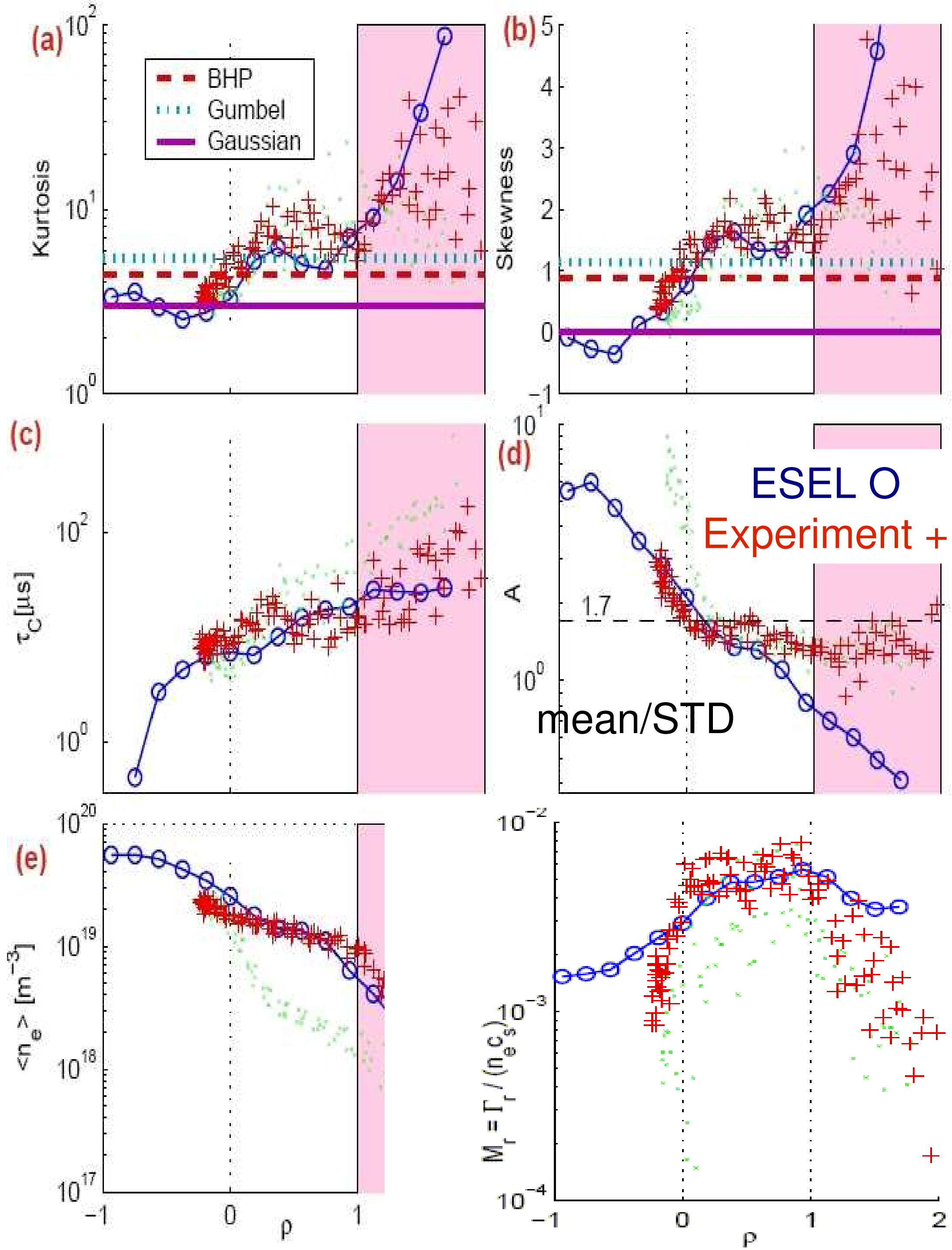
Radial profiles
$n(r), \Gamma_r(r), \phi(r), \ldots$
$D_{n,eff} \sim 10^{+1} m^2/s$

Experimental radial profiles
$n(r), \Gamma_r(r), V_{fl}(r), \ldots$

Experiment x ESEL

at TCV

- Gradients, time-scales, blob frequency, μ,σ,S,K match for n_e, Γ_r *(T_e)* for density limit plasma (high ν*, the key parameter [Garcia PPCF'07 B47]).
- For low density on ASDEX, σ_T/T too high [J. Horacek, TTG'09]



Summary & outlook

- Theoretical Review [Krasheninnikov J Plas. Phys. 2008 679]
- SOL transport not easily parameterizable
- Calibrating visible cameras $S=f(n_e,T_e)$
- Blob interchange dynamics well described by models ... but predicting sputtering for ITER not yet possible
- Resolving T_i missing in both experiment and modelling
- Various (dimensional) models can address different questions
- Blob generation not understood
- *Blob is an atom of edge tokamak plasma turbulence*
- ESEL – recent progress & outlook
  - Joining with SOLF1D yields Ti & parallel dynamics. 100CPUweeks/run
  - Minor Problem: energy not well conserved => BESEL
  - Problem: simple || dynamics & boundaries => 3D DiESEL [Nielsen EU-US'08]
  - Problem: until T_i (FLR) resolved, no PWI prediction possible => GESEL