The X-divertor and recent experiments

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Heat Exhaust problem-Advanced divertors

- **The heat exhaust problem for burning plasma devices is a critical challenge for magnetic fusion which must be solved**
- **Over the past decade, *advanced divertors*- novel magnetic geometries - have been devised theoretically to solve this problem**
  - X-divertor (2004)
  - Snowflake divertor (2007)
  - Super-X divertor (2007)
  - "Asymmetric" snowflakes (2010)
- **We have, thankfully, reached the stage where experimental investigation of advanced divertors is progressing rapidly**
  - **TCV, NSTX, DIII-D**, in the near future **MAST**, possibly **EAST**, …
- **Particularly in the light of ongoing experimental progress, it is time to take stock, and examine the various geometries, and clarify the important underlying physics**

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Outline and Scope of this talk

1. A brief description of the first advanced divertor types, with salient features, from the Texas perspective

2. By focusing on the magnetic field in the plasma SOL where power is exhausted, a categorization scheme is proposed that, we suggest, is most appropriate for understanding physical behavior, and extrapolating to future devices

3. We compare this to very different perspective, based on a global analysis of vacuum fields, proposed by D. Ryutov in 2010 (R2010)

4. We describe how the magnetic field structure in the exhaust SOL could effect the behavior of a fully detached plasma

- This talk is restricted to discussing only divertor action- other effects, however important, of advanced divertor geometries on the pedestal/edge/core plasma are outside the scope of this talk.

Advanced divertors: Texas Perspective

- **Advanced divertors modify the physics of the SOL by changing the *magnetic field* *in the region where power is exhausted.* The magnetic field in the SOL, then, is the primary determinant of divertor action**

- **Combined with the well-known properties of the magnetic fields :**

  - **Inside a closed plasma region, one can create identical, or virtually identical, magnetic field in an infinity of ways**

  - **The field outside this region, and coils to create it are not unique**

One concludes that properties of fields outside the plasma region are not good labels to characterize plasma behavior- the mapping is many to one

- ***To understand divertor action, therefore, we must focus only on the magnetic field in the SOL :***

  - **To clarify the physics of the different divertor configurations, and to avoid confusion that is bound to result from specifying configurations in arbitrarily different ways**

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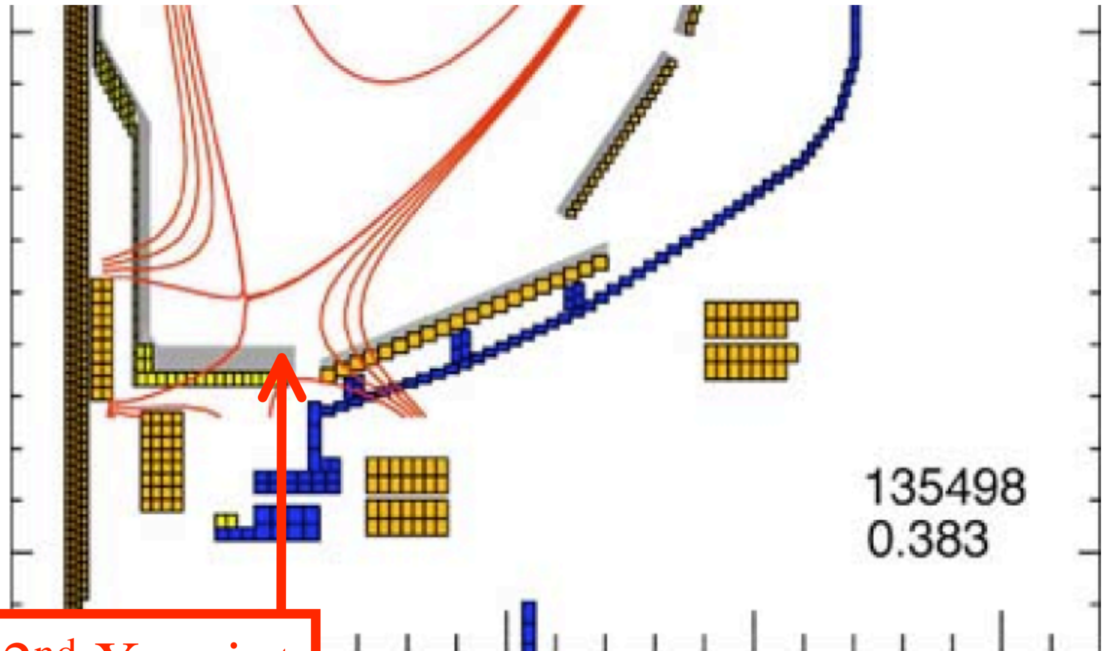
Realization of Advanced divertors on NSTX

NSTX experiment – 2009-2010



Strongly reduced heat flux on the plate

Strongly increased flux expansion and line length

Separation, normalized by a, between X-points (2009-2010) S_X~0.24 - 0.42

Kudos to the impressive success of the theory (led by Ryutov) and experimental (NSTX group) collaboration

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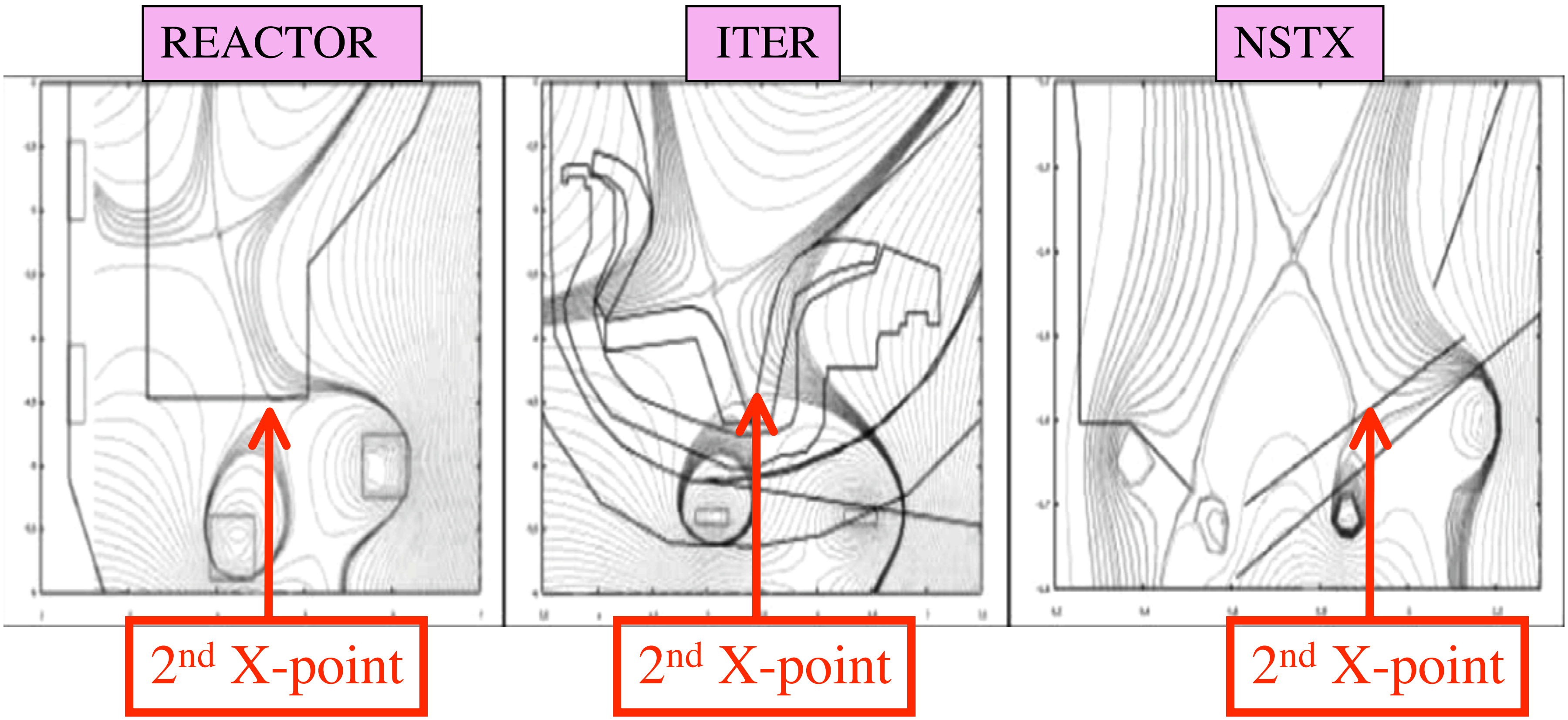
In 2004 - X-divertor (XD)

Introduced the concept of adding a second X-point to the divertor region for the first time



General prescription given, **for any** S_X – **no restrictions**

XD figures 2004-2007 : $S_X \sim 0.46\text{-}1.00$

Defining features of XD

Direct quotes from the abstract of 2004 paper:

“a novel magnetic divertor geometry is presented:

inducing a second axi-symmetric X-point downstream of main plasma X-point…

Field line lengths from the core X-point to the wall can be increased …, and

Flux expansion can be increased…“

With the predictions:

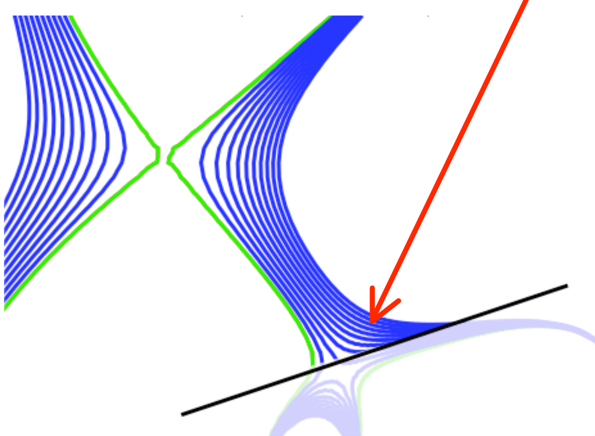
“greatly reduced heat flux on plate, ...”

higher level of acceptable detachment

Unique geometrical change for X-divertors *in the SOL plasma region*

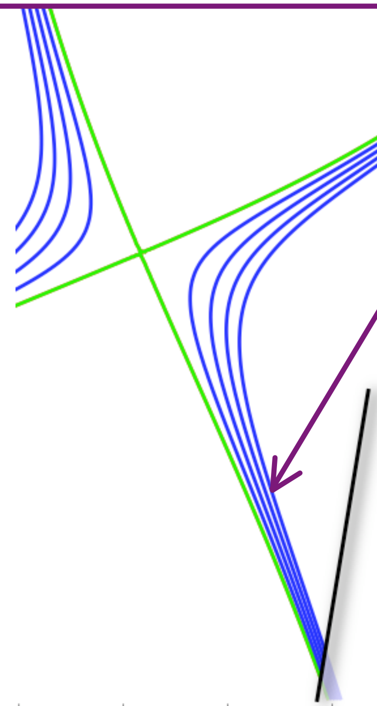
2004 X-divertor:

Flared SOL as the plate is approached-SOL gets fattened



Standard divertor

Contracting SOL as the plate is approached-SOL gets thinner

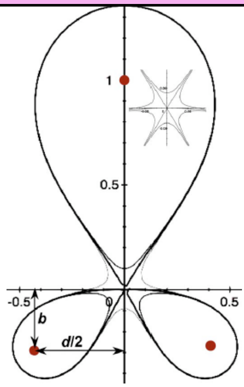


As a result of adding a 2nd *X-point* ***downstream in the SOL***, flux expansion increases downstream as lines approach the divertor

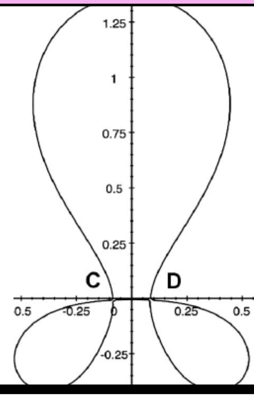
The Snowflake makes its debut in 2007

Introduces an exact or approximate second order null at the core X-point.

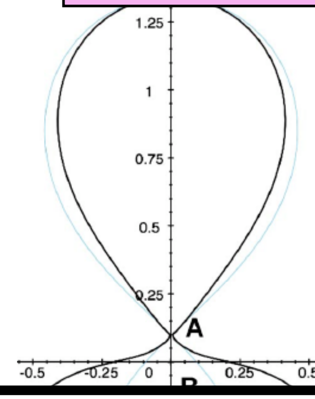
"Snowflake"



"Snowflake minus"

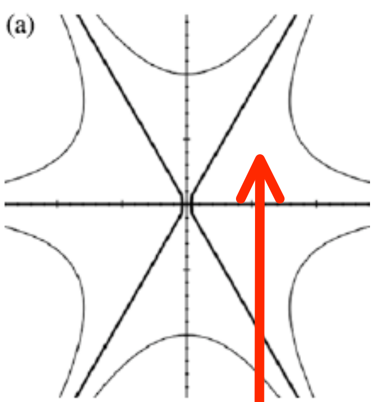


"Snowflake plus"



Greatly enhances flux expansion near the core X-point (and line length). S_X~0.37

(a)



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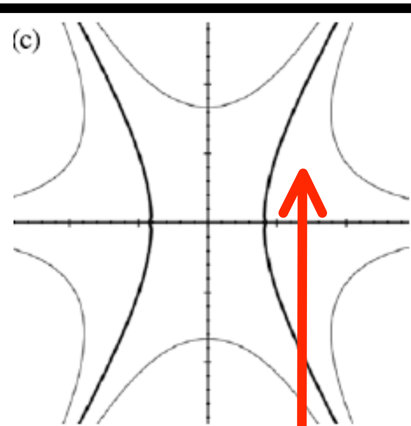

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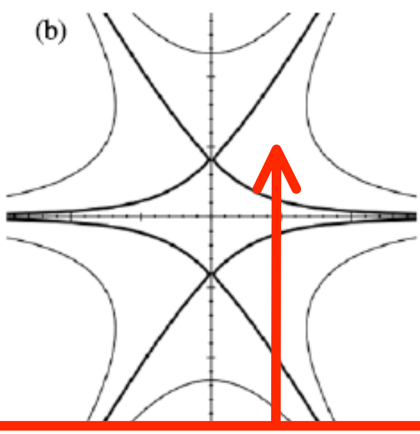

SOL contracts even more strongly that SD as one goes away from main X-point

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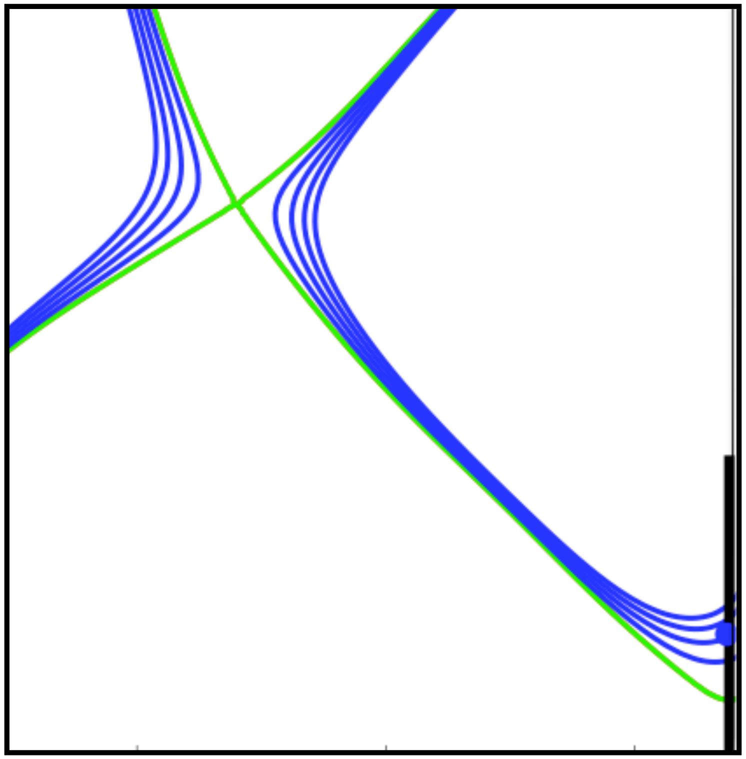
Super X divertor (SXD) also makes its debut in 2007

"Super" denotes a greatly increased separation between X-points: S_X ~ 1- 2

Large S_X so that major radius of the strike point is increased-

SXD is a *superposition* of toroidal and poloidal SOL expansion

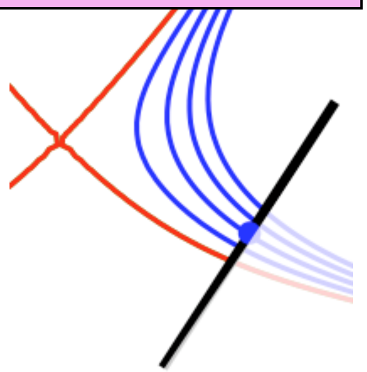


Large S_X: the specified domain of SXD, <u>never</u> of XD

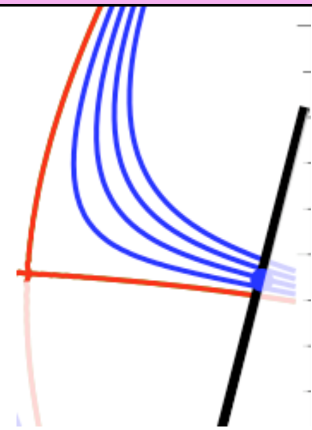
XD papers and talks never restricted the values of S_X

Close—up of flux surfaces pre-2010 (theory and experiment)

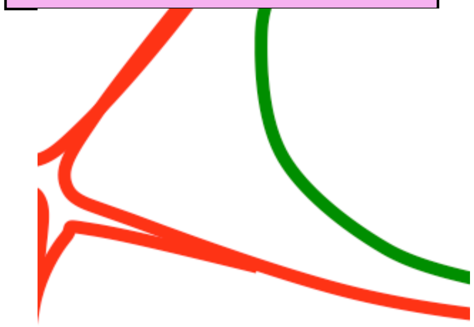
“Snowflake plus”



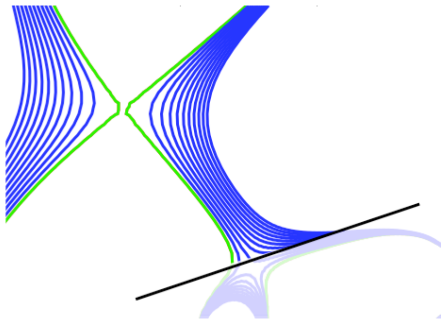
“Snowflake minus”



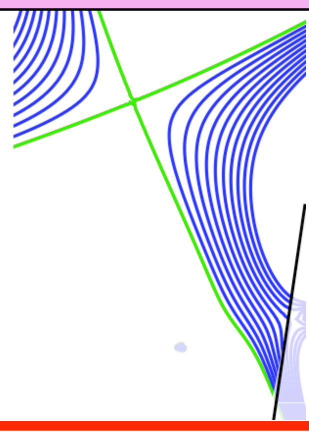
2008 TCV



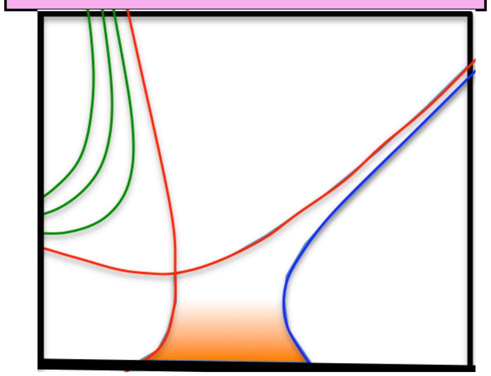
“XD”-NSTX



“XD”- ITER



2009 NSTX

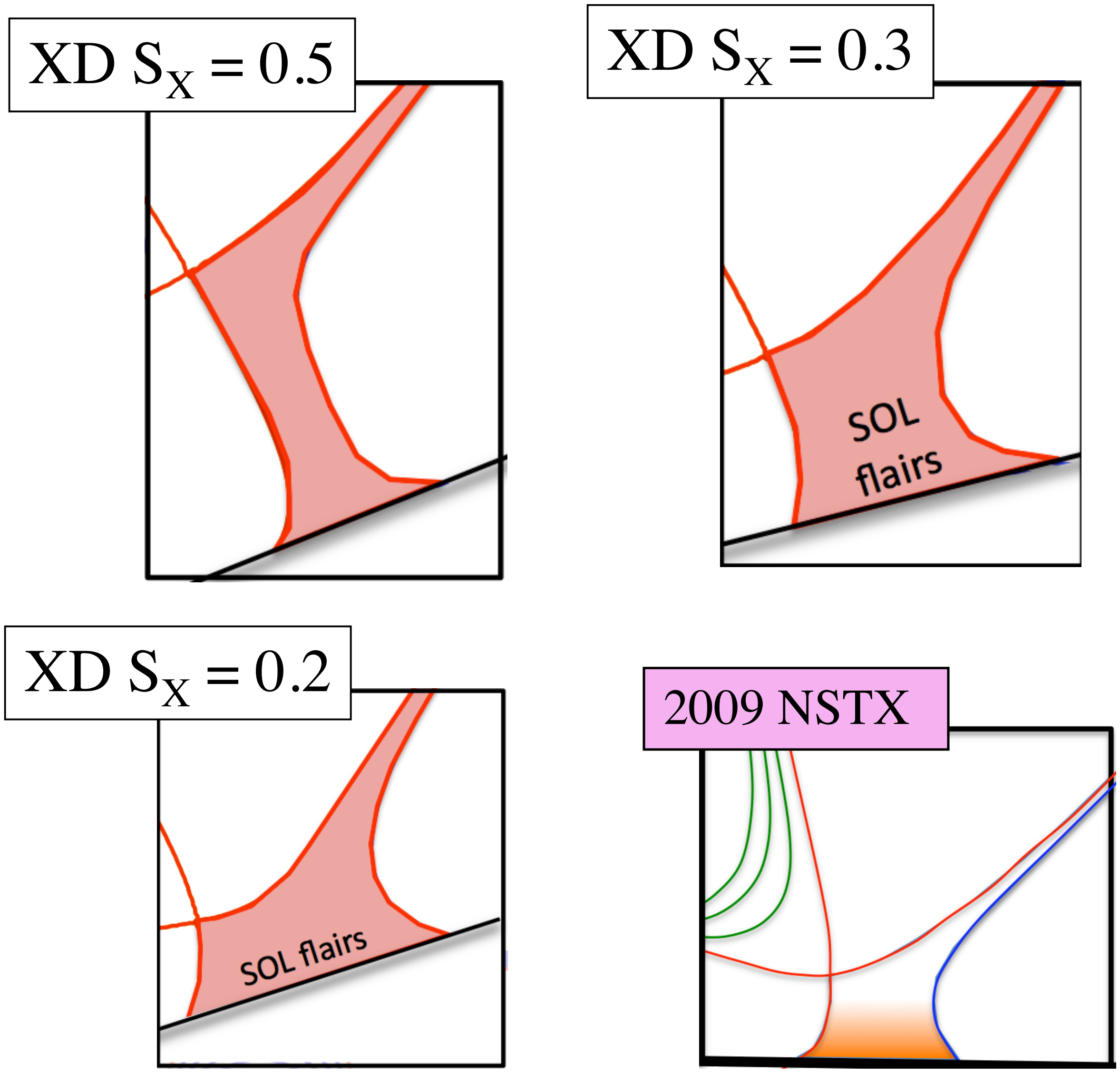


When successful NSTX experiments were first presented, there was no published snowflake category to describe them. NSTX behavior was predicted in 2004.

Trivial changes can extend XD examples to the range S_X ~ 0.2 (or below)

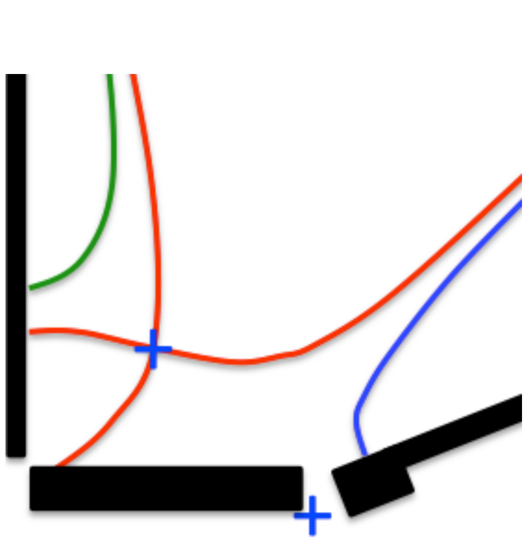
- **Trivial: change in dipole currents to make S_X ~ 0.2**
- **In 2004, there was no way to know that 2009 experiments would have S_X ~ 0.24-0.42**
- **We published a general method for making XDs by inducing an X-point downstream**

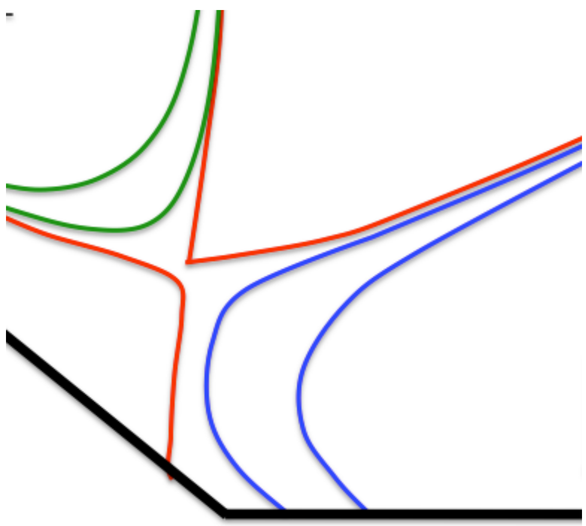
No significant change at S_X ~ 0.2 - the prescription has no limitation on S_X



Expanding experimental progress

NSTX 2010	DIII-D	MAST





SXD 2015

Theoretical frameworks must keep up
Need better metrics for experimental comparison and extrapolation to fusion devices

XD and the SFDs

- **Before 2009, XD and the SFD were independent theoretical alternatives**

- **XD strategy: flare the filed lines in the vicinity of the divertor plate (end of the SOL) by introducing a second Xpoint downstream in SOL.**

- **SFD strategy: 1) Modify the main X-point – in fact replace it with a second order null, 2) split the second order null into two first order nulls, placed strategically and close so the advantages of the double null remain, while curing it's main drawback- topological instability.**

One would think that these two categories should be distinguishable with finite effort.

Instead we have two independent classification schemes with an essential tension

Classification, based on physics, is of essence. XD and SFD, as we will see, imply different physics

Classification of Divertors

Two classification schemes will be discussed

Texas Scheme **TSOL**

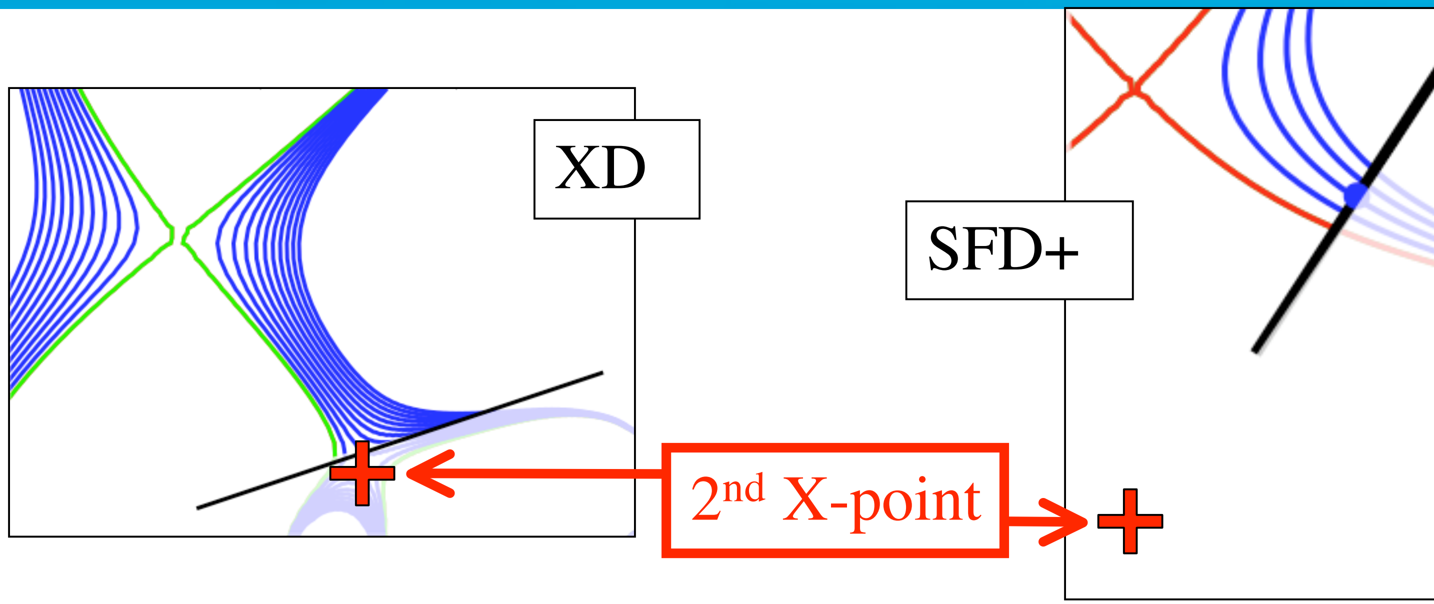
Based on the SOL dominated perspective (slide 4)

Snowflake Scheme of 2010 **R1020**

Based on the analysis of vacuum magnetic field

Then, we will describe how the new magnetic geometry of advanced divertors could affect detachment behavior

X-point position *by itself* does not determine divertor magnetic structure



- **Notice: in both cases, the X-point is outside the SOL plasma where power is exhausted (and this is typical)**

- **The SOL plasma only knows about the B field in the SOL**

The X-point position has no intrinsic significance – it is relevant only by its effect on the field structure in the exhaust SOL

- **We should characterize advanced divertors based on the field in the exhaust SOL**

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TSOL
Divertor characterization via the magnetic structure in the SOL where power is exhausted?

- We began by posing the question: What is the “best” way to characterize the divertor geometry ?

- There seems to be a natural answer- Follow the method used to characterize the magnetic field structure of the core plasma

- We will do precisely that to “study” the exhaust SOL plasma

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A Lesson from: how do we characterize the magnetic geometry of the core?

- **The *shape* of the boundary flux surfaces is ubiquitously employed to describe the gross core geometry**
  - Elongation, triangularity, squareness, etc.
  - Obviously, this depends on the magnetic field **in the plasma**
- **Example- "similarity" experiments on JET, DIII-D, Alcator C-mod, ASDEX-U, etc.**
  - Virtually identical shapes, regarded as effectively identical
  - There are small differences, but the gross characteristics, which are most important, are the same
- **The PF coils are very different in these devices, so the fields outside the plasma boundary become very different**

Only the fields in the plasma matter

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Characterizing advanced divertors by the shape of exhaust SOL flux surfaces (1)

- **“Common sense” analogy with the approach used for the main plasma would compel us to**
- **Use the shape of flux surfaces in the relevant SOL - the region where power is exhausted – to characterize divertors**

The SOL shape indicates the variation of B_{pol} in the region of the exhaust plasma SOL

- **In fact, the SOL thickness is a perpendicular cord average of B_{pol}**

The structure of B_{pol} in the exhaust SOL is the essence of an advanced divertor

- **Note- to implement this in practice-** could map SOL lines from an upstream width (estimated per Goldston?),or, map the measured divertor heat footprint upstream

Characterize advanced divertors by the shape of SOL flux surfaces (2)

Let us further pursue the analogy with core plasma shape

- **A circular core plasma is considered the "paradigmatic" case**
- **Shaping is defined by deviations from it**
  - The "lowest order moment" is elongation- can go toward either
    - elongated (higher vertical extension)
    - oblate (lower vertical extension)
    - important properties vary oppositely with this (MHD stability, etc.)

- **What is the analogue to the "paradigmatic case" and "lowest order moments" for the exhaust SOL?**

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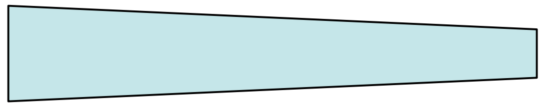
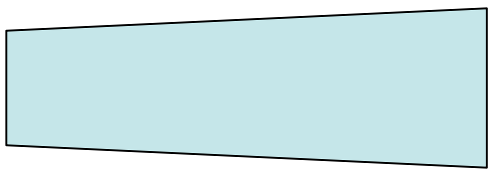
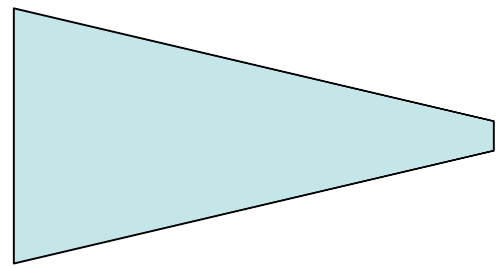
Characterize advanced divertors by the shape of SOL flux surfaces (3)

- **Paradigmatic case: standard divertor with a simple X-point**



- **The "lowest order moment" that can distinguish an SOL shape from some example of the paradigmatic case is**

- **This**  **verses this:** 

- **i.e., along SOL path to the divertor plate:**
  - SOL flux expansion becoming larger than a standard divertor
  - SOL flux expansion becoming smaller than a standard divertor

The XD and the SFD (2007-2008): diametrically opposite modifications of SOL flux surfaces

Relative to a standard divertor:

•XD-like- flux expansion increases toward the plate, since an X-point is induced "downstream" (e.g. near the plate)

•SFD-like- flux expansion increases toward the the core X-point, due to the creation of a (perhaps approximate) 2nd order null. Away from the null, flux expansion decreases

THIS WILL BE OUR PHYSICS BASED METRIC TO CHARACTERIZE ADVANCED DIVERTORS

–We'll describe in more detail how to implement this metric

–Then, we'll compare it to the scheme of Ryutov introduced in 2010

–Then, we'll describe how behavior of full detachment is modified in advanced divertor- in opposite ways for the XD and the SFD

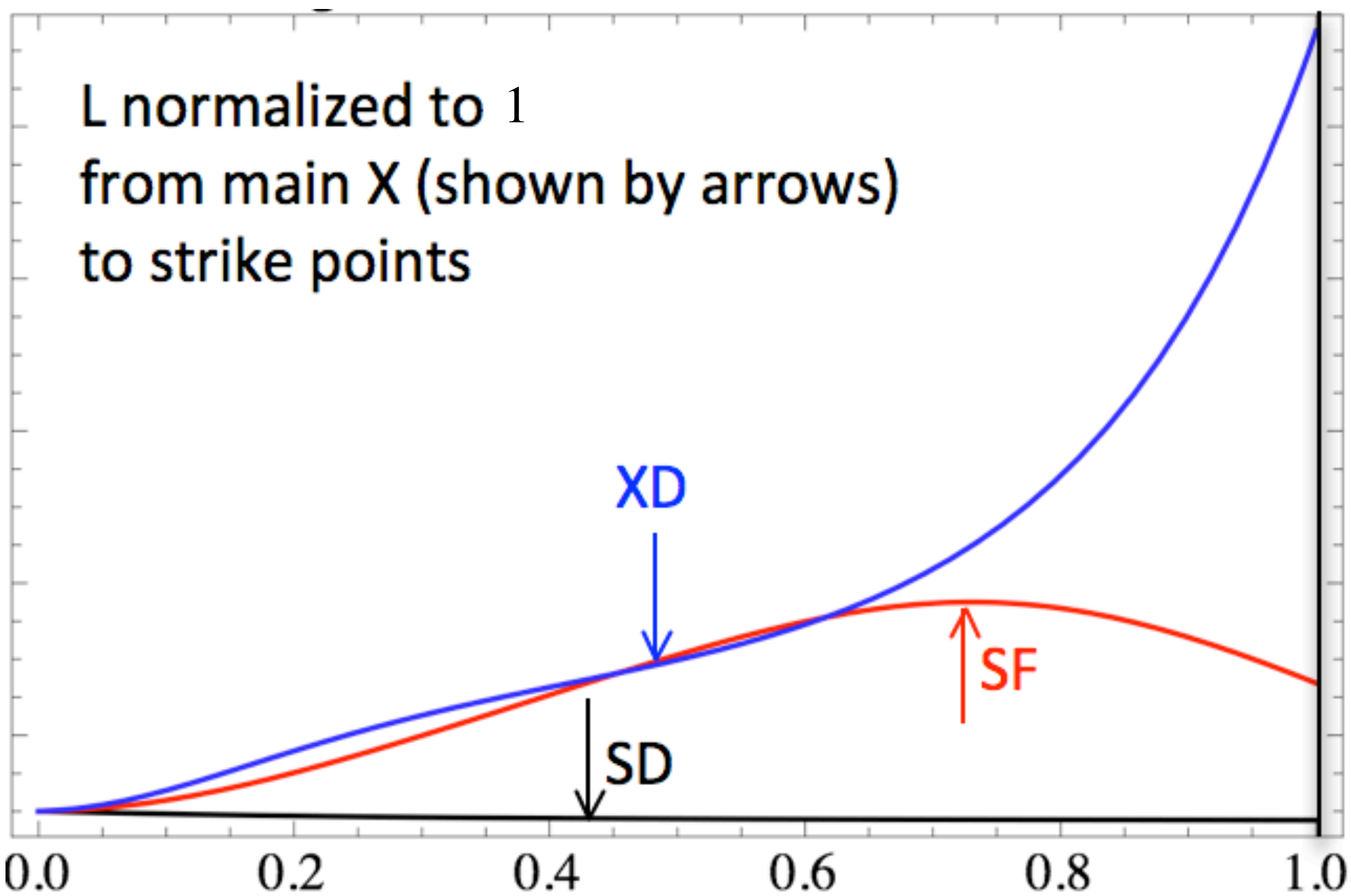
A visual discriminating metric

- **Pick a field line in the center of the SOL**
  - **either mapped downstream from midplane using a formula like Rob Goldston's,**
  - **Or mapped upstream from the plate using measurements**

- **Local flux expansion is $1/B_{pol}$**
- **For a standard divertor, $1/B_{pol} \sim 1/d$, the distance from the main plasma X-point**

- **Plot d/B_{pol} - in the region of the exhaust SOL (between the main plate and the main plasma), note if this is**
  - **Increasing-flared field lines relative to standard divertor- XD like**
  - **Decreasing- contracting field lines relative to standard divertor- SFD like**

Delineating the Differences



Normalized distance along SOL field line

Interval

Essential elements of the TSOL have been spelled out

Now we will outline the elements of the Snowflake classification R2010

The Broadened class of snowflakes introduced after the 2009 NSTX experiments

- **2010 paper (R2010):**

Considered geometries where there are 2 X-points-

a main plasma X-point and an additional X-point

  - Varied the angle between the X-points over the entire range possible
  - Considered distances between X-points smaller than minor radius, to justify Taylor expanding the magnetic field in the SOL, which can be taken as a vacuum field
  - Showed that the Taylor expansion of the vacuum field, at distances large compared to the distance between X-points, has a snowflake-like character
  - Specifically, the flux function has a six sided “snowflake-like” character at large distances

THE POSITION OF THE DIVERTOR PLATE, OR LOCATION AND SHAPE OF SOL PLASMA, IS NOT MENTIONED

R2010 defines the X-divertor as a type of snowflake (an "asymmetric snowflake minus")

- *All configurations with an X-point in any angular location are labeled snowflakes*

The 2004 X-divertor introduced the concept of "inducing a 2^{nd} …X-point..downstream"

Since all X-divertor configurations (for sufficiently close X-points) will necessarily correspond to some angle

All XD configurations are now labeled snowflakes

Thus R2010 eliminates a category invented and elaborated six years before the paper was written (after 2009 experiments)

Let us now examine what TSOL has to say on this subject

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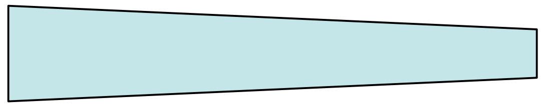
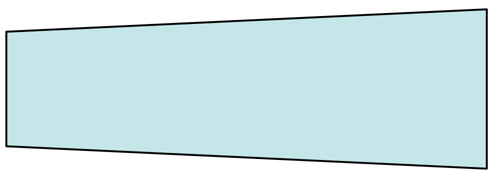
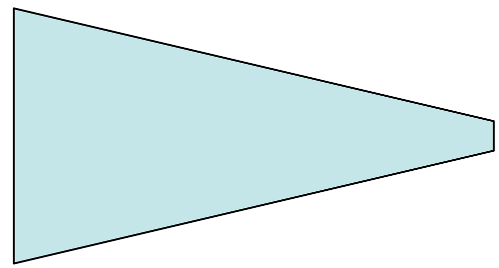
Characterize advanced divertors by the shape of SOL flux surfaces (3)

- **Paradigmatic case: standard divertor with a simple X-point**



- **The "lowest order moment" that can distinguish an SOL shape from some example of the paradigmatic case is**

- **This**  **verses this:** 

- **i.e., along SOL path to the divertor plate:**
  - SOL flux expansion becoming larger than a standard divertor
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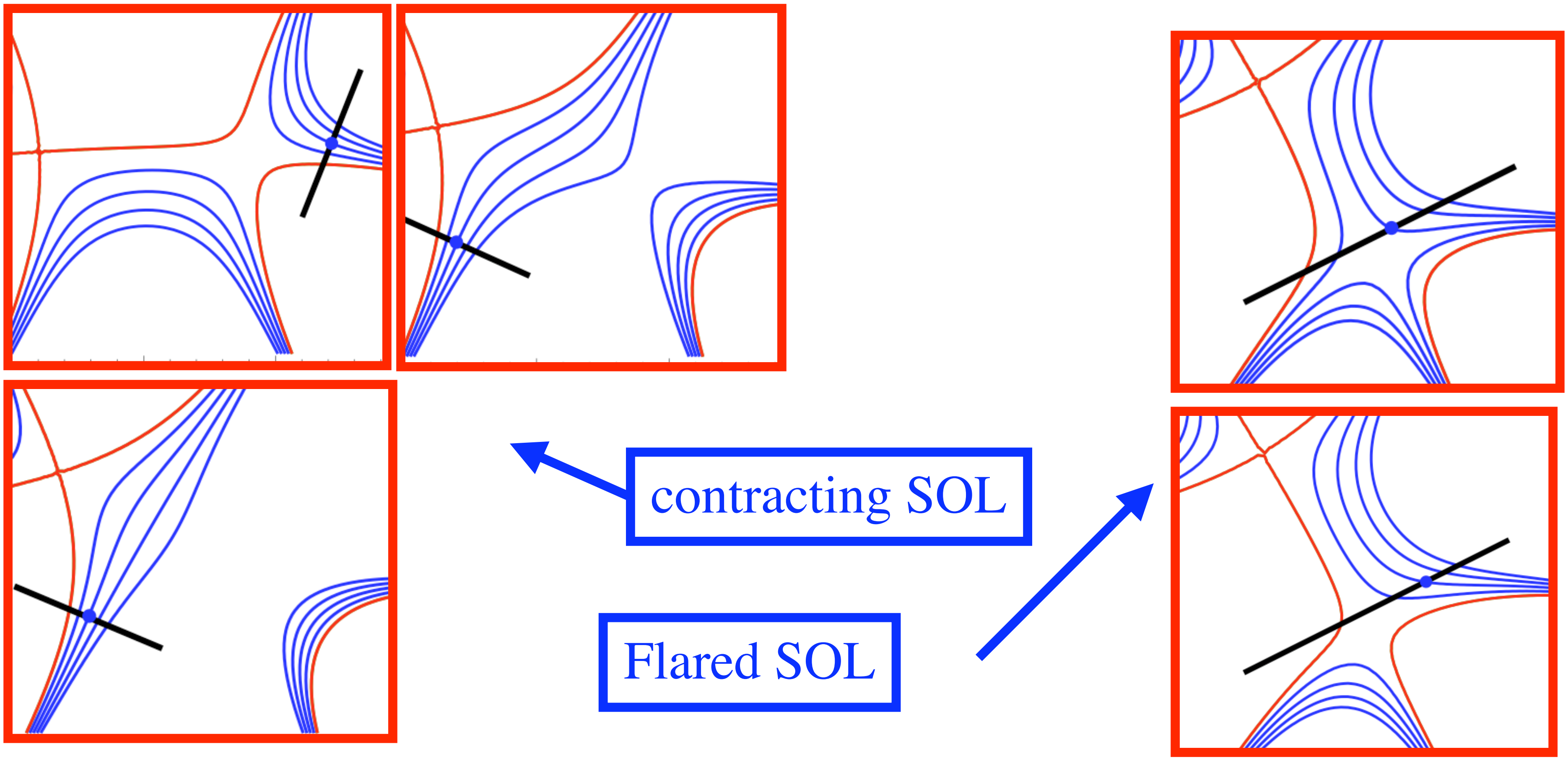
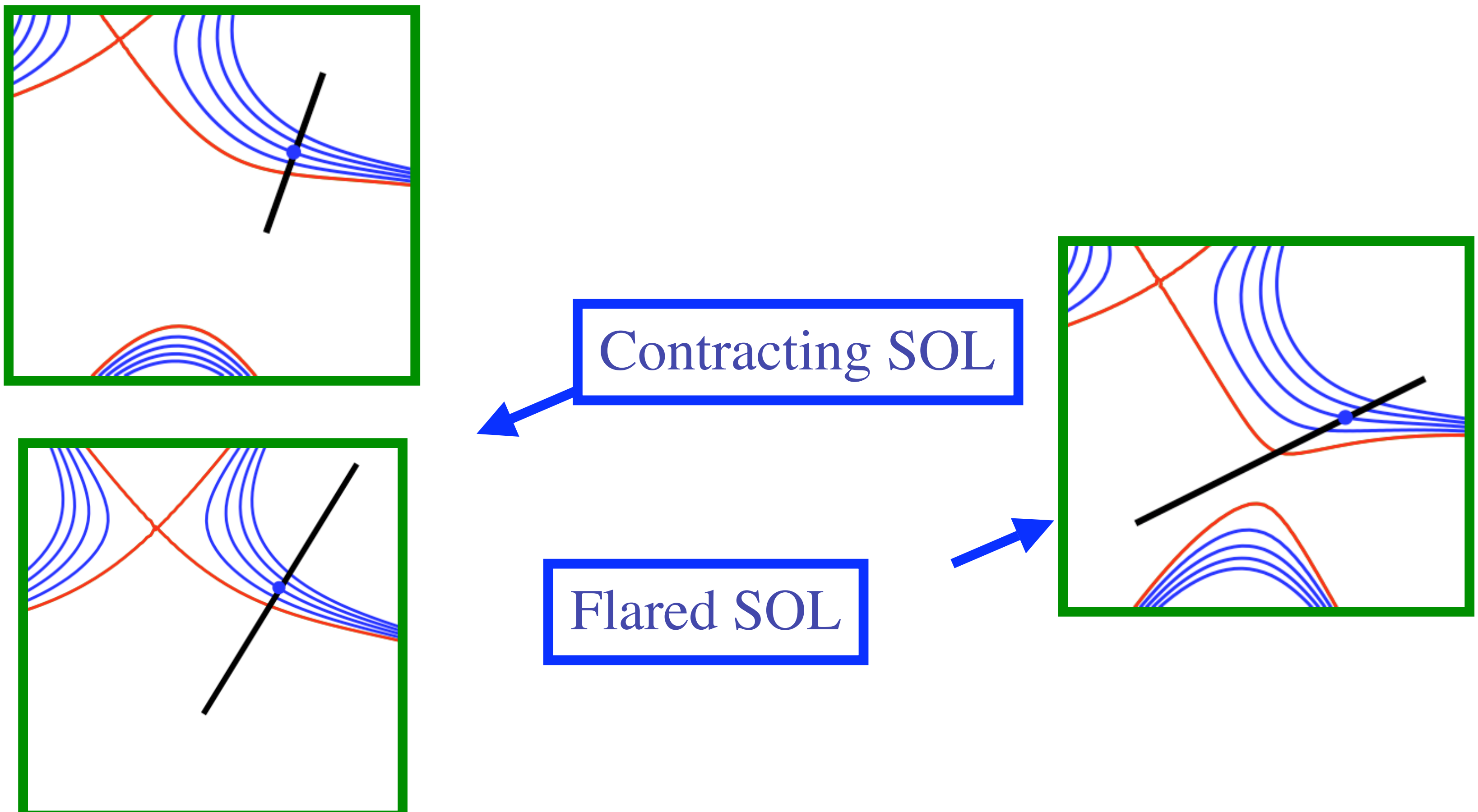
Samples from R2010 classification
"asymmetric SF minus"



The same category mixes together different SOL shapes: flared and contracting- modifications of the B_{pol} structure, relative to a standard divertor, in opposite directions

Samples from R2010 classification "asymmetric SF plus"



The same category mixes together different SOL shapes: flared and contracting- modifications of the B_{pol} structure, relative to a standard divertor, in opposite directions

R2010 does not reflect SOL differences

- **Categorizations based on X-point positions outside the plasma do not correlate with SOL field structure**

Very different B_{pol} structures in the SOL are named the same thing

- **There are, however, *more fundamental* problems with characterizing divertors via magnetic fields outside the SOL**

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The fundamental problem with categorization in terms of vacuum fields outside the plasma SOL

An infinite number of current distributions outside a region generate the same magnetic fields inside a region

Categorizing fields in the plasma by the currents and fields well outside the plasma is profoundly ill-posed and arbitrary

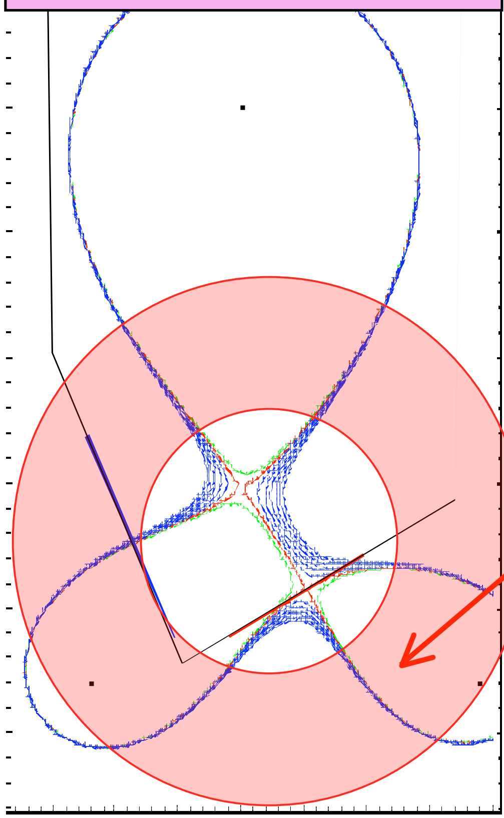
- This is why the main plasma configurations are categorized by parameters in the physically relevant region of the plasma

Divertor plasma configurations must be categorized under the same guidelines to avoid being fundamentally ill-posed and arbitrary

Examples follow

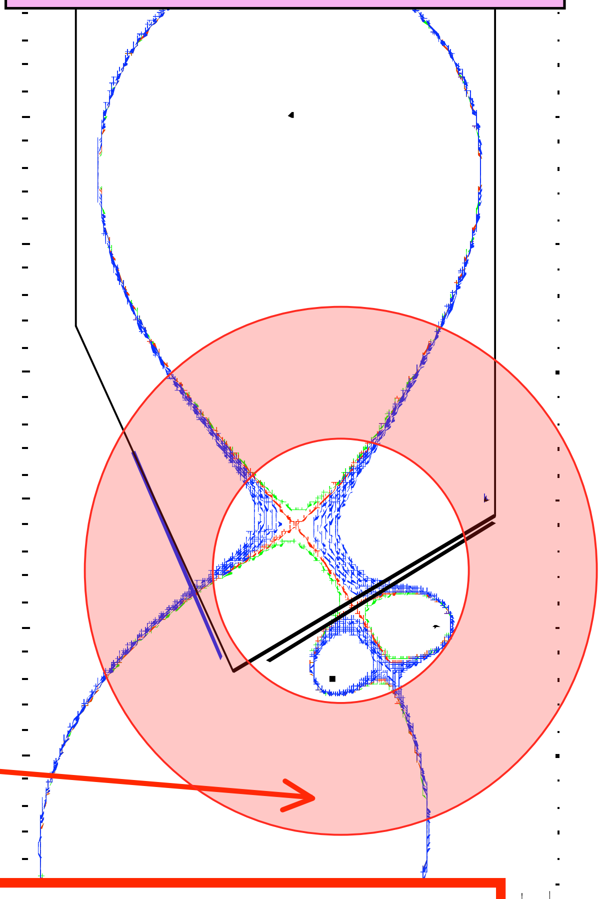
Why should the magnetic field behind the plate matter?

"Asymmetric snowflake minus"



Asymptotic region far from 2 Xpts: 6 lobed "snowflake"- BEHIND PLATE

XD- made from dipole coils like 2004



Asymptotic region- no snowflake

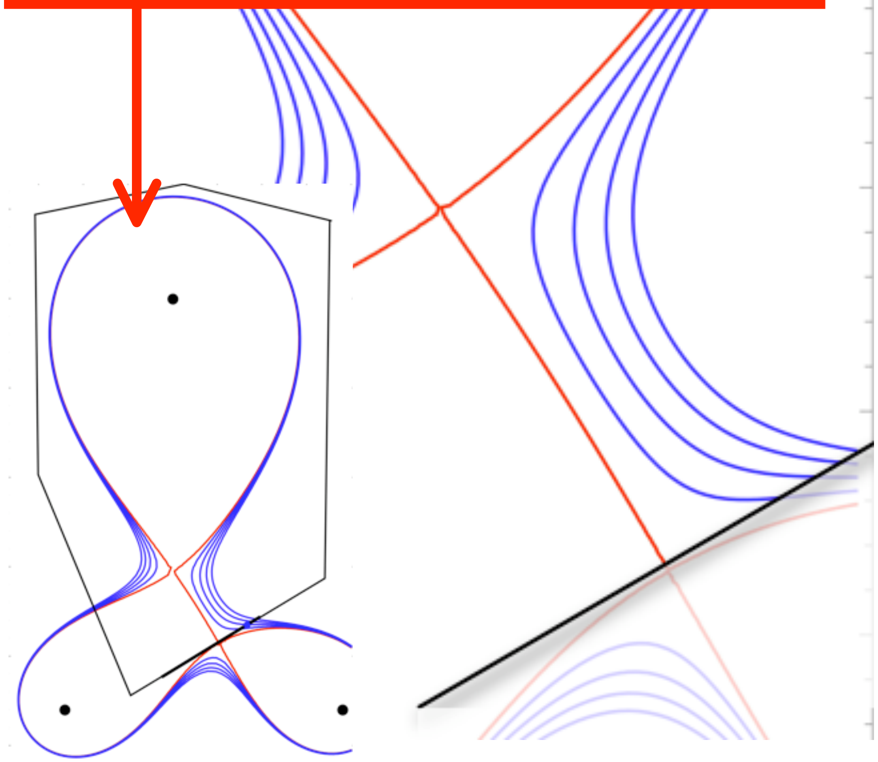
Magnetic Field:

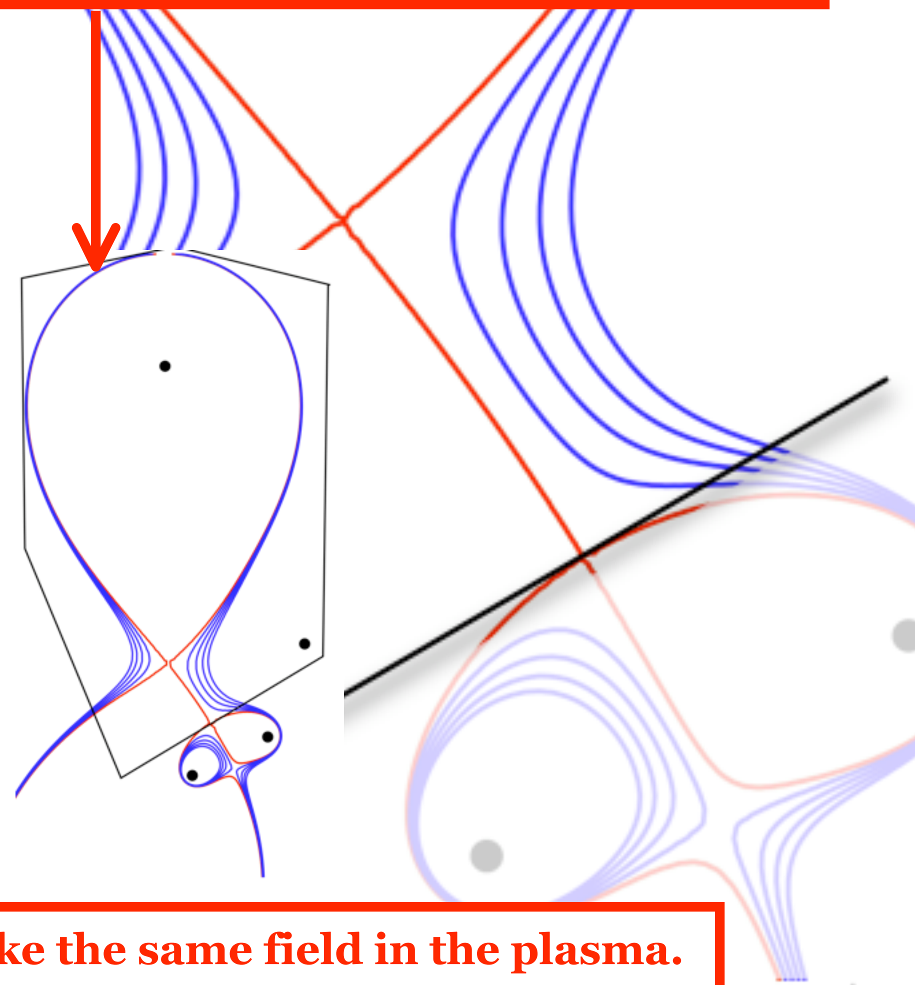
Same <u>in the plasma SOL region.</u> Very different outside the plasma.

X-divertors and “asymmetric snowflake minus”
Close-ups indistinguishable in the plasma region

Asymmetric snowflake minus
Made with coils as in R2010

XD made with coils as in 2004





Different coil configurations make the same field in the plasma.
Particular coil configuration irrelevant.

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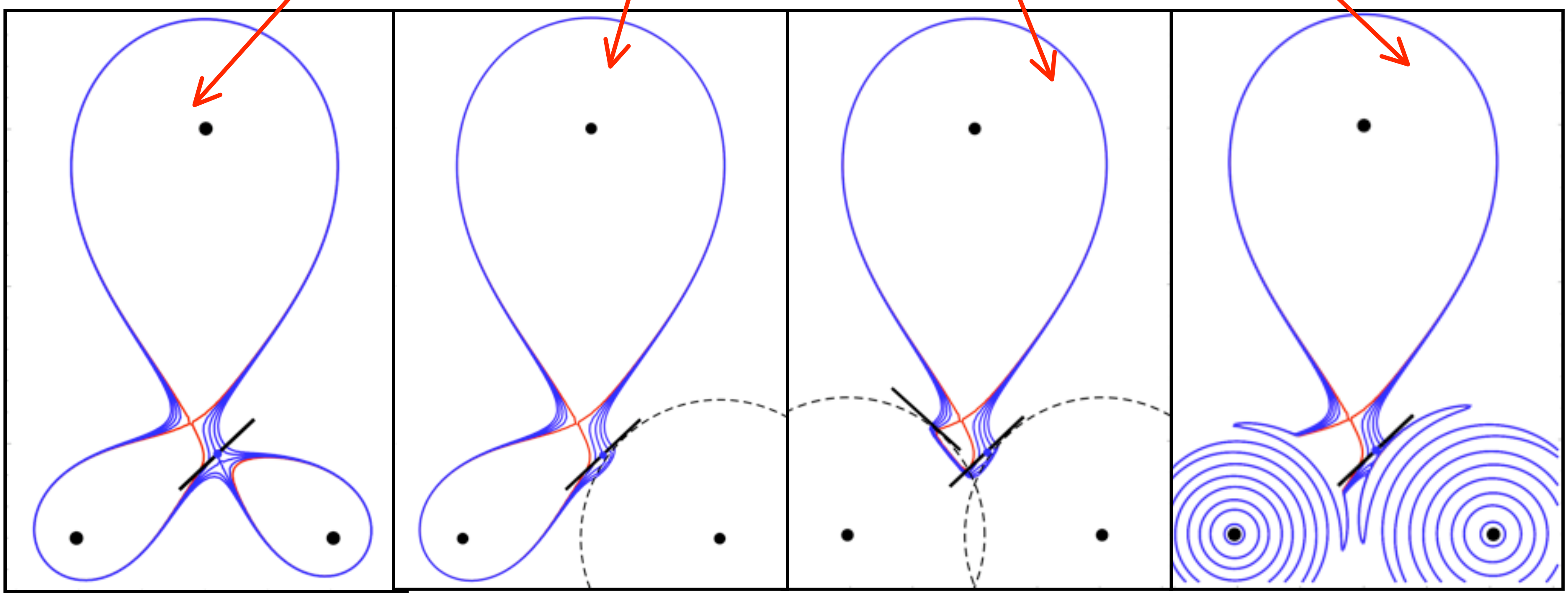
Example: for point current models *IDENTICAL* magnetic fields can be generated by finite radius coils with a arbitrary radial current distribution

Magnetic field inside the physical region is **IDENTICALLY EQUAL**

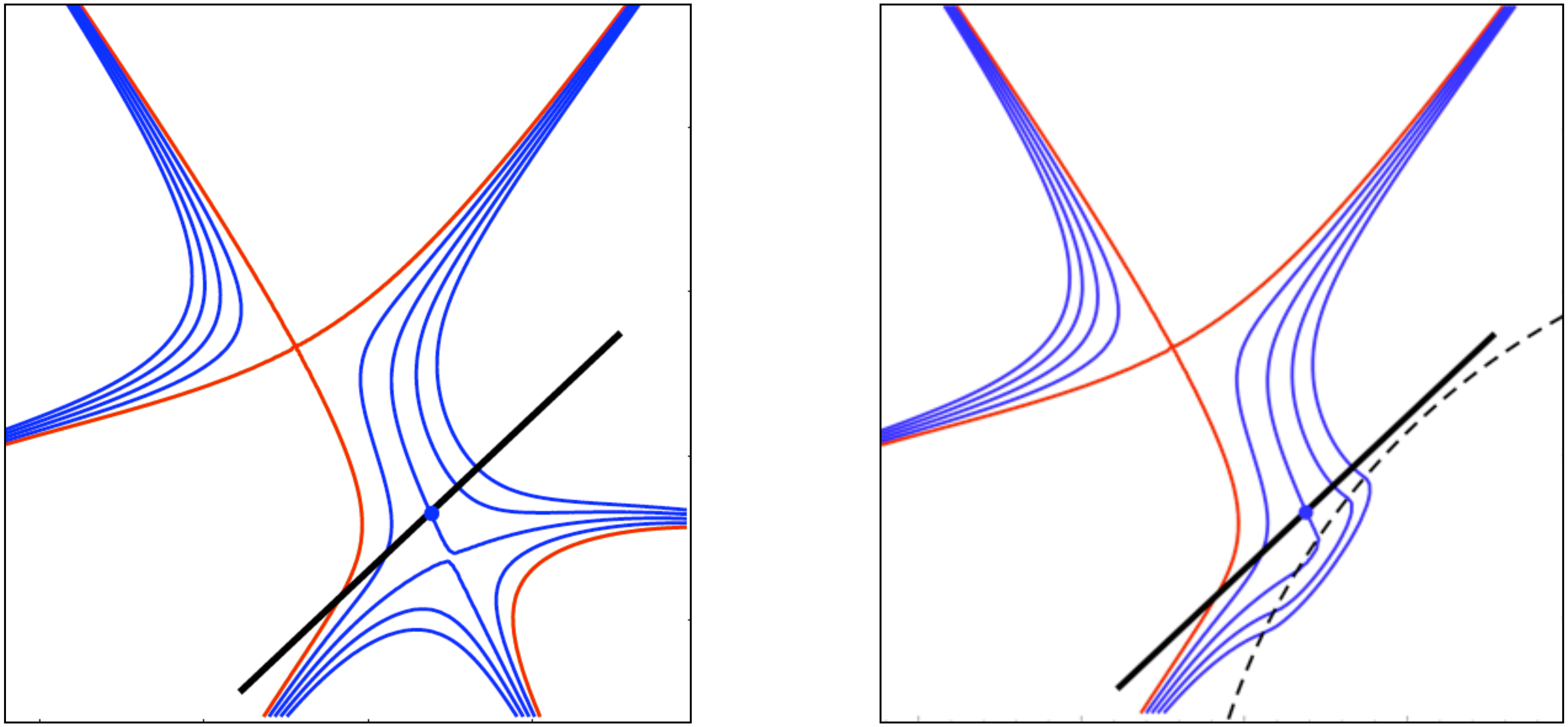


Magnetic field outside the plasma region varies hugely, unlike physical region

NO snowflake structure- the snowflake structure is physically irrelevant

The X-point behind the divertor plate is ALSO physically irrelevant: identical plasma fields can be made with NO X-point

Magnetic field inside the physical region is **IDENTICALLY EQUAL**



X-point distance cannot be a fundamental factor in characterizations
One must classify configurations based on the magnetic structure of the exhaust SOL

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Extrapolating to reactors

- Extrapolation to future devices must be done on the basis of the physics determining divertor action
- Metrics based on the relevant physics are essential
- This process starts with a classification scheme based on the relevant physics
- One aspect of extrapolating to a fusion reactor is:

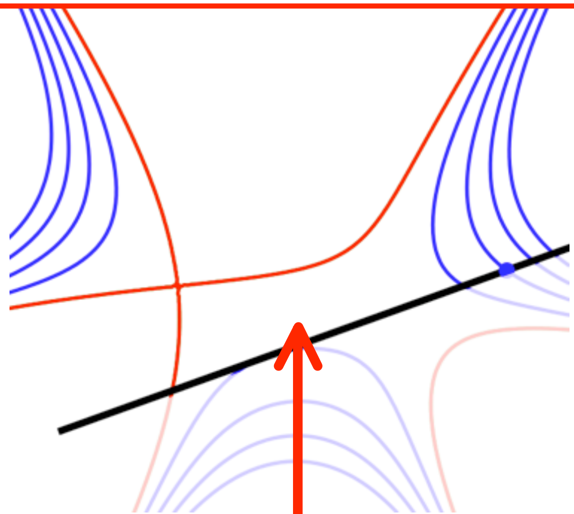
The ratio of SOL width to minor radius is smaller by an order of magnitude compared to present devises

Extrapolation methods based on vacuum field structure, rather than the field in the SOL, will encounter severe extrapolation errors in such cases

Same magnetic field can have either high flux expansion or low flux expansion- depending on the SOL width Δ

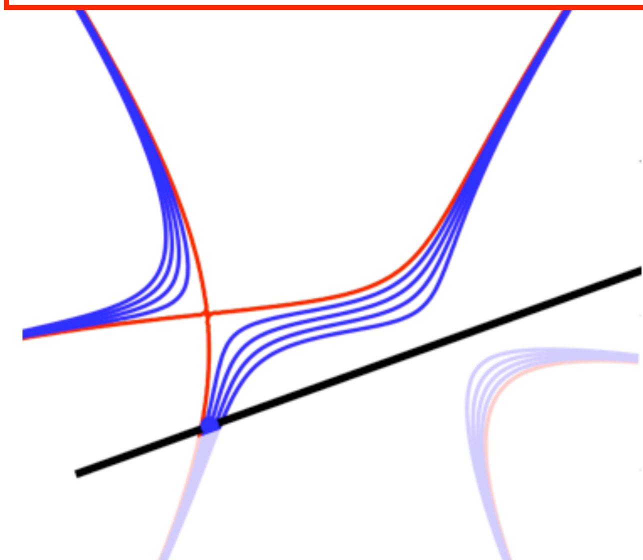
Keeping the magnetic configuration exactly the same- change only Δ

$\Delta/a \sim .01$



SOL behaves like X-divertor

$\Delta/a \sim .001$



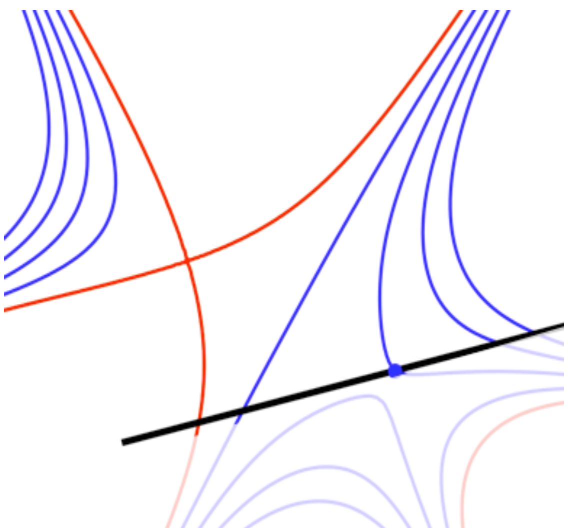
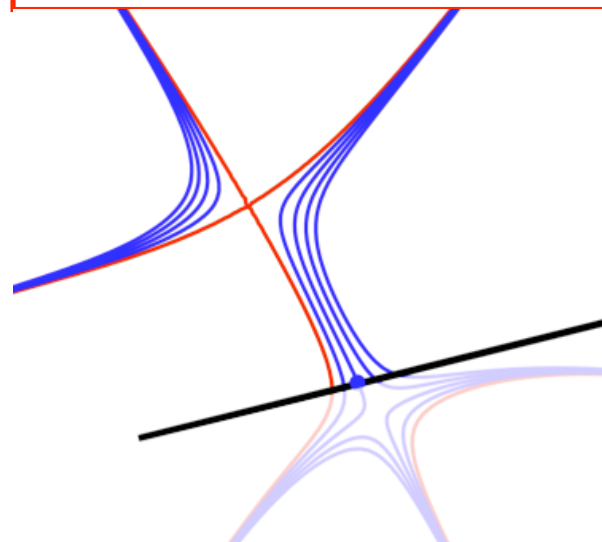
SOL behaves like standard divertor

Merely specifying the vacuum field does enable an extrapolation of the physical effect

★IFS

The same flux expansion can be maintained, but only by changing the magnetic field to follow the changing the SOL width Δ

Keeping the magnetic configuration exactly the same- change only Δ

$\Delta/a \sim .01$	$\Delta/a \sim .001$
	

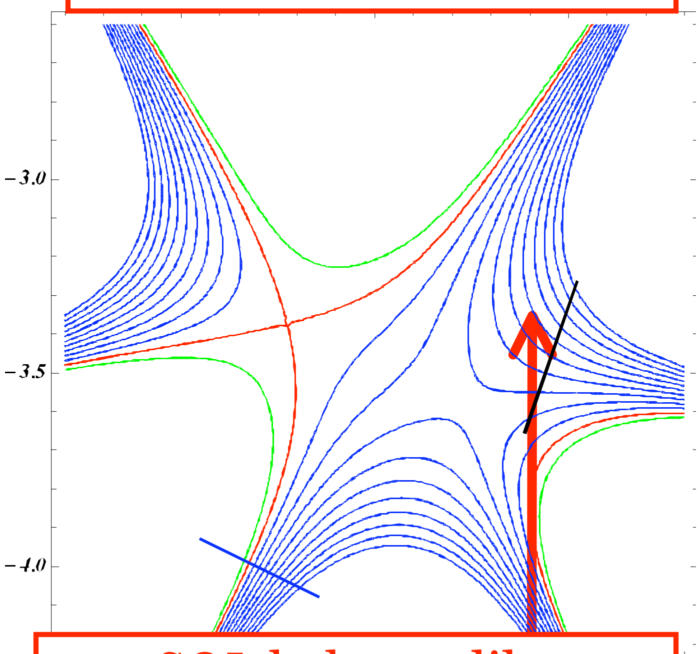
Flux expansion is kept constant by changing the position of maximum field line flaring to track the SOL footprint

Specifying the field in the SOL is the key to obtaining the desired physical effect

An asymmetric snowflake minus can behave either as a snowflake minus or as a standard divertor- depending on SOL width

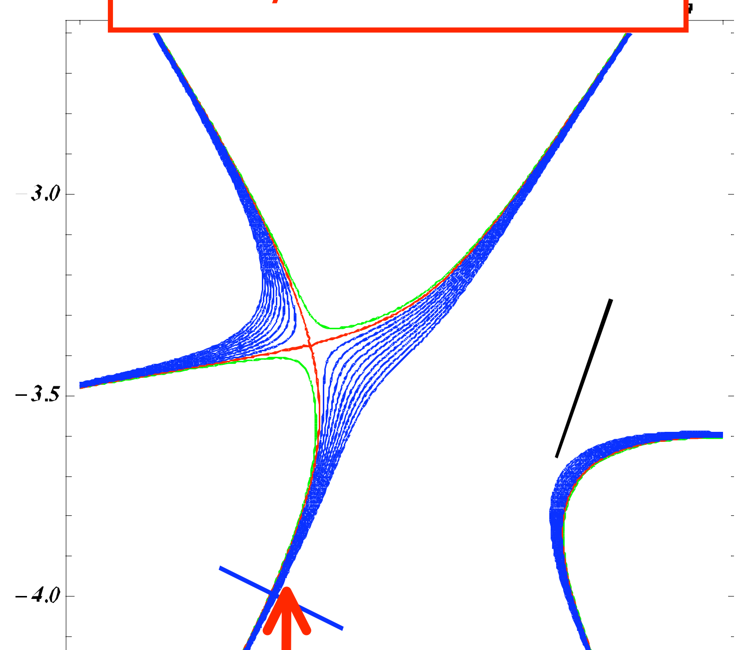
Keeping the magnetic configuration exactly the same- change only Δ

$\Delta/a \sim .01$



SOL behaves like snowflake minus

$\Delta/a \sim .001$



SOL behaves like standard divertor

Merely specifying the vacuum field does enable an extrapolation of the physical effect

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Summarizing the critique of R2010

- The 2010 attempt to categorize X-divertors as a form of snowflake (asymmetric snowflake minus) is unjustified since it is based on to arbitrary mathematical properties without physical relevance
  - the character of the vacuum magnetic field outside the SOL- including **behind the divertor plate-** which is demonstrably **ill posed and arbitrary**
  - **Positions of X-points that are also typically behind the plate- also ill posed**
  - **Different B_{pol} structures - modifications from the standard divertor in opposite directions- are grouped together** in the categories “asymmetric snowflake minus” and “asymmetric snowflake plus” - hence they **do not express salient physical properties**

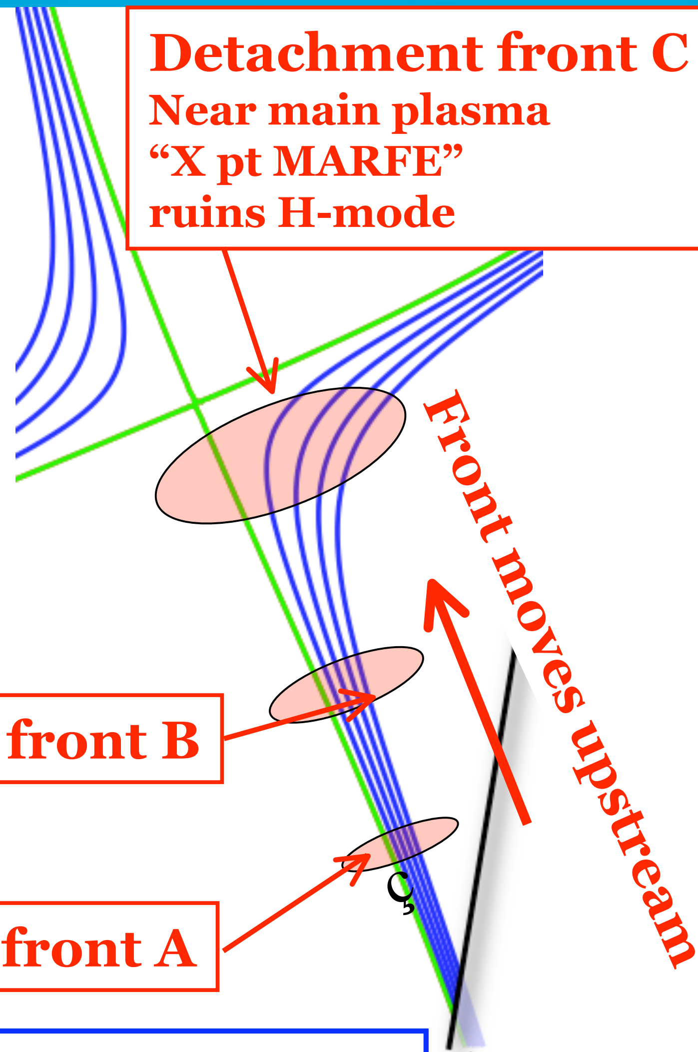
According to *physically relevant* characteristics, the experimental configurations on NSTX and DIII-D are X-divertors

Full detachment

- **Detachment fronts in standard divertors are observed to progress from the divertor plate to the main plasma X-point**
  - serious degradation of the H-mode barrier
  - higher disruptivity close to the density limit
- **A divertor geometry that can prevent these consequences for full detachment would be highly desirable**
- **The 2004 paper predicted that the XD would make higher levels detachment acceptable**
- **Recently, the same prediction has been made for snowflakes**
- **Since the detachment front traverses exactly the region where the B field is different for an XD and an SFD, we expect differences in detachment behavior**

Energy losses at the detachment front: larger losses for larger area * (and the converse)

- Consider detachment in a standard divertor
- Experiments: the front progresses from A -> B -> C
- As detachment front moves upstream, area increases => energy losses increase
- =>Radiation collapse, and upstream (closer to the heat source)



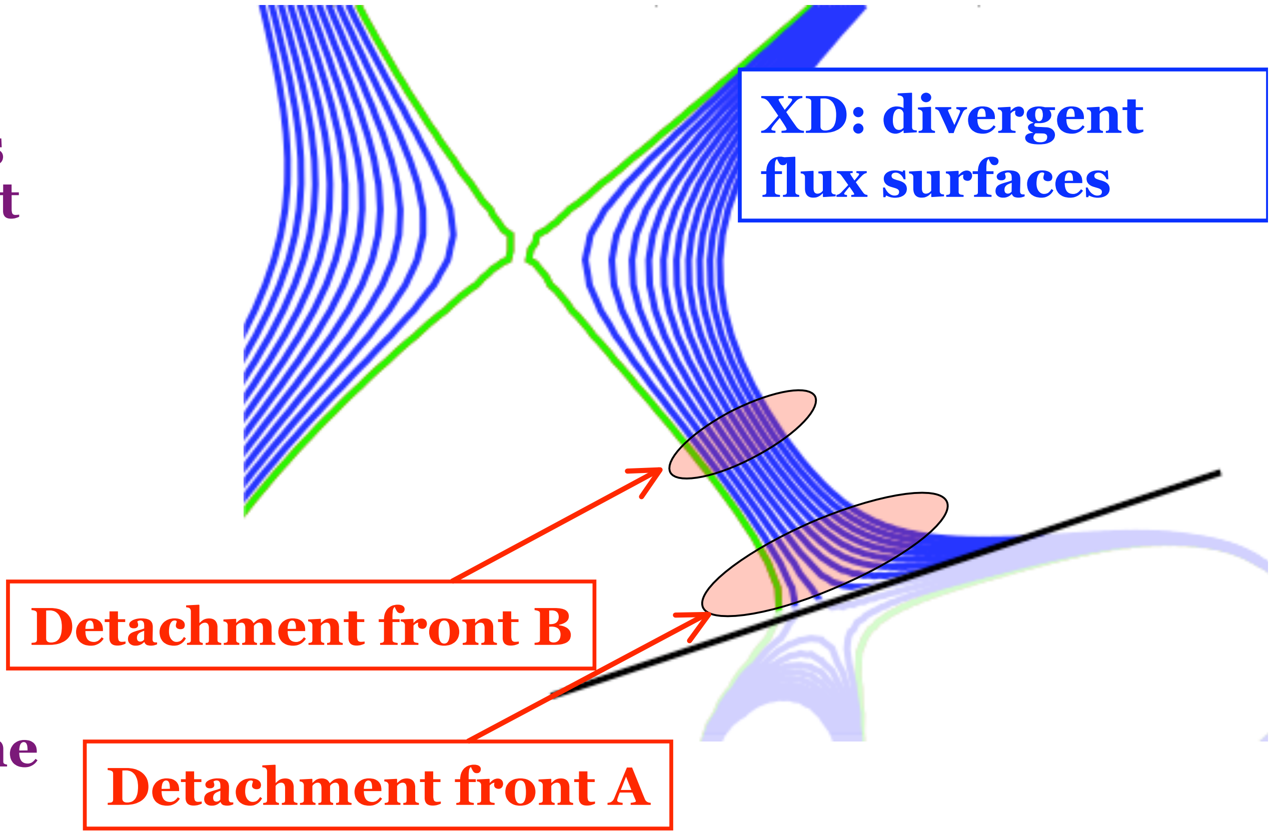
*Sergei Krasheninnikov, private communication
See also S.I. Krasheninnikov, Journal Nucl. Mat. 266-269 (1999)

The feedback changes if the flux surfaces become more convergent or divergent

- **Standard divertor: positive feedback since area increases toward the core X-pt**

- **SFD: more strongly convergent flux surfaces imply even stronger positive feedback**

- **XD- stabilizing feedback since area *decreases* toward the core X-point => energy losses decrease**



X-divertor: detachment tends to stay near plate
SFD: detachment front progresses to core X-point

A poor theorist's interpretation of reported experimental results

- NSTX and DIII-D state that the highly radiating region is near the divertor plate
- TCV states that the highly radiating region is near the core X-point
- In gross terms, these behaviors are in accord with the expectations of their respective magnetic geometries
- Detachment is a very complex process, and more detailed analysis is obviously necessary
- Nonetheless, we expect that detachment behavior will by significantly affected by whether the SOL is flared or highly contracting

CONCLUSIONS

•As experiments on advanced divertors proceed, we must strive to understand their behavior based on the properties of the magnetic field in the plasma exhaust SOL

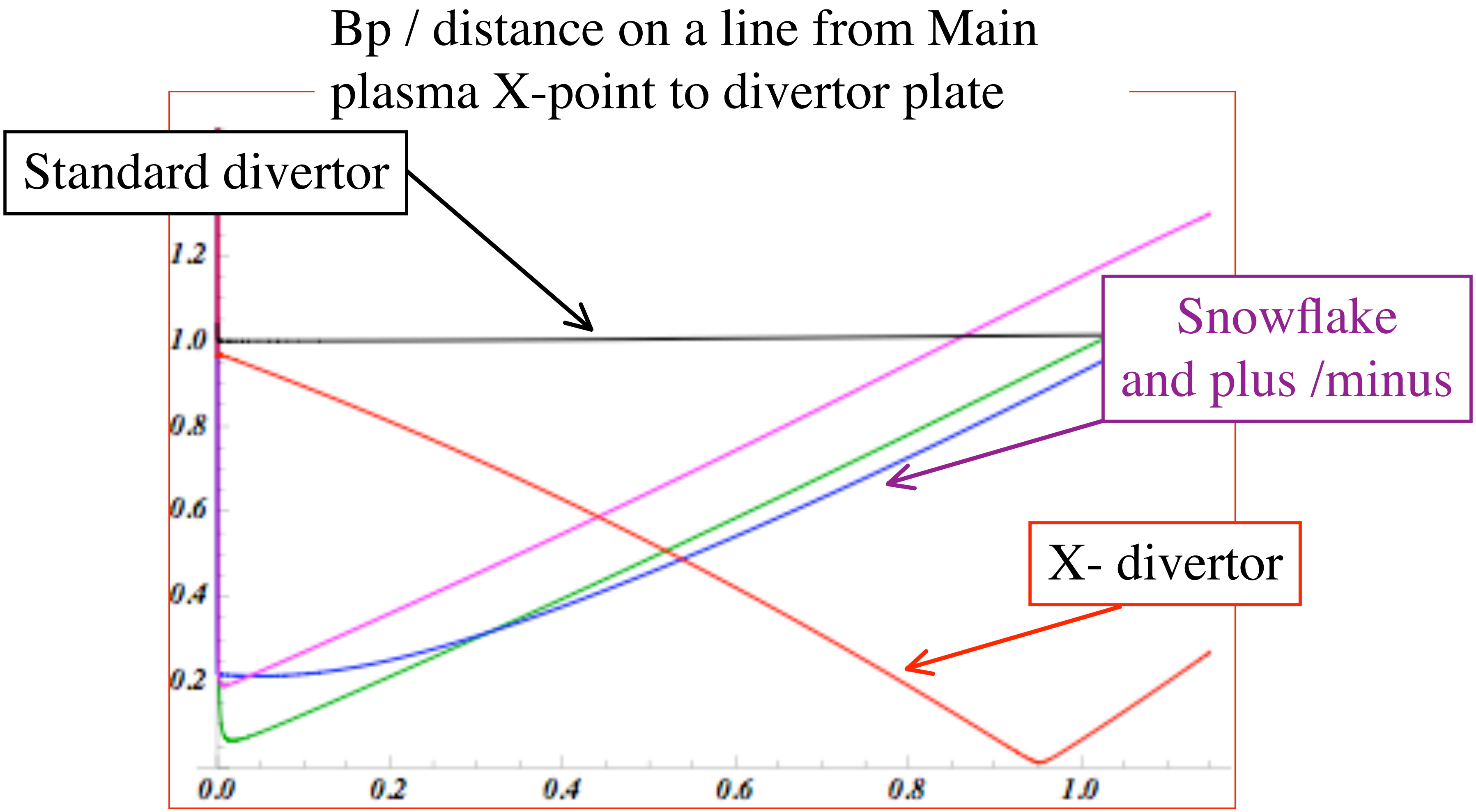
•Only these properties can be proper "metrics" for classification - we have also provided a possible such metric

•Any classification scheme based on the properties of the vacuum field outside the plasma SOL, and behind the PFCs, is intrinsically ill posed; it cannot be physically useful

•Based on physically relevant properties, the reported successful experiments on NSTX and on DIII-D display the defining characteristics and predicted behavior of X-divertors

•Modifications of the magnetic geometry of the SOL should alter the behavior of full detachment front, and X-divertors may allow acceptable operation with higher levels of detachment than a standard divertor

Plot of Bp/d to distinguish between Snowflake and X-divertor



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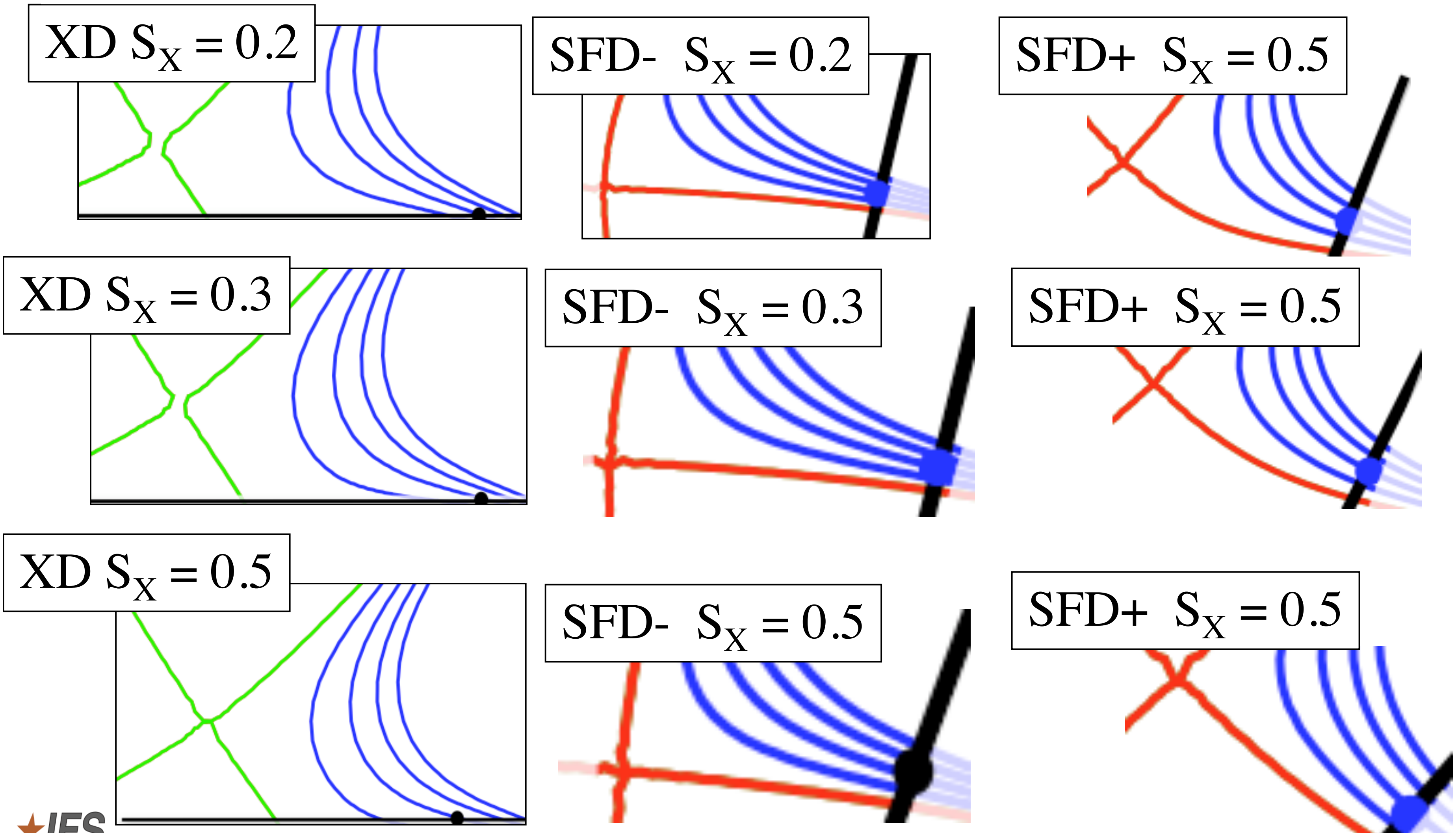
For all S_X ~ 0.2 – 0.5, the differences in SOL between XD and SFD always remain

Changing S_X does not change the divergent or convergent behavior



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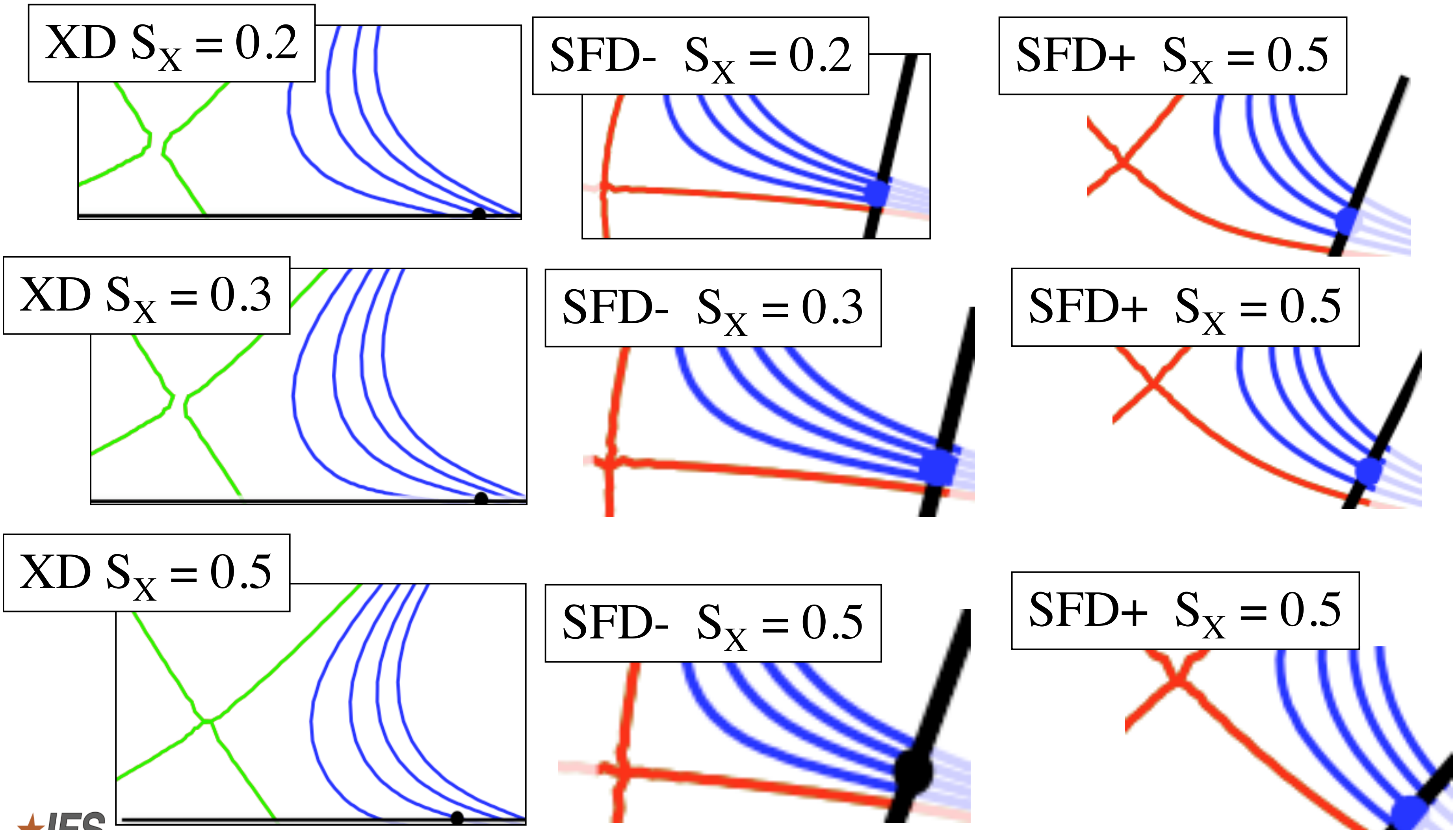
As a reminder, this is what the SOL looks like



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