Progress & plans for advanced components

Xianzhu Tang

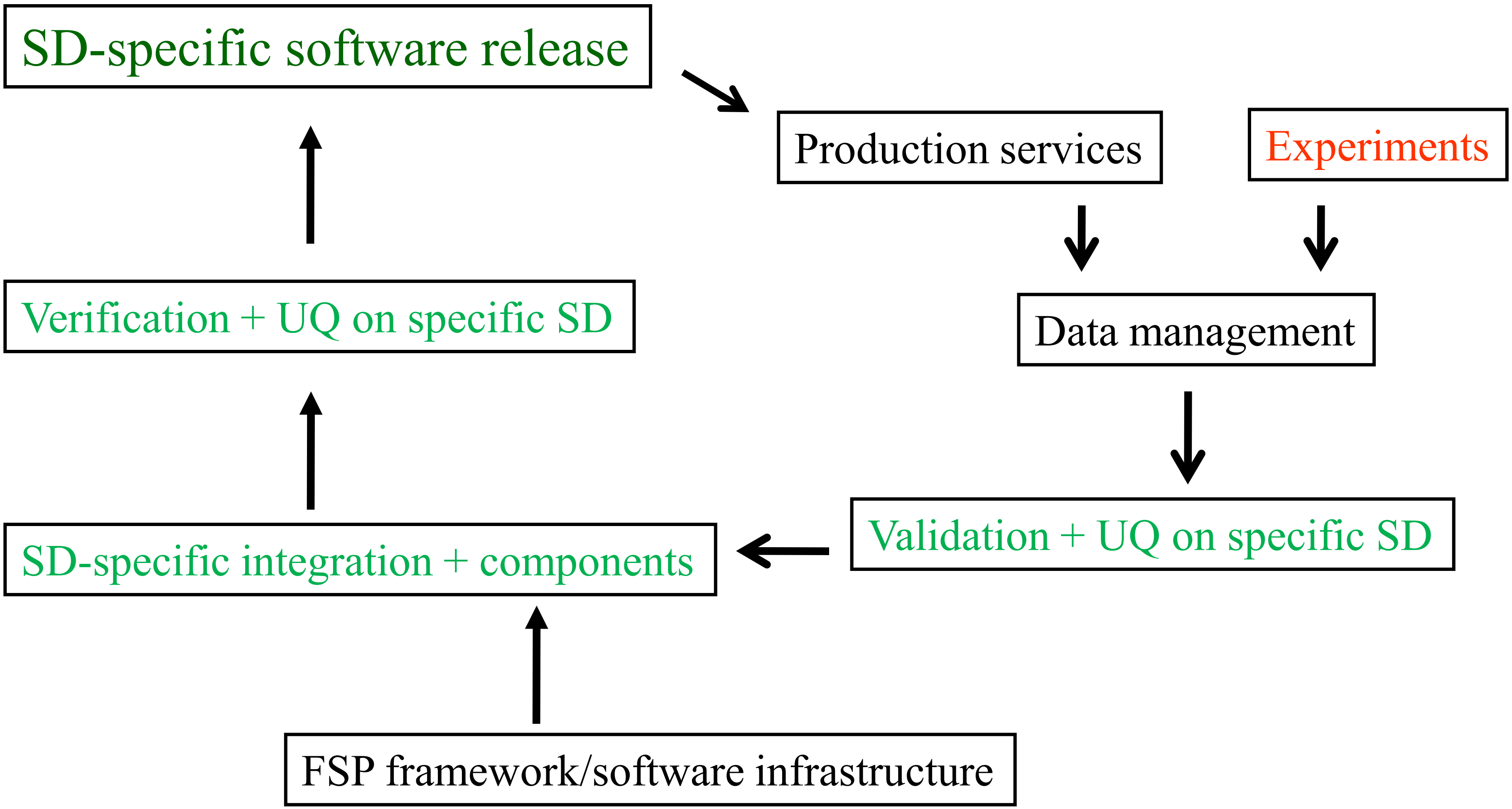
On behalf of the FSP component team

Outline

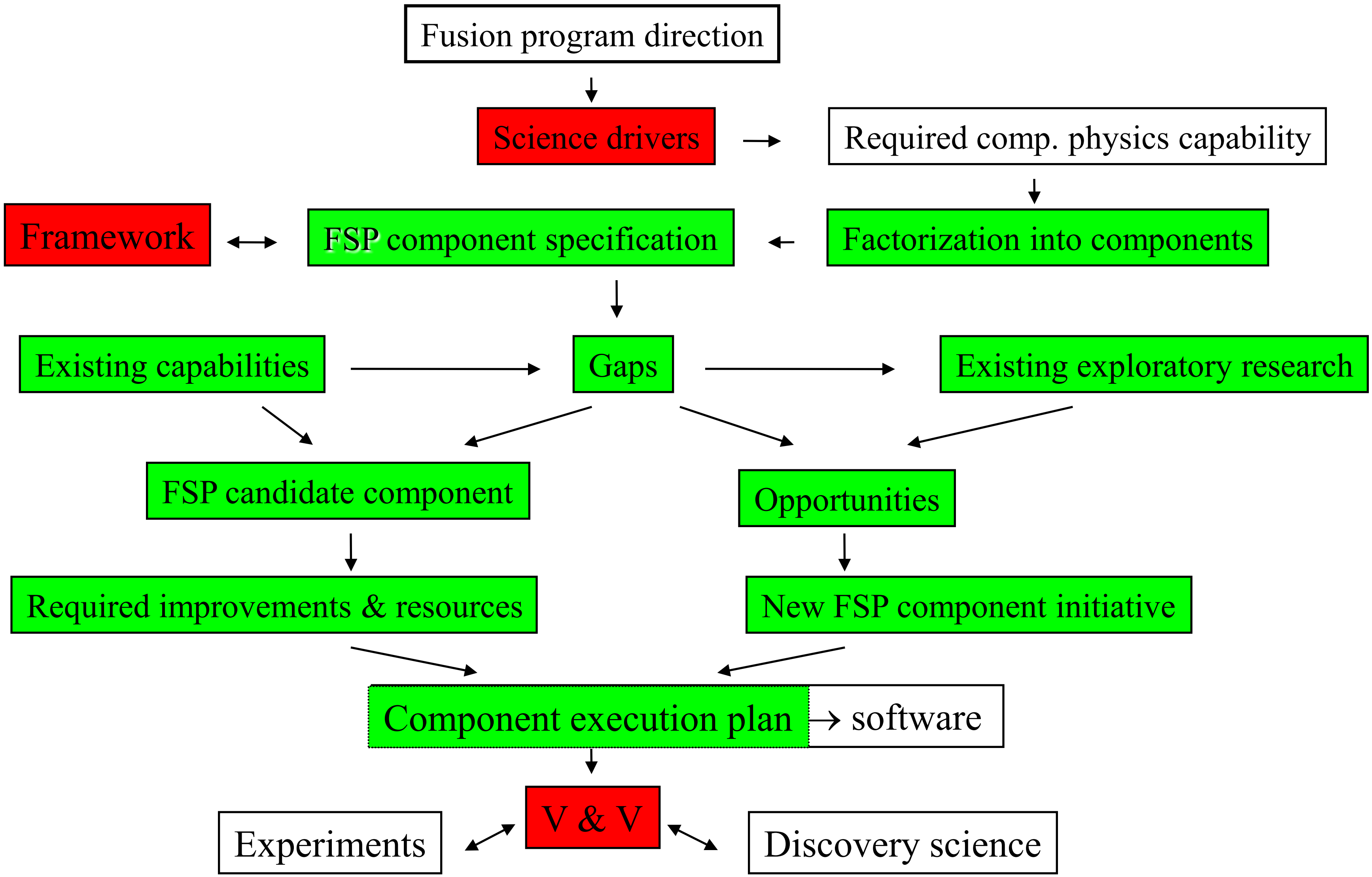
- **PAC charge addressed**
  - **Community engagement**
  - **FSP scope**
    - **Define component relationship to other parts of FSP**
    - **The process to define FSP component scope**
    - **Initial findings on component scope via community input**

- **FSP component strategy**
- **Community engagement to carry out the strategy**
- **Specific tasks to date**
- **Accomplishments to date**
- **Next step action items**

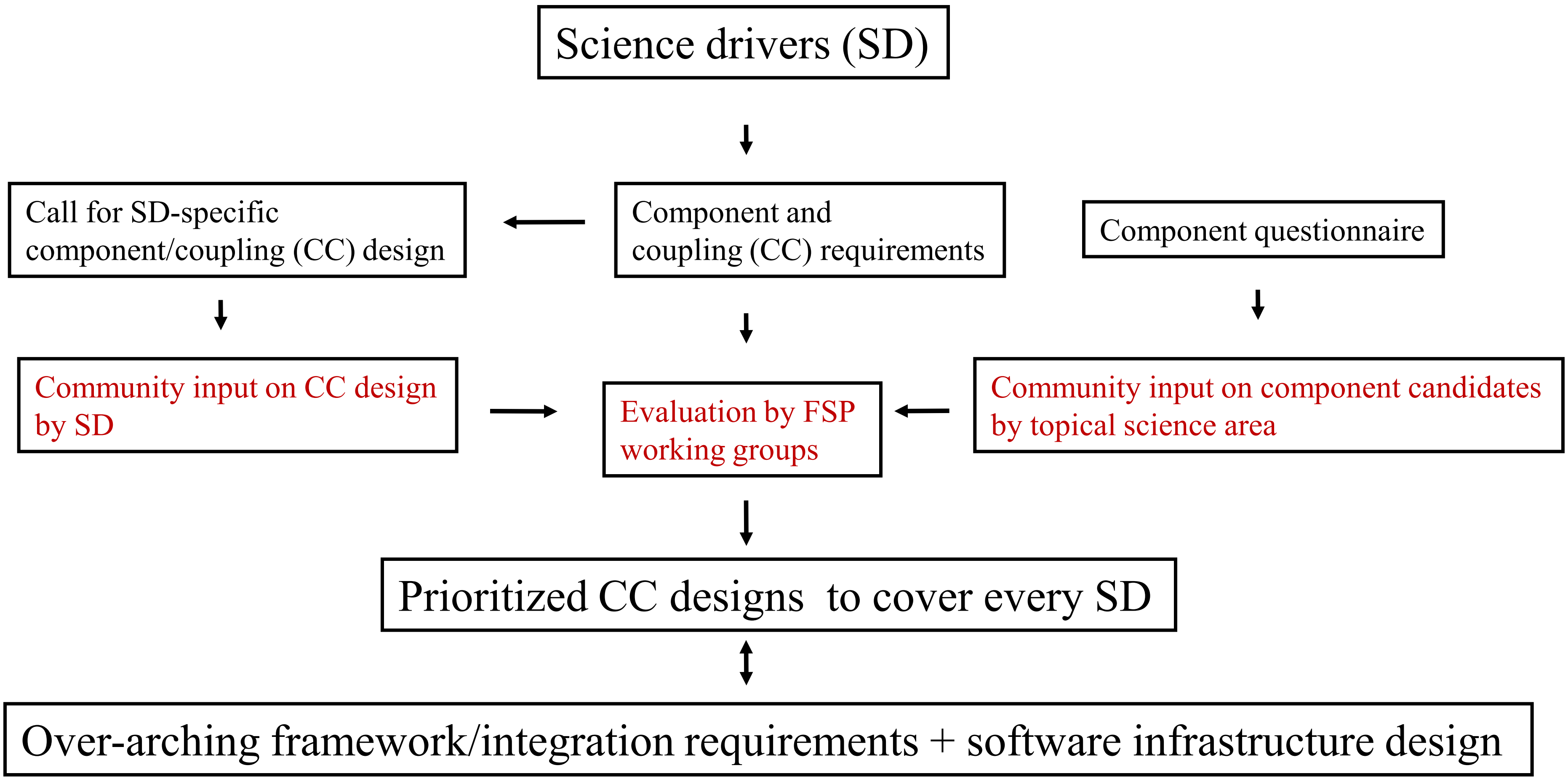
FSP scope/deliverables are guided by science drivers (SD)



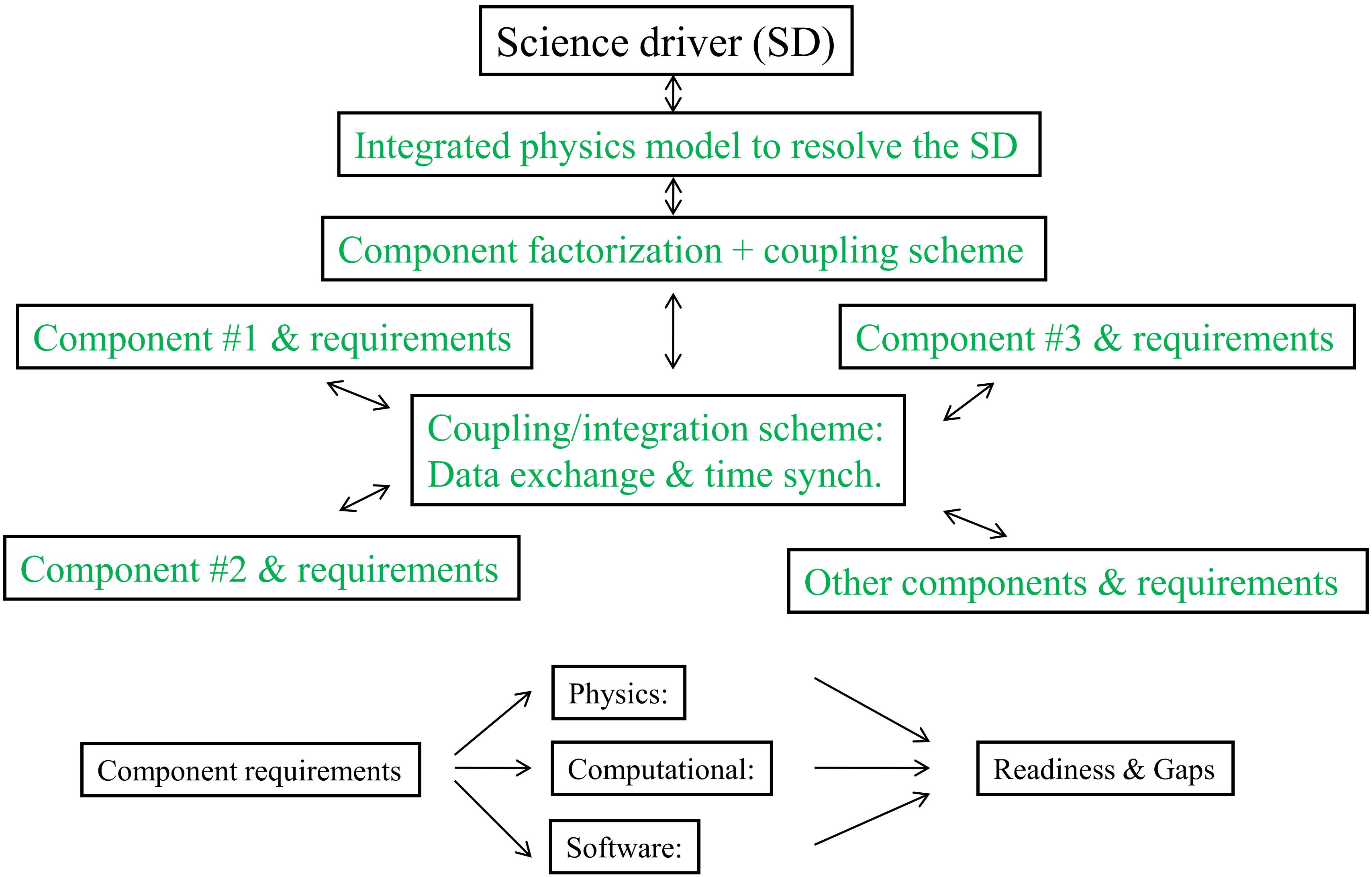
FSP component strategy unchanged from last PAC meeting!



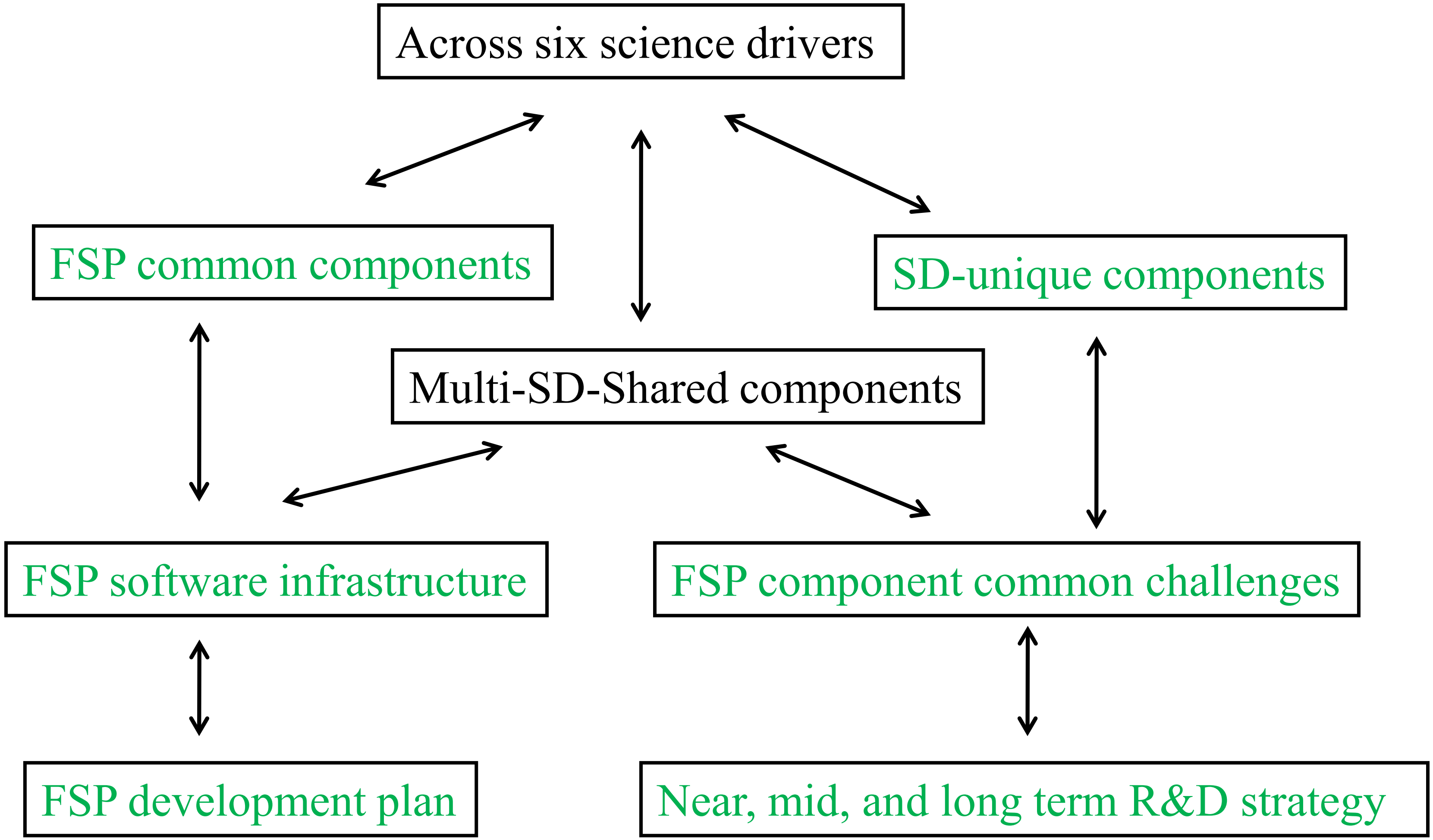
Carrying out the component strategy in FSP planning



Engaging the community on specific component tasks I



Engaging the community on specific component tasks II



Component work @ march workshop

- Gathering solutions to specific SD's from design proposal presentations
  - How physics challenges are broken down into computable components which are coupled to resolve the integrated physics models.
    - Input from 3 proto-FSP,s, 5 SciDAC's, 3 community code projects
- Discussing and comparing proposed solutions for each SD.

- Component breakout group discussion
  - Establish component specification for individual SD in the context of its likely coupling scheme.
    - Carried out in multiple subgroups by computational physicists, theorists, experimentalists, & AM/CS experts.
  - Across six SD's, identify common components and common or SD-unique challenges.

Accomplishments to date

- **Component factorization + coupling scheme for all six science drivers with near term and long term perspectives**
  - **Pedestal science driver**
  - **Edge-wall science driver**
  - **Disruption science driver**
  - **Wave-particle science driver**
  - **Core profile science driver**
  - **Whole device modeling science driver**
  - **See backup slides for preliminary reports!**
- **Illustrative examples**
  - **Disruption**
  - **Wave-particle**
  - **Whole device modeling**

Disruption Impact Reduction Science Driver

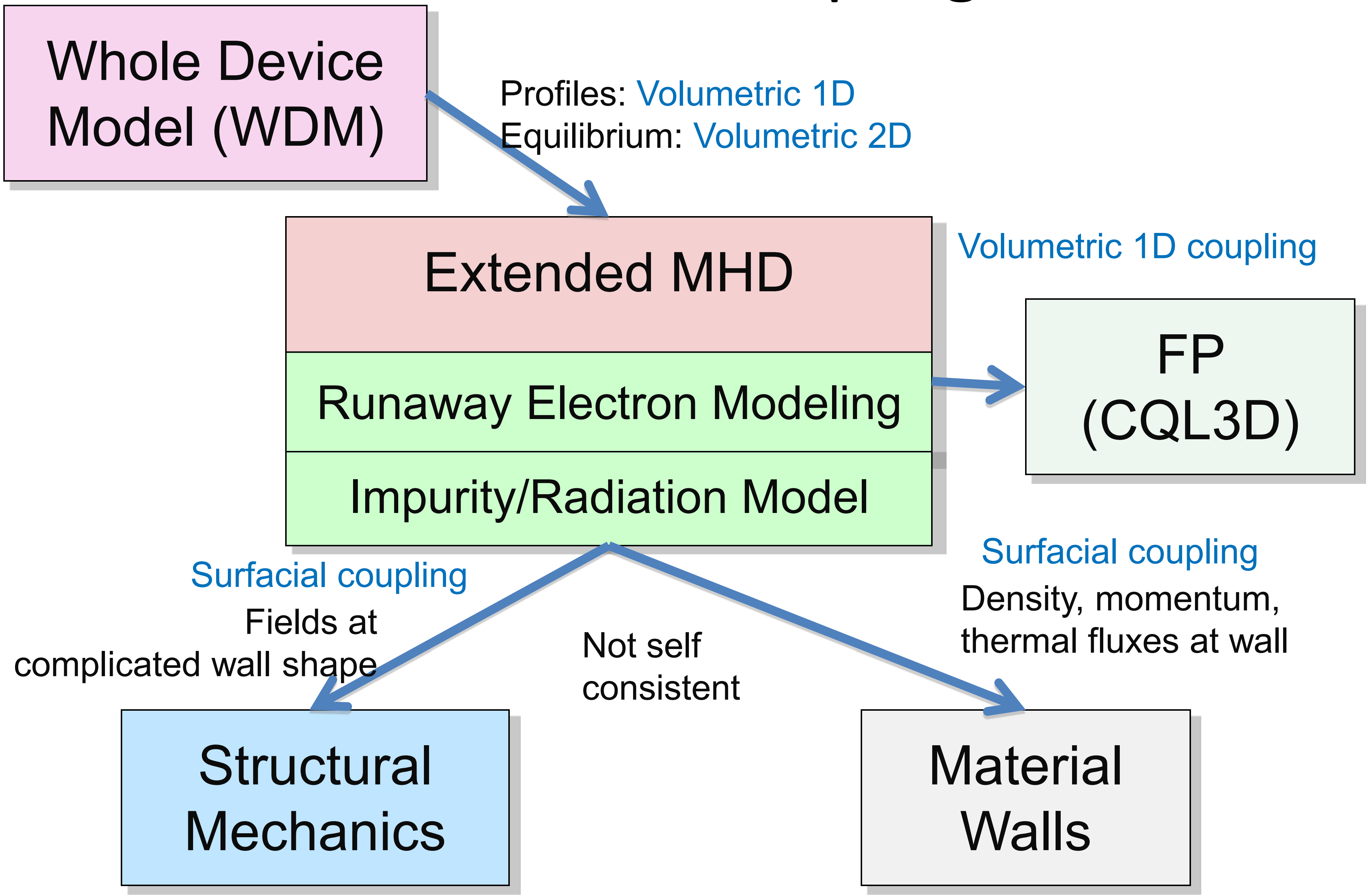
Scientific Goal:

To understand the dynamics of mitigated and unmitigated disruptions in order to understand how to limit their effects.

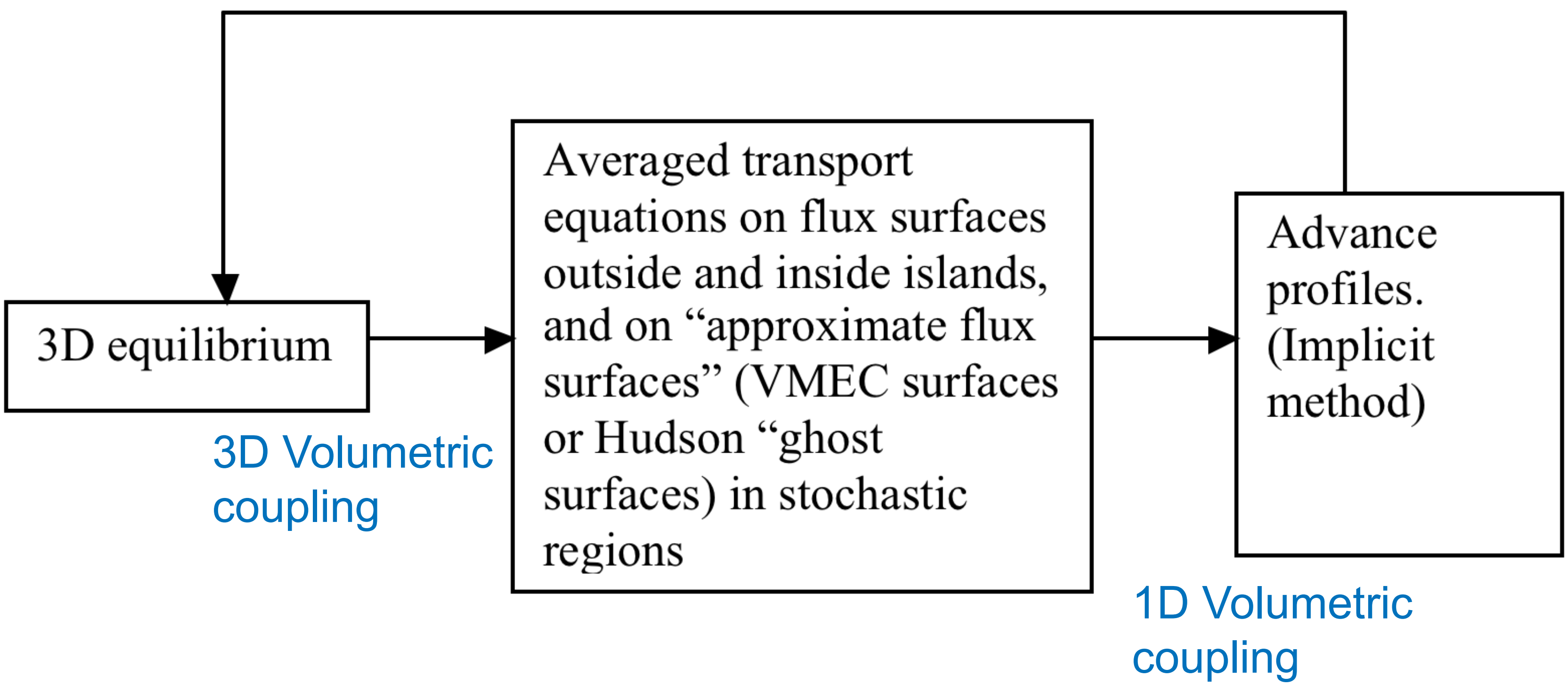
Scientific impact:

Enable the robust operation of tokamaks by allowing more aggressive operating regimes and by enabling faster recovery from off-normal events

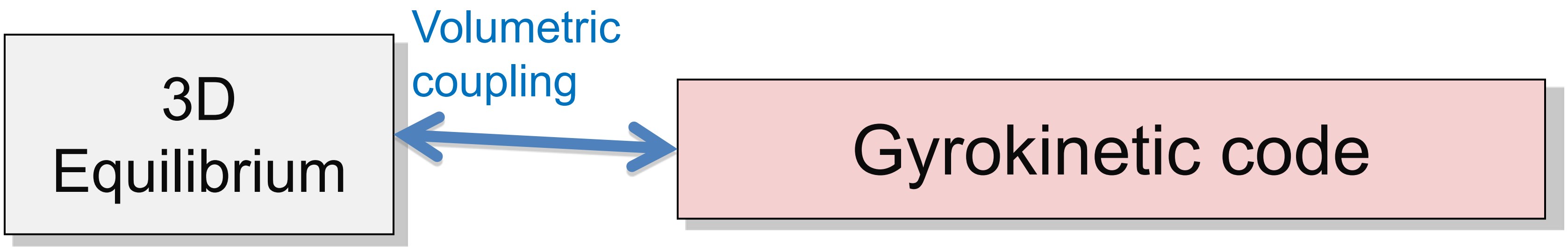
Near term coupling



Mid-term coupling: long time-scale modeling



Example advanced component: Kinetic MHD in 3D field for Modeling Thermal Quench



Output:
3D B fields

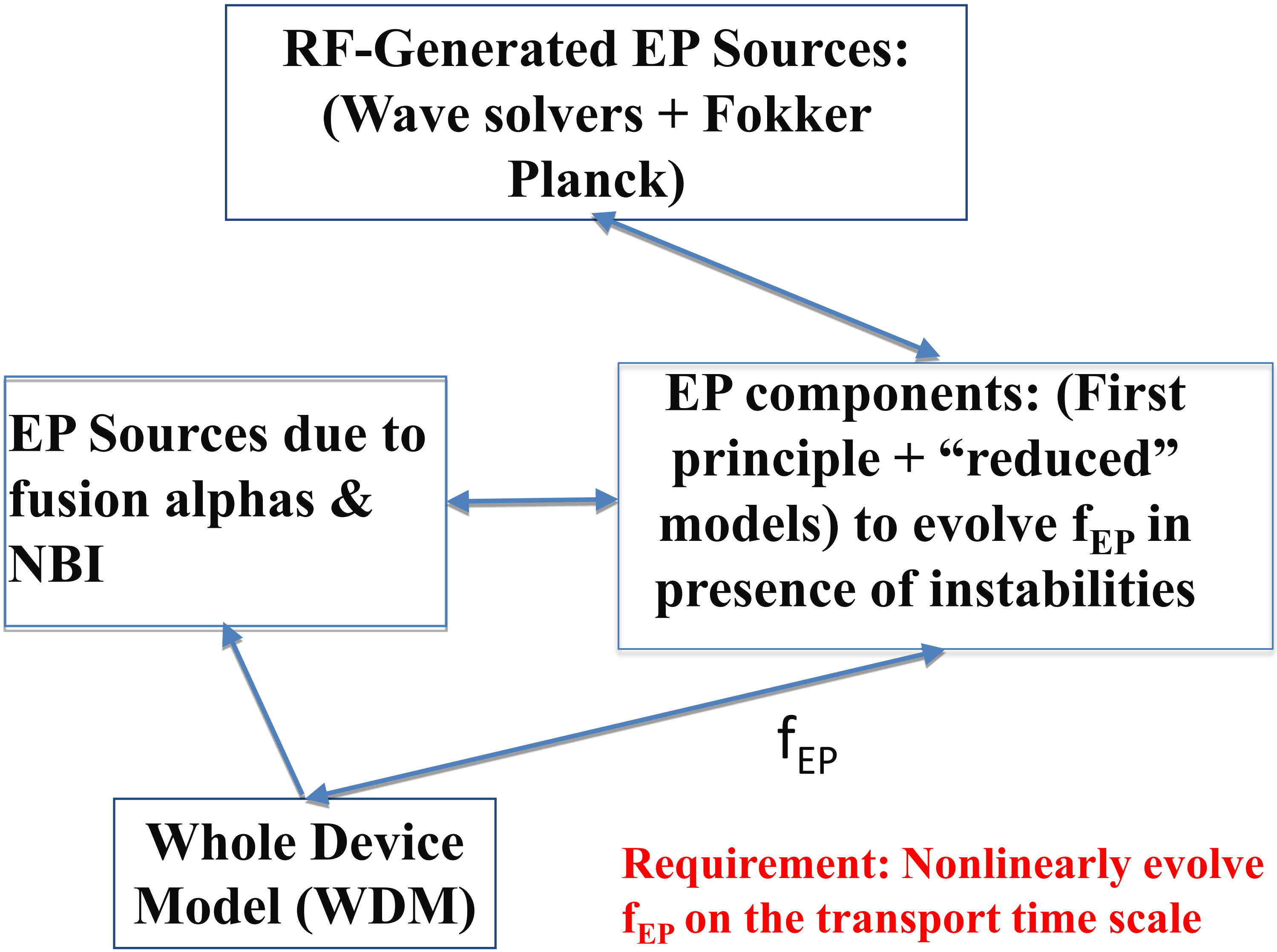
Output:
3D density, T fields

Early: Single-helicity island
Eventually: Stochastic field

Wave-Particle Science Driver - Goals

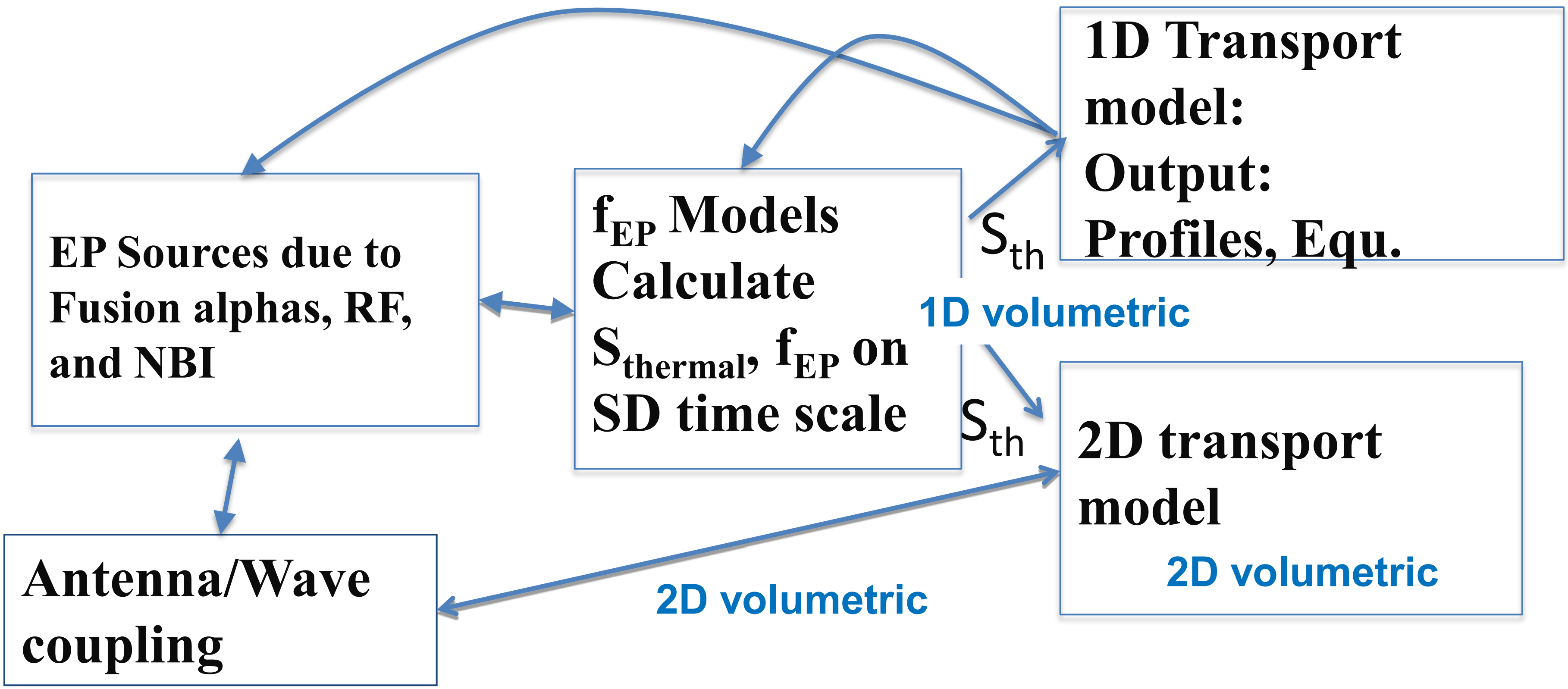
- **In alpha dominated burning plasmas, can collective fast particle phenomena significantly affect discharge evolution, fusion performance and facility integrity?**
- **Can RF waves couple into the core of a fusion plasma and be used to effectively control the plasma in the presence of multiple energetic particle species and edge dissipation mechanisms ?**

Coupling schemes for integrated core wave – particle simulation



Requirement: Nonlinearly evolve f_{EP} on the transport time scale

Coupling schemes for EP simulation with linear RF physics

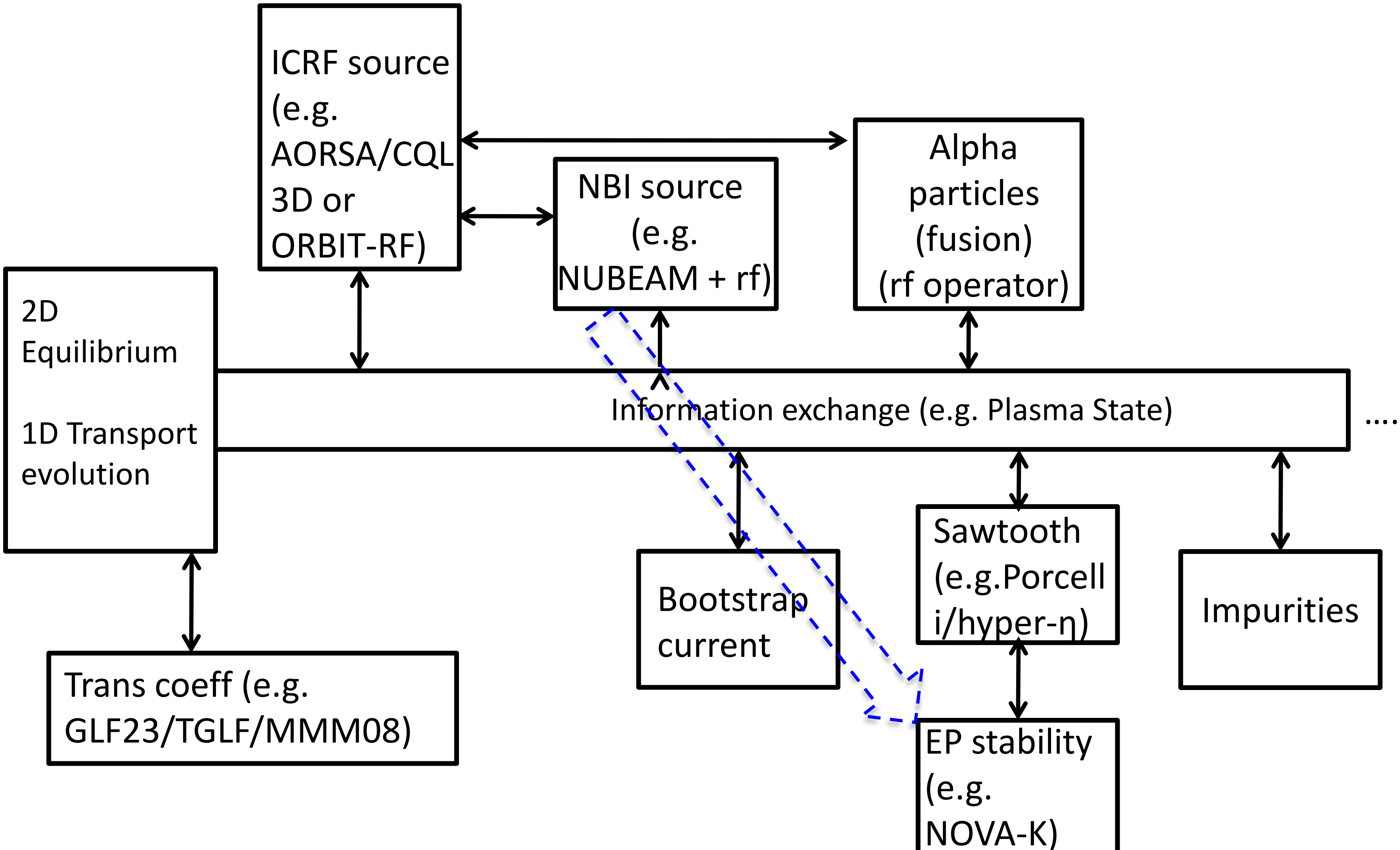


Requirement: Include linear effects as wave propagates through SOL

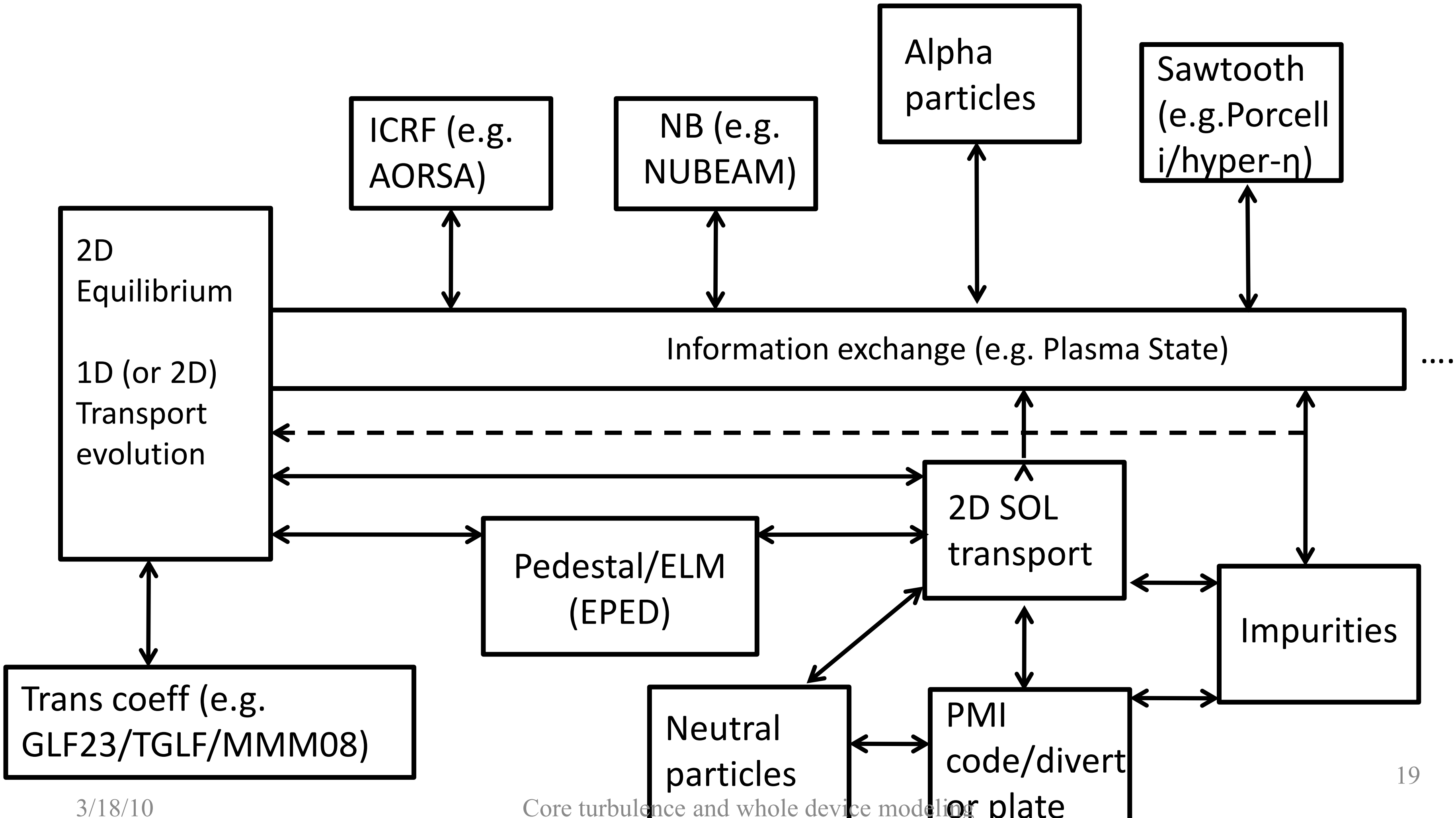
Whole device modeling science driver

- A comprehensive model of the whole device, magnetic axis to wall, containing all relevant physics
  - Provides a platform for predictive simulation, interpretive analysis of experiments, and experimental data comparison for validation
  - Provides a framework that allows coupled components and multi-scale integration for time-dependent simulations
    - Platform for testing components in development from the rest of the program
  - Allows multiple models of the same physics (models with progressive physics fidelity)
    - Import from other SDs.
  - Accommodates production running AND highest physics fidelity demonstrations (“capacity” computing and “capability” computing)

Short term (2-5 years)
Treating multiple fast particle species (NB, minority ICRF, and alphas) with FP in ITER burning plasma discharge simulation



Long term (5-10 years)
Simulation of the core/pedestal/SOL/divertor target and chamber wall interaction during ELM pulses in ITER



Summary Findings

Near term perspective (deliverables)

- FSP readiness: There is a solid base of existing (component) capabilities and credible integration schemes to produce meaningful integrated software to tackle every science driver within the first 5 years.
  - Most if not all expect significant improvement in fidelity beyond current integrated modeling capability in every SD area.
  - At the same time, limitations are clearly identifiable and identified.
  - Excellent platform for verification and (in)validation.
- The diversity of potential components/integration schemes (approaches) for the same SD reflects the reality that significant gaps exist between current capability and
  - a truly first-principle-based predictive capability,
  - the need to predicting range of current experimental observations.

Summary Findings

Long term perspective

- All SD's converge to common component R&D needs in key areas
  - 2D equilibrium and transport solver from B axis to wall.
  - Self-consistent 3D plasma equilibrium and transport solver from B axis to wall.
- imbedded calculation poses similar challenges to coupling/framework.

- R&D thrusts in the physics integration area are on converging paths:
  - Core transport moves to include edge
  - Edge transport moves to include core
  - XMHD moves to include effect of GK transport
  - GK transport moves to include impact of low-n to medium-n magnetic activities

Summary Findings

The long term prospect of FSP is inspiring

- The challenges to achieve predictive simulation for FSP are daunting
- Because of the converging paths, success of any one of them make a successful FSP.
- We have gotten some time to work on them.
  - Almost a necessity here.
  - Start early or you will regret.
- Different SD's are increasingly being tackled by fewer but highly integrated (physics-wise) components.
- The long term prospect of FSP is intellectually appealing and cleaner in terms of #'s of components/coupling schemes.
- 5 SD's converge nicely into WDM.

Future plans

- Complete the reports
  - Science challenges
  - Near and long term perspectives by SD
    - Component factorization
    - Component functionality and coupling scheme specification
    - Requirements and gaps
- Complete the analysis/report
  - Across SD's
    - Common components
    - SD-unique components
    - Common physics/integration challenges
- Reach out to broader fusion community for comments & suggestions on the workshop findings.
- Engage OASCR on algorithmic needs and performance issues (with specificity).
- Call for community input to address critical gaps.
- Evaluate community input on ideas/approaches to address critical gaps.

Back Up Slides
(Findings from march workshop: component factorization/coupling scheme on all six science drivers)

FSP Planning Meeting, Boulder, 3/14-19/2010

Edge component

(Pedestal and scrape-off to wall)

T.Rognlien, P.Snyder, D.Stotler, X.Xu,
R.Cohen, M.Dorr, D.Knoll,
S.Krasheninnikov, M.Greenwald,
J.Shadid, J.Cummings, J.Hittinger,
S.Klasky, S.Parker, L.Sugiyama, et al.

Edge component itself is composed with multi-spatial, multi-time scale sub-components.

Edge physics requires codes integration framework which will be as complex, if not more, as the core plasma.

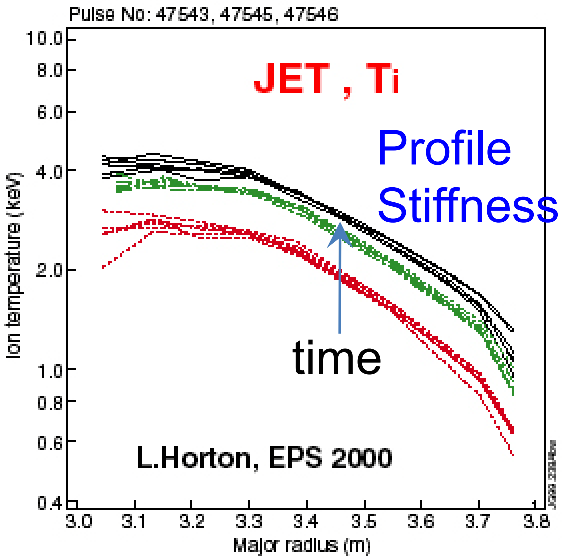
- Edge plasma has all the basic multi-physics complexity of core plasma:
  - Neoclassical, micro/meso-turbulence, MHD events, (+ rf and hot ions).
- Added complexity from the atomic physics, impurity, radiation, material wall, diverted geometry, 3D magnetic field, etc.

We have categorized the edge codes into three spatial areas.

- Codes crossing the magnetic separatrix
- Codes on closed magnetic field lines
- Codes on open magnetic field lines and/or in contact with material wall

  – All the code couplings in the edge framework need to be volumetric (avoid error from spatial interface), requiring in-memory coupling for large data exchange or mathematically tight coupling.
  – Coupling with small data exchange can in file.
  – A reliable grid interpreter is very important to accommodate different grids used by different codes.

Science drivers in the edge



Experimental findings which need to be understood by numerical simulation

- Strong core heating generates edge pedestal (**H-mode transition**)
- Core fusion quality goes up together with the edge pedestal height (**nonlocal core-edge interaction**)
- Core plasma rotation increases as the **edge rotation** increases → more stable plasma

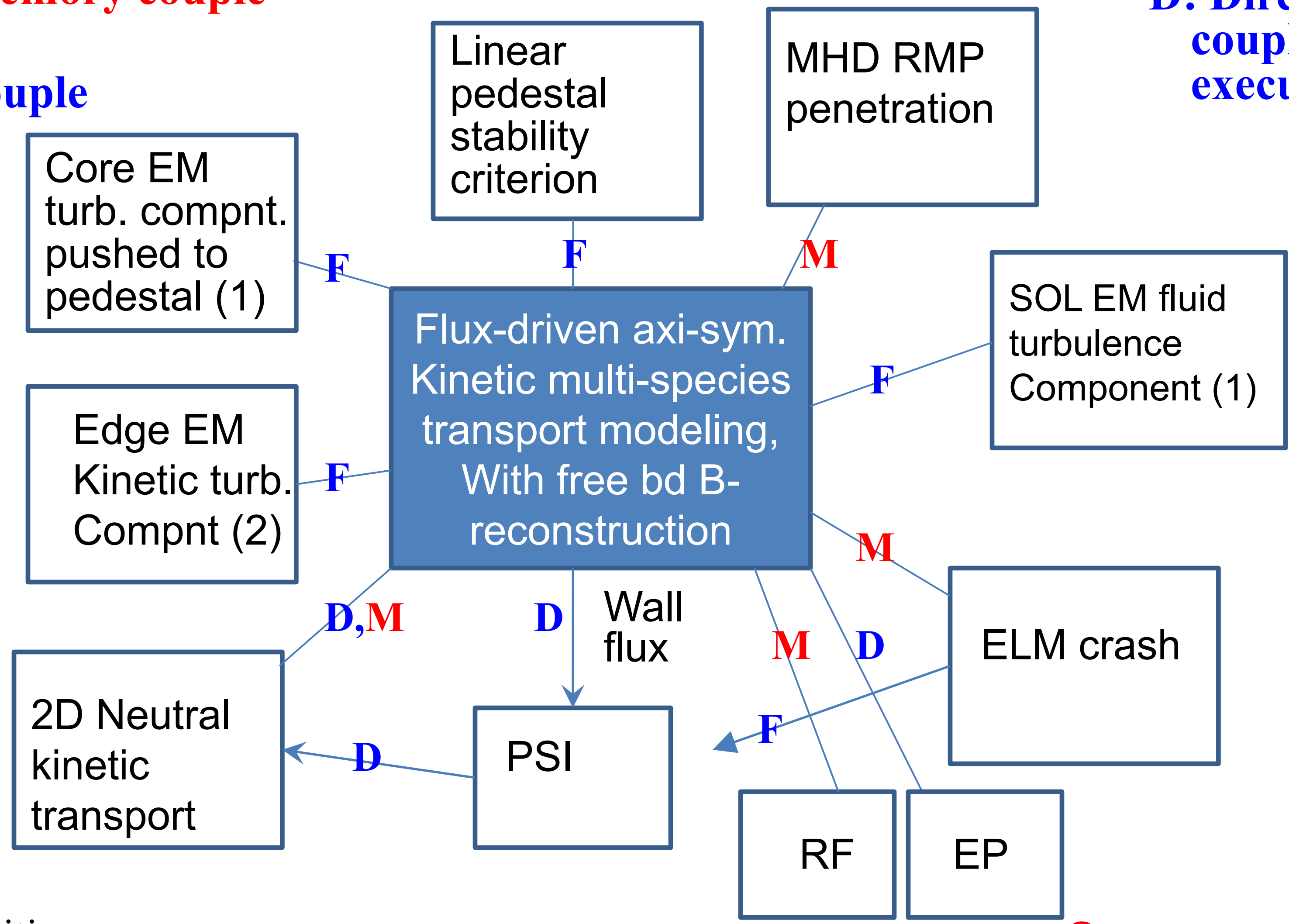
- As the edge pedestal grows too steep, a rapid instability collapses the edge pedestal (Edge Localized Modes – **ELMs**)
- **ELMs** degrade the fusion quality in the core
- Collapsed plasma energy by **ELMs** damages the wall material
- Edge-localized stochastic magnetic field perturbation by external-coil-driven resonant magnetic perturbations (**RMPs)** show signs of ELM mitigation.
- **Localized heat loss** in the open magnetic field lines damages the material wall even in the absence of ELMs.
- **Plasma-surface interaction** generates neutral protons and impurities

Short term goal (2-5 yrs), Pedestal-ELM cycle in H-mode (whole edge)

M: In-memory couple (nxm)

F: file couple

D: Direct coupling, one executable



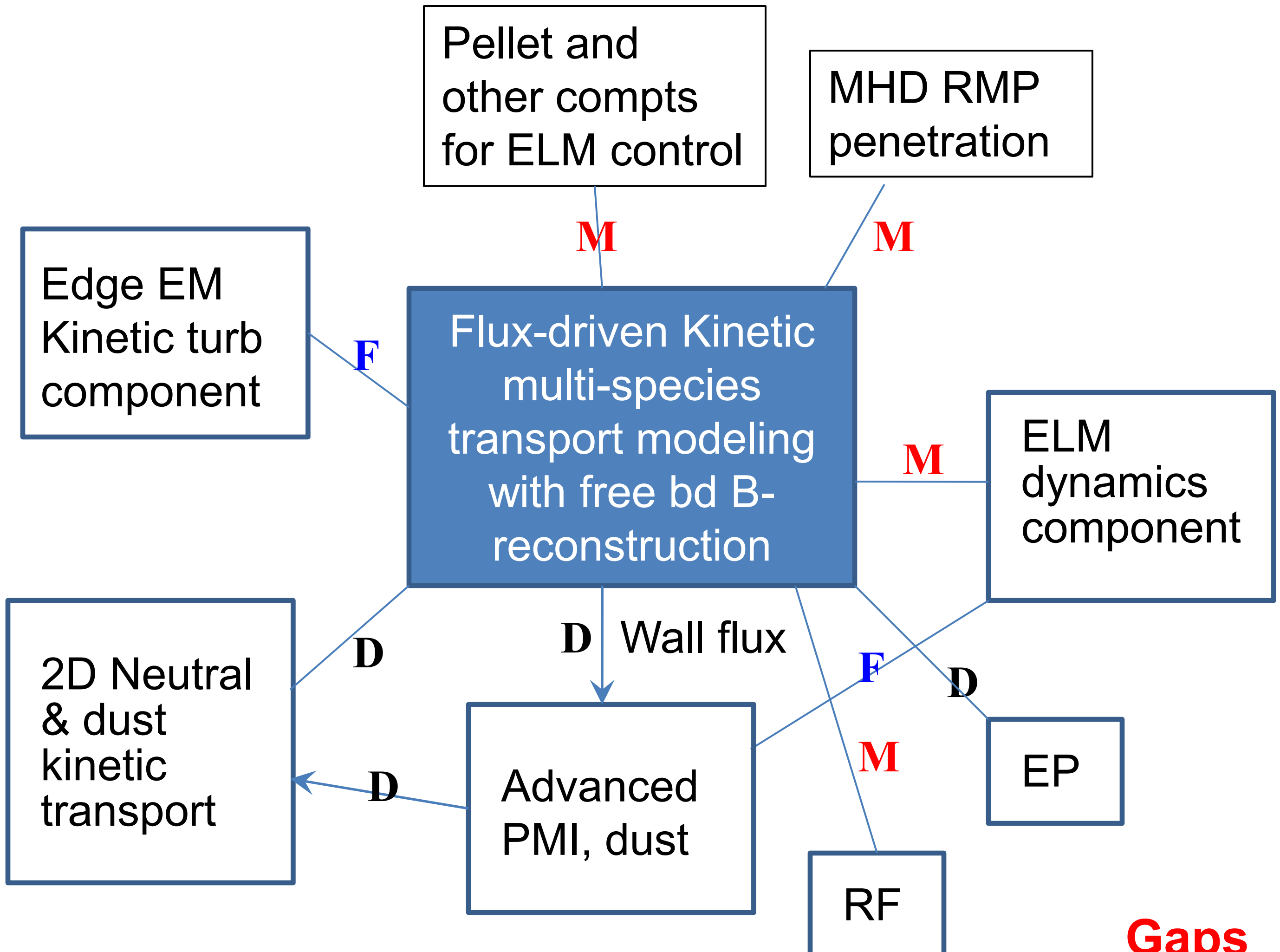
Gaps

L-H transition
Tighter Kinetic-MHD
Effect of RF-EP
RMP penetration

Gaps

Free bd. Equi. Solver accurate to SOL plasma

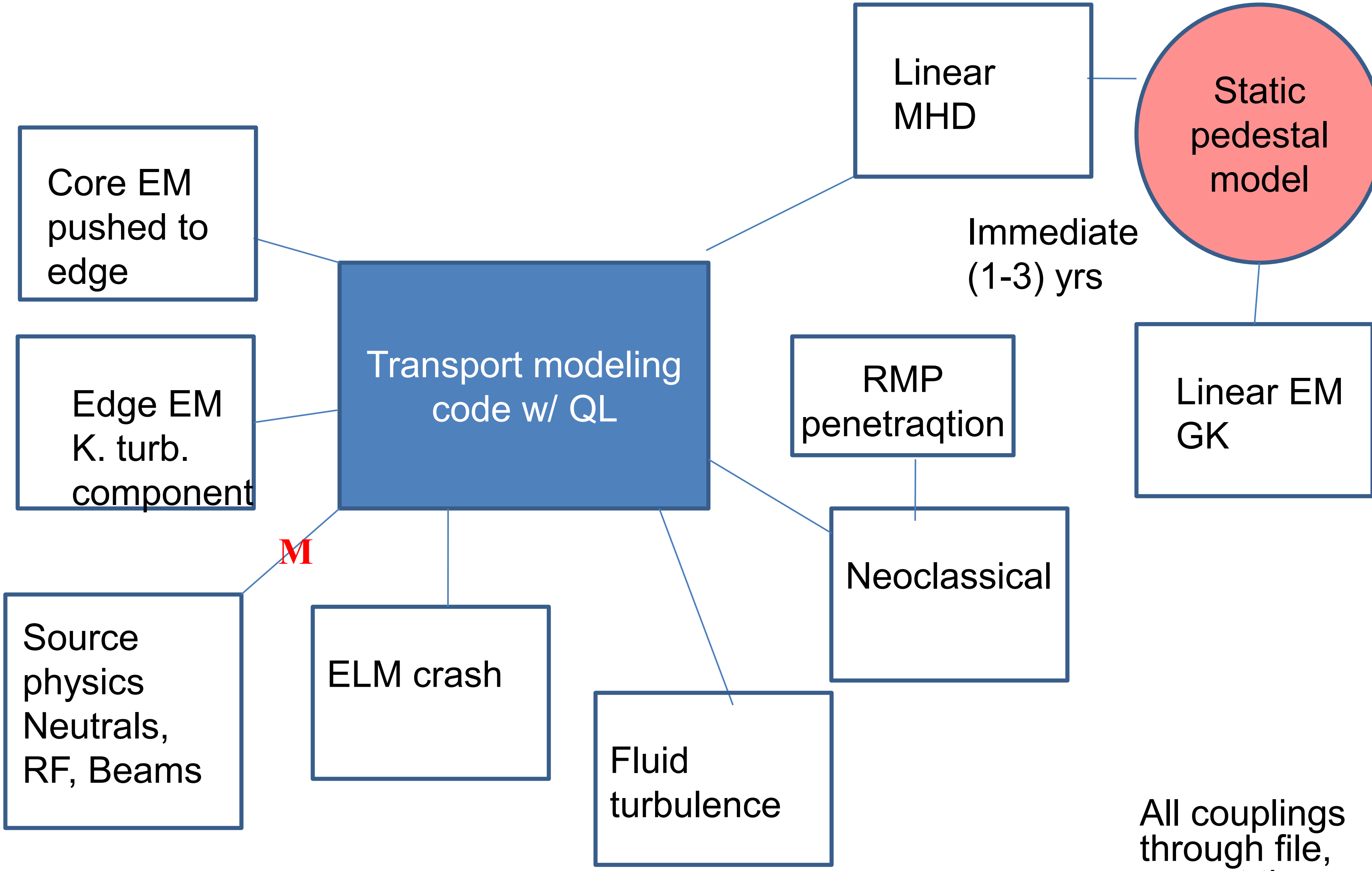
Long term goal (10yrs), L-H-ELM dynamics (whole edge)



Gaps
All-n kinetic EM
Radiation transport

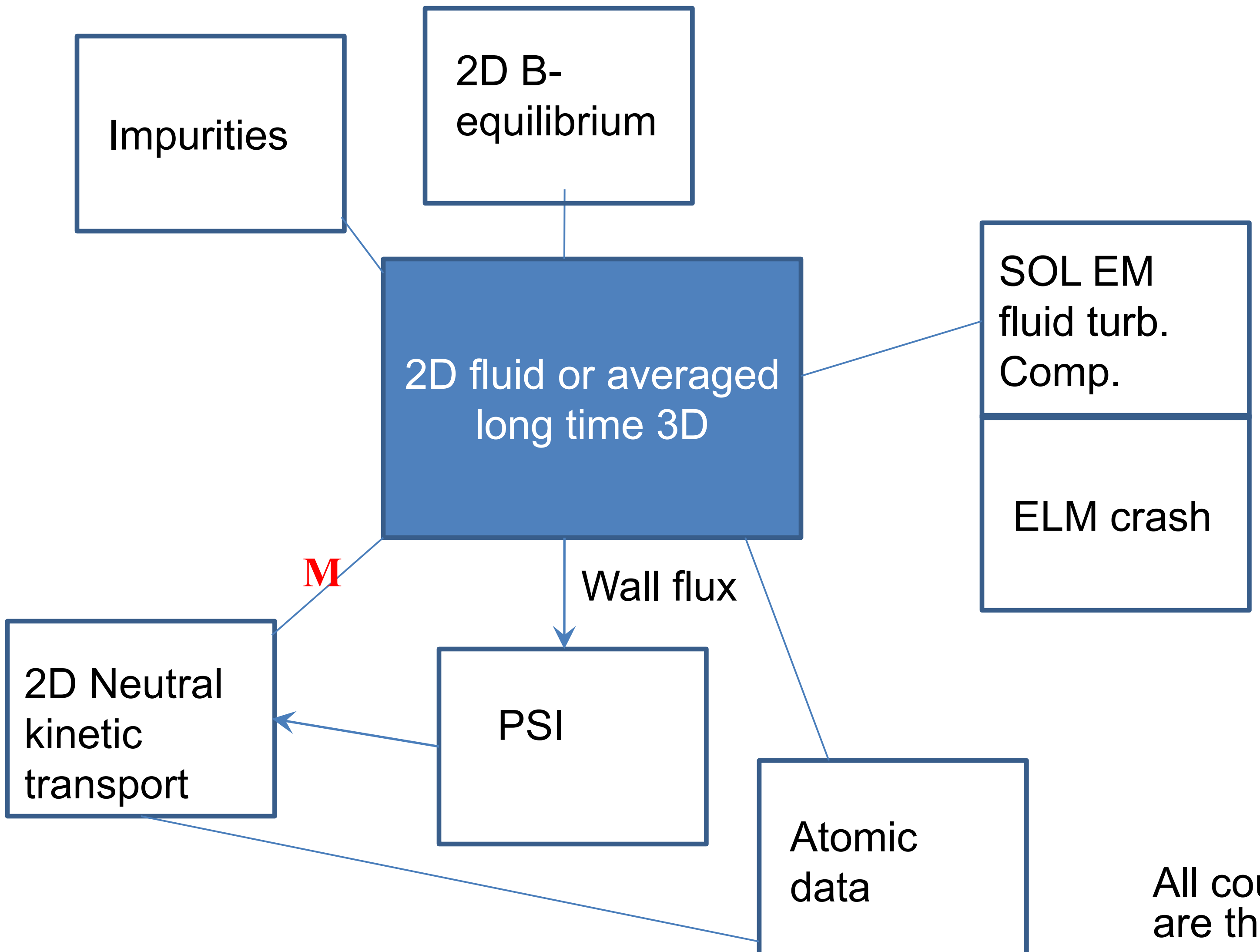
Gaps
Pellet phys
Various ELM types

Short term goal (2-5 yrs) Static Pedestal only component



All couplings through file, except the source physics

Short term goal (2-5 yrs), dynamic SOL-divertor-wall only component



All couplings are through file, except the neutral transpt

Disruptions and Wave-Particle Science Drivers: Components, Gaps Analysis, and Common Components

H. L. Berk,V. S. Chan, GY. Fu, S. E. Kruger, R. Nazikian, A. Reiman, D. Spong, L. Sugiyama, and Others

FSP Planning Workshop, Boulder, CO

March 15-18, 2010

Disruption Impact Reduction Science Driver

Scientific Goal:

To understand the dynamics of mitigated and unmitigated disruptions in order to understand how to limit their effects.

Scientific impact:

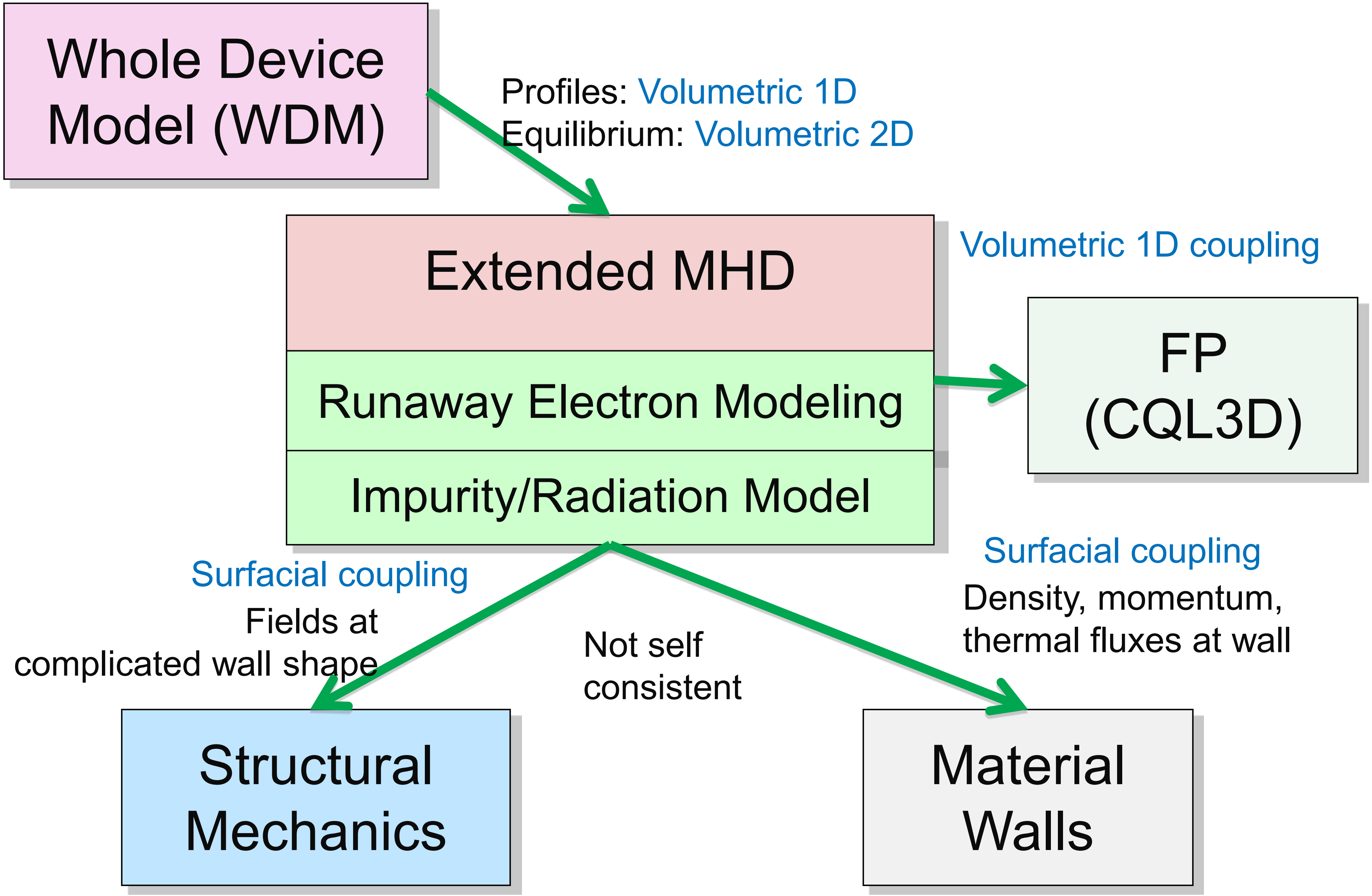
Enable the robust operation of tokamaks by allowing more aggressive operating regimes and by enabling faster recovery from off-normal events

Needed elements of disruption modeling

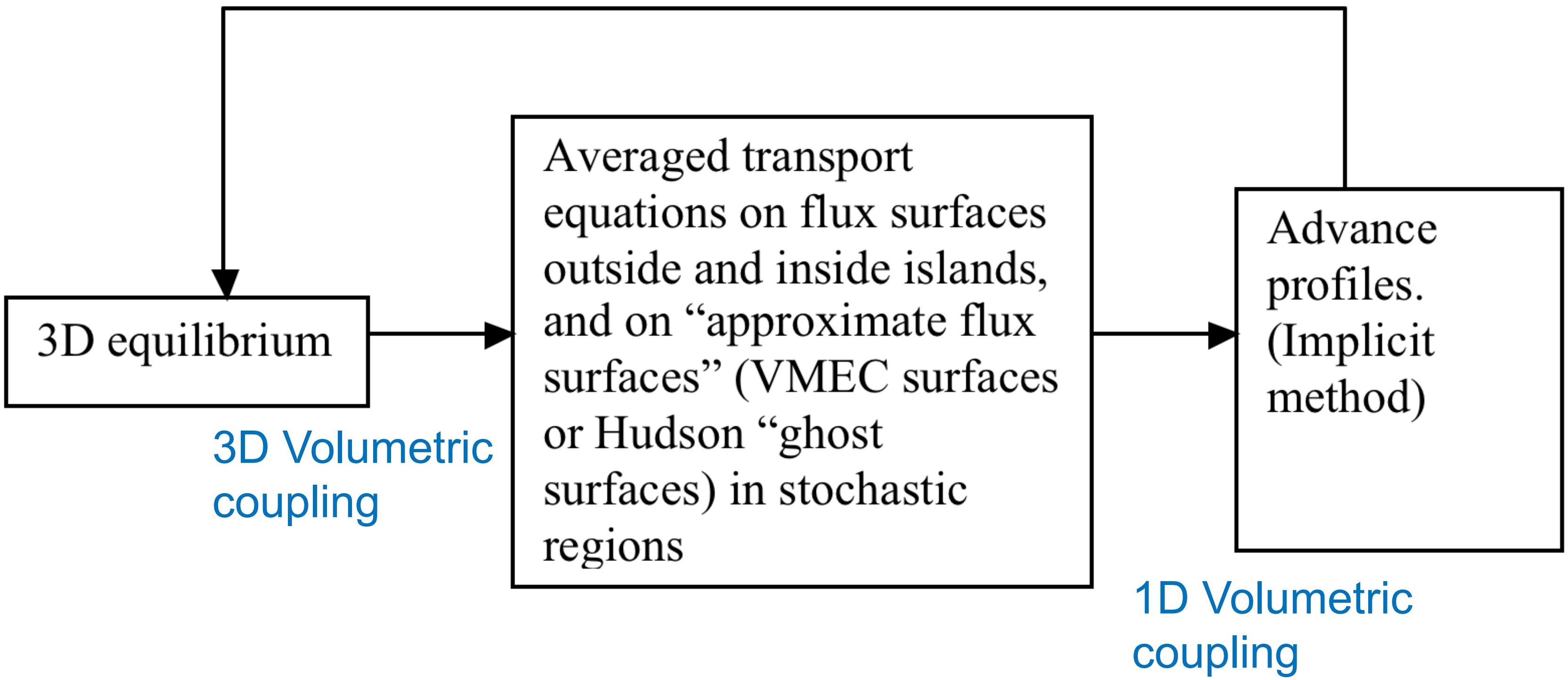
Validation

Plasma Model	Free-bndr transport, Extended MHD, …
Radiation Modeling	
Material Wall Model	Thermal hydraulics, Erosion codes, …
Structural Wall Model	Structural mechanics, heat transfer, …
Mitigation actuator models	Pellet, MG injection, …

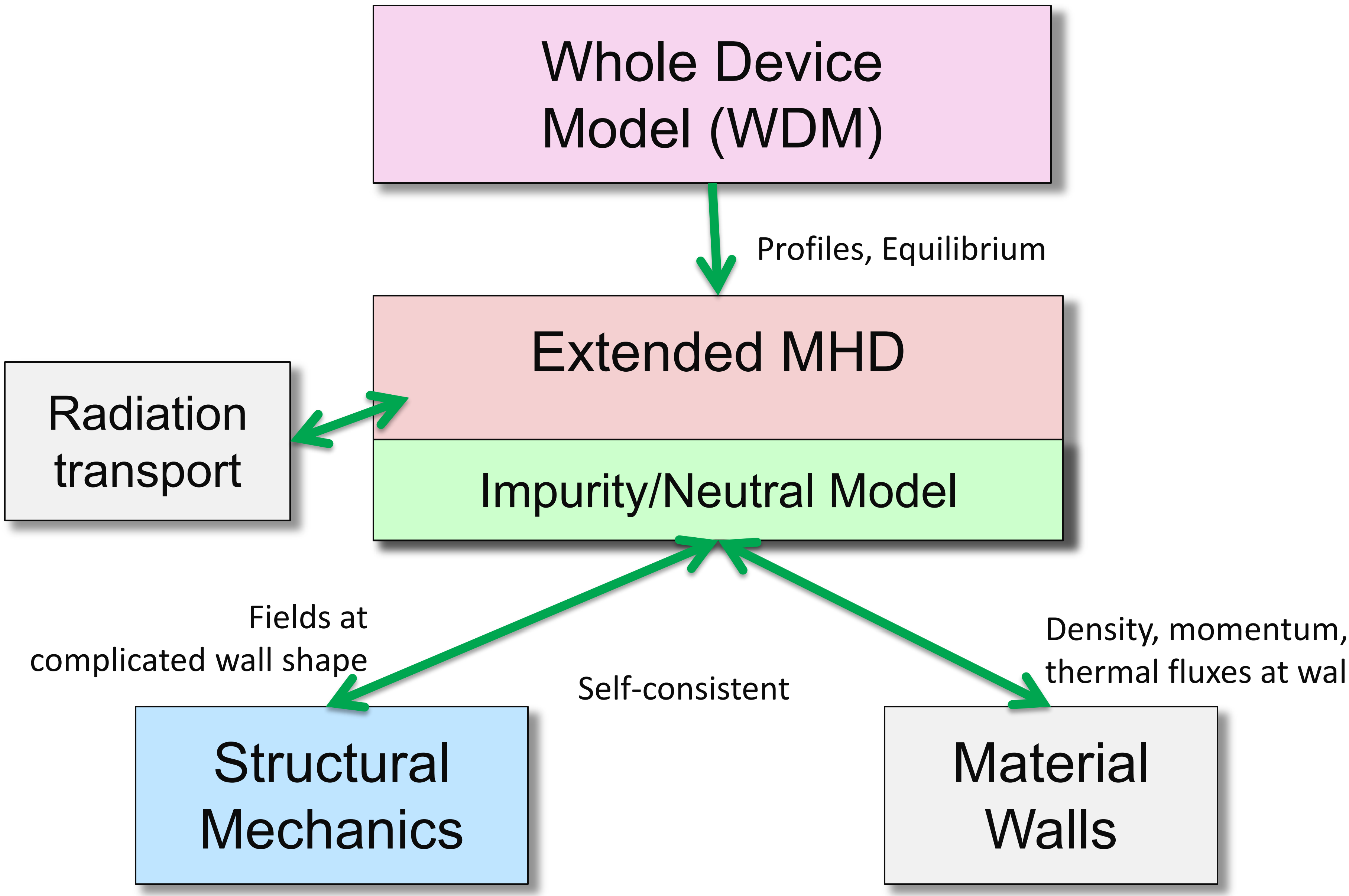
Near term coupling



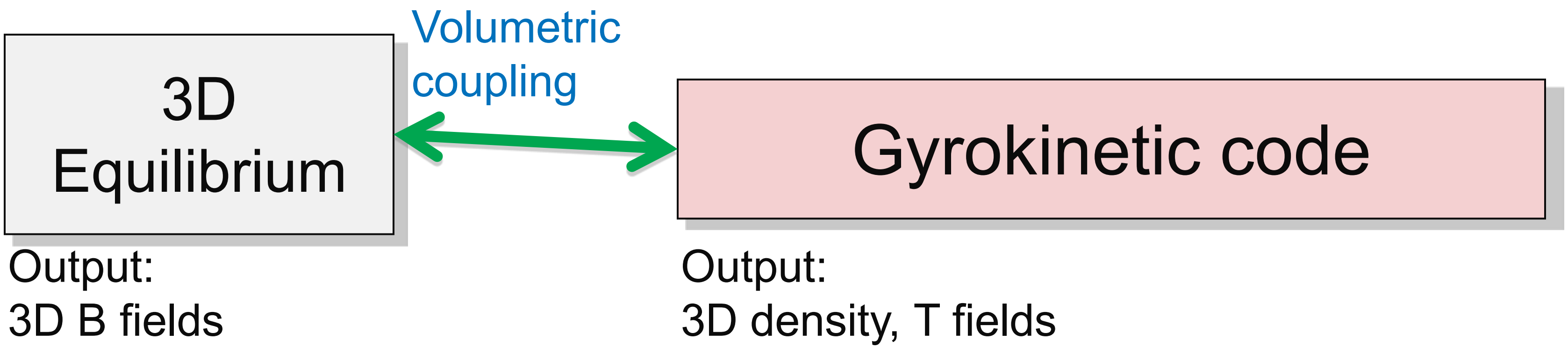
Mid-term coupling: long time-scale modeling



Long-term coupling



Example advanced component: Kinetic MHD in 3D field for Modeling Thermal Quench



Early: Single-helicity island
Eventually: Stochastic field

Wave-Particle Science Driver - Goals

- In alpha dominated burning plasmas, can collective fast particle phenomena significantly affect discharge evolution, fusion performance and facility integrity?
- Can RF waves couple into the core of a fusion plasma and be used to effectively control the plasma in the presence of multiple energetic particle species and edge dissipation mechanisms ?

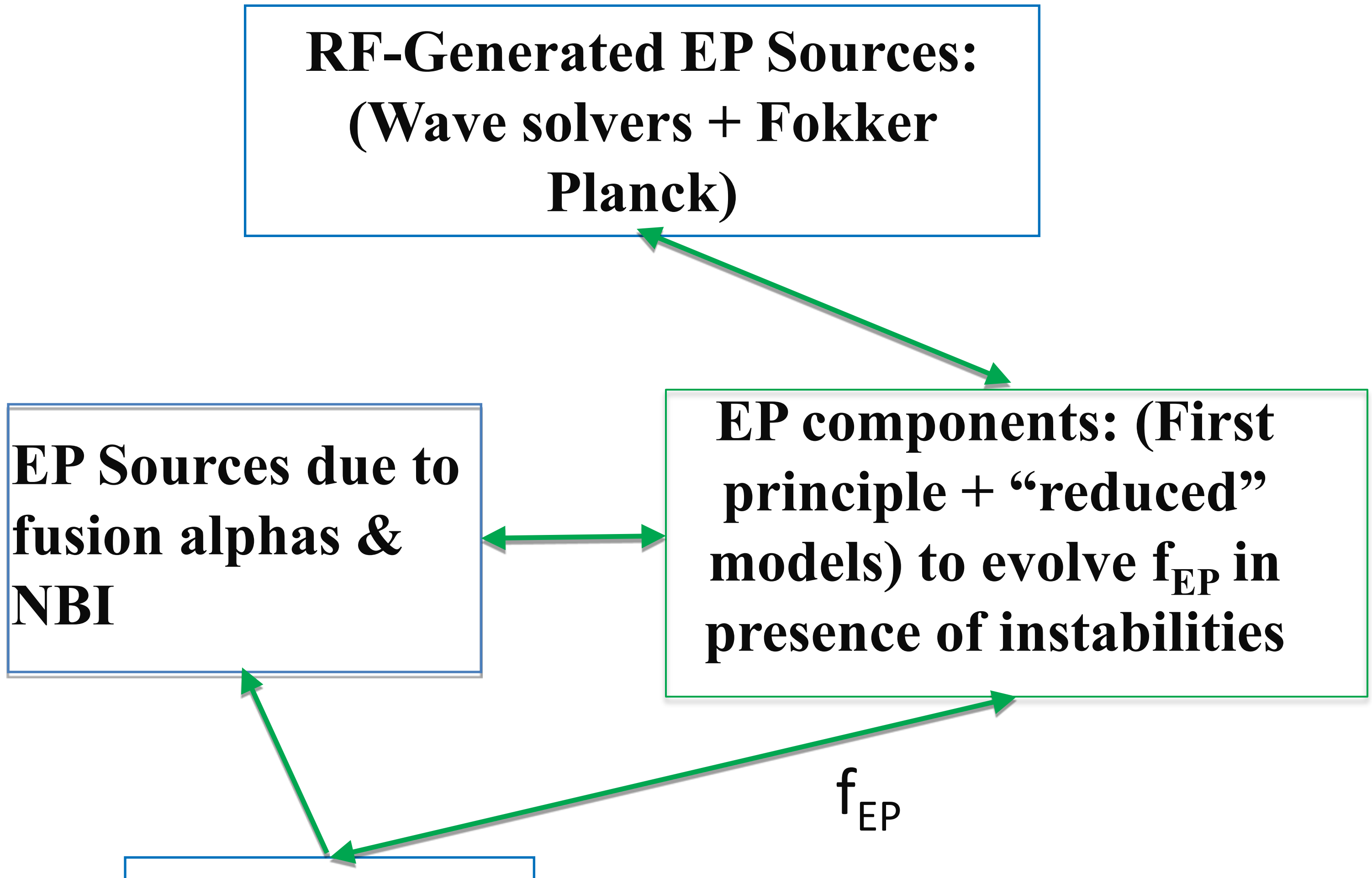
Requirements: EP Component

- **Near Term: (2-5 years):**
  - **Describe evolution of EP distribution due to Alfvénic/acoustic instabilities and other macroscopic MHD modes and collisions for whole device simulation, using lower dimensional model.**
  - **First principle simulation of nonlinear evolution of Alfvénic/acoustic instabilities and EP distribution in experimentally relevant conditions on the mode saturation time scale.**
- **Long Term (5-15 years):**
  - **First principle simulation of nonlinear evolution of EP driven Alfvenic/acoustic instabilities with macroscopic MHD in the presence of RF on transport time scales.**
  - **Predict fast ion transport and mode saturation levels and effects on macroscopic MHD in burning plasmas.**

Requirements: RF Wave-Particle Component

- **Requirements (2-5 Years):**
  - **Must describe linear edge-to-core coupling of ICRF and LHRF waves in realistic 3-D launcher & vessel geometry.**
  - **Core RF wave – fast ion interaction with finite ion orbit width effects.**
  - **Inclusion of ECRF wave induced flux in the MHD closure hierarchy.**
- **Requirements (5-10 Years):**
  - **Nonlinear RF effects (sheaths and PDI) combined with boundary layer and core wave solve.**
  - **Inclusion of ICRF generated energetic particle tails in the MHD closure hierarchy.**

Coupling schemes for integrated core wave – particle simulation



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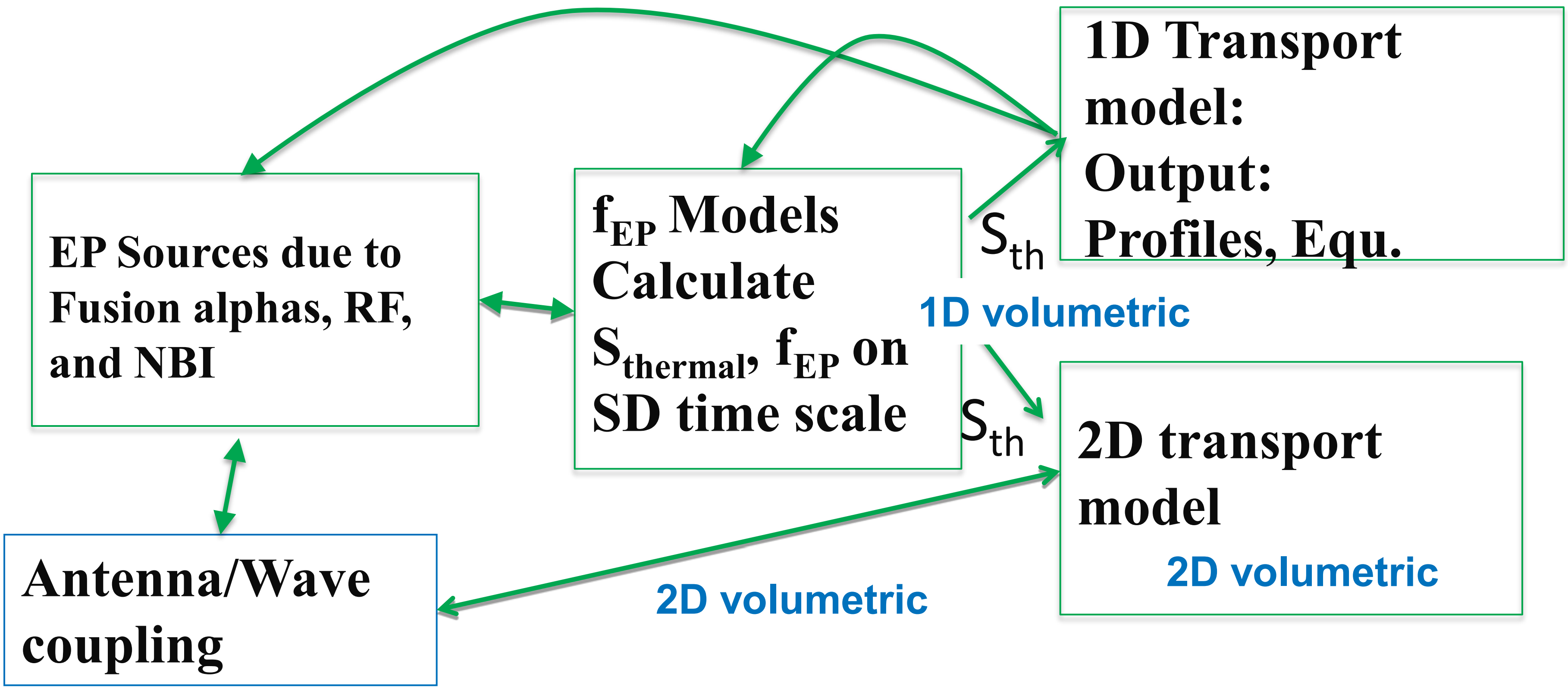
Coupling schemes for EP simulation with linear RF physics



Requirement: Include linear effects as wave propagates through SOL

Gaps: Energetic Particle Components

- **Gaps:**
  - **Must be able to simulate instability near marginal stability.**
  - **Synthetic diagnostics, including dynamic losses of energetic particles to the wall.**
  - **Realistic particle distribution functions in EP components.**
  - **Longer term:**
    - **Codes need to be extended to 3D equilibria.**

Gaps: RF Wave-Particle Components

- **Gaps:**
  - **Core wave solver plus 3-D description of RF launcher / vessel.**
  - **Core wave solver plus continuum Fokker Planck with finite orbit effect (improvement of bounce average resonant description from zero orbit width to finite orbit width).**
  - **Coupling of RF and energetic particle distributions with Alfven instabilities.**
  - **Inclusion of ECRF wave induced flux in the MHD closure hierarchy – implicit numerical scheme needs development.**
  - **Inclusion of ICRF generated ion tails in the MHD closure hierarchy**

Core profile and Whole Device Modeling

C. Kessel and W. M. Nevins for

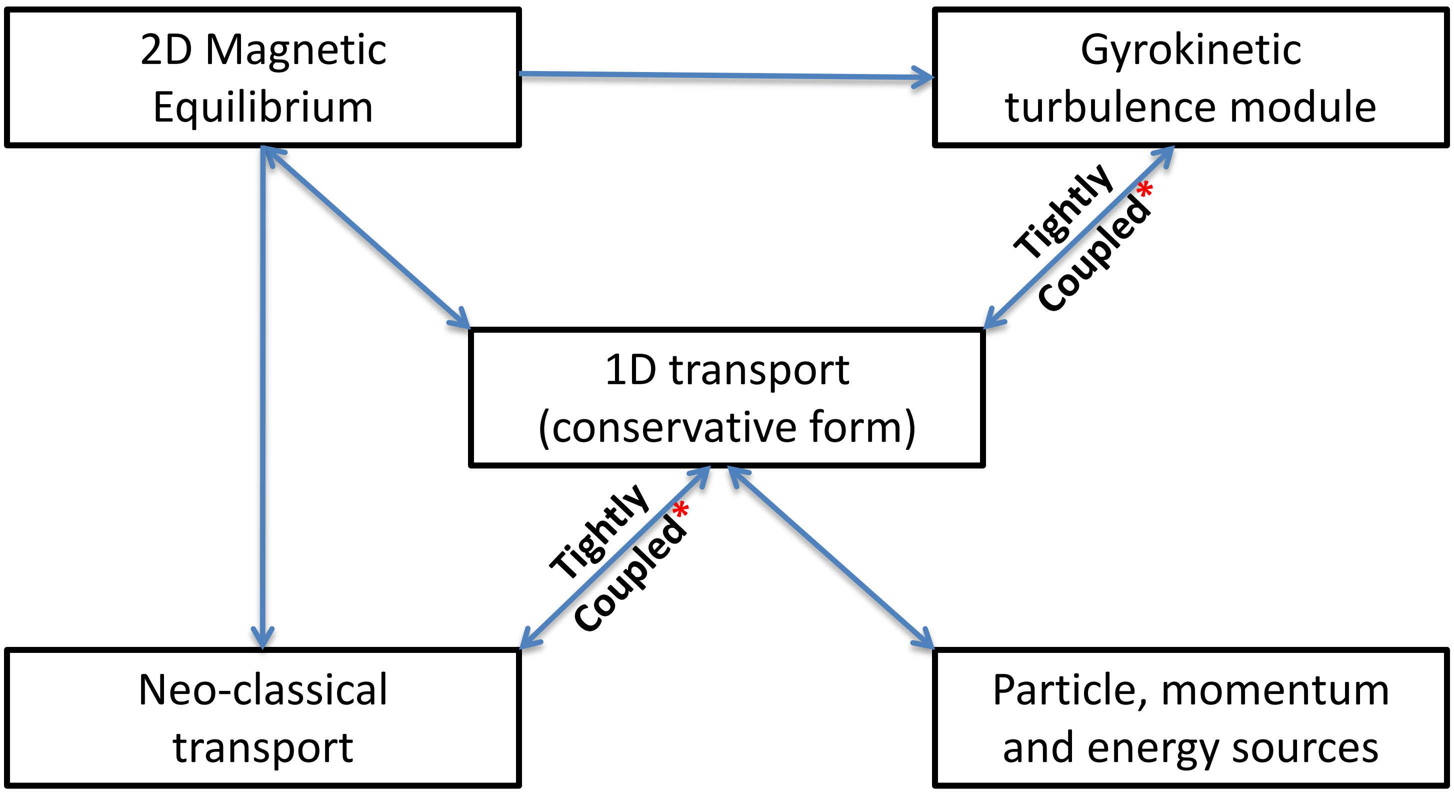
J. Candy, S. Parker, X.Tang, A. Reiman, D. McCune, T. Casper,
A. Hakim, J. Cummings, Tuesday breakout folks….

The core profile science driver

- A validated transport model, which reliably predicts, for each plasma species, profiles of
  - Density
  - Rotation
  - Temperature
  - Current

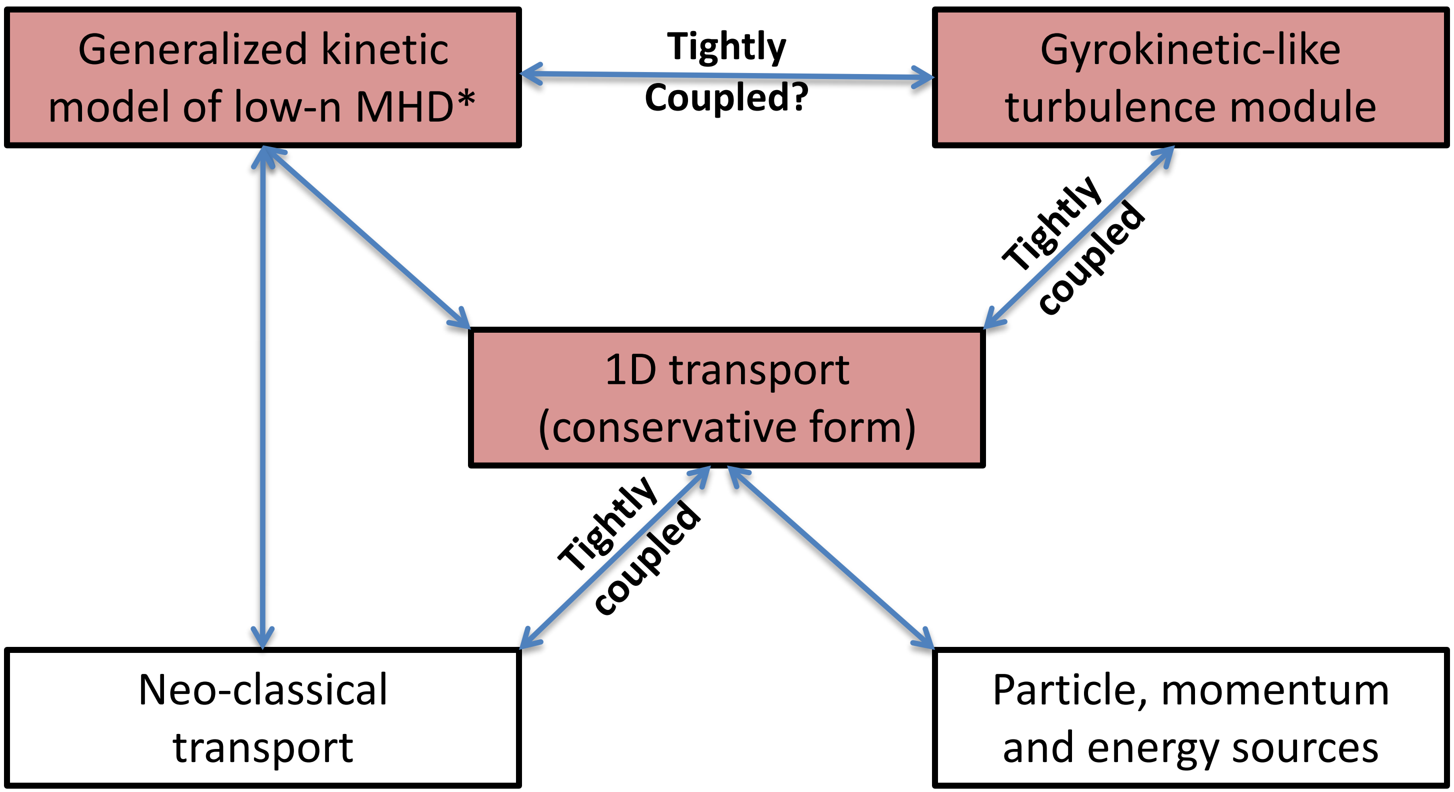
  and their evolution on the transport time-scale.
- Short-term (2-5 yr) objective:
  - A validated transport model which reliably predicts transport in MHD-free L-mode plasmas
  - Understanding the density profile, anomalous particle pinches and density peaking
- Longer-term (5-10 yr) objective
  - Understanding the interactions between neoclassical tearing modes and plasma microturbulence
  - Origin of Intrinsic Rotation

Components to meet short-term objectives



*Implicit coupling; transport passes advanced profiles; GK and neoclassical pass advanced fluxes

Components to meet long-term neo-classical tearing mode objective



*Describes evolution of 3D magnetic geometry including island

Indicates gap

Whole device modeling science driver

- A comprehensive model of the whole device, magnetic axis to wall, containing all relevant physics
  - Provides a platform for predictive simulation, interpretive analysis of experiments, and experimental data comparison for validation
  - Provides a framework that allows coupled components and multi-scale integration for time-dependent simulations
  - Allows multiple models of the same physics (models with progressive physics fidelity)
  - Accommodates production running AND highest physics fidelity demonstrations ("capacity" computing and "capability" computing)

Short term (2-5 years)

Equilibrium/transport evolution core component
Source components
Transport models (multiple models must be included)
Additional physics

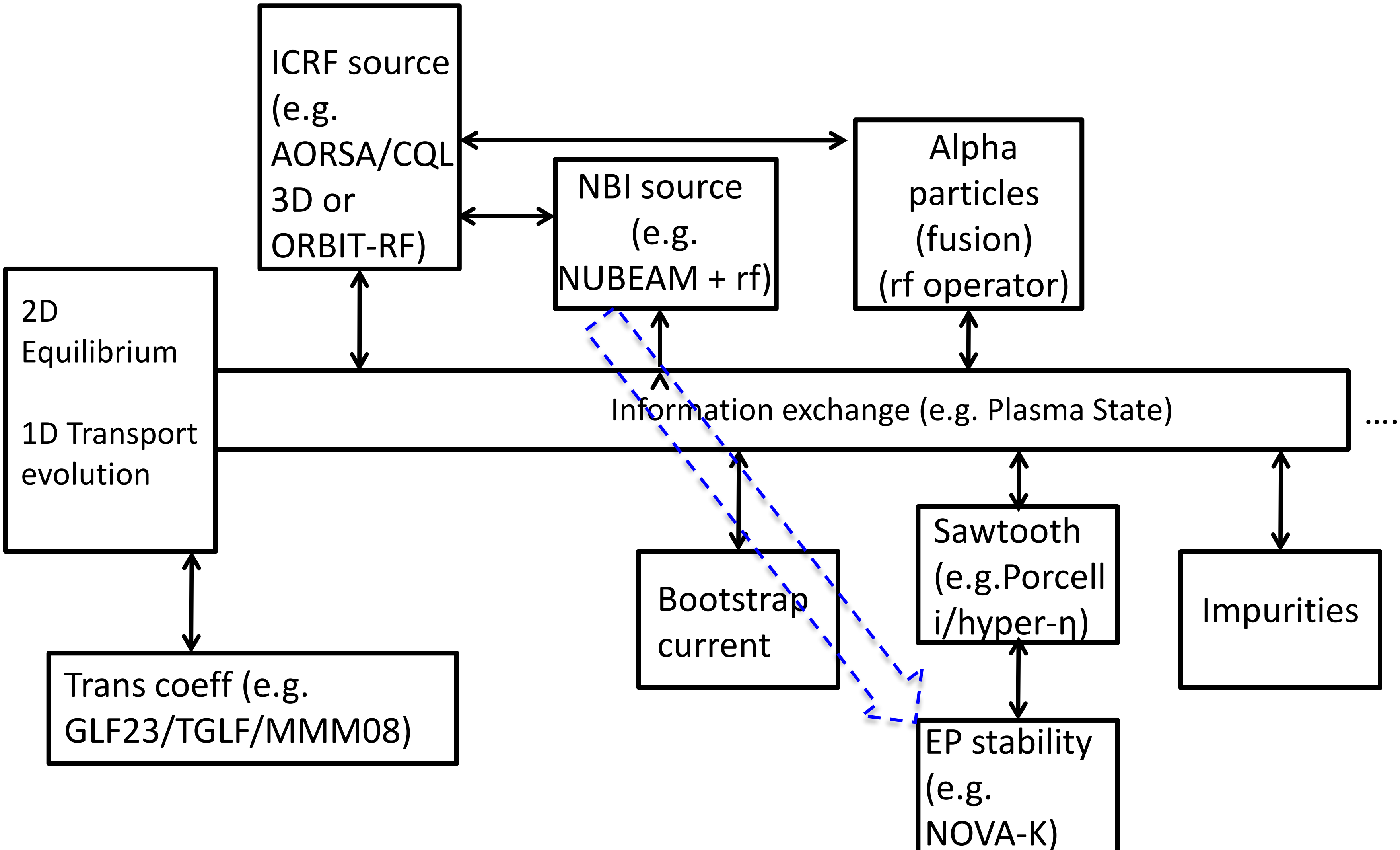
Perform simulations with WDM for both existing experiments and ITER leading to *identification of important "integration" physics*

Extend experimental validation demonstrations to time-dependent, exercising core synthetic diagnostic tools, across multi-devices

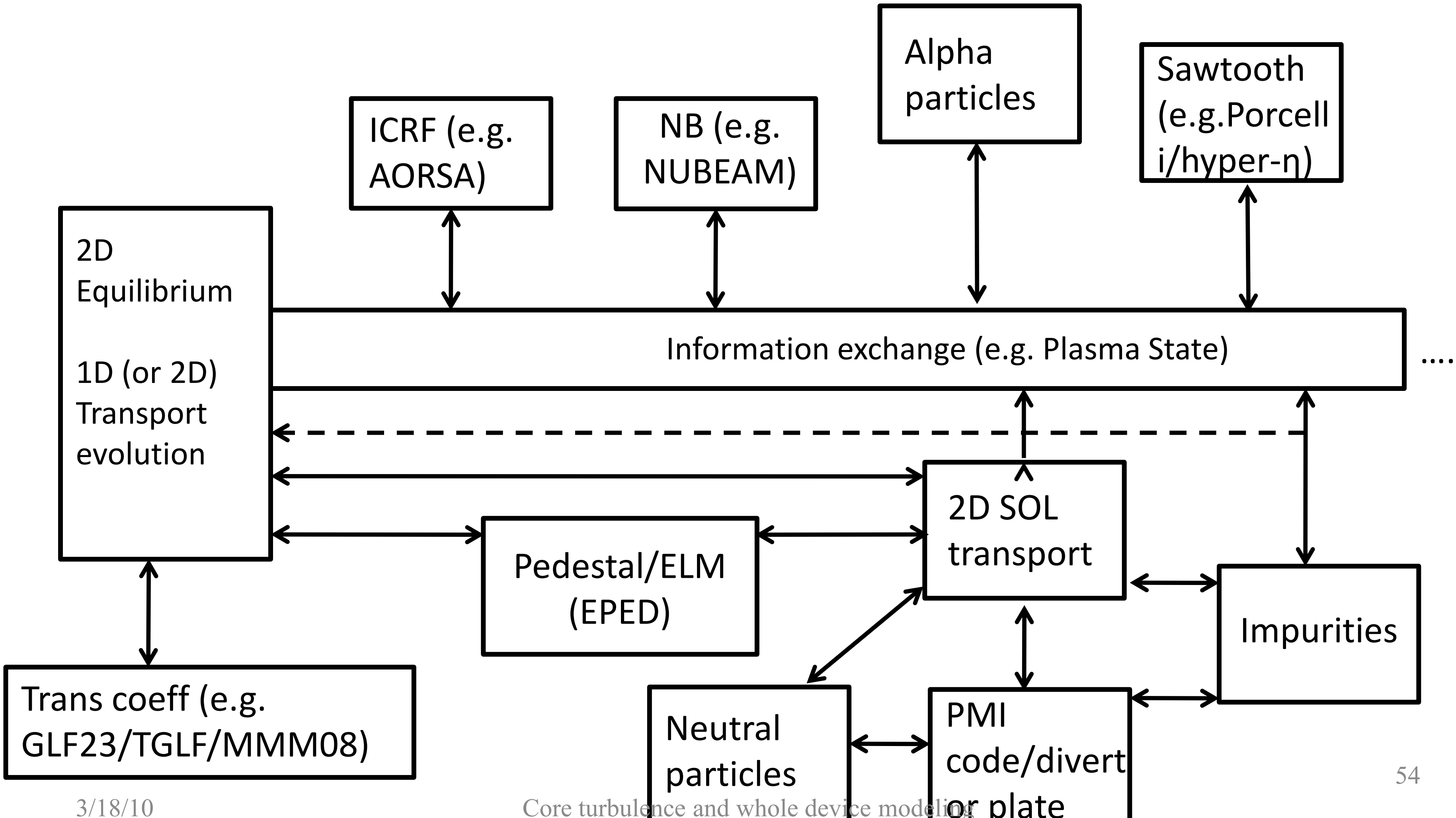
Access to high-fidelity core turbulence module, source models

Provide interpretive capability equivalent of TRANSP within framework

Short term (2-5 years)
Treating multiple fast particle species (NB, minority ICRF, and alphas) with FP in ITER burning plasma discharge simulation



Long term (5-10 years)
Simulation of the core/pedestal/SOL/divertor target and chamber wall interaction during ELM pulses in ITER



Longer term (5-10 years)

Implement tight coupling between the core and edge plasma, including the pedestal, the scrape-off layer and plasma wall interactions

Implement high fidelity models for interactions between fast particles and thermal particles, waves and plasma turbulence and instabilities

Implement 3D fixed and/or free-boundary equilibrium that can handle magnetic islands and stochastic regions, along with reduced models for phenomena associated with 3D geometry such as sawteeth, neo-classical tearing modes, and plasma edge phenomena

Implement nonlinear extended MHD models for plasma instabilities and disruptions

Examine how the introduction of more elaborate physics models may change the framework and component connectivity requirements