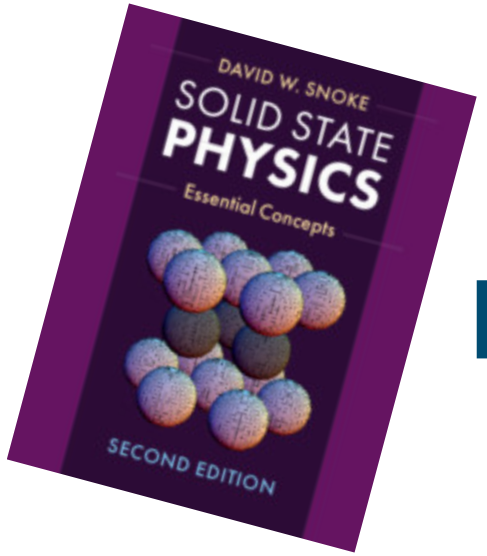
Commercialization of fusion energy

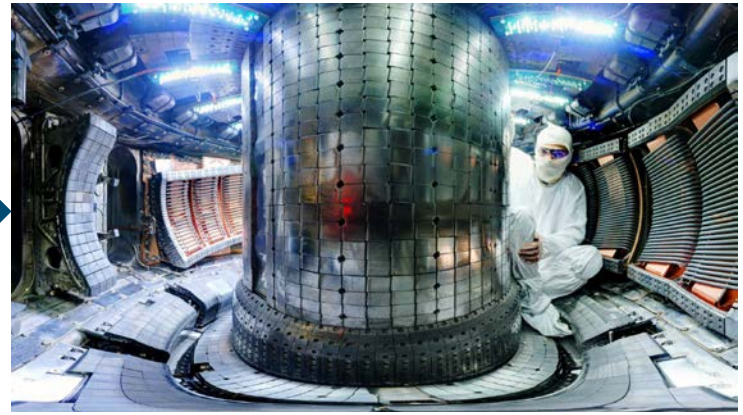
Bob Mumgaard

Commonwealth Fusion Systems

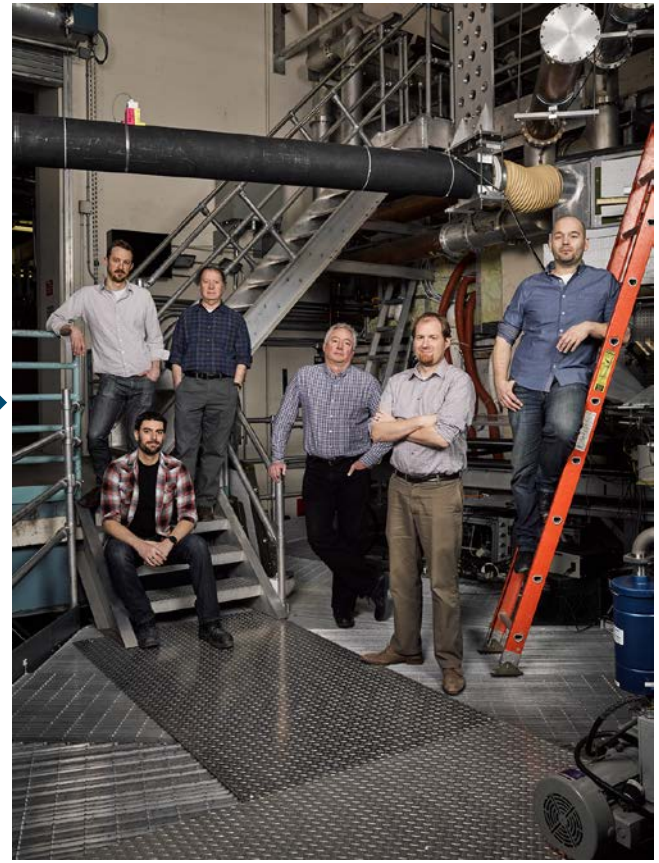
My road to founding a fusion company



The beauty of physics



MIT PhD, Alcator C-Mod



CFS

The world needs reliable, carbon free energy - Now

THE HILL

Climate change is no longer a future problem

BY SHAHIR MASRI, OPINION CONTRIBUTOR — 12/03/18 03:30 PM EST

468 COMMENTS

THE VIEWS EXPRESSED BY CONTRIBUTORS ARE THEIR OWN AND NOT THE VIEW OF THE HILL

SCIENCE

The Atlantic

California's Wildfires Are 500 Percent Larger Due to Climate Change

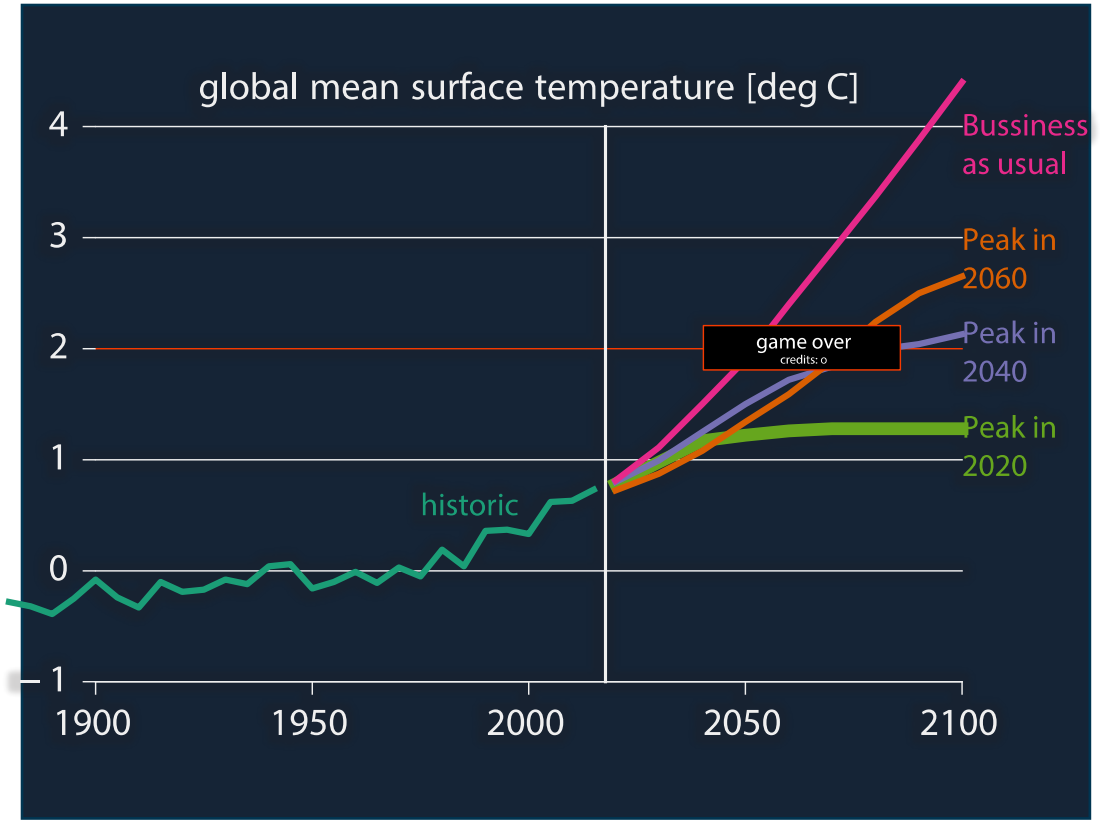
The Washington Post

Capital Weather Gang

After a blistering heat wave boosted by climate change, Europe just notched its hottest June on record

Is fusion relevant to the climate crises?

- If so, this sets the timing:



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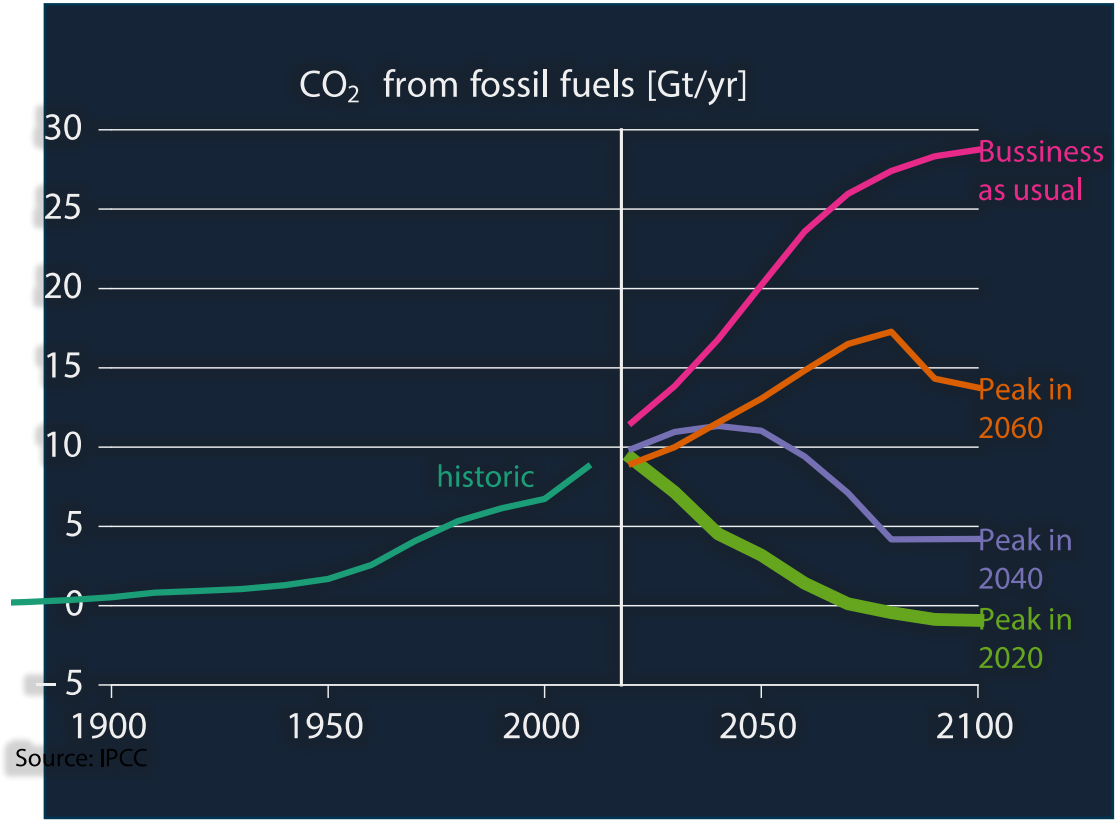
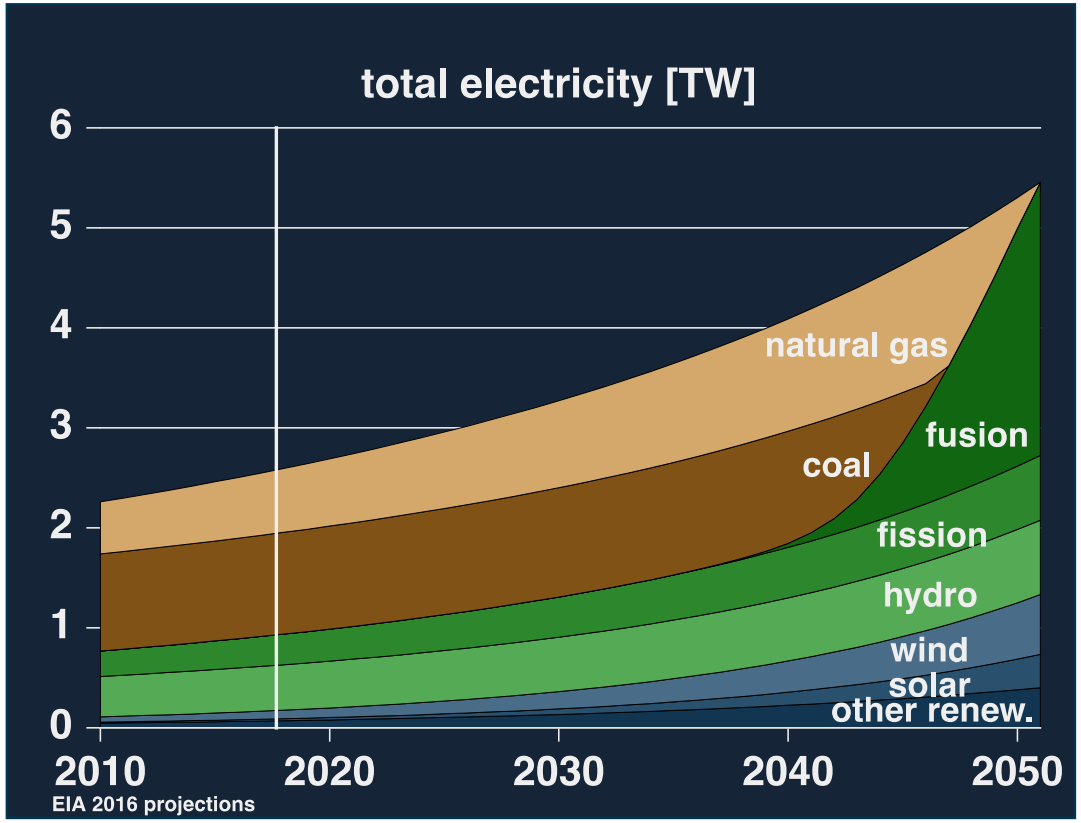


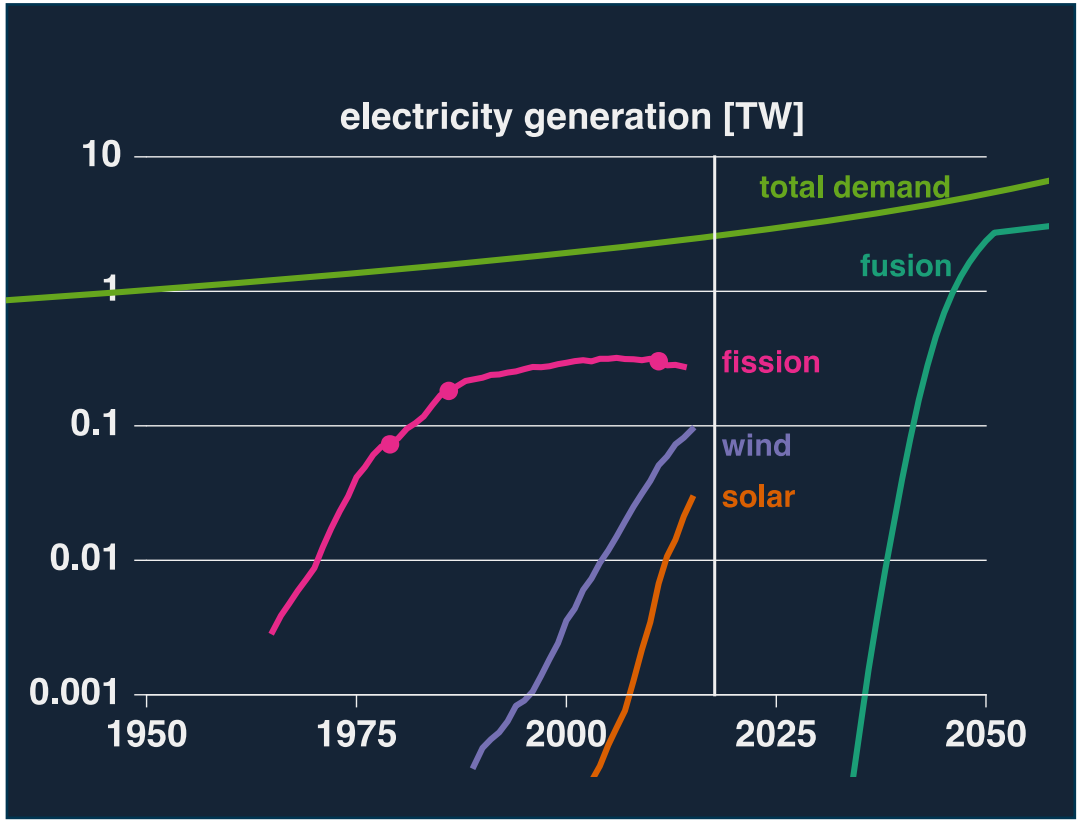
Is fusion relevant to the climate crises?

- If so, this sets the timing:
  - Scaling rapidly in the 2040s



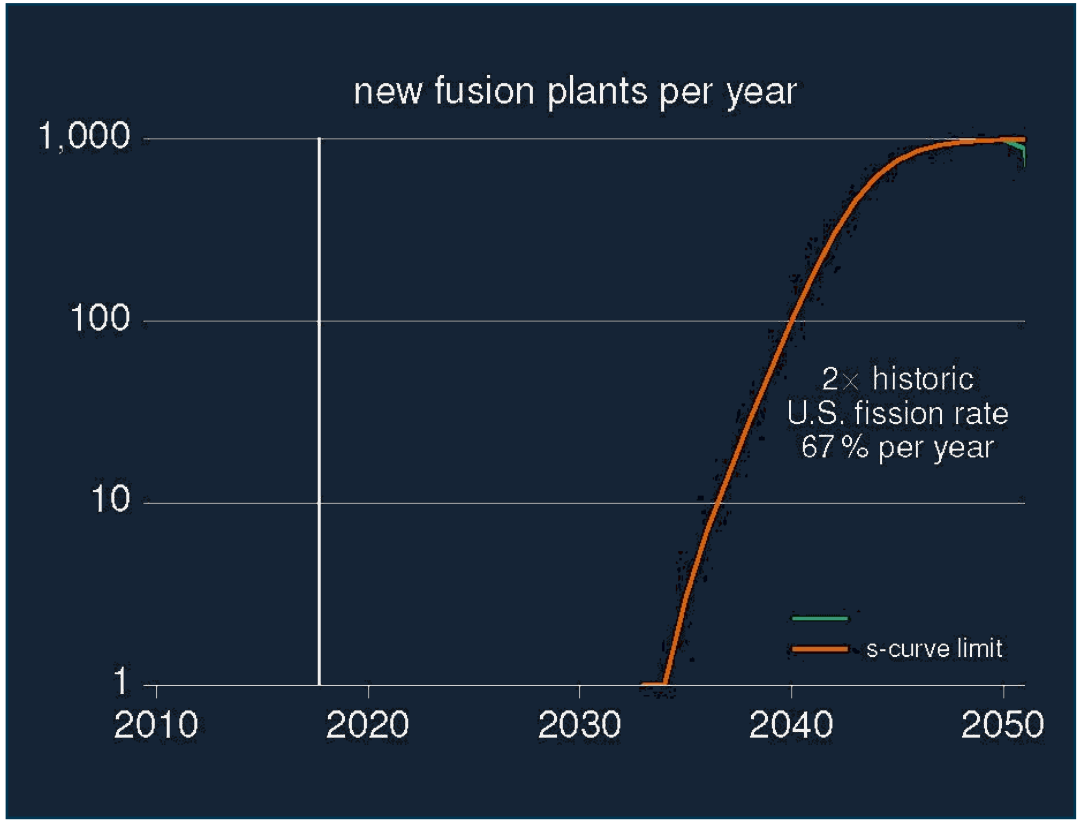
Is fusion relevant to the climate crises?

- If so, this sets the timing:
  - Scaling rapidly in the 2040s
  - Deploying first plants in 2030s



Is fusion relevant to the climate crises?

- If so, this sets the timing:
  - Scaling rapidly in the 2040s
  - Deploying first plants in 2030s
  - Demonstrating market-indicators in 2020s



Is fusion relevant to the climate crises?

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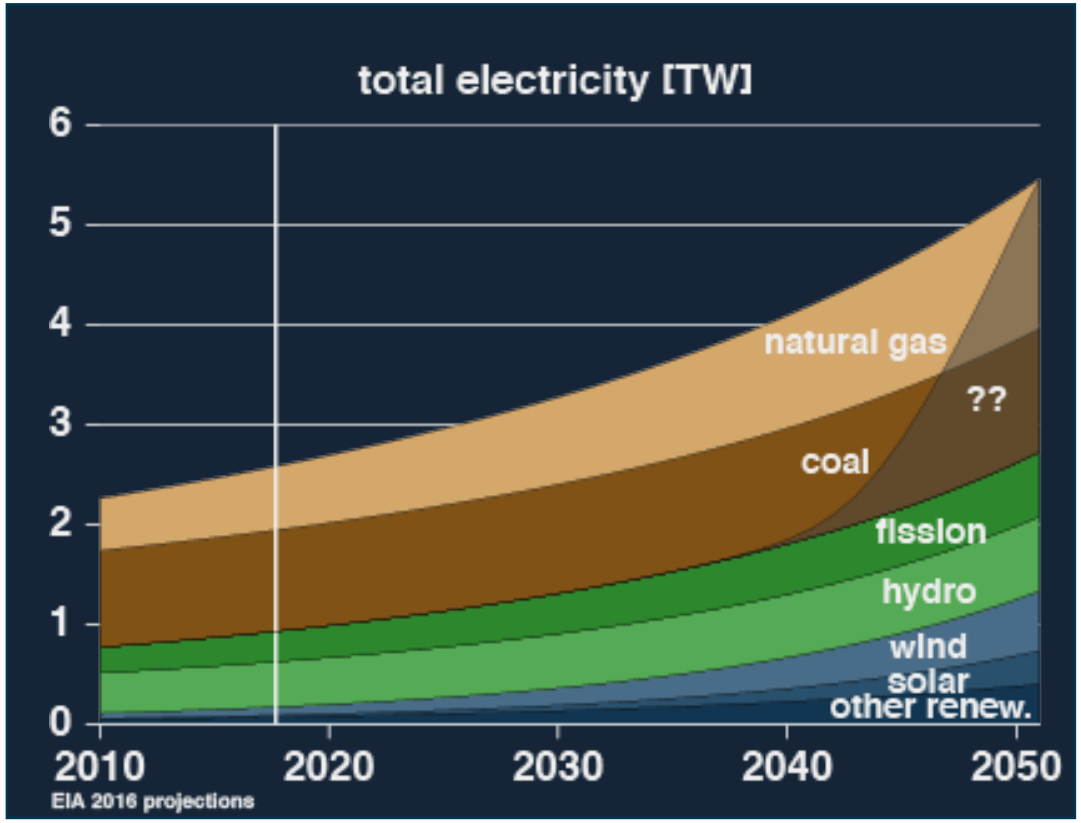
- If we can't hit the timing:
  - Something else will, or things won't go well



The market will decide

Is fusion relevant to the climate crises?

- If so, this sets the timing:
  - Scaling rapidly in the 2040s
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- If we can't hit the timing:
  - Something else will, or things won't go well

2015-era Bob:

"So… what am I doing to make this happen?"

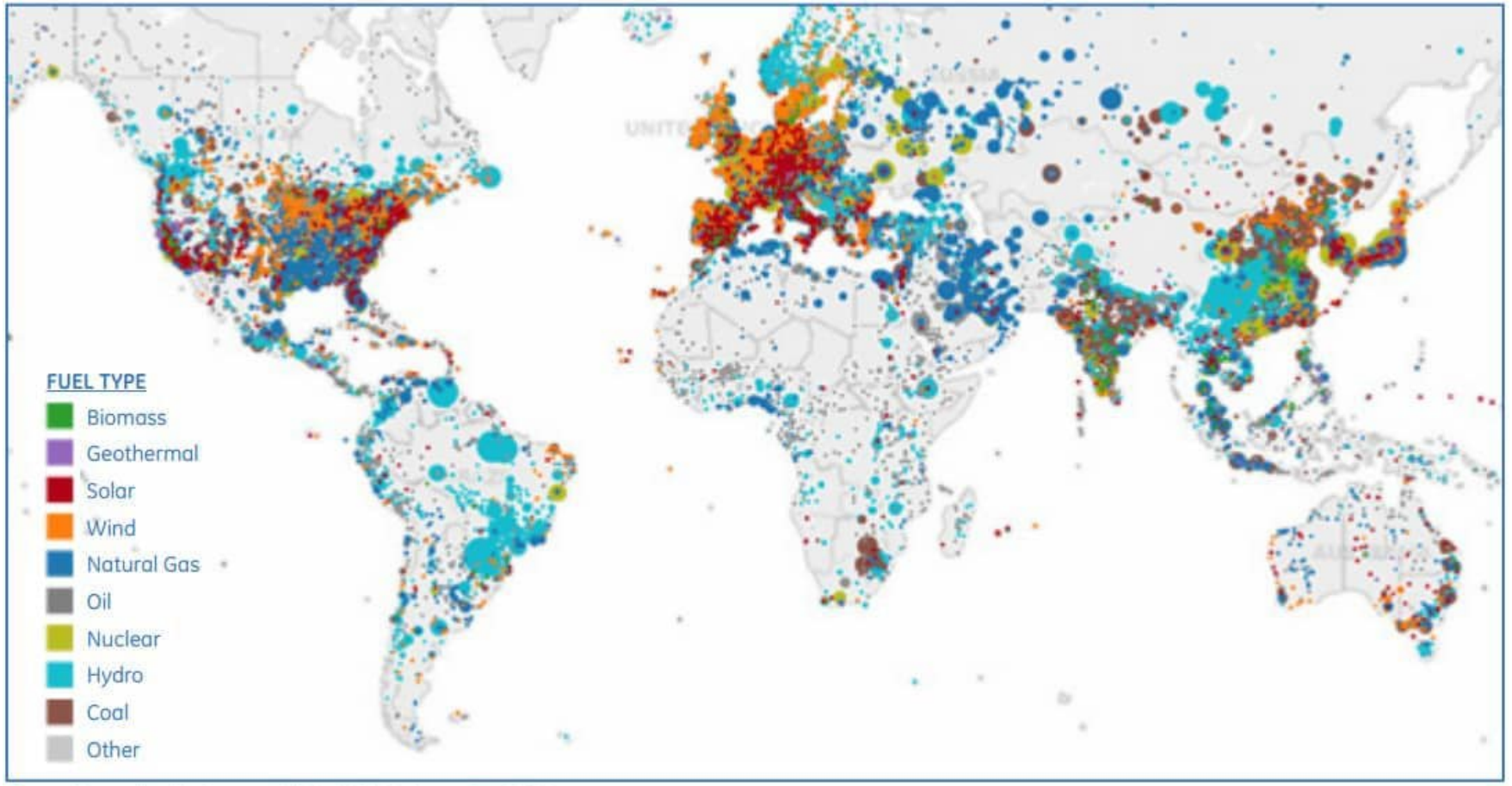
If fusion does not have a plan to participate in climate change mitigation we need to be honest with our stakeholders:

- The public
- Governments
- Our young people
- Ourselves

What is commercialization?

Imagine a world powered by fusion…..

Figure 7. Global Power Plant Fleet by Technology

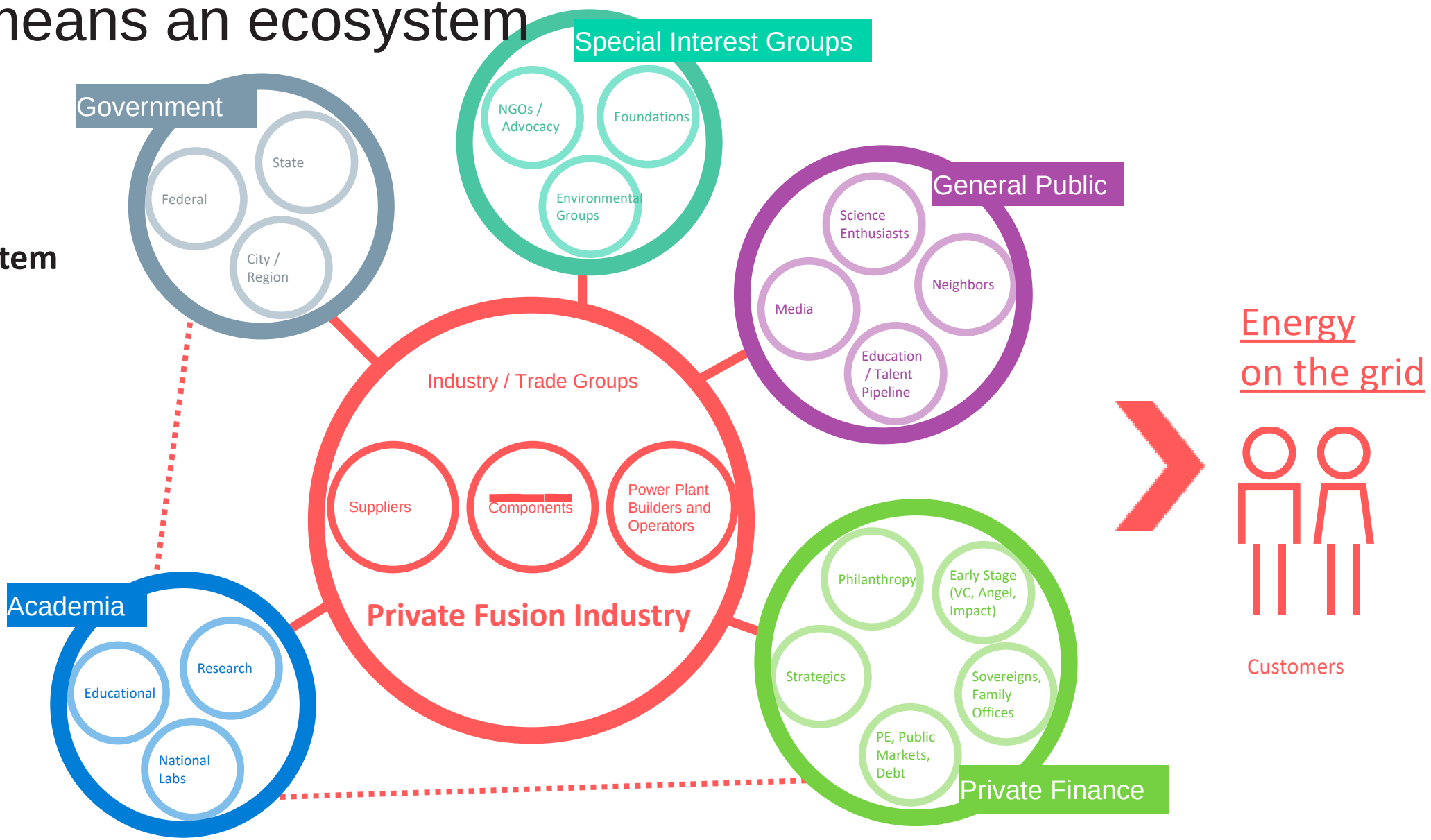


Source: Power plant data source Platts UDI Database, June 2012
Note: Circle size represents installed capacity (MW).

To make the impact on climate we need ~10,000 plants (of anything)

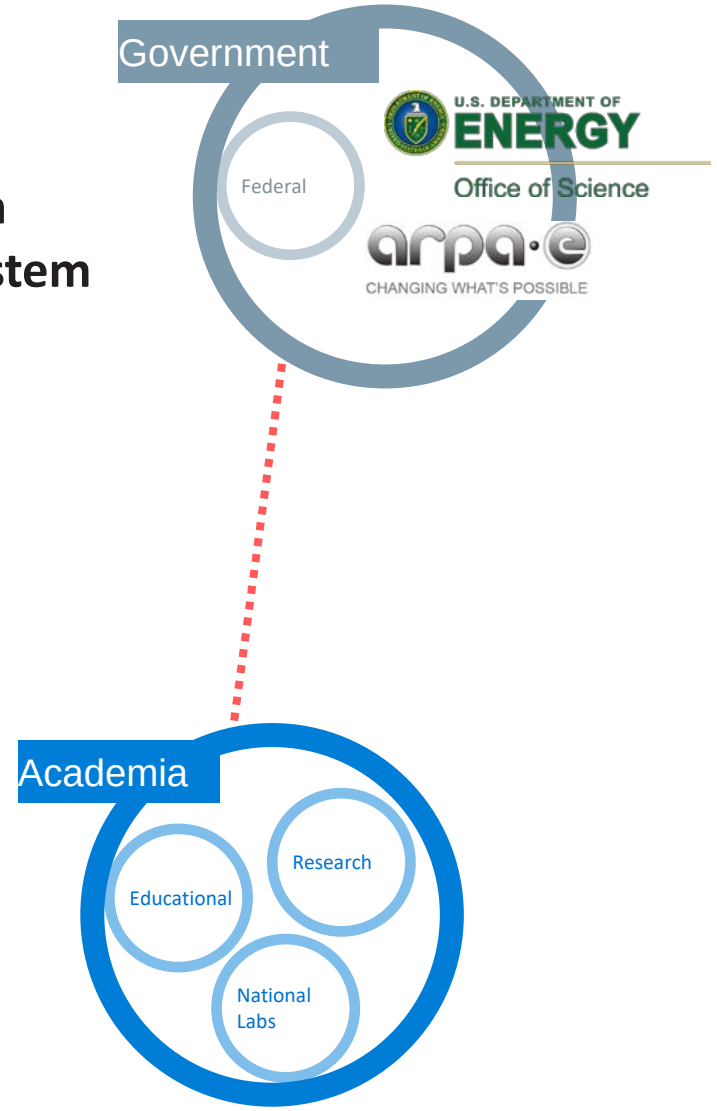
That means an ecosystem

Fusion Ecosystem



Where are we today?

Fusion Ecosystem

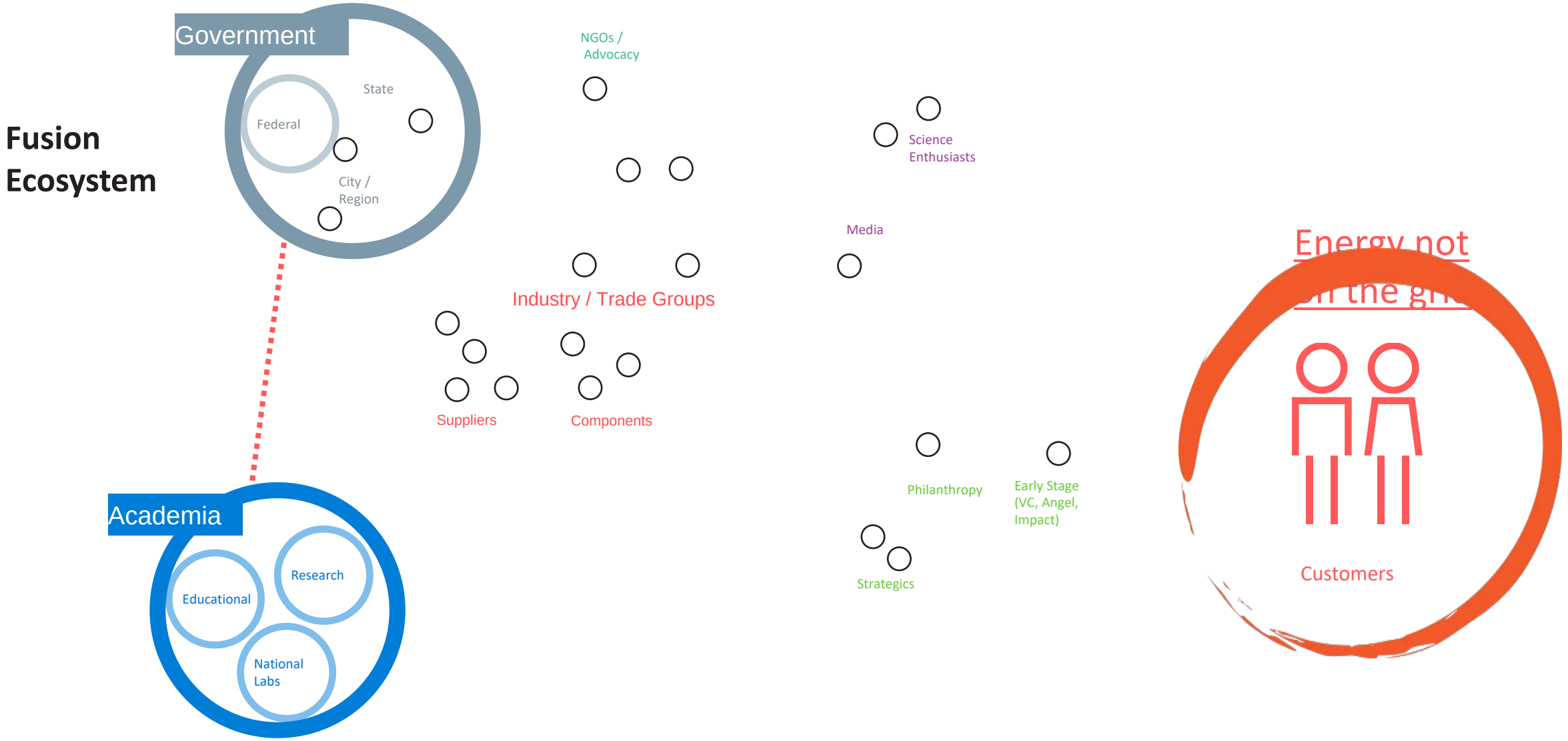


DOE office of science: 600M/yr
NNSA: 400M/yr
ARPA-E: 20M/yr

Energy not on the grid

Customers

To get there we're going to need to make fusion sellable



Enter the fusion companies

There is a nascent fusion industry

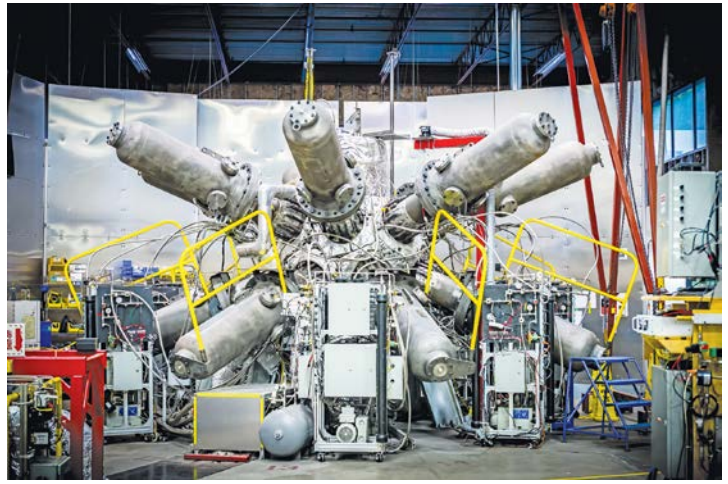
- There are many companies, the list is growing ~28
- They are optimizing for things beyond physics
  - Indicators about the fusion value proposition
- They can be extremely capable organizations
  - Move faster than gov't programs
  - Tight focus on deliverables and milestones
  - With less $ (now) and different resources than gov't
  - High-growth potential
- They are serious and thoughtful

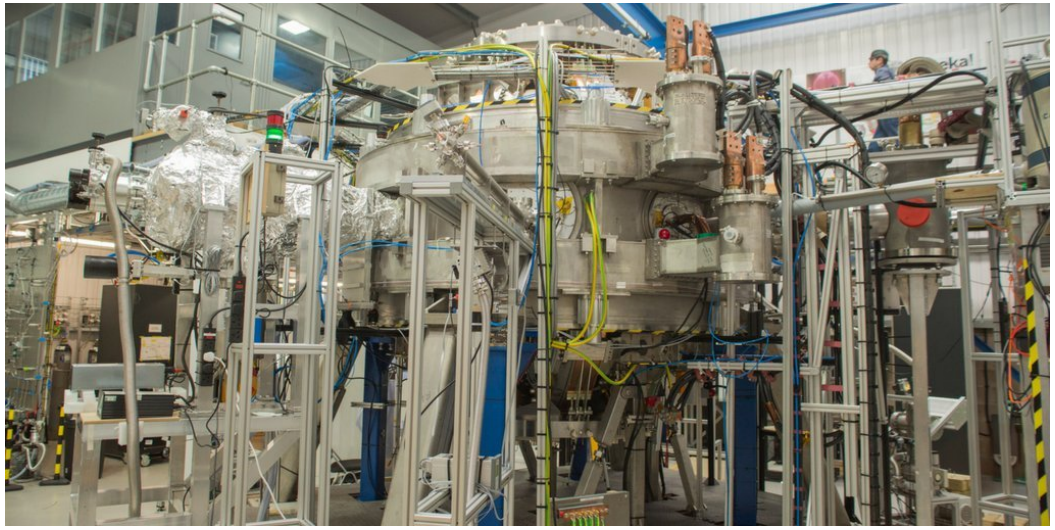
Fusion industry association is a convener

- FIA has been instrumental in bringing together the companies and pushing the government
  - Now up to 22 member companies with over $1.9B invested in companies ($1.4B last 5 years)
- Forum for discussion and coordination, data collection etc
- Strong report out to NGOs and government
- Leading the cost-share and public-private partnership pushes
- Three goals for FIA:
  - 1) Partner with gov. for applied fusion research
  - 2) Drive financial support
  - 3) Ensure regulatory certainty

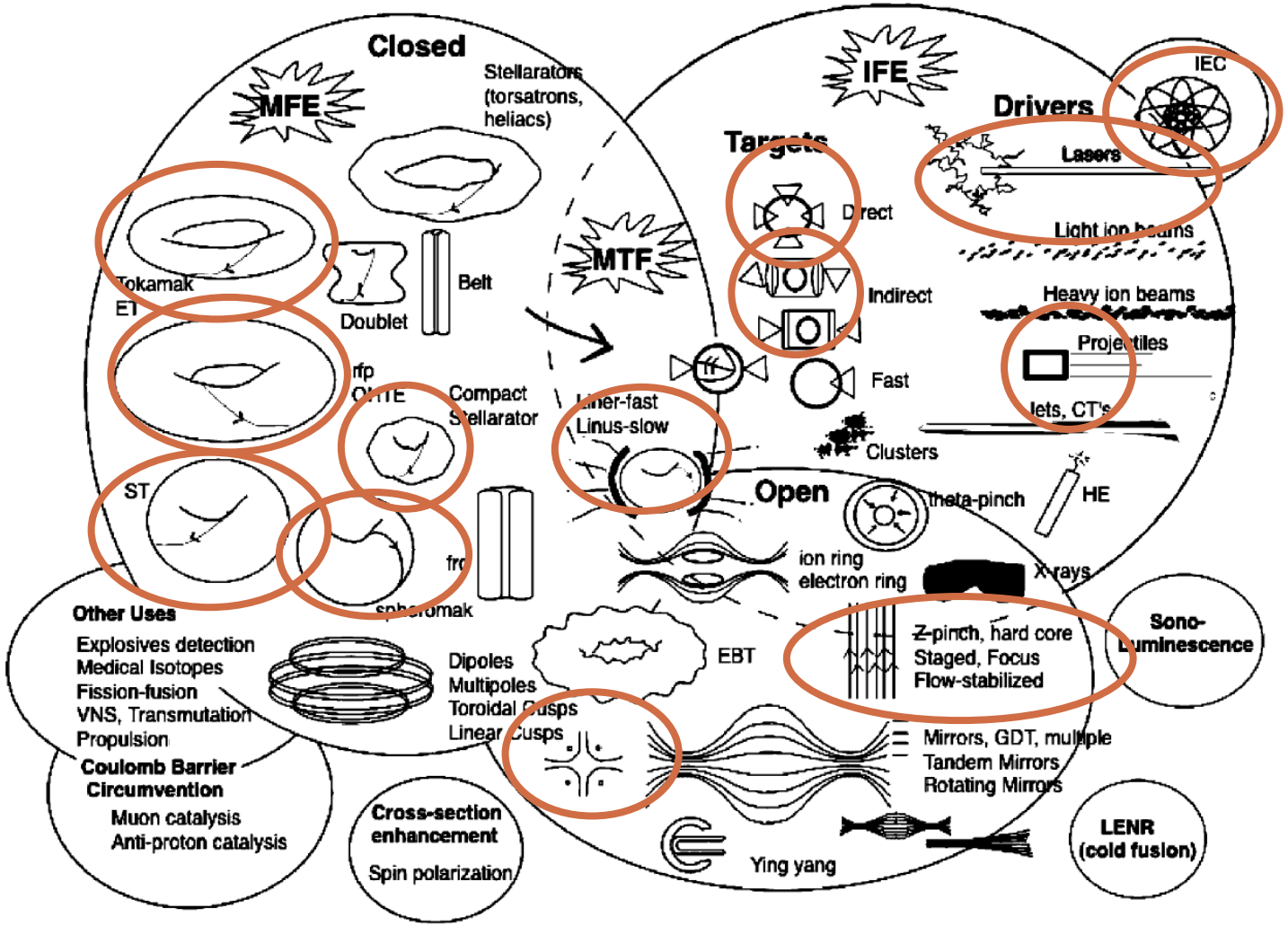
Good overview from FIA at the APS DPP CPP, recommended reading: https://drive.google.com/file/d/1xW8VEgrCTH5XCToXO1aJ-O3Fmv6AFJ7t/view

Growing fast… in number and capability



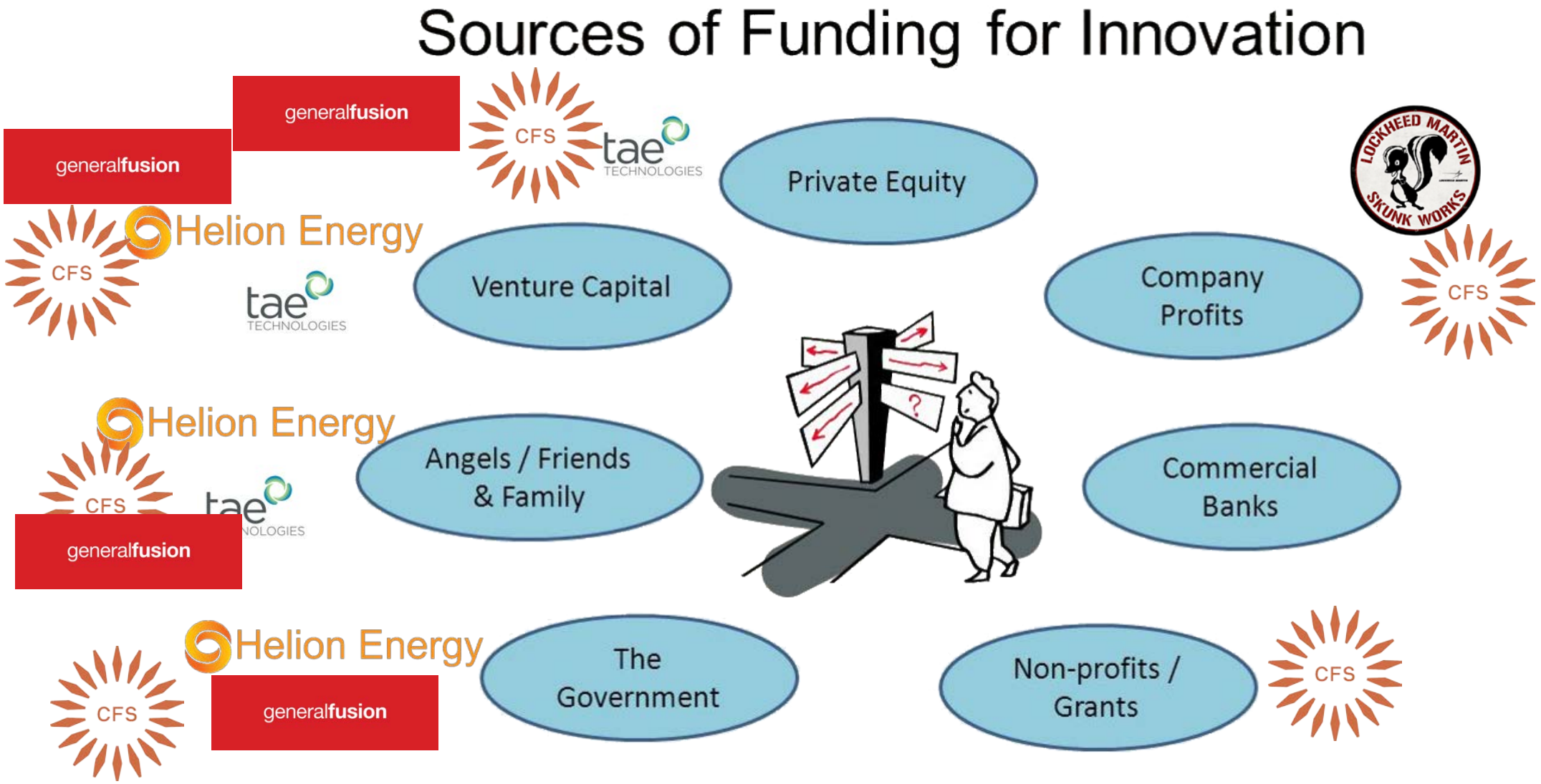


Different approaches but lots of things in common…

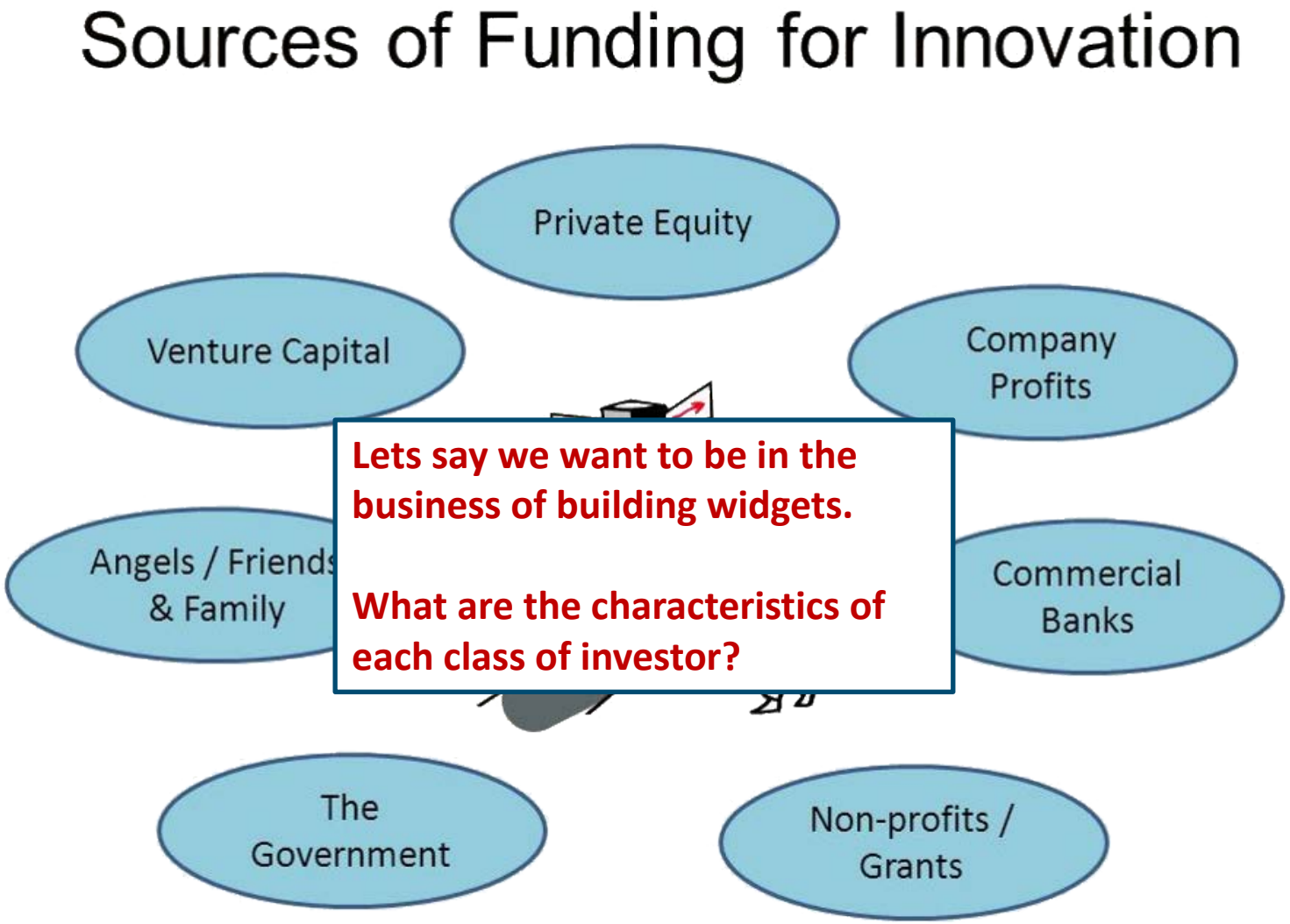


[1] S. Woodruff, *Journal of Fusion Energy*, **23** (2004) 27-40.

Backed by serious people



Lets review our options



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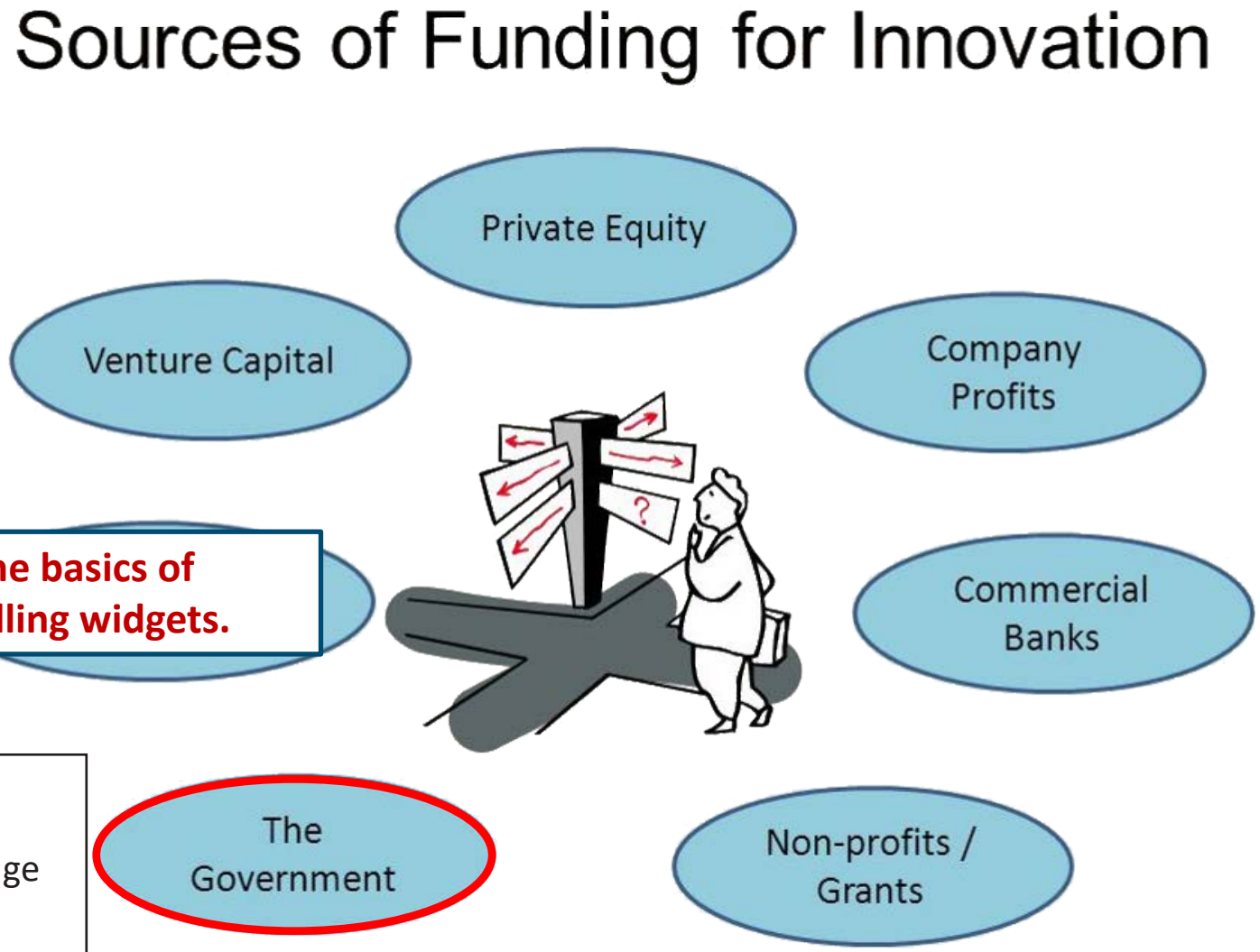


Will pay for research into the basics of widgets. But not to start selling widgets.

Who: The public
Risk tolerance: High
Return: Basic scientific knowledge
Timeline: Open-ended
Exit: None
Amount: $150B/yr in $M chunks

Lets review our options

Sources of Funding for Innovation

Private Equity

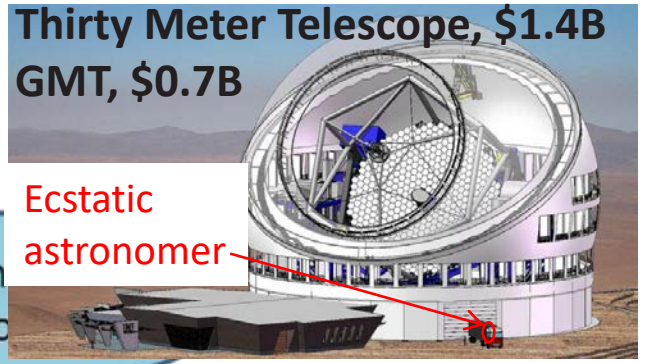
Venture Capital

Com
Pro

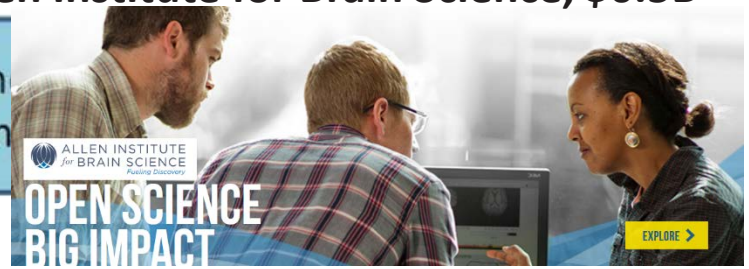
Angels / Friends & Family

Comm
Ban

Thirty Meter Telescope, $1.4B
GMT, $0.7B



Allen Institute for Brain Science, $0.5B



If you have given to the American Heart Association, you have participated in this.
…They spend that money giving grants to researchers.

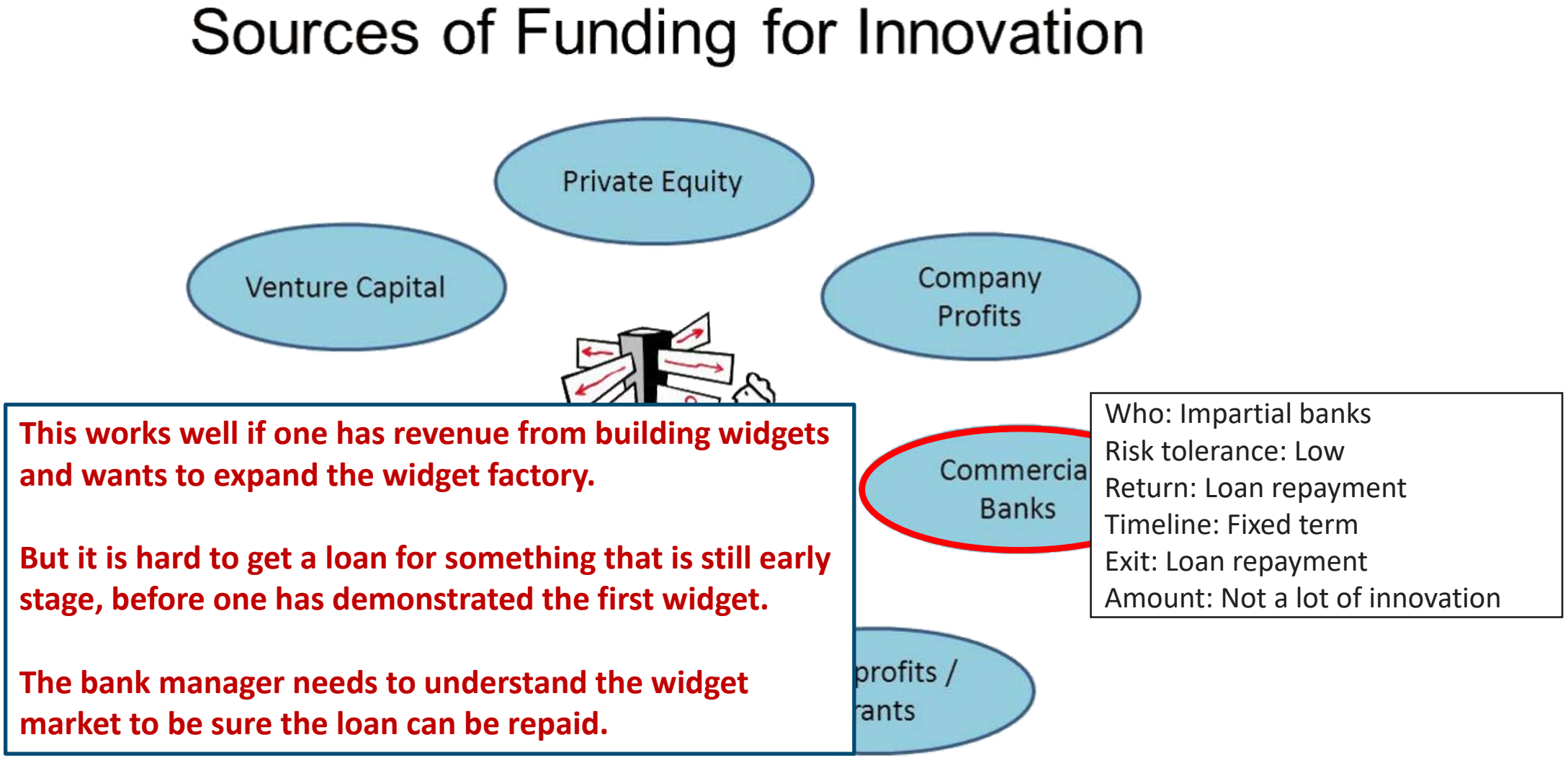
Passionate widget enthusiasts (or well off individuals) could start a non-profit to raise awareness of the impact of widgets on things or money to study widgets.

Non-profits / Grants

Venture philanthropy

Who: Passionate individuals
Risk tolerance: High
Return: Knowledge or Social good
Timeline: Open-ended
Exit: None
Amount: Unknown

Lets review our options



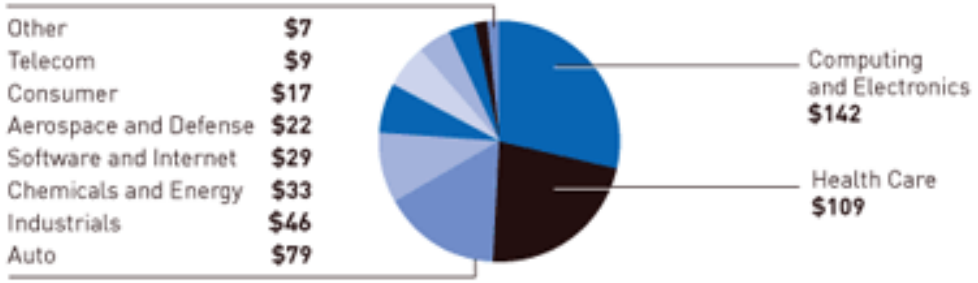
Lets review our options

Sources of Funding for Innovation

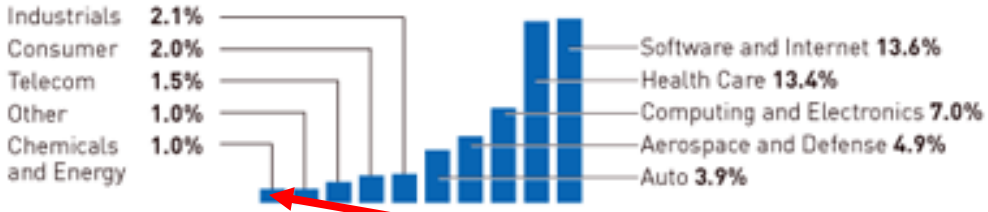
Exhibit 7: **Innovation Spending and Intensity by Industry**

The computing and electronics, health-care, and auto sectors continue to dominate overall R&D spending, with a combined total of $330 billion. The software and Internet sector, along with health care, spent the most on R&D as a percentage of sales by a wide margin.

Total 2007 Spending: US$492 billion

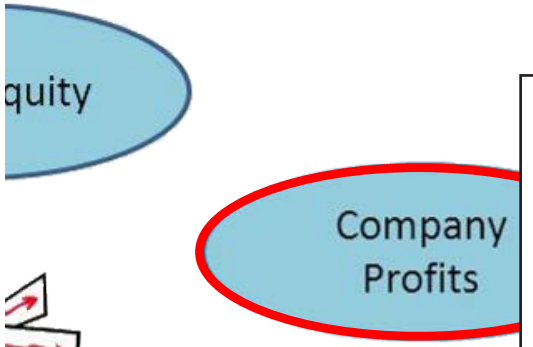


2007 Intensity (R&D as a % of Sales)



Note: Sums do not add up to the total due to rounding.

Source: Bloomberg data (2007), Booz & Company analysis



Who: The company
Risk tolerance: Moderate
Return: Better products
Timeline: Ongoing
Exit: Product launch or cancel
Amount: 1% of sales in energy sector

Future of the Widget Company is tied to future leadership in the widget market.

This works well if one has revenue from building and selling widgets and wants to develop the next generation of widgets. They might even sponsor widget research at a place like MIT.

If it is an energy-related widget, industry doesn't do as much as if it is a pharma or software widget.

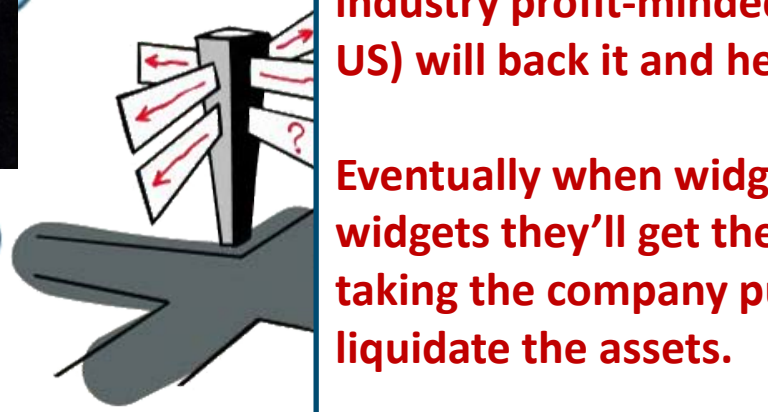
Lets review our options

Funding fo

Private Equity

Who: Private individuals looking for solid return
Risk tolerance: Low-moderate
Return: Steady profits from established companies
Timeline: 10 yrs
Exit: Grow company to IPO or acquisition
Amount: Lots

Angels / Friends & Family



The Government

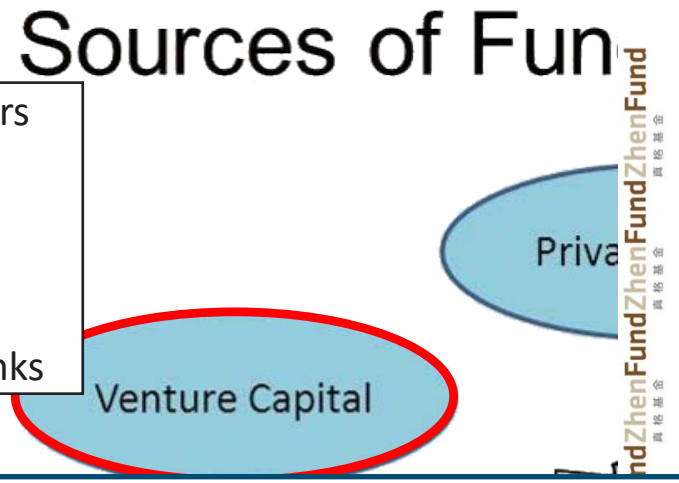
If it looks like the widget works and is going to be a solid industry profit-minded people and governments (not the US) will back it and help it grow.

Eventually when widget factories are pumping out widgets they'll get their return by selling their stake or taking the company public or if things go bad they'll liquidate the assets.

They are not widget enthusiasts, They are money enthusiasts.

Lets review our options

Who: Pool of like-minded investors
Risk tolerance: High
Return: “Unicorns”
Timeline: 7 yrs
Exit: Sell shares
Amount: $30B/yr in 1-10$M chunks

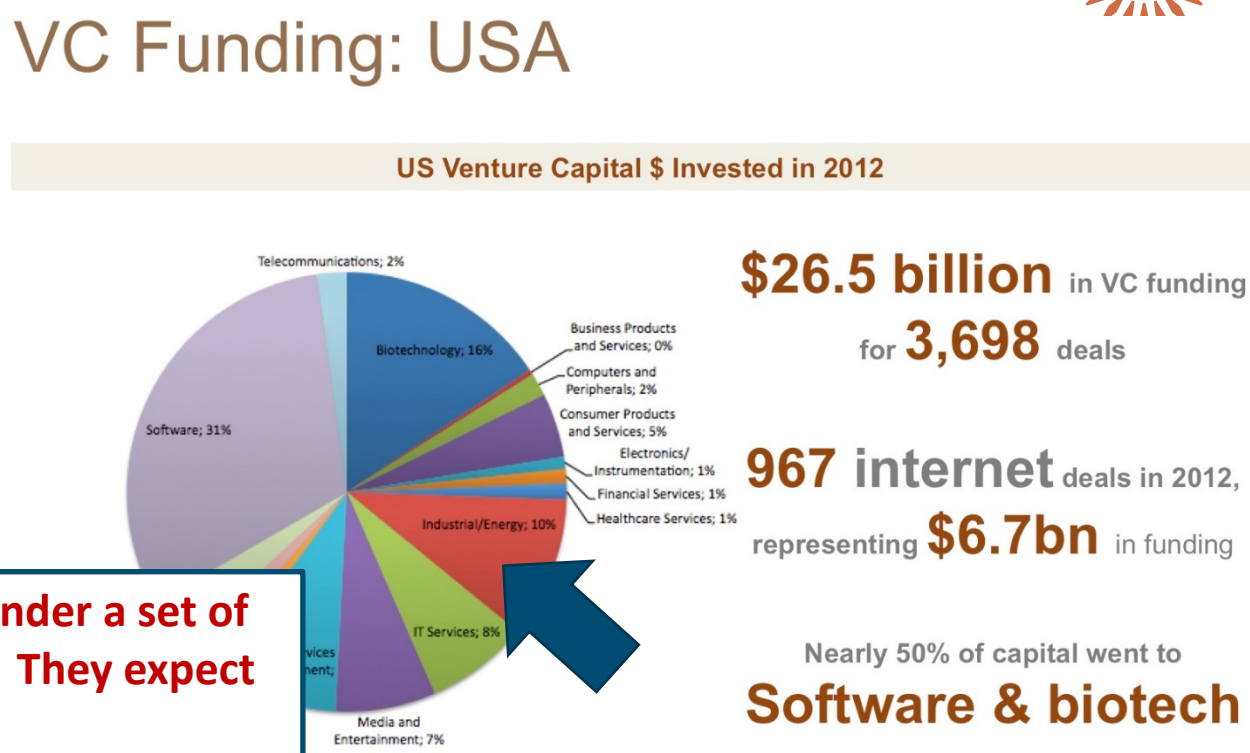


Well-off people who try to predict the future pool their capital under a set of investment rules and invest in many different early stage things. They expect 9/10 to fail but 1/10 to return 20x-50x.

If they think widgets could be “The Next Big Thing” they hire experts to look into it and try to map out all the research that needs to be done to retire risks. If it looks feasible they invest and try to guide the company toward the future.

They believe in the power of the widget to transform society but are realistic that it might not happen.

They invest in software widgets and not as many energy widgets.



Lets review our options

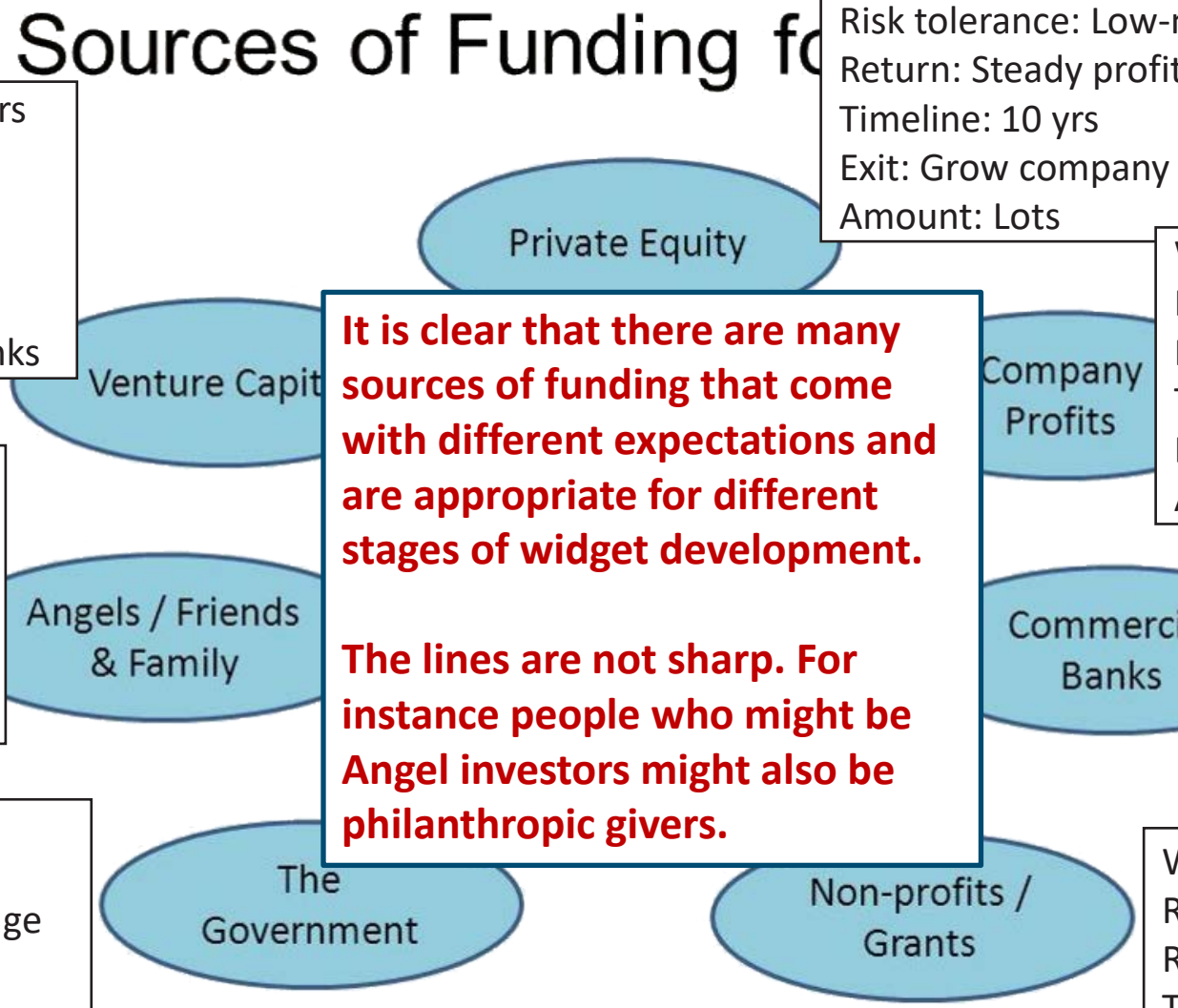
Wealthy individuals believe that the world must have widgets. Or family and friends really like and trust the individual widget-teer and want to see him/her do well.

Usually this passion translates to very heavy involvement or even leadership in the company and desire to see it through. They believe it but also need to see their money grow sometime in the future.

Sometimes they can be so committed they look crazy. Sometimes they are right.

Who: Passionate individuals
Risk tolerance: Very high
Return: High-impact and return
Timeline: Long
Exit: Sell shares
Amount: Unknown/yr

Lets review our options



Who: Private individuals looking for solid return
Risk tolerance: Low-moderate
Return: Steady profits from established companies
Timeline: 10 yrs
Exit: Grow company to IPO
Amount: Lots

Who: Pool of like-minded investors
Risk tolerance: High
Return: Unicorns
Timeline: 5 yrs
Exit: Sell shares
Amount: $30B/yr in 1-10$M chunks

Who: The company
Risk tolerance: Moderate
Return: Better products
Timeline: Ongoing
Exit: Product launch or cancel
Amount: 1% of sales in energy sector

It is clear that there are many sources of funding that come with different expectations and are appropriate for different stages of widget development.

The lines are not sharp. For instance people who might be Angel investors might also be philanthropic givers.

Who: Passionate individuals
Risk tolerance: Very high
Return: High-impact and return
Timeline: Long
Exit: Sell shares
Amount: Unknown/yr

Who: Impartial banks
Risk tolerance: Low
Return: Loan repayment
Timeline: Fixed term
Exit: Loan repayment
Amount: Not a lot of innovation

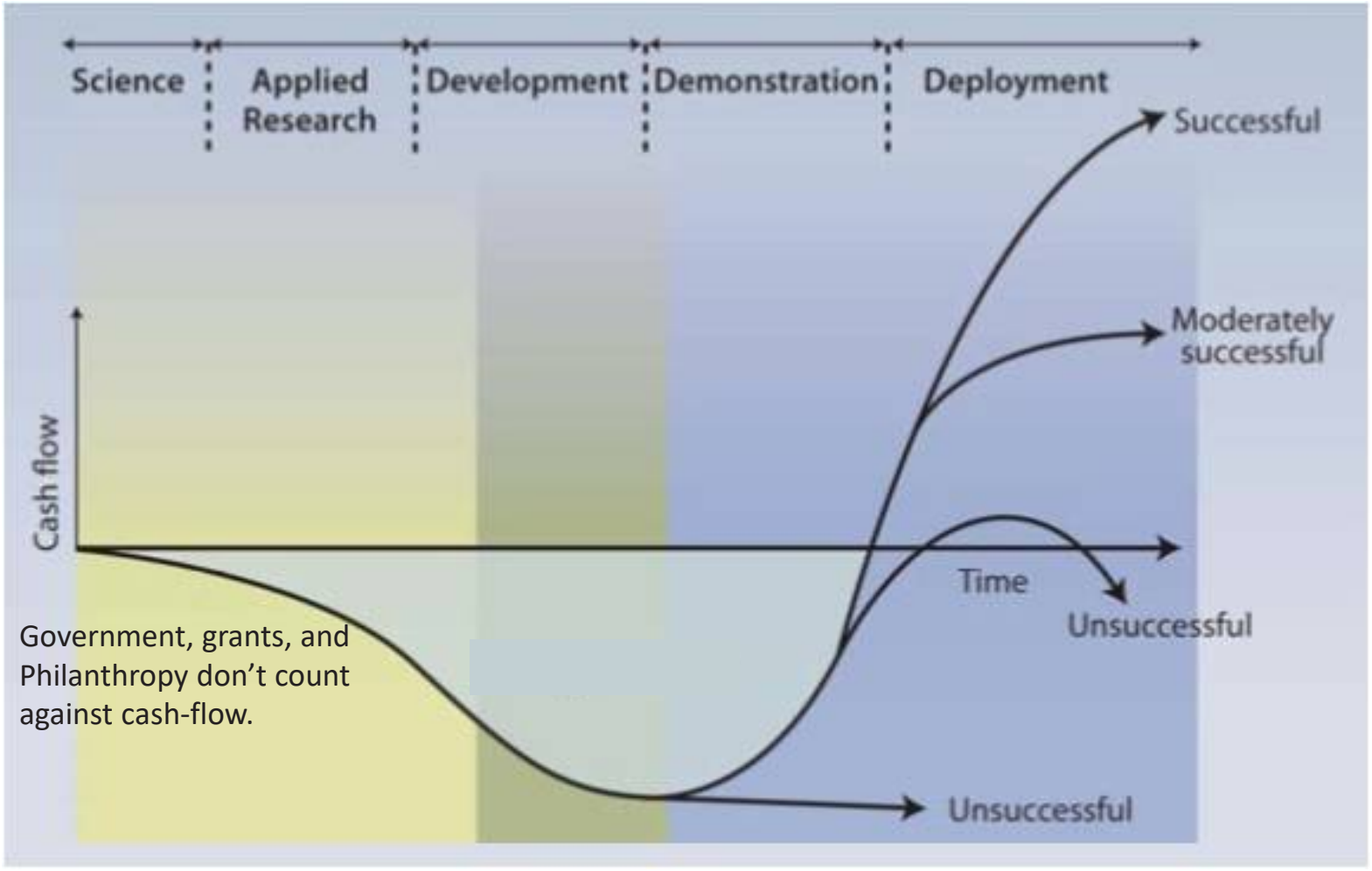
Who: The public
Risk tolerance: High
Return: Basic scientific knowledge
Timeline: Open-ended
Exit: None
Amount: $150B/yr in $M chunks

Who: Passionate individuals
Risk tolerance: High
Return: Knowledge or Social good
Timeline: Open-ended
Exit: None
Amount: Unknown

They can take risks… as long they learn fast

Why are they like that?

They must return capital



Angels Venture Capital Private equity Banks/IPO

During the R&D stage the company is spending investor money to retire risks:

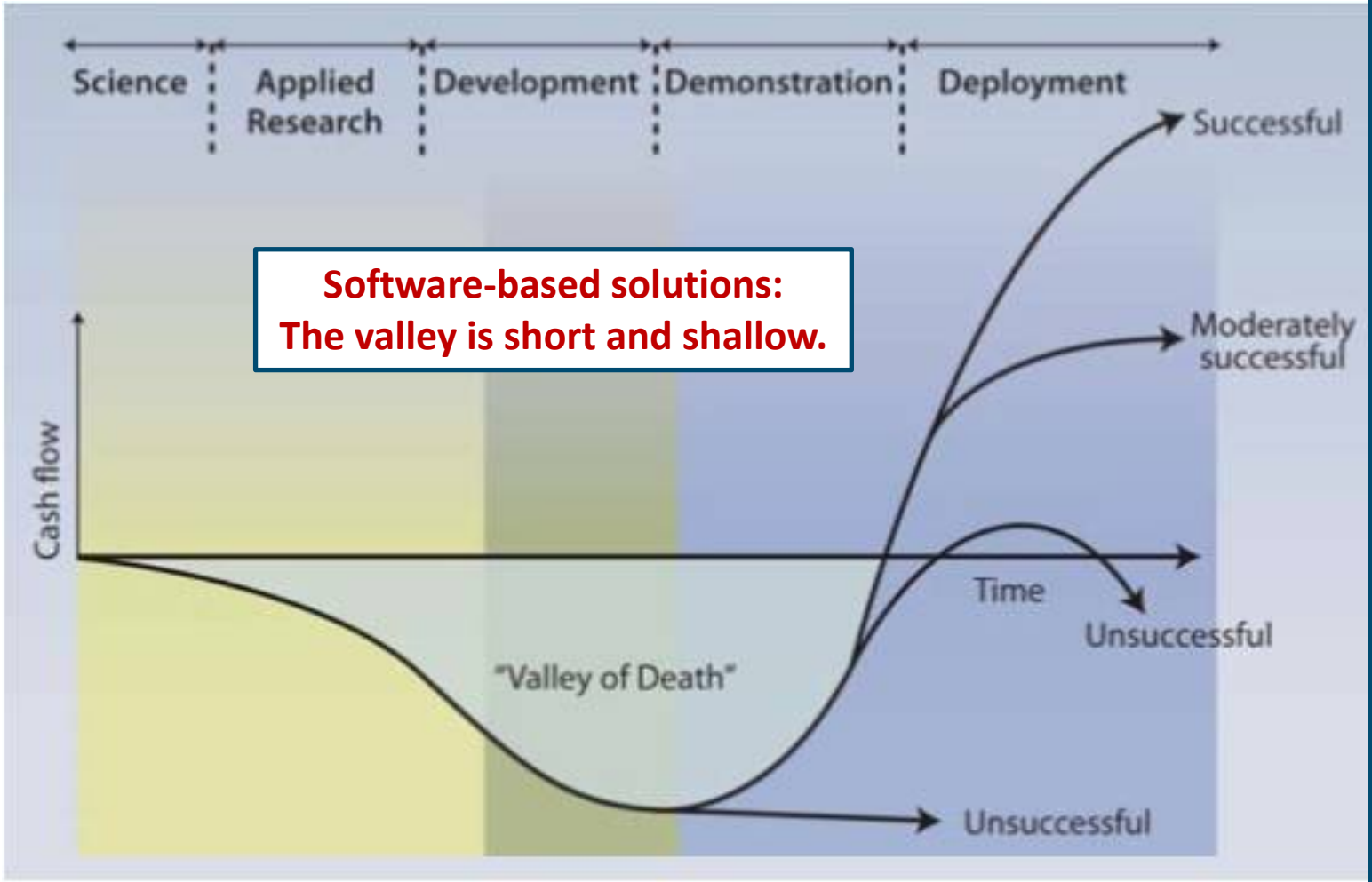
- **Learning about the technology.**
- **Learning about the eventual market.**
- **Developing the Intellectual Property (IP) that will protect it's lead.**

The goal is to learn about these things as fast and efficiently as possible.

The investors change as the risks change. Each one paying according tot their risk tolerance. The company's worth is *hopefully* growing since risks are being retired.

If a show-stopper is found then the company worth plummets.

The best way to do this is to go fast and find a fit

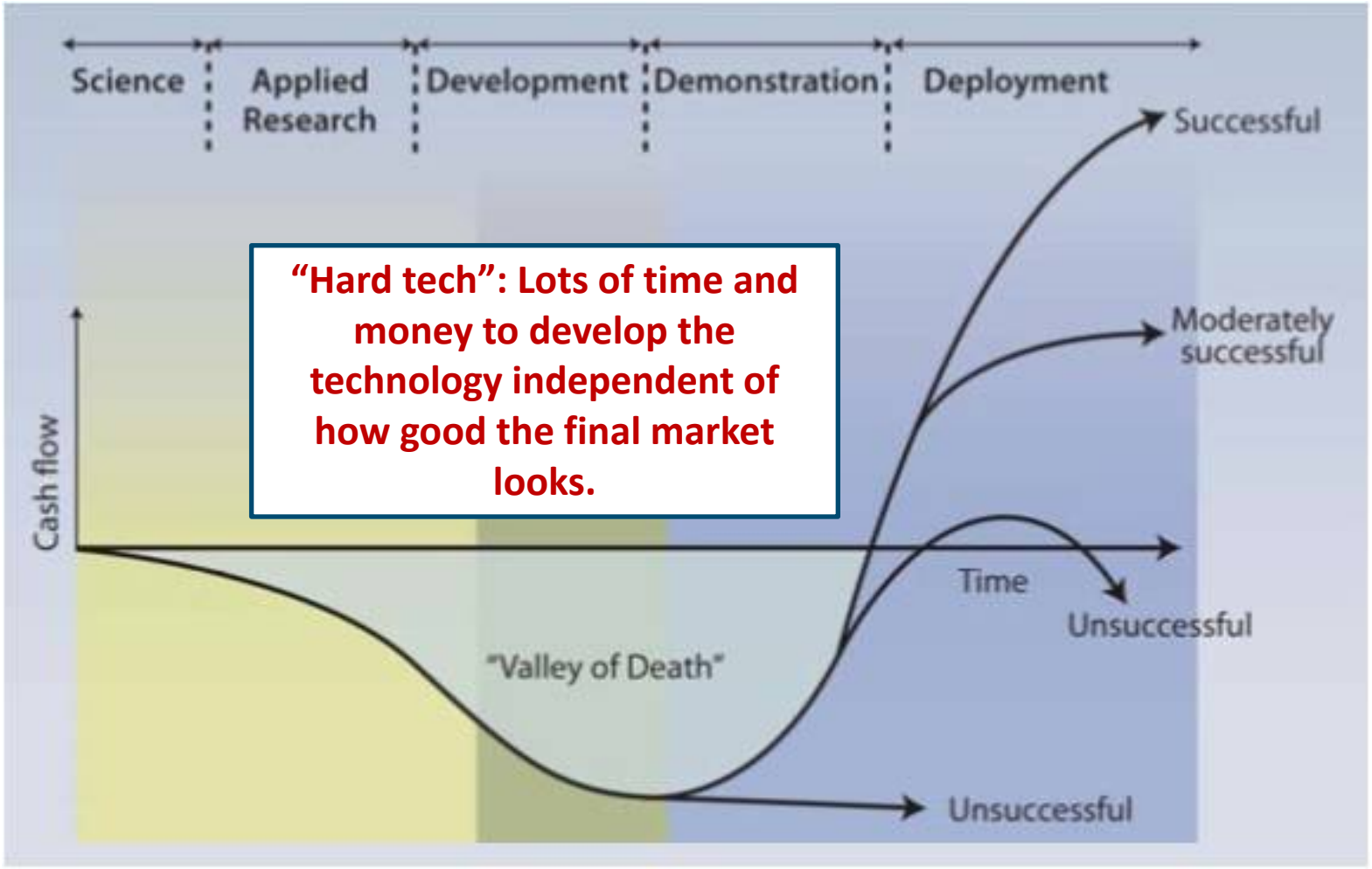


In a internet startup this can go very quickly.

An example: Instagram

- **Have idea, raise $500k from VC**
- **Company hires coders**
- **They build the platform architecture**
- **The platform attracts users**
- **Sell 50% of company for $50M after 18 months**
- **Invest in more development and servers**
- **Attract more users**
- **Sell stake to Facebook for $1B after 30 months with 13 employees.**
- **Facebook puts ads in front of users and grabs their data**
- **Facebook makes money on this**
- **Original VC made 400x return**

But hardware companies have a deep valley



"Hard tech": Lots of time and money to develop the technology independent of how good the final market looks.

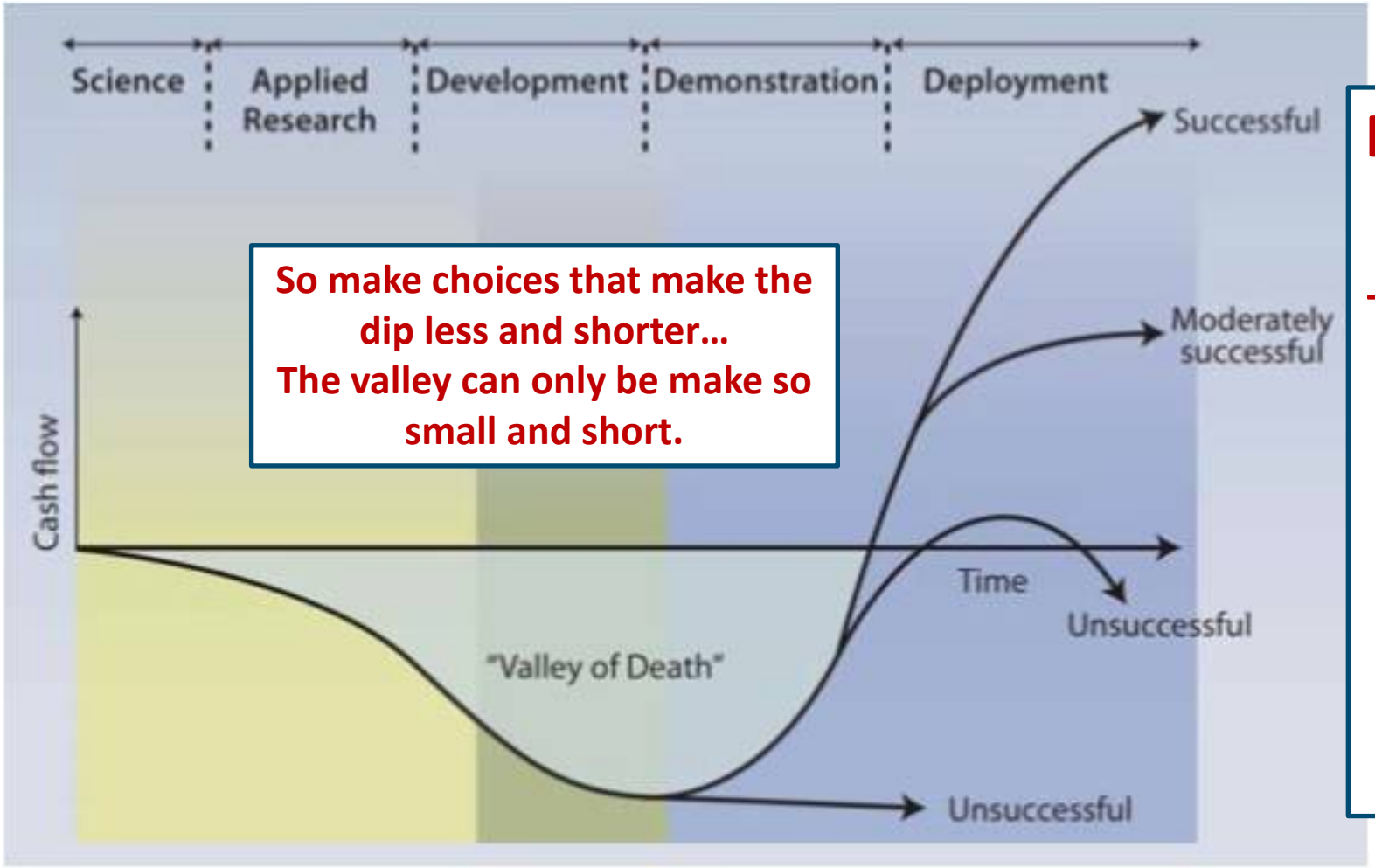
But the hardest, most pressing problems require more hardware and science, they must build demonstration plants or production lines.

Therefore, the R&D period before the product is very long (time) and deep ($$$).

- **A pharmaceutical company might take $1B and 10 years to go through the valley of death.**
- **Many clean tech companies get mired in this period.**

There is strong incentive to come up with plans that have a smaller valley.

This informs their choices as much as science

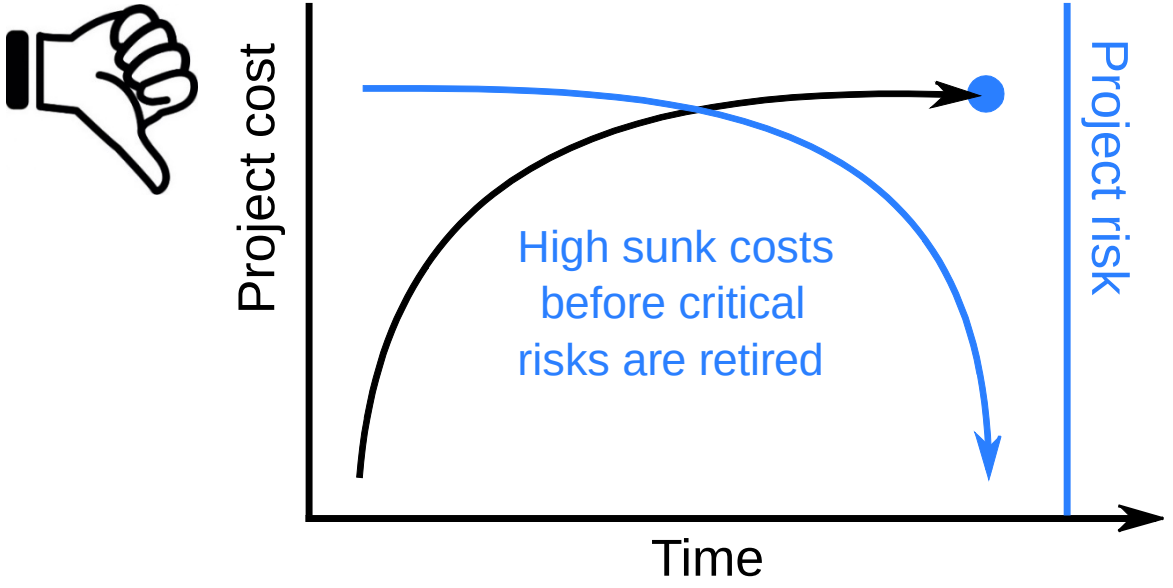


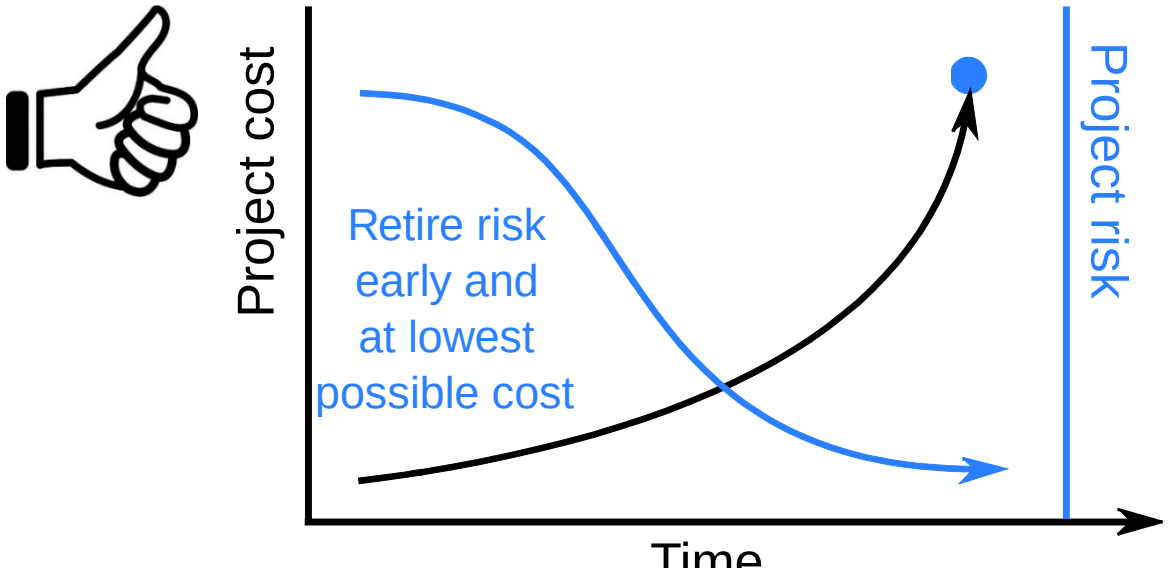
Angels Venture Capital Private equity Banks/IPO

Bottom line:

- **Focus on ideas and concepts that can be attempted quickly, can prove they will or will not work, and that lead to a scalable and attractive outcome for a product**

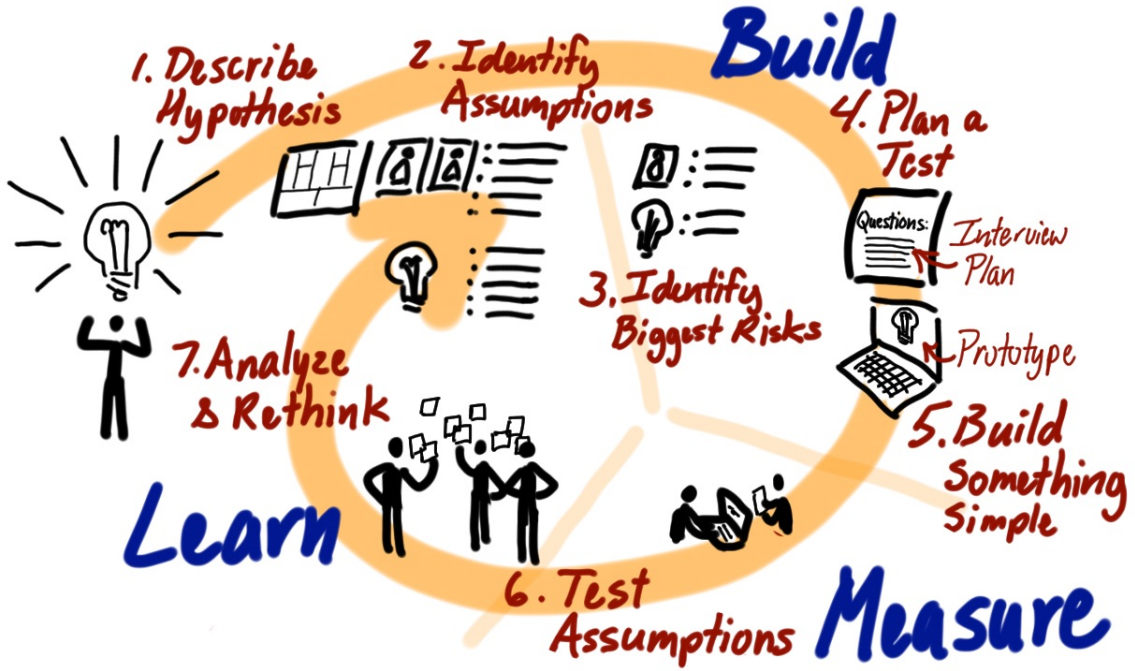
Must break down systems so risk is highest upfront





They are trying to learn as quickly as possible

A way to break down problems, identify what is important and solve it.



Avoids trying to solve all the problems at once.

Success then breeds success.

Key ideas:

- Cycle **as fast as possible**
- Focus on the **most valuable** feature set, the sponsor helps you figure this out at each stage.
- Always build the simplest, fastest, cheapest thing somebody **will pay for** that retires risk. The minimally-viable product.
- **Learn** about your **technology** and also about the **market** at every cycle, refine as you go.
- **Involve user/customer/sponsors early and often** so you don't make the wrong thing.
- **Take risks** and then quickly pivoting **away from failure**, small size and rapid action prevents sinking.
- **Measure success** so it can be and **rewarded**, prove the team can be successful and grow it.
- **Eventually integrate and scale up solutions**

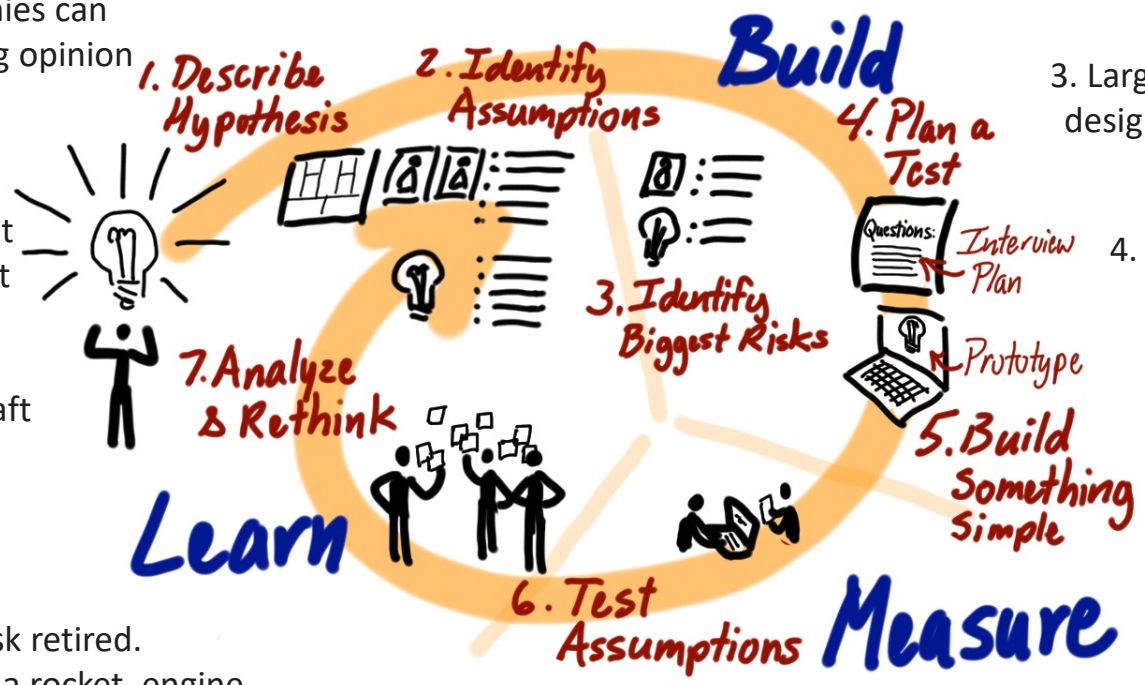
Extra: SpaceX's goal to develop the technologies needed to colonize Mars is an illustrative example.

SpaceX could have try to build a giant Mars capable rocket and spacecraft from the outset (NASA would).
Q: Why did they instead make a small rocket first?
A: Because a Mars rocket is too large of a risk to attract the money, better to retire risks small and fast instead of in a mega-step.

1. Cheaper rockets are required. They should be developed before spacecraft. SpaceX hypothesized that private companies can build effective rockets but prevailing opinion was it can't be done.

Each cycle leverages the last:
√ First cycle: Build and launch a rocket
√ Next cycle: Build the Falcon 9 rocket
√ Next cycle: Land and reuse it
√ Next cycle: A cargo spacecraft
√ Next cycle: A human-rated spacecraft
Next cycle: The Falcon Heavy
Next cycle: Land things on Mars
Next cycle: Land people on Mars

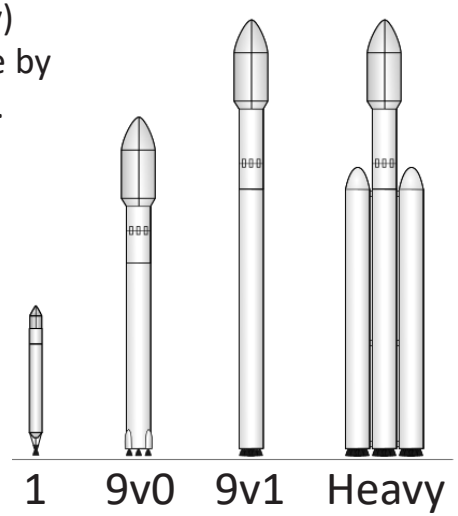
2. Successfully launching a privately-developed rocket will show that it can be done and lead to money for more rockets and spacecraft.



3. Largest risk is system integration and engine design, can be proven even in a small rocket.

4. Build a company to rapidly design, prove and integrate totally new engine and rocket.

5. Make the (tiny) Falcon 1. Laughable by NASA standards.



6. Launch it. First 3 fail, 4th a success.

7. Integration and engine risk retired. Now proven that SpaceX can build a rocket, engine, and an organization that works. Backers give more money (>$400M) to develop the next, bigger, rocket which utilizes what was learned. Hypothesis and assumptions were correct.

They must grow and protect value

- They need to be able to innovate in some aspect where they can gain a competitive advantage against others who might want to copy them or stomp them out
  - Technology innovation
  - Business model innovation
- Can be a strategy, a patent, a network…
- Then get to market as soon as possible, grow big, and make lots of fusion power plants

They are singularly focused on getting to market

Feedback from the energy world:
We have worked extensively with utilities, operators, investors, bankers, energy companies, manufacturers, NGOs around the world. They are excited to participate in a fusion commercialization effort.

What they need to see:

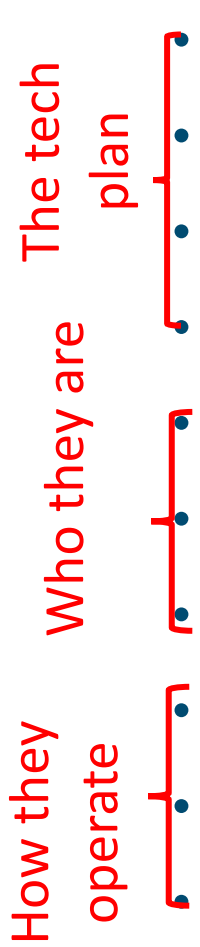
- Show net-energy high power production ASAP – net electricity if possible
- In a package that scales to an economical and market-relevant power plant
- In a robust and simple as possible configuration
- In a market-relevant timeframe
- With concrete risk retirement milestones to track progress

This means its often not just plasma physics

- In the whole development cycle it might mean you take more risk on the plasma physics to enable a better, more defensible product, a faster path to market, a lower capital cost in market, etc.
- These different strategies and the corresponding company structures are the heart of innovation – that is competition that works.

What's the difference in the bottom line between a product that works and nobody buys and a product that doesn't work? -- Nothing!

What are the ways to get speed?



- Decrease the capital outlay required to retire risk – make it smaller
- Make a plan that you can derisk upfront – cut loses if it doesn't work
- Minimize technology interdependencies – modularize and parallelize
- Make it economically attractive – increase the TAM
- Increase private capital participation – success acts as accelerator
- Decrease the number of stakeholders – keep them aligned
- Recruit outside expertise – people have done similar things
- Demonstrate by building – roadmaps and plans are easy
- Build momentum with early success – hit meaningful milestones
- Focus on unique value creation – leverage work done elsewhere

Lets talk about 15 years…

- Our aim is to put fusion electricity on the grid in this timeframe
- Why do we think we can do this?
- **15 years is a long time in the real world!**
  - **– Especially when there is a breakthrough + a substantial need**

Game changer definition:
a newly introduced element or factor that changes an existing situation or activity in a significant way

Breakthrough definition:
A sudden advance especially in knowledge or technique

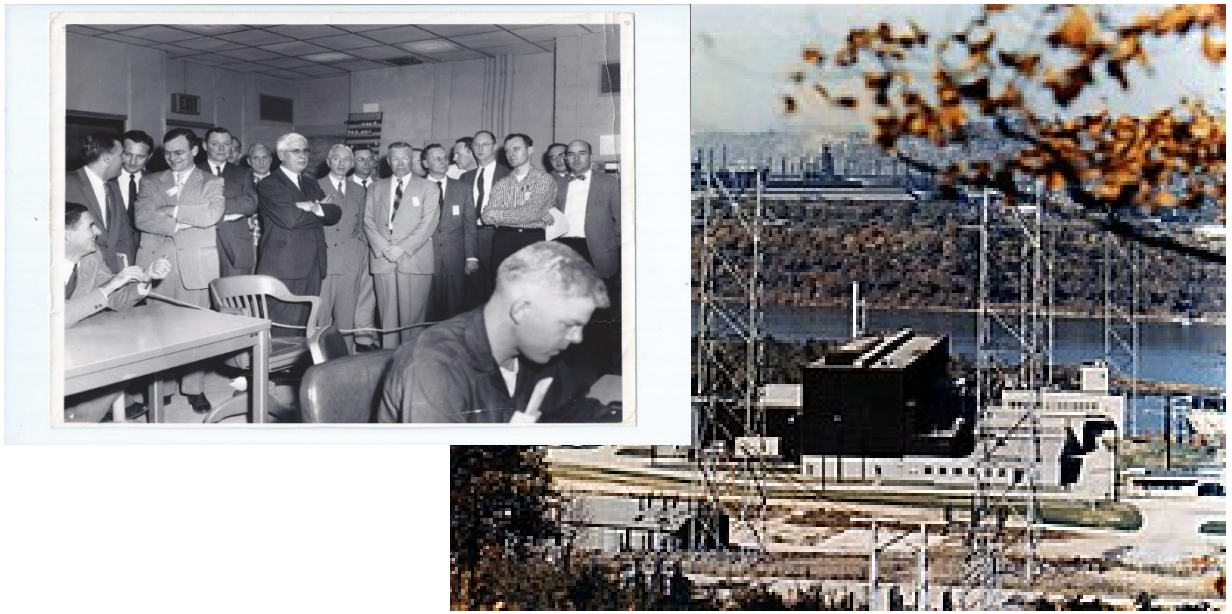
An act or instance of moving through or beyond an obstacle

Lets talk about 15 years… Fission power

1942 – Pile 1
0.5 W thermal

War drives science.
Very basic nuclear physics, no materials knowledge, no applications, no industry

1957 – Shippingport
60 MW electrical, public-private
Market drives engineering



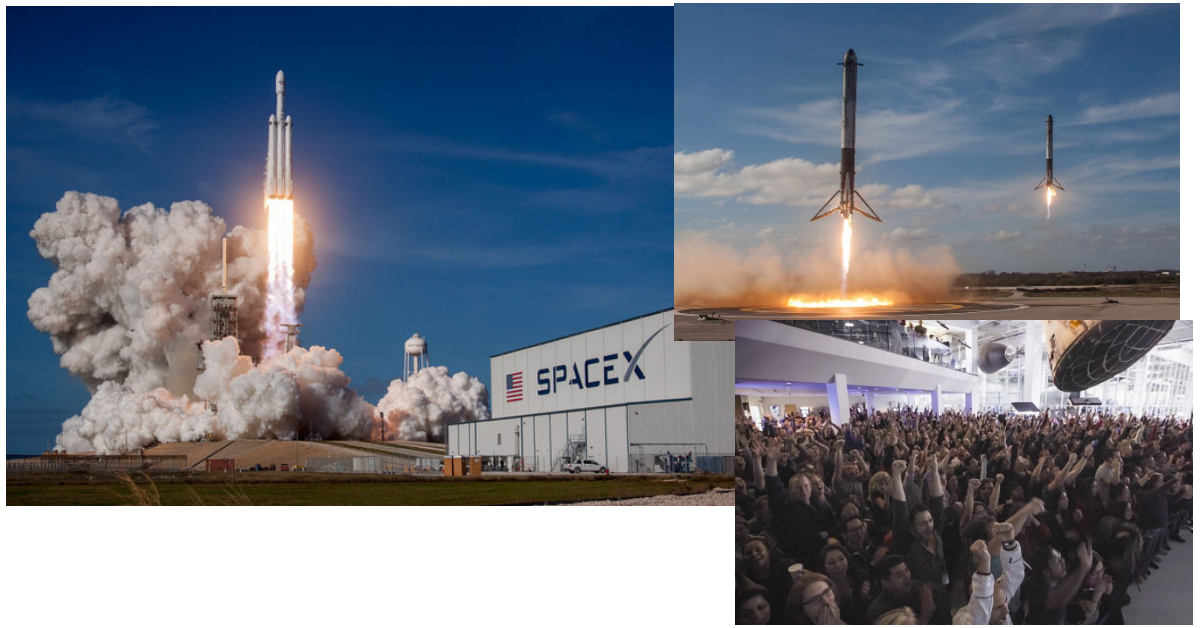
+ 2 fully-private full-scale plants under construction
Architecture fixed, soon to scale to 20% of US power

Lets talk about 15 years… SpaceX

2002 – SpaceX founded

Launch is a very expensive, hide-bound program dominated by government-funded contractors with very little innovation.

2018 – Falcon Heavy
Innovation applied to orgs and tech, supercharged by finance

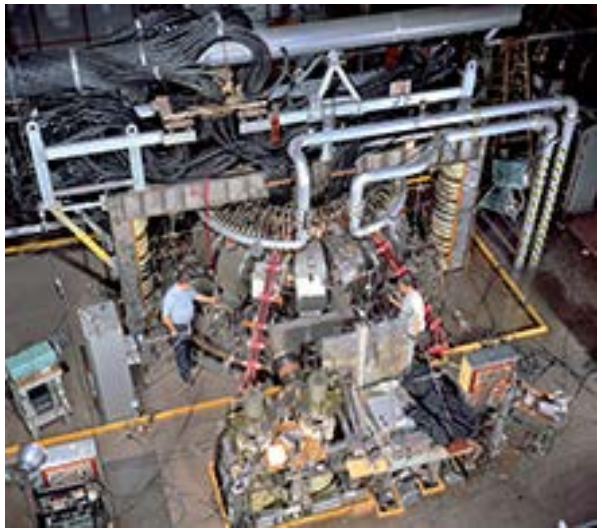


Falcon 9: 4 years + $300M from napkin to launch
Cuts the cost to orbit by factor of 10, built a market

This is what people can do, fusion is no different

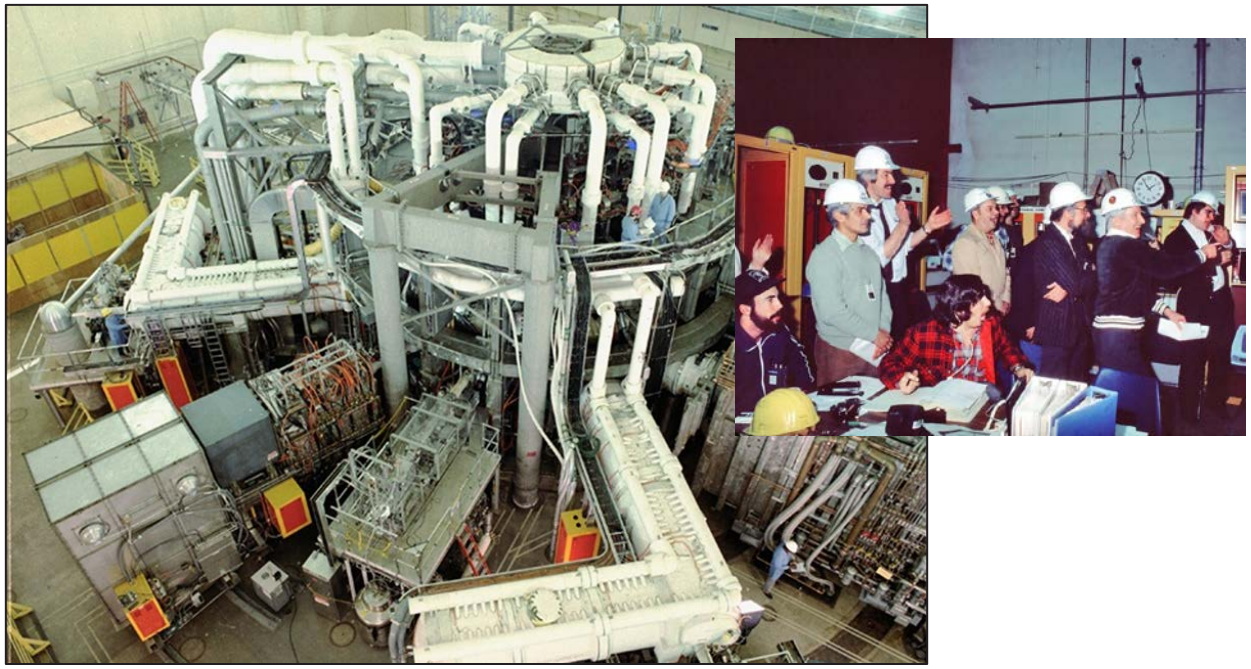
Lets talk about 15 years… Fusion

1971 – ST shows tokamaks work



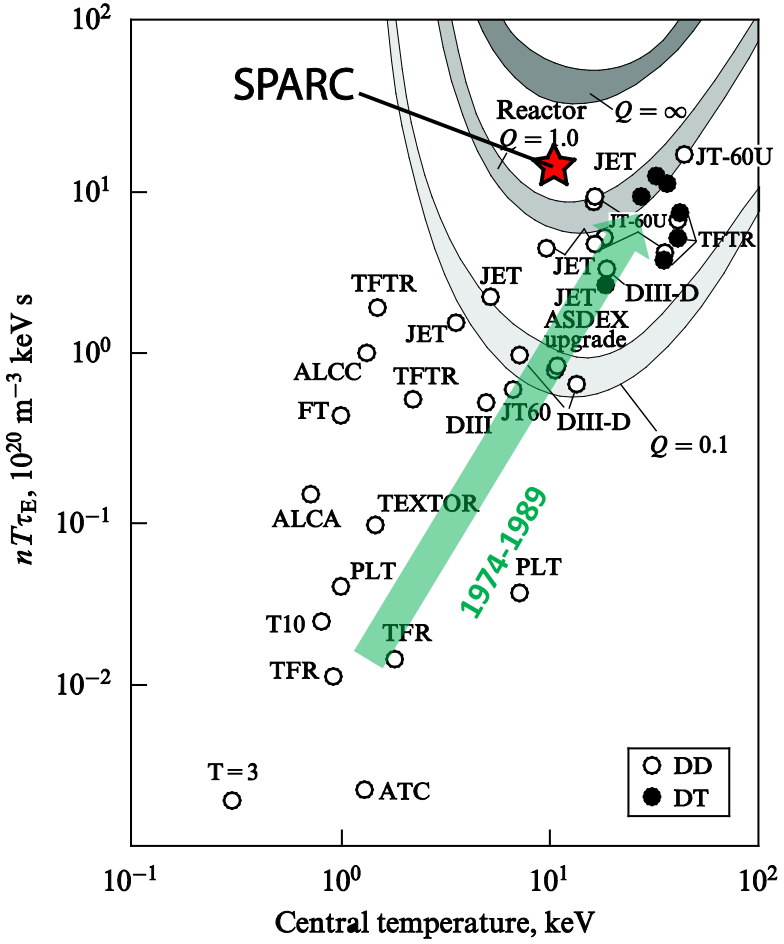
Tokamaks are performing good enough, the world needs energy, we have sights on the technology.
Make push for DT.

1986 – JET, JT-60, TFTR running, supershots, prepping



Drastically expanded the operating space for tokamaks, developed most of the technologies we now use.
It wasn't that expensive.

Lets talk about 15 years… Fusion

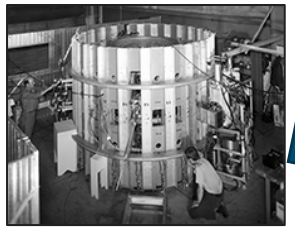


Extrapolations in performance		
Parameter	1974-1989	Today-ARC
Plasma current	10	1.5
Toroidal field	2	1
Magnetic energy	100	18
Pulse length	1000	??
Auxiliary heating	100	0.75
Ion temperature	10	0.5
Triple product	1000	~2-5
D-T fuel	DT	Done
Fusion power	10000000	>15
Q	10000000	>10

Why can't we do this again?... We don't have so far to go.

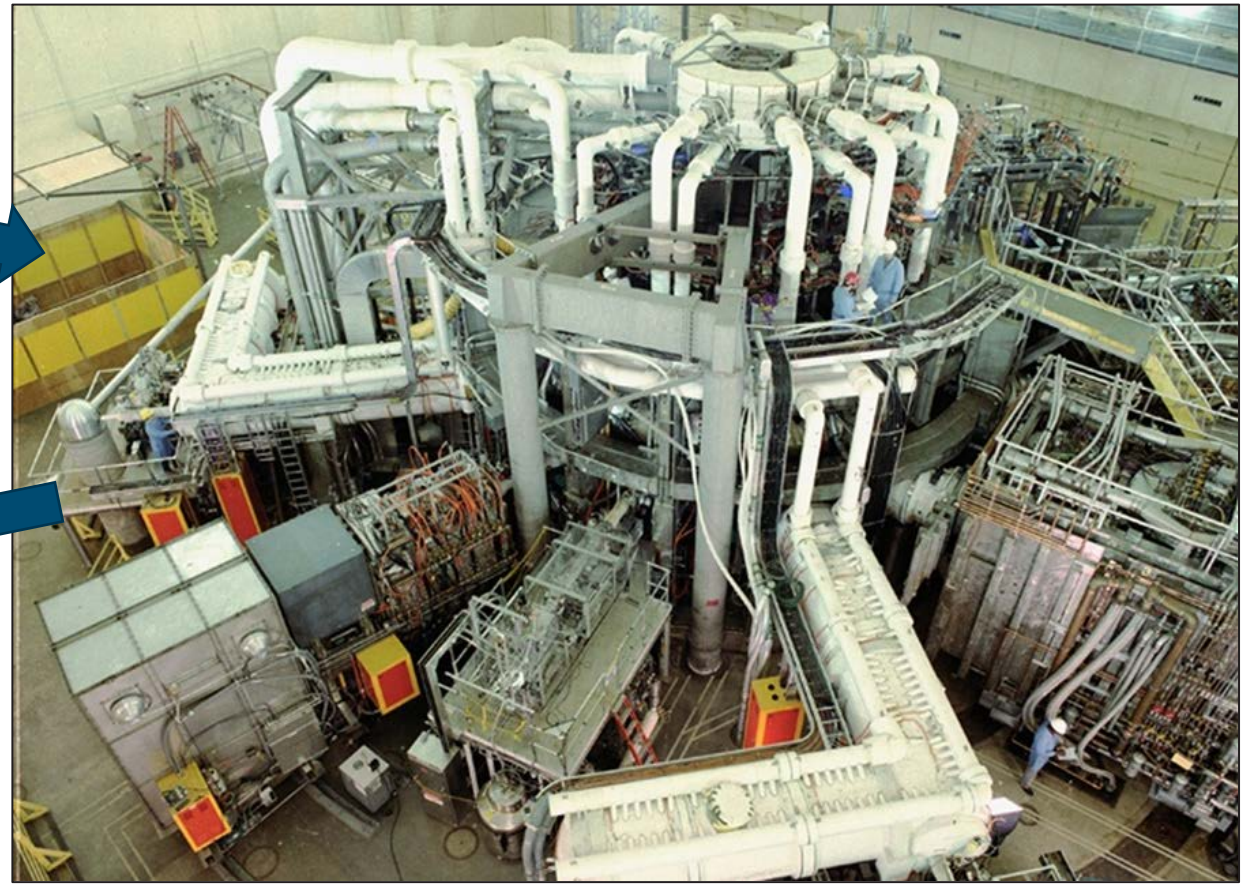
Lets talk about 15 years… Fusion

ATC, 2T



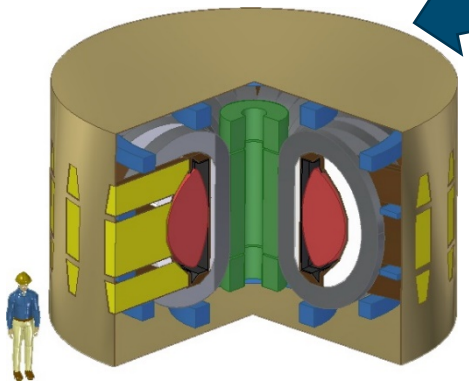
1974:
Tokamak
physics mature
enough to try
DT

TFTR, 6T



2016:
HTS mature
enough to build
a tokamak

SPARC V0, 12T



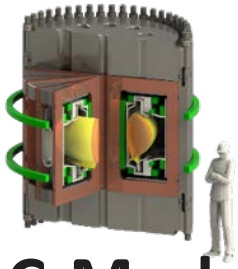
Approximately to scale

An example: CFS

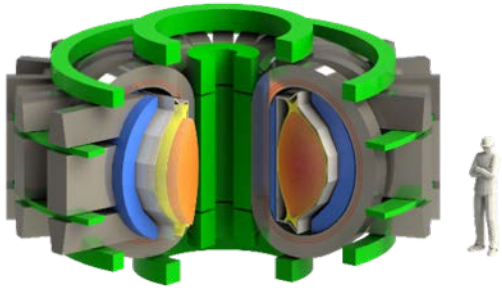
CFS was built to fast track fusion

- Start from the plasma physics we know today
  - Require as little advances and discovery in plasma physics as necessary
  - Use the tokamak and ITER physics basis
- Use innovation to drive tokamak size down and economic attractiveness up
  - High field HTS magnets
- Break the problem into discrete tractable technical milestones
  - Have a strategy that is flexible and can pivot when necessary
  - Turn physics unknowns into engineering problems wherever possible
- Build a team and stakeholders who are aligned with the mission
  - A team that is deeply mission-aligned and highly capable
  - An investor syndicate that has the capital to not just see it through but accelerate
  - Partnerships the grow a big ecosystem around fusion – to launch an industry
- Always be focusing on delivering a commercial fusion product

How are we going to get there? Physics and technology.

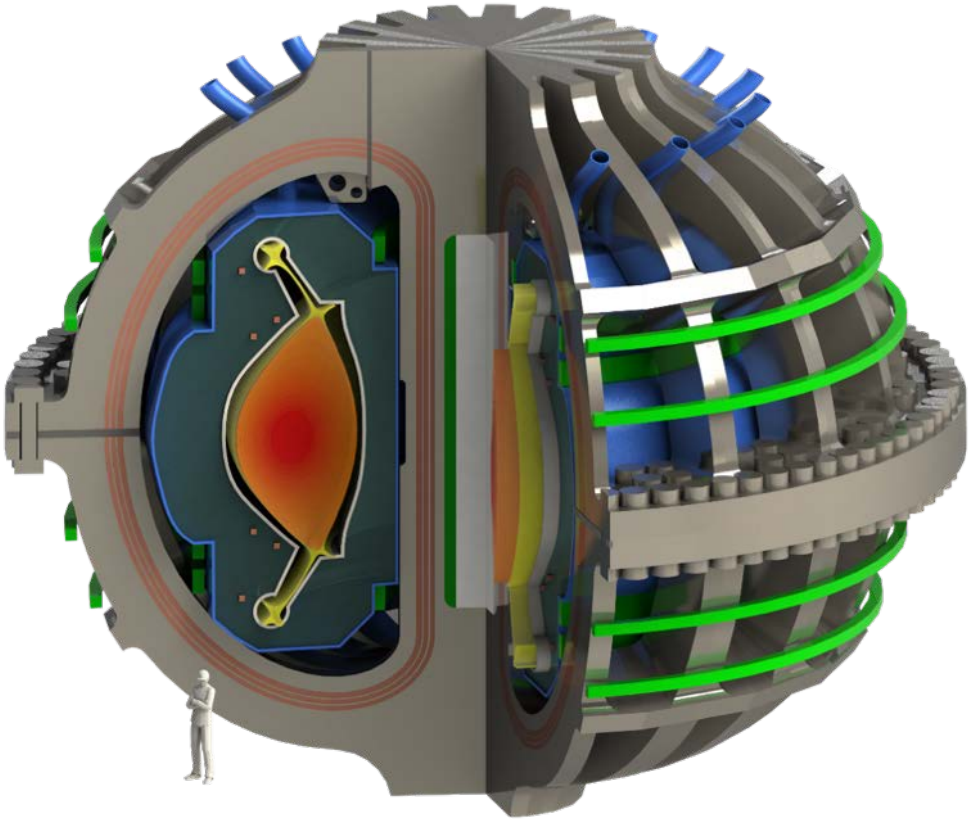


C-Mod



SPARC

HTS Magnets

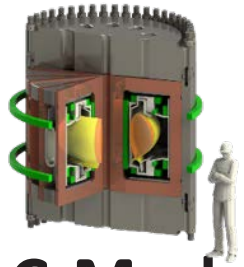


ARC

2021 **2025**

How are we going to get there? Physics and technology.

Physics



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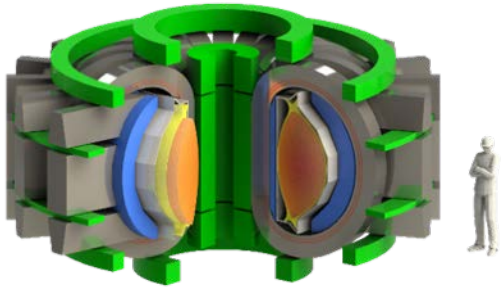

SPARC

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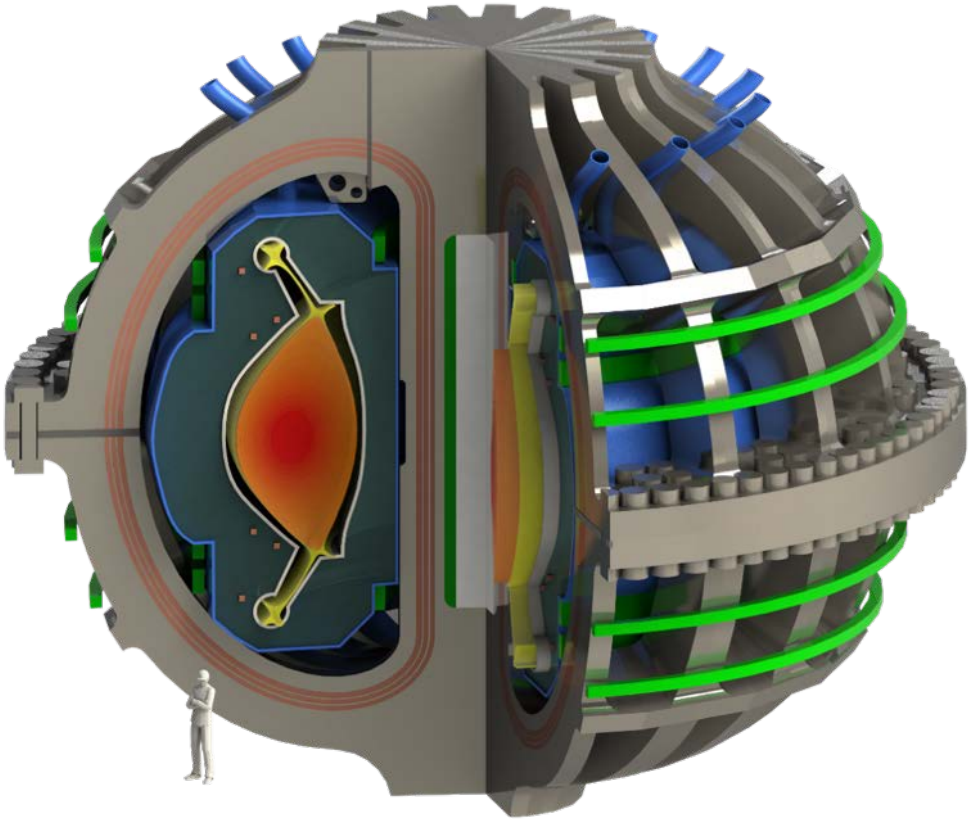

ARC

2021

2025

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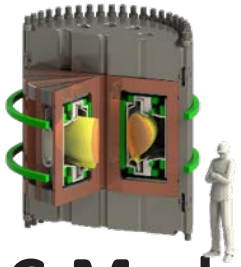

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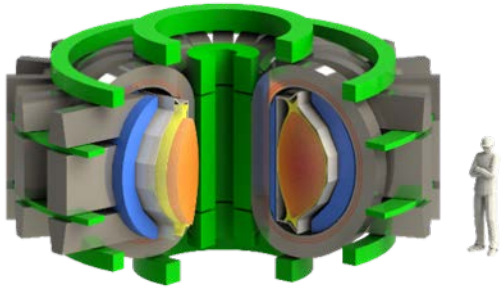
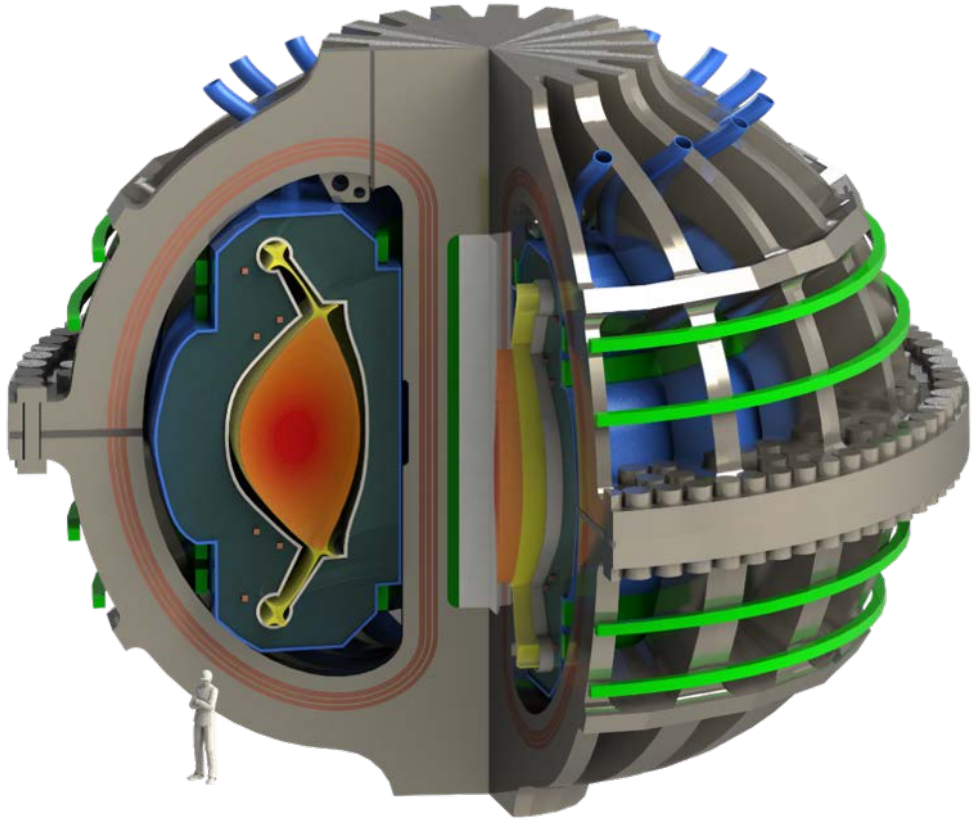


SPARC



ARC

Technology

HTS Magnets

2021

2025

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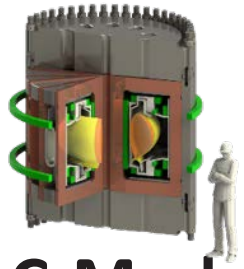
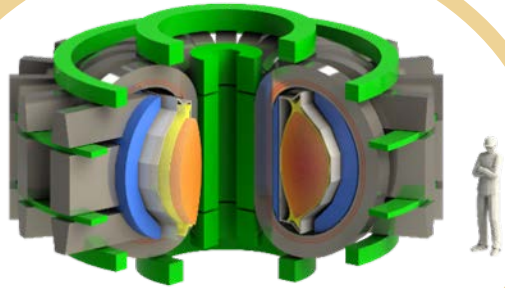
Physics



C-Mod

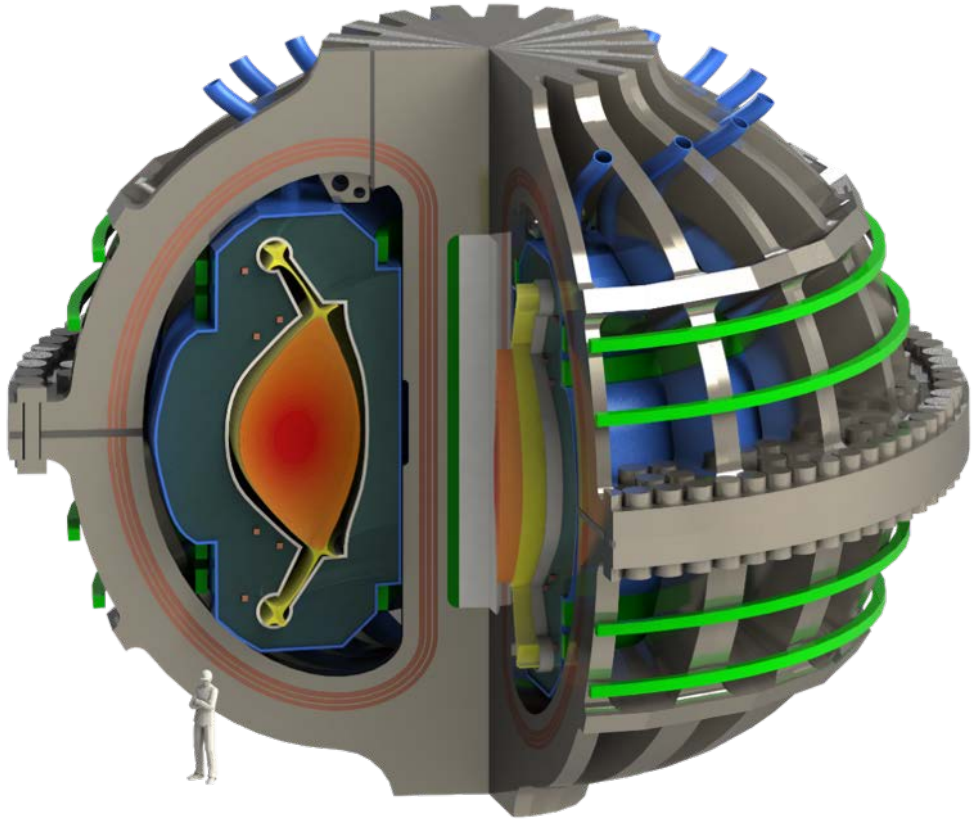
Technology (+ Physics)



SPARC

Technology

HTS Magnets



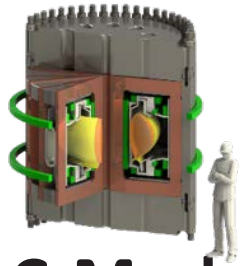
ARC

2021

2025

How are we going to get there? Physics and technology.

Physics



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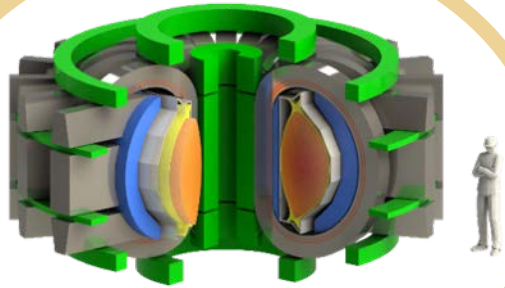
Technology (+ Physics)



SPARC

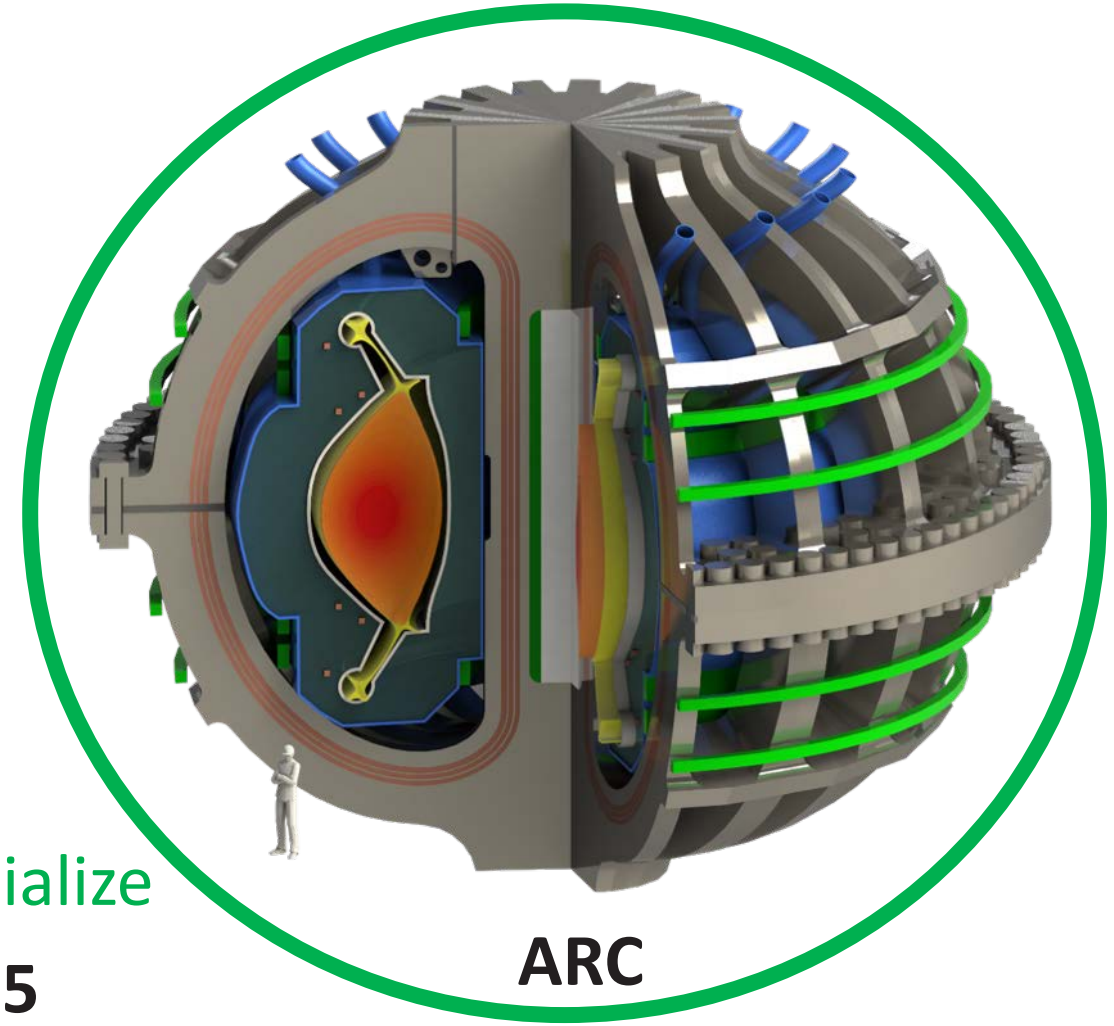
HTS Magnets

Technology

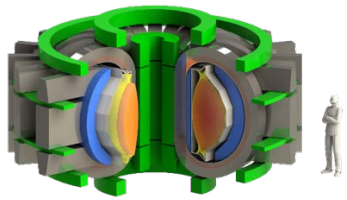
2021

Commercialize

2025



ARC



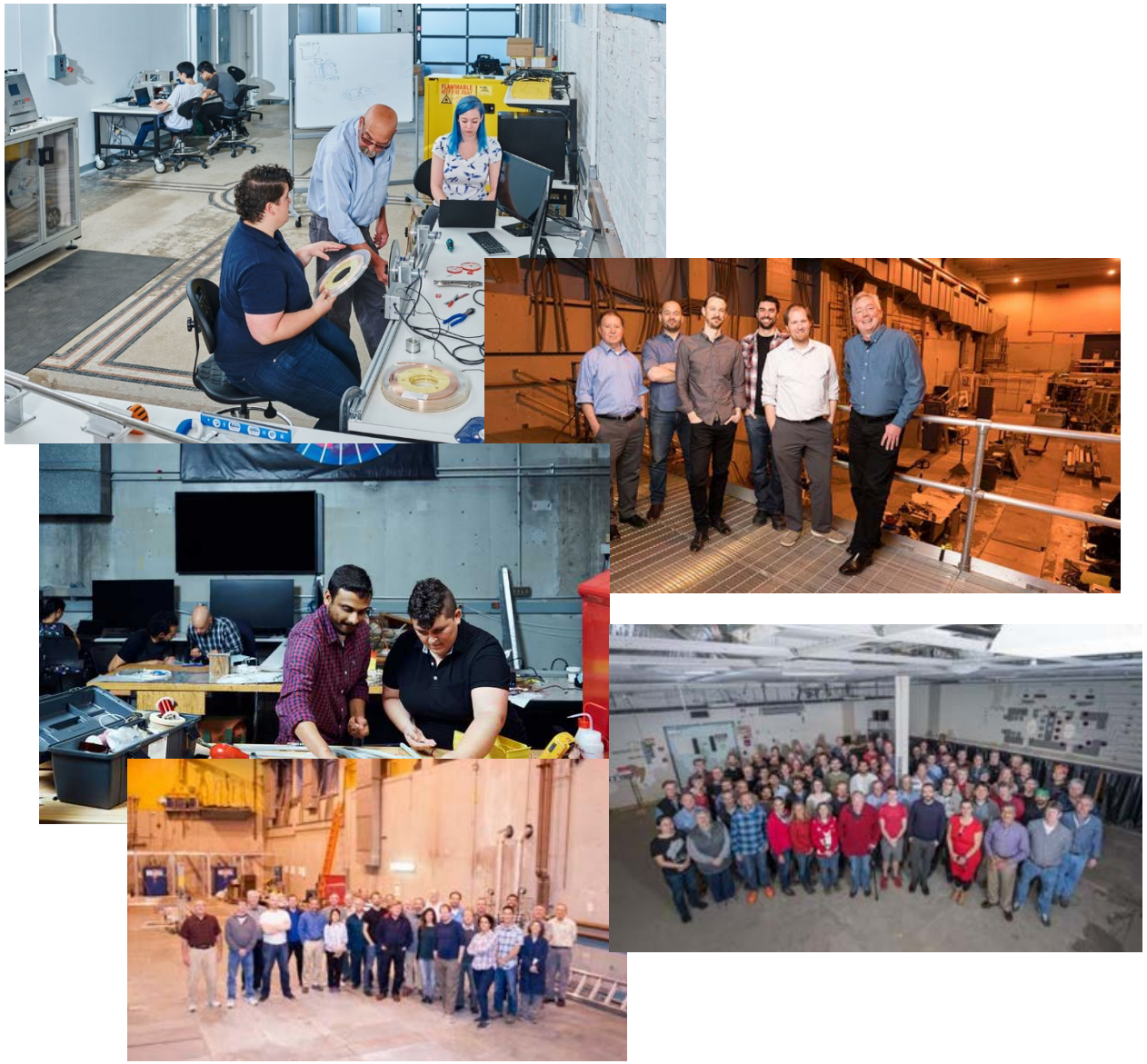
Backed by capital to put fusion power on the grid

- Investors committed to displacing CO2 and building a fusion business
  - High net-worth individuals
  - Large energy companies
  - Large investment funds
  - Hedge funds
- Early investors in Google, SpaceX, Tesla, Amazon
- Enough capital to get it done and to accelerate while doing it
- Understanding of and appetite for the technical risks
- Anything less than power on the grid is a failure

eni · THE ENGINE Built by MIT · Breakthrough Energy VENTURES · khosla ventures · FUTURE VENTURES · LOWERCASE CAPITAL · Moore Venture Partners · SCHOONER CAPITAL · STARLIGHT VENTURES

A top-notch team to tackle this problem has been assembled

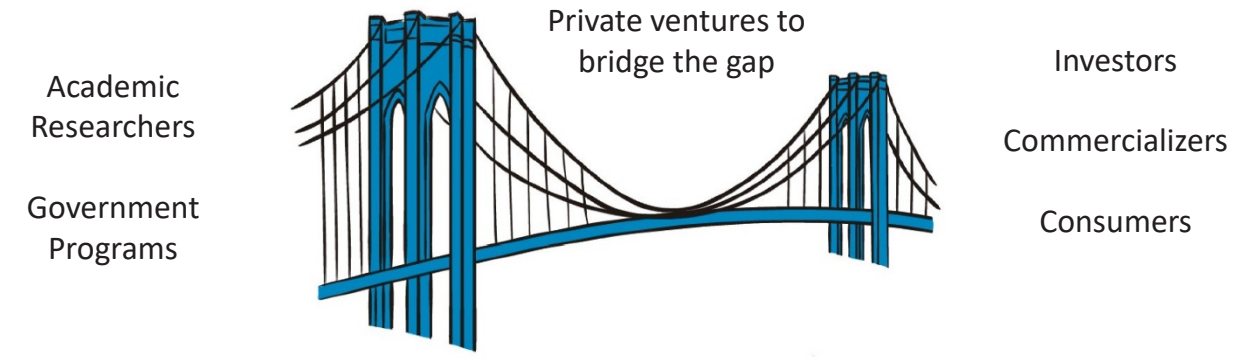
- CFS is building a team to develop and field fusion devices
- Currently >100 head count
- Fusion experience:
  - MIT PSFC, ITER, GA, PPPL
- Magnets
  - MIT, NHMFL, CERN, LBNL, Fermi, GE, Phillips
- Adjacent high-tech industries
  - SpaceX, Hyperloop, TerraPower, Tesla, GM, Google, COMSOL, Intel
- A wide range of experience under one roof solving problems together as fast as possible
- 30 job postings – cfs.energy/careers



Where do we go from here?

Technology gets to market using the whole ecosystem

- The entire funding environment is evolving
- Fusion is following a well-worn tech-development arc
  - Computers, AI, Robotics, Drugs, Aerospace, Energy, Quantum, Materials, etc
- **An evolving pathway is how fusion is going to get on the grid**
  - The US government doesn't build reactors, pilot plants, etc – industry does
  - Look to fission, fossil, ARPA-E, EERE, New Space
- Each side does what it is good at
  - Government does basic research, deep expertise, tool sets, seeds innovation
  - Private finds market fit, selects architectures, scales solutions, manages costs



Part of a required evolution: Look at fission

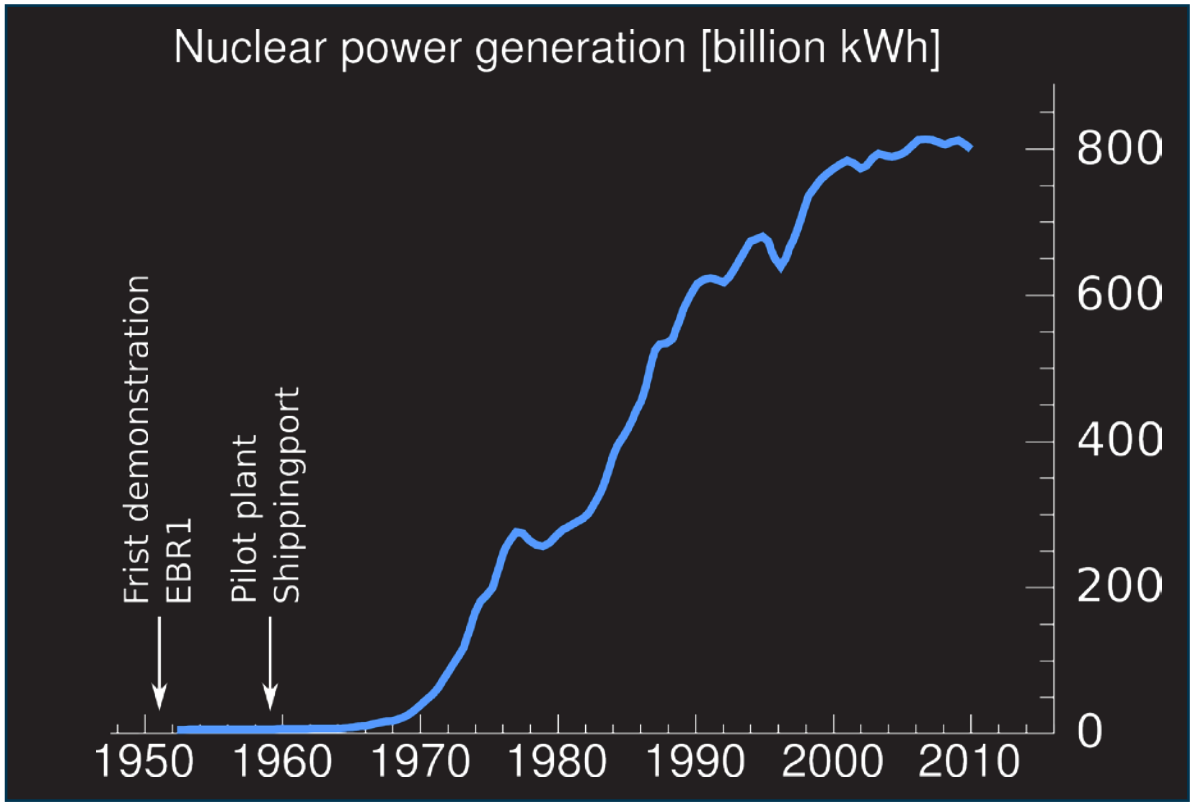
Activity	Test Reactors	Small Demonstration Reactors	Large Demonstration Reactors	First Commercial Reactors
Site Acquisition				
Nuclear Island Owner				
Conventional Island Owner				
Pre-Construction R&D				
Post-Construction R&D				
Nuclear Island Design				
Conventional Island Design				
Fuel Design				
Fuel Fabrication and/or Supply				
Nuclear Island Operator				
Conventional Island Operator				
Nuclear Island Constructor				
Conventional Island Constructor				
Rate Assistance				

LEGEND

- Predominately Government
- Majority Government
- Government and Industry
- Majority Industry
- Predominately Industry
- Limited Data: Gov't & Industry
- Insufficient Data

8yrs

Year	Accomplishment	Reactor	Power
1942	First chain reaction	Chicago Pile 1	0.5 W
1951	Lightbulb lit	EBR1	200 kWe
1953	Useful power	Nautilus proto	70 MWt (est)
1955	Power offsite	BORAX III	2 MWe
1957	Pilot plant	Shippingport	60 MWe
1959	Fully privately funded	Dresden I	180 MWe



Lesson: Prove the physics and technology at as small of size as feasible. Then scale up an industry.

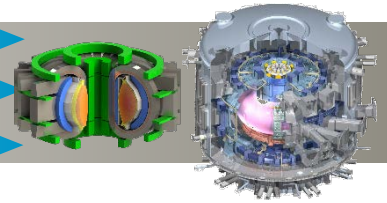
ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics

Fast particles — NSTX-U

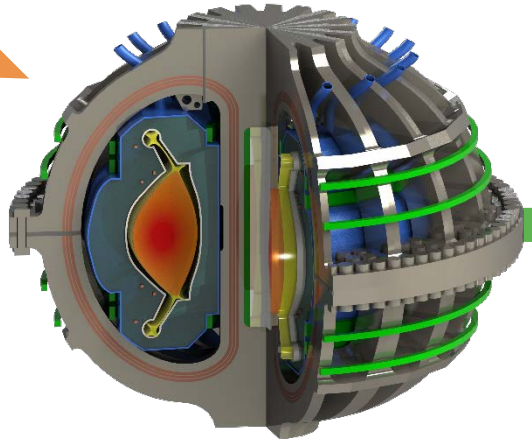
HTS magnet development



SPARC+
ITER

Burning-plasma physics

ARC:
Compact fusion
Power Plant



Show fusion makes more power as soon as possible:
Burning plasmas are key.
Collaborate on SPARC and ITER which are complimentary.

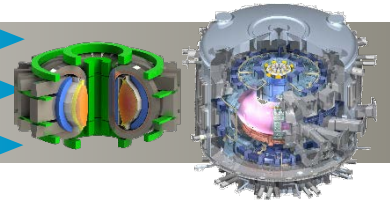
Covered in APS DPP CPP White paper:
Greenwald – Collaborations on the SPARC device

TODAY 2025+ 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

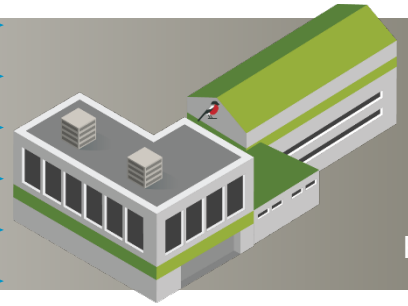
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

Burning-plasma physics

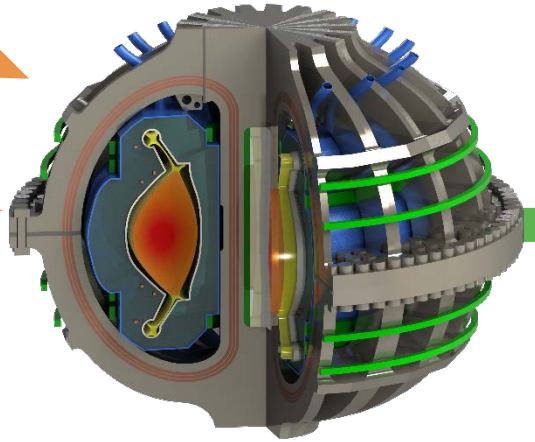
Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



FINCH

Nuclear qualified components, materials, and systems, minus the burning plasma

ARC:
Compact fusion
Power Plant



But without nuclear-compatible materials and components the first fusion system is very sub-optimal.
Its been 25 years since the US did DT– do it now for FM&T.

Covered in CPP White paper:

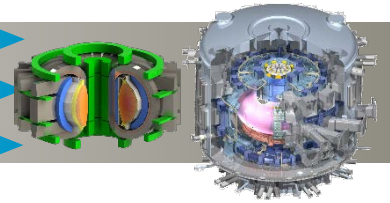
Sorensen- FINCH: The Fusion Integrated Nuclear Component Hall and the papers it references (FPNS, VNS, GDT, Materials, BTCF, etc)

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



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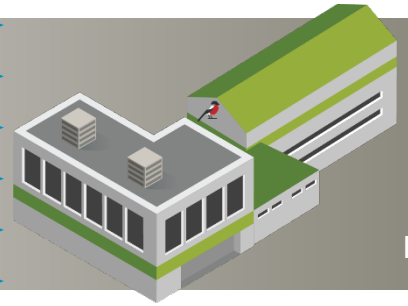


FINCH

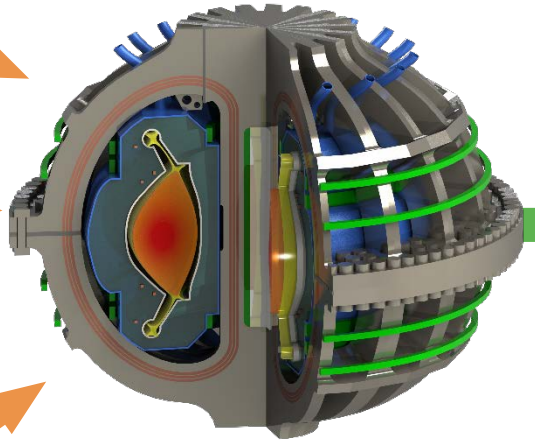
Nuclear qualified components, materials, and systems, minus the burning plasma

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

ARC:
Compact fusion
Power Plant



The divertor and boundary are long-identified show-stoppers. They are rich in science for all of fusion. We need a modest, modular, flexible, near-term test bed.

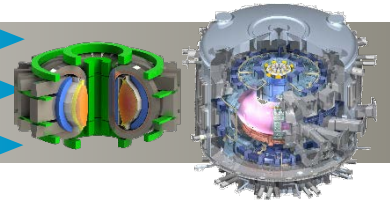
Covered in CPP White papers:
Canik –An Initiative to Establish Power Exhaust Solutions for a Compact Pilot Plant
Kuang – Construction of a Divertor Test Tokamak (US-DTT)

TODAY 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

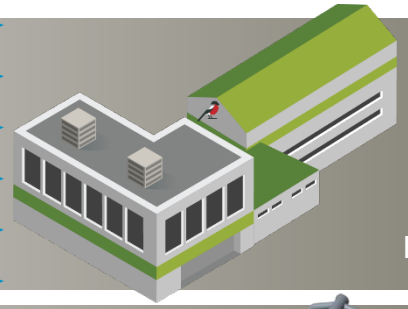
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

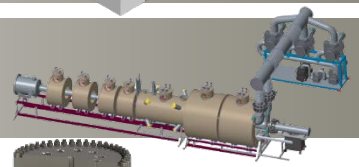
Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



FINCH

Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

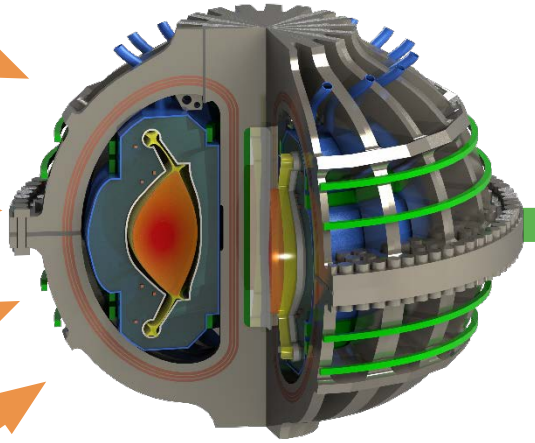
Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

ARC:
Compact fusion
Power Plant



We need the materials for the first wall qualified in long pulse to match to any plasma solution.
Do MPEX now. Do Liquid Metals on NSTX-U.

Covered in CPP White papers:
Rapp – MPEX
Youchison – Advanced PFCs
Goldston – Liquid Metal Divertor
Battaglia – NSTX-U in the 2020s

TODAY

2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

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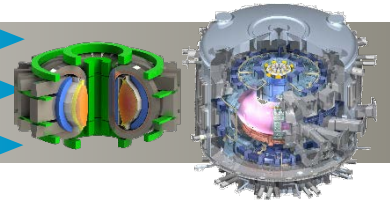

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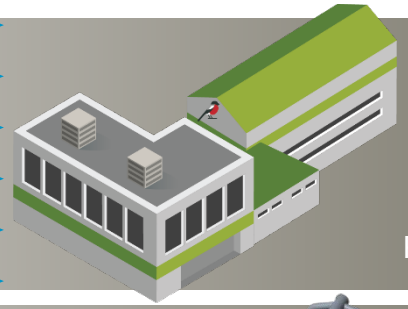

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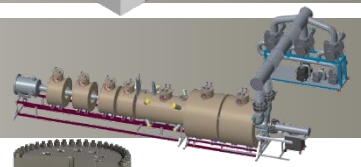

MPEX

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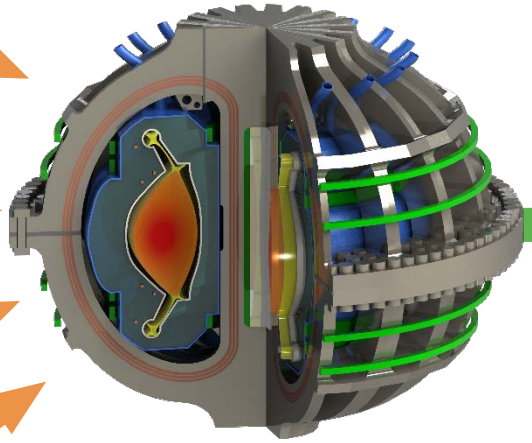
Compact fusion Power Plant



For EVERYTHING we need validated mod-sim.
Data + Simulation = design tools. FM&T, boundary, core.

Covered in many CPP White papers

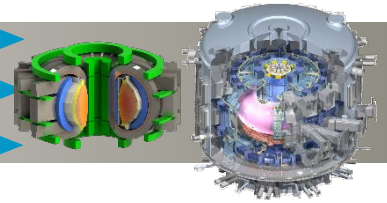
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
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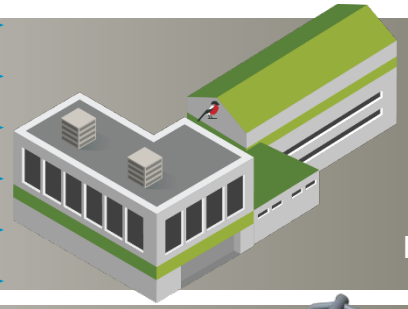

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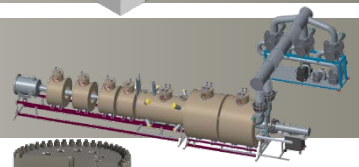

MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

Fusion power plant:

A black box that confines plasmas to get to burning conditions, captures the energy, breeds the fuel, survives long enough, designed with validated design tools, that fits a market.

This path is almost entirely architecture independent.
We don't need to decide CPP now, we need to get decision quality data now.

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
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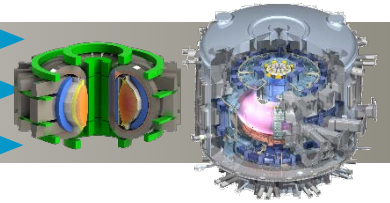

SPARC+
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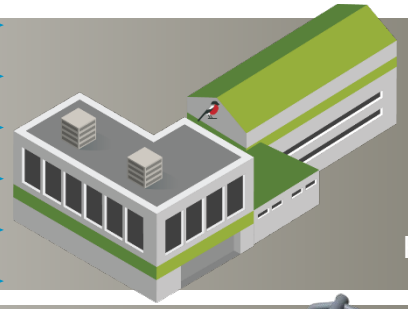

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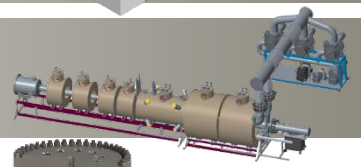

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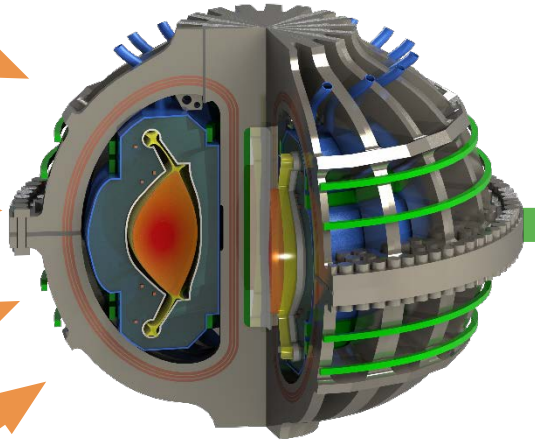


Covered in CPP White paper:
CFS – CFS and the Path to Fusion Energy

We will need all the same things to do a high-field tokamak.
We don't need to decide CPP now, we need to get decision quality data now.

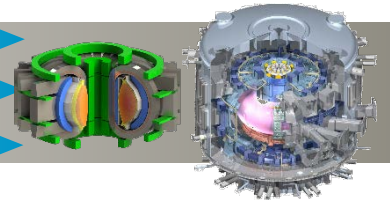
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
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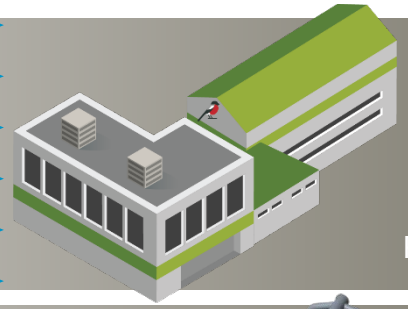

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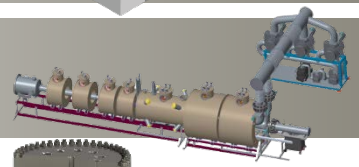

MPEX

Fusion-qualified first wall materials

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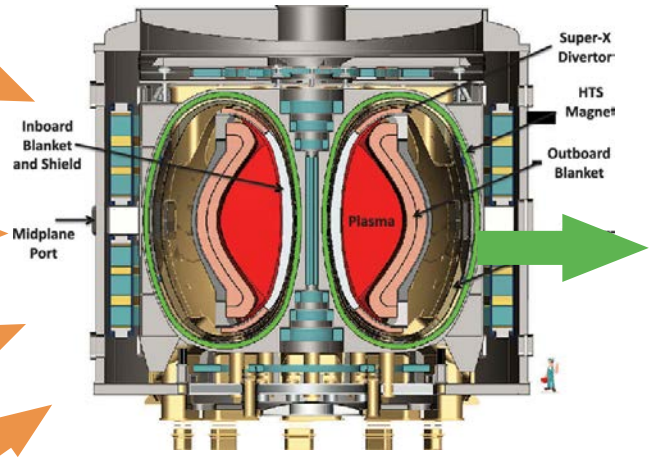
US-DTT

Fusion-qualified plasma exhaust scenarios

ST-based Compact Fusion Power Plant



Covered in CPP White paper:
Battaglia – NSTX-U in the 2020s
Tokamak Energy – Plan

We will need all the same things to do an ST. We'll also have NSTX-U, MAST-U, ST-40.
We don't need to decide now, we need to get decision quality data now.

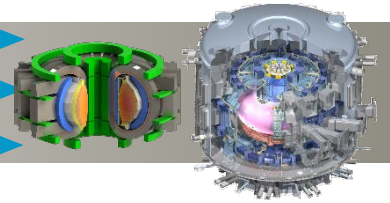
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

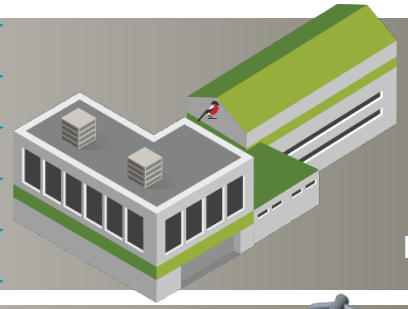
Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



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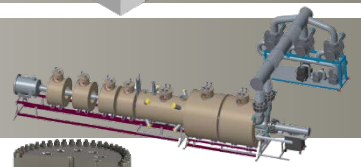

MPEX

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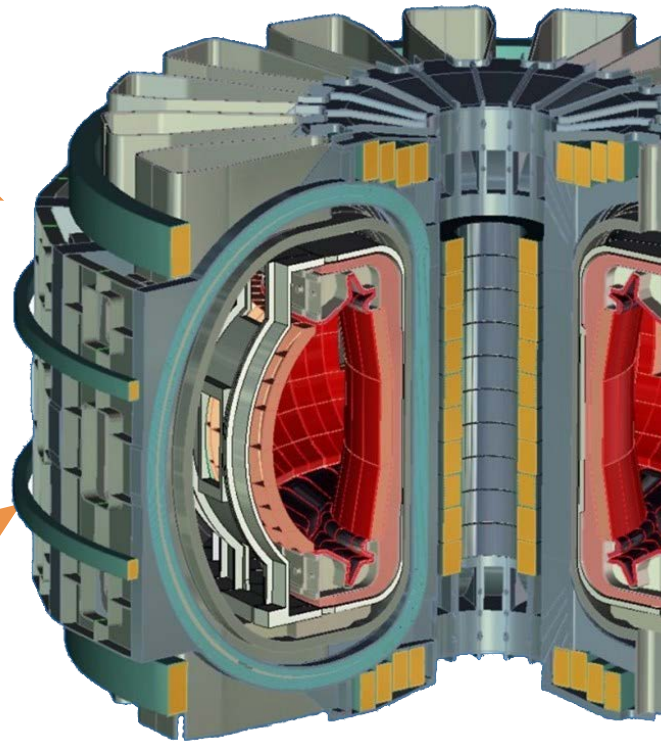
US-DTT

Fusion-qualified plasma exhaust scenarios

ITER-based
Not- Compact
Fusion Power
Plant



We'll need all the same things if we wait for ITER and then do EU-DEMO-like plants.
We don't need to decide now, we need to get decision quality data now.

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

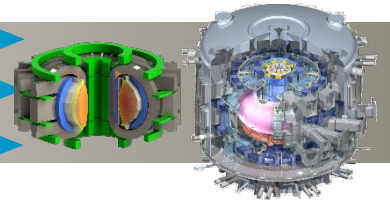
US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR

Confinement Physics

Fast particles — NSTX-U

HTS magnet development



SPARC+
ITER

Burning-plasma physics

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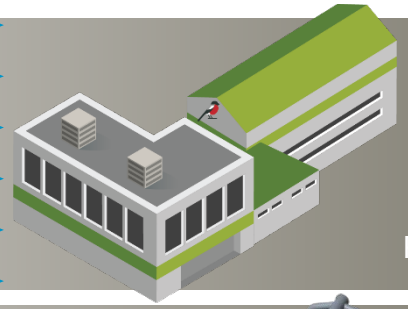
Tritium extraction technologies

Materials characterization tools — LAMBDA

Fusion Prototypical Neutron Source

Fusion-relevant materials program



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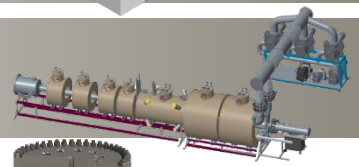


MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

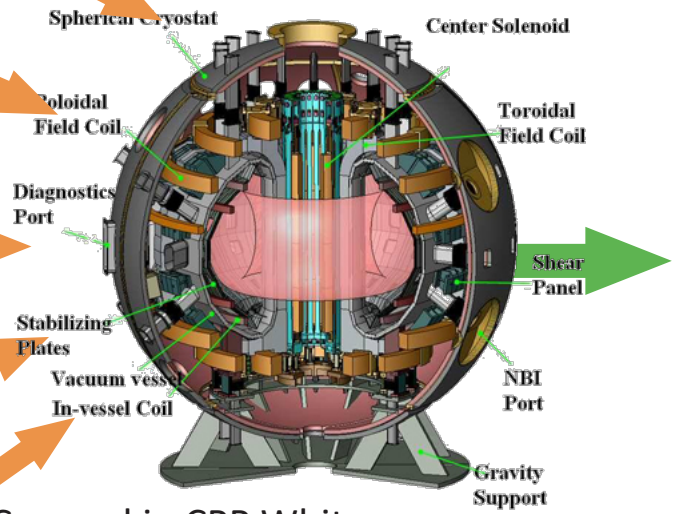
Liquid metals — NSTX-U

US-DTT

Fusion-qualified plasma exhaust scenarios

AT option

AT-based Compact Fusion Power Plant



Covered in CPP White paper:
Knolker – Initiate Collaboration with QST on new Japanese tokamak JT60SA

We'll need all the same things if we do AT. And we'll have JT-60SA + DIII-D results.
We don't need to decide now, we need to get decision quality data now.

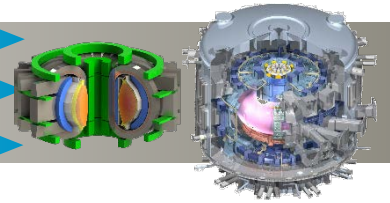
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

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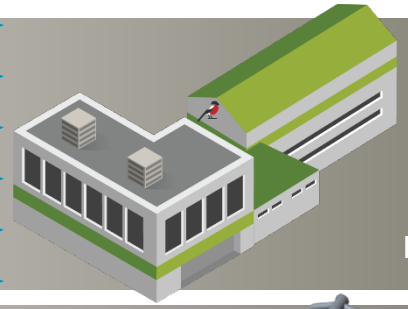

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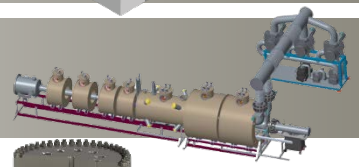

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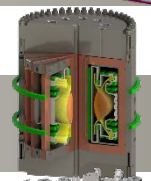
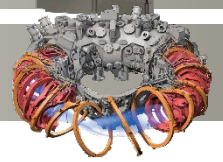


US-DTT

Fusion-qualified plasma exhaust scenarios

Stellarator optimization — W7-X, LHD

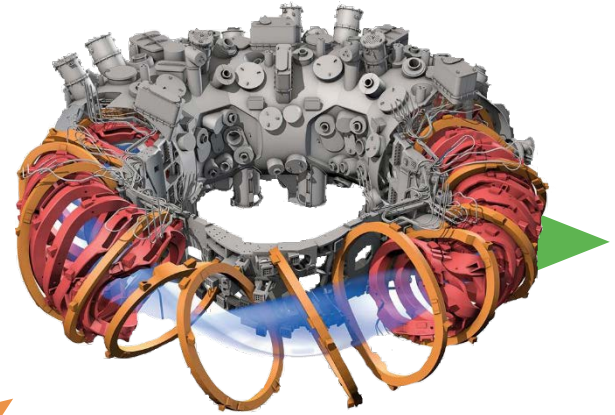


Mid-scale
STELLARATOR

Inherently steady-state fusion system

High-Q stellarator

Stellarator-Based Compact Fusion Power Plant



Covered in CPP White paper:
Schmitz – [Overview of and Reasoning for a Stellarator Strategic Block in the U.S. Fusion Program]

TODAY

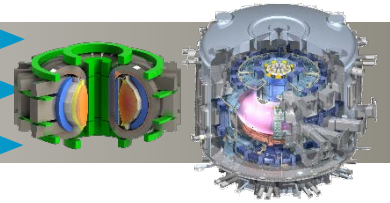
We'll need all the same things if we do a Stellarator. And should do a mid-scale one.
We don't need to decide now, we need to get decision quality data now.

ROADMAP TO FUSION ENERGY

Covered in CPP White paper:
Sutherland – The need for a diverse fusion energy research and development portfolio for the pursuit of economically competitive fusion power

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

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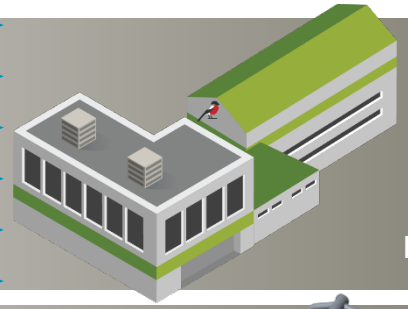

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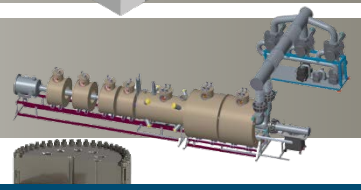
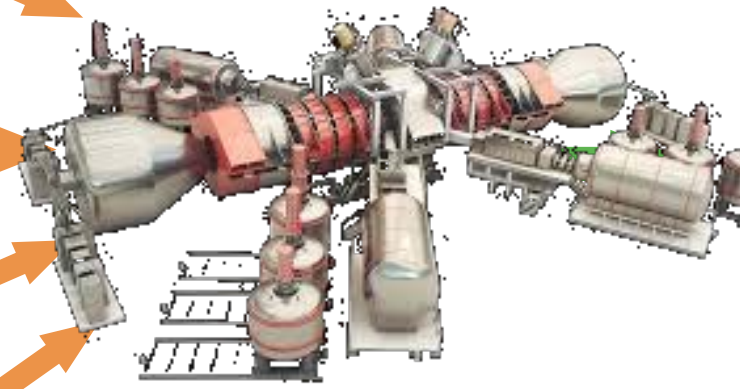


MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

FRC-based Compact Fusion Power Plant



We'll need all the same things if we do a an alternate. Let's keep seeding this area. We don't need to decide now, we need to get decision quality data now.

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

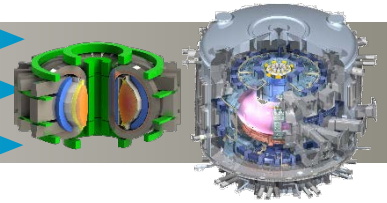
Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

US FUSION PROGRAM

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



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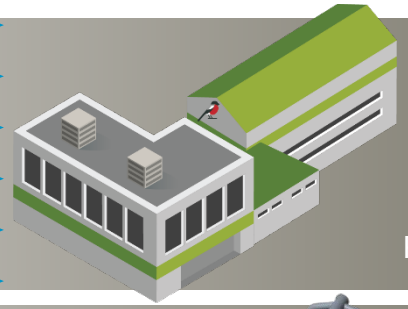

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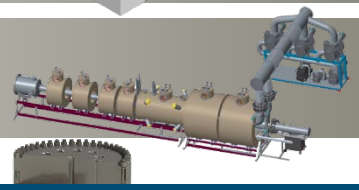

MPEX

Fusion-qualified first wall materials

Boundary simulation and collaborations

MIF- based Compact Fusion Power Plant

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Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

ROADMAP TO FUSION ENERGY

Covered in CPP White papers for HEDP

US FUSION PROGRAM

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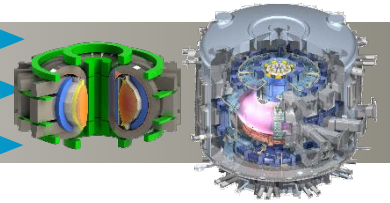
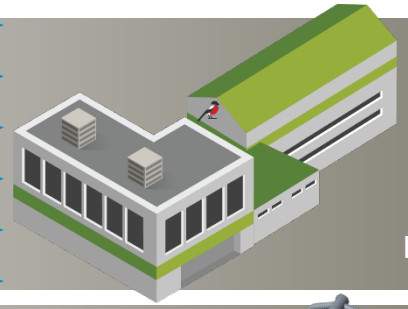
Fast particles — NSTX-U
HTS magnet development



SPARC+
ITER

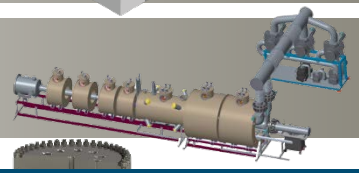
Burning-plasma physics

Volumetric neutron source development
Blanket test stands
Tritium extraction technologies
Materials characterization tools — LAMBDA
Fusion Prototypical Neutron Source
Fusion-relevant materials program



FINCH

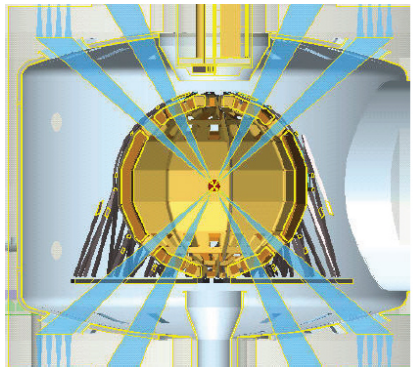
Nuclear qualified components, materials, and systems, minus the burning plasma



MPEX

Fusion-qualified first wall materials

ICF- based Compact Fusion Power Plant



We'll need most of the same things if we do ICF.
We don't need to decide CPP now, we need to get decision quality data now.

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation — Full device modeling — Validation

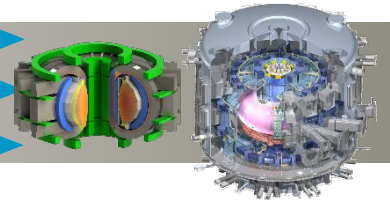
TODAY — 2025+ — 2030+

A ROADMAP TO FUSION ENERGY THAT CFS WOULD SUPPORT

US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR → AT option

Confinement Physics
Fast particles — NSTX-U
HTS magnet development



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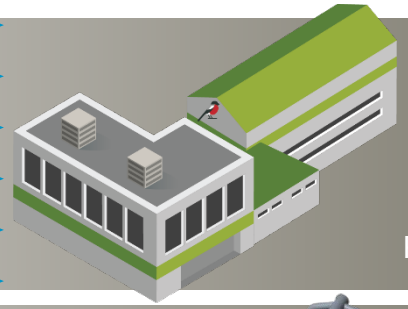

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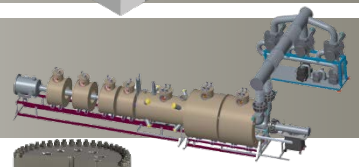
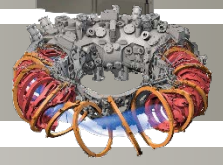


MPEX → Fusion-qualified first wall materials

Boundary simulation and collaborations
Liquid metals — NSTX-U

US-DTT → Fusion-qualified plasma exhaust scenarios

Stellarator optimization — W7-X, LHD



Mid-scale STELLARATOR → Inherently steady-state fusion system → High-Q stellarator

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation → Full device modeling → Validation

TODAY → 2025+ → 2030+

Covered in CPP White paper:
CFS and SPARC – A Comprehensive US Research Program to Accelerate the Path to Commercial Fusion Energy

We support a program that supports as broadly as possible fusion concepts in a flexible manner.

Put options on the table, don't focus on down-selecting.

ROADMAP TO FUSION ENERGY

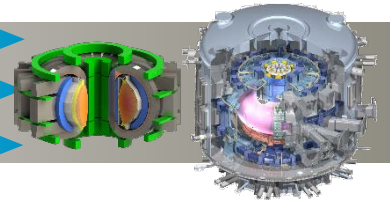
US FUSION PROGRAM

Advance tokamak — DIII-D, JT-60SA, EAST, KSTAR

Confinement Physics

Fast particles — NSTX-U

HTS magnet development



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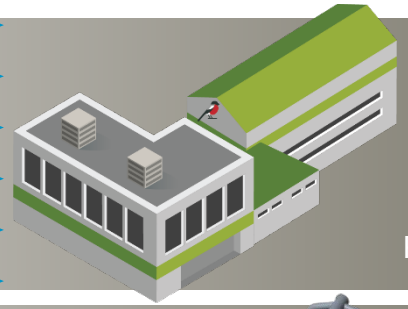

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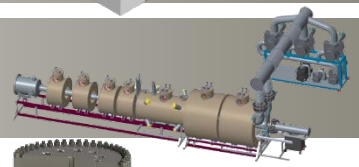

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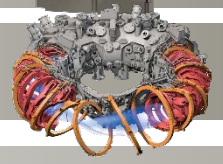


Mid-scale
STELLARATOR

Inherently steady-state fusion system

Innovative concepts — Z-pinch, FRC, Spheromak, RFP

Modeling and Simulation — Full device modeling — Validation

TODAY — 2025+ — 2030+

The important thing is that we start NOW.

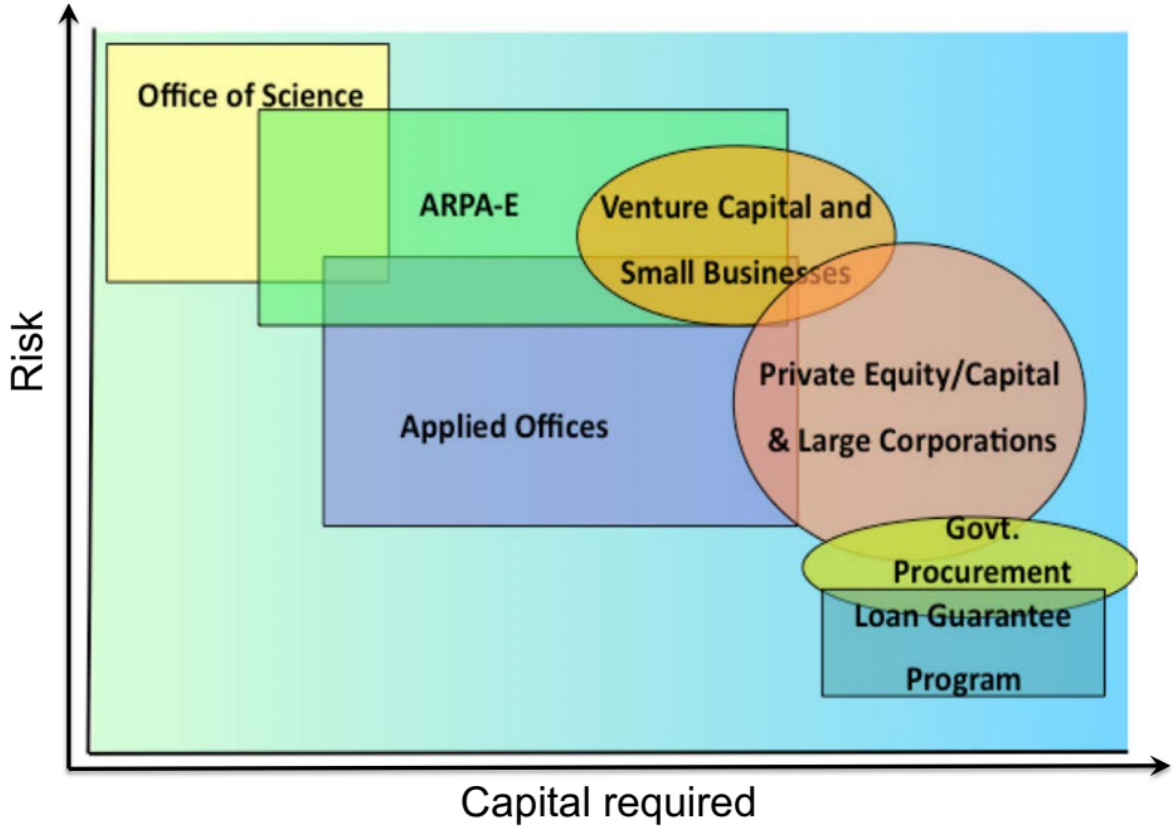
If we wait and don't do the early things then we will lose.

It would be a travesty for somebody to have a concept that works and have fusion stall because we, the APS CPP, *CHOSE* not to prioritize the parts that help everybody.

Waiting is a CHOICE.

In modern tech transfer, the partnerships form a ladder

For energy technologies to have commercial impact, must understand downstream processes and create market pull



Must demonstrate both technical and economic performance before risk is reduced sufficiently for large-scale investments.

Private sector sharpens the thinking on downstream processes and needs, and must have increasing stake/responsibility as development progresses.

Fusion clearly challenges the established DOE commercialization pathway.

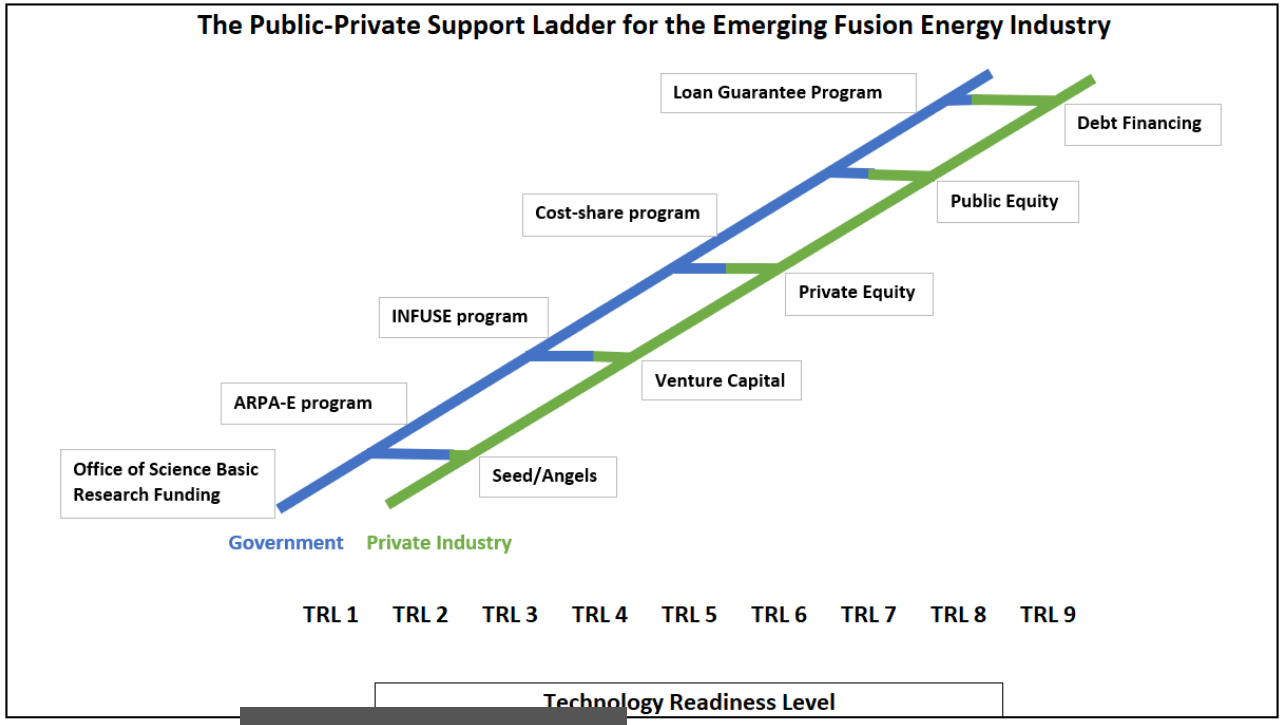
arpa·e CHANGING WHAT'S POSSIBLE

Figure and some content on this slide adapted from former ARPA-E director A. Majumdar's testimony to the U.S. House Committee on Science and Technology, 2010.

3

A ladder for gov’t and industry to climb together

- The US is very good at industry –academia – government
- There are many relevant precedents, look to commercial space for example
- We need to build a ladder that builds up capabilities
- A vibrant fusion ecosystem supports all of fusion



Fusion Science and Technology

Fusion Energy Development

Fusion Energy Industry

- NASA COTS: From Shuttle to SpaceX

Diversifying the funding and partnerships

INFUSE Innovation Network for Fusion Energy

4 INFUSE grants in 2019

1. BNL: HTS cable quench
2. ORNL: Divertor materials tests
3. LLNL: Divertor plasma siumlations
4. PPPL: Alpha particle simulations

SBIR

Applying to SBIRs to support spin-out R&D

arpa·e

FOA: BETHE (Breakthroughs Enabling Thermonuclear-Fusion Energy) submitting applications

COTS

COTS-like (Commercial Orbital Transportation Services) cost share working way through Congress, potential to support SPARC and collaborations

Summary:
Q: Is fusion relevant to the climate crises?
A: Yes

- Fusion commercialization is a good sign of a healthy and growing field
- Lots of exciting research and applications going on in the companies
- Lots of opportunities for growth and ways to work together
- Success looks like a growing field with more innovation, more people paying attention, producing a product that can fit in an eventual market

Questions