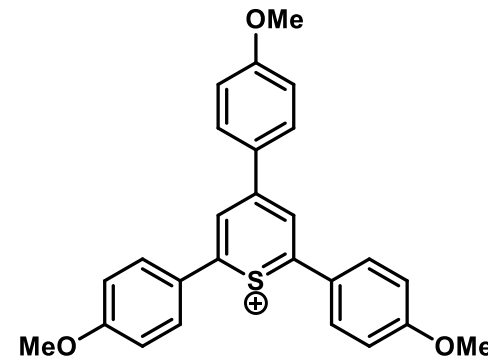
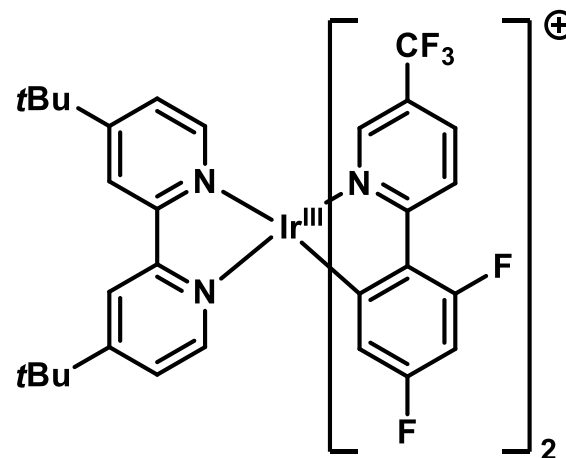
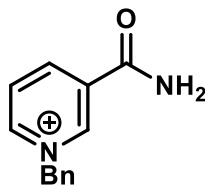


The basic principles of Photoredox Catalysis



Moritz Ottenbruch
AG seminar, 07.09.2022



Introduction – history and background

What is (visible light) photoredox catalysis?

„Photoredox catalysis implies a catalysis system that can accelerate redox reactions by electron transfer between a photocatalyst and an organic substrate, driven by light.”

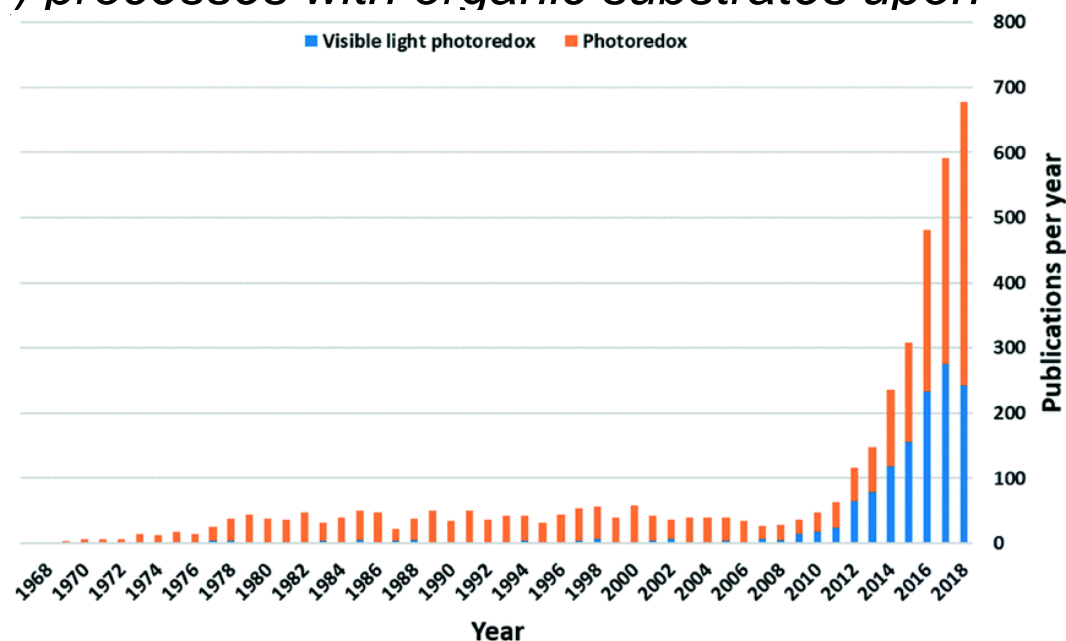
M. Grätzel, 1982.

„In a general sense, this approach relies on the ability of metal complexes and organic dyes to engage in single-electron-transfer (SET) processes with organic substrates upon photoexcitation with visible light.”

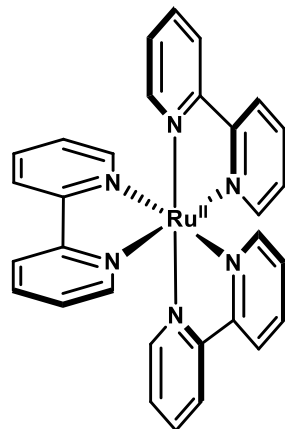
D. W. C. MacMillan, 2013.

Huge increase of reports since 2007 →

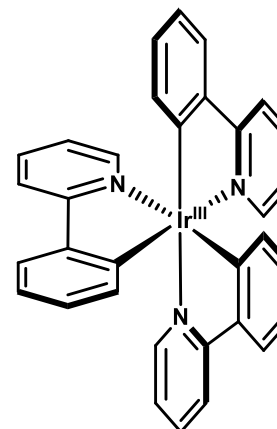
J. Kiwi, K. Kalyanasundaram, M. Grätzel, *Solar Energy Materials*, Springer Berlin Heidelberg, **1982**, 37 – 125;
B. M. Hockin, C. Li, N. Robertson, E. Zysman-Colman, *Catal. Sci. Technol.* **2019**, 9, 889 – 915;
C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, 113, 5322 – 5365.



Introduction – catalysts and properties



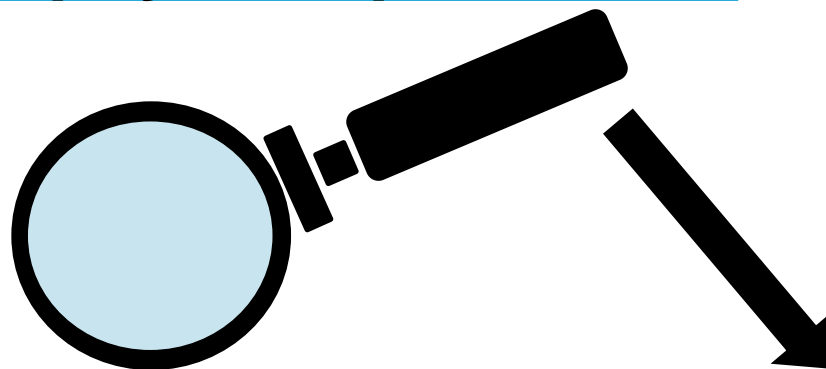
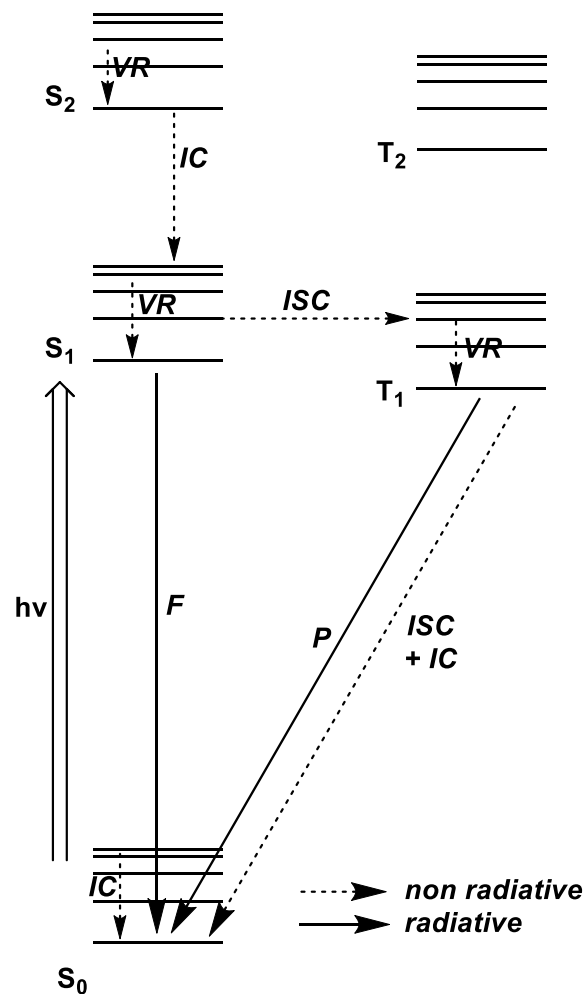
Ru(bpy)₃²⁺



Ir(ppy)₃

- Absorption at 452 nm
 - Stable, long-lived excited state ($\tau = 1100$ ns)
 - 55.2 € / 250 mg (Sigma, chloride & hexahydrate)
- Absorption at 425 nm
 - Stable, long-lived excited state ($\tau = 1900$ ns)
 - 339€ / 250 mg (Sigma)

Introduction – photophysical processes

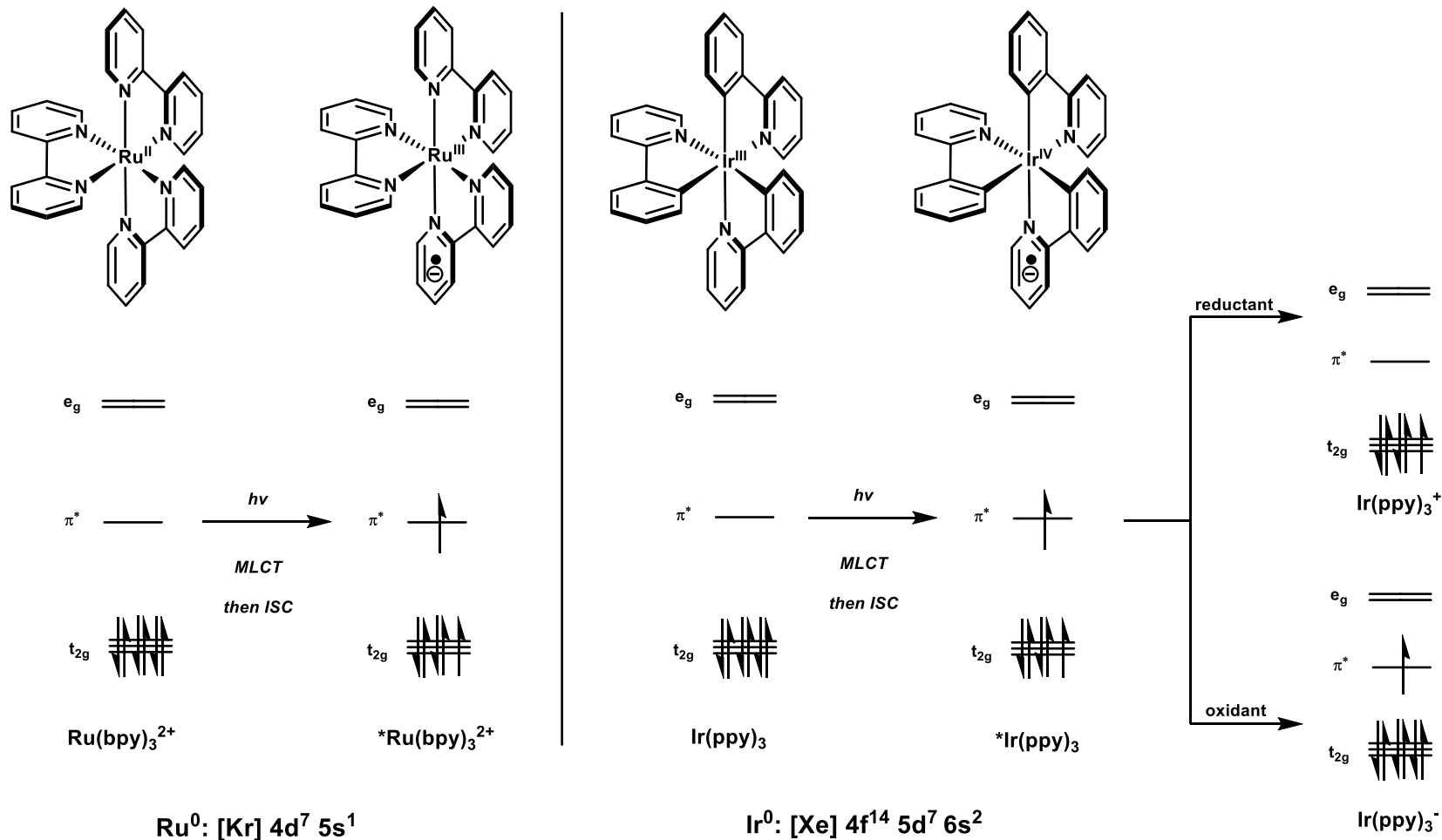


F - fluorescence *IC* - internal conversion
P - phosphorescence *ISC* - intersystem crossing

N. A. Romero, D. A. Nicewicz, *Chem. Rev.* **2016**, *116*, 10075 – 10166;
C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, *113*, 5322 – 5365.

Introduction – catalysts and properties

→ why are ruthenium and iridium based catalysts so common?

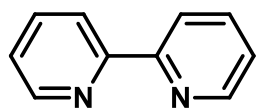


J. Twilton, C. C. Le, P. Zhang, M. H. Shaw, R. W. Evans, D. W. C. MacMillan, *Nat. Rev. Chem.* **2017**, 1, 1 – 19; C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, 113, 5322 – 5365.

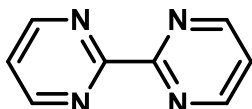
Introduction – catalysts and properties

entry	photocatalyst	$E_{1/2}$ (M^+/M^*)	$E_{1/2}$ (M^*/M^-)	$E_{1/2}$ (M^+/M)	$E_{1/2}$ (M/M^-)	τ [ns]	Excitation λ_{\max} [nm]	Emission λ_{\max} [nm]
1	$\text{Ru}(\text{bpm})_3^{2+}$	-0.21	+0.99	+1.69	-0.91	131	454	639
2	$\text{Ru}(\text{bpz})_3^{2+}$	-0.26	+1.45	+1.86	-0.80	740	443	591
3	$\text{Ru}(\text{bpy})_3^{2+}$	-0.81	+0.77	+1.29	-1.33	1100	452	615
4	$\text{Ru}(\text{phen})_3^{2+}$	-0.87	+0.82	+1.26	-1.36	500	422	610
5	$\text{Ir}[\text{dF}(\text{CF}_3)\text{ppy}]_2(\text{dtbbpy})$	-0.89	+1.21	+1.69	-1.37	2300	380	470
6	$\text{Ir}(\text{ppy})_2(\text{dtbbpy})^+$	-0.96	+0.77	+1.21	-1.51	557	-	581
7	<i>fac</i> - $\text{Ir}(\text{ppy})_3$	-1.73	+0.31	+0.77	-2.19	1900	375	494

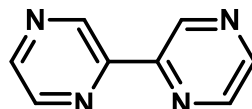
least to most reducing ex. complex
 → check $E_{1/2}$ (M^+/M^*)



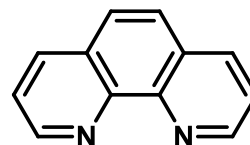
bpy



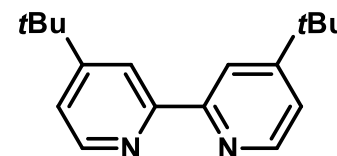
bpm



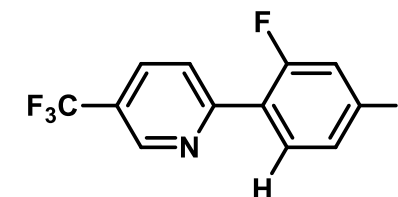
bpz



phen



dtbbpy

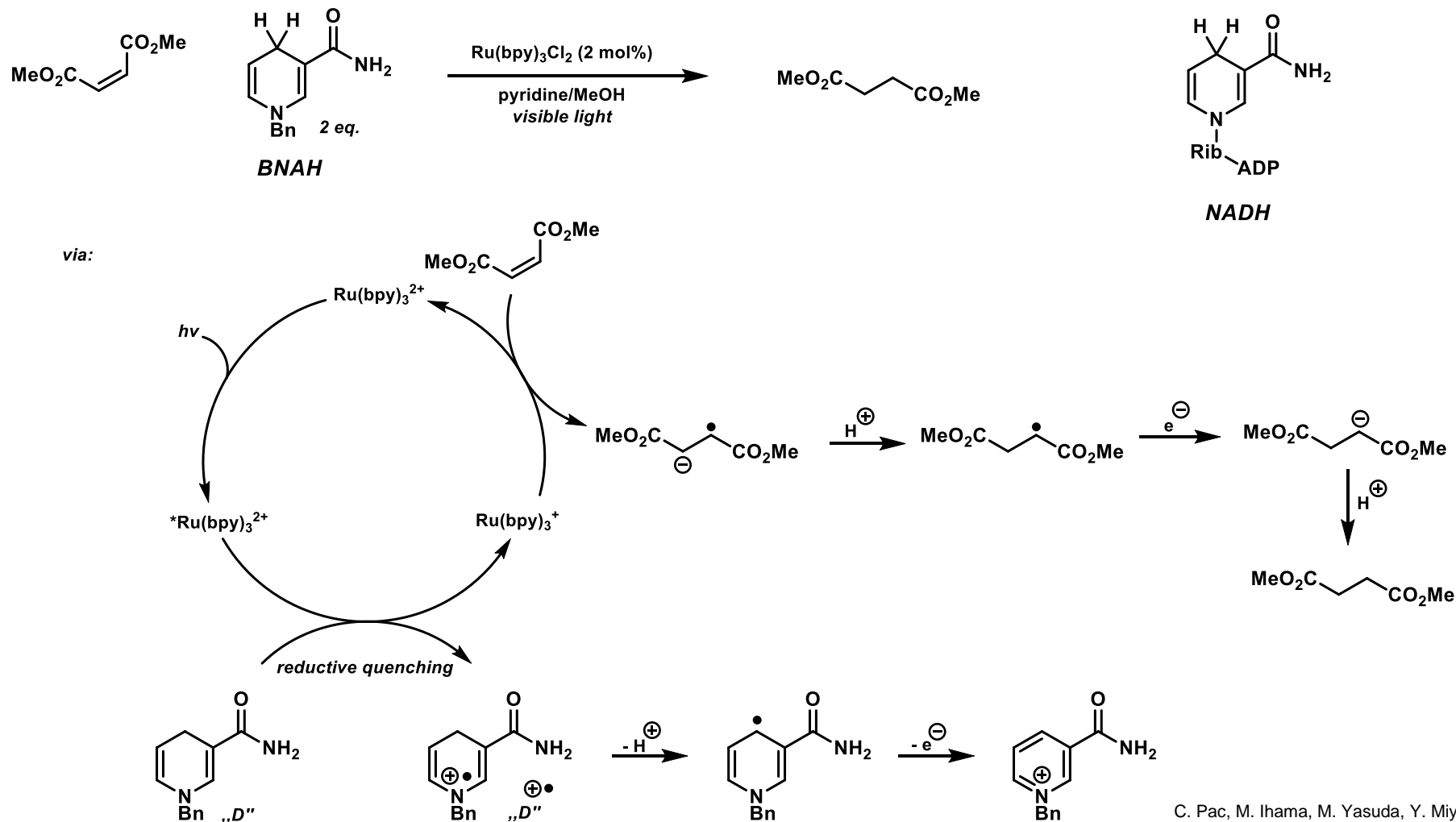


dF(CF₃)ppy-H

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.* **2013**, *113*, 5322 – 5365.

Reactivity determination

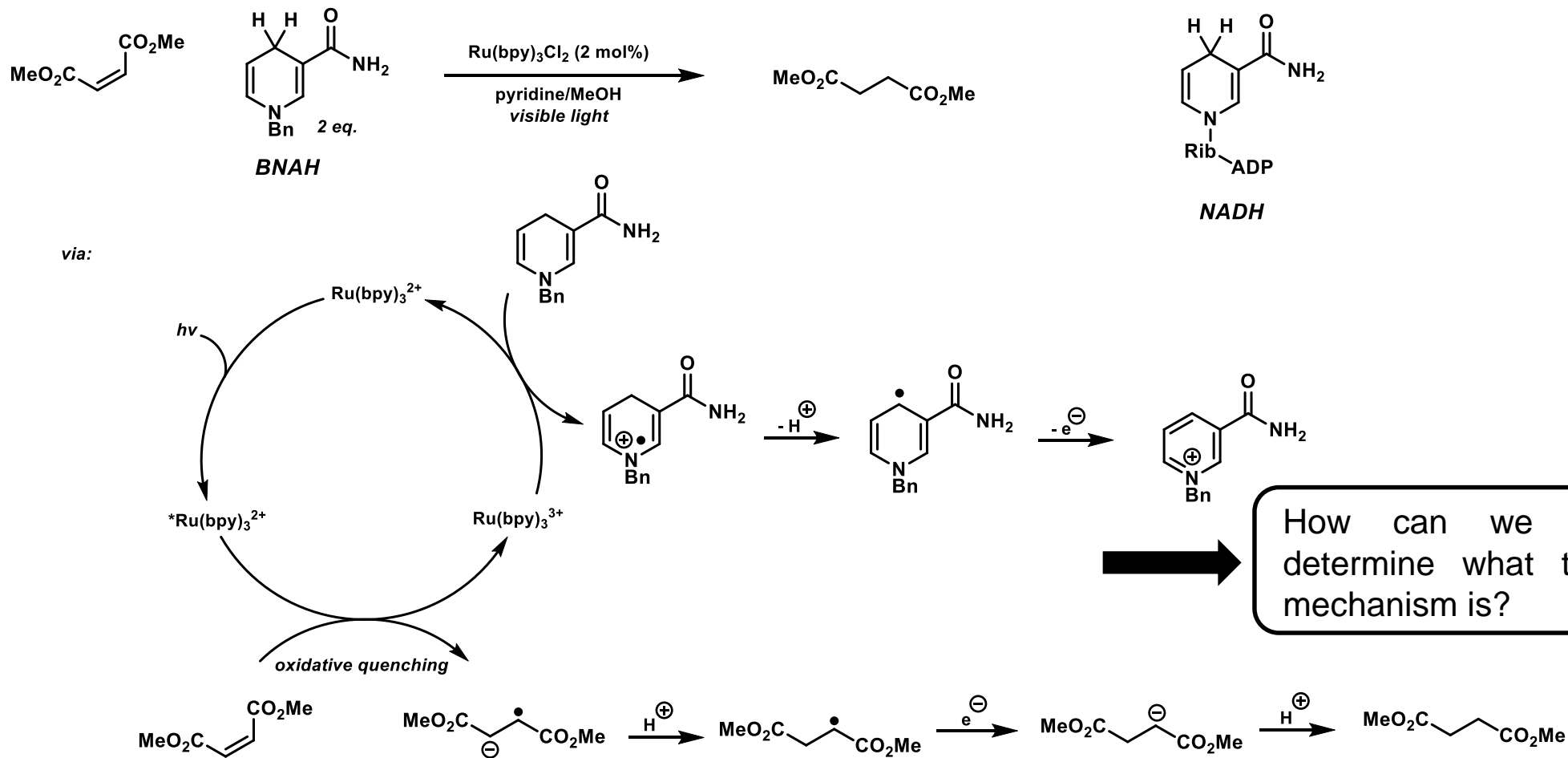
- „simple“ reduction of an electron poor olefin



C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.* **1981**, *103*, 6495 – 6497.

Reactivity determination

- „simple“ reduction of an electron poor olefin



Reactivity determination

- **Stern-Volmer relationship**

→ allows the description of the kinetics of a photophysical inter(!)molecular deactivation process

→ correlation between quantum yield/intensity of luminescence and the concentration of quenchers

- $\frac{I^0}{I} = 1 + K_{SV} \times [Q]$ or $\frac{I^0}{I} - 1 = K_{SV} \times [Q]$

- I^0 = luminescence intensity in absence of the quencher

- I = luminescence intensity in presence of the quencher

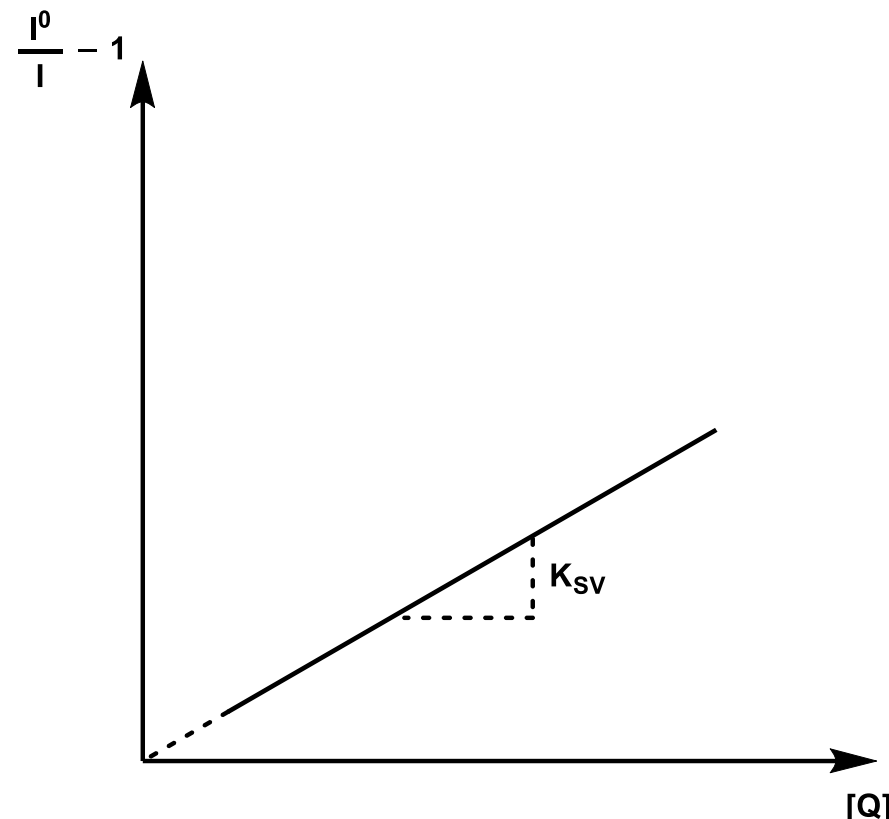
- $[Q]$ = concentration of the quencher

- K_{SV} = Stern-Volmer constant



bigger K_{SV} → more efficient quenching process

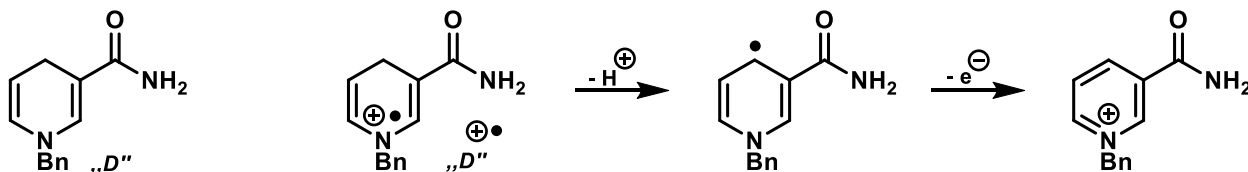
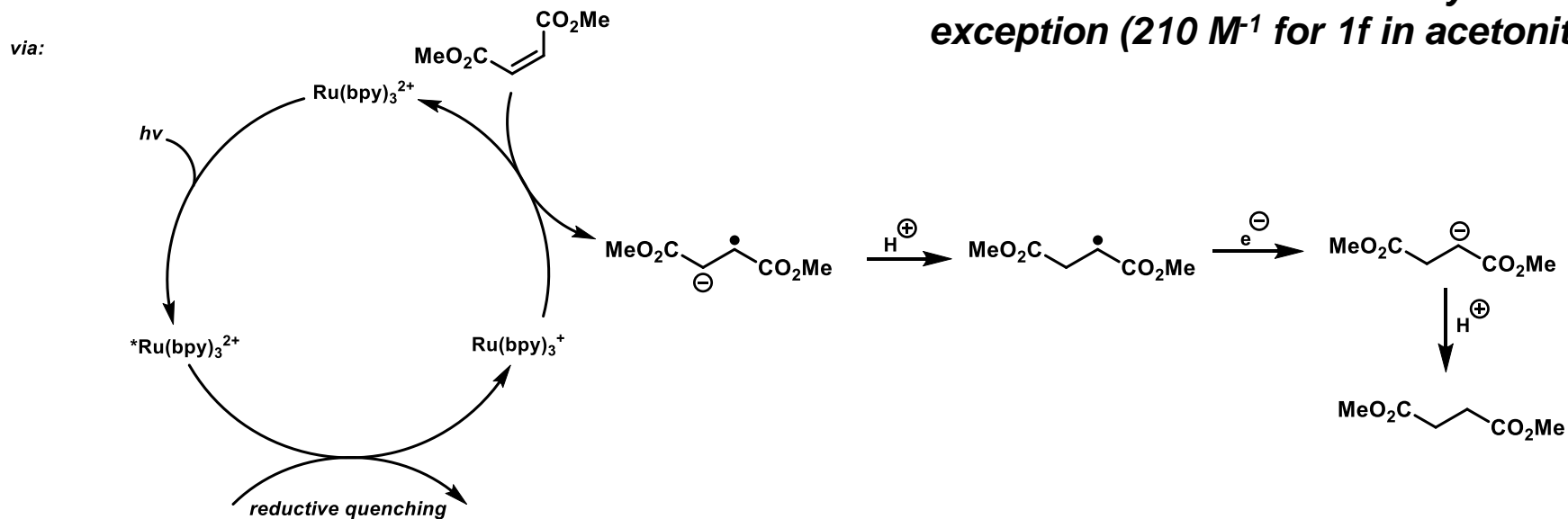
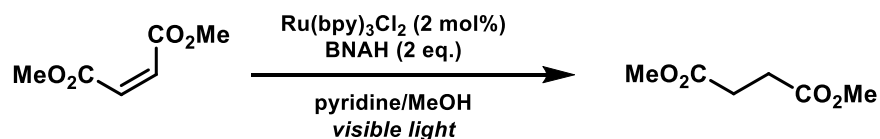
→ K_{SV} is a parameter for the „availability” of the lumophore for the quencher.



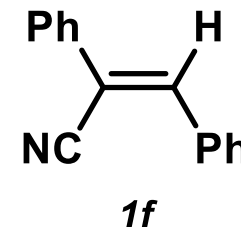
O. Stern, M. Volmer, *Physikalische Zeitschrift* 1919, 20, 183 – 188.

Reactivity determination

- „simple“ reduction of an electron poor olefin



„It was found that the luminescence of Ru(bpy)_3^{2+} was efficiently quenched by BNAH but not by the olefins except **1f**. The Stern-Volmer constants ($K_q\tau$) for the phosphorescence quenching by BNAH under deaerated conditions are 358 (10:1 pyridine-methanol), 294 (acetonitrile), 184 (DMF), and 120 M^{-1} (methanol), while the values for the quenching by the olefins are less than 5 M^{-1} in any solvent with one exception (210 M^{-1} for **1f** in acetonitrile).”



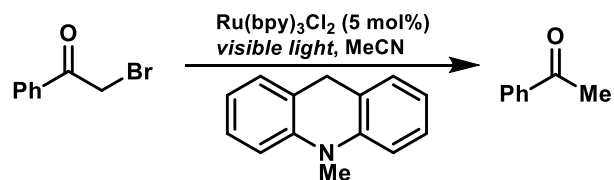
C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.* **1981**, *103*, 6495 – 6497.

Reactivity examples

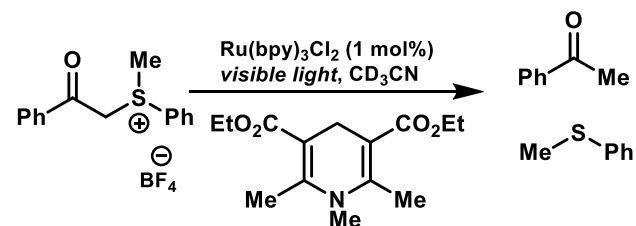
I. Net reductive reactions

→ reduction of substrates using photoredox catalysis *via* a stoichiometric reducing agent

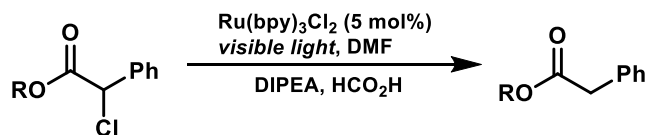
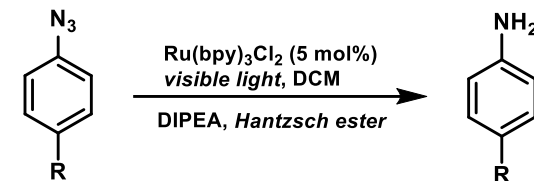
▪ Reductive dehalogenation



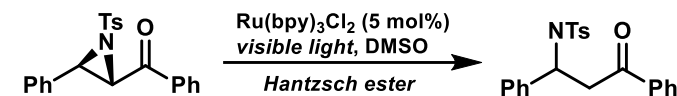
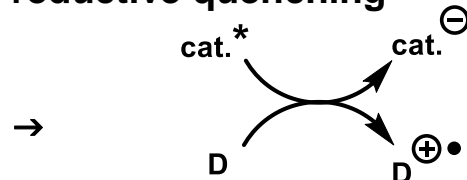
▪ Reduction of sulfur motifs



▪ Reduction of nitrogen motifs



Most of these reactions proceed *via* reductive quenching



S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Phy. Chem.* **1990**, *94*, 722 – 726;
J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *J. Am. Chem. Soc.* **2009**, *131*, 8756 – 8757.

D. M. Hedstrand, W. M. Kruizinga, R. M. Kellogg, *Tetrahedron Lett* **1978**, *19*, 1255 – 1258;
T. J. van Bergen, D. M. Hedstrand, W. H. Kruizinga, R. M. Kellogg, *J. Org. Chem.* **1979**, *44*, 4953 – 4962.

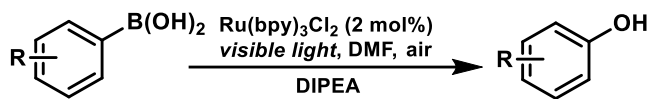
Y. Chen, A. S. Kamlet, J. B. Steinman, D. R. Liu, *Nat. Chem.* **2011**, *3*, 146 – 153;
M.-H. Larraufie, R. Pellet, L. Fensterbank, J.-P. Goddard, E. Lacôte, M. Malacria, C. Ollivier, *Angew. Chem. Int. Ed.* **2011**, *50*, 4463 – 4466.

Reactivity examples

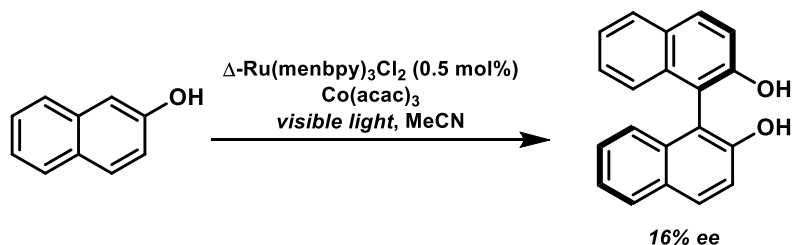
II. Net oxidative reactions

→ oxidation of substrates using photoredox catalysis *via* a stoichiometric oxidizing agent

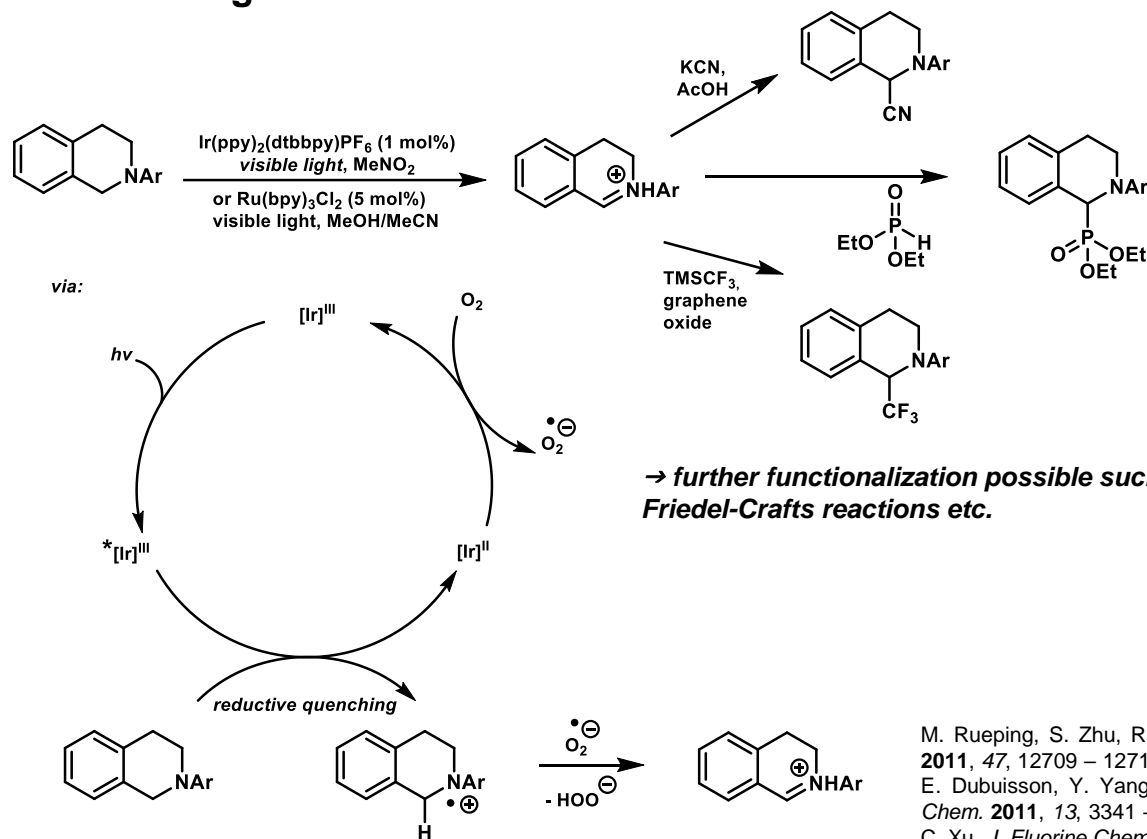
- oxidative hydroxylation of aryl boronic acids



- oxidative biaryl coupling



- oxidative generation of iminium ions



Y.-Q. Zou, J.-R. Chen, X.-P. Liu, L.-Q. Lu, R. L. Davis, K. A. Jorgensen, W.-J. Xiao, *Angew. Chem. Int. Ed.* **2012**, *51*, 784 – 788;
 T. Hamada, H. Ishida, S. Usui, Y. Watanabe, K. Tsumura, K. J. Ohkubo, *J. Chem. Soc., Chem. Commun.* **1993**, 909 – 915; H. Ishida, S. Usui, K. Tsumura, K. J. Ohkubo, *J. Mol. Catal.* **1994**, *88*, L1.

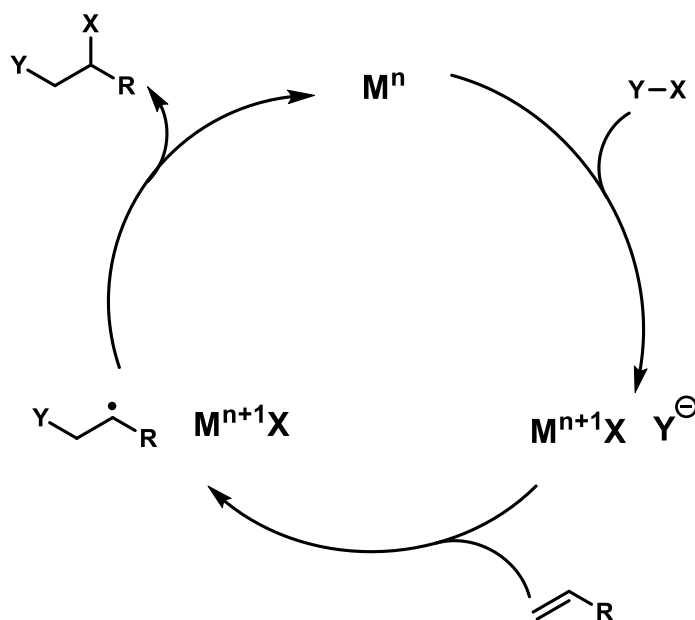
M. Rueping, S. Zhu, R. M. Koenigs, *Chem. Commun.* **2011**, *47*, 12709 – 12711; Y. Pan, S. Wang, C. W. Kee, E. Dubuisson, Y. Yang, K. P. Loh, C.-H. Tan, *Green Chem.* **2011**, *13*, 3341 – 3344; W. Fu, W. Guo, G. Zou, C. Xu, *J. Fluorine Chem.* **2012**, *140*, 88 – 94.

Reactivity examples

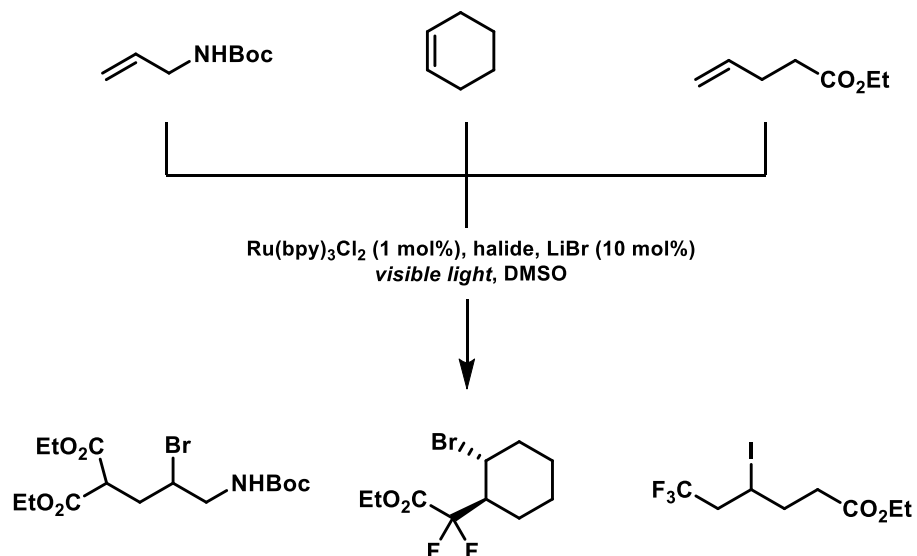
III. redoxneutral reactions

- Atom Transfer Radical Addition (ATRA) cycle

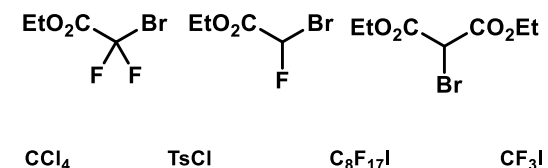
general approach



- olefin functionalization



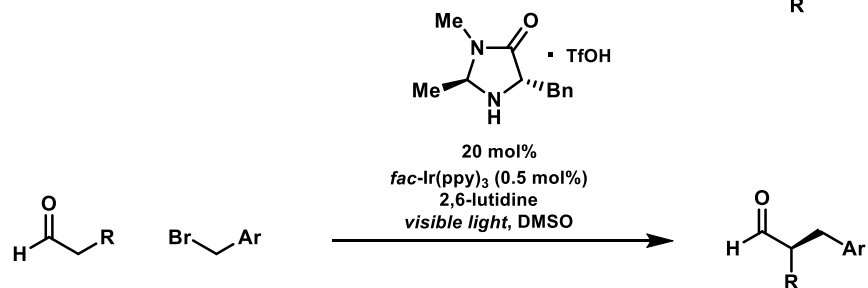
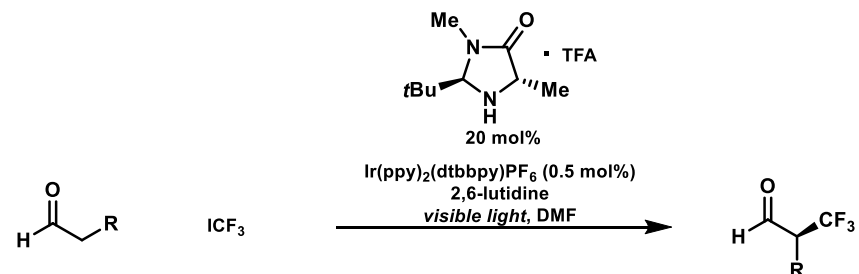
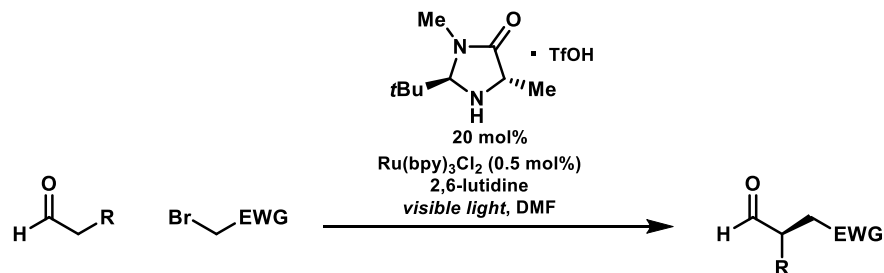
potential halides



Reactivity examples

IV. enantioselective photoredox catalysis

via chiral enamine addition

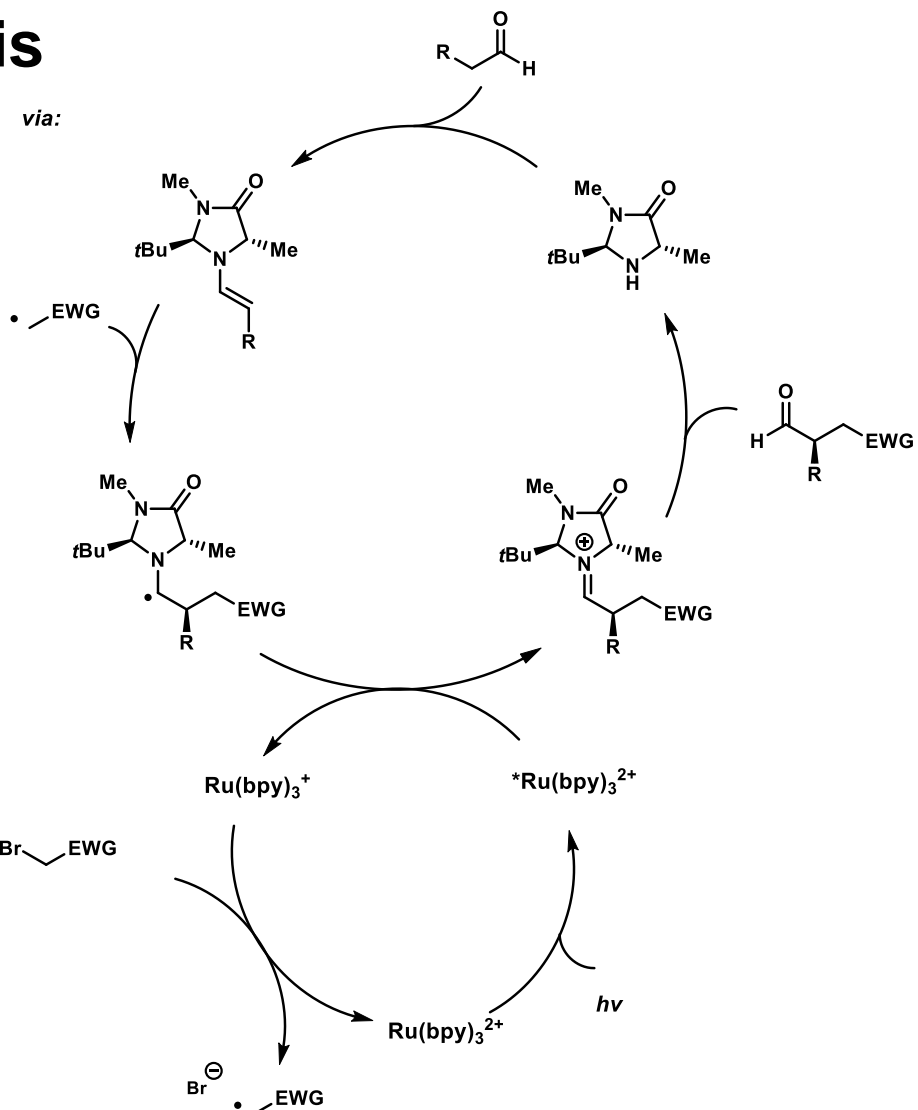


D. A. Nicewicz, D. W. C. MacMillan, *Science* **2008**, 322, 77 – 80;

D. W. C. MacMillan, *Nature* **2008**, 455, 304 – 308;

D. A. Nagib, M. E. Scott, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2009**, 131, 10875 – 10877;

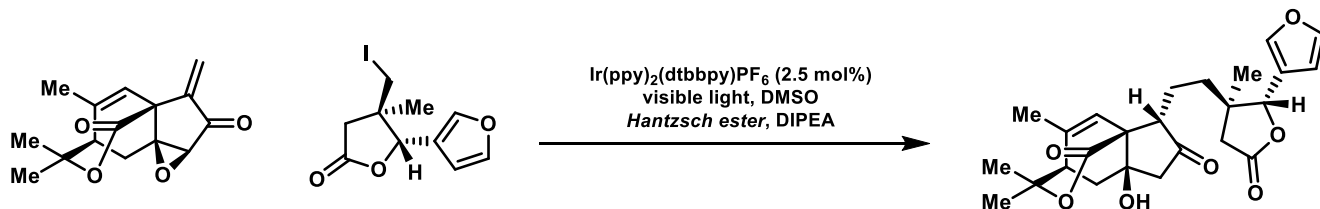
H–W. Shih, M. N. Vander Wal, R. L. Grange, D. W. C. MacMillan, *J. Am. Chem. Soc.* **2010**, 132, 13600 – 13610.



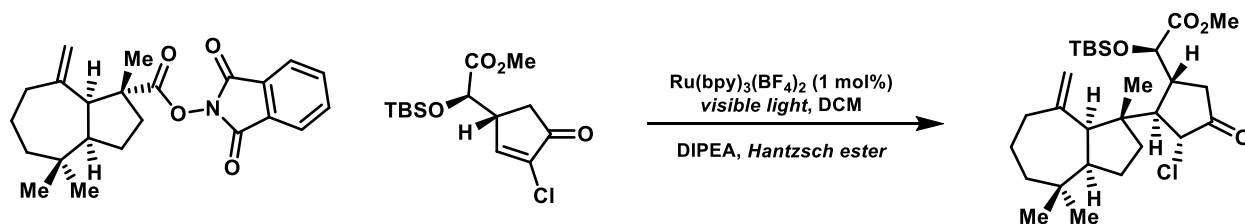
Reactivity examples

V. applications of photoredox catalysis in total synthesis

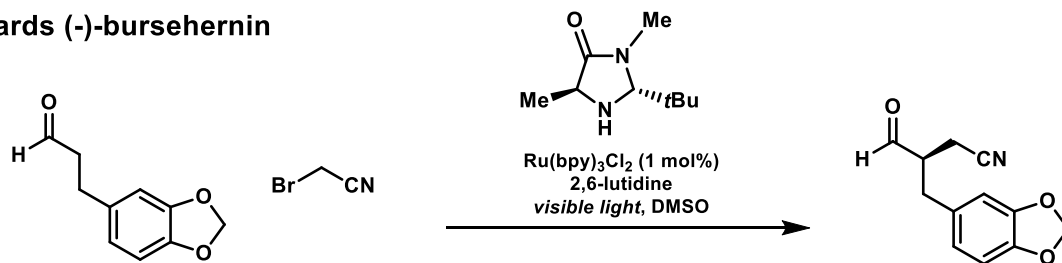
towards (+)-haperforin G



towards (-)-aplyviolene



towards (-)-bursehernin



S. P. Pitre, L. E. Overman, *Chem Rev.* **2022**, *122*, 1717 – 1751;

W. Zhang, Z. Zhang, J. C. Tang, J. T. Che, H. Y. Zhang, J. H. Chen, Z. Yang, *J. Am. Chem. Soc.* **2020**, *142*, 19487 – 19492;

M. J. Schnermann, L. E. Overman, *Angew. Chem. Int. Ed.* **2012**, *51*, 9576 – 9580;

E. R. Wein, A. A. Warkentin, J. C. Conrad, D. W. MacMillan, *Angew. Chem. Int. Ed.* **2015**, *54*, 9668 – 9672.